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BENDWAY WEIRS: COULD THEY CREATE HABITAT FOR THE ENDANGERED RIO GRANDE SILVERY MINNOW

KRISTOPH-DIETRICH KINZLI[a,b]* and CHRISTOPHER A MYRICK[b]

[a] *Civil and Environmental Engineering, Colorado State University, 1372 Campus Delivery, Fort Collins, Colorado 80523, USA*
[b] *Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, Colorado, USA*

ABSTRACT

Rehabilitation of the Middle Rio Grande in central New Mexico has become necessary to mitigate the effects of over a century of water and land development. The primary driving force behind rehabilitation efforts is the federally endangered Rio Grande silvery minnow (*Hybognathus amarus*). Bendway weirs, erosion control and channel-stabilization structures placed transverse to the channel flow, have been used to prevent river migration while enhancing aquatic habitat. Habitat improvement plans on the Middle Rio Grande include the installation of bendway weirs, but the potential benefits of these structures for Rio Grande silvery minnow are unknown. We conducted a theoretical study on the flow conditions created by bendway weirs to determine if it is possible to create physical habitat for Rio Grande silvery minnow while simultaneously protecting the riverbank. Our study suggested that bendway weir installation could lead to the reduction of downstream displacement of Rio Grande silvery minnow eggs, the creation of Rio Grande silvery minnow feeding and refugia habitat, and the creation of drought or low flow habitat through scour hole formation. We also noted that the weirs could also serve as potential habitat for predators, and suggest further studies to better quantify the possible role of bendway weir installation. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: Rio Grande silvery minnow; bendway weirs; fish habitats; stream improvement; river rehabilitation,

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INTRODUCTION

Throughout recent history, the demands that humans place on rivers and river systems have increased exponentially (Grigg, 1996). Due to increasing demands, water resources have been over-allocated, and river ecosystems have been permanently altered, often to the detriment of fish and wildlife. The Middle Rio Grande, located in central New Mexico, is a prime example of a river that has been significantly modified by human impacts (Oad *et al*., 2009).

The Middle Rio Grande Valley (Figure 1) runs north to south through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 282 km (175 mi). The cities of Albuquerque, Rio Rancho and Belen, along with several smaller communities (with a total population of 690 000) are located in or adjacent to the Middle Rio Grande Valley (USCB, 2000). Significant alterations to the hydrology of the Rio Grande began in the 1500s with the arrival of Spanish settlers and continue to this day (Scurlock, 1998). Changes initiated on the Rio Grande through human alteration have had wide-reaching negative effects on the aquatic ecosystem and its fauna, including some of the endemic fishes, such as the Rio Grande silvery minnow (*Hybognathus amarus*).

The decline in native fish species in the Rio Grande has been well documented, and is directly linked to human influences. Historically, there were 27 native fishes in the New Mexico section of the Rio Grande (Cowley, 2006). Currently 45 species of fish are found, yet only 14 native species remain (Cowley, 2006). The Rio Grande silvery minnow is now the only extant pelagic spawning minnow in the river because the Rio Grande shiner (*Notropis jemezanus)* and speckled chub (*Macrhybopsis aestivalis)* have been extirpated (Cowley, 2006), and the bluntnosed shiner (*Notropis simus simus)* and phantom shiner (*Notropis orca)* are extinct (Cowley, 2006).

*Correspondence to: Kristoph-Dietrich Kinzli, Civil and Environmental Engineering, Colorado State University, 1372 Campus Delivery, Fort Collins, CO 80523, USA. E-mail: kkinzli@engr.colostate.edu

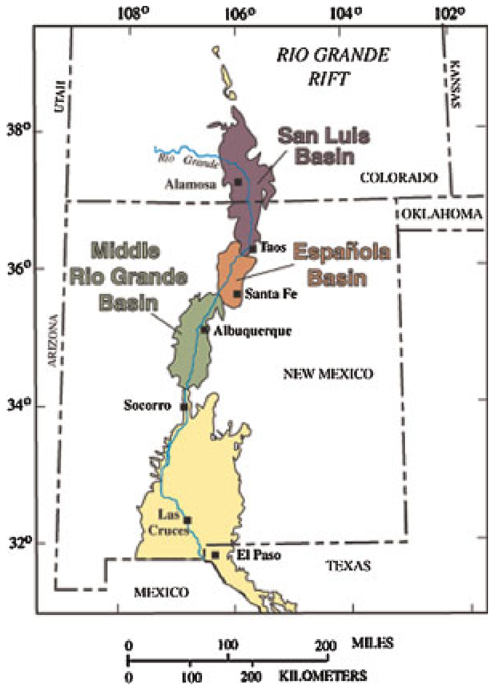

Figure 1. The middle Rio Grande River valley and surrounding basins (USGS, 2008). This figure is available in colour online at www.interscience.wiley.com/journal/rra

Historically the Rio Grande silvery minnow thrived in 3970 km (2465 mi) of rivers in New Mexico and Texas. Today the Rio Grande silvery minnow has been extirpated from 95% of its historical range and it only exists in the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir (Propst *et al*., 1987; Bestgen and Platania, 1991; Edwards and Contreras-Balderas, 1991; USFWS, 2003a). Due to the extreme decline of the Rio Grande silvery minnow it was classified as a Federal Endangered Species in 1994 (Federal Register, 2002).

The Rio Grande silvery minnow is one of seven species in the genus *Hybognathus* found in the United States (Bestgen and Propst, 1996). The onset of Rio Grande silvery minnow spawning coincides with increased stream flow from spring runoff (Bestgen and Propst, 1996). Spawning involves broadcast fertilization with each female laying between 1000 and 10 000 eggs over a period of 8 h (Bestgen and Propst, 1996). The eggs are semi-buoyant, expand as water is absorbed, and drift downstream in the water column until they hatch 24–48 h later (Bestgen and Propst, 1996; Platania and Altenbach, 1998). Larval and juvenile silvery minnows prefer low velocity habitats (Dudley and Platania, 2007). Low velocity habitats provide areas where drifting algae, organic matter and aquatic organisms collect and provide a critical food source for juvenile Rio Grande silvery minnow (Tetra Tech, 2004). Habitats utilized by adult Rio Grande silvery minnow are mostly areas such as eddies, pools, debris piles, backwaters and side channels (USFWS, 2003a). Rio Grande silvery minnow favour these areas for their low velocity and high rates of primary productivity. Rio Grande silvery minnows prefer to use habitat with moderate depth (15–40 cm) and low water velocity (4–9 cm/s) with silt or sand substrates (Propst *et al*., 1985; Sublette *et al*., 1990; Bestgen and Platania, 1991; Dudley and Platania, 1997; Wetzel and Likens, 2000). Rio Grande silvery minnow prefer mud, silt and sand substrates based on habitat and diet analysis of 1874 specimens (Cowley *et al*., 2006) and are opportunistic omnivores (Magaña, 2007). Shirey (2004) found that Rio Grande silvery minnow feed mainly on diatoms in nutrient-rich areas, along with detritus, pine pollen, cyanobacteria and algae. Larval and adult minnows have similar diets, but it is believed that algae are crucial during early life stages (Tetra Tech, 2004).

