Improving Design Guidance for In-Stream Structures Used in Stream Restoration

Elizabeth Louise Hickman

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Theresa M. Thompson; Chair.
William C. Hession; Member.
Kyle B. Strom; Member.

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ABSTRACT

Vane-type in-stream structures and step pool storm conveyance (SPSC) are more ecologically friendly alternatives to traditional stream channel stabilization and stormwater conveyance techniques. Vane-type structures have been widely accepted as elements of stream restoration projects and are regularly implemented in streams throughout the United States. However, these structures commonly experience partial or total failures of function or stability, often due either to improper installation or misapplication. This study undertook a thorough review of the available design guidance for the single-arm vane, j-hook vane, cross vane, and w-weir, which revealed that the existing guidance is composed of non-standardized recommendations largely based on practitioner experience and rules of thumb. Existing guidance was synthesized with current structure research and practitioner surveys to create factsheets for each of the four structures and the SPSC, with the intent of improving structure application and offering concise general guidance. This study also endeavored to improve the design of the SPSC by determining the most accurate of several common prediction methods for Manning's roughness coefficient *n*, used in SPSC design velocity calculations. This was done by using Rhodamine WT dye tracer experiments to determine *n* values during storm flows in two SPSC structures in Annapolis, MD, which were then compared to predicted *n* values. Values of Manning's *n* determined in the SPSCs at low flows (0.28-12) often exceeded the predicted *n* values (-0.17-3.9) by several orders of magnitude. Though the applicability of these results is limited, an increase in design *n* to 0.1-0.2 is still recommended.

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GENERAL AUDIENCE ABSTRACT

Vane-type in-stream structures are stone or wood structures installed within a stream channel for purposes such as streambank stabilization or aquatic habitat creation. Step pool storm conveyance (SPSC) is a technique which converts an existing steep stream or gully into a step-pool channel. Both of these techniques are more ecologically friendly than many traditional stream channel stabilization or stormwater conveyance techniques such as riprap or concrete storm drains. Vane-type structures in particular have been widely accepted as elements of stream restoration projects and are regularly implemented in streams throughout the United States. However, these structures commonly experience partial or total failures, either through structural collapse or failure to function properly. This is often either because they were improperly installed or because they were installed at a stream site where they were inappropriate or unnecessary. A review of the available guidance for the design of these structures revealed that the existing guidance is composed of non-standardized and sometimes contradictory recommendations which are largely based on designer trial and error and rules of thumb, rather than on the results of scientific experiments or modeling. The goal of this study was to improve the success of vane-type in-stream structures and the SPSC by providing factsheets offering clear and concise general design guidelines and sound recommendations for structure application. Flow studies of two SPSC structures in Annapolis, MD were also conducted to improve the design of that structure by measuring its flow characteristics in the field.

Dedication

To my parents, for their unwavering love, support, and patience.

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Chapter 1: Introduction

Urban watersheds have very different patterns of stormwater runoff behavior than their agricultural or forested counterparts. The high proportion of impervious surfaces in urban systems leads to high levels of direct runoff relative to infiltration. This causes urban stormwater runoff flows to be larger, more rapid, and more variable (flashier), which can lead to dangerous flash floods that threaten infrastructure, property, and human life. In addition, urban sources of water pollution (including chemical, microbial, sediment, and temperature pollution) significantly impair the quality of stormwater runoff. Both the highly variable flows and impaired quality of urban stormwater runoff adversely affect the morphological stability and water quality of receiving streams, which, in turn, impairs the aquatic and riparian habitat and ecosystems of those streams. (National Research Council, 2008).

The historical paradigm of stormwater conveyance seeks to treat the immediate problem posed by urban stormwater runoff by safely conveying runoff flows from large, infrequent storm events into hard infrastructure such as concrete-lined ditches or storm drains. While these structures do indeed safely convey stormwater when properly designed, they also do nothing to improve stormwater runoff quality or promote infiltration, especially during smaller, more frequent storm events that regularly flush pollutants from impervious urban surfaces into receiving streams. (National Research Council, 2008). In addition, where stormwater is routed from a storm drain into a steep ephemeral stream or gully or onto a steep slope, runoff flows can cause considerable erosion, destabilizing the channel or slope, and further decrease stormwater quality through the addition of sediment. Step pool storm conveyance (SPSC) is a relatively new type of stormwater conveyance structure that is often used in conjunction with stream restoration projects. It combines elements of open channel design and urban stormwater best management practices (BMPs) into a single technique. (Flores et al., 2012).

Even as the continued construction and expansion of human cities increases the overall proportion of urban watersheds, growing population pressures have forced a widespread realization that the natural environmental resources of the planet must be properly managed to provide for future generations. As one of the most critical elements necessary for human life and the balance of the greater ecosystem, freshwater resources are at the forefront of ecological restoration efforts and scientific scrutiny. Stream restoration for ecosystem services – including aquatic habitat, water quality, and water quantity – is now a multi-billion dollar industry, yet most of the currently available design standards and specifications are still based on anecdotal rules of thumb, practitioner experience, or empirical data. This lack of scientifically rigorous design guidance is an issue both for the field of stream restoration as a whole and for the stone or wood vane-type (also called Rosgen-type) in-stream structures often used for such purposes as streambank stabilization and grade control. (Bernhardt et al., 2007; Kauffman et al., 1997; Palmer et al., 2014; Wohl et al., 2015).

Vane-type in-stream structures are made of natural materials – stone or wood – and are installed as elements of stream restoration projects for the purposes of streambank stabilization, grade control, and aquatic habitat enhancement. Common examples of vane-type structures include the single-arm vane (rock or log), j-hook vane, and cross vane. (MDE, 2000; Rosgen, 2001). Vane-type in-stream structures have been largely accepted by the stream restoration community and by environmental agencies at every level of the US government as valuable additions to the stream restoration field, in part because, not only do they assist in streambank stabilization without interfering with ecosystem services (unlike the use of riprap bank armor), they can actually create or enhance in-stream aquatic habitat (Cramer, 2012; Rosgen, 2001).

Though they bear a high cost of money, labor, and time for design and installation, up to 70% of vane-type in-stream structures may experience at least partial failures of structural stability or effective function (Gordon et al., 2016). This high failure rate is largely attributed to the lack of rigorous and standardized design guidance and methodologies. Complex, three-dimensional numerical modeling of flow around in-stream structures is expensive, and it is difficult to account for all variables during field or laboratory studies of structures. However, if current rates of structure installation are to continue, the best way to ensure future structure successes is to improve design guidance by rigorous experimentation and modeling of structure design configurations under various site conditions. (Gordon et al., 2016; Holmquist-Johnson, 2011; Johnson et al., 2002b; Radspinner et al., 2010; Sotiropoulos & Diplas, 2014; Thornton et al., 2011).

The overall goal of this study was to improve the application, design, installation, and general success of four in-stream structures commonly used in stream restoration and channel design projects – the single-arm vane, j-hook vane, cross vane, and w-weir – as well as step pool storm conveyance (SPSC) structures used for regenerative stormwater conveyance and stormwater outfall stabilization. Current engineering guidance and scientific knowledge concerning the application, design, installation, and post-installation monitoring of these structures was collected, evaluated, and synthesized. Information and recommendations were collected from three general categories: government- and academic-issued engineering guidance, peer-reviewed literature, and practitioner experience. Once evaluated and synthesized, this information was used to develop a series of factsheets intended to summarize and clarify structure definitions and general recommendations for structure application, design, installation, and post-installation monitoring. The literature synthesis and factsheet development process are detailed in Chapters 2 and 3, respectively, and the factsheets can be found in Appendix A, as well as on the publically accessible study website (https://sites.google.com/view/vtstreamstructures). The final portion of this study is detailed in Chapter 4, which describes field flow studies of two SPSC structures in Annapolis, MD. The flow studies were conducted with the intent of improving SPSC design guidance by improving prediction of the Manning's roughness coefficient, *n*, during design calculations.

Chapter 2: Literature Review

The following chapter details much of the currently available literature regarding vane-type in-stream structures and step pool storm conveyance (SPSC), including existing guidance for structure application, design, installation, and post-installation monitoring; peer-reviewed research; academic dissertations and theses; and government-issued reports and technical notes.

Current Engineering Guidance for In-Stream Structures

Structure Descriptions and Purposes

Within the context of this study, the term "in-stream structures" refers specifically to stone or wood structures installed within the stream channel as elements of stream restoration or channel design projects, for the purposes of stream channel stabilization by flow deflection, thalweg redirection, and flow energy dissipation; streambed scour pool (also called scour hole or plunge pool) formation; grade control; and/or aquatic habitat creation or enhancement (Doll et al., 2003; NRCS, 2007a; Rosgen, 2001; Sotiropoulos & Diplas, 2014). These structures are sometimes collectively referred to as "loose rock structures" because, when made of stone, binding agents such as cement or mortar are not traditionally used to hold the individual boulders together or to set them into the stream channel (Gordon et al., 2016; NRCS, 2007d). This study focused on only four in-stream structures: the flow-deflecting single-arm vane and j-hook vane and the channel-spanning cross vane and w-weir.

The single-arm vane (also called the single-wing vane, straight vane, rock vane, or log vane) is a rigid, flow-deflecting structure consisting of a partially-submerged straight line of boulders or single straight log, which spans a portion of the channel width at an upstream-directed angle and causes the formation of a downstream scour pool, as shown in Figure 2.1 (MDE, 2000). The j-hook vane (also called the j-vane or fishhook vane) is similar, with an added parabolic extension beyond the mid-channel vane tip at approximately right angles to the flow. This extension, known as the "hook," gives the j-hook vane its name and characteristic sideways "J" shape, as shown in Figure 2.2. The j-hook vane also causes greater energy dissipation and the formation of a deeper, wider downstream scour pool than the simpler single-arm vane because it serves as a larger flow obstruction. (Rosgen, 2001). Particularly in smaller streams, the hook can be further extended using a cut-off sill so that the j-hook vane spans the entire channel width. Unlike the regular j-hook vane, the modified j-hook vane can be used to provide grade control. (NRCS, 2007d).

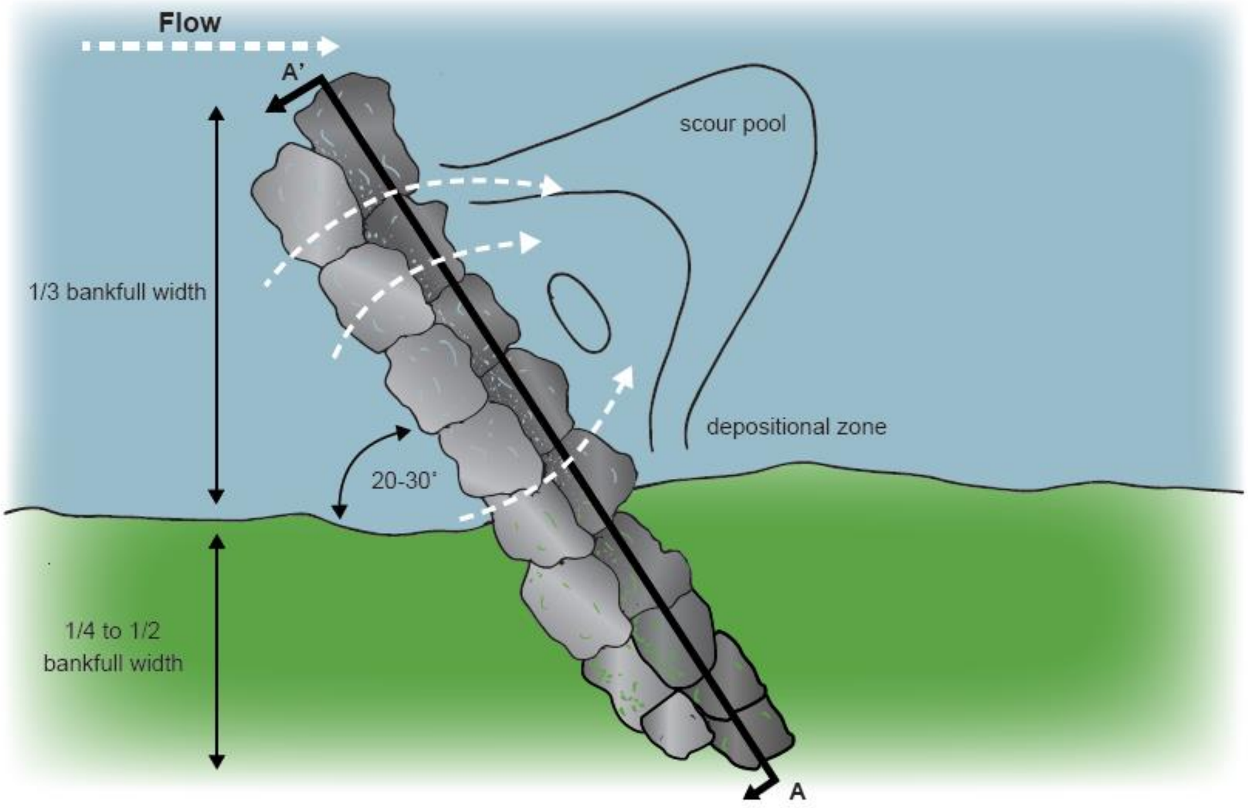


Figure 2.1: Plan view of a single-arm vane. Illustration by Sarah Cisneros (2017), created for this study.

The cross vane (also called the u-weir, v-weir, or channel-spanning weir) is a rigid, channel-spanning grade control structure consisting of two upstream-directed single-arm vanes (called vane arms), which extend from opposite banks and are connected across the center of the channel by a straight or parabolic crosspiece at approximately right angles to the flow. As with the single-arm and j-hook vanes, the configuration of the cross vane (Figure 2.3) causes the formation of a downstream scour pool. (Rosgen, 2001). A modified version of the cross vane, called the A-type cross vane (or A-vane), features a second crosspiece, which connects the two vane arms 1/3 to 1/2 of the vane length downstream of the main crosspiece. The second crosspiece provides additional flow energy dissipation, reducing the downstream scour depth and decreasing the risk of structure failure by undermining, the failure mode in which scour exceeds the depth of the footer rocks and the structure collapses into the downstream scour pool. (NRCS, 2007a; Sotiropoulos & Diplas, 2014). The cross vane is sometimes incorrectly considered to be the same structure as the similarly-configured vortex rock weir. The vortex rock weir also consists of two upstream-directed vane arms connected by a parabolic crosspiece, but the description of the vortex rock weir specifies that gaps be left between the surface rocks of the crosspiece. (MDE, 2000; Rosgen, 1996). Past monitoring studies showed that these gaps caused the vortex rock weir to create greater turbulence than the cross vane, leading to undesirable channel erosion and structure undermining. In addition, without the support of rocks to either side, the mid-channel surface rocks of a vortex rock weir were vulnerable to displacement during high flow events. (Rosgen, 2001). The w-weir (also called the double cross vane) is another rigid, channel-spanning grade control structure, consisting of four vane arms that span the channel in a "W" formation (when looking downstream), as shown in Figure 2.4, with the two outer vane arms directed upstream like single-arm vanes. The configuration of the w-weir, which creates two downstream scour pools, was originally developed to mimic the effects of natural exposed bedrock controls in wide streams. Double w-weirs are occasionally installed in very wide streams or to protect bridges with multiple center piers. (Rosgen, 2001).

According to Rosgen (2001), in-stream structures should be multi-purpose by design and should fulfill at least the following when properly implemented: the channel cross-section should be held in place due to decreased near-streambank flow velocity, energy, and shear stress, as caused by flow deflection; the stream must still be able to transport water and sediment as required; the structure should allow for unimpeded fish passage; and, the structure should remain in place during and after above-bankfull discharge flow events (floods). Other proposed structure purposes may not be applicable to every project, based on site characteristics, project objectives, and the functions and limitations of the individual structures. These purposes include providing grade control; protecting roads, bridges, or other infrastructure; creating or enhancing aquatic habitat; ensuring that the stream remains navigable and suitable for recreational use; creating irrigation diversions; stabilizing the confluence of two streams (for which the w-weir alone is recommended); being aesthetically pleasing or having a "more natural" appearance than other applicable techniques; and being the least costly of all applicable techniques. The above list of structure purposes (Rosgen, 2001) is essentially reiterated by many other sources of in-stream structure design guidance (Doll et al., 2003; Gordon et al., 2016; MDE, 2000; NRCS, 2007a; Sotiropoulos & Diplas, 2014; VDSWC, 2004).

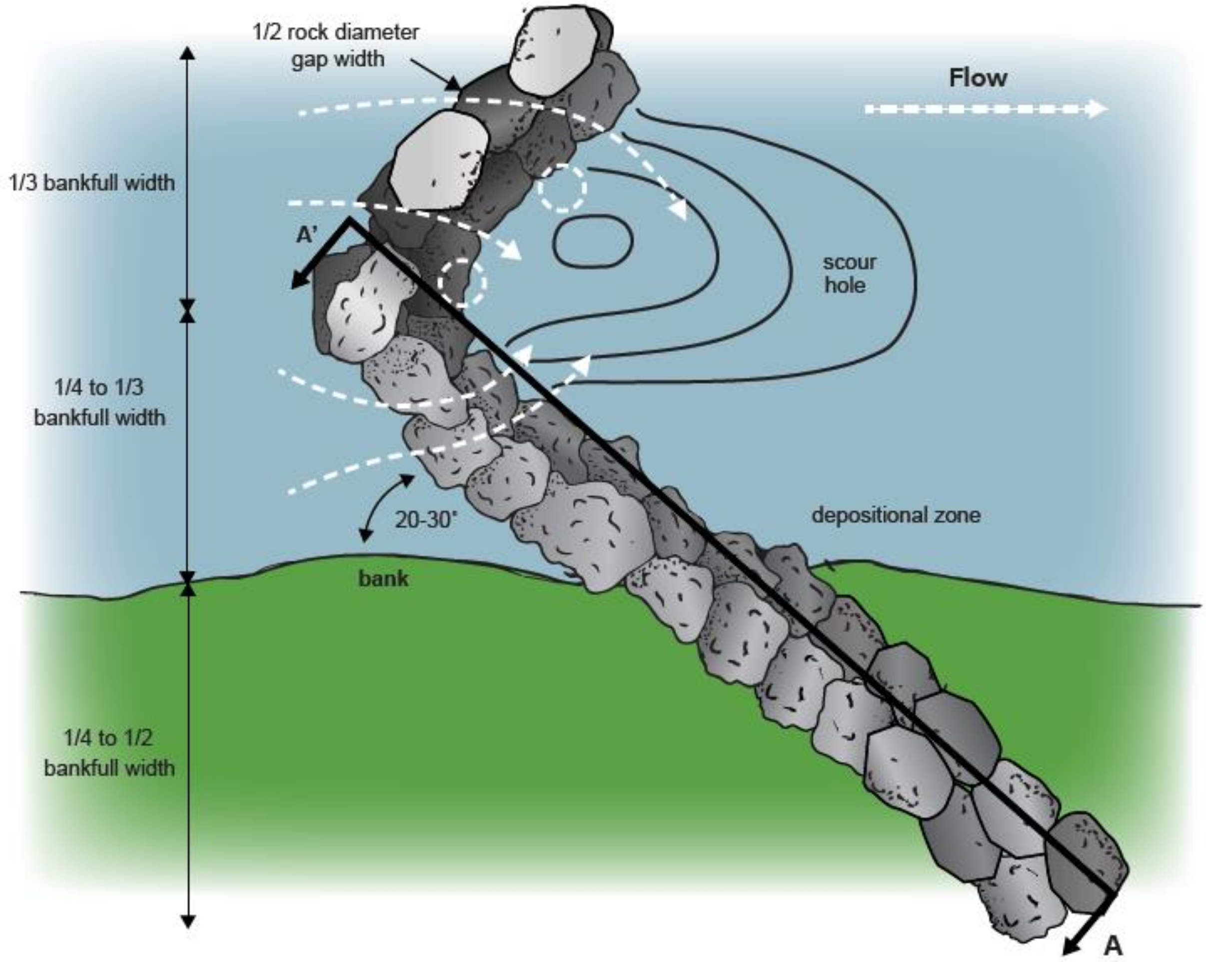


Figure 2.2: Plan view of a j-hook vane. Illustration by Sarah Cisneros (2017), created for this study.

Typically, the primary purpose for the inclusion of in-stream structures in a stream restoration project is so that the structures may provide some form of channel stabilization, especially at sites where streambank vegetation is absent or immature or where regrading a steep or unstable bank is unfeasible (Keystone Stream Team, 2003; NRCS, 2007a). Flow deflection indirectly stabilizes streambanks against erosion, grade control stabilizes the streambed, and flow energy dissipation assists in stabilizing the entire stream reach. These functions are not performed by more traditional, “hard” bank armoring techniques, such as the placement of concrete, riprap, or gabion baskets over eroding or erosion-susceptible streambanks or bank toes. Furthermore, in-stream structures promote channel stability in a manner that interferes less with ecosystem services than most hard bank armoring techniques and can, in fact, actually create or enhance aquatic habitat. (Keystone Stream Team, 2003; Rosgen, 2001; Sotiropoulos & Diplas, 2014).

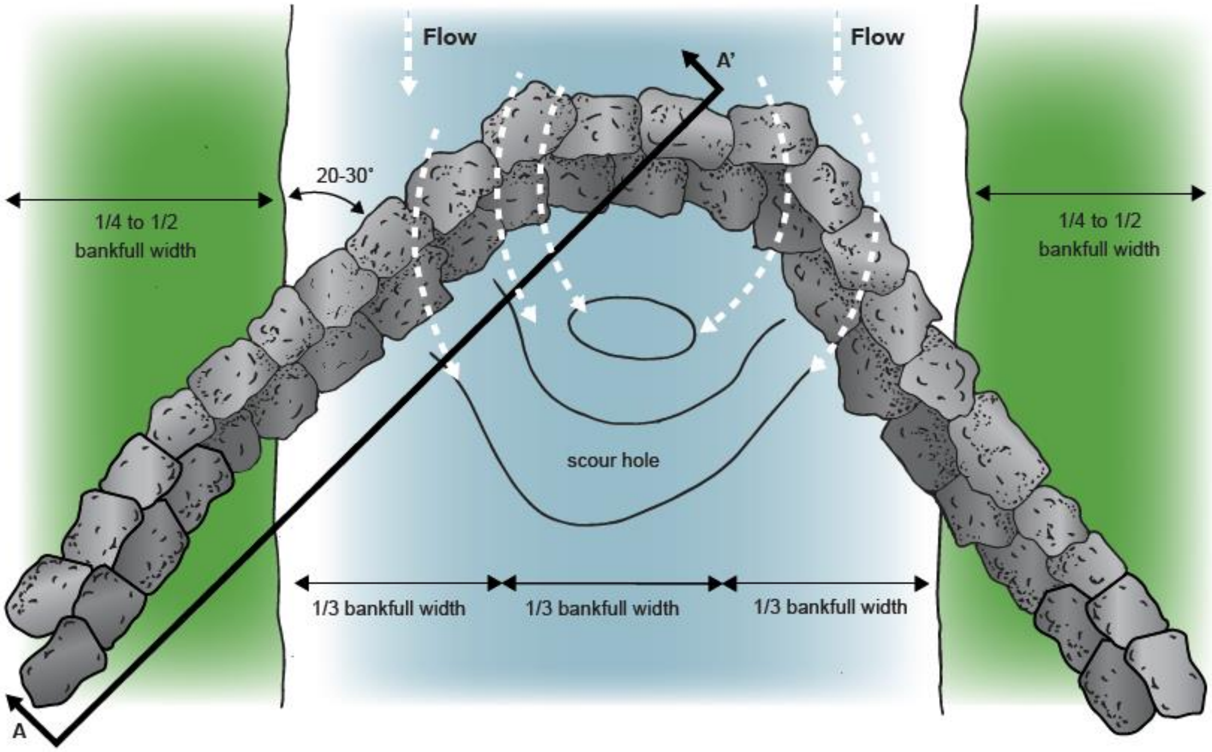


Figure 2.3: Plan view of a cross vane. Illustration by Sarah Cisneros (2017), created for this study.

All four of the in-stream structures examined in this study act as flow-deflecting structures (sometimes called flow-redirecting structures). Single-arm vanes, j-hook vanes, and the outer vane arms of cross vanes and w-weirs are installed in the stream channel at upstream-directed angles, deflecting high-energy, high-velocity flows towards the center of the channel and away from erosion-susceptible streambanks. Flow deflection also relocates any potentially damaging effects of those flows, such as high near-streambank shear stress, which could cause or accelerate streambank erosion. (NRCS, 2007e). Due to the relocation of high shear stress, flow deflection has the effect of causing the thalweg to migrate towards the center of the channel, away from the banks. The relocation of high shear stress is also what causes the formation of the downstream scour pool. For the w-weir, the configuration of the inner vane arms (Figure 2.4) actually causes the formation of two parallel thalwegs, just as it forms two scour pools. (Doll et al., 2003; Rosgen, 2001). Furthermore, flow energy dissipates as water is physically forced to flow over the structure. As flows are deflected towards the channel center and the thalweg migrates, sediment deposition increases in the slower flow zones that develop near the banks, just upstream of the vane arms (Sotiropoulos & Diplas, 2014). Some references (FISRWG, 2009; MDE, 2000; NRCS, 2007a) claim that this redistribution of the zones of erosion and deposition is how the placement of a series of single-arm flow-deflection structures on alternating banks can induce the formation of a meandering channel planform in currently straight reaches, if desired. For single-arm vanes and j-hook vanes, one flow-deflecting vane arm constitutes all or most of the structure and only protects the bank on that side of the channel. For channel-spanning cross vanes and w-weirs, both outer vane arms of the structure provide flow deflection, protecting both banks.

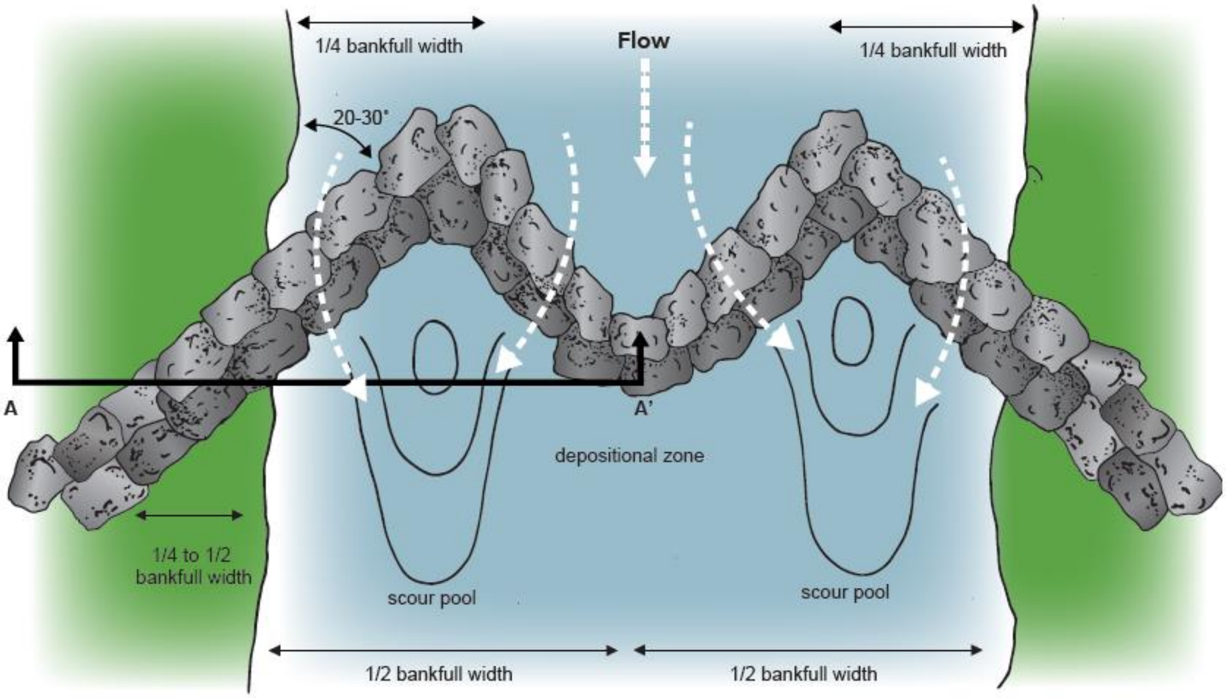


Figure 2.4: Plan view of a w-weir. Illustration by Sarah Cisneros (2017), created for this study.

Cross vanes, w-weirs, and modified j-hook vanes can also serve as grade control structures because they span the entire channel width. Grade control structures stabilize the streambed by establishing a permanent bed elevation at a certain point (Biedenharn & Hubbard, 2001). Typically, this point is defined by the lowest elevation of the exposed portion of the structure, which is the elevation of the surface rocks in the crosspiece of a cross vane, at the upstream-directed outer apexes of a w-weir, or at the mid-channel vane tip of a modified j-hook vane (Doll et al., 2003). The structure then steps the flow down to a lower water surface elevation, indirectly decreasing streambed erosion through flow energy dissipation. This controlled step also allows for gentler channel slopes both upstream and downstream of the structure, further decreasing erosional forces, especially when multiple structures are placed in series, allowing for a greater controlled elevation change over the entire project reach. (Biedenharn & Hubbard, 2001; NRCS, 2007d). Because the footer rocks of a grade control structure should extend below the expected scour depth, they can also prevent the upstream migration of knickpoints (also called headcuts). Knickpoints are points of sudden streambed elevation change which appear as small waterfalls that erode upstream (Biedenharn & Hubbard, 2001; Rosgen, 2001; Sotiropoulos & Diplas, 2014).

In some cases, in-stream habitat creation or enhancement for fish and other aquatic wildlife may be a secondary purpose for the inclusion of in-stream structures in a project (Rosgen, 1996). The scour pools formed by structures, in addition to the structures themselves, add in-stream habitat and cover to the channel (Biedenharn & Hubbard, 2001; Cramer, 2012; Gordon et al., 2016; Keystone Stream Team, 2003; VDSWC, 2004) and create zones of slower flow and flow separation that allow fish to rest and feed, respectively (Rosgen, 2001). Redirection of the thalweg to the channel center facilitates fish passage in otherwise shallow, plane-bed streams (Cramer, 2012). Water is aerated as it flows over a structure, increasing dissolved oxygen content. In a stream where woody debris would naturally occur, use of wood as a construction material may further enhance aquatic habitat. (Doll et al., 2003). The j-hook vane, cross vane, and w-weir may be better than the simpler single-arm vane at providing aquatic habitat improvements (MDE, 2000). Some references (Biedenharn & Hubbard, 2001; Cramer, 2012; MDE, 2000; NRCS, 2007a; Rosgen, 2001) claim that gravel depositions which form a riffle in the slower flow zone just upstream of a grade control structure may help create fish spawning habitat. These gravel depositions are more likely to occur when channel-spanning structures are properly placed in series, which can induce the formation of an approximately natural riffle-pool sequence. (FISRWG, 2009; MDE, 2000).

Structure Application

In-stream structures are well-suited to slightly-to-moderately sinuous streams with high-velocity flows and shallow-to-steep banks that are actively eroding or erosion-susceptible. Structures are also well-suited to streams with high bedload sediment transport, with the exception of the j-hook vane, as the gaps between the surface rocks in the hook section would make those rocks more vulnerable to displacement in a bedload-heavy stream. (MDE, 2000). W-weirs work well in highly-variable (flashy) flow regimes. They should generally only be installed in large streams with bankfull channel widths over 12 m (40 ft), so that their geometry will fit within the channel cross-section and to prevent the two scour pools they create from threatening bank stability. (Doll et al., 2003; MDE, 2000; VDSWC, 2004). Log vanes are generally more appropriate than rock vanes in sand-bed streams and in streams where large woody debris would naturally occur. (MDE, 2000). Overall, in-stream structures are best suited to plane-bed and riffle-pool type streams with gravel or cobble beds. Single-arm and j-hook vanes perform best in streams with final, post-project channel slopes of less than 3% (MDE, 2000; VDSWC, 2004), while cross vanes and w-weirs are better suited for streams with moderate-to-steep channel slopes (MDE, 2000; Sotiropoulos & Diplas, 2014).

In contrast, in-stream structures should be used with caution in low-velocity streams, including streams with very shallow flow, standing water, or backwater, as excessive aggradation may render the structure ineffective or even bury it completely (MDE, 2000; MDNRC, 2001). In silt- or sand-bed streams, the structure will be more vulnerable to failure by undermining (FISRWG, 2009; MDE, 2000). In clay-bed streams, the structure may sink into the streambed, especially during installation (VDSWC, 2004). Structures should also be used with caution in highly-sinuous streams and in streams with highly-variable flow regimes (except, as previously stated, for the w-weir). For the structure to be most effective, actively-eroding or erosion-susceptible streambanks just upstream of the structure should be stabilized against erosion by methods such as bank regrading and vegetation planting. Stabilizing the upstream banks also helps to avoid structure failure by flanking, the failure mode in which streambanks upstream of the structure erode away, enabling the flow to bypass the structure entirely. (Biedenharn & Hubbard, 2001). Single-arm vanes and regular j-hook vanes, which cannot provide grade control, should be used with caution in streams with an unstable or actively-eroding (incising) streambed. When installing a single-arm vane or regular j-hook vane across from an actively-eroding or erosion-susceptible bank, the opposite bank should be monitored to ensure that deflected flows are not impinging there and causing increased erosion. Channel-spanning structures should not be installed in streams that already have an established riffle-pool system because they may alter the existing structure of the project reach. (MDE, 2000). The necessary geometry of an in-stream structure should reasonably fit within the channel cross-section, making large rock or log structures inappropriate for very small streams. Conversely, log vanes may be inappropriate for very large streams, as a log long enough to span the minimum portion of the channel width required for effective flow deflection may not be available. (VDSWC, 2004). Structures cannot be installed in bedrock streams and should not be installed in streams with bedload transport of very large sediment (cobbles or coarser) or which often transport large debris, which is likely to damage the structures by causing rock displacement (MDE, 2000). In general, structures should be used with caution in streams that have a natural tendency to migrate, unless there is some particular reason to attempt to hold the channel cross-section in place, such as when channel migration threatens infrastructure, property, or human life. Structures installed in actively-migrating streams are likely to fail after a relatively short period of time due to the dynamic nature of these systems (Cramer, 2012).

Several references encourage designers and practitioners to carefully tailor their choice of in-stream structures – including their decision whether or not to use structures at all – to the specific goals and site constraints of the project. Considerations of stream and structure hydraulics and structure installation costs may not be enough to determine whether or not it would be appropriate to include structures in a particular project, as many other variables are at work in any stream system (Biedenharn & Hubbard, 2001). One important consideration when deciding whether or not to include structures is site accessibility, as structure installation requires heavy construction equipment. Another factor to consider is whether or not the inclusion of structures will actually promote the core goals of the project. (Cramer, 2012; VDSWC, 2004). In addition, due to the unique combination of parameters involved in each individual stream restoration project, a structure that is appropriate and useful to meet a certain goal at one site may not be appropriate at another site. When dealing with streams in different ecoregions or in watersheds with different land use, for example, these differences may be quite drastic. (Doll et al., 2003). Structures installed at a site where they are inappropriate, often due to a flawed understanding of site-specific stream hydraulics, can actually cause increased channel instability and accelerate bank and bed erosion. At other times, structures fail to hold the channel cross-section in place because the root causes of channel instability were not corrected during the project. (Cramer, 2012; Gordon et al., 2016; Rosgen, 2001). Analyzing the stream hydraulics and fluvial processes of a reference reach can assist designers in understanding which elements should be added, removed, or altered in the project reach to restore certain stream functions or prevent undesired erosion or channel migration (Doll et al., 2003; Keystone Stream Team, 2003). Gordon et al. (2016) recommends securing the expertise of a professional geomorphologist to conduct a thorough study of the project site, as well as any reference reaches, before deciding whether or not to include structures in the project design.

Design Flow

One crucial consideration of in-stream structure design is the selection of the design flow, which is the return period (also called the recurrence interval) of the flow event during which the structure is designed to remain in place and perform effectively. During flow events of higher return period than the design flow, some damage to the structure may be expected. Design flow selection plays an important role in determining the ultimate failure risk for the structures installed (Cramer, 2012; Gordon et al., 2016). However, due to site-specific differences in stream hydraulics, the design flow will be different for every project, even for structures of the exact same type in streams of similar morphology and ecoregion. In addition, certain failure modes (such as aggradation or the decomposition of woody construction materials) may occur and cause the structure to fail even if a flow event greater than the magnitude of the design flow does not occur. (Gordon et al., 2016).

Some references (Cramer, 2012; Gordon et al., 2016) recommend that designers identify more than one design flow, taking into account lower flows that are crucial to effective structure function as well as the highest flow event the structure should be designed to withstand, which would then be specifically called the high design flow. Which flows are chosen and which flows are given the highest priority depends largely on the overall project goals. A structure installed primarily for enhancement of fish habitat should prioritize the maintenance of deep enough baseflow to allow for unimpeded fish passage at all times. On the other hand, a structure installed primarily for infrastructure protection should prioritize structure stability during the high design flow event. When the downstream scour pool formed by a structure is a prominent component of the habitat creation goals of a project, the potential structure responses to the effective discharge, the discharge that moves the most bed sediment (Biedenharn et al., 2000), should be examined to ensure that the pool will not only be formed, but will also be maintained without either undermining the structure or being buried due to aggradation (Cramer, 2012). In any case, the effects of both high and low flows upon structure stability and performance should be examined in the course of every structure design.

In urban watersheds, the high design flow may be as high as the 50- or 100-yr flow event, as required by regulations in an environment where structure failure could endanger property, infrastructure, or human life and the level of acceptable failure risk is correspondingly low. However, it can be difficult to accurately predict discharges and shear stresses for very high, infrequent flow events, even when a long stream gage record is available. A certain level of uncertainty and risk is unavoidable when sizing structure materials to withstand flow events of such high return period. (Cramer, 2012).

Bankfull discharge is generally defined as the flow that fills but does not exceed the channel capacity, and it is usually assumed to have a return period of 1.5-2 years. Other open channel flow characteristics associated with the bankfull discharge are called the bankfull width, depth, velocity, shear stress, etc. (MDE, 2000). Bankfull discharge is sometimes used to approximate the channel-forming discharge, which is the discharge that determines the stable channel morphology. Bankfull discharge can be determined by using various natural indicators, such as the presence of streambank benches or the extent of certain types of bank vegetation. Once determined in the field, the measured bankfull width and depth can be used to determine bankfull discharge using an equation such as Manning’s formula (Eq. 2.1). Alternatively, resources such as stream gage records (from either the project stream or a reference reach) or regional curves can be used to predict the discharge of the 1.5- or 2-yr flow event. (Biedenharn et al., 2000).

Rosgen (2001) suggests using the return period of bankfull discharge to define the high design flow of a structure and provides an empirical relationship for sizing individual boulders to withstand the bankfull shear stress (see “Material Sizing”). Use of the bankfull return period to define the high design flow is also recommended by other guidance references (Doll et al., 2003; MDE, 2000; NRCS, 2007a; VDSWC, 2004). The bankfull discharge used should always be the designed bankfull discharge of the restored reach. MDE (2000) suggests approximating bankfull velocity using Manning’s formula,

$$V = \frac{C}{n} R^{2/3} S^{1/2} \tag{2.1}$$

where V is bankfull velocity in m/s (ft/s); C is a constant equal to 1 when using SI units (1.486 when using English units); n is the Manning’s roughness coefficient, adjusted for bankfull conditions if necessary; R is the hydraulic radius in m (ft), calculated using the designed bankfull depth and width of the restored reach; and S is the final channel slope in m/m (ft/ft). However, as the bankfull return period is relatively low (1.5-2 years, compared to 50 or 100 years), using bankfull discharge to define the high design flow for a structure will give that structure a higher failure risk during flow events greater than bankfull. This higher risk of structure failure may not be acceptable for every project, based on specific project goals or applicable regulations.

Other references recommend different methods for selecting design flows. Gordon et al. (2016) recommend selecting the discharge that will cause the greatest bed scour as an important design flow and provides steps to determine this discharge using HEC-RAS modeling software. Cramer (2012) notes that different projects will require different design flows because the structures involved will have different levels of acceptable failure risk based on their differing objectives and site characteristics. For example, a structure installed to protect infrastructure will need a higher design flow because it will need to remain in place as long as the infrastructure is present, while for a structure installed to protect streambanks from erosion while bank vegetation matures, a lower design flow may be acceptable.

Material Selection

In-stream structures can be constructed from stone (rocks and boulders), wood (logs), or some combination of the two. Single-arm vanes can be composed of a straight line of boulders; a single large, straight log; or, occasionally, a straight bundle of smaller logs (MDE, 2000). The vane arm of a j-hook vane can be similarly constructed of either stone or wood, though the hook section should always be made of stone, as shown in Figure 2.5. Cross vanes can be constructed entirely of wood using three large logs, though the configuration is slightly different than that of a stone cross vane (see “Structure Placement within the Stream Cross-Section”). Alternatively, logs can be used for the vane arms of a cross vane, with the mid-channel crosspiece constructed of stone. (Rosgen, 2001). While a w-weir could perhaps theoretically be made of wood, this is neither commonly practiced nor recommended. A structure built entirely or partially of wood should be able to fulfill the same functions with the same effectiveness as a structure built entirely of stone, with the sole exception of grade control. Cross vanes and modified j-hook vanes that are intended for grade control should be built entirely of stone, because the absence of footer rocks beneath log vanes prevents channel-spanning wood structures from holding the bed elevation in place. (MDE, 2000; VDSWC, 2004). Though wood-based grade control structures do exist, they are different structures that were developed specifically for woody materials, whereas these “loose rock structures,” though they can be modified to accommodate wood, were originally developed to be built in stone (NRCS, 2007d; VDSWC, 2004).

There are multiple factors which might make wood either a more or less desirable construction material for in-stream structures than stone. If aquatic habitat creation or enhancement is a goal of the project, use of wood in a stream where woody debris would naturally occur may work to further this goal. This is especially true if woody debris is no longer present in the degraded stream, in which case reintroducing wood may be a key goal of the stream restoration project. (Doll et al., 2003; NRCS, 2007a). In such streams, wood structures are also considered to have a more natural, “fitting” appearance than stone structures, and in forested areas, logs of the necessary size might be able to be sourced from the immediate surroundings of the project site. Subjectively, wood is generally considered to be a more aesthetically-pleasing construction material than stone (NRCS, 2007a). On the other hand, wood may be an inappropriate material for very large streams, as a log long enough to span the minimum portion of the channel width required for effective flow deflection may not be available (VDSWC, 2004). The logs used to construct wood structures will also decompose over time, decreasing the design life of a wood structure even when measures are taken to slow the process, such as selecting rot-resistant tree varieties or designing the structure to avoid regular wetting-and-drying cycles such as, for example, those that would be experienced by a wood structure in an urban stream with a highly-variable flow regime. Because woody material will inevitably decompose, use of wood is not recommended where infrastructure protection is a key project goal, as that generally requires the structure to have a long design life and low acceptable failure risk. Replacing entire logs used in wood structures is costly and labor-intensive. (Cramer, 2012; FISRWG, 2009; VDSWC, 2004).

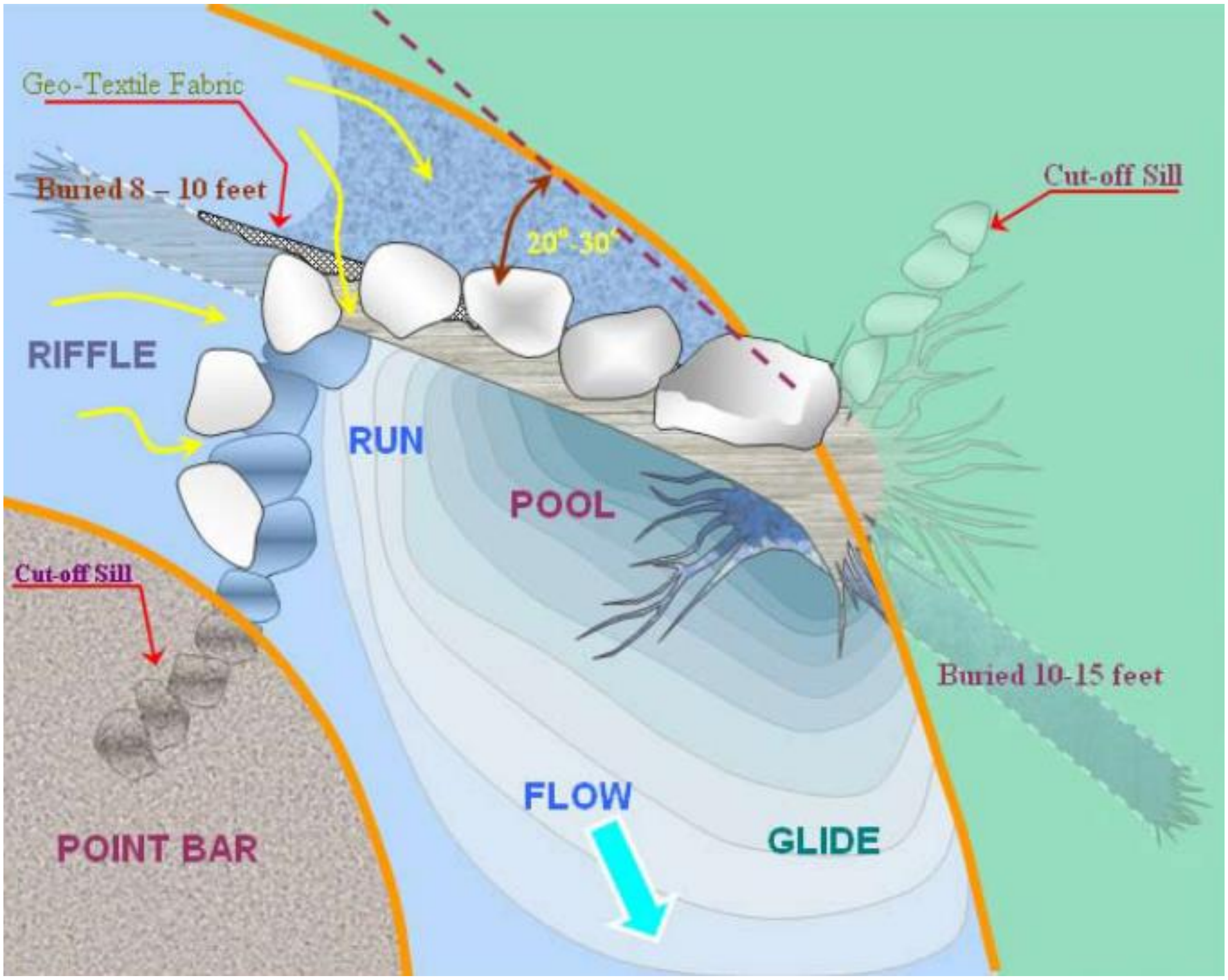


Figure 2.5: Plan view of a j-hook vane incorporating woody material (NRCS, 2007a).

One important factor that should be taken into account when selecting structure materials, both in the decision whether to use stone or wood and in the selection of the actual boulders or logs to be used, is the type of debris that would naturally occur in the stream. The type of debris typically found in local streams can be observed during preliminary surveys and assessments of the site or a reference reach, combined with an understanding of pre-disturbed streams of that type in the ecoregion. As a general rule of thumb, upland streams (especially cascade or step-pool streams) are more likely to have a natural occurrence of in-stream boulders, while streams in lowland and/or forested areas are more likely to naturally have in-stream wood. Another rule of thumb recommends that stone is more appropriate for use in gravel- or cobble-bed streams, while wood is more appropriate for use in sand-bed streams (Doll et al., 2003; VDSWC, 2004). However, wood structures are more prone to failure by undermining, a particular danger of sand- or silt-bed streams (Cramer, 2012; Doll et al., 2003; MDE, 2000; VDSWC, 2004). It is also important to select varieties of stone or wood that are as similar as possible to those that would naturally occur as in-stream debris, if they are not actually sourced from the immediate surroundings (Doll et al., 2003). At the very least, the construction materials should react to and interact with stream processes in the same manner as native materials, both physically and chemically. The manner in which the construction materials react to and interact with stream processes is especially important if aquatic habitat creation or enhancement is an objective of the overall project, as any alterations to stream processes could negatively affect the overall quality of the habitat formed by the structure. (Cramer, 2012).

Material Sizing

The materials used to construct an in-stream structure must be large enough for the structure to remain in place during and after the high design flow event, while still creating the required structure geometry within the confines of the channel cross-section. Material sizing may also depend on factors such as streambed substrate size or expected scour depth. (Doll et al., 2003; FISRWG, 2009; Sotiropoulos & Diplas, 2014; VDSWC, 2004).

Single logs used for vane arms should be no less than 20-30 cm (8-12 in) in diameter (MDE, 2000; VDSWC, 2004). When log bundles are used in place of large single logs, they must be bound together with sturdy cable (Rosgen, 2001) or with 0.9 m (3 ft) long rebar rods that are 1.3-1.6 cm (1/2-5/8 in) in diameter (MDE, 2000; VDSWC, 2004). Smaller logs used as support pilings for log vanes should be 8-15 cm (3-6 in) in diameter and long enough to extend at least 0.3 m (1 ft) beneath the expected depth of scour (VDSWC, 2004). Alternatively, minimum log diameters necessary for structure stability, based on the bankfull width of the channel and the length of log required for the vane arm, are provided in Table 2.1 (Cramer, 2012; Schuett-Hames et al., 1999). Note that the minimum log lengths given in Table 2.1 only refer to the in-stream log length and do not take into account the additional length needed for the bank key. If woody debris is already present in the project stream or a reference reach, it may be used as a rule of thumb for the size of large woody material that would naturally occur in the stream (Cramer, 2012; Doll et al., 2003). In all cases, locally-sourced wood may constrain the range of log sizes available for use.

Table 2.1: Minimum log diameters and lengths necessary for in-stream stability (Cramer, 2012; Schuett-Hames et al., 1999).

Minimum Log Diameter (m)	**Minimum Log Length (m) based on Bankfull Width**			
	BW 0-5 m	**BW 5-10 m**	**BW 10-15 m**	**BW 15-20 m**
0.50	6	13	31	
0.55	5	11	26	
0.60	4	9	22	32
0.65	3	8	19	28
0.70		7	19	24
0.75		6	14	21

Many references offer widely-varying general rules of thumb for rock sizing. Castro (2000) and Cramer (2012) recommend that the d_{50} (the median rock diameter) used in structures should be two times the d_{50} of riprap sized to withstand the same high design flow. Doll et al. (2003) recommend boulder weights of 900-1800 kg (1-2 tons) in gravel- or cobble-bed streams, though the largest possible boulders that can still create the structure geometry within the channel cross-section are preferable. Gordon et al. (2016) suggest using boulders with a diameter of 0.9-1.2 m (3-4 ft) that are heavy enough that they cannot be displaced by vandals. In addition to the riprap-sizing relationships provided in the following paragraphs, MDE (2000) also suggests that vane rocks should weigh 90 kg (200 lbs.) at minimum, with a minimum diameter of 0.75 m (2.5 ft). MDNRC (2000) recommends that rocks be sized to withstand the shear stress of the high design flow and extend below the expected depth of scour, but notes that boulders used in structures often have a diameter of 0.6-1.2 m (2-4 ft). VDSWC (2004) recommends the use of boulders with an intermediate (b-axis) diameter of at least 0.5 m (1.5 ft). In addition, the surface and footer rocks in the mid-channel vane tip of a single-arm or j-hook vane, the hook of a j-hook vane, the crosspiece of a cross vane, and the apexes of a w-weir are exposed to the greatest hydraulic forces, as flow deflection redirects higher flow velocities and shear stresses towards the channel center. The hydraulic forces experienced by vane rocks nearer the channel center can be as much as three times greater than the forces experienced by vane rocks nearer the bank, which should be taken into account when sizing vane rocks for the mid-channel portion of the structure. (Sotiropoulos & Diplas, 2014).

Rosgen (2001) recommends a minimum rock diameter designed to withstand the bankfull shear stress, providing the empirical relationship

$$y = 0.1724 \ln x + 0.634 \tag{2.2}$$

where x is bankfull shear stress in kg/m^2 and y is minimum boulder diameter in m. Use of this relationship is limited to streams with bankfull discharges between 0.6 and 110 m^3/s (20-4,000 ft^3/s) and bankfull depths between 0.3 and 1.5 m (1-5 ft). Eq. 2.2 (Rosgen, 2001) is also cited and recommended by later references (NRCS, 2007a; VDSWC, 2004).

MDE (2000) also suggests using the bankfull flow condition for rock sizing and provides a riprap sizing chart (Figure 2.6), which relates bankfull velocity (ft/s) to rock diameter (in) and rock weight (lbs.) based on the 1936 Isbash formula (Eq. 2.3; English units only). The Isbash formula, when solved for rock diameter, describes the minimum diameter of a loose boulder (assumed spherical) that can withstand a certain flow velocity, as follows:

$$d = V^2/\{1.479g[(SG_s - SG_w)/SG_w]\} \tag{2.3}$$

where d is rock diameter in ft; V is flow velocity in ft/s; g is the acceleration due to gravity, 32.2 ft/s^2; SG_s is the specific gravity of the boulder, which depends on the variety of stone; and SG_w is the specific gravity of water, often assumed to be 1.0. The Isbash formula is recommended by both Cramer (2012) and MDE (2000) as a reasonable method for sizing vane rocks. However, MDE (2000) also notes that more detailed modeling of potential rock movement under a range of shear stresses may be necessary, depending on the specific project objectives and applicable regulations. Cramer (2012) also recommends the 1983 Costa equation (Eq. 2.4; English units only) as a potential rock sizing method. Solved for rock diameter,

$$d = (V/9.571)^{2.05} \tag{2.4}$$

where d is rock diameter in ft and V is flow velocity in ft/s.

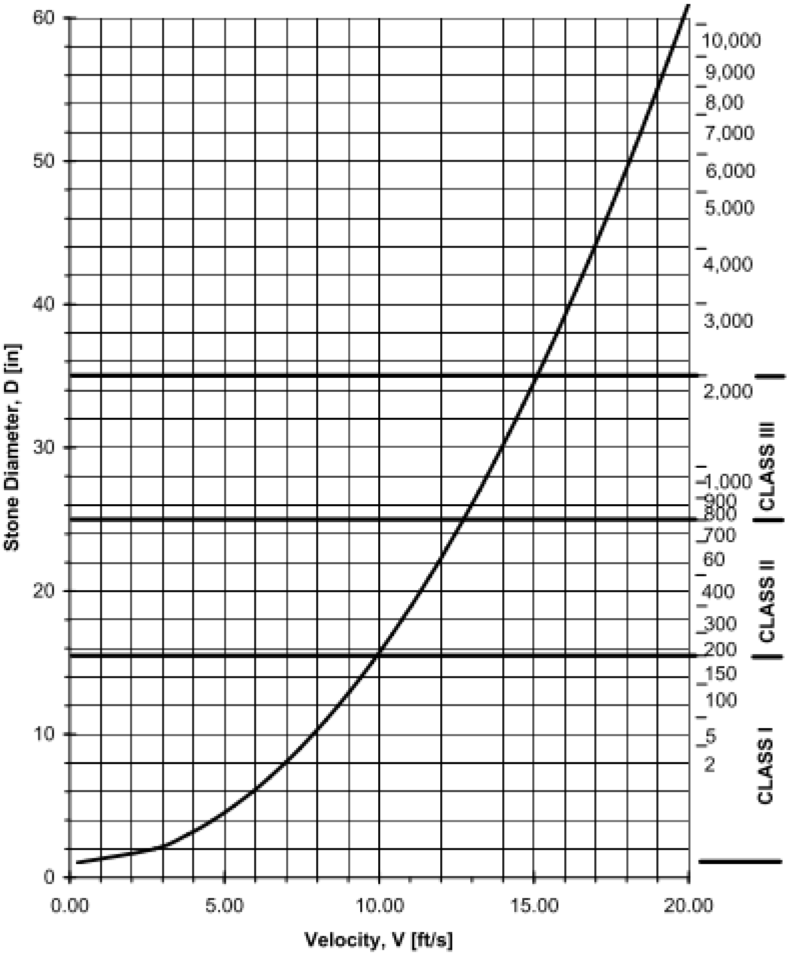


Figure 2.6: Riprap sizing chart based on the 1936 Isbash formula (MDE, 2000).

A thorough list of riprap and boulder sizing equations and methods, including their development histories and limitations, can be found in Technical Supplement 14C: Stone Sizing Criteria of the NRCS *National Engineering Handbook 654: Stream Restoration Design* (NRCS, 2007c). For those equations that were originally developed for riprap sizing, Gordon et al. (2016) recommends only using them when large boulders fitting the rules of thumb listed above are not available for the project.

