RECLAMATION
Managing Water in the West

Middle Rio Grande River Maintenance Program Comprehensive Plan and Guide

Appendix A: Middle Rio Grande Maintenance and Restoration Methods

Middle Rio Grande Project, New Mexico
Upper Colorado Region

U.S. Department of the Interior
Bureau of Reclamation

April 2012

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Appendix A: Middle Rio Grande Maintenance and Restoration Methods

Middle Rio Grande Project, New Mexico
Upper Colorado Region

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Acronyms and Abbreviations

cfs	cubic feet per second
CSU	Colorado State University
ESA	Endangered Species Act.
FEMA	Federal Emergency Management Agency
FES	fabric encapsulated soil
GIS	geographic information system
GRF	gradient restoration facilities
Interior	U.S. Department of the Interior
LFCC	Low Flow Conveyance Channel
LWD	large woody debris
Reclamation	Bureau of Reclamation
Rc	the centerline radius of curvature
RGSM	Rio Grande silvery minnow
RM	river mile
SRH-1D	Sedimentation and River Hydraulics One-Dimensional Model
SRH-2D	Sedimentation and River Hydraulics Two-Dimensional Model
SWFL	Southwestern willow flycatcher
UK	United Kingdom
USACE	U.S. Army Corps of Engineers
W	channel top width
WDFW	Washington Department of Fish and Wildlife

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Tables and Figure

Chapter 1. Introduction

This appendix contains a description of the potential channel maintenance and restoration methods that are applicable to the Middle Rio Grande. The available publications have been reviewed and combined with experience to develop a list of potential maintenance methods. Those methods that are most applicable to the geomorphic characteristics of the Middle Rio Grande and are consistent with project authorization have been selected for inclusion in this document.

1.1 General Description of Methods

Many channel stabilization, dredging, and channel restoration methods are used on rivers for multiple purposes. An extensive, but not exhaustive, literature review has been conducted to identify a suite of methods found in this appendix. The methods that apply to the Middle Rio Grande are included in this river maintenance plan. For each method, there is a description of the general range of application, method objectives and benefits, features, common modes and failures, common countermeasures if needed, advantages, disadvantages, geomorphic response, ecological benefits and effects, requirements, level of reliability, potential construction issues, design criteria, peak flow criteria, durability, and project life.

In this chapter, the terms “maintenance” or “river maintenance” include river restoration/rehabilitation, dredging, bank stabilization, and other methods. The applicable methods for the Middle Rio Grande have been organized into groups of methods (categories) with similar features and objectives as follows:

- Infrastructure relocation or setback
- Channel modification
- Bank protection/stabilization
- Cross channel (river spanning) features
- Conservation easements
- Change sediment supply
- Habitat improvements and mitigation

Multiple methods can be used within each category. It is often advisable to combine methods at a single project site to meet multiple objectives as discussed in the main report in section 3.4. The development of new or revised methods likely will occur in the future. Reviewing new or revised methods and updating method summaries on a periodic basis are advisable so that existing and newer methods receive full consideration during the planning and design phases. A systematic geomorphic and engineering analysis at a reach scale should be undertaken prior to project planning, design, and implementation. This will help reduce the likelihood of project failure or excessive ongoing maintenance costs. No single method or method combination is applicable in all situations. Although there is little guidance available for method selection (including combinations of methods), the selection process should include an evaluation of geomorphic response, engineering effectiveness, economics (cost), and habitat benefits and effects. The suitability and effectiveness of a given method are a function of the inherent properties of the method and the physical characteristics of each reach and/or site.

1.2 Ranking and Ranking Criteria

Ranking (see below) is assigned to each method, based upon performance, reliability of design criteria, the general amount of case studies, and the geomorphic response. Those methods ranked Level 3 are well established, widely used, have well documented performance, reliable design criteria, and known geomorphic response.

A brief description of the ranking methodology follows. The remainder of this document is organized by river maintenance categories and methods as identified and reviewed by the Middle Rio Grande River Maintenance Plan preparation team members at several team meetings. Ranking of whether the local response is well known, has limited information, or little information has been made using the following definition of levels:

- **Level 3.** Well established, widely used, well documented performance, reliable design criteria, numerous case studies, and well known local geomorphic response that is well documented.

- **Level 2.** Often used but lacks the level of detail, quality of information, and reliability that characterize Level 1; little or no long-term monitoring; limited design criteria; limited knowledge about the local geomorphic response; and limited documentation.

- **Level 1.** Emerging promising technique does not have a track record, field or lab data, or design or test data; few literature citations; little is known about local geomorphic response, and little documentation.

The advantages and disadvantages and general applicability for each method are described in the rest of this appendix.

1.3 Biological/Ecological Response and Geomorphic Processes and River Response to Method Application

This appendix contains information on potential geomorphic responses for the application of each method, an assessment of the level of documentation, and a determination of how well the geomorphic response is understood. If geomorphic response has not been documented or documentation could not be located, professional experience and judgment have been used to develop a conceptual geomorphic response. Some information is provided on method requirements where requirements have an impact upon geomorphic response.

In general, there is little information on the upstream and downstream effects of these methods, based upon literature reviewed, beyond a relatively short distance such as one-fourth to one-half of a meander wave length (Fischenich 2000). Most of the available information would be best characterized as a “local response.” Many reaches of the Middle Rio Grande channel are going through a geomorphic threshold from a wide, sand bedded, low-flow, braided channel to a single-thread, slightly sinuous channel, with a gravel-controlled bed (often bimodal sediment transport condition). Determination of the geomorphic response is more difficult than for rivers that are closer to dynamic equilibrium.

A general response for biological/ecological riparian zone and aquatic resources has been determined for each method based upon its characteristics and potential geomorphic response. Biological/ecological effects have been determined, based on the amount of potential lateral or vertical movement of the channel, potential ground water elevation changes, amount of low depth and velocity habitat, variable of depth and velocity habitat for different riverflows, flood plain connectivity, backwaters and side channels, sediment transport, and sediment deposition areas. The biological response will be based on similar river conditions and habitat use in these situations. There are often microhabitat features that form with variable biological use; for example, there have been two similar backwaters observed, about 200 yards apart, with Rio Grande silvery minnow (RGSM) occupying one of the backwaters but not the other. It is not known why RGSM did not occupy both of the similar backwaters. RGSM use of various microhabitats has been documented by Porter and Massong (2004). Methods are grouped by categories. This document also contains the riparian and aquatic habitat responses to the maintenance methods, as much as possible, with the state of knowledge. Predicting the biological response is difficult.

1.4 Engineering Effectiveness

The overall engineering effectiveness of each method is identified as a consideration in the Engineering Effectiveness Evaluation Factor for each strategy in each reach of the Middle Rio Grande River. See the discussion of how Engineering Effectiveness is evaluated overall in appendix C, section 1.7, and the main report section 4.7. It is incumbent upon engineers to determine the most effective solution to specific problems by recognizing the methods that match the hydraulic capacity, water delivery, and effectiveness and duration against the river conditions. Some methods promote dynamic equilibrium without direct or indirect bank protection. The ability of these methods to provide the needed hydraulic capacity and water delivery, while promoting sediment transport continuity, must be considered.

This appendix includes a summary of engineering goals and objectives, an evaluation of the method durability, design life, level of confidence in being able to perform its intended functions, ability to deliver water, hydraulic capacity, adaptability to changing river conditions, and level of public safety. The ability to implement a method is a measure of the ease or difficulty of obtaining land instruments, size, construction location, and the overall scope of environmental effects. A method can be effective only when it is implementable. The criteria for determining the level of confidence of methods are described in section 1.2 of this appendix.

The implementation cost of a method, or combination of methods, can determine which are applied, especially in a situation where a fixed amount of funds is available for implementation. For this maintenance plan, costs associated with planning and design, obtaining environmental compliance, implementation (construction), monitoring and evaluation, frequency and amount of maintenance, and frequency and amount of adaptive management are suggested for consideration. A workshop was held on August 12–14, 2009, in Albuquerque, New Mexico, to determine appraisal level cost estimates for each method. The estimated costs are internal to the Albuquerque Area Office and are not of suitable quality for distribution. Their only purpose is to compare strategies by reach, and these estimated costs are determined to be of suitable quality for this exclusive purpose. Costs are not reported in this appendix; rather, the range of cost for each strategy is given in the discussion of strategies by reaches in the main report, chapters 5 through 15 and in appendix C, chapters 2 through 12.

1.5 Overall Project Development Process

Channel maintenance and rehabilitation projects are very diverse, and the use of a "rigid blueprint approach" is not applicable to all conditions (Watson et al. 2005).

In addition, various project goals will require different application of evaluation, planning, methods selection, and design. In general, the project development process involves:

1) Identifying problems and opportunities
2) Inventorying and forecasting conditions
3) Formulating alternative plans
4) Evaluating alternative plans
5) Comparing alternative plans
6) Selecting a plan
7) Preliminary design
8) Implementing
9) Monitoring and feedback
10) Maintenance and adaptive management (Orth and Yoe 1997; Watson et al. 2005).

Inventory and forecasting conditions involves identifying:

- Historical and existing conditions
- Future conditions without the project
- Background investigations
- Field investigations
- Computational methods for estimating preproject and postproject conditions

Inventorying and forecasting conditions, both on the temporal and spatial scales, are accomplished on a watershed and stream system basis. Assembling and synthesizing the geology, climate, sediment, geography, hydrology, and historical stream channel state and stability are components of this step (Watson et al. 2005). Geographic information system (GIS) analysis is useful to determine channel changes in relationship to habitat assessment (Porter and Massong 2004). Geomorphic assessments provide a process-based framework to determine past and present watershed dynamics, develop a suite of integrated alternates, and evaluate the effects and benefits of proposed actions (Watson et. al. 2005). A geomorphic assessment, including sediment impact analysis, is essential to assess the long-term stability of restoration and channel maintenance actions. A sediment budget approach can be used for relatively simple projects, or a numerical model such as the Sedimentation and River Hydraulics One-Dimensional Sediment Transport Dynamics Model (SRH1-D), which incorporates the solution of sediment and water continuity for more complex conditions. The geomorphic analysis for method implementation on the Middle Rio Grande is influenced by water operations since the system is highly controlled and managed.

Water operations influence channel morphology because the width, depth, slope, and channel form and process are, in part, determined by the magnitude and duration of peak flows and various lower flows. The range of flows resulting from water operations and those from uncontrolled tributaries would become part of the method evaluation and selection during the project formulation stage. Having sufficiently high flows at frequent intervals, such as annually or every 2 to 3 years, to maintain channel width and processes is vital for maintaining channel capacity and the health of the riparian zone.

Geomorphic assessment alone will not provide a basis for engineering and design, but it provides a system context and framework within which the designer can:

1) Select hydrodynamic and sediment transport equations for the channel conditions

2) Match, if possible, stable stream dimensions to project goals

3) Use computer models to incorporate geologic and human-induced controls, to predict channel response to proposed project features

4) Integrate environmental features into the engineering aspects of the project

5) Anticipate maintenance requirements and optimize design for sustainability

6) Develop the scope of postproject monitoring and adaptive management after Watson et al. 2005).

1.6 Description of Method Selection

The approach based on geomorphology and ecology process described above can be used to determine and evaluate the physical and ecological processes at a reach scale, which are essential for project success. Methods that work best with geomorphologic process can be identified and evaluated. Other applicable methods provide local change to the geomorphic process to meet project goals. In all cases, maximizing sustainability and reducing future requirements should be a consideration.

The suitability and effectiveness of a given method are a function of the inherent properties of the method and the physical characteristics of the worksite. As such, there is no single method that applies to all situations. Although there is a general lack of guidance and criteria to evaluate methods, evaluating method characteristics, ecological benefits and effects, geomorphic response, advantages, disadvantages, range of applicable river conditions, and cost within the broad context of geomorphology, environmental, engineering, and economics cost, suitable implementation can be planned, designed, and implemented.

The value of riverside infrastructure or water delivery benefits should be determined. First, value infrastructure, such as a flood control levee and large water delivery channel or road, etc., would require a more stable bank protection scheme such as riprap revetment or longitudinal stone toe with bioengineering. Alternatively, the infrastructure or channel can be relocated. Channel relocation also can involve developing a main channel with an inset flood plain to dissipate erosive flow energy. It has been determined that, on the Middle Rio Grande, all projects will provide a combination of methods, as described in chapter 3 in this appendix, for there to be a net positive benefit for endangered species under the Endangered Species Act (ESA). The selected combination of methods may not be the lowest cost to meet this objective.

Formulation of project plans involves identifying potential alternatives consisting of multiple methods to meet project purposes and goals, within identified constraints, in the broadest context possible. Evaluation and selection of methods involve many general tasks. The tasks described in this section draw significantly from the descriptions found in Orth and Yoe (1997) and Watson et al. (2005). First, forecast as much as practical the most likely future project condition for each alternative. Second, compare each alternative project condition with the estimated future condition without the project. Third, describe and characterize effects in terms of magnitude, location, timing, and duration and develop a summary. Fourth, determine which plans qualify for further consideration by assessing if each alternative is consistent with a minimum standard of meeting project objectives. The types of standards to evaluate are cost, environmental effects and benefits, social effects and acceptability, and engineering. Tradeoff analysis can be used to determine the direction of change in each alternative relative to cost, environmental effects and benefits, and engineering.

Projects will be coordinated with other agencies to ensure compatibility with their activities and goals to maintain long-term effectiveness. Stakeholders and regulatory agencies need to be satisfied with the project. This often may result in several alternatives being evaluated from a multidisciplinary point of view.

1.7 Method Summary Tables

Tables A-1 and A-2 provide a general summary of methods contained in subsequent sections of this appendix. Method performance confidence rating, advantages, disadvantages, and general range of applicability are summarized for methods in each group (table A-1). Table A-2 contains method, geomorphic response, engineering effectiveness, economics cost, and habitat characteristics.

Table A-1. Method Categories and Summary of Performance Confidence Rating, Advantages and Disadvantages, and General Range of Applicability

Method	Performance Confidence Rating	Advantages	Disadvantages	General Range of Applicability
INFRASTRUCTURE RELOCATION OR SETBACK	Level 3 (infrastructure) and Level 2 (limited postproject field studies-river response).	Greater area for lateral migration. Infrastructure is protected by relocation.	Can be higher cost than other methods; lateral migration may continue to new infrastructure location with the same erosion issue as before.	Applicable to all ranges of river conditions.
CHANNEL MODIFICATION		Can be used to address geomorphic disequilibrium to reduce risks associated with bank erosion.	The scale of effects can be large, so a thorough understanding of geomorphic effects is essential. Channel response estimates can be improved by using SRH1-D and Sedimentation and River Hydraulics Two-Dimensional Model (SRH2-D) models.	Applicable to all ranges of river conditions.
Complete Channel Reconstruction and Maintenance	Level 3.	Provides for effective water and sediment delivery to the reservoir, increases upstream channel capacity, and improves valley drainage. Provides for a wider channel at arroyo mouths.	Ongoing maintenance activity. RGSM and eggs generally are carried to the reservoir; lower upstream flood plain connectivity.	Applicable to the upper end of Elephant Butte and arroyo mouth deposits.
Channel Relocation Using Pilot Channels or Pilot Cuts	Level 2 (construction and hydraulics) and Level 1 (limited post project field studies).	River can be relocated away from infrastructure; excavating narrow channel reduces cost and provides a small amount of sediment augmentation. Greater flood plain connectivity; meandering alignments can be in dynamic equilibrium and aesthetically pleasing.	Excavated sediments may take years to be eroded by riverflows; must be enough land available for re-meandering alignment and future lateral migration; difficult to predict response with precision.	Applicable to a wide range of rivers where a meandering planform is sustainable.
Island and Bank Clearing and Destabilization (Includes Channel Widening)	Level 1.	Promotes a wider shallower river. Provides increased flood plain connectivity; provides pockets of RGSM habitat, sediment balance, and increased sediment supply.	Sediment balance may be temporary; clearing and destabilization may need to be done several times.	Platte River, Middle Rio Grande Project at Santa Ana Pueblo, Switzerland, Austria, other European Rivers where annual scouring flows can occur.
Pilot Cuts Through Sediment Plugs	Level 2.	Re-establishes preplug channel capacity; inexpensive; re-establishing main channel capacity returns the river to the preplug riverine habitat conditions.	Does not address the root cause of the plug formation.	Middle Rio Grande upstream of and downstream from the San Marcial Railroad Bridge and upstream into the Bosque del Apache National Wildlife Refuge.
Side Channels (High Flow, Perennial, and Oxbow Re-establishment)	Level 2 (design methods available) and Level 1 (limited postproject field studies).	Inexpensive method to reconnect abandoned flood plain areas. Method decreases main channel sediment transport capacity, which could reduce channel incision, raise ground water table, and provide surface flows for developing riparian vegetation.	High-flow side channels tend to fill with sediment at entrance and exit locations. Too much flow in the side channels can lead to excessive sediment deposition in the main channel.	Applicable to a wide range of rivers where there is opportunity to reconnect flood plain areas.
Longitudinal Bank Lowering or Compound Channels	Level 2 (design methods available) and Level 1 (limited postproject field studies).	Main channel shear stress is reduced during peak flows. There is a lower tendency for channel incision, reduces peak flow water surface elevation, can provide a small amount of downstream sediment enrichment, establishes flood plain connectivity, and promotes new riparian vegetation growth.	Future vegetation will restrict floodflows in the overbank over time, and the lowered terrace or bank will experience sediment deposition.	Used on many rivers in Europe, on incised channels in the United States, and in the State of Washington.
Longitudinal Dikes	Level 3 (fixed bed design methods available) and Level 2 (few sets of field or lab data and limited information on mobile bed applications).	Where sediment transport capacity is much lower than supply and plugs form, the velocity and sediment transport can be increased to promote a channel where plugs no longer form. Can provide protection from low-level flooding upstream of low-head diversion dams such as in the Espanola Valley.	Under certain circumstances, the increased peak flow velocity and sediment transport capacity can lead to downstream sediment deposition and aggradation. Upstream backwater effect can be created, leading to higher upstream water surface elevations. Can prevent periodic inundation of valuable riparian zones unless culverts are added. Easily overtopped.	All types of channels with gravel, sand, silt, and clay beds that are meandering, braided, or anastomosing. Various types of dikes have been used throughout the United States and the world.
Levee Strengthening	Level 3 (fixed bed design methods well established) and Level 2 (less knowledge on elevation for mobile bed cases).	Provides continued protection of riverside infrastructure and lands from high peak flow inundation.	Levee strengthening is typically accomplished using the 2- to 5-year return period interval discharge, downstream from San Antonio, New Mexico, which can be easily overtopped.	All types of channels with gravel, sand, silt, and clay beds that are meandering, braided, or anastomosing. Various types of dikes have been used throughout the United States and the world.

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Method	Performance Confidence Rating	Advantages	Disadvantages	General Range of Applicability
BANK PROTECTION/ STABILIZATION		In general, these methods are widely tested and used, while transverse features are less well understood.	Can cause the channel width to decrease, creates a static bank line, and can in some, but not all, cases lead to acceleration of bank erosion in downstream bends.	Generally applicable to all types of channels.
Longitudinal Features - Fixed Bank Line and Thalweg Location				
Riprap Revetment	Level 3.	Thoroughly tested and used for a wide range of conditions and can be designed with a high degree of precision and confidence. Provides maximum protection for riverside infrastructure.	Decreased channel width and increased depth. Creates a local static bank line. In some cases, riprap revetments can lead to accelerated bank erosion of downstream bends.	Used on virtually all types of rivers found in the North America and Europe.
Longitudinal Stone Toe with Bioengineering	Level 3 (riprap design, scour, and longitudinal extent of placement are well known) and Level 2 (elevation of the top of the stone toe and bioengineering in arid climates is less known).	Thoroughly tested and used in a wide range of conditions. Vegetation provides aesthetic benefits, shading, and reduces bank line velocity during high flows.	Decreased channel width and increased depth. Creates a local static bank line. In some cases, riprap revetments can lead to accelerated bank erosion of downstream bends. In arid climates, Koir fabric or bio-D blocks are needed to provide suitable conditions for vegetation to grow, and vegetation may need to be replanted to provide the desired benefits.	All types of channels throughout the United States.
Longitudinal Features - Erosion to Bank Line Stabilization				
Trench Filled Riprap	Level 2.	Allow stabilization along a predetermined alignment. Generally effective for controlling lateral channel instability.	Requires large areas of right-of-way. Self-launching riprap does not distribute evenly along the bank line. Requires supplemental riprap placement to ensure even distribution and revetment stability. Creates a static bank line.	Used on Arkansas, Red, Missouri, and Mississippi Rivers and is most suitable for noncohesive banks and where emergency sites exist.
Riprap Windrow	Level 2.	Allow stabilization along a predetermined alignment. Generally effective for controlling lateral channel instability.	Requires large areas of right-of-way. Self-launching riprap does not distribute evenly along the bank line. Requires supplemental riprap placement to ensure even distribution and revetment stability. Requires more supplemental riprap than trench filled riprap, because the launch distance is greater. More susceptible to continued bank erosion due to uneven launching than trench filled. Creates a static bank line.	Used on Arkansas, Red, Missouri, and Mississippi Rivers and is most suitable for noncohesive banks and where emergency sites exist.
Longitudinal Features - Mobile Bank Line and Thalweg Location				
Deformable Stone Toe/ Bioengineering and Bank Lowering	Level 2 (riprap sizing) and Level 1 (lack of design guidelines and post project studies).	Began in 1990s. Limited field applications and documentation. The riprap design is well established. Allows bank line deformation after vegetation is established. Increases flood plain connectivity and can bring sediment transport capacity more in balance with sediment supply.	There is a risk that the stone toe design event will be exceeded before vegetation is established. The purpose of the bio-degradable fabric is to prevent erosion until vegetation is established. The method should not be used where high value infrastructure is near the eroding bank because the method depends upon a lateral migration area. The lateral migration area required is not well established.	The method has been applied to small streams with little or no reports of use on large rivers. Has been used on the Middle Rio Grande Project at the Santa Ana site. Coir fabric may have limited longevity on rivers with high bed material load
Bioengineering	Level 1.	Uses natural materials, assists in stabilizing banks by trapping sediment and adding root strength to the bank line. Creates additional boundary shear resistance.	Vegetation has lowest erosion resistance of all available methods. Application is limited to bank elevations above the base level flow. Does not protect against toe erosion, and most applications include toe protection in the form of rock or logs. Does not work well in sandy soil banks.	This method is not recommended as a stand-alone treatment because toe erosion and sandy banks are common on the Middle Rio Grande.

