DEVELOPMENT OF A VELOCITY-BASED QUANTITATIVE DESIGN METHODOLOGY FOR BENDWAY WEIRS

Nathan Holste, Hydraulic Engineer, Bureau of Reclamation, Denver, CO, nholste@usbr.gov

INTRODUCTION

Transverse features such as bendway weirs have become a popular alternative to traditional bank protection methods in recent years because they offer more environmental benefits and often have a lower cost. Bendway weirs are river training structures that redirect flow and energy throughout a channel bendway while moving the thalweg and most severe hydraulic forces away from the outer bank. Installation consists of a discontinuous field of multiple transverse structures placed in series and angled into the flow. A flat crest slope and low crest elevation distinguish bendway weirs from other transverse features such as spur dikes (flat, high crest elevation near top of bank) and vanes (upward sloping crest from low instream tip elevation to near top of bank). Scour at the weir tips due to flow acceleration shifts the thalweg toward the channel center. Eddies between the weirs may encourage variable depth, velocity, and sediment deposition that is favorable to aquatic species. Geometric based design guidelines are available in the existing literature such as HEC-23 (Lagasse et al., 2009) and NCHRP 544 (McCullah and Gray, 2005); however, no methodology exists to quantify the effects of bendway weirs on channel hydraulics.

A new method is presented that supplements existing geometric guidelines with an equation to predict velocity at inner, center, and outer channel locations as a function of bendway weir geometry. This equation was developed by researchers at Colorado State University (CSU) (funded by the Bureau of Reclamation) from data collected during a series of laboratory physical model tests. A group of physically significant terms was analyzed to develop the empirical, statistically-derived velocity ratio equation. The proposed method is illustrated with a design example for a project constructed in 2013 on the Rio Grande north of Albuquerque, New Mexico. Bendway weirs were implemented at this site to restore habitat in an incised river while stabilizing the eroding outer bank. A floodplain bench was also designed and constructed within the weir field to provide riparian habitat with energy dissipation at high flows. The combination of bendway weirs and a floodplain bench provides increased lotic and riparian habitat diversity and complexity at multiple flow stages while reducing hydraulic forces at the outer bank.

INITIAL ASSESSMENTS

Prior to beginning a detailed bendway weir design, an interdisciplinary project team should be assembled. Purpose, need, goals, and objectives must be well thought out, and a list of several alternatives should be developed and assessed. Typical considerations include fluvial geomorphology, engineering, ecology, economics, and constructability. A project that addresses the causes of channel instability and is compatible with the desired river form and function will be the most effective. The selected alternative is the option that best accomplishes the project team's goals within the identified constraints. The remainder of this paper assumes that bendway weirs have been selected as the preferred alternative, although some of the initial assessments described below should be completed during the alternatives evaluation.

Conduct Geomorphic Analysis: It is important and often difficult to distinguish local instability from system instability. A dynamically stable system will still exhibit local adjustments such as channel lengthening through bank erosion in growing meander bends that is offset by cutoffs at other bends. Local instability exists where there are adjustments at individual locations, while reach-averaged parameters such as hydraulic geometry and slope remain steady. Conversely, system instability propagates throughout a stream network as a result of water and sediment discontinuity, changes to downstream base level, and land use changes. System instability is visible through reach-wide aggradation, degradation, or

planform metamorphosis (Watson et al., 2007). Transverse features such as bendway weirs may not be appropriate or effective if reach-wide instability exists.

For the Rio Grande project site, it was determined that the eroding bank was not the result of system instability, thus suggesting that goals could be achieved through a local project without being jeopardized by reach-scale factors. Historical aerial photos were used to calculate reach sinuosity over time compared to the local sinuosity trends. Cross section surveys, longitudinal profiles, and a low flow specific gage analysis (i.e., stage vs. specific discharge at a nearby gaging station) showed that the reach bed elevation had been relatively stable over time. Other important geomorphic factors that were considered include hydrology, sediment supply, bed and bank material, channel width, and slope.

Determine Hydraulic Conditions: Hydraulic modeling is recommended as a component of a robust bendway weir design methodology. Depending on project goals, risks, and resources, multi-dimensional modeling can provide significant benefits when evaluating hydraulics associated with transverse features. However, 1-D models have the advantage of less intensive data requirements and can be set up and run relatively quickly. Executing a hydraulic model requires the selection of flow rates that are important for the design and analysis. The design flow will depend on individual project conditions and is typically specified with a return period or frequency. Appropriate design flows for bendway weirs often have a return period between five and twenty-five years. The following hydraulic conditions at the design flow should be determined for use in the CSU velocity ratio equation: (1) bend-averaged, cross section averaged channel velocity, (2) bend-averaged channel top width, (3) bend-averaged maximum channel depth, (4) bend-averaged water surface elevation, and (5) bend-averaged channel cross-sectional flow area. Main channel values should be used instead of the entire cross section values because bendway weir performance is primarily affected by main channel hydraulics, and the CSU physical model was not constructed to include a floodplain. The mean annual peak flow and base flow, and their associated water surface elevation and depth, are also needed for the geometric design guidelines.

Determine Rock Size: Transverse, discontinuous features are subject to more direct and severe hydraulic forces than longitudinal, continuous methods of protection such as traditional riprap revetments. A comprehensive, quantitative method for determining rock size of transverse features is not available in the existing literature. However, de Almeida and Martin-Vide (2009) performed an experimental study to compare riprap stability for transverse, longitudinal, and continuous protection methods. They tested a transverse bed sill structure and proposed a range of discontinuity factors to increase riprap size based on protrusion height above the bed and length of protection. The discontinuity factor allows riprap sizing results from the Maynord equation (Maynord et al., 1989) to be converted to a transverse rock size. For the Rio Grande project site, a bendway weir D_{50} rock size of 24 inches was determined by applying a discontinuity factor of 2.5 to a calculated riprap revetment size of 9.6 inches.