Factors linked to the decline of the Rio Grande silvery minnow include habitat modifications, altered flow regimes resulting from dam operations, periodic drying of the river, non-native fishes, hybridization and disruption of egg dispersal (Bestgen *et al*., 1989; Bestgen and Platania, 1990; Bestgen and Platania, 1991; Platania, 1991;

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Cook *et al*., 1992; Bestgen and Propst, 1996; Platania and Altenbach, 1998; Dudley and Platania, 2007). According to the United States Fish and Wildlife Service, channelization of the Rio Grande and water management have resulted in a large reduction of suitable habitat for the Rio Grande silvery minnow (USFWS, 2003b). Additionally, conversion of the river to a floodway was extremely detrimental to the Rio Grande silvery minnow (Cowley, 2006). Altering river geomorphology to quickly pass floods disconnected the river from the floodplain and reduced the historically braided planform to a single thread channel. Elimination of side channels decreased structural complexity of the river and reduced low velocity habitats available for native fishes (Cowley, 2006). Additional habitat was lost when large woody debris was removed from the river, eliminating snags and debris piles that historically helped create backwater and eddy habitat.

A habitat restoration plan was developed by the Endangered Species Act Collaborative Program (Tetra Tech, 2004) as a template for improving habitat for Rio Grande silvery minnow. The overall goal of the habitat restoration plan is to increase habitat along the Middle Rio Grande and promote completion of Rio Grande silvery minnow life history (Cowley, 2006). Bendway weirs are one proposed habitat restoration option for the Middle Rio Grande. The weirs would be used to stabilize eroding meander bends encroaching on levees and infrastructure while hopefully creating habitat for the Rio Grande silvery minnow

Bendway weirs

Bendway weirs are linear jetty-like rock structures placed on the outside of meander bends protruding into the channel to redirect flow away from the outside bank (Figure 2; Derrick, 1999). The concept of bendway weirs was first conceived by Thomas J. Pokrefke Jr at the US Army Engineer Waterways Experiment Station for use in a physical movable-bed model of a 32 km (20 mi) reach of the Mississippi River (Derrick *et al.*, 1994). Bendway weirs are also referred to as spur dikes, jetties and groynes. Bendway weirs are constructed out of readily available native rock, in most cases the same material that is used for rip-rap. Bendway weirs are constructed of native materials that are easily obtainable; some investigators report that habitat is enhanced when rocks are placed perpendicular to the thalweg (Rapp, 1997). Slack water aquatic habitat is created in eddies formed behind weirs. Additionally, habitat is created when drop-offs form between the main thalweg and depositional areas between weirs. Low flow habitat is also created in the form of a scour hole, located at the tip of a weir; habitat for aquatic invertebrates is created between individual rocks on each weir (Knight and Cooper, 1991). When installed properly, bendway weirs are reported to decrease bank erosion while improving aquatic habitat through the creation of backwater eddies (Shields *et al*., 1998).

Bendway weirs have numerous ecological benefits to fish, macro and microinvertebrates. Studies show that bendway weirs enhance aquatic habitat by creating pools in unstable streams (Klingeman and Kehe, 1984: Schlosser, 1987). Bendway weirs create and maintain pools, and are reported to be more beneficial to aquatic habitat than traditional measures of bank protection such as rip-rap, jetty jacks, gabions or erosion control blocks (Knight and Cooper, 1991; Hildrew, 1996; Kuhnle *et al*., 1999; Shields *et al*., 2000; Kuhnle *et al*., 2002). Shields *et al*. (1998) documented significant increases in fish density, size, species diversity and overall biomass in an

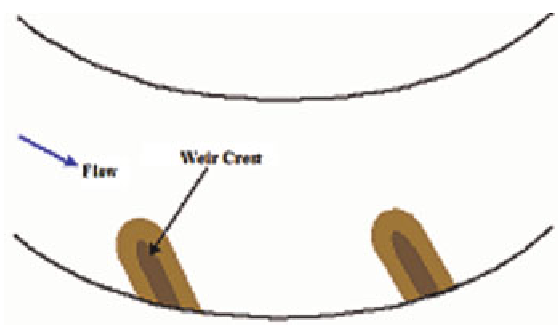

Figure 2. Schematic of bendway weirs placed in a meander bend. This figure is available in colour online at www.interscience.wiley.com/journal/rra

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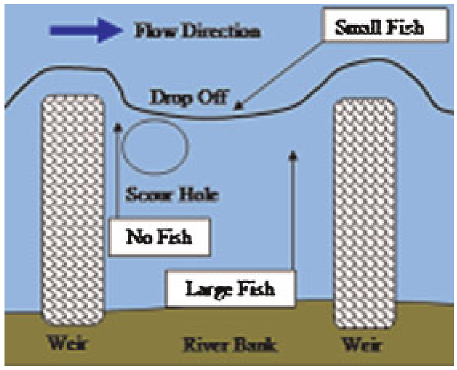

Figure 3. Fish holding locations in bendway weir fields (adapted from Zeidler 1999). This figure is available in colour online at www.interscience.wiley.com/journal/rra

incised stream (Goodwin Creek, Mississippi) following the installation of bendway weirs, concurrent with a 24% increase in stable bank length and the establishment of a bed equilibrium condition after 2 years. Davinroy *et al*. (1998), found that areas on the Mississippi River stabilized with bendway weirs yielded anywhere from 2 to 13 times as many fish compared to similar sites using other types of bank protection. Unique currents produced by bendway weir fields create conditions that attract large numbers of fish (Zeidler, 1999). Observations by sport anglers on the Rhine River, Germany, suggest that weir fields have higher densities of fish than other areas of the river, thus making them popular areas for angling. Anglers have also noted that large colonies of freshwater mussels have attached themselves to the bendway weirs and provide forage for fish. Fish also congregate at drop-offs created by the main current between weirs.