Table A-1. Method Categories and Summary of Performance Confidence Rating, Advantages and Disadvantages, and General Range of Applicability

Method	Performance Confidence Rating	Advantages	Disadvantages	General Range of Applicability
Transverse Features or Flow Deflection Techniques	Level 2 (limited design guidelines available) and Level 3 (lack of quantitative design guidelines and postproject studies).	Little or no bank preparation is needed for construction. Existing channel alignment and geometry can be modified. Geotechnical bank stability can be increased by sediment deposition between structures.	These methods do not address geotechnical instability. These methods change flow alignment, channel geometry, and roughness; thus, attention must be given to morphological response. These methods can be a safety hazard to recreation because flow is redirected and part of the structure may be submerged, depending upon the method. These structures are subject to severe hydraulic conditions because flow accelerates as it passes over and around the tips of transverse features.	Transverse features have been used in all types of rivers as noted below. One caution is that, when these structures are used in sand bed channels, scour often undermines the riprap, leading to failure.
Bendway Weirs	Level 2 (limited design guidelines available) and Level 1 (lack of quantitative design guidelines and postproject studies).	Flows are redirected throughout the flow field. The outer bank can become a zone of low velocity and a zone of sediment deposition. Aquatic habitat is improved because bendway weirs create variable depth and velocity habitat.	Weir fields must have sufficient spacing to protect the banks and weir roots so that if bank scalloping occurs, the weirs riverside infrastructure remains protected. Regular monitoring and maintenance are required.	Large rivers, such as the Mississippi, to small streams have documented use of bendway weirs. Bendway weirs also are applied to protect highway bridge crossings on braided or meandering rivers in many States in the United States. On the Mississippi, the main purpose was to create a wider and deeper shipping channel.
Spur Dikes	Level 2.	Spur dikes modify channel alignment and provide erosion protection for riverside structures. Provides variable velocity and depth habitat. Can induce sediment deposition.	The bank line between spur dikes can erode when the spur dike spacing is too large. Over time, the channel deepens, increasing flow capacity. Local channel narrowing can occur. The extent of channel deepening and narrowing cannot always be predicted with great reliability. The bank line is fixed, thus interrupting fluvial processes.	Most commonly used in shallow, wide streams with moderate to high suspended sediment load. Spur dikes are used widely for protecting highway bridge crossings in the United States.
Vanes or Barbs	Level 2 (limited design criteria) and Level 1 (very little design test data).	Reduces streambank erosion, modifies flow direction, creates local scour, and gains environmental benefits. Vegetation can grow on sediment deposits between vanes where sufficient supply exists for sediment to deposit between vanes. Vanes require less rock than other structures for a similar length of bank line.	The low volume of rock near the tip of the vane often launches into the scour hole, requiring regular maintenance. Bank scalloping between vanes is common and can lead to vane failure. Long-term bank protection is usually only achieved when sediment deposition occurs between vanes.	Used when channels have a width-to-depth ratio of 12 or greater. Vanes have been used extensively throughout the United States.
J-Hook	Level 2 (limited design criteria) and Level 1 (does not have a documentable track record and very little design test data.)	Same as vanes with a “J” hook added. The “J” tip creates a scour pool in the channel bed, which increases the amount of pool habitat. The rest of the vane provides variable depth and velocity habitat.	“J” hook at the center of the channel is subject to scour erosion. This structure requires more riprap and more in channel construction than vanes. The “J” tip can fill with sediment in sand and fine gravel bedded channels. The remainder of the disadvantages is the same as for vanes.	Same as vanes.
Trench Filled Bendway Weirs	Level 1.	Assuming that erosion of the bank line is slowed or halted and the bendway weirs remain in place, the bank line can be stabilized along a predetermined alignment. Can be applied during high flows provided the water table is sufficiently low for installation, and avoids in water construction.	Long-term performance is unknown. During active bank erosion, the bendway weir tips may erode because there is not a long enough weir length to interrupt the secondary currents and redirect flow towards the center of the channel.	This method has not been applied at any known location other than the Middle Rio Grande.
Large Woody Debris (LWD)	Level 2.	Can create in stream cover, pool formation, deflect flows, retain gravels, and create complex hydraulics. LWD is a natural material.	Cottonwood has low life span and decays rapidly; thus, LWD is not recommended as a bank stabilization method. Rather, it is recommended as part of other methods to locally enhance river habitat.	LWD is used in many areas of the world but is not used much in the arid Southwest.

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Method	Performance Confidence Rating	Advantages	Disadvantages	General Range of Applicability
CROSS CHANNEL (RIVER SPANNING) FEATURES	Level 1 (gradient restoration facilities [GRF]), Level 2 (rock sills and riprap grade control), and Level 3 (deformable riffles).	Prevention or slowing of continued incision and can raise the bed and water surface elevation (some methods). Improves flood plain connectivity, channel stability, bank stability, and prevents the ground water table from lowering.	The fluvial process of bed elevation change over time is interrupted. Can prevent fish passage without special design features. For high structures, downstream degradation could occur.	These types of structures have been used on many rivers in the United States and Europe.
Grade Control				
Deformable Riffles	Level 3.	Provides for some measure of grade control and bank stability. Helps the river remain in the current alignment. Provides for some sediment enrichment and fish passage.	This is a more conceptual method with limited applications, except at Santa Ana Pueblo. It may be difficult to select the proper bed material sizes. The structure would be limited to a 1-foot drop. The channel will continue to degrade, although at a lower rate.	The only known application of this method is Santa Ana Pueblo on the Middle Rio Grande.
Rock Sills	Level 2.	Economical to design and easy to construct. When spaced properly, with adequate scour protection, they can provide variable depth and velocity habitat.	Limited to 2- to 3-foot drop height (1-foot may be best, but unknown). These can easily fail when placed too far apart. Seepage flows can cause failure, and they are not suitable when rapid bed degradation is likely.	Used successfully in Europe for many types of channels.
Riprap Grade Control (With or Without Seepage)	Level 2.	Improves pool habitat. The steep upstream slope and mild downstream slope are similar to natural riffles. Economical to design and relatively easy to construct. There are limited environmental impacts. When spaced properly, with adequate scour protection, they can provide variable depth and velocity habitat.	Riprap that launches into the scour hole comes to rest at the angle of repose. This steep slope would limit RGSM fish passage. Drop height is generally 2 to 3 feet. This is a more complex design and construction than rock sills.	Cobble and gravel bed material sizes used throughout western Canada and in many locations in the United States.
Gradient Restoration Facility	Level 3 (hydraulic design is well documented) and Level 2 (limited post project field studies).	Controls grade with long, low slope apron which provides for RGSM fish passage. The raised channel bed can increase flood plain connectivity, cutoff walls provide seepage protection, and the structure location remains constant. Flood carrying capacity can be accurately estimated.	Most complex design and highest construction cost of all grade control methods. Not suitable when rapid or extensive future bed degradation is likely. Requires flanking countermeasures.	Intended for rivers with high bed load transport rates and where low-apron slopes are needed for fish passage. This method can be applied to rivers with a wide range of conditions.
Low Head Stone Weirs (Loose Rock)	Level 2 (limited design criteria and level 1 (limited postproject field studies and design test data).	Low construction and maintenance costs. Creates fish cover and resting pools for certain fish species with a more natural appearance. Can reduce upstream channel aggradation, promote flood plain connectivity, and raise upstream ground water levels.	Sediment may deposit in the downstream pool. Not useable in sand or fine gravel bedded streams. Susceptible to rock dislodgement and flanking. Not useful for controlling rapid channel incision. Current design standards are based upon anecdotal information with limited applicability to a wide range of river types.	The method is applicable to steep slope river conditions and in bends. Most applicable for cobble and gravel bed streams without well defined riffles and pools.
CONSERVATION EASEMENTS	Level 2.	Provides land for river migration corridor reducing or eliminating the need for other bank stabilization work. Preserves riparian areas and allows for at least some natural lateral migration of the river channel. Provides great flexibility for the river to adjust hydraulic geometry, and lateral channel position.	Few landowners may be interested in potentially changing their land use, and site selection is critical to have sites with river dynamics.	Used on many rivers in the United States, Europe, and Canada. Applicable to all rivers.
CHANGE SEDIMENT SUPPLY				
Sediment Augmentation (Sand Sizes)	Level 2 (examples exist of the benefits of adding sediment to rivers) and Level 1 (Middle Rio Grande is a nonequalibrium river where changes in sediment supply could have large effects).	Adding sediment (sand) would address the problem of limited sediment supply. Limited sediment supply causes the channel to incise, narrow, and migrate laterally. Sand augmentation halts continued incision and may reduce the number of future river maintenance sites by reducing lateral migration. Would provide sediment for bars to promote new riparian areas and increases the potential for flood plain connectivity.	Would require careful monitoring of the timing, amount, and location of sediment reintroduction. Aggradation may occur in downstream reaches. This method will require perpetual application; otherwise, the river would revert back to the condition prior to augmentation. Locating perpetual sources of sediment may be difficult.	Gravel augmentation has numerous applications throughout the world. Sand augmentation is not well documented.

Table A-1. Method Categories and Summary of Performance Confidence Rating, Advantages and Disadvantages, and General Range of Applicability

Method	Performance Confidence Rating	Advantages	Disadvantages	General Range of Applicability
Natural or Constructed Sediment Basins	Level 2 (examples exist of the benefits of reducing sediment supply to some rivers) and Level 1 (Middle Rio Grande is a nonequalibrium river where changes in sediment supply could have large effects).	Decreasing sediment supply would address the root cause of channel aggradation and reduce the size of delta deposits upstream of Elephant Butte Reservoir.	Alternative sediment deposition areas are necessary. These areas have a finite life depending upon the size and amount of sediment deposition. May have high cost due to sediment removal from deposition areas.	Upper end of Elephant Butte Reservoir. Potentially establish settling basins in the Tiffany Junction area and on the west side of the current levee.
HABITAT IMPROVEMENT AND MITIGATION				
Rootwads	Level 2.	Tend to increase flow resistance along the bank line and dissipate energy. Can retain sediment and creates variable depth and velocity fish habitat and fish cover.	For banks with less than 15 percent (%) silt and clay, bank erosion is likely around the rootwads.	Best in rivers where other large wood is available in the channel.
Log Jams/Large Woody Debris	Level 2 .	Provides habitat improvements, promotes side channel formation and maintenance, and creates low velocity and overhead cover.	Wood that is subject to repeated wetting and drying will increase decomposition rate. On the Middle Rio Grande, cottonwood are available but have a short lifespan of around 5 years.	Used throughout the United States and Canada on sand bed channels and gravel bed rivers of all sizes.
Island and Bank Clearing and Destabilization (Includes Channel Widening)	See island and bank clearing and destabilization above.			
High Flow Side Channels	See high flow side channels above.			
Longitudinal Bank Lowering	See longitudinal bank lowering above.			
Boulder Groupings	Level 2.	Adds local roughness elements, local areas of variable depth and velocity, and is simple and natural looking.	Can often become mobile and lose the shape of the cluster. Do not provide benefits in depositional zones.	This method is used throughout North America, but bed material should be coarser than medium gravel or about 50 millimeters.
Riparian Vegetation Establishment	Level 2.	Restores flood plain riparian areas.	Plantings can have a large mortality rate unless planted at the specific elevation to receive water but not too shallow to be excessively inundated.	All but the driest Southwest ephemeral rivers would benefit from riparian vegetation establishment.
Bank Line Embayment	Level 1.	Provides habitat suitable for retaining RGSM eggs. Relatively low cost and low level of effort, which can be easily reconstructed and maintained	Can create sediment depositional zones, which reduces the effectiveness of egg and larval retention.	Most applicable where there is a lack of backwater habitat or channel features which produce complex eddy currents and that generate near-zero flow velocity.
Jetty Removal	Level 1.	In some cases, lateral migration and channel widening could be promoted. Can promote flood plain connectivity, especially when accomplished with bank lowering or bed raising. Increases aesthetics for recreation.	May not initiate flood plain reconnection without either bank lowering or bed raising. The bank line is often more stabilized by riparian vegetation than the jetties themselves, such that jetty removal would not result in channel widening or bank migration. Banks could become destabilized, leading to levee or other infrastructure erosion.	Can be accomplished on any river where jetties have been installed.

Table A-2. Summary of Geomorphic Response, Engineering Effectiveness, and Economics-Cost, and Habitat Characteristics

Method	Geomorphic Response	Engineering Effectiveness and Economics Cost	Habitat Characteristics
INFRASTRUCTURE RELOCATION OR SETBACK	Can encourage current geomorphic processes to continue, such as lateral migration and the creation of new flood plain and riparian areas. Opportunity to connect to historical channels and oxbows. For incised channels, may provide an opportunity to establish new inset flood plain and riparian zone.	Effectively protects riverside infrastructure by moving it from the erosion zone. Level of confidence is medium to high.	Lateral river movement creates broader flood plain and more favorable riparian zone habitat. Lateral bank movement should result in deposition of sediment downstream. The river will establish bars and low surfaces, where vegetation can become established. Longer meander bends may establish greater pool depth and eroding banks with vegetation falling into the channel, providing fish cover and habitat complexity.
CHANNEL MODIFICATION			
Complete Channel Reconstruction and Maintenance	Increased sediment transport through a delta, can lead to channel bed lowering upstream of the project site, and low-flow alternate bars can form within the excavated channel.	Effective for moving sediment through the delta; medium to high level of confidence in the method contingent upon annual maintenance and periodic channel relocation. Durability depends upon reservoir stage and maintenance needs.	Uniform width, depth, and velocity. Limited amount of low or no velocity habitat; low amount of cover. Reduces braiding and distributary channels and, thus, provides less opportunity for riparian growth. Lowers ground water table and reduces the size of river bars. If medial and alternate bars are not removed as part of ongoing maintenance, then the amount of smaller depth and velocity habitat increases.
Channel Relocation Using Pilot Channels or Pilot Cuts	Can bring sediment transport capacity more in balance with sediment supply in supply-limited reaches. Re-establishes meanders, increases channel stability, and initiates new areas of bank erosion and deposition.	Effective for protecting riverside infrastructure by moving channel away from infrastructure. Level of confidence is medium to high.	Can provide overbank flooding and establish new areas of riparian vegetation. Can increase the complexity of habitat by creating connected flood plain/wetted areas for RGSM egg entrainment and larval development.
Island and Bank Clearing and Destabilization (Includes Channel Widening)	Promotes a wider channel with greater flood plain connectivity and balances sediment. New sediment balance may be temporary unless incoming loads also increase.	Can provide for increased flood carrying capacity. Durability and project life depend upon the elevation of cleared surfaces and frequency of scouring flows and sediment deposition. Project life span could be many years or may be short lived. Level of confidence is low because there are not many examples of using this method.	Reduces further degradation of the channel and lowering of the water table. Sediments from destabilized areas may deposit new bars suitable for vegetation. learing and destabilization would result in the loss of this habitat. Islands/bars that are more connected to the main channel can provide RGSM with a greater variety of depth and velocity habitat types. Egg and larval entrainment and development are often enhanced.
Pilot Cuts Through Sediment Plugs	Connecting small channels through sediment plug enables plug material to be transported downstream to re-establish preplug riverine conditions. Restores flow velocity and depth conditions found in the main river channel.	Level of confidence and reliability is medium to high for plug removal. Plug removal has been an ongoing periodic maintenance requirement. Flood carrying capacity of the channel is restored to preplug condition. Durability and project life can be only a year or two because method does not address the cause of sediment plug formation.	Allows sediment transport to continue, which may possibly provide new areas for riparian vegetation establishment. While the sediment plugs block main channel flows, RGSM do use overbank channels through the riparian corridor created by the plug. There is increased potential for RGSM stranding during receding flow conditions.
Side Channels (High Flow, Perennial, and Oxbow Re-establishment)	Important to natural systems for passage of peak flows. Sediment tends to fill in high-flow side channels over time. Can decrease peak flow water surface elevation and may decrease sediment transport capacity until sediment blocks the side channel.	Method provides for reduced main channel sediment transport capacity. Durability and reliability depend upon the size of the side channel and amount and timing of sediment deposition in side channel inlets and outlets. Maintenance could include periodic sediment removal. Level of confidence is medium.	Side channels result in raising the ground water table and surface flows to developing riparian areas. Maintains higher water surface elevation and ground water table, adding to the health of the riparian zone. Can reconnect the flood plain to the channel, creating nursery habitat for RGSM with variable depth and velocity habitats.
Longitudinal Bank Lowering	Lowered bank line can promote a wider channel width and decreases in main channel velocity, depth, shear stress, and sediment transport capacity. During subsequent years, sediment may deposit in the lowered bank line area occupied by vegetation, which may reduce overbank conveyance capacity.	Increased flood carrying capacity. If sediment transport is in balance with capacity project durability, design life and project life may extend several decades. Level of confidence is medium.	Promotes overbank flooding favorable for establishment of riparian vegetation. Reduces potential for channel degradation, thereby maintaining a higher water table and more connectivity with backwaters and side channels. Increases overbank flooding, creating variable depth and velocity habitat types, including potential spring runoff nursery habitat.
Longitudinal Dikes	Can create a zone of higher main channel velocity resulting in increased sediment transport capacity. This potentially can cause the channel to deepen and create a sediment depositional zone downstream.	Increased main channel velocity and sediment transport capacity can be beneficial to reduce the potential for future plug formation in reaches where sediment plugs tend to form. Can reduce inundation of adjacent lands and infrastructure for 2- to 5-year return period flood peaks. The method is economical because they are constructed using native material.	Can decrease overbank flows, reducing the health of riparian zone. This can be partially mitigated by providing culverts for wetting the riparian zone. Can result in more uniform channel velocity and depth.

Table A-2. Summary of Geomorphic Response, Engineering Effectiveness, and Economics Cost, and Habitat Characteristics

Method	Geomorphic Response	Engineering Effectiveness and Economics Cost	Habitat Characteristics
Levee Strengthening	The geomorphic response associated with levee installation has already occurred for the levee strengthening method.	The benefits of the initial levee construction continue to be realized but are limited by only raising the levee to the water surface elevation of the 2-year return period flood peak, plus 2 to 3 feet for levee freeboard. Levees of this height are easily overtopped.	Initial levee construction and the accompanying flood plain narrowing affect the habitat. Raising or enlarging the levee causes very minor to no habitat effects. Small amounts of clearing may be required to enlarge the levee and reduce the side slope.
BANK PROTECTION/ STABILIZATION			
Longitudinal Features – Fixed Bank Line and Thalweg Location			
Riprap Revetment	Eliminates local bank erosion; causes local scour and channel deepening. Studies about longer reach response are contradictory. Can be susceptible to flanking if upstream channel migration occurs.	Durable, high level of confidence in method. Provides long-term bank protection	Prevents lateral migration and the establishment of new depositional zones where vegetation could become established. Reduces local sediment supplied from bank erosion. The steep bank angle on the outside of the bend limits fish cover, except for the riprap interstitial spaces. The point bar remains connected to the main channel and remains static. The flow velocity and depth are greater than typically found in natural channels along the outside bank of a river bend.
Longitudinal Stone Toe with Bioengineering	Same as riprap revetment.	Durable, high level of confidence in method provided that the elevation of the top of the riprap stone toe is adequately established to provide complete toe protection.	Same as riprap revetment. Bioengineering provides very minimal benefits to riparian community.
Longitudinal Features - Erosion to Bank Line Stabilization			
Trench-Filled Riprap	Bank erosion processes continue until erosion reaches the location of the trench. After launching, response is the same as for riprap revetment.	Riprap placed in a trench can be placed below the high-flow water surface elevation, so this method is more durable than riprap windrow. High level of confidence, durability, and reliability provided that additional riprap is placed in gaps or where riprap is thin after launching.	Same as riprap revetment.
Riprap Windrow	Same as trench-filled riprap.	Riprap windrow has longer launching distance than trench-filled riprap and is initially less durable than trench-filled. Medium to high level of confidence, durability, and reliability provided that additional riprap is placed in gaps or where riprap is thin after launching. After adding more riprap, there is a high level of confidence, durability, and reliability.	Same as riprap revetment.
Longitudinal Features - Mobile Bank Line and Thalweg Location			
Deformable Stone Toe/ Bioengineering and Bank Lowering	The design is intended to allow lateral migration at a slower rate than is occurring, which leads to the need for maintenance by establishing a new vegetated flood plain that is erodible. Water surface elevations could be lower with bank lowering. After installation, and before the toe of the riprap becomes mobile, the channel bed may scour along the deformable bank line. Bank erosion occurs during peak flow events, which mobilizes the small sized riprap along the bank toe.	Level of confidence is medium. Lifespan of the biodegradable fabric is generally 3–5 years. Method depends on adequate vegetation growth in this time period. Level of durability and reliability can be great when there is sufficient land available for lateral migration.	If flood plain is created behind the stone toe and vegetation becomes established before the toe is lost, an expanded riparian area could develop. Future bank migration would allow new depositional surfaces to establish, which would become new riparian areas.
Bioengineering	Vegetation has the lowest erosion resistance of all available methods. Plantings require time to establish before any bank protection is realized. Lateral and down valley bank line movement can continue because bioengineering does not permanently fix the bank location.	Level of confidence is very low. Plant roots do not prevent bank erosion below the base flow level. This is especially true in sandy bank material. Because the banks of the Rio Grande are mostly sandy and toe erosion is common, bioengineering is not recommended as a standalone treatment. Generally, bioengineering includes toe erosion protection.	If the technique is successful, it could promote the establishment and development of riparian vegetation without significant armament to the bank line. Allows more natural movement of river channel.

