United States Department of Agriculture

NRCS

Natural Resources Conservation Service
760 South Broadway
Salina, Kansas 67401-4604

Phone: 785-823-4500
FAX: 785-823-4540
www.ks.nrcs.usda.gov

January 23, 2013

KANSAS ENGINEERING TECHNICAL NOTE NO. KS-1 (Revision 1)

SUBJECT: ENG–Design of Stream Barbs

Purpose. To provide guidance on the design of stream barbs

Effective Date. Upon receipt

Background

Stream barbs have been used by the Natural Resources Conservation Service (NRCS) for river and streambank protection since the late 1980s. Although stream barbs have been extensively used, limited documentation exists of long-term performance and specific design criteria. Oregon Technical Note 23, Design of Stream Barbs (Version 1.3, 2000), and Idaho Technical Note 12, Design of Stream Barbs (2001), provided some design guidance. Since the release of those documents, significant efforts have been made to document field performance of new projects and review literature on barbs and meander bend mechanics. Revised Oregon Technical Note 23 (Version 2.0) represents the culmination of field monitoring performance data and contemporary research for river and stream barb applications. This Kansas technical note utilizes the information contained in the aforementioned Oregon and Idaho technical notes to provide guidance for the design of stream barbs in Kansas.

Description

Stream barbs are rock structures that extend into the stream flow to modify flow patterns and bed topography. They are very low structures that should be completely overtopped during channel-forming flow events (approximately a 1.5-year flow event). Channel-forming flow or bankfull is defined as the flow that transports the greatest amount of sediment over a long period of time and controls the channel geometry. Bankfull flow DOES NOT mean flow to the top of the channel bank. Barbs are used for streambank stabilization, erosion mitigation, and fisheries habitat improvement in meandering, alluvial river systems. Barbs are constructed from a variety of materials that constitute a series of upstream-directed structures (facing flow) located on the outside of a meander bend.

Barbs transfer erosive velocity away from the streambank through interruption of helicoidal currents and cross stream flow that develop within the meander bend. This redistribution of hydraulic forces controls the location of the thalweg (location of maximum bed shear) to a position away from the project bank. Barb systems that function correctly meet streambank

(more)

DIST: A, F

stability and habitat goals without transferring excess energy out of the project reach. Most importantly, barbs are able to meet multiple project objectives without causing unanticipated impacts downstream.

Stream barbs are used for bank protection measures, to increase scour of point and lateral bars, to direct stream flow towards instream diversions, and to change bedload transport and deposition patterns. Other benefits of stream barbs include reducing the width to depth ratio of a stream channel and providing pool habitat for fish. Although trees with rootwads can be added into barbs to increase habitat value, they increase the risk of voids in the rock fill, poor foundation conditions, and increased uplift forces. If fish habitat is limited, consider creating habitat elements separate from the rock barbs (if feasible).

Using stream barbs in conjunction with bioengineering methods is the most favorable combination. The barbs relieve direct streambank pressure from flow, and vegetation provides for energy dissipation and sediment deposition. The vegetation is the long-term stabilizing factor.

Geomorphic Setting

Geomorphic characteristics, such as meander pattern, width/depth ratio, radius of curvature, particle size distribution, channel gradient, and pool/riffle spacing, all impact the effectiveness of stream barbs. On-site evaluation of the appropriateness and utility of stream barbs is necessary.

Barbs are effective for controlling tractive stress-induced erosion on the outside of meander bends in lower gradient alluvial river systems. These rivers are generally lowland meandering systems with cobble or gravel beds positioned within valley bottoms adjacent to broad flood plains. Appropriate channel morphology for barb applications are generally C3 and C4 stream types (Rosgen, 1994) that consist of the following parameters: width to depth ratio greater than 12, channel slope less than 2 percent, sinuosity greater than 1.2, and cobble or gravel streambed substrate.

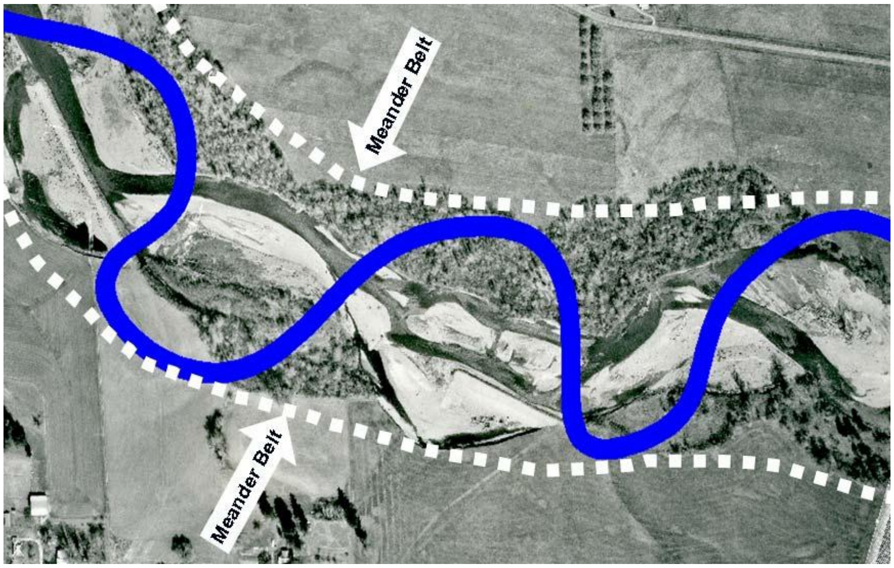
The use of barbs is not necessarily constrained by these values or channel types, but this criterion should be used as a general guideline for identifying appropriate river systems. The width to depth (w/d) ratio exerts an important influence on the pattern of flow in meander bends (Knighton, 1998). Barbs are not recommended for narrow, deep channels (w/d <10), where bars are less likely to form and near bed flows move inward reducing near bank stress. When the ratio is relatively large (w/d >10), point bar development is more extensive, potentially leading to meander migration, bank erosion and the suitability of barbs as a stabilization option.

Vertical stability of the project reach should be evaluated using standard fluvial geomorphic protocols to identify active aggradation or channel incision. If the channel is experiencing active deposition and aggradation of the streambed, barbs may be used to reduce the w/d ratio and increase sediment transport competence. Note that aggrading streams often experience significant plan-form instability and may result in a braided (Rosgen D stream type) channel. Entrenched or incised channels will require a different treatment alternative, such as full-span rock weirs, as barbs will only mitigate lateral erosion.

If the thalweg (deepest part of the channel) is in the center of the channel, other bank protection measures should be considered. Stream barbs will not protect banks that are eroding due to rapid drawdown or mass slope failure.

The use of barbs is also evaluated within the proper context of the larger geomorphic setting. To improve the likelihood of barb performance and success, barbs should be located near the outside of the historical meander migration corridor. This reduces the risk of unforeseen large-scale river changes and potential flanking of the structures. The migration corridor will often correspond to the meander belt width in Rosgen C stream types as illustrated in Figure 1.