Select large, fairly-uniform boulders with flat surfaces and angular, rather than rounded, edges to allow them to line up squarely with the boulders to either side and above or below them. All rocks must be flush with one another, minimizing the size of any gaps or holes between them, except when gaps are intentionally left between the surface rocks of the hook of a j-hook vane. Minimizing any potential gaps or holes between footer rocks is especially important, as gaps left between footer rocks leave the structure vulnerable to undermining and collapse. (Cramer, 2012; FISRWG, 2009; MDE, 2000; MDNRC, 2001; Sotiropoulos & Diplas, 2014; VDSWC, 2004).

Footer Depth

After water flows over an in-stream structure, it drops to impinge on the streambed, which is what causes the formation of the downstream scour pool. If the depth of the scour pool exceeds the depth of the structure materials, the structure can be undermined and collapse into the scour pool. Therefore, it is necessary to use footer rocks, or support pilings for log vanes, beneath all surface materials to ensure structure stability.

Rosgen (2001) asserts that the depth of the footer rock at the point of lowest surface rock elevation should be three times the protrusion height of that surface rock, for structures in cobble- and gravel-bed streams. In sand-bed streams, which experience greater bed scour, the footer depth should be doubled to six times the protrusion height of the surface rock. The point of lowest surface rock elevation is usually located at the mid-channel vane tip of a single-arm or j-hook vane, the crosspiece of a cross vane, or the upstream-directed outer apexes of a w-weir. Presumably, these recommended footer depths are meant to apply along the entire vane length, not only at the point of lowest surface rock elevation. This Rosgen (2001) method is also recommended by NRCS (2007a) and VDSWC (2004). Rosgen (2001) claims that, after the structure has been installed and the downstream scour pool has formed, maximum scour depth can be measured in the scour pool at 0.9 vane lengths past the mid-channel vane tip, crosspiece, or apex.

Other references suggest that footer depth be based on the predicted scour depth expected for the downstream scour pool. Various methods of predicting the expected scour depth can be found in Technical Supplement 14B: Scour Calculations of the NRCS *National Engineering Handbook 654: Stream Restoration Design* (NRCS, 2007b), under the heading "Scour Associated with Structures." Gordon et al. (2016) also provides an extensive list of scour depth prediction formulas and methods, with evaluations of their applicability to structure hydraulics, and ultimately recommends that an experienced engineer use professional judgment to select a scour prediction after applying several different calculation methods.

Some references recommend that footer depth extend at least to the expected scour depth and agree that one or two layers of footer rocks beneath the surface rocks is often sufficient (Doll et al., 2003; MDE, 2000; NRCS, 2007d). MDE (2000) recommends that two layers of footer rocks always be used when designing stone structures for sand-bed streams, and that the in-stream support pilings for wood structures should always extend below the expected scour depth. Sotiropoulos & Diplas (2014) recommend that footer rocks extend about 1.5 times the expected scour depth. VDSWC (2004) recommends that log vane support pilings extend at least 0.3 m (1 ft) below the expected scour depth. If a layer of bedrock exists above the depth of expected scour (since scour depth predictions are largely based on bed sediment properties and stream hydraulics), the footer rocks may end there (Doll et al., 2003; Gordon et al., 2016). Despite the fact that the vane arms are sloped vertically upward as they approach the bank, footer depth should remain constant at or below the expected scour depth, and not similarly slope upward, which would leave the structure vulnerable to failure by undermining (Gordon et al., 2016).

Structure Placement within the Stream Cross-Section

See Figures 2.1-2.4 for basic plan view diagrams of the single-arm vane, j-hook vane, cross vane, and w-weir.

Vane arms should be directed upstream at a 20^{o} to 30^{o} horizontal angle, as measured between the vane and the streambank (Doll et al., 2003; MDE, 2000; MDNRC, 2001; NRCS, 2007a; Rosgen, 2001; Sotiropoulos & Diplas, 2014; VDSWC, 2004). A larger horizontal vane angle allows for a shorter vane arm length to span the desired fraction of the channel width and protects a longer length of bank. However, larger vane angles also result in the formation of deeper downstream scour pools, increasing the risk of structure failure by undermining. (Doll et al., 2003; Sotiropoulos & Diplas, 2014). Larger vane angles should be used in gravel- and cobble-bed streams, while smaller vane angles should be used in silt- and sand-bed streams, especially if those streams are also meandering (Sotiropoulos & Diplas, 2014). One exception to this recommended range of horizontal vane angles applies to cross vanes and w-weirs intended for irrigation diversions. In that case, the structures are designed with an asymmetrical configuration to deflect flow into the diversion, and the horizontal vane angles may be greater or lesser than the 20^o-30^o range. (Rosgen, 2001).

Recommendations for vane arm length vary somewhat across references. Doll et al. (2003) allow for a single-arm vane to span as much as 1/2 of the baseflow width, since a longer vane with a lower vertical slope protects a longer streambank length. MDE (2000) recommends that a single-arm vane only be allowed to span so far in channels less than 6 m (20 ft) wide, as a general rule of thumb states that the wider the channel, the smaller the fraction of the channel width that a single-arm vane should span. By the same logic, single-arm vanes installed in very wide streams should span less than 1/3 of the channel width, saving material costs and allowing vane angle and slope to take precedence over vane length in design decisions (Sotiropoulos & Diplas, 2014). Most references recommend that a single-arm vane should span at least 1/4 but no more than 1/3 of the channel width (MDE, 2000; Sotiropoulos & Diplas, 2014; VDSWC, 2004). A single-arm or j-hook vane protects a bank length of 2-3 times the vane arm length (NRCS, 2007a; Rosgen, 2001). For single-arm and j-hook vanes in meandering streams, Table 2.2 provides equations to determine the ratio between required vane arm length and stream bankfull width (V_L/W) as a function of the ratio between meander radius of curvature and bankfull width (R_c/W) and selected vane angle (20^o or 30^o) (Rosgen, 2001).

The main vane arm of a j-hook vane should span 1/4 to 1/3 of the baseflow width, while the hook should span the center 1/3, as shown in Figure 2.2 (Doll et al., 2003; MDE, 2000; Rosgen, 2001; Sotiropoulos & Diplas, 2014; VDSWC, 2004). MDE (2000) recommends limiting potential j-hook span to 60% of the channel width. The hook section of a regular j-hook vane should be parabolic, rather than straight (MDE, 2000; Rosgen, 2001), while the hook of a modified j-hook vane may be either parabolic, with the cut-off sill extending straight out from the end of the hook, or straight, such that it is nearly-indistinguishable from the cut-off sill (NRCS, 2007a). Some references allow for gaps to be intentionally left between the surface rocks of the hook of a regular j-hook vane. According to Rosgen (2001) and VDSWC (2004), these gaps should be between 1/4 and 1/3 the diameter of the surface rocks themselves, while Doll et al. (2003) and MDE (2000) allow gaps to be up to 1/2 the diameter of the surface rocks. The gaps further facilitate energy dissipation and cause the formation of an even larger scour pool. Gaps should not be left between the surface rocks of the hook of a channel-spanning, modified j-hook vane intended for grade control.

Table 2.2: V_L/W as a function of R_c/W and selected vane angle. V_L and W are in m. (Rosgen, 2001).

R_c/W	Vane Angle (degrees)	Equation
3	20	$V_L/W = 0.0057W + 0.9462$
3	30	$V_L/W = 0.0089W + 0.5933$
5	20	$V_L/W = 0.0057W + 1.0462$
5	30	$V_L/W = 0.0057W + 0.8462$

For channel-spanning cross vanes, each section of the structure – the two vane arms and the crosspiece – should span 1/3 of the baseflow width so that the weir forms a “U” shape when looking downstream (Figure 2.3). The two vane arms should have a vertical slope towards the streambed, and their mid-channel vane tips and the entire crosspiece should be submerged at baseflow, as shown in Figure 2.7. (MDE, 2000; Rosgen, 2001; Sotiropoulos & Diplas, 2014; VDSWC, 2004). For the modified version of the cross vane called the A-type cross vane (or A-vane), a second crosspiece is constructed 1/3 to 1/2 of the vane length downstream of the main crosspiece. The configuration of the A-type cross vane forms two scour pools, one between the two crosspieces and one downstream of the second crosspiece, thus reducing overall bed scour through greater energy dissipation. (NRCS, 2007a; Sotiropoulos & Diplas, 2014). The configuration of cross vanes constructed entirely of wood is somewhat different. Two log vane arms each span 1/2 of the channel width so that they meet in the channel center, forming a “V” shape, although the "V" cannot be seen, since each log should pass beneath the streambed at a point 1/3 of the channel width from the bank. The crosspiece log is then placed across the center 1/3 of the stream channel at this point, partially buried in the stream bed so that it protrudes no more than 10% of bankfull depth. (Rosgen, 2001).

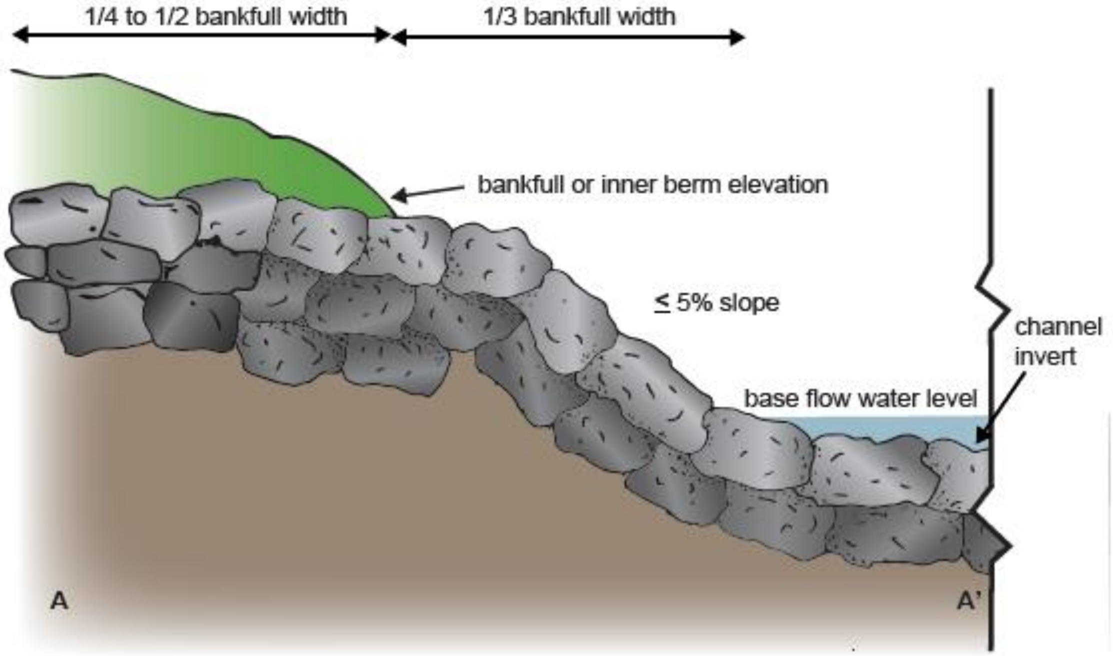


Figure 2.7: Cross vane section A-A', referring to Figure 2.3. Illustration by Sarah Cisneros (2017), created for this study.

Each section of a channel-spanning w-weir – the two outer and two inner vane arms – should span 1/4 of the baseflow width so that the weir forms a "W" shape when looking downstream, as shown in Figure 2.4. The two outer vane arms should have a vertical slope towards the streambed so that the two upstream-directed outer apexes of the w-weir are submerged at baseflow. The two inner vane arms should have a slight vertical slope upwards again so that the downstream-directed inner apex protrudes no more than 50% of bankfull depth (Figure 2.8). (Doll et al., 2003; MDE, 2000; Rosgen, 2001; Sotiropoulos & Diplas, 2014; VDSWC, 2004).

According to Rosgen (2001), the protrusion height of the surface rocks at the mid-channel vane tip of a single-arm vane, in the hook of a j-hook vane, in the crosspiece of a cross vane, or at the upstream-directed outer apexes of a w-weir should be no more than 10% of bankfull depth (Figure 2.9). For the surface rocks at the downstream-directed inner apex of a w-weir, the protrusion height should be no more than 50% of bankfull depth, as shown in Figure 2.8. VDSWC (2004) recommends that the protrusion heights of mid-channel structure features be no more than 15 cm (6 in). In contrast, MDE (2000) and Sotiropoulos & Diplas (2014) recommend that the mid-channel vane tip should be embedded in the streambed at approximately thalweg elevation. Sotiropoulos & Diplas (2014) add that the protrusion height of the surface rocks at the inner apex of a w-weir should be no higher than the average baseflow depth.

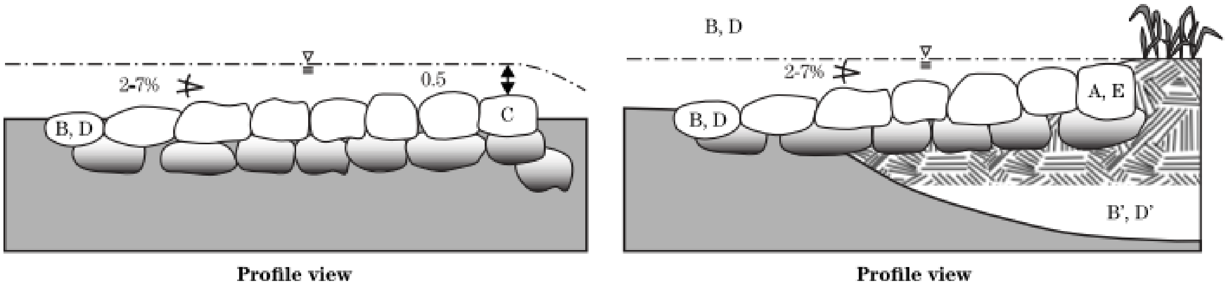


Figure 2.8: Profile view of the vane arms of a w-weir, both the inner (left) and outer (right) vane arms (NRCS, 2007a).

Vane arms should have a vertical slope from their bank key to their lowest exposed elevation at the mid-channel vane tip, crosspiece, or apex, which should be submerged at baseflow, as shown in Figures 2.7-2.9. (Doll et al., 2003; MDE, 2000; Sotiropoulos & Diplas, 2014). For cross vanes and w-weirs, this requirement applies for both outer vane arms, and the surface rock elevation at the crosspiece of a cross vane or the upstream-directed outer apexes of a w-weir should be low enough to allow unimpeded fish passage at baseflow (VDSWC, 2004). Recommendations for the vertical vane arm slope vary. NRCS (2007a) and Rosgen (2001) recommend a range of slopes from 2-7%, while MDE (2000) suggests 3-7%. Doll et al. (2003) and VDSWC (2004) give wider ranges of 2-20% and 2-15%, respectively, allowing for design alterations to fit individual site characteristics. VDSWC (2004) cautions against using a slope of less than 7% in wide streams, as low vane angles will necessitate very long vane arms, but also warns that steeper vanes protect a shorter bank length. Steeper vanes may also be more prone to failure by undermining because, the steeper the vertical slope of a vane arm, the greater the flow drop near the bank, increasing scour as the flow impinges on the bed just downstream of the structure. For this reason, steeper vanes should also be used cautiously in sand-bed streams, where the potential for structure undermining is already relatively high. Most references recommend that the vane arm should be keyed into the bank at or just below bankfull height (MDE, 2000; Rosgen, 2001; Sotiropoulos & Diplas, 2014; VDSWC, 2004), or between bankfull height and the inner berm height (Doll et al., 2003). If the bank height is greater than the bankfull height, the vane can be keyed into a constructed bankfull bench (NRCS, 2007a; Rosgen, 2001; VDSWC, 2004).

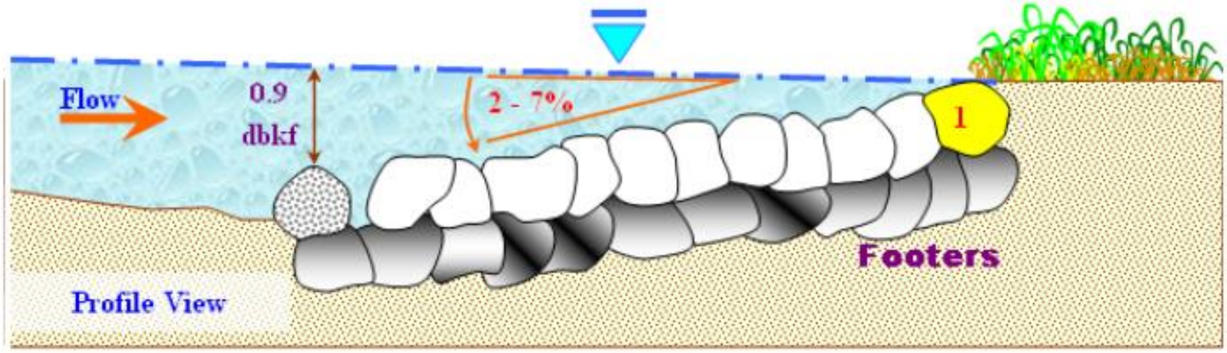


Figure 2.9: Profile view of a j-hook vane (NRCS, 2007a).

Structure Placement within the Stream Planform

In-stream structures should be sited within the stream planform after careful analysis of how the altered stream hydraulics created by the structure will interact with the fluvial processes (including sediment transport) and current or designed channel morphology (including sinuosity or lack thereof) of the stream. Hydraulic modeling may be necessary to fully understand the response of the channel to structure installation. (Cramer, 2012; Gordon et al., 2016). In some cases, the installation of a structure in a meandering channel may actually decrease channel stability, rendering the use of structures inappropriate either at that location along the planform or in the project reach as a whole (Doll et al., 2003; Rosgen, 2001). Use of structures is generally not recommended in highly-sinuous channels (MDNRC, 2001).

Single-arm vanes and j-hook vanes should be placed on the outer bank of a meander bend, just downstream of the apex where the flow impinges on the bank at an acute angle, to avoid causing erosion in the meander bend (Doll et al., 2003; VDSWC, 2004). According to Sotiropoulos & Diplas (2014), this placement is appropriate for slightly-sinuous streams with a ratio of meander radius of curvature to channel width (R_c/W) greater than three, but in highly sinuous streams, the structure should be placed one channel width upstream of the meander apex. In general, a vector analysis using the Sotiropoulos & Diplas (2014) methodology (see "Guidance from In-Stream Structure Research") is recommended to properly site structures in meandering streams.

Some references (FISRWG, 2009; MDE, 2000; NRCS, 2007a) claim that when properly spaced, a series of single-arm or j-hook vanes can be used to induce meandering or lateral migration in a straight channel. For this purpose, structures should be spaced 5-7 bankfull channel widths apart on alternating banks. For single-arm or j-hook vanes intended primarily for aquatic habitat creation or enhancement, structures should be spaced at least one bankfull channel width apart, based on the spacing of scour pools or large debris observed in a reference reach. MDNRC (2001) recommends that single-arm vanes be spaced about 23-46 m (75-150 ft) apart in very wide streams. For single-arm and j-hook vanes in meandering streams, Table 2.3 provides equations to determine the ratio between vane spacing and stream bankfull width (V_S/W) as a function of the ratio between meander radius of curvature and bankfull width (R_c/W) and selected vane angle (20° or 30°) (Rosgen, 2001). Vanes can be spaced farther apart – the vane spacing increased by up to 40% of bankfull width – if the banks have a BEHI erosion-susceptibility rating of less than 30 (NRCS, 2007a).

Table 2.3: V_S/W as a function of R_c/W and selected vane angle. V_S and W are in m. (Rosgen, 2001).

R_c/W	Vane Angle (degrees)	Equation
3	20	$V_S/W = -0.006W + 2.4781$
3	30	$V_S/W = -0.0114W + 1.9077$
5	20	$V_S/W = -0.0057W + 2.5538$
5	30	$V_S/W = -0.0089W + 2.2067$

Channel-spanning structures can be used to induce formation of a riffle-pool sequence and should be spaced based on the riffle-pool sequence observed in a reference reach, especially when intended primarily for aquatic habitat enhancement. Understanding the hydraulics and fluvial processes that created the reference reach pool spacing is preferable if possible. Equations that have been developed to approximate the natural spacing of in-stream pools are provided in Table 2.4 (Gordon et al., 2016). Where an applicable reference reach is not available, channel-spanning structures should be spaced about 1-4 bankfull channel widths apart in streams with channel slopes of about 3-7%, and about one bankfull channel width apart in streams with slopes greater than 7%. (MDE, 2000). In any case, channel-spanning structures should be spaced far enough apart that the scour pool formed by the upstream structure does not undermine the crosspiece or vane arms of the next downstream structure (Gordon et al., 2016). Because channel-spanning grade control structures hold the bed elevation in place, they are often placed in the glide section of a stream or at the head (the beginning) of a riffle, so that the bed elevation of the riffle will remain constant. This placement prevents streambed erosion from encroaching on the riffle. (Doll et al., 2003).

For the spacing of cross vanes or w-weirs, Rosgen (2001) provides the empirical relationship

$$P_s/W = 8.2513S^{-0.9799} \tag{2.5}$$

where P_s is pool-to-pool spacing in m, W is bankfull width in m, and S is the channel slope (%). Biedenharn & Hubbard (2001) also provide forumlas for determining the number of channel-spanning grade control structures needed to reduce the channel bed slope to a desired value.

$$H = \left(S_0 - S_f\right)L \tag{2.6}$$

where H is the total desired elevation change to be controlled by a series of structures in m; S_0 is the original channel slope in m/m; S_f is the designed, post-project channel slope (between each structure) in m/m; and L is reach length in m. Having determined H, the number of grade control structures required can be found using

$$N = H/h \tag{2.7}$$

where *N* is the required number of structures and *h* is a selected value in m for the elevation change controlled by each individual structure (also called the step height).

Table 2.4: Natural pool spacing (P_S) estimation methods. See Gordon et al. (2016) for details.

Equation	**Channel Type and Location**	**References**
$P_S = 0.3133S^{1.188}$ where S is channel slope (SI units)	step-pool streams in New Zealand, western US, and Israel	Grant et al. (1990); Whitaker (1987); Wohl & Grodek (1994)
$P_S = 2.67S^{0.206}$ where S is channel slope (SI units)	step-pool streams in southern California	Chin (1999)
P_S = 2-3 channel widths		Knighton (1998)
$P_S = f(h, W, S, q_d)$ where h is step height W is channel width S is channel slope q_d is design unit discharge	step-pool streams	Thomas et al. (2000)
P_S = 0.43-2.4 channel widths	step-pool streams in southern California	Chin (1989)
$R = 4.5/S^{0.42}$ where R is the ratio of mean step length to mean step height S is channel slope	step-pool streams in Israel	Wohl & Grodek (1994)
$R = 1.5S$ where R is the ratio of mean step height to mean step length S is channel slope	flume data and step-pool streams in upstate New York and the Lake District in England	Abrahams et al. (1995)
$P_S/W = 8.2513S^{-0.9799}$ where W is channel width S is channel slope in %		Rosgen (1996); Rosgen (2006)
P_S = 5-7 channel widths	alluvial and bedrock riffle-pool streams	Leopold et al. (1964); Keller & Melhorn (1978)
$P_S = 5.42W^{-0.9799}$ where W is channel width (SI units)	alluvial and bedrock streams in California, Indiana, North Carolina, and Virginia	Keller & Melhorn (1978)

Doll et al. (2003) suggests that the elevation step controlled by any individual grade control structure should be “minimized.” Because scour depth increases with step height, a large step may cause the formation of a scour pool that undermines the structure. MDE (2000) thus recommends that the total elevation change controlled by one or more structures be no greater than 0.6 m (2 ft) for reasons of structure stability alone, not taking into account fish passage. MDNRC (2001) recommends that each structure control a step of no more than 0.5 m (1.5 ft), while VDSWC (2004) recommends that the controlled step be limited to 0.15 m (0.5 ft).

When structures are installed primarily for infrastructure protection, they should be placed at least two channel widths upstream of that infrastructure. Because A-type cross vanes create a longer (though shallower) downstream scour pool, they should be placed 2.5-3.0 channel widths upstream of infrastructure. (Sotiropoulos & Diplas, 2014).

Structure Installation

Heavy construction equipment is necessary for in-stream structure installation (Cramer, 2012; Keystone Stream Team, 2003; VDSWC, 2004). Mid-channel structure features, such as the crosspiece of a cross vane or the mid-channel vane tip of a single-arm vane, should be installed first. For single-arm vanes and regular j-hook vanes, heavy equipment access should be limited to the side of the channel where the vane is to be installed, to avoid destabilizing the opposite bank and to minimize damage to existing riparian vegetation. (Keystone Stream Team, 2003). Hiring contractors and heavy equipment operators who are experienced and skilled in the installation of in-stream structures can mean the difference between project success and failure (Cramer, 2012; MDNRC, 2001; VDSWC, 2004). Even so, it remains essential that a stream restoration designer with knowledge of the project oversee the installation process. The more details concerning exact structure layouts (such as elevations and coordinates) are included in the construction plan, the more likely it is that the structure will be installed to the exact design specifications. (Cramer, 2012; Keystone Stream Team, 2003; NRCS, 2007a; VDSWC, 2004).

To prevent the surface rocks from toppling into the downstream scour pool or being displaced by turbulent flow, footer rocks should be slightly offset from the surface rocks in the downstream direction. Surface rocks should also be horizontally offset from footer rocks so that each surface rock is centered on the meeting of two footer rocks, resting on half of each, as shown in Figures 2.1-2.4 (Doll et al., 2003; MDE, 2000; Rosgen, 2001; Sotiropoulos & Diplas, 2003; VDSWC, 2004). Cobbles or riprap can be placed on the upstream face of a vane arm, near the bank, to prevent erosion around the bank key (MDE, 2000; VDSWC, 2004). When installing wood structures, Rosgen (2001) recommends using a cable-and-anchor system at the mid-channel log end to ensure that the log remains in place. MDE (2000) and VDSWC (2004) recommend the use of support pilings that extend past the expected scour depth.

The vane key should extend into the bank at the same elevation as the surface rock closest to the bank (whether that rock is at the bankfull height or another elevation), as shown in Figure 2.7. According to MDE (2000), the vane key should extend at least 1.5 m (5 ft) or “2 to 3 rocks” into the bank. Log vane arms should extend into the bank at least 1.5-1.8 m (5-6 ft). MDNRC (2001) recommends a bank key of up to 4.5 m (15 ft), while VDSWC (2004) requires at least 0.6 m (2 ft). The bank key prevents structure failure by flanking and is particularly important for a vane installed on an exposed or newly-regraded bank (Doll et al., 2003). At least one of the footer rocks should be partially embedded in the bank as well (MDNRC, 2001). Additional boulders can be set against the downstream face of the vane where it meets the bank to provide further protection and stability, if necessary (MDE, 2000).

When log bundles are used in place of large single logs for wood structures, they must be bound together with sturdy cable (Rosgen, 2001) or with 0.9 m (3 ft) long rebar rods that are 1.3-1.6 cm (1/2-5/8 in) in diameter (MDE, 2000; VDSWC, 2004). The rebar must be driven into the log bundles until only 10 cm (4 in) is left exposed; the exposed rebar should be bent flush to the log bundle. (MDE, 2000). These rebar rods should be spaced every 1.5 m (5 ft) along the log bundle (VDSWC, 2004).

Geotextile fabric should be placed beneath the structure on the upstream side to the depth of the footer rocks to prevent sediment, water, or other materials from eroding through unavoidable small gaps between the footer rocks. For extra security, the fabric can be weighted in place with cobbles or, for wood structures, nailed to the log. (Doll et al., 2003; FISRWG, 2009; Rosgen, 2001;

VDSWC, 2004). In gravel- and cobble-bed streams, small gaps between footer rocks may also be hand-chinked on the upstream side of the footer rocks with gravel or bed substrate in a wide range of particle sizes (Doll et al., 2003; VDSWC, 2004). Chinking will help prevent structure failure by undermining and is thus particularly crucial in sand- or silt-bed streams. (VDSWC, 2004).

Monitoring and Maintenance

The two primary forms of monitoring recommended for in-stream structures are implementation monitoring, which ensures that the structure was built according to the design specifications, and effectiveness monitoring, which evaluates whether or not a structure is functioning correctly according to the project objectives. Implementation monitoring is conducted once, directly following structure installation, often in the form of an as-built survey. Effectiveness monitoring should be conducted over a longer period of time, with specific, predetermined goals. Two fundamental goals of effectiveness monitoring are to ensure that the structure remains in place and to evaluate whether the structure is fulfilling the intended purposes. (Cramer, 2012; Doll et al., 2003; FISRWG, 2009; Keystone Stream Team, 2003; VDSWC, 2004).

Structure stability can be assessed through visual inspections and photographic records. Visual inspection of the stream channel provides a preliminary understanding of how effective the structure is at preventing streambank erosion or providing grade control. Photographs should be taken at predetermined locations, so that changes can be compared over time, as well as of any new features of interest. (Doll et al., 2003). Depending on how crucial it is that the stream channel morphology be held in place and remain stable, standard morphological stream surveys may be used to assess changes with greater accuracy, to determine whether the stream channel is tending towards stability or instability and to monitor the formation of the downstream scour pool and migration of the thalweg (FISRWG, 2009; Keystone Stream Team, 2003; MDE, 2000; VDSWC, 2004). In that case, permanent cross-sections should be established for use in monitoring surveys. Placement of bank pins or use of standardized indices such as BEHI are other options for evaluating bank stability. Structure stability assessments should be conducted at regular intervals over a predetermined period of time using a standardized report format. (Doll et al., 2003; VDSWC, 2004).

For single-arm vanes and j-hook vanes, which deflect flow away from only a single bank, it is important to monitor the opposite bank as well to ensure that high-energy flows are not merely being redirected into the opposite bank and causing erosion there. For channel-spanning structures, it is important to ensure they do not hinder fish passage. All structures should be monitored for excessive aggradation or degradation of the streambed (MDE, 2000; Sotiropoulos & Diplas, 2014) and for the establishment of riparian vegetation on the banks, if applicable (Keystone Stream Team, 2003). Structures should be inspected for structural stability after the first flow event near or above the high design flow (Cramer, 2012; Sotiropoulos & Diplas, 2014). When a structure is failing to fulfill the stated objectives, it should be repaired if possible by, for example, replacing displaced vane rocks (Rosgen, 2001; VDSWC, 2004). Therefore, some expected maintenance costs should be built into the project budget (Cramer, 2012).

When compiled, monitoring data from in-stream structures used in many different projects may help pinpoint endemic flaws in structure application, design, and installation and assist in their correction (Rosgen, 2001). Use of standardized and well-organized report formats can also facilitate this process (Keystone Stream Team, 2003).

Guidance from In-Stream Structure Research

Despite having been largely accepted as useful and valuable elements of stream restoration and natural channel design projects by both by the stream restoration community and by environmental and natural resource agencies at every level of the US government, vane-type in-stream structures are still lacking in rigorous, experimentally-tested engineering design guidance, with only a modest body of government reports, academic dissertations and theses, and peer-reviewed literature dedicated to structure fluvial mechanics and failure modes.

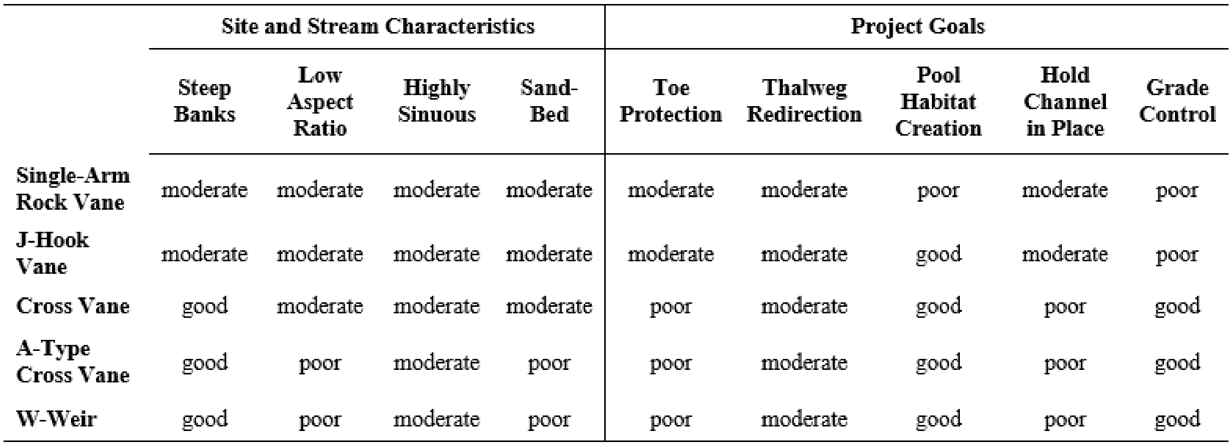
In spite of the lack of rigorous, data-based design guidance, vane-type in-stream structures continue to be installed for streambank stabilization and aquatic habitat creation or enhancement. Radspinner et al. (2010) conducted a survey of 64 stream restoration practitioners with experience in projects including in-stream structures and concluded that structures are regularly implemented as elements of stream restoration projects in 76% of US physiographic provinces, encompassing a wide range of stream morphologies, ecoregions, and aquatic habitat needs. Their finding that nearly three-fourths of surveyed practitioners believed that structures are a better choice for streambank stabilization than traditional hard bank armoring techniques, such as riprap, for multiple reasons – including lower installation costs and the potential for aquatic habitat enhancement – suggests that the installation of vane-type structures will likely continue regardless of whether advancements are made in the rigor of structure design guidance. This is especially likely given that, while some respondents expressed a desire for more rigorous design guidance during follow-up conversations, 80% still believed that preexisting design guidance was adequate for structure design and installation in the immediate term. Radspinner et al. (2010) also analyzed a set of 39 case studies of stream restoration projects including structures and found that the most common reasons for structure failure were incorrect material sizing, insufficient bank key length, and poor installation. Projects that included series of structures tended to be more successful than those with only single structures.

The same lack of rigor observed in the design of in-stream structures can also be found in the field of stream restoration as a whole. Upon surveying 317 stream restoration project managers, Bernhardt et al. (2007) found that almost half of their stream restoration projects were implemented with the core goal of correcting ecological and/or hydraulic problems in a stream reach. However, a lack of funding for rigorous monitoring led to the success or failure of 47% of projects being judged on the basis of the reach having a “more natural,” aesthetically pleasing post-restoration appearance, rather than on quantifiable, physically measurable criteria. Quantifiable criteria were only used to even partially determine project success about 59% of the time. Almost two-thirds of all projects were thus deemed to have been wholly successful, sometimes irrespective of whether their originally established project goals, which were quantifiable about 55% of the time, were actually met.

Structure Application

Sotiropoulos & Diplas (2014) conducted hydraulic studies of stone in-stream structures using three different approaches: laboratory studies of scale model structures in a flume, studies of full scale structures in an outdoor channel, and virtual studies using numerical modeling of the three-dimensional stream flow around structures. Use of structure design recommendations attributed solely to their findings should be restricted to streams sharing the characteristics of those on which their experiments and models were conducted: straight or mildly-sinuous gravel- or sand-bed streams less than 9 m (30 ft) wide. Sotiropoulos & Diplas (2014) compiled Tables 2.5 and 2.6. Structure suitability to site characteristics and project goals is summarized in Table 2.5, while structure susceptibility to common failure modes is summarized in Table 2.6.

Table 2.5: Structure suitability to site characteristics and project goals (Sotiropoulos & Diplas, 2014).



	Site and Stream Characteristics				Project Goals				
	Steep Banks	**Low Aspect Ratio**	**Highly Sinuous**	**Sand-Bed**	**Toe Protection**	**Thalweg Redirection**	**Pool Habitat Creation**	**Hold Channel in Place**	**Grade Control**
Single-Arm Rock Vane	moderate	moderate	moderate	moderate	moderate	moderate	poor	moderate	poor
J-Hook Vane	moderate	moderate	moderate	moderate	moderate	moderate	good	moderate	poor
Cross Vane	good	moderate	moderate	moderate	poor	moderate	good	poor	good
A-Type Cross Vane	good	poor	moderate	poor	poor	moderate	good	poor	good
W-Weir	good	poor	moderate	poor	poor	moderate	good	poor	good

Table 2.6: Structure susceptibility to failure modes (Sotiropoulos & Diplas, 2014).

	Failure Mode		
	Scour (Undermining)	**Flanking**	**Rock Displacement**
Single-Arm Rock Vane	moderate	high	moderate
J-Hook Vane	high	moderate	high
Cross Vane	high	moderate	moderate
A-Type Cross Vane	high	moderate	high
W-Weir	high	moderate	high

Newlin & Schultz (2015) discovered an example of poor structure application when they reviewed three years of monitoring data from a project which included a cross vane both upstream and downstream of a bridge crossing. The cross vanes were intended to prevent aggradation beneath the crossing by increasing water and sediment transport. Unfortunately, the flow condition created by the bridge crossing caused upstream backwater effects which promoted aggradation, preventing the upstream cross vane from forming a scour pool. Meanwhile, bed scour downstream of the bridge crossing undermined the downstream cross vane.

Use of Numerical Modeling in Structure Design

Endreny & Soulman (2011) analyzed monitoring data from the Batavia Kill stream restoration project in the Catskill Mountains of New York state, which had been collected for two years after the project was completed in 2002. They recommend the use of at least two-dimensional modeling, both in structure design and to anticipate needs in post-structure maintenance. For the cross vane in particular, the three-dimensional numerical modeling study conducted by Holmquist-Johnson (2011) is suggested as a possible template for designers to use to predict the hydraulic conditions – upstream water surface elevation and downstream flow velocity and bed shear stress – that may result from installation of cross vanes of different configurations. Kang & Sotiropoulos (2015) suggest their three-dimensional numerical modeling methodology as a means to simulate changes to the flow condition that would be caused by proposed single-arm rock vane configurations.

Gordon et al. (2016) used a three-pronged approach similar to Sotiropoulos & Diplas (2014) to improve structure design guidance through observation, experimentation, and modeling of stone cross vanes (both regular and A-type) and w-weirs. Their research included field surveys of existing in-stream structures, laboratory studies of scale model structures in a flume, and virtual studies comparing one-, two-, and three-dimensional numerical modeling of the stream flow around structures. Gordon et al. (2016) strongly recommend that numerical modeling be an integral part of the structure design process to better understand how the installation of structures will affect the stream flow condition. Based on the error produced by one-, two-, and three-dimensional numerical models when predicting water surface elevations and flow velocities around channel-spanning structures, they recommend that one-dimensional modeling be limited to modeling of the pre-restoration stream flow, as it is not sufficiently rigorous and detailed to capture the complexity of flow around an in-stream structure. However, pre-restoration stream flow modeling is still critical to structure design, especially in the prediction of expected downstream scour depths. Two- or three-dimensional modeling can then be used, with those predictions, to model flow around a prospective structure design.

Holmquist-Johnson (2011) determined stage-discharge equations for cross vanes in a large range of configurations, which might be used in design or for evaluation of existing structures. Thornton et al. (2011) did the same for cross vanes, A-type cross vanes, and w-weirs using laboratory studies conducted in an indoor flume.

Material Selection and Sizing

Harman et al. (2001) compiled their personal experiences with in-stream structures during the design of over two hundred North Carolina stream restoration and streambank stabilization projects to offer their own rules of thumb. They recommend that boulders selected for use in vane-type in-stream structures be no larger than 1.8 m (6 ft) in diameter, so that they are not too large to be lifted and placed by the installation equipment. Johnson et al. (2002a) conducted laboratory studies of scale model single-arm vanes, cross vanes, and w-weirs in flume conditions designed to mimic the flow conditions near bridge crossings and piers. They recommend that structures intended for infrastructure protection be considered elements of the infrastructure, and that therefore structure materials should be sized to withstand the forces of the same high design flow as the infrastructure, usually the 100-yr flow event.

Footer Depth

Johnson et al. (2002b) evaluated the failure modes of existing cross vanes at a completed urban stream restoration project on Minebank Run in Maryland. The cross vanes of the Minebank Run project experienced both undermining and flanking due to frequent clear water conditions (an influx of nearly sediment-free stormwater which causes significant scour to the bed and banks). They recommend that channel-spanning structures installed in urban streams which might experience clear water conditions be designed with a footer depth with a factor of safety of two.

The field surveys of existing structures conducted by Gordon et al. (2016) strongly suggest that proper sizing and depth of footer rocks, so that they exceed the long-term depth of the downstream scour pool, is critical to structure success. Proper footer design requires accurate methodologies for the prediction of downstream scour depth. For channel-spanning structures, Scurlock et al. (2012) recommend the equations developed from their scale model flume experiments. In addition, Gordon et al. (2016) assert that footer depth must be maintained below the expected depth of scour. Footer rocks must not share a vertical vane arm slope with surface rocks, which leaves the structure vulnerable to undermining and collapse.

Structure Placement within the Stream Cross-Section

Johnson et al. (2002a) found that larger horizontal vane angles of 25-30^{o} tended to more effectively protect infrastructure from scour during laboratory scale model flume experiments. Puckett (2007) conducted studies of full scale cross vane models of different configurations in an outdoor flume and also recommends vane angles of 25-30^{o}. Sotiropoulos & Diplas (2014) recommend larger vane angles, approaching 30^{o}, to protect longer bank lengths in mildly sinuous streams, and smaller vane angles, approaching 20^{o}, to avoid deflecting flows into the opposite bank in highly sinuous streams.

Based on their own personal experiences, Harman et al. (2001) allow for vertical vane arm slopes to be as steep as 10% if required by the specific site conditions. Puckett (2007) recommends vane arm slopes of 7% or less.

Despite the fact that the basic configuration of the cross vane (Figure 2.3) causes flow constriction, Puckett (2007) recommends that cross vanes installed in streams with highly erodible banks be designed to moderate flow constriction (with horizontal vane angles greater than 25^{o} and vertical vane arm slopes less than 7%) because high flow constriction in a highly erodible channel can lead to scour around the bank key and, eventually, structure failure by flanking. This finding was corroborated by the application of a rapid assessment methodology also developed by Puckett (2007) to 120 existing cross vanes in North Carolina.

Bhuiyan et al. (2007) conducted laboratory studies of a scale model w-weir in a sinuous, scaled experimental channel. They recommend that the horizontal vane angle of the outer arms of a w-weir be limited to 20-25° to more effectively redirect flows to the channel center. Where the two inner vane arms meet, the angle between them should be about 40°. This overall configuration necessitates longer vane arms for the w-weir, reducing their vertical slopes and the possibility of hydraulic jump formation at the downstream-directed inner apex. It also causes the formation of longer but shallower downstream scour pools, reducing the risk of structure undermining.

Structure Placement within the Stream Planform

According to Sotiropoulos & Diplas (2014), single-arm or j-hook vanes should be installed one bankfull channel width or less downstream of the meander apex in sinuous streams, except when the channel radius of curvature is low compared to the bankfull channel width, in which case the structure or the beginning of a structure series should be shifted one bankfull channel width upstream from the meander apex. In general, Sotiropoulos & Diplas (2014) recommend the following vector analysis for the planform placement and spacing of single-arm vanes and j-hook vanes in series of up to three structures, as shown in Figure 2.10. First, a line is drawn tangent to the meander apex, representing the horizontal (0°). The first structure of the series is placed here, with a horizontal vane angle of 20-30°, optimized to the site conditions, especially channel sinuosity. Next, draw another horizontal line parallel to the first, starting from the mid-channel vane arm tip of the first structure and continuing in the downstream direction. Then, draw a line with a 5° offset angle from the second horizontal. Place the second structure of the series where the offset angle line intersects with the streambank, so that it is collinear with the offset angle line. This process can be repeated once more for a third structure, if necessary, this time with an offset angle of 20°.

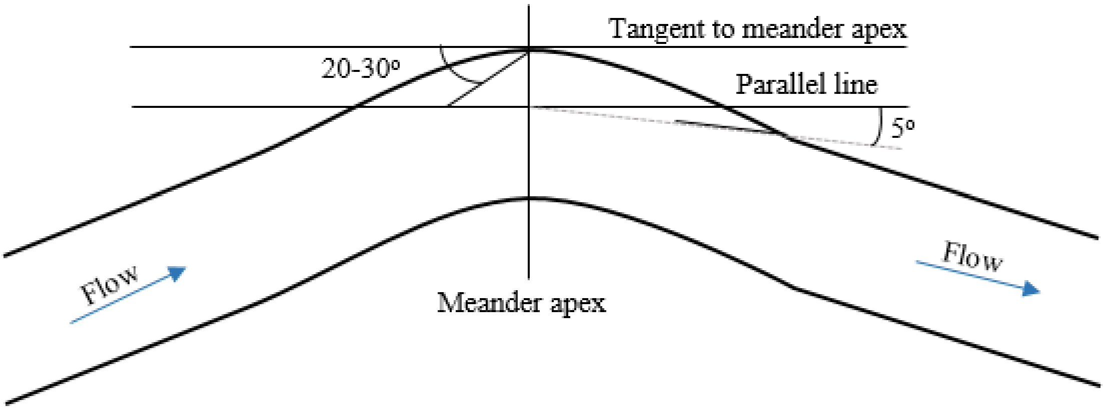


Figure 2.10: Planform placement of a two-structure series of single-arm vanes, based on the vector analysis method developed by Sotiropoulos & Diplas (2014).

Because the downstream scour pools formed by structures can extend as far as two channel widths downstream, especially for j-hook vanes, Sotiropoulos & Diplas (2014) recommend that structures installed to protect bridge piers or other infrastructure should be installed at least two channel widths upstream of that infrastructure, if not farther. A-type cross vanes, which create a longer downstream scour pool than regular cross vanes, should be installed at least three channel widths upstream of infrastructure or installed in series, which limits the length of the scour pool formed by each individual structure. W-weirs are not recommended for protection of in-stream infrastructure. This contradicts most preexisting design guidance with regards to the w-weir and is due to their observation that the two downstream scour pools formed by the w-weir may eventually merge, which would cause scour around a mid-channel bridge pier. However, it should be noted that their studies were limited to streams less than 9 m (30 ft) wide, while preexisting design guidance recommends that w-weirs only be installed in streams over 12 m (40 ft) wide; the scour pools formed by a w-weir might not merge in wider streams.

Water and Habitat Quality Benefits

Field and modeling studies conducted by Hester & Doyle (2008) support claims of the secondary ecological benefits of structures. In their experiments and models, channel-spanning rock structures were shown to be effective at inducing hyporheic exchange, flow between stream water and riparian groundwater which allows the exchange of nutrients. However, they note that the effectiveness of hyporheic exchange is dependent on the hydraulic conductivity of the bed sediment.

Collins et al. (2015) monitored streambed sediment composition and distribution for two years after the 2007 completion of a stream restoration project on the Little Coal River in West Virginia, which included j-hook vanes and cross vanes. By the end of the two-year monitoring period, gravel and cobbles constituted about 46% of bed sediment, and the portion of fine sediment (silt and sand) had been reduced by 27%. The stream restoration project was considered successful in increasing bed sediment heterogeneity for aquatic habitat purposes.

Structure Installation and Monitoring

Johnson et al. (2002a) stress the importance of placing geotextile fabric beneath structures in sand-bed streams, where they found that structures are at greater risk of failure by undermining. According to Gordon et al. (2016), grouting between the boulders of a stone structure can decrease the risk of rock displacement.

Because the new flow condition created by the presence of structures can affect the stability of the stream bed and banks downstream of a structure, Sotiropoulos & Diplas (2014) recommend that basic monitoring for undesired erosion or aggradation should be conducted at least five channel widths downstream of a structure. In accordance with their recommendation that structures intended to protect infrastructure from scour be considered elements of the infrastructure, Johnson et al. (2002a) recommend that those structures be inspected as often as regulations require the infrastructure to be inspected.

Recommendations for Future Research

Multiple references note that most of the currently accepted engineering design guidance for in-stream structures relies on sets of rules of thumb which are either largely unsupported by any data or which are only supported by empirical data from a limited set of streams. The lack of rigorous design guidance is largely attributed to the complexity of structure hydraulics and how they affect the overall fluvial system, which makes numerical modeling, as well as accounting for and controlling all applicable variables during field experimentation, correspondingly difficult. (Gordon et al., 2016; Holmquist-Johnson, 2011; Johnson et al., 2002b; Radspinner et al., 2010; Sotiropoulos & Diplas, 2014; Thornton et al., 2011). In addition, there is no standardized method of monitoring for structure success or failure, and monitoring regimes are rarely rigorous enough for monitoring data alone to be used to identify the fluvial processes which caused structure success or failure (Gordon et al., 2016).

Many references agree that, if in-stream structures are to be retained as a commonly-used element of stream restoration projects, the development of rigorous, experimentally-tested design criteria, guidance, and methodologies is imperative to avoid structure failures of stability and function, which bear a high cost of time, money, and effort (Gordon et al., 2016, Holmquist-Johnson, 2011; Radspinner et al., 2010; Sotiropoulos & Diplas, 2014). However, while studies which improve the general understanding of hydraulics and sediment transport around structures are valuable and necessary, they cannot improve structure success without being linked to specifics of structure configuration, site selection, or other design criteria (Bernhardt et al., 2007; Gordon et al., 2016). Further numerical modeling of structures with different configurations and in streams with different characteristics may be an effective way to continue to refine structure design guidance (Holmquist-Johnson, 2011; Kang & Sotiropoulos, 2015). One useful means of selecting structure design criteria or configurations for further experimental testing or numerical modeling might be to use records of structure success or failure from many case studies to identify specific, shared design choices which might have caused that success or failure (Gordon et al., 2016). The development of standardized methods for monitoring data collection and reporting, as well as increased funding for in-stream structure monitoring, would be invaluable in pinpointing structure failure modes as long as stream restoration projects that include in-stream structures continue to be implemented without the aid of rigorous engineering design guidance (Bernhardt et al., 2007; Endreny & Soulman, 2011; Johnson et al., 2002b).

Current Engineering Guidance for Step Pool Storm Conveyance

Step pool storm conveyance (SPSC) is a relatively new type of stormwater conveyance structure that is often used in conjunction with stream restoration projects. It combines elements of open channel design and urban stormwater best management practices (BMPs) into a single technique.

Sometimes also called the coastal plain outfall or regenerative stormwater conveyance (RSC), the steep SPSC combines step-pool channel morphology with filtration and infiltration capabilities similar to those of a bioretention cell or rain garden. The installation of a steep SPSC converts an existing, ephemeral first-order stream or gully (Figure 2.11) with a moderate-to-steep channel slope, generally 2% or greater, into a stable step-pool channel (Figure 2.12). The step-pool morphology is established through the use of a series of parabolic rock weirs for grade control, designed to behave like the large debris that controls elevation changes in naturally-occurring step-pool channels. The rock weirs are separated by shallow pools with beds of mixed sand-woodchip filtration media. One or more cascade sections controlling larger elevation changes may also be included in a steep SPSC. The pool areas and banks are often planted with native aquatic and riparian vegetation. (Flores et al., 2012).

Figure 2.11: Eastern Tributary site in Annapolis, MD before SPSC construction. Photo by Terry Schuman with Bay Engineering, Inc. (2011), used with permission.

Figure 2.12: Eastern Tributary SPSC in Annapolis, MD several years after its 2013 construction. Photo by Tess Thompson (2016), used with permission.

There are two other SPSC design variations intended for lower-slope channels, though they are less-commonly implemented and were not evaluated during this study. Sometimes also called the wetland seepage system, the first variation of lower-slope SPSC uses parabolic rock weirs to redirect the flow of a perennial stream into a shallow diversion with a bed of mixed sand-woodchip filtration media. The wetland seepage system is installed in streams with a low-to-moderate channel slope, generally 2% or less, which flood often, fostering wetland ecosystems on their floodplains. The filtration media bed of the stream diversion promotes infiltration back into main streamflow over time, allowing the stream to convey large, highly variable flows of urban stormwater runoff without losing its wetland-promotion functions. The second variation of lower-slope SPSC is sometimes called the constructed in-stream riffle and is implemented in incised perennial streams that also have low-to-moderate channel slopes of 2% or less. It uses in-stream parabolic rock weirs to slow streamflow, promoting sediment deposition in the pools between the weirs and increasing interaction between the stream channel and the floodplain, with the eventual end goal of improving in-stream water quality. (Flores et al., 2012).

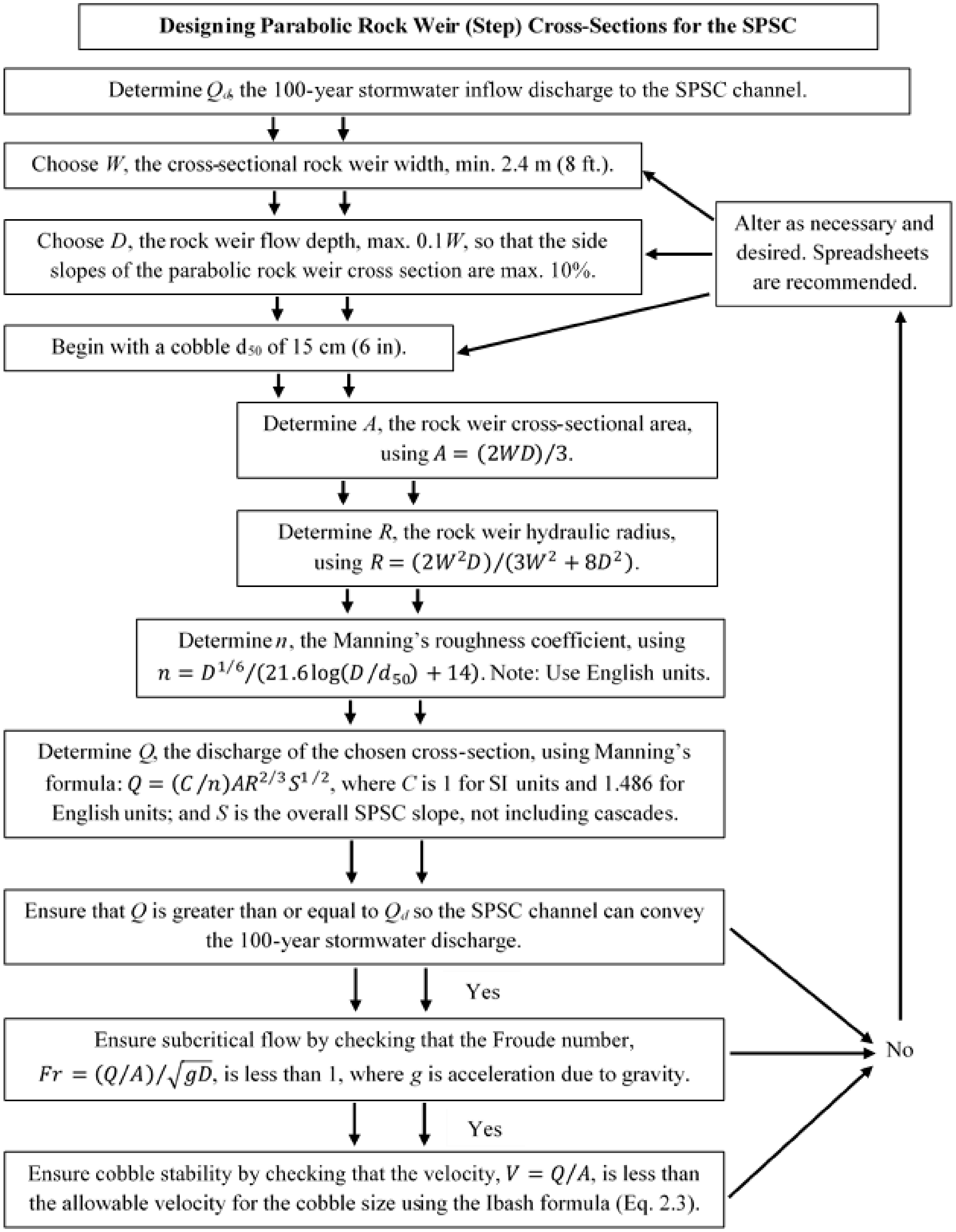
The focus of this study was the steep SPSC (also called the coastal plain outfall), which has four primary design purposes. First and foremost, the SPSC channel must be able to safely convey the design storm, which is usually a large, infrequent storm event such as the 100-yr storm. This condition must be met for the SPSC to be implemented in place of hard stormwater conveyance infrastructure such as storm drains and is thus the primary concern when designing the dimensions of the step-pool channel and rock weirs. (Flores et al., 2012).

Secondly, the steep SPSC stabilizes the existing first-order stream or gully in which it is installed, thus reducing stormwater runoff quality impairment due to sediment pollution and preventing critical failure of a steep slope due to frequent erosion. Stream channel or gully stabilization is partially achieved through energy dissipation as flow passes over the parabolic rock weirs. Reducing flow energy in the SPSC channel also reduces flow energy, flow velocity, and fluvial shear stress in the receiving stream, contributing to morphological stability due to reduced erosion there as well. Once mature, aquatic plant life in the SPSC channel will also assist in dissipating flow energy by increasing resistance. (Flores et al., 2012).