Fish distribution in a bendway weir field has also been reported to be size dependent (Figure 3). Zeidler (1999) reported that large fish and the greatest density of fish in weir fields are found near the toe of the downstream weir (Figure 3). Smaller fish and smaller densities of fish were observed between the two weirs at the drop-off created by the current interface. During normal flow conditions, no fish were observed in the scour hole directly downstream of the upstream weir (Zeidler, 1999). The scour hole created by upstream weirs creates suitable fish habitat during low-flow conditions, but fish favour other locations during normal flow regimes. In 1997, the US Army Corps of Engineers (Keevin *et al*., 2002) surveyed fish populations in bendway weir fields on the Mississippi River near St. Louis, MO, to test the assumption that fish habitat was improved. The survey recorded 217 fish, double the amount of fish found in a simple meander without bendway weirs (Rapp, 1997; Keevin *et al*., 2002). Another study conducted on the Mississippi River in 1997 revealed that bendway weir substrate provided better invertebrate habitat compared to a homogenous sand bed substrate (Ecological Specialists Inc., 1997). Both taxonomic richness and diversity were higher at Price's Bend, a bendwith weirs, than at Thompson's bend, a bend without weirs (Ecological Specialists Inc., 1997). The authors contend that since completion of tests in 1997, bendway weirs have become one of the most ecologically beneficial choices in erosion control (Ecological Specialists Inc., 1997).

The studies completed to date highlight some of the ecological and hydraulic benefits of bendway weirs, but they also have some drawbacks. One drawback is the formation of eddies between individual structures that results in unpredictable velocities due to variations in weir length, angle and spacing. Field observations have demonstrated that eddies can cause outer bank degradation and scalloping between weirs and scour at the tip of the weirs (Derrick, 1999). Past and present projects incorporating bendway weirs for bank stabilization have relied mostly on experience and engineering judgment. Lack of design methods for prediction of eddy velocities has resulted in failure of several bendway weir projects (Finley *et al*., 2001).

METHODS

Through recent research, a design methodology to predict post-installation velocities in bendway weir fields was developed at Colorado State University (Kinzli and Thornton, in press). Four predictive equations were

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developed through laboratory modelling of the Middle Rio Grande (Kinzli and Thornton, in press). The equations allow for the prediction of post-installation velocities in bendway weir fields based on weir design variables such as weir length, weir angle and weir spacing. The four equations allow the prediction of the maximum velocity in eddies, the maximum difference velocity in eddies, the maximum velocity at the toe of bendway weirs and the maximum velocity one foot out from the toe (Kinzli and Thornton, in press). The equations allow the calculation of a velocity ratio that represents to what degree weirs will change velocities from the pre-weir condition. A detailed description of the model study, equation development and design procedure can be found in (Kinzli and Thornton, in press) and in (Kinzli, 2005). These equations allow engineers and fisheries biologists to quantify local and between weir scour and the creation of velocity specific habitat.

The equations are presented here along with a design example that focuses on the Middle Rio Grande. Further detail and clarification can be found in (Kinzli and Thornton, in press).

Maximum Eddy velocity ratio (MEVR)

$$\mathrm{MEVR} = e^{-38.1}\frac{L_{\mathrm{cw}}^{2.32}A_{\mathrm{w}}^{.513}L_{\mathrm{proj,w}}^{14.044}}{L_{\mathrm{proj,cw}}^{15}\nu_{\mathrm{w}}^{2.39}u_{\mathrm{w}}^{*2.39}} \tag{1}$$

where L_{cw} is the length of the weir crest measured along centreline,

A_{w} is the projected weir area, $L_{\mathrm{proj,w}}$ is the projected length of weir to cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow, $L_{\mathrm{proj,cw}}$ is the projected length of weir crest to a cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow, ν_{w} is the kinematic viscosity and u_{w}^{*} is the shear velocity with weirs present.

Maximum difference Eddy velocity ratio (MDEVR)

$$\mathrm{MDEVR} = e^{-1.20}\frac{A_{\mathrm{c}}^{.225}L_{\mathrm{arc}}^{.526}}{L_{\mathrm{proj,w}}^{1.502}} \tag{2}$$

where A_{c} is the cross sectional flow area, L_{arc} is the arc length between weirs along design waterline and $L_{\mathrm{proj,w}}$ is the projected length of weir to cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow.

Maximum velocity ratio toe (MVR_{Toe})

$$\mathrm{MVR}_{\mathrm{Toe}} = e^{-.475}\frac{L_{\mathrm{proj,cw}}^{.916}}{n_{\mathrm{w}}^{.127}u_{\mathrm{w}}^{*\,.127}L_{\mathrm{proj,w}}^{.8313}} \tag{3}$$

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

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Maximum velocity ratio 1 foot ($MVR_{1\ foot}$)

$$\mathrm{MVR}_{1\mathrm{foot}} = e^{-1.72} \frac{L_{\mathrm{proj,cw}}^{.417}}{n_{\mathrm{w}}^{.293} u_{\mathrm{w}}^{*\ .293} L_{\mathrm{proj,w}}^{.2216}} \tag{4}$$

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

RESULTS

Detailed design example

Consider a meander bend in the Middle Rio Grande that is migrating roughly 2 ft (0.60 m) per year and is threatening adjacent levees, farmland and infrastructure. The meander migration is to be halted using bendway weirs due to habitat concerns for the Rio Grande silvery minnow. The design flow rate for the Middle Rio Grande is 6000 cfs (170 cms) and was chosen because it represents the bankfull discharge of the Rio Grande. The channel through the migrating bend has a bottom width of 140 ft (42.6 m) and can be assumed to have a trapezoidal geometry with side slopes of 3:1 (H/V). Flow depth for the design flow was determined to be 5 ft (1.5 m). Bedslope of the Middle Rio Grande at this location is 0.000863 ft/ft (m/m). River geometry for the design example was determined from GIS data and site visits that were conducted to develop the hydraulic model (Kinzli and Thornton, in press). Weir height was set to 0.5 of the flow depth of the design flow according to guidelines set forth by Lagasse *et al*. (1997). Weirs were assumed to occupy 15% of the channel width in length, angled upstream 60 degrees and spaced using a ratio of 4.1. The slope from the tip of the crest to the toe of the weir was be 1 ft/ft (m/m). Equations 1 and 2 were used to determine eddy velocities after installation and Equations 3 and 4 to determine velocities at the toe and tip of the weirs after installation. *Caution:* although metric units are included in this example only English units should be used to determine the velocity ratios. If metric velocities are needed the final velocities can be converted from English units