Figure 1–Historic meander migration limits



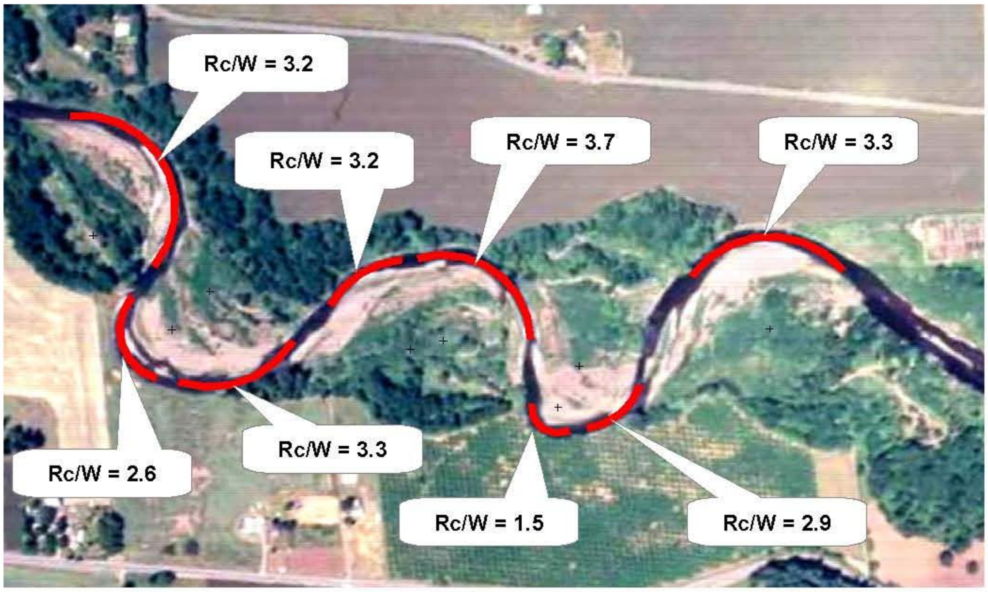
Hydrology

Meander geometry and channel characteristics are not related to a single dominant discharge (for example, a 100-year flood) but to a range of flows whose sediment transport competence varies with the channel's boundary materials. A surrogate for this range of flows is the channel forming flow (CFF) or dominant discharge that is defined as a frequent, moderate magnitude discharge that transports the greatest amount of sediment over a long period of time and maintains the average morphologic characteristics of the channel. Bankfull discharge is often used synonymously for CFF and refers to the discharge where water begins to flow out-of-bank (in non-incised channels) and onto the flood plain. The bankfull stage generally coincides with the regulatory interpretation of "ordinary high water."

Meander Hydraulics

The magnitude of hydraulic forces is affected by the degree of curvature of the meander bend and the channel width. Knighton (1998) identifies a consistent relationship between meander parameters and channel width (w) where the latter operates as a scale variable of the channel system. The term "tortuosity" is introduced as an index of the effect of meander geometries on these forces and is defined as the radius of meander curvature divided by the channel top width (Rc/w). The channel radius is measured through the meander bend along the thalweg, and the width is taken as the water surface top width at bankfull stage in the uniform riffle section upstream of the meander. Tortuosity generally varies throughout the bend since natural meanders often exhibit compound bends rather than continuous curves as shown in Figure 2.

Figure 2–Examples of variable tortuosity through a river segment



Chang (1988) identified the median value for tortuosity to be 3, which correlates well with the median value of 2.7 determined from measurements performed by Leopold et al. (1964). Leopold also noted that the radius is often about 2.3 times the channel width. Chang states that because this ratio results from using conditions of minimum stream power, it represents the maximum curvature for which a river does the least work in turning. Additional research by Williams (1986) identified 42 percent of tortuosity indexes ranging between 2 and 3 with a corresponding mean of 2.43 for his data set. Henderson (1966) suggests that "values of the Rc/w (tortuosity) ratio are found to be as small as 1.5 and as large as 10; but the median value occurs in the range 2 to 3, and it is within that range that the river engineer should look when planning to simulate natural meanders in river training works."

Barbs are designed to influence meander bend hydraulic forces caused by water flowing against an irregular channel boundary. The primary hydraulic flow components accounted for in design are (1) longitudinal velocity, (2) helicoidal flow, and (3) cross stream flow. Longitudinal velocity is the velocity vector component that parallels the channel boundary in the stream-wise direction and is relatively simple to understand. The more complex helicoidal flow and cross stream flow are described in more detail as follows:

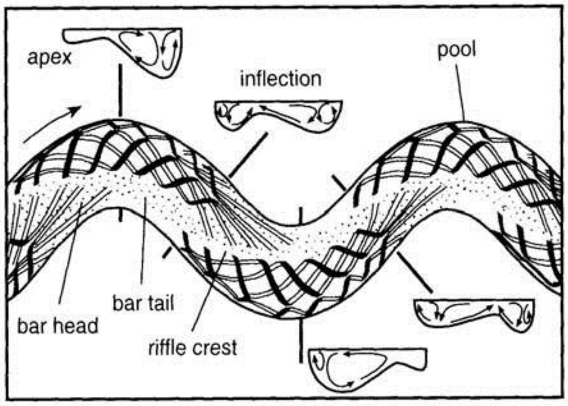
1. Helicoidal Flow–The transverse spiraling current directed toward the outer bank near the water surface and toward the inner bank (point bar) near the streambed to give a helicoidal circulation around the primary longitudinal downstream velocity component
2. Cross Stream Flow–The maximum velocity and current that occurs as the thalweg swings from one bank to the other across the channel centerline (Chang, 1988)

Helicoidal Flow

Centrifugal acceleration acts outwardly on water as it flows through a meander bend and leads to a differential water surface elevation (super elevation). This results in a downward acting pressure gradient that is magnified by the degree of curvature and tortuosity of the meander. The combination of this super-elevation-induced pressure gradient and the main downstream velocity component are major factors affecting the spiraling circulation referred to as helicoidal flow.

Helicoidal flow revolves around the primary stream-wise component of discharge (and velocity) with rotational flow behavior as shown in Figure 3. The section views within this figure illustrate the velocity vector orientations relative to change in morphologic form through the stream reach. The pool sections below illustrate the fully developed helicoidal flow that results in significant near-bank shear stress, the primary force affecting streambank erosion.

Figure 3–Helicoidal flow through a series of meander bends (Knighton, 1998)

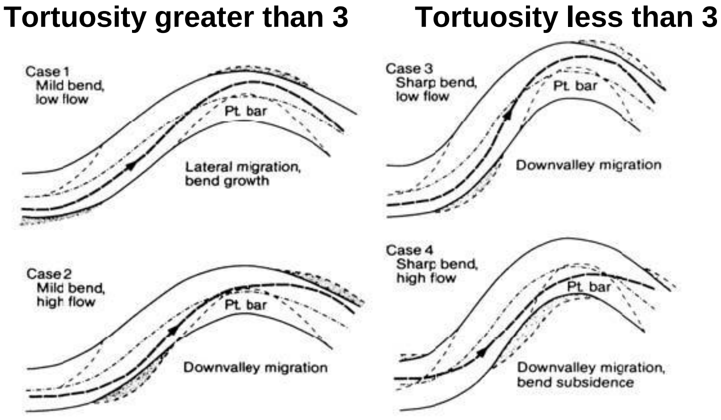


The strength of the helicoidal flow and the potential for bank erosion increase as the tortuosity lowers. Field data and project monitoring have identified helicoidal flow as the primary design consideration in meanders with tortuosity greater than 3. For tortuosity less than 3, helicoidal flow is a primary factor as is cross stream flow that is described below.

Cross Stream Flow

When tortuosity is 3 or less, the primary component of longitudinal velocity impacts the outer streambank at a very abrupt angle. The resulting momentum transfer of the fluid mass directly into the streambank and the work the bank performs in turning the flow may result in significant bank erosion. The impact of fluid mass into the streambank within tight meander bends is termed cross stream flow and results from the angular difference between the discharge centerline (thalweg) and channel centerline and occurs as the primary longitudinal velocity shifts from one bank to the other (Figure 4).

Figure 4–Cross stream flow as a function of tortuosity (Chang, 1988)



Tortuosity greater than 3 **Tortuosity less than 3**

Bathurst et al. (1979) found that at intermediate discharges helicoidal flow is relatively strong, but at high discharges (greater than bankfull), the effects of the primary (cross stream) flow becomes dominant as the main flow follows a straighter path. Thorne (personal communication 2005) suggests that the most pronounced effects of cross stream flow occur between an intermediate flow and flood discharge. It is critical that the design engineer account for the effects of cross stream flow in addition to the amplified magnitude of helicoidal flow in meanders with tortuosity less than 3. For design, this requires tighter barb spacing through the meander bend, tighter barb angles relative to the bank-line, and potentially large-scale roughness elements (such as large wood) placed between the barbs.

