Development of Design Guidelines For In-stream Flow Control Structures

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Abstract

The use of in-stream flow control structures for channel stabilization has become increasingly popular due to its potential cost-effectiveness and ecological benefits. These structures help to protect the bank from erosion and lateral migration. However, a large number of these projects fail due to inadequate design guidelines. This study aims to create authoritative design guidelines which are based on hydraulic and physical criteria attributed to the channel reach. In this report, some of the most common types of in-stream structures have been reviewed and results from a practitioner experience survey have been analyzed. This research has allowed for the selection of the most promising structures which will be studied later in the project.

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List of Symbols

α	Angle of attack with respect to flow
b	Bankfull channel width
d_{100}	Diameter of largest sediment grains
d	Flow depth
d_i	Depth to top structure at installation
d_m	Maximum scour depth without vane array
d_o	Bankfull flow depth
d_v	Expected near-bank bed depth with vanes present
δ_b	Vane to bank distance
δ_n	Streamwise vane spacing
H_o	Submerged structure height
L	Structure length
r_i	Inner radius
r_o	Outer radius
T	Vane submergence or depth to top of vane
y	Y-coordinate value, lateral distance from left bank
w	Structure width

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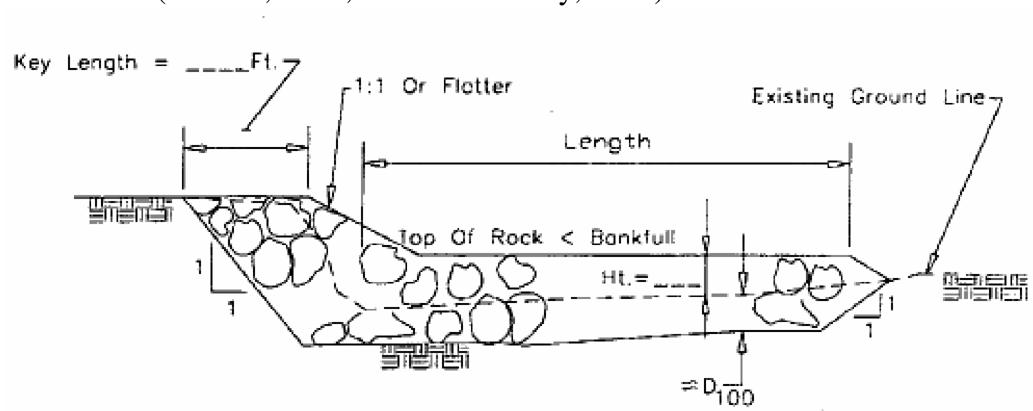
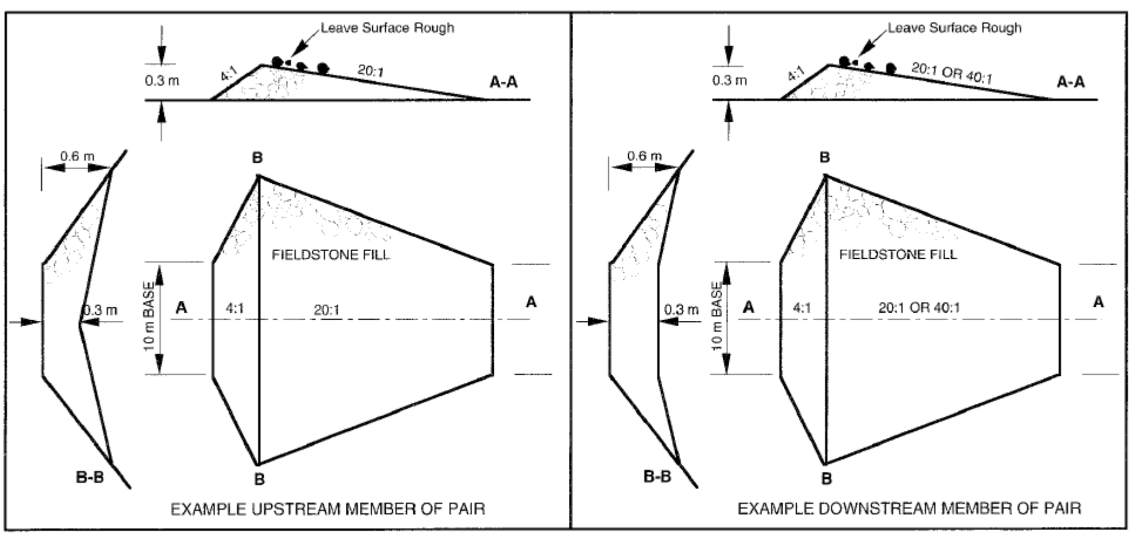
Glossary

Bendway weir---single-arm rock structure extending from the bank; submerged in all but low flows; flat or nearly flat across its length; mitigates erosive flow patterns through weir mechanics (Derrick, 1998; Evans & Kinney, 2000).



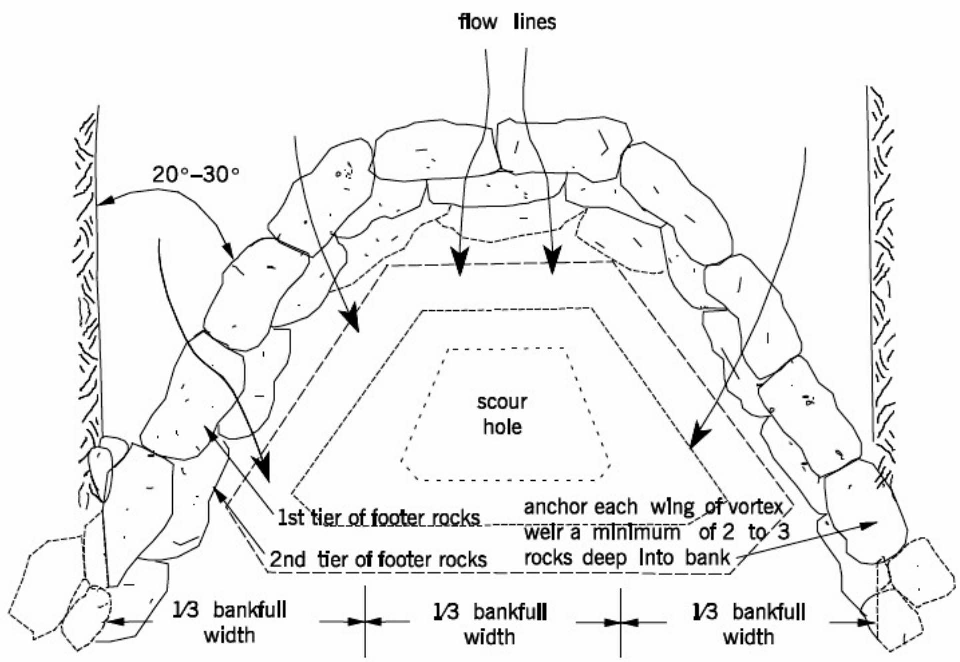
(Evans & Kinney, 2000)

Constructed riffles---arrays of rock located within a channel reach where depth decreases and the channel may widen; riffles are found in pool-riffle series where deep pools are located between upstream and downstream shallow riffle sections; they help regulate sediment transport and diversify flow regimes through the formation of secondary currents such as standing waves, hydraulic jumps, and backwater eddies (HEC-20, 2001; Newbury & Gaboury, 1993).



(Newbury & Gaboury, 1993)

Cross vane---dual-arm rock structure made by connecting the tips of two rock vanes from opposite banks with rocks arranged perpendicular to the flow; this rock vane variation primarily functions as a grade control structure while still providing a reduction in near-bank shear stress (Doll et al., 2003).

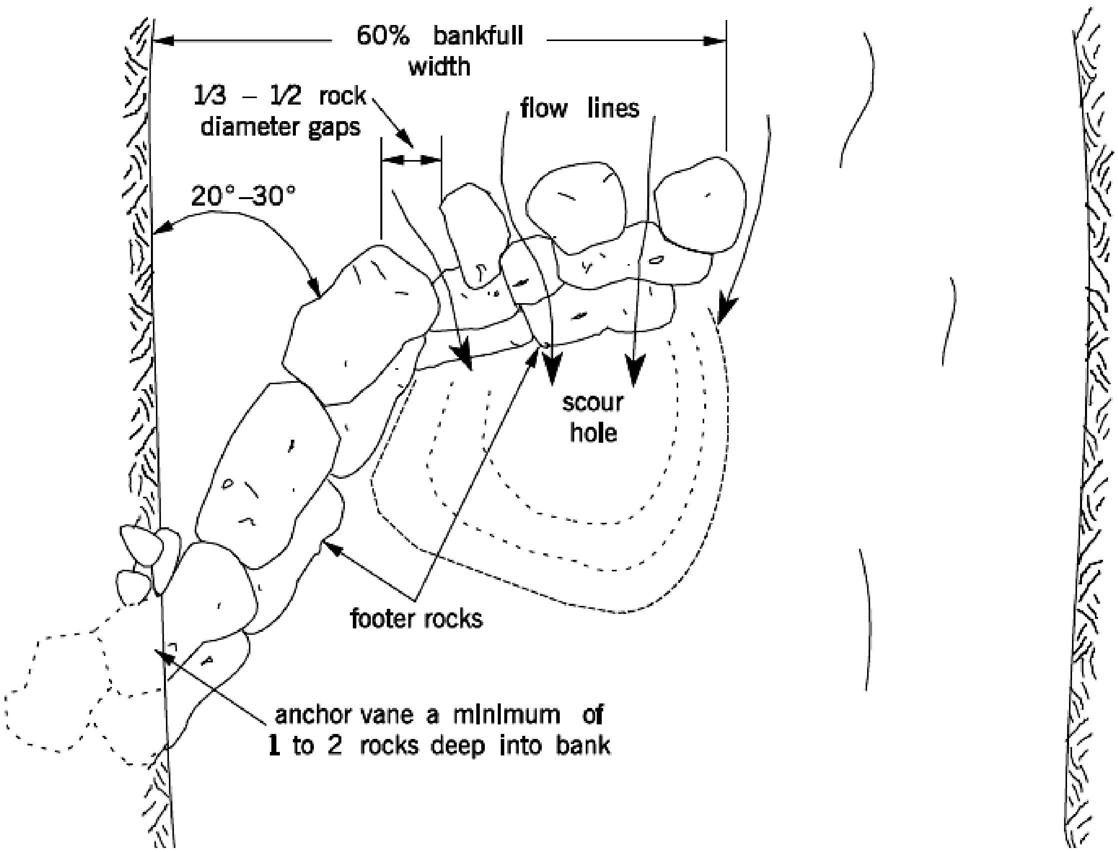


(MWCG, 2000)

Erosion---displacement of soil particles due to wind or water action (HEC-20, 2001).

Horseshoe vortex---turbulent eddy, oriented streamwise at the upstream face of a bridge pier or abutment induced by the downflow of oncoming current (HEC-20, 2001).

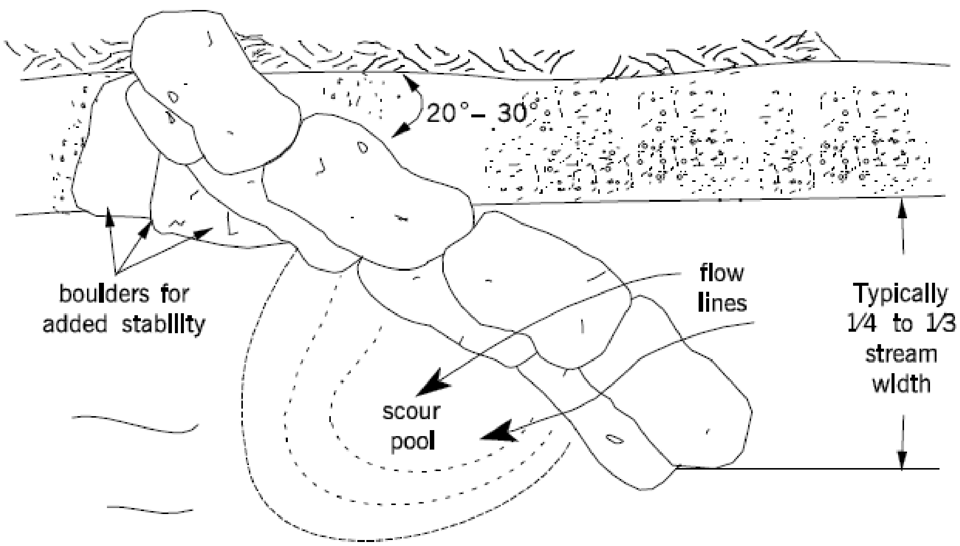
J-hook vane---constructed exactly like a rock vane except there are additional boulders placed at the tip of the vane in a hooking pattern with gaps between them. This layout creates scour by forcing the flow in the center of the channel to converge between the gaps. While this modification is primarily to create habitat, it also provides energy dissipation (Harman et al., 2001; Rosgen, 2001). The hook portion of the structure provides a longer, deeper, and wider scour pool than that created by a rock vane only (Rosgen, 2001).



(MWCG, 2000)

Local scour--- Removal of material from around piers, abutments, embankments, and other structures caused by an acceleration of flow and resulting vortices induced by obstructions to the flow (HEC-20, 2001).

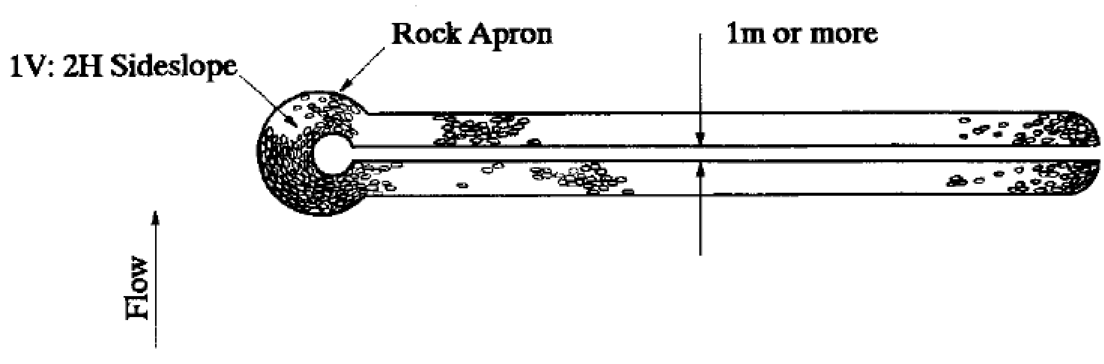
Rock vane---single-arm rock structure extending from the bank; gradually slopes from the bank into the bed at free end; tip is submerged during low flow, but other sections will be exposed; mitigates erosive flow patterns by diverting high-velocity flow away from the bank and creating quiescent conditions near the bank (MWCG, 2000; Harman et al., 2001).



(MWCG, 2000)

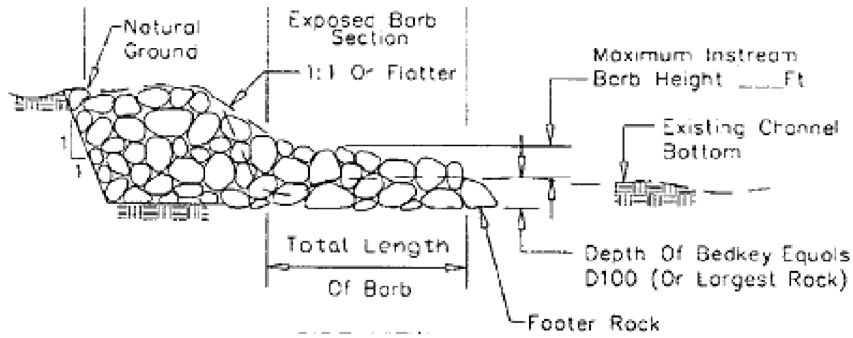
Secondary circulation---fluid phenomena often found along channel bends in which the high-velocity near-surface water current is forced toward the outer bank and lower velocity near-bed current toward the inside bank (ACOE, 1991).

Spur---single-arm rock structure extending from the bank; varying degrees of permeability; mitigates erosive flow through deflection and retardation; higher than most flow stages (HEC-23, 2001)



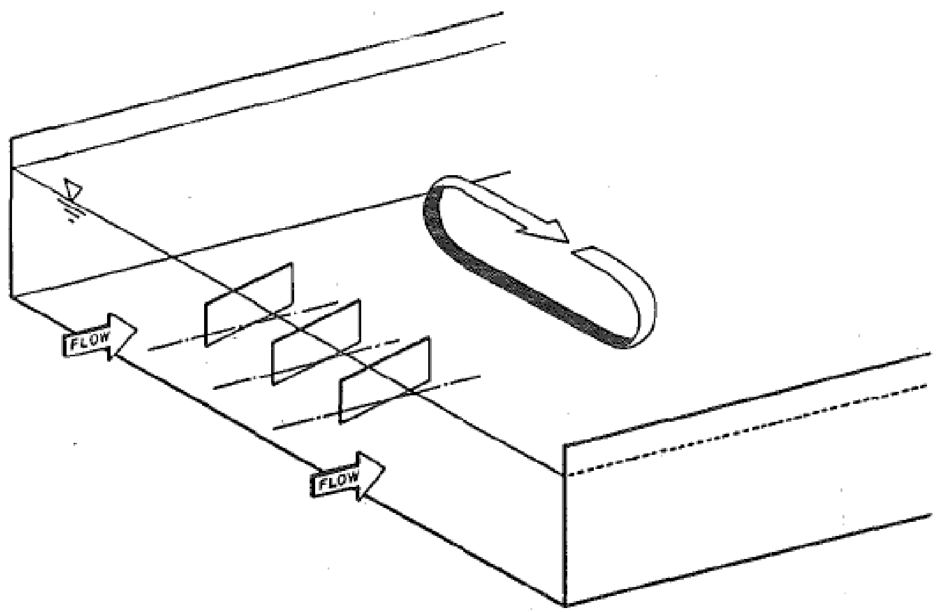
(HEC-23, 2001)

Stream barb---single-arm rock structure extending from the bank; submerged in all but low flows; gradually slopes from the bank into the bed at free end; mitigates erosive flow patterns through weir mechanics by forcing overtopping flow perpendicular to the weir alignment; barbs are shorter and spaced closer together and more effective in small radius bends (Wittler & Andrews, 1998).



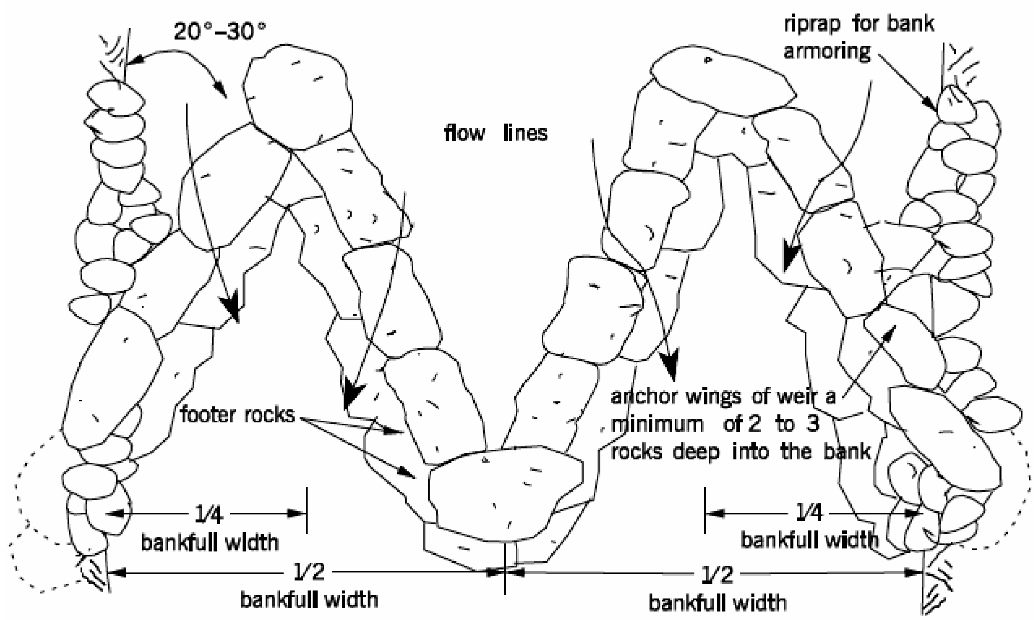
(Evans & Kinney, 2000)

Submerged vane---thin foils angled into the upstream flow and submerged even during low flow periods; normally used in arrays which counter erosive secondary circulations triggered by channel meanders; generally not in contact with the bank (Odgaard & Wang, 1991).



(Odgaard & Wang, 1991)

W-weir---structure layout in this rock vane variation is a "W" shape looking downstream; dual arm rock vanes extending from both banks are joined by two rows of rock in the shape of a "V" pointing downstream; this arrangement creates dual thalwegs and therefore more flow diversity (Rosgen, 2001).



(MWCG, 2000)

Chapter 1: Introduction

Channel stabilization and restoration efforts across the nation have grown dramatically in the last 15 years with over $1 billion spent every year since 1990 (Bernhardt et al., 2005) but it is estimated that at least 50% of these projects fail (O'Neil & Fitch, 1992). This is due to the complex physical processes governing interaction of turbulence in the water column with sediments in the stream and bank (Dancey et al., 2002). Consequently, stream restoration today is more of an art than a science and relies heavily on an analog method that emphasizes a prescribed design approach, rather than the application of physically-based hydraulic engineering principles to attain performance-based criteria (Simon et al., 2007; Slate et al., 2007).

The use of in-stream, low-flow structures as channel stabilization measures has become a preferred solution of federal, state, and local governmental agencies (Johnson et al., 2002b). These measures have gained acceptance because of their potential to enhance aquatic habitat while directing flow away from the banks and dissipating flow energy (Kauffman et al., 1997). Despite their potential for success, these structures suffer from a lack of proven engineering design criteria which if available, would certainly reduce the risk of failure and increase cost-effectiveness.

The aim of this research is to determine specific hydraulic engineering design guidelines for in-stream flow control structures based upon controlled experiments. These guidelines will address (1) erosion protection, channel stability, sediment transport, and scour stability of the stream; (2) cost-effectiveness, long-term performance in terms of the low-flow structure stability, durability, and survivability; (3) recommended installation practices; and (4) maintenance requirements.

This thesis constitutes work completed for tasks related to Phase I of NCHRP Project 24-33; tasks are provided below:

- Task 1.1 Perform a comprehensive literature review of relevant published articles, technical papers, and project reports of field installations, laboratory physical models, and numerical models of flow, turbulence, deposition, and erosion in the vicinity of in-stream structures.

- Task 1.2 Identify and establish contact with on-going research projects on in-stream structure installation, inspection, maintenance, ability to prevent bank erosion, and stability over time.

- Task 2.1 Develop survey for all state DOTs, state DNRs, appropriate federal agencies to describe and evaluate existing low-flow structure applications including effective uses, limitations, design methods, material specifications, installation guidelines, installation costs, maintenance costs, performance, and failure modes.

- Task 2.2 Administer, collect, and follow-up on survey results.

- Task 3.1 Prepare an interim report that includes the results from the Task 1 literature search and the Task 2 survey. The interim report will describe the prevalent low-flow structures and their current installation guidelines and practices; identify practices that results in exemplary performance; describe limitations of existing design guidance; and summarize typical inspection and monitoring requirements. The interim report will include a list of different types of structures in a matrix format that (a) classifies them according to their hydraulic type and common characteristics, (b) identifies the top six (plus or minus) most common and successful types, and (c) identifies modes of failure and possible failure reasons.

The specific set of structures to be studied will be determined by a combination of thorough literature review and a survey of practitioner experience. From this collection of information, approximately six structures will be selected for in-depth research. This document comprises reviews of several of the most studied and/or installed structures, including submerged vanes, rock vanes, j-hooks, cross vanes, w-weirs, spurs, bendway weirs, stream barbs, and constructed riffles.

The information provided in this report provides two major components of the project; the major conceptual and practical issues documented in literature and the design and results from the practitioner experience survey. Literature sources were obtained from researchers who performed laboratory and field experiments based on current design practices and standards in addition to rigorous investigation of grey literature. There are also several government agencies and research groups that have researched in-stream flow control structures in the lab and field. Based on the reviewed literature and practitioner feedback, the most promising structures have been determined for further study.

Chapter 2: Literature Review

Hydraulic and Geomorphic Background

Scouring is the result of bed material being subjected to shear stresses greater than the threshold value. Scouring is frequently made apparent at bridge piers, abutments, or any other obstructions to flow where water erosion lowers the riverbed level exposing foundations (HEC-18, 2001). The scour directly attributed to a pier or abutment is defined as local scour. Local scour occurs when the flow field near bridge piers or abutments is strong enough to remove bed material (Melville & Coleman, 2000; TAC, 2004). Lateral migration, which we are primarily concerned with in this study, is also a consideration when evaluating the total scour at infrastructure. Lateral migration occurs naturally in a channel and can affect the total scour by changing the flow angle of attack (HEC-18, 2001).

Three specific flow features lead to local scour around a flow obstruction. A pressure gradient on the upstream face of the pier causes downflow which impinges upon bed material at the base. An eddy is created by this action which transports dislodged particles away from the pier; this eddy is referred to as a horseshoe vortex. Additionally, wake vortices caused by separation as flow passes the pier entrain sediments through suction (Melville & Coleman, 2000; HEC-18, 2001; TAC, 2004). Figure 1 shows vortices and scour holes commonly found at bridge piers.

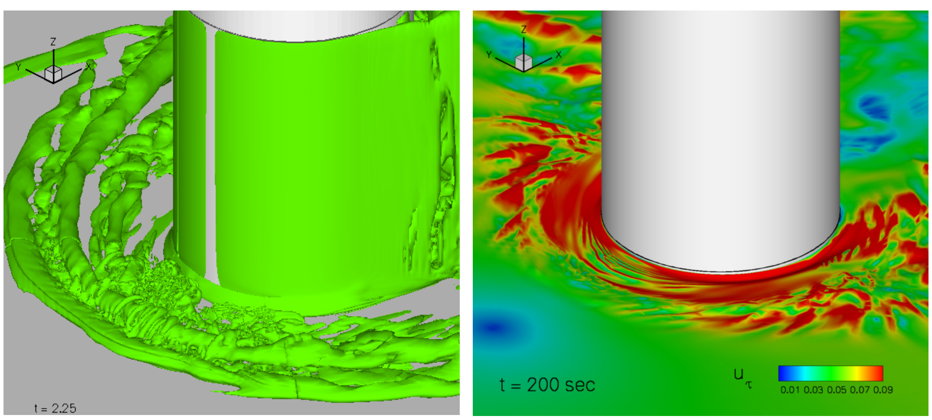


Figure 1: Turbulent flow patterns in the vicinity of a bridge foundation obtained from high resolution numerical simulations (Escauriaza 2008; Escauriaza and Sotiropoulos 2008). Left: Instantaneous vortical structures showing the complexity of the turbulent horseshoe vortex; Right: Scour hole and bed forms induced by the vortices colored with instantaneous bed shear stress.

Some bridges have been constructed with spans smaller than the channel they are crossing meaning that flow is constricted at these points (Chang, 2002; TAC, 2004). Even, when crossings are designed to span the entire floodplain, piers and abutments will inevitably constrict the flow. This constriction creates an area of higher velocity and in turn, higher shear stress which leads to contraction scour. In periods of high flow, the effect is even more pronounced and the severity of scour increases accordingly. Contraction scour and local scour are directly attributable to the existence of the bridge and can lead to structural instability (HEC-18, 2001; TAC, 2004). For example, Figure 2 shows how scour processes adjacent to a hypothetical bridge crossing can drastically alter the bed profile adjacent to both piers and abutments. Figure 3 shows a bridge having undergone dangerous scour levels.

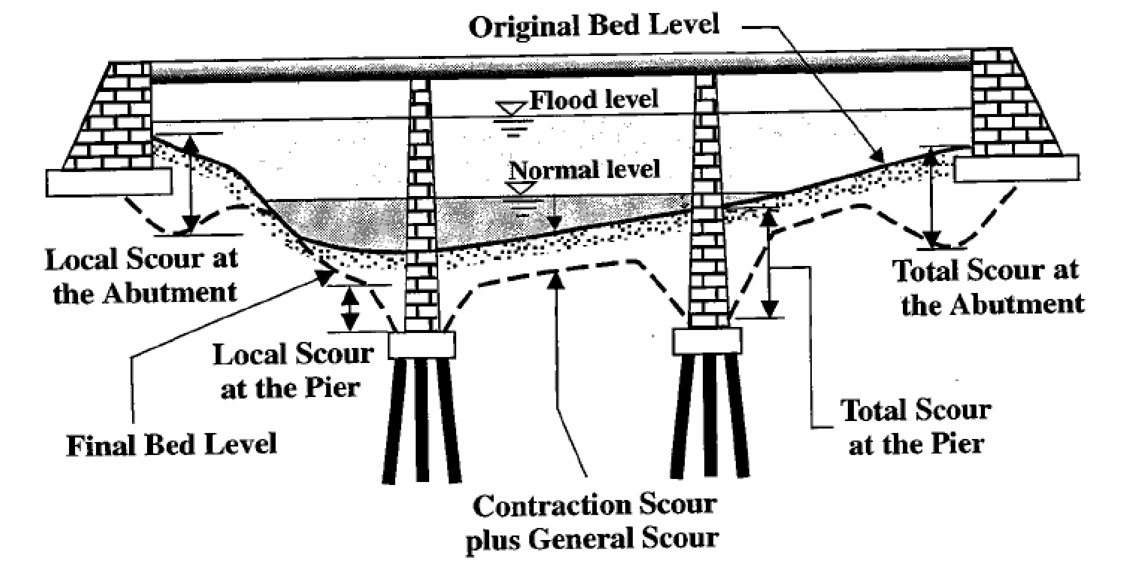


Figure 2: Types of Scour Occurring at a Bridge (Melville & Coleman, 2000)

The magnitude of scour depends on geomorphic factors such as climate and topography in addition to sediment size, flooding frequency, and instream infrastructure geometry. The magnitude will also be influenced by the presence of scour countermeasures and their effectiveness. Final scour depth is achieved when equilibrium between erosive capability and bed resistance to motion is reached (Melville & Coleman, 2000).

Figure 3: Low Flow Revels Severe Scour; Note original bed elevation (USGS, 1997)

The second primary cause of stream instability is bank erosion. Erosion, like scour, is the result of fluid forces acting on sediment and causing it to be dislodged and transported. Accelerated erosion, sometimes referred to as mass wasting, is normally the result of high flows (HEC-20, 2001). Erosive forces during high flows can be 100 times greater than during normal or low-flow periods. Additionally, 90% of all changes to a river occur during these periods of high flow which are relatively infrequent (Richardson, et al., 2001). Figure 4 shows exposed piles from sever bank erosion.

Figure 4: Abutment Scour Caused by April 1979 Flood Leake County, MS (USGS, 1979)

Groundwater levels, bank material, stratification, and freeze/thaw cycles, all play a role in determining the erosion potential of a channel (Simons, 1995).

Bank erosion has been observed to be especially pronounced at the apex of meander bends due to the centrifugal force caused by the curved flow. This force results in a decreased water surface elevation around the inside bank and an increased water surface elevation on the outside bank: this phenomena is known as super-elevation. These curved sections also tend to create helicoidal flows which can shift the path of maximum velocity away from the center of the channel and closer to the outside bank near the bend apex and immediately downstream of it. This secondary circulation can persist downstream leading to undesired scour or depositions (ACOE, 1991). Unchecked scour at the toe of the banks will eventually lead to their failure (Odgaard, 1988).

Channel stability can be determined by the use of geomorphic, hydraulic, and analytical stability assessments. Field reconnaissance must be completed to determine basic information about the channel and watershed it flows through (Rosgen, 2006). A theoretical model can then be used to asses channel stability. An appropriate software model that combines several field indicators of the reach stability with the desired final hydraulic geometry can be utilized create a stable channel design (Copeland et al., 2001).