Step 1. Establish a design flow rate:

Design flow for the Middle Rio Grande is 6000 cfs (170 cms)

Step 2. Determine the maximum pre-weir centreline velocity:

Flow measurements indicate that the maximum pre-weir velocity at the design flow is 7.7 ft/s (2.3 m/s)

Step 3. Determine the parameters of the design equations:

L_{w} = Length of the weir = 164 ft (49.98 m) × 0.15 = 24.6 ft (7.5 m)
$L_{\mathrm{proj,w}}$ = Length of the weir projected on the perpendicular transect = Cos 30 × 24.6 ft (7.5 m) = 21.3 ft (6.5 m)
L_{cw} = Length of the weir crest = 24.6 ft (7.5 m)−2.5 ft (0.76 m) = 22.1 ft (6.74 m)
$L_{\mathrm{proj,cw}}$ = Cos 30 × 22.1 ft (6.74 m) = 19.14 ft (5.83 m)
A_{w} = Area of the weir = 49 ft^2 (4.55 m^2)
A_{c} = Area of the channel at design flow before weirs = 775 ft^2 (72 m^2)
L_{arc} = Spacing Ratio × $L_{\mathrm{proj,w}}$ = 4.1 × 21.3 ft (6.5 m) = 87.33 ft (26.6 m)
v_{w} = Kinematic viscosity of water at 15.5 C (60 F) = 0.0000122 ft^2/s (.000001134 m^2/s)
P = Wetted perimeter with weirs = 179.14 ft (54.60 m)
R = Hydraulic radius with weirs = A/P = (Ac-Aw)/P = 4.05 ft (1.23 m)
$U_{\mathrm{w}}^{*} = \sqrt{gRS_0}$ = Shear velocity with weirs present = 0.335 ft/s (0.102 m/s)

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n_w = Apparent roughness due to the weir field = 0.0134.

Step 4. Find MEVR using Equation 1:

$$\mathrm{MEVR} = e^{-38.1}\frac{L_{cw}^{2.32}A_w^{.513}L_{proj,w}^{14.044}}{L_{proj,cw}^{15}\nu_w^{2.39}u_w^{*2.39}}$$

Plug in values

$$\mathrm{MEVR} = e^{-38.1}\frac{(22.1\mathrm{ft})^{2.32}(49\mathrm{ft}^2)^{.513}(21.3\mathrm{ft})^{14.044}}{(19.14\mathrm{ft})^{15}(.0000122\mathrm{ft}^2/\mathrm{s})^{2.39}(.335\mathrm{ft/s})^{2.39}}$$

MEVR = 0.55

Step 5. Find MDEVR using Equation 2:

$$\mathrm{MDEVR} = e^{-1.20}\frac{A_c^{.225}L_{arc}^{.526}}{L_{proj,w}^{1.502}}$$

Plug in values

$$\mathrm{MDEVR} = e^{-1.20}\frac{(775\mathrm{ft}^2)^{.225}(87.34\mathrm{ft})^{.526}}{(21.3\mathrm{ft})^{1.502}}$$

MDEVR = 0.14

Step 5. Find $\mathrm{MVR}_{\mathrm{Toe}}$ using Equation 3

$$\mathrm{MVR}_{\mathrm{Toe}} = e^{-.475}\frac{L_{proj,cw}^{.916}}{n_w^{.127}u_w^{*\,.127}L_{proj,w}^{.8313}}$$

Plug in values

$$\mathrm{MVR}_{\mathrm{Toe}} = e^{-.475}\frac{(19.14\mathrm{ft})^{.916}}{(.0134)^{.127}(.335\mathrm{ft/s})^{.127}(21.3\mathrm{ft})^{.8313}}$$

MVRToe = 1.45

Step 6. Find $\mathrm{MVR}_{\mathrm{1foot}}$ foot using Equation 4:

$$\mathrm{MVR}_{\mathrm{1foot}} = e^{-1.72}\frac{L_{proj,cw}^{.417}}{n_w^{.293}u_w^{*\,.293}L_{proj,w}^{.2216}}$$

Plug in values

$$\mathrm{MVR}_{\mathrm{1foot}} = e^{-1.72}\frac{(19.14\mathrm{ft})^{.417}}{(.0134)^{.293}(.335\mathrm{ft/s})^{.293}(21.3\mathrm{ft})^{.2216}}$$

MVR1foot = 1.51

Step 7. Establish channel velocities from MEVR, MDEVR, $\mathrm{MVR}_{\mathrm{Toe}}$ and $\mathrm{MVR}_{\mathrm{1foot}}$

To establish channel velocities after weir installation multiply the found ratio by the pre-weir centreline velocity of 7.7 ft/s (2.35 m/s)

Maximum Eddy Velocity = MEVR × 7.7 ft/s = 0.55 × 7.7 ft/s = 4.23 ft/s (1.29 m/s).
Maximum Difference Eddy Velocity = MDEVR × 7.7 ft/s = 0.14 × 7.7 ft/s = 1.08 ft/s (0.33 m/s).
Maximum Velocity Toe = $\mathrm{MVR}_{\mathrm{Toe}}$ × 7.7 ft/s = 1.45 × 7.7 ft/s = 11.16 ft/s (3.4 m/s).
Maximum Velocity 1 Foot = $\mathrm{MVR}_{\mathrm{1foot}}$ × 7.7 ft/s = 1.51 × 7.7 ft/s = 11.62 ft/s (3.54 m/s).

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Construction of 15% length weirs, angled upstream by 60 degrees and set at 0.5 of the depth of the 6000 cfs (170 cm) design flow will result in several changes in channel velocity. Pre-weir maximum channel velocity was 7.7 ft/s (2.35 m/s). Maximum eddy velocity and maximum difference eddy velocity with weirs will be 4.23 ft/s (1.29 m/s) and 1.08 ft/s (0.33 m/s) respectively. These velocities represent the maximum velocities that will be found in the eddies. Due to the swirling nature of the created eddies a significant amount of zero velocity habitat will be created. Velocities associated with scour at the tip of the weirs will be higher than the pre-weir velocity of 7.7 ft/s (2.35 m/s). Toe velocity will be 11.16 ft/s (3.4 m/s) and velocity one foot from the toe will be 11.62 ft/s (3.54 m/s). The increased velocities will require a rock size of 14 inch (35 cm) diameter for weir construction using the ASCE rip-rap sizing equation. Fourteen inch diameter rock will provide for weir toe stability at the design flow of 6000 cfs (170 cm).

