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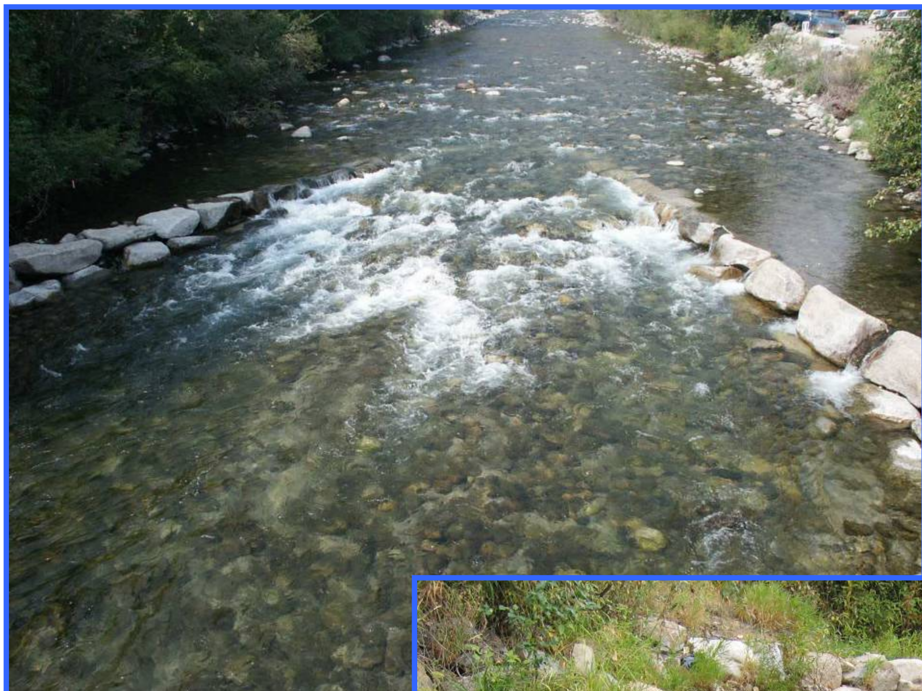
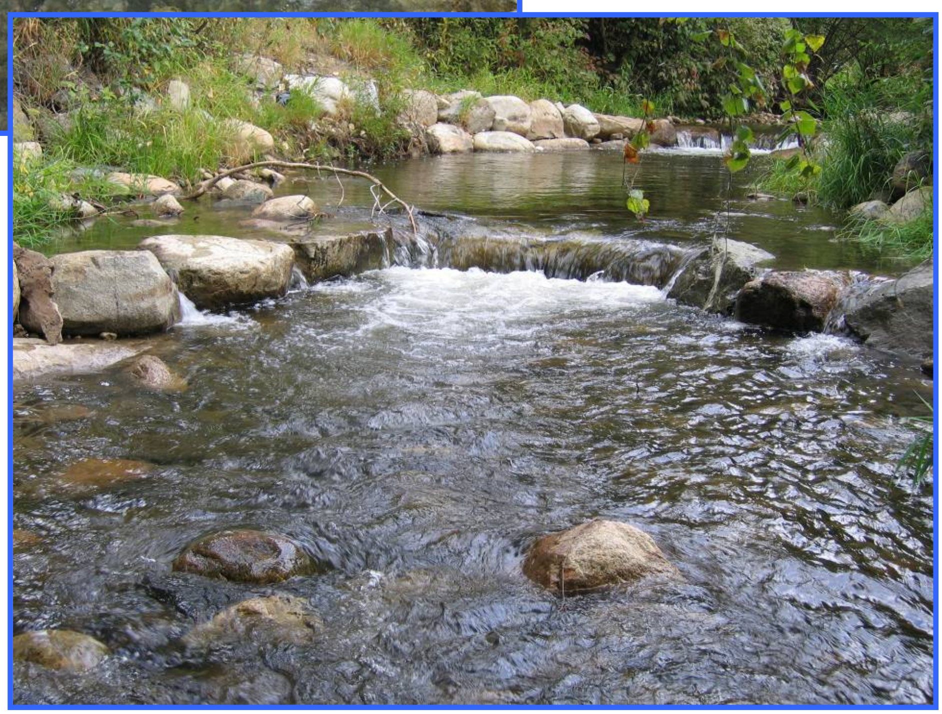
Qualitative Evaluation of Rock Weir Field Performance and Failure Mechanisms





U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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U.S. Department of the Interior
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Qualitative Evaluation of Rock Weir Field Performance and Failure Mechanisms

Authored by

David M. Mooney, PhD, PE
Hydraulic Engineer
Division of Planning, MP-700
Mid Pacific Regional Office
Sacramento, CA

Christopher L. Holmquist-Johnson, MS, PE
Hydraulic Engineer
Sedimentation and River Hydraulics Group, 86-68240
Technical Service Center
Denver, CO

Elaina Holburn, MS, PE
Hydraulic Engineer
Sedimentation and River Hydraulics Group, 86-68240
Technical Service Center
Denver, CO

Reviewed by

Blair P. Greiman, PhD, PE
Hydraulic Engineer
Sedimentation and River Hydraulics Group, 86-68240
Technical Service Center
Denver, CO

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1 Introduction

River spanning loose-rock structures provide sufficient head for irrigation diversion, permit fish passage over barriers, protect banks, stabilize degrading channels, activate side channels, reconnect floodplains, and create in-channel habitat. These structures are called by a variety of names including rock weirs, alphabet (U-, A-, V-, W-) weirs, J-hooks, and rock ramps. These structures share the common characteristics of:

1. Loose rock construction materials (individually placed or dumped rocks with little or no concrete);
2. Extents spanning the width of the river channel; and
3. An abrupt change in the water surface elevation at low flows.

River spanning loose-rock structures share common performance objectives, which include the ability to withstand high flow events and preserve functionality over a range of flow conditions. Functionality is often measured by a structure's ability to maintain upstream water surface elevation and/or downstream pool depths. Vertical drop height, lateral constriction, size of rock material, and construction methods are common design considerations for these structures.

The use of in-stream structures for habitat and stream restoration dates back to the early 1900's; however, the design, effectiveness, and performance of these types of structures have not been well documented. A review of international literature on grade control structure design by Nagato (1998) found that no official standard guidelines for designing low-head drop structures exist. He found that design guidelines were relatively tentative or provisional and site specific in nature. While recently there have been a large number of laboratory data and empirical relationships developed, efforts to link these relationships with field engineering practices are lacking. Roni *et al*. (2002) reported that the lack of design guidance stems from limited information on the effectiveness of various habitat restoration techniques.

Monitoring of in-stream restoration projects has focused primarily on whether structures produce the desired physical response rather than understanding the physical processes that cause the physical response and how that response might change with differing structure configurations. Cox (2005) found that available guidelines and literature related to rock weirs were scarce and consistently lacked investigation of hydraulic effects and/or performance. Restoration projects that have been thoroughly evaluated and provide some insight into their effectiveness, or lack there of, have been highly debated within the scientific community (Frissell and Nawa 1992; Kondolf 1995, 2005; Kauffman et al. 1997; Reeves et al. 1991; Schmetterling and Pierce 1999; Wohl et al. 2005). Roni *et al.* (2002) found that reported failure rates for various types of boulder structures were highly variable, ranging from 0% to 76%. These researchers state that the conflicting results are probably due to differences in definitions of "failure" and/or "function," structure age and type, and design and placement methods. While general monitoring of in-stream restoration projects provides some information pertaining to success and failure rates, they usually do not provide enough detailed information to determine the physical processes associated with the success or failure of a given structure geometry. As a result, current design methods are based upon anecdotal information applicable to narrow ranges of channel conditions. Methods and standards based upon predictable engineering and hydraulic performance criteria currently do not exist.

In 2005, the Bureau of Reclamation (Reclamation) initiated a study program to evaluate the performance of these structures and develop design guidelines using a multi-faceted approach that consists of field reconnaissance, physical modeling, and computer modeling. Field reconnaissance provides long term performance data under actual conditions, including how different river processes affect the structures and how the structures in turn affect river processes. Physical laboratory modeling provides information under carefully controlled conditions that isolate one or more variables to test the impact of specific changes on structure performance. Computer models provide a cost effective method for evaluation of a range of structure geometries and channel conditions to develop a more complete understanding of structure performance and optimize structure design. Integration of field, lab, and numerical data sets provides a scientific basis for predicting structure performance under various river conditions and for developing the most-effective design criteria.

This document describes the initial observations and hypotheses developed through field reconnaissance as the first step in evaluating river spanning rock structures. The objective of the effort was to identify physical processes resulting in the failure or success of an installation. Specifically, structure visits sought to identify common failure mechanisms, site characteristics of successful installations, and structure characteristics of successful installations. Qualitative evaluations relied on interviews with owners and designers of the structures, photo documentation of existing and previous conditions, and the original construction plans and maintenance records when available. Qualitative data was collected during several field trips for use in future analyses.

Observations relied upon the authors' experiences in evaluating river structures. Conclusions from the field reconnaissance effort require verification in both laboratory physical modeling and numerical programs. Planned additional documentation leading to design guidelines includes:

1. Rock Ramp Design Guidelines: Literature Review and Synthesis of Existing Design Methods
2. Qualitative Evaluation of Rock Weir Field Performance and Failure Mechanisms: *This Report*
3. Quantitative Evaluation of Rock Weir Field Performance: synthesis of field observations using the measured data to draw conclusions on best practices and system interactions.
4. Quantitative Evaluation of Laboratory Physical Modeling: synthesis of physical modeling measurements to determine hydraulic performance and depth of scour predictors.
5. Quantitative Evaluation and Development of Numerical Modeling: synthesis of numerical modeling runs to develop optimization criteria for meeting specific river engineering objectives.
6. Rock Weir Design Guidelines: synthesis of field, lab, and numeric analyses for the purpose of designing rock structures to meet river management and design objectives.

Results from the study program will assist designers in predicting the performance of rock weir structures. The end product aims to address the major components of structure success or failure. Where knowledge gaps exist, structure installations require more conservative designs to address uncertainty. This work will identify areas where improvements in future analyses may result in superior design reliability and predictability.

2 Methods

Reclamation and other Agency offices requested field personnel to select a range of river spanning structures, including those performing well in addition to those requiring periodic maintenance. Older structures were preferred over newer installations due to the increased likelihood of experiencing high flow events and modifications from the original design. These structures offered the greatest potential to indicate areas for design improvements.

Individual structures were divided into distinct components identified as arms, throats or cross bars. Different components were present in different quantities depending on the structure. Arm components were designated as either left or right, as referenced looking downstream. Appendix A shows definitions of each component for structures designated as A-, U-, or W-Weirs. An example component diagram is illustrated in Figure 1.

Multiple different types of structures were evaluated for performance and failure mechanisms (Figure 2). A-weirs, also called double drops consist of two distinct crests. U-weirs (sometimes called V-weirs) contain a single crest in which the throat is perpendicular to the flow. Older U-weir structures tended towards design of a narrow throat, sometimes with the arms meeting at a point. W-weirs consist of one or more U-weirs, typically with a narrow, or no, throat. Several different J-hook designs were observed in this study. J-hooks designs that spanned the entire river width and were clearly tied into the opposite bank were categorized as asymmetric U-weirs. J-hook designs that spanned the channel during the time of the survey, but were not obviously tied into the opposite bank were considered typical J-hooks. Older J-hook designs, which did not span the channel width and tended to act only as deflectors, were neglected from this evaluation.

Weirs consist of a line or row of individually placed boulders where the absence of a single rock creates a gap in the crest. Ramps consist of multiple rows or randomly placed rocks where the absence of any single rock does not change the crest. Several sites required multiple structures to meet the design goals. At those sites, structures were grouped into a single site if the hydraulic influence from one structure extended to the adjacent structure or structures.

Initial evaluation of structure performance was intended to consider the ability of a structure to meet the design goals, including:

- Maintaining a given water surface elevation difference across the structure for various discharges;
- Maintaining a downstream scour pool; and/or
- Bank stabilization.