It should also be noted that NRCS (2007) recommends that the riprap size of stream barbs should be twice the size determined from standard riprap sizing criteria. NCHRP 568 (Lagasse et al., 2006) evaluated seven of the most commonly used revetment riprap sizing equations and recommended the EM 1601 equation (USACE, 1994) on the basis of discriminating between stable or failed riprap, bank and bend correction factors, and the reasonableness of safety/stability factors. The EM 1601 equation is similar to the Maynord 1989 equation with additional safety and correction factors.

Estimate Scour Depth: Properly estimating and designing for scour is an important element of any stream erosion countermeasure project. Transverse features such as bendway weirs typically experience the largest scour (depth and volume) near the tip or nose of the structure. Scour holes that form adjacent to or underneath bendway weirs will cause riprap from the structures to launch into the scour holes, potentially leading to failure. The goal of this design component is to provide enough riprap volume so that the bendway weirs can adjust to any scour without compromising their function. More specifically,

the crest elevation and tip location should be maintained after some of the sacrificial riprap falls into the scour hole. Bendway weirs can be keyed into the bed if practicable to account for scour, but this is difficult unless construction occurs in dry conditions.

An extensive, but not exhaustive, review of scour equations was conducted to identify several methods that would be appropriate for the Rio Grande project site. The selected scour equations can be categorized as a mean velocity equation, regime equations, bend equations, and a transverse structure equation. Table 1 presents the calculated scour results along with notes describing specific methods. The equations are generally empirical and were developed from lab or river measurements for a given set of conditions. Most of the equations represent a best-fit curve, although the USACE (1994) method is an upper envelope curve designed to overpredict scour for about 95 percent of the data.

Table 1 Scour equation results (at design flow of 14,200 cfs).

		Regime Equations[1]			Bend Equations			
	Mean Velocity[1]	Neill (1973)	Lacey (1930)	Blench (1969)	Maynord[2] (1996)	Zeller[2] (1981)	USACE[3] (1994)	Blench[4] (1957)
Total Scour[5]	5.43	5.61	3.88	4.31	5.21	7.57	9.67	5.65
Total Scour (w/SF = 1.1 if applicable)	5.97	6.17	4.27	4.74	5.21	7.57	9.67	6.21
Average = 6.23 ft		Median = 6.07 ft		**Design Scour Depth = 7 ft**				

[1]Reference: Pemberton and Lara (1984)
[2]Developed for sand bed rivers, assumed conservative for gravel bed (no safety factor)
[3]Upper envelope curve (no safety factor)
[4]Cox (2005) compared 10 equations to lab bendway weir results and found that the Blench (1957) equation had the best prediction of observed scour depths
[5]Includes general, bend, and thalweg scour components. No long term scour component was included because of reach bed stability.

The design scour depth can be used to estimate the riprap volume needed to protect bendway weirs from failure due to scour. As a means of simplifying the analysis of a complex three-dimensional process, the scour pattern was examined within the context of a typical cross section view of the bendway weir tip. It is assumed that riprap will launch into the scour hole at the angle of repose and form a type of revetment that is similar to longitudinal, continuous bank protection. USACE (1994) and NCHRP 568 (Lagasse et al., 2006) recommend a revetment thickness of $1.5*D_{50}$ or D_{100}, whichever is greater. The D_{100} is largest for the example project, resulting in a 4-ft revetment thickness. At the angle of repose, a simplified parallelogram representing the launched riprap has a top and bottom width of 6 ft, resulting in an area of 42 ft^2 at the design scour depth. Incorporating a safety factor of 1.5 to account for uncertainties during the launching process yields a cross-sectional area of 63 ft^2 at the tip that should be available for scour. This is in addition to the area required to maintain the design crest elevation and tip location, which can be calculated based on a minimum a crest width of at least $1* D_{50}$ (2 ft) after scouring occurs. The cross-sectional area is a function of the crest width, weir height, and side slope angle. (Bottom width is also governed by crest width, weir height, and side slope.) The constructed bendway weir cross section side slopes were set at 1.5H:1V (34°), which is slightly flatter than the riprap angle of repose for increased stability.

INITIAL GEOMETRIC DESIGN

After completing the initial assessments, the next phase of the proposed design methodology is to incorporate established geometric design guidelines for bendway weirs. The most important geometric parameters that govern bendway weir function and effectiveness are length, planform angle, spacing, and

crest elevation (height). Other bendway weir variables that must be specified in the design include top width and key length. HEC-23 (Lagasse et al., 2009) and NCHRP 544 (McCullah and Gray, 2005) provide recommendations for determining these geometric components. A range of values is determined for each geometric parameter and the CSU velocity ratio equation is subsequently used for optimization.

Sketch Desired Thalweg and Bank Line Location: An important conceptual factor when designing a bendway weir field is the location of the bendway weir tips. Derrick (2012) recommends laying out the desired thalweg relocation throughout the bend and then placing the stream ends of the bendway weirs just short of the anticipated thalweg realignment. Smooth upstream and downstream transitions should be included, and different attack angles at a variety of flow stages should be considered. If a floodplain bench is included such as for the Rio Grande example project, this alignment should be determined as well. Historical aerial photos provide a useful tool for laying out the thalweg and floodplain bench location, and a previously observed stable channel alignment may be a helpful template for the new alignment.