Bendway weir data collected during Kinzli and Thornton's (in press) laboratory study confirmed the creation of slack water habitat. Using the program Surfer™, velocity plots show that during pre-weir conditions only 2% of the available habitat falls below the 9 cm/s (0.3 ft/s) velocity preferred by the Rio Grande silvery minnow (Figure 4) at bankfull flow conditions. With the installation of bendway weirs low velocity habitat is increased to be 32% of total habitat (Figure 5) for the same flow conditions. Although the weirs in the downstream bend increased the maximum observed velocity due to constriction these velocities did not exceed the 120 cm/s (3.9 ft/s) critical swimming velocity reported for the Rio Grande silvery minnow. These results of the modelling study suggest that the design example would increase low velocity habitat for the meander bend in question by approximately 30%.

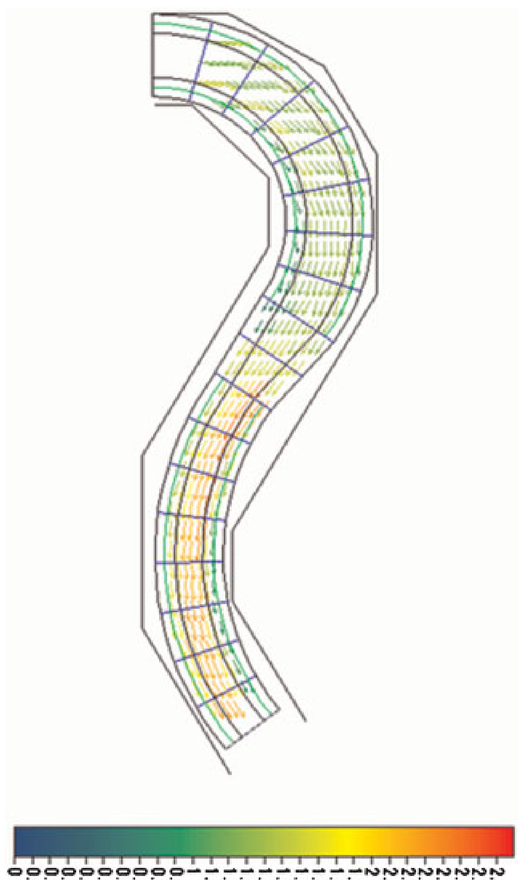

Figure 4. Surfer Plot™ showing velocity (ft/sec) in the model before the installation of bendway weirs. Velocity preferred by the Rio Grande silvery minnow represents only 2% of the available habitat. This figure is available in colour online at www.interscience.wiley.com/journal/rra

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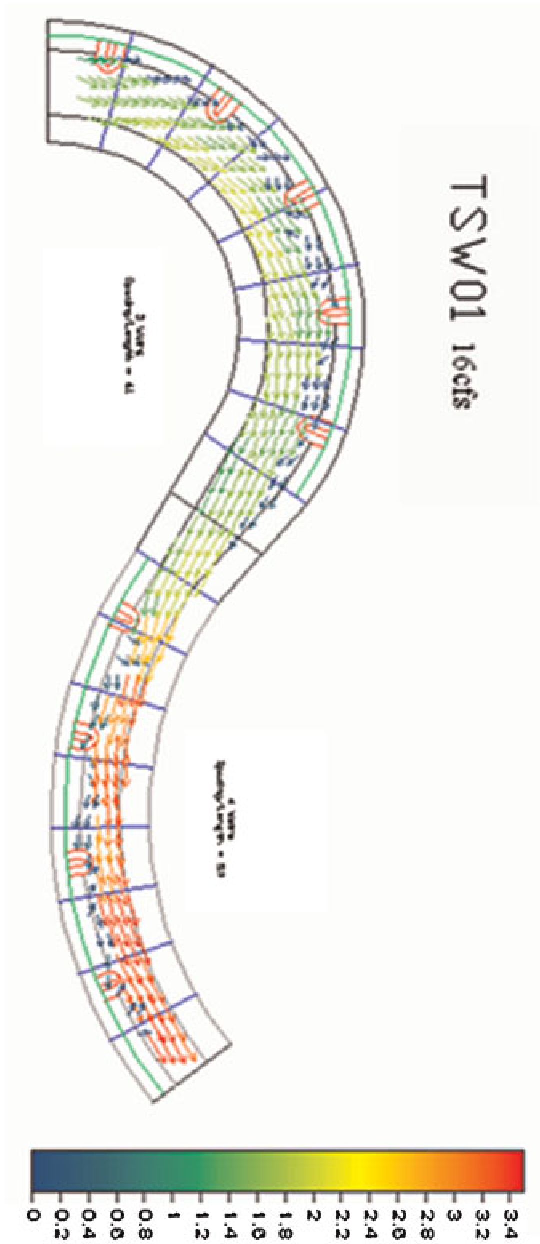

Figure 5. Surfer Plot™ showing velocity (ft/sec) in the model after the installation of bendway weirs. Velocity preferred by the Rio Grande silvery minnow represents 32% of the available habitat. This figure is available in colour online at www.interscience.wiley.com/journal/rra

DISCUSSION

The Middle Rio Grande has become one of the most intensely managed rivers in the United States, having been reduced to a high velocity, single thread channel that does not provide appropriate habitat for Rio Grande silvery minnow (K.R. Bestgen, personal communication). Bendway weirs, if properly designed and installed, are useful tools for several habitat restoration strategies (Tetra Tech, 2004) including;

(1) Establishing channel conditions that reduce downstream egg displacement (Tetra Tech, 2004).
(2) Establishing suitable feeding habitat and cover for juveniles and adults (Tetra Tech, 2004).

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(3) Creating local deepwater habitat that will provide perennially wetted pools during drought (Tetra Tech, 2004; Cowley, 2006).

The following sections address how bendway weirs can be used to achieve the three major habitat restoration goals.