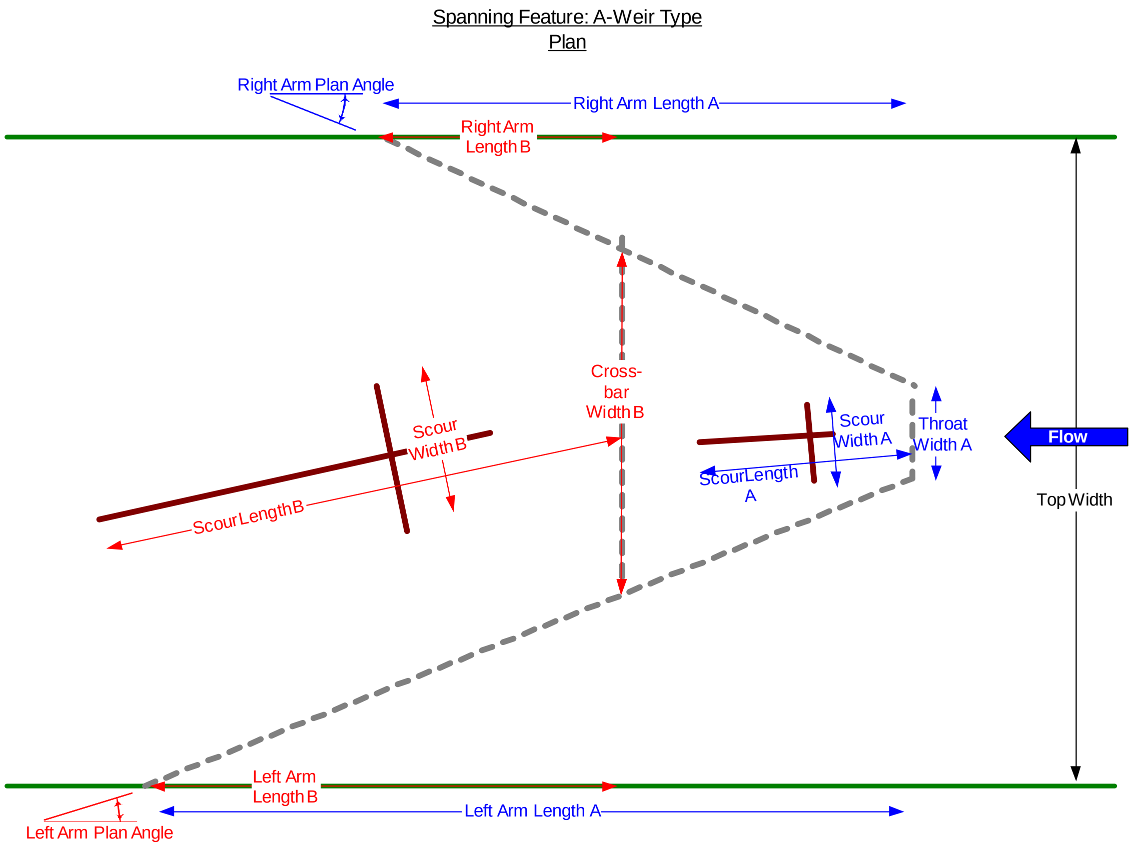


Figure 1. Example Component Diagram using an A-Weir Structure

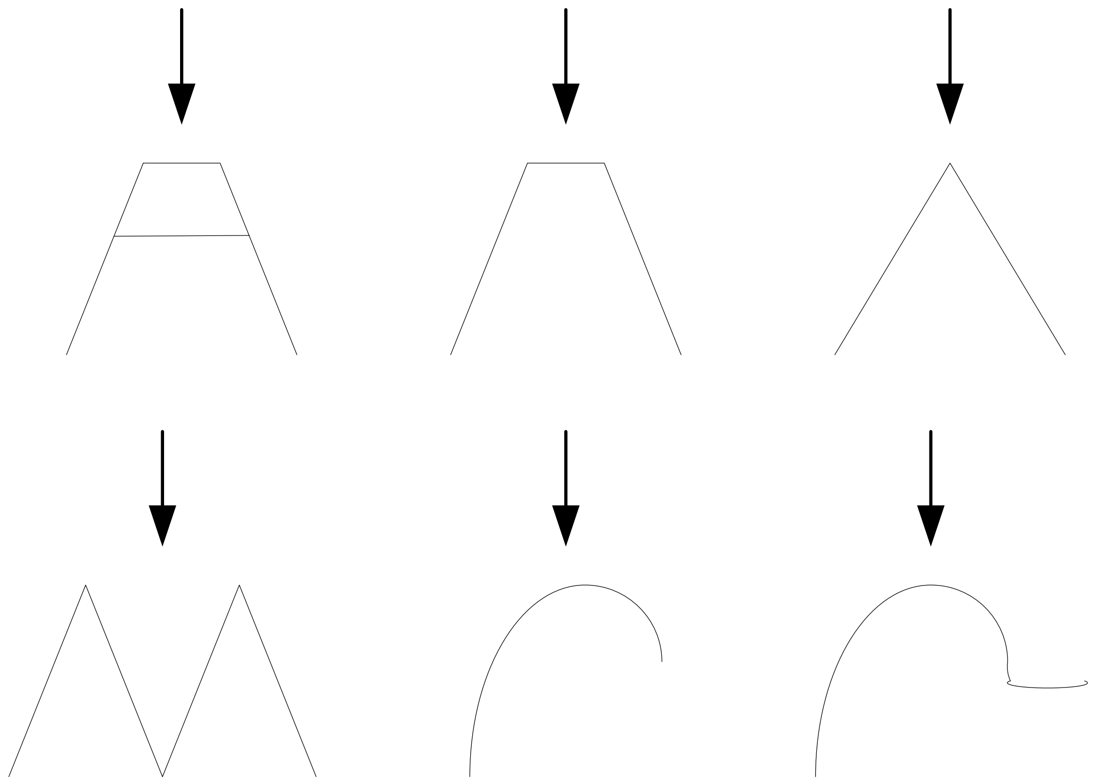


Figure 2. Depiction of Weir Structure Types. Arrows indicate direction of flow.

Maintaining a given water surface elevation difference across the structure is necessary for diversion purposes or for grade control. The elevation difference depends, in part, on flow rate. At high flows, the structure may become submerged and no longer alter water surface elevations (Figure 3). Site visits primarily occurred during low flow conditions and on structures designed to maintain a water surface elevation for irrigation diversions. Maintenance of a downstream pool provides depth diversity for habitat and entrance conditions for fish passage over a structure. Sedimentation filling the downstream pool can be deleterious to fish habitat and passage. Bank stabilization in the vicinity of the structure may be necessary for proper structure performance in addition to proper structure tie-in with the floodplain so that flow passing over the structure and the river do not flank it, as shown in Figure 4.

Figure 3. Examples of submergence conditions at high flow. Little Snake River, CO.

Figure 4. Example of Bank Disturbance. Little Snake River, CO.

Field evaluation of structure failure or success was measured by the ability of the structure to maintain its intended function. Initially, a successful structure was determined to be one in which the structure's purpose was fulfilled without maintenance, while a failed structure was one in which the original design goals were clearly not met. However, the determination of a structures ability to maintain its intended function was often ambiguous. In the field, a range of conditions were present where structures experienced motion of the constituent rocks, but continued to serve the intended purposes to some extent. Evaluation of structure performance was therefore adjusted to include a classification of partial failures as those structures where rocks intended to be static have moved from the initial position but still perform part of their intended function. Mobility of the constituent rocks occurs when one or more piece of the structure moves out of the original alignment. Structures may continue to at least partially perform their intended function despite experiencing some degree of motion. Stakeholders and designers categorize these structures as "requiring maintenance".

Most structures were visited during lower flow rates, conditions under which individual rocks were visible and the alignments were easily observed. Although the specific evaluation varied depending upon the type of structure, photographs of the plan and profile along the axis of each component could identify inconsistencies in alignment. Discontinuities were assumed to result from the movement of rocks. Figure 5 illustrates an example of discontinuity in structure alignment, in which some rocks appear to have become dislodged and moved downstream of their initial position in the cross bar.

Figure 5. Rocks Out of Alignment Example Photo Documentation. Rio Blanco, CO.

Most rock structures were intended to have a level crest. Tilting or turning was assumed to indicate motion. Figure 6 shows an example of photo documentation of tilted and rotated rocks.

Figure 6. Tilted/Rotated Rocks Example Photo Documentation, San Juan River, CO.

Structures were assumed to be constructed in contact with the bank. Therefore, gaps between banks and arms might indicate motion or piping processes. Figure 7 demonstrates an example of rocks appearing separated from the bank.

Figure 7. Structure without a tie-in showing flanking around the right arm. Little Snake River, CO.

At numerous sites, structure movement resulted in isolated rocks moving into the scour pools or downstream channel. However, some designs call for the intentional placement of such rocks. The size and shape of the rock in relation to gaps in the crest and location within the pool were used to estimate whether the rocks were intentionally placed in the pool or were initially part of the crest. When available, initial construction plans provided additional clues.

Other qualitative observations recorded at each site included: rock shape (Figure 8), rock spacing (Figure 9), rock alignment (Figure 10), and foundation. Common rock configurations included the staggering of the header and footer rocks, where the header rocks were placed over the seams of the footer rocks.

Figure 8. Rock Shape a) Blocky versus b) Angular

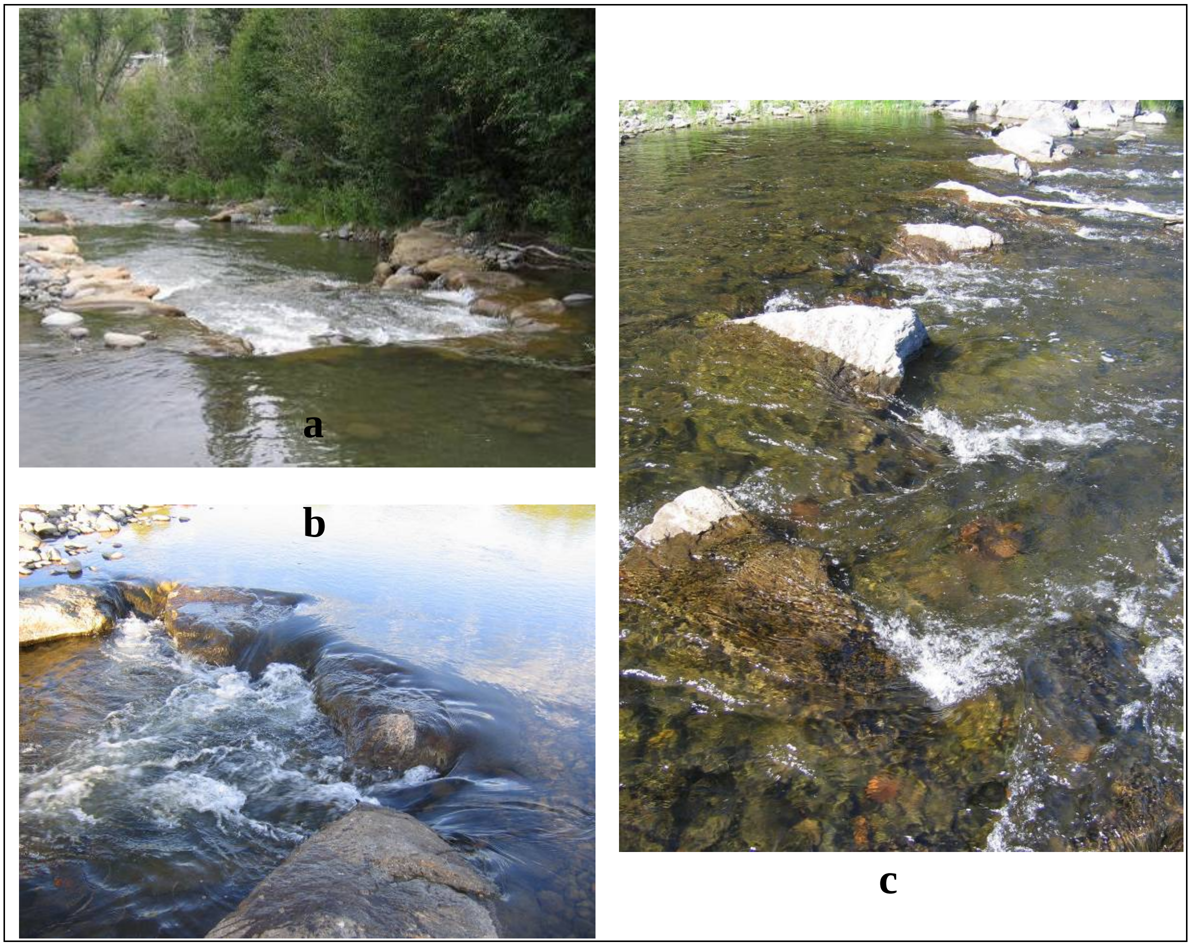


Figure 9. Rock Spacing a) Interlocking versus b) Small gaps versus c) Spaced apart

Figure 10. Staggering of header and footer rocks. Beaver Creek, WA.

Foundation observations examined whether the rocks rested on bedrock or alluvium and estimated the depth of header and footer stacks. Figure 11 depicts a typical header-footer foundation configuration and the presence of bedrock in the scour pool.

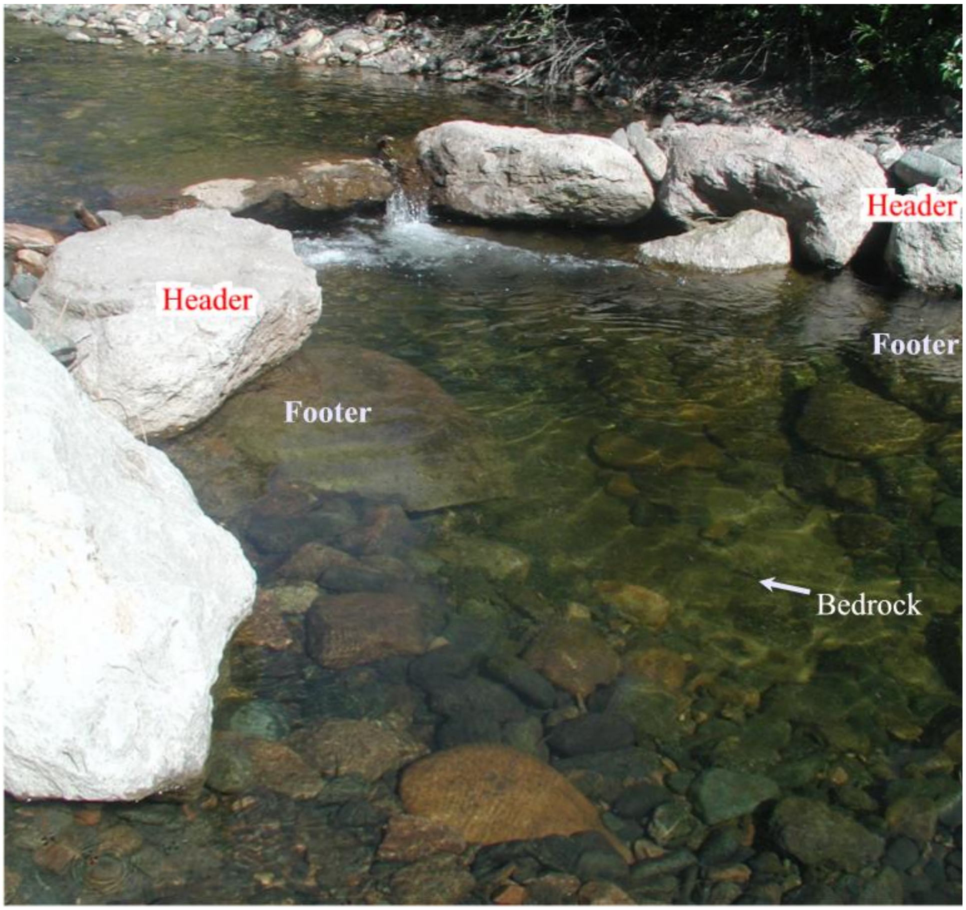


Figure 11. Header-Footer configuration with exposed bedrock in scour pool. Little Snake River, CO.