Ecological Background

The use of in-stream structures, such as those discussed in this review, can have an additional effect than just that of infrastructure and bank protection. Federal and state regulatory agencies are growing increasingly receptive to these structures because they often enhance and protect stream habitat for target species. Riprap lined channels are a known detriment to fish spawning areas and riparian growth in general. In contrast, in-stream structures create alternate flow patterns which can increase local flow diversity and other characteristics needed for a healthy ecosystem. Properly installed and maintained in-stream structures can therefore protect infrastructure while promoting aquatic habitat.

Bernhardt et al. (2007) compiled information from 317 restoration project managers nationally in order to compare project goals versus project outcomes as well as what monitoring and evaluation techniques, if any, were employed. Approximately 25% of the surveyed projects had primary goals of channel reconfiguration or bank stabilization. However, the authors note that habitat improvement may be accomplished as a secondary benefit (Bernhardt et al., 2007).

This type of secondary benefit was realized in several studies where spurs and stone weirs intended for streambank erosion prevention created new and stable habitat (Shields et al., 1994; Shields et al., 1995a; Kuhnle et al., 1999; Kuhnle et al., 2002). Unstable channels lead to severe bank erosion and eventual widening causing the local ecosystem to be very susceptible to temporal variations such as drought or heat wave (Carline and Klosiewski, 1985). A channel with a defined thalweg and stable pools provides an environment much more conducive to sustaining a diverse assemblage of aquatic species.

Groin extensions were installed in Hotophia Creek, Mississippi, to perform restoration research on an incised channel. Previously existing riprap spurs were found to be of insufficient length to create significant scour holes during baseflow. The stone extensions and structure dimensions were based on US Army Corps stone size gradations and similar projects. Two post project surveys indicated that while there was little impact on the average flow width, pool habitat area increased three to five times the area measured prior to restoration. Pool habitat in this study was defined as areas of depth greater than 20 cm and velocity less than 10 cm/s. Post restoration studies also show that both the diversity of fish species and length of fish in the reach increased by 50% (Shields et al., 1995a).

In a study comparing habitat restoration and streambank protection provided by bendway weirs, willow posts, and stone toes on Harland Creek, Mississippi, Shields et al. (1995b) found that bendway weirs harbored the greatest number of fish of the three methods. Bendway weirs also created more pool habitat and more desirable bed type than reaches protected by stone toes (Shields et al., 1995b). More details can be found in this review about the design specifications and results of the bendway weirs on bank protection which are provided by Derrick (1995 & 1998).

Kuhnle et al. (1999) performed lab experiments to determine the size of shape of scour holes that could be produced by 90 degree spurs. These scour holes are areas of potential aquatic habitat. Though not intended to be the primary method of long-term aquatic habitat recovery, stone spurs will create stable pools in channels damaged by widening and erosion (Kuhnle et al., 1999). Kuhnle et al. (2002) later determined that spurs at an angle of 135 degrees to the downstream channel provides the best potential for improving aquatic habitats while still minimizing erosion potential along the bank. Table 1 provides a summary of additional fish surveys relating to various restoration measures.

Table 1: Reported Effects on Fish Biomass from Adding or Extending Spurs in Eroded Warmwater Streams (Kuhnle et al., 1999)

Condition	Spur Impact on Fish Biomass	Reference
Spur compared with stone toe protection	Increased 5.7 times	Knight & Cooper (1991)
Spurs extended 4 times original length	Increased 15 times	Shields et al. (1995a)
Spur compared with stone toe protection	Increased 1.6 times	Shields et al., unpublished data (n.d.)
Spur compared with stone toe protection	Increased 1.2 times	Shields et al., unpublished data (n.d.)

Constructed riffles are also rock structures with possible side benefits of ecosystem enhancements. Studies detailed in this review mention ecological benefits of riffles used in stream stabilization (Newbury & Gaboury, 1993; Newbury et al., 1997; Newbury et al., 1999; von Euw & Boisvert, 2002; Walker et al., 2004). Additionally, there are studies which have measured the biological response of a reach with constructed riffles (Ebrahimnezhad & Harper, 1997; Pretty et al., 2003; Walther & Whiles, 2008).

Ebrahimnezhad & Harper (1997) studied the biological impact of constructed riffles on Harper's Brook in Northamptonshire, England. They determined that if constructed correctly, artificial riffles increase the biodiversity of macro invertebrates to levels consistent with natural riffles. The authors concluded that a maximum depth of 25 cm and a minimum velocity of 40 cm/s during low flow are necessary constraints for artificial riffles to mimic natural riffles (Ebrahimnezhad & Harper, 1997).

Pretty et al. (2003) studied 13 rehabilitated rivers in the United Kingdom to monitor impacts of fish populations. Rivers had either artificial riffles or deflectors installed as the rehabilitation measures. Results showed that while species richness and diversity appeared to respond positively to restored reaches, no significant statistical relationship was found between the increase of habitat diversity and species diversity. The authors do concede that the rehabilitation schemes may have been inappropriately designed and scaled (Pretty et al., 2003)

Walther & Whiles (2008) studied macroinvertebrate response to constructed riffles in the Cache River, Illinois. Results indicated a positive response by environmental indicator insects as well as other aquatic insects. Additionally, new and older weir colonization rates were observed and it was found that within a few months, new weirs were colonized to levels very close to that of two year old weirs (Walther & Whiles, 2008).

Submerged Vanes

Introduction:

This section summarizes available information on submerged vanes. Submerged vanes, sometimes called Iowa vanes, are stream training structures designed to mitigate stream bank erosion and rebuild bed elevation by inducing secondary circulation. This action stabilizes the stream and prevents it from moving laterally. Vanes are also referred to as foils due to their flat rectangular structure. An examination of the underlying theory as well as laboratory work and case studies will be presented here. This thorough review of literature suggests that submerged vanes are a promising scour countermeasure and should be studied in further detail.

The cost of submerged vane projects has been found to be less, in most cases, than comparable bank armoring techniques (i.e. riprap) (ACOE, 1981) and no reported cases of extensive maintenance have been published. Submerged vanes are useful in a variety of applications ranging from the aforementioned prevention of bank erosion and lateral migration to the protection of bridge piers, abutments, and intake structures. Submerged vanes can also have the added benefit of being an aesthetically pleasing solution; when designed correctly, sediment and vegetation tend to bury the vanes leaving the stream in a more natural looking state.

There are currently, however, only a handful of cases where submerged vane use has been documented in the field. As a result, their effectiveness in many settings is unknown as are their ecological impacts.

Theory:

Submerged vanes were developed to prevent bank erosion and failure in curved channel sections. It is believed that the first study of vane applications in flow training was developed by Russian engineers Potapov and Pyshkin (1947). The first theoretical design works are credited to Odgaard and Kennedy (1983). They concluded that vanes are to be arranged in such a manner as to induce a secondary current which counteracts motion triggered by stream sinuosity and topography.

The fluid motion caused by stream sinuosity is the end result of centrifugal forces which are present in a channel bend. Centrifugal force leads to the phenomenon of superelevation, in which the water surface in a curved reach is higher on the outer bank. Superelevation results in a secondary circulation, or vortex, that forces the high-velocity near-surface water outwards toward the outer bank and lower velocity near-bed current toward the inside bank. As the vortices are carried downstream, this secondary flow is responsible for changes in shear stress and bed topography. The major consequences of these changes are bank erosion and deposition of sediment at undesirable locations.

When properly used, vanes are placed in such a way as to counteract this secondary circulation within the channel bend. As flow reaches the vane, a counter-circulation develops as a result of the pressure gradients across the vane. The pressure decreases from bottom to top on the upstream (high pressure) face; while on the downstream (low pressure) face, pressure increases from bottom to top. As fluid flows over the vane, these pressure regimes trigger the formation of vertical vortices that counteract the naturally occurring secondary circulation (Odgaard & Wang, 1991). Figure 5 shows the orientation and location of high and low pressure zones within a curved channel reach. α is the vane angle of attack with respect to the bend flow, b is the bank-full channel width, r_i and r_o the inner and outer radii respectively, and L the length of the vane. Figure 6 shows how the counter-current vortices emerge and are carried downstream as flow passes over the vane.

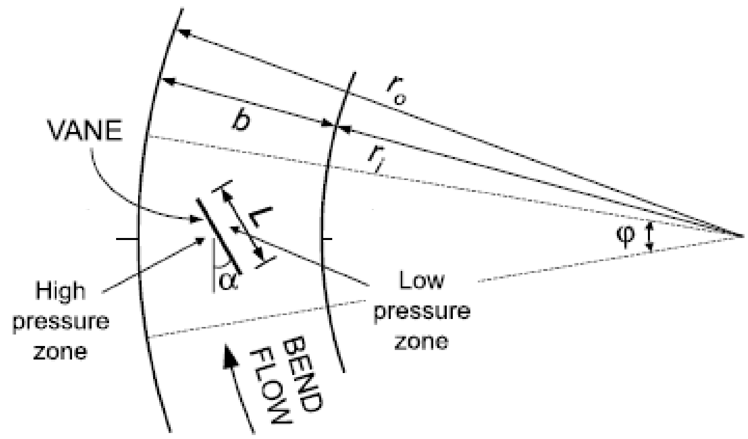


Figure 5: Typical Vane Orientation and Location of High and Low Pressure Zones (Voisin & Townsend, 2002)

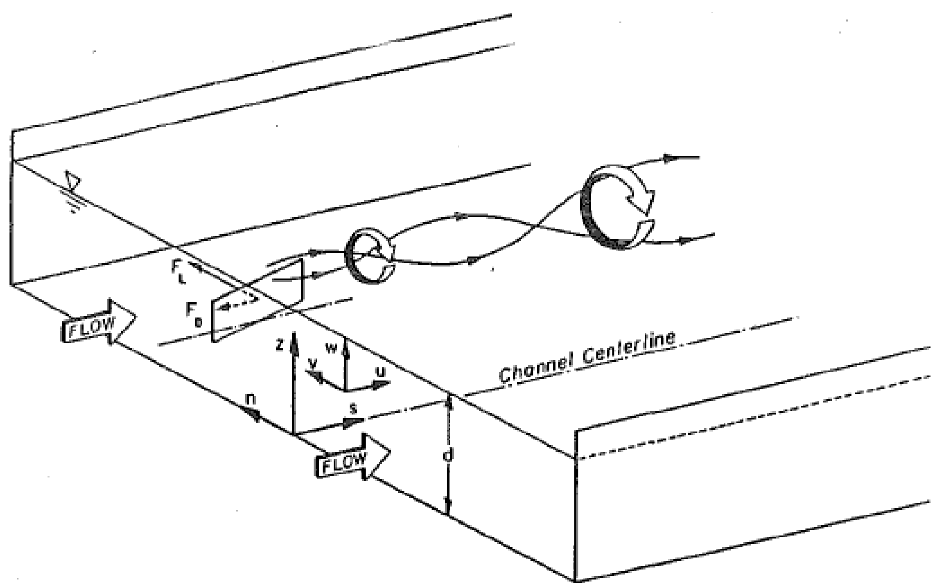


Figure 6: Schematic of Flow Situation Showing Vane-Induced Circulation

(Odgaard & Wang, 1991)

The goal of submerged vane use is to rebuild bed material near the bank as well as relocate the channel thalweg toward the center of the channel. Figure 7 shows an ideal situation in which starting from an originally flat bed, a single submerged vane has caused a change in the lateral bed material profile. There is a clear increase in material between the vane and the outer bank as well as an area of scour toward the center of the channel.

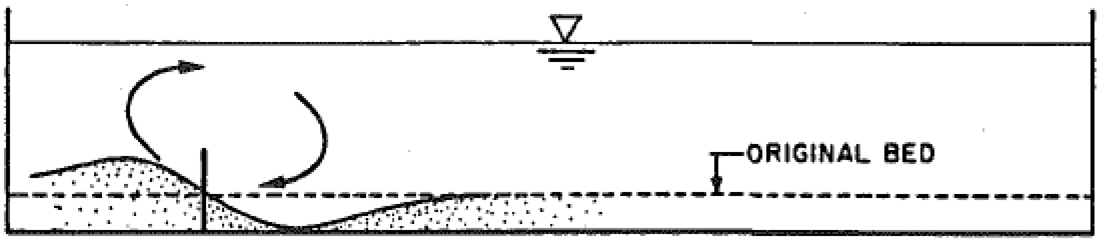


Figure 7: Schematic Showing Vane-Induced Change in Bed Profile

(Odgaard & Wang, 1991)

Since a single vane can rarely produce the desired results, two or more vanes are typically used together to impact a much wider region of the channel. Figures 8 and 9 below show the changes in circulation and bed profile resulting from a three vane array.

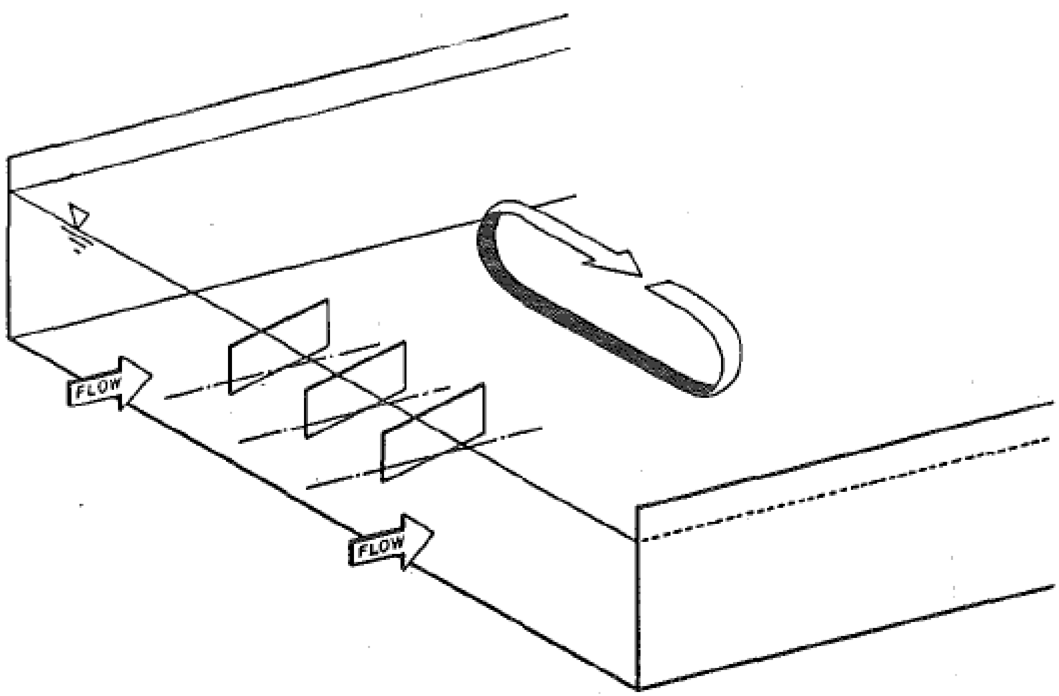


Figure 8: Schematic Showing Circulation Induce by Array of Three Vane

(Odgaard & Wang, 1991)

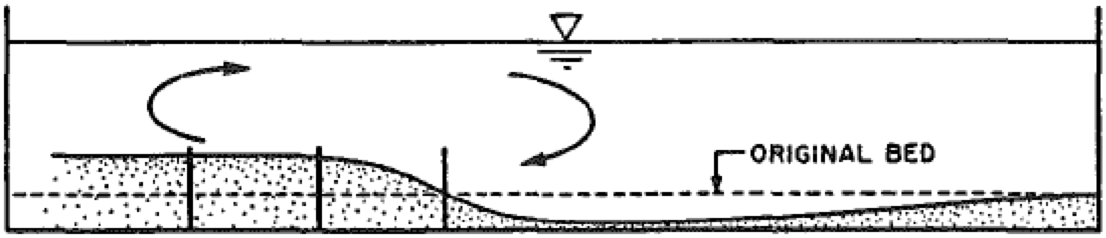


Figure 9: Schematic Showing Change in Bed Profile Induced by Array of Three Vanes (Odgaard & Wang, 1991)

Wang (1989) concludes that the total circulation induced by an array can be approximated by adding the circulation of the individual vanes, provided they are the same dimensions and at the same angle to the flow. Additionally, an interaction coefficient, which accounts for vane spacing and dimensions, is needed to accurately approximate the circulation induced by an array. Vanes need to be spaced less than two to three times their height; any larger distance will produce results more reflective of a group of individuals which could cause multiple points of scour laterally instead of the desired single thalweg. Severe erosion problems generally require multiple vane arrays in the stream-wise direction (Wang, 1989).

Figure 10 represents the expected curved channel cross-section at the installation (a), bank-full (b), and low-flow (c) periods after vane structure installation. δ_b and δ_n are the distance between the bank and the nearest vane and the stream-wise vane spacing, respectively. H_o is the vane height and T the vane submergence, or height of water above the top of the vane. Maximum scour depth without the array is represented by d_m. d_i and d_o are the installation and bank-full flow depths, respectively. d_v is the expected depth of the near-bank bed with vanes present. The use of a vane array will create a buildup in bed material near the array resulting in a smaller d_v value compared with the predicted scour depth in the absence of vanes, d_m.

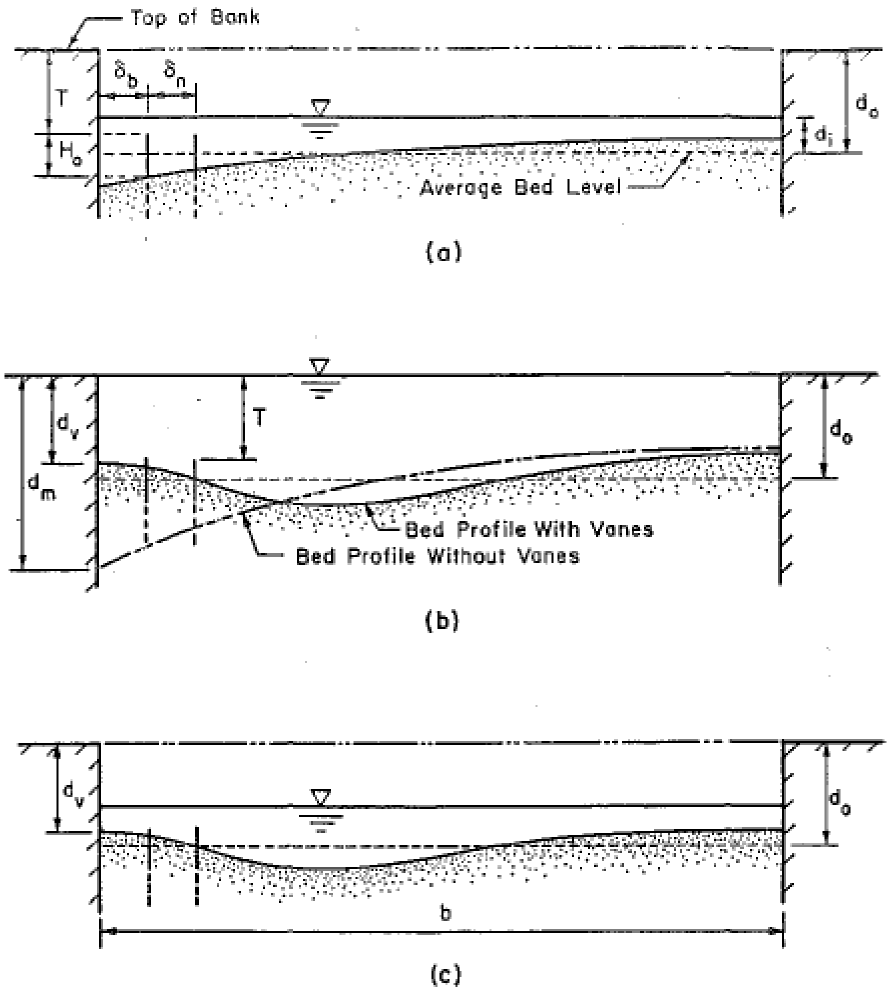


Figure 10: Schematics Showing Primary Design Variables and Flow Sections at: Installation; (b) Subsequent Bank-Full (Design) Flow; and (c) Subsequent Low Flow (Odgaard & Wang, 1991)

In order to determine the conditions for maximum vane-induced increase in bed level, a series of trials were completed by Odgaard & Wang (1991) which vary by number of vanes in array, Froude number, resistance parameter, and width-depth ratio. This allows for vane performance to be determined for a variety of structure configurations. Plots of these trials are found below in Figures 11 and 12. Variables are the same as in Figure 10.

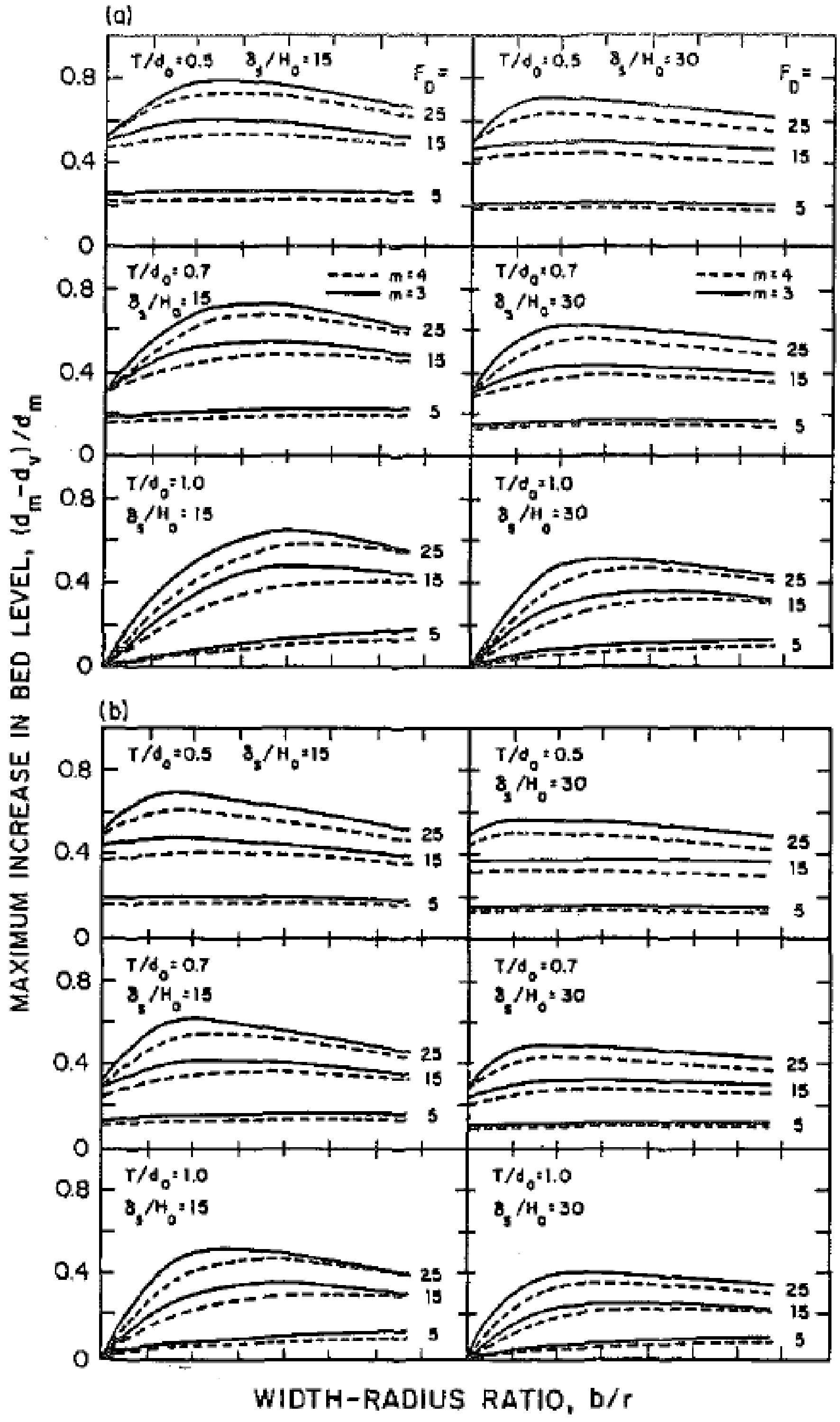


Figure 11: Computed Vane-Induced Maximum Increase in Bed Level along Bank with: (a) Three Vanes per Array; (b) Two Vanes per Array; Depth-width ratio, / b= 0.03; Vane-Aspect Ratio, = 0.3; Vane Angle = 20d; and Vane Spacing = 3

(Odgaard & Wang, 1991)

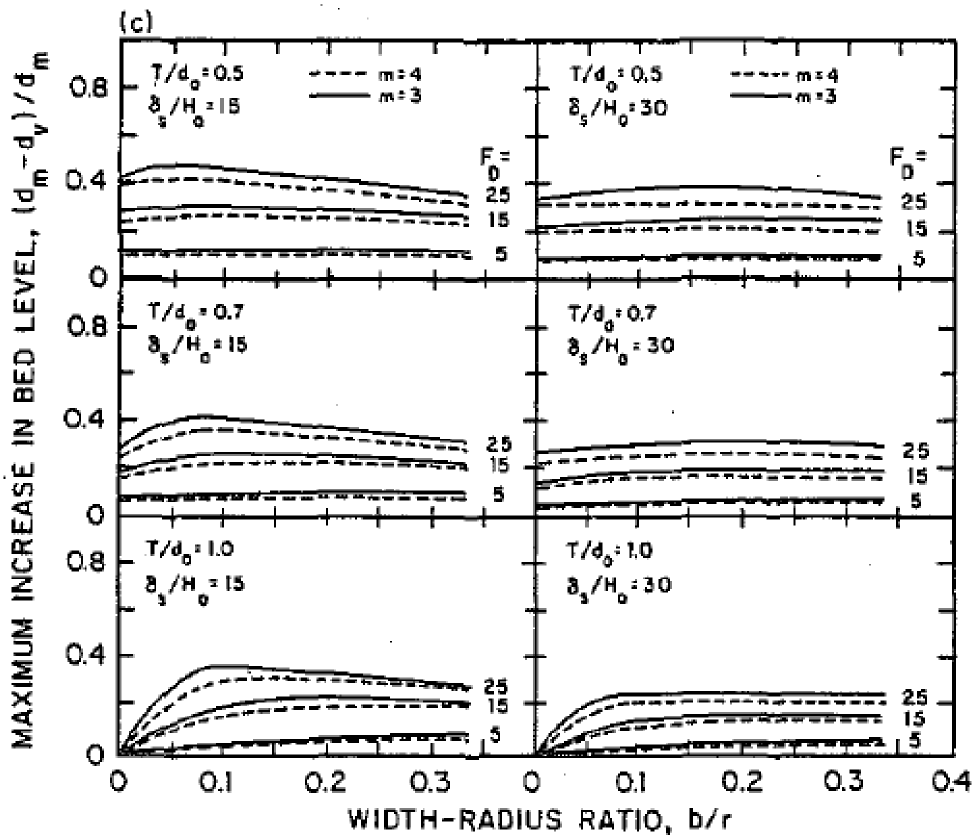


Figure 12: Computed Vane-Induced Maximum Increase in Bed Level along bank with: (c) One Vane per Array; Depth-width ratio, / b= 0.03; Vane-Aspect Ratio, = 0.3; Vane Angle = 20d; and Vane Spacing = 3 (Odgaard & Wang, 1991)

Odgaard & Wang (1991) make the following conclusions based on results found in the above graphs:

- Three vanes minimum are needed to increase bed level to the top of the vane.
- Induced bed elevation increase is independent of the channel depth/width ratio when it is less than 0.05.
- For large channel width to array width ratios, distance to far bank has no effect on bed level changes within the vane field.

Description/Guidelines:

Vanes have been constructed with wood planks, concrete, fiberglass, high-density polyethylene (HDPE), and sheet metal. The vanes used in Odgaard and Wang's (1991) experiments were made from sheet piling and fiberglass; however, there are records of other successful trials that utilize supported planks, round wooden poles, and reinforced concrete. The major consideration appears to be the prevention of flow separation, which leads to slightly angled and twisted designs (Odgaard & Wang, 1991). All recent lab work studies have used sheet metal and one field case reported using HDPE (USGS, 2005). Sheet metal appears to be the preferred material since it is very rigid even at small thicknesses. The vanes are usually anchored with rebar or piles.

Odgaard and Wang (1991) discuss general vane sizing criteria which are widely cited and accepted. These criteria are based primarily on studies completed by Odgaard and Kennedy (1983), Odgaard and Spoljaric (1986), and Odgaard and Mosconi (1987).

- Angle of attack is 15-25 degrees to flow
- Height is 20-40% of the bank-full flow depth

Wang (1991) conducted studies on flat, fixed beds as well as movable beds. His experiments furthered guidelines on array size and spacing. Wang suggests vane-induced velocities are small beyond two vane heights laterally (i.e., for $y > 2H_o$), and therefore spacing within an array should be less than 2 or 3 vane heights.

Marelius & Sinha's (1998) work, which provides more extensive coverage of the flow surrounding a vane and focuses on determining the vane configuration that produces the strongest secondary circulation, is discussed in the Laboratory Work section. Their results suggest that an angle of attack of 40 degrees will produce the strongest secondary circulation.

Tan et al. (2005) note that limited experimentation has been done concerning vane length and the implications of using small-scale model studies, which may not properly represent how sediment is transported around the vane and in some cases over top of it. This research also looks at the effect that bedform dimensions play on sediment diversion. Experimental results and conclusions from Tan et al. (2005) on vane dimensions are found in the Laboratory Work section below.

A table of vane and channel properties for all laboratory experiments and field work summarized here is included in Appendix A. This table provides a summary of all the design elements for each study and provides the researchers' results and conclusions.

Lab Work:

Lab experiments were performed by Odgaard & Wang (1991) in both a straight and curved channel with a median sediment size of 0.41 mm and a geometric standard deviation of 1.45 mm. The purpose of these experiments was to confirm the previously discussed theoretical predictions of altered bed topography through implementation of vanes.

The curved channel experiment had the following properties:

- Flume width is 1.94 m
- Flow depth is 0.6 m
- 13.1 m radius bend following a 20 m straight approach
- Double-curved, fiberglass foils with a 10 degree twist
- 7.4 cm tall and 15.2 cm long vanes
- 2 to 3 vanes in a singe array at a 15 degree angle toward flow

The straight channel experiment had the following properties:

- Flume width is 2.44 m
- Flow depth is 0.6 m
- Vanes constructed from 0.8 mm thick sheet metal
- 7.4 cm tall and 15.2 cm long vanes
- 4 vanes in a single array at a 20 degree angle toward flow

Figure 13 shows results from Odgaard and Wang (1991) comparing the effect of vanes on channel depth distribution and average velocity.