The magnitude of hydraulic forces depends on the tortuosity of the meander bend and is summarized in the following table:

Hydraulic Force	Relationship to Tortuosity
Helicoidal Flow	Principle force considered with Rc/w > 3 Magnitude increases as tortuosity decreases
Cross Stream Flow	Critical consideration for Rc/w < 3 Magnitude increases as tortuosity decreases

Hydraulic Effects on Meander Bend Erosion

Hydraulic forces are highest near the outside bank with maximum shear generally occurring near the bend exit. This often results in the highest rates of erosion concentrated against the outer bank, downstream of the bend apex. Across the channel along the opposite bank, point-bar building occurs with sediment and bed material supplied by both primary longitudinal and helicoidal currents, a process that results in a down valley tendency to meander migration.

Chow (1959) noted that the downstream portion of the meander bend should be the first area considered in bank protection and Klingeman et al. (1984) found that, in general, the place where bank erosion is most frequent and where streambank protective measures most commonly fail is just downstream from the axis of the bend.

These observations agree with Leopold's (1964) discussion of the zone of maximum boundary shear stress close to the outer bank beyond the bend apex in the lower third of the meander.

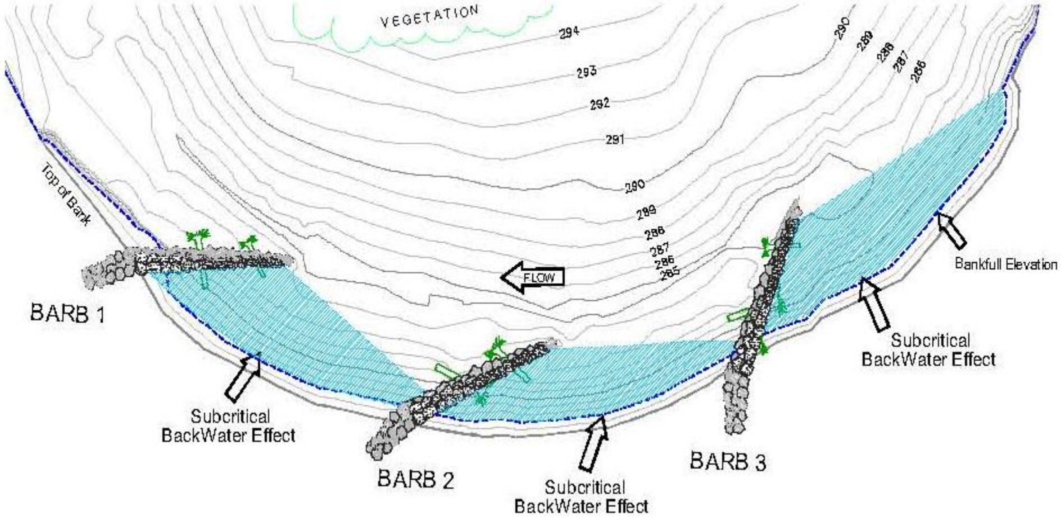
Barb Hydraulics

Barbs influence near-bank velocity and shear stress distribution through disruption of helicoidal currents and partial interception of cross stream flow. Control of these hydraulic forces results in the redistribution of energy from the near-bank region to the center of the channel. Flow across the barb occurs somewhat normal to the longitudinal axis of each structure and intersects the contraction-accelerated discharge at each barb end. The convergence of these flow components results in energy dissipation through turbulent flow mixing and forces the resultant vector flow direction away from the protected bank as shown in Figure 5.

Figure 5–Turbulent zone at intersection of cross structure flow and contraction accelerated flow at 75 percent bankfull discharge

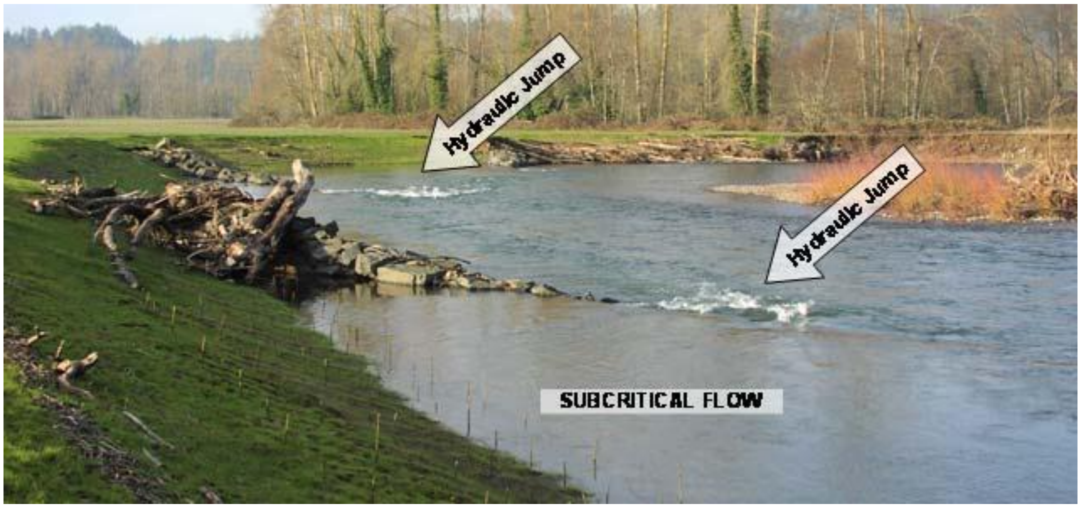
Effective barb design results in a structure-induced zone of subcritical flow upstream and along the protected streambank. Head (potential energy) increases in the zone upstream of the barb through the backwater effect described by Chow (1959). This is an important design concept in that each structure effectively backwaters a zone upstream to the next barb location. The upstream progression of subcritical reaches in the near-bank region controls erosion and ultimately leads to deposition of sediments along the protected bank-line as illustrated in Figures 6 and 7.

Figure 6–Upstream progression of subcritical backwater reaches



The sloping weir crest of each barb results in a stage-progressive hydraulic effect along the longitudinal axis of the structure. Critical depth occurs immediately upstream of the barb weir crest, and a supercritical flow transition occurs across the structure. This results in a hydraulic jump that is influenced by the downstream tailwater elevation (Case III Condition, Chow, 1959). The hydraulic jump provides energy dissipation through the transition of potential energy (increased upstream head) to kinetic energy (supercritical velocity) across each structure for increasing stages and discharge.

Figure 7–Hydraulic effects across and upstream of stream barbs at intermediate discharge



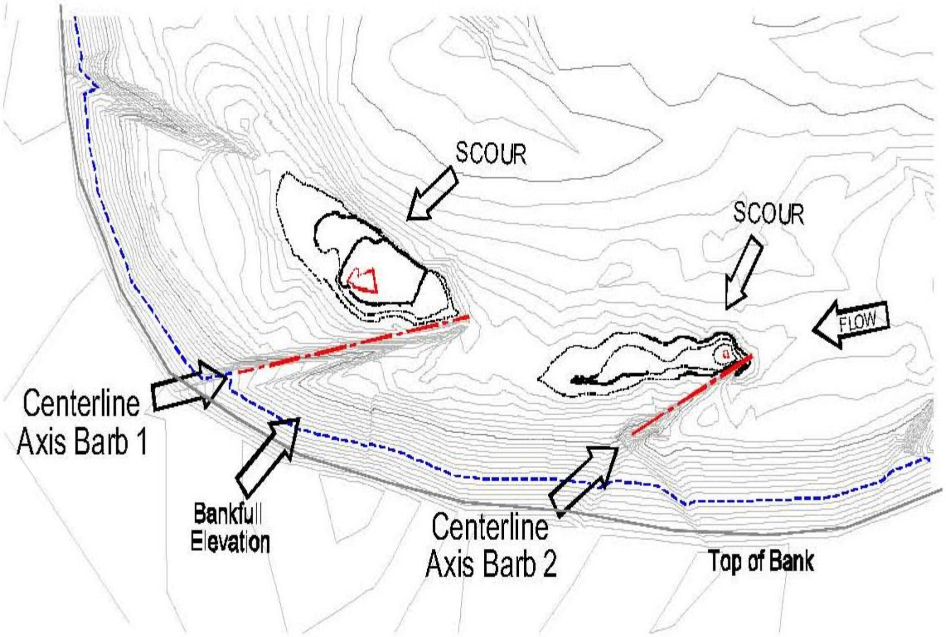
Flow leaving the meander bend is an important factor in locating the first structure. The first barb is placed to transition flow leaving the meander into the downstream receiving riffle.