Over the course of this study, a systematic method of photographing and describing different attributes of sites and structures was developed. Future work will attempt to correlate the success or failure of a structure with observed site characteristics including:

- Scour pool location and dimensions
- Substrate
- Flow Pattern
- Sediment Filling
- Backwater Effects
- Interactions between Structures
- Structure Geometry

Additional data were collected to support a future quantitative evaluation. Data varied between structures but included measurements of: velocity, structure and channel dimensions, and full topographic surveys.

3 Results

The field evaluation included 21 sites consisting of 127 structures (Figure 12) and included various structure designs by Reclamation, Natural Resources Conservation Service (NRCS), Dave Rosgen, and Oregon Department of Fish and Wildlife (ODFW). The observed range of conditions included:

- 28 J-hooks
- 12 A-weirs
    - 1 of which was an A-weir rock ramp
- 75 U-or V-weirs
    - 22 of which were Asymmetric U-weirs
    - 2 of which were V-weir rock ramps
- 4 W-weirs
- 2 Pole-weirs
- 2 simple rock ramps
    - 1 of which was a partial rock ramp
- 1 angled rock dam
- 3 unidentified structures
- Approximate channel widths from 15 feet to 250 feet
- Approximate channel slopes from 0.5% to 2%

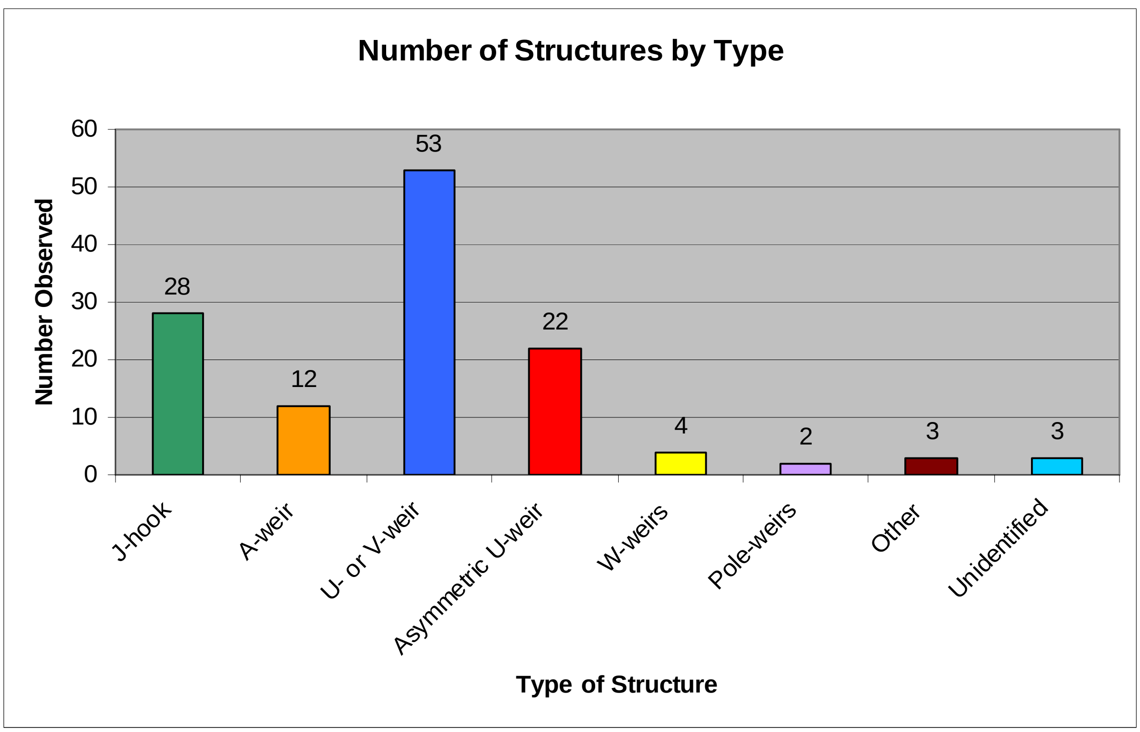


Figure 12. Evaluated Structure and the Breakdown by Type.

Key sites included:

- Three forks of the Little Snake River, CO.
- Rio Blanco, CO.
- San Juan River, CO.
- East Fork of the Salmon River, ID.
- Entiat River, WA.
- Beaver Creek, WA.
- Bear Creek, OR.
- Lemhi River, ID

At each of these sites, at least three structures were evaluated. Although structure spacing at these sites varied, each provided an opportunity to observe how structures in series performed with respect to one another and to compare structure performance within a system. At several of the other sites, only isolated structures were available for evaluation. These sites were helpful in observing impacts to structures independently from upstream or downstream structure performance.

Observations from multiple sites resulted in some general characteristics of the structures and their performance including: flow patterns, sedimentation, scour pool location and dimension, structure materials and construction, bank conditions and observed motion of the constituent rocks.

3.1 Structure Performance

Field investigations identified structure performance and hypothesized failure mechanisms at each structure. Determination of structure success or failure is complicated by the definition of success, whether it was sufficient fish passage, adequate head for irrigation diversion, habitat complexity, or other project goal. For the purpose of the present research, failures were categorized as either partial or full failures. Partial failures were those that may have undergone some minor shifting of the rocks from the original design, but the structures were still meeting intended purposes to some extent. Full failures were characterized as those structures that required significant design modifications post-construction, those that have substantially departed from the original design, or those that were no longer serving their functional role.

Of the 127 structures evaluated, most were determined to have partially or fully failed (Figure 13). Although the sample of structures assessed was not random, both functioning and non-functioning structures were inventoried. However, an emphasis was placed on evaluating structures that appeared to have partially or completely failed to improve our knowledge base of failure mechanisms. Percentages presented in Figure 13 are limited only to the definitions offered in this paper and may vary according to definitions of other studies. For example, Meyer (2007) determined structure performance as a function of mobilization. He categorizes rock structures as being “mobilized” if visual observation suggested that at least 20% of the crest rocks have moved significantly from the ideal or constructed shape. However, this definition does not account for structure performance with respect to functional purpose and physical processes other than mobilization, such as sediment transport and geotechnical slumping. The definitions presented in this paper aim to cover the realm of hypothesized failure mechanisms for determining structure performance. The number of failures for each structure type is provided in Figure 14.

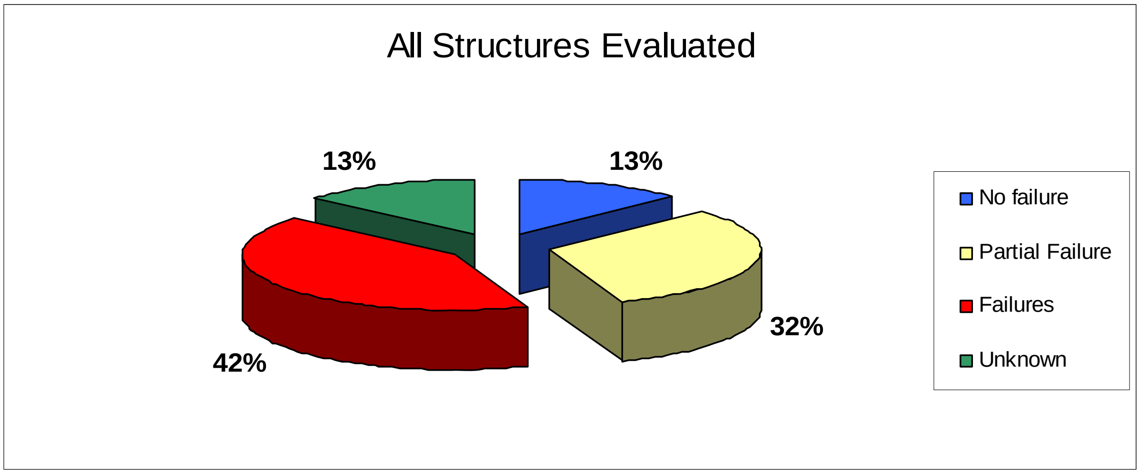


Figure 13. Percentage of failures of all structures evaluated as part of this study.

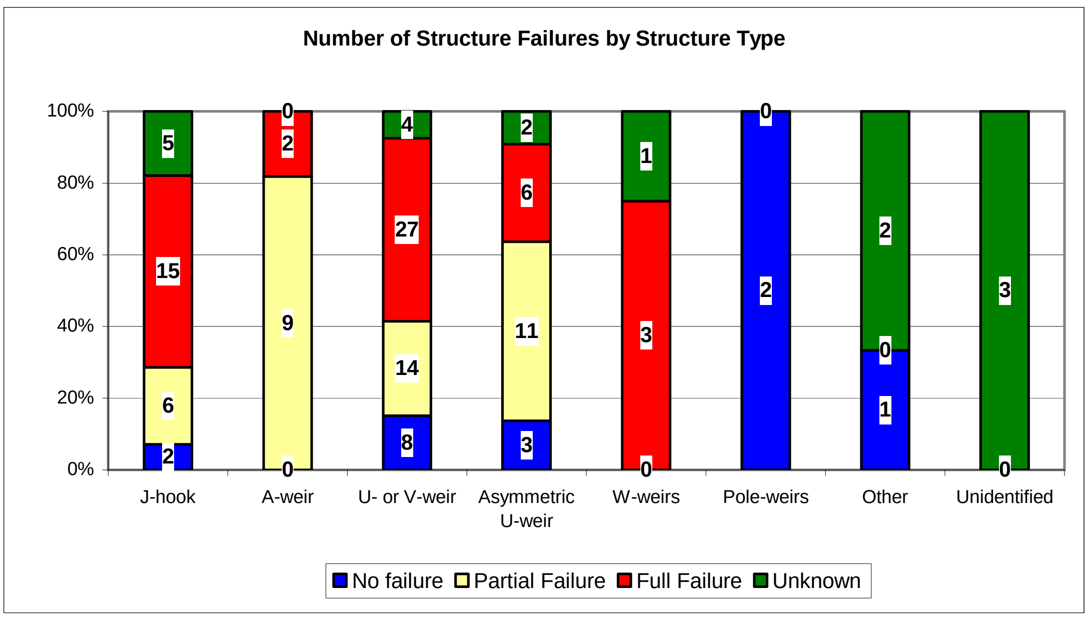


Figure 14. Number and Percentage of partial and full failures for each type of structure.

For each of the full or partial structure failures investigated, a failure mechanism was hypothesized to explain the observed cause of failure. Descriptions of the failure mechanisms are presented in Table 1. In several cases where more than one failure mechanism was hypothesized to contribute to the structure condition, a primary and a secondary failure mechanism were identified.

The percentage and number of full or partial failures and their primary failure mechanism are presented in Table 2. Growth of the scour pool was the most commonly hypothesized failure mechanism among all structures. Of the 95 structures that were noted to be in partial or full failure, 67% were hypothesized to fail as a result of scour pool growth followed by geotechnical slumping of the footer and header rocks. The second most common primary failure mechanism was filling and burying, accounting for only 13% of the failures.

Table 1. Descriptions of each hypothesized failure mechanism

Growth of Scour Pool	Geotechnical failure due to an increase in the depth of the scour pool. The failure commonly resulted in shifting of the footer rock followed by tilting of the header, often into the downstream scour pool.
Sliding or Rolling	Movement of the rock material due to physical forces of incipient motion.
Filling and Burying	Substantial filling both upstream and downstream of the scour pool resulting in no defined scour pool downstream of the structure
General Bank Migration/ Flanking	Migration around the structure or flanking of the bank due to lack of a sufficient tie-in or lateral channel migration processes (e.g. around the outside of a structure bend).
Piping through arm resulting in flanking	Substantial water flowing between the crest rocks comprising the arm or localized scour between the arm and the bank.
Piping underneath header rocks	Substantial water flowing between the header and the footer rocks, resulting in a reduction in the upstream and downstream water surface elevation difference.

Table 2. Primary failure mechanisms hypothesized for partial and full failures.

	Primary Failure Mechanism						
Structure Type	Growth of Scour Pool	Sliding or Rolling	Filling and Burying	General Bank Migration/ Flanking	Piping through arm resulting in flanking	Piping underneath header rocks	Total Number of Partial or Full Failures
J-hook	52% (11)	5% (1)	24% (5)	5% (1)	14% (3)	0% (0)	21
A-weir	67% (8)	17% (2)	8% (1)	0% (0)	0% (0)	8% (1)	12
U- or V-weir	76% (32)	2% (1)	7% (3)	7% (3)	5% (2)	2% (1)	42
Asymmetric U-weir	65% (11)	0% (0)	12% (2)	12% (2)	6% (1)	6% (1)	17
W-weirs	33% (1)	33% (1)	33% (1)	0% (0)	0% (0)	0% (0)	3

Note: The numbers in parentheses are the number of structures represented by the percentage.

Secondary failure mechanisms were identified for 45 of the 95 structures that experienced full or partial failures (Table 3). Secondary failure mechanisms were generally assigned when field evidence suggested that multiple failure mechanisms were responsible for the structure failure. The secondary failure mechanism was not chiefly responsible for causing the failure, but was sufficiently substantiated in the field to be noted as a possible contributing factor. Sliding or rolling was the most common secondary failure mechanism (38%) followed by filling and burying (29%). Structures that were observed to initially fail due to scour pool growth frequently demonstrated signs of additional rock mobilization or subsequent filling of the scour pool, which likely accounts for the recurrent identification of these two secondary mechanisms.

Table 3. Secondary failure mechanisms hypothesized for partial and full failures.

