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Environmentally Friendly and Sustainable Stream Stability in the Vicinity of Bridges

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Environmentally Friendly and Sustainable Stream

Stability in the Vicinity of Bridges

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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This report was sponsored by the Utah Department of Transportation (UDOT) to determine if stream restoration structures could be used as scour countermeasures near state highways and bridges. Scour countermeasures that are effective in preventing erosion exist but that are not so friendly for aquatic organisms. UDOT is interested in finding a countermeasure that is both effective in preventing erosion while not harming aquatic organisms. Stream restoration structures are friendly for aquatic organisms but are prone to failure when flows exceed the design levels.

David Rosgen has developed restoration structures that are friendly for aquatic organisms and that have provided streambank protection. These structures are the J-Hook vane, Cross-Vane and W-Weir. Based research done in this report, Cross-Vanes and W-Weirs are best suited to protect bridges because they will protect both sides of a streambank.

For these restoration structures to be reliable at higher flows and shear stresses experienced at bridges, they must follow the design criteria specified in this report. One of the most important design requirements is that the structures designed by David Rosgen have an attached floodplain where the structure meets the steambank. The floodplain disperses the energy of the flow, reducing shear stress. In the vicinity of some bridges, a floodplain cannot be implemented. In such cases, culverts can be installed at the floodplain level, that pass under the bridge to help reduce shear stresses, mimicking a floodplain.

Cross-Vanes and W-Weirs can be used to protect bridges and other infrastructure. Based on modeling and comparing restoration structures to a labyrinth weir, they still have an impact on higher flows. At higher than design flows, such as experienced at bridges, the structures help to reduce shear stresses. To further investigate their use as a scour countermeasure near bridges, it is recommended that a structure be installed near a bridge following this report's design criteria. This will be determined depending on available funding.

Keywords: stream restoration, David Rosgen, bankfull, scour, bridge stability, streambank stability, Cross-Vane, W-Weir, abutments, piers

ACKNOWLEDGEMENTS

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1 INTRODUCTION

1.1 Objective

The purpose of this research project is to determine if stream restoration structures can be used as scour countermeasures and to protect streambanks near state bridges and highways. The Utah Department of Transportation (UDOT) is responsible for over 1800 bridges; more than 800 of these bridges span over water (Zundel, Fazio, 2006). UDOT is responsible for making sure that scour does not cause any of these structures to fail. Thus, any scour countermeasure that is used must be able to protect the bridge structure, including piers and abutments, at the design flow.

Many different forms of scour countermeasures exist. Some are highly effective in preventing erosion but no so environmentally friendly for aquatic organisms. Countermeasures have been developed that are good for aquatic organisms but appear to be more prone to failure. UDOT is interested in finding a scour countermeasure that is both effective in preventing scour and in not harming aquatic organisms.

Stream restoration countermeasures made from rocks are more natural than concrete structures and may provide more environmental benefits. David Rosgen has created a series of stream restoration structures that are popular with the Utah Division of Natural Resources (DNR). However, many of these structures have proven to be insufficient or unreliable during return period floods approaching design levels. One of the issues faced with stream restoration structures is that at bridges where there is no floodplain, flow is contracted, shear stress increases and contraction scour is also present. This increase in shear and presence of contraction scour has caused a number of stream restoration structures to fail (Dahle, 2008).

The effectiveness of a stream restoration structure in preventing scour under higher than design flows is also in question. A similar question was encountered for labyrinth weirs being effective under higher than design flows. Research of a labyrinth weir's effectiveness at higher flows has been performed and helps in determining whether a stream restoration structure also continues to be effective under higher flows.

1.2 Scope

The stream restoration structures considered for use in this report are rock vane structures designed by David Rosgen. This report proposes design principles for a more reliable stream restoration structure that will not fail in return period floods that are larger than normal design levels for such structures. Installation based on the proposed design criteria in this report will depend on available funding and is not discussed or studied in this report.

1.3 Report Outline

The following sections are presented:

- A literature review of different scour countermeasure practices near bridges
- Proposed design guidelines for a more reliable restoration structure
- The effectiveness of restoration structures in high flows
- Conclusions and Recommendations

2 LITERATURE REVIEW

The literature review includes a description of the scour that occurs near bridges and various scour countermeasure methods.

2.1 Scour at Bridges

Scour near bridge piers and abutments occurs due to converging flow. The converging flow on piers and abutments produces a recirculating current. The recirculating current begins to scour the streambed around the pier or abutment, exposing the footings (Figure 2-1). The exposed footings put the bridge at risk of failure (Arneson et al., 2012).

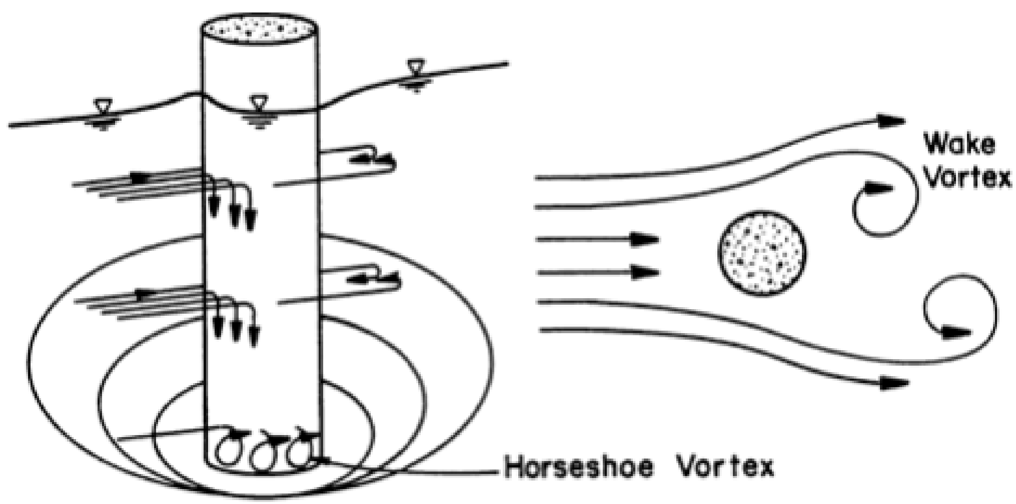

Figure 2-1: Recirculating Current at a Bridge Pier (Arneson et al., 2012).

When bridges are constructed, floodplains are often eliminated to reduce the bridge span. The eliminated floodplain decreases the effective flow area, which forces the stream's flow to be confined to the main channel as it passes under the bridge (Figure 2-2). The smaller effective flow area increases water velocity and the shear stress in the channel, which in turn increases scour; this is known as contraction scour (Arneson et al, 2012).

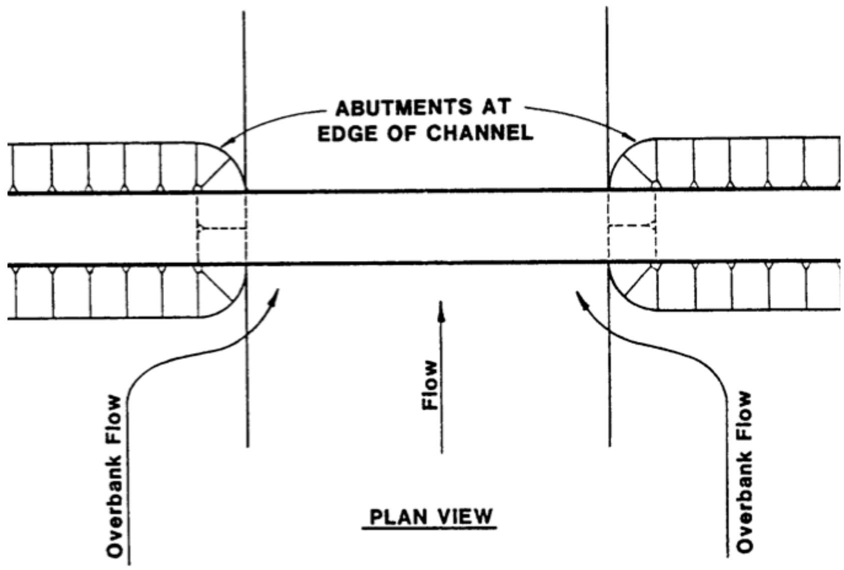

Figure 2-2: Restricted Effective Flow Area Due to Bridge Abutments (Arneson et al., 2012).

2.2 Riprap

The most common practice for protecting streambanks and infrastructure from scour is the use of riprap (Lagasse et al., 2009a). Riprap armors the area where scour is a concern with larger rocks that will resist the scouring flows; this is used along streambanks, bridge piers and bridge abutments (Figure 2-3). This is a popular method because it is cost effective and has in many cases, provided reliable protection (Grinderland, 2013).

Figure 2-3: Riprap Used to Protect a Bridge Abutment. Flow From Top to Bottom (Picture Taken by Evan Cope).

Reliable riprap is graded instead of uniform in size. The different rock sizes in a graded riprap help the riprap layer to interlock, creating a stronger and more resistant revetment. A well-graded riprap also has fewer void spaces than uniform riprap; the decreased void spaces reduce the passing of underlying finer bed material through the riprap layer (Lagasse et al., 2009a).

When using riprap, it is important to armor the bank to a depth that is deeper than the maximum scour near the toe of the riprap revetment. If scour occurs and undermines the toe of the riprap revetment, the riprap will begin to slide down the slope of the streambank into the scour hole and will eventually fail. The riprap must also have a smooth transition from native streambank to riprap revetment. An abrupt change can cause scour to occur at the transition's location and will begin to undermine the riprap (Figure 2-4), causing failure (Grinderland, 2013).

Riprap can be very effective in protecting bridges and other infrastructure from scour, but does not eliminate scour. The area that is armored with riprap is protected, but exaggerated scour can occur elsewhere where riprap armoring is not present (Lagasse et al., 2009a); the exaggerated scour can occur in the streambed near the riprap or downstream from the riprap (Figure 2-4) (Grinderland, 2013). Riprap can even increase near bank velocity and shear stress (Rosgen, 2006).

Figure 2-4: Abrupt Change from Riprap to Streambank, Causing Downstream Scour. Flow from Top to Bottom (picture taken by Evan Cope).

2.3 Restoration Structures

Stream restoration structures provide protection against streambank erosion by redirecting the flow away from the streambank and towards the center of the channel. They do not eliminate scour but create a scour hole in the center of the channel instead of eroding the streambank or bridge abutments (Johnson et al., 2001). These structures can reduce or eliminate the need of riprap as the flows are directed away from the banks (Sotiropoulos, 2013). They are very popular with natural resource agencies because they promote habitat for aquatic organisms in the scour hole created in the center of the channel. The restoration structures researched for this report are constructed from rock and are designed for submersion in shallow flows.

While natural resource agencies are in favor of restoration structures, their reliability and use to protect bridges is doubted. Bridges are designed for high flow events (100-year) while restoration structures are designed for lower flow events (not exceeding 5-year); their effectiveness and durability at higher flows differs from that at lower flows. Many of these structures have failed when high flows pass over them, creating doubt for using them as a viable scour countermeasure near bridges (Zundel, Fazio, 2006).

2.3.1 Bendway Weirs

Bendway weirs are small weirs comprised of riprap (Figure 2-5) that extend into the channel no more than one third of the channel width. They are designed to be submerged most of the time so they are typically not seen. They are built at an upstream angle of 60 to 80 degrees from the streambank tangent line (Figure 2-6). Bendway weirs realign flow and reduce near bank velocities (Lagasse et al., 2009b).

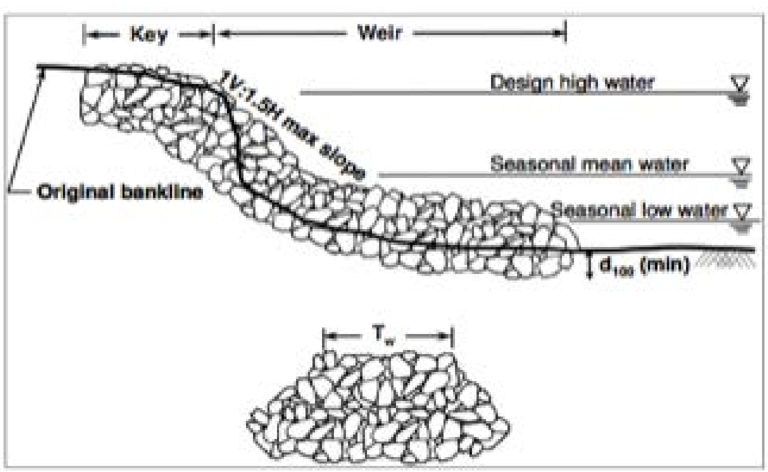

Figure 2-5: Bendway Weir Cross Section (Lagasse et al., 2009b).

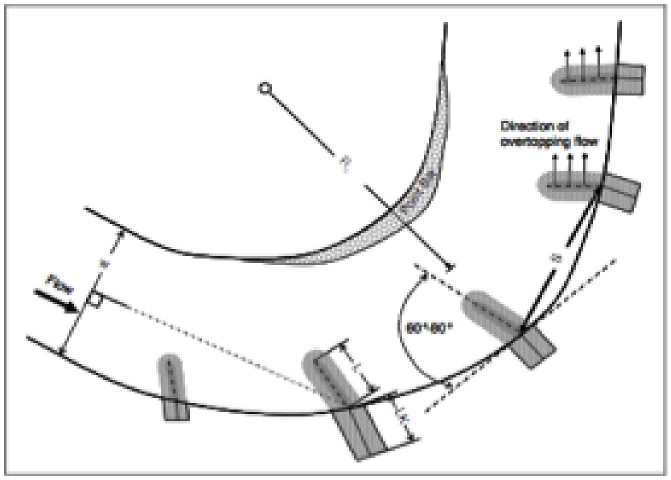

Figure 2-6: Bendway Weir Plan View (Lagasse et al., 2009b).

Bendway weirs create smaller scour holes than rock vane type structures but the scour is very high near the tip of the structure; this must be considered when designing footers (Sotiropoulos, 2013). Due to the smaller scour hole in the center of the channel created by bendway weirs, they do not create as much habitat for aquatic organisms. Bendway weirs were initially intended to scalp point bars and relocate the thalweg to the inside of the bend. It was later observed that they also induced sediment deposition near streambanks. The large angle of bendway weirs from the streambank tangent line creates a recirculating current on the upstream side of the structure where the structure meets the streambank (Rosgen, 2006).

