RIVER RESEARCH AND APPLICATIONS

River Res. Applic. **26**: 823–834 (2010)

Published online 21 June 2009 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1289

PREDICTING VELOCITY IN BENDWAY WEIR EDDY FIELDS

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ABSTRACT

Rehabilitation of the Middle Rio Grande (MRG) in central New Mexico has become necessary because of changes in morphology resulting from the installation of dams, and because of habitat restoration considerations for the endangered Rio Grande silvery minnow (*Hybognathus amarus)*. Bendway weirs are erosion control and channel-stabilization structures placed transverse to the channel flow that have been increasingly used to prevent river migration while simultaneously enhancing aquatic habitat. Plans for rehabilitation along the MRG include the use of bendway weirs; however, past projects using these structures have relied on field experience and engineering judgment rather than specific design guidelines. A physical model of a reach of the MRG was constructed to develop empirical design equations for eddy velocities in bendway weir fields. Data from physical model simulations were used to develop two empirical expressions for predicting eddy velocities behind bendway weirs, along with two expressions for predicting velocities at the toe of installed weirs. These equations relate the velocity found after bendway weir installation to weir design characteristics and pre-weir channel conditions. A designer can use the described approach to predict velocities in eddies and velocities at the toe of bendway weirs using only weir design variables and pre-weir channel conditions, and thus avoid some of the uncertainty with weir design that previously existed. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: hydraulic design; bendway weirs; river restoration; velocity prediction; Rio Grande silvery minnow; Hybognathus amarus

Received 13 January 2009; Revised 27 March 2009; Accepted 21 May 2009

INTRODUCTION

The Middle Rio Grande (MRG), located in New Mexico, is an example of a river that has become unstable due to human impacts and demands. Construction of several large dams coupled with agricultural demand has decreased the flow and subsequently the sediment transport capacity of the river. Reservoirs on the Rio Grande and several tributaries act as sediment traps and have caused the river to meander, resulting in actively destabilizing banks. This destabilization, along with low flow due to agricultural extraction, has led to decreased aquatic habitat. Using aerial photography from 1918 compared to current images the aquatic habitat has decreased by roughly 58% (Kinzli and Myrick, in press). Because of this resulting channel instability, the U. S. Bureau of Reclamation (USBR) has initiated a project in an attempt to stabilize stream banks on the Rio Grande and increase aquatic habitat using bendway weirs.

For the purpose of this study bendway weirs, also known as spur dikes, groynes or jetties (Thornton *et al*., 2005), are defined as linear rock structures placed on the outside of meander bends protruding into the flow to realign flow away from the outside bank (Derrick, 1999). Bendway weirs are constructed out of native rock, in most cases the same material that is used for riprap. These native materials tend to be easily accessible; they also have the benefit of potentially enhancing or creating aquatic habitat when placed in the river (Rapp, 1997). Habitat is created when drop offs in the channel bed form between the main thalweg and the depositional area between weirs. Low-flow habitat is created by the scour hole at the tip of a weir and, habitat for aquatic invertebrates is created on and between the individual rocks on each weir. When installed properly, bendway weirs greatly decrease bank erosion

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while improving aquatic habitat (Shields *et al*., 1998a), and have been reported to be more beneficial to aquatic habitat resources than other forms of bank protection (Knight and Cooper, 1991; Shields *et al*., 1995; Shields *et al*., 2000; Kuhnle *et al*., 2002; Thornton *et al*., 2005). The ecological benefits of bendway weirs to the endangered Rio Grande silvery minnow (Hybognathus amarus) are presented in Kinzli and Myrick (in press). The benefits include reduced egg drift, creation of low velocity eddies, scour hole formation to provide low flow habitat, refugia and cover from rock substrate and deposition of organic material which can provide a food source.