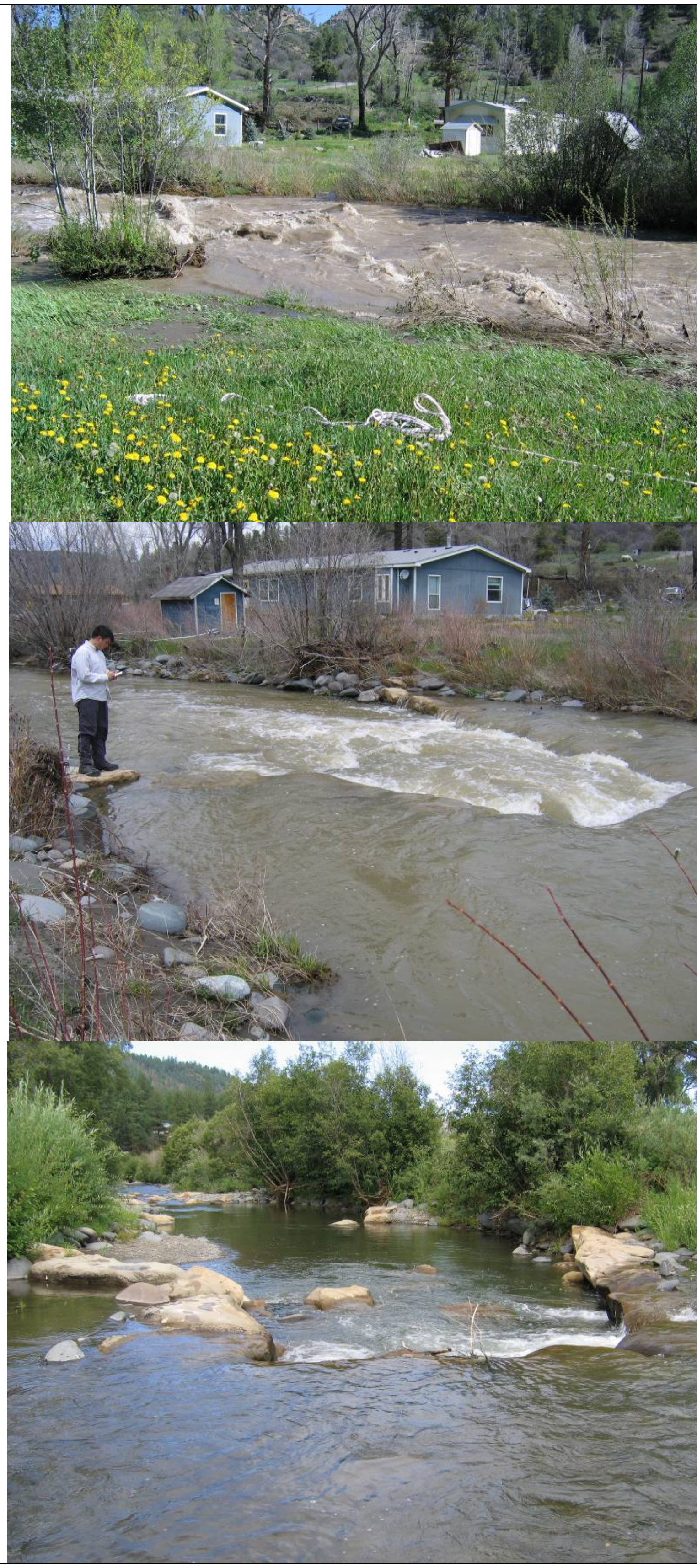
	Secondary Failure Mechanism						
Structure Type	Growth of Scour Pool	Sliding or Rolling	Filling and Burying	General Bank Migration/ Flanking	Piping through arm resulting in flanking	Piping underneath header rocks	Total Number of Partial or Full Failures with secondary failure mechanisms
J-hook	13% (1)	25% (2)	50% (4)	13% (1)	0% (0)	0% (0)	8
A-weir	33% (3)	67% (6)	0% (0)	0% (0)	0% (0)	0% (0)	9
U- or V-weir	14% (3)	38% (8)	38% (8)	0% (0)	5% (1)	5% (1)	21
Asymmetric U-weir	20% (1)	60% (3)	0% (0)	0% (0)	20% (1)	0% (0)	5
W-weirs	0% (0)	50% (1)	50% (1)	0% (0)	0% (0)	0% (0)	2

Note: The numbers in parentheses are the number of structures represented by the percentage.

3.2 Flow Patterns

An increased velocity jet was visible downstream of the crest, extending 3 to 4 times the length of the structure. Backwater effects caused by flow constrictions of the structure created the energy head that caused the noted velocity jets through the structure. Low flow observations nearly always showed some level of water surface drop over the structure, except in locations where the structure and downstream pool had completely filled with sediment. High flow observations indicated a variety of submerged, free flow, and mixed conditions. In free flow conditions, changes to the water surface below the structures do not influence the upstream water depths. Submerged conditions were defined as the downstream water surface elevation influencing the elevation upstream of the structure. Determination of this condition was subjective. Rollers are frequently present even under submerged conditions. Several structures appeared completely drowned out during higher flows with no visible water surface disturbance. Figure 15 shows examples of submerged and free-flowing conditions at a single structure on the Rio Blanco.

In general, backwater effects on the Little Snake River during low flows appeared to extend the entire length between structures. If sediment buried the structure, this backwater effect was not evident. On the Rio Blanco, flow depths between structures appear to return to normal depth in most cases. The sites that did not appear to have one structure's backwater affecting the hydraulics of the upstream structure had larger spacing between the structures. Structures with voids still created a significant backwater effect.



a

b

c

Figure 15. Backwater Effects of (a) Submerged, (b) transitional, and (c) Free-Flow Conditions. Rio Blanco, CO.

For structures on bends, the thalweg generally approached the structure on the outside of the bend and then shifted to the throat (center of the structure) before continuing downstream. Structures on bends that did not appear to maintain the thalweg over the throat generally exhibited evidence of failure due to scour pool growth or flanking around the structure arm. One key example of a structure failure along the bend of a river is on the Lemhi River in Idaho. Figure 16 shows flow patterns at the site before and after failure of the right arm. After the right arm failed, the flow pattern returned to the original path on the outside of the bend. Upon a temporary repair to the structure, the main flow thread turned to pass over the throat.

a

b

Figure 16. Lemhi River, ID a) before failure versus b) after right arm failure.

3.3 Sediment Deposition and Erosion Patterns

Sites frequently indicated sediment deposition creating a ramp beginning upstream of the structure and ending at the crest. Sediment tended to fill in the voids between header rocks and created a more solid wall. On the Little Snake River, structures with notches between the headers tended to maintain a low flow thread just upstream of the structure, while structures without gaps between the headers tended to create a plane bed upstream. On the Grande Ronde River, structures that were buried by large amounts of sediment did not contain a low flow thread despite the gaps between the headers.

Downstream pool depths and the amount of gravel within the pool varied between structures. In some cases, pools appeared completely filled with materials, while in others, the pool scoured down to bedrock.

On sites with multiple structures in series (San Juan River, Bear Creek, Little Snake River), the upstream structures tended to accumulate more deposition behind the crest and to have smaller scour pools than downstream structures. In the downstream end of the Middle Fork and South Fork of the Little Snake River, pools consisted entirely of exposed bedrock with little gravel deposition upstream of the crests or within the pools.

Structures along bends appeared to accelerate bar growth on the inside of the bend. On the Little Snake River, rocks forming asymmetric U-weirs typically located on bends appeared to protrude less into the flow and had more deposition upstream of the arms than structures on straight reaches. Similarly, on the downstream side of the arms, increased deposition occurred locally on the inside of the bend when compared to straight reaches.

3.4 Scour Pool Location and Dimension

Each structure that was not submerged/buried by sediment was characterized by a scour pool just downstream from the structure. The longitudinal location of the scour pool varied, but the maximum depth tended to occur at the end of the shortest arm of each structure. Lengths of the scour pools also varied but appeared to stretch approximately twice the length of the shortest arm. The lateral width of each pool tended to span the entire area within the structure arms. Isolated rocks were often observed at the maximum sour depths. At sites where bedrock control was present, the downstream pool often scoured down to the depth of bedrock. Many pools showed deposition at the downstream extent of the scour hole, resulting in a longitudinal profile depicted in Figure 17. Several structures no longer maintained depths in the scour pool because a substantial amount of material had been deposited in the scour pool location.

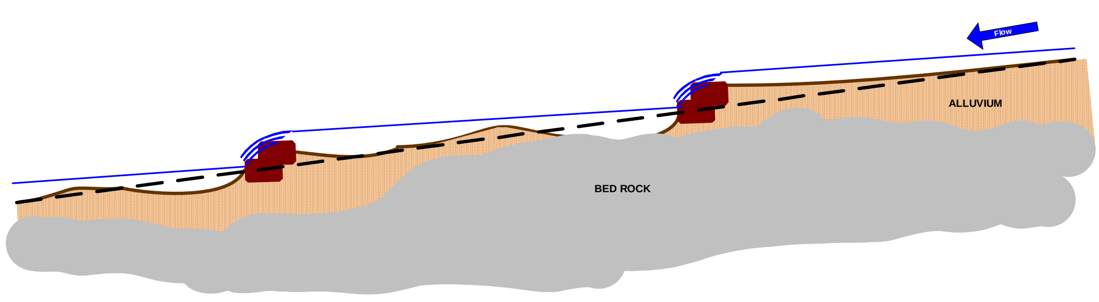


Figure 17. Longitudinal Profile of Sediment Deposition and Pool Patterns

3.5 Structure Materials and Construction

Rocks composing the structures generally appeared blocky and very large in relation to bed material size on the Little Snake River, San Juan River, and Rio Blanco. However, the rock type and rock placement used in the designs was variable. They ranged from elongated rectangular rocks forming the crest of a single rock width to more angular rocks of smaller diameter, in which the crest was several rocks wide. At the majority of sites visited, footers were installed at an upward slope from the throat of the structure toward the bank such that the flow was directed away from the streambank.

Rio Blanco and San Juan River weir rocks were placed tight together forming an interlocking arch. Little Snake River rocks varied from tight interlocking formations to large voids between crest rocks. Structures with small voids (meaning a gap less than approximately 1 foot) between the header rocks did not appear to fail any more frequently than structures with interlocking rocks. On the Little Snake River, fish frequently ran up the voids between rocks. Structures with large voids between the header rocks (meaning a gap greater than approximately 1 foot) appeared to fail more frequently than structures with small voids or no gaps at all. Failures of structures with large voids were observed to include filling and burying (Figure 18b) and movement of the headers downstream (Figure 18a).

Figure 18. Failure of structures with large voids between header rocks. Grande Ronde River, OR.

Variations in Structure Materials and Construction:

- Of all structures evaluated, PN region tended to use more rocks of smaller diameter and a more regular shape with multiple stone widths forming a crest.
- PN structures typically had steep sloped ramps of multiple rocks (Figure 19) and used a geomembrane in some instances to create a notch. Footers appeared staggered in some instances and not in others.
- Typical Rosgen designs were observed to be constructed out of fewer elongated rocks, resulting in the crest being defined by a single rock width (Figure 20).

Figure 19. Steep sloped ramps frequently used in PN Regional Designs. Lemhi River, ID

Figure 20. Typical Rosgen design with a single rock width of rocks defining structure. Little Snake River, CO

4 Discussion

4.1 Structures Influence on flow and sediment patterns

All structures appeared to successfully modify river flow patterns even under partial failure conditions. Observed influences of the structures included higher velocity flow jets through the center of structures, breaks in water surface profiles during low flow events, and presence of scour pools in numerous incidences (Figure 21). High flow events reduced the influence of the structures on the water surface elevation.

Figure 21. Pre- and Post- construction photos on the East Salmon River. Note changes in velocities and water surface profiles. East Fork Salmon River, ID

Lower discharges exhibit free and rapidly varying flow conditions. As flow rate increases, a transitioning phase occurs, in which the downstream conditions influence the upstream water surface elevation. Finally, the flow conditions progress to a fully submerged condition, in which the structure behaves more as an element of channel form roughness. Field investigations identified all stages of these weir processes; therefore, design of each structure must consider the range of expected conditions. We hypothesize that the most critical case for structure design occurs before the structure is submerged and at the point when the maximum plunge (energy loss) occurs.

Observations on sediment patterns were less consistent. Sediment deposits on the Little Snake River and Rio Blanco River appeared to have waves of sediment deposits spanning several structures. Within a series of weirs spanning a sediment wave, the upstream weirs exhibited more deposition of material than downstream weirs. The pattern then repeated. Structures appear to have the ability to alter local sediment transport rates. Multiple structures were observed to have altered reach transport rates at least temporarily. The younger age of the structures suggests that the channels viewed are likely still adjusting and that the sediment transport is episodic, meaning the pools upstream and downstream of the structures go through cycles of erosion and deposition. Ultimately, channels adjust to inflowing sediment loads, and the structures have a finite amount of sediment storage upstream of the header rocks. Eventually, the sediment entering upstream of the structure will pass over the structure.

Sediment filled in the scour pool and buried the structure under some conditions. This is hypothesized to result from general aggradation of the river and/or inadequate transport capacity through the structure to maintain the original scour pool as designed. Variation in the depths of scour pools, deposition upstream of structures, and growth of adjacent bars suggests the amount of sediment supplied and moving through the system may play a strong role in structure success or failure. While the design of structure geometry is critical to structural success, field observations indicate that geomorphic channel responses may be equally important to structure sustainability and require evaluation for adequate structure design.

4.2 Failure Mechanisms

Identification of failure mechanisms provides information on how to design more robust structures, retrofit existing installations, or develop countermeasures.

4.2.1 Growth of the Scour Pool

The most common failure mechanism identified was the growth of the scour pool and undermining of the footer rocks. During high flow events, increased flow velocity and depth over the crest transports material out of the scour pool, removing support for the footer rocks during a period of increased pressure and momentum transfer from upstream flow. As the scour pool grows, the footer becomes geotechnically unstable and slumps. The footer and supported header either tips upstream as in a rotational failure (Figure 22) or rolls downstream toward the scour pool (Figure 23). Observed pool depths during low flows, however may not represent the maximum depth of scour or the scour depth that resulted in failure during higher flows. During the receding limb of the hydrograph, deposition in the scour pool may refill material removed during the ascending limb.

Figure 22. Footer pushed out, header tilted upstream. Little Snake River, CO.