Determine Key Length: Bendway weirs must be keyed into the bank to prevent the structures from being flanked if lateral erosion continues at the site. The Rio Grande bendway weir design is slightly unusual because a majority of the total bendway weir length is buried within the floodplain bench, which can be considered as part of the key. GIS was used to draw the alignment of the key terminus using the following two methods, and the most conservative length was selected at each bendway weir location.

(1) Assuming that all of the floodplain bench fill material is eroded, HEC-23 states that the key length should not be less than 1.5 times the total bank height. For a nominal bank height of 10 ft the required key length is 15 ft, so the existing top of bank was offset by this distance.

(2) The maximum probable erosion based on historical aerial photographs was estimated to be 85 ft, so the floodplain bench bank line was offset by this distance.

It should be noted that HEC-23 also provides a method to estimate key length as a function of weir length and spacing, and this result should be compared to the above methods after the final geometry is determined.

Determine Weir Crest Width: HEC-23 and NCHRP 544 both recommend a crest width of (2 to 3)*D_{100}. Therefore, a range of recommended crest widths between 8 and 12 ft corresponds to the selected riprap size (D_{100} of 4 ft). A crest width of 8 ft was chosen for the portion of the weir buried within the floodplain bench and 12 ft was selected for the weir tip exposed to the flow to accommodate the required scour volume.

Determine Weir Length: Bendway weir length can be defined as the length along the crest axis, measured horizontally from water's edge at the design flow. (Effective length is a different parameter that also incorporates planform angle and is measured perpendicular to the bank tangent.) Both HEC-23 and NCHRP 544 recommend a minimum and maximum weir length as a function of stream width as shown in Table 2. The bend-averaged channel top width is 202 ft, which was calculated by averaging the bank-to-bank widths at cross sections within the bend. A range of bendway weir lengths between 20 ft and 100 ft was considered when analyzing geometry effects with the CSU equation.

Table 2 Recommended bendway weir length.

Design Guideline	Minimum	Maximum
HEC-23	Tw/10 = 20 ft	Tw/3 = 67 ft
NCHRP 544	Tw/3 = 67 ft	Tw/2 = 101 ft

Determine Weir Planform Angle: Bendway weirs are angled upstream so that flows over the top of the structure are redirected away from the outside bank and toward the channel centerline. HEC-23 states that

the angle of projection between the bendway weir axis and the upstream bankline tangent typically varies from 60 to 80 degrees. The NCHRP 544 planview diagram shows potential angles ranging from 45 to 90 degrees measured from the upstream bankline tangent. NCHRP 544 states that the most common and preferred angles are between 70 and 80 degrees. Therefore, angles from 60 to 80 degrees were considered for the Rio Grande bendway weir design.

Determine Weir Spacing: Bendway weir spacing is the distance between the centerline axes of two consecutive weirs as measured along the bankline. Spacing is determined by the radius of the bend and the length of the bendway weirs. HEC-23 provides two equations (S_1 and S_2) that establish a range of feasible weir spacing values and a third equation (S_{max}) to calculate the maximum spacing. All three equations are a function of weir length so results are dependent on whether the maximum or minimum length is used. NCHRP 544 outlines a simpler approach where only one recommended equation is provided to calculate spacing as a multiple of weir length. All of these equations and the calculated results are summarized in Table 3. The spacing values considered for additional analysis with the CSU equation varied between 85 ft and 190 ft for the Rio Grande project. Given the length of the bend to be protected (~760 ft), the total number of weirs could be as many as 9 (spacing ~85 ft) or as few as 4 (spacing ~190 ft). Increasing the number of weirs to 10 or more results in only small changes in spacing for each additional weir and was not cost effective.

Table 3 Recommended bendway weir spacing.

Design Guideline	Minimum*	Maximum†
HEC-23	$S_1 = 1.5L\left(\frac{R_c}{T_w}\right)^{0.8}\left(\frac{L}{T_w}\right)^{0.3} = 24ft$ $S_2 = (4\ to\ 5)L = 81ft$ $S_{max} = R_c\left(1-\left(1-\frac{L}{R_c}\right)^2\right)^{0.5} = 119ft$	$S_1 = 1.5L\left(\frac{R_c}{T_w}\right)^{0.8}\left(\frac{L}{T_w}\right)^{0.3} = 115ft$ $S_2 = (4\ to\ 5)L = 337ft$ $S_{max} = R_c\left(1-\left(1-\frac{L}{R_c}\right)^2\right)^{0.5} = 210ft$
NCHRP 544	$S = 1.5L = 101ft$	$S = 1.5L = 152ft$

*from HEC-23 (L_{min} = 20 ft) and NCHRP 544 (L_{min} = 67 ft) minimum lengths
†from HEC-23 (L_{max} = 67 ft) and NCHRP 544 (L_{max} = 101 ft) maximum lengths

Determine Weir Height: As discussed, bendway weirs are low elevation structures where the crest must be overtopped to work as designed. Weir height is not clearly defined in the existing literature because all typical cross section schematics show a flat riverbed. In field applications, the riverbed undulates significantly in both the transverse and longitudinal directions. For this reason it is easier to define a weir crest elevation rather than a weir height. Therefore, the existing height recommendations should be converted to a difference between the crest elevation and water surface, rather than a height above the bed.