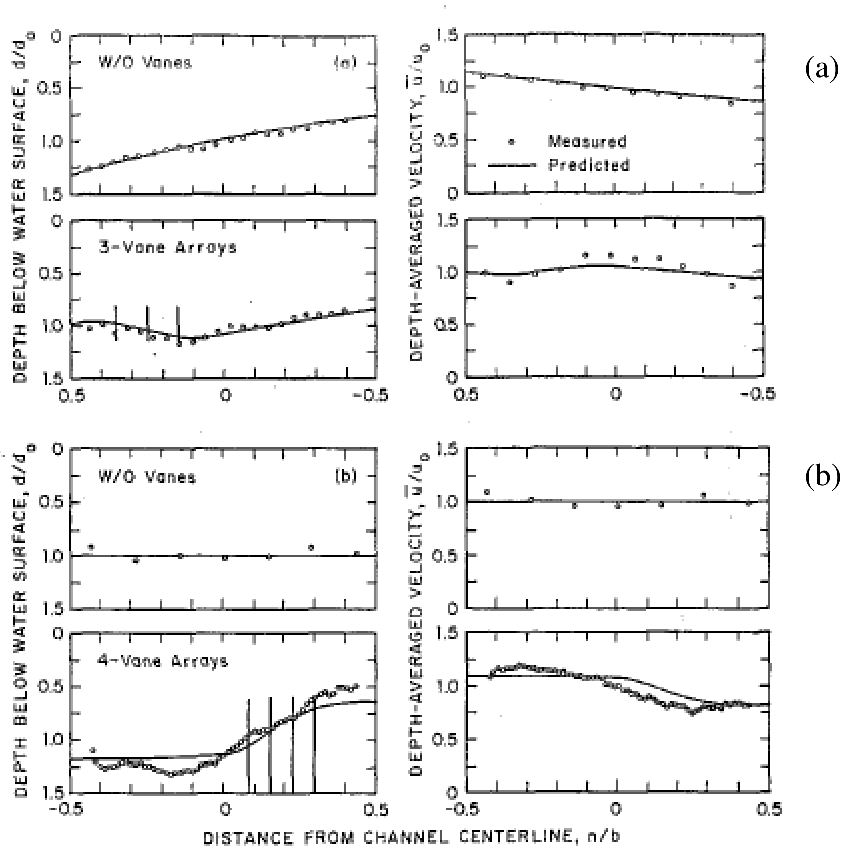
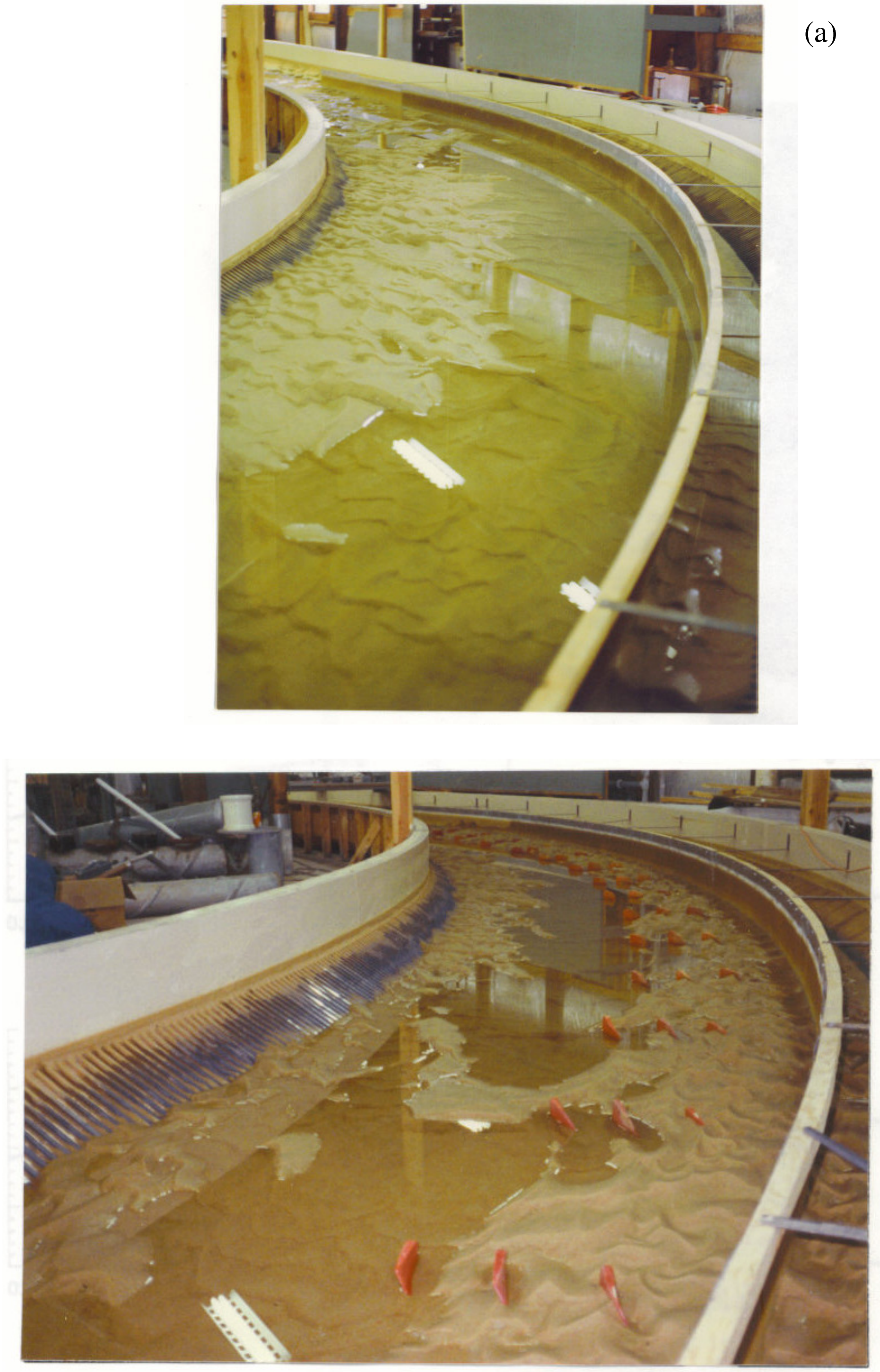


Figure 13: Comparison of Measured and Predicted Velocity and Depth Distributions without and with Vanes: (a) in Curved Channel; and (b) in Straight Channel Discharge = 0.14 cms (Odgaard & Wang, 1991)

In both the straight and curved channel situations the measured results agreed with numerical predictions. Without the use of vanes, the channel bed elevation in the curved flume decreased on the outer bank while increasing on the inner bank as shown in Figure 13(a). When vanes were implemented, they clearly caused the bed elevation to be raised in the vicinity of the array while causing the scour hole to occur along the channel centerline. In both instances, Figures 13(a) and (b) show the bed elevation near the array has increased due to sediment diversion. A decrease in average velocity was also observed at this location.

Figure 14 shows the before and after images of the experimental channel from which the altered bed topography is clearly evident. The channel thalweg which was initially present along the outer bank has migrated toward the channel center and sediment has built up at the previously scoured location.



(a)

(b)

Figure 14: Upstream View of Nearly Drained Channel Bend: (a)Without Vanes; and (b) With Vanes (Wang, 1991)

Odgaard and Wang (1991) observed little change in channel cross sectional area and longitudinal slope, which suggests that overall sediment transport characteristics of the stream were unaltered. Also, vane-induced redistribution of sediment was observed for multiple stream discharges (Odgaard & Wang, 1991).

Typically, submerged vanes are placed at a 15 to 25 degree angle (Odgaard & Wang, 1991). Odgaard and Spoljaric (1986) and Spoljaric (1988) report that low angles of attack are more desirable since larger angles can produce unacceptable local scour around the vane structure and potentially undermine it. Hossain et al. (2006) studied the possibility of problems associated with scour holes forming at the base of submerged vanes and determined there was no appreciable deterioration of river training ability.

Marelius and Sinha (1998) performed experiments that specifically focused on the angle of attack and its role in producing the maximum secondary circulation. The ideal angle of attack for this experiment was defined as the one producing the maximum moment of momentum, which is proportional to the force exerted by the induced vortex on the river boundary. For this study, it was determined that the optimal angle of attack is 40 degrees (Marelius & Sinha, 1998). Figure 15 shows the results for trials at various angles.

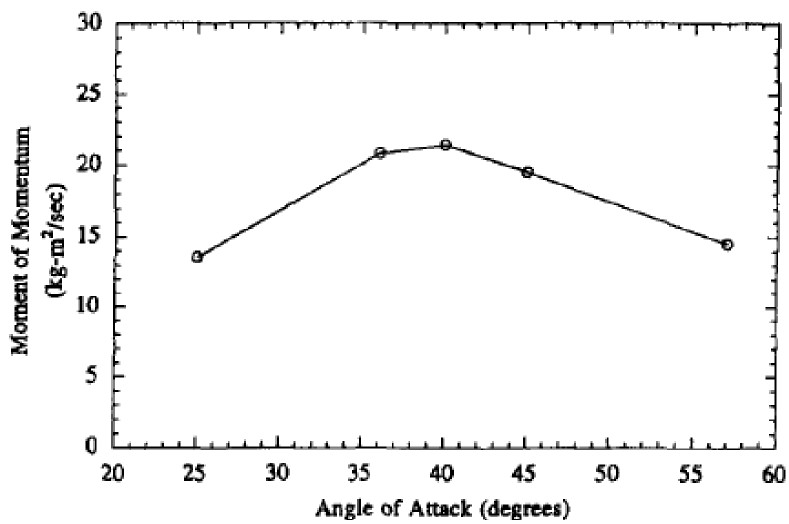


Figure 15: Moment of momentum measured 0.48 m past vane axis (Marelius & Sinha, 1998)

At an angle of attack of 40 degrees, a horseshoe vortex developed on the upstream side of the vane as well as two vortices on the downstream side. The development of multiple vortices affects circulation at high angles of attack. Marelius and Sinha (1998) suggest that the larger scour hole produced at this angle causes vortex stretching, which increases the effective width of each vane and so reduces the number of vanes necessary. However, vanes would have to be constructed in a way in which undermining of the vane itself would not be a concern. More research on vortex stretching is necessary before any standard design can be undertaken (Marelius & Sinha, 1998).

Voisin and Townsend (2002) performed studies that compared different vane configurations within physical scale models of strongly curved (i.e., radius of curvature to channel width ratio less than 3) and hydraulically narrow (i.e., width-depth ratio < 10) channels. The optimum values were found to be:

- Length / channel width, b = 0.33
- Height / bank-full flow depth = 0.35
- Angle of attack = 2 degrees
- Spacing from outer bank to vane centerline/b = 0.24
- Streamwise spacing / b = 0.70

Tan et al. (2005) use the following experimental parameters to analyze sediment transport in the vicinity of submerged vanes:

- 6 m wide, straight flume
- 0.6 m flow depth
- Uniform sediment with a diameter of 2.8-3.1 mm
- Vanes are 10 mm thick sheet metal
- Vane heights of 5, 8, 10, and 15 cm
- Vane length ranges from 1-4 m
- Vane angles are 15, 30, 45, 60, and 90 degrees

After establishing fully-developed flow, vane heights of 5, 8, 10, and 15 cm above the average mobile bed surface were subjected to a constant release of sediments until equilibrium transport rate was achieved: typically in about two days. The flow structure was divided into different zones as shown in Figure 16.

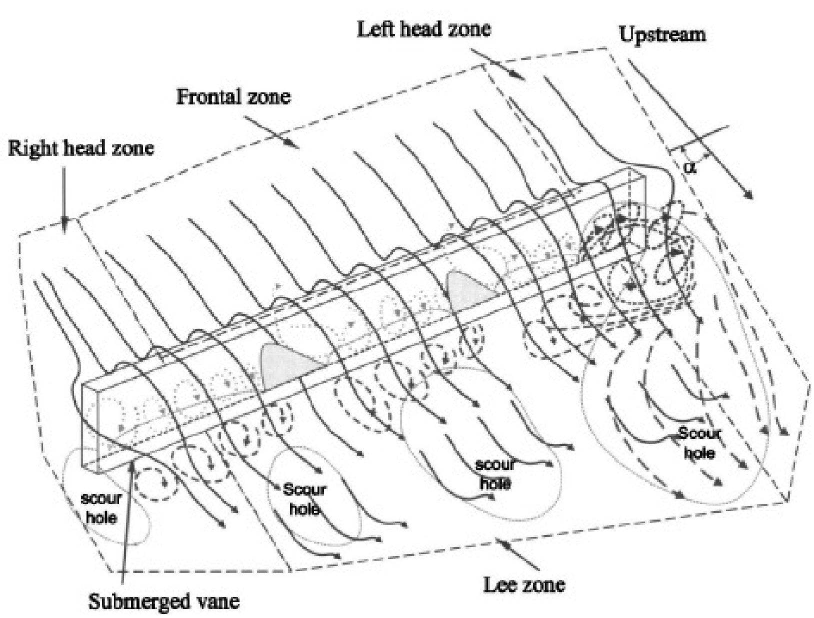


Figure 16: Flow Structures around Submerged Vanes (Tan et al., 2005)

Figure 17 illustrates how bedform dimensions can affect sediment diversion. The dunes shown in Figures 16 and 17 are the result of weir-like flow patterns overtopping the vane. While the upper region of this flow dove down and blocked propagation of helical cells, the lower region rolled backwards toward the toe of the vane digging a trench. It is at this trench where bedforms can arise and possibly reach the crest of the vane, allowing sediment particles to escape (Tan et al., 2005).

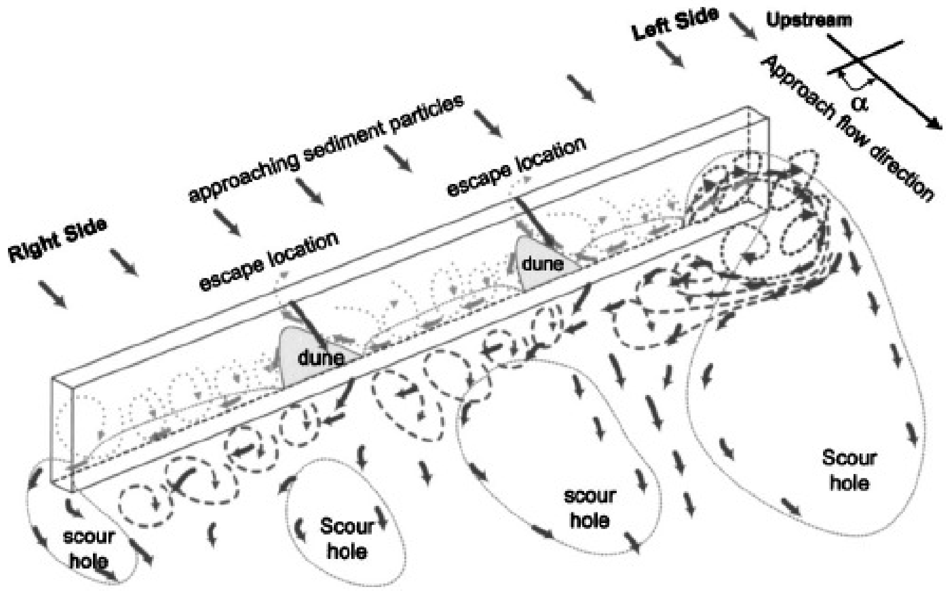


Figure 17: Flow Structures and Sediment Particle Motion around Submerged Vane (Tan et al., 2005)

This phenomenon was likely not present in Odgaard's work since the vane must be of sufficient length for large bedforms to appear. In this experiment, however, where vanes were at least three times as long as the bedforms, the effect of vane height was clearly recognizable. As flow passes the vane, the bed profile is altered. Figure 18 presents graphical results of the sediment diversion induced by three different relative vane heights. Sediment containers were used to compare changes in sediment distribution by weight laterally across the channel and compared to the weight measured in container No. 1 which was located at the farthest lateral distance from the right sidewall.

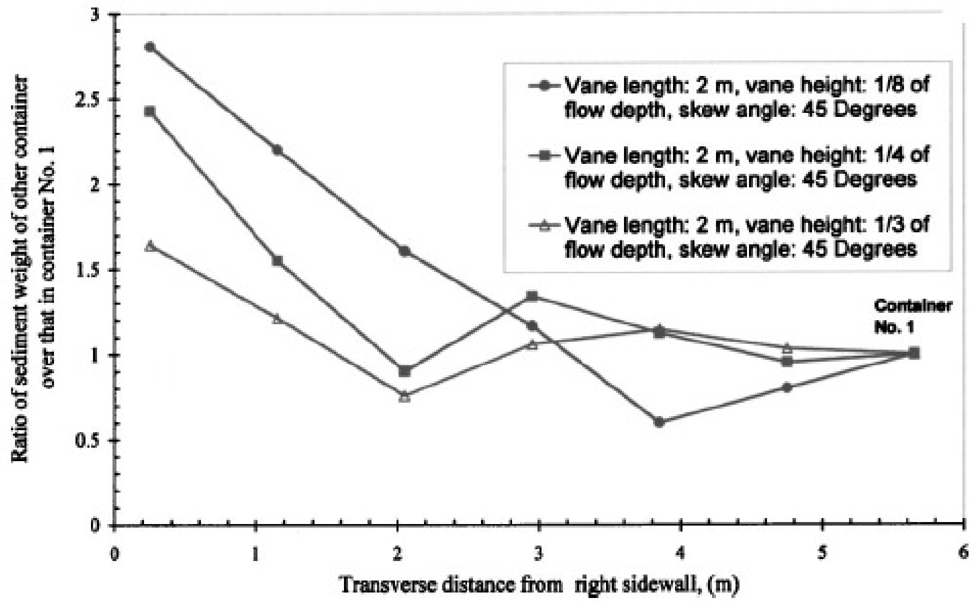


Figure 18: Lateral distribution of relative rate of sediment transport (Tan et al., 2005)

Further testing led the writers to suggest the most favorable vane height is one-fifth of the approach flow depth and optimally two to three times the bedform height so as to prevent sediment escape. A 30 degree angle is also suggested to achieve maximum sediment diversion (Tan et al., 2005).

Field Work:

Odgaard and Wang (1991) describe a field vane installation at a highway crossing of the West Fork Cedar River in Butler County, Iowa. During bridge construction, a portion of the channel was straightened, resulting in the creation of a large sandbar which became vegetated and forced flow toward the right bridge abutment, undermining the pier. Annual dredging was necessary until 4 arrays of 3 vanes each were installed in 1984. The goal of the arrays was to deflect the main flow away from the right bank to a more central location on the channel. Figure 19 shows a schematic of the river reach before and after vane installation. The vane and channel properties for this project are given below:

- Mean sediment is 0.5 mm
- Channel width is 35 m
- Bank-full depth is 2 m
- Vanes measure 3.7 m long X 0.6 m above channel bed
- Vanes are sheet metal, anchored with vertical piles
- Vanes are aligned at 30 degrees to main channel, 20 degrees to 1984 flow
- Vanes are up to 30 m from eroding bank
- Arrays are spaced stream-wise between 25-35 m

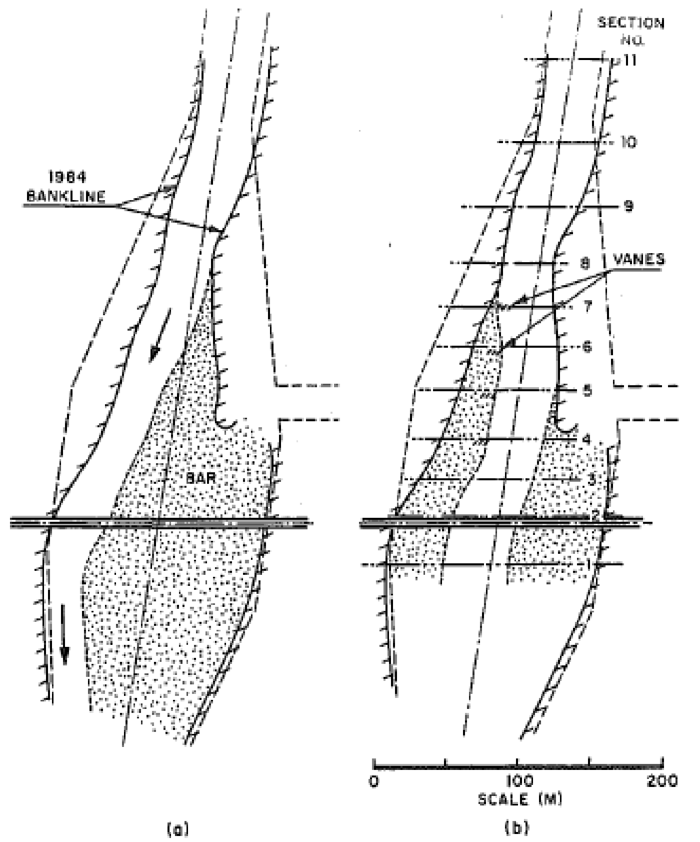


Figure 19: Plan of West Fork Cedar River Bridge Crossing: (a) Prior to Vane Installment in 1984; and (b) In 1989, Five Years after Vane Installation

(Odgaard & Wang, 1991)

As of 1991, no maintenance had been necessary. With an initial cost of $5000, the vanes were a cost-effective solution that induced a stable bed profile, eliminating the need for annual maintenance.

Other Practical Applications:

There is a wide range of practical applications for submerged vanes as they can be useful for a variety of protective or ameliorative schemes. One common use of submerged vanes is for the prevention of shoaling and lateral sediment diversions at intake infrastructure. Excessive sediment intake leads to pumping problems and failure to meet flowrate quotas. Nakato et al. (1990) and Barkdoll (1997 and et al. 1999), who performed experiments in this area, concluded that submerged vanes are an effective intake protection method. Barkdoll (1997) found that placing a vane at 10-20 degrees to the local flow direction led to less sediment entrainment at a flow diversion. Nakato et al. (1991) focused on creating an exact scale model vane for an intake on the Missouri River. The prototype was installed as designed and the results were deemed excellent. No dredging was required and no pump maintenance was needed for at least 3.5 years after installation (Nakato et al., 1991).

Other applications of vanes such as channel constriction/expansion, river confluences, and sand bar formation issues are demonstrated graphically in Figure 20.

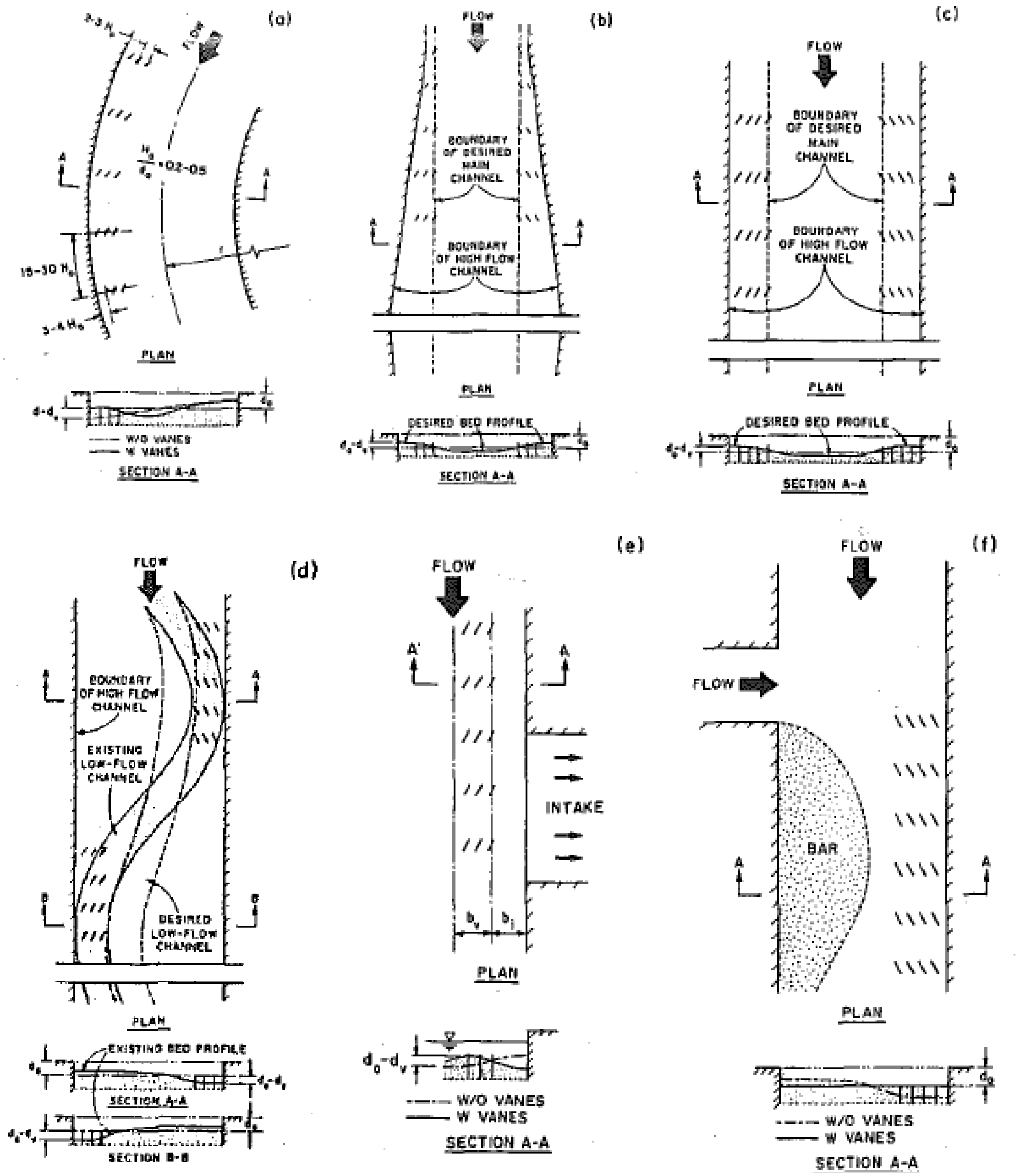


Figure 20: Typical Vane Layouts for Stream-Bank Protection and/or Shoaling Control: (a) In Curved Channel; (b) In Widened Bridge Waterway; (c) In Navigation Channel; (d) In Channel with Alternate Bars or Meanders; (e) At Water Intake; and (f) At River Confluence

(Odgaard & Wang, 1991)

Discussion/Conclusion:

Submerged vanes are a viable method for addressing channel and infrastructure instability by altering flow patterns. By attacking the patterns responsible for scour and erosion, submerged vanes are able to counteract erosive forces at stream banks and move the line of maximum velocity toward the center of the channel. The vane-induced counter-current has been shown to mitigate bank erosion and rebuild near-bank bed elevation. The most successful cases of submerged vane use alleviate danger to the bank and any adjacent infrastructure, while at the same time sediment is mounting over the vanes rendering them out of sight.

Aside from any riparian vegetation which may develop on aggraded material, there is little documentation of ecological impact to plants or wildlife. However, submerged vanes may indirectly aid the local environment by supplanting the need for riprap and other common forms of bank armor, which are known to make poor habitat (ACOE, 2003). It would be advantageous to obtain additional documentation of existing and potential environmental impacts.

A design issue that requires further clarification and research deals with the angle of vane installation. It is important to discern the angle of attack to local flow versus the angle with respect to the bank or main channel flow. Since the majority of lab research to date has utilized straight flumes, these terms have been used interchangeably in most studies. However, there can be substantial differences between the two types of angles in a curved channel, where bank erosion is often most problematic.

Finally, there is a lack of long-term monitoring and evaluation of vane installations. Engineers and planners must know what types of vane-induced behavior to expect over the long term or they may find a new solution is needed years later. Physically speaking, as bed material is deposited, flow direction will be altered and the original submerged vane angle of attack may change over time. It is difficult to say if there will be any positive or negative effects without long term monitoring. In addition, public agencies need reliable information regarding the frequency and magnitude of maintenance so they may make informed decisions about when vane installation is appropriate and also maintain the structure properly over the long term.

The information provided is this review focuses on the major conceptual and practical studies documented in literature. All relevant information from these and other studies can be obtained in the summary table located at the end of the review.

The best way to design and construct submerged vanes remains unknown. With limited case studies, it is difficult to predict the performance of submerged vanes in field situations.

Rock Vanes (with variations)

Introduction:

Rock vanes are rows of rock placed to create an arm extending out from a stream bank. The structures are angled into oncoming flow to help roll water away from eroding and collapsing banks. If the bank is allowed to erode, infrastructure such as bridge abutments can become undermined and fail. Rock vanes also aid aquatic habitat by creating flow diversity through the formation of scour pools. An examination of the underlying theory as well as laboratory work and field case studies will be presented here. This section also discusses other structures that are slightly modified rock vanes, such as J-hook vanes, cross vanes, and W-weirs. Cross vanes and W-weirs are more appropriate for grade control aspects of stream stability but are still effective as bridge pier and bank protection measures. These structures are also found to provide good habitat as well as produce recreational boating features.

Rock vanes have been found to be a viable scour countermeasure in many different studies. Multiple design handbooks provide detailed descriptions and guidelines for these structures, yet there remains relatively little research and field study information available to guide the practicing engineer on the optimum installation and maintenance of rock vanes.

Theory:

Rock vanes direct the faster portion of the flow toward the center of the channel and create quiescent flow conditions near the bank (Johnson et al., 2002a). A series of vanes in the stream-wise direction are required to create a secondary flow cell, or secondary circulation, which creates scour at the middle of the channel while simultaneously backfilling the bank, effectively relocating erosive flow patterns induced by channel curvature (Johnson et al., 2001). Rock vanes can reduce or eliminate the need for armor as high flows are redirected away from banks; additionally they compound the effectiveness of vegetative restoration techniques (NCHRP 544, 2005) Vanes have previously been studied and utilized in other forms such as submerged (Iowa) vanes and bendway weirs. Odgaard & Kennedy (1983), Odgaard & Spoljaric (1986), Odgaard & Mosconi (1987), and Odgaard & Wang (1991) provide many examples of lab work and some case studies associated with submerged vanes. Odgaard & Kennedy (1983) and Odgaard & Wang (1991) suggest that similar hydraulic principles are present in rock vanes as in submerged vanes and that for a large river with deeper pools they would be an attractive solution. However, Odgaard & Wang (1991) stress that their design guidelines are not valid for rock vanes.

Description/Guidelines:

General design criteria for rock vanes are consistent throughout the literature mentioned in this review. There are some discrepancies about material size and dimensions however. Common criteria are listed below:

- Vane angle should be 20 to 30 degrees upstream from bank
- Bank end of the vane should be at bank-full elevation with the vane tip partially embedded in the stream bed
- Vane slopes at 2% to 7% toward the channel
- Tightly formed configuration is required and rocks will be shingled upstream; no gaps present
- Vanes should be anchored with 2-3 rocks in the bank
- Long, flat rocks are preferred
- Riprap must withstand expected flows

Figure 21 shows the plan view of a typical rock vane design. In this case, Maryland's Waterway Construction Guidelines (MWCG) suggest that rock vanes extend into the channel a maximum of one-third the stream width. It can be seen here that as flow passes over the vane, it plunges into the downstream bed below, creating the associated scour pool. Doll et al. (2003) recommend that geotextile fabric always be used for any rock vane or modified rock vane structure and gives instruction on how to properly install the fabric.

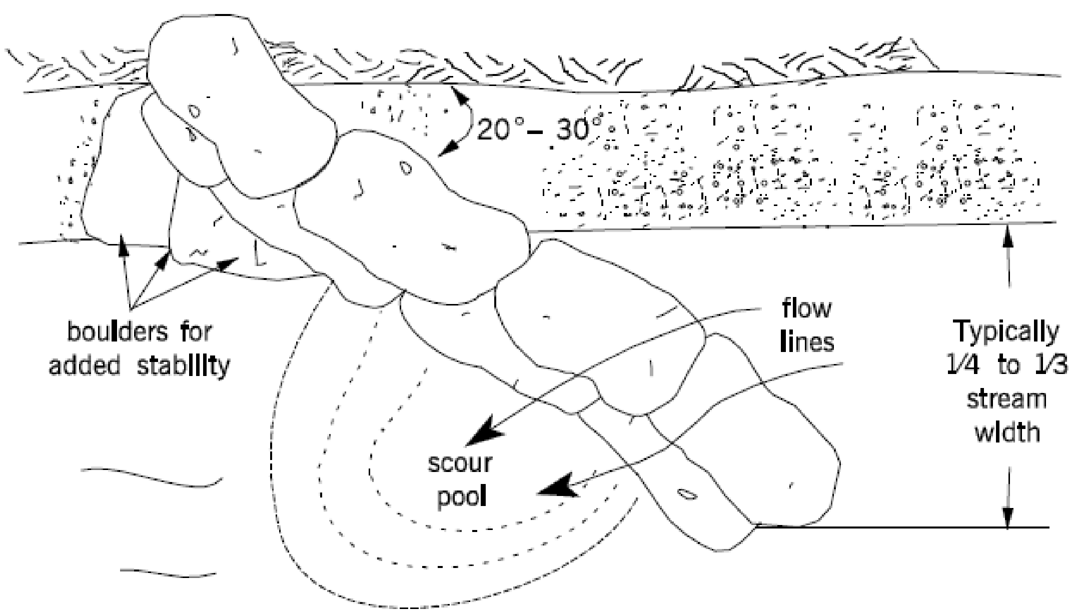


Figure 21: Typical Guidelines for Rock Vane Design (MWCG, 2000)

A minimum rock diameter of 2.5 feet or a minimum weight of 200 pounds is recommended by MWCG (2000) for streams with a width-depth ratio greater than 12 while Harman et al. (2001) suggests that rock size depends on the stream power but is generally heavier than four tons. Harman et al. (2001) also suggest that vanes may extend outwards two-thirds of the stream width while Doll et al. (2003) recommend a maximum of one-half. Rock vanes should be located just downstream of where flow intercepts the bank at acute angles (Doll et al., 2003). Johnson et al. (2002b) presents collective field experience from a diverse range of practitioners and concludes rock vanes are best suited for armoring and protecting the bank toe, redirecting flow, and creating flow diversity; the enhancement of mass stability is considered a common secondary benefit. Vanes are also well suited for reaches subjected to high velocity, limited backwater effects, high bedload transport, lateral channel migrations, steep banks, erodible banks, and rigid banks (Johnson et al., 2002b).