The last two design purposes are specifically achieved by the filtration media of the SPSC pool beds: namely, improving stormwater runoff quality by filtration and recharging shallow groundwater by infiltration. The more closely the SPSC pool bed media resembles the filtration media used in a bioretention cell, the more likely it becomes that the SPSC will fulfill these two purposes. Additional water quality improvements are achieved through the settling of sediment in the pools and the uptake of nutrients by aquatic plants. (Flores et al., 2012). The water quality benefits of an SPSC can also be improved by including other stormwater quality management BMPs in its drainage area (Palmer et al., 2014).

Structure Application, Design, and Installation

Detailed, step-by-step application, design, and installation procedures for the steep SPSC were published in 2012 by the Anne Arundel County Department of Public Works in Annapolis, MD. See Flores et al. (2012) for details. Other SPSC design guidance that has been published elsewhere uses the Anne Arundel County guidance (Flores et al., 2012) as the basis for their own recommendations (Center for Watershed Protection, 2012).



Designing Parabolic Rock Weir (Step) Cross-Sections for the SPSC

Determine Q_d, the 100-year stormwater inflow discharge to the SPSC channel.

Choose W, the cross-sectional rock weir width, min. 2.4 m (8 ft.).

Choose D, the rock weir flow depth, max. $0.1W$, so that the side slopes of the parabolic rock weir cross section are max. 10%.

Begin with a cobble d_{50} of 15 cm (6 in).

Alter as necessary and desired. Spreadsheets are recommended.

Determine A, the rock weir cross-sectional area, using $A = (2WD)/3$.

Determine R, the rock weir hydraulic radius, using $R = (2W^2D)/(3W^2 + 8D^2)$.

Determine n, the Manning's roughness coefficient, using $n = D^{1/6}/(21.6\log(D/d_{50}) + 14)$. Note: Use English units.

Determine Q, the discharge of the chosen cross-section, using Manning's formula: $Q = (C/n)AR^{2/3}S^{1/2}$, where C is 1 for SI units and 1.486 for English units; and S is the overall SPSC slope, not including cascades.

Ensure that Q is greater than or equal to Q_d so the SPSC channel can convey the 100-year stormwater discharge.

Ensure subcritical flow by checking that the Froude number, $Fr = (Q/A)/\sqrt{gD}$, is less than 1, where g is acceleration due to gravity.

Ensure cobble stability by checking that the velocity, $V = Q/A$, is less than the allowable velocity for the cobble size using the Ibash formula (Eq. 2.3).

Figure 2.13: Iterative method for designing rock weir cross-sections for the SPSC, as described in Flores et al. (2012).

One key element of SPSC design is determining the cross-sectional channel geometry and cobble size of the parabolic rock weirs, which must remain in place when subjected to the forces associated with the high design flow. Flores et al. (2012) details an iterative design calculation methodology using Manning’s formula (Eq. 2.1), as shown above in Figure 2.13.

Current Research on Step Pool Storm Conveyance

Because step pool storm conveyance (SPSC) is such a relatively new technique, little research has been conducted to evaluate SPSC water quantity and quality control in field applications. What literature there is mainly falls into one or more of the three following categories: case study evaluations of SPSC installation, as well as conditions immediately post-installation (Hall, 2016; Koryto et al., 2015); evaluations of the SPSC as a stormwater conveyance structure (Buchholz, 2017; Cizek et al., 2017; Cizek et al., 2018); or investigations of the stormwater quality improvement abilities attributed to the SPSC (Buchholz, 2017; Cizek, 2014; Cizek et al., 2018; Palmer et al., 2014).

Koryto et al. (2015) describe the 2014 installation of an SPSC in Durham, NC with a 10% overall channel slope and suggest that water quality benefits may not be as large immediately post-installation due to bank erosion where vegetation is not yet established. Hall (2016) details the 2015 installation process of an SPSC in Charlotte, NC, which was installed in an ephemeral erosion gully in a residential urban area. Due to the location of the structure, the presence of standing water in the SPSC pools between storm events generated concern and opposition from local residents. Eventually, the completed SPSC was extensively modified to allow the pools to drain quickly, undercutting its intended purposes of slow stormwater filtration and infiltration.

Cizek et al. (2017) conducted hydrologic monitoring on an SPSC with a channel slope of about 4% in Brunswick County, NC, in the mid-Atlantic coastal plain ecoregion. Cizek et al. (2018) conducted hydrologic and water quality monitoring on an SPSC with a 2.5% channel slope (not counting one cascade section) in Alamance County, NC, in the Piedmont ecoregion. Both studies found that the SPSCs converted a majority of surface stormwater runoff flow (86% and 78%, respectively) into seepage flow through infiltration into the pool bed media and through the rock weirs, reducing the peak velocity of stormwater runoff and mimicking a predevelopment hydrograph. Buchholz (2017) evaluated two SPSCs in Chapel Hill, NC (1.3% slope) and Durham, NC (8.2% slope) and confirmed that they safely conveyed stormwater runoff without experiencing excessive erosion or structural instability. Though preliminary findings from the new SPSC studied in Koryto et al. (2015) were developed during the condition of a seasonal high water table, peak surface flow discharge was still reduced by 41% during sufficiently small storm events of less than 13 mm (0.5 in).

Koryto et al. (2015) and Hall (2016) recognize that a seasonal high water table directly beneath an SPSC can lead to surface water ponding in SPSC pools and a reduction in the amount of stormwater runoff converted to seepage flow. The preliminary results of Koryto et al. (2015) suggest that a seasonal high water table condition might actually lead to the SPSC outflow discharge being greater than the runoff delivered from its drainage area during that period. Hall (2016) describes eventual, extensive SPSC modifications that were made to avoid surface water ponding in the SPSC pools, though Cizek et al. (2018) suggest that a habitat which more closely approximates a wetland environment will likely increase water quality improvement benefits to surface flow. However, the Charlotte, NC SPSC of Hall (2016) was installed in a residential urban area where standing water led to complaints from local residents. Hall (2016) also cautions against installation practices that lead to low infiltration rates of the porous SPSC pool bed media, namely compaction of the pool bed media during installation and exposure of the pool bed media to native fine soils below, which can be disturbed and clog the sand-woodchip filtration media. Hall (2016) recommends that filter fabric be placed beneath pools to prevent the filtration media from becoming clogged, though Flores et al. (2012) state that filter fabric would interfere with shallow groundwater recharge functions of the SPSC. Cizek et al. (2018) suggest specifically selecting sites with permeable native soils to avoid this conundrum.

The water quality monitoring conducted by Cizek et al. (2018) revealed that the Alamance SPSC reduced total suspended solids (TSS) in stormwater runoff by about 70%, and reduced total nitrogen (TN) and total phosphorus (TP) by 26% and 20%, respectively. Buchholz (2017) used the Chesapeake Bay Program removal adjustor curves to estimate similar removal rates at the two SPSCs evaluated during that study. The water quality monitoring of Cizek et al. (2018) included both surface flow at the SPSC outlet and seepage flow traveling beneath the SPSC rock weirs. It may be that a study which considered only the surface SPSC flow would not observe improvements of this magnitude, as many of the water quality benefits of an SPSC are attributed to runoff filtration through the porous pool bed media. In fact, Cizek (2014) reported that, when measuring nitrate and total Kjehdahl nitrogen (TKN) in seepage flow using monitoring wells in a Raleigh, NC SPSC with a slope of about 4%, concentrations decreased over time, suggesting that biological activity may be an important factor in nutrient reduction beneath the SPSC pool beds. In contrast to these studies, Palmer et al. (2014) earlier reported that SPSCs do not provide steady nitrogen removal that would lead to long-term benefits. Palmer et al. (2014) strongly recommend the use of stormwater management BMPs in the drainage area as opposed to SPSCs whenever possible, citing the damage caused by the installation process, including large sediment loads and removal of mature trees, and the fact that the water quality benefits of an SPSC will slowly be lost as suspended sediment settles in the pool beds.

Concerning habitat and ecosystem improvements caused by SPSCs, Cizek (2014) evaluated nine SPSC sites of various ages in Maryland and North Carolina and discovered that the habitat benefits of an SPSC increase over time, especially when care is taken to promote aquatic vegetation growth and a wetland ecosystem in and below the SPSC. However, the habitat creation potential of an SPSC is often limited by the pollutants and flashy runoff flows provided by the largely-impervious, urban drainage areas of most SPSCs.

Recommendations for Future Research

Cizek et al. (2017) identify a need for extensive monitoring of SPSC hydrologic performance over a range of seasonal conditions, which may increase understanding of the impact of seasonal high water table conditions as seen in Hall (2016) and Koryto et al. (2017). With regards to SPSC water quality benefit functions, Buchholz (2017) points out the need for a more rigorous understanding of SPSC nutrient removal processes, both in surface and seepage flow, and how they compare to similar processes in wetlands and open channels. Palmer et al. (2014) recommend extensive monitoring of SPSC sites before and after installation to gain a better understanding of hydrologic and water quality improvements. More peer-reviewed research on SPSC water quality improvement performance is desired in general.

The current literature is severely lacking in investigations of SPSC hydraulics and flow characteristics, knowledge that is crucial to design. While valuable and useful current research regarding hydraulics and design of steep or step-pool channels does exist (Chin et al., 2008; Lee & Ferguson, 2002; Schneider et al., 2015; Yochum et al., 2012; Yochum et al., 2014), it cannot necessarily be directly applied to SPSCs due to the hydraulic differences caused by the highly-porous sand-woodchip bed material of the SPSC pools, as well as the flashiness of the urban systems in which they are located.

Summary of Literature Review

Though vane-type in-stream structures (the single-arm vane, j-hook vane, cross vane, and w-weir) and step pool storm conveyance (SPSC) remain sorely lacking in rigorous design guidance developed from replicable experiments or numerical modeling, as well as in an understanding of how their presence changes the hydraulics, sediment dynamics, ecology, etc. of the fluvial system, they continue to be regularly installed as a preferred element of stream restoration projects for the purposes of streambank or outfall stabilization, grade control, aquatic habitat creation or enhancement, and water quality improvements. Until such guidance is developed, a certain risk of structure failure in stability or function must be accepted by designers and regulators due to this fundamental lack of physical understanding.

However, certain common failure modes and pitfalls can still be identified and avoided. Proper footer depth is widely acknowledged as crucial to structure stability, and a few options of more rigorous scour depth prediction equations or modeling templates have been developed. Additionally, structures should not be installed at project sites where they are fundamentally inappropriate, whether because restricting lateral stream migration is unnecessary or because existing hydraulics or sediment dynamics would almost certainly cause structure failure if they are not also addressed and altered. The rules of thumb contained in existing design guidance must not be treated as immutable, and alterations should be made to account for site-specific conditions.

Finally, many structure failures have been attributed to basic installation errors. Selection of experienced construction supervisors and heavy equipment operators, as well as designer oversight, is thus crucial to structure success.

The contents of existing design guidance and the design recommendations given in the research literature were synthesized with the insight and experience of agency representatives and practitioners to develop the structure factsheets produced by this study (see Appendix A), as detailed in Chapter 3: “Factsheet Development.”

Chapter 3: Factsheet Development

In-stream structure factsheets containing general guidance for the application, design, installation, and post-installation monitoring of the single-arm vane, j-hook vane, cross vane, w-weir, and step pool storm conveyance (SPSC) were produced during this study. The factsheets were developed by synthesizing and summarizing structure design recommendations contained in currently available design guidance and research literature (see Chapter 2: "Literature Review") and were revised with input from practitioners and agency representatives. The factsheets can be found in Appendix A as well as on the study website (https://sites.google.com/view/vtstreamstructures).

Agency Review Workshop

The first drafts of the structure factsheets were produced using existing design guidance and research literature alone. After their completion in April 2016, the first factsheet drafts were sent to participating agency representatives from Anne Arundel, Baltimore, Howard, and Montgomery Counties in Maryland and from the Maryland State Highway Administration (SHA). In June 2016, a workshop was held in Laurel, MD for review and suggested revisions of the factsheet drafts. Two highly experienced stream restoration designers and educators, Barbara Doll, PhD, PE with North Carolina State University and North Carolina Sea Grant and David Biedelspach, 5 Smooth Stones Restoration, were also consulted on factsheet revisions.

It was at the June 2016 workshop that the suggestion was made to select permit reviewers, regulators, and watershed and conservation groups as the target audience for the factsheets. Most stream restoration designers and practitioners who include vane-type in-stream structures in their projects are already familiar with the existing, available design guidance and rules of thumb, and may even have developed their own rules of thumb from personal design experience. Stream restoration designers who work in private consulting often also have access to proprietary design guidance and specifications, which they may have helped develop. For this reason, the finalized factsheets avoid detailed descriptions of calculation methodologies, which would primarily be used by designers, in favor of conveying concise general guidance and referencing currently-available methodologies deemed to be scientifically sound based on the current physical understanding of in-stream structures. Furthermore, a “factsheet” is, by nature, a source of concise and accessible general reference, not a detailed technical manual. Permit reviewers, regulators, and watershed groups do not necessarily require detailed technical specifications or calculation methodologies, but rather, sound and scientifically supported general information and guidance, as well as referrals to similarly sound and scientifically supported references to which they can turn to study the factsheet recommendations in further detail.

The selection of a target audience for the factsheets also illuminated what information would be most crucial to include: a correct understanding of structure purposes and appropriate application. The failures of many in-stream structures can ultimately be attributed to misapplication; they were installed in streams where they were unnecessary or inappropriate, or to fulfill functions they cannot perform. Though structures may indeed be useful for certain purposes associated with stream restoration, they are not a necessary element of every stream restoration project, and there are many other techniques and technologies which can be used to rehabilitate stream ecosystems or correct issues in stream hydraulics or channel instability. Structures should only be included in a stream restoration project when they would assist in meeting an overall project goal; are appropriate to the characteristics and limitations of the specific project reach; and would be able to fulfill their functions if installed in the existing or redesigned channel, considering the overall fluvial system (including but not limited to flow regime, channel substrate, or sediment transport patterns, for example).

Some specific design guidance and recommendations were also gleaned during the June 2016 workshop. Structures should be designed both to withstand a high design flow (either the 50- or 100-yr flow condition) and to function effectively at various low flows. Wood is an inappropriate construction material for urban streams, as highly variable (flashy) flow regimes expose logs to frequent wetting and drying cycles which accelerate decomposition, as well as to the high shear stresses and sudden changes in stream velocity, discharge, and flow depth that accompany flashy flow conditions. Design experience suggests that boulder sizes determined from sizing equations should be increased to prevent displacement, allowing for a more conservative design, and the density of the selected boulders should also be considered. Sandstone boulders should not be chosen for rock structures due to the relatively low density of sandstone. When predicting the depth of the downstream scour pool, the erodibility of the material beneath the streambed layer at the expected depth of scour should also be considered, as it is that material which would begin to scour if the pool exceeded the predicted depth. Visual inspection requirements for monitoring are preferred over survey requirements, as structures should be evaluated based on their effect on overall stream processes, rather than their ability to hold the channel cross-section in place.

Design of Practitioner Survey

An online survey of stream restoration practitioners was designed to gather their recommendations, experience, and insight with regards to in-stream structure application, design, installation, and post-installation monitoring, as well as the current perceived state of structure design guidance. Respondents were asked to answer questions about their own career experience; their use of or experience with structures in stream restoration projects; their preferred structure design guidance references; their preferred rules of thumb or calculation methodologies for various design parameters; knowledge gaps that they perceive in the existing structure design guidance; and their experiences with structure failures. This survey was sent to members of the Maryland Stream Restoration Association (MSRA), and the results were presented at their March 2017 quarterly meeting. After insights gained during the MSRA meeting, it was decided that the survey would be redesigned to target both stream restoration designers and project construction contractors, as they both have an integral role to play in bringing structures into reality. The construction firm Environmental Quality Resources, LLC was consulted in the development of further questions to target stream restoration contractors. The survey was then revised so that respondents who identified themselves as designers would be shown questions regarding their preferred design guidance, while those who identified themselves as contractors would be shown the added questions regarding structure installation and implementation monitoring (as-built surveys). The revised survey was sent to members of the Maryland Stream Restoration Association, as well as stream restoration listservs in Virginia and North Carolina. Both the questions and the results from the second, revised survey can be found in Appendix B.

Summary of Practitioner Survey Results

The survey questions and results can be found in Appendix B.

A total of 98 respondents completed the second, revised practitioner survey. A majority of respondents had at least some experience working for either private environmental consulting firms (93%) or government environmental or natural resource agencies (94%), and three-fourths of respondents had worked on both the design and construction of restored streams. The in-stream structures most frequently included in their stream restoration projects were the single-arm vane, j-hook vane, cross vane, and constructed riffle, while the stream barb and w-weir, which are more common in the western United States, were the least frequently included. Respondents reported only rarely or occasionally including step pool storm conveyance (SPSC) in a stream restoration project, likely due to the relative newness of the technique.

Questions targeted at the guidance preferences of those who indicated design experience revealed that 65% still relied primarily on specifications and rules of thumb authored by David Rosgen (1996; 2001), while 67% also relied on their own experiences from successful past projects. Proprietary or original structure specifications were used by 49%, while each of the other accepted design references (such as Doll et al., 2003; MDE, 2000; NRCS, 2007a) was a preferred resource for less than 40% of respondents.

The vast majority of respondents (96%) made the selection of a high design flow or design life an integral part of the design process. Of these, most (69%) selected the high design flow by prioritizing from a number of different predicted flows. Major factors driving the selection of wood as a construction material included log availability (55%) and increased habitat benefits compared to stone (38%). Perhaps the most obvious lack of designer consensus was in recommended footer depth. Despite nearly two-thirds (65%) of respondents having regularly used some type of equation or methodology to predict the ultimate depth of the downstream scour pool, only 17% actually used the results to help determine the necessary footer depth. Simply using one or two layers of footer rocks was acceptable for over a quarter (27%) of respondents. When asked to rank various monitoring strategies according to how well they believed they can indicate structure success, a majority (71%) of respondents stated that visual assessment was the best strategy. Nearly half (45%) of respondents stated that more rigorous monitoring and maintenance schemes would only be a partial solution to the problem of structure failures.

According to respondents, the most common reasons they have observed for structure failure are inappropriate use or misapplication of structures (43%) and improper installation (38%). Discussion at the March 2017 MSRA meeting confirmed that most practitioners recommend that the designers or design firm be involved in the selection of the construction contractor and that contractor selection be based on prior experience and success in stream restoration construction, rather than on bidding alone. According to the survey, only 28% of designers are always or almost always involved in the contractor selection process.

Questions targeted at construction contractors focused on structure installation and the interactions between contractors and designers during the installation process. Discussion at the MSRA meeting confirmed that in-stream structures were considered less likely to fail if a designer or other knowledgeable stream restoration professional was on site during the installation process to provide insight into the reasoning behind design choices and to help the construction team adapt to unanticipated problems or conditions. However, the survey revealed that construction oversight by a designer is almost equally likely occur (25-30%) during as little as 25% or as much as 100% of the construction process. When a designer is unavailable, construction is most likely to be overseen by a client representative or property owner (49%), who is very unlikely to be as knowledgeable about the specific project as the designer and who may not have a sound understanding of stream restoration principles whatsoever.

Summary of Factsheet Recommendations

Factsheet recommendations were developed through a synthesis of existing design guidance, review of research literature, and practitioner insight from the June 2016 agency review workshop and the 2017 online practitioner surveys. As recommended in the 2016 workshop, factsheets were targeted at permit reviewers, regulators, and watershed and conservation groups. The factsheets include “Caution” boxes interspersed throughout to highlight common pitfalls and failure modes to avoid.

The first section of each factsheet focuses on structure descriptions and purposes, giving clear and concise descriptions of the mechanics of important structure functions, such as flow deflection, flow energy dissipation, and grade control. As noted in the 2016 workshop, the first section emphasizes appropriate decision-making regarding when and whether to use structures, as does the second section of each factsheet, which covers structure application. Readers are warned that structures should only be included in a stream restoration project when they are truly necessary to fulfill a project goal and should not be installed when there is no sufficient justification for holding the stream channel morphology in place and preventing lateral stream migration.

The third section of each factsheet details general design guidance, with several subsections covering design flow selection, material selection, material sizing, footer depth, and structure placement within the stream cross-section and planform. The third section begins by encouraging readers to view the included guidance as rules of thumb rather than strict requirements, and to design structures to site-specific characteristics using calculations and numerical modeling. A range of design flows is recommended, both to ensure structure function at low flows and to ensure structure stability at high flows. An explanation of recurrence interval (return period) is given for those unfamiliar with the term, along with an example of how to use recurrence interval to calculate the structure stability risk associated with any individual flow event. It is recommended that every structure be accompanied by a selected design life and accompanying acceptable risk of failure. Recommendations for material selection largely follow those in preexisting design guidance. In the material sizing subsection, a brief explanation of shear stresses (including applied and critical shear stress) and their importance in rock sizing is given, and readers are referred to NRCS (2007c) for rock sizing methods. A factor of safety of 1.1-1.5 is recommended for rock sizing to create a conservative design. As mentioned during the 2016 workshop, readers are discouraged from selecting sandstone boulders, as the low density of sandstone makes it more vulnerable to displacement. Readers are referred to NRCS (2007b) and Gordon et al. (2016) for scour prediction calculations, and a footer depth of 1.5-3.0 times the expected scour depth is recommended. To predict scour depths in sand-bed streams, readers are referred to Wilcock et al. (2008). In general, the use of at least two-dimensional modeling in design, as described in Gordon et al. (2016), is strongly encouraged.

Concerning structure configuration, the horizontal vane arm angle recommendation of 20-30° found in most design guidance literature is retained, though with a warning that a larger horizontal angle protects a longer bank length but can cause greater downstream scour. The exception to this recommendation is the w-weir, for which the 20-25° bank angle range recommended by Bhuiyan et al. (2007) is given. Low vertical vane arm slopes are recommended to avoid causing scour on the downstream vane face, and an upper limit of 5% is recommended. Structures are not recommended to induce channel meandering, as has been suggested by some existing guidance (FISRWG, 2009; MDE, 2000; NRCS, 2007a). For structure placement near infrastructure, readers are referred to Johnson et al. (2002a). The vector analysis method developed by Sotiropoulos & Diplas (2014) is recommended for structure planform placement in meandering channels. Structure installation guidance does not deviate from that found in existing guidance references, though designer oversight during installation is strongly recommended.

Monitoring recommendations were heavily revised based on practitioner input during the 2016 workshop and 2017 online surveys. Visual assessment and a photographic record can be used to monitor most structure functions and provide success criteria. Other recommended monitoring activities, if the necessary funds and personnel are available, include the following: scour pool depth measurement and examination of scour and/or aggradation around structures; examination of streambanks for scour and vegetation establishment; and examination of structure stability after flow events equal to or greater than the magnitude of the high design flow. Stream and structure surveys may be useful, but should not necessarily be required for all projects.

The factsheets are mostly focused on design of structures intended primarily for streambank stabilization and/or grade control, rather than those intended primarily for aquatic habitat creation or enhancement. The latter is largely considered a secondary benefit of vane-type stream channel stabilization structures, and different in-stream aquatic habitat enhancement techniques exist which are designed to be deformable, to decay over time, and/or not to prevent natural channel migration. Many such techniques are detailed in Cramer (2012). However, because habitat quality is only a secondary benefit of vane-type in-stream structures, the factsheets do not cover how to design vane-type structures to prioritize habitat creation or enhancement.

The factsheet written for step pool storm conveyance (SPSC) was almost entirely based on Flores et al. (2012), as that is the only comprehensive and unique design guidance which has been published on that structure to date.

Chapter 4: Step Pool Storm Conveyance Flow Studies

Introduction

The Anne Arundel County, MD design guidance (Flores et al., 2012) currently recommends the use of Manning's formula in an iterative calculation process when designing the parabolic rock weirs and the step-pool channel of a steep step pool storm conveyance (SPSC) structure (Figure 2.13 in Chapter 2: "Literature Review"). Manning's formula is an empirical equation that describes uniform flow in open channels and was developed for low-gradient channels with regular geometry (Fischenich, 2000; Manning, 1891). The steep SPSC is none of these things except an open channel, and yet in this and many other situations, Manning's formula remains the standard prediction method for flow velocity due to its simplicity. It is widely acknowledged that selection of the Manning's roughness coefficient, n, is key to making accurate velocity predictions using Manning's formula (Diaz, 2005; Noss & Lorke, 2016). Thus, many methods for the prediction or estimation of Manning's n are available, from widely-accepted tabular references such as Chow (1959) to more recently-proposed methods such as use of relative bedform submergence (Yochum et al., 2012).

According to Yochum et al. (2012) and practitioner reports, accepted methods of predicting Manning's n tend to significantly under-predict n in step-pool channels. Accurate prediction of Manning's n during SPSC design is crucial because under-prediction of channel roughness leads to over-prediction of flow velocity, which in turn leads to under-prediction of the SPSC channel flow area needed to convey the design discharge. For example, consider an SPSC channel with a 5% slope, a chosen cobble d_{50} of 0.30 m (1.0 ft) and a design discharge of 2.8 m^3/s (100 ft^3/s). According to the Anne Arundel County design methodology for SPSC parabolic rock weir cross-sections (Flores et al., 2012; Figure 2.13 in Chapter 2: "Literature Review"), an SPSC for which an n of 0.05 was chosen could safely convey the design discharge with a width of 4.9 m (16 ft) and a depth of 0.46 m (1.5 ft), while one for which an n of 0.10 was chosen would need a greater width of 6.1 m (20 ft) and a greater depth of 0.61 m (2 ft). Note also that the first case returns a predicted velocity of 2.0 m/s (6.5 ft/s), while the second, with higher channel roughness, returns a lower predicted velocity of 1.2 m/s (4.0 ft/s). When large discharges with lower flow velocities than predicted enter an undersized SPSC, they spread out of the channel onto the surrounding steep slope, which can cause scour on the slope and around the sides of the parabolic rock weirs. Because SPSC channel roughness is consistently under-predicted, more recently-installed SPSCs have been oversized to compensate, adding to the already considerable cost of their construction.

The goal of this study was to evaluate different methods of predicting Manning's *n*, as well as one method of predicting the Darcy-Weisbach friction factor, *f*, to determine which method is most accurate when compared to roughness values calculated from measured flows through SPSC structures.

Methods

To determine how the different predicted values of the Manning's roughness coefficient, *n*, and the Darcy-Weisbach friction factor, *f*, compare to values calculated from measured SPSC flows, flow studies were conducted on two existing, steep SPSC (coastal plain outfall) structures in Anne Arundel County. Detailed topographic surveys of the SPSCs were conducted, and continual water level data from SPSC monitoring wells were collected for one year (July 2016 – July 2017). Flow velocity in the SPSCs was measured during storm events using a Rhodamine WT fluorescent dye tracer. This information, along with the reported design specifications of the study SPSCs and the Anne Arundel County design guidance methodology, was used to calculate *n* and *f*, both from measured flow velocities, six existing prediction methods for *n*, and one existing prediction method for *f*. The predicted values were then compared to the field-determined values.

Study Area

The two study SPSCs are located in the city of Annapolis within Anne Arundel County (Figures 4.1-2). The first is in the Eastern Tributary at the Annapolis Commons, located on Anne Arundel County property (38.9776^o N, 76.5587^o W). An ephemeral first-order stream, the Eastern Tributary drains a stormwater detention pond near the Anne Arundel County Board of Education office building and has a total drainage area of 7.6 ha (18.8 ac). The Eastern Tributary SPSC was constructed in 2013. (Bay Engineering, 2013). The second study SPSC is in an unnamed tributary to Broad Creek at Camp Woodlands, located on property of the Girl Scouts Council of Maryland (38.9690^{o} N, 76.5666^{o} W). An ephemeral erosion gully created by stormwater runoff flowing into Broad Creek, the Broad Creek Tributary has a total drainage area of 5.1 ha (12.5 ac). Construction of the Broad Creek SPSC was completed in 2015. (South River Federation, 2015).

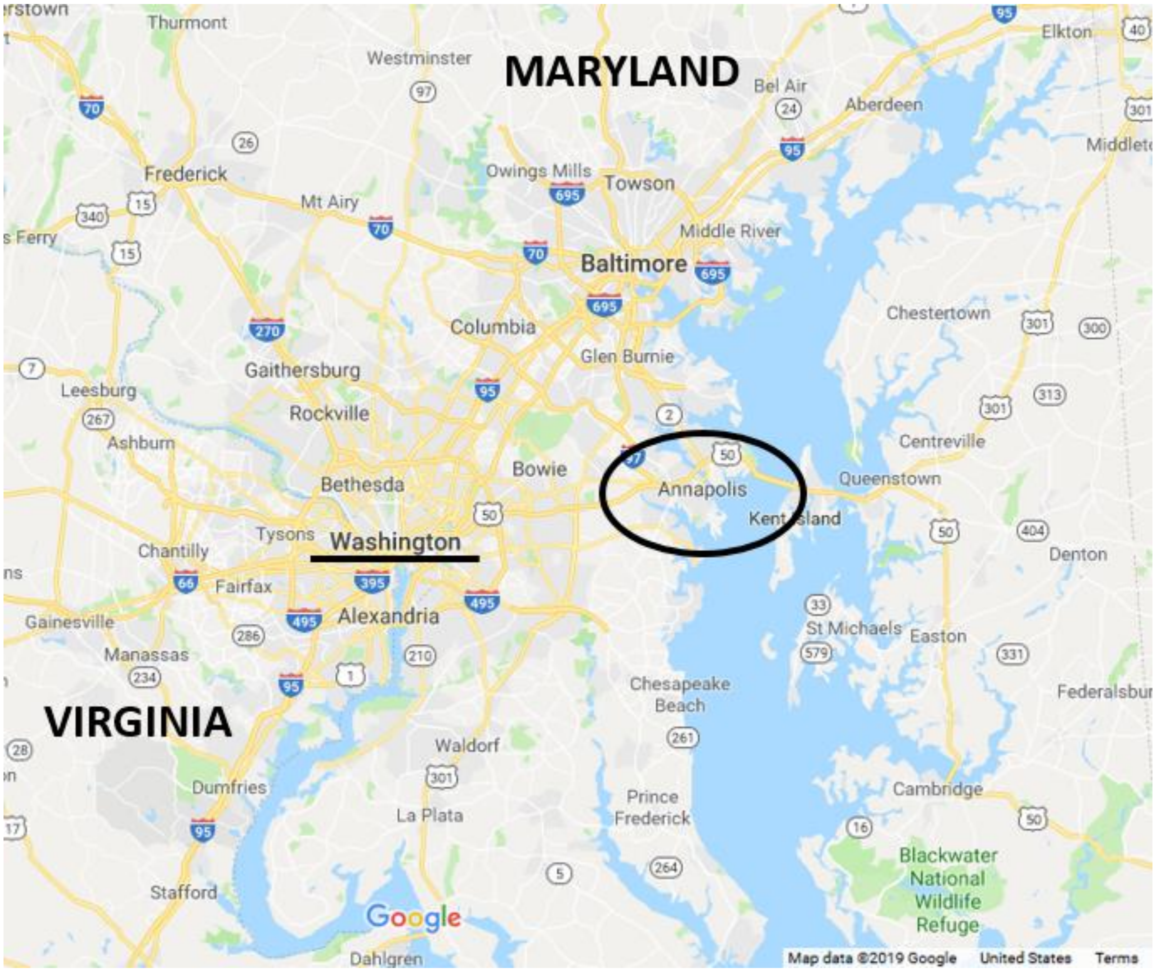


Figure 4.1: Annapolis, MD and its surroundings (Map data © 2019, Google).

Flow within these two SPSC structures is primarily urban stormwater runoff. The Eastern Tributary drains a stormwater detention pond that receives runoff from a complex of parking lots within a corporate office park. The Broad Creek Tributary receives runoff from Riva Road and from the parking lot of the Sts. Constantine and Helen Greek Orthodox Church across Riva Road from Camp Woodlands. Both SPSCs convey this runoff through their channels during and immediately after storm events. Between storm events, some water may remain in the pools until it is removed via a combination of surface runoff, infiltration, and evapotranspiration.

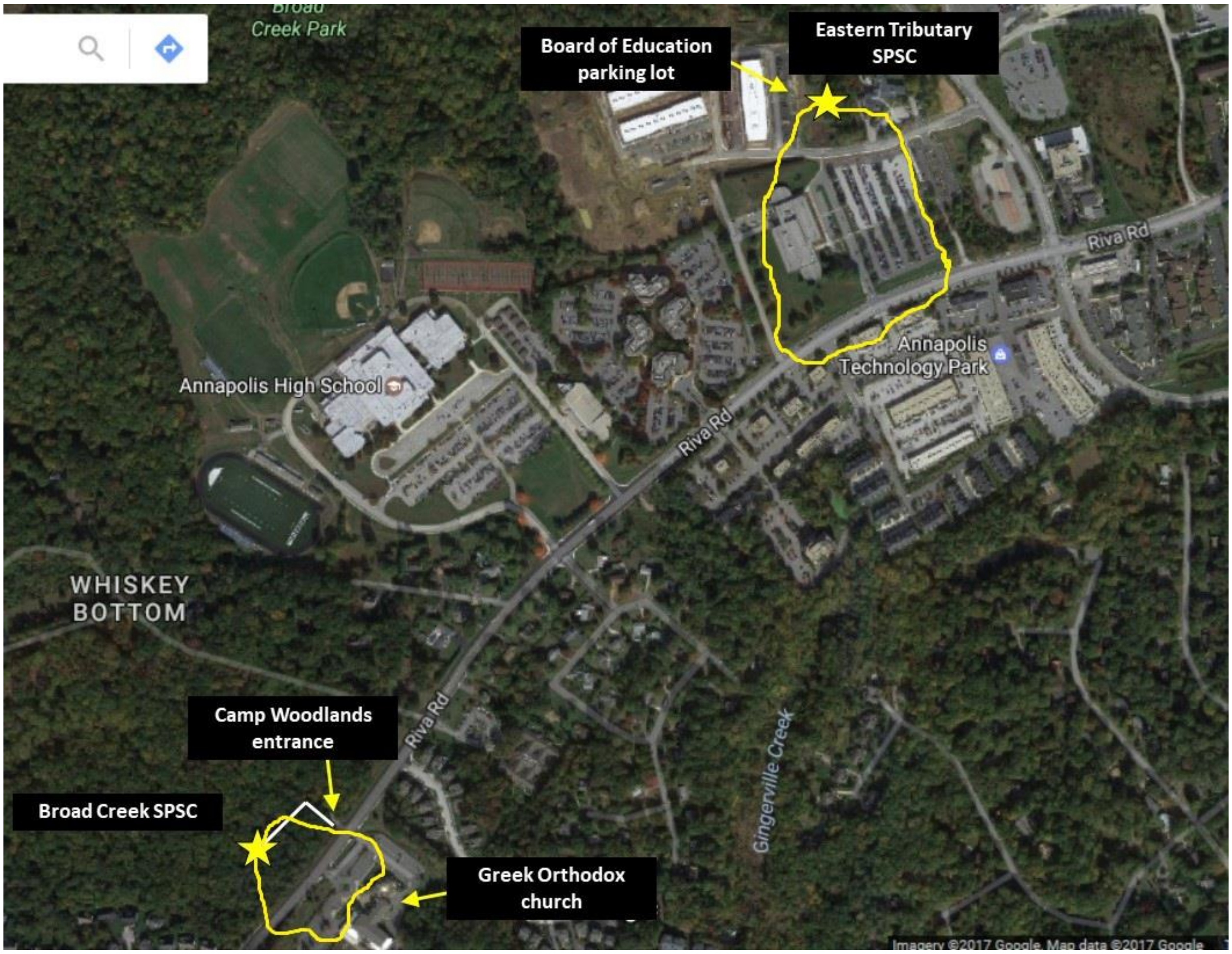


Figure 4.2: Location of the two study SPSC structures in Annapolis, MD (Map data © 2017, Google). Approximate drainage areas are shown in yellow (USGS, 2019).

At the Eastern Tributary, a smaller study reach was selected within the SPSC for two reasons. First, the length of the SPSC raised some concerns about the time it would take a dye slug to traverse the entire channel length. Second, a nearby bioretention cell drains via an outflow pipe into the fifth pool of the SPSC. This bioretention cell would have served as a lateral inflow to the study reach, complicating analysis of the dye tracer experiments, so the selected study reach began below the inflow point. The study reach for the Eastern Tributary consisted of the sixth through the fourteenth pools, terminating just before the first cascade. In contrast, the study reach at the shorter Broad Creek SPSC ran from the first pool to the fifth, nearly the entire length of the SPSC.

Figure 4.3: Eastern Tributary SPSC with upstream compound weir during the May 11, 2017 controlled flow releases. Photo by Tess Thompson (2017), used with permission.

According to the design plans for the SPSCs, the Eastern Tributary SPSC has an overall slope of 6.0%, which includes two steeper cascade sections (Bay Engineering, 2013). The 50-m (163-ft) long study reach contained no cascades and thus had a slightly gentler slope of 5.0%, as calculated from the topographic surveys. The Broad Creek SPSC overall and study reach slopes were very similar, at 7.3% and 7.4%, respectively, because the Broad Creek study reach contained the steepest sections of that SPSC. The Broad Creek study reach was 28 m (92 ft) long.

Instrumentation

Three 5.1-cm (2-in) diameter PVC monitoring wells were installed in each SPSC, with one well in the top (first) and bottom (last) pools of each SPSC study reach, as well as one well in the middle of each study reach. This middle well was installed in the tenth pool of the Eastern Tributary SPSC and the third pool of the Broad Creek SPSC. Each well contained an Onset U20-series HOBO water level data logger (Bourne, MA). A final data logger was placed above ground at the Broad Creek SPSC site to provide concurrent air pressure data for use in converting absolute water pressures to water levels. The sites were close enough geographically that the same air pressure data were used for both sites. See Appendix D for water level monitoring data from the storm events and controlled flow releases during dye tracer experiments.

Discharge in the Eastern Tributary SPSC was measured using a wooden compound weir installed across the top pool of the study reach, just downstream of the top water level monitoring well at that site. As shown in Figure 4.4, the weir consisted of three identical, small v-notch weirs set within the rectangular notch of a larger weir. Metal plates were affixed to the v-notch weirs on the upstream side to give them sharp crests. Similar weirs were installed at the bottom pool of the Eastern Tributary SPSC study reach and at the top and bottom pools of the Broad Creek SPSC study reach. The weir installation was featured in a news story in the Capitol Gazette on July 14, 2016 (http://www.capitalgazette.com/news/environment/ph-ac-cn-virginia-techrestoration-0715-20160714-story.html). Annapolis experienced record rainfall in July 2016 – 230 mm (9.1 in) total for July, including five storms in excess of 25 mm (0.98 in) – immediately following weir installation. This, combined with the highly erodible nature of the pool bed media and the presence of large rocks at a shallow depth, which limited the depth of the weir foundations, caused three of the four weirs to experience extensive undercutting. Despite efforts to reinforce the weir foundations and prevent undercutting, all of the weirs except the top weir at the Eastern Tributary SPSC were eventually removed.

Figure 4.4: Top pool compound weir at the Eastern Tributary SPSC with accompanying monitoring well. Note red dye entering the pool. Photo by Tess Thompson (2017), used with permission.

Topographic Surveys

Detailed topographic surveys of both SPSC study reaches were conducted June 21-24, 2016; July 28-29, 2016; and July 17, 2017 using a TopCon GT series total station (Livermore, CA). As all the dye tracer experiments were conducted between February and June 2017, the final, July 2017 survey was temporally closer and thus used in calculations. Longitudinal profiles of the study reaches were used to calculate reach slopes and lengths. Detailed cross-sectional surveys of each parabolic rock weir within the study reaches were conducted at each site. These surveys can be seen in Appendix C.

Velocity and Discharge Measurement

Rhodamine WT dye tracer experiments were conducted in the SPSC study reaches to measure time of travel and reach-averaged velocity. A Cyclops-7 Logger by Turner Designs (San Jose, CA) with a Rhodamine WT sensor was placed at the bottom of the study reach in close proximity to the bottom monitoring well at each site (Figure 4.5). Once the pools were filled and steady flow was achieved, a Rhodamine dye slug was introduced into the flow in the pool above the top pool of the study reach to allow for sufficient mixing. When the resulting time-concentration curve was evaluated (Figure 4.6 and Appendix E), the time (x-coordinate) of the centroid of the area beneath the curve was used as time of travel. The centroid was determined by using spreadsheet-based block integration to estimate the area beneath the time-concentration curve and find the centroid of that area. Study reach length was then divided by time of travel to obtain reach-averaged velocities.

Unfortunately, a good deal of the study period (July 2016 to July 2017) fell during a drought period in which there were few storms sufficient to conduct dye tracer experiments. Monthly precipitation during the study and long-term average precipitation are shown in Figure 4.7. At the Eastern Tributary, several tracer experiments were conducted by blocking the outlet of the stormwater detention pond, allowing the pond to fill during a storm event and its volume to be released into the SPSC for a tracer experiment.

Figure 4.5: Rhodamine WT dye sensor in the bottom pool of the Broad Creek SPSC during the May 11, 2017 controlled flow releases. Photo by Tess Thompson (2017), used with permission.

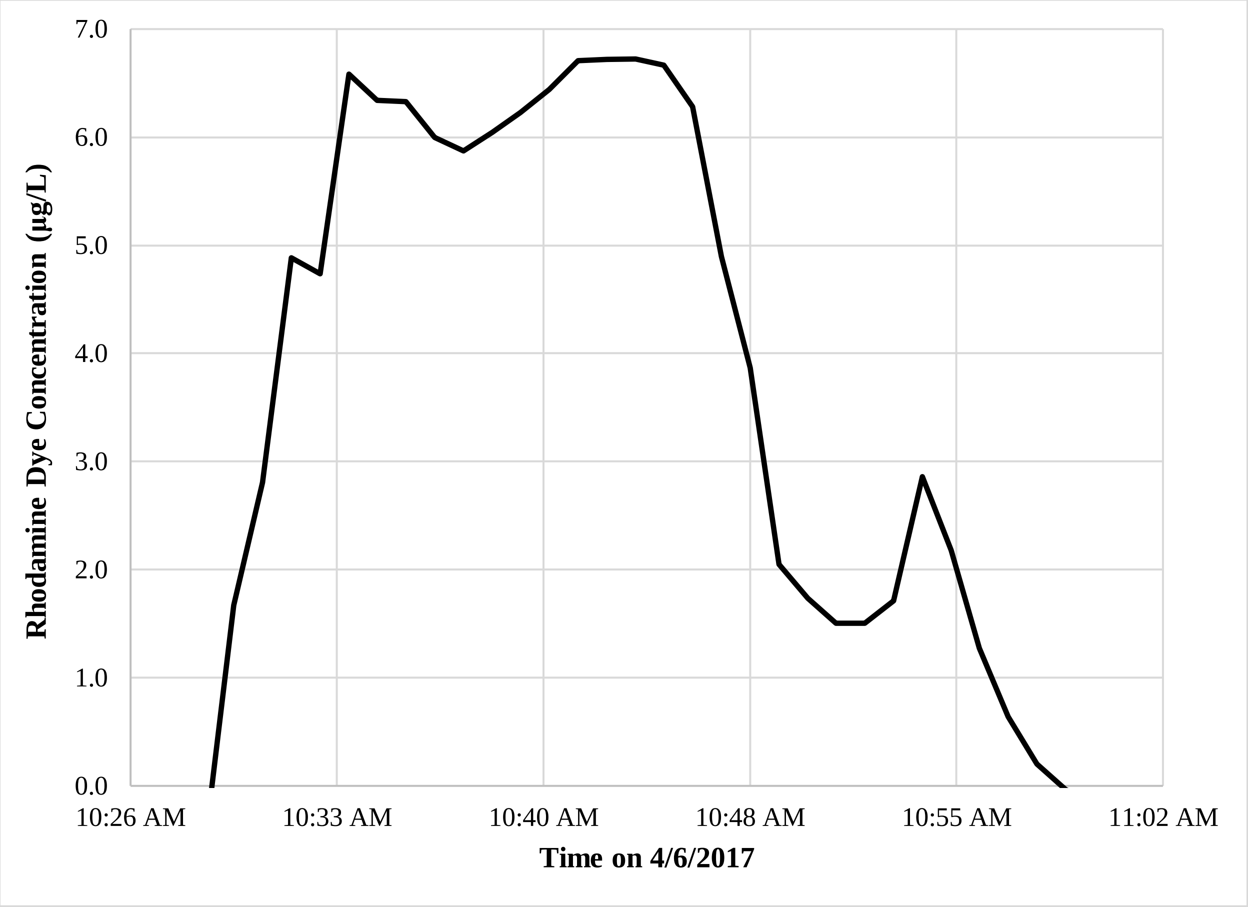


Figure 4.6: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during a storm on Apr 6, 2017. Dye slug was introduced to the stream at 10:15 AM.

In addition to dye tracer experiments conducted during storm events, controlled flow releases were conducted using constant discharges from fire hydrants on May 11, 2017. Flow rates were measured using the flow meter associated with the Pollard LPD250 dechlorinating diffuser (Hyde Park, NY) supplied by the Anne Arundel County Department of Public Works. Three flows ranging from 0.023 to 0.055 m^3/s (365-870 gpm) were released at the Broad Creek SPSC, while two flows of 0.038 and 0.015 m^3/s (600 and 230 gpm) were released at the Eastern Tributary SPSC. The maximum flow rate that could be achieved at each location was determined by local water pressures in the water supply pipes.

As well as providing additional velocity measurements, these controlled flow releases enabled the calibration of the standard sharp-crested v-notch and rectangular compound weir discharge equations for the Eastern Tributary SPSC (Eq. 4.1-2, English units only) and the development of a stage-discharge relationship for the Broad Creek SPSC (Eq. 4.3, English units only), where the compound weirs had been removed because they were repeatedly undermined. The compound weir equations developed for the Eastern Tributary SPSC were

V-notch weir equation: $$Q = 7.5h^{2.5} \tag{4.1}$$

Rectangular weir equation: $$Q = 0.73 + (7.4)9.6h^{1.5} \tag{4.2}$$

where Q is discharge (ft^3/s) and h is head above the weir crests (ft), determined using the water depth in the top monitoring well and the surveyed elevations of the water monitoring well and weir crests. The value of 0.73 in the rectangular weir equation represents the discharge (ft^3/s) of the three v-notch weirs when full, while 7.4 represents the calibrated weir coefficient *C* and 9.6 is measured weir length (ft). The stage-discharge equation developed for the Broad Creek SPSC was

$$Q = e^{2.3h+1.5} \tag{4.3}$$

where Q is discharge (ft^3/s) and h is water depth in the middle monitoring well (ft).

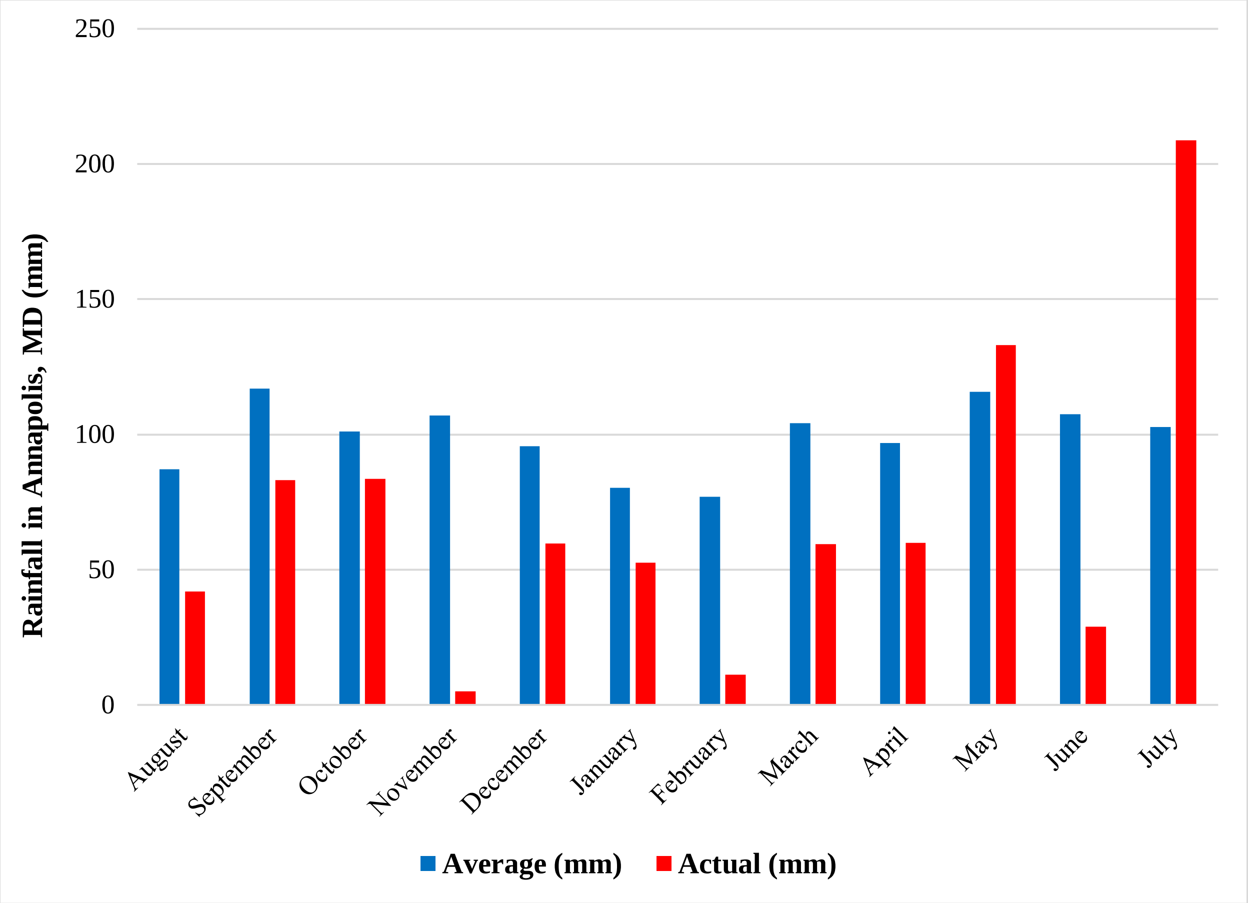


Figure 4.7: Average monthly precipitation during the study period (Aug 2016-Jul 2017) in Annapolis, MD and for 1981-2010 in nearby Laurel, MD.

Calculation of Manning's n and the Friction Factor f

Reach-averaged velocities from the dye tracer experiments and measured discharges were used to calculate Manning's n and the Darcy-Weisbach friction factor f from Manning's formula and the Darcy-Weisbach equation, respectively. Using the continuity equation,

$$Q = VA \tag{4.4}$$

where Q is discharge in m^3/s, V is velocity in m/s, and A is cross-sectional flow area in m^2, the cross-sectional flow area, A, of the channel was calculated from measured velocity and discharge. Flow area was, in turn, used to calculate the flow depth, h in m, above the parabolic rock weirs and the hydraulic radius R in m of the flow, using the parabolic cross-sectional geometry equations

(Eq. 4.5-6) recommended in the iterative channel design methods outlined in the Anne Arundel County SPSC design guidance (Flores et al., 2012; Figure 2.13 in Chapter 2: “Literature Review”) and the weir widths, w, from the SPSC design plans (Bay Engineering, 2013; South River Federation, 2015).

$$A = (2wh)/3 \tag{4.5}$$

$$R = (2w^2h)/(3w^2 + 8h^2) \tag{4.6}$$

where w is weir width in m for both equations (4.5-6).

Both h and R were calculated from measured flow velocities rather than directly measured themselves because the nature of flow through the highly porous and irregular rock weirs made direct measurement difficult. The Anne Arundel County design methodology was utilized to minimize variation in everything except n from calculations similar to those which would be made during design, as the purpose of this study was to improve SPSC design by varying the prediction of roughness parameters only. Manning’s n and the Darcy-Weisbach friction factor f were then back-calculated from their respective equations, Manning’s formula (Eq. 2.1 in Chapter 2: “Literature Review”) and the Darcy-Weisbach equation,

$$V^2 = \frac{8}{f} gRS \tag{4.7}$$

where S is reach slope in m/m and g is the acceleration due to gravity, 9.81 m/s^2.

Six methods of predicting n and one method of predicting f were calculated (Table 4.1). Chow (1959) was selected as a widely-accepted tabular reference. Strickler’s relation is a common method of predicting n based on the median grain size (d_{50}) of the bed sediment, here approximated by the design d_{50} of the of the cobble aprons of the SPSC rock weirs. The method recommended in the Anne Arundel County design methodology is also included (Flores et al., 2012). The SPSC design guidance indicates the source of that equation as the 2006 NRCS standard for lined waterways; however, the source is a prior version of this standard, USDA-SCS (1989). The method from the 2006 NRCS standard was included as well. It should be noted that the Anne Arundel County recommended method of *n* prediction (Flores et al., 2012; USDA-SCS, 1989) specifically calls for h_{100} because the design is based on the stormwater runoff flows resulting from the 100-yr storm event. For comparison to *n* values determined from measured flows, the depths associated with those measured flows were used to predict *n* using the 1989 USDA-SCS equation.

h/d_{84} and h/σ_z are methods of calculating relative bedform submergence in a step-pool channel that can be used as predictors of *n*, as described in Yochum et al. (2012; 2014). The longitudinal and cross-sectional surveys were used to determine σ_z, which is the standard deviation of the residuals of the bed elevations and is used to calculate h/σ_z. To determine σ_z, a simple linear regression of the combined longitudinal and cross-sectional bed elevations was first conducted to determine a single elevation at each parabolic rock weir cross section. Residuals (error) between the measured cross section elevations and the single elevation from the linear regression were calculated. The standard deviation of those residuals is σ_z. In-stream structures constructed of large, interlocking rocks, σ_z represents the protrusion height of those rocks, which can be more representative of flow resistance than prediction methods that use rock diameter (d_{50}; Yochum et al., 2012).

Finally, the Colebrook-White equation is a method of predicting the Darcy-Weisbach friction factor, *f*, which takes into account both flow depth and grain size. Where used in these calculations, *h* and *R* are those which were calculated from measured flow velocities, as detailed above.

Table 4.1: Methods of predicting *n* and *f* used in this study.

Manning's *n*	h/d_{84}	$n = h/d_{84}$
	h/σ_z	$n = h/\sigma_z$
	NRCS (2006)	$n = 0.047(d_{50}S)^{0.147}$
	Flores et al. (2012); USDA-SCS (1989)	$n = h^{1/6}/(21.6\log_{10}(h/d_{50})+14)$
	Chow (1959)	tabular
	Strickler’s relation	$n = 0.04d_{50}^{1/6}$
Darcy-Weisbach *f*	Colebrook-White eq.	$f^{-1/2} = 2.03\log_{10}(xR/3.5d_{84})$; $x = 11.1(R/h)^{-0.314}$

Results

As stated above, a significant drought occurred during the study period. Ironically, the most significant rainfall occurred just before and just after the monitoring equipment was installed (Figure 4.7). As such, the flow events that occurred during the study period were one to two orders of magnitude lower than the design storms (Table 4.2). The 100-yr discharge and velocity used in design calculations were 3.4 m^3/s (120 ft^3/s) and 2.2 m/s (7.2 ft/s), respectively, for the Eastern Tributary SPSC (Bay Engineering, 2013). For the Broad Creek SPSC, the 100-yr design discharge and velocity were 1.4 m^3/s (49 ft^3/s) and 0.8 m/s (2.5 ft/s), respectively (South River Federation, 2015). Statistically speaking, the probability of a 100-yr recurrence interval event occurring in any given year is 1/100, or 1%. Therefore, natural storms were supplemented with controlled flow releases from nearby fire hydrants. Fire hydrants can typically produce flows up to 0.095 m^3/s (3.3 ft^3/s or 1500 gpm), depending on local water pressure.

Table 4.2: Results of time-of-travel dye tracer experiments at the SPSC reaches. Controlled flow releases were conducted on May 11, 2017.

	Date	Velocity (m/s)	Discharge (m^3/s)	Fr	Manning's *n*	Darcy-Weisbach *f*
Broad Creek	2/25/2017	0.009	0.010	0.002	12	17000
	3/31/2017	0.018	0.058	0.003	11	10300
	4/6/2017	0.017	0.003	0.003	1.7	710
	5/11/2017	0.037	0.023	0.005	2.0	590
	5/11/2017	0.049	0.055	0.005	2.2	590
	5/11/2017	0.037	0.041	0.004	2.9	1030
	6/19/2017	0.055	0.003	0.010	0.28	26
Eastern Tributary	3/31/2017	0.042	0.011	0.005	0.50	65
	5/11/2017	0.031	0.038	0.004	1.8	520
	5/11/2017	0.015	0.015	0.002	3.5	2040
	5/22/2017	0.021	0.041	0.003	3.8	1900
	6/19/2017	0.029	0.101	0.004	4.0	1700

During storm events, water initially flowed through, rather than over, the parabolic rock weirs, filling the pools. Once the pools were filled, the water would typically overtop the rock weirs, with flow occurring primarily in the center of the weir, as shown in Figure 4.9. In the pools, most of the flow traveled straight through the center of the pool, with slower eddies circulating on either side of the main core of flow.