Figure 23. Footer shifted, header tilted downstream. Bear Creek, OR

Evidence for the growth of the scour pool and undermining of the footer rocks includes header-footer groupings in odd alignments, footers pushed into the pool and out of contact with headers, and repositioning of original header rock locations. Many scour pools contained isolated rocks that appeared to originate from footers that have slumped into the scour hole, or headers that have fallen in after the footer shifts. Some of the rocks observed within the scour pool may actually have been placed intentionally to provide refugia and pocket-pool habitat. The determination of rock origin considered original construction plans, the distance from the crest, and correlation between gaps in the crest and size of the isolated rocks.

Structures contacting bedrock appear to remain intact or show only minor tipping of the header in an upstream direction. It is not known if these structures were originally constructed in contact with the bedrock or their substrate was eroded away. The preponderance of intact structures that were situated upon bedrock is consistent with the geotechnical failure mechanism commonly noted for structures lacking such foundation.

On the end of the arms, the tie-in was occasionally seen to be pulled away from the bank, and in some cases flanking was evident. Figure 24 shows an example where dislodging of the footer rock caused the header to shift away from the bank. Sloping of the arms upwards toward the bank causes the footers supporting the arms to have shallower foundations than the throat. Therefore, a lesser amount of scour is required to undercut footer rocks along the arms than those under the throat.

Figure 24. Header/footer pulled away from bank. Little Snake River, CO.

Most of the failures due to scour pool growth occurred when footer rocks along the arms became dislodged, typically located one-half to two-thirds of the distance from the crest throat to the bank tie-in. Failures are hypothesized to occur most frequently at these location due to (1) the depth of the footer rocks relative to the depth of the scour pool, and (2) the amount of drop over the structure at these locations. Under high flow conditions, the greatest drop over the structures occurs along the structure arms due to sloping toward the bank. The location where the drop height and flow rates combine to create the greatest energy for scour appears to be correlated with scour pool depth and failure location. Additional investigation through physical and numerical modeling may provide supporting evidence for these statements.

4.2.2 Filling and Burying

While still in place, several structures were seen to be buried by sediment and no longer maintain scour pools or drop. Figure 25 illustrates an example in which a structure was designed for the purpose of creating pool habitat and was subsequently buried due to high sediment load. Based upon fish habitat criteria, the structure has failed.

Figure 25. Structure has completely filled in with sediment. Grande Ronde River, OR

Structure-specific sediment transport conclusions will likely require quantitative analysis. There may be specific design techniques for higher or lower load systems not evident by visual observation. Sediment transport is likely more important in high load systems where periodic maintenance is less feasible. Such systems may fail to maintain a downstream scour pool.

4.2.3 Sliding or Rolling

Sliding or rolling of the constituent rocks was hypothesized as another possible mechanism of failure. Differentiating sliding or rolling and growth of the scour pool was often complicated by the fact that movement of weir material almost always included some footer shifting. Sliding or rolling of a header would have been expected to initially leave an exposed, level footer, which at some later point in time may or may not have undergone further undercutting and shifting of the footer. On the other hand, if the geotechnical slumping was the initial method of failure, sliding or rolling of crest rocks may have subsequently occurred. Field observations from this study suggest that sliding or rolling primarily acts as a secondary mechanism of failure, most often following growth of the scour pool and footer displacement.

Sliding or rolling was most commonly identified as the primary mechanism of failure when the structure materials were clearly undersized for the anticipated shear stress. Structures comprised of large blocky rock crests did not experience sliding or rolling in most cases.

Structures on bedrock appeared intact and showed no visible difference in rock size than structures on alluvium. When comparing structures constructed on bedrock and alluvium under similar flow conditions and structure design, structures on bedrock did not appear to fail but structures on alluvium did. If sliding or rolling through incipient motion caused the structures to fail, one would expect that both the structures on alluvium and the structures on bedrock would fail. These findings suggest that sliding or rolling through incipient motion is not likely the primary mechanism for most failed structures and indicates that growth of the scour pool and structure foundation are critical parameters in structure design.

Several sites, particularly ramp structures, did show evidence of sliding or rolling through incipient motion, in which the top layer of material was removed and the bottom layer seemed otherwise intact. However, the high degree of success on the majority of ramp structures suggests this mechanism is less critical or more adequately understood by designers than other failures. Further research into the sliding or rolling mechanisms is not being conducted at this time.

4.2.4 General Bank Migration/Flanking

General bank migration and flanking was noted as the mechanism of failure for structures that showed evidence of lateral channel migration around the structure or flanking of the bank due to lack of a sufficient tie-in. Observations suggest this failure mechanism to be in part a system characteristic, but also a mechanism that the presence of a structure can potentially accelerate.

At several sites, active lateral migration of the channel caused bank erosion around the structure's location. A geomorphic evaluation of the system could determine if the lateral migration was inherent to the system. Historic, present, and future channel patterns may improve understanding of channel migration rates and extents, and thus guide appropriate placements of in-stream structures.

Structure tie-in appeared to be an important factor in the success or failure of many of the structures investigated. Lack of a sufficient tie-in to the bank frequently instigated the development of a flow path between the arm of the structure and the bank, resulting in major scour of bank material during high flow events. Downstream migration of point bars were also noted to cause flanking around a structure, particularly if the structure was not adequately tied into the bank. Figure 26 is an example of a structure that appeared to fail as a result of the left arm not being tied-in to the top bank. Instead, the arm was tied-in to the point bar, and higher flows were able to transport bar material downstream resulting in the failure of the structure.

Figure 26. Structure tie-in and flanking. Little Snake River, CO.

4.2.5 Piping Underneath the Header Rocks

Piping underneath the header rocks was recognized as a mode of failure when substantial flow was visible between the header and the footer rocks, which influenced the ability of the structure to maintain the intended difference in water surface elevation. Piping underneath the header rocks was observed at a few sites, but was generally an uncommon mode of failure. We hypothesize that piping underneath the headers may encourage crest rocks to tilt backwards and upstream. At the few sites where flow between the headers and footers was observed, diagnosis of the causes for movement of the header rocks was difficult and scour pool slumping may have been at least partially responsible.

4.2.6 Piping through the Arm Resulting in Flanking

Piping through the arm of the structure was characterized by flow between the header rocks comprising the arm or localized scour between the arm and the bank without notable shifting of the header and footer rocks. Piping of the fine bank material through voids in the arms may be responsible for these failures. This mechanism was identified as the primary failure mechanism for only six sites and typically resulted in a partial failure designation. All of the sites where this mechanism was observed were located in the Little Snake River. This could be attributed to the fact that the structures on the Little Snake River did not have any geomembrane installed on the upstream side of the structure. In the Pacific Northwest, the majority of the structures built include a geomembrane on the upstream side of the structure to eliminate this process and assure the required water surface elevation at low flows are met for water diversions.

The piping failure mechanism was distinguished from general bank migration/ flanking by evidence of the processes responsible for failure and by the scale of the flanking. Structures that completely or partially failed as a result of general bank migration/ flanking typically coincided with lateral channel migration, bar migration, or lack of structure tie-in, which caused considerable flanking around the structure. Structures hypothesized to have failed from piping through the arm showed evidence of substantial seepage between the header rocks or between the header rocks and the bank, which resulted in localized erosion (Figure 27). Piping between the header rocks and the bank may act as a preliminary process for future general bank migration/ flanking. Future monitoring is recommended at those sites where this mechanism was hypothesized to observe future trends in channel adjustment.

Figure 27. Piping through the Arm Resulting in Flanking. Little Snake River, CO.

4.3 Successful Techniques

4.3.1 Foundations

Structures placed on bedrock were observed to remain intact and in the original location. Foundations may provide a limit to the formation of the scour and prevent geotechnical failure. Meyer (2007) hypothesized greater susceptibility to sliding due to a decrease in friction on bedrock foundations. No evidence was identified in this study to support this hypothesis. At the sites visited in this study, structures with bedrock foundations generally appeared more intact than alluvium foundations, and structure failure was most often related to geotechnical slumping of the footer rocks resulting from scour pool growth. Results of this study suggest that eco-blocks and other concrete elements may increase the longevity and functionality of the structure. These types of foundations can be installed in a manner that limits their visibility.

4.3.2 Grout

Grout can measurably increase the lifespan of cross-channel structures. However, the use of grout is often unacceptable to stakeholders because it is comprised of material foreign to natural stream systems. In field observations of the San Juan River, a U-weir filled with grout sustained a larger drop without damage during high flow events compared to other structures in the system without grout. Though non-native, the cost of summarily dismissing grout could prove significant.

4.3.3 Series not Singles

Early field evidence suggests that structures performed best when placed in series rather than individually. Field observations suggest multiple hypotheses for why structures in series outperform individual structures. First, structures in series provide redundancy for meeting management objectives. For example, the probability of success for structures used to prevent channel incision may increase through the placement of multiple structures. If the downstream-most structure fails, upstream structures will continue to provide grade control. A second hypothesis is that the difference in water surface elevations on the upstream and downstream sides of one large structure may create sufficient backwater pressure (potential energy) to instigate structure failure. To produce the same head, several structures in series distribute the energy dissipation and may increase the potential for structure success and longevity.

Individual structures with multiple cross bar members (e.g. Triple Drop A-weir) were generally observed to be successful. Multiple steps within the longitudinal length of a structure limit the scour depths of the pools. Structure components in series may be expected to create some backwater during high flow events, which would in turn reduce the transport capacity through the structure.

While structures in series were observed to outperform individual structures, the appropriate spacing of the structures may be a key parameter for sustainable design. Meyer (2007) found that structure spacing on the Little Snake River was related to pool volume loss and structure condition. Structures that were spaced closer than observed average pool spacing for natural pool-riffle channels generally experienced scour pool volume loss through sedimentation upstream of a structure. Design of structures in series may use natural pool spacing to guide the longitudinal proximity of the structures.

4.3.4 Interlocking and Rock Shape

Interlocking structures appeared to resist sliding into a scour pool following the geotechnical slumping of footer rocks. Interlocking structures are characterized by the staggering of the header and footer rocks, in which the header rocks are placed over the seams of the footer rocks, and by the ability of the structure to remain intact if one of the footer rocks becomes dislodged (Figure 28). Although structures may still maintain some degree of functionality after rock dislodgement, the interlocking temporarily provides support and most-likely only delays failure.

Rock shape is hypothesized to be an important factor in sizing of stable materials (Ullmann, 2000), but field evidence is not available to quantitatively support this. Size appears a more critical factor than rock shape in the success of structures investigated. If the size of the rock was significantly larger than the critical rock diameter for which the structure was designed, then the shape of the rock did not appear to be a factor of structure failure. However, when structures are designed within a close proximity to the stability limit, shape may be an important design parameter. Rock shape also may impact the ability of rocks within the structure to interlock. Field observations suggest that blocky rock structures have a greater ability to interlock than angular rock structures. This may be due to the increased surface area available for contact with adjacent and supporting rocks.

Figure 28. Interlocking of rocks providing additional structure support.

5 Conclusions

Site visits to existing installations provides critical information for identifying processes working for and against successfully using structures to meet management goals in a sustainable manner. Identifying the processes influencing structure sustainability permits a scientific evaluation of the controlling parameters and potential techniques for modifying structure designs.

Of the 127 sites visited during the field investigations, 74% of the structures were considered to be in partial or complete failure. The most commonly hypothesized primary failure mechanism was growth of the scour pool and geotechnical slump of the footer rocks. Sliding and rolling through incipient motion was observed as the primary failure mechanism for only 5% of the sites where complete or partial failures were identified. Sliding and rolling had a greater impact as a secondary failure mechanism, most often following growth of the scour pool and slumping of the footers. Although the methods used to size the rocks were not evaluated in this analysis, field investigation suggests that most structures were comprised of rocks adequately sized to prevent failure by sliding and rolling through incipient motion.

System effects, such as filling of the structures from sediment deposition and lateral channel migration were observed to occur relatively frequently. Impacts of these processes on structure function identify the need for a greater understanding of sediment transport, geomorphology, and physical processes encountered by these types of structures and may ultimately require new and improved types of structures or different techniques to accommodate channel change.

Observations also indicate that structure tie-in to the bank is critical to sustaining intended structure function. Structures that are tied into point bars rather than into the bank are susceptible to flanking of the structure by downstream migration of the gravel bar.

Several installation and design methods were identified to enhance structure performance. The most successful technique observed was the presence of a deep foundation for the structure, which prevented scour from undermining the footer rocks. Structures in series may increase the likelihood of maintaining project objectives over longer periods of time. In general, interlocking blocky rocks and grout increase resistance to failure and allowed the structure to sustain more damage before losing function. These techniques may increase the longevity of the structures, but do not guarantee permanent structure function.

Results from the qualitative evaluation have been used to inform design retrofits on several structures on the Salmon River, ID, Lemhi River, ID, and the Entiat River, WA. Future work will apply quantitative techniques to develop empirical correlations with site characteristics and integrate field results with the laboratory physical modeling and numerical simulations. The analysis and results of the field data, laboratory modeling, and numerical modeling provide a process-based method for understanding how structure geometry affects flow characteristics, scour development, fish passage, water delivery, and overall structure stability. The end product will develop tools and guidelines for more robust structure design or retrofits based upon predictable engineering and hydraulic performance criteria.