A disadvantage of bendway weirs are the eddies that form between individual structures, producing unpredictable velocities due to variations in weir length, orientation angle and spacing ratio (Thornton *et al*., 2005). Field observations have shown that these eddies can cause outer bank degradation between weirs and unacceptable amounts of scour at the tips of the bendway weirs (Prezedwojski *et al*., 1995; Prezedwojski, 1995; Derrick, 1999; Kuhnle *et al*., 1999; Uijttewaal *et al*., 2001; Kuhnle *et al*., 2002; Rahman and Haque, 2004; Sukhodolov *et al*., 2004). Due to the unpredictable nature of eddies, design criteria relating eddy and toe velocity to weir length, orientation angle and spacing ratio have not been developed at this stage (Thornton *et al*., 2005). Past and present projects incorporating bendway weirs for bank stabilization have relied mostly on experience and engineering judgment (Thornton *et al*., 2005). While this experience and judgment sometimes succeeds in developing a viable weir field, the lack of test-based design methods for prediction of eddy velocities has resulted in the failure of several bendway weir projects (Finley *et al*., 2003). Therefore, we suggest that a design methodology that provides predictions of post-installation velocities would allow engineers to quantify local and between bendway weir scour. If empirical design standards existed to predict eddy and toe velocities, bendway weirs would provide engineers with another solution to erosion control and habitat loss, and could be implemented more often (Darrow, 2004).

PHYSICAL MODEL DEVELOPMENT

A rigid bed physical model was constructed to collect data for the development of design guidelines. The model, designed to be representative of the MRG, consisted of two typical bends arranged using a S-curve geometry, and was built using a 1:12 undistorted Froude scale. Two typical bend types were determined using aerial photographs and geographic information system (GIS) analysis of the MRG. The two bends were designed with a significant transition between the bends which allowed for independent analysis of each bend. Both bends were constructed using a trapezoidal cross-section with side slopes of 1:3. The characteristics of the model and prototype bends are provided in Table I.

A movable data-acquisition cart allowed the collection of flow data throughout the model. Data-acquisition cart instrumentation included a point gage, acoustic doppler velocimeter (ADV), Preston tube and computer for measurements of flow depth, velocity and bed shear stress. One hundred and twenty piezometers were installed throughout the model to measure water-surface elevations. The overall model dimensions were 180 ft in length by 42 ft in width. A complete description of the model can be found in Heintz (2002) and Darrow (2004). A plan view of the model showing the 18 cross-section configuration is displayed in Figure 1.

Table I. Characteristics of the model and prototype bends

Bend characteristics	Type I bend		Type III bend	
	Model	Prototype	Model	Prototype
Channel length	84 ft	1014 ft	83 ft	1006 ft
Top width	19.167 ft	230 ft	15 ft	180 ft
Bottom width	10.167 ft	122 ft	6 ft	72 ft
Radius of curvature	38	456	65	780
Bend angle	125°	125°	73°	73°

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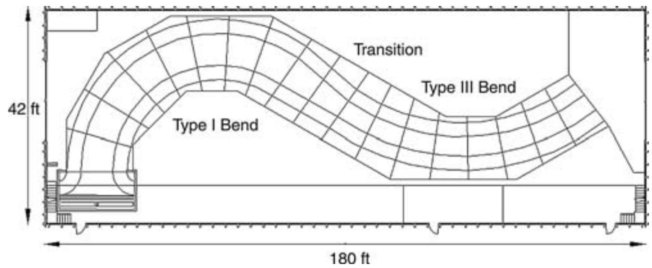

Figure 1. Plan view of model

DATA COLLECTION AND DATABASE DEVELOPMENT

A test program was developed to ascertain the effect of varying weir characteristics on resulting flow conditions. Weir characteristics that varied from test to test were length, orientation angle and spacing ratio. Length is defined as a percentage of the overall channel top width; orientation angle is defined as the angle with respect to the upstream bank and spacing ratio is defined as the distance between weirs along the waters edge at a design flow, to the projected length of the weir normal to the flow. A 60°weir is angled 30° upstream of perpendicular. The weir variables examined during this study are illustrated in Figure 2.

Weir configurations were placed in the upstream and downstream bends of the model (Figure 3). Influence of the upstream bend on downstream conditions was examined and it was determined that the two bends could be analysed as individual tests.

We used a combination of different flows and weir configurations to develop a robust data set for the equation development process. Flow rates of 8, 12 and 16 cfs were tested on both bends in the model, resulting in two tests for each flow rate. Overall, 12 weir configurations were examined. These 12 configurations were tested in the two bends at the three discharges resulting in 72 overall tests to determine the affect of the three varying weir characteristics on resulting flow conditions. Weir crest width, bottom width, height and particle size were constant across all trials. Variables that were changed throughout the test program were weir length, weir orientation angle and weir spacing ratio (Table II). Weir heights were set to coincide with the flow depth at 12 cfs, or bankfull discharge and were 0.77 ft in the upstream bend and 0.78 ft in the downstream bend. Weir crest width was held constant at 1 ft and sloped down creating a weir bottom width of 4 ft. Crest widths of 1 ft were selected to simulate widths wide enough to accommodate construction vehicles for simplified weir placement in the field.