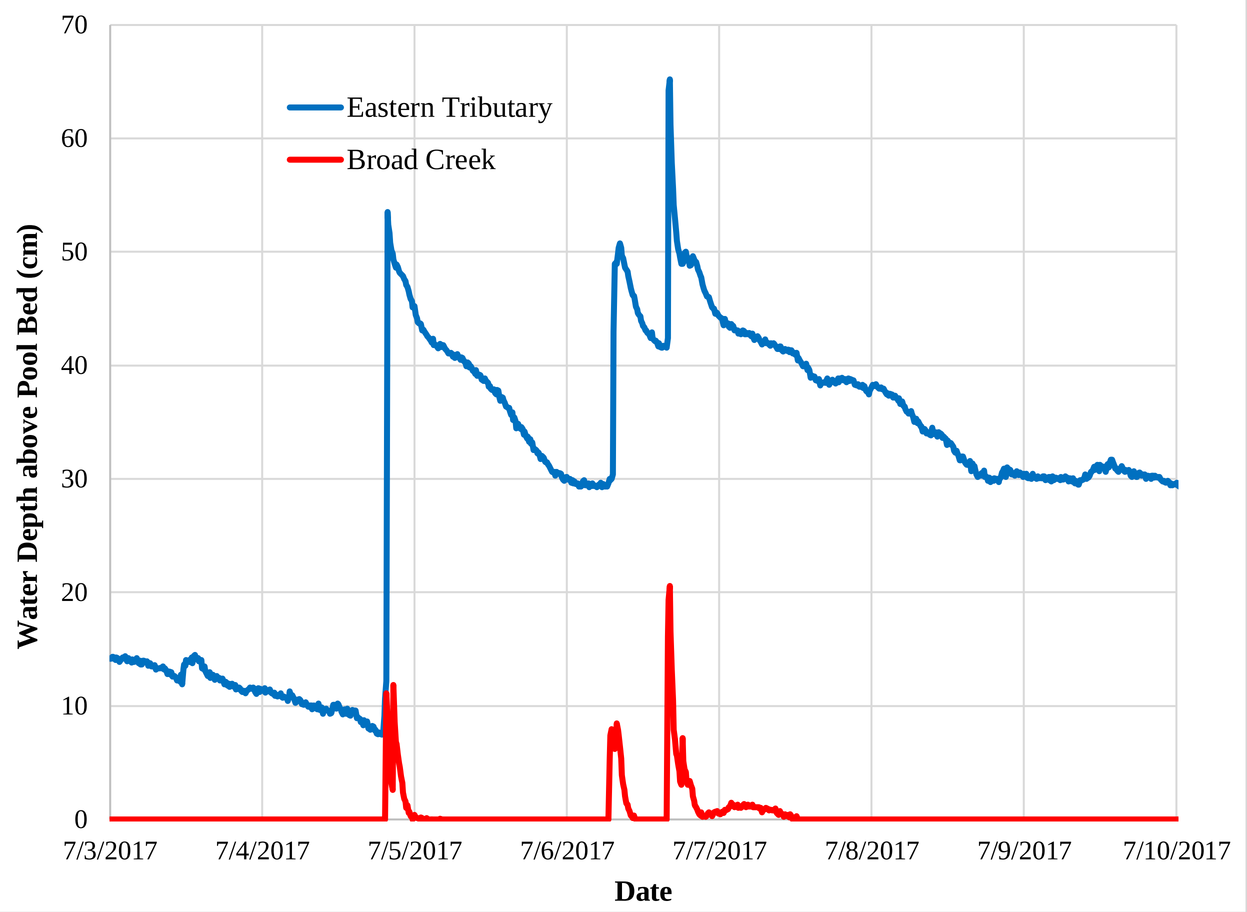


Figure 4.8: Water depths in the middle pools of the study SPSCs. Rainfall depths of 20.3, 1.3, 4.1, and 35 mm occurred Jul 4, 5, 6, and 7, 2017 respectively.

Water depths above the bottom of the middle pool of each SPSC during a series of storm events in July 2017 are shown in Figure 4.8. Water levels in the SPSCs increased sharply in response to storm events, with water flowing over the weirs. Once the rainfall ended, the pools slowly drained, first through the rock weirs and then through the porous pool bed media. The pools at the Broad Creek SPSC typically drained below the level of the pool bed comparatively quickly. However, the pools at the Eastern Tributary SPSC held water for longer periods, either due to higher local groundwater levels or lower infiltration rates through the pool beds. A larger number of amphibians and insects were observed at the Eastern Tributary SPSC site, likely due to the longer periods of ponding there.

During the dye tracer experiments, the bulk of the dye traveled within the higher velocity core of the water, although mixing occurred in the pools. The reach-averaged velocities measured during the dye tracer experiments are listed in Table 4.2. These velocities incorporate the faster flow over the rock weirs and the slower flow through the pools, and are therefore lower than what is predicted for the rock weirs during design. Similarly, each of these velocities yields a Froude number solidly in the subcritical range, ranging from 0.002 to 0.010, despite the fact that flow over the rock weirs is likely supercritical during low flow conditions, based on observations during flow events.

Figure 4.9: Flow over rock weirs at the Broad Creek SPSC on May 11, 2017, just prior to dye release. Photo by Tess Thompson (2017), used with permission.

Field-determined values of both *n* and *f* varied significantly between storm events (Tables 4.2-3 and Figures 4.10-11), with ranges of 0.28 to 12 for Manning's *n* and 26 to 17000 for *f*. Differences among the multiple roughness predictions are likely due to changes in the SPSCs over time due to vegetation growth, scour, and debris accumulation. During the spring, large leaf packs in the Broad Creek SPSC blocked the tops of the weirs, raising water levels and limiting flow over the weirs. Additionally, there were likely errors in the flow measurements, which could occur due to changes in flow rates resulting from variations in rainfall rates, as well as from errors inherent in flow measurements in natural systems. Average Manning's *n* values were 4.5 and 2.7 for the Broad Creek and Eastern Tributary SPSCs, respectively; these average values are not statistically different, as determined using a two-sample t-test with unequal variances (p=0.38).

Table 4.3: Ranges of field-determined and predicted *n* and *f* values for each study SPSC. Note that the tabular Chow (1959) reference and methods based on grain size have only one value.

	Broad Creek	**Eastern Tributary**
Manning's *n*		
Field-determined	0.28 – 12	0.50 – 4.0
h/d_{84} as *n*	0.07 – 3.4	0.08 – 1.1
h/σ_z as *n*	0.08 – 3.9	0.14 – 1.9
NRCS (2006)	0.03	0.03
Flores et al. (2012); USDA-SCS (1989)	-0.13 – 0.17	-0.17 – 0.11
Chow (1959)	0.05	0.05
Strickler's relation	0.04	0.04
Darcy-Weisbach *f*		
Field-determined	26 – 17000	65 – 2040
Colebrook-White eq.	0.32 – 5.6	0.49 – 94

Both Manning's *n* and the Darcy-Weisbach friction factor *f*, as calculated from measured velocities and discharges, were consistently and considerably higher (Table 4.3) than the values reported in Chow's accepted tabular reference (1959) or predicted from common methods based on grain size (Colebrook, 1939; Strickler, 1923). The same is true for the method recommended in the Anne Arundel County SPSC design guidance (Flores et al., 2012; USDA-SCS, 1989), which predicts *n* based on grain size and flow depth, as well as the NRCS lined waterway method (2006), which is also based on grain size. The Anne Arundel County predicted values were even occasionally negative when h/d_{50} was less than 1.0, due to the use of the common logarithm in the calculations. While closer to the field-determined values than the rest, use of h/d_{84} or h/σ_z as predictors of *n* could still be up to an order of magnitude lower than the field-determined values. The d_{84} and d_{50} values for the Eastern Tributary and Broad Creek Tributary SPSCs were 30 cm (12 in) and 53 cm (21 in) and 15 cm (6 in) and 30 cm (12 in), respectively, as determined from the construction specifications. The σ_z for the Eastern SPSC was 0.86 while the σ_z for the Broad Creek SPSC was 1.00. Calculated water depths over the weirs ranged from 0.044-0.57 m (0.14-1.9 ft) for the Eastern Tributary and from 0.020-1.02 m (0.07-3.4 ft) for Broad Creek.

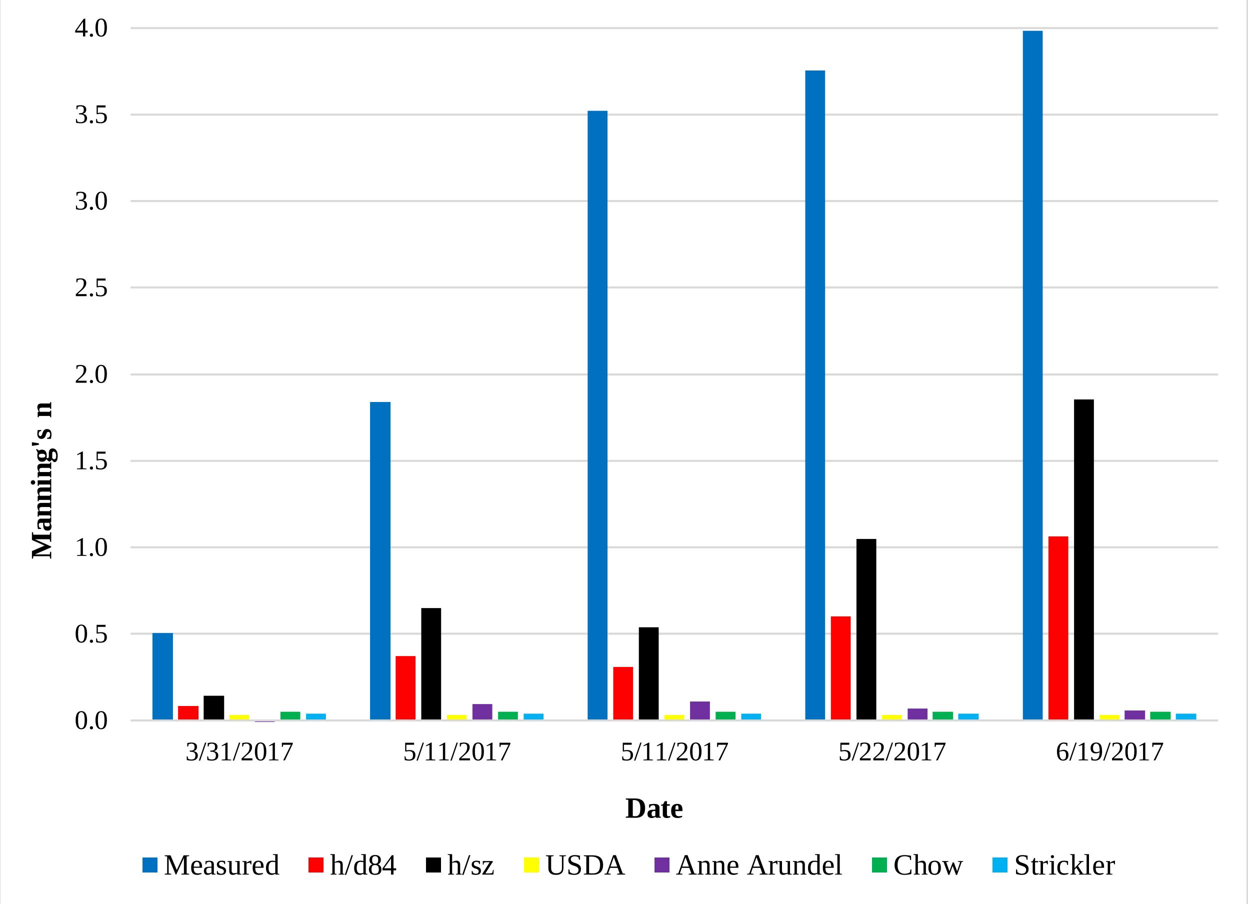


Figure 4.10: Field-determined and predicted Manning's *n* for each storm event at the Eastern Tributary SPSC. Controlled flow releases were conducted on May 11, 2017.

While the field-determined values are one to two orders of magnitude higher than *n*-values predicted using traditional methods, studies of natural step-pool channels have reported similar values. Yochum et al. (2012) determined roughness coefficients in 15 mountain streams in Colorado, with watersheds of 0.43-5.3 km^2 (0.27-3.3 mi^2). Manning's *n* ranged from 0.10 to 0.52 at low flows and 0.05 to 0.30 at bankfull flows. Lee & Ferguson (2002) found *n*-values as high as 8.0 using a salt tracer in steep step-pool streams in the UK. The authors also noted that the values were not only high, but also highly variable, similar to the findings of this study.

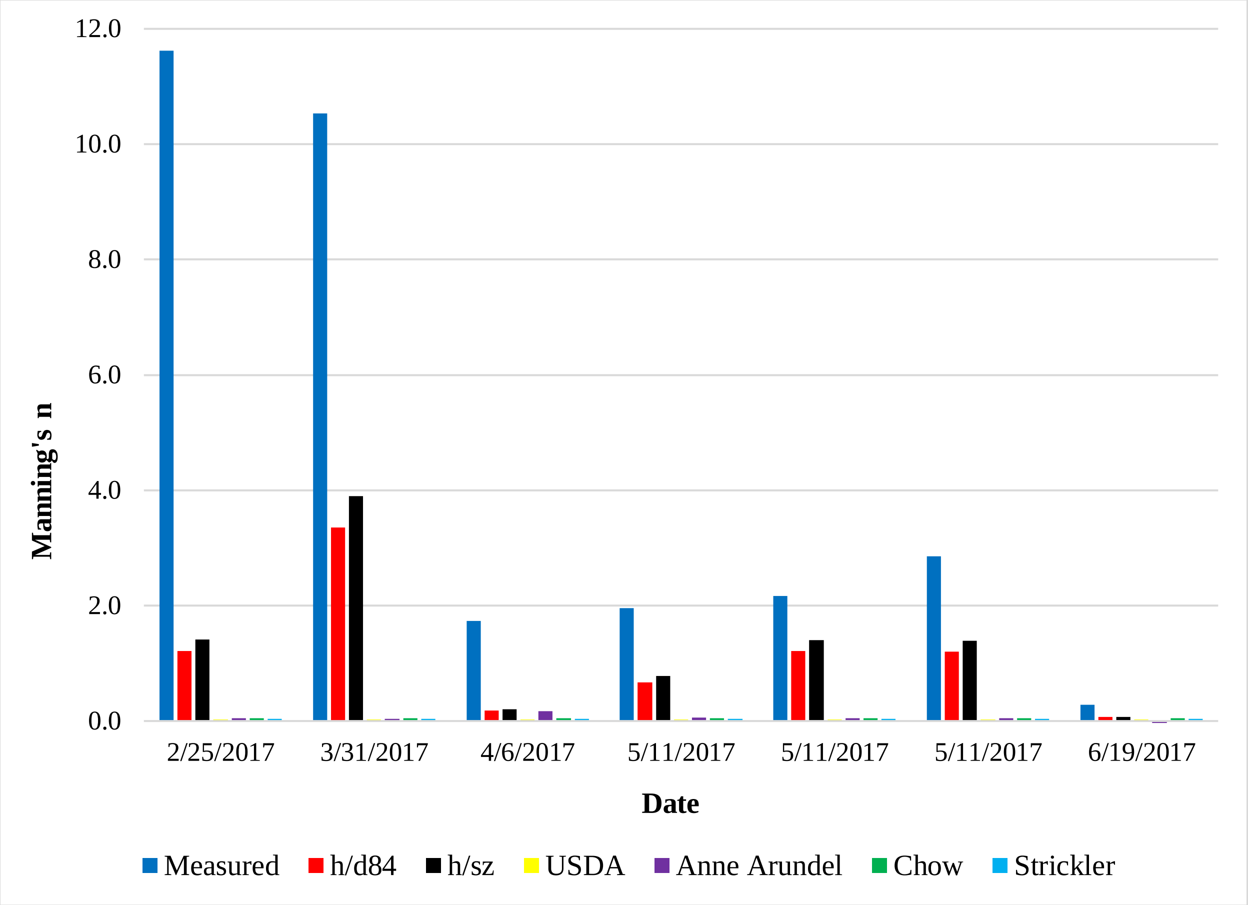


Figure 4.11: Field-determined and predicted Manning's *n* for each storm event at the Broad Creek SPSC. Controlled flow releases were conducted on May 11, 2017.

The effectiveness of each method of predicting roughness was evaluated with the root mean squared error (RMSE) between the field-determined values and each set of predicted values, reported in Table 4.4. RMSE is a common method of comparing modeled and observed values, with RMSE closer to 1 indicating a better prediction method:

$$RMSE = \sqrt{\sum(x_c - x_m)^2/n} \tag{4.8}$$

where x_c are the calculated (predicted) values, x_m are the measured (field-determined) values, and n is the number of values in each set.

Overall, substituting measures of relative bedform submergence (h/d_{84} or h/σ_z) for *n* in Manning's formula provides the most accurate roughness values at low flows. These two prediction methods have the lowest RMSE (4.07 and 3.84, respectively). The h/σ_z method appears to perform best as a prediction of *n*, with the lowest RMSE (4.07). The RMSE values reveal that the Anne Arundel County recommended method of predicting *n* (Flores et al., 2012; USDA-SCS, 1989) is as accurate as other accepted methods, with an RMSE of 5.08.

Table 4.4: Root mean squared error (RMSE) of predicted Manning's *n* and Darcy-Weisbach *f* values versus field-determined values.

Prediction Method	**RMSE**
Manning's n	
h/d_{84} as n	4.07
h/σ_z as n	3.84
NRCS (2006)	5.08
Flores et al. (2012); USDA-SCS (1989)	5.06
Chow (1959)	5.06
Strickler's relation	5.07
Darcy-Weisbach f	
Colebrook-White eq.	5800

Discussion

The results of this SPSC flow study suggest that measures of relative bedform submergence such as h/d_{84} or h/σ_z substituted for the Manning's roughness coefficient *n* are more accurate than many commonly-used methods of predicting Manning's *n*, including tabular references and predictors based solely on grain size (d_{50} or d_{84}). Within the rock weir (riffle) sections of an SPSC, cobbles and large boulders can be seen to act as large bedforms or flow impediments rather than as simple bed sediment roughness during low flows and are often not even completely submerged. Thus, a roughness prediction method relating flow depth to a measure of grain size or protrusion into the flow is understandably more accurate than one which treats the relationship of grain size to flow behavior as constant under the assumption that flow depth is orders of magnitude larger than grain size. Many of these prediction methods were developed under very different hydraulic conditions than those which occur in an SPSC, particularly at low flows. Manning's formula itself was developed with assumptions that SPSC flow clearly lacks (Fischenich, 2000) and the Strickler relation for the prediction of *n*, for example, assumes that flow depth is very large relative to the grain size of bed sediment (Ward & Trimble, 2004). This overall conclusion agrees with the findings of Yochum et al. (2012), who found that in steep channels with large bedforms, such as step-pool channels, flow resistance varies with stage (flow depth).

In addition to the inherent limitations of Manning's formula and the assumptions made in many of the prediction methods for *n*, the poor predictions and variation among the field-determined values could also be the result of the flow conditions present in SPSCs. Given the size of the study SPSCs, the occurrence of subsurface flow, and the highly variable flow conditions, making discharge and flow area measurements in these structures was challenging, limiting the accuracy of the field flow studies. Also, the determination of roughness coefficients from field measurements was based on the assumption that the weirs were solid (i.e. flow was only occurring over the weirs, not through the weirs) and that the flow extended across the entire designed width of the weirs. Neither of these conditions exist in the field; however, there are currently no models of flow through and across rock weirs that account for these conditions. Therefore, it is likely that both the discharge and velocity field measurements are inaccurate to a degree that is difficult to quantify. If the discharge measurement alone was 20% greater or lesser during, for example, the dye tracer experiment at Broad Creek on April 6, 2017, *n* would increase to 1.9 (with 20% greater discharge) or decrease to 1.5 (with 20% lesser discharge) compared to the reported *n*-value of 1.7.

Another consideration in the interpretation and use of the study results is that this study was limited to low flow conditions. Many months of the study took place during a drought period, and measured stormwater runoff discharges were very low compared to the 100-yr design discharges (3.4 m^3/s and 1.4 m^3/s for the Eastern Tributary and Broad Creek, respectively, whereas the largest discharges captured at each site were 0.101 m^3/s and 0.058 m^3/s, respectively). As flow depth increases with increasing discharge, the influence of the rock weir boulders on flow resistance decreases (Lee & Ferguson, 2002). As a result, the relative roughness of the rock weirs will decrease, improving the flow velocity predictions made using more traditional roughness prediction methods (Table 4.1).

In addition to a need to evaluate techniques for velocity prediction in step-pool systems in general, there remains much to be done to better understand the flow characteristics of SPSC structures. This study focused solely on evaluating the roughness parameters used to design these steep stormwater structures. Design of all rock weir structures, including those used in stream and wetland restoration design, is based on the assumption that the rock weirs are solid, parabolic channels. Visual observation of SPSCs during storm events reveals that a fraction of the surface flow passes through the rock weirs rather than over them, before emerging again in the pools. An understanding of the flow characteristics of rock weirs is crucial to understanding the flow characteristics of SPSCs and similar rock structures used in stream restoration. However, few studies exist which even document the percentage of flow moving through the rock weirs. Given that a common failure mode of rock weirs is piping, better understanding of the flow characteristics of these common stormwater and stream structures may reduce the occurrence of failures due to piping or lateral erosion resulting from under-sizing of the weirs.

Recommendations

The study results show that field-determined roughness coefficients for SPSCs at low flows exceed standard design values by one to two orders of magnitude. However, the study results are influenced by the limited range of flows measured during the study period. Based on studies conducted in natural step-pool channels, it is anticipated that Manning's *n* values in SPSCs will be lower than determined during this study at higher flows, such as the 100-yr design discharge. Based on the results of this study and studies in natural step-pool channels at higher flows, it is recommended that the Manning's *n* values used in SPSC design be increased to a minimum of 0.10 to 0.20 when used to size SPSCs based on the runoff generated by the 100-yr storm event. These values are slightly lower than the lowest values determined during this study and are similar to values calculated in natural step-pool channels under high flows. While measures such as relative bedform submergence provided the best prediction of *n* when flow depths were the same order of magnitude as the weir rock protrusion heights, as flow depths increase, the roughness values can be expected to decrease, similar to values determined in natural step-pool channels.

Chapter 5: Overall Conclusions

The most overwhelming consensus found in the course of this study and synthesis of in-stream structure design guidance, research findings, and practitioner surveys is the existence of a distinct lack of clear knowledge concerning both the response of stream systems to structure installation and the performance of structures under various stream conditions. In terms of scientific experimentation and knowledge, the field of in-stream structure fluvial mechanics has barely begun. However, in-stream structures are also already a commonly-implemented element in the multi-billion dollar US stream restoration industry. Judging from the results of the practitioner survey gathered during this study, as well as others (Radspinner et al., 2010), they are unlikely to be an element that will be abandoned in the near future, despite repeated catastrophic structure failure and very common partial failures. Despite an encouraging positive trend in the development of more rigorous methodologies and templates for detailed design calculations and numerical modeling (Gordon et al., 2016; Sotiropoulos & Diplas; 2014), industry designers are slow to adopt these techniques, whether due to lack of knowledge or lack of funding for endeavors such as three-dimensional numerical flow modeling, and most continue to rely on their own trial and error or on largely-unsupported rules of thumb. However, both the development and adoption of more rigorous structure design guidance is necessary for structure success rates to increase. The development and maintenance of official structure design standards by professional engineering societies, regularly updated to reflect the cutting edge of structure research findings and understanding, could ease this transition.

Another potential road that could be paved for the increased success of in-stream structures is the improvement of regulators’ and permit reviewers’ understanding of structures and their proper application, as well as the proper role of stream restoration as a whole. Many stream restoration designers understand that streams naturally migrate, both laterally and vertically, suggesting that structures which prevent stream migration should only be installed to protect infrastructure, property, or human life. However, many stream restoration permits still uphold stream migration prevention as a success criteria, driving the inclusion of structures in more projects than is necessary. It is hoped that the factsheets developed during this study will reach their target audience and assist in the further development of a more ecologically- and hydraulically-sound paradigm for structure application and stream restoration as a whole.

Recommendations for Future Research

The development of more stringent and rigorous design guidance for in-stream structures, including step pool storm conveyance (SPSC), will require copious future research in a variety of specific areas, including but not limited to the following: structure response to stream and site conditions; structure success with different design configurations; stream and structure response to structure placement within the stream planform; use of structures to develop and maintain in-stream aquatic habitat; performance of wood structures over time; water quality improvements of the SPSC; the nature and process of flow through porous rock weirs; and, identification of the failure mechanisms of existing structures and the physical mechanisms which caused them.

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Appendix A: In-Stream Structure Factsheets

The in-stream structure factsheets produced during this study can also be found at the publically accessible study website (https://sites.google.com/view/vtstreamstructures).

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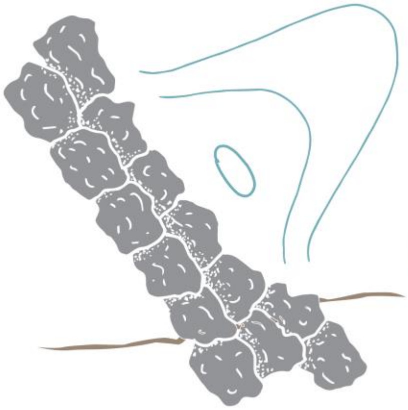
Fact Sheet Number 2



Stream Restoration Series

Single-Arm Vane

Authors: E.L. Hickman and T.M. Thompson, Biological Systems Engineering

ALTERNATE NAMES:

(single-arm) rock vane,

(single-arm) log vane, single-wing vane, straight vane

STRUCTURE TYPE:

rigid structure; flow deflector; river training structure

Single-arm vanes are flow deflection structures that dissipate energy, deflect stream flow to the center of the channel, reduce streambank erosion, and create pools. The single-arm vane deflects flows away from the bank and creates turbulence, dissipating energy. This new flow condition also causes the thalweg to migrate towards the center of the stream and a scour pool to form downstream of the vane, which can provide habitat for fish and other aquatic wildlife.

Where applicable, the single-arm vane may be used as a more ecologically sound alternative to traditional bank armor, such as riprap. Vanes may improve the establishment of protective vegetation on bare or newly regraded banks by deflecting flows away from vulnerable new plantings (Figure 1). By protecting the bank from fluvial erosion, this structure promotes the overall stability of the stream cross-section. Single-arm vanes can be constructed of wood (logs), stone (boulders), or a combination of both materials (Figure 2).

CAUTION: If the forces driving bank erosion are not those addressed by the function of the single-arm vane, vane installation is unnecessary and will likely be ineffective, such as when streambank erosion or instability is actually caused by overland surface runoff or seepage. Single-arm vanes 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 by preventing bank erosion.

Figure 1. Single-arm vanes redirect flows from banks, reducing erosion caused by high flows.

Figure 2. Single-arm vane, Paint Branch, College Park, Maryland.

Application

The single-arm vane is effective for stream reaches which…

- have no site constraints which would require that the stream not naturally migrate laterally across the floodplain;
- are slightly-to-moderately meandering/sinuous;
- would naturally possess either a plane-bed or a riffle-pool sequence (i.e. Rosgen stream types B2-B5 and C2-C4 as described in Rosgen's 1996 text Applied River Morphology);
- 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.

Use a single-arm vane to halt or prevent bank erosion or lateral migration in situations where it is desirable for the stream cross-section to remain constant at flows equal to or less than the SDF.

Consider use of the single-arm vane carefully for stream reaches which…

- are deeply incised or have a low width to depth ratio, as the vane slope may exceed recommended values;
- are currently incising or experiencing substantial change in their cross-sectional geometry, as additional structural stabilization measures may be required;
- have beds of very fine, mobile material (fine sands and/or silt), which increases the risk of structural failure by undercutting; or,
- have an opposite bank which is also experiencing or in danger of undesirable erosion, especially in small or narrow streams where flows may be deflected directly into the opposite bank, causing higher erosion rates there.

CAUTION: Do NOT install a single-arm vane in streams which…

- are composed of exposed bedrock;
- have a gradient greater than 3%
- regularly experience heavy loads of large sediment (cobbles and larger) or other large debris (i.e. large logs) or
- otherwise have no sufficient 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's Waterway Construction Guidelines (2000) and Sotiropoulis and Diplas (2014).

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 vane remains in place for flows up to a given recurrence 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 vane 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 single-arm vane designed for an SDL of 50 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 vane must resist and then determining the recurrence interval of the associated flow.

Material Selection

The choice between use of logs or rocks for the single-arm vane should be made considering both the goals and requirements of a particular project, the materials which occur naturally in

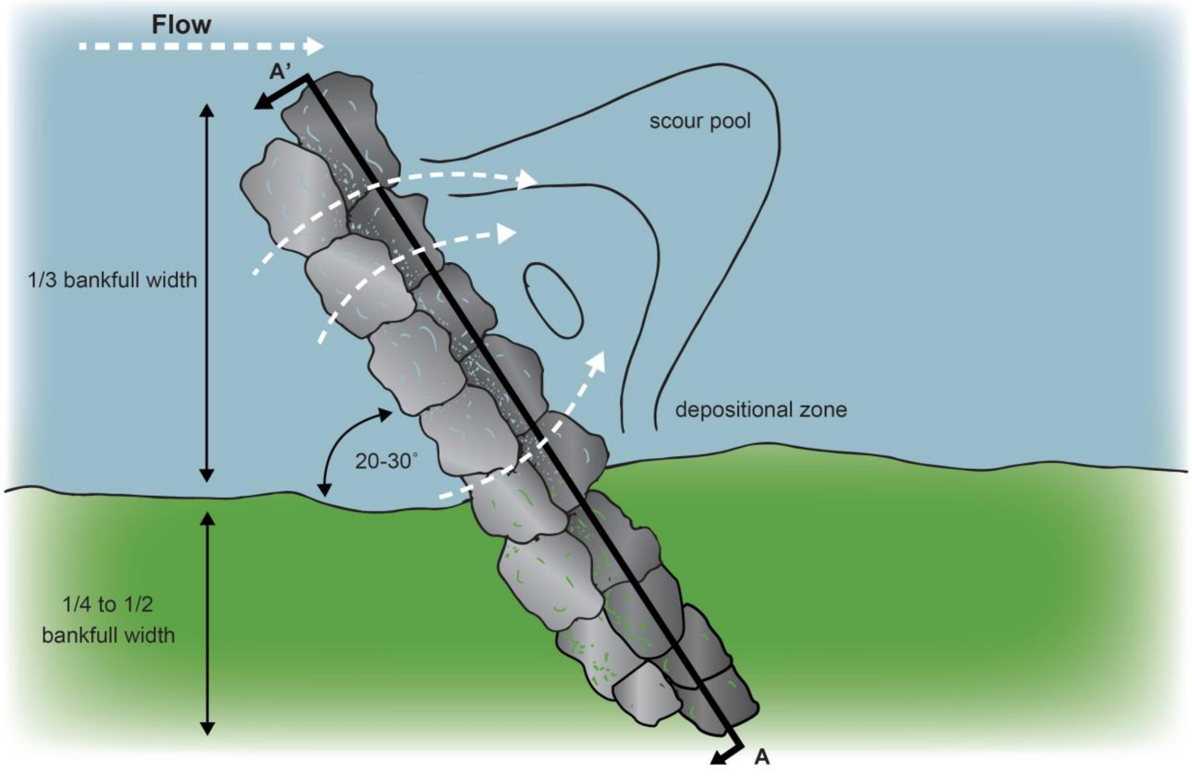


Figure 3. Single-arm vane plan view.

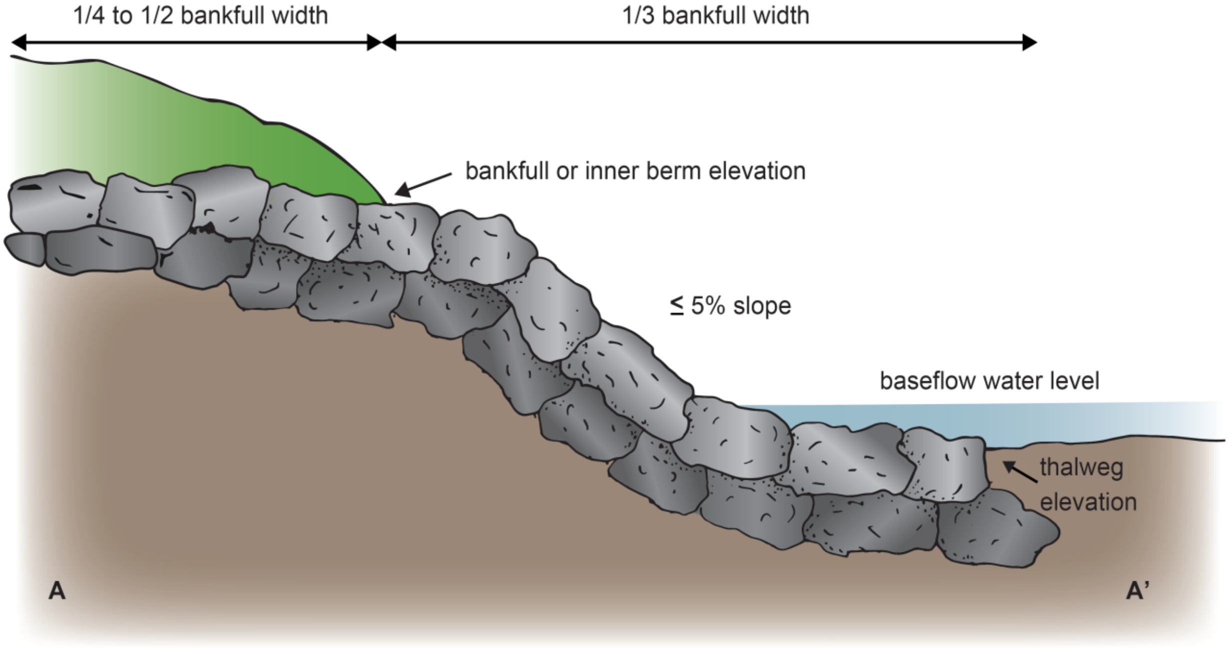


Figure 4. Single-arm vane cross section A-A'.

the stream (or a reference reach), and materials available on site.

Woody material (logs) is generally less expensive than rocks, and may be more readily available. Use of logs should be seriously considered in streams that naturally have a high occurrence of large in-stream woody debris, rather than large in-stream boulders. Since wood is a biological material, natural decay will significantly limit the life expectancy of a log-arm cross vane, so if a longer SDL is required by the project, a log vane may not be a viable option. Wood that is continuously submerged will have a greater life than wood exposed to wetting and drying.

Boulders are more expensive than logs, but are more durable, as their natural decay occurs over a much longer period of time. Rock vanes may also be easier to construct, as the key is made of multiple individual boulders, rather than the same single log as the vane. Rock vanes are particularly recommended for projects which require a long SDL or involve the protection of infrastructure, and for streams in which large boulders and rocks are normally found.

Material Sizing

Material used for a cross vane must remain structurally sound during the design flow. When sizing woody material for log arms, note the size of material locally available and the size of material naturally occurring as debris in the stream or a reference reach. In general, use of single logs less than 8 in. (20 cm) in diameter is not recommended. Additionally, logs should be long enough to key into the bank 1/4 to 1/2 bankfull width. Smaller logs may be used in a bundle if they are bolted together.

To size boulders for the single-arm vane, 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 important 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 vane 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 single-arm vanes typically are 2-4 ft. (60-120 cm) in diameter. Designers should also consider using stones which are large enough to prevent movement by vandals.

Choose rocks which have flat, rather than round, surfaces to allow the vane rocks to sit securely on the footer rocks and to line up with adjacent rocks. When placing rocks, remember that the rocks nearer the tip will experience the strongest hydraulic forces. In general, larger rocks will produce more turbulence, leading to a deeper scour pool. 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.

Footer Depth

The highest hydraulic stresses and the deepest part of the scour hole occur at the tip of the vane. 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 over a range of flows to ensure the footers or piles for log vanes 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). Once the maximum bed degradation is estimated, the footer depth or piling should extend 1.5-3.0 times this expected depth, or until a resistant layer, such as bedrock, is reached.

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.

Placement within Stream Cross-Section

Install the vane arms at a 20° to 30° horizontal angle from the bank, such that the vane points upstream. Measure the angle between the vane and the upstream bank (see plan view diagram, Figure 3). A larger angle between the arm and the bank protects greater lengths of bank against erosion, but also results in more intense bed scour and greater risk of failure. In highly sinuous channels, a smaller horizontal angle reduces the risk of erosion just upstream of where the vane is keyed into the bank. However, because water will flow perpendicular to the vane arm, in smaller streams, smaller horizontal angles can direct flows into the opposite bank, causing bank erosion downstream of the structure. Each vane arm typically does not extend over more than 1/3 of the bankfull width.

CAUTION: Use of a large verticale angle in a stream with a bed of fine gravel or sand (highly erodible) may cause undesirable bed erosion as the scour depth immediately down stream of the vane increases with increasing vertical vane angle.

The in-stream vane tip should be submerged at all times. This condition requires the rocks at the vane tip (not just the footer rocks) or the log tip be buried in the stream bed at approximately thalweg elevation. In general, the steeper the vertical slope of the vane arm, the greater force the water gains as it passes over the vane, causing a greater scour depth downstream of the vane. The location at which the vane is keyed into the bank may be lowered if necessary, to ensure the vertical slope of the vane from bank key to tip does not exceed 5% for rock structures and 4% for log structures. Although prior design guidance (Rosgen, 1996) indicated the vane should be keyed in at bankfull height, this will not be appropriate for every stream, and log vanes in particular may be keyed in lower than bankfull height, as they generally require a lower vertical slope (B.A. Doll, personal communication, April 11, 2016).

CAUTION: The greater the vertical slope of the vane, the shorter the length of bank that is protected from erosion.

Placement within Stream Planform

Single-arm vanes are designed to prevent natural migration of the channel across the floodplain. If infrastructure protection is not a project goal and the stream has room to migrate naturally, it is best to design the stream without the use of an in-stream structure, as these structures will prevent natural channel migration.

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 approximation of specific natural habitat conditions is desired, consult reference reaches to determine how far apart pools naturally form in the desired condition, and space vanes appropriately.

Single-arm vanes can be used to redirect flows upstream of bridges and culverts. The vane tip should be placed 1.5 to 2.0 times the bankfull width upstream of the upstream end of the bridge/culvert abutment. This location reduces the likelihood that the scour pool will form adjacent to the bridge foundation while still directing flows away from the embankment. For more information, see Johnson et al. (2002).

To protect the outer bank of a meander in a slightly sinuous stream reach, place a vane or begin a vane series at the apex of a meander bend, where flow impinges on the bank at an acute angle. If the stream is highly sinuous, move the vane location downstream from the meander apex about one bankfull channel width to avoid promoting erosion in the turbulent zone at the apex. In general, use of a series of vanes promotes better and longer-lasting bank protection than use of a single vane. Vector analysis can be used to determine vane spacing as a function of the radius of curvature of the bend [see Sotiropoulos and Diplas (2014)].

Construction

The most common failure modes for single-arm vanes are undermining of the structure, structure flanking, and loss of vane rocks.

Footer rocks/logs and wooden pilings 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 a bit of the footer rock is

Figure 5. Vane rocks should fit snugly together and be chinked with smaller rock with a wide range of sizes. (Design by Wetland Studies and Solutions, Inc.)

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 may be placed on the downstream side of the vane arms to increase structural stability (Figure 3). 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 single-arm vane should fit together snugly (Figure 5). Offset vane rocks from footer rocks such that each vane rock is 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 a pool is forming and the pool depth does not exceed the depth of pilings or footer rock layers;
- regularly examine the adjacent streambanks for erosion or a lack of vegetation establishment;
- examine the vane 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; and,
- regularly examine the vane for aggradation or bed degradation upstream of the structure.

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.

Acknowledgments

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MARYLAND
DEPARTMENT OF
NATURAL RESOURCES

Illustrations by Sarah Cisneros and Layout by Tim Poff

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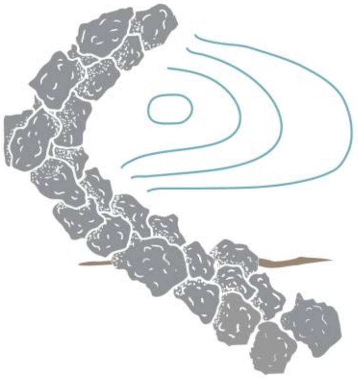
Fact Sheet Number 3



Stream Restoration Series

J-Hook Vane

Authors: E.L. Hickman and T.M. Thompson, Biological Systems Engineering

ALTERNATE NAMES:

j-vane

STRUCTURE TYPE:

rigid structure; flow deflector; river training structure

J-hook vanes are flow deflection structures that dissipate energy, deflect stream flow to the center of the channel, reduce streambank erosion, and create pools. The original j-hook vane differs from the similar single-arm vane in that it extends beyond the vane tip at approximately right angles to downstream flow. This extension is the "hook" which gives this vane type its characteristic "J" shape. Particularly in smaller streams, the j-hook structure can be modified to span the channel to provide grade control (Figure 1). J-hook vanes may be constructed of wood (logs), stone (boulders), or a combination of both materials.

Where applicable, the j-hook vane is a more ecologically beneficial alternative to traditional bank armor, such as riprap. The j-hook vane deflects flows away from the bank and creates turbulence, dissipating energy. The flow deflection and resulting drop in applied shear stress improves the establishment of protective vegetation on bare or newly regraded banks. By protecting the bank from fluvial erosion, this structure promotes the overall stability of the stream cross-section.

This new flow condition also causes the thalweg to migrate towards the center of the stream and a scour pool to form downstream of the vane, which can provide habitat for fish and other aquatic wildlife. The scour hole formed downstream of a j-hook vane is typically deeper than the pool formed by a single-arm vane, as the hook induces stronger turbulence in the region of scour.

In modified j-hook vanes, the hook extends across the entire baseflow channel, such that it resembles a cross vane without one vane arm. The modified j-hook structure 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 vane creates an elevation change in the channel longitudinal profile, which allows lower bed slopes upstream and downstream of the vane, decreasing the forces driving channel erosion.

CAUTION: If the forces driving bank erosion are not those addressed by the function of the j-hook vane, vane installation is unnecessary and will likely be ineffective, such as when bank erosion or instability is caused by overland surface runoff or seepage. J-hook vanes are costly and have a relatively high risk of structural failure due to their position within the stream itself, so they should be installed to protect infrastructure or to prevent channel migration and/or downcutting (modified j-hook only).

J-hook vanes can also increase flow diversity in uniform channels. Water ponded upstream of modified vanes induces gravel deposition. By forcing the flow over a drop and concentrating it in the center of the channel, these structures cause the formation of a scour pool downstream of the vane, further increasing flow diversity. In this way, a single modified j-hook vane creates a single riffle-pool structure while a series of vanes develops a riffle-pool sequence.

Figure 1. Modified j-hook vane.
(Project by Ecotone, Inc.)

Application

The j-hook vane is effective for stream reaches which…

- are slightly-to-moderately meandering/sinuous;
- are actively incising;
- would naturally possess a riffle-pool sequence (i.e. Rosgen stream types A3-A4, B3-B4, C3-C4, F3-F4, and G3-G4 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.

Use a j-hook vane to halt or prevent bank erosion or lateral migration in situations where it is desirable for the stream cross-section to remain constant at flows less than or equal to the design flood, and to improve pool habitat.

Consider use of the j-hook vane 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;
- have an opposite bank which is also experiencing or in danger of undesirable erosion, especially in small or narrow streams where flows may be deflected directly into the opposite bank, causing higher erosion rates there;
- have high bedload transport, as the longer span of a j-hook vane makes it more susceptible to aggradation than the single-arm vane; 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 j-hook vane in streams which…

- are composed of bedrock;
- have a gradient greater than 3%;
- regularly experience heavy loads of very large sediment (cobbles and larger) or other large debris (i.e. large logs);
- already have a well developed riffle-pool system; or,
- have no design constraints which prevent natural lateral 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), Gordon et al. (2016), and Sotiropoulis and Diplas (2014).

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 vane 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 vane 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 j-hook vane designed for an SDL of 50 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 vane must resist and then determining the recurrence interval of the associated flow.

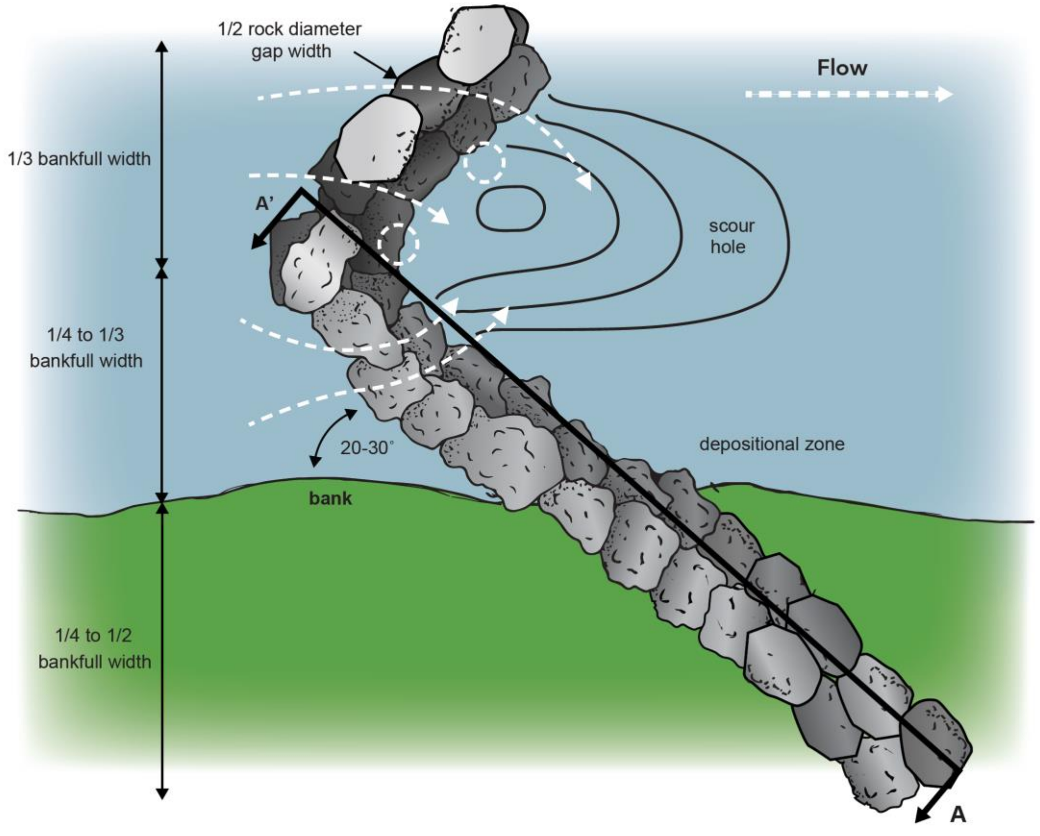


Figure 2. Plan view of traditional j-hook vane.

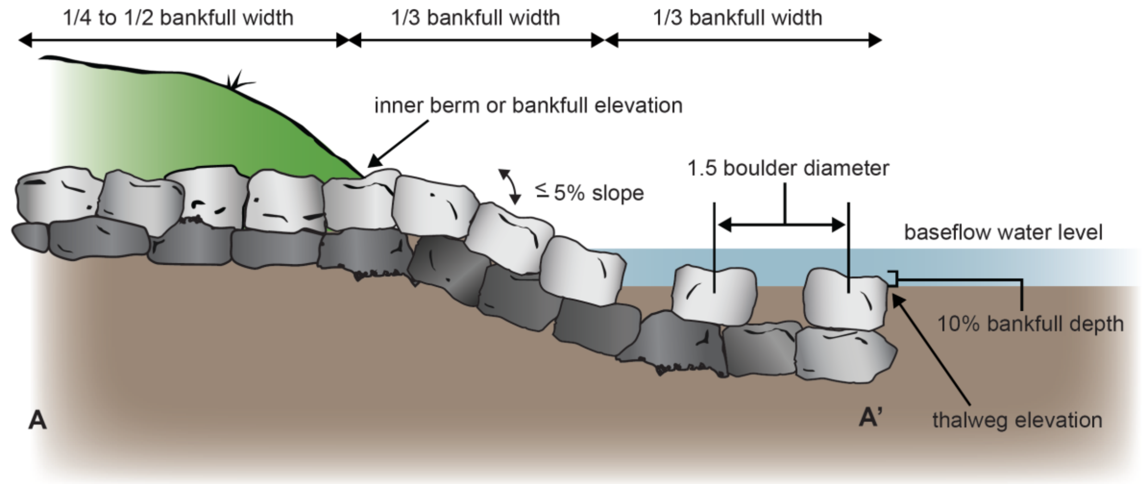


Figure 3. J-hook section A-A'.

Material Selection

The choice between use of logs, rocks, or combination thereof for the j-hook vane should be made considering both the goals and requirements of a particular project, the materials which occur naturally in the stream (or a reference reach), and materials available on site.

Woody material (logs) is generally less expensive than rocks, and may be more readily available. Use of logs should be seriously considered in streams that naturally have a high occurrence of large in-stream woody debris, rather than large in-stream boulders. However, logs are generally not recommended for use in grade control structures unless the stream would typically have a high occurrence of large in-stream woody debris. Since wood is a biological material, natural decay will significantly limit the life expectancy of a log j-hook vane. So if a longer SDL is required by the project, which is likely for a grade control structure, a modified j-hook vane constructed with logs may not be a viable option. Wood that is continuously submerged will have a greater life than wood exposed to wetting and drying.

CAUTION: Use of log vanes in streams with highly variable flows (especially those in ultra urban settings) or for projects involving infrastructure protection is not recommended due to the lower durability of logs. In addition, log vanes are more easily undercut than rock vanes, so use caution when designing a log arm for a stream with fine, mobile bed material.

Boulders are more expensive than logs, but are more durable, as their natural decay occurs over a much longer period of time. Rock vanes may also be easier to construct, as the key is made of a series individual boulders, rather than the same single log as the vane. Rock vanes are particularly recommended for projects which require a long SDL or involve the protection of infrastructure, and for streams in which large boulders and rocks are normally found.

Material Sizing

Material used for a j-hook vane must remain structurally sound during the design flow. However, the materials used must also be small enough to create the vane geometry described below. Selected material sizes may need to be altered based on the geometry and size of the stream to produce a j-hook vane which has the correct configuration. As a result, the design life of the structure may be reduced. Alternatively, the rocks can be grouted to increase vane strength.

When sizing woody material, note the size of material locally available and the size of material naturally occurring as debris in the stream or a reference reach, and select materials that will replicate a natural condition for the stream. In general, use of single logs less than 8 in. (20 cm) in diameter is not recommended. Additionally, logs should be long enough to key into the bank 1/4 to 1/2 bankfull width. Smaller logs may be used in a bundle if they are bolted together.

To size boulders for the j-hook vane, 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 important to assess the stability of the materials using shear stress, rather than an allowable velocity. Technical Supplement 14C

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.

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 vane rocks are more exposed to the flow than riprap. Once a material size is calculated, the required diameter can be multiplied by 1.1-1.5 to add a factor of safety. Commonly, rocks used in j-hook vanes are 2-4 ft. (60-120 cm) in diameter. Designers should also consider using stones which are large enough to prevent movement by vandals.

Choose rocks which have flat, rather than round, surfaces to allow the vane rocks to sit securely on the footer rocks and to line up with adjacent rocks. When placing rocks, remember that the rocks nearer the vane tip will experience the strongest hydraulic forces. In general, larger rocks will produce more turbulence, leading to a deeper scour pool. 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.

Footer Depth

As water crosses over the vane arm, 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 footers or piles for log vanes 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 softwater 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 arm is sloped up from the hook, the greatest drop will occur along the vane arms, closest to the bank. However, this is also the area with the lowest footer depth (since the footers are parallel to the vane arm). To provide greater support along the arms, the footer depth can be extended or larger rocks can be used under the vane arm.

If a modified j-hook vane 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 expected bed degradation due to the knickpoint. Once the maximum bed degradation is estimated, the footer depth or piling should extend 1.5-3.0 times this expected depth, or until a resistant feature, such as bedrock, is reached.

CAUTION: Be sure to estimate the expected scour depth prior to selecting a piling length (for log vanes) or number of tiers of footer rocks (for rock vanes). The expected scour depth can be easily determined using the methods described in Technical Supplement 14B ("Scour Calculations") of the NRCS Stream Restoration Design Handbook (NRCS, 2007).

Placement within the Stream Cross-Section

Install the vane arm at a 20° to 30° horizontal angle from the bank, such that the vane points upstream. Measure the angle between the vane and the upstream bank (see plan view diagram, Figure 1). A larger angle between the arm and the bank can protect greater lengths of bank against erosion, but also results in more intense bed scour and greater risk of failure. In highly sinuous channels, a smaller horizontal angle reduces the risk of erosion just upstream of where the vane is keyed into the bank. However, because water will flow perpendicular to the vane arm, in smaller streams, smaller horizontal angles can direct flows into the opposite bank, causing bank erosion downstream of the structure.

CAUTION: Placing the vane arms at a larger angle to the bank (30 degrees) in a stream with a fine gravel or sand (highly erodible) bed may cause undesirable bed erosion as the scour depth immediately downstream of the vane increases with increasing horzinontal vane angle.

The vane should be keyed into the bank so that the vertical slopes of the arms do not exceed 5% for rock arms and 4% for log arms. As the verticle angle of the vane 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 occur. Although prior design guidance (Rosgen, 1996) indicated the vane should be keyed in at bankfull height, this may not be appropriate for every stream, and log vanes in particular should be keyed in lower than bankfull height, as they generally require a lower vertical slope (B.A. Doll, personal communication, April 11, 2016).

CAUTION: The greater the vertical slope of the vane, the shorter the length of bank the vane will protect from erosion.

Unlike the main arm of the vane, the hook of a traditional rock j-hook vane should not be straight, but should have a slight arc or curve to it. Additionally, the vane rocks along the hook should protrude slightly above the bed, a distance of approximately 10% of bankfull depth and should be spaced at a distance of 1.5 times the rock diameter to produce gaps approximately half the rock diameter wide. The hook portion provides additional turbulence, increasing the extent and depth of the scour pool.

For a modified j-hook, the j-portion is frequently straight, rather than curved. This section of the vane extends across the entire channel width and may also be keyed into the opposite bank. Similar to cross vanes, the rocks or logs forming the hook should be buried in the stream bed at approximately thalweg elevation to allow sediment transport and fish passage.

The length of the vane arm (excluding the hook) should not extend over more than 1/3 of the bankfull width, unless the channel is more than 20 feet (about 6 m) wide, in which case the vane may extend over as much as 1/2 of bankfull width. The vane length may be as short as 1/4 of bankfull width. With the addition of the hook, the entire j-hook structure may span as much as 60% of bankfull width. In general, the ratio of the structure length to bankfull channel width should decrease as the channel width increases. Note that a longer vane will protect a greater bank length from erosion.

Placement within Stream Planform

Because j-hook vanes deflect flows away from a bank, they 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, j-hook vanes should not used.

To protect the outside of a meander bend in a slightly sinuous stream reach, place a vane or begin a vane series at the apex of the meander bend. If the stream is highly sinuous, move the vane location downstream from the meander apex about one bankfull channel width to avoid erosion in the zone of changing flow patterns at the apex.

Because bed material will deposit upstream of a modified j-hook vane and a scour pool will form downstream, modified j-hook vanes should be placed in a run on meandering channels.

Note that no modified j-hook vane 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. Due to the lower durability of log arms and greater susceptibility to undermining, no modified log j-hook vane should create an elevation change in the bed of more than 0.5 ft. (0.15 m). The bed elevation change should also be limited to 0.5 ft. (0.15 m) if fish passage is a design goal.

J-hook vanes designed to protect infrastructure, such as bridges, should be installed at least two channel widths upstream from the bridge piers, to prevent pool formation at the structure. If applicable, the hydraulic behavior of the existing bridge should also be evaluated as part of the design.

Construction

The most common failure modes for j-hook vanes are undermining of the structure, structure flanking, and loss of vane rocks.

Footer rocks/logs and wooden pilings 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 a bit of the footer rock is 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 may be placed on the downstream side of the vane arms to increase structural stability. 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 j-hook vane should fit together snugly, except those on the hook of a tradition rock j-hook. For the vane rocks of the hook, half the boulder diameter should be left. These gaps allow safe passage of fish and sediment, since the traditional j-hook vane, while not a stream-spanning structure, extends across a greater portion of the channel width than a single-arm vane. Since modified j-hook vanes extend across the entire channel, the hook/sill portion should be buried in the stream bed at approximately thalweg elevation to allow sediment transport and fish passage. The sill may also be keyed into the bank.