HEC-23 recommends that weir height should be 30 to 50 percent of the depth at the mean annual high water level. It is not clear if the depth at mean annual high water level is the maximum depth (thalweg depth) or average depth (hydraulic depth). The suggested interpretation of this guideline is that the weir crest elevation should be the water surface at the mean annual peak flow minus 70 to 50 percent of the bend-averaged maximum channel depth. It is assumed that HEC-23 refers to maximum depth because it also states that bendway weirs should cross the stream thalweg. NCHRP 544 shows that the crest elevation should be within (+/–) 1 ft of the typical base flow water surface elevation. Table 4 presents the results as interpreted from HEC-23 and NCHRP 544 and converted to a crest elevation. Crest elevations between 5505 ft and 5510 ft were analyzed for the Rio Grande site. The crest elevation of 5510 ft was

included based on the alternate HEC-23 interpretation using hydraulic depth, which results in recommended elevations that are about 2.5 ft higher than what is shown in the table for HEC-23.

Table 4 Recommended bendway weir crest elevation.

Design Guideline	Minimum	Maximum
HEC-23	(0.3H) → $WSE_{m.a.p.} - 0.7 \times D_{m.a.p.} = 5505.4\ ft$	(0.5H) → $WSE_{m.a.p.} - 0.5 \times D_{m.a.p.} = 5507.5\ ft$
NCHRP 544	$WSE_{base} - 1ft = 5507ft$	$WSE_{base} + 1ft = 5509ft$

FINAL VELOCITY-BASED DESIGN

The goal of a bendway weir field for bank protection projects is to minimize lateral erosion by reducing velocity and shear stress along the outer bank. Over the course of several years, CSU performed physical modeling of transverse structures in a trapezoidal, rigid bed channel as detailed by Heintz (2002), Darrow (2004), and Schmidt (2005). The model includes two distinct channel bends and was constructed at an undistorted, 1:12 Froude scale based on geometry of the Rio Grande. Scurlock et al. (2012) performed a statistical regression analysis of hydraulic results from 130 unique tests to develop predictive equations for maximum velocity ratio (MVR) and average velocity ratio (AVR). Channel planform zones were delineated as outer (o), center (c), and inner (i) locations throughout the bend so that MVR and AVR equations could be developed for each of the three locations. MVR is defined as the maximum velocity for a given channel location with structures installed divided by the bend-averaged velocity without structures ($MVR = Vmax_{structures}/Vavg_{baseline}$). AVR is defined as the average velocity for a given channel location with structures installed divided by the bend-averaged velocity without structures ($AVR = Vavg_{structures}/Vavg_{baseline}$).

The CSU velocity ratio equation is robust, but is also affected by significant limitations. The equation is generalized for all transverse features rather than being specific to bendway weir hydraulics. Spur dikes and vanes are included in the database because there were not enough bendway weir tests to generate a valid regression equation. Important elements of natural geometry and topography such as the pool depth ratio and cross-sectional transverse bed slope are also neglected because the modeled channel is prismatic. Therefore, it is not surprising that the trapezoidal equations have been found to underpredict outer bank maximum velocity for a channel with natural topography (Baird, 2014). Scurlock et al. (2012) also note that "maximum velocity data are difficult to capture spatiotemporally, and may behave erratically; therefore, the concept of AVR may represent a more reliable predictive method." There are currently a limited number of native bed model runs with bendway weirs, and the data are insufficient to develop a new regression equation. Equation 1 and Table 5 present the regression coefficients used to predict velocity values for the Rio Grande design project. Scurlock et al. (2014) have since revised the coefficients based on a new statistical regression that excludes certain outlier points from the original dataset. The velocity ratio equation is comprised of dimensionless terms that represent the following parameters: an area contraction ratio, a spacing ratio, a channel curvature ratio, a lateral contraction ratio, a submergence ratio, and a planimetric angle ratio.

$$MVR, AVR = a_1 (A^*)^{a_2} \left(\frac{L_{arc}}{T_w}\right)^{a_3} \left(\frac{R_c}{T_w}\right)^{a_4} \left(\frac{L_{w-Proj}}{T_w}\right)^{a_5} \left(\frac{D_B}{D_B - \Delta Z}\right)^{a_6} \left(\frac{\theta}{90}\right)^{a_7} \quad (1)$$

where:

$a_1, \ldots, a_7$ = regression coefficients

A^* = percent of baseline channel cross-sectional flow area blocked by transverse structure [percent]

L_{arc} = arc length (spacing) between centerline of structures, measured along bankline [ft]

T_w = bend-averaged baseline channel top width [ft]

R_c = centerline radius of curvature of channel bend [ft]
$L_{w\text{-}Proj}$ = projected length of structure into channel, measured horizontally from water's edge along perpendicular channel cross section at design flow [ft]
D_B = bend-averaged maximum cross-section baseline flow depth [ft]
Δz = elevation difference between water surface and structure crest at the tip [ft]
θ = structure planview angle, measured from upstream line tangent to bank [degrees]

Table 5 Coefficients for MVR and AVR regression equations (all data) (Scurlock et al., 2012).