2.3.2 Rosgen Structures

Rosgen structures, designed by David Rosgen, are modified rock vane structures. They redirect flows to the center of the channel, thus protecting the streambank and creating a large scour hole in the center of the channel. The large scour hole in center of the channel promotes fish habitat (Rogen, 2006). The restoration structures developed by David Rosgen are the J-

Hook Vane, Cross-Vane and W-Weir. All of the structures are constructed at an angle between 20 and 30 degrees from the streambank tangent line; this is to eliminate recirculating eddies behind the structure near the bank. They are also all built sloping down from the bank at a slope between two and seven percent.

The J-hook Vane is a rock vane with a hook at the end. The vane portion extends 1/4 to 1/3 across the channel width with the next third being hooked to create a scour hole in the center of the channel for fish habitat (Figure 2-7). The J-hook is used to protect the stream bank on one side of the channel by decreasing the near bank slope, velocity, and shear stress (Rosgen, 2006).

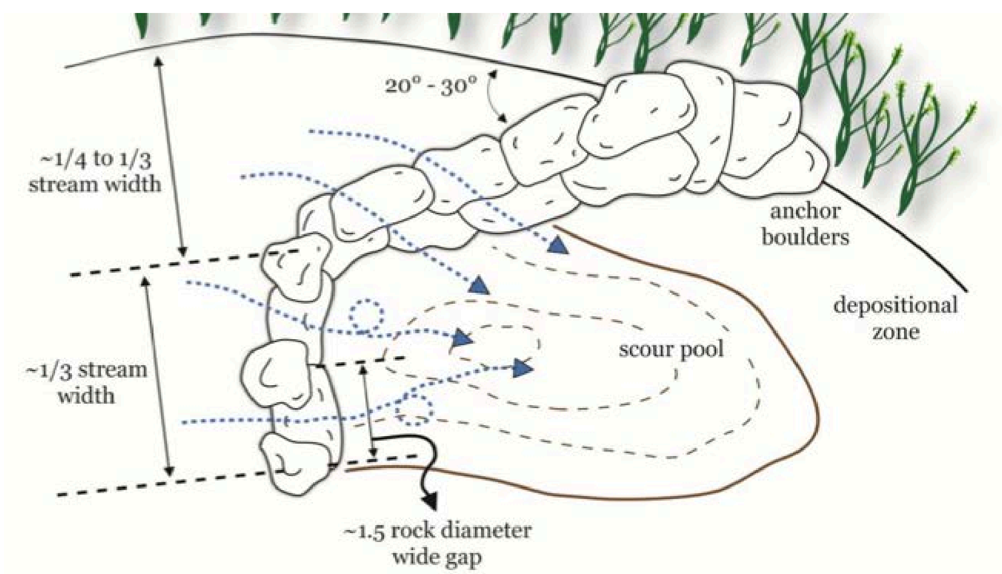

Figure 2-7: J-hook Vane (Sotiropoulos, 2013).

The Cross-Vane consists of two vanes, one on each side of a stream each extending into 1/3 of the channel width that connect together in the center third of the channel (Figure 2-8). Cross-Vanes are effective when the streambanks on each side of the stream must be protected such as in the vicinity of bridges. They establish grade control and reduce bank erosion by directing flow to the center third of the channel (Rosgen, 2006).

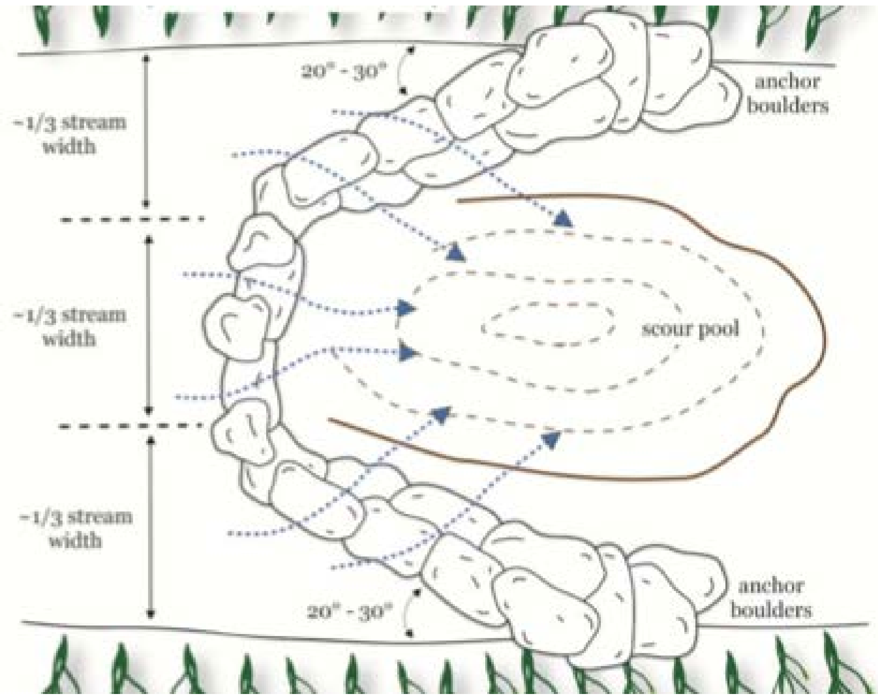

Figure 2-8: Cross-Vane (Sotiropoulos, 2013).

The W-Weir, like a Cross-Vane, uses a vane on each side of the stream. The vanes are connected in the center to create a W-shaped structure (Figure 2-9). The purpose of the W-shape is to keep the stream banks and the center portion of the streambed free from scour; two scour holes are created, one on each side of the centerline of the channel. The W-Weirs have been recommended for use when there are bridges piers in the center of the channel that need to be protected against scour in addition to the streambank on each side (Rosgen, 2006Figure 3-1).

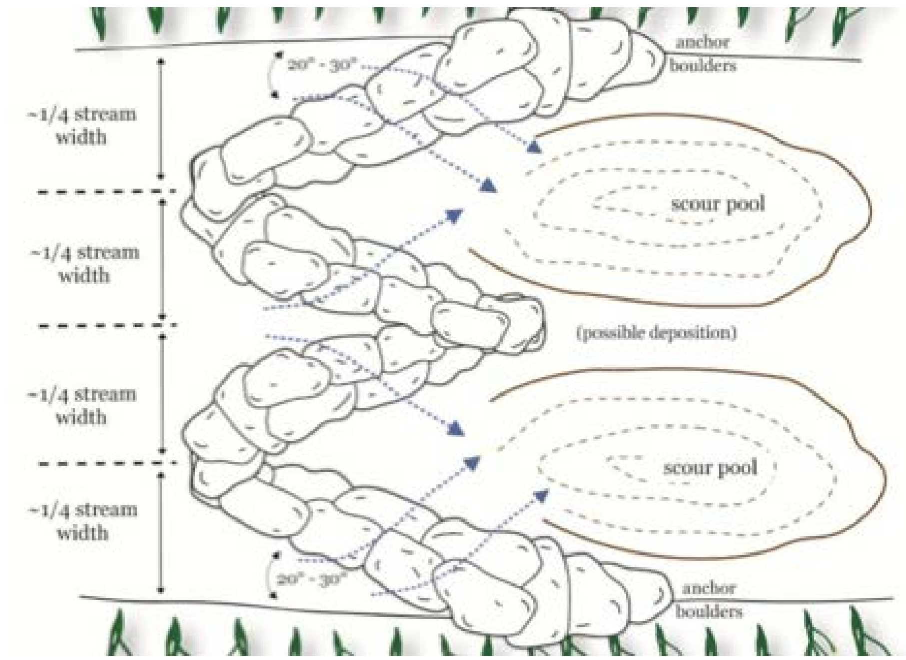

Figure 2-9: W-Weir (Sotiropoulos, 2013).

3 DESIGN GUIDELINES

Design guidelines for the Cross-Vane and W-Weir will now be discussed. Based on literature review, these two structures best satisfy the study objectives of this report to protect bridge piers and abutments while providing greater habitat for aquatic organisms. In particular, their design to prevent failure at larger design flows, such as the 100-year flood, will be emphasized.

3.1 Determine Bankfull

The restoration structures considered in this report are designed and constructed to bankfull height. Bankfull conditions were originally described as the elevation at the top of stream banks where flooding begins. The term bankfull is primarily used for rivers that have an attached floodplain (Rosgen, 1996) but can, with care, be identified for incised channels where the original floodplain is more commonly called a terrace. Restoration structures are built to bankfull height, when the water depth is greater than the structure's height flow, shear stress and energy dissipation occur on the floodplain. At higher flows, this reduces the shear stress in the main channel preventing the failure of the structure.

Depending on the source, preferred bankfull ranges anywhere from 1.2 to 5 year flows (Lave, 2008; Zundel, 2006). The determined bankfull flow corresponds to the discharge at which channel maintenance is most effective at moving sediment, forming and removing bars (Dunne, Leopold, 1978). Identifying a preferred method for identifying bankfull discharge is beyond the scope of this project. Whatever method is used, however, a submerged structure is desired to keep a more natural appearance and to keep from damming the stream upstream from the structure.

For the restoration structures of this report to function properly, a floodplain must be present at the determined bankfull height. David Rosgen explained in a conference call that a restoration structure that is constructed without a floodplain connected to the top of the structure is susceptible to greater flow convergence and shear stress where the structure meets the streambank. The higher converging flow and shear stress can lead to eventual failure of the structure due to scour. A connected floodplain at the top of the structure where the structure meets the streambank allows the energy of the water to be dissipated over the floodplain, reducing the flow convergence and shear.

If no floodplain is present at the determined bankfull height, a floodplain must be created (Rosgen, 2006). Excavating a bench at the bankfull height will create a floodplain (Figure 3-1).

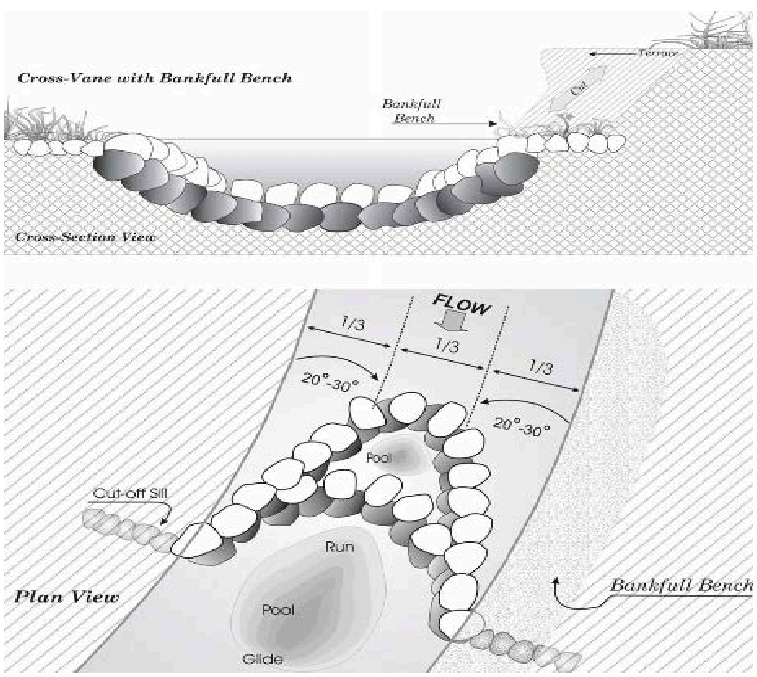

Figure 3-1: Excavated Bankfull Bench for a Restoration Structure (Rosgen, 2006).

Proposed guidelines for sizing an excavated bankfull bench have been given by David Rosgen (Table 3-1).

Table 3-1: Guidelines For Sizing a Bankfull Bench.

Bankfull Channel Width (ft.)	**Minimum Bankfull Bench Width (% of Channel Width)**
< 20 ft.	75%
20 – 50 ft.	50%
> 50 ft.	25%

In some cases such as near a bridge, a floodplain cannot be implemented. Bridges are constructed with shorter spans to keep construction costs down, frequently eliminating floodplains. A proposed solution for scenarios where floodplains cannot be implemented is the use of culverts along the streambanks at the bankfull elevation (Figure 3-2). Theses culverts mimic a floodplain.

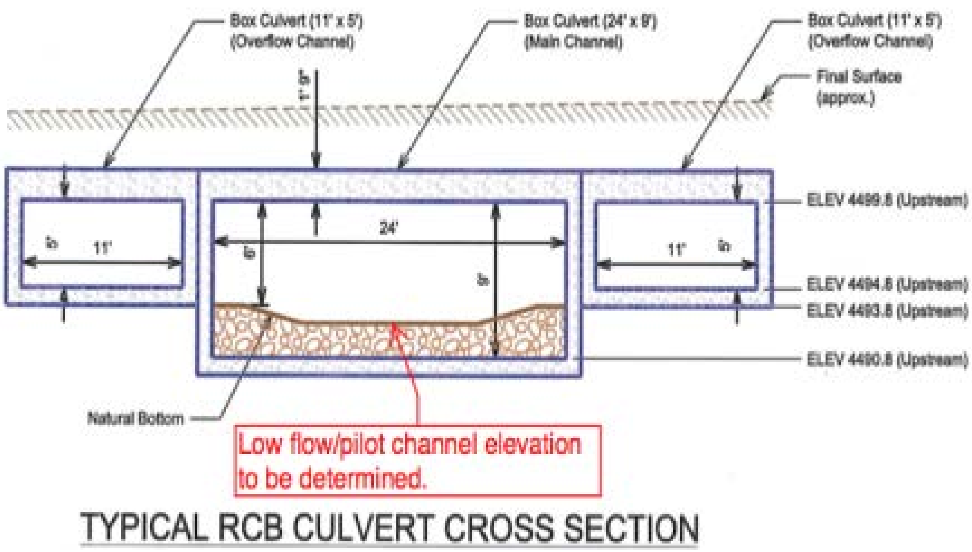

Figure 3-2: Cross-Section Drawing of Overflow Culverts (From Hobble Creek and I-15 Plan Set).