Reducing downstream egg displacement

Increased egg drift into unsuitable habitat such as reservoirs has negative effects for pelagophils (Dudley and Platania, 2007). Pelagic minnows such has the Rio Grande silvery minnow are short-lived species and are threatened by successive reproductive failures from increased egg drift (Dudley and Platania, 2007). In the Middle Rio Grande this is a significant concern because the downstream reach ends in Elephant Butte Reservoir. Bendway weirs could benefit Rio Grande silvery minnow reproduction by reducing the rate of downstream egg drift. Additionally, weirs would increase local egg retention and reduce the effects of habitat fragmentation caused by diversion dams. Studies on the Pecos River on the related plains minnow (*Hybognathus placitus*) demonstrated that young occur mostly in downstream reaches (Hoagstrom and Brooks, 2005) and adults are found in middle and upstream reaches. Using bendway weirs to improve egg retention could allow more juvenile fish to be retained in local stream reaches and perpetuate populations through fragmented habitat reaches. Egg retention in reaches with bendway weirs would be facilitated by increasing channel complexity and providing backwater and eddy habitat. Studies have shown geomorphic complexity of the riverine environments and reduced velocities limit downstream transport of drifting eggs in numerous fish families including Cyprinidae, Catostomidae, Clupeidae, Fundulidae, Poeciliidae and Percidae (Lancaster and Hildrew, 1993; Turner *et al*. 1994; Scheidegger and Bain, 1995; Winterbottom *et al*. 1997; Reckendorfer *et al*., 1999; Bond *et al*., 2000). Results from a study on the Pecos River by Medley *et al*. (2007) indicate that drifting egg retention is greatest in complex channel reaches (4.5%/km) as compared to 0.6%/km for narrow, deep channelized reaches. In another study, bankline embayments that have a similar geomorphic function to bendway weirs were shown to reduce the downstream drift of artificial eggs (Porter and Massong, 2002). Drifting egg transport on the Rio Grande is 138.7 km during sustained river flows (Dudley and Platania, 2007), which results in eggs travelling as far as Elephant Butte Reservoir. Studies suggest that drifting distance could be reduced through habitat modification by increasing channel complexity (Dudley and Platania, 2007). Bendway weirs would enhance this type of complexity in localized reaches. Reducing downstream egg drift using bendway weirs to increase channel complexity would reduce egg and larval mortality that occurs when eggs are washed into Elephant Butte Reservoir.

Creating feeding and refuge habitat for juveniles and adults

Bendway weirs create habitat for developing eggs, larvae and adults. In channel reaches currently dominated by gravel and cobble substrate, bendway weirs would induce sedimentation of finer particles and create adult Rio Grande silvery minnow habitat. Through sedimentation, sections between weirs would revert from gravel and cobble substrate to a sand and silt bed preferred by the Rio Grande silvery minnow. Large influxes of sediment from tributaries and arroyos would provide the required sediment. In the design example, a section of the Rio Grande lacking weirs with an instream velocity of 2.35 m/s (7.7 ft/s) would result in deposition of particles between 10 and 100 mm diameter. With the presence of weirs that create a maximum difference velocity of 0.33 m (1.08 ft/s), deposition of particles in the 0.1–1 mm size range would be expected. Shoreline habitat would also be increased through the placement of bendway weirs. The nature of bendway weir layouts would greatly increase areas where velocities mimic shoreline habitat along the length of weirs. Platania and Dudley (2003) collected fish along shoreline habitat indicating Rio Grande silvery minnow prefer this type of habitat. Additionally, rock substrate that composes weirs could provide refugia and cover. Based on laboratory experiments, Rio Grande silvery minnow were observed utilizing large substrate such as cobble when it was available (K.R. Bestgen, personal communication), which indicates that rocks used for bendway weir construction could provide structural refugia.

The main benefit bendway weirs would have for the Rio Grande silvery minnow would be the creation of eddies, pools and backwater habitat. The link between Rio Grande silvery minnow and eddy and pool habitat is well documented. In a study of eight cyprinid species on the Pecos River, including the congeneric plains minnow

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(*H. placitus*), cyprinids utilized habitat consisting of backwaters, eddies and slackwaters almost exclusively although it only represented 9% of available habitat (Kehmeier *et al*., 2007). Another study found that Rio Grande silvery minnow use rare habitats such as eddies formed by debris piles, pools and backwaters (Platania and Dudley, 2003). In a study on large woody debris for the New Mexico Interstate Stream Commission it was found that habitats created by large woody debris reduced channel velocities by 26% (SWCA, 2008). It was also found that when Rio Grande silvery minnow were observed they were more abundant at sites with large woody debris (SWCA, 2008). Bendway weirs would significantly increase the amount of eddy and pool habitat by creating eddy habitat between each set of weirs. Additionally, heterogeneity of available habitat would be increased through the placement of weirs.

Through the creation of eddies, bendway weirs would also result in deposition of organic material which provides a food source for the Rio Grande silvery minnow (D. Cowley, personal communication). This has been observed behind snag logs and other slack water areas along the river. Another important benefit that bendway weirs would have is the creation of nursery habitat. The complexity of habitat and structural refugia is important for juveniles (Schlosser, 1991) and is important for the survival of larval life stages of cyprinids in the Rio Grande (Pease *et al*., 2006). This type of habitat is limited in the Middle Rio Grande and the velocity reduction from bendway weirs would increase the amount of nursery habitat available.

Drought habitat creation through scour hole

The use of bendway weirs could also provide refuge habitat in times of drought. Long-term persistence of the species requires perennially wetted habitat (Cowley *et al*., 2003), but the Middle Rio Grande is a perched river and subject to drying. Although a critical minimum flow has been designated for the Rio Grande silvery minnow, sections of the Rio Grande still go dry during drought. The Rio Grande at San Acacia dries during one out of 10 years (MEI, 2002) and substantial portions of the river went dry below San Acacia during 2002 and 2003 (Tetra Tech, 2004). Due to the nature of bendway weir installation, velocities at the tip of the weirs are increased over pre-weir channel velocities. The increased velocities at the tip of the weirs will result in the creation of a scour hole at the tip of each weir. Although no study has been done on the creation of scour holes using weirs it is hypothesized that scour holes will be of substantial size in the sand bed channel of the Rio Grande. Scour holes with substantial depth would provide refugia during drought and reduce the avian predation that is prevalent as the river dries. Additionally, scour holes with significant depth could intercept the groundwater table and allow for pools to persist for a longer period of time. Rio Grande silvery minnow have been shown to utilize scour holes; scour points below large woody debris and diversion dams can be filled with Rio Grande silvery minnow (K.R. Bestgen personnel communication). This suggests that weirs would indeed provide refugia during drought. Additionally, scour points at the tips of weirs would result in the congregation of Rio Grande silvery minnow, creating areas where salvage efforts could be focussed during dewatering events.