Ratio Location	R^2	*MA%E*	a_1	a_2	a_3	a_4	a_5	a_6	a_7
MVRo	0.8429	20.8533	0.0068	0.0000	0.5546	0.3846	–2.1431	0.7003	0.3824
MVRc	0.8011	4.3100	0.3773	0.2695	0.0000	0.1973	–0.1563	0.0467	0.1155
MVRi	0.6087	4.4433	0.3400	0.3404	–0.1116	0.1065	–0.2084	0.0445	0.1580
AVRo	0.4861	40.7230	0.0138	0.0000	0.5917	0.7439	–1.1451	0.4629	0.5996
AVRc	0.7255	4.0327	0.3615	0.2710	–0.0739	0.1850	–0.1412	0.0536	0.1158
AVRi	0.7530	3.9452	0.1315	0.4894	–0.1308	0.1770	–0.4098	0.1170	0.1266

Determine Permissible Velocity: In order to use MVR and AVR to predict the physical effects of bendway weirs, the ratios must be analyzed within the context of existing baseline velocity and permissible velocity. Once the baseline velocity, MVR, and AVR are known, the predicted velocities with bendway weirs can be compared to the permissible velocities to determine if erosion is expected to continue at the site. Permissible velocity is primarily a function of the bed and bank material in addition to vegetation characteristics. It is expected that bank erosion would be greatly reduced if the predicted maximum and average velocities with bendway weirs are less than the permissible velocities along the outer bank. Channel centerline and inner bank velocities are important to the river conditions downstream of the protected bend and to the point bar across from the bendway weirs. As flow velocity is reduced along the outer bank due to bendway weir installation, it is likely that velocity will increase along the channel centerline and inner bank. This may cause erosion of the point bar and increased velocity downstream. Table 6 summarizes the maximum and average permissible velocity ratios at the outer, center, and inner channel locations for the Rio Grande example project. The bend-averaged baseline velocity at the design flow (5.81 ft/s) was used to convert permissible velocities to corresponding velocity ratios. Several references such as Kilgore and Cotton (2005) and Fischenich (2001) provide methods to determine permissible velocity as a function of soil and vegetation characteristics. Rock stability at the weir tips is a consideration when selecting center permissible velocity, and the inner permissible velocity will depend on the desired point bar characteristics and historical lateral migration. Downstream effects should also be considered when selecting inner and center velocities. Average velocities can be set at an appropriate ratio of maximum permissible velocities (e.g., 75 percent) based on local conditions.

Table 6 Permissible velocity ratios for Rio Grande bendway weir design.

MVRo = 0.34	AVRo = 0.26
MVRc = 1.72	AVRc = 1.29
MVRi = 2.07	AVRi = 1.55

Use Velocity Equation to Iterate Range of Geometric Parameters: A median or most recommended value should be selected for each of the primary geometric parameters in addition to the range described above. The median value for three of the parameters can be held constant while varying the fourth parameter over the complete range determined from the geometric guidelines. These predicted velocity results should then be plotted and compared to the permissible velocity to examine the sensitivity and effect of each parameter. Figure 1 shows the results from the Rio Grande design project. The y-axis is percent difference compared to the permissible velocity, and the x-axis is the value of the geometric

parameter that is being adjusted. A negative percent difference means that the predicted velocity with bendway weirs is less than the permissible velocity. A positive percent difference means that the predicted velocity is greater than the permissible velocity and erosion would be expected. All of the recommended geometric parameters from HEC-23 and NCHRP 544 yield acceptable velocities for this example, except for very short weir lengths (less than about 38 ft). It should be noted that weir lengths less than about 30 ft for this site fall outside the bounds of configurations tested in the laboratory. The weir angle results are somewhat counterintuitive because of the relationship between angle and projected length. After completing the graphs, the desired velocity reduction and safety factor should then be used to select a narrowed range of parameter values for final analysis. This narrowed range is represented by vertical lines in the plots shown below.