Velocity distributions within riffle sections are generally uniform with the highest velocity located near the channel centerline. Positioning of the first barb maintains this natural velocity distribution and prevents adverse effects on downstream banks.

Bed Scour and Sediment Transport

Barb-induced energy re-distribution away from the outer bank toward the center of the channel results in scour near the ends of the barbs and realignment of the thalweg. Based on field observations, laboratory results, Johnson et al. (2001), Matsuura and Townsend (2004), Klingeman et al. (1984), and Kuhnle et al. (2001), the greatest scour depths occur at the barb end and immediately downstream of the structure. This scour results from contraction flow acceleration by a local reduction of the width-depth ratio, a structure-induced hydraulic jump, and turbulence generated from flow mixing. The process aligns the channel thalweg away from the streambank to a position near the outer quarter to end of the barb as shown in Figure 8. The result is a barb design that re-distributes available energy within the project reach and does not transfer it downstream. The increased velocities mobilize bed material that transfers immediately downstream of the barb and/or to the receiving riffle. The resulting scour hole reduces the channel width to depth ratio and increases pool habitat.

Figure 8–Scour effects at the end of barbs (half-foot contour interval)



A reduction in near-bank velocity gradients through the subcritical backwater effect promotes sediment deposition upstream of the barb structures. The quiescent flow condition allows bedload and fine sediments to fall out of suspension resulting in deposition in the near-bank region. Many successful barb projects have been implemented, providing hydraulic control as designed, then transitioning over time to increased roughness through the propagation of riparian vegetation on the fine sediments that accumulate upstream of the structures. In time, several projects have become nearly indistinguishable through this process as the design hydraulic influence of the structures is reduced to large-scale roughness effects of the propagated vegetation species.

Habitat Effects

Erosion and sediment input is a natural process necessary to supply gravels and add complexity to streams. However, meanders that are “overextended” with unstable width-to-depth ratios can have a detrimental effect on habitat by creating shallow water depths, increased ambient turbidity, and increased water temperatures. Streambank stabilization in the agricultural setting typically involves an eroding bank that has little or no riparian buffer due to farming practices. As a result, erosion advances at an accelerated rate with little resistance from natural vegetation.

Barbs are an effective measure for stabilization of eroding banks that create unnatural sediment supplies and high levels of ambient turbidity. Complexity in habitat is important for aquatic species because it provides cover, shelter, and food resources and increases species interaction. Barbs provide habitat diversity and create holding (refugia) locations for aquatic species during high and low flows. Velocity shelter areas are generated during high flows, and the scour pools below the end of each structure provide low-flow habitat. Control of near-bank velocities allows bioengineering methods, including planting with native plants and trees, to be installed and provide wildlife and aquatic habitat enhancements such as food and cover. Barbs that incorporate large wood add additional complexity and aquatic habitat benefits by providing in-stream cover for fish and food for aquatic invertebrates. Monitoring of projects throughout the Pacific Northwest has found that there are higher fish densities at projects incorporating large wood than without large wood (Peters, 2003).

Figure 9–Large wood placement within barb section

Habitat restoration and enhancement associated with stream barb construction should be considered in all projects as part of a comprehensive plan that considers specific habitat needs for one or more species. Recommended electronic Field Office Technical Guide (eFOTG) conservation practices include Stream Habitat Improvement and Management (395) and Streambank and Shoreline Protection (580). Baseline and future conditions can be documented with the NRCS National Water and Climate Center Technical Note 99-1, *Stream Visual Assessment Protocol*.

Design Recommendations

This section contains recommendations and guidelines to assist with the design of barbs for bank stabilization and habitat enhancement and is based on historic performance monitoring of installed projects as well as published research. These guidelines are not a substitute for engineering judgment where site-specific conditions may require deviations. It is also assumed that a detailed geomorphic and historic channel analysis have been done to warrant the use of barbs as a streambank stabilization alternative.

Site Information

Preliminary information and data that will be collected includes historical and current aerial photography, soils information, survey bench mark coordinates, stream gage data, and endangered species information. The design engineer will stratify the erosion mechanism as either a tractive stress or geotechnical slope failure with the latter case requiring a bank stabilization treatment other than barbs. A topographic survey is performed of the project reach extending from the upstream riffle, through the project meander, to the downstream riffle. The survey should include all grade breaks and geomorphic features within bankfull stage such as bank lines, thalweg, point bar geometry, and vegetation lines. In addition, the survey should capture flood plain features to enable accurate modeling in the Hydrologic Engineering Center-River Analysis System (HEC-RAS).

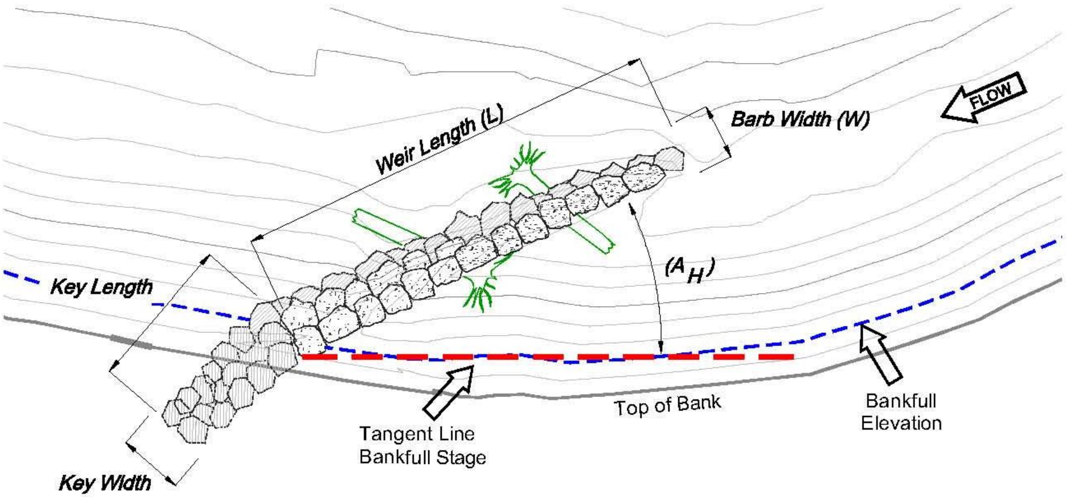
Hydraulic Analysis

A hydraulic analysis is performed to identify bankfull water surface elevations and profiles within the project reach. This analysis is based on cross sections taken from reach topographic surveys and imported into HEC-RAS. Discharge is obtained from United States Geological Survey (USGS) regional regression equations or statistical analysis of stream gage annual peaks (preferably from the river under consideration or a regional evaluation can be performed). Bankfull stage is obtained by modeling the 1- to 2-year peak discharge water surface profiles and correlating them to significant morphologic features. Bankfull field indicators include debris drift lines, bank scour lines, breaks in vegetation, and the top of the point bar at the inside of the meander bend.

Once bankfull discharge is determined and the HEC-RAS model calibrates with field indicators, additional discharges (up to the 100-year event) are analyzed to determine stage-velocity relationships. Velocity will generally increase up to bankfull stage at which point overbank flooding across the point bar occurs. At bankfull stage, a large increase in wetted perimeter occurs for a small increase in area that results in a reduction of the hydraulic radius.