One of the more common modifications to the traditional rock vane is the J-hook vane. The J-hook vane is constructed exactly like a rock vane except there are additional boulders placed at the tip of the vane in a hooking pattern with gaps between them. This layout creates scour by forcing the flow in the center of the channel to converge between the gaps. While this modification is primarily to create habitat, it also provides energy dissipation (Harman et al., 2001; Rosgen, 2001; NCHRP 544, 2005). The hook portion of the structure provides a longer, deeper, and wider scour pool than that created by the rock vane only (Rosgen, 2001).

Figure 22 shows the plan view of a typical J-hook rock vane. With this modification, it can be seen that the structure will span approximately 60% of the bank-full width, therefore approximately one-third the length of the structure is rock vane while another one-third is the additional J-hook section.

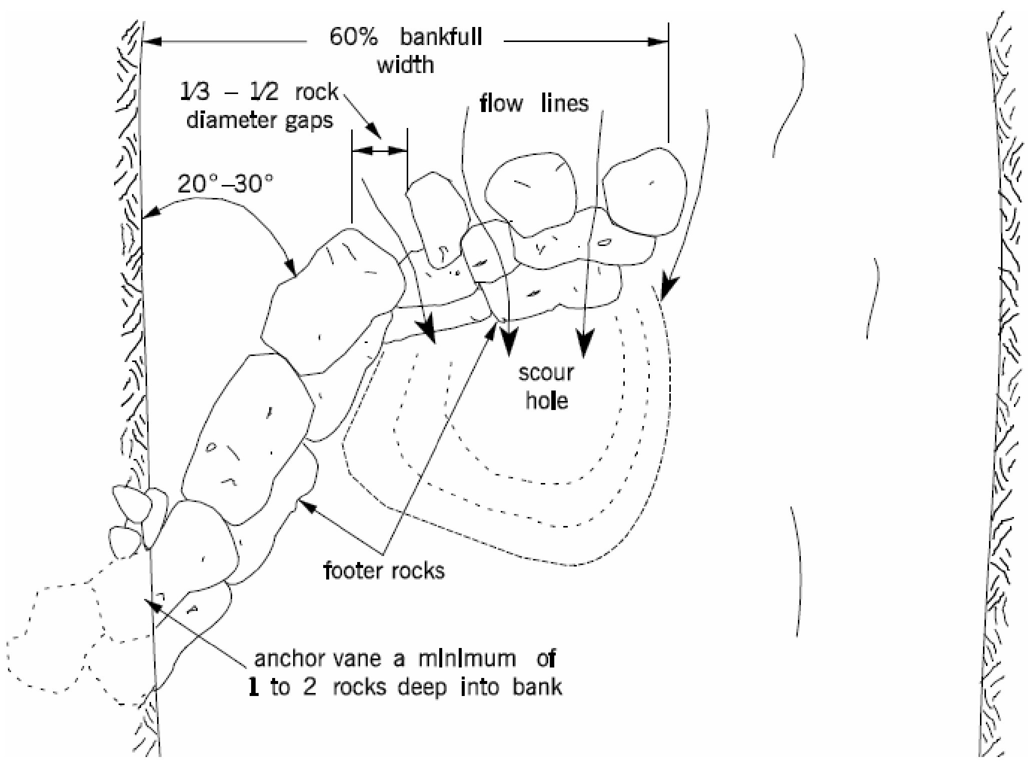


Figure 22: Typical Guidelines for J-Hook Rock Vane (MWCG, 2000)

Sediment transport capacity is unchanged by the addition of the structure since there is an increase in shear-stress and stream power at the center of the channel. The flow separation zones in the center of the channel where upwelling and downwelling currents are found provide excellent habitat for trout (Rosgen, 2001). The chutes that lie in the hook section can also create recreational boating (i.e., canoe and kayak) features in larger channels (Rosgen, 2001).

Cross vanes are another variation of the rock vane but have a primary function as grade control structures while still providing a reduction in near-bank shear stress. The structure raises or maintains the bed elevation, so it is normally installed within a section of little or no turbulence for larger streams or at the head of a riffle for smaller streams (Doll et al., 2003). Additionally, the structure will create a stable width-depth ratio while maintaining channel and sediment transport capacity (Rosgen, 2001). Cross vanes are constructed by connecting the tips of two rock vanes from opposite banks with rocks arranged perpendicular to the flow. Figure 23 shows the typical layout and location of the associated scour pool.

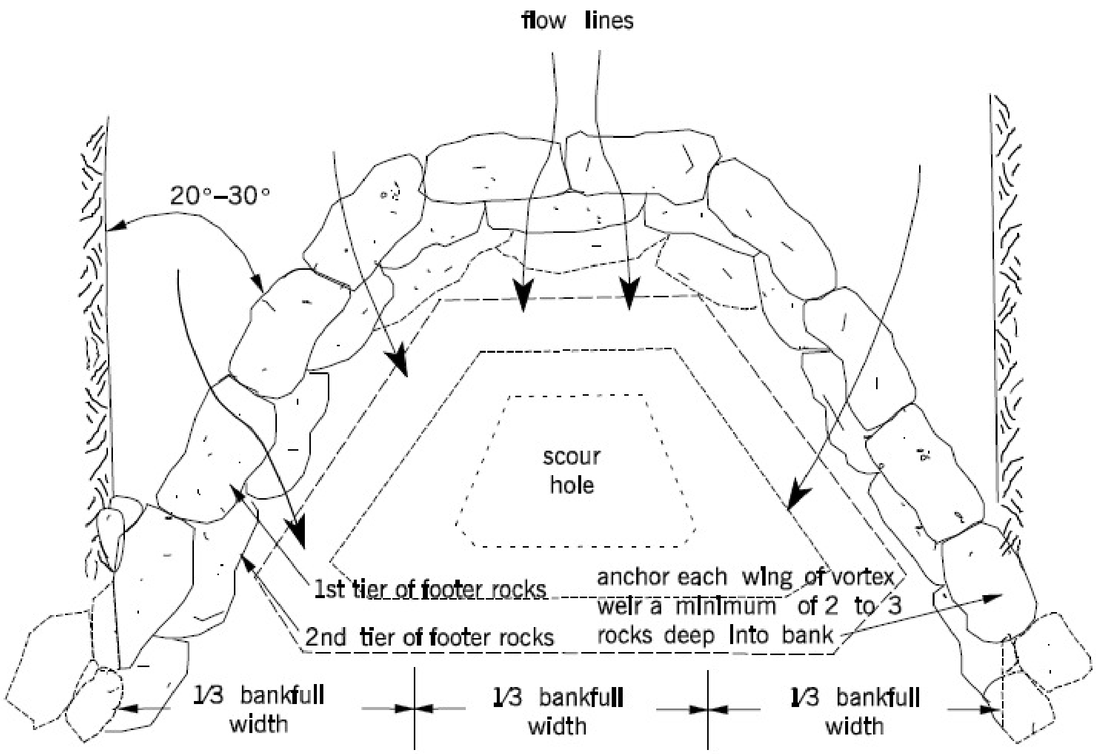


Figure 23: Typical Guidelines for Cross Vane (MWCG, 2000)

The cross vane creates a variety of habitat in the channel by increasing flow diversity and substrate complexity (NCHRP 544, 2005). The vane sections raise the water level in the near-bank area providing more cover, the scour pool allows a holding area in high and low flow periods, flow separation zones become feeding lines, and the downstream end of the scour pool is ideal for spawning beds. As with the J-hook, the cross vane also creates recreational boating features (Rosgen, 2001). Cross vanes should not be used in channels with well-developed pool-riffle sequences or channels with bedrock beds or unstable bed substrates (MWCG, 2000).

Like cross vanes, the W-weir is primarily a grade control structure that facilitates excellent habitat. The W-weir is normally only used in larger rivers since they are relatively large structures themselves. The layout of this structure is a "W" shape looking downstream. This arrangement creates dual thalwegs and therefore can lead to more flow diversity (Rosgen, 2001). Figure 24 shows typical guidelines for a W-weir.

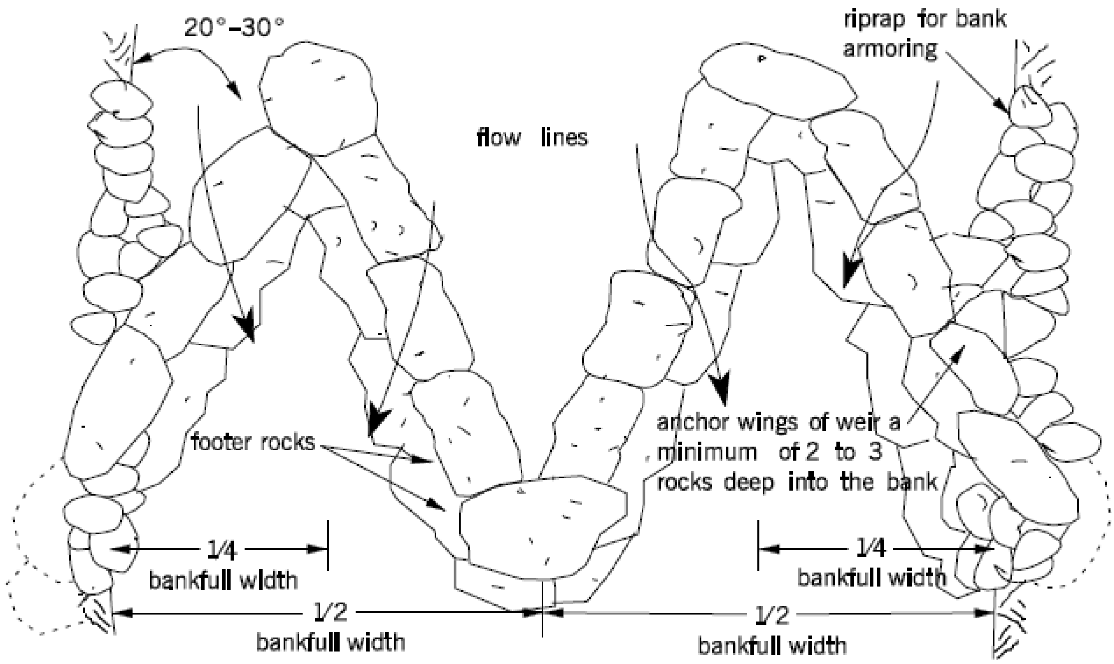


Figure 24: Typical Guidelines for W-Weir (MWCG, 2000)

W-weirs provide stream bank protection, improve recreational boating, facilitate irrigation diversions, and reduce bridge scour at the center pier. For larger rivers, double W-weirs can be used for protection of multiple piers (Rosgen, 2001). W-weirs functional applications are to armor and protect the bank toe, redirect flow, create flow diversity, and stabilize the bed. Secondary benefits include enhanced mass stability and instream habitat (Johnson et al., 2002b). W-weirs are also well-suited to reaches with high velocity, flashy flows, high bedload transport, lateral channel migration, and steep, highly erodible banks (Johnson et al., 2002b).

Lab Work:

Johnson et al. (2001a) performed lab experiments to determine if rock vanes were viable countermeasures to protect vertical abutments from scour. Analysis was also completed to determine the optimal design of the vane. Tests were completed in a straight flume under the following conditions:

- Flume measures 1.5 m wide by 15 m long
- Flow depth varies between 9 and 28 cm
- Slope set at 0.002
- Uniform sand size of 1 mm
- Flows ran at incipient sediment motion
- Vanes constructed of marine plywood with upstream tip set at bed level
- Vane effective length is 1/3 channel width
- Vertical abutment located in floodplain

Figure 25 shows the experimental setup.

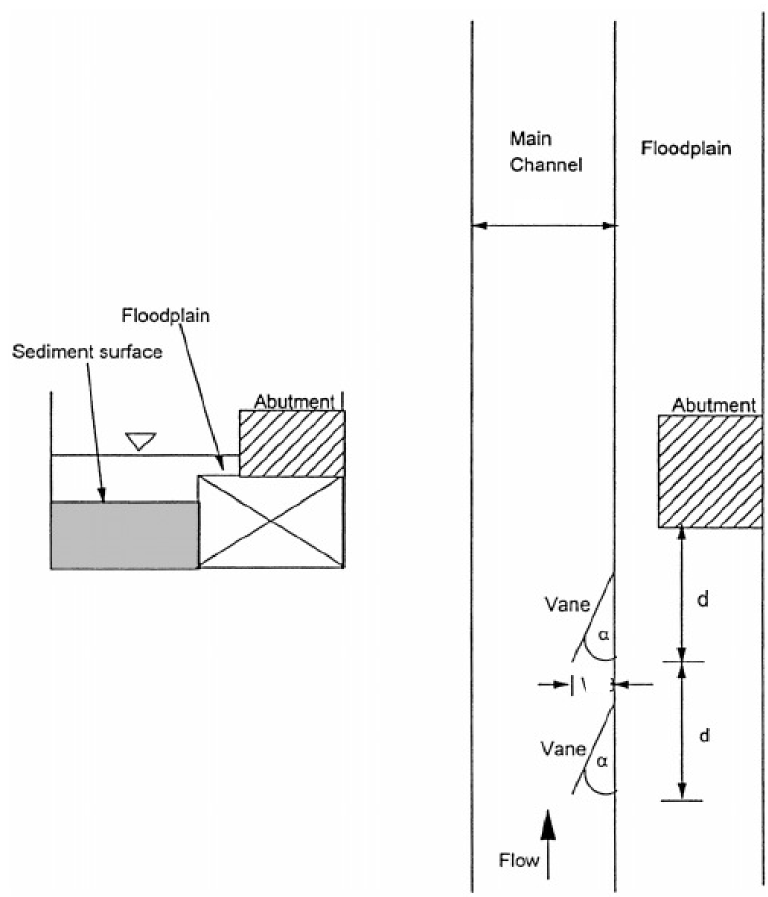


Figure 25: Experimental Flume Setup (Johnson et al., 2001(a))

Six runs were performed without vanes in place in order to assess scour conditions caused by the abutment alone. In each run, the scour hole developed immediately adjacent to the abutment. Thirty-one runs were performed with the vanes in place in a variety of configurations; all resulted in the reduction of near-bank velocity and the relocation of the scour hole to downstream of the vane near the channel center. Figure 26 shows channel profiles for one run with and without vanes. It can be seen in this comparison that the vane has forced the thalweg to migrate approximately 10% of the channel width, about 15 centimeters, farther from the bank than when no vane is present.

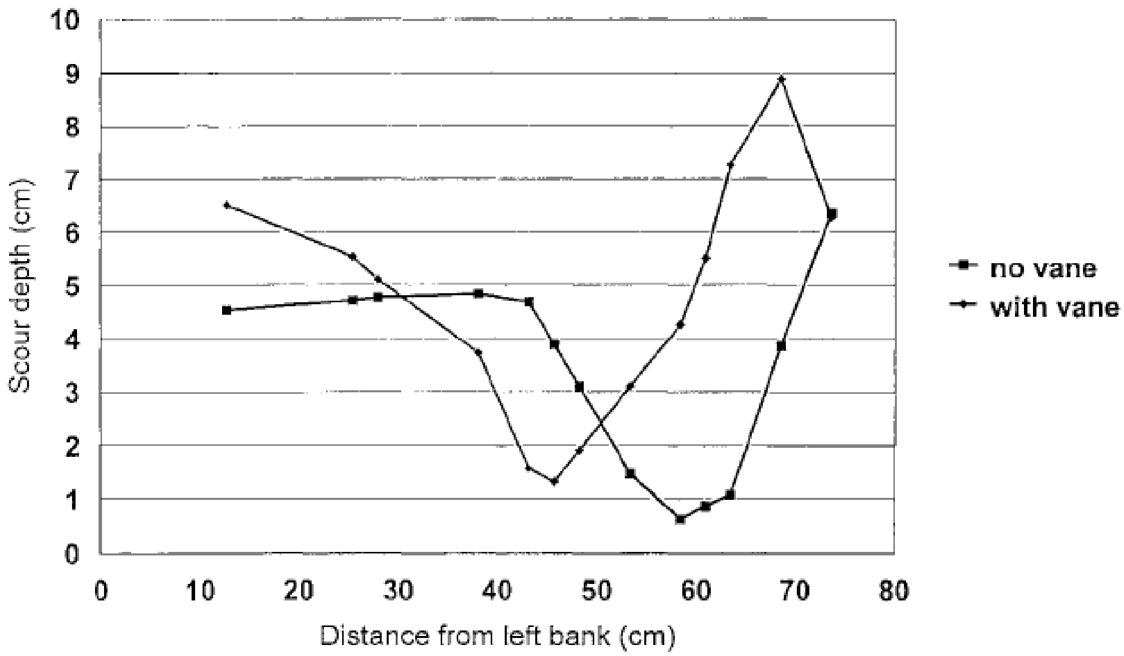


Figure 26: Location of Abutment Scour with and without Vane

(Johnson et al., 2001a)

Results from all trials suggest that rock vanes have the following optimum design values (Johnson et al. 2001a):

- Angle to the bank of 25 – 30 degrees
- At least two vanes should be used in succession
- Vane closest to the abutment should be located upstream twice the width of the channel
- Vane height should be bank-full at the bank, and slope down to channel invert elevation; slightly submerged

Johnson et al. (2001b) suggest that field procedures such as the use of geotextile fabric or well-graded material be used to mitigate structural porosity. Doll et al. (2003) recommend that geotextile fabric always be used for any rock vane or modified rock vane structure.

Johnson et al. (2002a) studied the use of rock vanes, cross vanes, and W-weirs for reducing scour at piers or abutments. Flume studies were conducted with flow depths up to 28 cm, corresponding to 100-year events and scour was measured with and without the structures in place. Results yielded the following design criteria (Johnson et al., 2002a):

- Rock vanes oriented at 30 degrees result in scour reduction of 64-90%
- Rock vane height should be bank-full at the bank, and slope down to channel invert elevation
- Series of two or more vanes results in 15% greater scour reduction than that of a single vane
- Rock vane should be located 1.5 to 2 times channel width upstream of the pier or abutment
- Cross vanes use the same parameters as rock vanes, section perpendicular to flow should be built at channel invert elevation
- W-weir central apex angle should be set to 40 degrees
- W-weir central apex elevation should be set at ½ to ¾ bankfull elevation

Bhuiyan et al. (2007) performed laboratory experiments on a W-weir in a meandering channel to determine its potential for river restoration applications and sediment transport. Detailed measurements were obtained of flow patterns, turbulence, scour deposition, and bedload transport adjacent to the W-weir. Tests were run at bankfull (97 L/s) and overbank (164 L/s) flows. Study parameters were as follows:

- Flume measures 50 m long X 1.6 m bankfull width; 10 m wide floodplain
- Sinuosity is 1.38; wavelength is 14.96 m
- W-weir angled 30 degrees upstream to the banks
- Mean sediment is 1.5 mm
- Downstream of W-weir was unarmored and allowed to scour

The W-weir was installed midway between the crossover and bend apex in Section H of Figure 27. This is the location of the run between the riffle and pool.

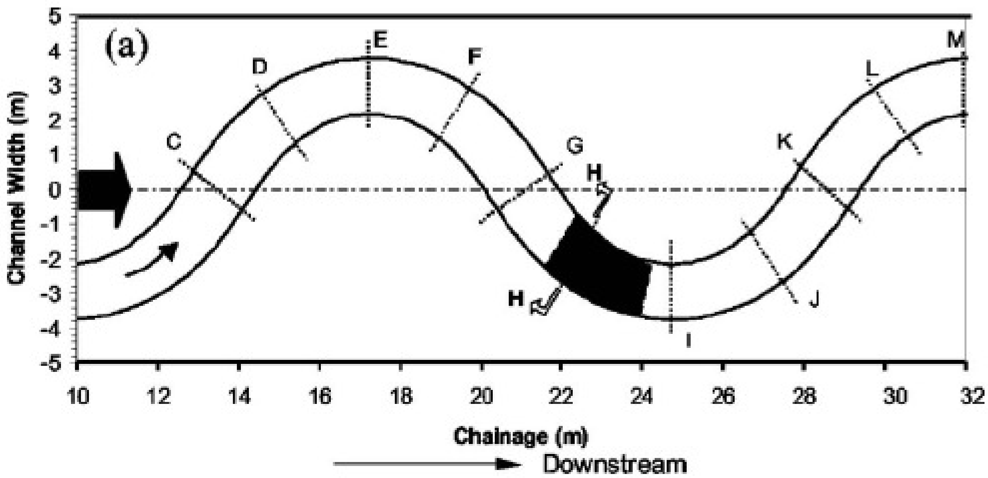


Figure 27: Plan View of Channel with Cross Sections; Measurements were concentrated in the shaded area adjacent to the W-weir (Bhuiyan et al., 2007)

Bhuiyan et al. (2007) recorded bed profiles at six cross sections upstream and downstream of the W-weir at bankfull and over-bankfull flow rates. Additionally, bed profiles were measured without the W-weir in place as a control. y is the lateral distance from the left bank and b is the channel width. The profiles are given in Figure 28.

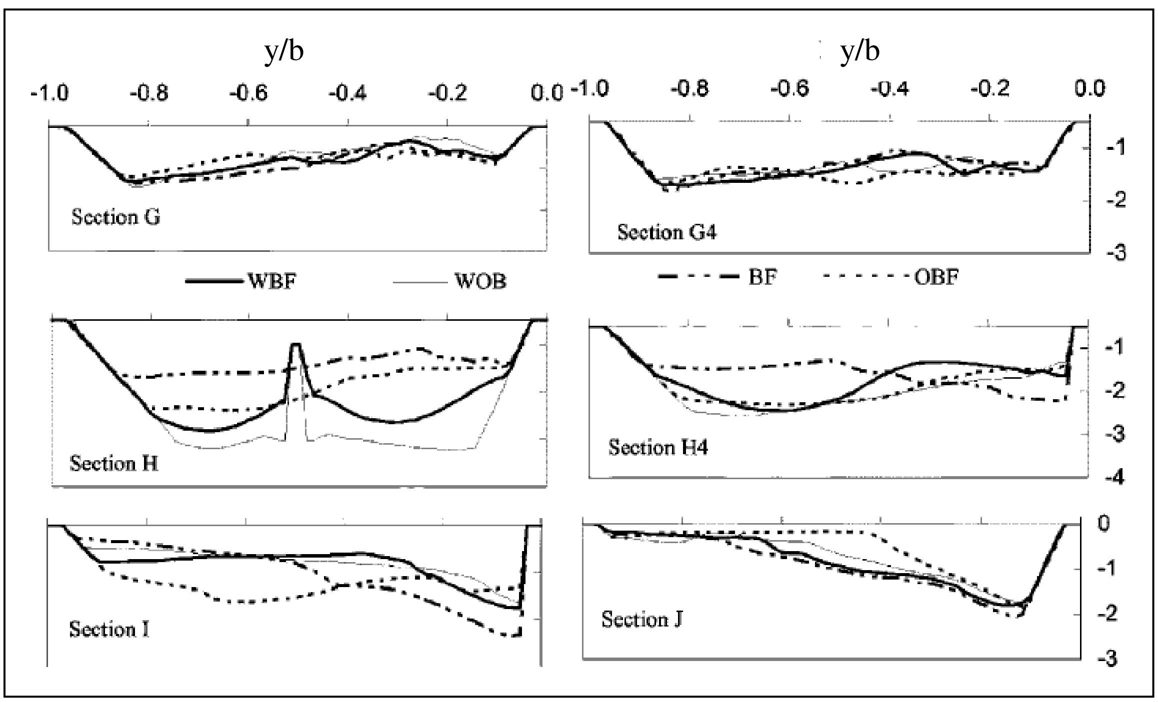


Figure 28: Bed Profiles at Cross Sections for: WBF-bankfull with weir, WOB-over bankfull with weir, BF-bankfull without weir, and OBF-over bankfull without weir (Bhuiyan et al., 2007)

In the sections located immediately downstream of the W-weir, the bed profile changed noticeably relative to the runs without the W-weir in place. Upstream reaches remained relatively unchanged from natural channel conditions. Final bed level contours from prolonged bankfull and over bankfull flows are found in Figure 29. As expected, two deep scour holes were formed downstream immediately adjacent to the W-weir. Over bankfull flow resulted in maximum scour occurring near the inner bank while bankfull flow produced maximum scour on the outer bank. The highest average velocities occurred toward the inner bank with lower velocities near the outer bank. Note that in the non-weir case, bankfull flow caused greater scour at the inner bank than the overbank flow scenario (Bhuiyan et al., 2007).

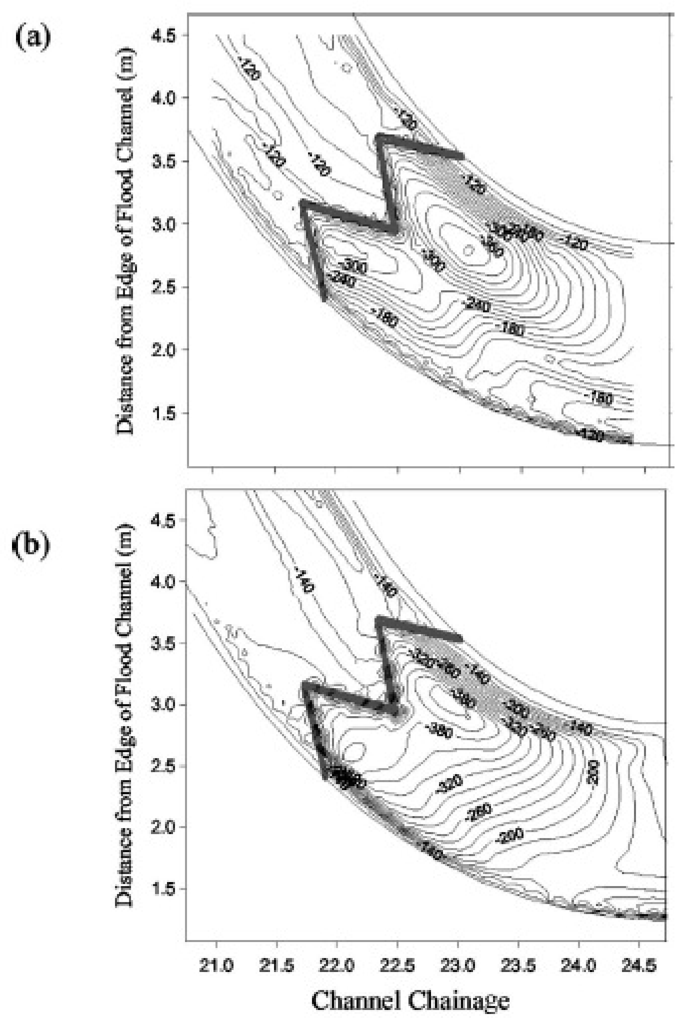


Figure 29: Bed Profile Contours (in mm); (a) bankfull flow; (b) over bankfull flow (Bhuiyan et al., 2007)

Bhuiyan et al. (2007) conclude that there is significant interaction between the structure and any floodplain flows that can potentially affect the W-weir stability. The most critical criterion for a successful project is the structure location within a channel meander. The downstream end of the riffle zone or the glides leading into the riffles are the most desirable locations since those areas will offer minimal interference with sediment transport capability (Bhuiyan et al., 2007).

Dahle (2008) performed field and numerical studies of cross vanes and J-hooks in order to determine their viability as scour countermeasures at bridges; specifically during high flow events. The study is considered valid for streams with baseflow depth less than 1 foot. Results from the analysis suggest that these structures have minimal effect on flow during flood events and therefore have no significant impact on scour prevention during these events. Dahle (2008) also suggests that these structures may actually induce unintended scouring, especially when construction has not been completed properly.

Field Work:

Johnson et al. (2002a) summarized findings for a flow improvement project at a small bridge on Bear Creek in Pennsylvania. Rock vanes and cross vanes were installed to help improve flow through the bridge opening where erosion was threatening the left bridge abutment. The rock vanes redirected erosive flow away from the endangered bank immediately after installation. The new flow patterns led to sediment deposition along the toe of the bank within three weeks and the cross vane which was installed immediately downstream of the bridge crossing to help pool the flow and assist in channeling flow to the center (Johnson et al., 2002a).

The North Carolina Stream Restoration Institute (SRI) has researched or administered over 200 in-stream structure projects designed and installed by consulting firms. These projects include three to five year pre- and post-installation evaluation and monitoring schemes. This work has allowed the SRI to identify common pitfalls associated with the design and installation of rock vanes.

- Large, rectangular boulders work best since gaps should be avoided, especially near the banks, which is the area of desired deposition
- Gaps among the bottom rocks allow winnowing and eventual undermining; this is the worst-case scenario
- Rock vane arm slopes may be as steep as 8-10 % in order to maintain lower width/depth ratios (Harman et al., 2001)

Johnson et al. (2002b) observed vanes, cross vanes, and J-hooks installed in Piney Creek, Maryland and cross vanes installed in Minebank Run, Maryland. Both sites were monitored with cross-sectional surveys for one year. The structures located in Piney Creek experienced an 8-year flow and did not fail. These structures were designed according to the MGWC publication and were implemented in the appropriate stream setting. Cross vanes along Minebank Run failed due to improper pitch of structure arm and lateral channel migration (Johnson et al., 2002b).

Johnson and Niezgoda (2004) proposed a method for selecting bridge scour countermeasures which includes assessment of various failure modes, ease of failure detection, and cost of preventative schemes. By assigning a rating for each of these criteria, an overall risk value can be assigned to possible scour countermeasures. The alternatives can now be compared using normalized values. This allows the designer to pay special attention to specific components which are at a higher risk in some situations (Johnson and Niezgoda, 2004).

The US Bureau of Reclamation published a study (2007) of failure methods for several different types of rock weir structures in the western US. Of the 127 structures analyzed, 28 were J-hook vanes and another 4 were W-weirs. Furthermore, 21 of the J-hooks were determined to have at least partially failed while 3 of the W-weir completely failed. It was determined that the growth of the scour pool was the primary failure mechanism in 52% of the J-hook failures and 33% of the W-weir failures. As the depth of the scour pool increased, footer rocks shifted, thus leading to the tilting of header rocks which often fell in the downstream pool. Secondary failure mechanisms were also identified at these sites with filling and burying being the most common contributor to failure. Filling and burying results from extensive deposition upstream and downstream of the scour pool resulting in an undefined scour pool (USBR, 2007).

Several techniques are described which aim to mitigate failure of these structures (USBR, 2007).