Offset vane rocks from footer rocks such that each vane rock is 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 j-hook vane function include the following:

- measure scour pool depth to ensure a pool is forming and the pool depth does not exceed the depth of pilings or footer rock layers;

- regularly examine the adjacent streambanks for erosion or a lack of vegetation establishment;
- examine the vane 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 vane for bed aggradation or degradation upstream of the structure; and
- ensure that modified j-hook vanes are 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.

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Illustrations by Sarah Cisneros and Layout by Tim Poff

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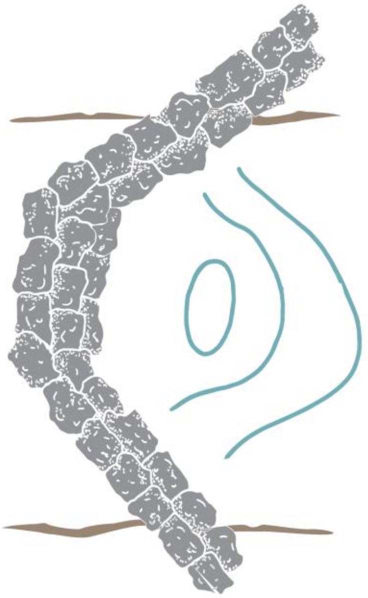

Fact Sheet Number 1

Stream Restoration Series

Cross Vane

Authors: E.L. Hickman and T.M. Thompson, Biological Systems Engineering

ALTERNATE NAMES:

channel-spanning rock weir, U-weir, V-weir, A-vane

STRUCTURE TYPE:

rigid structure; grade control structure; river training structure

Cross vanes are channel-spanning structures that provide grade control, dissipate energy, deflect stream flow to the center of the channel, and create pools. 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. It is also used to create pools and to direct flows to the center of the channel upstream of bridge crossings. The cross vane may be constructed of wood (logs), stone (boulders), or a combination of both materials.

The regular cross vane is configured as two single-arm vanes on opposite banks connected across the center of the stream by a straight or semicircular crosspiece called the "sill" section. The cross vane 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 a 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 vane creates an elevation change in the channel longitudinal profile, which allows lower bed slopes upstream and downstream of the vane, which in turn decreases the forces driving channel erosion.

While "stable" streams naturally migrate over time, and the restoration of water quality and ecological integrity in degraded streams should be conducted in the context of the entire watershed, it is sometimes necessary to prevent lateral and/or vertical changes in stream channels, particularly in urban areas. Examples of such situations include the protection of roads or bridges from lateral channel migration or knickpoint migration and the maintenance of bank stability during vegetation establishment.

Where applicable, the cross vane is a more ecologically beneficial alternative to traditional bank armor, such as riprap, or traditional grade control methods, such as check dams. The arms of the cross vane 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.

Cross vanes can also increase flow diversity and fish passage in uniform channels. Water ponded upstream of the vane induces gravel deposition, creating a riffle. By forcing the flow over a drop and concentrating it in the center of the channel, cross vanes cause the formation of a scour pool downstream of the vane, further increasing flow diversity. In this way, a single cross vane creates a single riffle-pool structure while a series of cross vanes develops a riffle-pool sequence.

Figure 1. Cross vane on Upper Little Patuxent River, Maryland used to protect a sewer line which crosses the channel just upstream of the vane. (photo courtesy of Johnson, Mirmiran & Thompson, Inc.).

Application

The cross vane is effective for stream reaches which…

- are slightly-to-moderately meandering/sinuous;
- are actively incising;
- would naturally possess a riffle-pool sequence (i.e. Rosgen stream types A3-A4, B3-B4, C3-C4, F3-F4, and G3-G4 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, cross vanes can be used to safely reduce the bed elevation and to prevent streambank erosion. Cross vanes can also be used to improve aquatic habitat.

Consider use of the cross vane 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: Cross vanes 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.

CAUTION: Do NOT install a cross vane in streams which…

- are composed of exposed bedrock;
- regularly experience heavy loads of 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), Gordon et al. (2016), and the Sotiropoulis and Diplas (2014).

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 vane 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 vane 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 single-arm vane designed for an SDL of 50 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 vane must resist and then determining the recurrence interval of the associated flow.

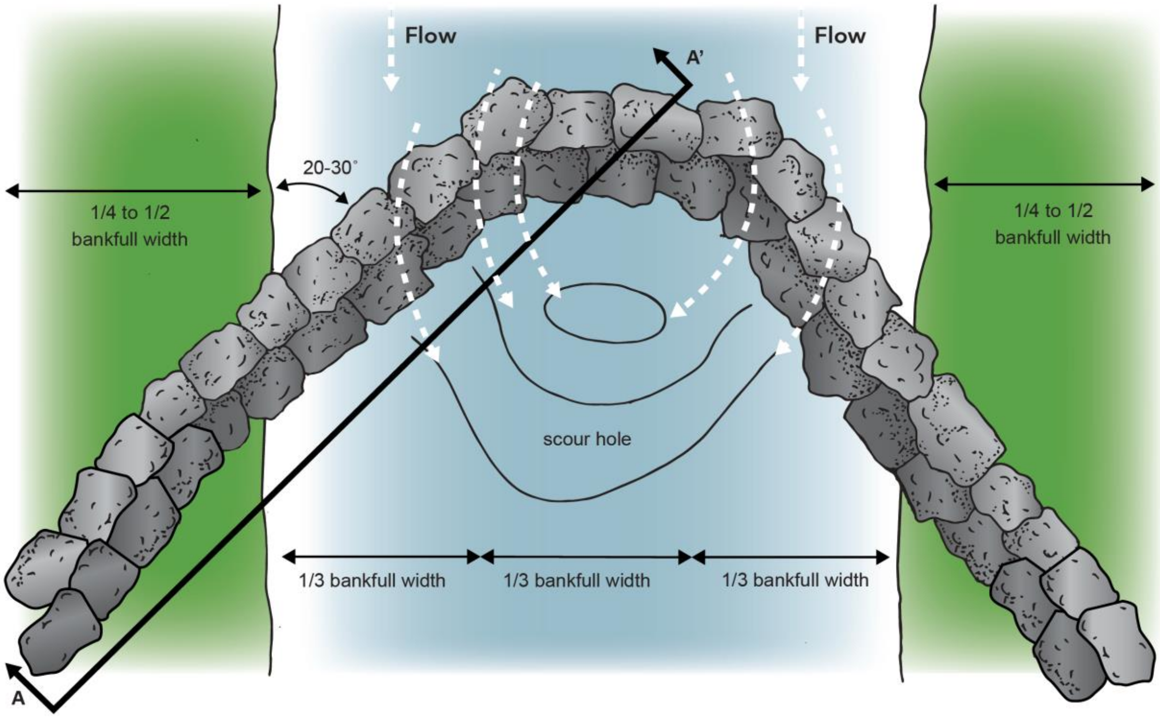

Figure 2. Cross vane plan view.

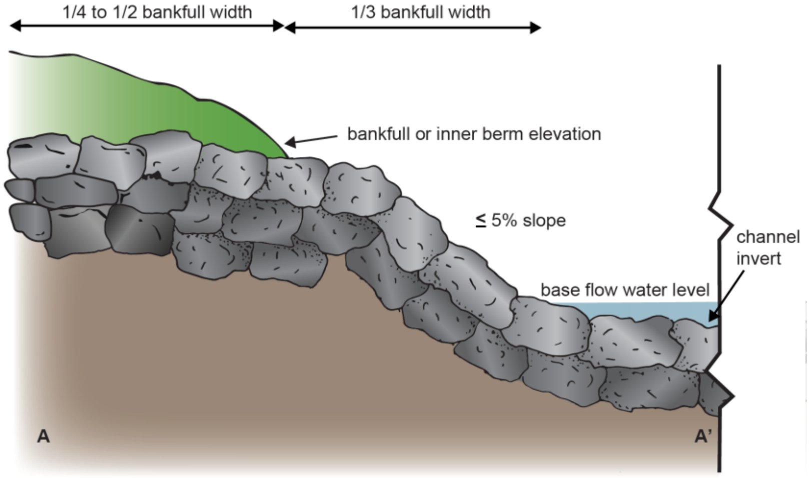

Figure 3. Cross vane section A-A'.

Material Selection

The choice between use of logs or rocks for the cross vane should be made considering both the goals and requirements of a particular project, the materials which occur naturally in the stream (or a reference reach), and materials available on site.

Woody material (logs) is generally less expensive than rocks, and may be more readily available. Use of logs should be seriously considered in streams that naturally have a high occurrence of large in-stream woody debris, rather than large in-stream boulders. However, logs are generally not recommended for use in grade control structures unless the stream has a high occurrence of large in-stream woody debris. Since wood is a biological material, natural decay will significantly limit the life expectancy of a log-arm cross vane. So, if a longer SDL is required by the project, which is likely for a grade control structure, a log cross vane may not be a viable option. Wood that is continuously submerged will have a greater life than wood exposed to wetting and drying.

Boulders are more expensive than logs, but are more durable, as their natural decay occurs over a much longer period of time. Rock vanes may also be easier to construct, as the key is made of multiple individual boulders, rather than the same single log as the vane. Rock vanes are particularly recommended for projects which require a long SDL or involve the protection of infrastructure, and for streams in which large boulders and rocks are normally found.

CAUTION: Use of log vanes in streams with highly variable flows (such as those in urban settings) or for projects involving infrastructure protection is not recommended due to the lower durability of log arms. In addition, log arms are more easily undercut than rock vanes, so use caution when designing log arms for a stream with fine, mobile bed material.

Material Sizing

Material used for a cross vane must remain structurally sound during the design flow. However, the materials used must also be small enough to create the cross vane geometry described below. Selected material sizes may need to be altered based on the geometry and size of the stream to produce a cross vane which has the correct configuration. As a result, the design life of the structure may be reduced. Alternatively, the rocks can be grouted to increase weir strength.

When sizing woody material for log arms, note the size of material locally available and the size of material naturally occurring as debris in the stream or a reference reach, and select materials that will replicate a natural condition for the stream. In general, use of single logs less than 8 in. (20 cm) in diameter is not recommended. Additionally, logs should be long enough to key into the bank 1/4 to 1/2 bankfull width. Smaller logs may be used in a bundle if they are bolted together.

To size boulders for the cross vane, 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 important 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 vane 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 cross vanes 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.

Sill rocks should be large enough to remain secure in the streambed. These rocks will bear the brunt of the hydraulic force. Footer rocks used below the sill should belarger than the sill rocks themselves.

Choose rocks which have flat, rather than round, surfaces to allow the vane rocks to sit securely on the footer rocks and to line up with adjacent rocks. When placing rocks, remember that the rocks nearer the sill will experience the strongest hydraulic forces. In general, larger rocks will produce more turbulence, leading to a deeper scour pool. 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.

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 footers or piles for log vanes 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 softwater such as HEC-RAS, as described in Gordon et al. (2016).

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.

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 from the sill, 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 cross vane 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 or piling 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 30° horizontal angle from the bank, such that the vane points upstream. Measure the angle between the vane and the upstream bank (see plan view diagram, Figure 2). Including the sill, the whole cross vane should form a "U" shape with the apex pointed upstream. A larger angle between the 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. In highly sinuous channels, a smaller horizontal angle reduces the risk of erosion just upstream of where the vane is keyed into the bank. However, because water will flow perpendicular to the vane arm, in smaller streams, smaller horizontal angles can direct flows into the opposite bank, causing bank erosion downstream of the structure.

CAUTION: Placing the vane arms at a larger angle to the bank (30 degrees) in a stream with a fine gravel or sand (highly erodible) bed may cause undesirable bed erosion as the scour depth immediately downstream of the vane increases with increasing horzinontal vane angle.

The vane should be keyed into the bank so that the vertical slopes of the arms do not exceed 5% for rock arms and 4% for log arms. As the angle of the vane 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 occur. Although prior design guidance (Rosgen, 1996) indicated the vane should be keyed in at bankfull height, this will not be appropriate for every stream, and log vanes in particular should be keyed in lower than bankfull height, as they generally require a lower vertical slope (B.A. Doll, personal communication, April 11, 2016).

The sill rocks or logs should be submerged at all times. The rocks or logs at the tips of the arms (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 typically does not extend over more than 1/3 of the bankfull width. The sill covers the middle 1/3 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. In smaller streams, the sill may not be included, forming a "V" shape; however, this shape is more prone to failure as the vane arms may redirect high-energy flow at the opposing arm, increasing bed scour and undermining the structure.

An alternative form of the cross vane is the A-type cross vane, which features an extra step linking the two arms 1/3 to 1/2 of the vane length away from the sill (Figure 4). This step acts as an additional vortex, creating a structure in which two scour

CAUTION: The greater the vertical slope of the vane, the shorter the length of bank the vane will protect from erosion.

pools are formed (one between the two vortices and the other downstream of the vane), reducing both the depth of scour and the elevation change at each sill.

Placement within Stream Planform

Not only will a cross vane 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, cross vanes should not used.

Because bed material will deposit upstream of a cross vane and a scour pool will form downstream, cross vanes should be placed in a run on meandering channels. Cross vanes placed in a meander bend tend to fail due to structure flanking as the meander bend migrates.

In channelized streams where there is not sufficient space to create meanders, due to the presence of buildings or other infrastructure in the floodplain, a series of cross vanes can be used to create a step-pool channel, which reduces boundary shear stress and improves aquatic habitat, as compared to hardening the channel with riprap or concrete. Cross vanes are more successful when spaced closely together; however, when used for grade control, they should be placed no closer than the net drop height divided by the channel slope. Additional detail on siting grade control structures is provided by Biedenharn and Hubbard. Also, the cross vanes should not be so closely spaced that downstream structures are affected by the scour pool of the upstream structure. A study by Gordon et al., 2016 showed pool length can extend from the sill to a distance equal to two times the vane arm length. Additionally, each vane should not increase the water surface elevation above the height of the upstream vane. Water depth over the vane can be estimated using stage-discharge relationships developed by Gordon et al. (2016).

Note that no individual cross vane 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. Due to the lower durability of log arms and greater susceptibility to undermining, no log cross vane should create an elevation change in the bed of more than 0.5 ft. (0.15 m). The bed elevation change should also be limited to 0.5 ft. (0.15 m) if fish passage is a design goal.

Cross vanes designed to protect infrastructure, such as bridges, should be installed such that the sill is 1.5 to 2.0 times the bankfull width upstream of the bridge abutment. This location reduces the likelihood that the scour pool will form adjacent to the bridge foundation while still diverting flows towards the center of the channel For A-type cross vanes, extend this distance to 2.5 to 3.0 bankfull channel widths. If applicable, the hydraulic behavior of the existing bridge should also be evaluated as part of the design.

Construction

The most common failure modes for cross vanes are undermining of the structure, structure flanking, and loss of vane rocks.

Footer rocks/logs and wooden pilings 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 a bit of the footer rock is 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 may be placed on the downstream side of the vane arms to increase structural stability. 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 cross vane should fit together snugly (Figure 4). Offset vane rocks from footer rocks such that each vane rock is centered on the intersection


Figure 4. A-vane, Paint Branch, College Park, Maryland.

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 a pool is forming and the pool depth does not exceed the depth of pilings or footer rock layers;
- regularly examine the adjacent streambanks for erosion or a lack of vegetation establishment;
- examine the vane 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 vane for aggradation or bed degradation upstream of the structure; and
- ensure that the vane 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.

Figure 5. Vane rocks should fit snugly together and be chinked with smaller rock with a wide range of sizes. (Design by Wetland Studies and Solutions, Inc.)

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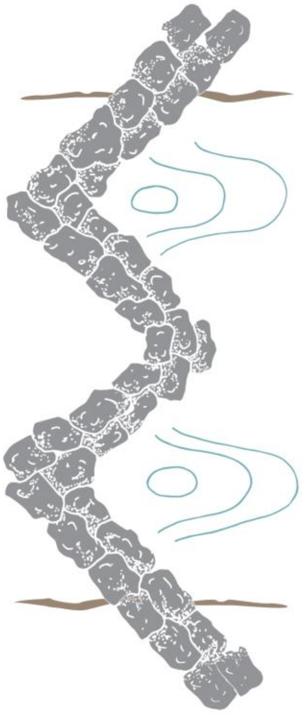
Fact Sheet Number 4



Stream Restoration Series

W-Weir

Authors: E.L. Hickman and T.M. Thompson, Biological Systems Engineering

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 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 important 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 midsection. 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.

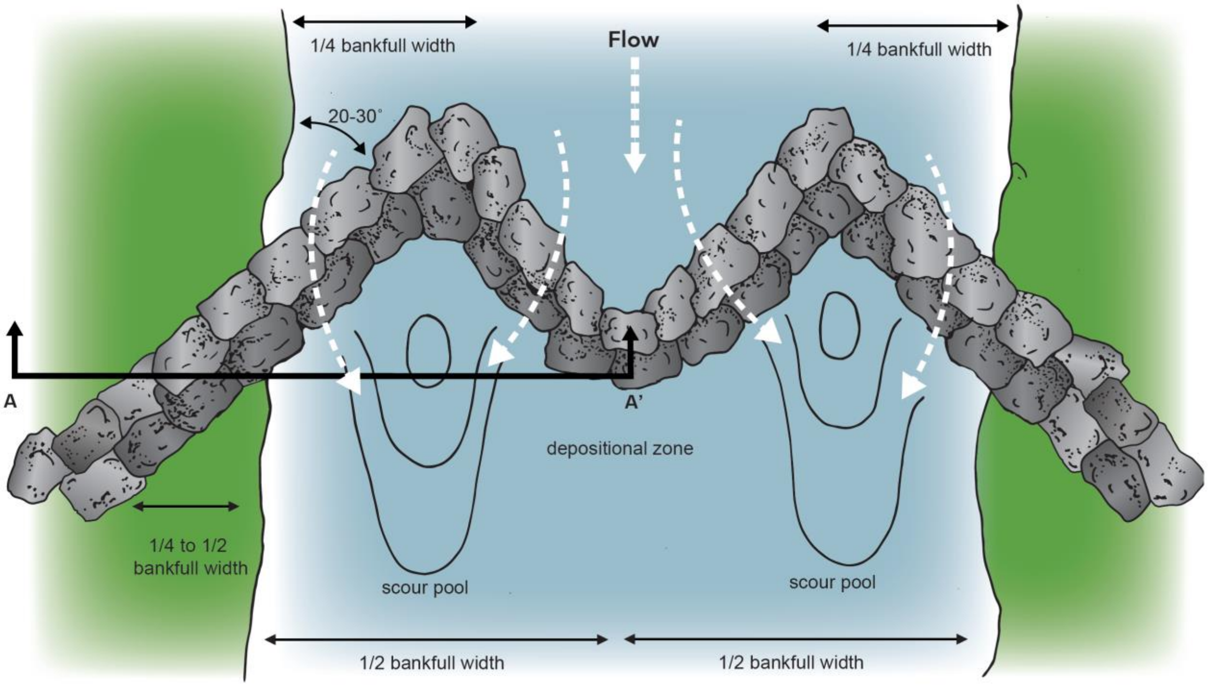


Figure 1. W-weir plan view.

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

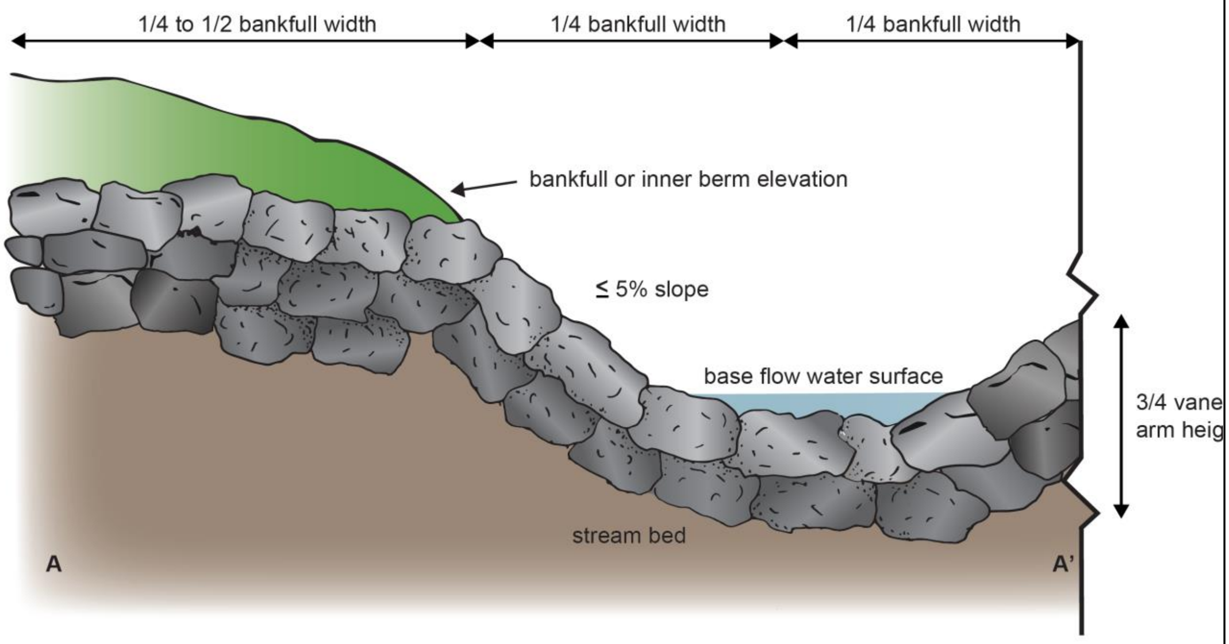


Figure 2. W-weir cross section.

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 resulting 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.

Acknowledgements

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Illustrations by Sarah Cisneros and Layout by Tim Poff

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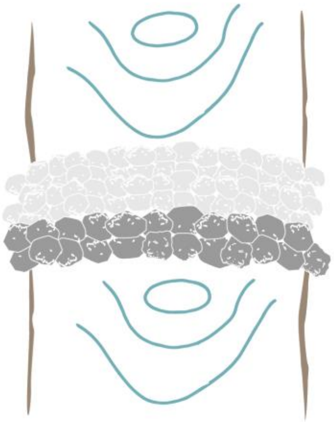
Regenerative Step Pool Storm Conveyance (SPSC)

Authors: E.L. Hickman and T.M. Thompson, Biological Systems Engineering



ALTERNATE NAMES:

coastal plain outfall; regenerative stormwater conveyance

STRUCTURE TYPE:

stormwater conveyance

Stormwater infrastructure concentrates storm runoff into pipes. When these pipes end at the top of steep slopes, the concentrated flow can cause extensive erosion, creating deep gullies (Figure 1) and contributing sediment to the receiving stream. These gullies also become drains, lowering local groundwater levels.

Regenerative Step Pool Storm Conveyances (SPSC) are used to safely convey stormwater runoff from developed areas to streams, while also improving stormwater quality, and replenishing shallow groundwater. SPSCs direct stormwater runoff through a series of pools with beds composed of a permeable, sand-based filtration media similar to that found in rain gardens and bioretention cells.

On steep slopes, rock weirs are placed in series to prevent further erosion and to create a series of shallow pools. These rock weirs are designed to behave like the rocks and logs found in naturally occurring step-pool channels. The step-pool channel morphology of steep SPSCs dissipates flow energy during storm events and filters and absorbs water through the pool beds during low flow conditions.

Application

Regenerative SPSCs are effective for channels which are first-order streams or erosion gullies/outfalls with intermittent or low flow, with both valley and channel slopes of 2-10%. While an SPSC may be designed for a site with a valley or channel slope greater than 10%, this must be done with caution, and the design should be modified to compensate for the increased hydraulic forces which will result (e.g. by reinforcing the rock weirs). An SPSC with a slope greater than 5% will generally provide fewer water quality benefits.

Figure 1. Eroded gully due to stormwater runoff (copyright Erik Michelsen, Anne Arundel County Department of Public Works).

Figure 2. Regenerative step pool conveyance directs runoff from parking lots to Broad Creek, Annapolis, MD.

CAUTION: If pools are too large, flow velocities in the pools will be low enough to cause aggradation, which can interfere with the function of the sand filtration media. In that case, sediments must be removed regularly for the SPSC to continue functioning, increasing maintenance costs.

General Design Guidelines

Allthough the SPSC is technically a constructed or modified channel, it should be designed to minimize alterations to the receiving stream and surrounding habitat. By constructing the SPSC in an existing first-order stream or erosion gully, stormwater runoff may continue to be discharged into the receiving stream at the same location, but with less energy. Therefore, designs should be modified on a site-by-site basis based on what is required to fit the SPSC within the existing channel, while ensuring the SPSC can safely convey the design flow. It is also important that the SPSC be connected to the receiving stream in a way that minimizes potential erosive damage at the SPSC outlet.

At its most basic, the SPSC is a modified channel consisting of pools alternating with steps or cascades. Steps are constructed of large boulders and cobbles (Figure 3) and have drops of no more than 1 ft. Cascades are larger structures that can have drops up to 5 ft. The rock weirs are constructed in a shallow parabola, such that the arms of the weir form 70° angles with the bank. This shape will direct flows towards the center of the SPSC channel.

Pools are located between steps or cascades and should be at least 10 ft. long and more than 2 times the length of the preceding rock weir or cascade to dissipate energy. If desired for habitat purposes, root wads may be placed vertically (roots up) in pools, as long as they do not take up more than 10% of the pool volume. The overall slope of each pool should be less than 1%.

If the channel or gully in which the SPSC is constructed does not already have an outlet to the receiving stream, it is recommended that an armored-bed, constructed riffle be installed in the receiving stream to limit stream bed incision or knickpoint formation. If the receiving stream is actively eroding, a rock weir may need to be placed in the receiving stream to further dissipate the SPSC flow energy.

Construction

Material selection and sizing for the SPSC is largely dependent on the requirements that the rock weirs and channel remain structurally stable during the design flow while also creating the required weir and pool geometry. Detailed design guidance is available from the Anne Arundel County Department of Public Works. When selecting materials for the various SPSC components (rock weirs, pool beds, and vegetation), it is important to select materials which will not affect water chemistry or clog the sand filtration media.

Sand filtration media should be placed in the pools for shallow groundwater recharge using locally-sourced sand. Where water quality benefits are a project goal, a sand-woodchip filtration media mixture similar to those used in bioretention cells should be used, with an estimated 20% woodchip content by volume. Where water quality benefits are not a project goal, native soil with a comparable infiltration rate may be left in place instead, as long as the design guidelines are still met.

Construction of the SPSC should begin at the outlet and progress upstream to the inlet. It is not recommended that SPSC construction take place during simultaneous construction upstream from the SPSC, as sediments in runoff may contaminate or clog the bed filtration media.

Filter fabric should be placed beneath weir footer rocks to ensure that rock weirs will not fail by winnowing or undercutting.

Filter fabric must not extend beneath the pools, or it will interfere with filtration and infiltration functions.

Mulch should be used on the side-slopes of the SPSC for scour protection if construction does not take place during a planting season. Invasive and nonnative vegetation should be removed from the site before planting.

Post-Construction Monitoring

It is recommended that post-construction monitoring be conducted for at least three years. Some monitoring activities to ensure that the SPSC functions as intended include the following:

- Monitor pool depth to ensure the pools are not aggrading or degrading;
- remove accumulated sediments or replace the bed media as necessary to maintain infiltration;
- examine the SPSC vegetation to ensure that establishment is sufficient for erosion prevention;
- regularly examine the surrounding slopes for erosion, particularly where the weirs meet the surrounding slopes;
- regularly examine the weirs for rock displacement after large flow events; and,
- regularly examine the receiving stream for aggradation or degradation caused by the SPSC structure.

Corrective action should be taken if and when problems arise. However, aggraded sediment in pools should only be removed when the infiltration into the pool beds is impeded.

Figure 3. Regenerative step pool conveyance weirs have a cobble apron on the upstream side, reinforced with boulders.

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 scarce.

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Layout by Tim Poff

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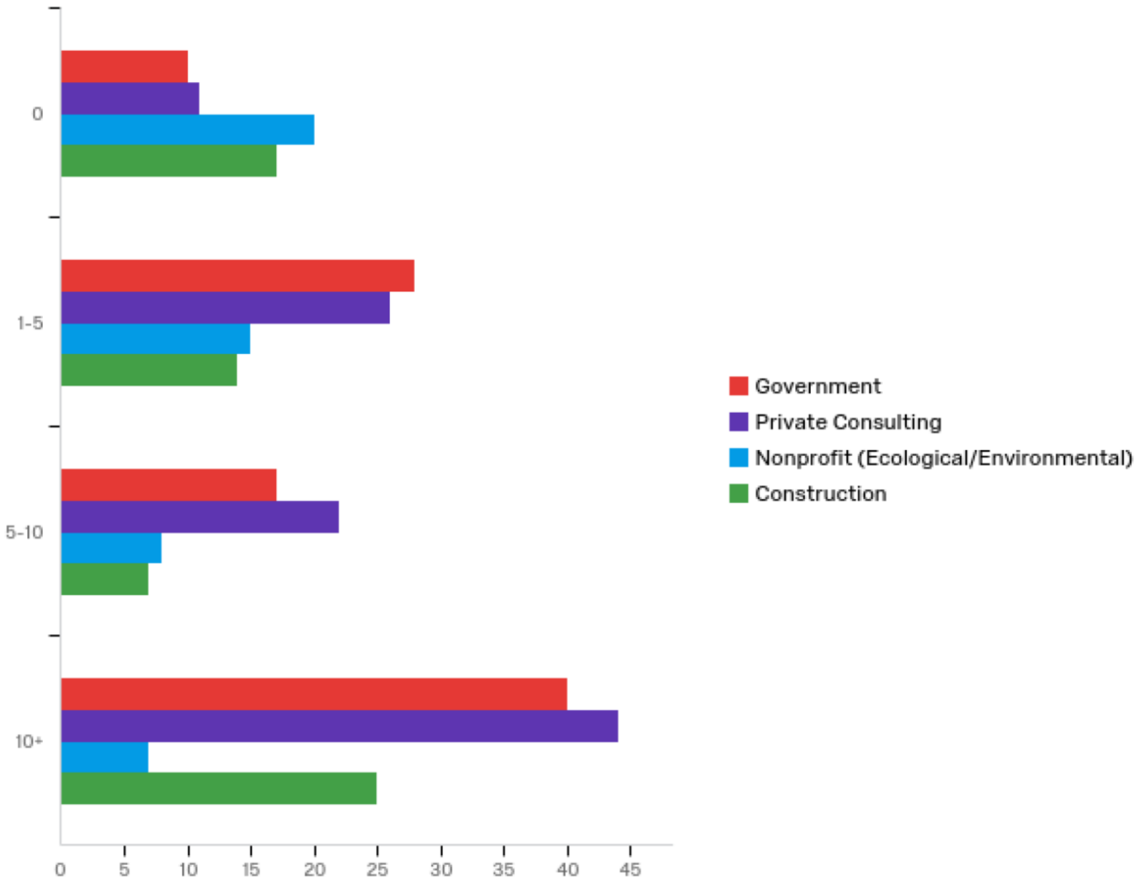
Appendix B: Results of the Second Practitioner Survey

Both of the online practitioner surveys, as well as the following graphical representations of the results of the second, revised survey, were created using survey software by Qualtrics International, Inc. (Provo, UT & Seattle, WA).

Please note that question 26, concerning horizontal and vertical tolerances allowed during the installation of in-stream structures, had incorrect units on its numerical values, and thus has not been included or considered in the official results.

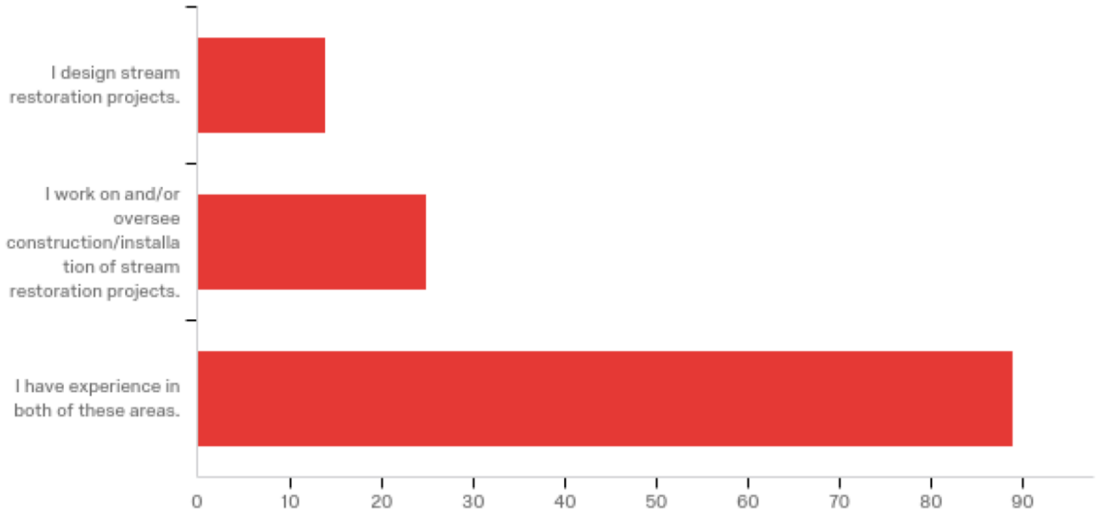
In-Stream Structures Survey 2.0

1 - How many years of work experience do you have in each of the following sectors?



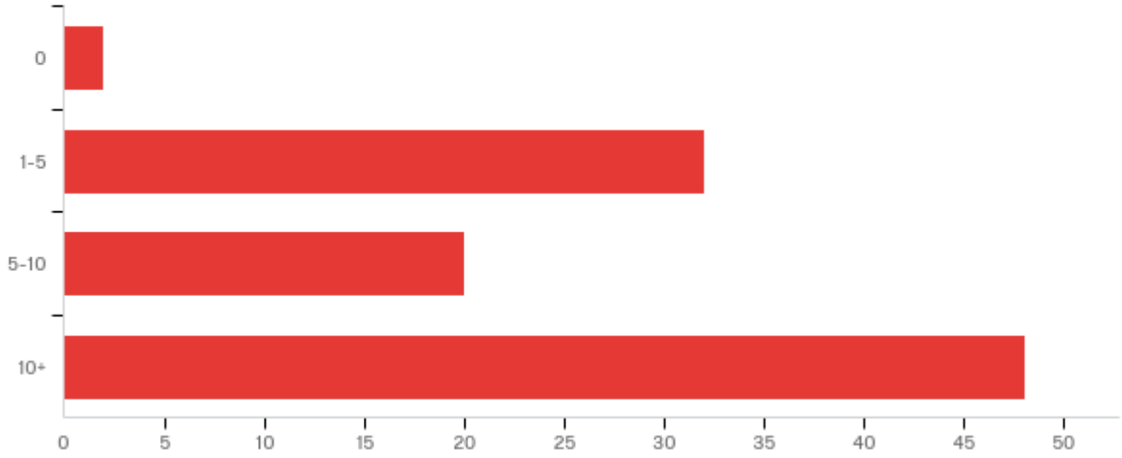
#	Question	0		1-5		5-10		10+	
1	Government	17%	10	34%	28	31%	17	34%	40
2	Private Consulting	19%	11	31%	26	41%	22	38%	44
3	Nonprofit (Ecological/Environmental)	34%	20	18%	15	15%	8	6%	7
4	Construction	29%	17	17%	14	13%	7	22%	25
	Total	Total	58	Total	83	Total	54	Total	116

2 - Which best describes your work with stream restoration?



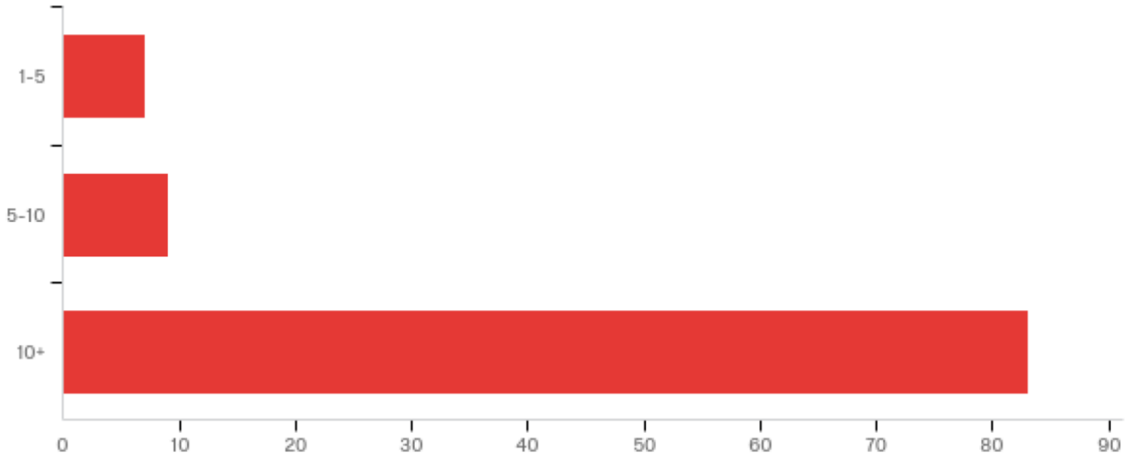
#	Answer	%	Count
1	I design stream restoration projects.	11%	14
2	I work on and/or oversee construction/installation of stream restoration projects.	20%	25
3	I have experience in both of these areas.	70%	89
	Total	100%	128

3 - How many years of experience do you have in stream restoration design?



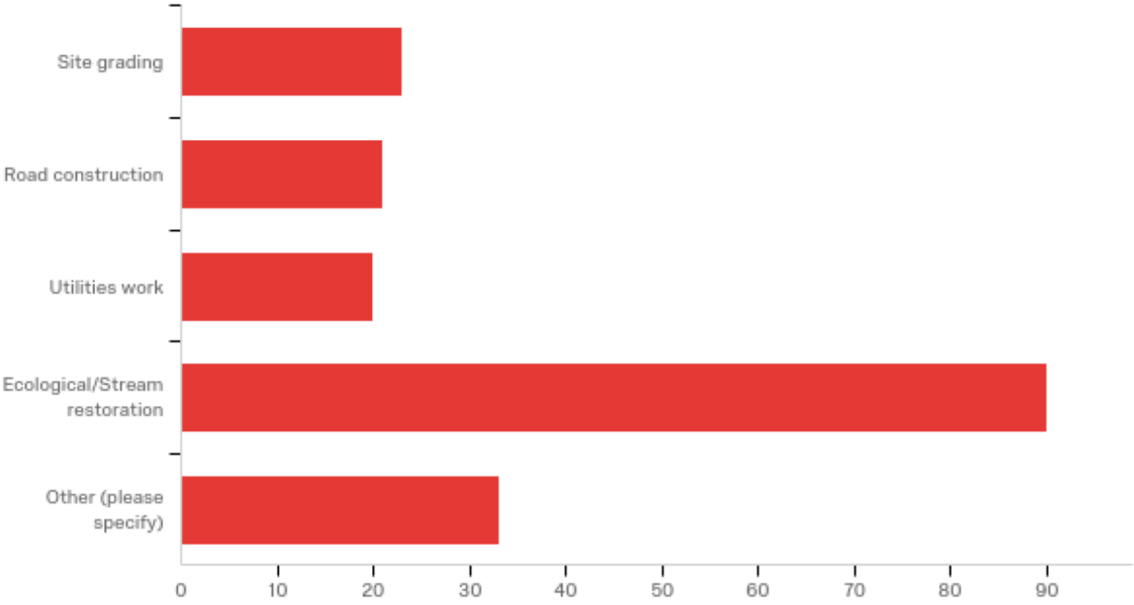
#	Answer	%	Count
1	0	2%	2
2	1-5	31%	32
3	5-10	20%	20
4	10+	47%	48
	Total	100%	102

4 - How many years has your company been in business?



#	Answer	%	Count
1	1-5	7%	7
2	5-10	9%	9
3	10+	84%	83
	Total	100%	99

5 - What types of work does your company typically perform? Select all that apply.



#	Answer	%	Count
1	Site grading	12%	23
2	Road construction	11%	21
3	Utilities work	11%	20
4	Ecological/Stream restoration	48%	90
5	Other (please specify)	18%	33
	Total	100%	187

Other (please specify)

Other (please specify)
Phosphate mining.
Water & Wastewater Treatment Design
As government, I oversee all the above work, but I don't directly perform any of them.
Now in Government
Land Surveying services
Highway and bridge design, construction and maintenance
water resources engineering
plan design and review
natural and cultural resource consulting
Local government completing stream restorations, detention basin retrofits, GSI's, and other ecological/water quality projects.
I work for the forest service designing and constructing all types of infrastructure and restoration projects associated with water bodies
stream barrier removal (dams and culverts) with associated stream restoration activities
native plantings
i work for the government
Full Service Engineering Company
wide range of A-E sectors
Detention basin retrofits/constructed wetlands; GSIs; other BMP clearinghouse approaches
Design, contract, inspect
Intergrater
Gov. Agency
Wetland and upland habitat restoration
Oversight and hiring consultants/construction companies
golf course construction
Stormwater Infrastructure of all kinds, Wetland Restoration
we implement projects through private consultants and oversee work and monitoring

As a government entity we do these, often through contractors

E&S, WQ Improvements, Site Planning, Landscaping

stormwater control

stormwater managment/WQ design

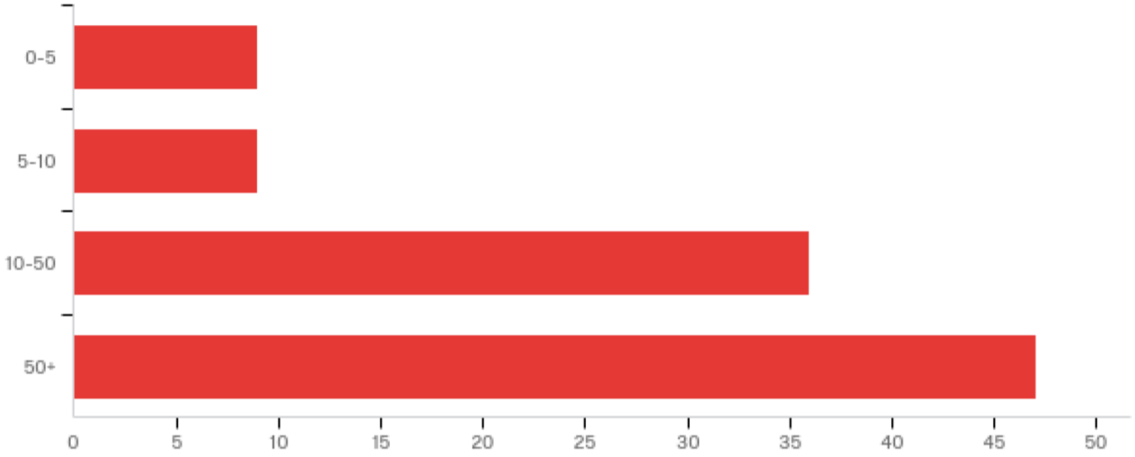
Stream assessment

municipality

We are a full service engineering design firm working in diverse services. My group is Ecosystem Restoration.

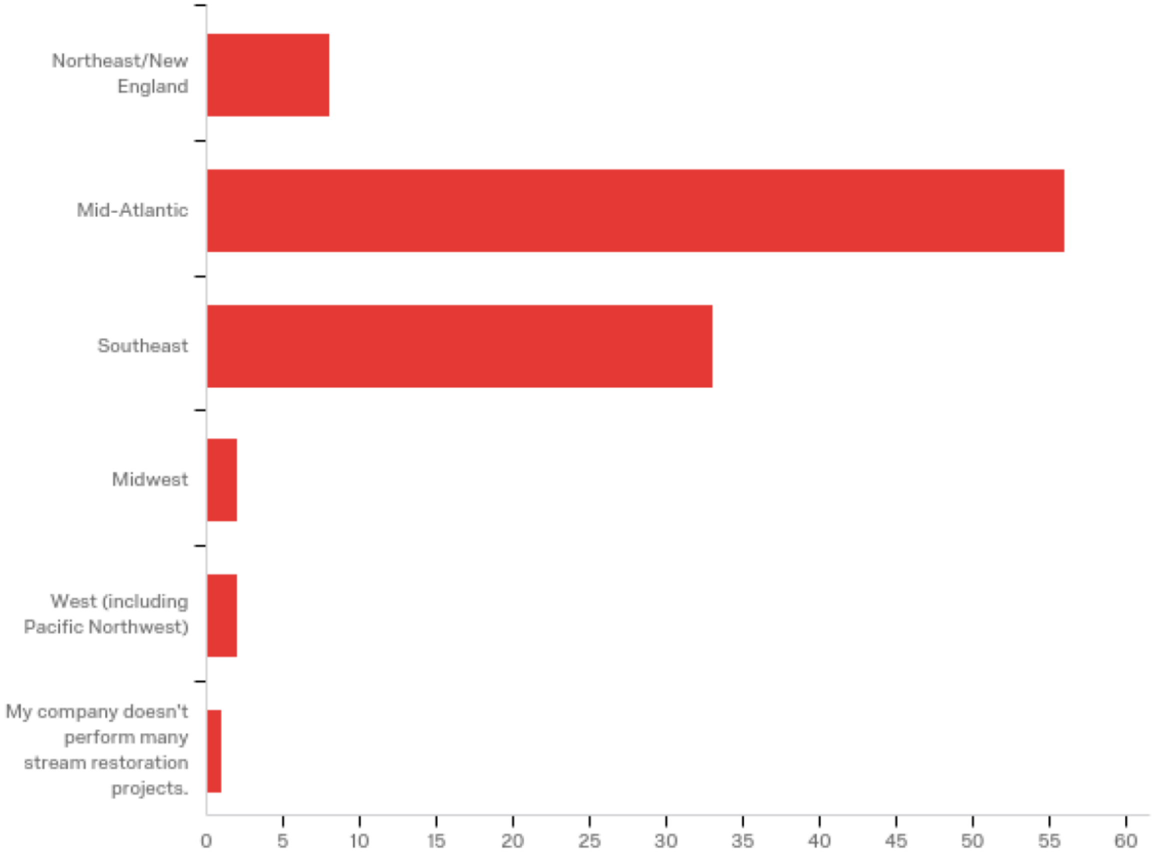
Environmental consulting: permitting, mitigation, conservation

6 - How many stream restoration projects has your company completed?



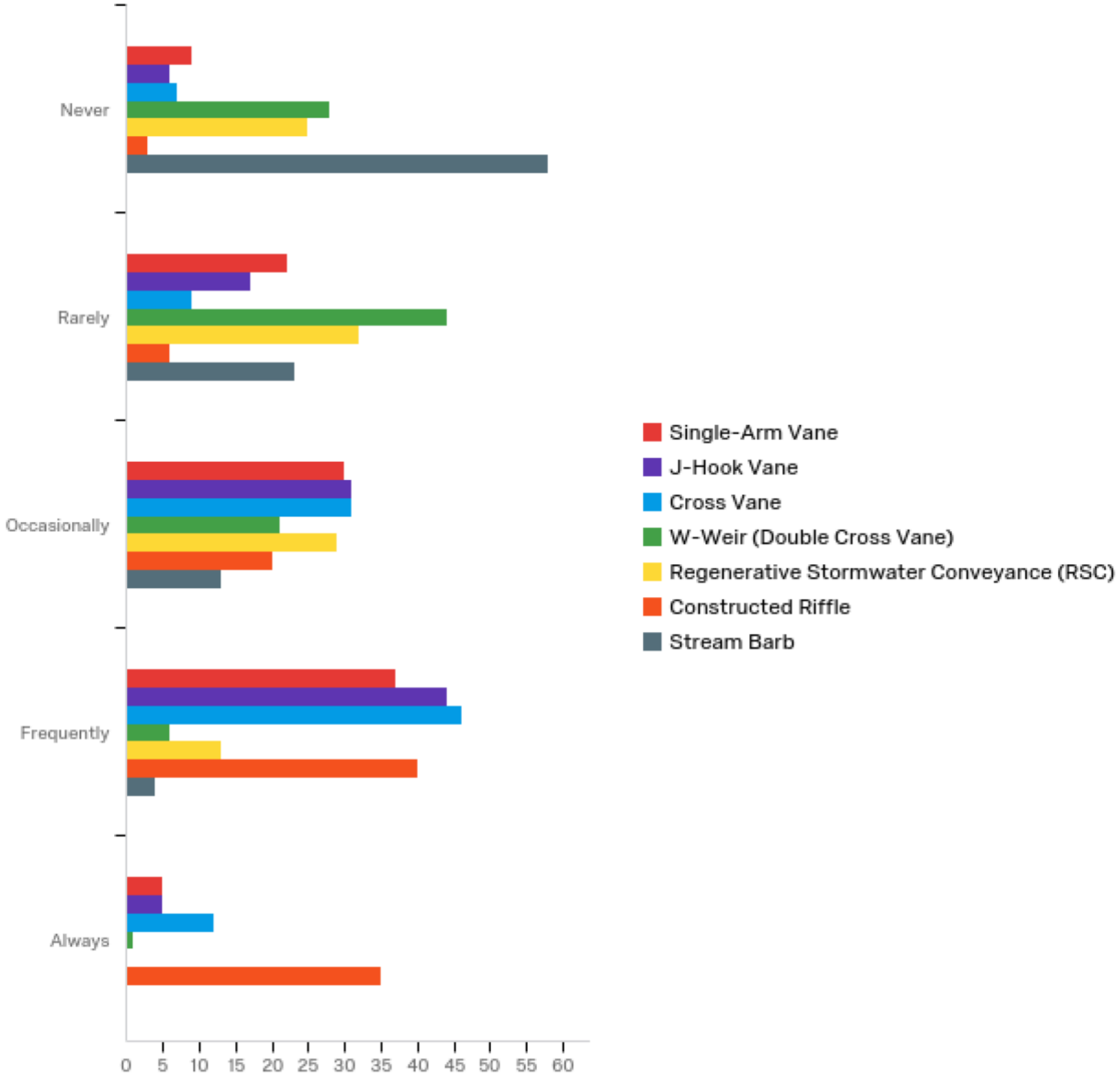
#	Answer	%	Count
1	0-5	9%	9
2	5-10	9%	9
3	10-50	36%	36
4	50+	47%	47
	Total	100%	101

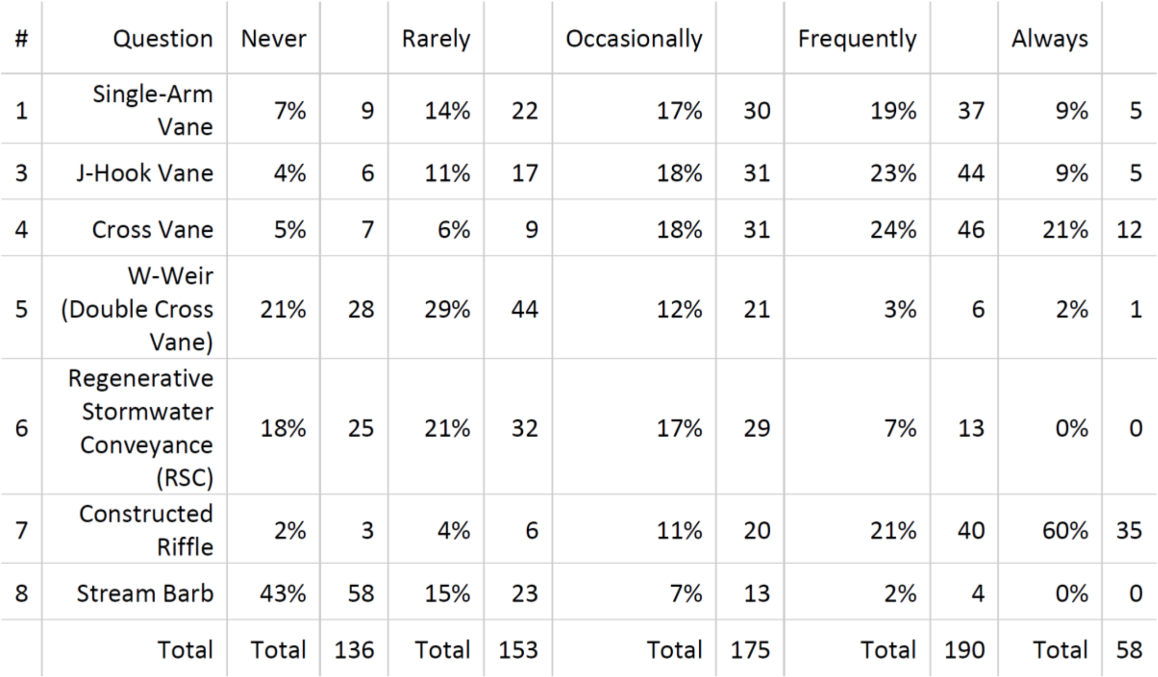
7 - In which region does your company primarily perform stream restoration projects?



#	Answer	%	Count
1	Northeast/New England	8%	8
2	Mid-Atlantic	55%	56
3	Southeast	32%	33
4	Midwest	2%	2
5	West (including Pacific Northwest)	2%	2
6	My company doesn't perform many stream restoration projects.	1%	1
	Total	100%	102

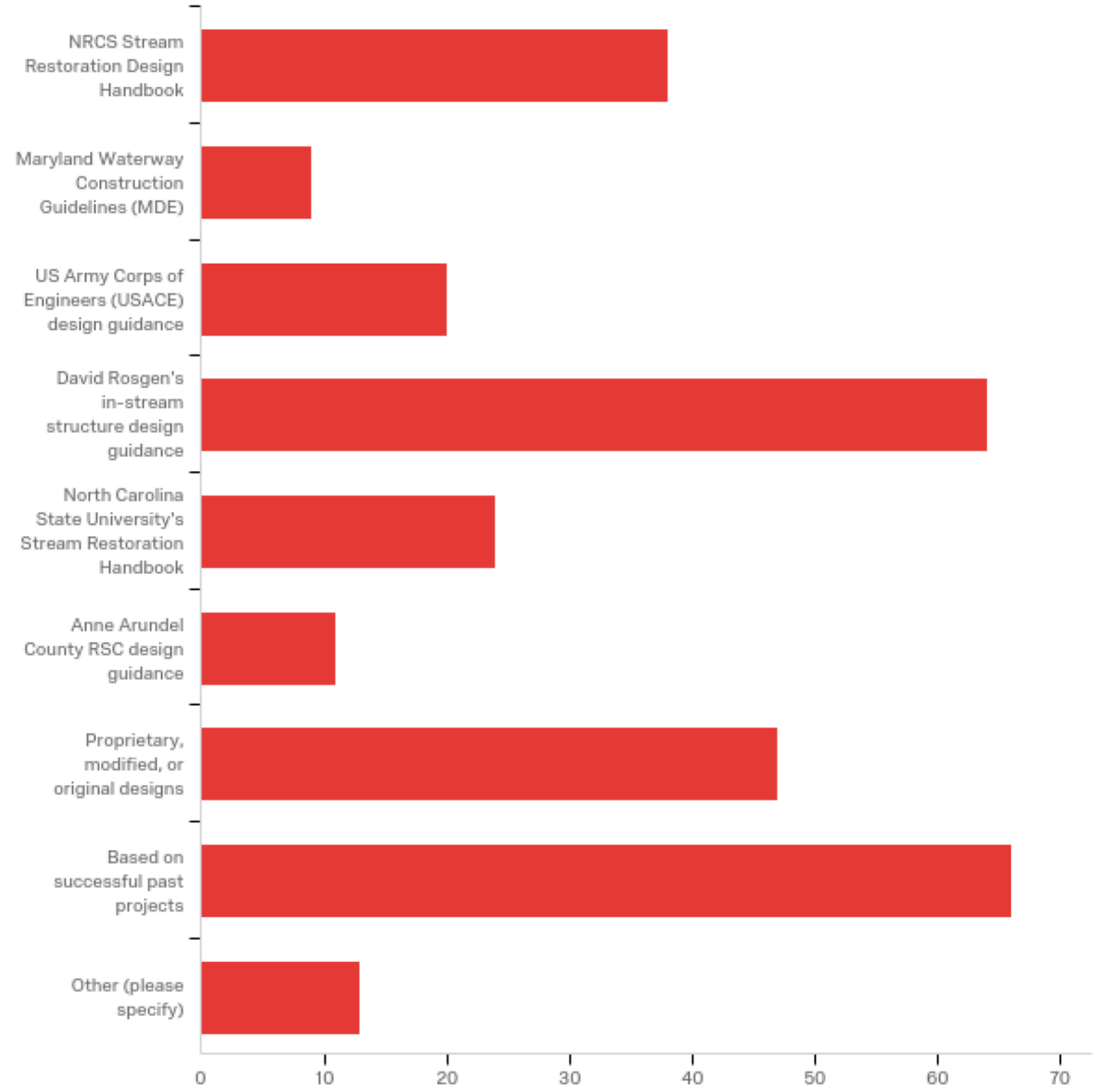
8 - How often do you include the following in-stream structures in stream restoration designs, or see them included in a design you construct?