3.2 Rock Sizing

Unlike riprap or bendway weirs, Rosgen structures do not have interlocking rock; they require larger rock than riprap or bendway wiers (Sotiropoulos, 2013). The riprap equations that yield the largest sizes are found in Hydraulic Engineering Circular 23 (HEC-23) Volume 2. These equations are specifically designed to size riprap for bridge piers and abutments and yield larger rock sizes compared to other riprap equations due to the greater shear stresses at bridges. HEC-23 also recommends using a 20% factor of safety when using these riprap equations for rock structures such as bendway weirs. The formulas give the D50 diameter, which is then doubled to yield the D100 diameter (Lagasse et al., 2009b).

David Rosgen used empirical data to relate shear stress to rock size and then created a best-fit equation for rock size (Figure 3-3).

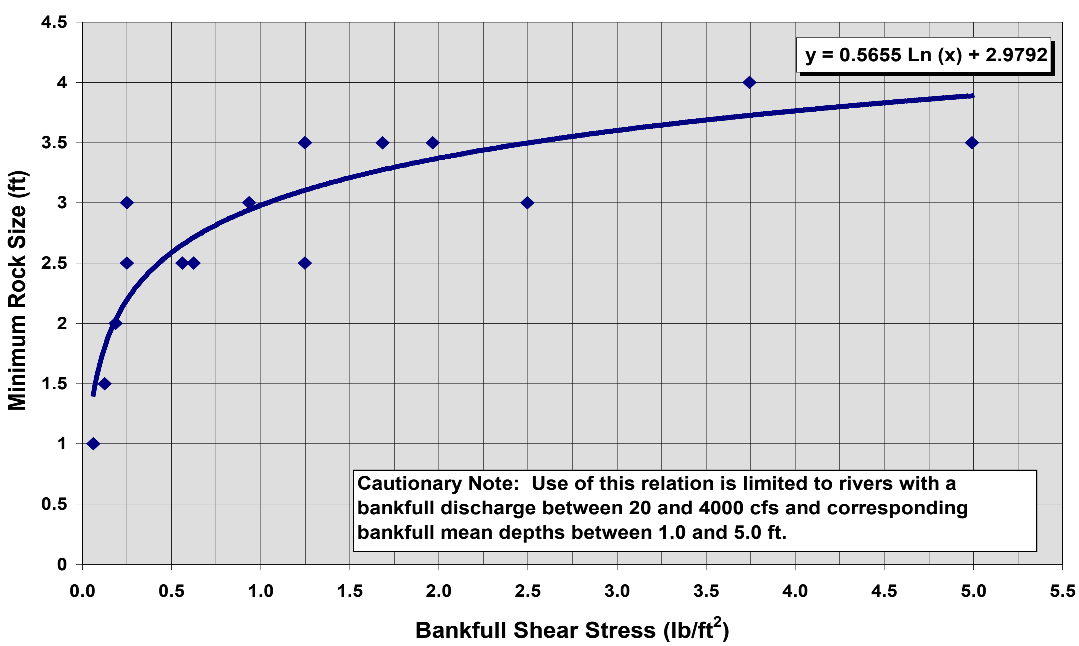

Figure 3-3: Rock Sizing Based off of Shear Stress (Chart Provided by David Rosgen).

To demonstrate that the Rosgen structures require larger rock than the HEC-23 equations, data were analyzed from the Division of Natural Resources (DNR). Cross-sections, slopes and Manning's coefficients were provided for the Spanish Fork River near Thistle, Utah. The provided data were used for sizing rock with HEC-23 and Rosgen's equations. The results for all equations were plotted (Figure 3-4) and show clearly that Rosgen structures require larger rock.

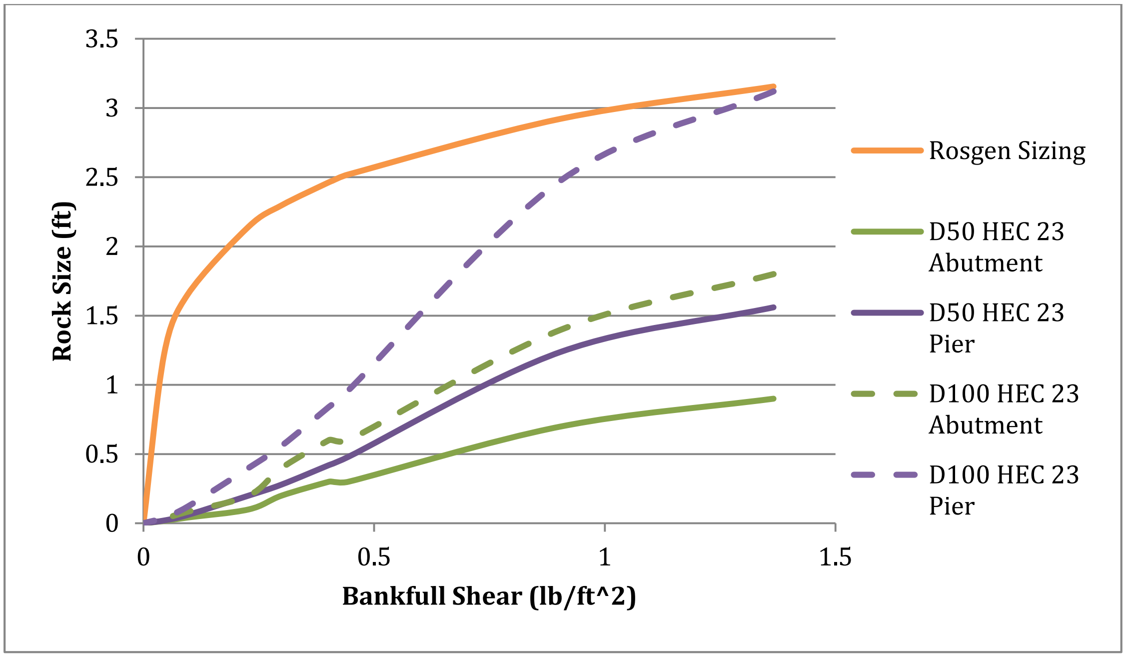

Figure 3-4: Rock Sizing Equations vs. Shear Stress.

To implement Rosgen's structures near bridges, rock sizing should be done with the shear stress calculated from a 100-year flow. Sizing rock for a 100-year flow will allow restoration structures to be built to withstand the higher flows without failure; this enables restoration structures to be more reliable because the rocks can resist the shear stresses present (Johnson et al., 2002).

3.3 Angle of Structure from Bank

If the angle of a stream restoration structure from the tangent line of the streambank is too large, recirculating eddies occur where flow converges with a restoration structure and the steambank (Rosgen, 2006). The recirculating eddies can actually cause greater bank erosion and eventual failure of the structure (Figure 3-5). The angle from the tangent line of the streambank must be small to eliminate the recirculating eddies. The optimum angle range for Rosgen structures to prevent the recirculating eddies is between 20 and 30 degrees from the streambank tangent line (Figure 3-6) (Johnson et al., 2001).

David Rosgen mentioned in a conference call that a 20-degree angle is recommended for the greatest length of bank protection. The smaller angle allows for the construction of a longer structure because it leaves the streambank and enters the stream more gradually. The longer structure protects a greater amount of streambank (Figure 3-7) (Rosgen, 2006). The 20-degree angle also minimizes scour at the toe of the structure, providing greater protection to the structure and its footers (Sotiropoulos, 2013).

Figure 3-5: Large Vane Angle that Created a Recirculating Eddy and has Actually Increased Streambank Erosion. Flow from Right to Left. (Picture taken by Evan Cope).

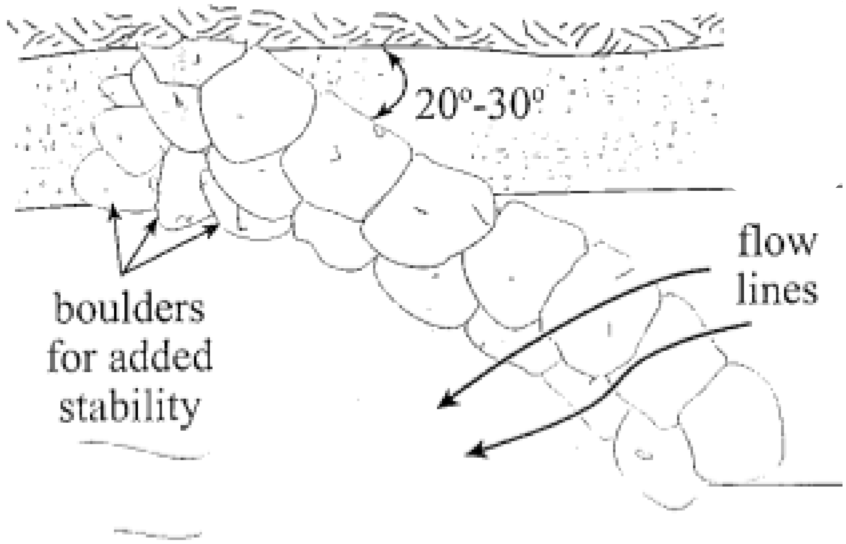

Figure 3-6: Optimum Angle Range from Streambank Tangent Line for Vanes (Johnson et al., 2001).

Figure 3-7: Tight Vane Angle Protected and Stabilized the Streambank. Flow from Right to Left (Picture Taken by Evan Cope).

3.4 **Vane Slope**

To best redirect flow to the center of the channel, the vane must slope upstream. The adverse slope help force the flow away from streambanks. The vane slope should be between 2 and 7 percent (Figure 3-8, Rosgen, 2006). If slopes are too steep, the vane can actually cause greater streambank erosion (Figure 3-9).

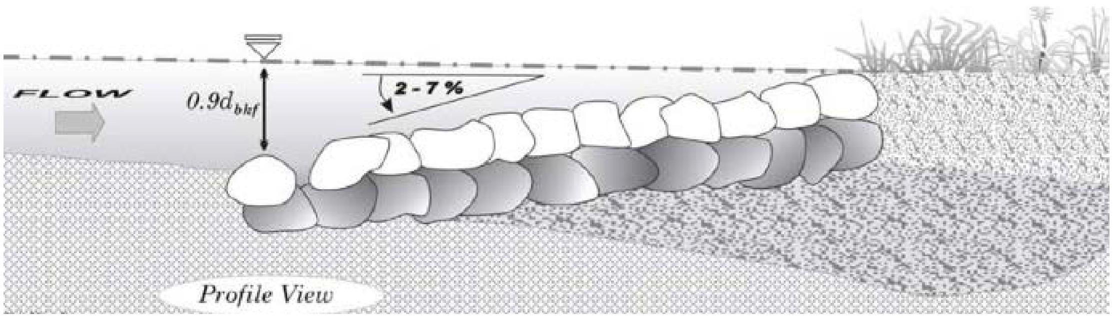

Figure 3-8: Vane Slope (Rosgen, 2006).

Figure 3-9: Steep Vane Slope has Increased Steambank Erosion. Flow from Right to Left. (Picture Taken by Evan Cope)

3.5 **Footers**

Footers must be set deeper than the maximum scour hole depth to prevent structure failure. One method proposed for cross-vanes and W-weirs is to have footers that are two to three times deeper than the maximum scour hole present in a structure-free channel (Sotiropoulos, 2013). Rosgen recommends having the footers be three times deeper than the structures protrusion height above the streambed for gravel streambeds; for sand streambeds, the depth should be doubled to six times (Figure 3-10, Rosgen, 2006).

In addition to being placed deep, the footer must be designed and installed correctly. The footers must be angled back to the flow so that the above rocks can lock into the footer below, giving the structure greater strength. The footers are placed farther forward than the rocks placed above so that a hydraulic jump is not created and so scour is reduced. Flat rocks are better so that there is more contact surface between the footers and protruding rocks. Footer rocks should be larger or at least equal in size to the protruding rocks (Figure 3-10). Following these guidelines protect the footers from scour and from eventual failure of the structure (Rosgen, 2006).

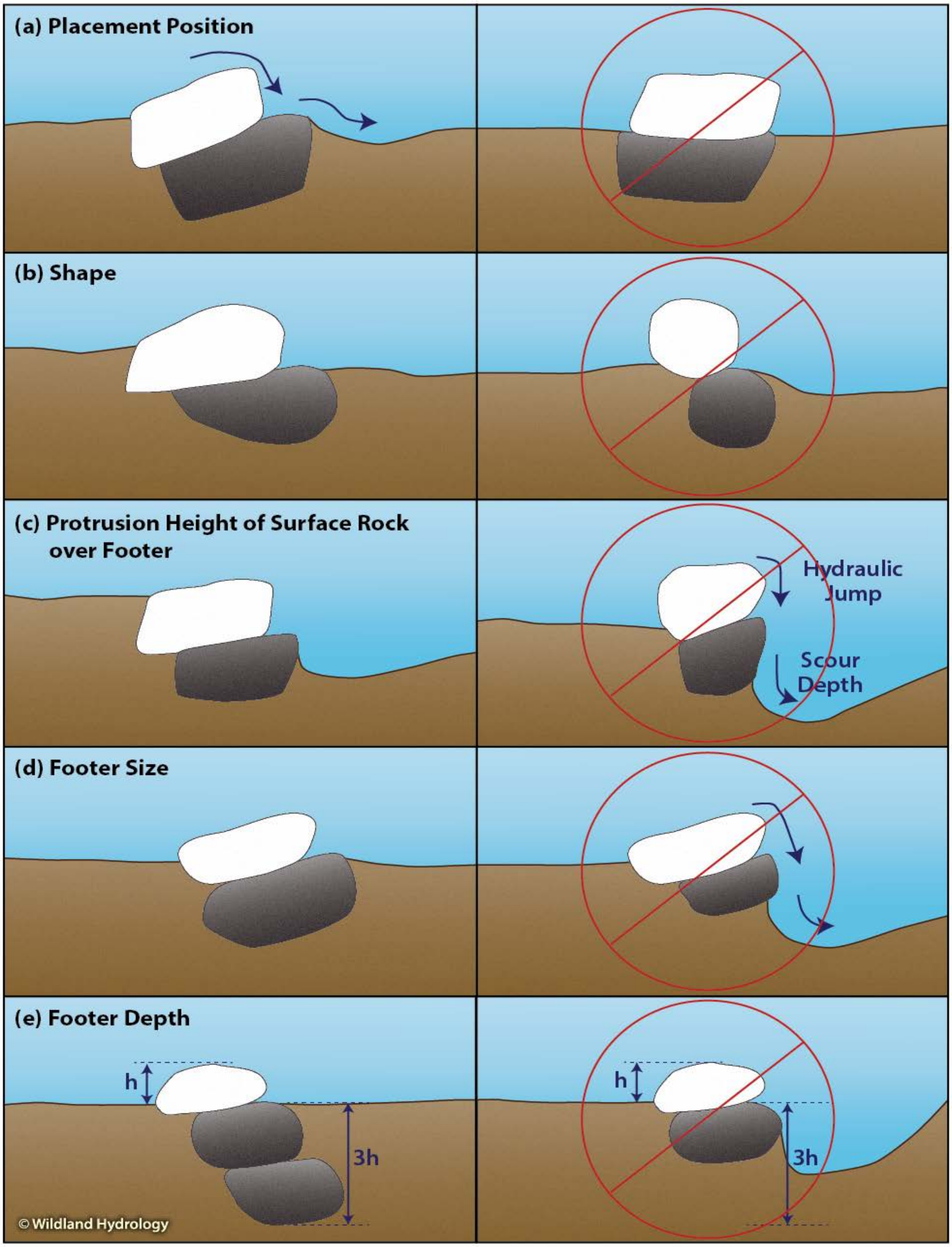

Figure 3-10: Footer Design and Installation. Flow Left to Right (Image Provided by David Rosgen).