Table A-2. Summary of Geomorphic Response, Engineering Effectiveness, and Economics Cost, and Habitat Characteristics

Method	Geomorphic Response	Engineering Effectiveness and Economics Cost	Habitat Characteristics
Transverse Features or Flow Deflection Techniques	These methods may cause local sediment deposition between structures and/or local scalloping along the bank line. Flow is deflected away from the bank line, thereby altering secondary currents and flow fields in the bend. Eddies, increased turbulence, and velocity shear zones are created. Methods induce local channel deepening at the tip. Shear stress increases in the center of the channel, which maintains sediment transport and flow capacity.	The level of confidence for these structures ranges from low to medium. Durability is lower than longitudinal features because these structures redirect currents and are subject to excessive hydraulic conditions. When upstream entrance conditions change, the effectiveness of these structures is reduced. Reduces bend migration.	Sediment deposition between structures may allow establishment of riparian vegetation and backwater areas. Channel deepening and tip scour could locally lower the riverbed. Depending on site-specific conditions, transverse features could allow for overbank flooding conditions improving the health of the riparian zone. Local scour could provide habitat diversity and deep habitat during low-flow conditions.
Bendway Weirs	The location of the thalweg is shifted away from the outer bank line. Local scour at the tip occurs because of the three-dimensional flow patterns. Secondary currents are interrupted, and flows are redirected away from the bank. The outer bank can become a zone of lower velocity. The combined effect of the tip scour and lower velocity along the bank line creates a flow condition of variable depth and velocity. Scalloping also can occur along the bank line.	Level of confidence ranges from low to medium. Can reduce local bank erosion. Bendway weirs can erode away in gravel and sand bed channels due to downstream scour. Regular maintenance in the form of adding rock to the structures is necessary. The entrance angle must remain the same over time for continued redirection of the flow patterns. Durability and reliability are low to medium. Improved design criteria and methods are being developed at Colorado State University (CSU), which is important to improve the level of confidence.	Same as transverse features or flow deflection techniques above.
Spur Dikes	Spur dikes block the flow up to bank height, thus shifting the thalweg alignment to dike tips. Peak flow capacity can be reduced initially until the channel adjusts. The channel adjusts to the presence of spur dikes by forming a deeper, narrower cross section with additional scour downstream from each spur dike. Sediment deposition can occur between spur dikes.	Level of confidence is medium. Can halt local bank erosion. Spur dikes are more durable than bendway weirs and can remain functional if there are small changes to the upstream entrance conditions. Future maintenance (adding riprap on the spur dike tips) may be required, especially in gravel and sand bed streams.	Same as transverse features or flow deflection techniques above. There is a greater tendency for sediment deposition between spur dikes than the other transverse features.
Vanes or Barbs	These structures redirect flow from the bank toward the channel center and reduce local bank erosion while providing a downstream scour hole. Sediment deposition or bank scalloping can occur along the outer bank, depending upon spacing.	Level of confidence is medium; local bank erosion is reduced. The tip is relatively thin, owing to the sloping top. Tip stones often roll into the downstream scour hole, requiring replacement on a regular basis. A sufficient riparian buffer zone between the actively eroding bank line and the structure being protected should exist because of the potential scallop formation between vanes.	Same as transverse features or flow deflection techniques described above.
J-Hook	Redirects flow away from eroding banks the same as vanes or barbs with an added downstream pointing "J" configuration. The J-hook creates an additional scour hole pool and can produce a local downstream riffle. Remainder of the geomorphic response is the same as for vanes.	Level of confidence is low to medium. Engineering effectiveness is largely the same as for vanes, except the J-hooks may require the replacement of more rocks due to shape of the J-hook.	Same as transverse features or flow deflection techniques described above. Additional pool habitat is created by the J-hook.
Trench Filled Bendway Weirs	Once the bank erosion reaches the bendway weir tips, the flow is redirected away from the eroding bank. The location of the thalweg is shifted away from the outer bank line. Local scour at the tip occurs because of the three-dimensional flow patterns. Secondary currents are interrupted, and flows are redirected away from the bank. The outer bank can become a zone of lower velocity.	This is an experimental application, and the level of confidence is low. The tips of trench-filled bendway weirs can be eroded as they become exposed due to the concentration of hydraulic forces on the tip of the bendway weir.	Provided the bendway weirs constructed in a trench remain intact, the habitat characteristics will be about the same as bendway weirs constructed in the channel.

Table A-2. Summary of Geomorphic Response, Engineering Effectiveness, and Economics-Cost, and Habitat Characteristics

Method	Geomorphic Response	Engineering Effectiveness and Economics Cost	Habitat Characteristics
Large Woody Debris	LWD can provide local stream cover and scour pool formations, deflect flows, and create complex hydraulics. LWD in the Middle Rio Grande can lead to sediment deposition, including formation of islands, in reaches with large sand material loads.	Level of confidence is low. Cottonwood trees are the dominant species available on the Middle Rio Grande. Dead cottonwoods decay rapidly (in about 5 years); therefore, LWD is not recommended as a bank stabilization method but can add habitat enhancement when incorporated into projects. It is difficult to predict whether LWD would result in local scour or sediment deposition in sand bed systems.	Provides short-term habitat value. Could establish new sediment deposition areas where new riparian vegetation could grow. LWD can add structure and cover for fish.
CROSS CHANNEL (RIVER SPANNING) FEATURES			
Grade Control	Grade controls can reduce the gradient upstream by controlling the bed elevation and dissipating energy in discrete steps. At least during low flows, the upstream water surface is raised, depending on structure height above bed. Upstream velocity is reduced. There can be a local effect on sediment transport, scour, and deposition, depending on the structure characteristics. For low head structures (1–2 feet), the amount of upstream sediment storage is low and usually does not cause downstream bed level lowering as a result of upstream sediment storage. In supply-limited reaches, channel degradation downstream from the structure will continue as a result of excessive sediment transport capacity. Slope of the downstream stream apron will affect local scour downstream from the structure.	Each structure has its own level of confidence based on its features. Methods stabilize channel bed elevation and reduce lateral channel migration when migration is caused, at least in part, by bed lowering.	Reduces channel degradation upstream of this feature and can promote connectivity with side channels at low flows, creating variable depth and velocity habitat. By preventing future upstream local degradation the current level of floodplain connectivity can continue. Increased upstream water levels (except for peak flows) and raise the water table which would likely increase vegetative health. This provides may provide more opportunity for riparian zone establishment and development. Backwater areas could develop upstream, which would raise the water table. Downstream degradation could continue if sediment supply is less than transport capacity before the structure installed. Apron slopes would be sufficiently low to provide for fish passage.
Deformable Riffles	During flow conditions, where these structures are fixed, the effects upon channel morphology are described in the grade control geomorphology response in the above row. When the riprap material forming the riffle launch or deform downstream, the bed can lower a relatively small amount.	Level of confidence is low due to the experimental nature of these structures. Engineering data and design criteria do not exist for this specific method. This is promising technology, which could slow bed lowering to an acceptable rate.	Same as grade control above.
Rock Sills	Riverbed elevation is held constant, while rock launches into the downstream scour hole. Since bed is fixed, the effects on geomorphology are the same as for grade control.	Level of confidence is medium. Provides for bed stability. Fish passage capability would need to be determined.	Same as grade control above.
Riprap Grade Control (with or without seepage)	Trench filled grade control that is flexible deforms into a scour hole. Can be at bed level or above. Can have short or long low slope apron. Because the bed is fixed, the effects upon geomorphology are the same as for grade control.	Level of confidence, durability, and reliability is medium. Provides for bed stability.	Same as grade control above.
Gradient Restoration Facility	Bed is fixed. The effects upon geomorphology the same as for grade control.	Maintains bed elevation. The long, low slope on the downstream apron facilitates fish passage for the RGSM. Level of confidence durability and reliability are high.	Same as grade control above.

Table A-2. Summary of Geomorphic Response, Engineering Effectiveness, and Economics-Cost, and Habitat Characteristics

Method	Geomorphic Response	Engineering Effectiveness and Economics Cost	Habitat Characteristics
Low Head Stone Weirs (loose rock)	These structures typically are constructed above the bed elevation without grout. During low flows, there is an abrupt change in the water surface elevation through the structures, creating an upstream backwater effect. Generally, these structures do not raise the water surface during high flows. Sediment continuity can be re-established after the scour pool and tailout deposit are formed. A series of structures can dissipate energy and reduce channel degradation. Can interrupt secondary currents and move main current to the center of the channel if constructed in bendways.	Level of confidence, durability, and reliability are low to medium. Can be used to reduce the velocity in bends, thereby providing some limited reduction in bank erosion. These weirs can be used to provide grade control and as water diversion check structures. May be applicable for increasing the local velocity in secondary channel inlets and outlets. This is an untested use of these types of structures. Method durability is highly dependent on the boulder size and shape used in the construction.	Same as grade control above. Can provide pool habitat. Could restrict fish passage.
Conservation Easements	Allows space for existing fluvial processes to continue, which can preserve flood plain connectivity.	Level of confidence is high and depends on the amount of setback. Often, this is done in conjunction with riverside facilities and structures.	Allows more natural river movement and promotes greater area of undisturbed habitat.
Sediment Augmentation (sand sizes)	When the river is sediment supply-limited, the addition of sediment can stabilize or even reverse channel incision. Addition of sand-sized sediment can reduce bed material size, especially where coarser material is available in an incising channel. May result in sand deposits in pools, reduction of gravel riffle height, decreased depth, and increased width-to-depth ratio.	Level of confidence is low to medium. Little information is found in available literature on adding sand-sized material to the river. Could stabilize channel grade and reduce lateral migration that is initiated by channel incision. The minimum amount of sediment to halt incision would be the quantity being mined from the bed. Replacement sources of sediment include bank lowering, bar/island clearing and/or lowering, and island and bank destabilization. Sources outside Middle Rio Grande Project authority include sediment bypass at upstream U.S. Army Corps of Engineers reservoirs and arroyo bank destabilization.	Additional sediment could result in the establishment of river bars and terraces, which would be conducive to the establishment and development of riparian areas. Could increase the potential for overbank flooding and raise the water table elevation.
Natural or Constructed Sediment Basins	When the river has excess sediment supply; the reduction/removal of sediment supply can stabilize or reverse aggradational trends. Reduction of sediment supply could cause the bed material to coarsen.	Level of confidence is low to medium. Little information is found in the literature about sediment removal. The amount of sediment removal would be based on the quantity necessary to halt aggradation. Settling basins on a river the size of the Middle Rio Grande would be experimental.	In general, more uniform depth and velocity habitat would result, which decreases habitat complexity for the RGSM. The opportunity for the channel to braid and form distributary channels would be reduced, providing less opportunity for riparian growth.
Habitat Improvement and Mitigation			
Rootwads	Creates local scour pools and variable velocity habitat. Increases flow resistance along the bank line, which dissipates energy, traps and retains sediments, and creates turbulence that can move the main current away from the bank line.	Level of confidence for bank protection is low. Limited design guidelines are available. Cost is low. Cottonwood tree rootwads have a design span of about 5 years; therefore, their use for long-term bank protection is not recommended for the Middle Rio Grande. This method is recommended to be used with other methods to create habitat.	Adds complexity to the system. Variable depth and velocity conditions can be created. Some potential for creating areas of sediment deposition (depending on specific placement), which is generally beneficial to the establishment and development of riparian vegetation. Can provide structure and habitat for fish. Can provide isolated pools for fish refugia habitat during low-flow periods.
Log Jams/Large Woody Debris (LWD)	Creates pools, generates scour and substrate sorting, and increases depth and velocity complexity. Can promote side channel formation and maintenance. LWD in the Middle Rio Grande can lead to sediment deposition, including formation of islands, in reaches with large sand loads.	Level of confidence is medium. Some design guidelines are available. Short design life span for cottonwood trees on Middle Rio Grande.	Adds complexity to the system. Sediment deposition can create areas where new riparian vegetation becomes established. Can create variable depth and velocity habitat. Reliability for providing fish habitat is high for a short period of time. Can provide structure and habitat for fish. Can provide low-flow refugia habitat during low-flow periods.
Island and Bank Clearing and Destabilization	Same as channel modification; island and/or bank clearing and destabilization.	Same as channel modification; island and/or bank clearing and destabilization.	Same as channel modification; island and/or bank clearing and destabilization.
High-Flow Side Channels	Same as channel modification; high -flow side channels.	Same as channel modification; high-flow side channels.	Same as channel modification; high-flow side channels.

Table A-2. Summary of Geomorphic Response, Engineering Effectiveness, and Economics-Cost, and Habitat Characteristics

Method	Geomorphic Response	Engineering Effectiveness and Economics Cost	Habitat Characteristics
Longitudinal Bank Lowering	Same as channel modification; longitudinal bank lowering.	Same as channel modification; longitudinal bank lowering.	Same as channel modification; longitudinal bank lowering.
Boulder Groupings	Creates a zone of local scour immediately downstream from the boulders. Creates variable depth and velocity habitat. Creates velocity shear zones. Effects are localized to the immediate vicinity of the boulders. Increases channel roughness at high flows.	Level of confidence is medium. Cost is low. Boulders can migrate into the downstream scour hole.	Can provide structure and habitat for fish.
Riparian Vegetation Establishment	Can cause sediment deposition in overbank areas due to increased flow resistance. Sediment deposition in the overbank can increase main channel sediment transport capacity by raising the bank height.	Level of confidence is medium. Planting elevation and ensuing hydrology must provide appropriate conditions for plant growth.	Directly adds to the amount of riparian vegetation.
Bank Line Embayment	Historical channel slow water velocity and shallow depth bank line habitat is restored/rehabilitated.	Level of confidence is low. Bank line embayments are zones of sediment deposition and have a finite lifespan without periodic re-excavation.	Provides vital high-flow egg retention and nursery larval habitat that has largely been lost on the Middle Rio Grande. Increases likelihood of native vegetation growth and potential flycatcher habitat.
Jetty Removal	Jetty removal may result in channel widening and increased flood plain connectivity.	Vegetation often promotes more bank stability than jetties; thus, removal may not result in channel widening and increased flood plain connectivity. Removal creates a more aesthetic riparian forest.	The habitat may not change if the existing vegetation has more effect on bank stability than the jetties themselves. Otherwise, channel widening could reduce channel flow depth and velocity and create more bank line habitat.

Chapter 2. Infrastructure Relocation or Setback

- The confidence level is between Level 3 and Level 2 because there are few documented cases that provide geomorphic response and long-term information.

- Riverside infrastructure and facilities constructed near the riverbanks may laterally constrain river migration. Potential facilities to be relocated include levees, dikes, access roads, canals, drains, culverts, siphons, utilities, etc.

- Relocating riverside infrastructure may provide the best opportunity for geomorphic processes to occur unencumbered by local lateral infrastructure constraints. This method can encourage geomorphic processes to continue and may provide for long-term channel dynamic equilibrium (Newson et al. 1997; Brookes et al. 1996). These processes include lateral migration, which maintains the health of the riparian zone through erosion of banks and sediment deposition. Bank erosion can remove older growth riparian areas, while deposition can create new flood plain and riparian areas, thus maintaining a riparian zone with a mosaic of different age classes of native plant communities (Brookes 1996).

- Levee relocation can provide the potential for riverflows to access historical flood plain areas (Bauer et al. 2004; Brookes 1996; and Petts 1996). The magnitude and frequency of access depend on local topography and availability of flows that go overbank into adjoining flood plain riparian zones.

- Levee relocation can provide opportunity for the river to relocate into historical channels and oxbows in flood plain areas cut off by levee installations (Bauer et al. 2004; Brookes 1996), depending on local topography and channel changes since levee installation.

- For cases in which lateral bank erosion is threatening the integrity of a riverside facility, relocation can allow continued lateral migration. When riverside infrastructure is placed outside the meander belt width or braid plain, future bank protection is generally not needed.

- For the case of incised channels, lateral migration may provide an opportunity to establish a new inset flood plain and riparian zone surfaces. This is especially important when incision has led to the main channel being disconnected from its historic flood plain. Riparian zones that are narrower than historical widths have been considered successful rehabilitation projects (Brookes et al. 1996; Kondolf et al. 2007).

- Levee relocation, in many reaches of the Middle Rio Grande, involves moving the existing levee and the riverside drain. When a riverside drain is reconstructed, the drain excavation may provide material for the relocated levee, thus leaving the existing levee to provide some small amount of sediment enrichment if the project is located in a reach that is supply-limited.

- Common modes of failure of relocated infrastructure would include future lateral channel migration, which may erode the infrastructure. In the case of levee relocation, modes of failure are seepage through the embankment and levee foundation and slope failure. Countermeasures are future bank protection, adequate drainage, foundation preparation, and suitable top width and side slopes.

2.1 General Range of Application

- Levees or other riverside facilities can be relocated on any river corridor where the channel is laterally confined by these structures.

- Riverside dikes and levees have been removed to provide for lateral channel and flood plain connectivity on the Puyallup River, Washington (Jennifer Bountry,2008, personal communication, U.S. Department of the Interior [Interior], Bureau of Reclamation [Reclamation], Technical Service Center [TSC], Sedimentation and River Hydraulics Group, Denver Federal Center, Denver CO).

- 2008); Pite River, Sweden; Trinity River, California; and Chorro Creek, California (Kondolf et al. 2007). No documentation of geomorphic response was included in these examples.

2.2 Advantages and Disadvantages

2.2.1 Advantages

- In a study conducted of 18 flood alleviation schemes in England and Wales, the most stable schemes were those incorporating distant flood banks (levees set back) and two stage channels, because the sediment transport regime of the channel was not affected (Thorne et al. 1997).

- Sediment transport capacity is expected to decrease for discharges that flow overbank, allowing for a more natural exchange of sediment transport and deposition within the flood plain (Marriott 1996; Brookes 1996; Bauer et al. 2004). Having more overbank flows potentially can reduce the effects of main channel lowering as a result of narrowing the flood plain corridor with human infrastructure (Kondolf et al. 2007). Sediment deposition would be expected in the newly connected flood plain (Marriot 1996).

- Bed shear stress in incised channels is reduced by levee relocation (Bravard et al. 1999)

- In environmentally sensitive areas, construction of works in the river channel is avoided, benefiting both the RGSM and the Southwestern willow flycatcher (SWFL).

- There is no direct effect upon the main channel river characteristics, which can be an advantage or disadvantage depending upon the situation.

- In the case of migrating incised channels, continued lateral and downvalley migration can result in establishing a new inset flood plain with hydraulic connectivity as well as a functioning riparian zone located within the inset flood plain. Longer meander bends may establish greater pool depths, and eroding banks with vegetation falling into the channel provide fish cover and habitat complexity.

- This may or may not be the least expensive alternative.

- If project lands are involved or the landowner is willing, then infrastructure relocation will allow the river the greatest flexibility to adjust its hydraulic geometry and to migrate laterally as determined by channel processes.

- Flood alleviation schemes that include “distant flood banks” or levees that are at the edge of the meander belt width have been shown to provide the necessary flood carrying capacity while having minimal effect upon sediment transport, bed elevation, and flood plain connectivity and can have minimal effect upon aquatic and riparian environments (Newson et al. 1997; Thorne et al. 1997). For braided channels, it is also best for levees to be at the edge of the braid plain to realize the same benefits.

- Infrastructure relocation is generally favorable for riparian health by allowing greater lateral movement of river and broadening the flood plain.

- Beneficial if high-flow channels and backwater areas are formed that support a higher water table to establish and maintain riparian vegetation.

- Eroding banks can destroy large native trees that serve as a seed source for newly established flood plain surfaces, but the advantage is that these processes provide opportunity for habitat regeneration.

- Lateral bank movement (i.e., erosion) should result in deposition of sediments downstream, forming bars and low terraces where vegetation and variable depth and velocity RGSM habitat can become established and protected from subsequent high flows. High flows may scour newly established vegetation, which could create RGSM habitat.

- The broadening of the flood plain, resulting from lateral bank movement, also creates RGSM nursery habitat. Overbanking flows in the broader, more connected flood plain increase the amount of wetted areas for egg entrainment and larval development.

- Could develop an inset flood plain increasing overbank flooding and riparian zones that creates variable depth and velocity habitat types, including potential high-flow, low velocity fish habitat.

- Bend migration and associated bar deposition provide more opportunity for successional age classes of potentially native vegetation.

2.2.2 Disadvantages

- The land use may need to be altered. Changes in land use may be dictated by public policy or private preferences. Changes in land use may not be acceptable to landowners and water users.

- Infrastructure would need to be set back beyond the edge of the meander belt or braid plain; otherwise, bank erosion and stability problems may, in time, relocate to the new infrastructure location.

- Protection of infrastructure/bank stabilization still may be required as the channel migration approaches infrastructure.

- Lateral movement may erode banks, destroying large native trees that serve as a seed source for newly established areas downstream, but the advantage is that these processes provide opportunity for habitat regeneration.

- May or may not be the least expensive alternative.

- New easements, change in land use, and/or land purchase may be necessary to relocate riverside infrastructure.