Figure 10 defines the geometric variables associated with stream barbs. The following sections contain specific guidance on barb design including desired thalweg location, barb position, horizontal angle, and barb length and spacing. Several iterations should be performed to gain familiarity with the geometric constraints and potential alternatives as there are several possible successful solutions. Developed alternatives should be taken to the project site and evaluated for “fit” with further design iterations performed as necessary.

Figure 10–Barb definition diagram

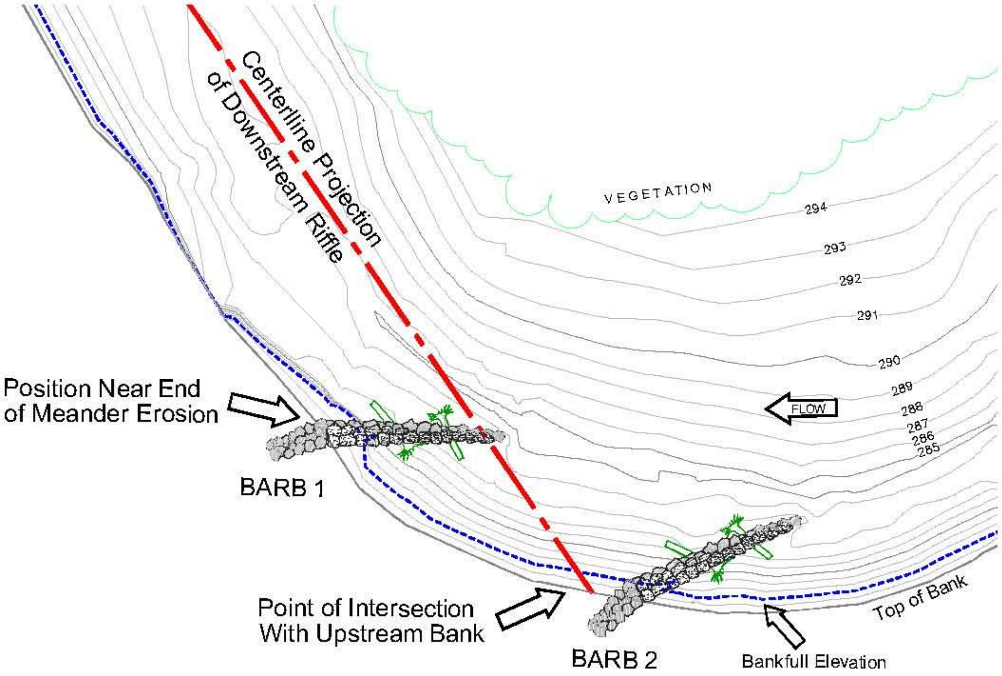


Location and Spacing

Barbs are generally located as a series of 2 or more structures on the outside bank of meander bends. The barb array begins with placement of the first structure at the downstream end of the project site with spacing of subsequent structures proceeding upstream to the beginning of erosion or project terminus. The following steps aid in locating the first barb:

1. Place the first barb in the downstream quarter of the meander bend or near the downstream end of erosion and streambank instability.
2. The hydraulic influence of the first barb should transition flow into the downstream channel and receiving riffle. To aid in locating this barb, establish a line of projection through the centerline axis of the downstream riffle and extend upstream to the point of intersection with the project meander as illustrated in Figure 11. The first barb (keyed at a position in the bank near the end of erosion) should intersect this riffle centerline projection near the middle to end of the barb.
3. The position of the first barb is also dependent on the horizontal angle (A_H) of the barb as referenced to the tangent line of the bank and weir length (L). It is critical that A_H not exceed 25° when tortuosity is less than 3 due to the potential for splitting of cross stream flow, a condition that results in a strong upstream back-eddy that may erode the bank. Positioning recommendations described in Step 1 may require adjustment to maintain the recommended angle and intercept of the downstream riffle line of projection.

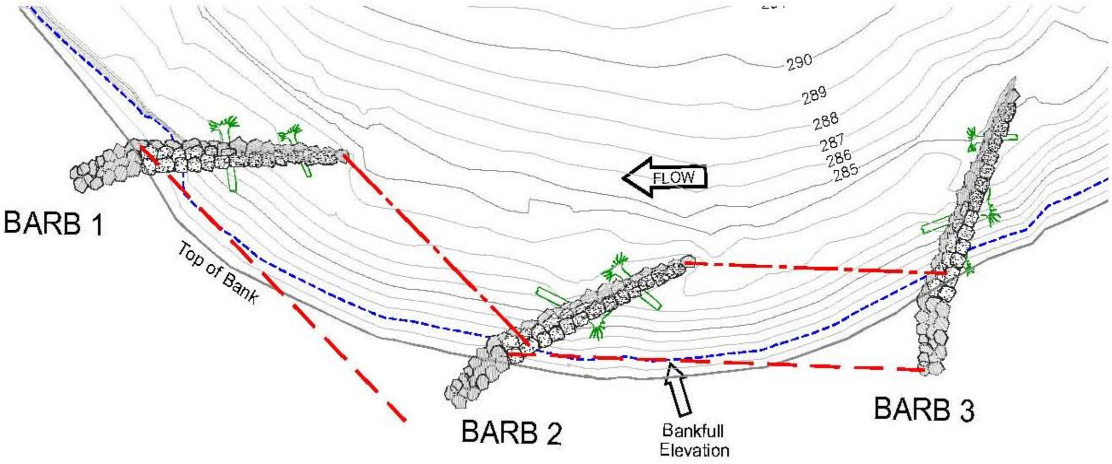
Figure 11–Location of Barb 1



4. Spacing is dependent on meander tortuosity, L and AH. Once the first barb is located, draw a tangent line (with the upstream bank) at the bankfull elevation. Translate this line out to the end of the barb and extend it upstream to a point of intersection with the upstream bank. The point of intersection of this line with the bankfull elevation is an approximate location where Barb 2 should key into the bank. This represents the maximum spacing and should generally be used for tortuosity greater than 3. Tighter spacing is advised when tortuosity is less than 3 with spacing performed by the same process as above, except for translation of the bank tangent line to the mid-point of the barb rather than the end. Repeat this process working upstream as illustrated in Figure 12.

Earlier design guidance recommended vector analysis for barb spacing. While this method correctly identifies the direction of cross structure flow, it is not appropriate for barb spacing (particularly when tortuosity is less than 3). The method results in barbs with either excessive spacing or a large horizontal angle that potentially captures too much cross stream flow, a condition that creates back-eddies and erosion upstream of each structure.

Figure 12–Example of barb spacing methodology



Length

Aerial photo analysis, survey information, and field investigations are used to identify ranges of stable tortuosity and target radii of curvature for the project reach. A curve is placed through the meander bend representing the proposed thalweg location. Each barb extends from the bank-line to the proposed thalweg curve at the design A_H. This process generally involves some iteration with the understanding that an increase in meander radius increases the tortuosity and decreases the magnitude of helicoidal and cross stream flow. Barb layout should result in a range of lengths that do not exceed 1/3 the cross section top width at bankfull stage.

The key extends into the bank from 1/4 to 1/3 of the barb length to protect the structure from flanking, a common mode of failure. Lower tortuosity (less than 3) may require longer key lengths for additional protection, depending on soil types.

NOTE: Stream barbs should not be used to change the meander pattern of an entire stream system or to "channelize" the stream flow.