#	Question	Never		Rarely		Occasionally		Frequently		Always	
1	Single-Arm Vane	7%	9	14%	22	17%	30	19%	37	9%	5
3	J-Hook Vane	4%	6	11%	17	18%	31	23%	44	9%	5
4	Cross Vane	5%	7	6%	9	18%	31	24%	46	21%	12
5	W-Weir (Double Cross Vane)	21%	28	29%	44	12%	21	3%	6	2%	1
6	Regenerative Stormwater Conveyance (RSC)	18%	25	21%	32	17%	29	7%	13	0%	0
7	Constructed Riffle	2%	3	4%	6	11%	20	21%	40	60%	35
8	Stream Barb	43%	58	15%	23	7%	13	2%	4	0%	0
	Total	Total	136	Total	153	Total	175	Total	190	Total	58

9 - Which of the following references do you use the most when designing in-stream structures? Select up to 3.

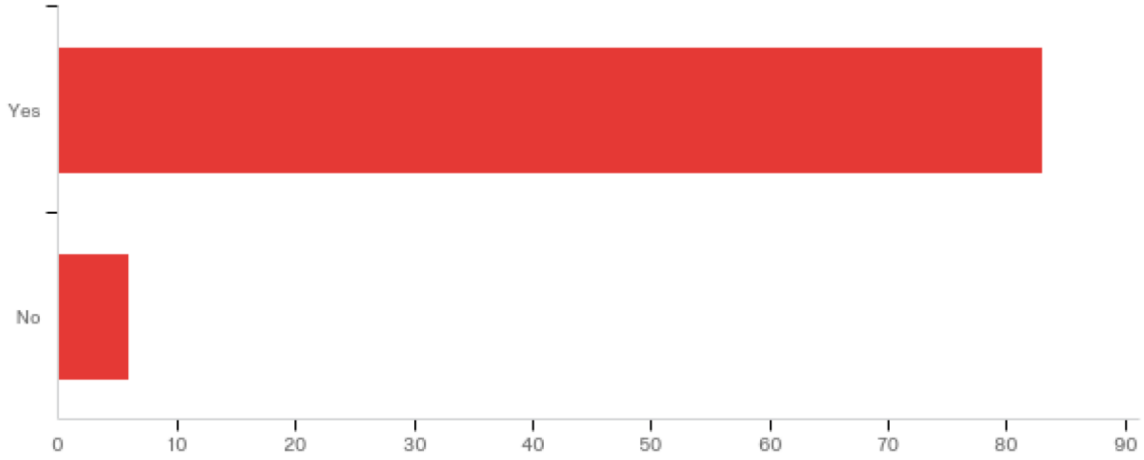


#	Answer	%	Count
1	NRCS Stream Restoration Design Handbook	13%	38
2	Maryland Waterway Construction Guidelines (MDE)	3%	9
3	US Army Corps of Engineers (USACE) design guidance	7%	20
4	David Rosgen's in-stream structure design guidance	22%	64
5	North Carolina State University's Stream Restoration Handbook	8%	24
6	Anne Arundel County RSC design guidance	4%	11
7	Proprietary, modified, or original designs	16%	47
9	Based on successful past projects	23%	66
8	Other (please specify)	4%	13
	Total	100%	292

9_8_TEXT - Other (please specify)

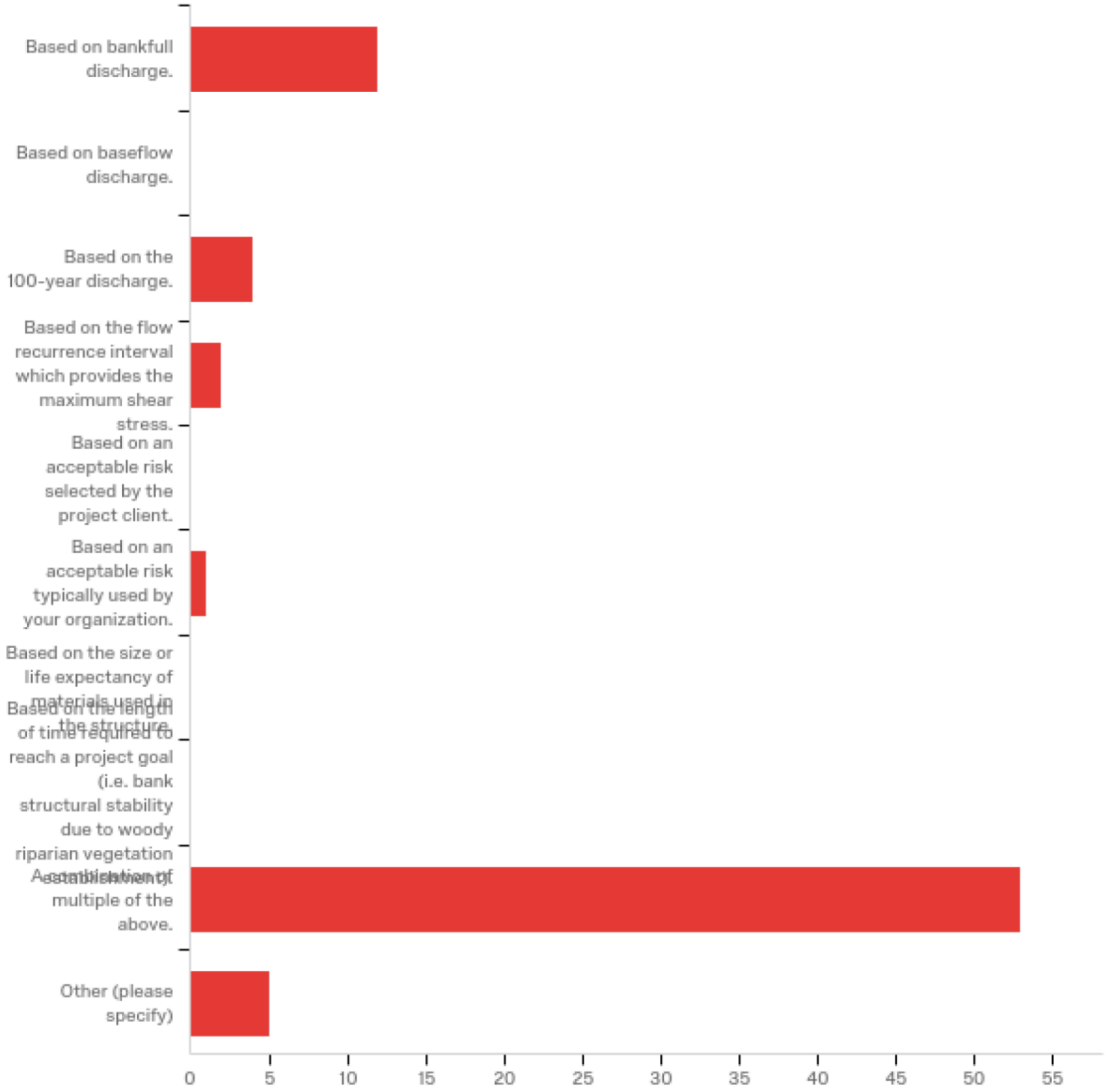
Other (please specify)
VA BMP and stream restoration handbook
DCR Virginia Restoration Guide
sediment mobility, legacy sediment removal, 2-D modeling to isolate potential problem areas
stay abreast with industry practices, lessons learned, and academic research
Stream simulation: An ecological approach to designing road-stream crossings. Stream simulation working group. San Dimas Technology Development Center USDA Forest Service. May 2008
USFS Stream Simulation Guidelines; NOAA Rock Ramp Design Guidance
Function Based Framework - Will Harmon
National Large Wood Manual
PA Fish and Boat Commission approved structures
2D Ecohydraulic Modeling Approach
Existing and proposed hydraulics
Other design consultant experience
USBR-USACE National Large Wood Manual

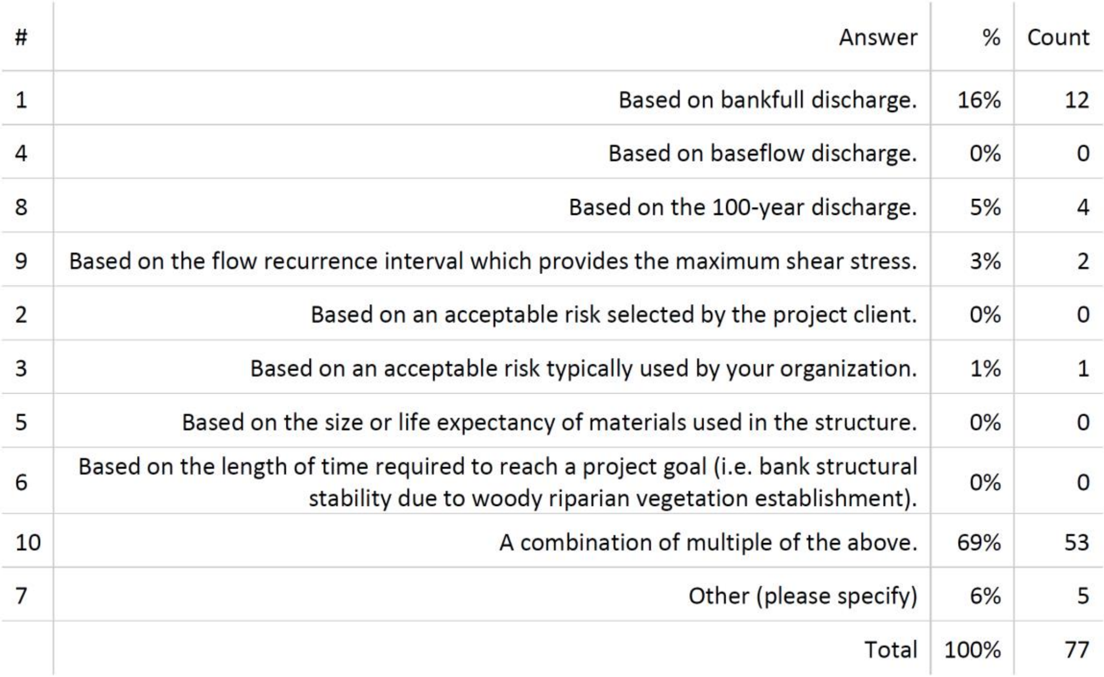
10 - When designing a structure, do you consider a specific design life or design flow? (Design life: the period of time for which a structure is expected to remain structurally sound and functional.)



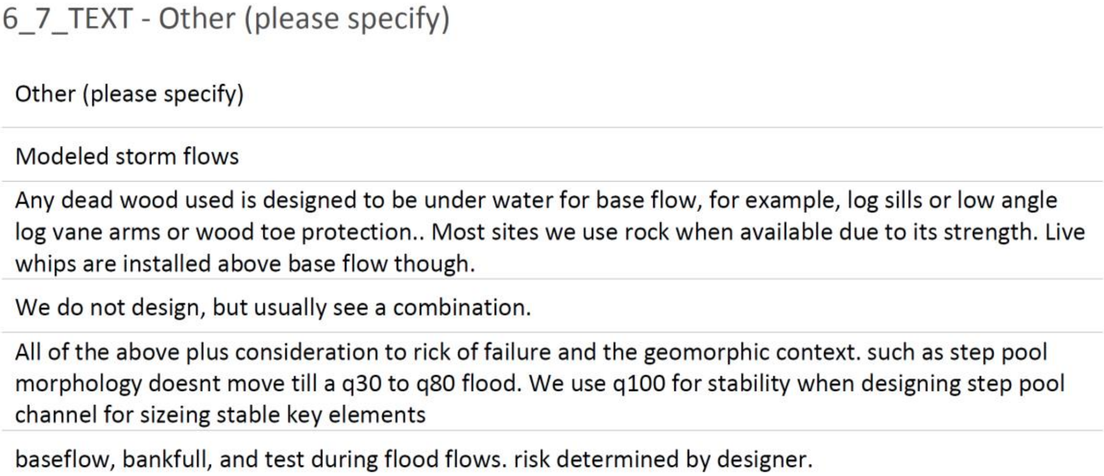
#	Answer	%	Count
1	Yes	93%	83
2	No	7%	6
	Total	100%	89

11 - How do you determine a design life or design flow for an in-stream structure?





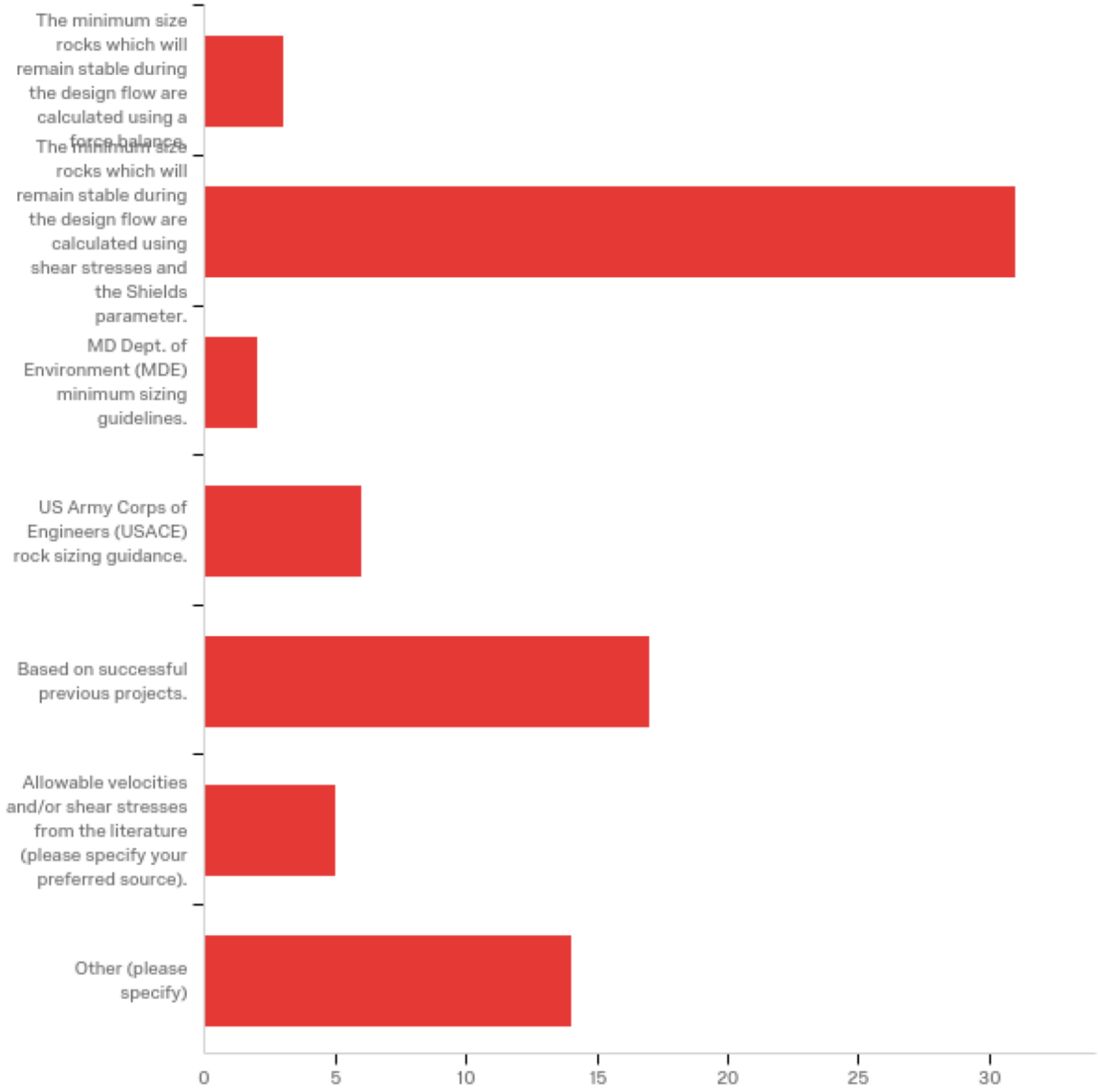
#	Answer	%	Count
1	Based on bankfull discharge.	16%	12
4	Based on baseflow discharge.	0%	0
8	Based on the 100-year discharge.	5%	4
9	Based on the flow recurrence interval which provides the maximum shear stress.	3%	2
2	Based on an acceptable risk selected by the project client.	0%	0
3	Based on an acceptable risk typically used by your organization.	1%	1
5	Based on the size or life expectancy of materials used in the structure.	0%	0
6	Based on the length of time required to reach a project goal (i.e. bank structural stability due to woody riparian vegetation establishment).	0%	0
10	A combination of multiple of the above.	69%	53
7	Other (please specify)	6%	5
	Total	100%	77



6_7_TEXT - Other (please specify)

Other (please specify)
Modeled storm flows
Any dead wood used is designed to be under water for base flow, for example, log sills or low angle log vane arms or wood toe protection.. Most sites we use rock when available due to its strength. Live whips are installed above base flow though.
We do not design, but usually see a combination.
All of the above plus consideration to rick of failure and the geomorphic context. such as step pool morphology doesnt move till a q30 to q80 flood. We use q100 for stability when designing step pool channel for sizeing stable key elements
baseflow, bankfull, and test during flood flows. risk determined by designer.

12 - What method do you use to size rocks/boulders for use in vanes?



#	Answer	%	Count
1	The minimum size rocks which will remain stable during the design flow are calculated using a force balance.	4%	3
2	The minimum size rocks which will remain stable during the design flow are calculated using shear stresses and the Shields parameter.	40%	31
3	MD Dept. of Environment (MDE) minimum sizing guidelines.	3%	2
4	US Army Corps of Engineers (USACE) rock sizing guidance.	8%	6
7	Based on successful previous projects.	22%	17
5	Allowable velocities and/or shear stresses from the literature (please specify your preferred source).	6%	5
6	Other (please specify)	18%	14
	Total	100%	78

7_5_TEXT - Allowable velocities and/or shear stresses from the literature (please spec...

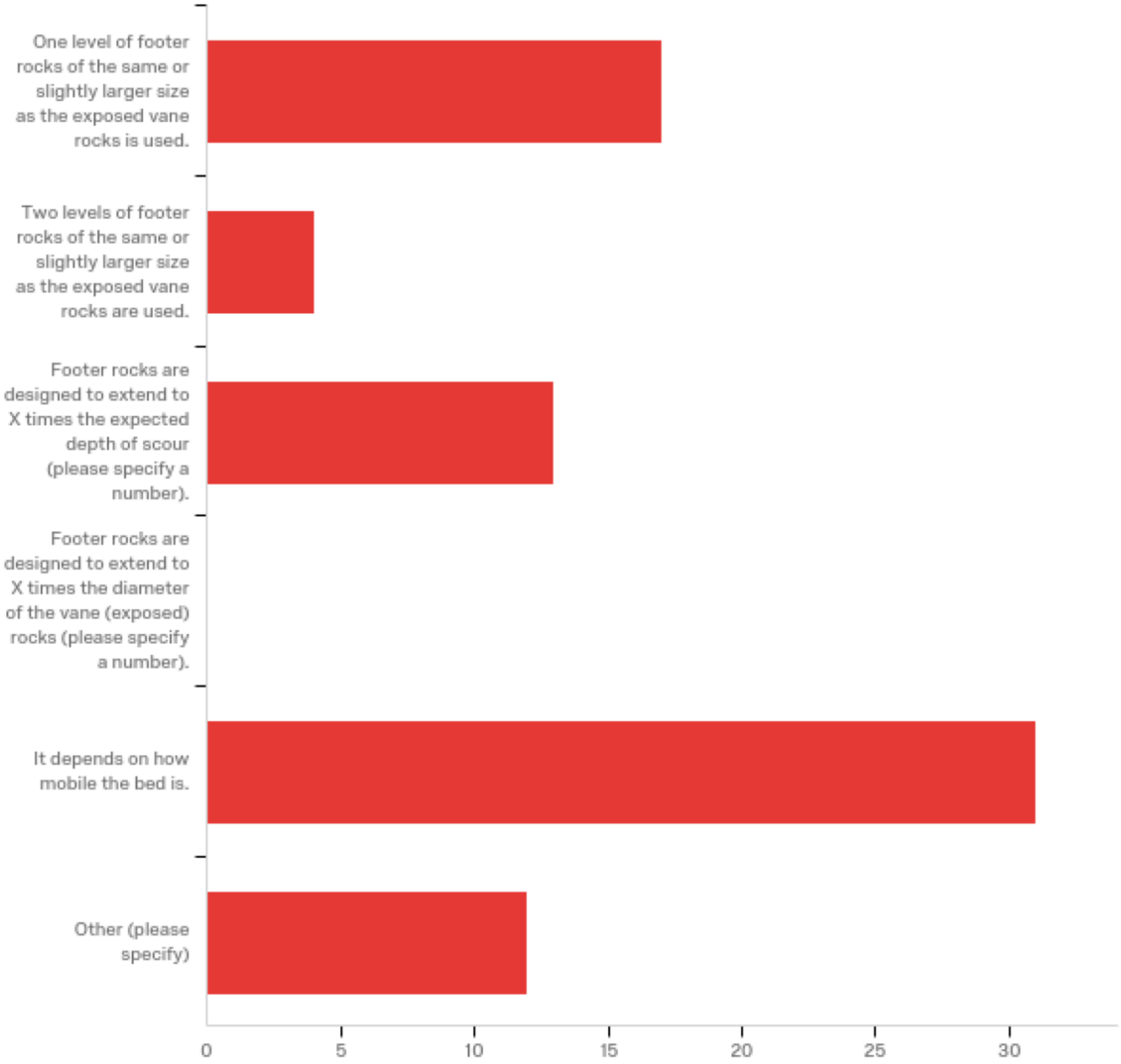
Allowable velocities and/or shear stresses from the literature (please spec...
USACE EMRRP SR-29
Rosgen - Applied Fluvial Geomorphology
NRCS stream desgin handbook NEH 654
Non mobile for 100 year velocities and stress, interlocking of boulders and backfill will then provide higher protection
Variety, but I like Craig Fischenich's compiled table

Other (please specify)

Other (please specify)
We usually oversize our boulders since they typically are easier to install and more uniform in shape (flatter for sills, arms). Smaller boulders, even if sized to handle the shear stress, are harder to install, making for a less secure structure. Fit and finish seem to be a better means to tell if a structure will stay put
We do not design

Multiple methods above are used and results compared
Based on successful past projects, but also site specific assessment of shear stress and risk profile
Rosgen structure rock relationship (based on stress balance and D100)
we use the reference reach sizes then match mobility and stability depending what type of stream and structure you are designing
My experience has been with log structures.
Fischenich, 2001
A combination of above
Combination of above
National Engineering Handbook 654
combination of stability at risk management flow and low-flow hydraulics for habitat
combo of shear stress calcs and based on experience
We have developed proprietary stone sizing worksheets that look at different sizing criteria from sources such as MDE, USACE, Shields/Rosgen, Zimmermann with different weights/risks based on applicability to design stream hydraulic conditions. We also look at upstream and downstream conditions and rock sizes to add evidence for likely transport conditions.

13 - To what depth do you place footer rocks for a vane?



#	Answer	%	Count
1	One level of footer rocks of the same or slightly larger size as the exposed vane rocks is used.	22%	17
2	Two levels of footer rocks of the same or slightly larger size as the exposed vane rocks are used.	5%	4
3	Footer rocks are designed to extend to X times the expected depth of scour (please specify a number).	17%	13
4	Footer rocks are designed to extend to X times the diameter of the vane (exposed) rocks (please specify a number).	0%	0
6	It depends on how mobile the bed is.	40%	31
5	Other (please specify)	16%	12
	Total	100%	77

8_3_TEXT - Footer rocks are designed to extend to X times the expected depth of scour...

Footer rocks are designed to extend to X times the expected depth of scour...
1.5
1 to 2
1-3
1.5
1.5-2.0
1.5
at least 1.5 to 2
2
min 1.0
1.5
2+

Footer rocks are designed to extend to X times the diameter of the vane (ex...

8_5_TEXT - Other (please specify)

one level of footer rocks of the same or slightly larger size as exposed unless site requirements require otherwise (i.e. raising a channel several feet may require additional footers or clay core)

We do not design, but usually see one level of footer rocks.

Depends on the stream, typically one level of footer rocks

To 1-2 ft below max pool depth

To maximum scour based on material size and pool depth

At least 6" below deepest part of following pool

Footer stones extend 1 foot below expected depth of scour or designed Dmax of pool, whichever is deeper

typically one level, but dependent on expected scour or drop across the vane

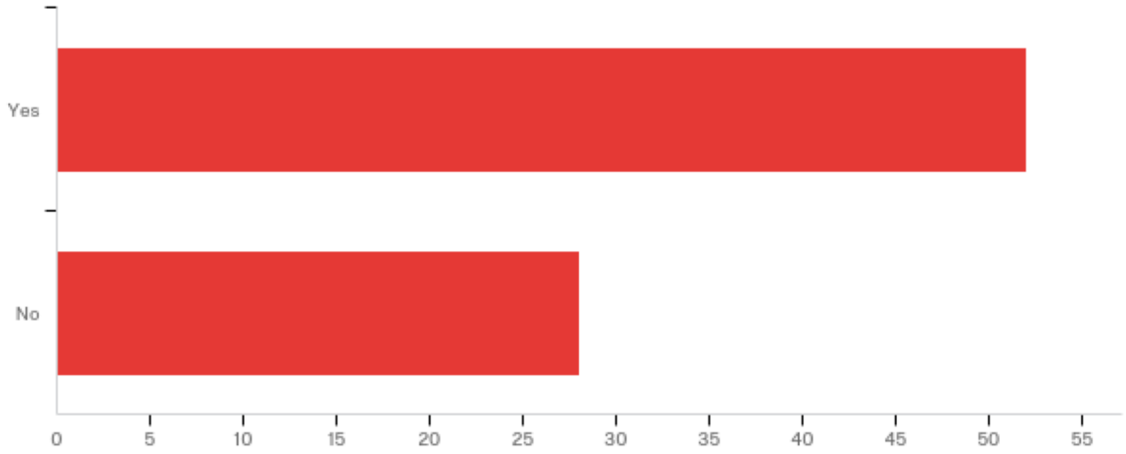
Don't know, never designed a vane myself

Typical Minimum depth ~2.5 feet below stream thalweg

Generally, I want footers to extend twice the expected scour depth and this is depends on bed mobility.

min 18" below expected scour depth and place splash rock at ~half that depth just below head of structure between vane arms

14 - Do you calculate expected depth of scour? (For footer rock depth, expected plunge pool depth, etc.)

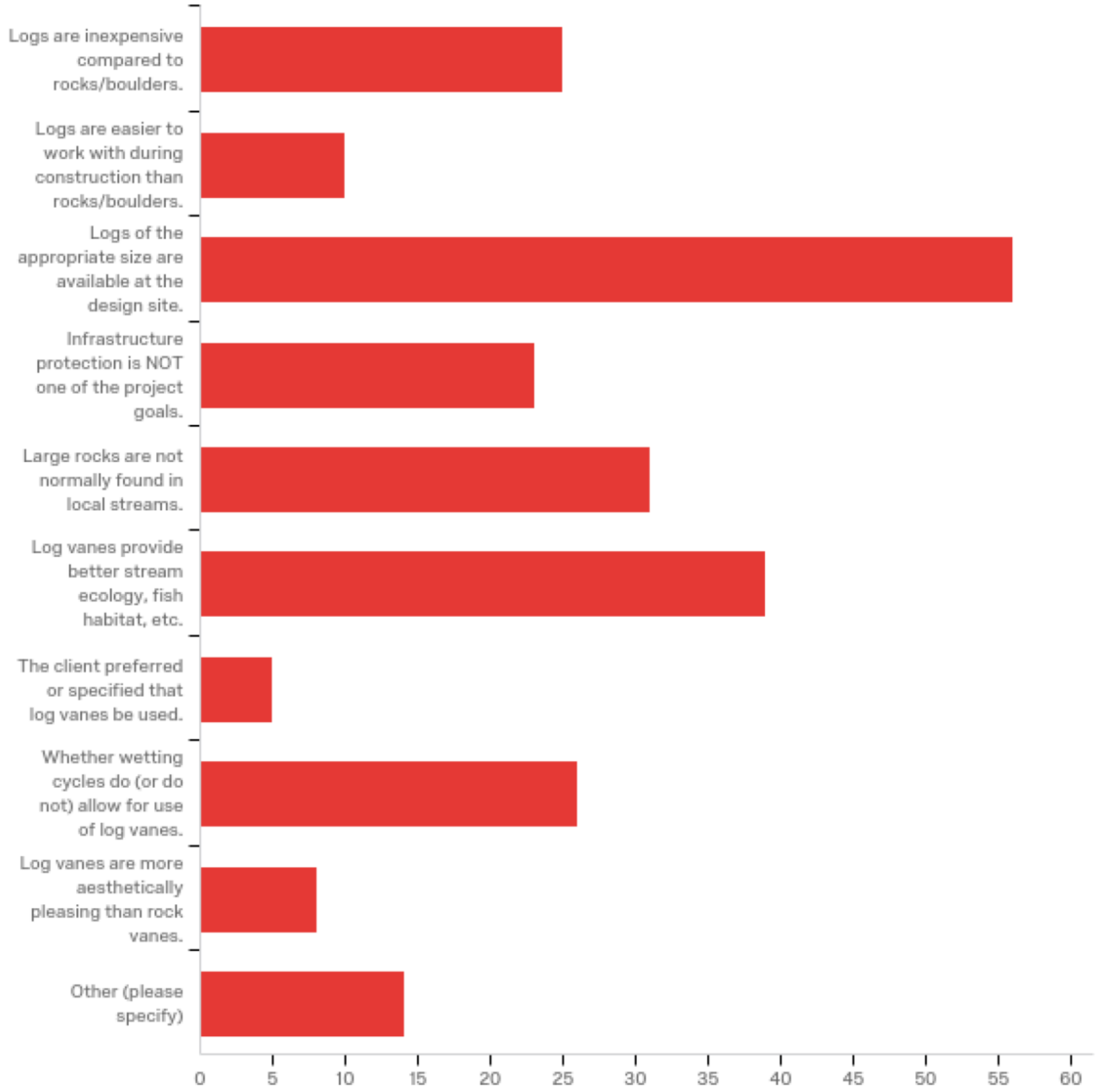


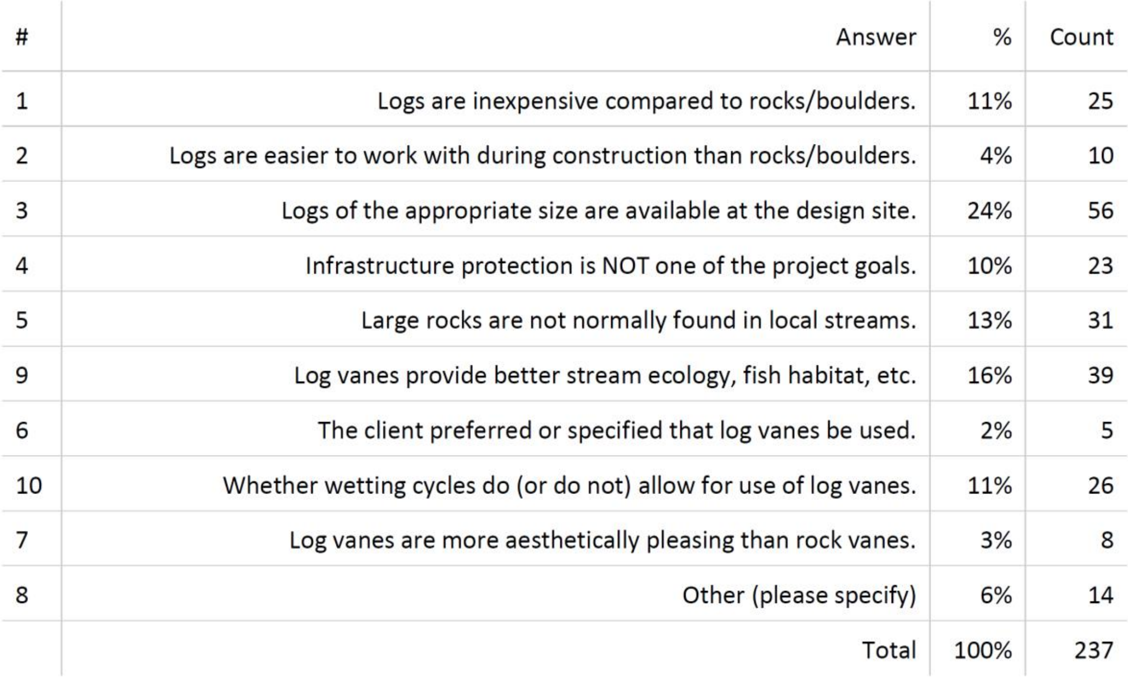
#	Answer	%	Count
1	Yes	65%	52
2	No	35%	28
	Total	100%	80

15 - How do you determine spacing between structures in a meandering channel?

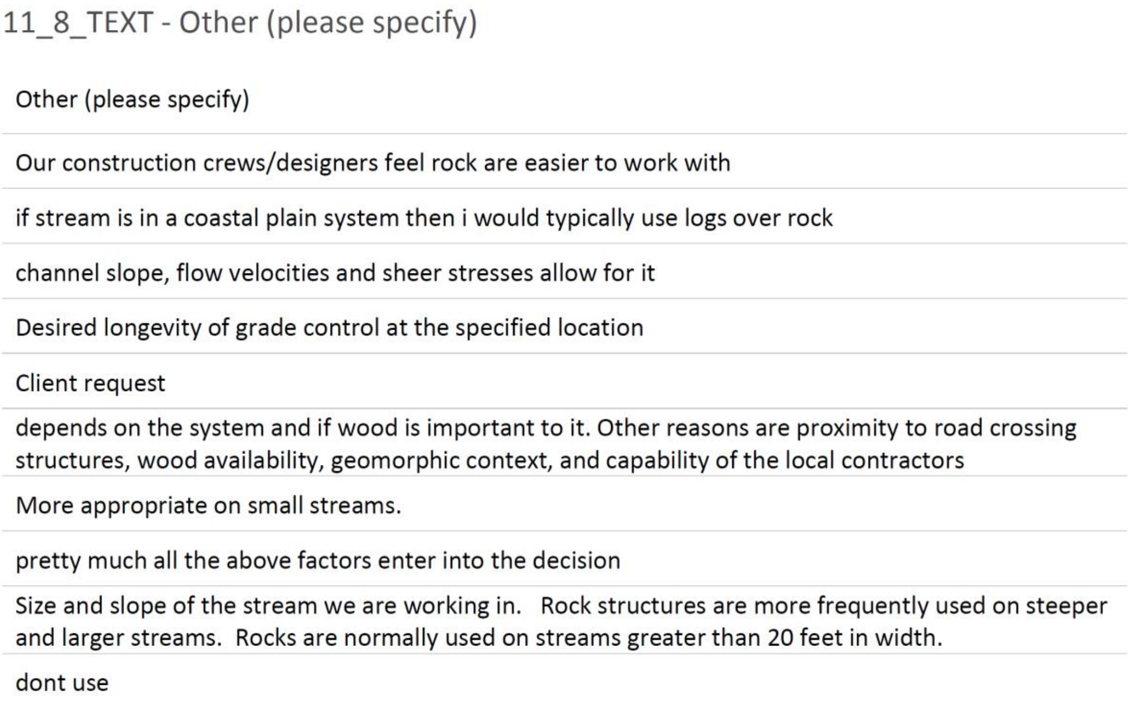
Data source misconfigured for this visualization

16 - What factors affect whether or not you might use a log vane in place of a rock vane? Choose up to 3.





#	Answer	%	Count
1	Logs are inexpensive compared to rocks/boulders.	11%	25
2	Logs are easier to work with during construction than rocks/boulders.	4%	10
3	Logs of the appropriate size are available at the design site.	24%	56
4	Infrastructure protection is NOT one of the project goals.	10%	23
5	Large rocks are not normally found in local streams.	13%	31
9	Log vanes provide better stream ecology, fish habitat, etc.	16%	39
6	The client preferred or specified that log vanes be used.	2%	5
10	Whether wetting cycles do (or do not) allow for use of log vanes.	11%	26
7	Log vanes are more aesthetically pleasing than rock vanes.	3%	8
8	Other (please specify)	6%	14
	Total	100%	237



11_8_TEXT - Other (please specify)

Other (please specify)
Our construction crews/designers feel rock are easier to work with
if stream is in a coastal plain system then i would typically use logs over rock
channel slope, flow velocities and sheer stresses allow for it
Desired longevity of grade control at the specified location
Client request
depends on the system and if wood is important to it. Other reasons are proximity to road crossing structures, wood availability, geomorphic context, and capability of the local contractors
More appropriate on small streams.
pretty much all the above factors enter into the decision
Size and slope of the stream we are working in.   Rock structures are more frequently used on steeper and larger streams. Rocks are normally used on streams greater than 20 feet in width.
dont use

If feasible, making use of project site materials, i.e. trees/logs and incorporate into the design
Small streams
Use of logs is primarily for habitat enrichment within pools and riffles, independent of rock grade control structures

17 - What are some knowledge gaps in the current in-stream structure design guidance?

What are some knowledge gaps in the current in-stream structure design guid...
ecological benefits
This is a vague question
longevity of log structures due to decay
guidance is vague. assumes one size fits all. i've developed design requirements for smaller intermittent channles vs. larger perenial channels so that they look more natural and function to meet the need
Appropriate structure selection for use in different size channels, geomorphologic setting, the effect of contributing drainage area imperviousness.
The use of riffles versus cross vanes for channel slope modification; how to allow for undercut bank for habitat; better habitat - biological lift
providing accurate typical section measurements in plans.
computational modeling within budgetary and schedule constraints
too many options need one complete guidance with all potential designs
deciding to design based on centerline or thalweg
Design specificationsn for steep stream practices
construction techniques. I sse good designs fail because of poor construction technique
Better ways to determine flow resistance
good construction details/instructions for contractors to ensure the quality of the structures installed
expected life of structures as well as common failures of structures
Filter fabric specifications
long term performance
use and placement of structures
Many designers working at transportation engineering firms use boiler plate standards for safety from liability suits instead of pursuing a process of continuous improve the
placement of sturctures based on multidimensinal hydraulics
Manuals are old (MD waterway constr guidelines) or heavily Rosgen based
implementation experience

Most guidance is not inclusive of all methods

The knowledge base is not the problem. The biggest problem is people designing projects without proper training, background and experience. The basic science behind stream restoration is pretty well developed. Too many people are looking for a shortcut around getting the proper training.

long-term monitoring results of previously installed structures - very often see structures installed in improper locations

Not designing for 100 year storms

MORE ACCURATE ROCK SIZING

examples of why structers fail

It would be helpful to have more information on what makes live stakes and other live woody material used in structures succeed or fail. There are so many variables, it's hard to predict how well they will do.

1- lifetime of woody structure in different settings, 2-value of certain structures for habitat function

I think the footer depth guidelines could be strengthened; some designs are getting creative, i.e. not following cookie cutter; seems manuals/guidelines should open this up to adhere to fundamentals, but show/allow/encourage new approaches. Try to minimize disturbance to a adjacent stream valley by making use of in-situ/local materials as much as possible. If this makes sense.

maximizing in stream habitat using rock structures

effect on aquatic life

I don' t use design guidance very often. My experience is that too many designers use rock structures too often and place them improperly.

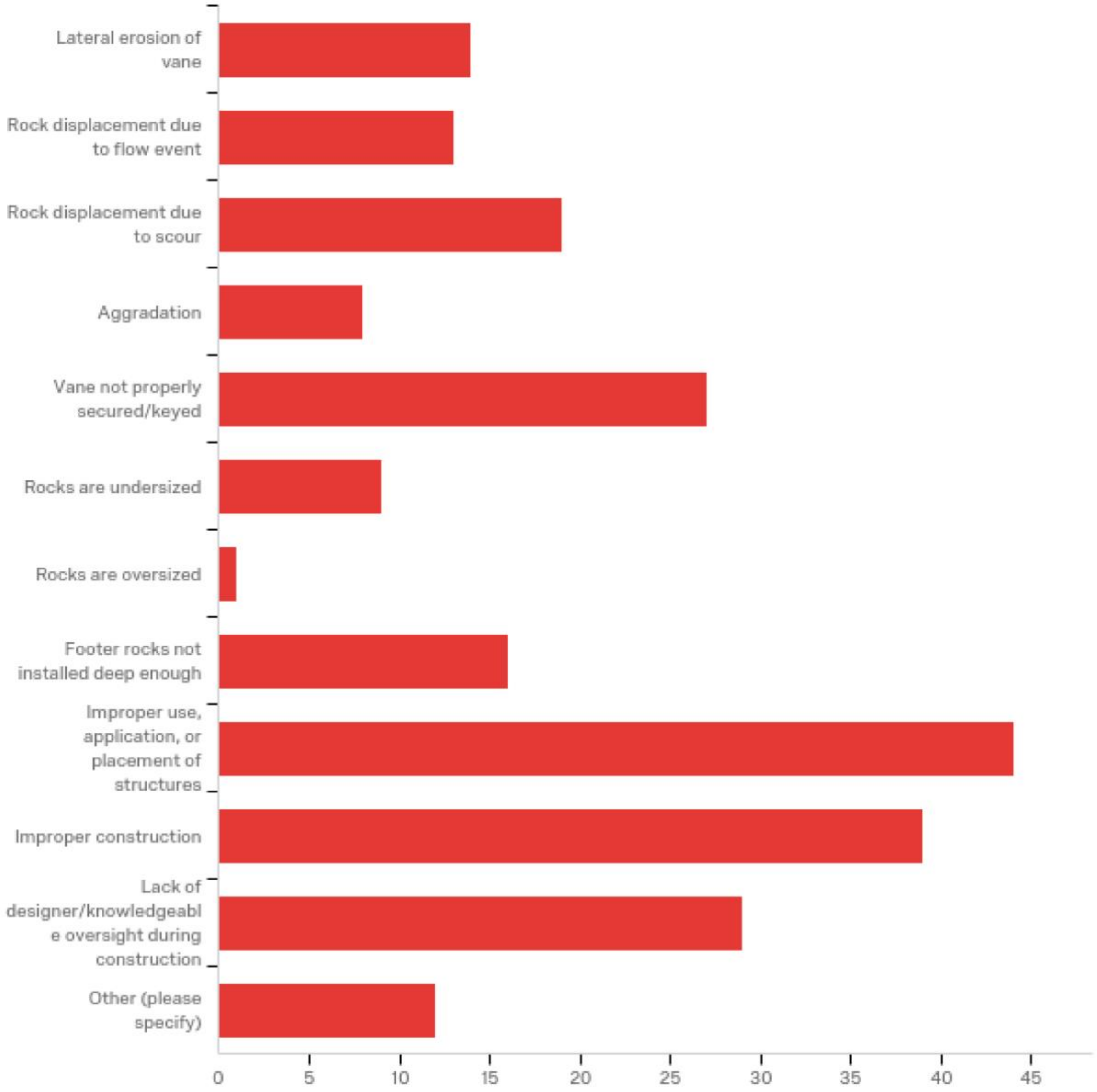
Type and placement

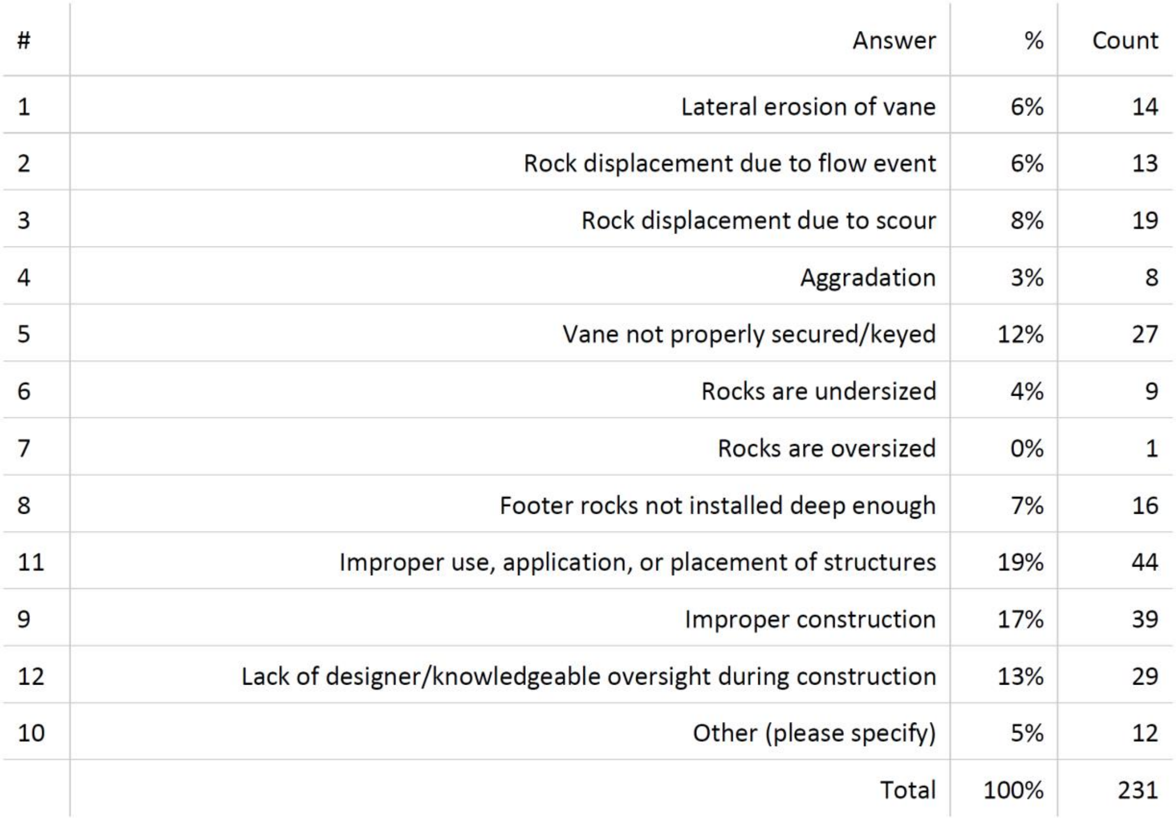
Long-term performance

Variation in how various structures are installed by different companies and which are more stable, actual longterm life and stability, conditions which cause instability and structures that tend to attract beavers or other wildlife.

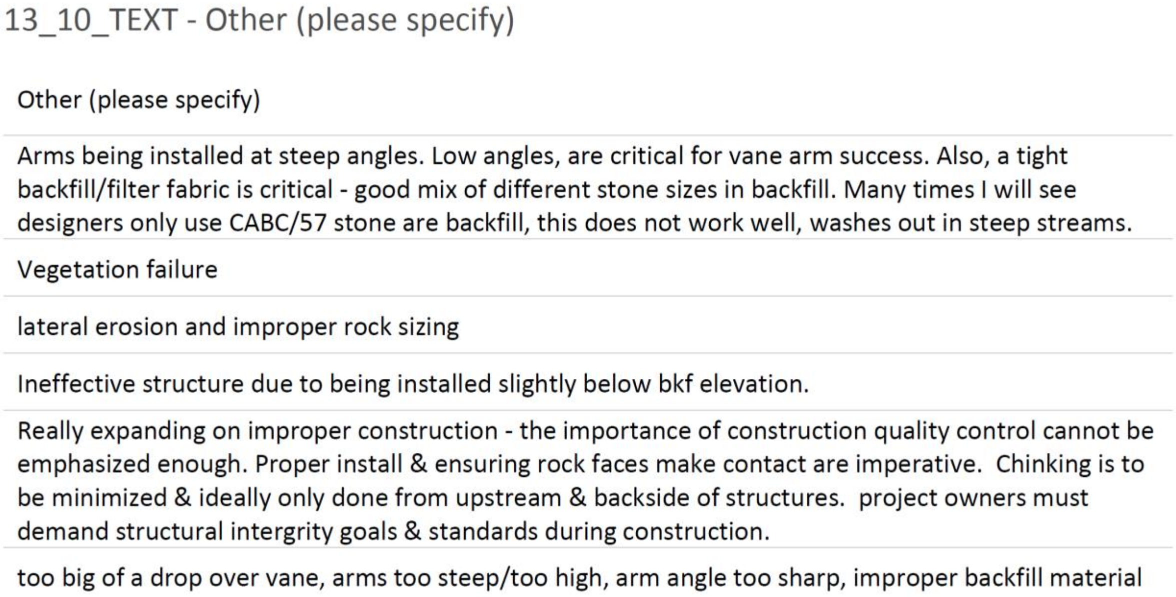
Sediment Transport

18 - In your experience, what are the most common reasons for in-stream structure failure? Choose up to 3.



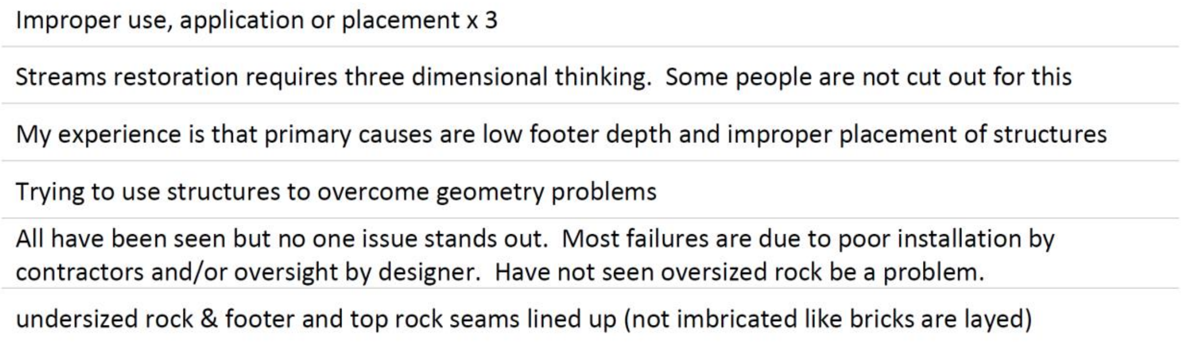


#	Answer	%	Count
1	Lateral erosion of vane	6%	14
2	Rock displacement due to flow event	6%	13
3	Rock displacement due to scour	8%	19
4	Aggradation	3%	8
5	Vane not properly secured/keyed	12%	27
6	Rocks are undersized	4%	9
7	Rocks are oversized	0%	1
8	Footer rocks not installed deep enough	7%	16
11	Improper use, application, or placement of structures	19%	44
9	Improper construction	17%	39
12	Lack of designer/knowledgeable oversight during construction	13%	29
10	Other (please specify)	5%	12
	Total	100%	231



13_10_TEXT - Other (please specify)

Other (please specify)
Arms being installed at steep angles. Low angles, are critical for vane arm success. Also, a tight backfill/filter fabric is critical - good mix of different stone sizes in backfill. Many times I will see designers only use CABC/57 stone are backfill, this does not work well, washes out in steep streams.
Vegetation failure
lateral erosion and improper rock sizing
Ineffective structure due to being installed slightly below bkf elevation.
Really expanding on improper construction - the importance of construction quality control cannot be emphasized enough. Proper install & ensuring rock faces make contact are imperative. Chinking is to be minimized & ideally only done from upstream & backside of structures. project owners must demand structural intergrity goals & standards during construction.
too big of a drop over vane, arms too steep/too high, arm angle too sharp, improper backfill material



Improper use, application or placement x 3

Streams restoration requires three dimensional thinking. Some people are not cut out for this

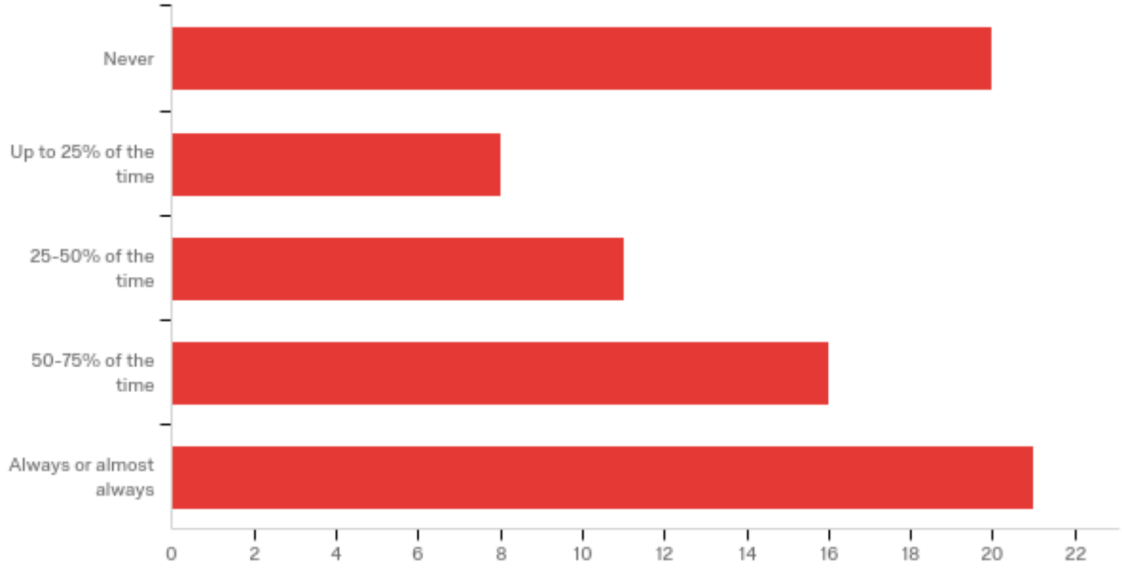
My experience is that primary causes are low footer depth and improper placement of structures

Trying to use structures to overcome geometry problems

All have been seen but no one issue stands out. Most failures are due to poor installation by contractors and/or oversight by designer. Have not seen oversized rock be a problem.

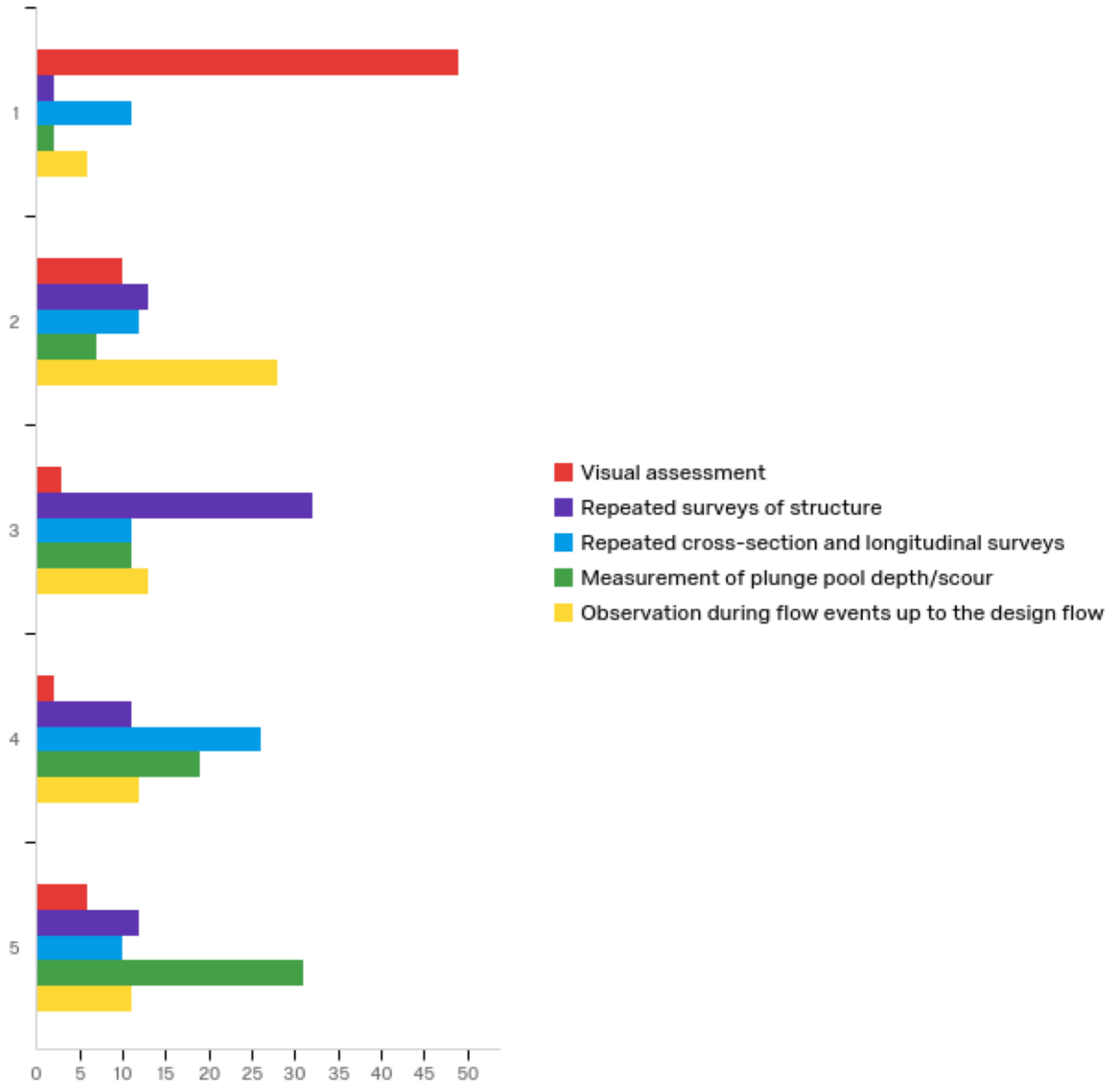
undersized rock & footer and top rock seams lined up (not imbricated like bricks are layed)

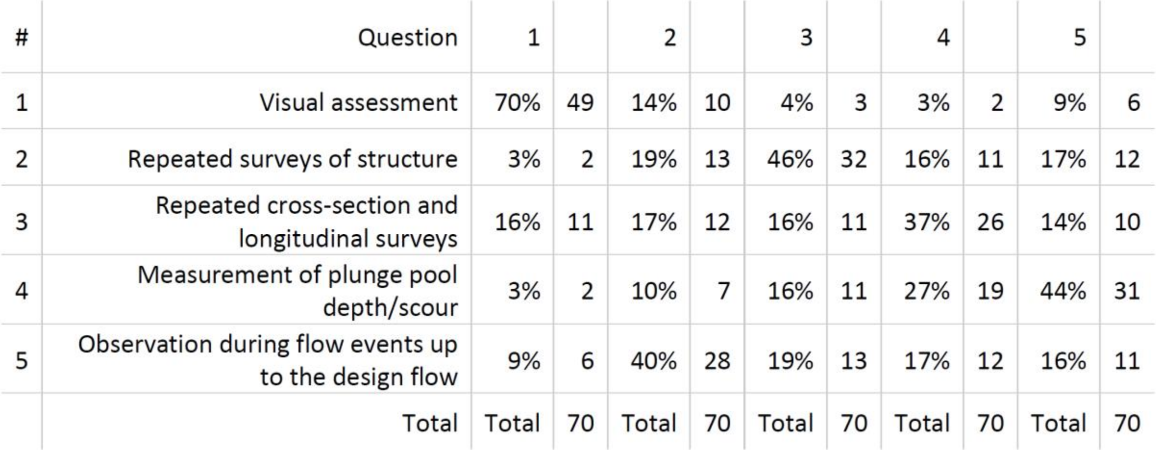
19 - How often are you involved in the contractor selection process?