Along with the 72 tests examining varying weir variables, multiple base-line tests were conducted to determine the velocities in the model before the installation of bendway weirs. These baseline results are shown in Table III. Base-line testing was necessary to establish flow patterns and velocities in the model prior to weir installation so

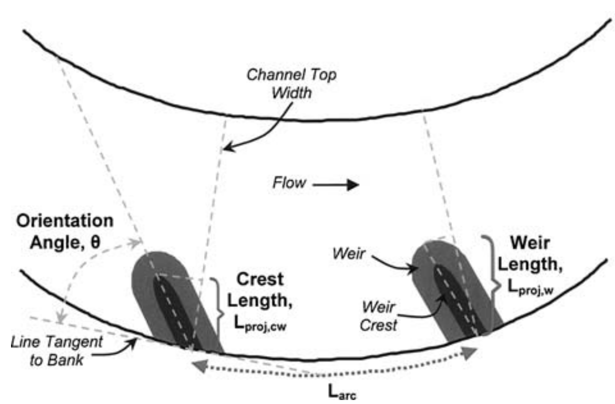

Figure 2. Schematic of weir variables examined

DOI: 10.1002/rra

Figure 3. Bendway weirs installed in model channel. This figure is available in colour online at wileyonlinelibrary.com

that flow patterns with and without weirs could be compared and the effect of weirs on flow conditions determined. The test matrix and a detailed explanation of the testing can be found in Kinzli (2005).

To establish the effects that bendway weirs had on flow conditions in the channel, two separate data sets were developed. The first data set, designated as the *weir data set*, was collected to examine the flow conditions in proximity to bendway weirs and to address scour concerns at the weir tip. The weir data set consisted of data points collected at the tip of each weir and 1 ft out from the tip perpendicular to the flow direction. The second data set, designated as the *eddy mapping data set*, was collected to investigate flow conditions within the eddies created behind each weir. The *eddy mapping data set* was developed to address the variable nature of eddy currents. The eddy mapping data set consisted of a set of points located along four cross-sections set between each pair of weirs. Cross-sections were set at 1/8, 3/8, 5/8 and 7/8 of the distance between the weirs at the 12 cfs water line. Three data

Table II. Weir variables changed during testing in 8, 12 and 16 cfs flow rates

	Tested values			
Spacing ratio	3.4	4.1	5.9	7.62
Weir length (%)	15	22	28	
Weir orientation angle (degrees)	60	90		

Table III. Results of base-line testing

Bend	Flow rate (cfs)	Maximum centerline velocity, Max$V_{Centerbase}$ (ft/sec)
Upstream	8	1.10
Upstream	12	1.30
Upstream	16	1.43
Downstream	8	1.79
Downstream	12	2.07
Downstream	16	2.23

points were taken at each cross-section. Two of the three points were taken along the bank and were 1/2 and 1/4 of the way up the bank, with the third point being located at the toe of the channel. Data points for the weir data set and eddy mapping data set consisted of a velocity reading taken at 60% depth using an ADV. Data collection locations for the 72 tests are shown in Figure 4. Collected data can be obtained in Kinzli (2005).

ANALYSES

The goal of analyses was to develop a design methodology such that channel and eddy velocities after bendway weir installation could be predicted using base-line flow conditions and specified weir characteristics. Development of a prediction methodology utilized the concept of a maximum velocity ratio (MVR) (Heintz, 2002). A dimensionless variable, MVR was defined as the ratio of the post-weir velocity and the pre-weir centerline channel velocity. An in-depth explanation of MVR can be found in Heintz (2002).

Four specific velocities were defined during data analysis:

- maximum velocity in each eddy;
- largest velocity gradient in each eddy;
- maximum velocity at the toe of the bendway weir and
- maximum velocity 1 foot from the toe of the bendway weir.

Maximum eddy velocities along with the largest velocity gradient (difference velocity) in each eddy were examined due to concerns regarding bank erosion in bendway weir fields and certain habitat considerations. Velocities at the toe and one foot out from the toe of each weir were of concern due to scour and weir instability.