Overall benefits

The overall benefit bendway weirs would provide for the Rio Grande silvery minnow is in aiding the completion of its life history in an environment that has been significantly altered from the environment in which the minnow evolved. Promoting completion of the Rio Grande silvery minnow life history has been identified as crucial to the survival of the species (Cowley, 2006) and bendway weirs provide another tool for accomplishing this restoration goal.

Bendway weirs would also be beneficial in the Rio Grande because they exhibit many benefits over other forms of bank protection that are necessary to protect infrastructure and the human population along the river. First, bendway weirs address the goal of channel stabilization and simultaneously create aquatic habitat. Channel stabilization measures such as rip-rap, concrete and concrete blankets, gabions, erosion control fabrics, planted vegetation, Ajacks and reticulated erosion control blocks protect river banks but do not create as much in-channel aquatic habitat (Knight and Cooper, 1991). Second, bendway weirs are less expensive than continuous bank protection such as rip-rap and gabions (Watson, 2003). On the Missouri River bendway weirs deflected flow away from the eroding bank and project costs ranged from US$216 to $244 per foot of bankline, approximately half the cost of traditional designs (Lagrone and Remus, 1998).

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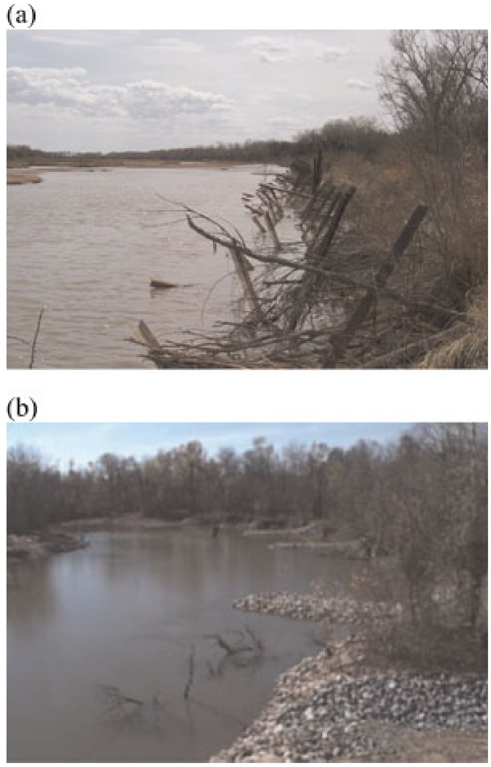

Figure 6. (a) Jetty Jacks along the Rio Grande River compared to (b) a bendway weir field (USFWS, 2008; Federal Highway Administration, 2008). This figure is available in colour online at www.interscience.wiley.com/journal/rra

Traditional bank protection measures such as rip-rap and Kellner Jetty Jacks also have the drawback of narrowing the channel, thus preventing overbank flooding (Tetra Tech, 2004). Over 115 000 Kellner Jetty Jacks were installed along the Rio Grande (Figure 6: Lagasse, 1980), and their removal without a suitable bank protection alternative has become impossible due to containment of the floodplain between levees. It is now necessary to prevent migration of the river when it encounters levees and infrastructure due to human interests. Bendway weirs offer a naturalized look (Figure 6) through the use of native rock and are inundated frequently which limits visibility. Bendway weirs would also protect significantly more bankline for a similar number of structures than Jetty Jacks.

Much success in habitat creation has been realized using snag logs that protrude from the bank into the flow. These structures are quite similar to bendway weirs but are limited in application. The relatively small size of the available logs leads to a small positive impact in a large channel; predictive flow and deposition equations are difficult to develop due to the variability in each snag log.

Possible drawbacks

Several questions regarding the use of the bendway weirs remain unanswered. First it remains to be determined if bendway weirs would be a financially feasible option in the Middle Rio Grande Valley. A detailed cost-benefit analysis should be completed wherein the cost of construction and maintenance is compared to the benefits of creating more Rio Grande silvery minnow habitat, and, potentially helping to stabilize the population in the Middle Rio Grande.

Another issue concerning the use of bendway weirs is their longevity. Traditionally bendway weirs have been installed on streams and rivers where the sediment balance is in equilibrium and degrading of the channel bed is

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minimal. The shifting and degrading nature of the current Rio Grande does not resemble an environment where weirs have been used in the past and therefore longevity concerns could arise. This issue could be addressed through a pilot study.

Bendway weirs could also have negative effects on the already highly impacted Rio Grande system. The alteration of channel velocities and sedimentation through the use of weir fields could lead to degradation downstream. The use of weirs could also alter the meander geometry that currently characterizes the Rio Grande planform. By stabilizing one bank, bendway weirs could channelize flow towards the opposite bank which might lead to erosion and a change in planform. The previously mentioned pilot study would also shed light on changes to channel planform. If it is observed that weirs do indeed cause erosion on the opposite channel banks weir angles could be reduced to be perpendicular to the flow (90 degree weirs) to prevent flow alignment towards opposite river banks.

Other concerns with bendway weirs focus on potentially negative effects they could have on the Rio Grande silvery minnow. Large predatory fish may use the eddy currents created by bendway weirs as ambush points from which they could attack unsuspecting minnows and other forage fish. On the Mississippi River, the main species inhabiting bendway weir fields are the gizzard shad (*Dorosoma cepedianum*; a prey species) and the predatory freshwater drum (*Aplodinotus grunniens)* and blue catfish *(Ictalurus furcatus)* (Keevin *et al*., 2002).

The potential predators on the Middle Rio Grande include channel catfish (*I. punctatus*), largemouth bass (*Micropterus salmoides*) and northern pike (*Esox lucius*). It does not appear gizzard shad and freshwater drum actively feed on the Rio Grande silvery minnow (Tetra Tech, 2004), but channel catfish could be a significant predator. Therefore, diet studies in the Middle Rio Grande should be completed to rule out catfish predation as the channel catfish are known to prey on Rio Grande silvery minnow (Tetra Tech, 2004). Northern pike and largemouth bass are ambush predators that should have limited impacts on the silvery minnow because of the turbid conditions in the main river channel.