#	Answer	%	Count
1	Never	26%	20
2	Up to 25% of the time	11%	8
3	25-50% of the time	14%	11
4	50-75% of the time	21%	16
5	Always or almost always	28%	21
	Total	100%	76

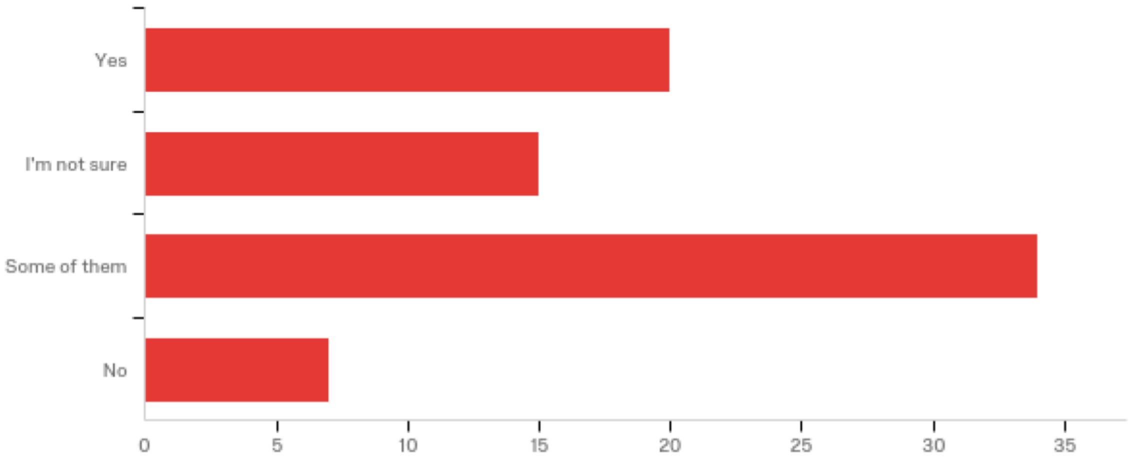
20 - Rank the following monitoring techniques according to how well they indicate structure success, assuming that the goal of the structure(s) is to help prevent streambank erosion and promote geomorphic stability. Items may be ranked by dragging and dropping.





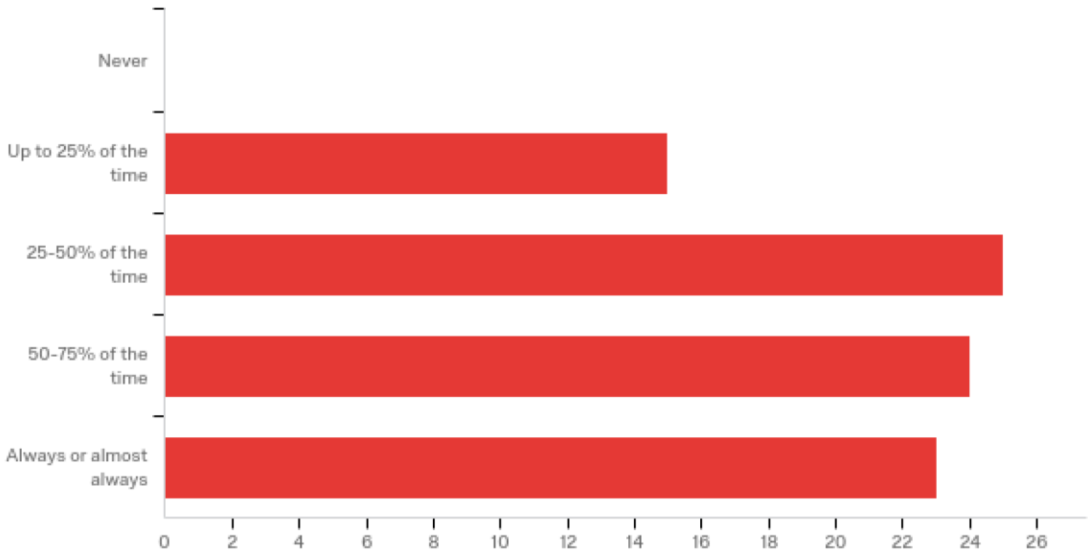
#	Question	1		2		3		4		5	
1	Visual assessment	70%	49	14%	10	4%	3	3%	2	9%	6
2	Repeated surveys of structure	3%	2	19%	13	46%	32	16%	11	17%	12
3	Repeated cross-section and longitudinal surveys	16%	11	17%	12	16%	11	37%	26	14%	10
4	Measurement of plunge pool depth/scour	3%	2	10%	7	16%	11	27%	19	44%	31
5	Observation during flow events up to the design flow	9%	6	40%	28	19%	13	17%	12	16%	11
	Total	Total	70	Total	70	Total	70	Total	70	Total	70

21 - Would structure failures occur less frequently if a monitoring/maintenance initiative was required for each stream restoration project?



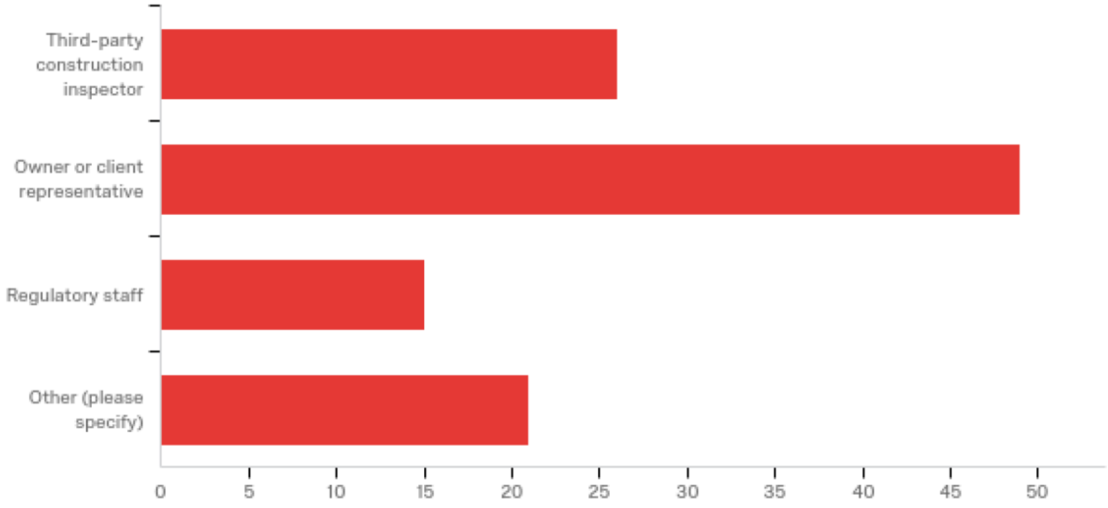
#	Answer	%	Count
1	Yes	26%	20
2	I'm not sure	20%	15
4	Some of them	45%	34
3	No	9%	7
	Total	100%	76

22 - On stream restoration projects, how often is the designer on-site and involved during the construction phase?



#	Answer	%	Count
1	Never	0%	0
2	Up to 25% of the time	17%	15
3	25-50% of the time	29%	25
4	50-75% of the time	28%	24
5	Always or almost always	26%	23
	Total	100%	87

23 - If the designer is not on-site during the construction phase, who confirms that the work is completed according to plan? Select any that apply.



#	Answer	%	Count
1	Third-party construction inspector	23%	26
2	Owner or client representative	44%	49
3	Regulatory staff	14%	15
4	Other (please specify)	19%	21
	Total	100%	111

Other (please specify)

Other (please specify)
Project manager
Someone from the design consultant's company performs daily construction oversight.
the Inspection staff. within the government the designer is not always present
Project Manager/QA team
Engineer overseeing the designer

Oversight engineer - not typically the PE responsible for design, but same firm

Contractor, on occasion

Contractor with occasional check by designer

Owners employee

Owner rep

designer subordinate/inspector

Construction contract dependent

NA We always have the designer on site or on call.

contractor

We do

We do design build and in that regard the designer is always onsite. However, if we do a bid job we often have little oversight - hopefully because of a high trust level. On our current bid job the owner representative stops by every day.

most are up to the contractor

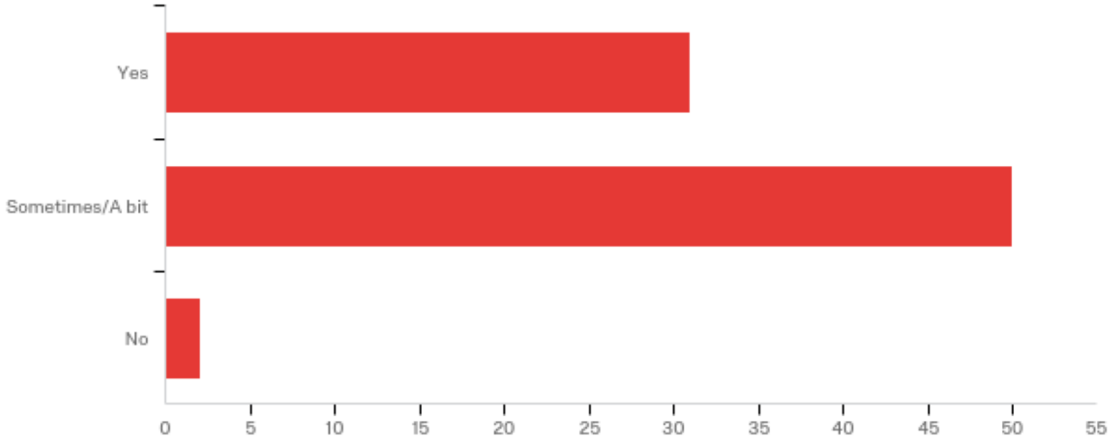
our own construction inspector

Designer inspects work on next visit.

For our projects we generall use well qualified contractors that we trust and their foreman provides oversight when our designer is not on site.

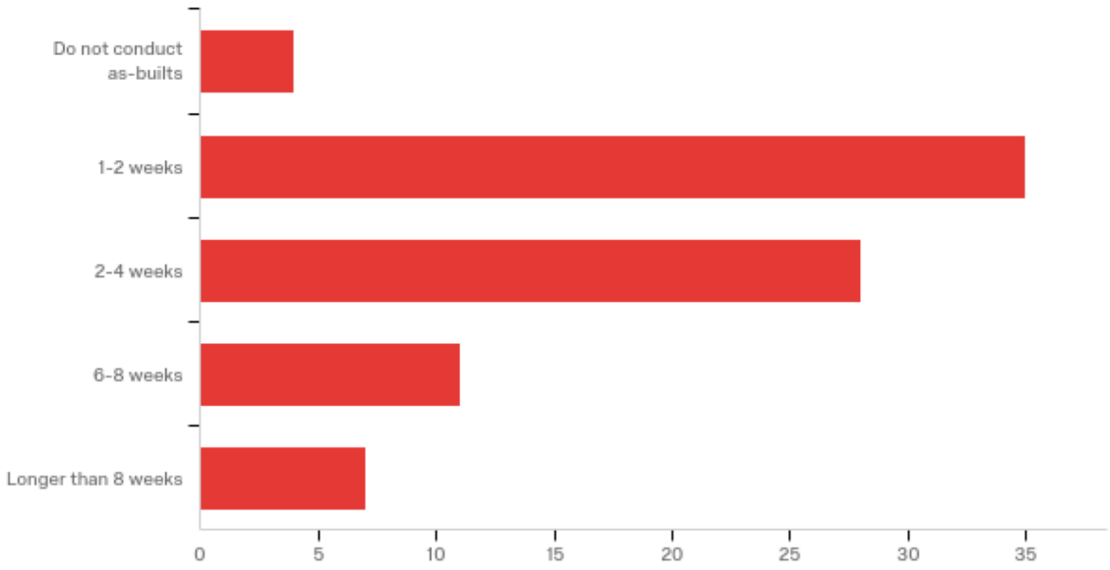
Co-worker/colleague that worked with designer

24 - In your opinion, do the people listed in the above question (#23) typically understand the intent and purpose of elements of stream restoration projects?



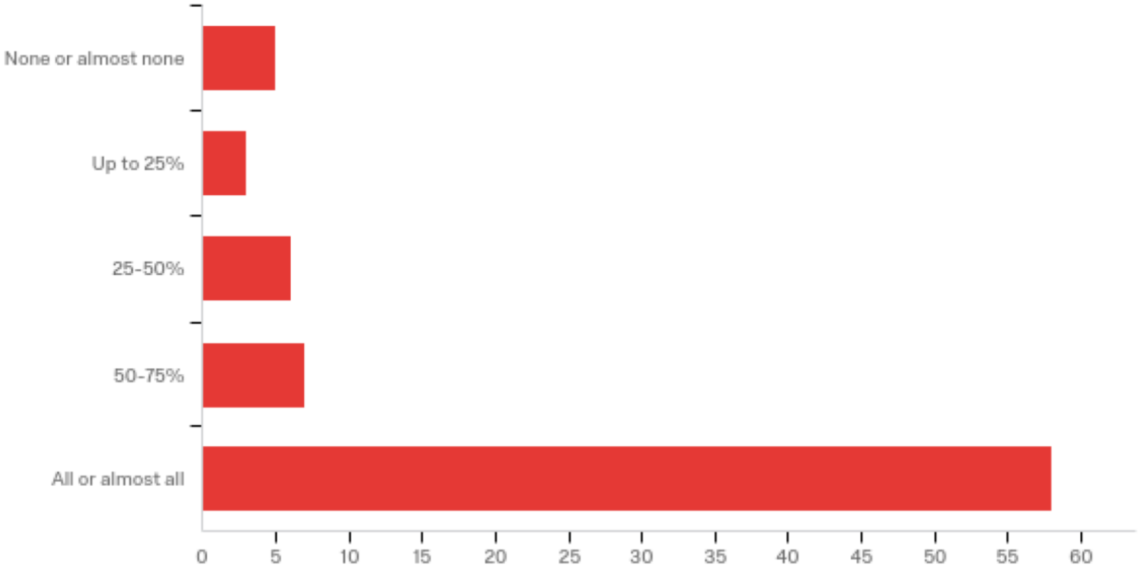
#	Answer	%	Count
1	Yes	37%	31
2	Sometimes/A bit	60%	50
3	No	2%	2
	Total	100%	83

25 - How long after project completion do you perform an as-built survey?



#	Answer	%	Count
5	Do not conduct as-builts	5%	4
1	1-2 weeks	41%	35
2	2-4 weeks	33%	28
3	6-8 weeks	13%	11
4	Longer than 8 weeks	8%	7
	Total	100%	85

27 - How many of your projects have tolerance requirements on the slopes of vane arms?



#	Answer	%	Count
1	None or almost none	6%	5
2	Up to 25%	4%	3
3	25-50%	8%	6
4	50-75%	9%	7
5	All or almost all	73%	58
	Total	100%	79

Appendix C: Surveys of the Step Pool Storm Conveyance Structures

The following figures show the surveyed longitudinal profiles of both study step pool storm conveyance (SPSC) structures (Broad Creek and Eastern Tributary), as well as the surveyed cross-sections of each parabolic rock weir within the study reaches of both study SPSC structures. The surveys shown are those which were taken on July 17, 2017, which were temporally closer to the dye tracer experiments.

For the longitudinal profiles, the top of the SPSC is assigned coordinates (X, Z) of (0 m, 30 m). The X-coordinates of each point along the SPSC represent the distances of those points from the top of the SPSC, while their Z-coordinates represent their elevations.

For the parabolic rock weir cross-sections, the left side of each rock weir is assigned an X-coordinate of 0 m. The X-coordinates of each point along the rock weir represent the distances of those points from the left side of the weir, while their Z-coordinates represent their elevation corresponding to the longitudinal profile of that SPSC.

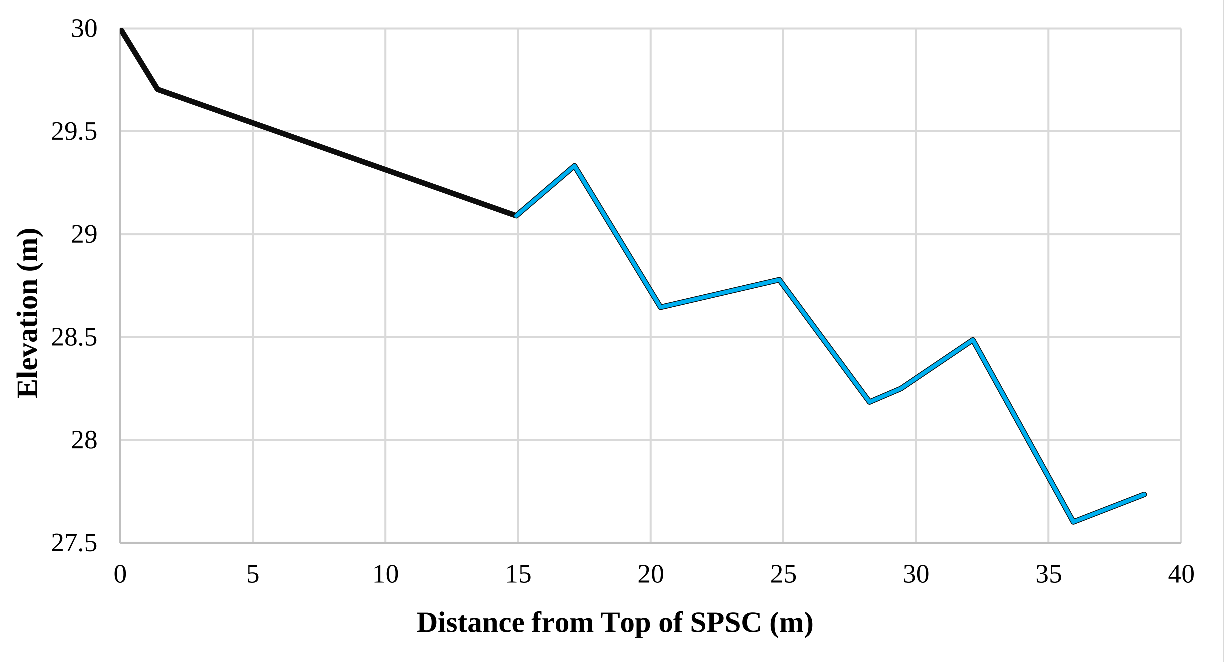


Figure C.1: Longitudinal profile of the Broad Creek SPSC, with the study reach outlined in blue.

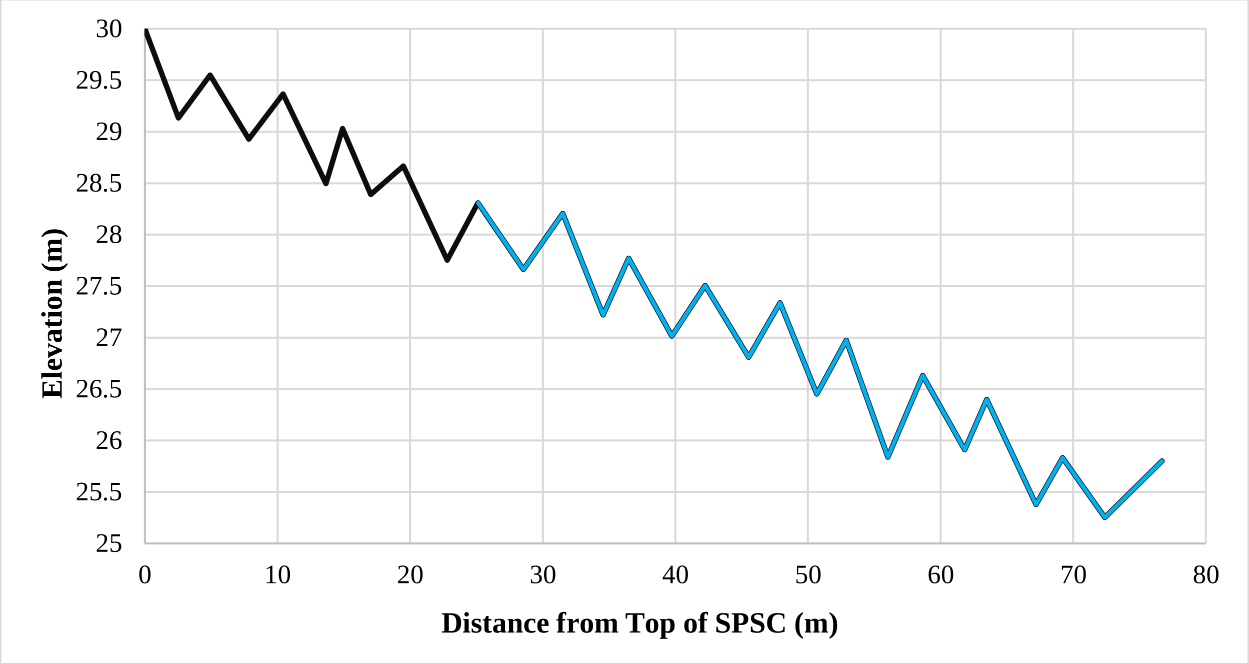


Figure C.2: Longitudinal profile of the Eastern Tributary SPSC, with the study reach outlined in blue.

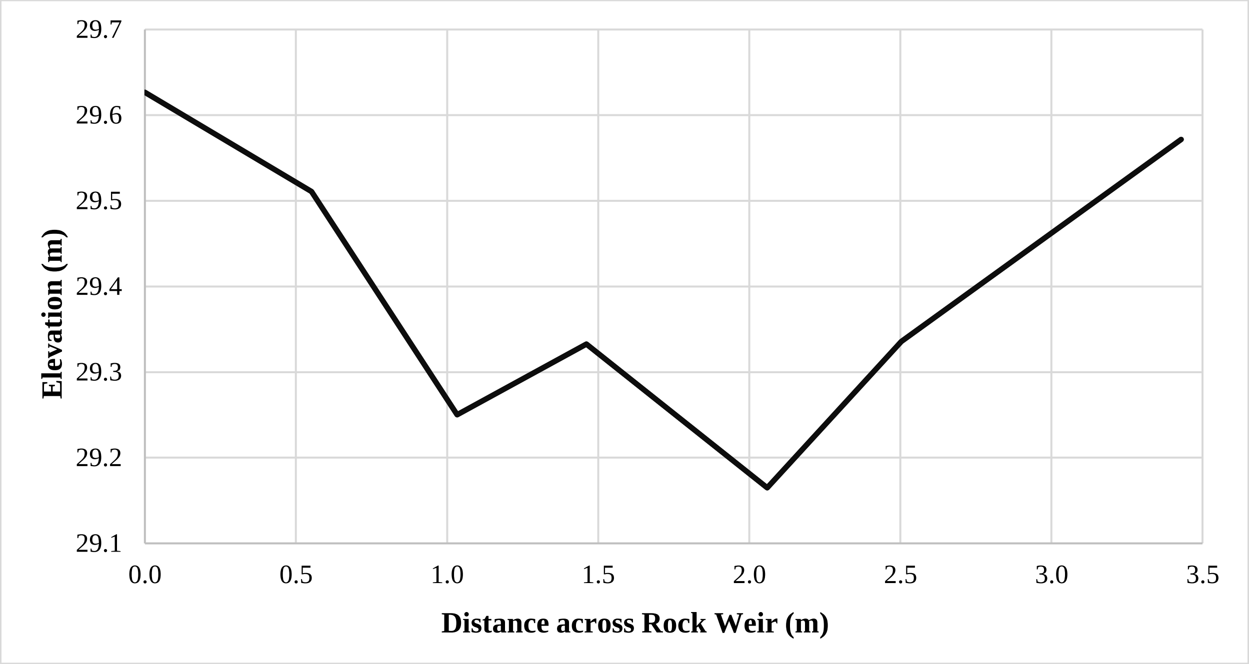


Figure C.3: Cross-section of the second parabolic rock weir of the Broad Creek SPSC, located at X=17.1 m along the longitudinal profile.

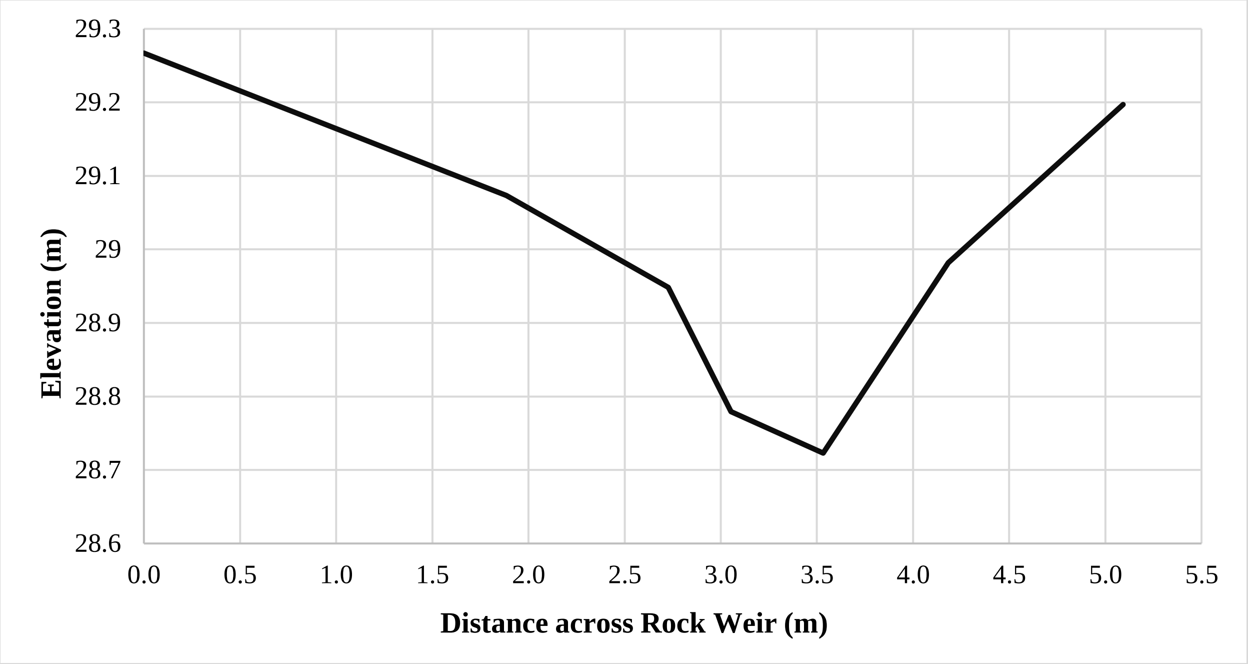


Figure C.4: Cross-section of the third parabolic rock weir of the Broad Creek SPSC, located at X=24.8 m along the longitudinal profile.

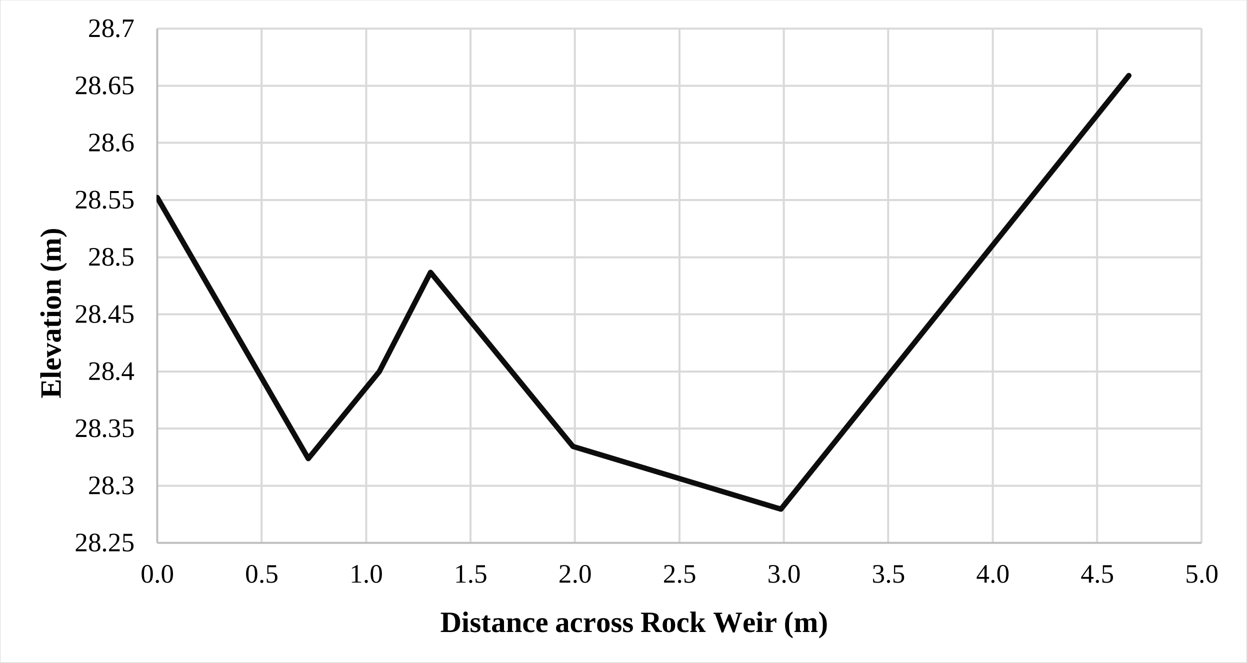


Figure C.5: Cross-section of the fourth parabolic rock weir of the Broad Creek SPSC, located at X=32.2 m along the longitudinal profile.

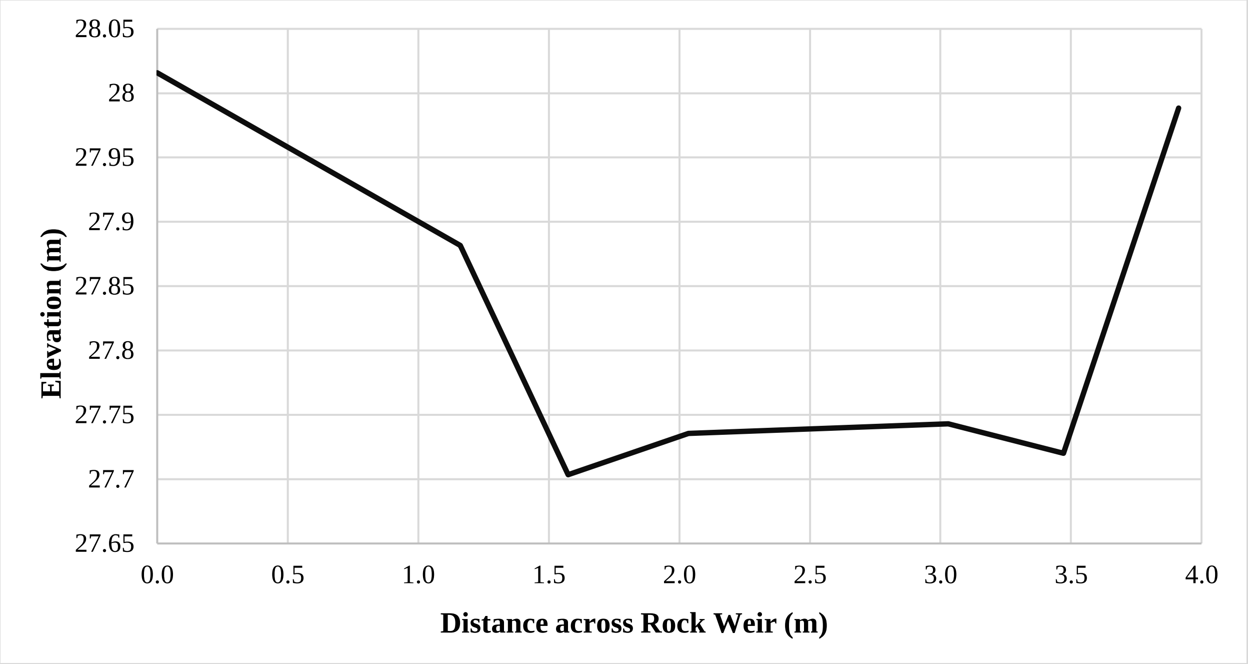


Figure C.6: Cross-section of the fifth parabolic rock weir of the Broad Creek SPSC, located at X=38.6 m along the longitudinal profile.

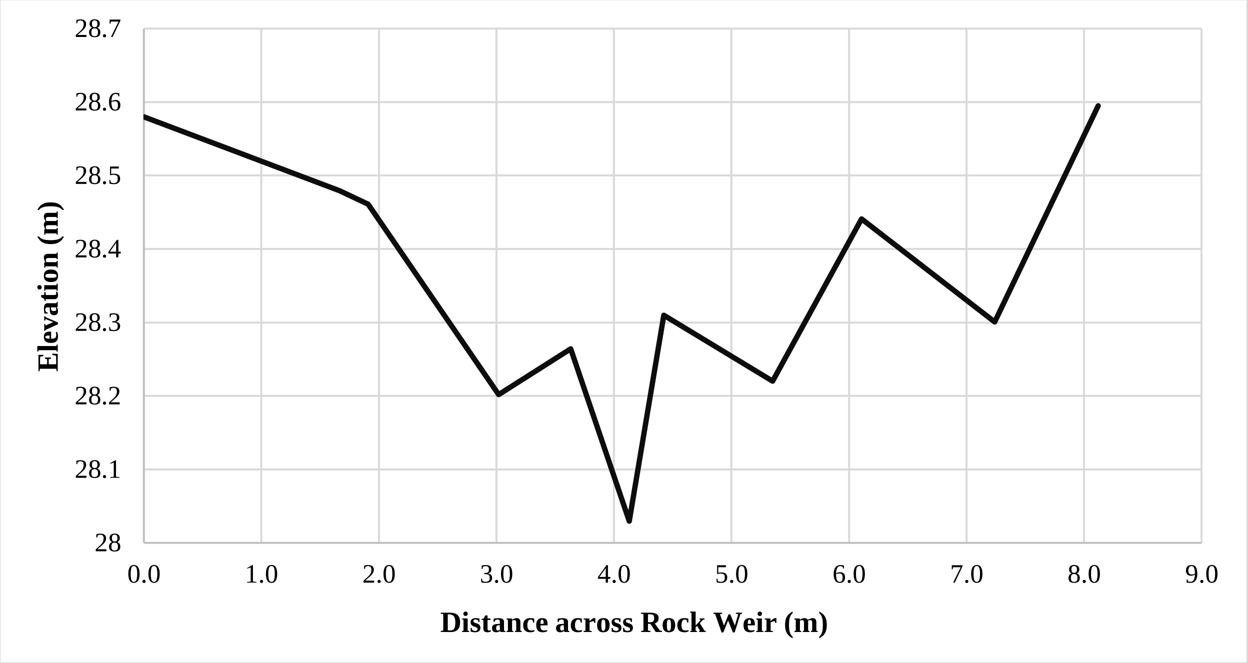


Figure C.7: Cross-section of the seventh parabolic rock weir of the Eastern Tributary SPSC, located at X=31.5 m along the longitudinal profile.

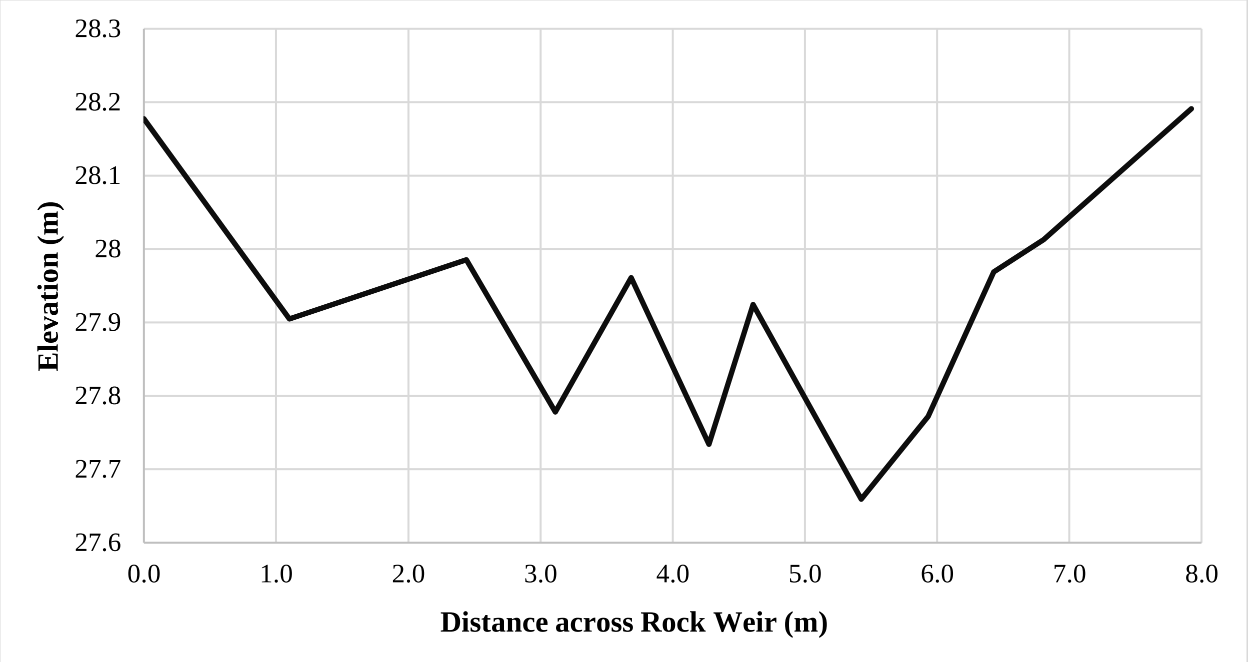


Figure C.8: Cross-section of the eighth parabolic rock weir of the Eastern Tributary SPSC, located at X=36.5 m along the longitudinal profile.

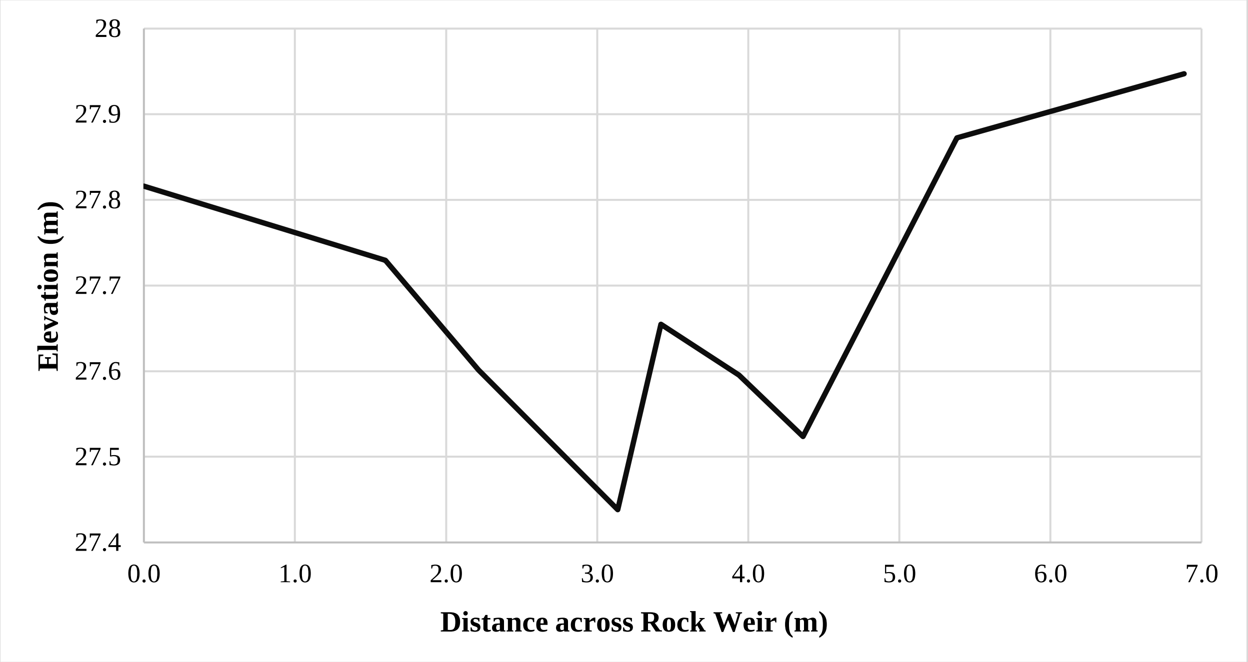


Figure C.9: Cross-section of the ninth parabolic rock weir of the Eastern Tributary SPSC, located at X=42.2 m along the longitudinal profile.

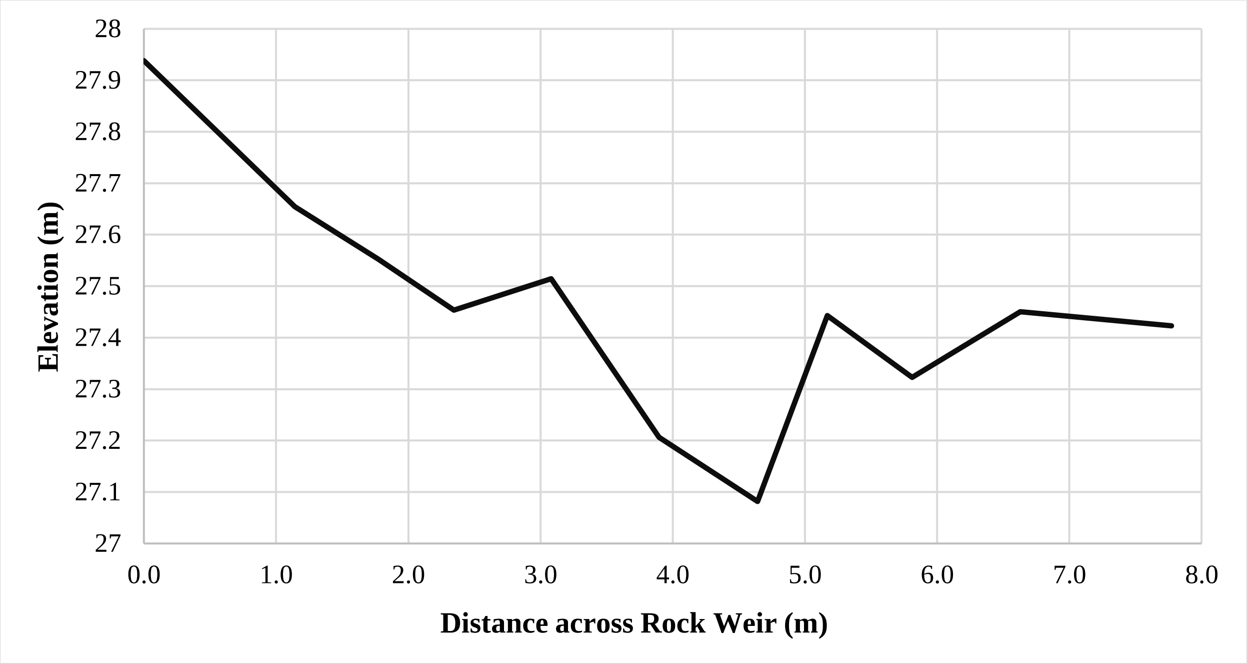


Figure C.10: Cross-section of the tenth parabolic rock weir of the Eastern Tributary SPSC, located at X=47.9 m along the longitudinal profile.

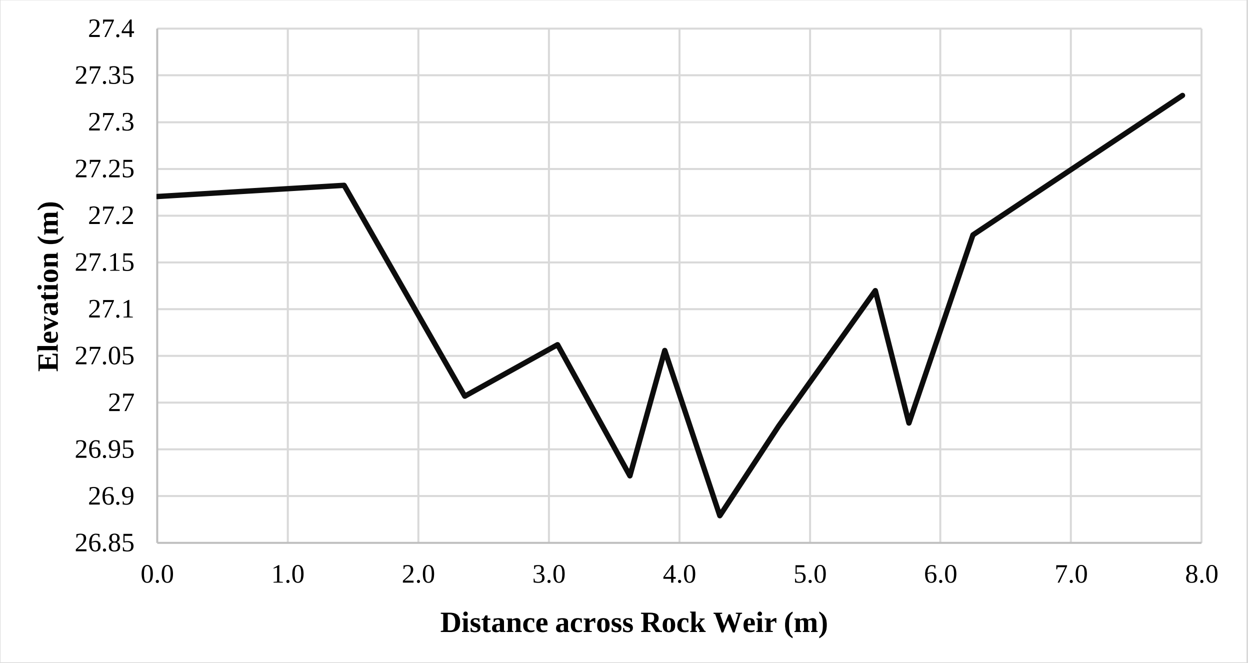


Figure C.11: Cross-section of the eleventh parabolic rock weir of the Eastern Tributary SPSC, located at X=52.9 m along the longitudinal profile.

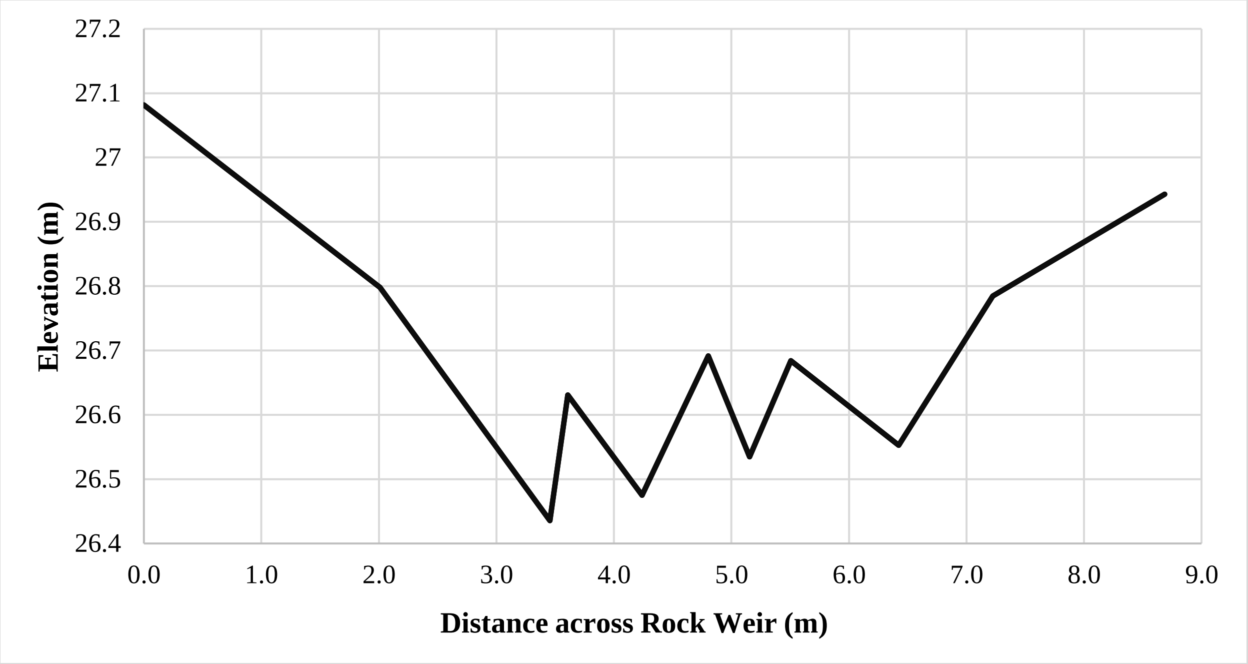


Figure C.12: Cross-section of the twelfth parabolic rock weir of the Eastern Tributary SPSC, located at X=58.6 m along the longitudinal profile.

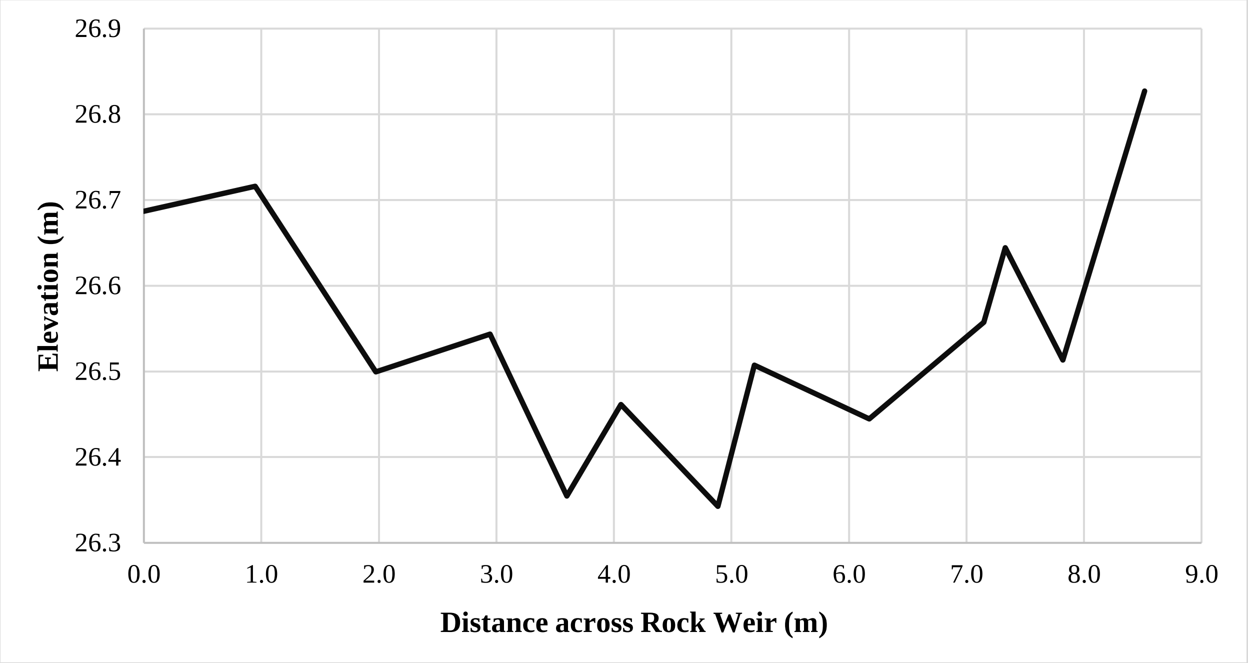


Figure C.13: Cross-section of the thirteenth parabolic rock weir of the Eastern Tributary SPSC, located at X=63.5 m along the longitudinal profile.

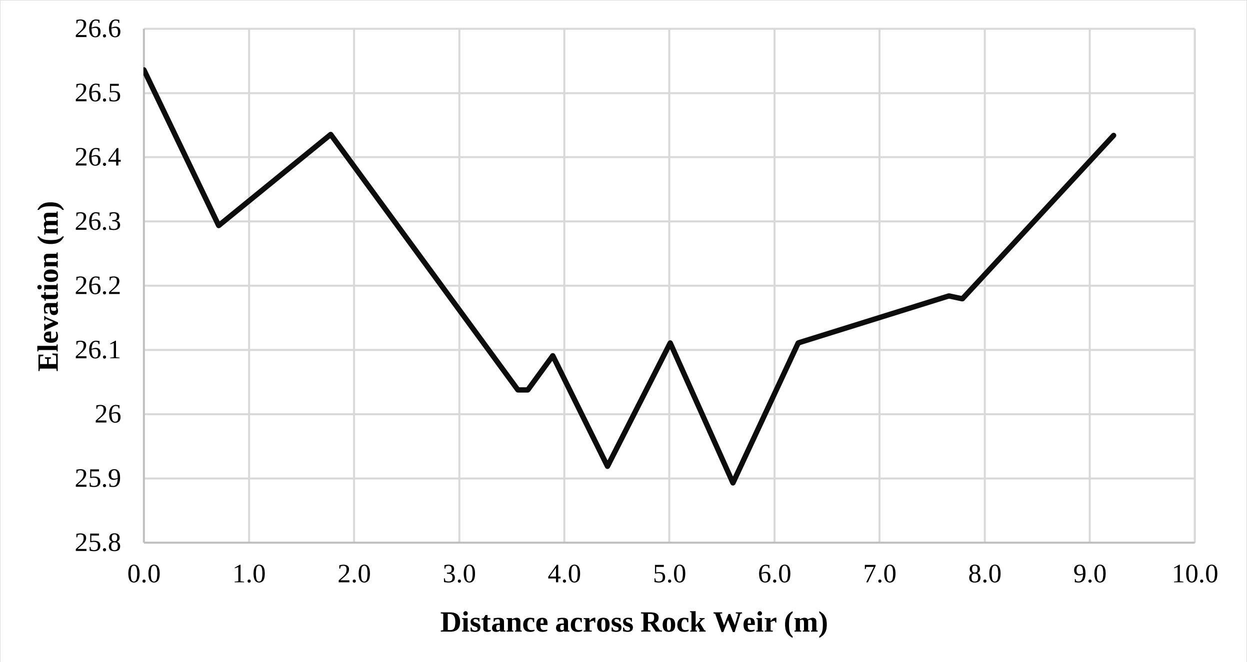


Figure C.14: Cross-section of the fourteenth parabolic rock weir of the Eastern Tributary SPSC, located at X=69.2 m along the longitudinal profile.