- Placing structures on bedrock or concrete footers to provide a more stable foundation
- Grouting structures can better help them survive high flow events
- Series of structures outperform a single in terms of project goals
- Interlocking rock placement and rock size reduce failure possibilities

Discussion:

Rock vanes and associated structures are a promising method for addressing channel and infrastructure instability by altering flow patterns. Though specific mechanics have not yet been identified, it has been suggested that rock vanes alter the flow patterns responsible for scour and erosion in a way comparable to that of submerged vanes. By forcing the scour hole toward the center of the channel away from the bank, rock vanes can protect infrastructure and bridge abutments. Additionally, the W-weir should be able to alleviate scour at bridge piers when the downstream nodes of the weir are aligned with the submerged pier. The most successful cases of rock vane use alleviate danger to the bank and any adjacent infrastructure, while at the same time providing flow diversity for the ecosystem and boating features for outdoor enthusiasts.

Rock vane structures create flow patterns and channel topography that may be beneficial to fish and other aquatic species. The channel also maintains a somewhat natural appearance, especially if the rock material is from local sources. Because the sediment transport rate is conserved, the rock vanes have limited effect on upstream and downstream river reaches.

A table of rock vane and channel properties for all laboratory experiments and field work summarized here is included in Appendix A. This table provides a summary of all the design elements for each study and provides the researchers' results and conclusions.

Multiple design handbooks authored by government agencies provide guidelines and recommendations for the use of rock vanes. However, these guidelines are based on only a limited number of lab and field studies. More research is necessary to determine optimal installation and maintenance guidelines for a wide variety of stream types and configurations.

Stream Barbs & Bendway Weirs

Introduction:

Both stream barbs and bendway weirs are rock structures placed along stream banks that extend from the bank into the channel flow. Flow patterns, especially those located around stream meanders, are often highly erosive. If the bank is allowed to erode, infrastructure such as bridge abutments can become undermined and fail.

Stream barbs and bendway weirs appear to be viable scour countermeasures. Several state agencies have published technical notes and case studies for streams of varying properties. Multiple journal articles summarizing laboratory and field studies are also available.

Theory:

Stream barbs and bendway weirs modify and move the helicoidal flow patterns of secondary currents typically associated with channel meanders. The presence of these in-stream structures relocates the erosive flow patterns from the vulnerable outer bank toward the center of the channel (Derrick, 1997). Stream barbs specifically protect the bank by disrupting velocity gradients in near-bed regions, deflecting currents away from the bank by forcing flow perpendicularly over the weir (see Figure 30), and shifting the channel thalweg to the streamwise end of the barbs (Matsuura & Townsend, 2004).

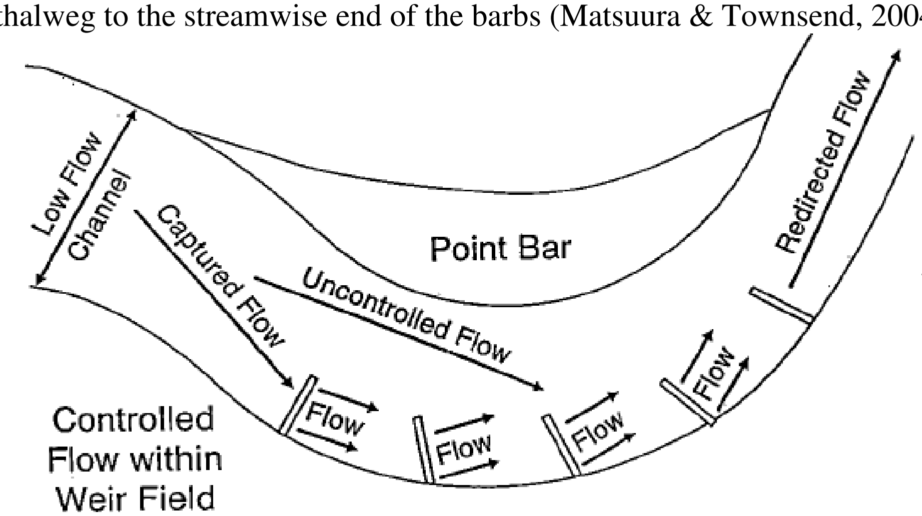


Figure 30: Bendway Weir Theory (Derrick, 1998)

An effective series of barbs will induce a subcritical zone of backwater which should reach the next upstream barb. This upstream progression of subcritical reaches controls erosion and eventually leads to sediment deposition in the near-bank region (EN-23, 2005). Bendway weirs are primarily used along meanders in larger rivers and tend to work best in high-flow, high-energy conditions but have been observed to function effectively in low-flow events (Derrick, 1997 & Abad et al., 2008).

Description/Guidelines:

Design criteria and appropriate settings for stream barbs and bendway weirs have been published by numerous authors. The Natural Resources Conservation Service (NRCS) has designed and documented the use of these structures in multiple states. Information regarding stream barbs and bendway weirs are often given interchangeably but, for this review, guidelines will be explicitly identified when possible. The primary difference between the structures is that stream barbs are used in small streams while bendway weirs are utilized primarily along major river reaches at meanders; barbs are also oriented at sharper upstream angles (NEH-654, 2007). Additionally, barbs are designed to extend farther up the bank than bendway weirs (Evans & Kinney, 2000).

Centerline side view profiles for typical stream barbs and bendway weirs are given in Figures 31 & 32, respectively. Note the slope specifications and the sections of structure that are keyed into the bank and bed. Also note the horizontal top of the bendway weir in Figure 32, as opposed to the sloped stream barb shown in Figure 31.

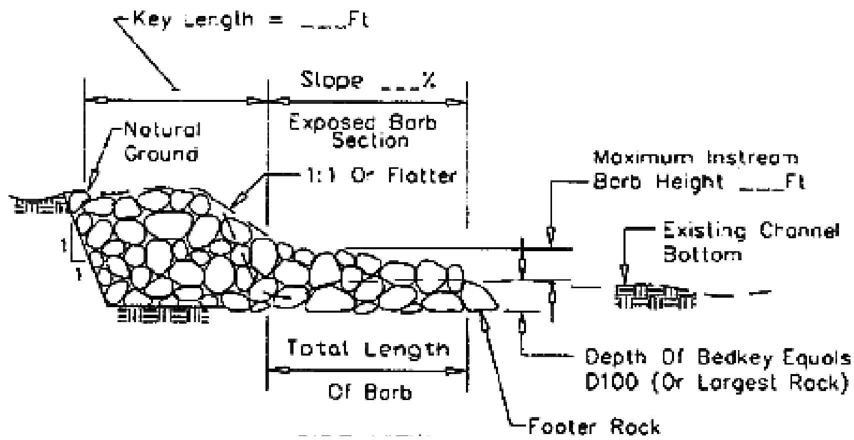


Figure 31: Typical Stream Barb Centerline Profile (Evans & Kinney, 2000)

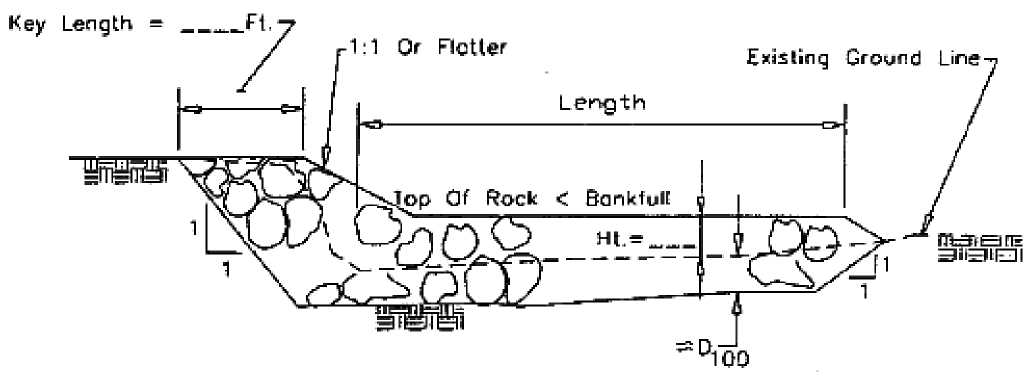


Figure 32: Typical Bendway Weir Centerline Profile (Evans & Kinney, 2000)

Figure 33 shows a series of installed bendway weirs.

Figure 33: Series of Exposed Bendway Weirs (Thornton et al., 2005)

Design criteria given for stream barbs as provided in NRCS Engineering Technical Note-Number 12 (EN-12, 2001) are summarized below.

- Farthest upstream barb shall be located just upstream of area first impacted by erosion
- Barbs should not be placed downstream of the ¾ turn length as shown in Figure 34
- Barb height is determined by channel forming flood event (~1.5 year return); typically 1/3 to ½ of the average channel forming flow depth
- Difference in height between barbs should approximate the energy grade line
- Barb will slope downwards from the bank no steeper than 1V:5H
- Vector analysis should be done to determine barb spacing
- Upstream angles tangent to the bank between 20 and 45 degrees
- Effective length should not exceed ¼ channel forming flow width
- Barbs must be keyed into the bank and bed to prevent water from flowing around and underneath the structure
- Barb width is generally one to three times d_{100}
- Structures should be installed during low flow periods with rock placement beginning at the upstream end of the structure
- Stream barb rock material should be twice the d_{50} lining the channel

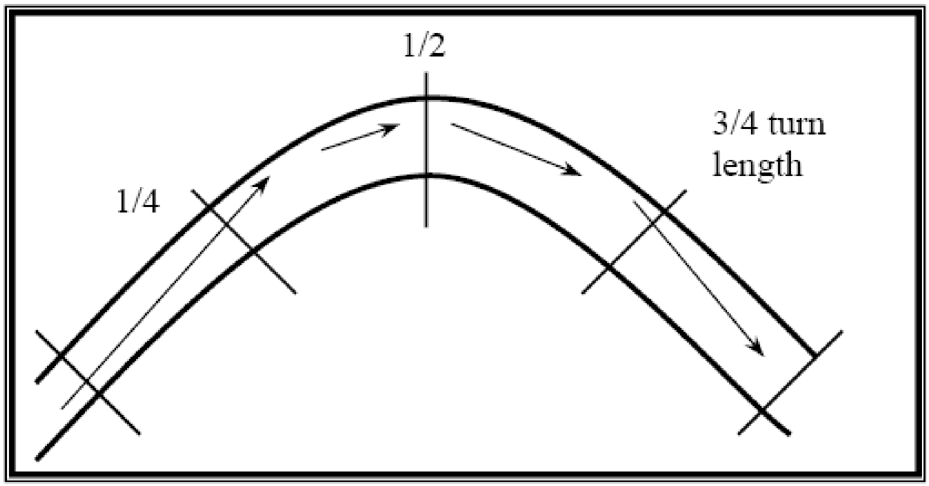


Figure 34: Channel Bend Turn Lengths (EN-12, 2001)

The property which comprises the greatest differences across practice and research is the angle of installation tangent to the bank. While some suggest optimum angles to be around 20-25 degrees (Derrick, 1995; EN-23, 2005), other researchers (Fox et al, 2005 & ACOE, 2002) contend that higher angles, such as 50 degrees, are most effective. Perpendicular bendway weirs have also been studied and implemented in the field (Thornton et al., 2005).

More recent research has determined additional constraints for the selection of stream barb angle based upon channel geometry (Saele & Fripp, 2005):

- If the ratio of bend radius to channel width is < 3; use another treatment
- If the ratio of bend radius to channel width is < 6; use $\theta < 30$ degrees
- If the ratio of bend radius to channel width is > 6; use θ between 30-45 degrees
- If the ratio of bend radius to channel width is < 9; use $\theta > 45$ degrees

Stream barbs are especially sensitive to changes in flow depth to a point in which the structural function is dependant upon it. During low flow, the barb will act as a deflecting device and as flow increases, hydraulic redirecting will take over. During high flow, the barbs become less significant, but still affect bottom currents. The design height is very important since barbs perform most efficiently during bankfull and channel-forming events (NEH-654, 2007).

The Federal Highway Administration (FHWA) has published design guidelines for bendway weirs in Hydraulic Engineering Circular No. 23 (HEC-23, 2001). This handbook suggests that bendway weirs and stream barbs are the same structure and the reason for the different names is due to the region where they are constructed. Guidelines given for stone bendway weirs are given below:

- Height should be 30 to 50 percent the mean annual high water depth
- Weir angle should be between 50 to 85 degrees tangent to the upstream bank
- Centerline of weir should be flat or no steeper that 1V:5H

- Weir must be keyed into the bed to a depth approximately equal to d_{100}
- Weir length should cross thalweg and not be greater than 1/3 stream width
- A shorter weir is recommended upstream of the meander
- Weir spacing based on site conditions, but generally 4 to 5 times length
- Weir must be keyed into the bank approximately 1/5 its length
- Width may be between 1 and 4 m depending on length
- At least three weirs are normally needed
- Rock material size determined from riprap sizing criteria

Lab Work:

Matsuura & Townsend (2004) studied stream barbs in narrow channel bends and compared different arrangements to a reference channel without barbs. Two channel curves were used with angles of 90 and 135 degrees. The experimental section of the flume measures 0.460 m wide by 0.406 m deep. Tests were completed under the following experimental conditions:

- Median sediment size is 0.78 mm with standard deviation of 1.3
- Barbs constructed of 2.7 mm opening wire mesh
- Barbs tested at angles of 20, 30, and 40 degrees
- Barb height set to 0.5 and 0.375 times bankfull depth

The reference channel was run until equilibrium was attained and the scour patterns were recorded. The thalweg was located near the outer bank and sediment deposition occurred along the inner bank as shown in Figure 35.

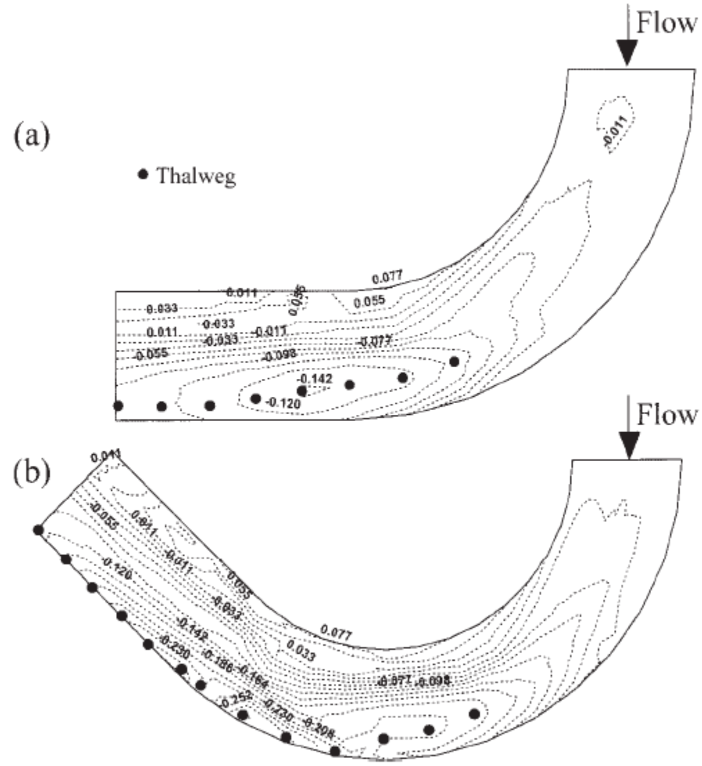


Figure 35: Reference Contour Patterns for (a) 90 degree bend; and (b) 135 degree bend (Matsuura & Townsend, 2004)

Several stream barb patterns were tested and erosion patterns for two of the tests are found in Figure 36. It can be seen in these plots that the primary scour regions have been moved toward the end of the stream barbs, which is also where the channel thalweg has migrated.

(a)

(b)

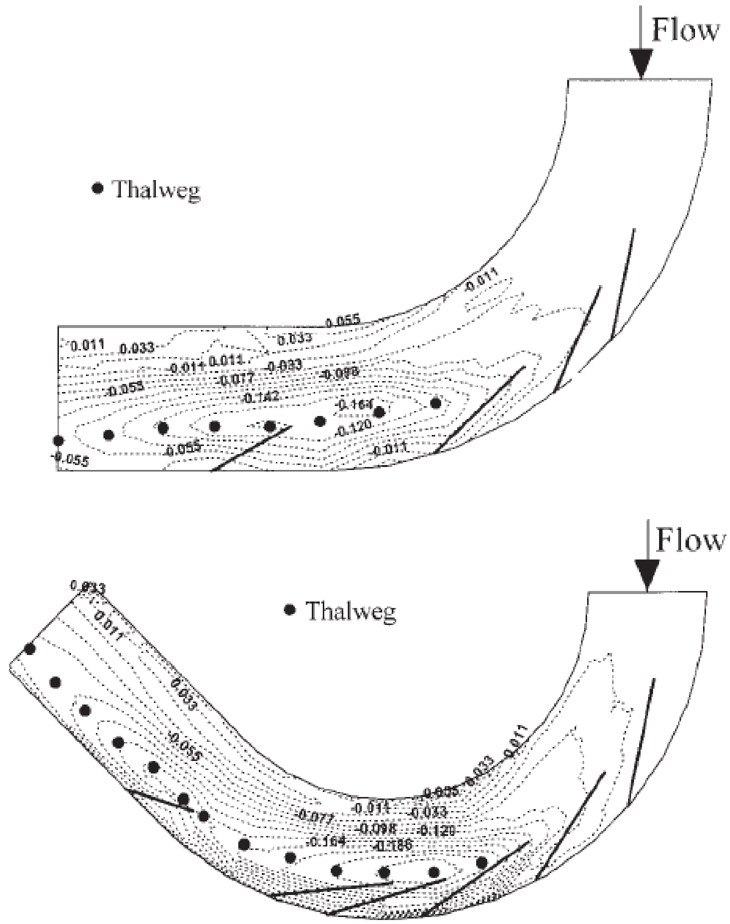


Figure 36: Contour Patterns Generated With Stream Barbs (a) in 90 degree bend; and (b) in 135 degree bend (Matsuura & Townsend, 2004)

The Washington State Department of Transportation (WSDOT) unveiled design for a stream barb specifically tailored for the mild slope, gravel-bed streams of the Pacific Northwest. Fox et al., (2005) performed a series of experiments to measure the fluid-sediment dynamics associated with WSDOT designed barbs. A model was created using Froude similarity based on the North Fork of the Toutle River in Cowlitz County. Three analyses were used to measure flow redistribution, scour, and stream bank protection.

The following experimental parameters were used in the flow redistribution and scour studies:

- Slope was 0.0045
- Flume was 1.22 m wide by 10.4 m long
- Flow depth was 0.152 m
- Median sediment size was 5.2 mm

Observations from the flow redistribution experiment showed a clear depiction of flow regimes associated with the barb (Fox et al., 2005). A stagnant wake region was present immediately downstream of the barb along the bank; this pattern was attributed to the unsubmerged portion of the barb. An accelerated flow region was found overtopping the weir adjacent to the stagnant region; in this area flow was pushed toward the channel center creating a hydraulic jump rather than a secondary circulation cell.

Results from the scour experiment showed that the scour hole was formed just upstream of the nose of the barb. The scour hole continued downstream in an elliptical pattern similar to what was found with unsubmerged flow control structures. Figure 37 shows the resulting bed topography and stream barb plan view. The y-coordinate system refers to distance from the bank where the structure was installed (Fox et al., 2005).

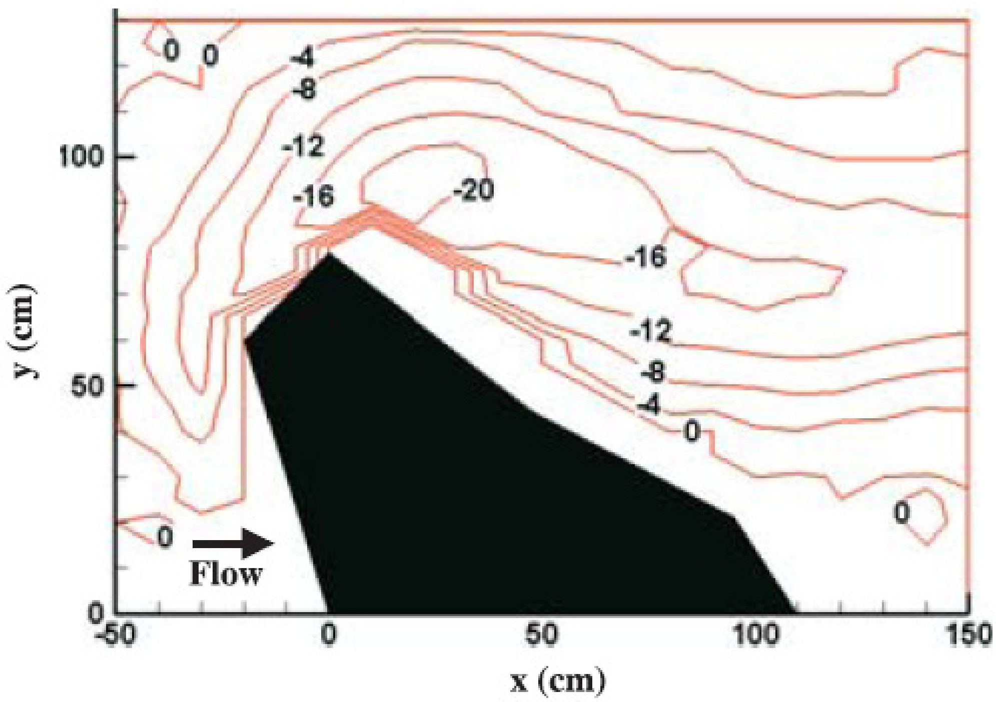


Figure 37: Resulting Scour Experiment Isolines in Centimeters (Fox et al., 2005)

Fox et al. (2005) suggest that in order to avoid winnowing failure of the barb, the toe of the structure must be embedded to a depth equal to the designed maximum scour depth. Winnowing failure results from small passageways forming through or under an instream structure causing local scour and eventually failure. Further analysis using particle image velocimetry revealed that near-bank velocities were significantly reduced downstream of the barb. Flows were reduced along the bank for a length several times the width of the structure, to some degree; this region constitutes the streambank protected region. This protected length can be used to determine streamwise spacing. It was also found that the optimal ratio of distance between successive barbs to barb protrusion length was 13. This result is valid for barb application in straight reaches of mild-sloped, gravel-bed streams typical of the Pacific Northwest (Fox et al., 2005).

Field Work:

In October 2002, the ACOE published a study of 18 bendway weir installations along the Mississippi River in order to document navigational impacts. Surveys were given to river pilots to determine the positive and negative impacts of the structures as they pertained to commercial navigation. While some projects successfully improved navigation and reduced the need for dredging, most of the projects were implemented without adequate model testing or navigation design (ACOE, 2002).

Most bendway weir fields had installation angles of around 55-70 degrees to the upstream flow, though there were multiple exceptions. No other design parameters were provided in the Corps publication. The majority of pilots were found to have the following opinions about the effect of the weirs on navigation (ACOE, 2002).

- All pilots agreed weirs improved downstream navigation
- Most projects caused difficulty immediately after construction because channel area was restricted
- Most projects decreased tow speed upriver

Due to the relative inconsistency across the projects, the Corps has begun research using large-scale models including 500 and 900 ft wide test channels. Thorough testing will be used to determine the optimum layout of a bendway weir field for several planform geometries. Analyses will be performed on the ability of vessels and their tow to successfully navigate the bendway weir fields in both the upstream and downstream direction (ACOE, 2002).

Derrick (1997) presented findings from two case studies using bendway weirs. A bridge crossing the Blue River near Manhattan, Kansas was subjected to intensive erosive forces during a flood, enough to cause one of the abutments to fail. After structural improvements were made, eleven bendway weirs were built to stabilize the channel bend and align the flow as it enters the bridge opening. Weirs were constructed in the following manner (Derrick, 1997):

- Weirs are spaced 200 ft apart at the bank end
- Weirs are constructed of well-graded, 500 lb maximum weight stone
- Bank end elevation is 1 ft higher than stream end elevation
- Weirs are 110-140 ft in length with a 12 ft width at the crest
- Weirs are angled from 2-16 degrees upstream

Project monitoring determined the bendway weir field reduced bank erosion and successfully aligned the flow approaching the bridge crossing; additionally, fish spawning areas and trees used for bald eagle nesting were spared without adversely affecting the desired hydraulic condition. The project also saved an estimated $610,000 versus the use of traditional bank paving (Derrick, 1997).

A similar project in Alton, Illinois used five bendway weirs to reduce bank erosion and align flow for a bridge crossing. Weirs were constructed in the following manner (Derrick, 1997):

- Weirs are spaced 110 ft apart at the bank end
- Weirs are constructed of well-graded, 400 lb maximum weight stone
- Bank end elevation is 1 ft higher than stream end elevation
- Weirs were 20-28 ft in length with a 4 ft width at the crest
- Maximum weir angle set at 20 degrees upstream

The flow was observed to behave as designed and in the spring of 1996, the weir field was subjected to approximately the 25-year flood event and performed exceptionally. Minimal damage was noted to the structures themselves. One year after project completion, several 8-16 ft willow trees have taken root along the bank from the first weir to just upstream of the bridge abutment (Derrick, 1997).

Derrick (1998) monitored a bendway weir system for four years following installation. Weirs were constructed based on guidance from the Corps' Waterways Experiment Station with some site-specific modifications. Properties for Harland Creek and the bendway weir field are as follows:

- Average stream width was 29 m
- Weir keyed into bank 4.6 m
- Maximum weir height was 1 m below top bank elevation
- Weirs spaced at 23 or 30 m
- Weir was 1.2 m above bed at bank end; 0.6 m above bed at structure tip
- Stone construction material was 650 pounds maximum
- Weir length ranged from ¼ to ½ base flow width
- Maximum weir angle was 20 degrees

The four-year-long monitoring period gave rise to the following conclusions. Over 2/3 of the weirs were located and angled incorrectly yet overall were still successful in stabilizing the outer banks (Derrick, 1998). Engineering judgment had been used to determine weir length; the length was determined by the anticipated relocation of the channel thalweg and reshaping of the point bar. Within months, bank steepness was notably reduced and natural vegetation had begun to cover the entire bank. After the four year period, many new willow trees were 20 to 30 ft tall. Six overbank floods occurred during the study period with minimal detriment to the weir structures. The reduced velocities near the outer bank led to the deposition of several inches of sediment in the area that was originally suffering from the highest levels of erosion (Derrick, 1998).

The bendway weirs did not subside or lose any rock near the toe due to thalweg migration (Derrick, 1998). Additionally, the USDA Agricultural Research Service (ARS) determined that the stable scour holes, pools between weirs, and pool-riffle regions enhanced flow diversity and ecological habitat, resulting in a doubling in the fish population in the reach (Derrick, 1998). Overall restoration costs were estimated to be ½ of other projects in the area that had used riprap and other traditional scour countermeasures (Derrick, 1998)

Abad et al. (2008) collected data from five bendway weirs installed in a meander bend on Sugar Creek in McLean County, Illinois. Two weirs were also installed in the straight, approaching reach. The bendway weirs were constructed of piles of large rock that allowed fluid to pass through but generally functioned as a barrier to flow. Field data collected during low stage established that streamwise velocities along the outer bank were greatly reduced and the high velocity flow had been relocated along the tips of the weirs. 3-D flow modeling software was compared with the observed values and found to be a good approximation. The model was then run at moderate and high stage and the overall effectiveness of the weirs diminished as high velocities were present along the outer bend. However, at the time of this study, the channel had not been subjected to flows of this magnitude and therefore actual values could not be compared with the model (Abad et al., 2008).

Discussion/Conclusion:

Bendway weirs and stream barbs are thus a viable method for addressing channel and infrastructure instability by altering flow patterns. Though detailed mechanics have not been documented, it has been suggested that these structures alter the flow patterns responsible for scour and erosion by capturing flow and forcing it over the weir perpendicular to the weir itself. Weirs thus create quiescent conditions in the near-bank region and force the scour hole to be located toward the center of the channel. Successful bendway weir and stream barb installations reduce bank erosion as well as provide flow diversity and reduce the need for dredging. The structures also have the ability to induce sediment deposition and rebuild bed elevation near-bank.

The Army Corps of Engineers study has shown that while bendway weir fields can improve channel stability, in many cases navigational dangers are created by the use of bendway weir fields. These dangerous situations could likely be predicted and prevented by computer and physical modeling which is often not performed.

A table of bendway weir and channel properties for all laboratory experiments and field work summarized here is included in Appendix A. This table provides a summary of all the design elements for each study and provides the researchers' results and conclusions.

The evidence presented in this review shows that stream barbs and bendway weirs can be useful for creating a stable channel environment, however more research is needed to determine the appropriate design parameters for specific situations.

Spurs

Introduction:

Spurs are river training structures projecting from a streambank into the channel. Also known as groins, jetties, or spurs, these structures can be made to be permeable or impermeable as a variety of construction materials can be used. Spurs are used to prevent the meandering of streams and river and to aid in the development of well-defined channels. Unstable channels can migrate and endanger infrastructure.

The use of spurs has been studied and researched extensively. Field studies, lab studies and literature review have led to the well received design guidelines published in Hydraulic Engineering Circular (HEC)-23. Spurs have good potential as channel stabilization structures and scour countermeasures.

Theory:

Bendway weirs and spurs constructed of stone have very similar appearances but alter the flow in very different ways. Bendway weirs use weir mechanics to alter flow while spurs work by retarding or deflecting the flow around or through the structure depending on the permeability (HEC-23, 2001). Combinations of retardation and deflection are also possible. This flow modification leads to sediment deposition, reduced near-bank velocities, and a general controlling of the flow (Brown, 1985).

The mitigation of large near-bank velocities removes the erosion mechanisms responsible for channel destabilization. Additionally, the migration of the concentrated portion of the high-velocity flow eliminates the sediment transport mechanism which is responsible for carrying away eroded material (Brown, 1985).

The erosive flow trough is relocated along the streamward end of the spur effectively creating a more centrally located thalweg and enhanced channel development (Brown, 1985).

Description/Guidelines:

Spurs are essentially linear structures of varying degrees of permeability which project from a streambank into the flow. Different applications of fencing, timbers, cables, and piles can be used to create more permeable spurs however the majority of experiments reviewed use less permeable designs normally constructed of rock.

General spur design guidelines are provided in HEC-23 (2001) and are based from field, lab, and literature studies such as the extensive research published by Brown (1985). The optimum angle for spur alignment has long been debated but most now agree that the structures be oriented normal to the flow in most scenarios (Copeland, 1983, Gisonni & Hager, 2008).

Standard design for an impermeable spur is the straight, round-nosed spur found in Figure 38.

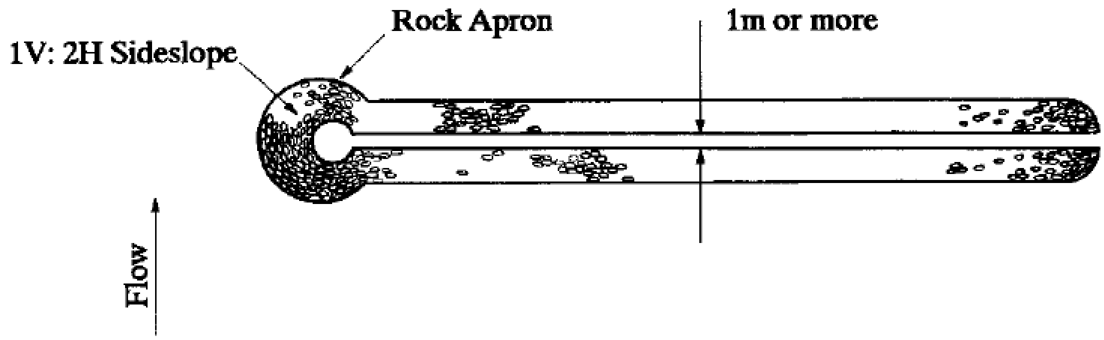


Figure 38: Typical Straight, Round-Nosed Spur (HEC-23, 2001)

Design guidelines provided in HEC-23 are summarized below (HEC-23, 2001).