2.3 Requirements

- General guidelines do not exist for levee or infrastructure relocation or for restoration of flood plain and riparian zones (Brookes 1996).

- Maintaining the existing function of levees, canals, drains, culverts, siphons, utilities, and riverside roads will usually be a requirement to provide beneficiaries of these facilities with the same level of service realized prior to relocation.

- Short-term considerations include planning, design, and construction sequencing.

- Relocated levee requirements include an adequate top width and stable side slopes, height, seepage protection, and a stable foundation. Either a spoil levee or an engineered levee, if it is warranted, can be used.

- The flood and riverside drain carrying capacity will need to be evaluated with the new channel length and flatter slope to ensure that capacity is maintained.

- Sufficient land area is necessary to relocate riverside facilities.

- The width and location of levee relocation should be based upon the river corridor, meander belt, or the braidplain width. Methods for estimating the river corridor width are found in Shields (1996), Ward et al. (2002), and Rapp and Abbe (2003). Current evaluation methods will give an indication of meander migration potential, but there is not a great degree of confidence in accurately predicting future channel locations. Lagasse et al. (2004) provide a method for predicting future channel migration.

- Long-term considerations include estimating the dynamic equilibrium channel length and potential channel plan view. This is especially helpful when the relocation is only for a short distance. This will help determine the optimum geographic location and the degree of safety provided.

- The practical geographic location and alignment of levee or other infrastructure relocation projects will most often be dependent on local land use, land ownership and availability, economics, political preferences and constraints, and other physical constraints (Brookes 1996). Relocation also can be based upon site-specific flood plain and habitat objectives. For example, aligning the levee to preserve existing trees, shrubs, and riparian zones would preserve current habitat.

- During the short term, pre-emptive limited bank stabilization may be necessary to preserve the function of riverside levees and facilities prior to relocation. The pre-emptive bank stabilization could be removed upon completion of the relocation project.

- If the relocated levee or other infrastructure remains within the active river corridor or meander belt width, bank protection measures still may be required, at a future time, to protect against lateral migration.

- Access to the levee and drain will need to continue for routine future maintenance activities after levee relocation.

- Project considerations also should include connection of tributaries and riverside drainage facilities to the river. Local site conditions will determine the types of constructed works to facilitate tributary connectivity while maintaining flood protection.

- The amount and frequency of overbank flooding and flood plain connectivity should be determined to evaluate project benefits.

- Increased flood peaks in regulated rivers also may be necessary for flood plain connectivity to be improved as a result of infrastructure relocation.

- A high level of flood protection and infrastructure stability can be realized if the infrastructure is relocated outside the meander belt or braidplain width.

- The design flood criteria for levees that provide flood control may need to meet a Federal Emergency Management Agency (FEMA) requirement, which is 100-year return period peak discharge. The U.S. Army Corps of Engineers (USACE) criteria may result in less than 100-year return peak discharge or more than 100-year return peak discharge, depending upon the benefit cost ratio. Discussions with the USACE, and possibly FEMA, would be recommended prior to any levee relocation project implementation.

- The level of complexity for implementation and maintenance could range from low to very high, depending upon the type of facility to be relocated and local conditions. For levee and riverside drain relocation, the complexity would be fairly low. For siphons, roads, and utilities, the construction would be more complex.

- The project life will depend on whether the relocation is outside the meander belt or braidplain width. The project life most likely will be shorter when the relocation is within the meander belt width or braidplain, depending upon the rate of future lateral migration.

- Potential constructability issues include construction timing to avoid potential peak flow periods and the amount of material or infrastructure to be relocated. Generally, water quality permitting needs and requirements would be minimal for a relocation project when there is no construction planned within the river channel.

- Costs for relocating infrastructure are highly variable, depending on the length, lateral distance of relocation, land acquisition (if necessary), and structure type. Typical costs could range from several hundred thousand dollars to several million dollars per mile. Ongoing maintenance costs will depend on the type of relocated facility and whether future bank protection will be necessary. Initial costs as well as maintenance costs should be estimated based on local conditions.

Chapter 3. Channel Modification

- Channel modifications are those actions that are used to reconstruct, relocate, and re-establish meander bends or relocate the channel in a more advantageous alignment consistent with project goals. Channel modification actions can also result in a larger channel capacity and change the channel shape. Excavating new channel alignments and plugging the existing channel entrance are part of this method.

- The entire river cross section and/or the channel locations can be affected by this method, whereas bank stabilization actions generally modify one bank line.

- Channel modification techniques have been used to address geomorphic disequilibrium, thereby reducing risks of bank erosion (Washington Department of Fish and Wildlife [WDFW] 2003).

- The scale of effects can be large for these methods, including changes to channel processes, channel profile, plan shape, cross section, bed elevation, and/or channel location in a segment or longer reach. Therefore, a thorough understanding of fluvial geomorphic processes is an essential part of developing channel modification projects. Changes to the channel profile or plan shape will result in a change in the energy and sediment transport capacity (WDFW 2003).

- Estimates of future channel response can be improved significantly by using the Sedimentation and River Hydraulics One-Dimensional (SRH-1D) and Sedimentation and River Hydraulics Two-Dimensional (SRH-2D) Models.

3.1 Complete Channel Reconstruction and Maintenance (e.g., Temporary Channel into Elephant Butte)

- The confidence level is Level 3.

- Channel reconstruction and maintenance, via excavation, provide a river channel through the delta sediment deposits at the headwaters of Elephant Butte Reservoir, thus maximizing sediment transport, resulting in lower upstream bed elevations, increased water delivery, and improved channel peak flow capacity.

The valley slope is flatter than the slope needed to transport the incoming sediment supply in the headwater area of Elephant Butte Reservoir. This was the case even before the reservoir was constructed (Leopold et al. 1964). The incoming sediment supply has reduced as a result of upstream reservoir construction and reduced sediment supply from tributary inflow, yet it still remains too large to be transported to the reservoir without mechanical removal.

- Mechanical removal of sediment deposits in river channels in this reach has been an ongoing activity since the project was authorized in the Flood Control Acts of 1948 and 1950.

- The minimum channel section that will transport the majority of the incoming sediment supply is excavated, maintained, and periodically relocated across the delta of Elephant Butte Reservoir. The nominal capacity of these channels since about 1991 has been 5,000 cfs.

- Capacity of the Temporary Channel could be increased by relocating or setting back the berms that form the current channel bank lines. This would lead to the development of a more naturally functioning flood plain and capture flow events above 5,000 cfs. Another term for this channel cross section is a “compound channel.”

- Reconstruction and maintenance of a channel into Elephant Butte provide for maximum water delivery to Elephant Butte Reservoir and maximum sediment transport into the reservoir pool. Estimates of the amount of water salvaged by the channel have been made by the area office.

- Channel reconstruction and maintenance reduce riverbed aggradation, which can occur nearly to San Antonio, New Mexico.

- Unabated riverbed aggradation will adversely impact flood carrying capacity and valley drainage. Should channel aggradation continue, eventually, there would be no ability for valley drainage and irrigation return flows to exit the Bosque del Apache National Wildlife Refuge.

3.1.1 General Range of Application

- This method is applied exclusively to the headwaters reach of Elephant Butte Reservoir (river mile [RM] 60 to the Narrows of Elephant Butte Reservoir).

- Bed lowering has occurred as a result of the lower reservoir pool and reconstruction and maintenance of a channel through the delta. Bed lowering currently extends to about the south boundary of the Bosque Del Apache or about 14 miles upstream of RM 60. RM 60 is where the Temporary Channel reconstruction began in the early to mid-1990s. There have been 14 miles of Temporary Channel construction between 2000–2006.

- Periodic sediment removal from local areas of deposition within the temporary channel is necessary to maintain channel capacity. When the reservoir level increases, sediments can deposit upstream in the temporary channel, requiring periodic removal. Immediately upstream of the reservoir pool, sediment deposition occurs on a continual basis. Thus, maintenance of the Temporary Channel is an ongoing activity.

- When a single channel is formed by excavation, river velocities are increased above the velocity found in delta distributary channels. This, coupled with increased slope by hydraulically connecting the river to the reservoir pool, results in greater sediment transport. Delta distributary channels are often disconnected from channels that flow into the reservoir.

3.1.2 Advantages and Disadvantages

3.1.2.1 Advantages

- Reconstruction and maintenance of the channel through the delta of Elephant Butte Reservoir provide for effective water delivery to the reservoir pool.

- Reconstruction and maintenance of the channel provide effective sediment delivery into the reservoir.

- The channel bed elevation upstream of the Temporary Channel is lowered as a result of channel excavation and increased sediment transport rates; thus, the water surface elevation is lowered, which increases flood carrying capacity of the main channel and floodway. Lowering the river channel also improves valley drainage. Valley drainage would be compromised by continued channel aggradation. Lack of valley drainage could result in waters being retained indefinitely in ponds in the Bosque del Apache National Wildlife Refuge.

- The Temporary Channel causes most of the delta sediment deposition to occur in the main pool of the reservoir instead of in the upstream channel. Absent the channel excavation, delta sediment deposition could extend many miles upstream past San Antonio to the mouth of Arroyo de las Canas. Bank erosion in the reconstructed channel area is generally minimal because banks are largely comprised of silt and clay material.

- Extensive SWFL habitat has been formed in the headwaters of Elephant Butte Reservoir. This habitat formed on sediments deposited when flows were directed to the east side of the reservoir between range lines 24 and about 28. When the lake elevation receded, Low Flow Conveyance Channel (LFCC) drainage and irrigation return flows entered the area, providing a water source. If the location of sediment deposition was relocated and a water source provided, then new, younger habitat could be established for the SWFL. This has occurred as the reservoir has receded below range line 28. Once the habitat reaches a certain height, its value for SWFL diminishes; thus, developing new habitat areas may become an important habitat objective. Lateral changes in the sediment deposition locations and providing a water source also would provide for new, younger SWFL habitat. On the other hand, should sediment deposit in the main channel, a breach into this valuable habitat could occur. A breach would result in sediment deposition, adversely affecting the current value. Until new habitat is available, the current channel maintenance activities provide for continuing viability of the current habitat area.

- Distributary channels, formed as a result of sediment filling the existing river channel, potentially would lead to stranding of RGSM because many of these channels do not connect back to a main river channel. The amount of distributary channels is reduced with this method, while the amount of flow water and habitat more connected to the main channel is increased.

- If medial and alternate bars remain as part of ongoing maintenance, then low depth and velocity habitat can be preserved.

3.1.2.2 Disadvantages

- Channel maintenance is an ongoing maintenance activity because the valley slope is too flat to transport the incoming sediment supply and sediment deposits at the upstream end of the reservoir pool annually. In this valley, these sediment deposits completely block the main channel, leading to water loss and loss of valley drainage.

- RGSM and their semibuoyant eggs entering the reconstructed channel during high flows generally are carried to the reservoir due to lack of channel features that slow the downstream transport or retain the eggs, and they are subject to predation by bass residing in the reservoir pool.

- Channel bed lowering upstream of the Temporary Channel results in a lower water surface elevation and less flood plain connectivity.

- Can reduce the surface distribution of water, eliminating the potential for braiding of river channel, formation of high-flow channels, or formation of backwater areas; promotes headcutting by reducing the base level of the river through the delta.

- Can lower the ground water level within a significant zone adjacent to the channel, which could result in stress and/or mortality of riparian vegetation.

- Eliminates the potential for the development of river bars where vegetation could become established and develop.

- Should this bed lowering extend below the root zone of the current elevation riparian area, lateral migration may ensue, leading to the formation of an inset flood plain.

- More uniform width, depth, and velocity. Limited amount of variable depth and velocity habitat; and there is a low amount of cover. Also, there would be a low amount of no velocity nursery habitat. The excavated channel can carry RGSM eggs into the reservoir where recruitment is negligible. This action and subsequent maintenance reduce backwater formation, isolate the flood plain, and reduce the potential for braiding.

3.1.3 Requirements

- The width, slope, alignment, and channel cross section must be designed so that the sediment transport rate through the Temporary Channel would equal or exceed incoming sediment supply so that upstream channel bed lowering occurs.

- The channel should be reconstructed in such a manner to provide some environmental features such as sediment bars, vegetated overbank areas, and mildly sinuous channel planform, while maintaining sediment transport capability.

- As sediment deposits in the delta, especially when the reservoir level rises above the Narrows of Elephant Butte Reservoir, new higher elevation flood plain, main channel, and distributary channels develop in the valley floor. When the deposits become sufficiently high to result in upstream channel aggradation, relocating the channel to topographic low areas in the valley floor is warranted. The new channel alignment through valley low areas will have a greater slope, thereby maximizing sediment transport rates. The practice of relocating the channel every few years results in different age classes of riparian vegetation developing and provides for a more even distribution of sediment deposition in the delta reach.

- The level of reliability is high when maintenance excavation continues on about an annual basis and the reservoir remains near or below the Narrows.

- Constructability issues include working in soft, unstable soil conditions with flowing water and limited access. The effects of soft, unstable soil conditions with flowing water upon construction is overcome through the use of amphibious excavators.

- The level of complexity can be high due to difficult site conditions.
- The channel is generally designed to accommodate 5,000 cfs,, which is less than the 2-year flood. This is due to the cost of the construction.
- The project life depends on the reservoir elevation. Should the reservoir rapidly rise as a result of large inflows, then the project life is short. In general, project life with annual sediment removal maintenance depends on reservoir stage.

3.2 Channel Relocation Using Pilot Channel or Pilot Cuts (also Includes Re-meandering or Meander Restoration, and Re-establishing Historical Abandoned Oxbows)

- The confidence level is Level 1 and Level 2 (re-meandering or meander restoration has some documentation, while pilot cuts and pilot channel have been relatively undocumented).
- Channel relocation usually is used to move a channel away from an eroding bank line (WDFW 2003).
- Channels can be entirely relocated to a new alignment or moved laterally within the existing alignment (WDFW 2003).
- Channel relocation can be used to create a more sinuous, longer channel to reduce channel slope and channel incision (Bravard et al. 1999; Watson et al. 2005). This brings sediment transport capacity more in balance with sediment supply in supply-limited, degrading rivers.
- Pilot channels are excavated channels along a desired alignment that is consistent with project purposes.
- Pilot channels are excavated to a narrower width than the current main channel to reduce construction costs and reduce the size of sediment disposal requirements. Excavated sediments typically form the banks of the relocated channel. By constructing a narrower channel than exists in the reach, the excavated sediments lining both banks will transport downstream as the channel establishes its dynamic equilibrium width. Excavated sediments along the pilot channel banks may need to be repositioned over time to fully

be transported downstream by high flows. The sediment available for transport downstream provides a small amount of sediment enrichment.

- The method generally includes vegetation clearing so that the pilot channel widens to the equilibrium width. Bank lowering also can aid in establishing the new channel width. Bank lowering could include creating a compound channel section and widening the channel.

- Channel relocation using pilot channels or pilot cuts has been documented in the literature, mainly for channel shortening projects. Historically, thousands of channels have been straightened to accommodate roadways, bridges, and other transportation facilities. These types of projects have been shown to have an adverse effect upon the river channel, flood plain, and riparian zone (Brookes 1988; Parker and Andrus 1976; Piest et al. 1977; and others). When a channel is shortened, slope, channel velocity, and sediment transport increase. This can lead to upstream channel incision, narrowing, and reduced flood plain connectivity. Downstream, the effects can be aggradation, channel widening, and loss of flood capacity. It is important to note that one of the primary goals of the channel narrowing and limited straightening on the Middle Rio Grande was to promote increased sediment transport, reduce channel aggradation, and increase flood carrying capacity.

- Channel relocation can be used to restore meander bends and increase the channel length if there is sufficient land available for meandering to occur. Increasing the channel length can result in increased hydraulic roughness, decreased bed load transport rates, decreased slope, and general increase in channel stability (Brookes 1996; Brookes et al. 1996; McCullah and Gray 2005). Re-establishing a river channel in historic oxbows, especially those disconnected as a result of past channelization, can have the same benefits as channel relocation to restore meander bends.

- In reaches where there is active incision/degradation due to sediment supply being less than the transport capacity, a longer channel length can reduce or eliminate continued incision. Reduced channel length through restoring meander bends has resulted in eliminating potential for erosion in some low energy rivers (Shields et al. 1999).

- Channel relocation does not always induce channel instability upstream or downstream, depending upon local site conditions (Biedenharn et al. 1997). Relocated channels can be stable provided that the sediment transport capacity is in balance with supply.

- This method has been used with some success on the Middle Rio Grande at Santa Ana Pueblo and the Bernalillo site.

- May initiate channel processes where new areas of bank erosion and deposition occur naturally, depending upon the channel curvature, local soil types, geology, and geomorphology (McCullah and Gray 2005); thus, new areas where site-specific bank erosion issues will occur are also possible.

- Re-meandering, in some cases, can rehabilitate ecological functions and increase visual diversity (McCullah and Gray 2005).

- Can increase the complexity of habitat by creating connected flood plain/wetted areas for RGSM egg entrainment and larval development. More variable depth and velocity habitat is created, along with no velocity areas needed for RGSM nursery habitat. Reestablishing oxbows in this section refers to channel relocation. For applying oxbows for creating and maintaining side channels, refer to section 3.1.

- Environmental benefits can be realized as a result of the formation of a new channel, while the abandoned channel can become a wetland, a backwater area, or a high-flow secondary channel.

- Sediment deposition in the abandoned channel can reduce the effective lifespan of remnant channel habitat.

- One of the most common circumstances for failure is inadequate sediment transport capacity in the re-meandered channel, leading to sediment deposition and reduced channel capacity. A second mode of failure can be when the channel plug or dike constructed at the junction of the existing channel and the relocated channel is washed away, leading to the flow being recaptured by the previous channel (McCullah and Gray 2005).

3.2.1 General Range of Application

- Channel relocation and re-meandering have been done on the Danube River, Germany (Bravard et al. 1999); many rivers in Denmark (Nielsen 1996; Shields et al. 1999); and Chorro Creek in the United States (Shields et al. 1999). Additional cases are described in Brookes and Shields (1996).

- The concept of pilot channels may not have wide application on other rivers but has been successfully used on the Middle Rio Grande.

- Channel relocation and meander restoration are most useful when channels have been straightened, channelized, or the flood plain width has been reduced, as well as where valley morphology supports meandering channels.

3.2.2 Advantages and Disadvantages

3.2.2.1 Advantages

- The river channel can be relocated away from infrastructure needing protection instead of stabilizing the riverbank.

- Excavating a narrower channel than the dynamic equilibrium width reduces construction costs when compared to full excavation.

- Erosion of the excavated sediments lining the riverbed provides a small amount of sediment enrichment to downstream reaches.

- Can be used to establish greater flood plain connectivity. If the channel is incised, then flood plain connectivity may need to be accompanied by terrace lowering.

- Greater flood plain connectivity also can be realized by relocating the river through recent depositional surfaces such as bars and inset flood plain features. (Inset flood plain features occur in an incised channel where a new, smaller flood plain is created within the historical higher elevation flood plain).

- Meandering alignments are visually appealing, ecologically valuable, and more sustainable over the long term than straight alignments, which may be subject to excessive erosion and deposition patterns because the channel length is not compatible with local geomorphology. Well designed meandering alignments can achieve dynamic equilibrium where the channel slope remains relatively constant and the banks migrate laterally.

- Using abandoned oxbows can take advantage of the natural topography, especially where abandonment was a result of past channelization.

- Pilot channel construction in conjunction with channel widening and bank lowering can provide overbank flooding of cleared areas and the establishing riparian vegetation. Removing native riparian vegetation should be minimized.

- The original river channel could provide a suitable substrate for establishing and developing riparian vegetation, assuming hydrologic conditions are favorable (i.e., saturated/moist).

- Potential for establishing river meanders that can create more variable depth and velocity habitat, which is desirable for the RGSM. This can occur by meander migration creating bars, which increase the high-flow wetted area and bank line embayments needed for egg entrainment and larval development.

3.2.2.2 Disadvantages

- If bed level lowering or a certain channel slope is part of the project plan, and there is more than about 5 percent (%) gravel or cobble sizes in the area of the pilot channel, armoring will occur (Pemberton and Lara 1984), which may need to be removed so the river can reach the desired bed elevation.

- May take several years for the pilot channel to reach its new dynamic equilibrium width, depending upon the magnitude and duration of peak flows.

- Excavated sediments often are piled along the pilot channel banks to be eroded by high flows. These excavated sediment piles may need to be repositioned in the years following initial construction so that they will be completely removed.

- Often, channel straightening is associated with channel deepening or incision, and the bed of abandoned meanders could be many feet higher than the current channel. In these situations, re-meandering or reconnecting oxbows may not provide desired flood plain connectivity.

- Channel re-meandering requires the availability of land to re-create a longer, more sinuous alignment and to allow future lateral migration.

- Channel response to re-meandering is difficult to predict with precision, and applications should be limited to sites with a low probability of loss of life or severe damage to riverside facilities and structures (McCullah and Gray 2005). Additional methods (found in this document) also could be added to use this method while protecting riverside facilities and infrastructure.

- Resources should be available, in most cases, for regular maintenance due to the inability to precisely predict future channel conditions (McCullah and Gray 2005).

- Riparian vegetation adjacent to the original channel could be deprived of surface flows and a lower water table, resulting in stress or mortality.

- While the channel is widening to the dynamic equilibrium width, over a several year period, the narrow channel has high-flow and uniform depth conditions, which is poor quality RGSM habitat. Once the equilibrium width is achieved, habitat should be similar to prechannel relocation conditions.