3.6 Rock Step

To prevent the downstream scour hole from getting too deep for Cross-Vanes and W-Weirs, a rock step can be installed within the vane arms (Figure 3-11 and Figure 3-12). This creates a series of structures; that reduces the size of the scour hole (Sotiropoulos, 2013). This provides additional protection so that the structure's footers will not be undermined and also to contain lateral scour (Rosgen, 2006).

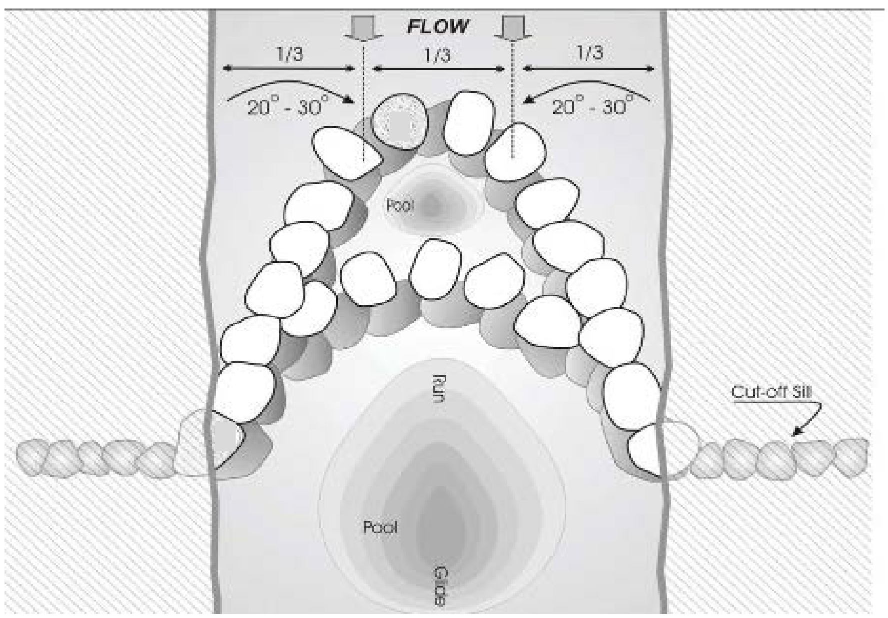

Figure 3-11: Plan View of Rock Step (Rosgen, 2006).

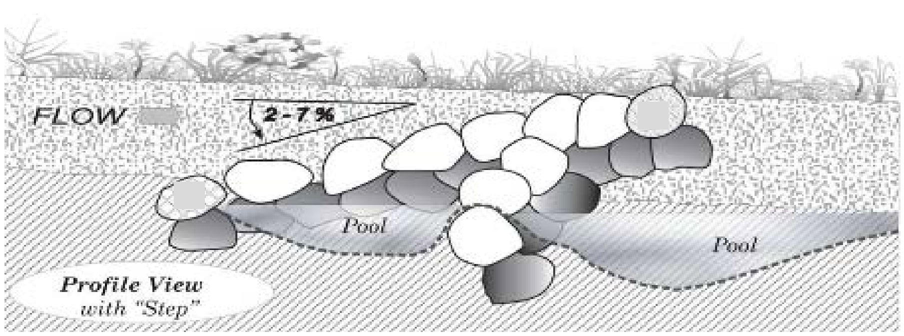

Figure 3-12: Profile View of Rock Step (Rosgen, 2006).

3.7 Upstream Distance from Infrastructure

Written literature recommends placing restoration structures two channel widths upstream from any bridge or infrastructure that is to be protected (Johnson et al., 2001; Sotiropoulos, 2013) measured from the infrastructure to the crest of the Cross-Vane or W-Weir (Figure 3-13). The maximum scour zone exists within one channel width downstream of a restoration structure, so they shouldn't be placed any closer than one channel width upstream from infrastructure (Sotiropoulos, 2013).

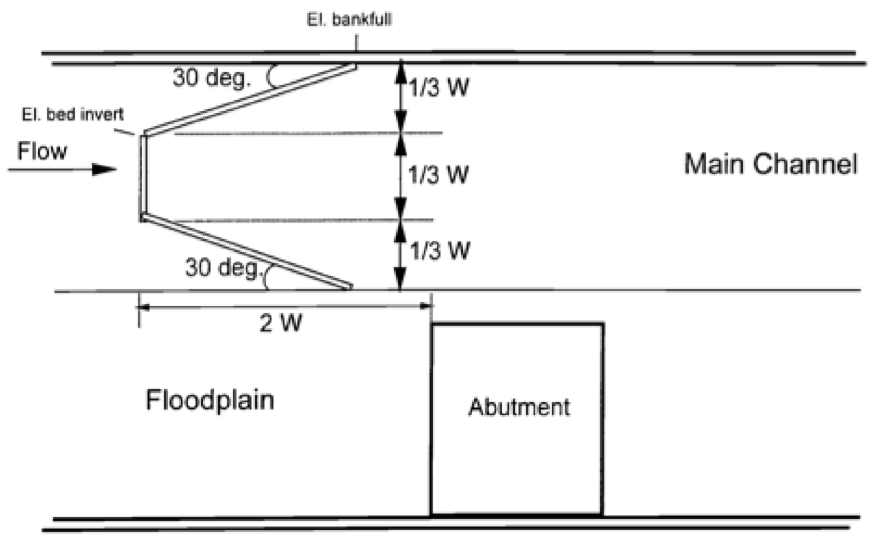

Figure 3-13: Cross-Vane Placed 2 Channel Widths Upstream of Bridge Abutment (Johnson et al., 2002).

In a conference call with David Rosgen, he explained that he disagrees with the claim of placing restoration structures two channel widths upstream of infrastructure. The restoration structures have the greatest impact on the flow immediately downstream and so they need to be placed closer to the infrastructure being protected. Rosgen says that the high scour area is contained inside of the arc of a Cross-Vane or W-Weir, which is within one channel width from the structure's crest.

To investigate which is the more accurate claim, a two-dimensional (2-D) model was created using Surface Water Modeling Software (SMS) and Sedimentation and River Hydraulics- 2D (SRH-2D). SMS was used to prepare a 2-D mesh for SRH-2D. The stream created was a straight trapezoid channel with an attached floodplain. A Cross-Vane was placed inside the stream to see how far downstream the impacts from the Cross-Vane cease (Figure 3-14).

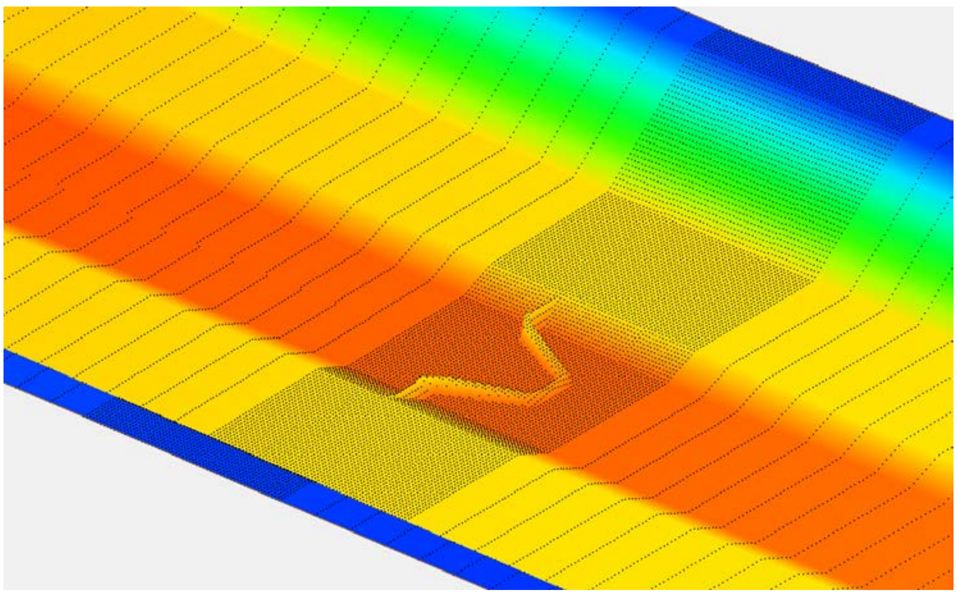

Figure 3-14: 2-D Mesh of River with Cross-Vane (Created with SMS).

To determine how far downstream the structure has an impact on streambank erosion, the calculated shear stress along the streambank was examined for various flows with a bankfull flow of 400 cubic feet per second (cfs). Streambank shear was plotted for different channel widths downstream from the Cross-Vane (Figure 3-15).

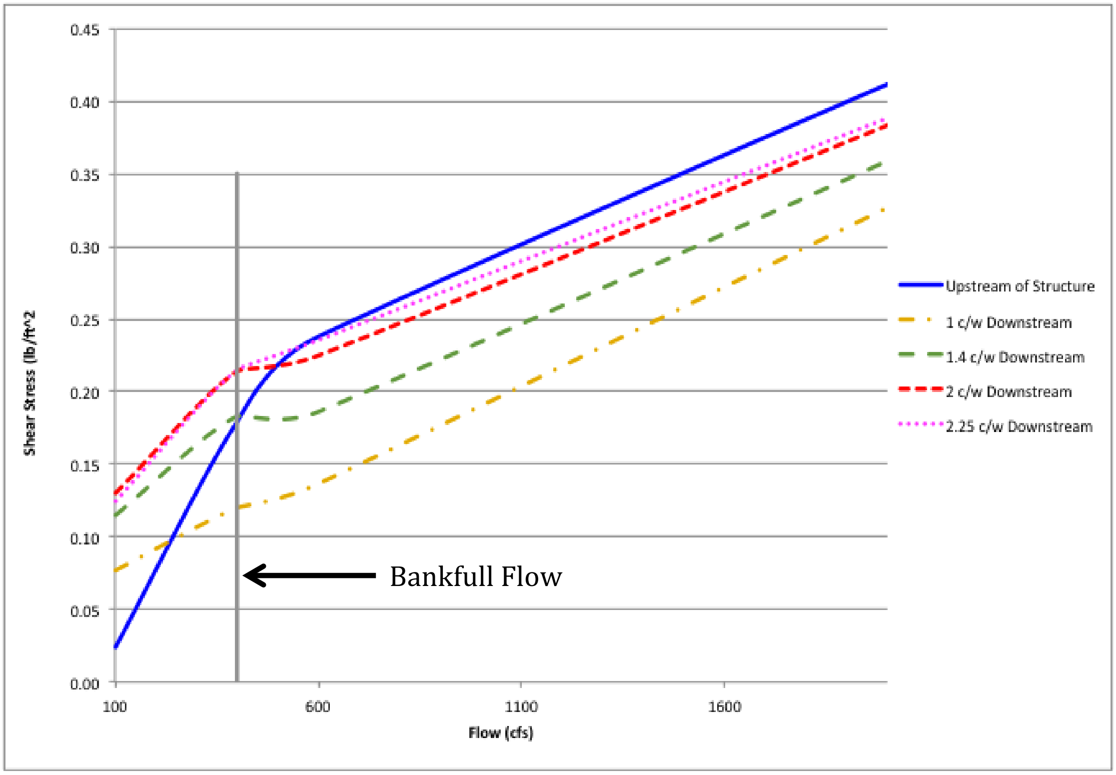

Figure 3-15: Bank Shear vs. Flow for Different Channel Widths Away from Cross-vane.

For flows near the bankfull flow, the bank shear stress would return to the same shear that was upstream of the structure once the flow was two channel widths or greater downstream from the crest of the Cross-Vane. For larger than bankfull flows, the shear is slightly less than upstream even more than 2 channel widths downstream. The shear stress at 1 and 1.5 channel widths downstream from the cross-vane is significantly lower than it is upstream of the cross-vane at bankfull and greater flows.

Based on this model, it is best to place a restoration structure between 1 and 1.5 channel widths upstream of the infrastructure to be protected. At these locations the streambank shear is still lower than without a Cross-Vane.

4 EFFECTIVENESS AT LARGER FLOWS

Restoration structures can be built to withstand larger flows without failure, but their impact on larger flows is questioned. As restoration structures become a smaller portion of the total flow depth, their impact diminishes (Sotiropoulos, 2013). Arguments have been made claiming that restoration structures are still effective at higher flows while others claim the contrary. An analysis of a restoration structure's impact on deeper flows will be considered in the sections that follow.