- Projected spur length should not exceed 20 % of channel width
- Spurs should be oriented approximately normal to the flow; however, the spur located furthest upstream should be angled downstream
- Impermeable spurs are most appropriate on sharp bends subject to severe erosion
- Impermeable spurs should not be higher than bank height
- Centerline crest profile should slope downwards away from the bank
- Top width should be at least 1 m
- Side slopes should not be steeper than 1V:2H

HEC-23 (2001) also provides a design example for typical spur installation.

Lab Work:

Rajaratnam and Nwachukwu (1983) performed an experimental study of flow patterns in the vicinity of groin-like structures using thin, aluminum plates which projected into the flow. The following experimental parameters are given:

- Flume width is 3 feet
- Experiments conducted with smooth sides and bed, 0.56 mm, and 6.3 mm roughness
- Aluminum plates are 3 mm thick
- Plates set normal to the flow direction
- Plates set to projection lengths of 0.25 and 0.5 feet
- Plate height set to above water surface
- Flow depths range from 0.5-0.84 feet

Results from the study show that the experimental groin was found to greatly alter the upstream and downstream flow. Additionally, the maximum bed shear stress was located near the end and the area immediately adjacent to the groin. The maximum bed shear stress was 3 times the approach bed shear stress for the 0.25 ft plate and 5 times the approach bed shear stress for the 0.5 ft plate (Rajaratnam & Nwachukwu, 1983).

A similar study by Zaghloul (1983) also found that local scour developed near the nose of the experimental spur.

Copeland (1983) studied spurs in a meandering, sand bed flume to determine the optimum orientation and spacing. Experimental parameters are provided below.

- Flume is 8 feet wide
- Flow depth is 0.24 feet
- Channel slope is 0.0012
- Channel sinuosity is 1.6
- Median sediment size is 0.45 mm
- Spur length is set to 2.2 feet
- Spurs tested at angles of 60, 75, 90, 105, and 120 degrees

Results of the experiment show that scour was more severe when spurs were oriented at an upstream angle and the scour hole was not located closer to the bank when oriented downstream. Spurs angled downstream protect the bank for a greater distance. Velocity along the bank in the spur field was 40 % of the velocity measured along the unprotected meander bends (Copeland, 1983).

Kehe (1984) modeled various spur configurations including a scale model sandy reach of the Willamette in Oregon. Results from the prototype demonstration are provided in the field study section. Experimental results noted diminishing returns as effective length was increased. Kehe (1984) found upstream oriented spurs cause greater scour and protect a greater length of streambank measured from the spur tip than other orientations.

Kuhnle et al. (2004) studied flow around a trapezoidal shaped, submerged spur. Experimental parameters are provided below.

- Flume is 1.219 meters wide
- Flow depth is 0.305 meters
- Channel slope is 0.0001
- Median sediment size is 0.8 mm
- Spur height is set to 0.152 meters
- Spur base width is set to 0.456 meters
- Spur projection at base set to 0.342 meters

Resulting flow patterns demonstrated a decrease upstream of the spur and increase over top of the spur. The eddy zone formed downstream of the spur was found to be 1.6 times the structure length and 4 times the structure height. The ratio of maximum bed shear stress to approach bed shear stress was found to be approximately 2.7 (Kuhnle et al., 2004).

Tang et al. (2006) simulated flow in the vicinity of a single, impermeable spur to create a model for the prediction of scour. Experimental parameters are given below.

- Flume is 0.5 meters wide
- Spur is 0.125 meters long
- Spur is 0.3 meters wide
- Spur oriented normal to the flow
- Flow depth is 0.085 meters

Results of the research show a strongly three-dimensional flow in the vicinity of the spur. There was also evidence of a dead zone directly downstream of the structure where sedimentation occurred. The model was found valid for the simulation (Tang et al., 2006).

Koken and Constantinescu's (2008) experiments analyzed flow and scour patterns in the vicinity of a single spur. Analysis of these patterns allows general predictions on the stability of the structure in the presence of severe scour and deposition. Experimental parameters are given below.

- Flume is 0.91 meters wide
- Flow depth set to 0.10 meters
- Spur is 0.15 meters long
- Spur is 0.02 meters thick
- Spur oriented normal to the flow

Koken and Constantinescu (2008) observed two distinct series of vortices are present, the necklace vortex fluctuates in intensity and shape but the vortex tubes in the detached shear layer (DSL) just upstream of the spur correspond to the region of highest bed shear stress.

The necklace vortices were found to oscillate leading to increased turbulence in the scour hole. Eventually the sediment deposited and the sediment becoming entrained reaches equilibrium such that the channel bathymetry is unchanged (Koken & Constantinescu, 2008).

Figure 39 shows the flow patterns observed at a single, impermeable spur

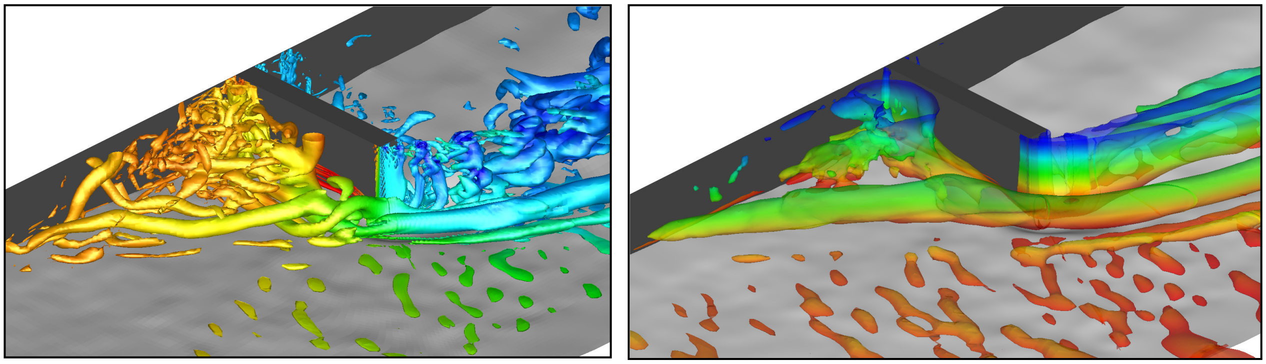


Figure 39: Vortical structures in the vicinity of a groin in an equlibrium mobile bed obtained from high resolution numerical simulations at Re=125,000 (Paik et al. 2009; Paik and Sotiropoulos 2005). Left: Instantaneous vortices colored with pressure; Right: Time averaged vortex structures colored with flow depth.

Gisonni and Hager (2007) studied the failure of spurs due to local scour. Experimental parameters are given.

- Flume width is 1 meter
- Flow depth is approximately 0.08 meters
- Median, uniform sand size is 0.0011 meters
- Spur lengths of 0.05, 0.10, 0.15, 0.20, 0.35, and 0.50 meters were tested
- Spurs are impermeable with thickness of 0.005 meters
- Spurs tested at various submerged heights
- Spur orientations of 60, 90 and 120 degrees

Undermining and sliding failure modes were observed by placing rock riprap rows on the tip of the spurs. A uniform riprap arrangement performed the best. The experiments demonstrate that spur slope effect is minimal and spur orientation other than normal to the flow has no advantage. Furthermore, the authors suggest the spur located furthest upstream be set to half the height of subsequent spurs (Gisonni & Hager, 2007).

Field Work:

Kehe's (1984) model and prototype study in a reach of the sandy, Willamette River compared well with one another. The specifications of the field spur system are provided below.

- Willamette River reach approximately 350 to 400 feet wide
- 8 spurs spaced 250 to 350 feet apart
- Length ranges from 50 to 115 feet
- Spur located furthest upstream in oriented 40 degrees downstream
- All subsequent spurs oriented normal to the bank
- Spurs constructed of quarry waste armored with specified riprap grades

Kehe (1984) concludes that some of the spurs in this system are probably ineffective and unnecessary in some locations but that additional spurs are likely needed downstream of the last structure.

Discussion/Conclusion:

Spurs are thus a viable method for addressing channel instability by altering flow patterns. Similar in appearance and objective to bendway weirs, flow is directed around a spur rather than over it. The impedance caused to near-bank flow leads to quiescent conditions and potential sedimentation in this region. It has also been shown that spurs can have the added benefit of habitat enhancement (Shields et al., 1994; Shields et al., 1995a; Kuhnle et al., 1999; Kuhnle et al., 2002). See the ecological discussion in this document. Additional research has been completed on the mass exchange between groin fields and the main stream to help predict the path and timeline of accidental pollutant discharges (Weitbrecht et al., 2007).

A table of spur and channel properties for all laboratory experiments and field work summarized here is included in Appendix A. This table provides a summary of all the design elements for each study and provides the researchers' results and conclusions.

The evidence presented in this review shows that spurs and similar structures can be useful for creating a stable channel environment, however more research is needed to determine the site conditions in which spurs are most appropriate.

Constructed Riffles

Introduction:

Riffles are arrays of rock located within a channel reach where depth decreases and the channel may widen. They are found in pool-riffle sequences where deep pools are located between upstream and downstream shallow riffle sections. Riffles help regulate sediment transport and diversify flow regimes through the formation of secondary currents such as standing waves, hydraulic jumps, and backwater eddies. These currents may work to counteract erosive conditions along stream banks and bridge piers in both straight and curved reaches. Flow patterns located around stream meanders are highly erosive and the scour potential is highest on the concave bank. In addition to grade control and flow diversity, riffles also promote and sustain a variety of aquatic habitat for invertebrates as well as excellent fish spawning grounds.

Constructed riffles appear to have potential as a scour countermeasure. At this time, detailed design guidelines have not been published and the majority of journal articles focus on ecological response and associated flow patterns rather than stream stability.

Theory:

Pools and riffles in natural streams maintain channel morphology as they are subjected to opposing patterns of scour and fill. During high flow, pools are scoured and riffles are filled while at low flow, riffles can scour and pools are filled providing a natural sorting of bed material where coarser materials are deposited on riffles (Keller, 1978 & Doll et al., 2003). Since the water is moving faster along riffles at low flows, fine sediments are removed and the stream is oxygenated by the turbulence. The slope along riffle sections is steeper than the mean stream slope while pool sections have little to no grade (Doll et al., 2003).

Keller (1971) hypothesized that velocity reversal between pool and riffles maintains pool depth at high stage and sorts areal bed material. As flowrate increases, the near-bed velocity in the pool eventually exceeds that of the riffle, maintaining or increasing the depth of the pool. At flows high enough to transport the coarse material found in riffles, this larger material does not settle in pools because of high near-bed velocity during high flows. Finer material settles in the pools as discharge diminishes and near-bed velocity decreases. Other researchers have since found that this hypothesis is plausible, however other conditions must be satisfied as well, (Carling, 1991; Thompson et al., 1999; Milan et al., 2001; MacVicar & Roy, 2007).

Studies show that pools and riffles occur in series and appear in predictable patterns throughout a stream meander. Pools are located at the meander bend while riffles form along the point of inflection at bend crossings (HEC-20, 2001). Figure 40 illustrates this sinuous pattern in plan view and centerline profile. Note the varying undulation of the water surface associated with different flow stages.

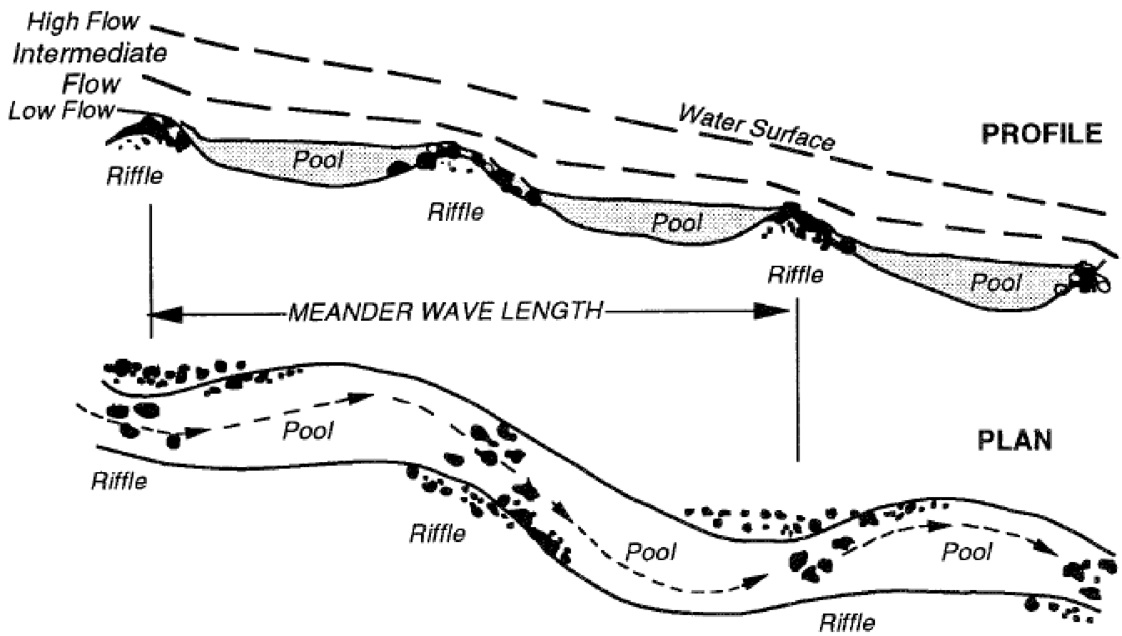


Figure 40: Centerline Profile and Plan View of Pool-Riffle Sequence (Newbury & Gaboury, 1993)

A singular pool and riffle span one half of a meander wavelength and the mean spacing between pools is often approximately 5 to 7 times the channel width (Keller & Melhorn, 1978; Roy & Abrahams; 1980; HEC-20, 2001).

Description/Guidelines:

Instructions for the design and installation of constructed riffles are not easily accessible; however some resources have provided detailed examples of their use in the field. Newbury & Gaboury (1993) and Newbury et al. (1997) provide case studies of constructed riffles including specific design details. Both documents recommend the same ten-step process to determine the best design for a specific reach. The steps and brief descriptions are as follows (Newbury & Gaboury, 1993).

- Drainage basin-identify watershed
- Profiles-determine elevation profiles and identify abrupt changes
- Flow-analyze possibly flows, including floods and minimum flows
- Channel Geometry Survey-determine relationship between discharge and channel geometry
- Rehabilitation Reach Survey- Prepare construction drawings and references
- Preferred Habitats-Summarize habitat factors for preferred reaches
- Selecting and Sizing Rehabilitation Works-Determine alternatives based on existing stream dynamics and geometry
- Instream Flow Requirements-Test design for minimum and maximum flows

- Supervise Construction-Ensure stream is constructed according to specification
- Monitor and Adjust Design-Schedule periodic surveys to determine effectiveness and repair as needed

To design a successful constructed riffle system, the gradients of the reach pre-channelization as well as information from other comparable natural streams should be incorporated. Design parameters for backwater constructed riffles are given below (Newbury & Gaboury, 1993).

- Riffle crest elevations follow average stream slope
- Crests are elevated from bed high enough to create pools extending to the midpoint of upstream riffle slope
- Downstream riffle face has slope of 2.5-5%
- Construction material is fieldstone ranging from 0.1 to 1 m in diameter
- Some boulders are emergent at bankfull stage
- Spacing should begin at approximately 6 bankfull widths

In some cases, pairs of riffles are used in order to create swirling eddies and deep pools. The upstream member of the pair has a V-notch crest which concentrates flow toward the center of the channel increasing scour at that location. Figure 41 gives example designs of a pair of such riffles. Note the V-notch cross section.

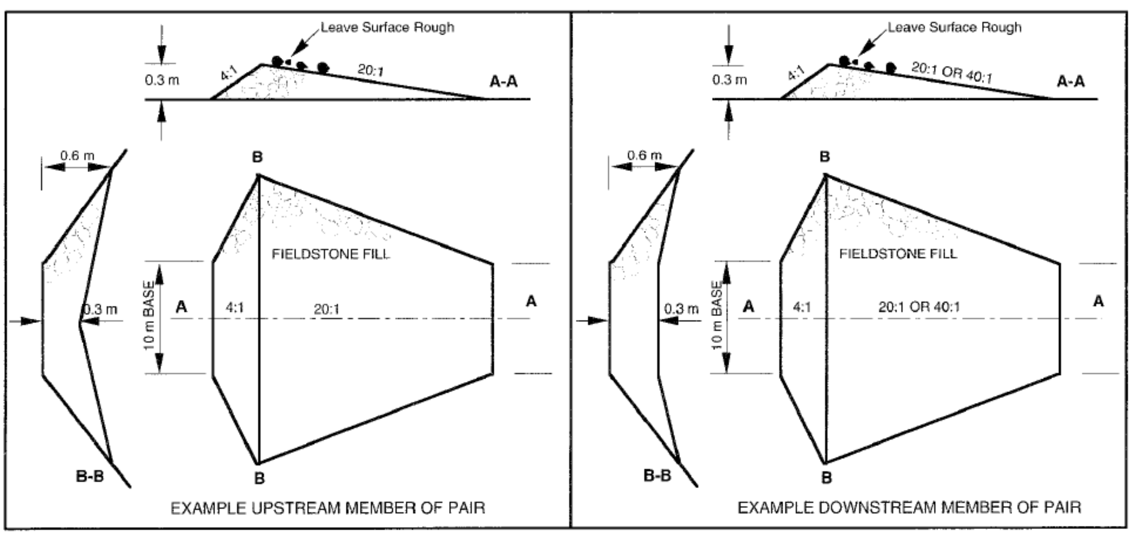


Figure 41: Constructed Riffle Schematics (Newbury & Gaboury, 1993)

A backhoe can be used to place the stones beginning with the largest, which are located along the crest cross section (Sections B-B in Figure 41). The face of the riffle should be left in a rough, porous arrangement to imitate rugged conditions found along natural sections of riffles (Newbury & Gaboury, 1993). In the event of instability due to flooding, the riffle can become a run with a properly planned failsafe. Repair materials should also be stockpiled near the riffle sites when possible (Newbury et al., 1998).

Newbury (2008) also suggests the use of CHUTE, HEC-RAS, and FishXing software packages to aid in the design of constructed riffle sequences.

Lab Work:

At this time, no published laboratory studies of the effect of constructed riffles on channel stability have been located. Periodic searching will continue.

Field Work:

MacVicar and Roy (2007) provide a table of multiple field studies pertaining to riffle-pool system hydraulics. Over thirty sites are listed; however, only Walker et al. (2004) and von Euw and Boisvert (2002) have studied constructed riffles as opposed to existing natural riffle systems.

Walker et al. (2004) studied the hydraulic characteristics of both natural and constructed systems by measuring energy profiles across riffle-pool sequences. Four creeks in British Columbia were chosen, all of which are considered steep, gravel-bed rivers with straight reaches. Constructed riffles were installed at these locations during the 1990's primarily to enhance flow diversity and aid aquatic habitats but also to stabilize the channel and protect a series of sewer connections. In all four channels, riffle-pool construction was based on design guidelines found in Newbury et al.'s (1997) Watershed Restoration Technical Circular No. 9. All of the constructed riffles were channel-spanning structures which induced localized scour immediately downstream (Walker et al., 2004).

To determine energy profiles across the riffles, steel rods were used as staff gages and placed throughout the system as shown in Figure 42. The gages allowed a water surface profile to be recorded for a variety of discharges and a Manning's roughness value for each section between gages was determined. One-dimensional energy equations were used between each section to determine headloss from grain roughness and bedforms (Walker et al., 2004).

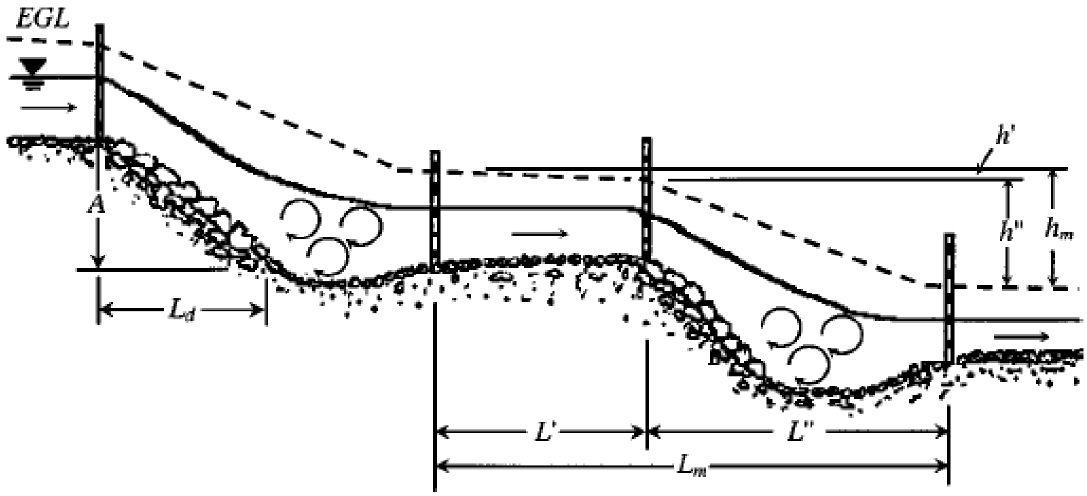


Figure 42: Experimental Setup Showing Staff Gages and EGL (Walker et al., 2004)

Results show the energy loss in riffles accounted for 50-100% of the total headloss within a riffle-pool section, even when the riffle region only comprised 18-56% of the section (Walker et al. 2004). The energy was dissipated on the riffle face and through downstream turbulence which maintained the scour pool. The study also shows that during high flows Manning's roughness values decreased, however the resistance created by the riffle was still larger than the section roughness meaning that riffles have an impact on energy dissipation even during periods of high flow.

The authors suggest that constructed pool-riffle sequences should be designed based upon the energy loss desired during a certain scale of flooding event along with parameters obtained through observation of natural channel morphology, sediment transport, native bedforms, and potential flooding effects (Walker et al., 2004).

Newbury and Gaboury's (1993) field manual contains design examples using riffles as means of channel stabilization as well as spawning beds. Channelization and heavy agriculture have been detrimental to walleye habitats and channel banks in Mink Creek and Wilson River. The design parameters for the constructed riffles in each channel are provided below.

Mink Creek:

- Riffle crest elevations follow average stream slope of 0.3% (see Figure 43)
- Riffle crests should be elevated an average of 0.6 m from the bed to create pools extending to the midpoint of upstream riffle slope
- Downstream riffle face has slope of 2.5-5%
- Construction material is fieldstone ranging from 0.1 to 1 m in diameter
- Riffles required approximately 100 cubic meters of fieldstone
- Some boulders will be emergent at bankfull stage
- Spacing should be between 5 and 7 bankfull width

Wilson River:

- Riffle crest elevations selected to create pools 0.5-1.5 m deep at bankfull
- Riffle pair used to imitate eddies and deep pools (see Figure 41)
- Riffle pair members are 40 m apart
- Average distance between riffle pairs is 83 m or 4.8 times bankfull width
- Some riffles in the array are designed to take advantage of preexisting profile peaks
- Downstream riffle face has slope of 2.5-5%
- Construction material is fieldstone ranging from 0.1 to 1 m in diameter
- Some boulders will be emergent at bankfull stage
- Spacing should be between 5 and 7 bankfull width

Monitoring was performed on the channels for several years following installation to determine the stability of the channels, particularly after the spring flood peak. Moderate settling of 0.3 m was evident on the upper two riffles of Mink Creek, and one riffle required 40 cubic meters of additional rock to repair scour damage after the first flood following construction. No further scouring has been recorded since the first flood peak, though erosion continues upstream and downstream of the rehabilitated reach. Minor settling was observed at the Wilson River site and some additional fill was required. Banks along the rehabilitated reach have been stabilized (Newbury & Gaboury, 1993).

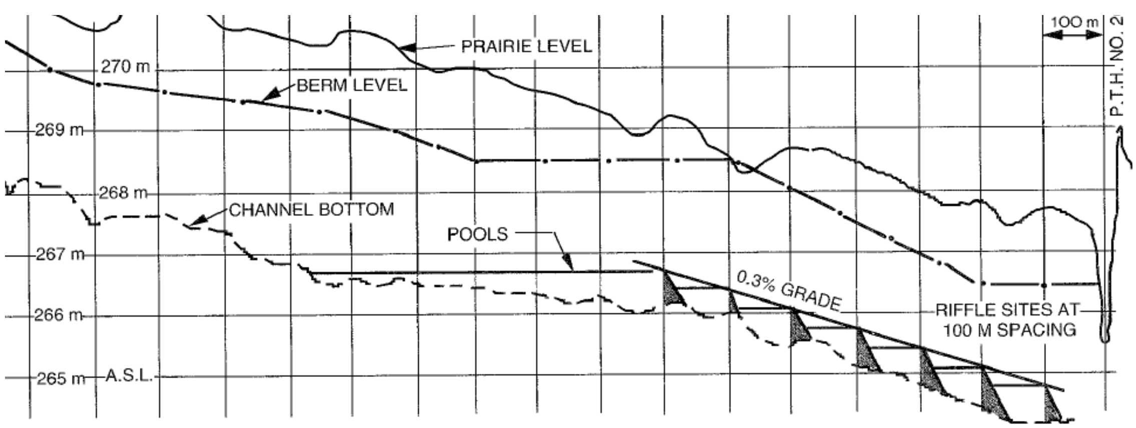


Figure 43: Elevation Profiles of Mink Creek Including Riffles

(Newbury & Gaboury, 1993)

von Euw and Boisvert (2000) designed and installed constructed riffles in Stoney Creek and the Brunette River in Canada. The primary purposes of the structures were to reverse channel instability and protect infrastructure. Creation of fish habitats and spawning grounds were also desired outcomes. Designs were based upon information obtained from Newbury et al. (1993) and from site conditions. Design parameters are listed below:

- Larger rocks used to minimize vandalism
- Riffle spacing was set to 6.7 bankfull widths
- Riffle crests designed to create backwater to toe of upstream riffle

- Spawning gravel was not used since it would be deposited naturally by floods
- Rocks are placed by hand when possible (von Euw & Boisvert, 2000)

Cost for each project is most directly related to the amount of rock needed to build the riffle to specifications. The 5 riffles in Stoney Creek cost an average of $2,200 Canadian and used a total of 110 metric tons of rock. Three riffles were built in the Brunette River at an average cost of $6,700 Canadian and a total of 630 metric tons of rock (von Euw & Boisvert, 2000).

Monitoring of the two sites has led to the following evaluations, observations, and conclusions:

- At low flows, water actually flowed through the riffles rather than over them; flooding however quickly made the structure non-porous through the deposition of natural material
- None to minor settling has occurred
- New erosion was noted at the Brunette River site where the bank was not protected high enough above the crest height
- Channel stability has improved at both sites
- Multiple fish species which had not been seen at the sites for decades have appeared and are spawning (von Euw & Boisvert, 2000)

While the projects are considered very successful, the authors do note the potential for future damage due to the changing hydraulic conditions in the channels triggered by the new structures (von Euw & Boisvert, 2000).

Discussion:

The evidence presented in this review shows constructed riffles can be a viable method for addressing channel instability by altering channel flow patterns. Though detailed mechanics are not available, it has been suggested that these structures encourage stable channels by mimicking natural geometric and bathymetric development in an unaltered channel. Riffles can also help control flow through weir mechanics (von Euw & Boisvert, 2000).

All field work and case studies reviewed in this document exemplify good successes by comparing before and after results. Bank slopes tend to become shallower and more stable as well as vegetated in the months following riffle installation. Dramatic increases in fish population and spawning are also evident after construction.

Though no lab work is available for constructed riffles, three software packages are useful for predicting riffles crest height based on channel morphology. While the field research reviewed shows a very consistent outcome of success, it would be useful to locate a case study where riffles are not quite so effective or even detrimental. This will allow typical pitfalls to be prevented and ensure successful outcomes in future projects.

Conclusion:

The information provided is this review focuses on the major practical studies documented in literature. Sources were obtained from researchers and practitioners who have designed and implemented constructed riffles based on prior experience and examples provided by nature. The complexity and ambiguity of flow associated with these structures may be the reason lab research has been minimal.

The majority of design guidelines presented in this review are the result of work completed by various Canadian environmental agencies. Using trial and error in collaboration with information provided through natural examples, most projects have enjoyed success on fronts of channel stabilization and habitat enhancement.

A table of constructed riffle and channel properties for all laboratory experiments and field work summarized here is included in Appendix A. This table provides a summary of all the design elements for each study and provides the researchers' results and conclusions.

The evidence presented in this review shows that constructed riffles can be useful for creating a stable channel environment, however more research is needed to determine the appropriate design parameters for specific situations.

Summary

The structures presented in this document represent some of the most promising and well-researched methods of altering channel flow. This literature review focused on the most commonly used in-stream structures, including cross-vanes, J-hook vanes, rock vanes, W-weirs, submerged vanes, stream barbs, bendway weirs, spurs, and constructed riffles. When properly installed and maintained, these structures provided bank protection and channel stabilization and will therefore protect transportation infrastructure adjacent to waterways.

These structures are also more cost efficient and typically take advantage of local materials. Except for submerged vanes, these structures are constructed using dumped or placed rock, which may be available on site. It is anticipated that the cost and effective lifetimes of these structures is much more attractive than other scour prevention schemes.

Additionally, many case studies displayed beneficial ecological and aesthetic impacts. An enhanced ecosystem is aided by the increased flow diversity and cover provided by these structures. New vegetation is often evident at the project site which further aids overall channel stability and aesthetic properties.

A survey was developed to determine the state of use and success for these structure types which will aid the selection of those which will be studied later in the project. These selections will be based on the popularity and perceived performance determined through the survey and specific projects submitted by practitioners around the nation.

Chapter 3: Survey

Survey Instrument

A survey to collect practitioner experiences was designed to compile the general state of practice with instream structures as well as determine possible characteristics leading to success and failure. Respondents were asked to describe and evaluate existing low-flow structure applications including effective uses, limitations, design methods, material specifications, installation guidelines, installation costs, maintenance costs, performance, and failure modes. The following performance dimensions were incorporated into the survey. All structure types were evaluated based on:

- Cost (as compared with the most likely alternative)
- Performance
- Environmental effects
- Maintenance
- Effective uses and limitations

Each performance dimension contained a series of questions to determine practitioners' general experience with each structure type. Specific questions as well as their wording were agreed upon by the research team and sponsor panel. The basic survey structure is found in Appendix B. The full survey for a single structure is provided in Appendix C.

The survey was divided into four separate sections. First, respondents were asked for their contact and demographic information. Next, for each structure type, the survey solicited responses to the performance measures listed above as well as basic information on specific projects. Section A was comprised of questions relating to the performance measures and the respondent's overall experiences for each structure type. These general questions synthesized respondents' experience. Next, Sections B and C asked for background information on specific successful and unsuccessful projects, respectively. The survey asked for the following readily available information:

- Project location
- Reason for project
- Design guidelines and whether structure was installed in accordance with specifications
- Monitoring of project site and any changes that have occurred
- Whether the project has experienced a design flood
- Why project was considered successful or unsuccessful

Questions were consistent for every structure type. It is estimated that each respondent required approximately 10-15 minutes to fully complete the survey for each structure type.

Survey respondents were able to choose to respond to either hard-copy or electronic forms of the survey. All respondents preferred the electronic method, which allowed the research team to monitor responses in real time, improve the survey after initial responses, and efficiently store and analyze data. The electronic version of the survey was created and administered using the web survey tool SurveyMonkey.com. A copy of the final electronic version of the survey is provided in Appendix C.

Based on the first few responses to the survey, the survey format was changed slightly by creating identical sections for every structure type instead of selecting the structure at the beginning of the survey. This change gave more continuity to the survey and led to higher response rates for practitioners who used more than one structure type. A second change was the addition of a question at the beginning asking the responder what types of structures they had worked with.