3.2.3 Requirements

- There are no generally accepted guidelines for channel relocation and re-meandering. Shields (1996) reviewed four different methods for designing meander rehabilitation. Several methods are described in Natural Resources Conservation Service (NRCS) (2007). The range of variability in these methods is great. The method of Julien and Wargadalem (1995) also can be used to estimate future channel slope and width based upon incoming sediment sizes and peak discharge. The new equilibrium channel width and flow depth will be determined by the size and amount of upstream sediment being supplied to the relocated reach, discharge, and the new channel alignment.

- If more than 5% gravel or cobble size materials are in the new bed of the pilot channel, these sizes will influence the new dynamic equilibrium width, bed slope, and substrate size. These sizes can lead to bed armoring.

  Careful analysis of sedimentation and erosion is necessary to ensure the stability of the new channel (McCullah and Gray 2005). The sediment transport capacity for the new alignment and resulting channel slope should be evaluated carefully to ensure the transport capacity and sediment supply are in balance. This will reduce upstream and downstream bed level changes. In certain circumstances, it may be desirable for the re-aligned channel to have an increased sediment transport capacity and cause the upstream bed elevation to decrease.

- Re-establishing an oxbow abandoned or cutoff by past channelization requires the same design considerations, geomorphic analysis, and requirements as any re-meandering project. Re-establishing an oxbow abandoned by natural processes should only be considered after detailed geomorphic analysis.

- A constructed width as narrow as 25 feet has been used successfully on the Middle Rio Grande when bed sediments are medium sand sizes. This width can carry low flows immediately following construction to minimize excavation costs and widen during high-flow events.

- In some cases, it may be beneficial to excavate part of a new channel, plant vegetation along the new channel alignment, and then allow several years for revegetation to develop prior to diverting flows into the new alignment (McCullah and Gray 2005).

- If the new channel alignment results in a shorter, steeper path for riverflows, countermeasures such as constructed riffles may be necessary to prevent upstream channel bed lowering. This is especially true in situations where the upstream channel is already incised and disconnected from the historical flood plain.

- The method is reliable as long as any sediment piles remaining as part of the construction are relocated, as needed, until excavated sediments are removed by riverflows. Another factor in reliability is to have enough land area for the relocated or re-meandered channel to adjust to the new dynamic equilibrium length and location.

- Factors that contribute to the stability of relocated or re-meandering channels include: growth of vegetation on the banks, some form of bank stabilization, the prior channel being stable, erosion resistance of bed or bank material, minimal change in channel length, check dam, preservations of original vegetation, and having a dual channel (Brice 1981).

- The method uses flows to determine the final width of the relocated channel, which is dependent upon the channel length and slope, incoming hydrology, and sediment supply and bed material size. Due to these conditions, the relocated channel generally would have a high level of reliability, durability, and a project life that could extend several decades.

- Maintenance requirements include possible repositioning of the sediment disposal piles if needed. In addition, selective sediment removal may be required as part of the river adjusting to channel lengthening to ensure that connectivity is maintained to the relocated features and abandoned oxbows.

- Level of complexity is generally high due to the difficulty of estimating future erosion and deposition patterns. The level of complexity also depends on local site conditions. For instance, restoring meander bends or relocating a channel that is incised is more complex than a channel that is connected with its flood plain.

- Potential construction issues include building a berm to close the existing river channel to divert flows into the relocation channel, cutting through old jetty jack fields, and preserving existing SWFL habitat and wetlands.

- Structural measures, such as a dike with riprap, may be required at the relocated channel entrance to prevent recapture of the river by erosion of the fill in the old channel entrance during high flows.

- Periodic visual monitoring and cross section surveys should be used to ensure the relocated channel is stable.

3.3 Island and Bank Clearing and Destabilization (Includes Channel Widening)

- The confidence level is Level 1.

- In river channels that are experiencing incision, flood plain disconnection, and are sediment supply-limited, clearing and destabilizing islands can provide flood plain connectivity, reduce island area, promote channel widening, and provide a small increase in sediment supply.

- Islands and banks can be cleared of vegetation and root plowed for destabilization to occur.

- Islands and banks can be cleared and destabilized for widening the channel at high flows and creating low-depth, low-velocity habitat.

- Islands and banks can be cleared and excavated to establish a wider channel creating lower velocity habitat.

- This method can be used to create two stage channels or lowered terraces or flood plains for greater flood plain connectivity. Excavation of the islands or bars may be necessary to lower their elevation for this purpose. Placing excavated sand material in the river channel can provide for a small amount of sediment enrichment. Sediments can be placed in areas of the channel where erosion will occur to enrich the sediment supply.

- On the Platte River in Nebraska, island and bar clearing and destabilization consist of an initial clearing and stockpiling, after which the vegetation stockpiles sit for a year and then are burned in place. After burning the vegetation piles, the cleared area is destabilized. (Timothy Randle, 2008, personal communication, Manager, Sedimentation and River Hydraulics Group, Interior, Reclamation, TSC, Denver, CO).

- On the Middle Rio Grande, there are many areas where the channel is narrowing and degrading. Areas that were the main channel are now flood plain or abandoned terraces. Areas that were the flood plain are now abandoned terraces. Sediments that historically have been mobilized at high flows are being stored in islands, bars, flood plains, and abandoned terraces.

- Bed shear stress is reduced through channel widening and, when the channel is widened, the slope increases (Jaeggi 1989; Habersack and Piegay 2008; Leon et al. 2009).

- For this method, a level of protection is difficult to access. The method does not provide direct bank protection but can be used to reduce erosive velocities and shear stresses. If the method is sustainable and the riverbank is a safe distance from the levee, the level of protection could be high.

- The goal is to promote a wider channel with greater flood plain connectivity and to balance sediment transport capacity with supply, thereby reducing channel incision.

- Channels can also be widened by excavation instead of clearing and destabilization.

- In the absence of documented reports and analysis, this section contains conceptualized channel responses.

3.3.1 General Range of Application

- In general, this technique is best used for river conditions where incision and channel narrowing have occurred and sediment supply is less than transport capacity.

- This technique has been used, in some cases, on the Middle Rio Grande, such as the Santa Ana Pueblo.

- This method is being used on the Platte River to clear cottonwood vegetation to increase the sight distance for endangered birds, mobilize sand, and promote a wider, shallower river (Lisa Fotherby, 2008, personal communication, Interior, Reclamation, TSC, Sedimentation and River Hydraulics Group, Denver Federal Center, Denver CO).

- Channel widening has become a common practice in Switzerland and Austria to restore rivers (Habersack and Piegay 2008) because the wider channel has a reduced bed shear stress (Bravard et al. 1999). Channel widening in these countries results in a locally steeper channel slope (Jaeggi and Zarn 1999).

- Vegetation from the active channel has been removed on several European rivers (Habersack and Piegay 2008), although no descriptions of the sites, criteria, or frequency of removal were given.

- If the cleared island or bar is not accessed by high flows, then vegetation will rapidly return. A countermeasure could be to alter the height of the cleared island or bar so that inundation and scouring flows occur annually.

- Ultimately, the future river width and bed elevation of the island and bank clearing and destabilization area will depend upon peak flows, amount and duration of inundation, sediment transport capacity, and sediment supply. Reaches that are widened will have less adjustment to reach dynamic equilibrium width. This method may have the most success in reaches where vegetation growth accelerated during drought years, followed by clearing and wetter high-flow years. During low-flow years, the vegetation growth can occur on surfaces normally mobilized by higher flow events. Providing clearing and destabilization during wetter years may result in a sustainable wider channel, as long as the higher flow period exists and sediment mining (bed degradation) does not occur.

- Island and bank clearing and destabilization are most sustainable when the flows are high enough and the surface elevation is low enough for bed surface sediments to mobilize annually (Timothy Randle, 2008, personal communication, Manager, Sedimentation and River Hydraulics Group, Interior, Reclamation, TSC, Denver, CO). The island could be partially or fully mobilized, depending upon local hydraulics, sediment transport capacity, and sediment supply. Reaches completely widened by excavation will also be most sustainable when flows are high enough to mobilize the bed surface of the widened channel annually.

- On the Platte River, vegetation modeling showed that annual scouring flows are necessary to maintain the area free from vegetation regrowth (Timothy Randle, 2008, personal communication, Manager, Sedimentation and River Hydraulics Group, Interior, Reclamation, TSC, Denver, CO).

- The level of protection is difficult to determine, but could be estimated by evaluating preproject and postproject water surface elevations and average channel velocity and shear stress.

3.3.2 Advantages and Disadvantages

3.3.2.1 Advantages

- Can be a means to enrich the sediment supply.

- Vegetation clearing and destabilization are relatively low cost, recognizing that, if the destabilization includes excavation, then project costs will increase.

- Can provide additional flood plain connectivity where channel incision has reduced or largely eliminated connectivity.

- Overbank flows that mobilize the surface sediments are essential to prevent vegetation from regrowing on cleared and/lowered islands or bars (Timothy Randle, 2008, personal communication, Manager, Sedimentation and River Hydraulics Group, Interior, Reclamation, TSC, Denver, CO).

- Island and bank destabilization could reduce further degradation of the channel and lowering of the water table if the channel is incised adjacent the island or bank.

- Sediments from destabilized areas may deposit new bars suitable for vegetation and RGSM habitat.

- Islands can become more connected to the main channel, thus providing RGSM with a variety of depth and velocity conditions. Greater wetted area during high flows creates opportunities for egg entrainment and larval habitat. If destabilized areas could be sloped after the initial erosion flow events, then better habitat would develop.

3.3.2.2 Disadvantages

- The new sediment balance may be temporary unless incoming loads also increased. On the Dray River (gravel bed), channel widening has reduced bed shear stress as well as increased lateral erosion processes and deposition of bed load. This led to channel aggradation and improved flood plain connectivity (Habersack and Piegay 2008). Reducing the sediment transport capacity such that bed load deposited is the key to this restoration on the Dray River (Muhar et al. 2008). No documentation of this approach type being successful in sand bedded channels was available.

- Whether cleared bars or island areas actually inundated depends on the magnitude of peak flows, which can be highly variable depending on weather and runoff conditions.

- Clearing and destabilization may need to be repeated for the island to remove the bar, or the elevation may need to be lowered. This is especially the case if there has been channel incision after the island or bar became established, rendering the bar or island surface less likely to become inundated during high flows.

- This method may provide local pockets of low velocity overbank flows at discharges greater than 2,500 cfs. Many channel features (important habitat for the RGSM) become inundated at 2,500 cfs with the current channel geometry. These pockets may require clearing about every 3 years, depending on the amount, timing, and duration of overbank flows. Areas on the Platte River that have been cleared of vegetation require reclearing about once every 3 years (Lisa Fotherby, 2008, personal communication, Interior, Reclamation, TSC, Sedimentation and River Hydraulics Group, Denver Federal Center, Denver CO), unless there are annual scouring flows (Timothy Randle, 2008, personal communication, Manager, Sedimentation and River Hydraulics Group, Interior, Reclamation, TSC, Denver, CO).

- Islands generally support a greater proportion of native vegetation than exotic. Removing mature native vegetation would limit the available seed source for newly established areas downstream.

- Channel widening by excavation can be costly and requires a method of material disposal. This can be overcome by creating stockpiles to be eroded during peak flows to enrich the downstream river with a small amount of sediment.

- Lower sediment loads and peak flows on the Middle Rio Grande may limit the sustainability of wider channels, especially when created by excavation.

- Clearing and destabilization would result in this habitat loss for SWFL.

- If the downstream sediment deposits were temporary and did not form bars, the habitat may not be useful for the RGSM.

3.3.3 Requirements

- The cleared, destabilized, and/or excavated surface will need to be at such an elevation that regular inundation occurs to function as a flood plain or as part of the high-flow channel.

- When islands or banks are destabilized, large (2–3 feet), deep root plows should be used several times through the area to provide sufficient destabilization for erosion to occur.

- If excavation is involved and material is being supplied to the river to provide sediment enrichment, periodic repositioning of the sediment deposits over a several year period may be required so that the excavated material completely becomes part of the sediment supply.

- A key element of this method is estimating the dynamic equilibrium bed slope and elevation. If the channel incises after the project is initiated, then some excavation may be needed so that the newly established surface will be regularly inundated. Leon et al. (2009) have shown that the river can adjust to a new equilibrium slope when the width changes. Field evidence from European rivers supports the conclusion that channel widening can result in a sustainable wider channel with increased bed elevation (Jaeggi and Zarn 1999). This may lead to the concept of initiating width changes instead of, or in combination with, island and bar clearing and destabilizing. The magnitude of slope change with width change may depend on the amount of the sediment load (Leon et al. 2009). Jaeggi (1989) also presented a method to predict the effect of width change on bed material load transport capacity. This method provides a family of solutions on a curve representing the relationship between sediment transport rate and channel width for a given slope and discharge.

- Capability to model the sustainability of vegetation removal based on scouring flows, desiccation (ground water table drops faster than plan root growth), inundation, and established vegetation growth rates is available as part of the SRH-1D model (Lisa Fotherby, 2008, personal communication, Interior, Reclamation, TSC, Sedimentation and River Hydraulics Group, Denver Federal Center, Denver CO).

- Islands generally provide higher quality riparian vegetation and habitat for wildlife species then shoreline habitats. Island habitat is isolated from human disturbance and some predators. Removal would result in this habitat loss.

- Islands that are subject to overbank flooding and are not perched high above the water table should not be removed or destabilized.

- A pilot channel or pilot cut, excavated through the island, may enable more sediment mobilization to take place.

- Active maintenance may be needed as described above.

- Potential construction issues will be: access through the existing riparian forest for equipment ingress and egress, operator entrance, refueling, and maintenance of equipment.

- The design flow should be the discharge that provides annual inundation with scouring flows.

- The durability and project life depend on the discharge and elevation of the cleared/destabilized island and whether annual inundation occurs with scouring flows, without additional channel degradation. Assuming these conditions are met, the project life can be multiple years.

- Implementation complexity could be medium to high, depending on the location where bar/island sediments can be placed in the river for removal by high flows, as well as the difficulty of obtaining access routes.

3.4 Pilot Cuts Through Sediment Plugs

- The confidence level is Level 2.

- On the Middle Rio Grande, sediment deposits can occur that entirely block the main channel with sediment. The river conditions for which plugs form are: (1) where there is channel aggradation over a long reach of river or

(2) where there is a downstream constriction that leads to sediment deposition in the main channel. Once channel aggradation reduces main channel capacity such that significant overbank flows occur, then sediment deposition is accelerated in the main channel, eventually leading to the complete plugging of the channel with sediment.

- The flood carrying capacity of the channel is restored to the preplug condition with this method.

- By connecting a small channel through the sediment plug, the hydraulic forces of the flow will transport sediment plug material downstream. Plugs are best removed by flows that do not go overbank. Overbank flows potentially would lead to reformation of the sediment plug.

- This activity consists of excavating a narrow width channel (20–30 feet) through areas where sediment deposits have completely obliterated or plugged the river channel. The action of excavating a small width channel through the sediment plug provides a hydraulic connection between the upstream and downstream river channels, which encourages flows to transport sediments forming the plug downstream, thereby opening the channel back up to the main river flows.

3.4.1 General Range of Application

- This technique is used with success on the Middle Rio Grande and is much cheaper than the method used prior to the mid-1980s. The method often used prior to the mid-1980s was to mechanically remove all of the plug deposits to the preplug channel dimensions.

- Pilot cuts through sediment plugs have been used successfully on the Middle Rio Grande upstream of and downstream from the San Marcial Railroad Bridge. The sediment plugs in this reach of the Middle Rio Grande are predominately comprised of very fine to medium sand sizes without cohesive material.

- Plug removal, using pilot cuts, can restore the channel to the preplug riverine condition, depending on the flow rate, sediment supply, and downstream channel bed slope and elevation. Plug removal restores flow velocity and depth conditions found in the main river channel.

- A level of protection is difficult to assess. No direct bank protection benefits are associated with this method. The peak flow channel capacity before and after plug removal is site specific and depends on the floodway width and levee elevation. The method has been shown, by observation, to provide the preplug formation channel capacity.

- A mode of failure of this method would be if the excavated channel is not sufficiently wide enough to carry eroding low flows. The 20- to 30-foot width has been used with success on the Middle Rio Grande. Another common mode of failure is the recurrence of the plugs during subsequent years. This method does not prevent future plug formation; it provides an economical way to remove plugs.

3.4.2 Advantages and Disadvantages

3.4.2.1 Advantages

- This method re-establishes presediment plug channel capacity.

- The method is inexpensive because excavated sediments are placed on top of the plug and are eroded downstream as flows widen out the channel to presediment plug conditions.

- Complete excavation of the sediment plug would result in the need for large sediment disposal areas and a much higher cost than the pilot cut method.

- Sediment plugs block the main channel, thereby eliminating main channel flow velocity and depth conditions. All of the river discharge travels through the flood plain as shallow flows that may become disconnected during low-flow periods. When riverflows become entirely overbank in thick riparian vegetation, the opportunity to develop significant side channels is reduced. This increases the potential for RGSM stranding. Thus, pilot cuts help maintain riverine fisheries environment and reduce the potential for stranding RGSM in the flood plain; however, RGSM currently do use the overbank channels through the riparian corridor created by the sediment plug.

- Pilot cuts would allow sediment transport downstream that could establish new areas for establishing and developing riparian vegetation and for RGSM habitat.

- While the sediment plugs block main channel flows, RGSM do use overbank channels through the riparian corridor created by the plug that does create the potential for increased RGSM stranding during receding flow conditions.

- Because bed elevation and slope are determined by downstream river conditions and sediment supply, the channel returns to the preplug condition after completely widening.

3.4.2.2 Disadvantages

- This method re-establishes the channel back to the presediment plug condition and does not address the root cause of the plug formation; therefore, plugs could reform during subsequent high-flow events.

- This method reduces the potential for developing multiple side channels, which could provide RGSM habitat through the riparian corridor.

- While the pilot cut is widening to its full width, the narrow channel has high velocity, which may create a locally incised channel. During this period of time in the local reach, the habitat would be less desirable for the RGSM. During this interim period while the river is widening in the plug areas, the transient channel bed lowering possibly can cause an upstream head cut, potentially temporarily lowering the water table. Once the channel reaches its full width, the bed elevation, slope, and habitat conditions would return to the preplug conditions.

- Pilot cuts would help reduce channel aggradation, sediment deposition in the immediate area, and limit overbank flooding potential, thereby reducing the potential for the establishment, development, and maintenance of the riparian vegetation within the immediate area.

3.4.3 Requirements

- Sediment deposits must be highly erodible, such as fine sand sizes, to enable the reintroduced flows to remove the plug. Re-introducing flows through the plug would not remove clay deposits and coarse sand deposits.

- The width and depth of the excavation must be sufficient enough to allow low discharges to flow through the plug.

- The level of reliability is high for plug removal. Using the method in the 1990s and as recently as 2005 have resulted in complete plug removal. As described above, the method does not eliminate future plug formation, only removal once a plug forms. No maintenance has been required for plug removal.

- Plug re-removal has been an ongoing periodic maintenance requirement.

- Construction issues include access requirements. Access through vegetated flood plain areas is necessary for equipment ingress and egress, fueling, operator access, and equipment maintenance.

- The durability and project life depend on the conditions that led to creation of the plug. As mentioned above, this method does not address the root cause, so durability and project life have not been determined.

- The level of implementation complexity is low.

3.5 Side Channels (High Flow, Perennial, and Oxbow Re-establishment)

- The confidence level is Level 2 and Level 1. The development of side channels has some documentation in selected cases; does not have the reliability of Level 3; and, for many river conditions, does not have a track record with field data.

- High-flow side channels consist of channels that can be accessed by river waters during peak flow events, which are adjacent to the main river channel located in the flood plain, bars, and islands.

- This method can reduce bed and bank erosion potential by reducing the discharge being carried in the main channel during large flow events. Main channel shear stress, velocity, and depths may be reduced, leading to reduced erosion. For incising channels, this could lead to sediment deposition in the main channel when the side channel carries sufficient flow to reduce the main channel sediment transport capacity below the supply.

- High-flow side channels may be reconnected where levees, roads, pushup berms, and other structures may have caused disconnection.

- High-flow side channels may be created by excavation. Excavation can consist of creating a completely new side channel or enlarging natural topographic low areas on bars or abandoned flood plain or abandoned terraces when the channel has incised.

- The importance of high-flow side channels has been documented in natural systems for passage of peak flows, reducing erosion potential of peak flows in the main channel, and ecosystem health (Richards 2004).

- High-flow side channels are often referred to as “flood bypass channels” (Richards 2004), “flood relief channels” (Hey 1994), or “overflow channels” (WDFW 2003).

- In rivers with suspended sediment, flood plains and high-flow side channels tend to store suspended sediment (Marriott 1996). In a natural system, high-flow side channels tend to fill with sediment over time (Hey 1994); and, as the channel avulses or migrates laterally, new side channels are created. When this natural channel dynamic condition does not exist, high-flow side channels tend to fill with sediment; and rehabilitating high-flow side channels provides an important morphological feature.

- High-flow side channels have the potential to decrease the peak flow water surface elevation in the main channel by increasing the total conveyance area.

3.5.1 General Range of Application

- High-flow side channels can be used on any river channel to reconnect flood plain areas. High-flow side channels will have greater sustainability in rivers with lower amounts of suspended sediment and sand bed load.

- Little information is available in the literature on the development and use of high-flow side channels.

- For channels experiencing incision, a conceptual channel response is that side channels may decrease main channel sediment transport capacity. This potentially will bring the sediment transport capacity closer to the sediment supply, thus decreasing the tendency for continued channel incision. In some cases, sediment transport capacity can reduce to the extent that sediment deposition will occur in the main channel. This could increase local slope, water surface elevation, and width-to-depth ratio (Schumm 1977). If the high-flow side channels result in reduced tendency for continued channel incision, or if there is sediment deposition in the main channel, the length of effects could be a considerable distance upstream of the project site. For channels experiencing sediment deposition and bed raising, a conceptual response is that high-flow side channels decrease sediment transport capacity, potentially leading to accelerated deposition. Accelerated deposition would lead to bed elevation rise, increased channel slope, and decreased width-to-depth ratio.