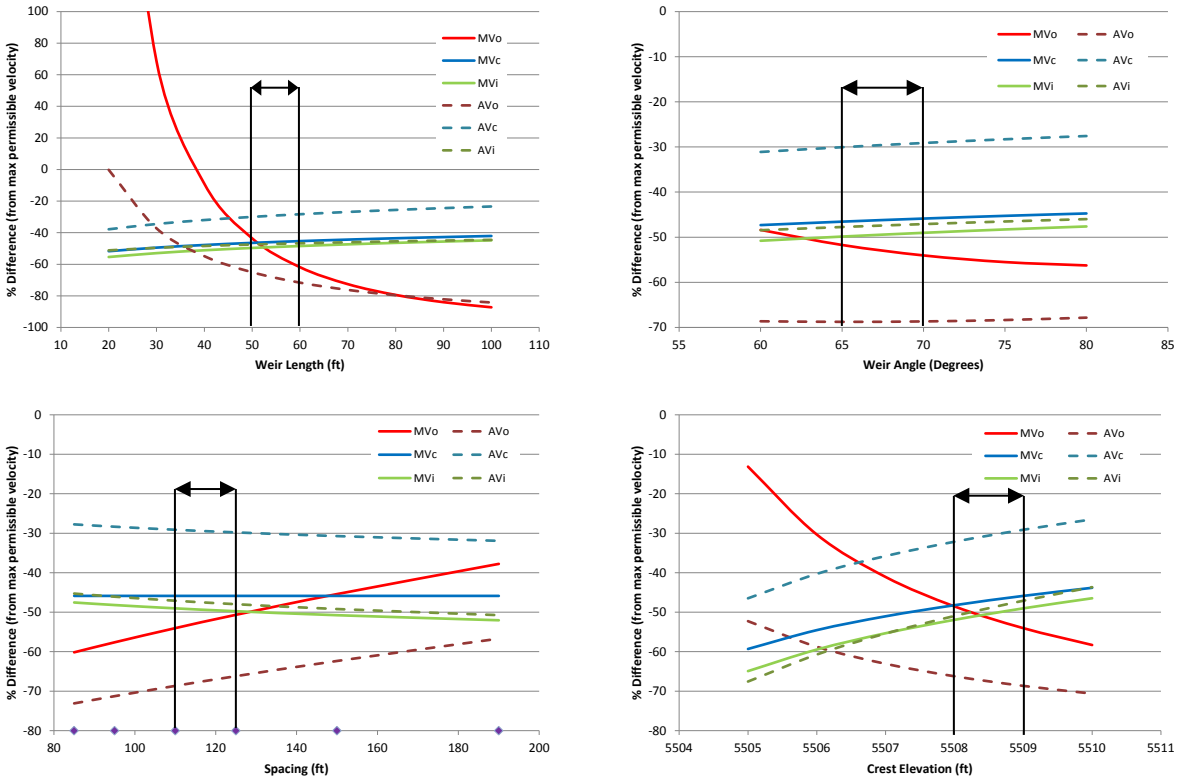

Figure 1 Velocity comparison as a function of weir length, angle, spacing, and height.

<u>Finalize Bendway Weir Geometry</u>: A matrix of potential final geometric values should be developed from a narrowed range based on the initial velocity calculations. The construction precision should also be accounted for, such as specifying elevation to the nearest 0.5 ft or 1 ft and specifying angles to the nearest 5°. For the Rio Grande project, the matrix consisted of 24 possible combinations based on 3 length values, 2 angle values, 2 spacing values, and 2 height values. The predicted velocities were then recalculated for every combination and plotted on a new graph. This is different than the initial iterations where only one geometric parameter was changed at a time. The selected values result in predicted maximum outer bank velocities that vary from 28 to 62 percent below the maximum permissible outer bank velocity. MVc, MVi, AVc, and AVi all remain fairly constant, but increase slightly as MVo and AVo are reduced. The final design is summarized in Table 7 and was selected based on: (1) a predicted MVo at least 50 percent smaller than the permissible MVo, (2) a balance of MVo reduction without an excessive increase in MVc and MVi, and (3) compatibility with existing bendway weirs installed further downstream in 2007. There is a balance between obtaining the greatest outer bank velocity reduction

while minimizing the amount of rock that is used for construction. Specifying a predicted MVo that is 50 percent less than the permissible MVo is similar to a safety factor of 2, although the difference in raw velocity values is only 1 ft/s.

Table 7 Design summary of final bendway weir geometric parameters.

	Exposed (active) Length*	Buried (key) Length	Total Weir Length	Angle	Spacing	Crest Elevation†	Top Width
Weir #1	37 ft	94 ft	131 ft	70°	105 ft	5509 ft	12 ft (exposed section) 8 ft (buried section)
Weir #2		98 ft	135 ft				
Weir #3		98 ft	135 ft				
Weir #4		123 ft	160 ft				
Weir #5		107 ft	144 ft				
Weir #6		90 ft	127 ft				
Weir #7		90 ft	127 ft				

*Original design length of 55 ft was modified to allow for placement of additional floodplain bench material so that final cut and fill volumes are balanced (see next section)
†On average, the modeled WSE drops about 0.6 ft between Weir #1 and Weir #7

Design Complementary Project Features: Bendway weir function and performance can be greatly improved with the addition of other compatible project features. Three additional components were included for the Rio Grande design example: point bar excavation, floodplain bench construction, and willow pole planting. Other features that should be considered are longitudinal stone toe, bioengineering, and locked logs. It may also be possible to retrofit existing projects with bendway weirs to improve aquatic habitat, relocate the thalweg, and manage energy throughout the bend. Although bendway weirs are low elevation structures, they block a portion of the main channel flow area and could reduce the effective channel width so excavating from the inner bend prevents channel narrowing. Maintaining sufficient channel width is important because a wider, shallower channel results in lower velocity and shear stress than a deep and narrow channel. Excavating the point bar at two different depths provides effective water and sediment transport with variable habitat over a range of flows. For the Rio Grande project, the upper point bar surface was also set at an elevation that promotes wetland establishment.

Creating an inset floodplain bench accomplishes the dual purpose of providing a cost effective method of disposing of the excavated material while offering significant hydraulic and environmental benefits. Reestablishing a floodplain surface allows higher flows to spread out at a shallower depth, thereby reducing velocity. Also, eddies that occur between the bendway weirs will cause scalloping of the floodplain bench rather than eroding the existing bankline. Figure 2 and Figure 3 illustrate the final design for the Rio Grande example project. An iterative process was used to design the floodplain bench and bar excavation elevation and alignment. The primary considerations while determining the floodplain bench elevation included depth to groundwater, typical inundation duration, and locations of existing willows near the site. A Reclamation biologist helped evaluate these factors and an average elevation of 5510.5 ft was selected for the floodplain bench. This is about 2.5 ft above the assumed groundwater table (base flow elevation) and corresponds to a river discharge of 3,500 cfs (1.25-yr return period). Balancing cut and fill volumes required a wider floodplain bench than originally estimated, thereby shortening the bendway weir length protruding into the flow. A final iteration was performed with the CSU velocity equations to refine the bendway weir layout based on the final floodplain bench design. A grid of coyote willows is included on the floodplain bench to stabilize the soil and create additional habitat. Vegetation provides increased hydraulic roughness to further reduce flow velocity and potentially encourage sediment deposition. Planting the willows in a grid pattern ensures that the technique will be effective regardless of flow rate and direction. It is essential that willow poles reach and maintain contact with groundwater to provide the best opportunity for survival.