Based on initial survey results, phone interviews were conducted with a subset of respondents to acquire additional information on project installations. In particular, the following detailed additional information was collected:

- Site information (channel width, reach morphology, sinuosity, slope, depth, floodplain composition, and design flood)
- Installation information (building materials)
- Structure description (type, number, reason, construction materials, and design guidelines)
- Structure installation (speed, design guidelines)
- Structure performance (effect on erosion and sediment deposition, ability to protect infrastructure, permanence)
- Environmental impacts (adverse effects, flow diversity, habitat, new vegetation)
- Maintenance (frequency, severity)

The contact population was comprised of state Department of Natural Resources (DNR) employees, state Department of Transportation (DOT) employees, US Forest Service (USFS) employees, and other federal contacts. Additionally, the request for practitioners to take the survey was sent to several related academic and professional listservs including, ECOLOG-L, GEOMORPH-L, and NCSTATE. In total, over 90 people were directly invited to complete the survey and several hundred people saw the survey announcement on a listserv.

Survey Results

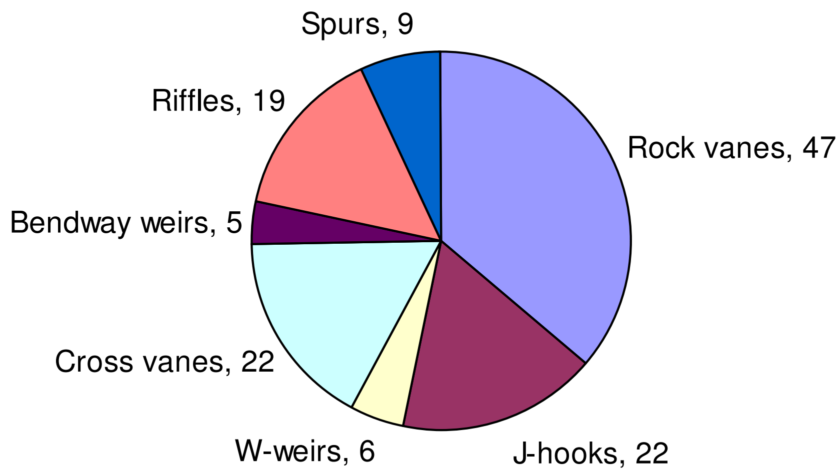


Figure 44: Survey Responses per Structure Type

A total of 64 individuals submitted usable information as part of this survey. This number represents a response rate of 71% of the people directly invited to participate in the survey, which indicates the widespread interest in and appreciation of need for this project. The responses per physiographic region are tabulated in Appendix E. A very good geographic distribution was observed, with at least one respondent in 66% of the USGS physiographic regions. Respondents also represented a wide range of backgrounds and agencies. A total of 47% were affiliated with transportation departments and 23% with natural resources departments (Figure 45).

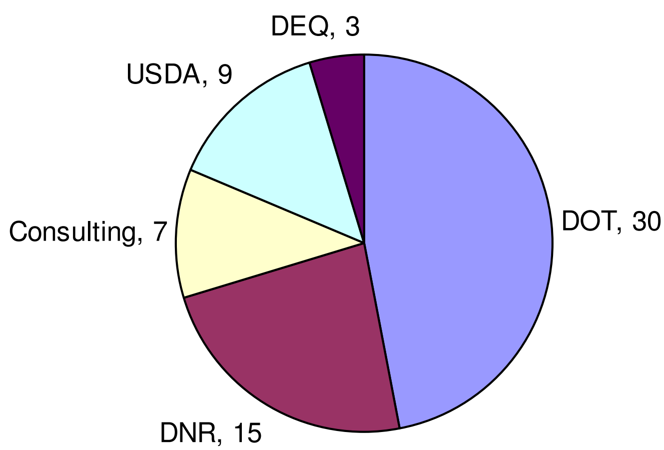


Figure 45: Respondents by Agency

Survey responses were obtained for a wide range of structure types (Figure 44). Many respondents had experience with more than one structure type, so the total number of detailed structure-specific responses (130 responses) was higher than the total number of respondents (64 people). No responses were received for submerged vanes, and only 5 responses were received for bendway weirs and 6 responses for W-weirs. The lack of responses for these structures could be attributed to the order of the survey but this is likely not the case. The cross vane and riffle section were also located in the latter half of the survey and still received high response rates.

The structure-specific survey results are presented in two sections. First, we summarize the general experiences and perceptions held by the respondents. These results are presented in table form for each structure, excluding submerged vanes, which received no responses. It should be noted that only nine respondents had experience with spurs, only five respondents had experience with bendway weirs, and only six respondents had experience with W-weirs. Because such a low response rate may bias the results, the presented results may not reflect a widespread consensus view for these structure types.

Results for most performance dimensions are given as the percentage of respondents who “Agree” or “Strongly Agree” with the statement for each structure type. For the most likely alternative, all choices that comprise over 30% of the results are shown. In the Maintenance performance dimension, results are given to show the most common answers selected, which were numerical or text. Results are displayed as Table 2. Average and standard deviations are also included within the table rated 1 to 4; 1 being strongly disagree, 4 being strongly agree.

As Table 2 shows, the most likely alternative to most structure installations is riprap, log structures, or other rock structures. Riprap was, in fact, the top alternative for all structure types. Because riprap does not offer the potential habitat benefits of a rock structure, habitat considerations likely motivate the decision to choose a rock structure instead. Log structures (lunker structures, tree wads) can offer many if not more of the benefits of rock structures, but they tend to be shorter-lived and therefore cannot provide longer term physical stabilization.

More guidance is clearly needed for the design of spurs, riffles, and W-weirs; approximately 60% or less of respondents believed that design guidelines were adequate for these structure types. In addition, these structure types were familiar to a relatively small percentage of respondents (Figure 44); these structures may become more prevalent if design guidelines are improved. For the most prevalent structure types (rock vanes, J-hooks, and cross vanes), over 80% of respondents believed these guidelines to be adequate. It is revealing that over 15% of respondents did not agree with this statement, given that published design guidelines exist for these structures. Perhaps this minority of respondents realizes that most design guidelines size in-stream structures based on channel geometry and average flow depth but will not provide insight into how the structure will perform in different geomorphological settings, during flood events, and over long time periods. In follow-up interviews, practitioners generally agreed on a need for quantitative predictive design guidelines

Rock instream structures are a large investment. In general, constructing these structures takes at least as much time as the most likely alternative; spurs are an exception. In addition, these structures tend to have large costs for both materials and labor during construction. Riffles and W-weirs are apparently the most expensive relative to the most

likely alternative; for the other structures, close to 50% of respondents found these structures at least as cost-efficient as riprap and other countermeasures.
The performance of the in-stream structures was generally much higher than the most likely alternative; riffles are an exception. At least 75% agreed that the structure halted further bank/bed scour and at least 72% agreed that sediment deposition was evident at the project site; riffles excluded. Performance of riffles during floods and as infrastructure protection measures was also low.

The environmental impact was found to be very positive for all structures except bendway weirs and to a lesser extent spurs. At least 78% agreed the remaining structures improved aquatic habitat and 71% said no adverse effects resulted from the structure implementation. While spurs and bendway weirs were not overwhelmingly viewed as having positive environmental impacts they are not seen to have negative impacts.

The in-stream structures all achieved good marks in the maintenance and repairs section with the exception of W-weirs. At least 61% responded that the first structural repair was greater than 2 years after the completion date. 100% of spurs did not need repairs before 2 years. The cost of normal maintenance was also very low, with all structure types between 50-75% agreeing the cost was less than 5% of the total project cost. The structures also appear to fare well after design flood events with 50-85% reporting that minor or no repairs were needed.

Table 2: Perception of Structures in Various Performance Dimensions

		Rock vane	J-hook	Cross vane	Spur	Riffles	Bendway weir	W-weir
	Most likely alternative	Riprap/log structure	Riprap/log structure	Riprap/Drop Structure	Riprap	Riprap	Riprap	Riprap/cross vane
	Design guidelines are adequate for this structure.	85% Agree or Strongly Agree 2.9+(.6)	82% Agree or Strongly Agree 3.2+(.6)	81% Agree or Strongly Agree 3.2+(.7)	50% Agree or Strongly Agree 2.6+(.5)	61% Agree or Strongly Agree 2.8+(.7)	75% Agree or Strongly Agree 2.3+(.5)	50% Agree or Strongly Agree 2+(1)
Cost	Construction is quicker than the most likely alternative.	45% Agree or Strongly Agree 2.5+(.9)	44% Agree or Strongly Agree 2.6+(.7)	23% Agree or Strongly Agree 2.4+(.8)	66% Agree or Strongly Agree 2.6+(.7)	20% Agree or Strongly Agree 2.3+(.5)	50% Agree or Strongly Agree 2.3+(1)	25% Agree or Strongly Agree 2.3+(.6)
Cost	Cost of materials is less than the most likely alternative.	53% Agree or Strongly Agree 2.6+(1)	39% Agree or Strongly Agree 2.6+(.7)	43% Agree or Strongly Agree 2.7+(.8)	62% Agree or Strongly Agree 2.6+(.8)	14% Agree or Strongly Agree 2.2+(.8)	50% Agree or Strongly Agree 2.3+(1)	25% Agree or Strongly Agree 2.3+(.6)
Cost	Cost of construction is less than the most likely alternative.	44% Agree or Strongly Agree 2.5+(.9)	55% Agree or Strongly Agree 2.8+(.7)	31% Agree or Strongly Agree 2.5+(.8)	62% Agree or Strongly Agree 2.6+(.8)	28% Agree or Strongly Agree 2.3+(.7)	50% Agree or Strongly Agree 2.8+(.5)	50% Agree or Strongly Agree 3+(1)
Performance	Structure successfully halts further bank/bed erosion or scour.	88% Agree or Strongly Agree 3.1+(.6)	94% Agree or Strongly Agree 3.2+(.5)	82% Agree or Strongly Agree 3.3+(.7)	75% Agree or Strongly Agree 2.9+(.6)	57% Agree or Strongly Agree 3+(.8)	100% Agree or Strongly Agree 3+(0)	75% Agree or Strongly Agree 3+(.8)
Performance	Structure results in sediment deposition at the project site.	73% Agree of Strongly Agree 2.8+(.7)	72% Agree or Strongly Agree 2.8+(.6)	82% Agree or Strongly Agree 3+(.6)	100% Agree or Strongly Agree 3.3+(.5)	50% Agree or Strongly Agree 2.5+(.8)	75% Agree or Strongly Agree 2.8+(.5)	100% Agree or Strongly Agree 3.5+(.6)
Performance	Structure prevents erosion during a flood event.	70% Agree or Strongly Agree 2.9+(.6)	77% Agree or Strongly Agree 2.8+(.7)	70% Agree or Strongly Agree 2.9+(.8)	75% Agree or Strongly Agree 2.8+(.5)	43% Agree or Strongly Agree 2.8+(.9)	100% Agree or Strongly Agree 3+(0)	75% Agree or Strongly Agree 2.8+(.5)
Performance	Structure can successfully protect infrastructure.	71% Agree of Strongly Agree 3+(.6)	72% Agree or Strongly Agree 2.9+(.6)	64% Agree or Strongly Agree 3.2+(.8)	87% Agree or Strongly Agree 2.9+(.4)	21% Agree or Strongly Agree 2.7+(.9)	75% Agree or Strongly Agree 3+(0)	75% Agree or Strongly Agree 3.3+(.6)
Environmental	Structure does not trigger adverse environmental effects.	88% Agree or Strongly Agree 2.3+(.7)	89% Agree or Strongly Agree 3.3+(.8)	76% Agree or Strongly Agree 3+(.9)	62% Agree or Strongly Agree 2.7+(.5)	71% Agree or Strongly Agree 3.1+(.8)	50% Agree or Strongly Agree 2.8+(.9)	80% Agree or Strongly Agree 2.8+(1.1)
Environmental	Structure improves aquatic habitat.	86% Agree or Strongly Agree 3+(.6)	83% Agree or Strongly Agree 3+(.7)	94% Agree or Strongly Agree 3.2+(.7)	57% Agree or Strongly Agree 2.6+(.9)	78% Agree or Strongly Agree 3.3+(.9)	50% Agree or Strongly Agree 2.5+(.6)	80% Agree or Strongly Agree 3+(1.2)
Maintenance	Estimated time until first repair	70% Greater than 2 years	81% Greater than 2 years	70% Greater than 2 years	100% Greater than 2 years	61% Greater than 2 years	75% Greater than 2 years	0% Greater than 2 years
Maintenance	Estimated cost of maintenance (as % Of project cost).	70% Less than 5%	61% Less than 5%	70% Less than 5%	50% Less than 5%	61% Less than 5%	75% Less than 5%	50% Less than 5%
Maintenance	Estimated repairs after design flood events.	85% Minor or None	83% Minor or None	76% Minor or None	75% Minor or None	69% Minor or None	75% Minor or None	50% Minor

Next we summarize details regarding specific successful and unsuccessful projects, including information obtained both through the initial survey and through follow-up contact. Project-specific responses varied greatly, but commonly recurring themes are presented whenever possible. The complete detailed data set is available in Appendix D. Survey raw data is available by request from the author.

Table 3: Successful and Unsuccessful Project Summary

	Rock vane	J-hook	Cross vane	Spur	Riffles	Bendway weir	W-weir
# projects	23	21	22	8	16	5	6
River types	Sand, gravel, cobble, boulders	Cobbles, gravels	Gravel, cobble	Sand, gravel	Gravel, sand, cobbles	Gravel, cobbles	Gravel, cobbles
Design guidelines used	Rosgen 64%	Rosgen 91%	Rosgen 100%	Army Corps 60%	Rosgen 54%	Rosgen 60%	Rosgen 100%
Deviations from design guidelines noted	None	None	12% altered structure slope	None	None	20% altered height	17% used smaller rocks
Monitoring	Visual inspection	Visual inspection, cross sections	Visual inspection	Visual inspection	Visual inspection, cross sections	Visual inspection, cross sections	Visual inspection
Sinuosity	NA	1.1-1.5	1.1-1.5	1.3-1.5	1-1.5	1.3	NA
# of structures	1-4	1-21	1-20	3-5	1-27	4-19	NA
Slope	0.003-0.008	0.003-0.02	0.0001-0.03	0.0002-0.0033	0.0007-0.03	<0.003	NA
Width/Depth	7-33	8.8-36	7.3-19.6	14.3-16.3	6-20	8.6-33	NA
% successful	78%	76%	73%	88%	75%	60%	66%

Rock vanes

Practitioners with experience using rock vanes constituted the vast majority of responses received, and their overall assessment of their effectiveness is positive. The most common comment in the open-ended responses regarding rock vanes was their use as bank protection and channel stabilization measures. Rock vanes were also said to be of little effectiveness in smaller channels. Six respondents mentioned that rock vanes are either best suited for larger channels or ineffective in smaller streams; one respondent gave a bankfull width of 30 feet as the lower limit for effective use. Specific rock vane project details were received from three respondents, totaling 10 rock vanes, with bankfull widths ranging from 22-135 feet. One of these structures however, is not redirecting the flow in the desired direction. Bankfull width-depth ratios range from 7 to 33 and channel slopes 0.003-0.008. Structure length-bankfull width ratios were 0.44-0.48 excluding the structure not functioning as intended. The number of similar structures per project ranged from a single structure to four rock vanes. The project utilizing a single structure is regarded as unsuccessful.

Consistent with literature review findings, 64% of rock vane practitioners use Rosgen guidelines (Rosgen, 2001) to design the structures.

J-hooks

There were 22 respondents who indicated experience with J-hooks. Since this structure is simply a rock vane with an additional gapped boulder section at the tip it received very similar open-ended feedback to rock vanes as far as bank protection and channel stabilization. In addition, eight respondents noted habitat enhancement. Details were received for eight J-hook projects totaling 67 structures. Aspect ratios ranged from 8.8 to 36 and channel slopes ranged from 0.003 to 0.02. The number of similar structures per project ranged from a single structure to 21 J-hooks.

Consistent with literature review findings, 91% of J-hook practitioners use Rosgen guidelines (Rosgen, 2001) to design the structures.

Cross vanes

There were 22 respondents who indicated experience with cross vanes. The common perceptions held by respondents show that cross vanes are one of the more difficult and costly structures to use but perform well in other dimensions. Open-ended responses point out the cross vanes assets as bank protection, channel stabilization, grade control, habitat enhancing, and infrastructure protection structures. Details were received for nine cross vane projects totaling 51 structures. Aspect ratios ranged from 7.3 to 19.6 for eight successful projects; the lone unsuccessful project had a ratio of 10. Channel slopes range from 0.0001 to 0.03 and reported sinuosity values were 1.1-1.5. The number of similar structures per project ranged from a single structure to 21 cross vanes. The project with a single structure was considered unsuccessful.

As with rock vanes and J-hooks, details were not submitted in great numbers for what is apparently a very common structure. Consistent with literature review findings, 100% of cross vane practitioners use Rosgen guidelines (Rosgen, 2001) to design the structures.

W-weirs

There were 6 respondents who indicated experience with W-weirs. In general, these structures are primarily used for grade control. The most common feedback was difficulty with installation and the overall cost. Details were received for a single W-weir.

Consistent with literature review findings, 100% of W-weir practitioners use Rosgen guidelines (Rosgen, 2001) to design the structures.

Bendway weirs/ Stream barbs

There were 5 respondents who indicated experience with bendway weirs or stream barbs. Details were received for four projects totaling 33 bendway weirs. Aspect ratios ranged from 8.6 to 33 with channel slopes as high as 0.003. The three projects reported as successful were located on channels with bankfull width of at least 80 feet. The number of similar structures per project ranged from a four to 19 bendway weirs. There was not enough data provided to make any other observations. These structures have been studied both in the lab and field extensively and design guidelines are readily available in HEC-23 and NEH-654.

Contrary to literature review findings, 60% of bendway weir practitioners use Rosgen guidelines while only 40% reported using Army Corps guidelines. Rosgen guidelines for bendway weirs have not been located.

Spurs

There were 9 respondents who indicated experience with spurs. In general, respondents believed that spurs were more cost effective than the other structures, but they were not as effective at either channel stabilization or ecological enhancement. Details for three projects were provided totaling 11 structures. Aspect ratios ranged from 14.3 to 16.3 and the three successful projects were located in channels ranging from 100 to 300 feet bankfull width. Channel slope ranged from 0.0002 to 0.0033 and the sinuosity was between 1.3 and 1.5. The number of similar structures per project ranged from three to five spurs. All projects were designed so the furthest upstream spur would align the flow for spurs further downstream. This was done by orienting the first spur at a normal or downstream angle to the flow.

Spurs have been studied extensively in both the lab and the field and design guidelines are readily available in HEC-23 (2001). Contrary to literature review findings, 60% of spur practitioners use US Army Corps guidelines to design the structures. No specific guideline documents were mentioned but Copeland (1983) and Burch et al. (1984) are well cited Corps publications detailing spur use. HEC-23 (2001) guidelines accounted for 20% of spur practitioners.

Constructed riffles

There were 20 respondents who indicated experience with constructed riffles. The common perceptions held by respondents show that constructed riffles under perform the other structures being studied in all performance dimensions, with the exception of environmental impact. According to respondents, positive environmental impact is the greatest asset of constructed riffles and is on par with other structures being studied in this category.

The most effective use of riffles, which was mentioned by 9 respondents, is as a habitat improvement structure. Six respondents added that riffles are effective as grade control structures. The most commonly observed limitation was a lack of stability during high flow periods. Specific constructed riffle details were received for 11 projects totaling 80 structures. The width-depth ratios were primarily 6-8 though one respondent gave values of 15 and 20 for two projects he was associated with. Channel sinuosity ranged from 1 to 1.5 and channel slope was 0.0007 to 0.03. The number of similar structures per project ranged from a single structure to27 riffles. All projects were deemed successful including those which had experienced flows greater than the design flood. Riffle material sizes are normally very large footer rocks with 3-5" cobbles making up the shape of the structure. Spawning gravel is then overlain and graded at 4:1 on the upstream face, and 10:1 on the downstream face. While gravels and cobbles are the primary bed materials riffles are installed on, one respondent reported successful installation on a clay bed.

Constructed riffles received a large amount of feedback and are used by practitioners looking to stabilize channels and aid fish populations. Contrary to literature review findings, 54% of constructed riffle practitioners use Rosgen guidelines while only 31% reported using Newbury & Gaboury's (1993) guidelines. Rosgen guidelines for riffles have not been located.

The following charts summarize data received for specific projects. Unsuccessful projects are denoted by unfilled symbols. Figure 46 shows the channel width-depth ratios corresponding to projects for each structure type In general, unsuccessful projects tend to be located in rivers with relatively low aspect ratios; these streams may not be geomorphically stable and therefore more difficult to control with rock structures.

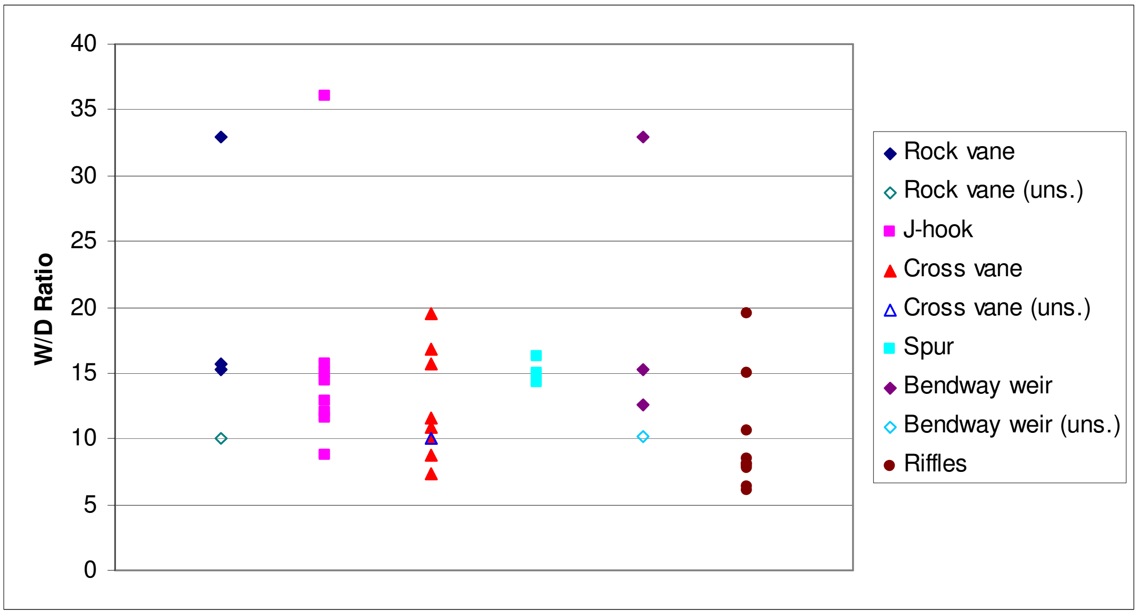


Figure 46: Channel Aspect Ratio per Structure Type

Figure 47 shows the channel slopes corresponding to projects for each structure type. Information was collected for projects from rivers with a wide range of hydraulic conditions. No clear trends separate successful and unsuccessful projects.

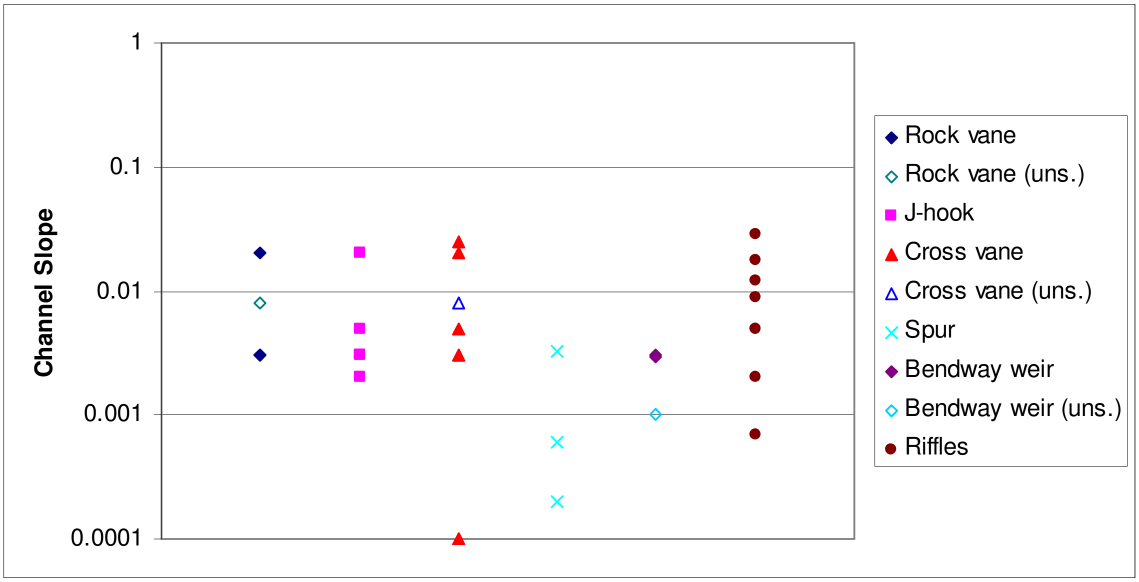


Figure 47: Channel Slope per Structure Type

Figure 48 shows the number of similar structures used in each specific project for each structure type. The vast majority of successful projects deployed more than one structure. For rock vanes and cross vanes, the unsuccessful projects utilized only one structure each. Deploying multiple structures reduces the stress on each structure, which may promote long-term success.

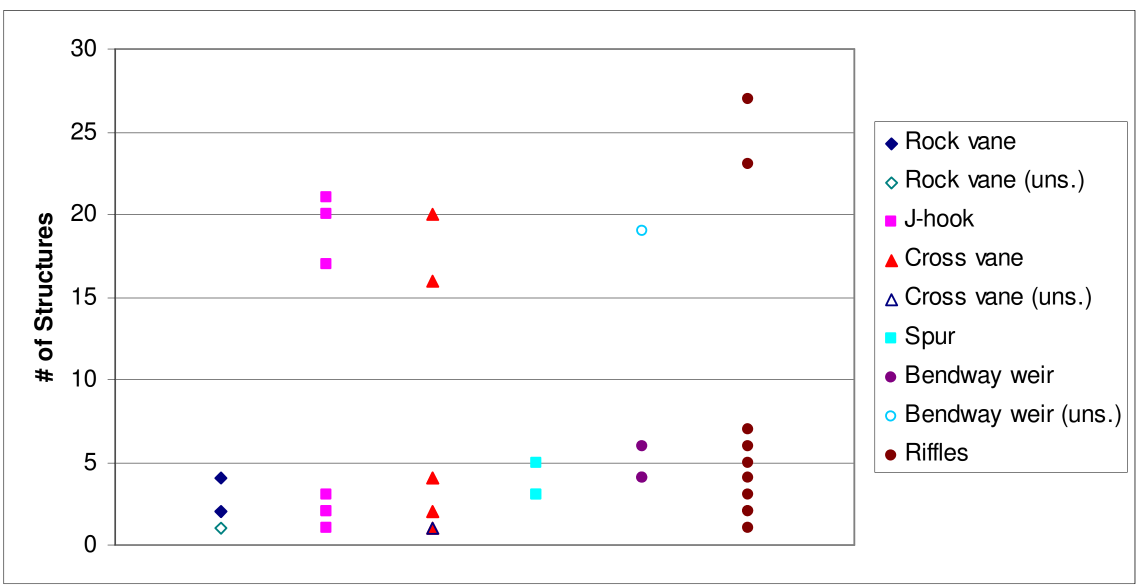


Figure 48: Number of Similar Structures per Project

Figure 49 shows the channel sinuosity corresponding to successful projects for each structure type; sinuosity values were not reported for any unsuccessful projects. In general, sinuosities were relatively low (1.5 or less), indicating that these streams had relatively little bend stress. Note that one constructed riffle project even occurred in a straight stream (sinuosity of 1).

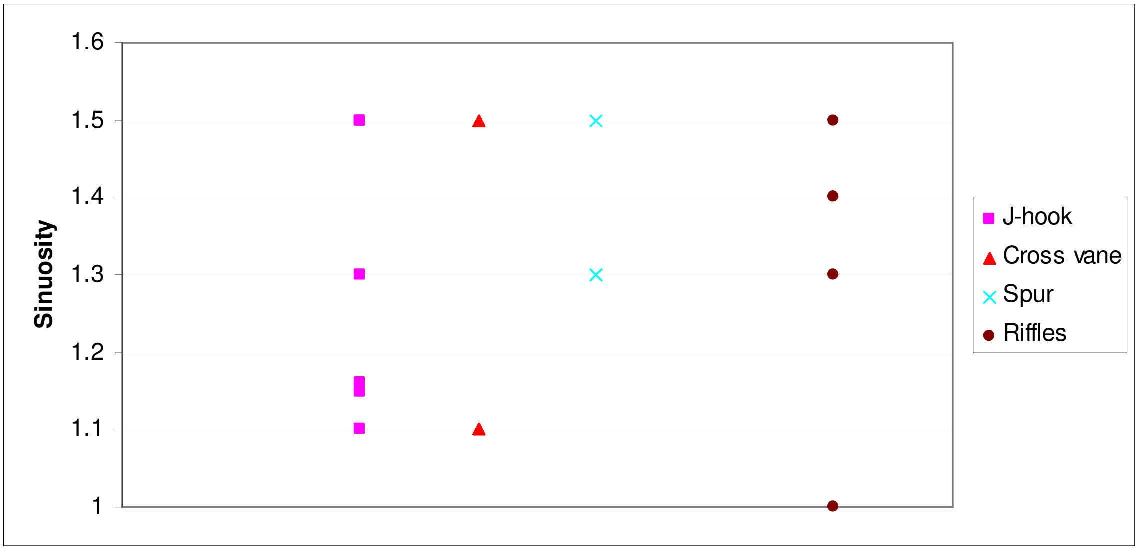


Figure 49: Channel Sinuosity per Structure Type

Chapter 4: Recommendations for Future Research

Table 4 presents the eight structures reviewed here. They have been classified according to hydraulic type, common characteristics, and common reasons for failure.

Table 4: Matrix of Reviewed Structures

Structure	Hydraulic Type	Characteristics	Possible Failure
Rock vane	Weir	Single-arm rock structure that redirects flow away from bank	Not keyed properly; rocks of correct size and shape
J-hook	Weir	Single-arm rock structure that redirects flow away from bank with added scour hole control	Not keyed properly; rocks of correct size and shape
W-weir	Weir	Channel spanning rock structure used to create dual thalwegs; grade control	Installation; rocks of correct size and shape
Cross vane	Weir	Channel spanning rock structure which creates a central scour area; grade control	Installation; rocks of correct size and shape
Bendway weir	Weir	Single-arm rock structure that redirects flow away from bank; normally in large meander bends	Navigational hazards, local scour
Submerged vane	Weir	Free standing plate structure that redirects flow away from bank	Limited field experience; local scour
Spur	Retarder, deflector	Single-arm, impermeable structure which obstructs flow in the near-bank region	Overtopping, unintended deflection, local scour
Constructed riffle	Natural weir	Channel spanning, rock structure used to mimic naturally occurring pool-riffle sequences; grade control	Streamwise migration; stability in flood events

Based on the literature review and survey results presented above, we recommend six of these eight structures for further study. The rock vane is widely used by both transportation and natural resources agencies. The rock vane also serves as a major component of several other structures, including J-hooks and cross vanes. The cross vane is widely used as a grade control and channel stabilization structure. Constructed riffles are popular as a grade control and channel stabilization structure and in addition mimic natural riffle habitat. Additional research on spurs and bendway weirs should use the existing published guidelines as a starting point.

Considering the lack of positive feedback, low popularity in general, and the difficulties described in lab studies and general correspondence, we recommend that the W-weir not be studied further. In addition, submerged vanes are apparently not being used in small streams, and we recommend that they not be studied further.