In order to properly address the possibility of increased predation due to weirs a diet and habitat use study of predatory fish in the Middle Rio Grande should be completed. With data from a diet study it would become possible to determine the primary predators of Rio Grande silvery minnow and address whether these species would feed on minnows congregating in eddies created by bendway weirs. Such a study would also establish if overlap in habitat use does indeed occur. A telemetry study on the possible predators over a realistic range of flow would also indicate whether predators would favour weir fields as habitat.

There are additional factors that affect the Rio Grande silvery minnow in the altered Rio Grande that need to be addressed as part of the restoration process. These include nutrient availability, pollutants and increased salinity, endocrine disruption from wastewater treatment plant effluent, altered temperature regimes, flow pulse timing, food availability, reduced productivity in the Rio Grande and a steep decline in Rio Grande silvery minnow genetic diversity. (Bestgen and Platania, 1991; Cowley *et al*., 2003; Tetra Tech, 2003; Shirey, 2004; Cowley *et al*., 2005; Cowley, 2006; Cowley *et al*., 2006; Dudley and Platania, 2007; Magaña, 2007). Creating velocity-specific habitat by using bendway weirs as an engineered solution only addresses some of the habitat considerations and still represents an artificial solution for a highly-altered system. The above mentioned factors merit further examination to provide a clearer picture of challenges facing the Rio Grande silvery minnow.

CONCLUSIONS

The installation of bendway weirs is a habitat restoration option for the Middle Rio Grande that would stabilize eroding banks threatening infrastructure and concurrently create habitat for the endangered Rio Grande silvery minnow. Past and present projects on other river systems incorporating bendway weirs for bank stabilization and habitat enhancement have relied on experience and engineering judgment. Lack of design methodology for prediction of post-installation velocities has resulted in variable success of bendway weir projects. The four design equations presented here can be used to predict velocities within installed bendway weir fields. Two of the equations can be used to predict eddy velocities behind weirs and two can be used to predict velocities at the toe of weirs. These equations should only be used within the constraints outlined in Kinzli and Thornton (in press). Using the developed design equations, habitat beneficial to the endangered Rio Grande silvery minnow can be created

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while concurrently preventing erosion of levees and infrastructure. Additionally the weirs provide an aesthetically superior alternative to the Kellner Jetty Jacks currently installed along the entire Middle Rio Grande.

Bendway weirs have a demonstrated record in habitat creation; fish communities respond strongly to the placement of weir fields (Rapp, 1997; Davinroy *et al*., 1998; Shields *et al*., 1998; Keevin *et al*., 2002). The number of fish present, along with species diversity, and taxonomic richness is significantly higher in areas with bendway weirs (Ecological Specialists Inc., 1997; Shields *et al*., 1998), and weirs provide more diverse invertebrate habitat compared to the homogenous substrate of a sand bed. Hydroacoustic studies have found that bendway weirs can increase the total abundance of fish in degrading river reaches nearly two-fold (Kasual and Baker, 1996). The unique currents created by weir placement are favoured by fish (Zeidler, 1999) and bendway weirs have been considered by some to be the most ecologically beneficial choice in erosion control (Ecological Specialists Inc., 1997).

If bendway weirs are installed on the Rio Grande the Rio Grande silvery minnow would benefit in three distinct ways. First, weirs would reduce channel velocities in certain areas behind weirs. This would lead to increased egg transport time which should increase survival and maintain minnow populations through segmented river reaches. Second, bendway weirs would create low velocity habitat linked to the survival of the minnow. Currently most sections of the Rio Grande are characterized by a single channel with high velocities and low channel complexity. Weirs would create additional low velocity areas and the channel complexity necessary to maintain rearing and feeding habitat. Additionally, where appropriate, weirs could be installed to initiate the formation of side channels and increase the number of side channels in the river. Third, bendway weirs would provide for scour hole refugia during low flow events ensuring habitat availability during drought.

RECOMMENDATIONS

Before actual implementation of bendway weirs in sections of the Rio Grande can take place several studies should be conducted to field-validate the equations and habitat benefits described in this paper. First, a laboratory study should be conducted to examine the behaviour of Rio Grande silvery minnow in bendway weir fields. Of key importance would be defining how Rio Grande silvery minnow utilize created habitat. A laboratory setting would allow for controlled flow rates, light patterns and would allow for the use of cameras to track the movement and behaviour of Rio Grande silvery minnow in bendway weir fields. Predator introduction into the laboratory system could also be examined. With the introduction of a predator it could be ascertained whether weirs provide cover and refuge habitat or result in increased predation. The installation of bendway weirs in a laboratory setting would also provide the opportunity to examine egg drift and retention within weir fields.

Second, several bendway weir fields could be installed on the Rio Grande as a pilot project. This would allow for field monitoring and observation. Monitoring and observation in the field could consist of presence and absence studies and overall abundance studies. With the installation of bendway weirs on the Rio Grande it would also be possible to perform egg drift studies to determine what percentage of eggs are retained by bendway weirs and to what extent they reduce drifting distance. Egg drift studies could be conducted using gellan beads and the Moore egg collector that has successfully been used on the Rio Grande (Altenbach *et al*., 2000). Egg drift study techniques for small cyprinids in the Pecos River (Medley *et al*., 2007) could be applied to the main stem Rio Grande with weirs installed to determine their effect on egg drift.

In tandem with a monitoring and observation study a predatory diet study should be conducted on the Rio Grande. A study of this nature would involve sampling piscivorous fish that are suspected of preying on the Rio Grande silvery minnow. The diet composition of the predatory fish in the Rio Grande could be determined from stomach analyses. Diet composition analyses would identify predatory fish that are the greatest threat to the Rio Grande silvery minnow and could result in management plans to limit these predatory fish.

Another aspect of bendway weirs that needs to be examined through field experiments is the sedimentation and scour that occurs in weir fields. The equations that were developed were developed under laboratory conditions using a rigid bed and therefore will require field calibration to examine sedimentation patterns. Laboratory tests using a live sand bed and bendway weirs are in progress at Colorado State University (Walker *et al*., 2007). Examining the effects of a varied hydrograph on the function of the weirs would also be a significant contribution of a field study

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To fully implement weirs in the Rio Grande a thorough field evaluation needs to be completed to calibrate the developed equations and validate the ideas set forth in this paper regarding habitat use by the Rio Grande silvery minnow.

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