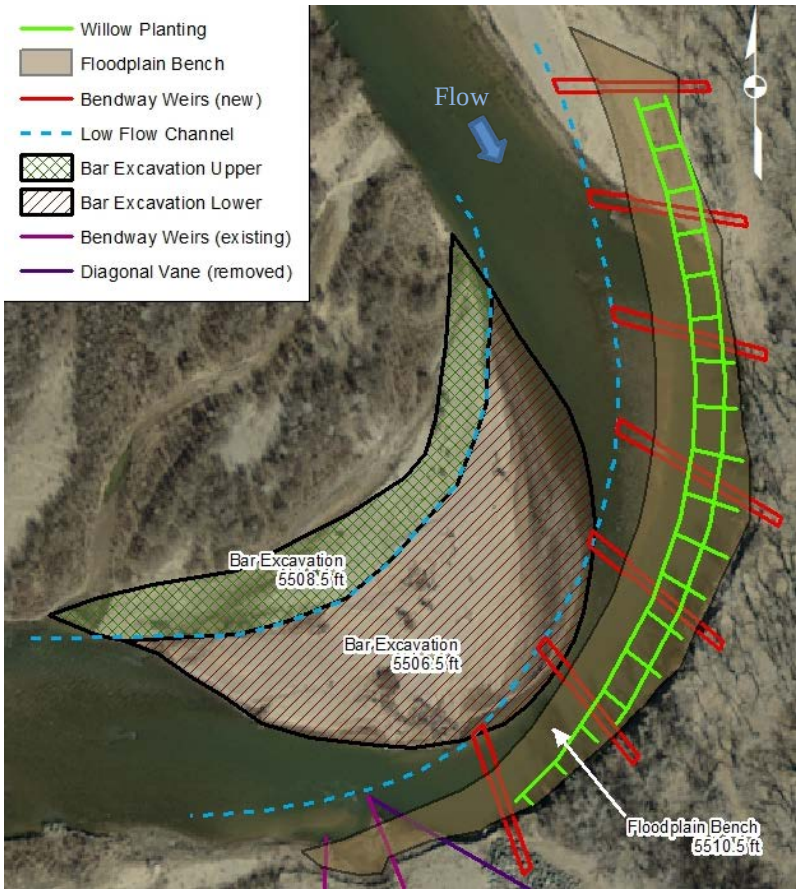

Figure 2 Site Plan with final location of project features.

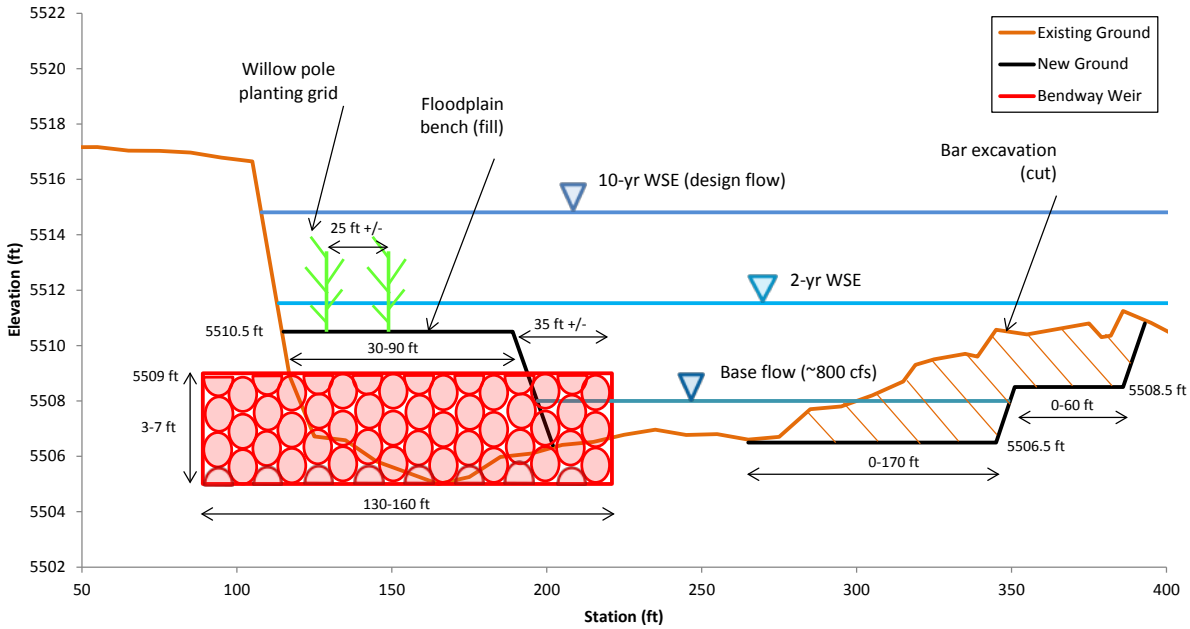

Figure 3 Typical cross section (looking downstream) with dimensions.

Summary and Recommendations: A bendway weir design methodology was described and illustrated with an example project that was constructed in 2013 on the Rio Grande north of Albuquerque, New Mexico. This project has only experienced two low spring runoff years since construction, but there have been a few high flow monsoon events. Sediment has been deposited along the bendway weirs and on the floodplain bench, indicating that the project has been effective so far. Existing guidelines were used near the beginning of the design process to establish a framework of feasible values for important geometric parameters. The existing guidelines do not quantify the effect of bendway weirs on channel hydraulics. However, they are based on field experience and designs of previous projects and should not be discounted. The CSU velocity ratio equation allows channel velocity to be predicted as a function of different bendway weir configurations. Comparing predicted velocities to the permissible velocity provides a method to estimate if the bendway weirs will be effective in preventing future bank erosion. Scurlock et al. (2012 and 2014) should be reviewed for a more detailed description of the velocity ratio equation including the range of applicability. This is an area of ongoing research by CSU for the Bureau of Reclamation, which includes the development of a 3-D numerical model.