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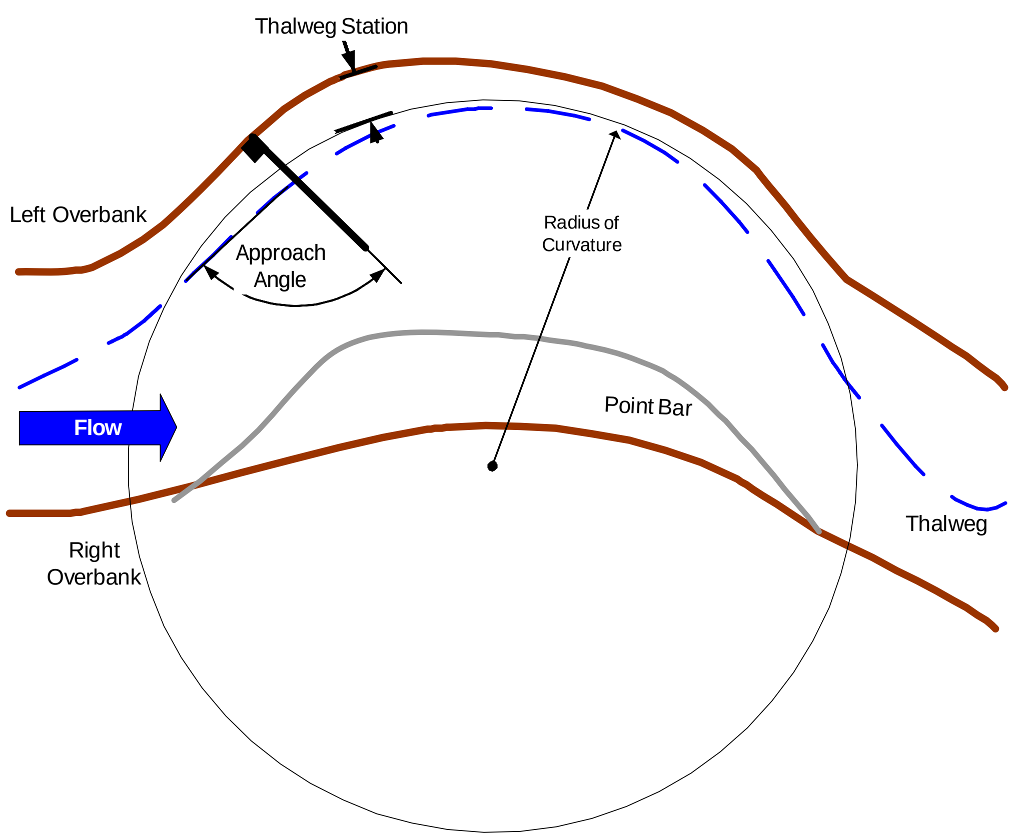
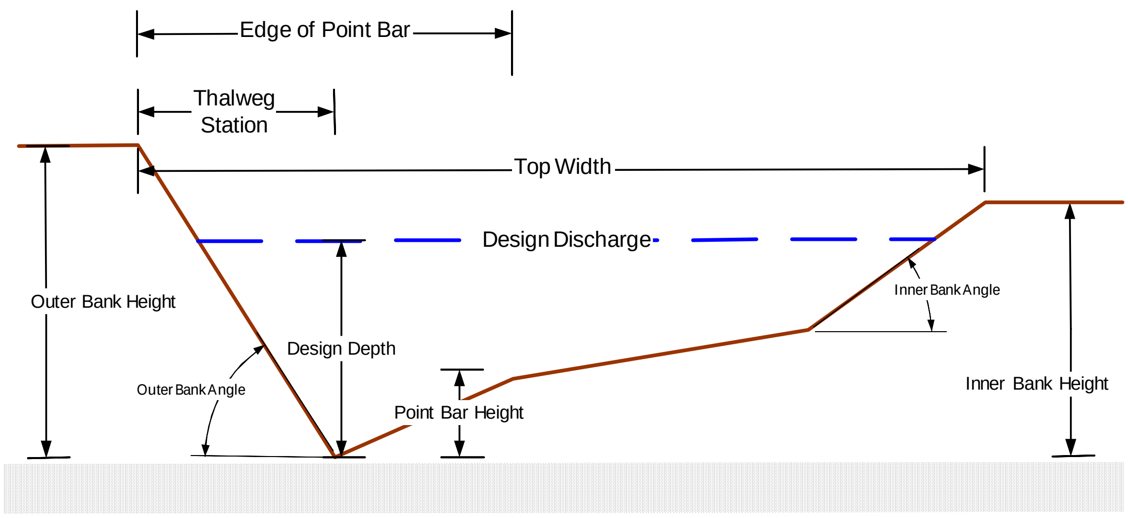
7 List of Appendixes

Appendix A - Definition of Structure and Channel Parameters.doc

Appendix A - Definition of Structure Geometry and Channel Parameters

Channel Geomorphology





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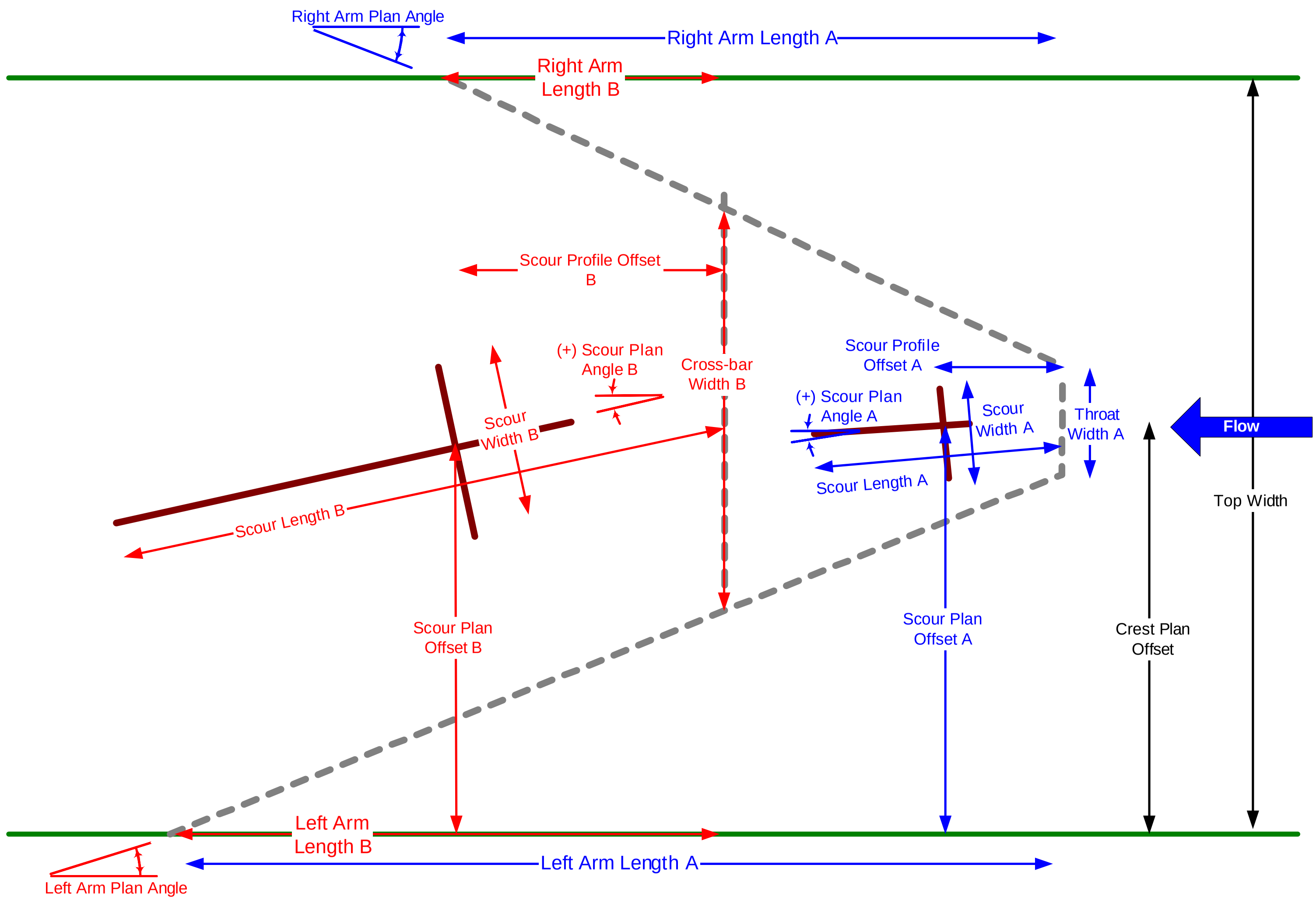

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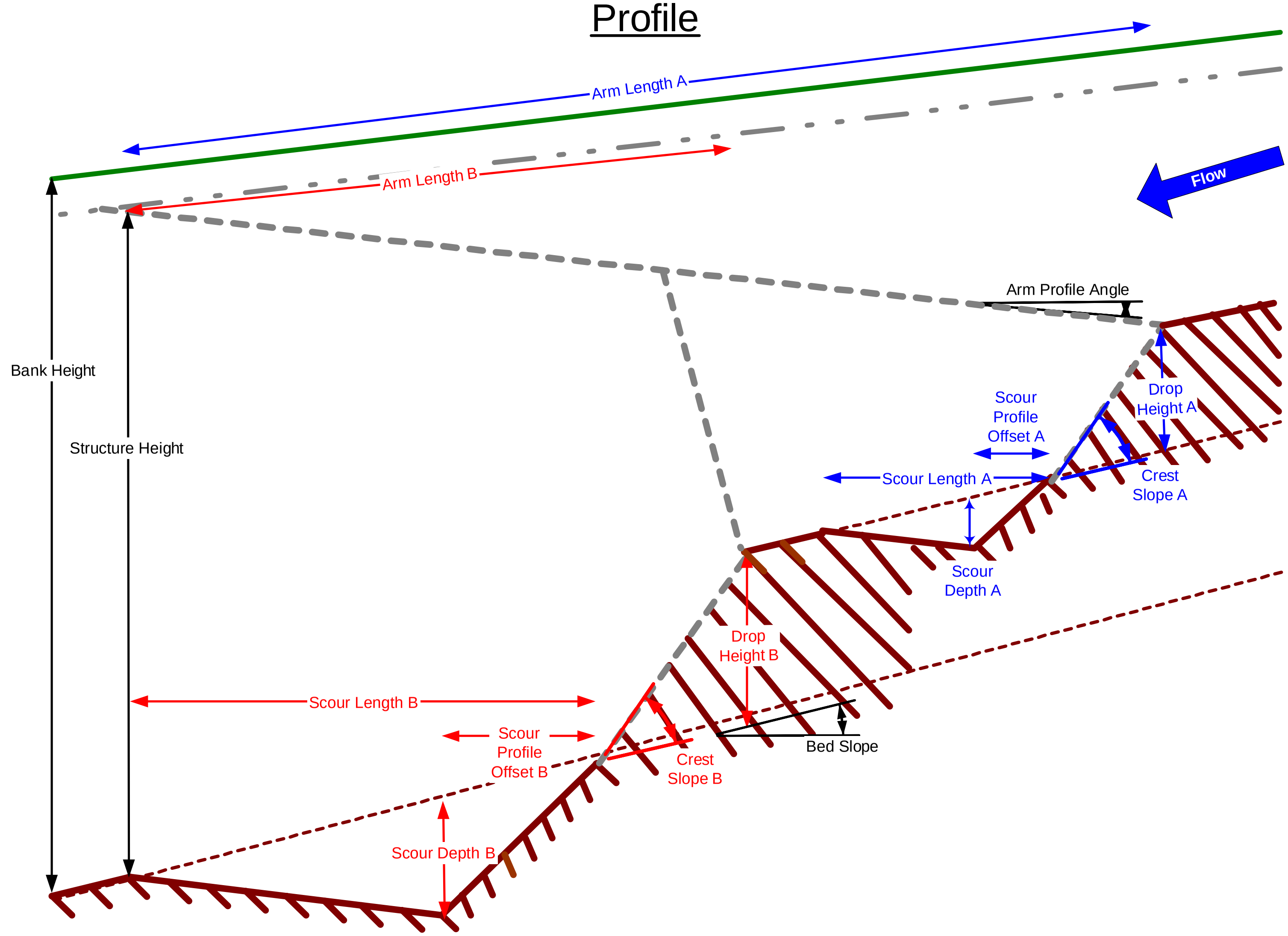

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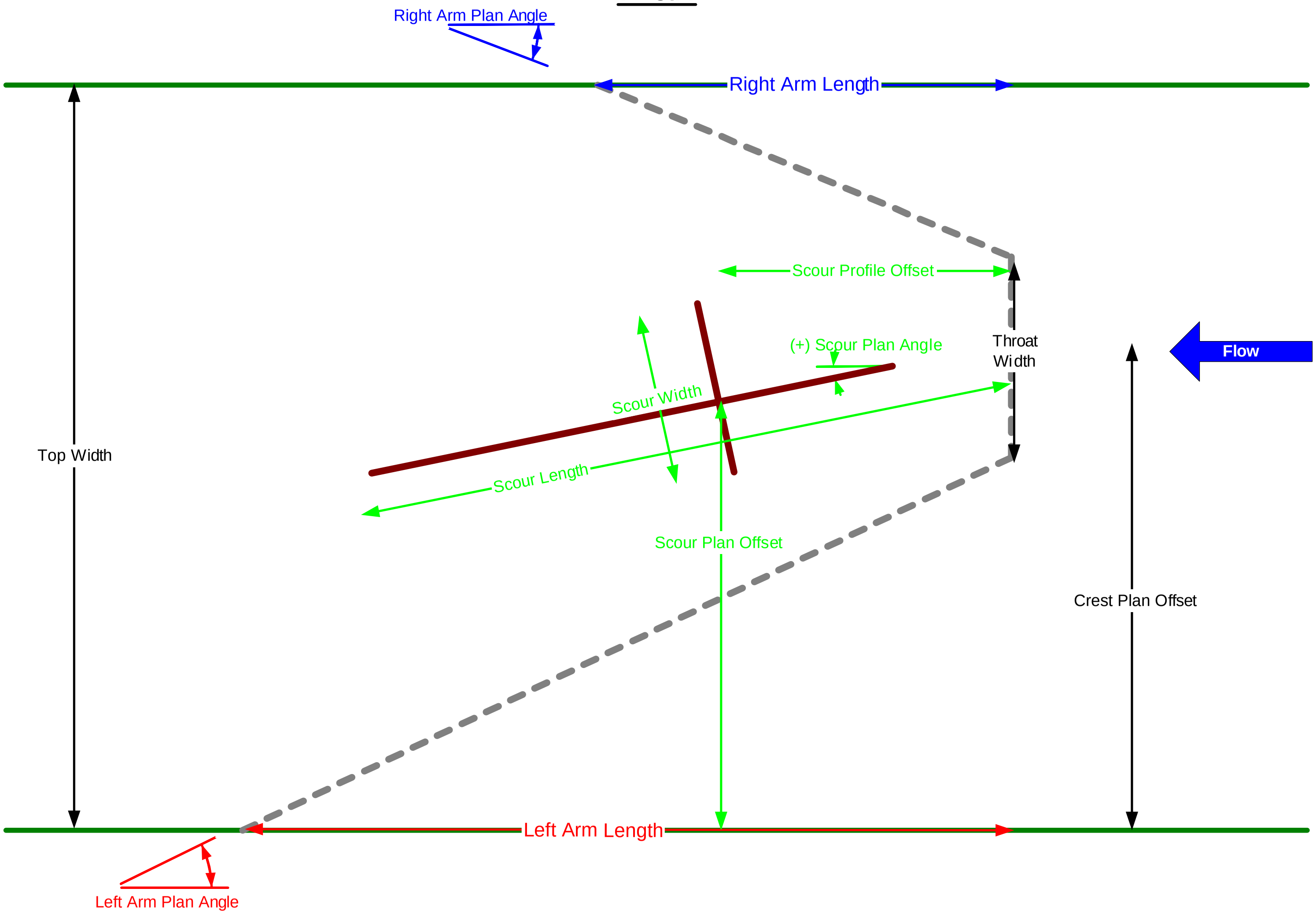