A_H

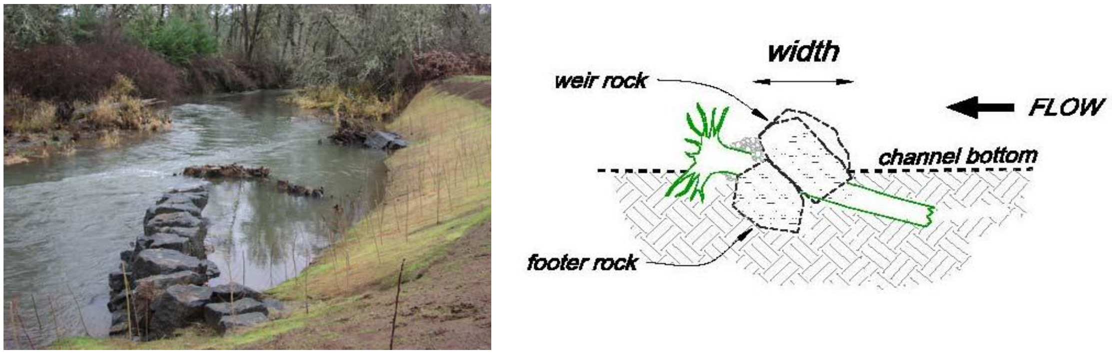
A_H is the angle between the tangent line placed along the upstream bank (at bankfull stage) and the centerline of the longitudinal axis of the barb (Figure 10).
Recommendations for this angle have varied throughout the development of barbs from 30° to 60°; however, field observations of failed structures and performance monitoring of successful projects warrant a reduction of horizontal angle recommendations. Based on field monitoring of successful sites and published research, the optimal angle for stream barbs is between 20º to 30º. When tortuosity is less than 3, it is critical that A_H not exceed 25º or the barb can capture too high a proportion of the cross stream flow, a condition that results in strong back-eddies upstream of the structure.

Width

The barb weir crest must fully develop critical flow near the leading edge of the structure for energy dissipation through a hydraulic jump. Therefore, the barb should approximate a broad-crested weir where the exposed weir top width (not including the footer) varies between 1 to 3 times the D_{100}. This is important considering likely impacts from large wood, ice, and other material against the structure.

The barb width (W) is typically narrow at the end ($W >= D_{100}$) and progressively widens to the intersection of the structure with the bank. The key maintains this width into the bank as shown in Figure 10. The total section width is somewhat wider considering the material available and the width of the footer combined with the weir. This combined width will be a function of the streamwise imbrication of the structure where the footer provides foundation support for the weir rock and is set to provide resistance to overturning and downstream translation. Regulatory agencies may require integration of large wood within barbs. The weir width may need adjustment to provide adequate ballast for the recommended buoyancy safety factor of 1.5 for the large wood.

Figure 13–Section views illustrating barb width

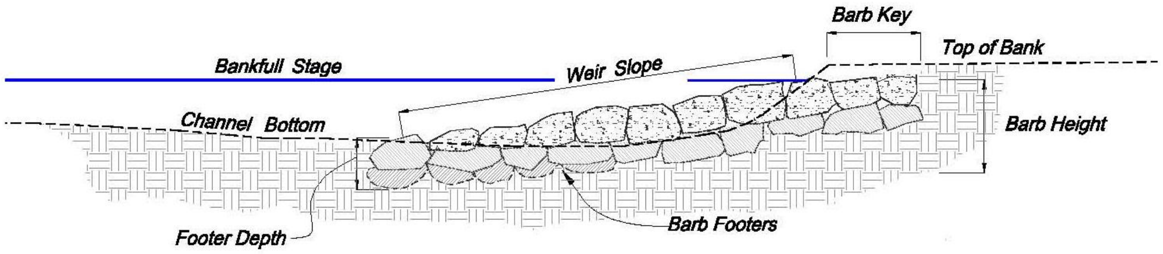


Barb Slope and Height

The bankfull stage obtained from the reach hydraulic analysis is used to set the structure height for each barb through the project reach. The top of the barb is set at bankfull stage, and the key extends into the bank at this elevation as illustrated in Figure 14. The end of each structure is set at the proposed thalweg location established by the spacing criteria. At a minimum, a D_{100} rock is set into the streambed at the barb tip. This is where the largest scour will occur; therefore, if the D_{100} does not extend below the calculated scour depth or 2.5 times the exposed height of the rock above the streambed (whichever is greater), footer rocks will be required. Calculated scour depths should be field-verified by observing scour around nearby logs, bridge abutments, and similar hydraulic elements.

Weir slope is calculated by the difference in elevation from the barb end and the bankfull elevation divided by the weir length (Figure 14). The constant slope range that exerts the maximum energy dissipation and progressive hydraulic effect is between 5 percent to 8 percent (or 1 foot vertical to 15 feet horizontal). As stage and velocity increase, the sloping crest controls the hydraulic jump and the subcritical zone upstream of the structure.

Figure 14–Barb profile looking downstream



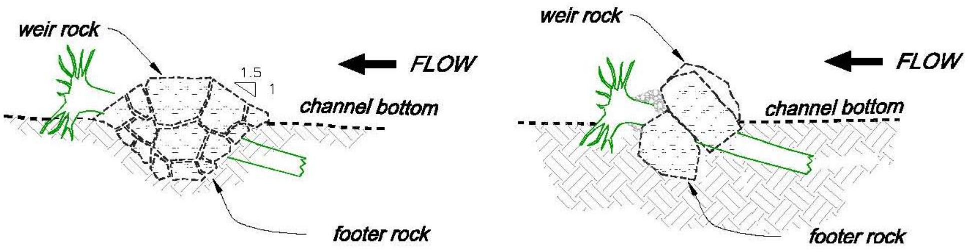
The structure is intended to function as a weir and is, therefore, nearly flat but MUST always have a downward slope away from the streambank.

Barb Rock Sizing

Barbs are usually constructed in one of two ways depending on availability of rock, site access, localized construction practices, and machinery. One method is to construct the barb section using successively rising graded layers of rocks that are built on top of each other with the D_{100} (usually less than 24 inches) as illustrated in Figure 15. References for determining the gradation of rock using this method are found in Minnesota Technical Release 3, "Loose Riprap Protection," or U.S. Army Corps of Engineers EM 1110-2-1601, "Hydraulic Design of Flood Control Channels."

The other method utilizes relatively large rock (usually greater than 36 inches) elements to construct the barb, and gaps are filled with small rock as necessary to make the structure impervious as illustrated in Figure 15. Large rock is generally preferred for ease of construction and resistance to displacement. Imbrication of the weir elements should be in the downstream direction against the footer to resist downstream translation. Material should be sound, dense, and free from cracks, seams, or other defects that could increase susceptibility to deterioration or fracture. The incorporation of large wood will require that ballast considerations be accounted for in the rock sizing computations.

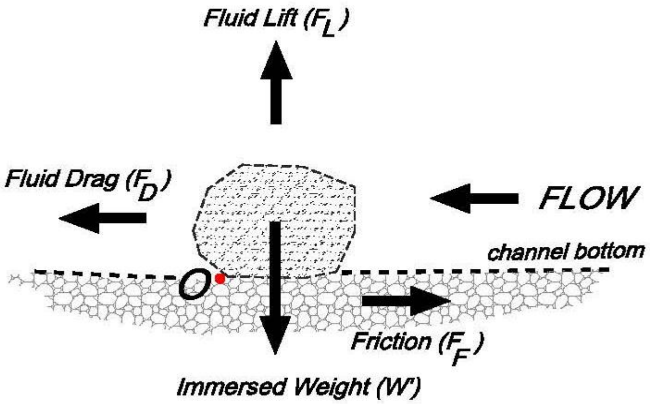
Figure 15–Barb section view using graded material (left) and large elements (right)



Several methods have been used for design of barb rock elements including the Far West States-Lane method; however, it is recommended that a physics-based threshold stability analysis be utilized for determining the minimum size of the weir and footer rock.

The project reach HEC-RAS model is used to identify the maximum anticipated velocities that are used in the solution of the following equations. Figure 16 is a free-body diagram (FBD) of a boulder resting on the streambed. The FBD is of an isolated rock that does not account for streambed slope because the sine component of the body force is insignificant. This analysis represents a conservative scenario as lateral anchoring and shielding of surrounding boulders provide for an additional factor of safety. A threshold stability analysis is carried out for 2 modes of failure: (1) sliding and (2) overturning or moment stability of the boulder element.