- The most common mode of failure is sediment deposition in the side channel or oxbow exit and entrance.

- No failure countermeasures are presented in the available literature. On Reclamation projects, small barbs or spur dikes have been used downstream from the entrance and exit to discourage sediment deposition. Small barbs or spur dikes create a zone of local velocity acceleration to encourage sediment transport through the side channel entrance and exit. In gravel bed systems, placing large woody debris (LWD) across the entrance has been suggested to create a local roughness zone that has local velocity acceleration, encouraging sediment transport through the side channel entrance.

- A second mode of failure is that a major shift in the river could capture the constructed channel during a large flood (WDFW 2003). Where the potential for this exists, constrictions made of boulders can be used to control how much flow the side channel can pass to reduce this risk. On the Middle Rio Grande, with its high level of flow control, there have not been observations of this mode of failure over about the last 10 years.

3.5.2 Advantages and Disadvantages

3.5.2.1 Advantages

- This method is a relatively inexpensive method of reconnecting abandoned flood plain areas, reducing velocity, depth, and shear stress in the main channel during high flows.

- Side channels and oxbows can improve wildlife and aesthetics.

- Conceptual channel response includes decrease main channel sediment transport capacity, which can halt channel incision and, in some cases, increase the bed elevation through sediment deposition. Side channels provide important off channel habitats for a variety of native plant and aquatic species.

- Smaller high-flow side channels would not decrease main channel sediment transport capacity in an amount large enough to lead to an increase in main channel bed elevation and yet would increase the habitat complexity with more variable depth and velocity habitat.

- High-flow channels transfer flows away from the main channel into adjacent flood plain areas, which raises the ground water and provides surface flows for riparian vegetation development.

- By transferring high flows to adjacent areas, degradation of the primary channel could be reduced and a higher water table would be maintained, which is beneficial to riparian vegetation.

- High-flow channels within riparian areas also aid in the dispersal of new sediments.

- This method can reconnect the flood plain to the channel, creating nursery habitat for RGSM. Side channels will create variable depth and velocity habitat, provide low velocity habitat during high flows for adult fish and developing larvae, and increased egg and larvae retention during high flows.

3.5.2.2 Disadvantages

- High-flow side channels can fill with sediment at the entrance and exit locations (Hey 1994). This is especially true for channels with large amounts of sand in suspension and traveling as bed load.

- Too much flow into the side channels can lead to excessive sediment deposition in the main channel, resulting in loss of floodflow capacity.

- Deposition of bed material and suspended sediment load in the entrance or exit will reduce or eliminate future effectiveness of side channels (Hey 1994).

- Removal of existing native vegetation to create high-flow channels would need to be considered. In situations requiring significant native vegetation removal to create the high-flow channel, construction may not be desirable.

3.5.3 Requirements

- There are no general guidelines for the application of this method (WDFW 2003).

- Very brief mention of this method is contained in Hey (1994), Nunnally and Shields (1985), and USACE (1989).

- Side channel can be constructed with variable dimensions that best match nearby side channels if they exist.

- Two-dimensional sediment transport modeling is recommended as a tool to determine the benefits, impacts, sustainability, and effects of entrance and exit sediment deposition countermeasures. This also will help to ensure that existing floodflow capacity is not compromised.

- The range of costs will be determined at a later time.

- The level of reliability depends on the amount and timing of sediment deposition in the side channel inlet and outlet.

- The design flood should not be impacted appreciably by using high-flow side channels. Peak flow carrying capacity may increase temporarily until sediment deposition occurs, unless countermeasures are effective over the long term.

- Maintenance requirements include removal and disposal of sediments deposited in the side channel (WDFW 2003).

- This method has a relatively low implementation complexity. Access requirements may be the largest item to overcome for construction and maintenance. Construction issues are relatively low and include access requirements, material disposal, and construction timing.

3.6 Longitudinal Bank Lowering or Compound Channels

- The confidence level is Level 2 and Level 1. (Compound channels are referred to in the literature often, and some design information is available, but there are few sets of field or lab data).

  Compound channels generally confine the range of normal flows to an inner channel, while floodflows expand to the larger channel constructed above the mean annual or 2-year return period flow by widening the flood plain (Brookes 1988; USACE 1989).

- When there is a need to reduce main channel bed shear stress, the flood plain can be established between the mean annual flood and 2-year return period peak flow water surface elevation (Brookes 1988; USACE 1989; Haltiner et al. 1996). The main channel also has been widened to reduce sediment transport capacity in channels that are incising (Bravard 1999).

- The range of discharges and specific configuration of terracing or flood plain lowering or widening should be adapted for local site conditions. For example, it may be more desirable, in cases where greater flood plain connectivity at lower flows is needed for habitat and sediment transport purposes, for the inner channel to contain flows lower than the mean annual or 2-year peak flow, and the enlarged channel would contain all other flows. In some cases, it may be more desirable for the outer channel to be accessed at larger flows than the mean annual or 2-year peak flow. Enlarging the channel from one bank also has been accomplished (Brookes 1988) so that a compound channel would exist along one bank.

- The channel described above is a two-stage compound channel. Three- or four-stage channels with multiple flood plain elevations may be appropriate to establish different age classes of riparian forest vegetation and have greater variability of flow depth and velocity for a wide range of discharges.

- Initiates some geomorphic and ecological processes within the levee system. Unlike restoration schemes in which meander patterns and channel bed elevations are fixed using structural measures, this approach uses geomorphic concepts to guide the channel from a present stage of instability towards dynamic equilibrium. Creating channel flood plain is a key component of this approach because it increases storage of floodflows and accommodates meander migration in the inner channel.

- Main channel depths, velocities, and shear stresses can be reduced, leading to lower sediment transport capacity and reduced bank erosion (McCullah and Gray 2005).

- Level of protection is difficult to assess. This method can address underlying causes of bank instability by initiating a different channel process. This could provide a high level of protection.

3.6.1 General Range of Application

- Two-stage channels have been used on the River Ray in Oxfordshire, United Kingdom (UK), and on the River Roding in Essex, England (Brookes 1988). They have been shown to be most applicable to relatively low bed load channels, with sand and silt bed material and cohesive banks (Brookes 1988).

- This type of channel is part of the USACE Flood Control Environmental Engineering manual published in 1989 (USACE 1989), and this method may have been applied to many rivers within the United States for which documentation is not readily available.

- Compound channels constructed by bank or terrace lowering can provide a means to re-establish flood plain connectivity in incised channels (Fishenich and Morrow 2000b).

- Compound channels have been used in Washington State (WDFW 2003).

- A common mode of failure (or reduced project benefits) is the deposition of sediment in the second stage channel (Geerling et al. 2008). Vegetation growth, which is desirable in many cases, also can initiate sediment deposition in the second stage channel. Developing flood plains at elevations where there are regular scouring flows will encourage the larger, second-stage, channel to maintain the originally constructed flood plain capacity and hydraulic efficiency over a longer term (Brookes 1988).

3.6.2 Advantages and Disadvantages

3.6.2.1 Advantages

- Main channel shear stress can be reduced, resulting in lower tendency for channel incision (WDFW 2003; Fishenich and Morrow 2000b).

- Can result in an inner low-flow meandering channel within the confines of the second-stage wider channel (Shields et al. 1999; Thorne and Soar 2000).

- Increasing vegetation in a lowered terrace that is frequently inundated can result in increased ground water storage during flood events, which will be released during base flow conditions.

- Water surface elevation during high flows can be reduced because there is increased flow width.

- Reconnecting the channel to its flood plain can increase storage of flood flows (Shields et al. 1999).

- Two-stage channels have been shown to provide necessary flood-carrying capacity while having minimal effect upon sediment transport, bed elevation when a channel is near dynamic equilibrium (Newson et al. 1997).

- This is a conceptual summary of the geomorphic river response to lowering the flood plain or terrace adjacent to an incised channel to create a two-stage channel. This description applies where there is some sediment being transported in suspension. The two-stage channel will cause increased flow width, decreased main channel velocity depth and shear stress, and reduced sediment transport capacity when compared to the original incised channel. After the two-stage channel is created, overall sediment transport capacity will decrease, potentially bringing sediment transport capacity in balance with sediment supply. This will slow or halt channel incision. Sediment supply may be larger than capacity, resulting in channel deposition. During flow events that inundate the second-stage channel, sediment deposition will occur in the newly established flood plain. Over time, the sediment deposition and vegetation growth in the flood plain may reduce overbank conveyance capacity, potentially leading to higher velocities in the main channel again. This could re-engage incision processes in the main channel. The time scales and magnitudes of these conceptual responses are unknown at the present time and will depend on the width and elevation of flood plain or terrace lowering, the amount of bed material and suspended sediment load, and frequency of inundation. This method has the potential to re-establish pockets of flood plain connectivity for a significant number of years.

- Excavated channel material can provide downstream sediment enrichment.

- The flood plain vegetation should provide additional bank stability over the long term.

- Promotes periodic overbank flooding of exposed soils favorable for the establishment of riparian vegetation.

- Reduces the potential for channel degradation, thereby maintaining a higher water table and connectivity with backwaters and side channels.

- Backwater areas and/or high-flow channels may become established, maintaining a higher water table. Growth of native riparian vegetation can be enhanced.

- Increased overbank flooding creates variable depth and velocity habitat, including potential spring nursery habitat even if sediment is deposited during high flows. Vegetation in the lowered bank can create slackwater and cover.

3.6.2.2 Disadvantages

- Riparian vegetation will grow in the flood plain. This vegetation growth may restrict floodflows in the overbank area, resulting in more discharge in the main or low-flow channel than when originally constructed. This will need to be considered during the planning and design phases.

- Can result in future sediment deposition in the lowered inundated areas (Brookes 1996). Deposition of bed material and suspended sediment load in the entrance or exit can reduce or eliminate future effectiveness of terrace lowering (Hey 1994).

- Longitudinal natural sand levees may form at the interface between the inner and outer (second-stage) channels, reducing future effectiveness.

- Native vegetation may be removed as part of the construction process.

- Any habitat improvements for the RGSM may last a few years due to sediment deposition in the lowered bank areas.

3.6.3 Requirements

- No design guidelines exist because these types of projects are relatively complex and have a high degree of variability (WDFW 2003).

- Requirements are included as a composite of available literature and conceptual design needs.

- The inner channel should be designed to be sustainable with the low-flow sediment size and load, as well as hydrology.

- The elevation and width of the second-stage channel should be designed to be inundated at the elevation that best suits local conditions for improving habitat and reducing shear stress, depth, velocity, and sediment transport capacity. Peak design flow water surface elevation, construction cost, and excavated material disposal also will be considerations.

- A decision would need to be made whether or not scouring flows are desired in the second-stage channel.

- Excavated material could be relocated within the low-flow channel to provide downstream sediment enrichment. Excavated material may need to be repositioned for several years before it is completely removed by high flows.

- Hydraulic aspects of overbank flow are complex (Brookes 1988) and generally require multidimensional modeling to determine the effects of the compound channel on sediment transport, flood peak water surface elations, scouring flows, and sustainability.

- Significant shear stress on the interface between the main channel and the overbank, due to lateral momentum exchange, must be accounted for in determining roughness for modeling. Thorne and Soar (2000) have developed a method to determine the Mannings 'N' multiplier for compound channels.

- This method can have a relatively high reliability if the newly established channel process is sustainable.

- Ranges of costs will be determined at a later time.

- This method has a relatively low implementation complexity. Access requirements may be the largest item to overcome for construction and maintenance. Construction issues are relatively low and include access requirements, material disposal, and construction timing. Material disposal may be the largest issue. Material from the lowered terrace can be placed in the channel for erosion by higher flows. Excavated material may need to be repositioned over a several-year period for flows to completely remove all sediments.

- The design flood for the two-stage channel could be a 10- to 25-year event, depending on the terrace elevation and existing channel capacity. More important to the design is the frequency when flows reach an elevation where they begin to flow into the second-stage channel. The discharge when waters begin to flow in the second-stage channel should be the value that best balances sediment transport capacity with supply.

- If the sediment transport is in balance with supply, including some overbank deposits, then the durability, design life, and project life would be long, potentially extending several decades.

- Maintenance requirements may include selective sediment removal from the second-stage channel surface and repositioning excavated material in the river periodically until it is completely eroded by high flows.

3.7 Longitudinal Dikes (Includes Training Dikes, Freeboard Dikes, Culverts, and Low Water Crossings)

- The confidence level is between:
  - Level 2 because there is good design information on the height assuming a fixed bed.
  - Level 3 because there is less knowledge of height and elevation for the mobile bed case and for using native material for dike construction. Native material is the least expensive; however, it may not be suitable to prevent seepage or soil mechanics failures. In addition, compaction may not be uniform.

Longitudinal Dikes

- Are parallel to the river and include training dikes, freeboard dikes, and the associated culverts and floodwater crossing structures.
- These features generally do not provide flood protection and function at lower frequency flows, such as the 2- to-5-year peak discharge with some freeboard.

Training Dikes

- Have been used where sediment plugs have formed. The objective is to concentrate high flows to a narrower width of the flood plain, thereby increasing main channel velocity, sediment transport rates, and channel capacity (Brookes 1988). This reduces the likelihood of future plug formation.
- Training dikes consist of a dike constructed along the river and set back to avoid toe erosion and at an elevation to accomplish the above objective; but they do not provide flood protection.

Freeboard Dikes

- Have been used on the Middle Rio Grande to raise the riverbank to prevent flooding upstream of diversion dams in the Velarde to the mouth of the Rio Chama reach and for increasing channel capacity in the Elephant Butte to Caballo Dam reach.

- Consist of a dike along the riverbank, or set back, and designed to contain the 2-year return period peak flow, with 2–3 feet of freeboard to provide added protection.

Culverts

- Training dikes have the effect of reducing flood plain inundation levels and frequency. Culverts can be used to wet the flood plain. For this application, culverts are placed at strategic elevations and locations, such that the flood plain can be inundated to similar levels and frequency as existed prior to the training dike installation. This also provides an opportunity to alter the flood plain inundation level and frequency if changes are beneficial to the site ecology. Concentrating flows to a narrower area via training dikes can result in a higher water surface elevation, which could allow the flood plain to be wetted more frequently.

- Freeboard dikes also act to contain flows, to the design discharge, in the main channel, thus preventing inundation of adjoining lands. The freeboard dikes also prevent surface runoff from flowing into the river during low river stages. Culverts can be used to provide drainage through freeboard dikes. The culverts are constructed at elevations of the adjoining lands and located in strategic locations that use the existing topography and surface runoff flow paths to maximize the flow through the culverts to the river.

Low Water Crossings

- Training dikes act to contain the flow and reduce flood plain inundation levels and frequency. Low water crossings are depressions placed in training dikes to allow controlled overtopping to provide water to inundate the adjoining flood plain at strategic discharges. The name “low water crossing” refers to the depth of flow in the crossing and not the river.

- The low water crossings are lined with riprap and have a suitable slope on the land side of the training dike to remain stable during high-flow events.

3.7.1 General Range of Application

Training Dikes

- Training dikes are applicable to all types of channels: gravel bed, sand bed, and silt and clay bed, meandering, braided, anastomosing, etc. Training dikes of various sizes (and in the form of flood control levees) have been used extensively on rivers throughout the United States (Environmental Defense 2002) and,indeed, the world (Brookes 1988).

- Recognize that, in this application, the dikes are not constructed for flood control but, rather, to increase channel and sediment transport capacity. The effects of training dikes are similar to flood control levees, except that training dikes implemented on the Middle Rio Grande occur over much shorter distances than typical levees. The other significant difference is that training dikes are implemented to contain the 2- to 5-year return period peak flow instead of the 50- or 100-year peak flow. Studies in Europe and the United States were conducted for levees and flood banks (UK term) (Brookes 1988; Mount 1995; Thorne et al. 1997; Environmental Defense 2002). Common modes of failure are unstable slopes, unstable foundations, seepage, erosion due to lateral channel migration (Brookes 1988; Mount 1995), and overtopping at flows greater than the 2- to 5-year peak flow. Seepage can be a more common mode of failure than overtopping (Mount 1995). Because these are low structures, foundation failure usually would not be a concern.

- Failure countermeasures include flat enough side slopes to provide for stability and geotextile filters to offset the effects of seepage (Brookes 1988). Overtopping countermeasure is to re-establish the dike.

- The flow range over which this method is effective is low flows up to the 2- to 5-year return period peak flow or larger, depending on the design. Above these flows, training dikes would be overtopped, fail due to seepage, and potentially be breached.

- Training dikes create a zone of higher channel velocity because they confine the design flows to a narrow region of the flood plain (Brookes 1988; Mount 1995), resulting in increased sediment transport capacity (Thorne et al. 1997). Increased velocity can lead to increased bank erosion and a wider channel (Brookes 1988), as well as increased channel depth. As a result of narrowing the design flow top width, the water surface elevation can increase above pretraining dike levels. This can result in increased water surface elevation upstream of the dike (Mount 1995). Conceptually, the amount of change in sediment transport capacity of training dikes designed to contain the 2- to 5-year peak flow would be significantly less than a levee designed to contain the 50- or 100-year peak flow. In the case of the Middle Rio Grande downstream from San Antonio, the bed is comprised of highly erodible sand sizes with intermittent thin layers of silts and clay. Thus, with increased sediment transport capacity, the bed can scour and enlarge during peak flow events. As a result, sediment plugs are much less likely to reform in the location of the training dike. Bed scour also reduces or eliminates a rise in water surface elevation experienced in coarser bedded rivers. On the Middle Rio Grande where training dikes have been installed downstream from the San Marcial Railroad Bridge to near Fort Craig, the channel has not widened, and the historical plug formations have not re-occurred through several cycles of channel bed filling and bed lowering. The channel may widen in this reach if base level lowering and downstream channel dredging continue. This would be caused by the bank height increasing to the point where the bank becomes unstable rather than fluvial erosion due to increased velocity.

- With locally increased sediment transport rates and bed and bank erosion, the downstream reach will receive increased sediment supply above pretraining dike levels (Brookes 1988). Under certain conditions, this can lead to potential sediment deposits downstream. In the case of the San Marcial berm, the increased sediment transport load has been carried through a series of dredged channels to the delta of Elephant Butte Reservoir as planned. This is one of the goals of channel maintenance activities in this reach.

- Lower bed elevations potentially can result in a lower ground water table in the adjoining riparian zone.

- Reduced overbank flows can reduce the supply of water and nutrients to the riparian zone. These effects can be partially mitigated through using culverts and low water crossings to wet the riparian zone.

- Reducing flood plain peak flow storage capacity can result in increasing water surface elevations immediately downstream from the training dikes (Brookes 1988). This is caused by reduced flood plain storage, which can increase downstream discharges. These effects are most pronounced when levees are constructed for long distances (hundreds of miles) and significant regions of the flood plain are cut off. However, in a study in the United States, in 31 out of 42 cases, studies showed that the increase in downstream water surface elevation was insignificant (Little 1973 as referenced in Brookes 1988). This is attributed to the fact that there were only slight changes in gradient or velocity.

Freeboard Dikes

- Freeboard dikes have the same general range of application, used on the same rivers, the same geomorphic response, the same modes of failure and countermeasures, the same level of protection, and the same usual local and spatial river response as training dikes, except as noted below.

- Freeboard dikes in Velarde to the mouth of the Rio Chama reach were often constructed along the river bank line to prevent inundation of low lying agricultural lands upstream of diversion dams where the dam backwater effect raised the water surface elevation. Thus, fluvial erosion can be significant. The countermeasure was to install erosion protection in the form of riprap, which was necessary to protect the dikes.

Culverts

- Culverts have a wide range of application and are used near or in rivers throughout the United States.

- Common modes of failure are seepage and piping, overtopping the above berm or road, collapsing due to large overburden loads, and material corrosion.

- Countermeasures include seepage collars and/or geotextile to prevent seepage and piping. Culverts should be sized to prevent overtopping. In this application, the culverts have the purpose of wetting the flood plain and are not designed to pass a peak runoff design flow. The training dike or freeboard dike may be overtopped because they are designed to pass the 2- to 5-year return period peak flow in the river—and not as a result of undersized culverts. Collapsing due to large overburden loads is not a concern unless loaded dump truck or other equipment will travel on top of the embankment; then, the design should include these loads to size the gauge of the metal culvert. Material corrosion is inevitable over extended periods of time. The countermeasure is replacement.

- The usual ecosystem response is increased riparian zone health including potential new growth of cottonwoods and willows, depending on the depth and frequency of inundation of the riparian zone.

Low Water Crossings

- Used throughout the Southwestern United States. Typical application is where rural unimproved roads cross ephemeral channels. The crossing is constructed of riprap so that vehicles can safely cross without sinking into potentially soft channel bottoms. They can be used during periods when the channel is either dry or has a low amount of flow. During high flow, these crossings are not safe for vehicles.

- In this application, they are intended to be used as controlled overflow for training dikes. They require a flatter slope than is generally found on the land side of dikes to prevent erosion of the riprap.
- The usual river response is increased riparian zone health, depending on the depth and frequency of inundation of the riparian zone.

3.7.2 Advantages and Disadvantages

3.7.2.1 Advantages

Training Dikes

- For cases where sediment transport capacity is much lower than supply and sediment plugs are forming, the increased velocity and sediment transport capacity as a result of dike placement can promote a channel where plugs no longer form. In such instances, the downstream channel is able to transport the additional sediment because the level of supply overall remained the same as before the plugs were forming. This is because the reach scale gradient was not significantly changed by the dike implementation.
- Because sediment transport is locally increased, dikes provide a longer-term solution than plug removal (via pilot cuts). Plug removal is a stop gap measure only and does not alter conditions that lead to plug formation.
- Dikes can be cheaper than frequent plug removal.
- Reduces distributary channels, thus reducing potential for fish stranding.