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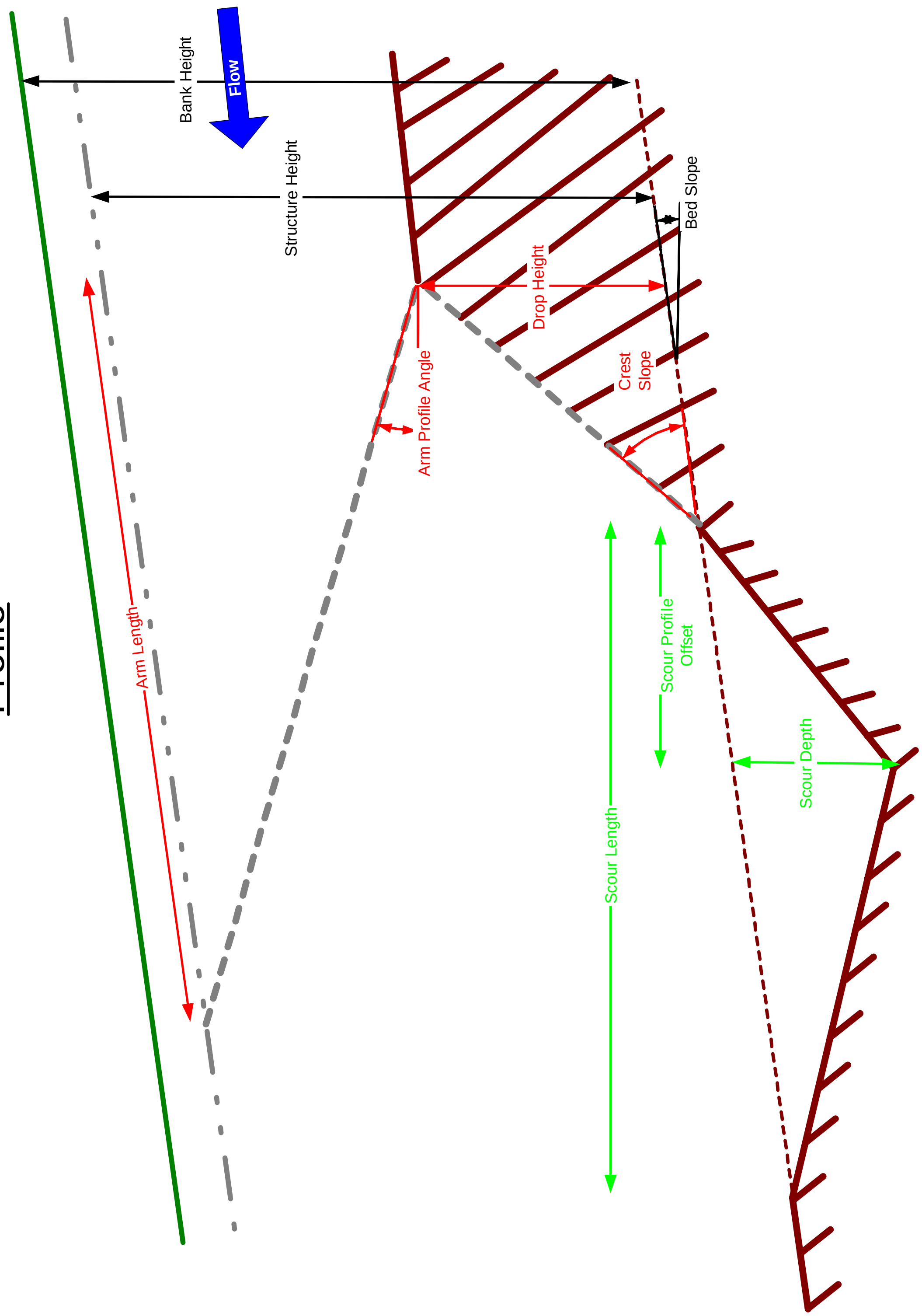

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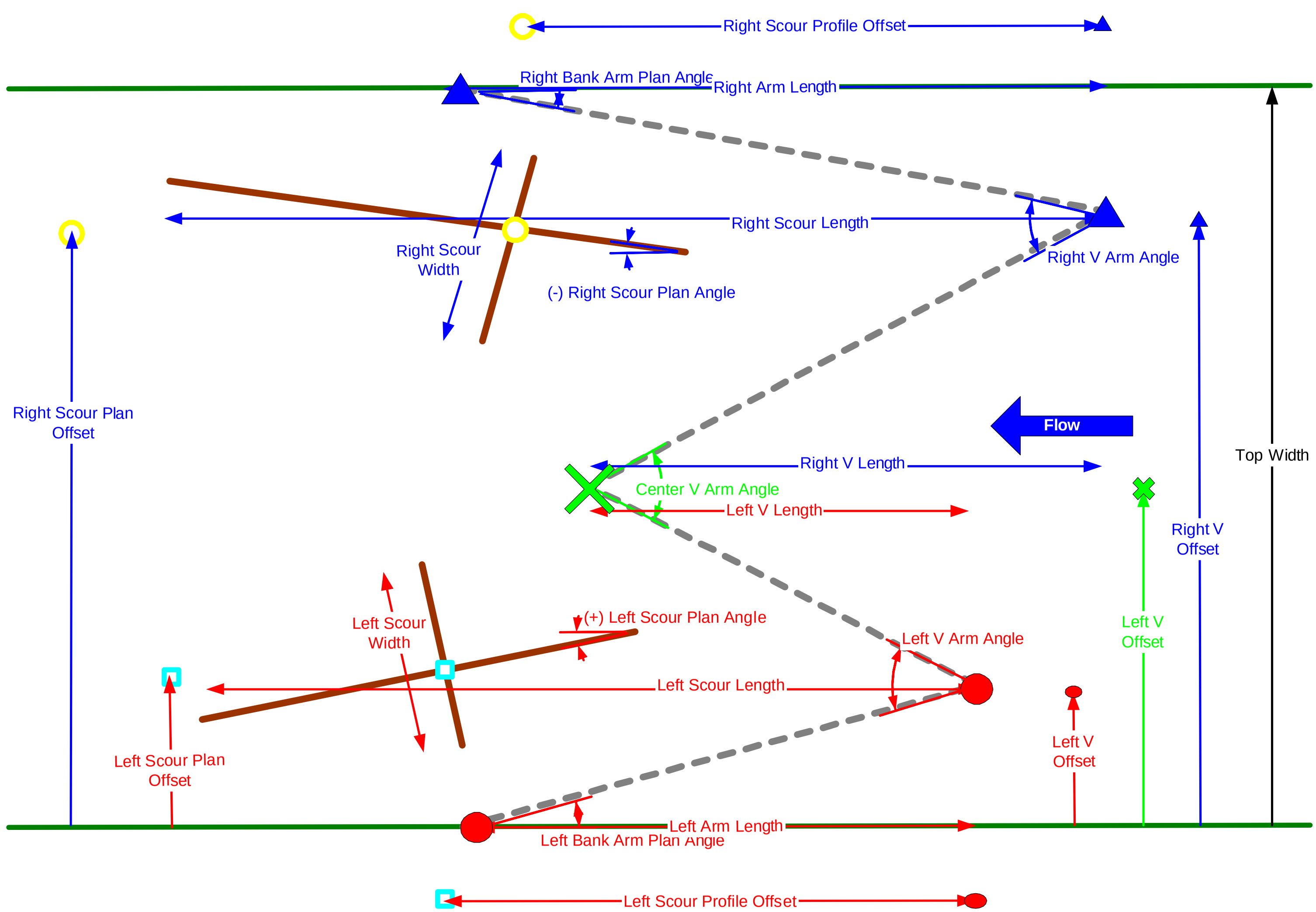

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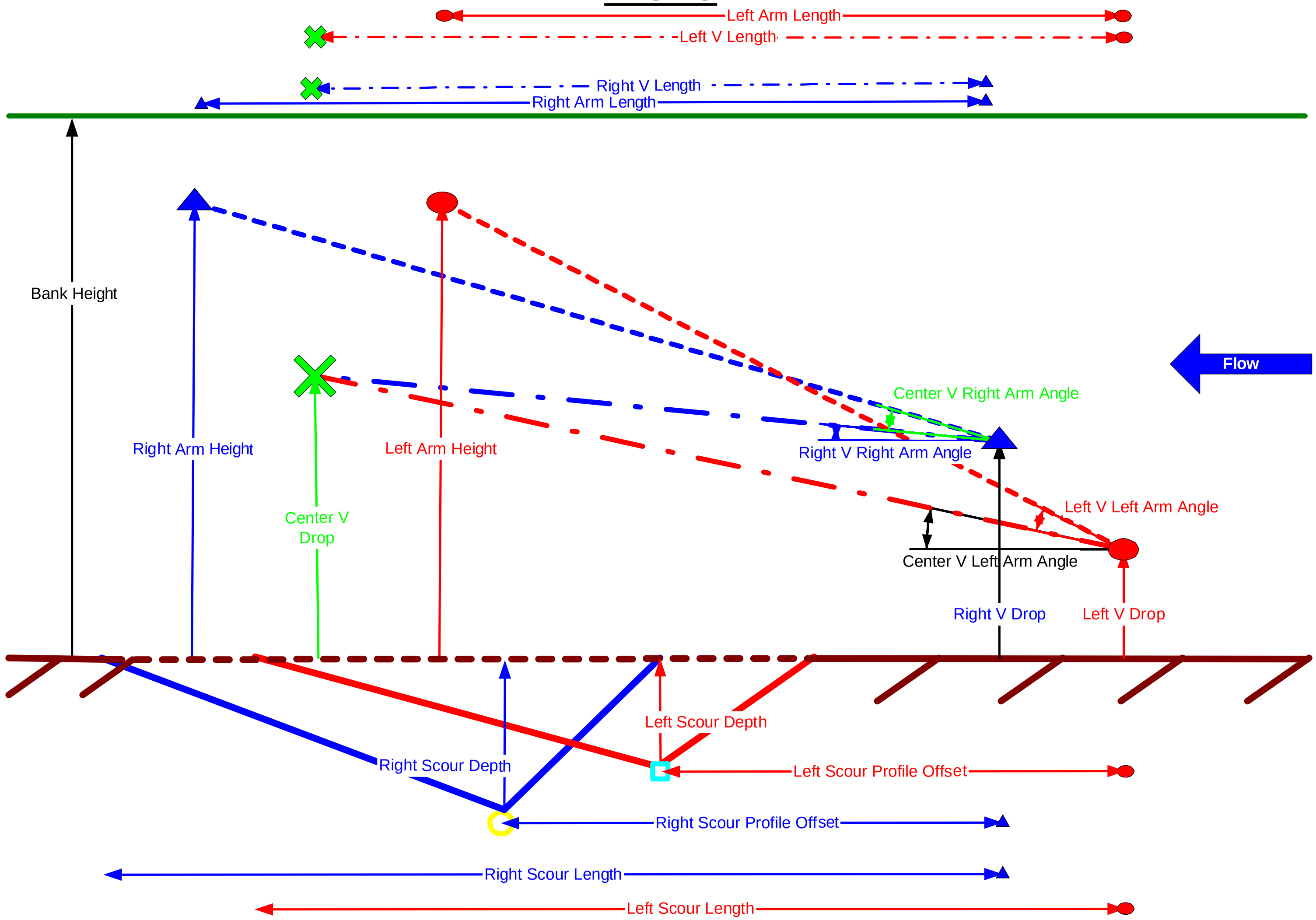
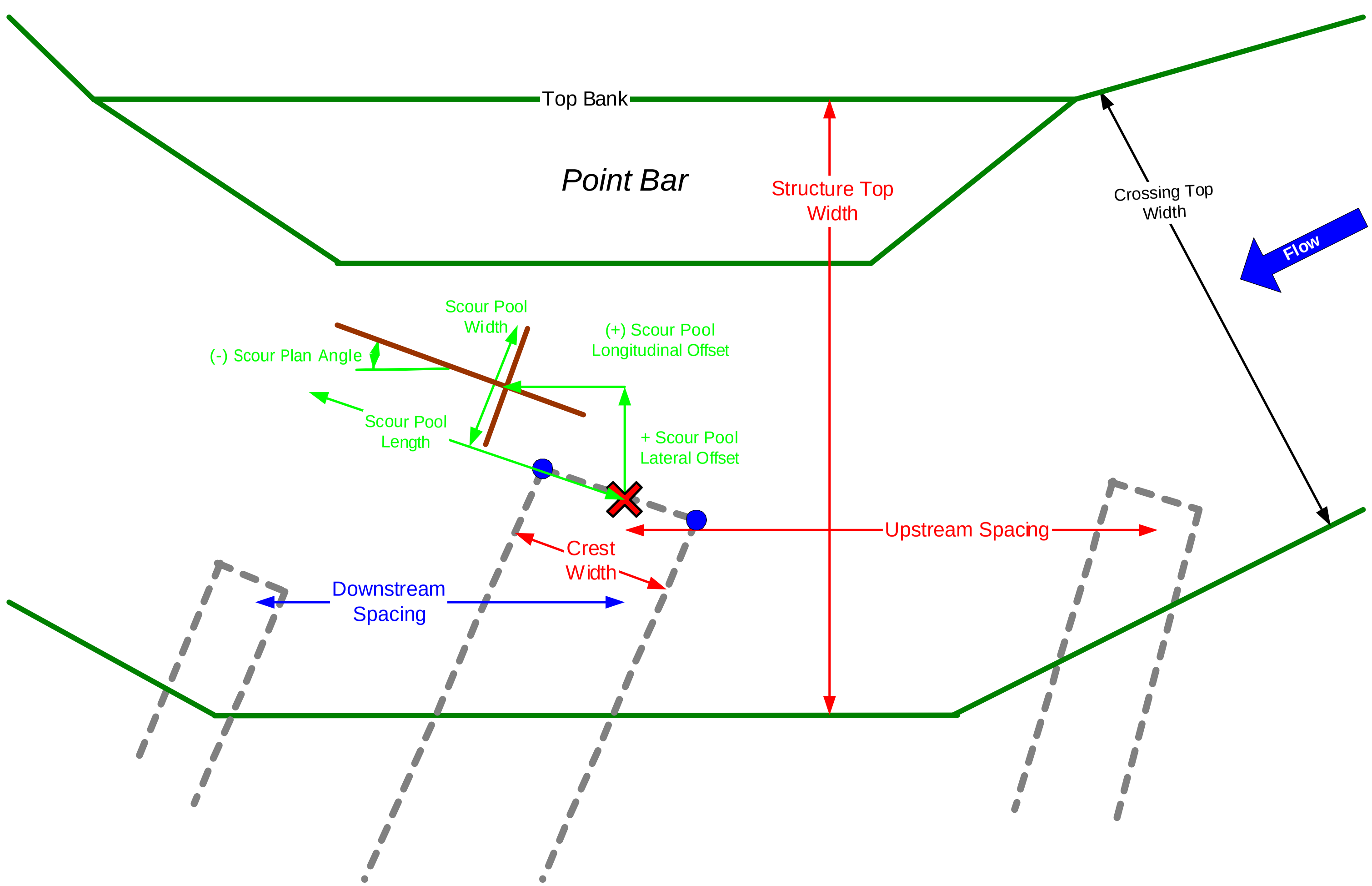