Figure 16–Free body diagram of immersed rock



1. Sliding Analysis

   Sum of the forces in the x-direction ($\sum F_x$) yields the following equations:

   $\sum F_x = 0 = F_D - F_F$ Equation 1

   where

   $F_D = C_D \times A \times \rho_w \times v^2 / 2$ Equation 2

   and

   $F_F = (W' - F_L) \times f = [(V_{boulder} \times \rho_w \times g \times (S_b - 1)) - 0.85 \times F_D] \times f$ Equation 3

   where:
   F_D = Fluid drag
   F_F = Friction
   C_D = 0.3 to 0.5 although can be as high as 2.0 for partially submerged rocks
   A = Projection of exposed rock area to hydraulic force (square feet)
   ρ_w = Density of water
   v = Maximum instantaneous stream velocity (foot per second)
   W' = Immersed weight
   F_L = Fluid lift (0.85 F_D based on work by Chepil, 1958)
   f = Friction factor [1]
   $V_{boulder}$ = Boulder volume (cubic feet)
   g = 32.2 feet per sec^2
   S_b = Specific gravity of boulder (typically 2.65)

[1] The friction factor is taken as the tangent of the friction angle of the boulder on the streambed. Based on graphs in the Bureau of Reclamation's Earth Manual (1999), this factor is generally greater than 0.80 for rocks greater than 3 inches and is often predicted by taking the tangent of the angle of repose for the material in question.

2. Moment Stability Analysis

   Assume the resultant fluid force acts through the centroid of the boulder and sum the moments about point "O" ($\sum M_O$) to eliminate the friction force:

   $\sum M_O = 0 = (W' - F_D - F_L) \times D / 2$ Equation 4

These equations are easily solved using a spreadsheet to determine stable rock sizes for a given maximum velocity. The design engineer should employ this method with reference to site-specific circumstances and evaluate the sensitivity of the various coefficients to ensure that adequate factors of safety are achieved with the design. At a minimum, a factor of safety of 1.5 should be used for resisting translation and rotation of the element.

An additional method is proposed by Julien (2004) which suggests a simplified analysis for incipient motion considering fully turbulent flow over a rough horizontal surface with the boulder fully immersed. This method is used as an additional check against results obtained using the preceding procedure.

$$D_B = \frac{21 \times y \times S_f}{S_b - 1} \qquad \text{Equation 5}$$

where:
d_B = Minimum boulder diameter (feet)
y = Flow depth at bankfull (feet)
S_b = Specific gravity of boulder (2.65 typically)
S_f = Friction slope (feet per foot)

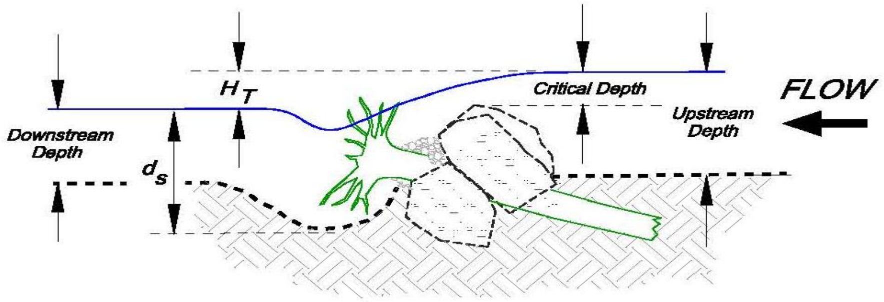
Scour

Barb-generated hydraulic forces transferred to the streambed generate a downstream scour hole that results in energy expenditure within the immediate project reach. The estimation of scour depth controls the placement of barb footer rocks below the streambed to prevent structure failure due to undermining. The bed key depth should be determined by calculating expected scour depth around the tip of the structure. If a bed key is not incorporated or if the bed key is too shallow, scour may erode the bed material downstream, causing the rock to fall into the scour hole. Scour equations are typically based on empirical laboratory experiments; hence, it is recommended that the results of the presented equation be field-substantiated by observing scour around nearby logs, bridge abutments, and similar hydraulic elements. The Bureau of Reclamation's Design of Small Dams identifies the Veronesse equation to determine ultimate scour depth that will stabilize irrespective of material size.

$$d_s = 1.32 \times H_T^{0.225} \times q^{0.54} \qquad \text{Equation 6}$$

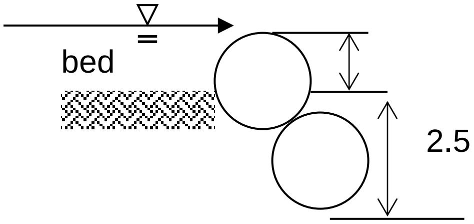
where:
d_s = Maximum depth of scour below the tailwater elevation (feet)
H_T = Hydraulic head differential between headwater and tailwater (feet)
q = Unit discharge per length of weir (cubic feet per second per foot)

Figure 17–Bed scour immediately downstream of barb



The equation typically yields conservative results which become more appropriate as the tortuosity decreases and the meander hydraulic forces increase. As a rule, the footer rock should be placed a minimum of the D_{100} into the streambed or 2.5 times the exposed height of the rock, whichever is greater. Note that scour depth will likely exceed the depth of the thalweg (deepest part of the channel).

In lieu of a scour analysis, scour depth can be estimated using the following:



Expected scour depth for gravel or cobble bed streams can be estimated by:

Scour = 2.5 x h

where:
h = height of exposed rock relative to bed elevation

For sand, use:

3 to 3.5 x h

To reduce scour depths, decrease the barb height. Higher barbs cause greater flow convergence and, thus, greater scour depths.

Common Failure Modes

Barbs have been installed throughout the United States with limited or no guidance. As a result, several failures have occurred that could have been avoided. Based on field observations, the following table summarizes these common modes of failure.

Failure Mechanism	Typical Cause of Failure
Flanking of Barb	Horizontal angle too large, key length too short, spacing between barbs too large
Structure Undermined Downstream	Footer rock depth too shallow
Erosion Between Barbs	Barb spacing too great, horizontal angle too large, capture of-stream flow causing back-eddy
Rock Displacement	Poor construction techniques resulting in weir rocks that are not locked in together

Construction

Regulatory considerations are that federal Clean Water Act permits and state permits may be needed before undertaking any stream, wetland, or riparian construction or manipulation. Contact with the appropriate agency(s) should take place in the planning process, and all permits that are needed must be in place before initiating construction.

Stream barbs should be constructed during low flow conditions to minimize in-stream disturbances. Short barbs can be constructed from the bank while long barbs may require the use of the barb surface as a platform during construction. The barb width can be reduced as the equipment works back from the tip of the barb toward the bank. The rock should never be end-dumped. Construction should always start at the upstream end of the project site. Alterations to the design during construction are sometimes necessary--be sure to have someone on-site to ensure proper installation and get concurrence from the designer.

Bank Shaping

Vertical banks on the outside of meander bends are inherently unstable and susceptible to undercutting and geotechnical failure. Once in an unstable position, the bank may continue to erode due to toe scour, mass block failure, and rapid drawdown/saturation. Barbs reduce toe scour and velocity-induced erosion; however, barbs do not address bank failure due to soil instability and drawdown/saturation. Barb projects should incorporate bank shaping and vegetative practices to address these additional failure mechanisms.

Bank shaping begins at the toe of the vertical bank and extends away from the stream at the optimal slope of 3 horizontal to 1 vertical (3:1) or flatter. This provides a stable slope and an adequate surface for vegetative planting and maintenance. Steeper slopes, such as 2:1, can be used but are difficult to access for planting vegetation and placing erosion control blankets.

Erosion control blankets should be installed on banks immediately after shaping and prior to high flows. Erosion blankets typically consist of decomposable materials such as coir (coconut husks) or straw. Due to the large number of manufacturers of erosion blankets, a performance specification should be used to specify the blanket that includes maximum shear stress and permissible velocities as well as longevity of material.
When installing erosion control blankets, ensure adequate anchorage of the blanket ends into the streambank.