Maximum eddy velocity ratio (MEVR) was defined as the ratio of the maximum velocity in an eddy and the pre-weir centerline channel velocity and is expressed as:

$$\mathrm{MEVR} = \frac{\text{Max Eddy Velocity}}{\text{Max Velocity}_{\text{Center(Pre-weir)}}} \tag{1}$$

where MEVR = maximum eddy velocity ratio; Max Eddy Velocity = maximum velocity in an eddy in the downstream direction; and Max $\text{Velocity}_{\text{Center(Pre-weir)}}$ = maximum base-line velocity in the center of the channel.

Analysis conducted on MEVR data revealed that bendway weirs greatly reduced near bank velocities. MEVRs were less than 1 for all 72 tests, indicating that eddy velocities were smaller than the base-line centerline channel velocity. Analysis of the data revealed that at all flow rates, longer weirs resulted in lower MEVR values along the outer bank. It was also observed that angled weirs resulted in smaller MEVR values than perpendicular weirs of the same length.

Due to the swirling nature of eddies, it was necessary to establish a parameter that accounted for the velocity gradient present in eddies. Swirling currents in eddies create velocities both in the positive and negative x directions. To account for the velocity gradient, the maximum difference eddy velocity was established.

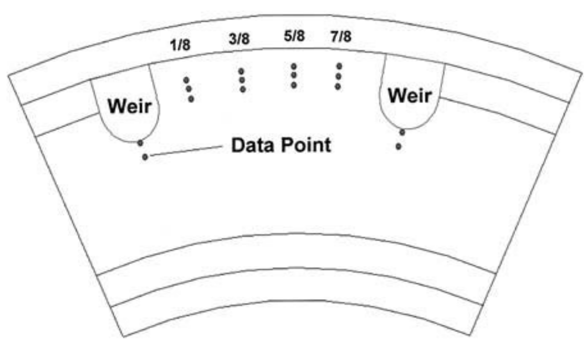

Figure 4. Data-collection locations for each weir configuration

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Maximum difference velocity is defined as the difference between the highest and lowest velocities in the x direction. In almost all cases, the lowest velocity found in an eddy was negative causing the maximum difference velocity to be higher than the maximum eddy velocity. Similar to the MEVR, the maximum difference eddy velocity ratio (MDEVR) was defined as the maximum difference velocity divided by the pre-weir centerline channel velocity and is expressed as:

$$\mathrm{MDEVR} = \frac{\text{Max Difference Eddy Velocity}}{\text{Max Velocity}_{\text{Center(Pre-weir)}}} \tag{2}$$

where MDEVR = maximum difference eddy velocity ratio; Max Difference Eddy Velocity = maximum difference in velocity in an eddy; and Max $\text{Velocity}_{\text{Center(Pre-weir)}}$ = maximum base-line velocity in the center of the channel.

Analysis conducted on MDEVR data revealed that the MDEVR values were higher than MEVR values. Higher MDEVR values indicate that the velocity gradient present in eddies is greater than the overall maximum eddy velocity. MDEVR values were nearly all less than 1 showing that bendway weirs reduce the velocity that river banks are subjected to. Similar to the MEVR, longer weir length and smaller orientation angle resulted in the lowest MDEVR values.

Maximum velocity ratio at the toe ($\mathrm{MVR}_{\text{Toe}}$) was defined as the ratio of the maximum velocity at the toe of a bendway weir and the pre-weir centerline channel velocity and is expressed as:

$$\mathrm{MVR}_{\text{Toe}} = \frac{\text{Max Velocity Toe}}{\text{Max Velocity}_{\text{Center(Pre-Weir)}}} \tag{3}$$

where $\mathrm{MVR}_{\text{Toe}}$ = maximum velocity ratio at the toe of a bendway weir; Max Velocity Toe = maximum velocity at the toe of a bendway weir; and Max $\text{Velocity}_{\text{Center(Pre-weir)}}$ = maximum base-line velocity in the center of the channel.

Analysis conducted on $\mathrm{MVR}_{\text{Toe}}$ data revealed that toe velocities were larger than pre-weir channel velocities. $\mathrm{MVR}_{\text{Toe}}$ values were larger than 1, indicating that channel velocities near the toe were increased by the placement of bendway weirs. Velocities in the channel increased because bendway weirs resulted in a constriction of the flow area.