It is intended that these data be used in conjunction with existing design methods to achieve an initial starting point for research that is both informed and efficient. Rigorous testing is needed to create design guidelines with which practitioners can confidently create the most appropriate solution in each scenario. This solution will achieve effective channel stabilization with the potential to be more cost effective and promote aquatic habitat.

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Appendix A
Summary of Reviewed Field Work

Field work			Channel Properties			Barb/Bendway Weir Properties							
Researcher	Year	Project Description	Sediment	Width	Depth	Angle	Length	Height	Slope	Spacing	# of	Cost	Results
Wittler & Andrews	1998	Protecting cultural resources using bendway weirs					12.1, 8, 6, & 5 m	1.31 m		200-250 m	4		Not provided
Derrick	1997	Stabilize channel and align for bridge				2 to 16	110-114 ft		~1 %	200 ft	11		Reduced bank erosion and succesful alignment
Derrick	1997	Stabilize channel and align for bridge				20 max	110-114 ft		~5 %	110 ft	5		Performed well during 25 year flood event
Derrick	1998	Bendway weirs for stream stabilization		29 m	2 m	20 max	Anticipated thalweg	2-4 ft above bed	2 ft vertical	23 or 30.5 m	54	$3000 per weir	Channel conditions improving even after several floods

Field work			Channel Properties			Submerged Vane Properties							
Researcher	Year	Project Description	Sediment	Width	Depth	Angle	Length	Height	Thickness	# Array	Total	Cost	Results
Odgaard & Wang	1991	Submerged vane use on West	0.5 mm	~35 m	~2 m	20	3.7 m	0.6 m		4	12	5000	Channel centered under crossing
Whitman et al.	2001	Submerged vane use in North Fish Creek, Wisconsin; bluff	Fluvial	25 ft		20	0.9 m	0.3 m * bankfull		11	35		Channel beginning to stabilize
Odgaard & Mosconi	1988	Submerged vane use on East Nishnabotna River, Iowa		~40 m	~2 m	12.2	4.22 m	91.5 cm	7.6 cm	34	77	174 / meter bank	Show that vanes are viable method but modifications necessary
Nakato et al.	1990	Pump-station intake shoaling control with submerged vanes		750 ft	16 ft	19.5	9 ft	9-12 ft below surface		1	2 rows of 13		Shoaling problems eliminated, dredging not required

Field work			Channel Properties				Rock Vane Properties						
Researcher	Year	Project Description	Sediment	Width	Depth	Slope	Angle	Length	Height	Slope	Spacing	# of	Results
Niezgoda	2006	Rigid structures affect on channel stability	20 mm	4.7-8.2 m	.34-.75 m	0.017					10-70m 30-80 m	3 cross 3 J-hook	Use minimum number of well designed structures
Dahle	2008	Study j-hooks and cross vanes as scour countermeasures	Numerical and field studies performed on many structures located in Provo River and Thistle Creek										Structures are not well suited as bridge scour countermeasures

Field work			Channel Properties				Constructed Riffle Properties					
Researcher	Year	Project Description	Sediment	Width	Depth	Slope	Height	Slope	Spacing	# of	Cost	Results
Newbury & Gaboury	1993	Riffles to stabilize channel and create spawning beds		~16 m		0.003	0.6 m	2.5-5%	5-7 BF	7		Settling and erosion required additional materials

Appendix A
Summary of Reviewed Lab Work

Rock Vanes	Lab Work			Flume Properties				Rock Vane Properties						
	Researcher	Year	Project Description	d 50	Width	Depth	Slope	Angle	Length	Height	Slope	Spacing	# of	Results
	Johnson	2001	Study rock vanes as possible scour countermeasures	1 mm	1.5 m	9-28 cm	0.002	20, 25, 30	Projects W/3	Bankfull ±1 cm	None	1.25 m	1,2,3	Well placed vanes move scour from bank to center of channel
	Bhuyian	2007	Study W-weirs as scour countermeasure	1.5 mm	1.6 m	150 mm		30			1:5 & 1:12	---	1	Best location for structure is at the end of the riffle zone

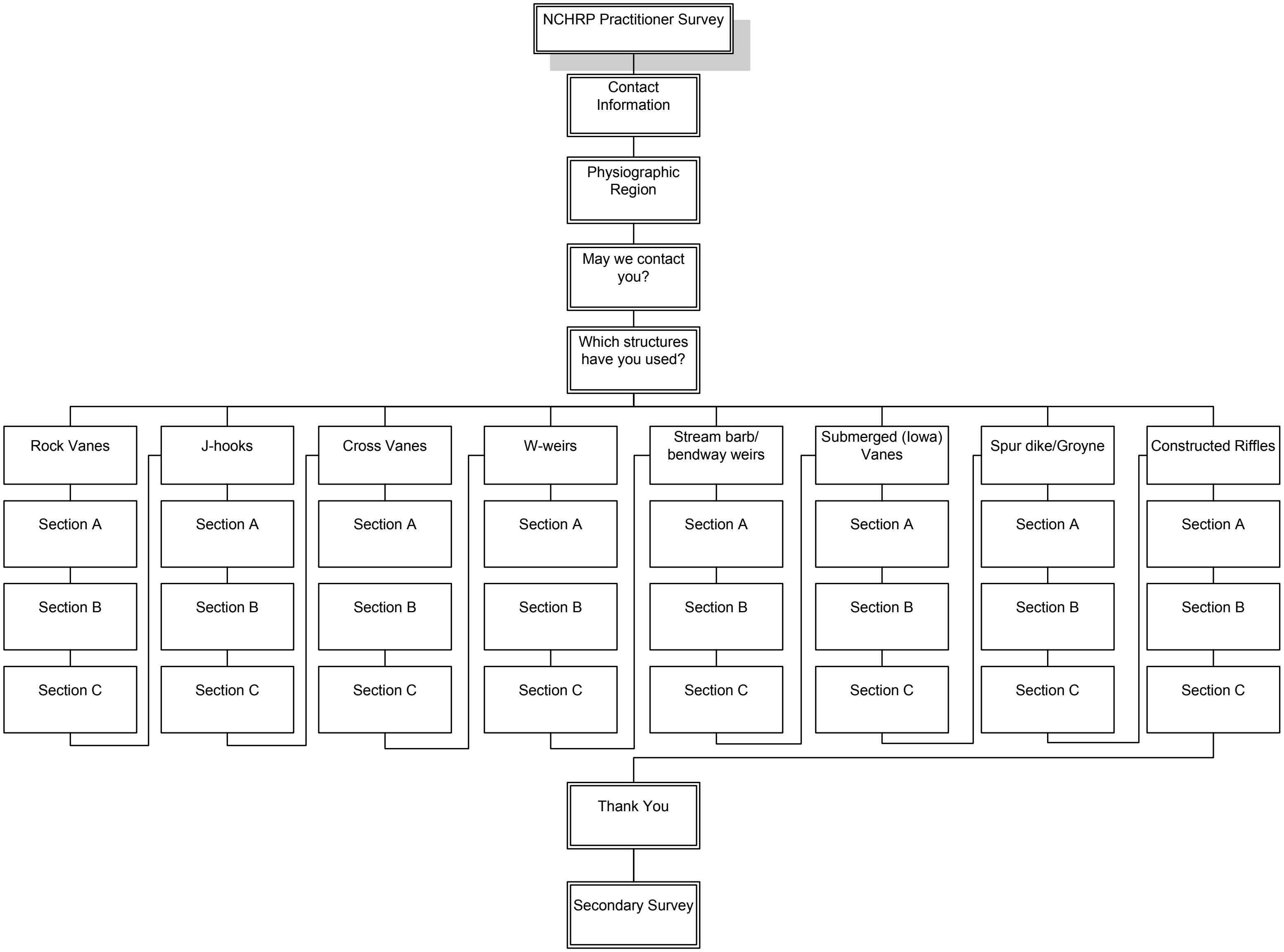
Submerged Vanes	Lab work			Flume Properties					Vane Properties							Results
	Researcher	Year	Project Description	d 50	SD	Width	Depth	Shape	Material	Height	Length	Thickness	Other	In Array	Angle	
	Odgaard & Wang	1991	Lab experimentation of vane properties	0.41 mm	1.45	1.94 m	17.8 cm	Curved	Fiberglass	7.4 cm	15.2 cm	-----	10º twist	2 to 3	15	Predicitons Confirmed, general design guidelines
							18.2 cm	Straight	Sheet			.08 mm		4	20	
	Marelius & Sinha	1998	Determine angle for max counter current	0.9 mm	Uniform	1.54 m	0.4 m	Straight	Sheet	0.12 m	0.24 m			1	25, 35, 40, 45, 57	Max counter current occurs at 40 degrees
	Tan et al.	2005	Effect of bedform dimensions & vane length	2.8-3.1 mm	Uniform	6 m	0.6 m	Straight	Sheet	/8-1/3 Flow	1-4 m	10 mm		1	15, 30, 45, 60, 90	30 degree angle optimal for sediment diversion; Height should be 2 to 3 times bedform height
	Spoljaric Thesis	1988	To improve design of submerged vanes	0.3 mm	Uniform	61.5 cm	10-25 cm	Straight	Sheet	6.4 cm	21.5 cm	-----	flat	1	5, 10, 15	Only moderate improvement by cambering; lateral spacing should not exceed 1.5 to 2 flow depths;
										7.7 cm	17.1 cm	-----	cambered w/ vertical	1	0, 10, 15, 20	
										7.7 cm	17.1 cm	-----	cambered w/ twist	1	0-30 by 5	
	Wang Thesis (Flat, Fixed Bed)	1991	Velocity distributions of single vanes and arrays	4 mm		6 ft	6-7 in	Straight	Sheet	0.25 ft	0.5 ft	0.75 mm	flat	Varied	20	Vane induced velocites small outside of 2 vane heights laterally; spacing within array
				5 mm		7 ft	6-7 in	Straight	Sheet	.125-0.25	0.25-0.5 ft	0.75 mm	twisted	Varied	20	
			Series of 15 arrays	4 mm		3 ft	4 in	Straight	Sheet	2 in	4 in	0.75 mm	flat	4	20	No conclusion
	Hossain et al.	2006	Flow field around bottom vane	-----	-----	2.45 m	0.3 m	Straight	Perspex	0.06, 0.09, 0.12, 0.18 m	0.4 m	8 mm			15, 15, 20, 30, 40	Scour at the base of a vane does not appreciably affect river training ability
	Voisin & Townsend	2002	Vanes in strongly curved channels	0.7 mm	1.3	0.305 m	0.1 m	Curved	Sheet	15, 25, 35, 50, 65 mm	50, 100, 150 mm	0.5 mm		1	-4*, 0*, 4*, 8*, 12*,	Optimum values for configuration: L/b=0.33, H/d=0.35, Angle=2, Bank to
	Gupta et al.	2006	Dike formation with submerged vane	0.405 mm	1.37	50 cm		Straight	Plastic sheet	6 cm	18 cm	4 mm	Some trapezoida		40	Heaps of sediment (dikes) formed downstream using angle of 40d, useful in
	Nakota et al.	1990	Intake shoaling prevention model	0.33 mm	1.41	6 ft	18 in	Straight	Sheet		9 ft			2 rows of 13	19.5	Successful model developed for protoype; vanes will prevent shoaling
	Barkdoll et al.	1999	Sediment Control at Lateral Diversion	0.9 mm	uniform	1.5 m	0.152 m	Straight w/ intake		3.2 cm	10 cm			3	20	Vanes elimnate bed-sediment ingestion up to a specific discharge ratio 0.2
	Odgaard & Spoljaric	1986	Sediment Control by Submerged Vanes	0.3 mm	1.5	0.61 m	0.17 m	Straight	Sheet	8.5 cm	21 cm	20 gage (.92 mm)		1	15	Arrays increase lateral transport without increasing streamwise transport
				0.4 mm	1.4	1.83 m	0.15 m			9.4 cm	22.9 cm			4		

* Angles to main flow direction

Bendway Weirs & Stream Barbs	Lab work			Flume Properties				Barb/Bendway Weir Properties					
	Researcher	Year	Project Description	d 50	Width	Flow Depth	Other	Angle	Length	Height	Slope	Spacing	Results
	Thornton et al.	2005	Bendway weirs resultant flow conditions	Rough concrete	Varied, not provided	Varied, not provided		90	1.49 m	Constant, not provided	Flat	Arc length: weir length 3.4, 4.1, 4.7, 5.1, 5.9, 8.4	Weirs reduced outer bank velocities by 40% compared to centerline
									1.16 m				
	Fox et al.	2005	Fluid-sediment dynamics around a barb	5.2 mm	1.2 m	0.152 m	Straight channel	50	1/3 width	Leading edge is	10H:1V	Single structure	Scour in the nose region, stagnant flow along bank
						0.055 m							
	Matsuura & Townsend	2004	Stream barbs in narrow channels	.78 mm	0.46 m	0.102 m	90 and 135	20, 30, 40		0.038-0.051 m		0.818-3.312 m; many values	Importance of first barb placement; 30 degrees optimum

Spur Dikes	Lab work			Flume Properties				Spur Dike Properties					
	Researcher	Year	Project Description	d 50	Width	Flow Depth	Other	Angle	Length	Height	Slope	Spacing	Results
	Rajaratnam & Nwachukwu	1983	Flow paterns near spur dike	Smooth, 0.56 mm, 6.3 mm	3	0.5-0.84	Straight	90	0.25, 0.5	Above WS	None	Single structure	Maximum shear stress located at the dike tip
	Copeland	1983	Spur dikes in meandering sand bed	0.45 mm	8	0.24	Sinuosity is 1.6	60, 75, 90, 105, 120	2.2	NA	0.0012	Varied	Approximately 90 is optimum orientation,
	Kuhnle et al.	2004	Flow at submerged spur dike	0.8 mm	1.219 m	0.305 m	Straight	90	0.342 m	0.152	0.0001	Single structure	Eddy zone extends 1.6 times length downstream
	Koken & Constantinescu	2008	Flow and scour structure at single dike	NA	0.91 m	0.10 m	Straight	90	0.15 m	Above WS	None	Single structure	Maximum shear stress located at the dike tip

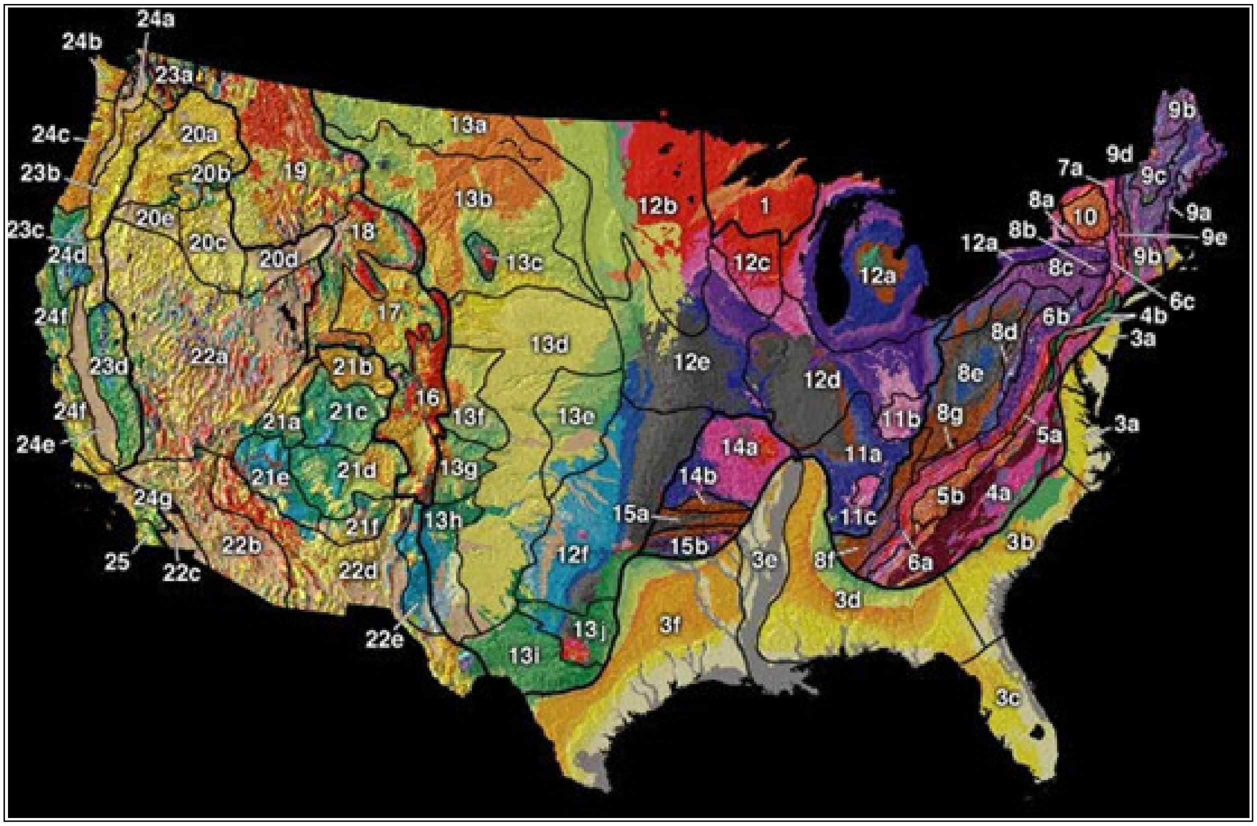
Appendix B
Survey Structure



Appendix D
Detailed Project Responses

Responder	Agency	Structure	Width	Depth	W/D	Slope	Sinuosity	Structure Length		# of	Design Flood	Actual Flood	Local Bed	Rock Size	Angle	Structure
			ft	ft				arm	weir	structures	cfs	cfs	Material	ft	deg	Slope
Wesley Peck	Tennessee DOT	Bendway weir	265	20-25	11.5	0.001		60		5	bf	Surpassed	sand	d100=3	52-70	
Brooks Booher	Arkansas DOT	Bendway weir	135	4.0	33.8	0.003	1.3	30-40		4			d50=121 mm		75	0%
Walter Ludlow	Montana DOT	Bendway weir	131	8.6	15.3	0.0029		33		4	2500			d50=1.3	65	4%
Bruce Rhoads	University of Illinois	Bendway weir	66	6.5	10.2	0.001				19			cobbles			
Bruce Rhoads		Bendway weir	82	6.5	12.6	0.003				6						
Forrest Bonney	Maine Dept. of Inland	Cross vane	26	2.4	10.9	0.0001				2			35-55 mm	4-5'	NA	
Forrest Bonney	Fish & Wildlife (DIFW)	Cross vane	30	3.0	10.0	0.0001				2			18-27 mm	3-4'	NA	
Brian Murphy	Connecticut DEP	Cross vane	45	2.3	19.6	0.005		30	15	4	430	1100	150mm	3-5'	NA	
Louis Wasniewski	USFS-Idaho	Cross vane	32	1.9	16.8	0.03	1.1	25		1	325			3-4'	25	10%
Brooks Booher	Arkansas DOT	Cross vane	50	5.0	10.0	0.008		80	Apex	1				400-500 lb	30-40	10%
John McClain	Virginia DOT	Cross vane	33	2.1	15.7	0.02	1.1	45		20	1.5 yr		gravel/cobble	1.5-2 tons	25	3-5%
John McClain		Cross vane	90	6.0	15.0	0.0018	NA		145	3	1.43 yr		gravel	3-5 tons	25	
Jamie Lancaster	North Carolina DOT	Cross vane	22	1.9	11.6	0.0053	1.5	18-20		16	2 yr	Trop Storm	gravel	2'	20-30	
Jamie Lancaster		Cross vane	22	2.5	8.8	0.0034	1.5	18-20		21	2 (bf)	>bf	gravel/sand	2'	20-30	
Chris Frieburger	Michigan DNR	Cross vane	30	4.1	7.3	0.003	1.1	30		1		50 yr	sand	2'	20	
Brian Murphy	Connecticut DEP	J-hook	90	2.5	36.0	0.003		100	30	1	1900	2300	64mm	3-5'	NA	
Louis Wasniewski	USFS-Idaho	J-hook	32	2.5	12.8	0.02	1.3	20 to 25		2	200-230	>bf	gravel/cobble	3-4'	25	10%
John McClain	Virginia DOT	J-hook	33	2.1	15.7	0.02	1.1	45		20						
Jamie Lancaster	North Carolina DOT	J-hook	1.4-9	.12-.75	12.0	.006-.03	1-1.3			Many				5'	30	4-10 %
Jamie Lancaster		J-hook	22	1.9	11.6	0.0053	1.5	18-20		17	2 yr	Trop Storm	gravel	2'	20-30	
Jamie Lancaster		J-hook	22	2.5	8.8	0.0034	1.5	18-20		4	2 (bf)	>bf	gravel/sand	2'	20-30	
Chris Frieburger	Michigan DNR	J-hook	15.5	1.1	14.5	0.003	1.16	17		2		50 yr	gravel	2'	20	
John Sours	Wisconsin DNR	Riffles	30	3.8	8.0	0.029	1.3			3	800	1300	gravel/sand	3-5"	NA	
Forrest Bonney	Maine DIFW	Riffles	19-36	2.35-4.52	8.0	0.018				6			40-95 mm	5 ft max	NA	
Bill Cody	Ohio DOT	Riffles	32	3.0	10.7	0.002				5						
Bill Cody	Ohio DOT	Riffles	16.5	2.6	6.3					27		Surpassed		2.5" min	NA	4 to 1; 10 to 1
Deane Van Dusen	Maine DOT	Riffles	27-42	1.6-2.1	17 to 22	0.005				2			2-4.9 mm		NA	
Deane Van Dusen	Maine DOT	Riffles	60	4.0	15.0					2					NA	
Robert Siegfried	Virginia Consulting Firm	Riffles	12	1.5	8.0	0.005	1.4	20-50		7	NA	Surpassed	Clay	riprap		
Louis Wasniewski	USFS-Idaho	Riffles	5.8	1.0	6.1	0.012	1.5	5 to 30		23	30		gravel/cobble			
Greg Koonce	Oregon Consulting Firm	Riffles	23-47	5.0	6 to 11	0.009			13-28	4		10 yr			NA	1.47-2.8%
Chris Frieburger	Michigan DNR	Riffles	32	4.1	7.8	0.0007	1		32	1		50 yr	sand	2'		
Brian Murphy	Connecticut DEP	Rock vanes	52	3.4	15.3	0.003		25	NA	2	670		50mm	3-5'	NA	
Brooks Booher	Arkansas DOT	Rock vanes	50	5.0	10.0	0.008		80		1				400-500 lb	30-40	10%
Brooks Booher		Rock vanes	135	4.0	33.8	0.003	1.3	40		4			d50=121 mm		30	10%
Jamie Lancaster	North Carolina DOT	Rock vanes	22	1.9	11.6	0.0053	1.5	18-20		3	2 yr	Trop Storm	gravel	2'	20-30	
Warren Bailey	Mississippi DOT	Spurs	300	20.0	15.0	0.0002	1.5	40-50		3					90, 75	None
Kevin Flora	California DOT	Spurs	100	7.0	14.3	0.0033	1.3	180		3	13500		1-2 inch		135, 90	2%
Brad Pfiefer	North Dakota DOT	Spurs	220	13.5	16.3	0.0006	1.3	40 & 70		5	35600	79500		riprap	135, 90	
Chris Frieburger	Michigan DNR	W-weir	229	4.0	57.3	0.0007	1.1		229	1		50 yr	sand/gravel	3-4'	25	

Appendix E
Structure Responses per Physiographic Region



Physiographic Region	#	Physiographic Region	#	Physiographic Region	#	Physiographic Region	#
1 Superior Upland	2	8f Cumberland Plateau section	1	13f Colorado Piedmont	0	21e Grand Canyon section	0
2 Continental Shelf (not on map)	0	8g Cumberland Mountain section	2	13g Raton section	0	21f Datil section	0
3a Embayed section	6	9a Seaboard Lowland section	0	13h Pecos Valley	0	22a Great Basin	4
3b Sea Island section	3	9b New England Upland section	4	13i Edwards Plateau	0	22b Sonoran Desert	1
3c Floridian section	1	9c White Mountain section	2	13j Central Texas section	0	22c Salton Trough	0
3d East Gulf Coastal Plain	1	9d Green Mountain section	2	14a Springfield-Salem plateaus	1	22d Mexican Highland	0
3e Mississippi Alluvial Plain	1	9e Taconic section	1	14b Boston "Mountains"	1	22e Sacramento section	0
3f West Gulf Coastal Plain	1	10 Adirondack Province	0	15a Arkansas Valley	0	23a Northern Cascade Mountains	1
4a Piedmont Upland	12	11a Highland Rim section	0	15b Ouachita Mountains	2	23b Middle Cascade Mountains	3
4b Piedmont Lowlands	6	11b Lexington Plain	0	16 Southern Rocky Mountains	1	23c Southern Cascade Mountains	3
5a Northern section	4	11c Nashville Basin	0	17 Wyoming Basin	0	23d Sierra Nevada	4
5b Southern section	7	12a Eastern Lake section	4	18 Middle Rocky Mountains	3	24a Puget Trough	1
6a Tennessee section	3	12b Western Lake section	2	19 Northern Rocky Mountains	5	24b Olympic Mountains	0
6b Middle section	0	12c Wisconsin Driftless section	1	20a Walla Walla Plateau	4	24c Oregon Coast Range	3
6c Hudson Valley	0	12d Till Plains	4	20b Blue Mountain section	2	24d Klamath Mountains	1
7a Champlain section	1	12e Dissected Till Plains	1	20c Payette section	1	24e California Trough	0
7b Northern section (not on map)	0	12f Osage Plains	2	20d Snake River Plain	3	24f California Coast Ranges	1
8a Mohawk section	1	13a Missouri Plateau, glaciated	2	20e Harney section	2	24g Los Angeles Ranges	0
8b Catskill section	2	13b Missouri Plateau, unglaciated	1	21a High Plateaus of Utah	0	25 Lower California province	0
8c Southern New York section	3	13c Black Hills	1	21b Uinta Basin	0		
8d Allegheny Mountain section	3	13d High Plains	0	21c Canyon Lands	0		
8e Kanawha section	4	13e Plains Border	1	21d Navajo section	0		

Appendix E
Structure Responses per Physiographic Region

Physiographic Region	#	Rock vane	J-hook	Spur dike	Bendway w	Cross vane	W-weir	Riffles
1 Superior Upland	2	2	2	0	0	2	2	2
2 Continental Shelf (not on map)	0	0	0	0	0	0	0	0
3a Embayed section	6	6	5	3	0	3	1	2
3b Sea Island section	3	3	2	1	0	2	0	2
3c Floridian section	1	1	0	0	0	0	0	1
3d East Gulf Coastal Plain	1	1	0	1	0	0	0	0
3e Mississippi Alluvial Plain	1	0	0	0	0	0	0	0
3f West Gulf Coastal Plain	1	1	0	0	0	1	0	1
4a Piedmont Upland	12	12	7	3	0	6	1	4
4b Piedmont Lowlands	6	6	3	1	0	3	1	3
5a Northern section	4	3	2	1	0	2	1	1
5b Southern section	7	7	6	2	0	5	2	3
6a Tennessee section	3	3	3	2	0	3	2	2
6b Middle section	0	0	0	0	0	0	0	0
6c Hudson Valley	0	0	0	0	0	0	0	0
7a Champlain section	1	1	0	0	0	1	0	0
7b Northern section (not on map)	0	0	0	0	0	0	0	0
8a Mohawk section	1	1	0	0	1	1	0	1
8b Catskill section	2	2	1	0	0	1	0	0
8c Southern New York section	3	0	0	0	0	0	0	1
8d Allegheny Mountain section	3	2	0	0	0	0	0	1
8e Kanawha section	4	1	0	0	0	0	0	0
8f Cumberland Plateau section	1	1	0	0	0	0	0	0
8g Cumberland Mountain section	2	1	1	0	0	1	1	1
9a Seaboard Lowland section	0	0	0	0	0	0	0	0
9b New England Upland section	4	4	2	0	0	3	0	2
9c White Mountain section	2	1	0	0	0	1	0	1
9d Green Mountain section	2	2	0	0	0	2	0	1
9e Taconic section	1	1	0	0	0	1	0	0
10 Adirondack Province	0	0	0	0	0	0	0	0
11a Highland Rim section	0	0	0	0	0	0	0	0
11b Lexington Plain	0	3	0	0	0	0	0	0
11c Nashville Basin	0	0	0	0	0	0	0	0
12a Eastern Lake section	4	0	2	0	0	2	2	2
12b Western Lake section	2	2	0	0	0	0	0	0
12c Wisconsin Driftless section	1	0	0	0	0	0	0	0
12d Till Plains	4	0	0	0	1	1	0	1
12e Dissected Till Plains	1	0	0	0	0	0	0	0
12f Osage Plains	2	0	0	0	0	0	0	0
13a Missouri Plateau, glaciated	2	1	1	2	1	1	1	1
13b Missouri Plateau, unglaciated	1	1	1	1	1	1	1	1
13c Black Hills	1	0	0	0	0	0	0	0
13d High Plains	0	0	0	0	0	0	0	0
13e Plains Border	1	0	0	0	0	0	0	0
13f Colorado Piedmont	0	0	0	0	0	0	0	0
13g Raton section	0	0	0	0	0	0	0	0
13h Pecos Valley	0	0	0	0	0	0	0	0
13i Edwards Plateau	0	0	0	0	0	0	0	0
13j Central Texas section	0	0	0	0	0	0	0	0
14a Springfield-Salem plateaus	1	1	0	0	0	0	0	0
14b Boston "Mountains"	1	1	0	0	0	1	0	1
15a Arkansas Valley	0	0	0	0	0	0	0	0
15b Ouachita Mountains	2	2	0	0	0	0	0	1
16 Southern Rocky Mountains	1	1	1	0	1	0	1	0
17 Wyoming Basin	0	0	0	0	0	0	0	0
18 Middle Rocky Mountains	3	2	2	0	0	1	0	1
19 Northern Rocky Mountains	5	5	3	1	1	1	1	1
20a Walla Walla Plateau	4	3	3	0	1	2	0	2
20b Blue Mountain section	2	1	1	0	0	0	0	0
20c Payette section	1	1	1	0	0	0	0	0
20d Snake River Plain	3	3	2	0	0	0	0	0
20e Harney section	2	2	2	0	1	1	0	1
21a High Plateaus of Utah	0	0	0	0	0	0	0	0
21b Uinta Basin	0	0	0	0	0	0	0	0
21c Canyon Lands	0	0	0	0	0	0	0	0
21d Navajo section	0	0	0	0	0	0	0	0
21e Grand Canyon section	0	0	0	0	0	0	0	0
21f Datil section	0	0	0	0	0	0	0	0
22a Great Basin	4	4	3	1	0	0	0	0
22b Sonoran Desert	1	0	0	0	0	0	0	0
22c Salton Trough	0	0	0	0	0	0	0	0
22d Mexican Highland	0	0	0	0	0	0	0	0
22e Sacramento section	0	0	0	0	0	0	0	0
23a Northern Cascade Mountains	1	1	1	0	0	0	0	0
23b Middle Cascade Mountains	3	3	3	0	1	1	0	1
23c Southern Cascade Mountains	3	3	2	0	1	2	0	1
23d Sierra Nevada	4	4	2	2	0	0	0	0
24a Puget Trough	1	1	1	0	0	0	0	0
24b Olympic Mountains	0	0	0	0	0	0	0	0
24c Oregon Coast Range	3	3	2	0	1	2	0	1
24d Klamath Mountains	1	1	1	0	0	0	0	0
24e California Trough	0	0	0	0	0	0	0	0
24f California Coast Ranges	1	0	0	1	0	0	0	0
24g Los Angeles Ranges	0	0	0	0	0	0	0	0
25 Lower California province	0	0	0	0	0	0	0	0