4.1 Modeling vs. Field Observations

It is important to understand the limits of modeling because models require assumptions. The assumptions that are made must be clearly understood because poor assumptions will result in poor results (Lagasse et al., 2012). Due to the limitations of models, they can have different results than what is actually observed in the field. This creates a difference of opinions among people, including for stream restoration structures.

A 2-D model performed at Brigham Young University by Ben Dahle demonstrated that at higher flows, restoration structures become ineffective in their purpose to protect streambanks. The 2-D model was performed by using survey and flow data for Thistle Creek in Thistle, UT. The surveyed data was loaded into SMS to create a mesh and prepare data for a 2-D model in Finite Element Surface Water Modeling System (FESWMS). The model was calibrated using known flow parameters for the area to create the most accurate model possible (Dahle, 2008).

The flow direction and velocity were checked at different locations along the structure in Thistle Creek and then compared to a location upstream of the structure. The flow direction and velocity at the different locations along the structure were compared to the upstream location to analyze the difference created by the structure. The difference for each location along the structure was plotted against depth to show the change of direction and velocity at different flow depths (Figure 4-1 and Figure 4-2).

The model showed that the Cross-Vane placed on Thistle Creek was effective in changing the flow direction and water velocity if the flow was less than four feet deep. Once the flow depth exceeded four feet, the change in direction and velocity was very small. This stream has a base flow of less than one foot but a greater depth of flow can be rapidly reached at Thistle Creek, meaning that the cross-vane was not an effective scour countermeasure (Dahle, 2008).

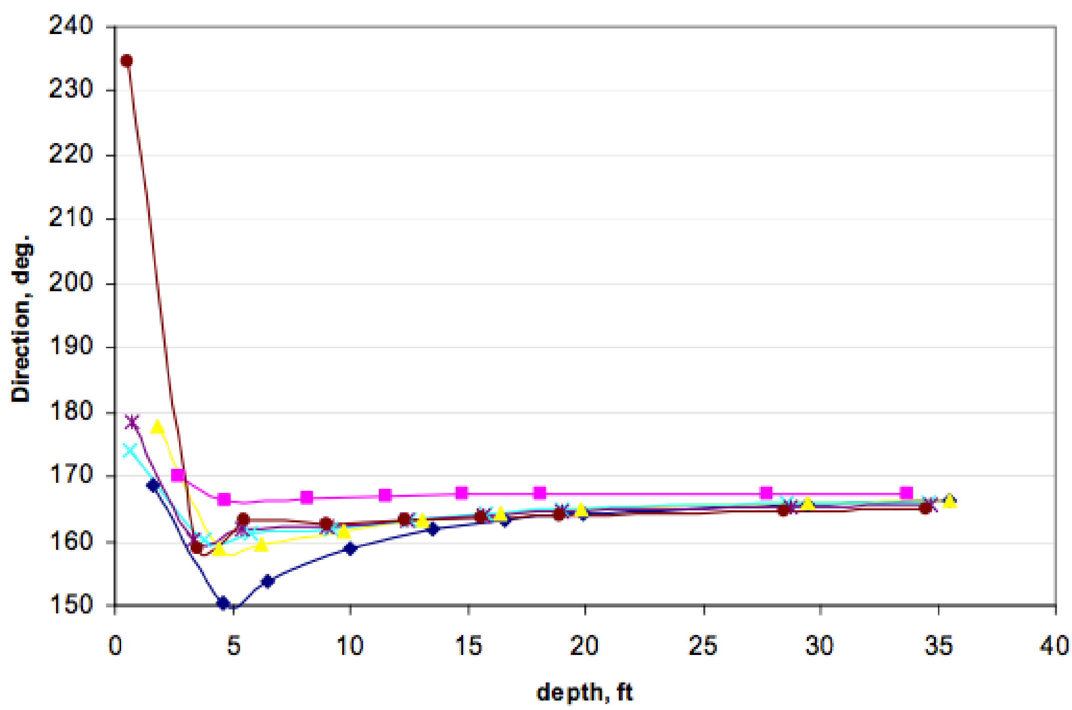

Figure 4-1: Cross-Vane Effective Depth from Change in Flow Direction (Dahle, 2008).

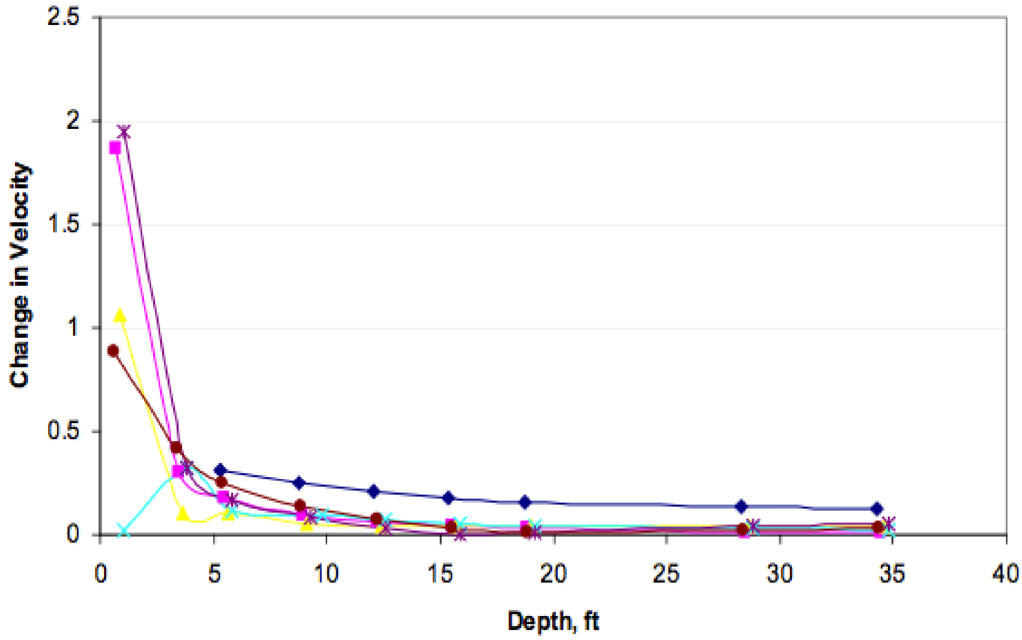

Figure 4-2: Cross-Vane Effective Depth from Change in Velocity Magnitude (Dahle, 2008).

The model showed that the Cross-Vane placed on Thistle Creek was effective in changing the flow direction and water velocity if the flow was less than four feet deep. Once the flow depth exceeded four feet, the change in direction and velocity was very small. This stream has a base flow of less than one foot but a greater depth of flow can be rapidly reached at Thistle Creek, meaning that the cross-vane was not an effective scour countermeasure (Dahle, 2008).

Actual field observations have shown that even when the flow is much higher than bankfull, restoration structures still have an effect on the deep flow. In a conference call David Rosgen stated that 2-D models do not very accurately reflect the impact on the water surface above bankfull; he has observed in the field that his structures continue to have an effect on the water surface above bankfull. He mentioned that a 2-D model is too limited to capture and simulate what is actually happening on the water surface. Two dimensional models have shown that when a restoration structure is exposed to deep flows, the water surface is not impacted.

Photographs of Cross-Vanes on the Batavia River in New York at base flow (Figure 4-3) and later above bankfull (Figure 4-4) visually show that even under high flow conditions, the water surface was impacted by the Cross-Vanes.

Figure 4-3: Batavia at Base Flow with Floodplain. Flow from Top to Bottom (Picture Provided by David Rosgen).

Figure 4-4: Cross-Vane Effecting Higher than Bankfull Flow on Batavia River. Flow from Top to Bottom (Picture Provided by David Rosgen).

4.2 **2-D Model**

The 2-D model used for analysis in Section 3.7 was used to analyze a Cross-Vane's impact on flow as the water depth increases. This was done to see if a 2-D model could support what has been observed visually in the field. Flow values less than, equal to and greater than bankfull were used; bankfull for the model was 2.5 feet. As expected, when depth increased, the redirection of flow decreased when observing the flow vector arrows. Flows below bankfull showed significant redirection when passing over the cross-vane (Figure 4-5). Bankfull flow was also redirected as water passed over the cross-vane (Figure 4-6), but when the flow was more than double the bankfull height, the flow was not very effectively redirected (Figure 4-7).

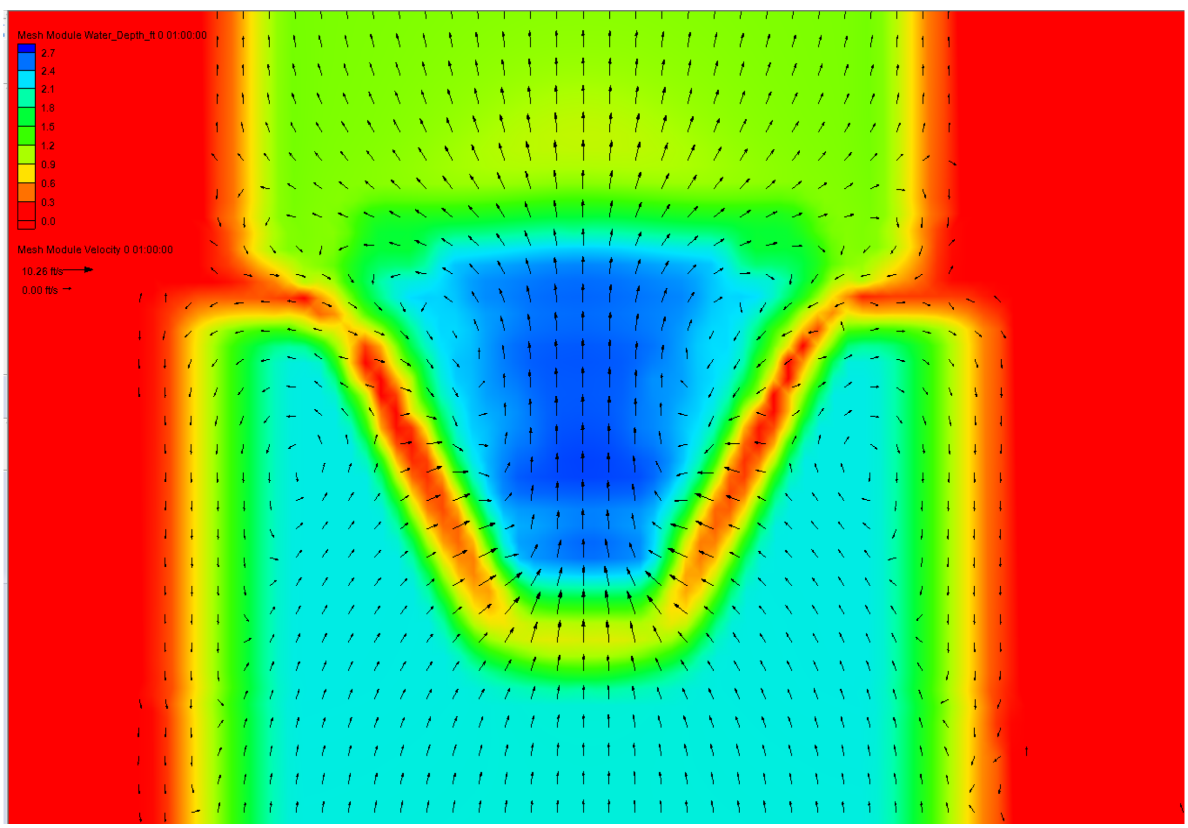

Figure 4-5: Flow Vectors Below Bankfull. Flow Depth = 1 Foot (Image from SMS).

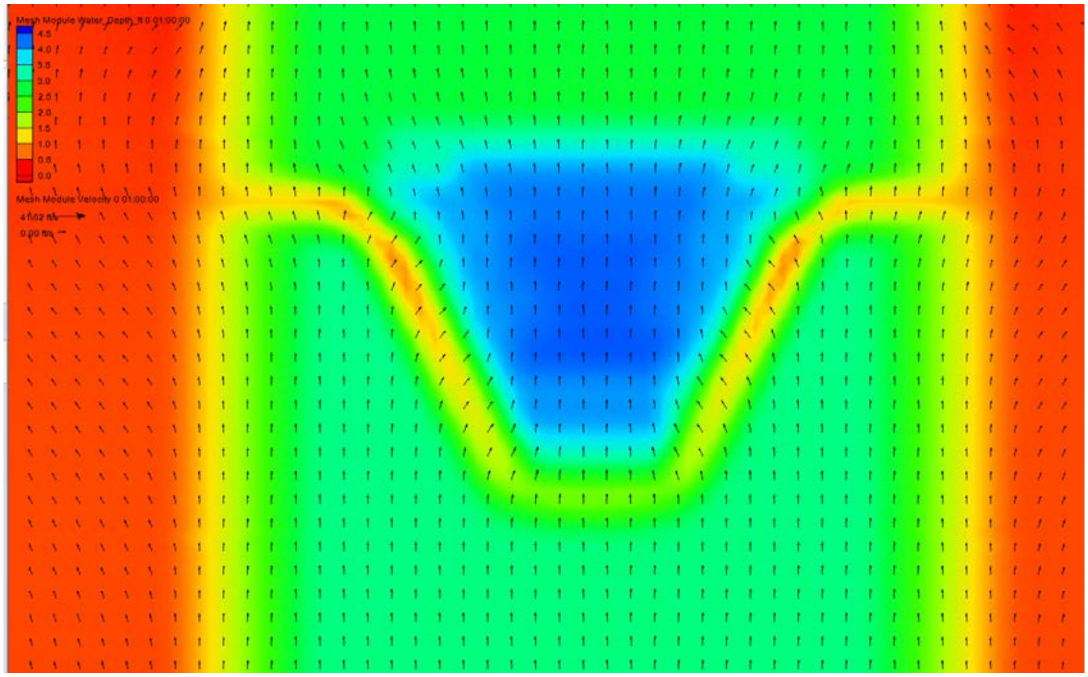

Figure 4-6: Flow Vectors At Bankfull. Flow Depth = 2.5 Feet (Image from SMS).