Deflector Plan



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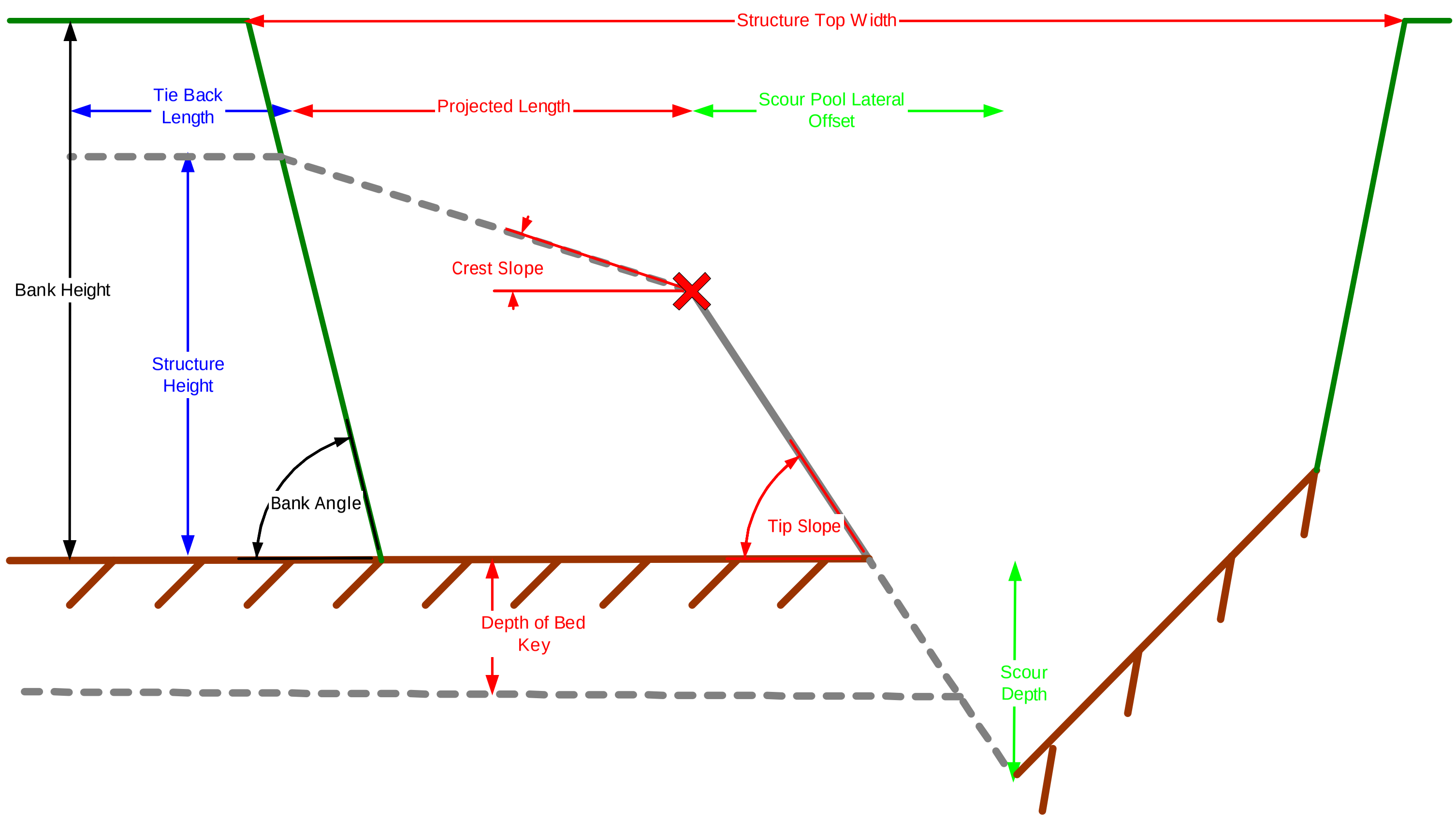

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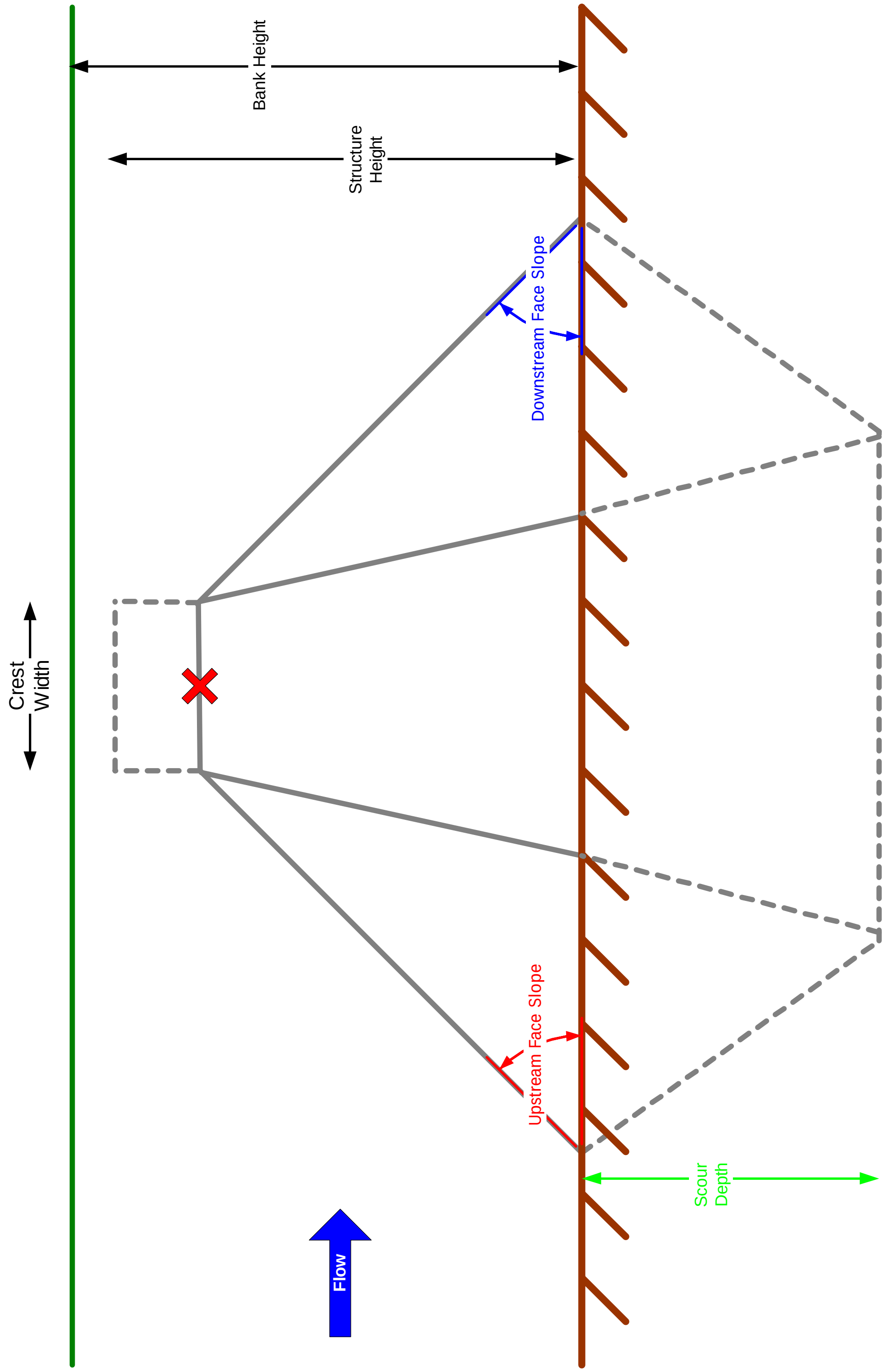
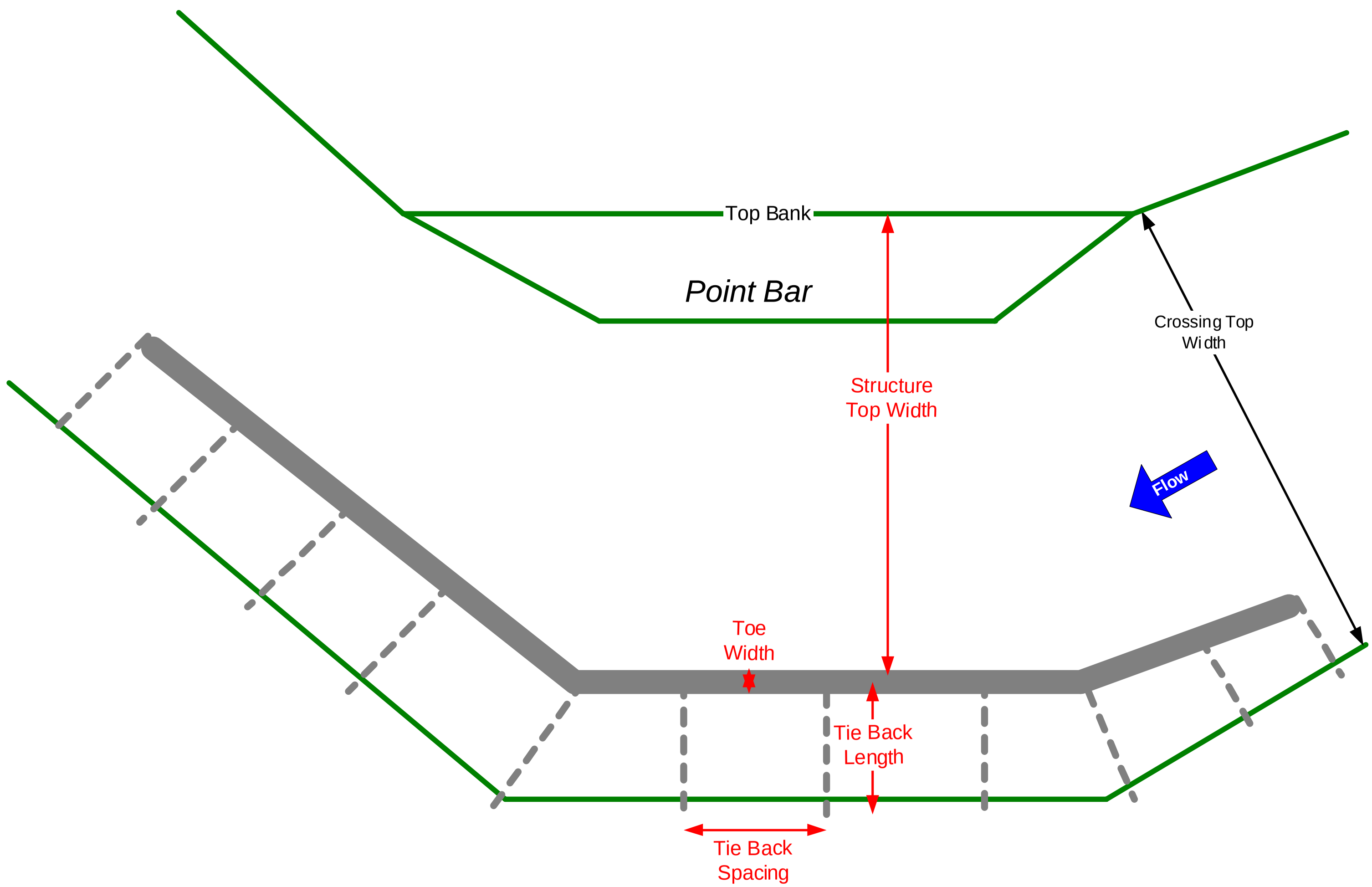


Longitudinal Feature Plan



Longitudinal Feature Profile