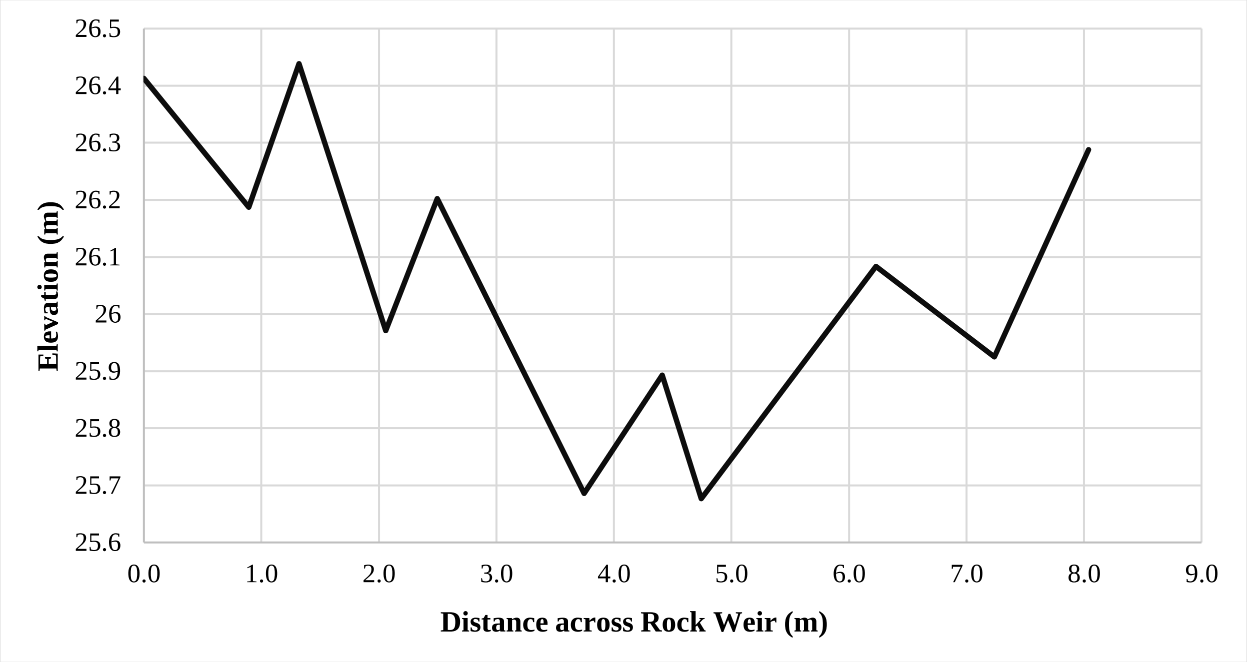


Figure C.15: Cross-section of the fifteenth parabolic rock weir of the Eastern Tributary SPSC, located at X=76.7 m along the longitudinal profile.

Appendix D: Water Depths in the Step Pool Storm Conveyance Structures

The following figures show water depths (cm) in the middle pools of both study step pool storm conveyance (SPSC) structures (Eastern Tributary and Broad Creek) before, during, and after each of the storm events or controlled flow releases during which a dye tracer experiment was conducted. Water depths are shown at both SPSC locations for each date, even if a dye tracer experiment was only conducted at one of those locations on that date.

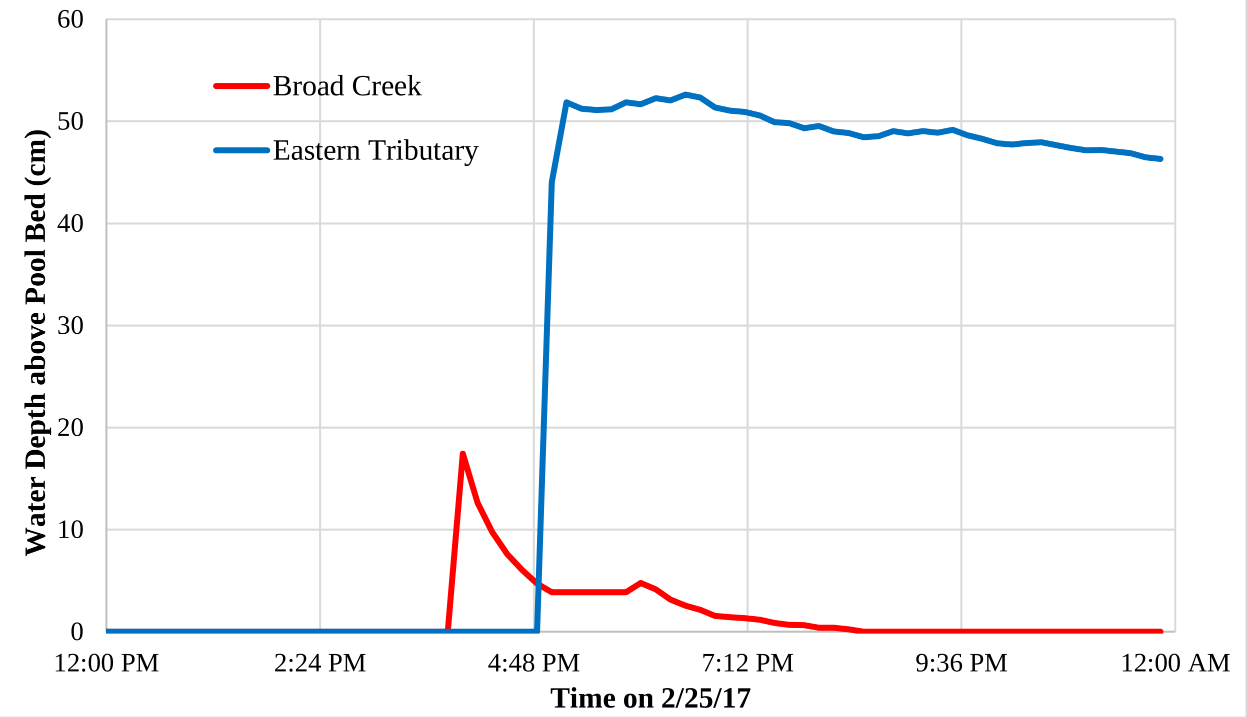


Figure D.1: Water depths in the middle pools of the study SPSCs on Feb 25, 2017. A dye tracer experiment was conducted at Broad Creek only.

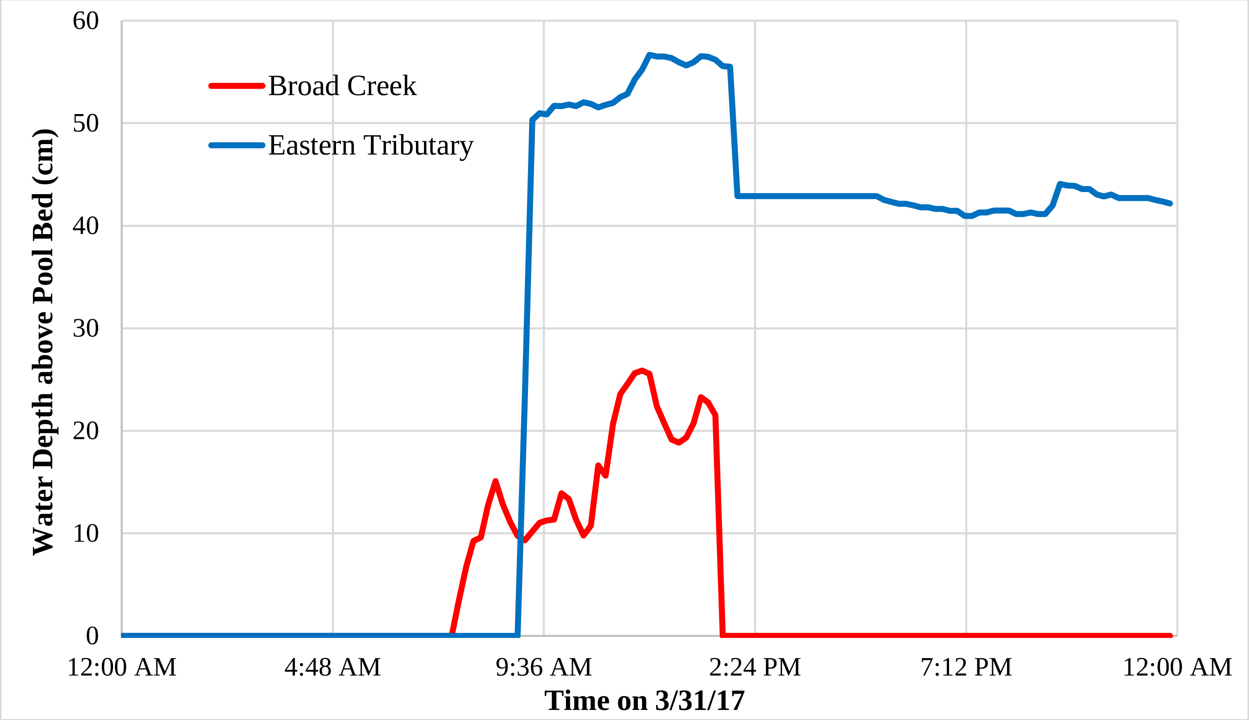


Figure D.2: Water depths in the middle pools of the study SPSCs on Mar 31, 2017. Dye tracer experiments were conducted at both SPSCs.

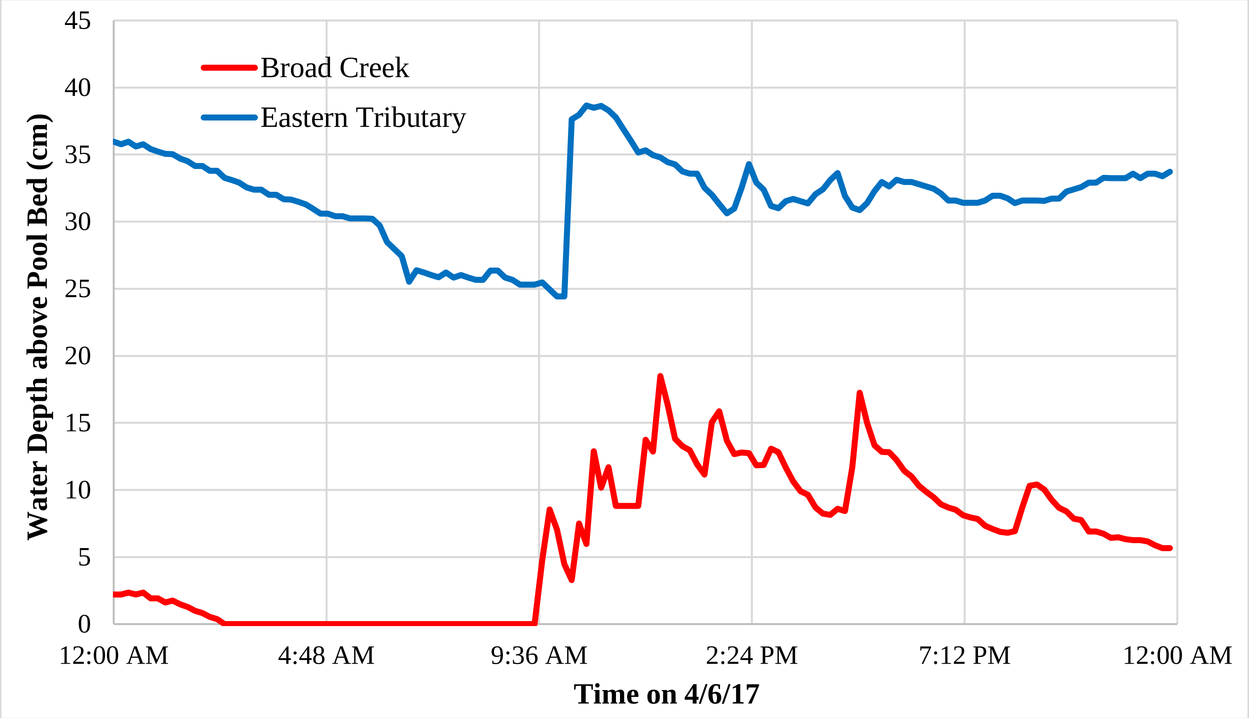


Figure D.3: Water depths in the middle pools of the study SPSCs on Apr 6, 2017. A dye tracer experiment was conducted at Broad Creek only.

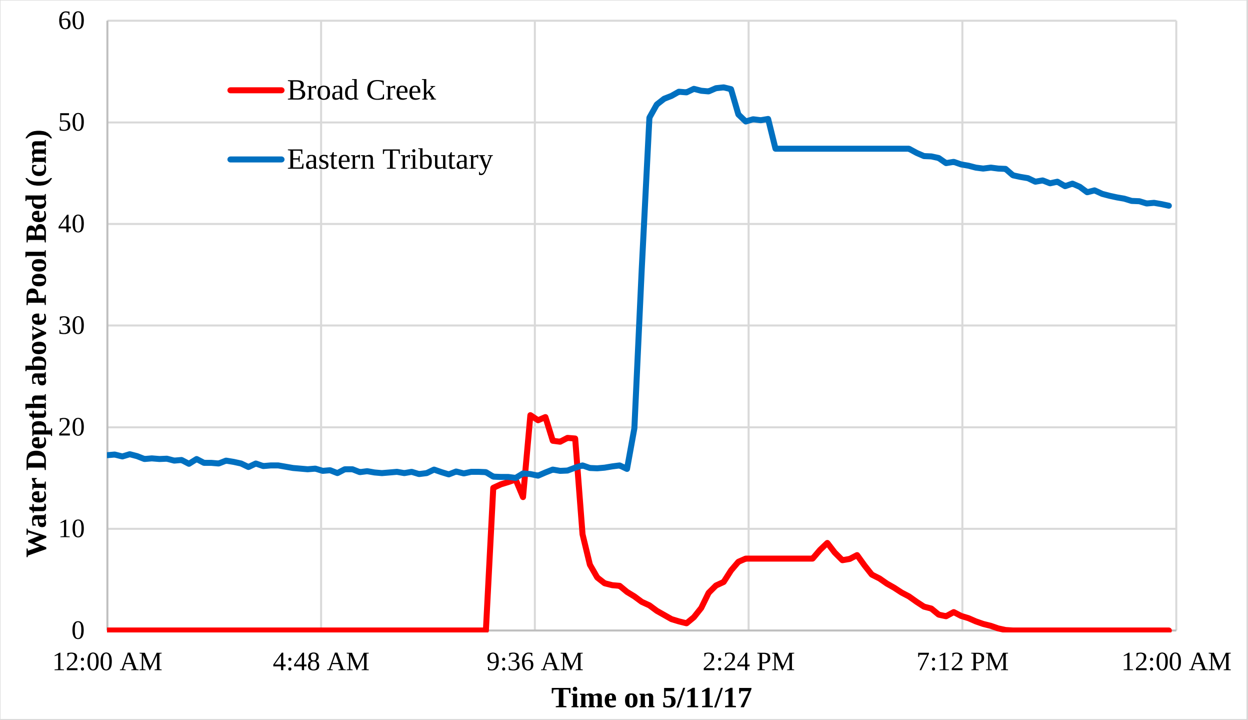


Figure D.4: Water depths in the middle pools of the study SPSCs on May 11, 2017. Dye tracer experiments were conducted at both SPSCs using controlled flow releases.

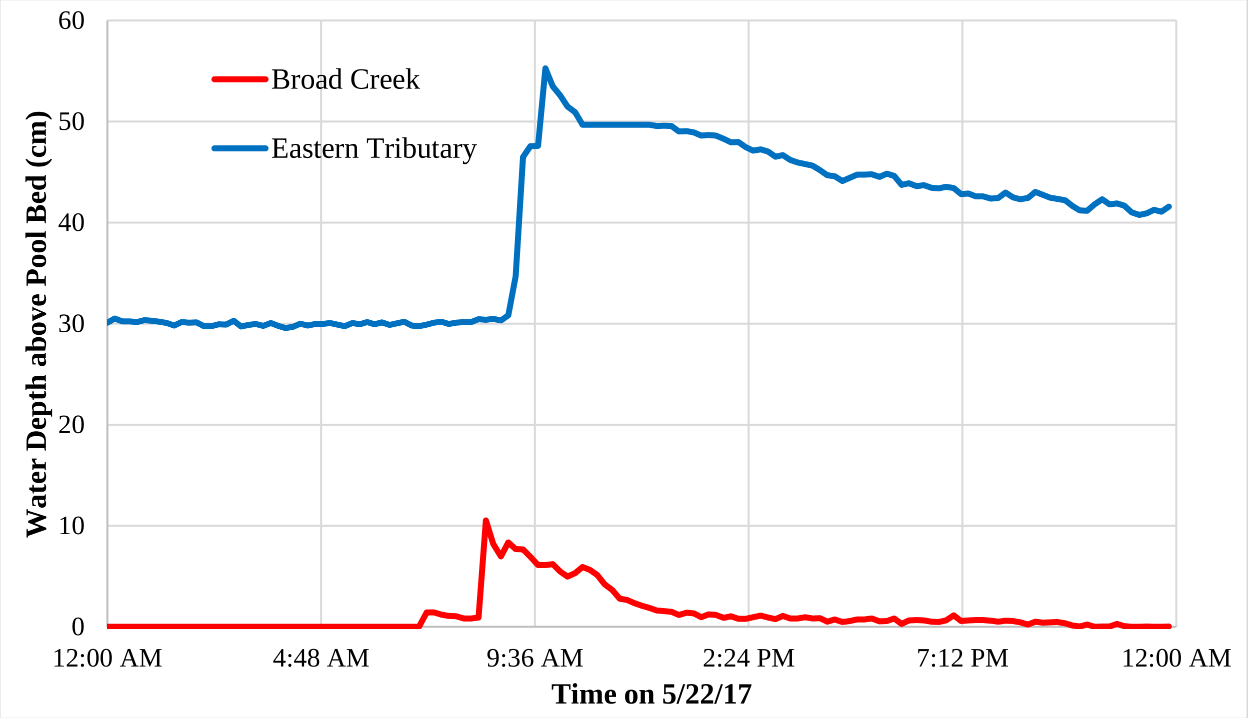


Figure D.5: Water depths in the middle pools of the study SPSCs on May 22, 2017. A dye tracer experiment was conducted at the Eastern Tributary only.

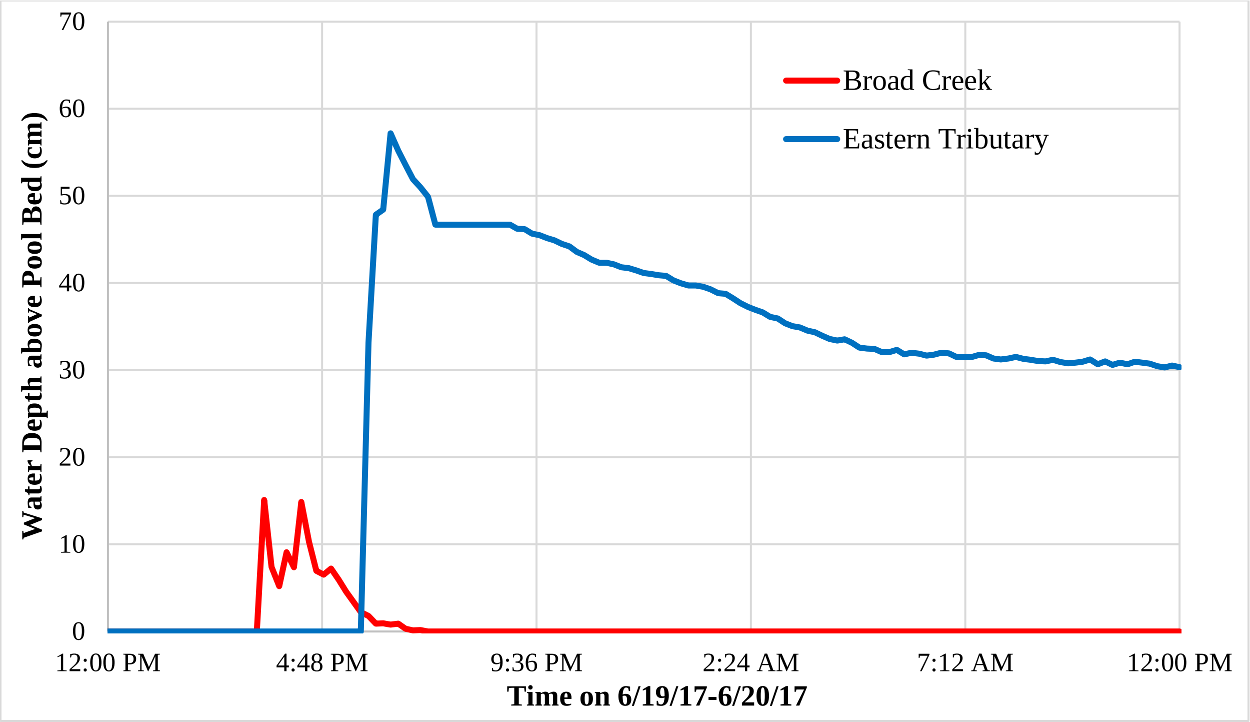


Figure D.6: Water depths in the middle pools of the study SPSCs on Jun 19-20, 2017. Dye tracer experiments were conducted at both SPSCs on Jun 19.

Appendix E: Dye Tracer Time-Concentration Curves

The following figures show Rhodamine WT dye tracer concentration (μg/L) over time during the dye tracer experiments. Date, time of dye release, and step pool storm conveyance (SPSC) site are specified for each figure.

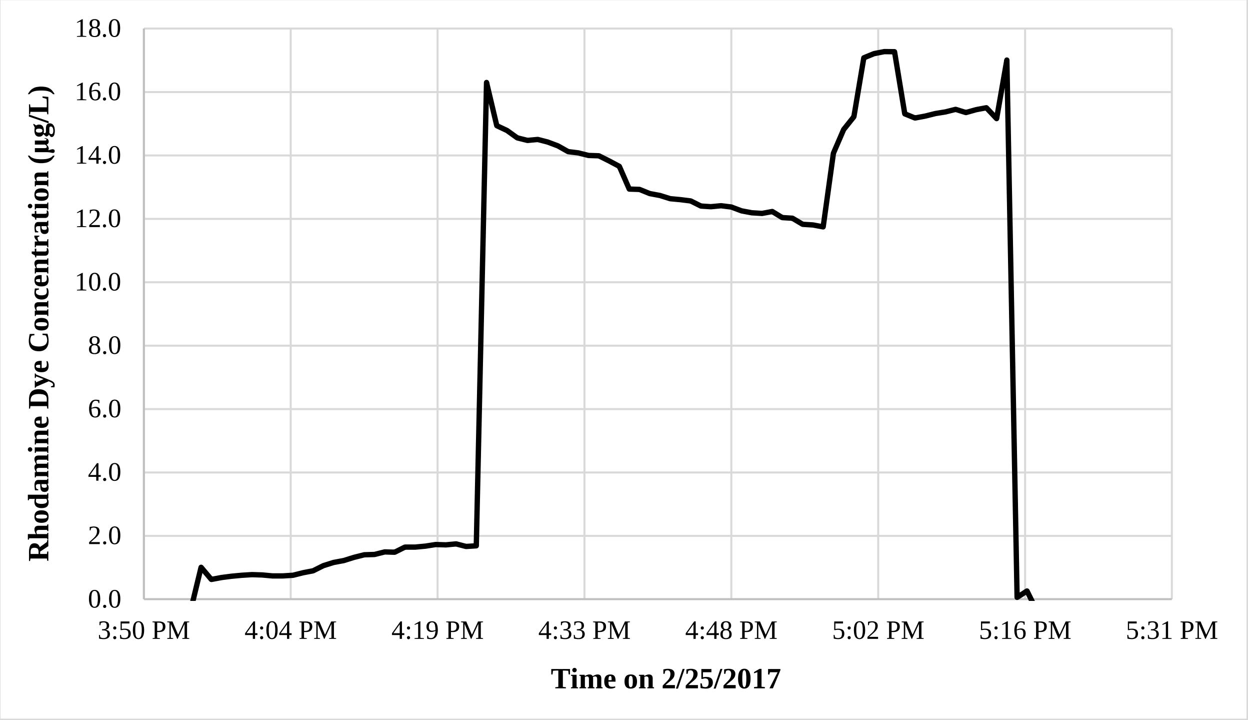


Figure E.1: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during a storm on Feb 25, 2017. Dye slug was introduced to the stream at 3:57 PM.

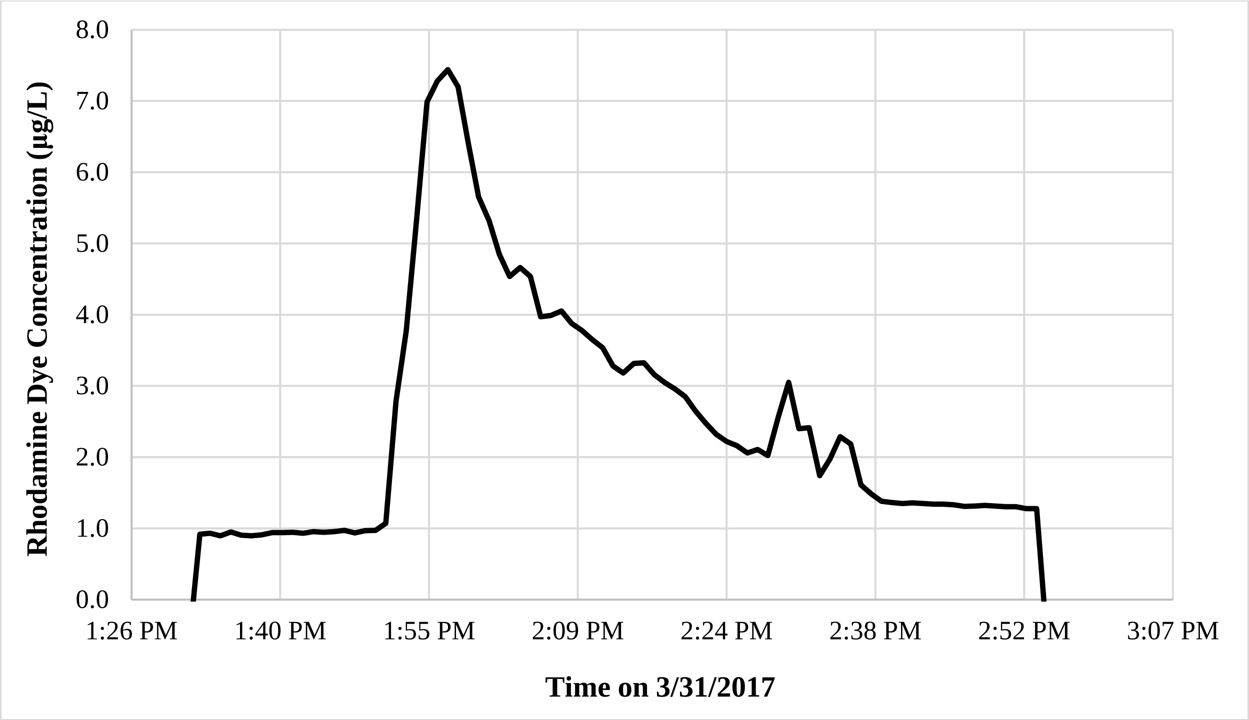


Figure E.2: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during a storm on Mar 31, 2017. Dye slug was introduced to the stream at 1:45 PM.

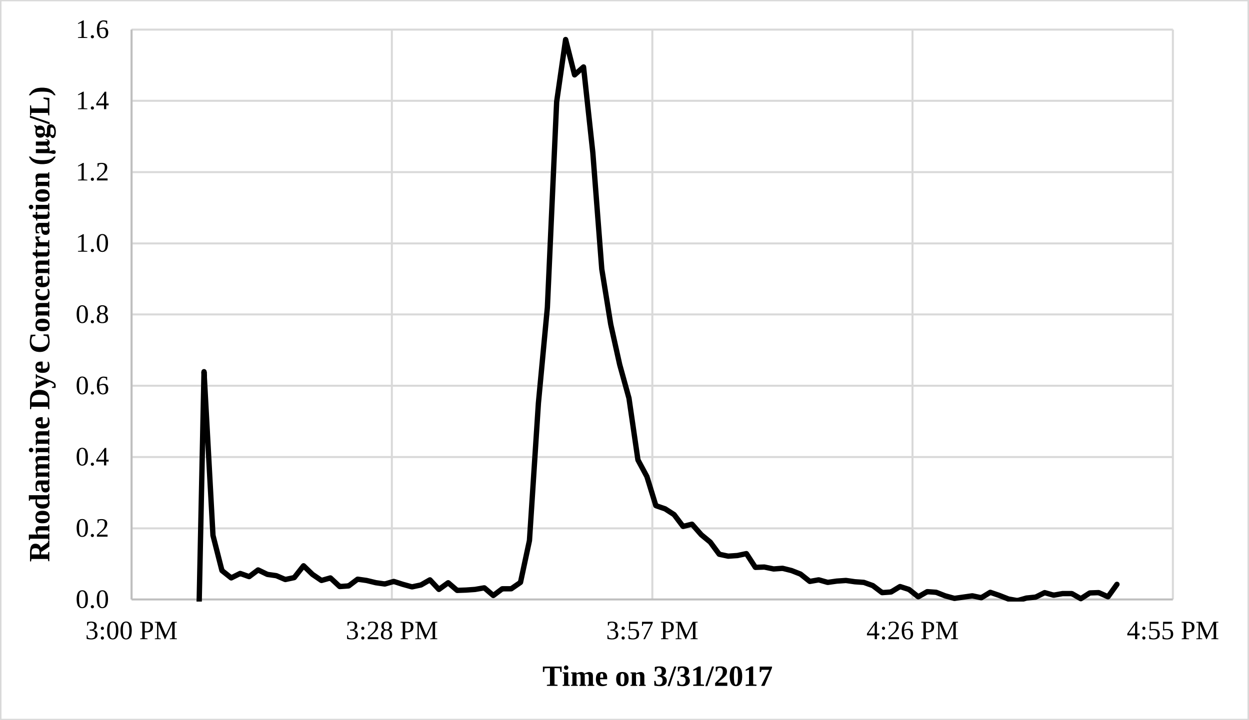


Figure E.3: Time-concentration curve of Rhodamine WT dye in the Eastern Tributary SPSC during a storm on Mar 31, 2017. Dye slug was introduced to the stream at 3:33 PM.

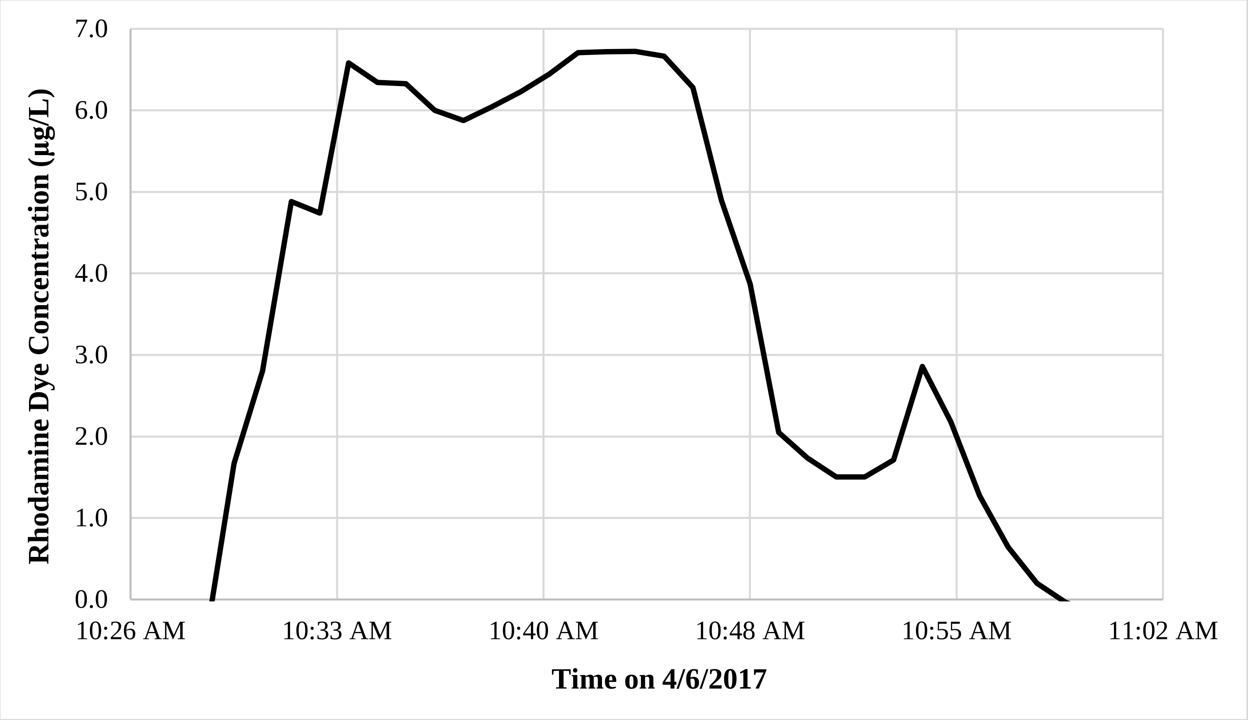


Figure E.4: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during a storm on Apr 6, 2017. Dye slug was introduced to the stream at 10:15 AM.

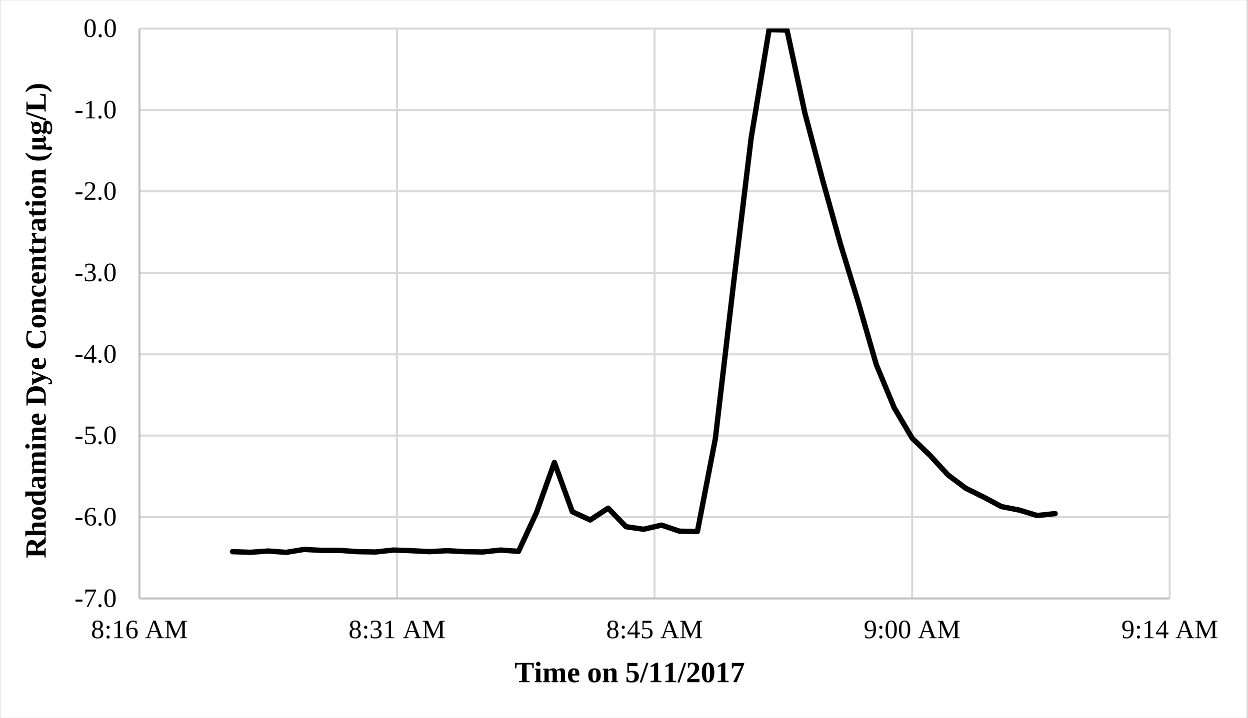


Figure E.5: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during the first controlled flow release on May 11, 2017. Dye slug was introduced to the stream at 8:45 AM.

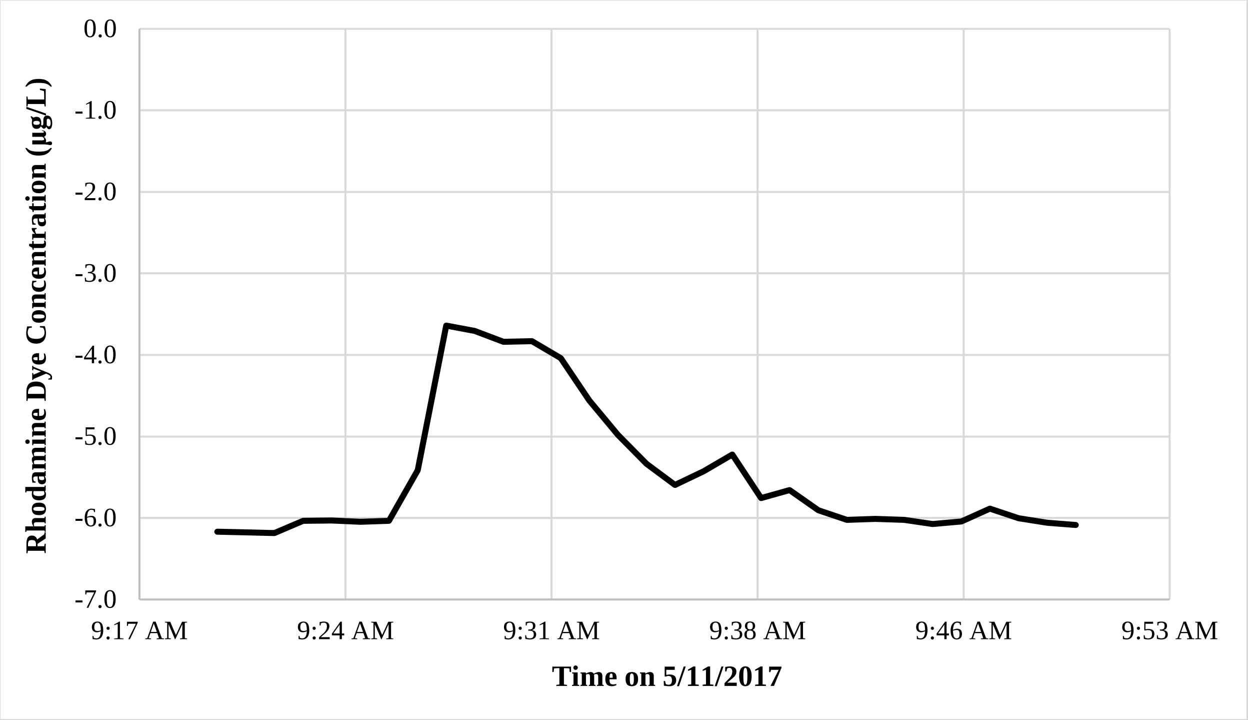


Figure E.6: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during the second controlled flow release on May 11, 2017. Dye slug was introduced to the stream at 9:25 AM.

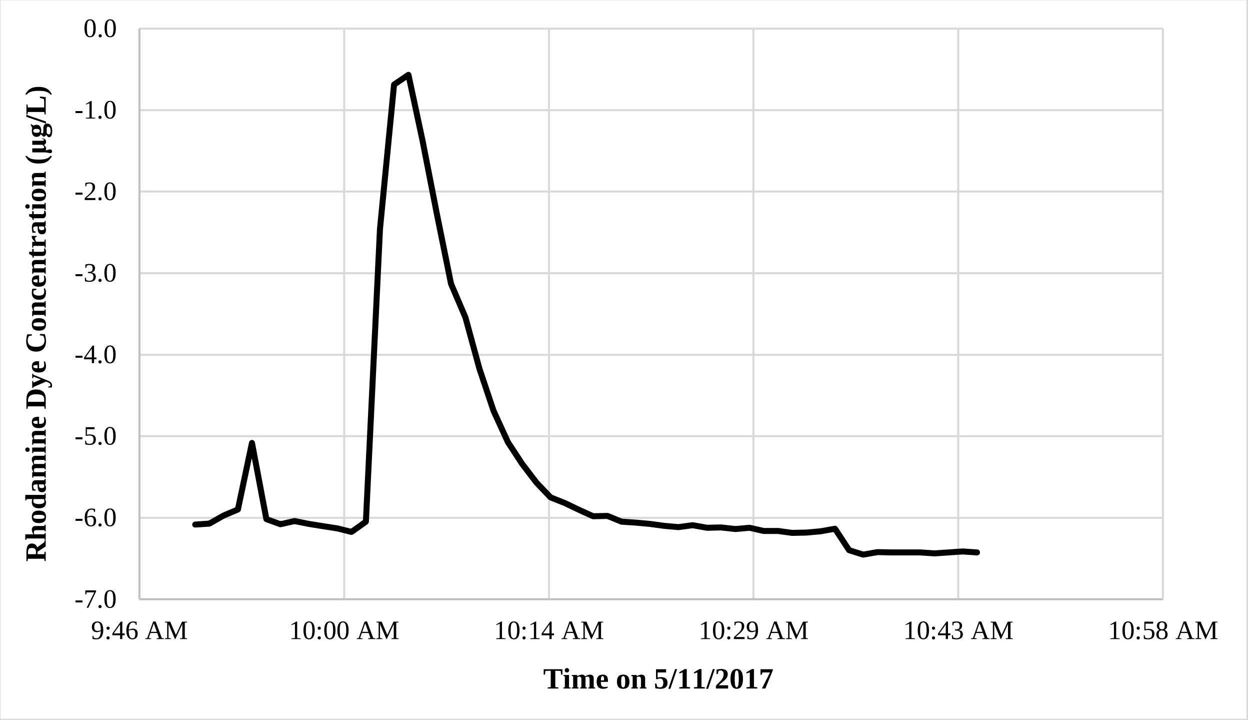


Figure E.7: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during the third controlled flow release on May 11, 2017. Dye slug was introduced to the stream at 10:00 AM.

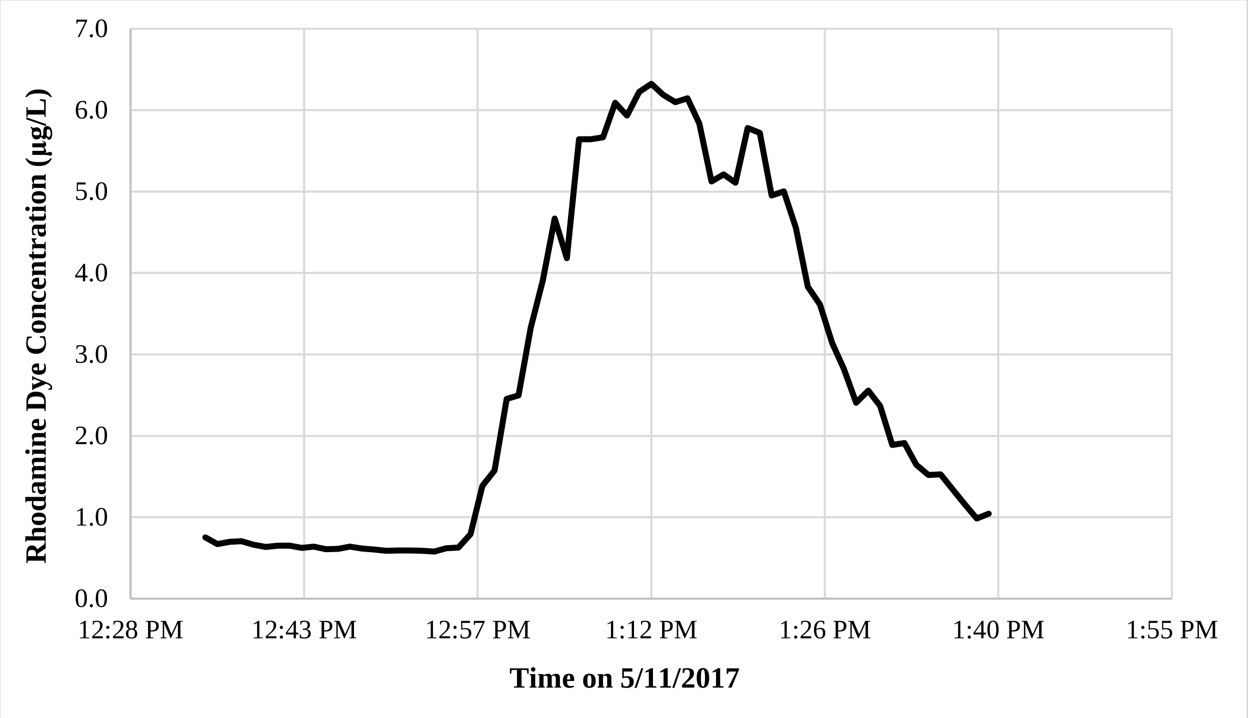


Figure E.8: Time-concentration curve of Rhodamine WT dye in the Eastern Tributary SPSC during the first controlled flow release on May 11, 2017. Dye slug was introduced to the stream at 12:50 PM.

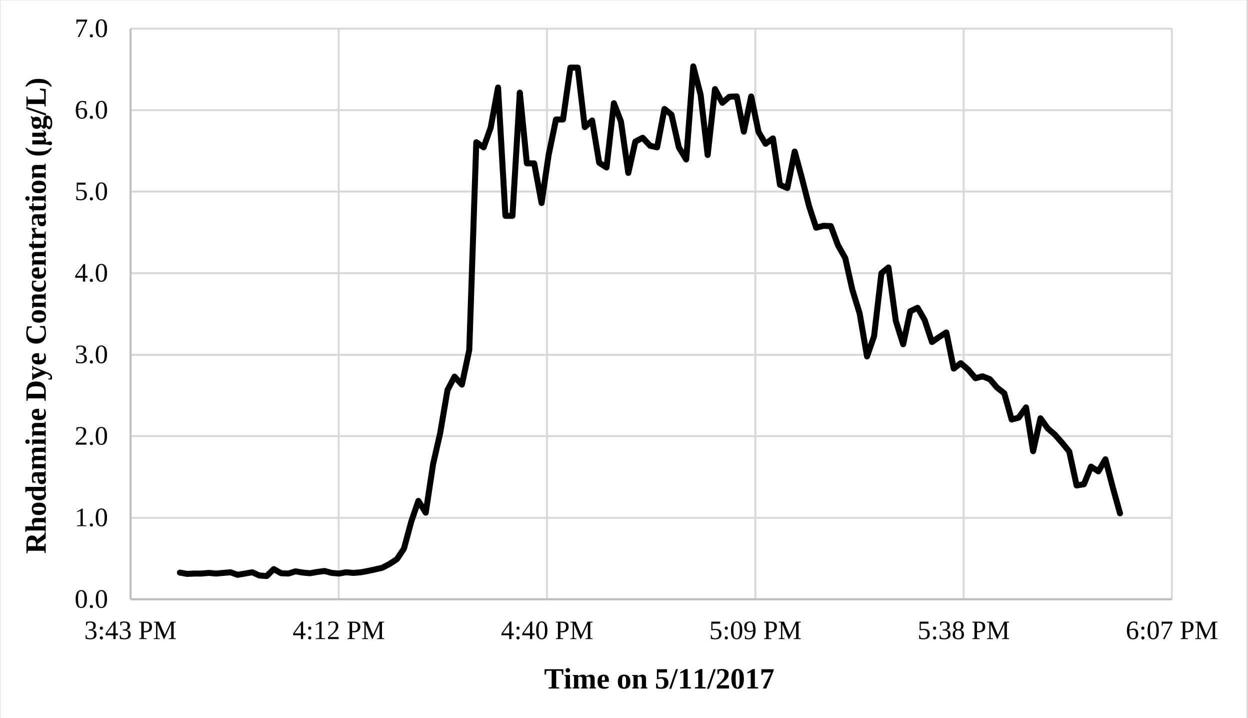


Figure E.9: Time-concentration curve of Rhodamine WT dye in the Eastern Tributary SPSC during the second controlled flow release on May 11, 2017. Dye slug was introduced to the stream at 4:07 PM.

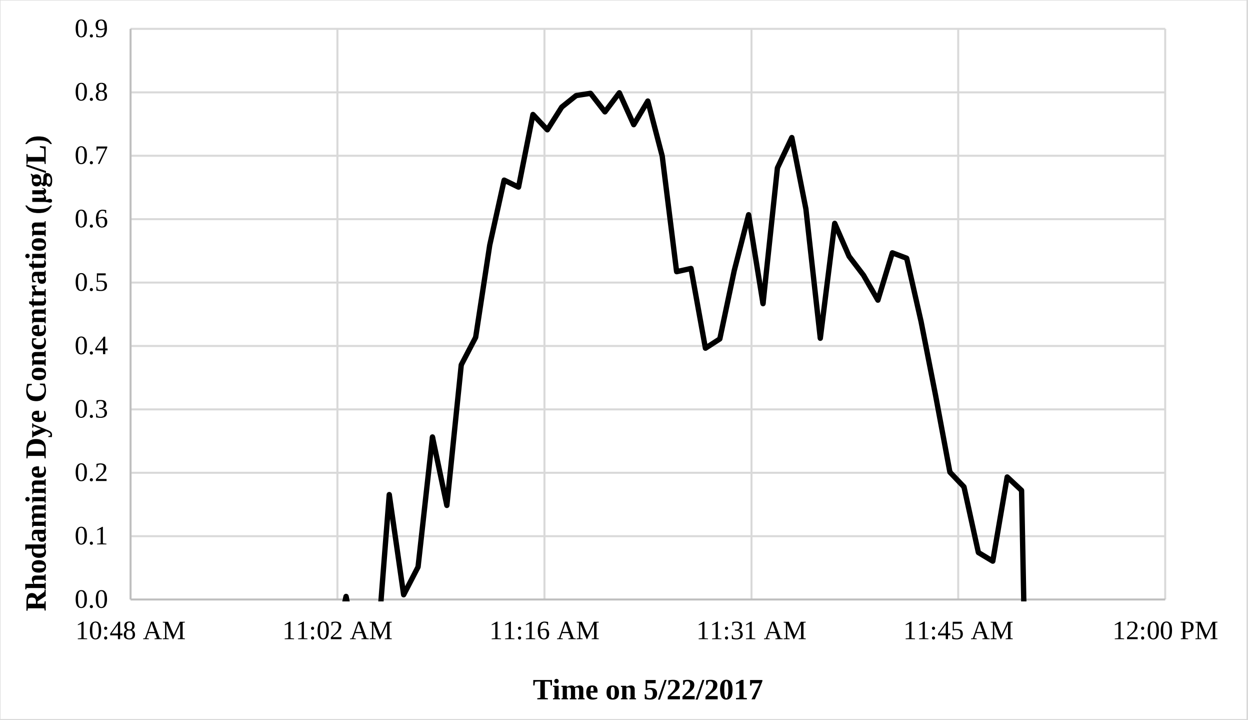


Figure E.10: Time-concentration curve of Rhodamine WT dye in the Eastern Tributary SPSC during a storm on May 22, 2017. Dye slug was introduced to the stream at 10:50 AM.

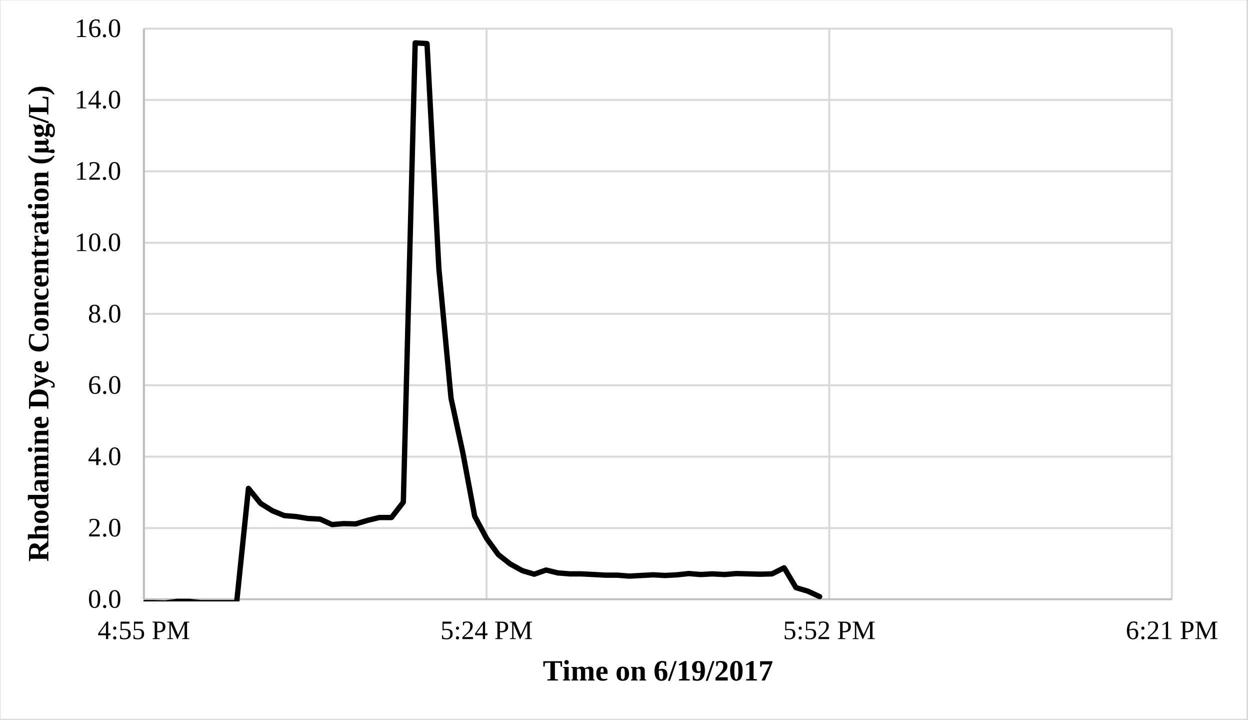


Figure E.11: Time-concentration curve of Rhodamine WT dye in the Broad Creek SPSC during a storm on Jun 19, 2017. Dye slug was introduced to the stream at 5:10 PM.

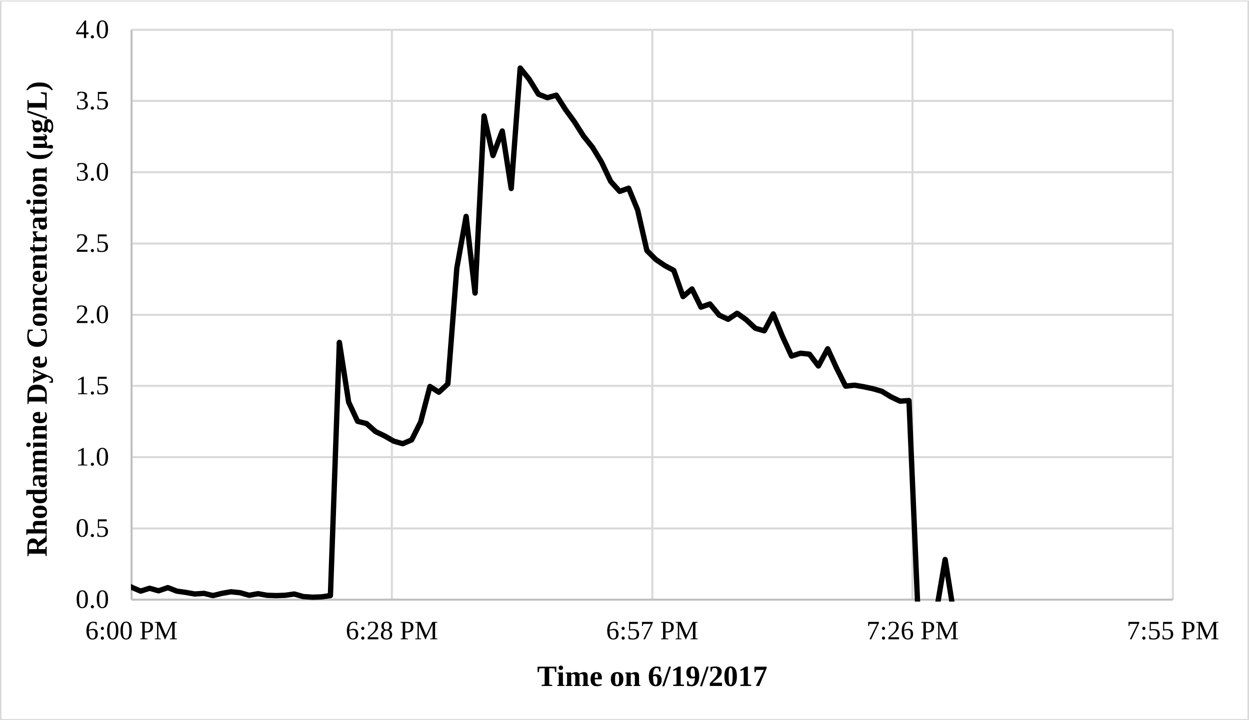


Figure E.12: Time-concentration curve of Rhodamine WT dye in the Eastern Tributary SPSC during a storm on Jun 19, 2017. Dye slug was introduced to the stream at 6:26 PM.