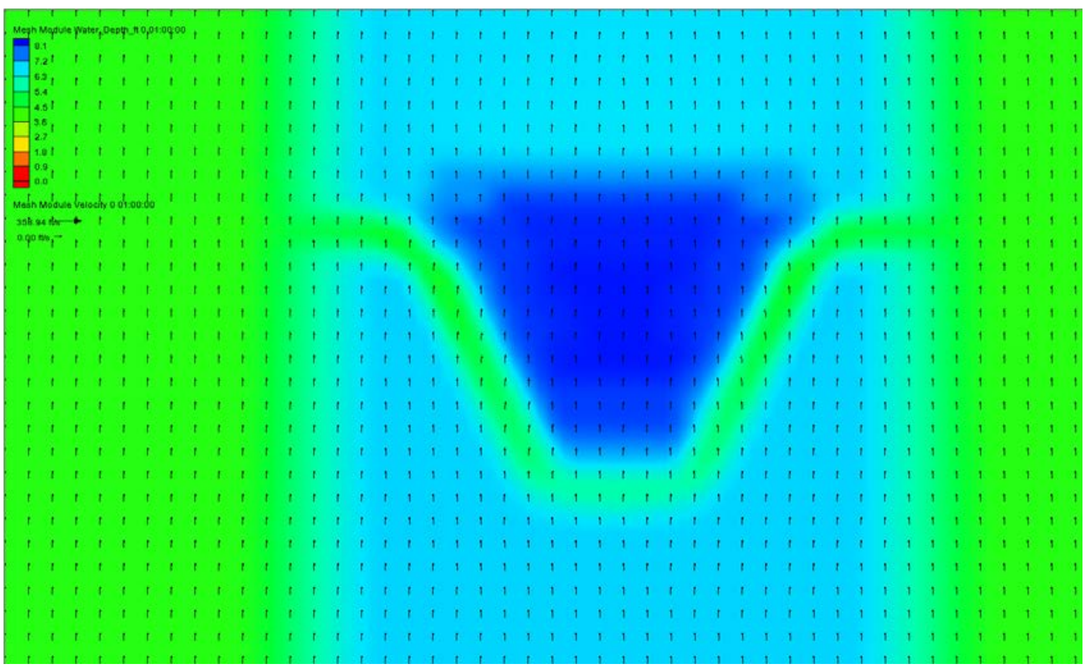

Figure 4-7: Flow Vectors Above Bankfull. Flow Depth = 6.5 Feet (Image from SMS).

According to the 2-D model created, higher flows may not be redirected by a restoration structure. In addition to the flow direction, the water surface elevation was analyzed for flow values less than, equal to and greater than bankfull flow. The model showed that water surface elevation was impacted as the water passed over the Cross-Vane for flows less than, equal to and greater than bankfull flow (Figure 4-8, Figure 4-9 and Figure 4-10). This shows that restoration structures do have some impact on water surface even if flows aren't redirected.

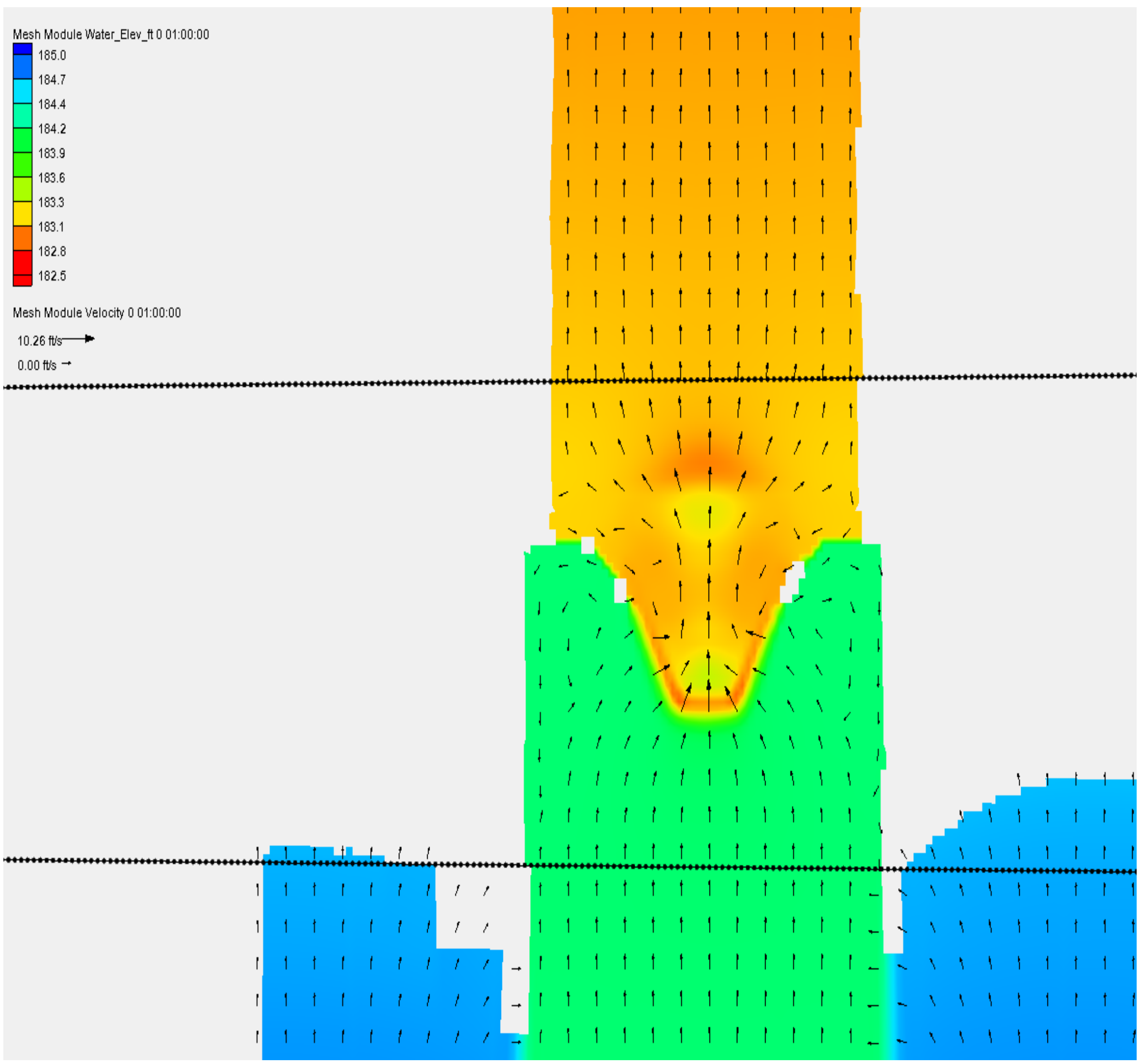

Figure 4-8: Water Surface Elevations Below Bankfull Flow. Flow Depth = 1 Foot (Image from SMS).

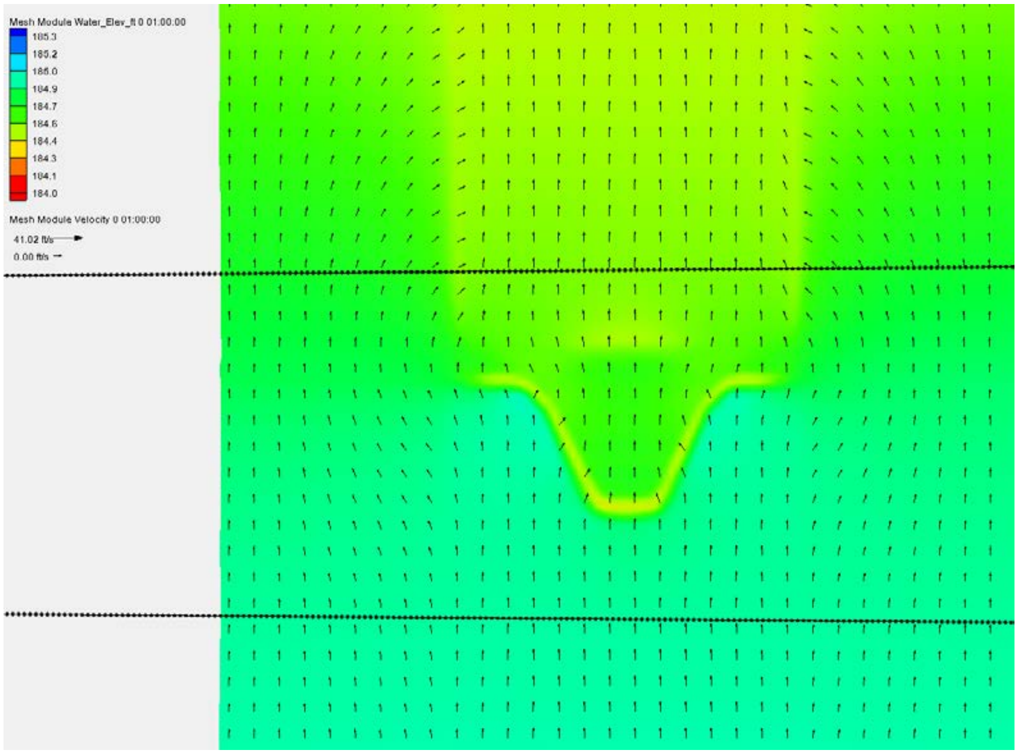

Figure 4-9: Water Surface Elevations for Bankfull Flow. Flow Depth = 2.5 Feet (Image from SMS).

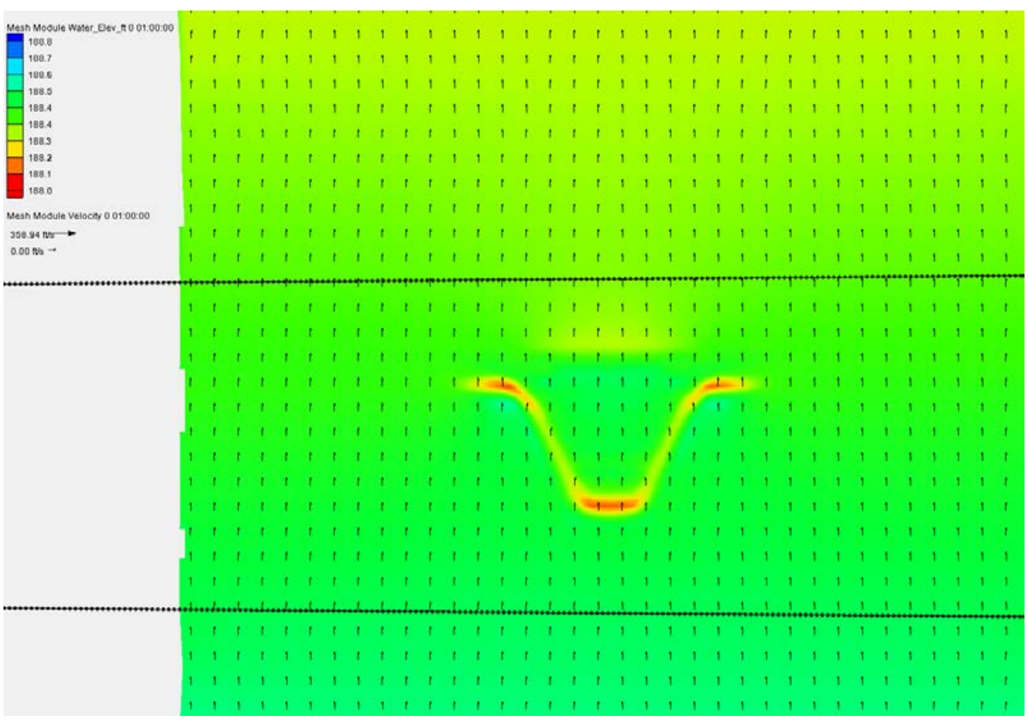

Figure 4-10: Water Surface Elevations for Above Bankfull Flow. Flow Depth = 6.5 Feet (Image from SMS).

In Section 3.7, bank shear stress in the model was analyzed under different flows at different locations downstream from a Cross-Vane. The same shear stress data were used to plot bank shear vs. flow depth. The flow depths analyzed began at the bankfull flow of 2.5 feet and go up to 10 feet deep, 4 times the bankfull flow depth (Figure 4-11). Based on the results from this model, even at higher flows, the cross-vane still helped to decrease the streambank shear stress. The decrease in shear stress at 1 channel width downstream of the Cross-Vane was greater near bankfull flows and less at high flows, but the shear stress is still decreased overall for all flows. The shear stress analysis in the model helps support field observations that restoration structures do have an impact on higher flows.