Maximum velocity ratio 1 foot from the toe ($\mathrm{MVR}_{\text{1foot}}$) was defined as the ratio of the maximum velocity 1 foot from the toe of a bendway weir and the pre-weir centerline channel velocity and is expressed as:

$$\mathrm{MVR}_{\text{1foot}} = \frac{\text{Max Velocity 1foot}}{\text{Max Velocity}_{\text{Center(Pre-weir)}}} \tag{4}$$

where $\mathrm{MVR}_{\text{1foot}}$ = maximum velocity ratio 1 foot from the toe of a bendway weir; Max Velocity 1foot = maximum velocity 1 foot from the toe of a bendway weir; and Max $\text{Velocity}_{\text{Center(Pre-weir)}}$ = maximum base-line velocity in the center of the channel.

Analysis conducted on $\mathrm{MVR}_{\text{1foot}}$ data revealed that velocities 1 foot from the toe were greater than pre-weir channel velocities. $\mathrm{MVR}_{\text{1foot}}$ values were greater than 1, indicating that channel velocities 1 foot from the toe were increased by the placement of bendway weirs. $\mathrm{MVR}_{\text{1foot}}$ values were larger than $\mathrm{MVR}_{\text{Toe}}$ values, indicating that velocities 1 foot from the tip of bendway weirs are more likely to cause scour and resulting weir instability.

Overall, four specific velocities in bendway weir fields were defined and examined. MEVR and MDEVR are measures of velocities in eddies created by bendway weir installation. $\mathrm{MVR}_{\text{Toe}}$ and $\mathrm{MVR}_{\text{1foot}}$ are measures of velocities occurring at the tip of bendway weirs. MEVR and MDEVR values were smaller than pre-weir centerline channel velocities. On average, MEVR was 49% smaller, while MDEVR was 32% smaller than the average pre-weir velocity. $\mathrm{MVR}_{\text{Toe}}$ and $\mathrm{MVR}_{\text{1foot}}$ values were greater than pre-weir channel velocities. On average, $\mathrm{MVR}_{\text{Toe}}$ was 18% greater, while $\mathrm{MVR}_{\text{1foot}}$ was 20% greater than the pre-weir velocity.

Data from the determination of eddy, toe and maximum velocity ratios suggested that a multivariate regression analysis was appropriate. Multivariate regression consisted of describing MEVR, MDEVR, $\mathrm{MVR}_{\text{Toe}}$ and $\mathrm{MVR}_{\text{1foot}}$ as functions of independent bendway weir variables. Using several statistical procedures, accurate modelling of specific affects of bendway weir variables on flow velocity was possible. Initially, a dimensional analysis was performed to identify appropriate descriptor variables. Significant descriptor variables were grouped into

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dimensionless groupings to diminish the overall number of variables using the Buckingham Pi theorem. A complete description of dimensional analysis can be found in Munson *et al.* (1998) and Julien (1998). Once the dimensional analysis was complete, multivariate linear regression was utilized to develop statistically significant equations to predict post-weir velocities. Predictive equations were then algebraically simplified to allow for ease of use.

From the dimensional analysis, several variables were found to be significant in affecting flow conditions. The significant variables are listed in Table IV. Several of the significant variables need to be defined. Apparent roughness of the weir field (n_w) was defined as the Manning's roughness due to bendway weir installation and was calculated using Manning's equation with channel geometry after bendway weir installation. Shear velocity created by the bendway weirs (u_w^*) was defined as the shear velocity using the hydraulic radius with the bendway weirs in place.

In order to create a successful regression model, it was necessary to check that the MEVR, MDEVR, MVR_{Toe} and MVR_{1foot} met the assumptions appropriate for multivariable linear regression. It was determined that the four velocity ratios met the five main assumptions of existence, independence, linearity, homoscedasticity and normality, which allowed for a multivariate linear regression model to be constructed for each velocity ratio.

Statistical analyses consisted of transforming collected data using a natural log transformation, performing regression analysis and inspecting regression results using the analysis of variance table, contribution of independent variables methodology and examination of outliers. Each model used the stepwise selection method to determine the best model since multiple regression models existed for each velocity ratio. After the most appropriate model was determined, variance, contribution of independent variables and associated errors were examined. A complete description of the statistical analysis can be found in Kinzli (2005).

RESULTS

A comprehensive statistical analysis resulted in the development of four models for the prediction of MEVR, MDEVR, MVR_{Toe}, and MVR_{1foot} using bendway weir design variables.