Freeboard Dikes

- Can provide protection from low level flooding upstream of low head diversion dams such as found in the Espanola Valley.
- Can provide increased channel capacity where the bank height is low due to channel aggradation; for example, downstream from dams, where the sediment sizes supplied by ephemeral tributaries are too large to be transported by peak reservoir releases such as below Elephant Butte Reservoir. In this example, banks were raised to provide increased capacity, together with long-term periodic removal of incoming sediment, to maintain the increased channel capacity.
- Relatively low cost method if implemented using native material, which can be excavated from the flood plain or river channel.

Culverts

- Can provide for inundation of the riparian zone where training dikes eliminate overbank flows during the 2- to 5-year return period peak flow events. Maintenance of connectivity with the flood plain increases the health of the riparian forest.
- Economical to implement.
- Failure modes have simple and easy to implement countermeasures.
- Low water crossings.
- Easy to implement.

3.7.2.2 Disadvantages

Training Dikes

- Under certain circumstances, dikes can lead to increased velocity, bed and bank erosion, increased sediment loads, and potential downstream sediment deposits ,which can be a disadvantage in situations where downstream channel aggradation creates an appreciable loss of channel capacity. Training dikes are known to create a water surface elevation upstream that is higher than without the training dike. Whether or not the gradient increase or upstream water surface change is significant would need to be determined by comparing alternatives using a sediment transport numerical model. These effects are not likely on the Middle Rio Grande due to the highly erodible sand bedded channel.
- Prevents overbank flows from inundating adjacent riparian zone. This can be mostly mitigated for by using culverts or low water crossings.
- Easily overtopped. If constructed of native sand material, seepage and piping failures may occur, requiring maintenance.
- Can decrease overbank flows, reducing the health of the riparian zone.
- Clearing for dike alignment would result in the loss of habitat.
- Can result in more uniform channel velocity and depth.
- Limited amount of low or no velocity habitat.
- Isolates the portion of the flood plain outside the training dikes.

Freeboard Dikes

- If the width of the river, as contained by riverside freeboard dikes, is narrower than the equilibrium width, then the river will tend to erode the banks and bed (Przedwojske et al. 1995).
- Can include the disadvantages of training dikes.
- Can prevent periodic inundation of valuable riparian zones unless strategic locations are found to protect only agricultural or other land uses.
- Easily overtopped.
- Can require frequent maintenance, depending upon the hydrology.
- Can decrease overbank flows, reducing the health of the riparian zone.
- Clearing for dike alignment would result in the loss of habitat.
- Can result in more uniform channel velocity and depth.
- Limited amount of low or no velocity habitat.
- Isolate the portion of the flood plain outside the training dikes.

Culverts

- Require frequent maintenance to ensure that flow capacity is available during peak flow events when installed in training dikes.
- Remain at the same elevation. If the riverbed aggrades or degrades, the culverts may need to be positioned. This also can be partially alleviated by placing culverts at various elevations. Also, more culverts than are necessary should be installed at various elevations through freeboard dikes.
- For the freeboard dike case, frequent maintenance is required to prevent inundation of protected lands during peak flow events.

Low Water Crossings

- Require frequent maintenance to ensure that flow capacity is available during peak flow events when installed in training dikes.
- Remain at the same elevation. If the riverbed aggrades or degrades, the culverts may need to be positioned. This can also be partially alleviated by placing culverts at various elevations. Also, more culverts than are necessary should be installed at various elevations through freeboard dikes.

3.7.3 Requirements

Training Dikes

- They are generally built to contain the 2- to 5-year peak flow. If the nature of plug formation results in a large loss of peak flow capacity, the design flow for training dikes may be increased above the 2- to 5-year peak.

- They are constructed parallel to the river and should be set back from the bank line a sufficient distance, such as 25 to 100 feet. In addition, the existing riparian zone between the riverbank and the dike should be retained. Both are needed to help prevent berm toe erosion by maintaining a zone of higher flow resistance. The alignment can be varied to selectively preserve or protect important riparian trees or habitats.

- The top width is determined by the method of construction, stability, and seepage requirements. If the dike can be constructed from the flood plain, then often, a 4- to 6-foot top width will be sufficient with 2:1 side slopes. If the dike needs to be constructed from the top, it will need to be sufficiently wide for construction equipment, such as 12–14 feet with 2:1 side slopes.

- A sediment routing model may be necessary to determine the fate of the additional sediment supply from the treated reach to the downstream reaches.

- Any seeding and planting should be with species that do not affect the structural integrity of the training dike. If there are areas of the riparian zone between the riverbank and the dike toe that are devoid of vegetation, then native species should be planted to reduce flow velocity at the dike toe.

- The level of complexity of installation is medium and depends highly on local site condition, habitat and environmental needs, and landowner preferences.

- Construction issues include access, clearing for the footprint, for material source areas, and forming and shaping the dike. Having the right size equipment for the combination of construction and access is imperative.

- Reliability is medium. Maintenance includes re-establishing the dike when it is overtopped, repairing seepage around the culverts, periodically filling any rills and gullies that can form during rainfall events, and removing vegetation that may establish root seepage paths through the dike.

- Side slopes will need to be stable. This can be determined using slope stability analysis.

Freeboard Dikes

- Designs call for the dike top to be 3 feet of freeboard above the 2-year return period instantaneous peak water surface elevation.

- The downstream extent of the dikes should continue to the riprap embankment located upstream of the diversion dams on both sides.

- The dikes should extend upstream of the dam until the water surface is no longer affected by the backwater from the dam and the 2-year return period peak is contained within the existing channel banks.

- They are parallel to the river and need to be set back from the bank line a sufficient distance so that flows do not erode the dike toe. When placed along the existing riverbank, the need for erosion protection should be evaluated. Erosion protection can be included when necessary to protect the dike. The top width is determined by the method of construction, stability, and seepage requirements. If the dike can be constructed from the flood plain, then often, a 4-foot top width will be sufficient with 2:1 side slopes. If the dike needs to be constructed from the top, the dike will need to be sufficiently wide for equipment, such as 12–14 feet with 2:1 side slopes.

- The level of complexity of installation is medium and depends highly upon local site condition, habitat and environmental needs, and landowner preferences.

- Construction issues include access, clearing for the footprint, locating nearby suitable construction material, and forming and shaping the dike. Having the right size equipment for the combination of construction and access is imperative.

- Reliability is medium. Maintenance includes re-establishing the dike when it is overtopped, repairing seepage around the culverts, and removing vegetation that may establish root seepage paths through the dike.

Culverts

- Culverts through training dikes should be at such an elevation and have a capacity that the desired flood plain inundation and frequency level are achieved. Culverts located at multiple elevations would enable flood plain inundation should the riverbed aggrade or degrade.

- The spacing of culverts should be determined based on the amount of inundation needed.

- Seepage collars or other seepage prevention measures may be needed, depending upon the soil type.

- Construction issues include uniform compaction around the culverts and proper installation of seepage prevention measures such as seepage collars, geotextile, clay core, soil cement, etc.

- Culverts through freeboard dikes need to be at an elevation and slope that drain the land, yet still be above the low-flow water surface elevation during periods of time when land drainage is necessary.

- The level of reliability is medium and depends on adequate maintenance. Maintenance includes removing debris so that flow is maintained in the culverts and closing any seepage paths adjacent to culverts.

- Culverts through freeboard dikes are oriented upstream with a flap gate on the riverside. By orienting the culvert upstream with a flap gate, high river waters force the gate closed, preventing flows through the culvert. Otherwise, high riverflows would inundate the protected land. Conversely, when riverflows are low, drainage flows can discharge into the river through the culvert.

- Culverts should be sized to pass the maximum runoff flow while minimizing the amount of ponded water.

- The level of reliability is medium and depends on adequate maintenance for freeboard dike applications. Maintenance includes removing debris so that flow is maintained in the culverts and the flap gates close during high flows.

- Culverts have low implementation and maintenance complexity. The application is durable. Culverts generally are made of corrugated metal pipe.

Low Water Crossings

- They should be constructed at an elevation where riverflows enter the adjoining flood plain to provide the necessary periodic (every few years) flood plain wetting while preserving the function of the training berm.

- These depressions can be made wide enough (long enough along the axis of the training dike) to pass enough discharge to wet the affected flood plain area.

- On the land side of the training dike, a riprap ramp is necessary to pass flows down the training dike slope.

- Seepage protection may be required to prevent seepage forces from dislodging riprap on the rock ramp and crossing.

- Riprap on the crossing and ramp should be sized to prevent erosion for the design event.

- The level of reliability is medium. Maintenance includes replacing dislodged riprap, removing woody debris from the crossing, and sealing any seepage paths that may develop after construction. The method is durable and has a design life, based on the desired flow rate through the crossing and the design flow used to determine the elevation of the training dike. The level of complexity for implementation and maintenance is low.

3.8 Levee Strengthening

- The confidence level is between:
  - Level 3 because there is extensive design information on the height, assuming a fixed bed.
  - Level 2 because there is less knowledge of height and elevation requirements for the mobile bed case. Generally, imported fill is used that has the proper gradation for levee strength and seepage minimization. Compaction is important for levee strength and seepage control.

- Levee strengthening includes raising, widening, and reducing the levee side slopes for increased stability. Widening and reducing the side slopes also can reduce the ground pressure underneath the structure to prevent bearing/foundation failure.

- Generally, levees are designed for a 50- to 100-year return period flood. Other return period floods also can be used based upon economic considerations (Przedwojski et al. 1995). Often, levee strengthening is accomplished for the 2-year return period flow plus 2–3 feet of freeboard on the Middle Rio Grande in the reach south of San Antonio, New Mexico.

- The objective of levee strengthening is to protect lands and facilities outside of the levees from inundation. Levees have the effect of narrowing the width of the flood plain, thereby increasing main channel velocity, sediment transport rates, and channel capacity (Brookes 1988). In the case of levee strengthening, the effects of reducing the width of the flood plain already have occurred.

3.8.1 General Range of Application

- Levee raising and strengthening are applicable to levees on all types of channels, including: gravel bed, sand bed, and silt and clay bed, meandering, braided, anastomosing, etc. Various sized flood control levees are extensively used on rivers throughout the United States (Environmental Defense 2002) and, indeed, the world (Brookes 1988).

- Levee strengthening provides for the benefits and effects of existing levees to continue. Common modes of failure are unstable slopes, unstable foundations, seepage, erosion due to lateral channel migration (Brookes 1988; Mount 1995), and overtopping at flows greater than the 2- to 5-year return period flow. Seepage can be a more common mode of failure than overtopping (Mount 1995). Because these are low structures, foundation failure would not usually be a concern.

- Failure countermeasures include reducing the side slopes to provide stability, and geotextile filters or internal drains to offset the effects of seepage (Brookes 1988). Excavation of weak subsurface material, accompanied by granular fill material, can be used to strengthen the levee foundation. Overtopping and breach countermeasure requires levee reconstruction.

- Levees are strengthened in the Middle Rio Grande south of San Antonio, New Mexico, using the 2- to 5-year return-flow period. Above these return period flows, the levee would be overtopped and potentially breach.

- Levee construction creates a zone of higher channel velocity because the design flows confine the river to a narrow region of the flood plain (Brookes 1988; Mount 1995), resulting in increased sediment transport capacity (Thorne et al. 1997). Increased velocity can lead to increased bank erosion, a wider channel (Brookes 1988), and increased channel depth. As a result of narrowing the flood plain, the design flow water surface can increase above prelevee elevations. This can result in increased water surface elevation upstream of the dike (Mount 1995). Conceptually, the amount of change in sediment transport capacity of levees, designed to contain the 2- to 5-year peak flow, would be significantly less than a levee designed to contain the 50- or 100-year peak flow. In the case of the Middle Rio Grande downstream from San Antonio, the bed is comprised of highly erodible sand sizes with intermittent layers of silts and clay. Thus, with increased sediment transport capacity, the bed can scour and enlarge during peak flow events. Bed scour also reduces or eliminates a rise in water surface elevation experienced in coarser bedded rivers.

- On the Middle Rio Grande where levees have been installed and strengthened downstream from San Antonio, New Mexico, the channel has not widened. The channel may widen in portions of this reach if base level lowering and downstream channel dredging continue. This would be caused by the bank height increasing to the point where the bank becomes unstable rather than fluvial erosion due to increased velocity. Lower bed elevations potentially can result in a lower ground water table in the adjoining riparian zone. Reduced overbank flows can reduce the supply of water and nutrients to the riparian zone. These effects can be partially mitigated through using culverts and low water crossings to wet the riparian zone. Reducing flood plain peak flow storage capacity can result in increasing water surface elevations immediately downstream from the training dikes (Brookes 1988). This is caused by reduced flood plain storage, which can increase downstream discharges. These effects are most pronounced when levees are constructed for long distances (hundreds of miles) and significant regions of the flood plain are cut off. However, in a study in the United States, in 31 out of 42 cases, studies showed that the increase in downstream water surface elevation was insignificant (Little 1973 as referenced in Brookes 1988). This is attributed to only slight changes in gradient or velocity. The effects of levee construction upon the Middle Rio Grande already have been experienced. Levee strengthening provides for the benefits to continue.

3.8.2 Advantages and Disadvantages

3.8.2.1 Advantages

- Levee strengthening provides for the continuation of protection of riverside infrastructure and lands from high peak flow inundation.

3.8.2.2 Disadvantages

- Levee strengthening to the 2- to 5-year return period interval can be easily overtopped.

3.8.3 Requirements

- The levees are generally strengthened to contain the 2- to 5-year peak flow plus 2–3 feet of freeboard. Consideration should be given in the Bosque del Apache National Wildlife Refuge to using higher peak flows because of the value of the refuge infrastructure.

- The top width is determined by safety and vehicle use considerations. Generally, 12–14 feet wide is sufficient for two-way vehicle traffic needed during emergency use by dump trucks to haul riprap or levee raising materials.

- Generally, a 2:1 or 3:1 side slope is sufficient; however, this should be determined from slope stability and foundation analysis (USACE 2000).

- A sediment routing model may be necessary to determine the capacity during bed scouring events and due to the effects of continued bed lowering or raising, depending upon Elephant Butte Reservoir stage.

- The level of complexity of installation is generally low and depends highly on local site conditions, access, and any environmental requirements.

- Construction issues include access and clearing vegetation for increasing the size of the strengthened levee footprint, for material source areas, and forming and shaping the levee strengthening. Having the correct size equipment for the combination of construction and access is imperative.

- Reliability is low because of the 2- to 5-year return flow period design discharge. Reliability would increase with larger return period flows. Maintenance includes future increases in levee height, repairing seepage paths by flattening the side slope, periodically filling any rills and gullies that can form during rainfall events, and removing vegetation that may establish root seepage paths through the levee. Future channel aggradation and increases in peak flows can result in a need for additional future levee strengthening.

- Design considerations include the location and type of material available to import for construction, the strength of the foundation material, the amount of settling anticipated by adding material to raise the levee, side slope stability, duration of peak flows, the amount of potential seepage, and necessary countermeasures to prevent seepage/piping failures, and the levee height. Design guidance can be found in Przedwojski et al. (1995) and USACE (2000).

Chapter 4. Bank Protection/ Stabilization Measures

- Bank protection works may be undertaken to protect against erosion and bank slips and to reduce the hydraulic load acting on the soil (Hey 1994; Brookes 1988; Escarameia 1998; McCullah and Gray 2005) at locations where undermining of a bank would result in erosion of riverside facilities and flood control levees.

- Bank protection methods apply to cases where erosion of the bank line and toe is the primary mechanism for bank failure. This includes small bank slope failures or slump block failures. In situations where the bank slope is unstable due to geotechnical processes, other methods would need to be applied in addition to bank stabilization (Escarameia 1998). These methods could include placing additional material at the toe of the slope or removing upslope material to eliminate rotational failure potential (Terzaghi et al. 1996). A failure of this type was repaired on the River Skerne by adding toe rock for ballast and erosion protection and excavating and resloping the bank line to reduce the weight on the top of the slope (Vivash and Murphy 1999).

- Bank protection is best applied when the river grade is stable. If the channel is incising, the toe of any bank protection could be undermined and fail. Countermeasures include additional toe protection, grade stabilization (Watson et al. 2005), or encouraging the river to reach a new dynamic equilibrium condition (Shields et al. 1999) may be required.

- Flood plain establishment and connectivity should be incorporated to bring sediment transport in balance with supply. Otherwise, there will be increased potential for channel degradation and lowering of the water table.

4.1 Longitudinal Features – Fixed Bank Line Location and No Change to Thalweg Location

4.1.1 Common Aspects and Channel Response Longitudinal Features (Riprap Revetments and Longitudinal Stone Toe with Bioengineering)

- Riprap refers to randomly or selectively placed, loose quarry stone used for protection against erosion. Revetment is a system of riprap used to protect sloping banks against erosion.

- Both riprap revetments and longitudinal stone toe with bioengineering involve placing stone riprap material along the bank line to provide erosion protection.

- Riprap revetment includes stones placed from the toe to the top of bank or to an elevation of a design flood, such as the 25-year event water surface elevation.

- Longitudinal stone toe with bioengineering involves placing stone riprap material from the toe of the slope up to an elevation where riparian vegetation normally grows. Vegetation is used to protect the remainder of the slope up to the top of the bank or a peak flow design discharge such as the 25-year event water surface elevation.

- Stone riprap has been thoroughly tested, and practical applications have been undertaken in a wide range of conditions and can be designed with a relatively high degree of precision and confidence (Watson et al. 2005).

- Well-graded riprap often can be placed without a separate filter blanket or material (Watson et al. 2005).

- Stone may be more costly than other materials, especially depending on local availability. Heavy equipment is required on large projects for efficient placement (Watson et al. 2005). Riprap may be considered unaesthetic for some locations and may not compare favorably with other types of bank stabilization or channel maintenance methods.

- These techniques generally do not cause a rise in water surface elevation beyond the influence of a change in bank resistance, unless the channel cross sectional area changes or as a result of an expansion or contraction. Expansions and contractions of less than 10% generally do not have a significant effect upon the water surface elevation (Fishenich 2000). This is especially the case when there are active channel degradation or incision processes underway. Dense plantings or bioengineering have potential to increase water surface elevation due to increased flow resistance.

  Both of these methods eliminate local bank erosion while inducing local channel deepening and local bank-toe scour (Stern and Stern 1980; Pemberton and Lara 1984; Brown 1985; Niezgoda and Johnson 2006). If there is a large change in flow resistance, sediment transport capacity can be reduced, but this is generally not the case (Fishenich 2000). There can be a short-term increase in bed material load as the channel deepens (Stern and Stern 1980). Both methods also result in decreased width-to-depth ratio, as a consequence of channel deepening, and sediment deposition on the inside of the bend (Niezgoda and Johnson 2006). There is an increased shear stress on the outside bank as a result of these channel changes, which often means the rock lining may require future maintenance or consideration needs to be made in the design process.

- Riprap increases the bed and near bank turbulence, secondary currents, and shear stress at the toe of the riprap, while the added roughness reduces near bank velocity (Jin et al. 1990). This is the likely physical mechanism that creates the increased channel depth and local scour.

- In channel conditions where the sediment supply from bank erosion is a significant part of the total sediment load, there could be increased downstream bed and bank erosion (Fischenich 2000).

- Bed material can coarsen after bank stabilization is installed (Niezgoda and Johnson 2006).

- The following is a summary of the vertical response to bank protection. In slightly incising channels with coarse bed material, the transport capacity can exceed supply, and the channel is often attempting to increase its length to decrease slope. This is the situation in some reaches of the Middle Rio Grande. In this situation, fixing the channel bank would result in mining material from the channel bed, causing local channel deepening. This channel deepening will continue until the gradient is reduced so that capacity matches supply, or the bed particle size increases (reducing sediment transport), or some combination of these. In general, the river will re-establish sediment transport continuity through the reach after longitudinal bank protection is installed (Fischenich 2000).

These techniques create a local static bank line that can interrupt downvalley and lateral channel migration. The effects of this are highly variable and depend on the channel stability, physical characteristics of the channel, and riparian zone (Fischenich 2000). For channels that are migrating slowly, impacts from stabilization measures would be more localized over a typical engineering design life. In general, if the channel has reached dynamic equilibrium, the effects would be less than channels that are either aggrading or degrading. For cases where the sediment supply from bank erosion is a major source of sediment, downstream bank erosion could be accelerated and bed lowering may occur (Fischenich 2001). Erosion can continue downstream if the riprap does not extend to the crossing (inflection point between successive bends). If the riprap is terminated upstream of the crossing, then the increased velocity along the riprap can result in increased bank line erosion and local scour. Brown (1985) suggests that fixing the location of a single bend may result in the upstream bend elongating and lateral migration eventually forming a cutoff channel. The USACE (1981 as cited in Brown 1985) supports Brown's findings in an investigation of the

North Fork Tillatoba Creek in northern Mississippi, upstream of a bridge crossing. Bridge crossings and the road embankment can be a different case than a single bend being fixed in location by a bank armor technique that is eroding into a levee. Overbank flows can still occur, in most cases, when armoring a bank line near a levee or other infrastructure. Bridge crossings with the approach road embankment can reduce the width of the flood plain.

- Static bank lines in meandering rivers (the Middle Rio Grande is not considered a meandering river, yet it does exhibit similar characteristics in some reaches) can cause side channels and oxbows to fill with sediment over time and not be renewed by river channel migration processes (Stern and Stern 1980). Static bank lines in a river with a history of avulsions also can cause abandoned channels to fill with sediment over time.