Vegetative Planting

Barbs reduce near-bank shear stress and velocity by redistribution of hydraulic energy away from the bank. The use of barbs for streambank stabilization should include bioengineering and vegetative practices. Vegetation provides additional roughness to dissipate energy along the streambank and enhances wildlife habitat and water quality. Willows are the most common vegetation used to enhance streambank stabilization projects. There are several ways to plant willows; however, the most effective is by installing willow clumps with a trackhoe. This is achieved by digging up entire willow plants with roots intact and planting in prepared holes along the streambank. There are several advantages to this technique including increased plant survival rate, quicker establishment of roughness, and greater energy dissipation in the near-bank region. Conservation Practice Standard 342, Critical Area Planting, should be consulted for additional guidance on vegetative plantings.

References Cited

Bathurst, J., Thorne, C. and Hey, R., *Secondary Flow and Shear Stress at River Bends,* Journal of the Hydraulics Division, 1979

Chang, H., Fluvial *Processes in River Engineering*, Wiley-Interscience, Wiley, NY, 1988

Chepil, W., *The Use of Evenly Spaced Hemispheres to Evaluate Aerodynamic Forces on a Soil Surface*, Transactions, American Geophysical Union, 1958

Chow, V.T., *Open Channel Hydraulics*, McGraw Hill, New York, NY, 1959

U.S. Army Corps of Engineers, EM 1110-2-1601, *Hydraulic Design of Flood Control Channels*, Department of the Army, Washington D.C., 1994

Henderson, *Open Channel Flow*, McMillan Co. New York, NY, 1966

Julien, P., *Erosion and Sedimentation*, Cambridge University Press, Cambridge, United Kingdom, 1994

Julien, P., *River Mechanics*, Cambridge University Press, Cambridge, United Kingdom, 2002

Klingeman, P.C., Kehe, S.M., and Owusu, Y.A., *Streambank Erosion Protection using Rockfill Dikes and Gabions,* Department of Civil Engineering, Oregon State University, 1984

Knighton, D., *Fluvial Forms and Processes*, Arnold, Baltimore Maryland, 1998

Kuhnle, R., Alonso, C., and Shields, D., *Local Scour Associated with Angled Spur Dikes*, Journal of Hydraulic Engineering, December 2002

Leopold, L., Wolman, M., and Miller, P., *Fluvial Processes in Geomorphology*, Dover Publications, Inc., New York, New York, 1964

Matsuura, T., and Townsend, R., *Stream-Barb Installations for Narrow Channel Bends*, Canadian Journal of Civil Engineering, NRC Canada

Minnesota Technical Release 3, *Loose Riprap Protection*, Natural Resources Conservation Service, United States Department of Agriculture, 1989

Natural Resources Conservation Service, Idaho, Engineering Technical Note 12, *Design of Stream Barbs,* United States Department of Agriculture, 2001

Natural Resources Conservation Service, Oregon, Engineering Technical Note 23, *Design of Stream Barbs Version 1.3,* United States Department of Agriculture, 2000

Natural Resources Conservation Service, Oregon, Engineering Technical Note 23, *Design of Stream Barbs Version 2.0*, United States Department of Agriculture, 2005

Peters, R., *Habitat Use by Juvenile Salmonids with Special Emphasis on Woody Debris and Large River Channels,* Presentation at 3rd Annual Northwest River Restoration Conference, 2003

Rosgen, D., *Fluvial Geomorphology for Engineers,* Course Notes, 2002 and 2004

Rosgen, D., *The Cross-Vane, W-Weir and J-Hook Vane Structures . . . Their Description, Design and Application for Stream Stabilization and River Restoration,* Presented at the American Society of Civil Engineers 2000 River and Wetland Restoration Conference, 2001

Thorne, C., *Personal Communication*, 2005

Williams, G., *River Meanders and Channel Size*, Journal of Hydrology, 1986

References Reviewed

Brater, E., King, W., *Handbook of Hydraulics for the Solution of Hydraulic Engineering Problems*, McGraw-Hill Book Company, New York, New York

Bureau of Reclamation, *Design of Small Dams*, United States Department of Interior, United States Government Printing Office, 1977

Carling, P., *The Concept of Dominant Discharge Applied to Two Gravel-Bed Streams in Relation to Channel Stability Thresholds,* Earth Surface Processes and Landforms, 1988

Derrick, D., *The Bendway Weir: An In-Stream Erosion Control and Habitat Improvement Structure for the 1990's*, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi

Federal Highway Administration, *Bridge Scour and Stream Instability Countermeasures*, U.S. Department of Transportation, 2001

Federal Highway Administration, *Evaluating Scour at Bridges*, U.S. Department of Transportation, 2001

Federal Highway Administration, *River Engineering for Highway Encroachments*, U.S. Department of Transportation, 2001

Federal Highway Administration, *Stream Stability at Highway Structures*, U.S. Department of Transportation, 2001

Federal Highways Administration, *Bridge Scour and Stream Stability Countermeasure,* U.S. Department of Transportation, Final Report, 1985

Federal Highways Administration, *Design of Spur-Type Streambank Stabilization Structures,* U.S. Department of Transportation, Final Report, 1985

Fischenich, C., and Landers, M., *Computing Scour*, Ecosystem Management and Restoration Research Program (EMRRP), U.S. Army Research and Development Center, Vicksburg, Mississippi, 2000

Fischenich, C., *Stability Thresholds for Stream Restoration Materials*, EMRRP, U.S. Army Research and Development Center, Vicksburg, Mississippi, 2000

Huang, H., Chang, H., and Nanson, G., *Minimum Energy as the General Form of Critical Flow and Maximum Flow Efficiency for Explaining Variations in River Channel Pattern*, American Geophysical Union, Water Resources Research, 2004

Johnson, P., Hey, R., Tessier, M., and Rosgen, D., *Use of Vanes for Control of Scour at Vertical Wall Abutments*, Journal of Hydraulic Engineering, 2001

Lenzi, M., *Stream Bed Stabilization Using Boulder Check Dams that Mimic Step-Pool Morphology Features in Northern Italy*, Geomorphology, 2001

Newbury, R., and Gaboury, M., *Stream Analysis and Fish Habitat Design*, Newbury Hydraulics, Gibsons, British Columbia, 1993

Nouh, M., and Townsend, R., *Shear-Stress Distribution in Stable Channel Bends,* Journal of the Hydraulics Division, 1979

Papanicolaou, T., Hotchkiss, R., and Barber, M., *Design of Bank Barbs in the State of Washington*, Proposal Submitted to the Washington Department of Transportation

Richardson, E., and Simons, D., *Spurs and Guide Banks*

Simons, D., and Sentürk, F., *Sediment Transport Technology*, Water Resources Publications, Fort Collins, Colorado, 1977

Simons, Li, & Associates, *Engineering Analysis of Fluvial Systems*, BookCrafters, Inc., Chelsea, Michigan 1982

Tominaga, A., Ijima, K., and Nakano, Y., *Flow Structures Around Submerged Spur Dikes with Various Relative Height*, Department of Civil Engineering, Nagoya Institute of Technology, 2004

Turner-Fairbank Highway Research Center, *Design of Spur-Type Streambank Stabilization Structures*, U.S. Department of Transportation, 1985

Washington Department of Fish and Wildlife, Washington State Department of Transportation, and Washington State Department of Ecology, *Integrated Streambank Protection Guidelines*, Washington State Aquatic Habitat Guidelines Program, 2002

Waterways Experiment Station, *Fact Sheet: Bendway Weir Theory, Development and Design*, Vicksburg, Mississippi

Williams, G., *Bank-Full Discharge of Rivers*, Water Resources Research, U.S. Geological Survey, Denver, Colorado, 1978

Contact

Technical assistance is available from NRCS at your local USDA Service Center (listed in the telephone book under United States Government). More information is also available on the Kansas Web site at www.ks.nrcs.usda.gov.

(signed)

ARVIL G. BASS, PE
State Conservation Engineer