Utilizing the statistical procedures described in the previous section, a best-fit regression equation was developed to predict MEVR and is expressed as:

$$\mathrm{MEVR} = e^{-38.1}\frac{{L_{cw}}^{2.32}{A_w}^{0.513}{L_{proj,w}}^{14.557}}{{L_{proj,cw}}^{15}{\nu_w}^{2.39}\left(u_w^*\right)^{2.39}} \tag{5}$$

where L_{cw} = length of the bendway weir crest measured along the centerline; A_w = projected bendway weir area; $L_{proj,w}$ = projected length of bendway weir to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow; $L_{proj,cw}$ = projected length of bendway weir crest to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow; ν_w = kinematic viscosity; and u_w^* = shear velocity with bendway weirs.

Table IV. Significant variables affecting flow conditions

	Symbol	Definition	Dimensions
Material properties	ν_w	Kinematic viscosity of water	L^2/T
Channel properties	A_c	Area of channel at test flow	L^2
Weirs	$L_{proj,cw}$	Projected length of weir crest	L
	L_{cw}	Weir crest length	L
	$L_{proj,w}$	Projected length of weir	L
	L_{arc}	Arc length between weirs	L
	A_w	Area of weir projected on perpendicular transect	L^2
	n_w	Apparent roughness created by weir field	$T/L^{1/3}$
	u_w^*	Shear velocity created by weirs	L/T

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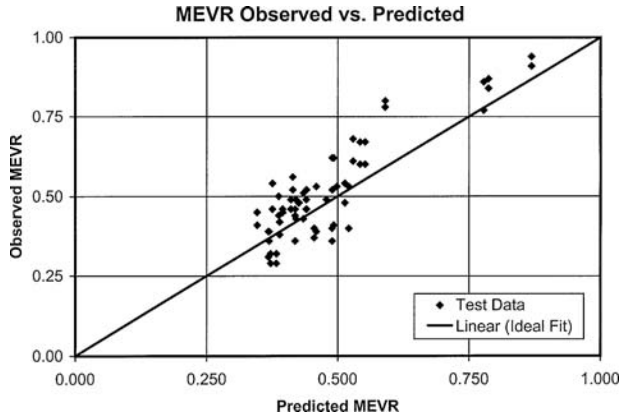

Figure 5. MEVR multivariate linear regression model

Figure 5 presents a plot of predicted values versus observed errors. The average error for the MEVR model was 0.046, indicating equal scatter above and below the regression line. Average absolute error for the regression equation was 0.138, indicating that the developed regression equation (Equation (5)) on average predicted MEVR to within 13.8% of the observed value. Standard deviation for the average absolute error was found to be $\pm$ 8.5%. Equation (5) exhibited a coefficient of determination (R^2) of 0.541. The R^2 value of 0.541 signifies that the regression equation accounted for 54.1% of the variability in the data. Overall, the predictive equation satisfied all significance tests, implying that the regression equation and the variables used were statistically significant.The equation developed to predict MDEVR is expressed as:

$$\text{MDEVR} = e^{-1.20} \frac{A_c{}^{0.225} L_{arc}{}^{0.526}}{L_{proj,w}{}^{1.502}} \tag{6}$$

where A_c = cross-sectional flow area of the channel before weir installation; L_{arc} = arc length between bendway weirs along design waterline; and $L_{proj,w}$ = projected length of bendway weir to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow.

Figure 6 presents a plot of predicted values versus observed errors. The average error for the MDEVR model was 0.031, indicating equal scatter above and below the regression line. Average absolute error for the regression equation was 0.153, indicating that the developed regression equation (Equation (6)) on average predicted MDEVR

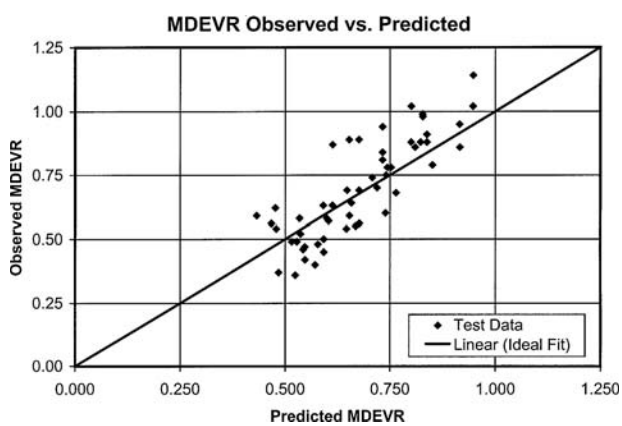

Figure 6. MDEVR multivariate linear regression model

DOI: 10.1002/rra

to within 15.3% of the observed value. Standard deviation for the average absolute error was found to be $\pm$ 10.8%. Equation (6) exhibited a coefficient of determination (R^2) of 0.46. The R^2 value of 0.46 signifies that the regression equation accounted for 46% of the variability in the data. Overall, the predictive equation satisfied all significance tests, implying that the regression equation and the variables used were statistically significant.The equation developed to predict $\mathrm{MVR_{Toe}}$ is expressed as:

$$\mathrm{MVR_{Toe}} = \mathrm{e}^{-0.475} \frac{L_{\mathrm{proj,cw}}{}^{0.916}}{n_{\mathrm{w}}^{0.293} \left(u_{\mathrm{w}}^{*}\right)^{0.127} L_{\mathrm{proj,w}}{}^{0.8313}} \tag{7}$$

where $L_{\mathrm{proj,cw}}$ = projected length of bendway weir crest to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow; n_{w} = apparent roughness with bendway weirs; u_{w}^{*} = shear velocity with bendway weirs; and $L_{\mathrm{proj,w}}$ = projected length of bendway weir to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow.

Figure 7 presents a plot of predicted values versus observed errors. The average error for the model was 0.031, indicating scatter above and below the regression line. Average absolute error for the regression equation was 0.074, indicating that the developed regression equation (Equation (7)) on average predicted $\mathrm{MVR_{Toe}}$ to within 7.4% of the observed value. Standard deviation for the average absolute error was found to be $\pm$ 4.6%. Equation (7) exhibited a coefficient of determination (R^2) of 0.401. The R^2 value of 0.401 signifies that the regression equation accounted for 40.1% of the variability in the data. Overall, the predictive equation satisfied all significance tests, implying that the regression equation and the variables used were statistically significant.The equation developed to predict $\mathrm{MVR_{1foot}}$ is expressed as:

$$\mathrm{MVR_{1foot}} = \mathrm{e}^{-1.72} \frac{L_{\mathrm{proj,cw}}{}^{0.417}}{n_{\mathrm{w}}^{0.293} \left(u_{\mathrm{w}}^{*}\right)^{0.293} L_{\mathrm{proj,w}}{}^{0.2216}} \tag{8}$$

where $L_{\mathrm{proj,cw}}$ = projected length of bendway weir crest to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow; n_{w} = apparent roughness with bendway weirs; u_{w}^{*} = shear velocity with bendway weirs; and $L_{\mathrm{proj,w}}$ = projected length of bendway weir to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow.

Figure 8 presents a plot of predicted values versus observed errors. The average error for the model was 0.079, indicating scatter mostly above the regression line. Average absolute error for the regression equation was 0.091, indicating that the developed regression equation (Equation (8)) on average predicted $\mathrm{MVR_{1foot}}$ to within 9.1% of the observed value. Standard deviation for the average absolute error was found to be $\pm$ 5%. Equation (8) exhibited a coefficient of determination (R^2) of 0.609. The R^2 value of 0.609 signifies that the regression equation accounted for 60.9% of the variability in the data. Overall, the predictive equation satisfied statistical significance tests.

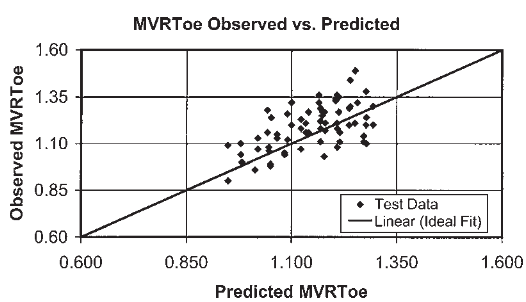

Figure 7. $\mathrm{MVR_{Toe}}$ multivariate linear regression model

DOI: 10.1002/rra

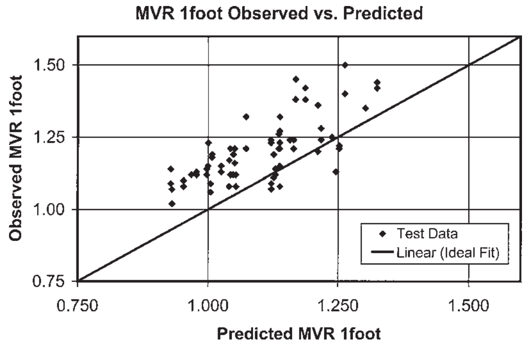

Figure 8. MVR_{1foot} multivariate linear regression model

CONCLUSIONS

Regression equations were developed for predicting MEVR, MDEVR, MVR_{Toe} and MVR_{1foot}. The four predictive equations were developed using test data from two characteristic bends of the MRG. Developed regression equations may be applied to weir design only if the following limitations are not violated:

- bendway weir spacing ratio is between 3.4 and 7.62;
- bendway weir length is between 15 and 28% of the design flow top width;
- bendway weirs must be oriented between 60° and 90°;
- bendway weir crests should be horizontal;
- bendway weir tips should have a rounded geometry and
- bendway weirs should be installed in channels that have similar geometries to the channels modelled in this study.

A design example of how to utilize the developed equations to create aquatic habitat for the Rio Grande silvery minnow can be found in Kinzli (2005) and Kinzli and Myrick (in press).

The four velocity prediction equations developed during the statistical analysis exhibit acceptable error rates. MEVR on average can be predicted to within 13.8%, while MDEVR can be predicted to within 15.3% of the observed value. Using the developed equations, the velocities (MVR_{Toe} and MVR_{1foot}) associated with scour can on average be predicted within 7.4 and 9.1% of the observed value, respectively.

This research investigated the effects of bendway weir characteristics on resulting flow conditions found in eddies created by bendway weirs and flow conditions created at the toe of bendway weirs. Bendway weir characteristics that were varied and examined throughout this study were length, orientation angle, and spacing ratio. A hard boundary model of the MRG with a Froude scale of 1:12 representing two characteristic bends in the study reach was constructed to study the effects of weir variables on the resulting flow conditions. Currently, mobile bed tests are being conducted in the same model to examine what changes in flow conditions in comparison to a rigid bed can be expected and results should be forthcoming.

This study presents a significant advance in bendway weir design as previous projects have been based on experience, trial and error and engineering judgment. The study resulted in four regression equations capable of predicting maximum and maximum difference velocity in eddies, and two maximum bendway weir toe velocities (toe and 1 foot), based on the weir design criteria of length, orientation angle and spacing ratio. With this developed methodology, designers can protect migrating meander bends and simultaneously create aquatic habitat using an empirical method to predict post installation flow conditions.

The habitat benefits that bendway weirs can provide for the Rio Grande silvery minnow such as reduced egg drift, creation of low velocity eddies, scour hole formation to provide low flow habitat, refugia and cover from rock substrate and deposition of organic material need to be examined. This could be accomplished through a pilot project and continued laboratory studies to determine and field validate the habitat benefits that bendway weirs provide. Details regarding such studies are provided in (Kinzli and Myrick, in press).

DOI: 10.1002/rra

NOTATION

The following symbols are used in this paper:

A_c	cross-sectional flow area
A_w	projected bendway weir area
L_{arc}	arc length between bendway weirs along design waterline
L_{cw}	length of the bendway weir crest measured along the centerline
$L_{proj,cw}$	projected length of bendway weir crest to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow
$L_{proj,w}$	projected length of bendway weir to a cross-section perpendicular to flow and passing through the point at which the centerline and waters edge meet at the design flow
Max Difference Eddy Velocity	maximum difference in velocity in an eddy
Max Eddy Velocity	maximum velocity in an eddy in the downstream direction
Max $\text{Velocity}_{\text{Center(Pre-weir)}}$	maximum base-line velocity in the center of the channel
Max Velocity 1foot	maximum velocity 1 foot from the toe of a bendway weir
Max Velocity Toe	maximum velocity at the toe of a bendway weir
$\text{MaxV}_{\text{Centerbase}}$	maximum centerline velocity
MEVR	maximum eddy velocity ratio
MDEVR	maximum difference eddy velocity ratio
$\text{MVR}_{\text{1foot}}$	maximum velocity ratio 1 foot from the toe of a bendway weir
MVR_{Toe}	maximum velocity ratio at the toe of a bendway weir
n_w	apparent roughness with bendway weirs
R^2	coefficient of determination
ν_w	kinematic viscosity and
u_w^*	shear velocity with bendway weirs.

ACKNOWLEDGEMENTS

The authors acknowledge the USBR for the funding to undertake this study. The authors thank Chris Myrick and everyone at the Colorado State University Foothills Fisheries Laboratory for reviewing previous versions of the manuscript.

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