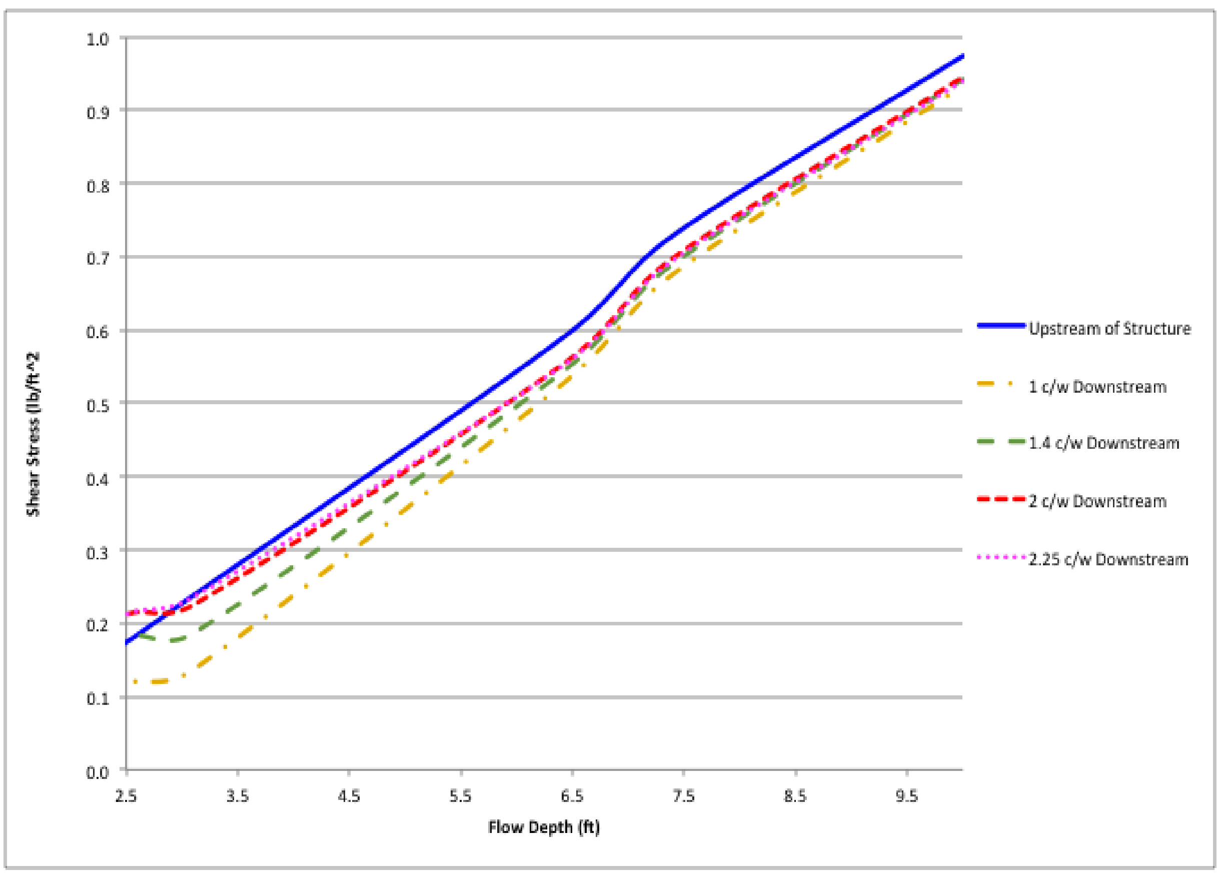

Figure 4-11: Bank Shear vs. Flow Depth for Different Channel Widths Away from a Cross-Vane.

4.3 Labyrinth Weir Comparison

Labyrinth weirs are used to increase the flow capacity of spillways. They have a longer effective length per unit width than a linear weir due to the zigzag-like configuration (Figure 4-12). The greater length per unit width of a labyrinth weir promotes higher flow than that of a linear weir. Restoration structures were compared to labyrinth weirs to help determine if they are effective at deeper flows. Studies have been performed to determine if labyrinth weirs should be used when flows get deeper.

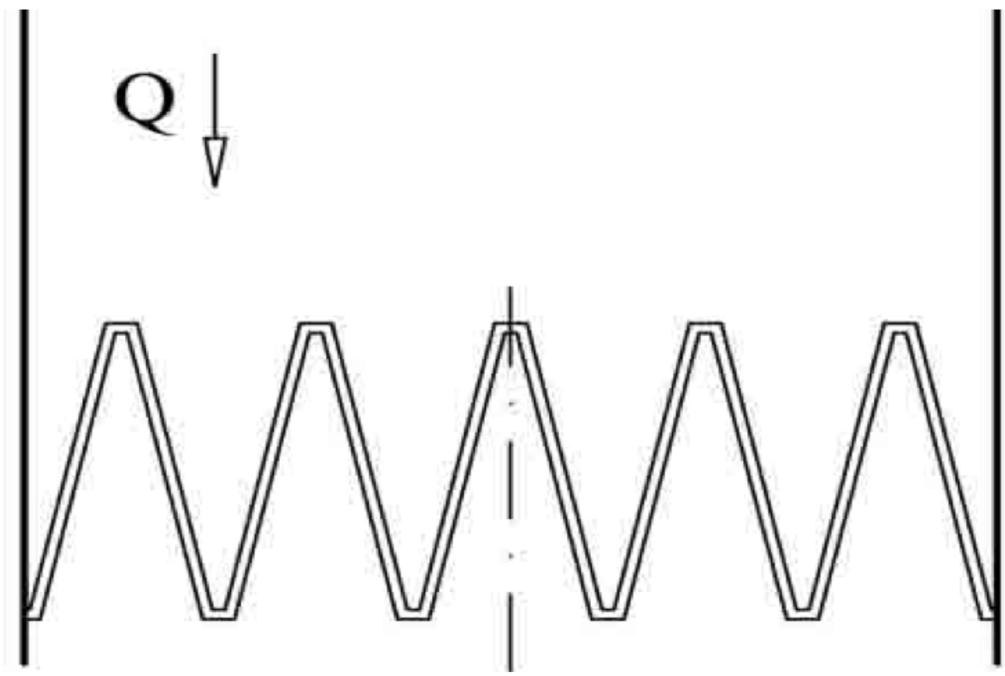

Figure 4-12: Labyrinth Weir Configuration (Crookston, 2010).

The flow that passes over a weir is represented by the weir equation. The equation is the general equation used for both labyrinth and linear weirs. The differences in calculated flow between a labyrinth and linear weir are resultant of the length of the weirs and the different weir coefficients used (Tullis et al., 1995).

$$Q = \frac{2}{3} C_d L \sqrt{2g} H_T^{3/2}$$

Where

Q = Flow, L^3T^{-1}

C_d = Dimensionless weir coefficient, 1

L = Effective weir length, L

g = Acceleration due to gravity, LT^{-2}

H_T = Total head above the weir crest, L

The effective weir length differs between a linear and a labyrinth weir. For a linear weir the effective length is the actual length of the weir. The effective length of a labyrinth weir is different due to the zigzag configuration, which means that the effective length must be calculated using an effective length equation for a labyrinth weir (Figure 4-13).

L = 2N(A+L2)

Where

L = Effective weir length, L

N = Number of cycles (4 shown in Figure 4-13), 1

A = Inner apex width, L

L2 = Effective length of side leg, L

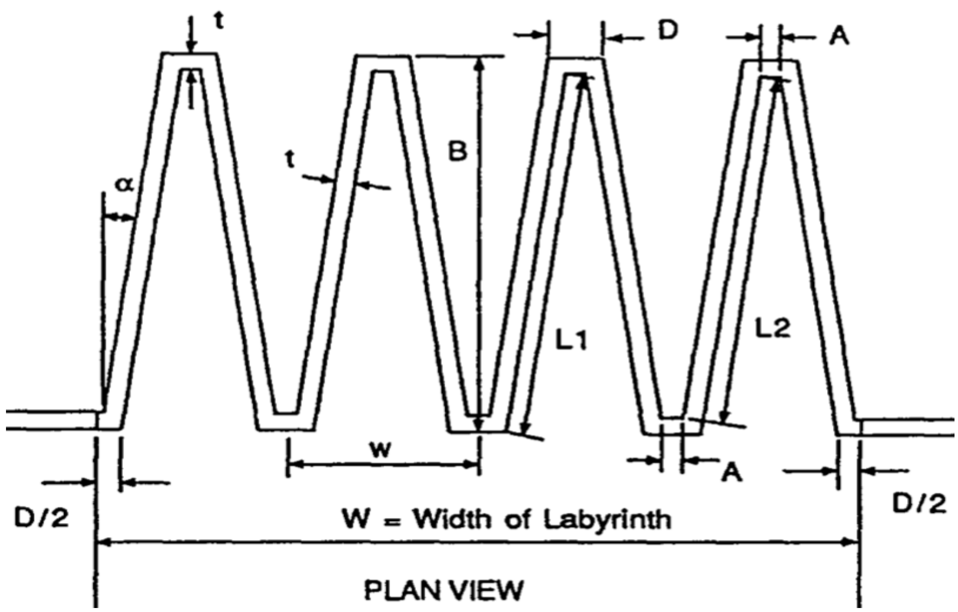

Figure 4-13: Effective Length Variables (Tullis at al., 1995).

The total upstream head (H_T) is the water depth and velocity head above the crest of the weir, calculated by summing the upstream piezometric head (h) and the average upstream velocity head (V^2/2g) (Figure 4-14).

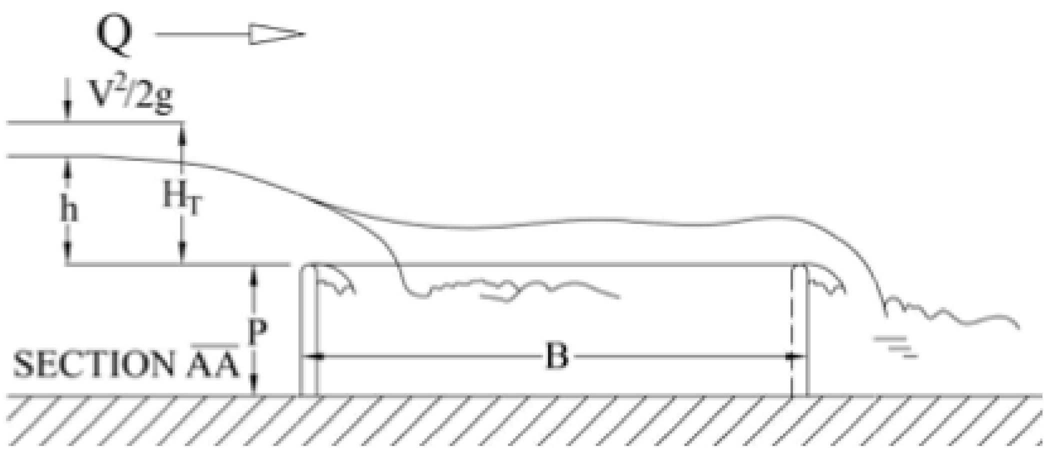

Figure 4-14: Labyrinth Weir Variables (Crookston, 2010).

Weir coefficients are used to compensate for viscosity, energy, momentum, weir geometry and crest shape (Crookston, 2010). Weir coefficients are provided for several different types of weirs and have been established with laboratory testing. As the total upstream head increases for a labyrinth weir, the weir coefficient begins to decrease, showing that the overall performance of the weir decreases (Figure 4-15). The effectiveness of a labyrinth weir is correlated with the ratio of the total upstream head (H_T) divided by the weir height (P) (Figure 4-14). Labyrinth weirs are more efficient when the headwater ratio is less than 0.9 (Crookston, 2010).

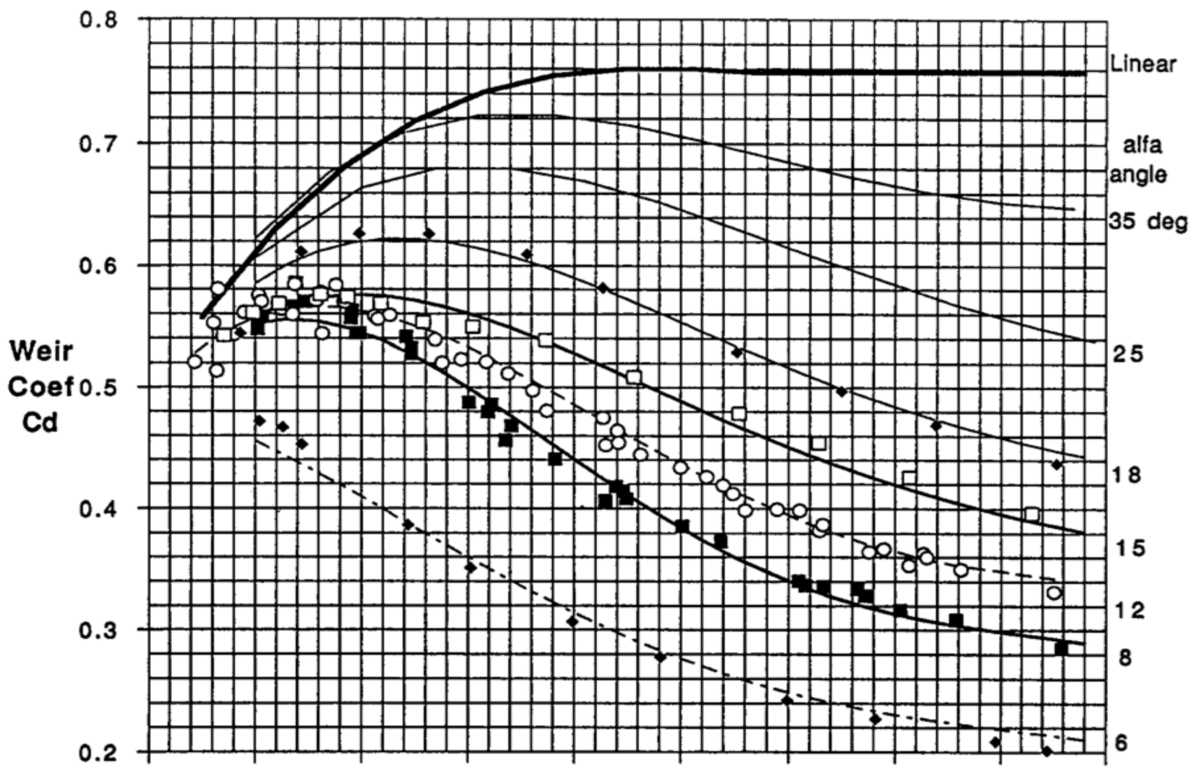

Figure 4-15: Weir Coefficients for Headwater Ratios Lower than 0.9 (Tullis et al., 1995).

Laboratory studies and 3-D numerical models were performed to verify the performance or labyrinth weirs with headwater ratios greater than one (Crookston et al. 2012). This was done to test the values presented by Brian Mark Crookston in 2010 and to see if labyrinth weirs were still effective at headwater ratios greater than one. Testing reflected that for headwater ratios greater than one, the labyrinth weir coefficients follow the Crookston values (Figure 4-16). The recommendation for labyrinth weirs is to maintain a headwater ratio under 0.9 but they will still accommodate more flow than a linear weir at greater headwater ratios (Crookston et al. 2012). Like the labyrinth weir, restoration structures are most effective at lower flow depths but still have some influence on deeper flows.