It is recommended that an as-built survey be completed soon after construction to document field conditions of completed projects. This is important regardless of the design methodology and provides a reference for evaluating future adjustments. Bendway weir projects should be monitored for performance over time, particularly during and after high flow events. The level of monitoring can range from visual observations to more sophisticated data collection techniques. Surveys of the river channel and banks can be compared to as-built data to evaluate erosion and deposition patterns. Monitoring bendway weir tip location, crest elevation, and crest width will indicate if the riprap has been mobilized and if the structures are still functioning as intended. Measuring velocity and water surface elevation throughout the bend during high flow events will provide valuable hydraulic information that can be used to evaluate the CSU equations and the effects of bendway weirs on the flow.

REFERENCES

Baird, D.C. (2014). Bendway Weir Physical Model Re-Evaluation and Future Modeling Recommendations to Complete Design Guidelines. Bureau of Reclamation, Technical Service Center, Denver, Colorado, 39 pp.

Blench, T. (1957). Regime Behaviour of Canals and Rivers. Butterworths Scientific Publications, London, 138 pp.

Cox, A.L. (2005). A Study of In-Stream Rehabilitation Structures in Sand-Bed Channels. M.S. Thesis, Colorado State University, Fort Collins, Colorado, 462 pp.

Darrow, J.M. (2004). Effects of Bendway Weir Characteristics on Resulting Flow Conditions. M.S. Thesis, Colorado State University, Fort Collins, Colorado, 265 pp.

de Almeida, G.A., and Martin-Vide J.P. (2009). "Riprap Stability: Transverse and Longitudinal versus Continuous Protections," Journal of Hydraulic Engineering, ASCE, 135(6), pp 447–456.

Derrick, D. (2012). Streambank Erosion and Protection Training Course. U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Fischenich, C. (2001). Stability Thresholds for Stream Restoration Materials, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-29). U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Heintz, M.L. (2002). Investigation of Bendway Weir Spacing. M.S. Thesis, Colorado State University, Fort Collins, Colorado, 225 pp.

Lagasse, P. F., Clopper, P.E., Pagan-Ortiz, J.E., Zevenbergen, L.W., Arneson, L.A., Schall, J.D., and Girard, L.G. (2009). Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance, Third Edition, Volume 2, Hydraulic Engineering Circular No. 23. Federal Highway Administration, Washington, DC.

Kilgore, R.T., and Cotton, G.K. (2005). Design of Roadside Channels with Flexible Linings, Hydraulic Engineering Circular No. 15, Third Edition. Federal Highway Administration, Washington, DC.

Lagasse, P.F., Clopper, P.E, Zevenbergen, L.W., and Ruff, J.F. (2006). Riprap Design Criteria, Recommended Specifications and Quality Control, National Cooperative Highway Research Program Report 568. Transportation Research Board, National Academies of Science, Washington, DC.

Maynord, S.T. (1996). "Toe-Scour Estimation in Stabilized Bendways," Journal of Hydraulic Engineering, ASCE, 122(8), pp 460–464.

Maynord, S.T., Ruff, J.F., and Abt, S.R. (1989). "Riprap Design," Journal of Hydraulic Engineering, ASCE, 115(7), pp 937–949.

McCullah, J., and Gray, D. (2005). Environmentally Sensitive Channel- and Bank-Protection Measures. National Cooperative Highway Research Program NCHRP Report 544 and Project 24-19, Transportation Research Board, National Academies of Science, Washington, DC.

NRCS (Natural Resources Conservation Service), (2007). Part 654 National Engineering Handbook – Stream Restoration Design.

Pemberton, E.L., and Lara, J.M. (1984). Computing Degradation and Local Scour, Technical Guideline for Bureau of Reclamation. U.S. Bureau of Reclamation, Denver, Colorado, 48 pp.

Schmidt, P.G. (2005). Effects of Bendway Weir Field Geometric Characteristics on Channel Flow Conditions. M.S. Thesis, Colorado State University, Fort Collins, Colorado, 364 pp.

Scurlock, S.M., Cox, A.L., Thornton, C.I., and Abt S.R. (2012). "Middle Rio Grande physical modeling – Transverse instream structure analysis: Maximum and average velocity ratios within the prismatic channel," Colorado State University, Department of Civil Engineering, Fort Collins, Colorado, 31 pp.

Scurlock, S.M., Thornton, C.I., and Abt S.R. (2014). Middle Rio Grande physical modeling – Quantification of Hydraulic Effects from Transverse Instream Structures in Channel Bends. Colorado State University, Department of Civil Engineering, Fort Collins, Colorado, 159 pp.

USACE (U.S. Army Corps of Engineers), (1994). Hydraulic Design of Flood Control Channels, Engineer Manual No. 1110-2-1601. Department of the Army, Washington, DC.

Watson, C.C., Biedenharn, D.S., and Thorne C.R. (2007). Stream Rehabilitation, Version 2.0. Cottonwood Research, LLC. Fort Collins, Colorado, 240 pp.

Zeller, M.E. (1981). Scour Depth Formula for Estimation of Toe Protection Against General Scour. Pima County Department of Transportation and Flood Control District, Tucson, Arizona.