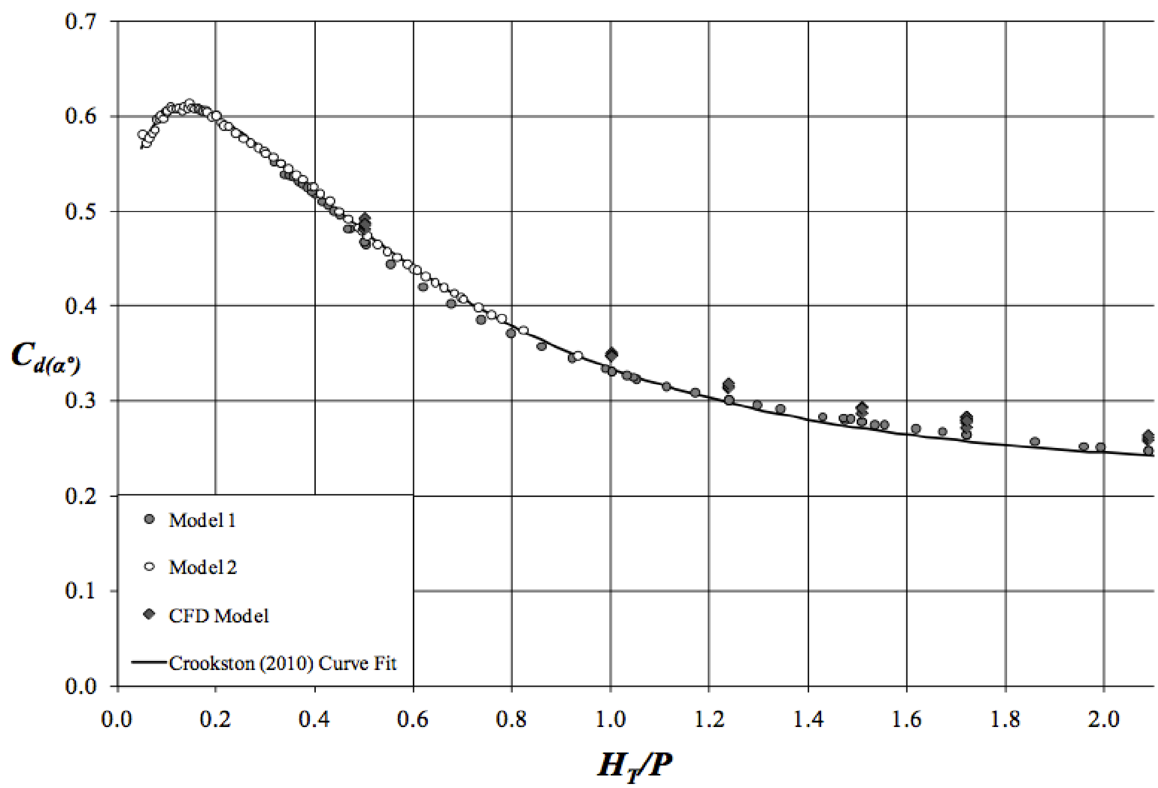

Figure 4-16: Coefficients for a 15-degree Labyrinth Weir (Crookston et al., 2012).

5 CONCLUSIONS

Based on a literature review, Cross-Vanes and W-Weirs were determined to be the best stream restoration structures for protecting bridges while promoting fish habitat. To eliminate the failure of Cross-Vanes and W-Weirs at higher flows near bridges, certain design criteria must be followed. There must be a floodplain present at the bankfull height to disperse the energy of higher than bankfull flows. This floodplain will either be an open floodplain or substituted with culverts along the streambank located at the bankfull height that run under the bridge. The design criteria are shown in Table 5-1.

Modeling illustrated that restoration structures do function better at lower flows, but they do still have some effect on larger flows; this was also reflected when comparing the restoration structure's effectiveness to that of a labyrinth weir. The decrease in bank shear stress occurred at all flows, meaning that even at higher flows, restoration structures will still decrease scour. Illustrations demonstrating the implementation of restoration near bridges can be seen in Figure 5-1, Figure 5-2 and Figure 5-3.

Table 5-1: Summarized Design Criteria for Implementation of Cross-Vanes and W-Weirs at Bridges.

Design Guideline	**Comments**
Floodplain	Must be present at the bankfull height. Must begin upstream of structure and extend downstream of the structure through the bridge If no attached floodplain is present, one must be excavated (Figure 3-1) or floodplain culverts should be installed (Figure 3-2).
Rock Size	Use the100-year shear stress and the Rosgen chart (Figure 3-3) to size rock. Floodplains are essential to help to reduce shear on rocks.
Angle from Bank Tangent Line	20 to 30 degree angle, 20 degree protects more streambank (Figure 3-6).
Vane Slope	2 to 7 percent slope (Figure 3-8).
Footers	3 to 6 times the height of structure above the streambed. Placement is important (Figure 3-10).
Rock Step Inside Vane Arms	Regulates the size of the scour hole and protects the footers from being undermined (Figure 3-11 and Figure 3-12).
Upstream Distance from Infrastructure	1 to 1.5 channel widths upstream, this is measured from the crest of the Cross-Vane or W-Weir (Figure 5-1).

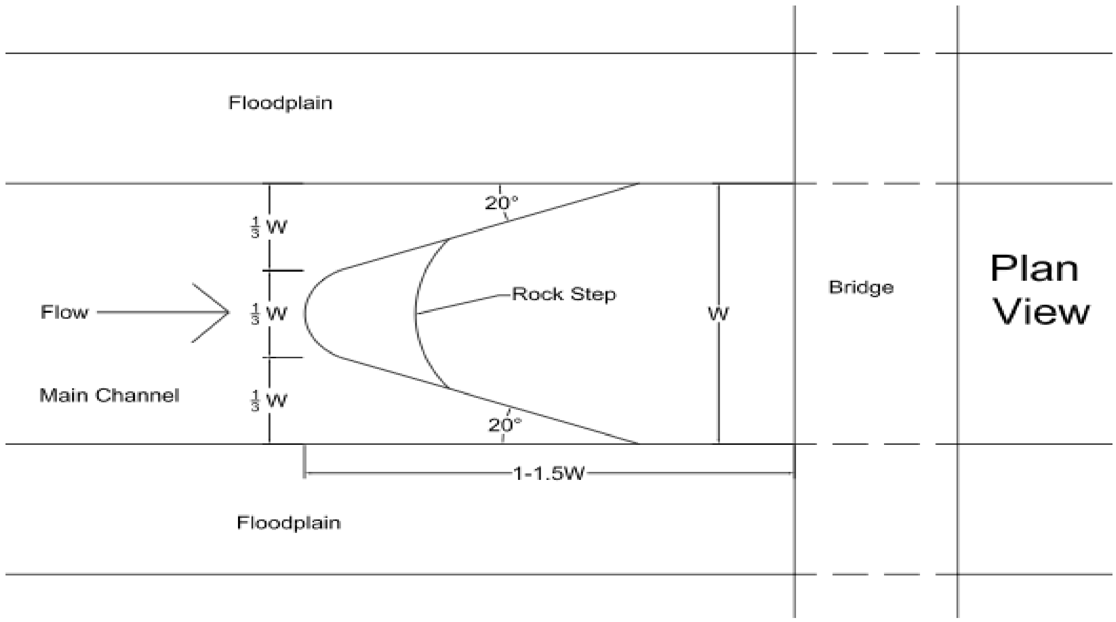

Figure 5-1: Plan View for Implementing a Cross-Vane Near Bridges.

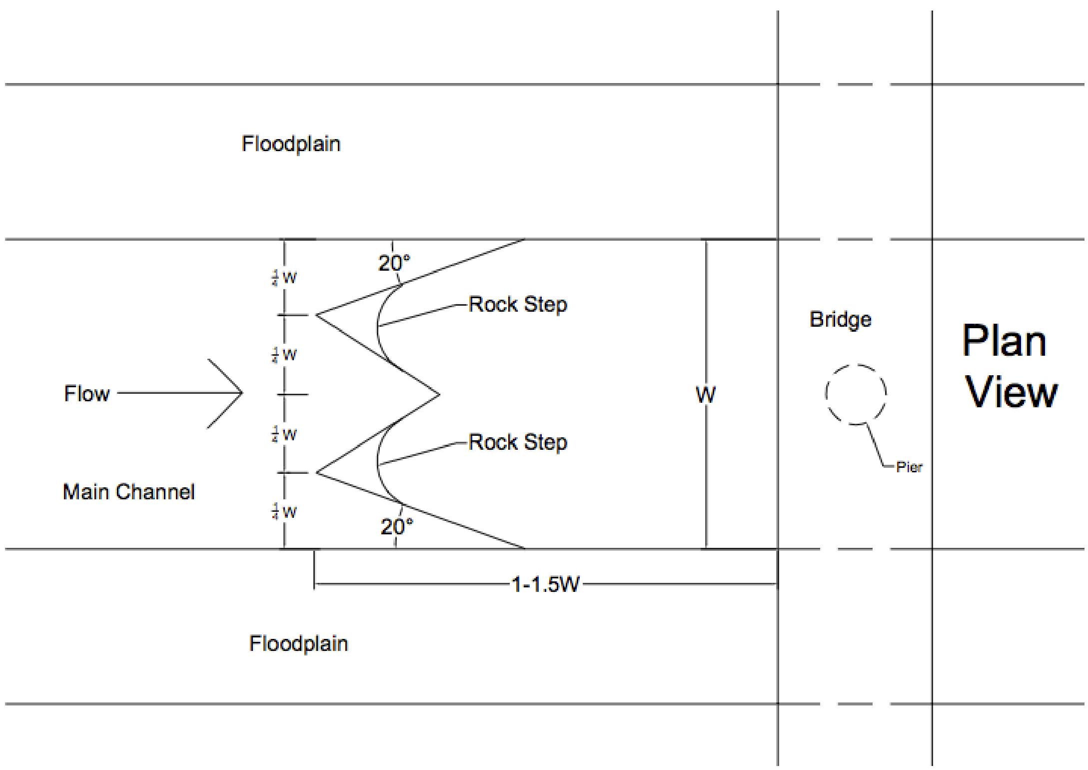

Figure 5-2: Plan View for Implementing a W-Weir Near Bridges.

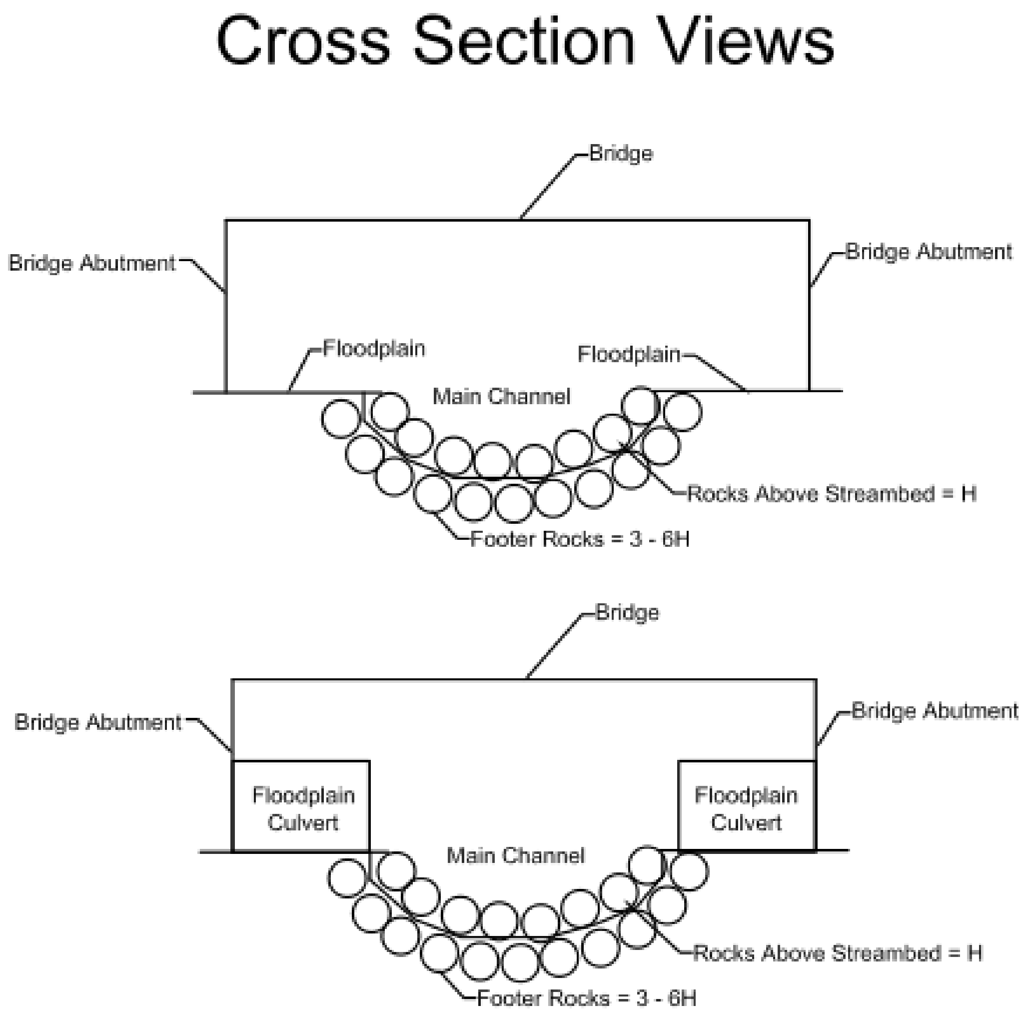

Figure 5-3: Cross Section Views for Implementing a Restoration Structure Near Bridges. Top Image with Attached Floodplain at Bankfull. Botttom Image with Floodplain Culverts at Bankfull.

6 RECOMMENDATIONS

Based on the research and modeling done for this report, Cross-Vanes and W-Weirs can be used as reliable scour countermeasures in the vicinity of bridges if the correct design procedures are followed. It is important to recognize that models are limited by the assumptions made while creating the model and that field observations are also important and must be taken into account. Further study and conclusion will require actual implementation of a Cross-Vane or W-Weir at a bridge; this will depend of further funding.

When implementing a Cross-Vane or W-Weir, some important things to consider are impact of floating debris on the structure, obtaining permits to use heavy equipment in the stream to install or maintain the structures, inspections after flooding events, and using trained/certified personnel to install or maintain the structures. As this report mentions, a floodplain must be present for a restoration structure to properly function. This means that it is possible that bridges with larger spans will need to be constructed to accommodate either an actual floodplain or floodplain culverts underneath the bridge, resulting in a higher cost.

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