- Two opinions are found in the literature regarding the length of influence riprap has on the river upstream of and downstream from the installation. First, fixing the bank line locations with riprap revetments can affect downstream channel processes (Schmetterling et al. 2001). The length of effects from stabilization, referenced by Schmetterling et al. (2001) is undefined; however, it is implied that the distance of effect can be larger than Fischenich (2000). Second, riprap generally does not affect the channel downstream beyond one-half meander wavelength (Fischenich 2000); however, no studies or documentation were shown to support these views in either Schmetterling, et al. (2001) or Fischenich (2000). Fischenich (2000) states:

  > "No generalization can be made regarding the stream lengths that bank stabilization impacts, except to note that the length is very closely related to the channel slope and bed material composition. Impact lengths are greatest over low-gradient streams and streams with sand beds. Impact lengths are least on steep-gradient streams, streams with erosion-resistant bed materials, and streams with controls."

  It is possible that both opinions are valid under specific sets of channel conditions and valley geology and climate conditions.

- Conceptually, in cases where the river channel is adjusting its length and/or actively degrading, fixing the bank line location along one bend may lead to accelerated lateral bank erosion in downstream bends.

- Channel instabilities including incision, effects of flow being captured in different channels of a braided system (Walker 1999), lateral migration, and potentially changing channel planform and channel evolution (Schumm et al. 1984) need to be accounted for in bank stabilization planning.

Bank stabilization has been shown to decrease channel width by sediment depositing on the inside of stabilized bends, accompanied by deepening of the channel (Niezgoda and Johnson 2006). This leads to a decrease in width-to-depth ratio. The outside of the bend experienced an increase in bank shear stress as a result of the decrease in width-to-depth ratio. The outside of the bend also experiences increased shear stress as a result of the presence of the riprap.

- Common modes of failure are: flanking, toe scour, riprap erosion, piping, undersizing, and poor gradation or lack of filter.

- If the channel upstream of the riprap revetment or longitudinal stone toe is migrating downvalley, then over time, the upstream bend may overtake and flank the protected bank line. There are two ways this condition can be addressed. First is to stabilize the upstream bends to a point where lateral migration is inhibited. Second is to construct a tieback that extends in the lateral direction perpendicular to the upstream end of the longitudinal feature. This provides flanking protection even if the upstream curve moved downvalley. Tiebacks are constructed back from the bank line to the point of maximum estimated lateral channel migration.

- A countermeasure for toe scour is to construct a thickened toe section with an adequate volume of riprap to launch into scour hole while preventing the rest of the revetment to dislodge. This countermeasure can be constructed in flowing or ponded water. A second countermeasure is to construct the revetment to the elevation of the maximum estimated scour plus a safety factor. This countermeasure must be constructed in a dry or dewatered condition. Without dewatering, unstable soil materials underlying the bed most likely will slough into the excavation trench. Thus, constructing a thickened toe is usually cheaper and easier. A third countermeasure is to add additional riprap over time as stones launch into the scour hole.

- Stone riprap can adjust to scour, settlement, and surface irregularities. Riprap can sustain minor damage and still continue to function without further damage (McCullah and Gray 2005).

- Riprap is often considered to be the benchmark against which other methods are judged (Watson et al. 2005).

- Riprap erosion can be prevented by ensuring that the riprap is large enough, angular, well graded, and placed such that voids are filled.

- Piping failures can be prevented by providing a filter layer underneath the riprap.

- Revetments and longitudinal stone toe can be constructed along one bank line from the upstream crossing to the downstream crossing. Cost savings can be realized when riprap revetments are constructed in the zone of highest shear stress, which is more towards the downstream part of the bend (Brown 1985; USACE 1981). These manuals recommend placing the riprap along the downstream portion of the meander bend only, instead of between the upstream and downstream bend inflection points.

- The level of reliability for riprap bank protection is generally high, especially if the 25-year or larger event is used to size riprap material. Adequate scour protection and flanking protection are needed for the method to be reliable.

- The geomorphic response of a riprap revetment and longitudinal stone toe protection are essentially the same with a few minor differences noted below.

4.1.2 Riprap Revetment

- Confidence level is Level 3.

- Bank protection is provided for the entire bank height or from the toe to an elevation of a design water surface elevation; thus, no sediment from bank erosion enters the watercourse.

- Riprap provides reliable bank protection near high value infrastructure where a high risk of failure is unacceptable, or where there is insufficient land between the top of the bank and adjacent infrastructure to allow alternative bank treatment methods.

4.1.2.1 Range of Application

- Riprap revetments have been used on virtually all types of rivers found in the United States and Europe (Brookes 1988; Biedenharn et al. 1997; Escarameia 1998; Lagasse et al. 2001).

4.1.2.2 Advantages and Disadvantages

4.1.2.2.1 Advantages

- Advantages have been included in section 4.1.1.

- Riprap revetments may protect occupied or suitable SWFL habitat, although it is unlikely that SWFL habitat has developed under these conditions.

- The point bar has connectivity, variable depth, and velocity habitat and remains static.

4.1.2.2.2 Disadvantages

- Disadvantages have been included in section 4.1.1.
- Increases potential for channel degradation and lowering of the water table, which may adversely affect riparian vegetation.
- Prevents bank erosion and subsequent transport of sediments downstream that could establish areas for native vegetation.
- Poor quality aquatic habitat associated with riprap revetments has made the use of riprap alone controversial (WDFW 2003).
- Continuous riprap provides minimal aquatic benefits (Shields et al. 1995).
- Prevents lateral movement and widening of flood plain. Eliminates sediment supply from bank erosion.
- There is a steep bank angle on the outside of the bend and limited fish cover, except for spaces between riprap.
- Deeper, faster water flowing along the riprap than typically found in the natural channel. In some cases, bank line scour can create habitat that predator fish species of RGSM can occupy.

4.1.2.3 Requirements

- Current design guidelines are found in USACE (1991), HEC-23 (Lagasse et al. 2001a), Biedenharn et al. (1997), Escarameia (1998), and HEC-20 (Lagasse et al. 2001b).
- Stone riprap material should be of sufficient size and gradation to withstand hydraulic forces, provide interlocking support, and prevent loss (erosion) of bank materials through the gaps between larger stones (Biedenharn et al. 1997). Sizes and gradations can be determined using Maynard (1995), Brown and Clyde (1989), USACE (1990), and Simons and Senturk (1992). The following is from Biedenharn et al. (1997) and USACE (1991) on stone sizing:

  > ". . . definite stone size results should be used for guidance purposes and revised if appropriate, based upon experience with specific project conditions, . . ." (Biedenharn et al., 1997).

- Stone riprap should be able to withstand toe scour and channel migration. For the launchable riprap design, sufficient volume of riprap should be added to the toe to allow a full thickness section to be launched to the toe of the bottom of the estimated scour hole plus several feet for a safety factor.

- Scour estimates can be made using the method by Maynard (1995) for the riprap revetment. Contraction and other types of scour can be estimated using the methods found in Lagasse et al. (2001).

- Upstream and downstream limits of the bank protection are included in section 4.1.1.

- Upstream and downstream tiebacks should be designed based on local experience and geomorphic analysis (section 4.1.1). Tiebacks should be angled about 30 degrees from the primary flow direction and be sufficiently long so that flows will not be able to get around them during the design storm. Tiebacks with an angle of 90 degrees have resulted in failures at the downstream end of the structure due to flow expansion (McCullah and Gray 2005).

- Bank shaping usually is required to provide a relatively uniform surface for the riprap placement.

- Level of reliability is high unless there are channel instabilities such as continuing incision and channel migration processes in the river.

- Countermeasures are included in section 4.1.1. Durability is high.

- Durability and design life depend on the design flood used. A 25-year event provides for an economical design life and a reasonable design flood. Design flood can range from the 2- to 100-year return period discharges. Typically, the return period design flood corresponds to the same level of the protection scheme itself (Escarameia 1998).

- Maintenance requirements include replacing riprap that has dislodged, adding additional tieback length, and stabilizing the upstream bend. Inspection following peak flows will help ensure continued success of the riprap by identifying potential weak points where riprap has eroded or been undermined. Inspection and maintenance will ensure continued stability of riprap.

- The level of complexity for installation is medium and depends highly on local site condition, habitat and environmental needs, and landowner preferences.

- Construction issues include access, bank clearing and shaping, having large enough equipment for large stone placement, and turbidity due to bank shaping and stone placement.

4.1.3 Longitudinal Stone Toe (Toe Protection) with Bioengineering

- Confidence level is Level 3 and Level 2 (due to the elevation of the top of the stone toe).

- Some of the method features and general characteristics are described in section 4.1.1. Additional features are described in this section. The cross section of the stone toe is triangular in shape, because there is riprap placed to launch into the scour holes. The purpose of the stone toe is to protect the toe from erosion and scour so that a stable slope can be maintained to be planted or colonized with vegetation.

4.1.3.1 General Range of Application

- Stone toe with bioengineering is well suited for areas where the toe is eroding and mid and upper banks are fairly stable due to vegetation and cohesion. This method also can be used for conditions where the banks experience general slope instability. Longitudinal stone toes can be used for situations where the bank line needs to be built back out into the stream, where the channel needs to be realigned, or where there are abrupt changes in the bank line, such as scallops (McCullah and Gray 2005).

- Used in channels in northwest Mississippi (Shields et al. 1995) with good success.

- Used on the upper banks of the La Canova site on the Middle Rio Grande.

- Applied to some rivers in California (McCullah and Gray 2005).

- Reported to be used throughout the United States (Lagasse et al. 2001) with no specific site information given.

- Armor benefits of bioengineering located above the riprap toe along the bank line are not immediate, so many schemes employ biodegradable fabrics, including fabric encapsulated soil lifts, biodegradable blocks, and fabric rolls (Fischenich 2000; NRCS 1996). Using biodegradable fabrics prevents bank erosion above the stone toe until vegetation is established. In arid climate zones, complete covering of the bank with vegetation can take many years to establish—if at all.

- This method is especially suitable when the upper bank slope is fairly stable (Biedenharn et al. 1997) or can be made stable during construction.

- Level of protection can be high for rivers where there is minimal future incision or planform change anticipated.

4.1.3.2 Advantages and Disadvantages

4.1.3.2.1 Advantages

- This method allows stabilization of the channel bank along a predetermined alignment.

- Longitudinal stone toe protection with woody vegetation is a cost-effective method of bank protection (Shields et al. 1995) and costs less than riprap revetments.

- Bank grading and reshaping or sloping is usually not needed; it is simple to design and is a thoroughly tested method that has been used in a variety of conditions and has been extensively monitored (McCullah and Gray 2005). It is easy to combine with other methods such as transverse features.

  Vegetation provides benefits, such as providing shading to maintain suitable temperatures, and contributes to aesthetic value. Leaves, twigs, and insects drop into the stream, providing nutrients for aquatic life (NRCS 1996). Additional benefits are realized by vegetation reducing bank line velocity and shear stress, trapping sediment, and holding the upper bank line soils in place.

- May protect occupied or suitable SWFL habitat, although it is unlikely that SWFL habitat has developed under these conditions.

- Bioengineering provides a minimal amount of riparian vegetation.

- The point bar has connectivity, and variable depth and velocity habitat, and remains static.

4.1.3.2.2 Disadvantages

- Longitudinal stone toe protects the toe and does not directly protect the mid and upper bank areas. Some erosion of the mid and upper banks can occur, especially prior to the vegetation becoming established. Using biodegradable fabrics or blocks will assist with bank stability prior to vegetation becoming established as described above.

- Less stone riprap material is available for launching into the scour hole along the bank line. If more scour occurs than available rock for protection via launching, toe erosion can continue. In general, scour depths at the toe should not be greater than the height of the toe (McCullah and Gray 2005).

- Increases potential for channel degradation and lowering of the water table.

- Prevents bank erosion and subsequent transport of sediments downstream that could establish areas for native vegetation.

- Very little research is available on the relationship between channel velocity and shear stress and the stability of woody vegetation on the bank line (Carlson et al. 1995).

- Prevents lateral movement and widening of flood plain. Eliminates sediment supply from bank erosion.

- A steep bank angle is on the outside of the bend as well as limited fish cover, except for spaces between riprap.

- Deeper, faster water flowing along the riprap than typically found in the natural channel. In some cases, bank line scour can create habitat that predators of RGSM can occupy

4.1.3.3 Requirement

- Current design guidelines are found in NRCS (1996), HEC-23 (Lagasse et al. 2001a), Biedenharn et al. (1997), and HEC-20 (Lagasse et al. 2001b).

- Stone riprap material should be of sufficient size and gradation to withstand hydraulic forces, provide interlocking support, and prevent loss (erosion) of bank materials through the gaps between larger stones (Biedenharn et al. 1997). Sizes and gradations can be determined using Maynard (1995), Brown and Clyde (1989), USACE (1990), and Simons and Senturk (1992). The following is from Biedenharn et al. (1997) and USACE (1991) on stone sizing:

  > ". . . definite stone size results should be used for guidance purposes and revised if appropriate, based upon experience with specific project conditions, . . ." (Biedenharn et al. 1997).

- Stone riprap should be able to withstand toe scour and channel migration (section 4.1.1). For the launchable toe scour protection design, sufficient volume of riprap should be added to the toe to allow a full thickness section to be launched to the toe of the bottom of the estimate scour hole plus several feet for a safety factor. Scour estimates can be made using the method by Maynard (1995) for the riprap revetment. Contraction scour and other types of scour can be estimated using the methods found in Lagasse et al. (2001).

- There are no guidelines on the elevation of the top of the stone toe. Various methods or elevations are used. The elevation of the top of the stone toe can be based on the mean annual water surface, bank-full elevation, or on the elevation at which vegetation grows in the river system. Bioengineering techniques generally employ woody plant species that are limited to growing on bank elevations above a base flow level (Fischenich 2000; NRCS 1996); thus, the top of the longitudinal stone toe should, as a minimum, be the elevation at which vegetation grows in the river system. In arid climate zones or situations where there can be large fluctuation in the mean annual flow, the long-term mean annual water surface may be above depositional surfaces where vegetation is growing. In low rainfall climate zones, plants need to have a root zone that extends down to the ground water table; thus, plants may need to be placed at lower bank elevations than in climates with sufficient rainfall to provide for plant growth. Vegetation in riprap has been shown to increase bank stability (Shields 1991).

- Upstream and downstream limits of the bank protection are included in section 4.1.1.

- Upstream and downstream tiebacks should be designed based on local experience and geomorphic analysis (section 4.1.1). These locations can be the zones of slackwater upstream of and downstream from the project site (NRCS 1996).

- Guidelines are available for estimating the maximum tractive forces in pounds per square feet for a limited set of bioengineering applications in the guide by Schiechltl and Stern (1994).

- Vegetation should be species indigenous to the riparian zone, collected live from nearby riparian zones, and can be planted using the live staking method (Sotir and Fischenich 2007). Containerized plants also can be used. Upper bank structures can be constructed using soil lifts enclosed by coir fabric with live willows planted in between and through the soil. Other bioengineering measures include prevegetated mats, brush trench, brush layers, pole plantings, grown sod, live fascines, live crib walls, brush mattresses, coconut fiber rolls, or wattles (Gray and Sotir 1996; Schiechtl and Stern 2000; Bentrup and Hoag 1998). Methods such as brush mattress, brush layers, and fabric encapsulated soils can provide the most initial bank stability.

- In arid climates, irrigation tubes may need to be installed down to the root zone so that plants will have sufficient water to grow roots to the water table.

- The site may require earthwork before installing soil bioengineering. Steep, undercut, or slumping banks should be graded to about 3:1 in preparation for planting. Planting is best accomplished during the dormant season.

- Armor benefits of bioengineering located above the riprap toe along the bank line are not immediate, so many schemes employ biodegradable fabrics, including fabric encapsulated soil lifts, biodegradable blocks, and fabric rolls (Fischenich 2000; NRCS 1996). Using biodegradable fabrics prevents bank erosion above the stone toe until vegetation is established. In arid climate zones, complete covering of the bank with vegetation can take many years to establish, if at all.

- Level of reliability is high, unless there are channel instabilities such as continuing incision and channel migration processes in the river. Countermeasures are included in section 4.1.1. Durability is high. Reliability and durability would be slightly less than full riprap revetment.

- Durability and design life depend on the design flood used. A 25-year event provides for an economical design life and a reasonable design flood in the absence of firm design guidance. Design flood can range from the 2- to 100-year return period discharges. Typically, the return period design flood corresponds to the same level of the protection scheme itself (Escarameia 1998).

- Maintenance requirements include replacing riprap that has dislodged, adding additional tieback length, and stabilizing the upstream bend. Inspection following peak flows will help ensure continued success of the riprap by identifying potential weak points where riprap has eroded or been undermined. Inspection and maintenance will ensure continued stability of riprap. Maintenance also may include replanting where die off is common. This is especially true in arid climate zones with fluctuating ground water tables. Inspection should focus on potential weak points such as the upstream and downstream transition between undisturbed and treated banks (WDFW 2003).

- The level of complexity for installation is medium and depends highly on local site condition, habitat and environmental needs, and landowner preferences.

- Construction issues include access, bank clearing and shaping, having large enough equipment for large stone placement, and turbidity due to bank shaping and stone placement.

4.2 Longitudinal Features—Where Erosion Can Continue To Reach the Bank Line Stabilization Treatment – Trench Filled Riprap Revetment and Riprap Windrow Revetment (Setback Revetment)

- Confidence level is Level 2.
- Trench filled revetment is a stone armor revetment with a large stone toe that is constructed in an excavated trench behind the riverbank. A windrow revetment is rock placed on the flood plain surface landward from the existing bank line behind the riverbank. For both trench filled riprap and riprap windrow, the river erodes to the predetermined location, and the riprap material launches into the river, forming an armored bank line (Biedenharn et al. 1997; McCullah and Gray 2005).
- The self-launching stones provide a less intrusive construction technique when compared with a riprap revetment placed along the entire bank line.
- Common failure modes include:
    - Installation on streambanks composed of cohesive soils.
    - Trench excavation causing bank instability as a result of vegetation disturbance.
    - Inadequate size and quantity of rock so it does not fully launch.
    - Installation on a bank in a river reach that is degrading or has contraction scour (McCullah and Gray 2005).
- Countermeasures include:
    - Construction on bank with noncohesive soil material.
    - Ensuring that there is adequate size and quantity of riprap to overcome any effects of loss of bank strength due to vegetation disturbance and the launching process, and river reaches should be stable for this method to be effective.
    - Additional riprap in selected reaches may be necessary after launching has occurred to compensate for inefficient launching or where there is inefficient launching with slab failures or small rotational slips (Biedenharn et al. 1997).

- The efficiency of launching is higher for trenched riprap than for riprap windrows because riprap launches a longer distance for windrows and experiences a less uniform launch rate and greater size sorting.

- A relatively uniform rate of launching at any point along the bank is necessary for success, although uniformity of bank recession along the riprap trench is not necessarily a requirement for a successful installation.

- Trench filled riprap often is used when a smooth alignment and stabilized channel are needed for navigation (Biedenharn et al. 1997). It is also a good method when construction within the stream channel is difficult due to rapid erosion, high velocities, or other factors (Biedenharn et al. 1997).

- Riverbank erosion processes continue until erosion reaches the location of the trench or windrow and riprap launches into the river to form a riprap revetment along the bank line.

- Once the riprap is launched to form the new bank line, the geomorphic response is the same as for riprap revetments. The geomorphic river response is essentially the same for these two methods.

- Bank protection typically is provided from the toe to near the top of the bank, so no sediment from bank erosion enters the watercourse once erosion progresses to the trench or windrow.

4.2.1 General Range of Application

- Trench filled riprap has been useful on the Arkansas, Red, Missouri, and Mississippi Rivers (Biedenharn et al. 1997).

- Sites with noncohesive bank materials are most suitable, or where emergency situations exist and the river stage is high and high velocities prevent usual construction practices. Windrows are especially suited for these circumstances so that critical infrastructure is protected until the crisis passes and a well-designed, longer-term solution can be designed. Suitable for actively eroding banks where some additional bank line erosion is acceptable.

- Trench filled riprap is used throughout the United States at highway bridge crossings (Lagasse et al. 2001), while riprap windrows were reported for use in Georgia, California, Illinois, and Pennsylvania (Lagasse et al. 2001).

- Would not be suitable for very high banks or for cohesive banks. Application to a braided river may not be suitable due to the irregularity of erosion and launch points.

4.2.2 Advantages and Disadvantages

4.2.2.1 Advantages

- Both methods allow stabilization along a predetermined alignment and are simpler and easier to design and construct than riprap placed along an actively eroding streambank (Biedenharn et al. 1997).
- A windrow is simpler than trench filled riprap because the material is placed on the flood plain surface without needing any excavation.
- Windrows can be used in emergency situations where there is not time for a detailed design (section 4.2).
- Generally effective for controlling lateral stream instability but not vertical stream instability, local scour, and contraction scour (McCullah and Gray 2005).
- May protect occupied or suitable SWFL habitat, although it is unlikely that SWFL habitat has developed under these conditions.
- Avoids in-water construction and bank shaping, thus avoiding disturbing RGSM habitat.
- The point bar has connectivity, variable depth, and velocity habitat and the point bar remains static.

4.2.2.2 Disadvantages

- Both methods allow the bank line to continue to migrate until the erosion reaches the riprap.
- Large areas of right-of-way may be required for construction.
- The self-launching process is not as efficient (more stone required) for the windrow when the stone must launch the entire bank height, rather than from the bottom of a trench excavated to a lower elevation (Biedenharn et al. 1997).
- Not usually suitable for addressing local scour, contraction scour, or vertical stream instability (McCullah and Gray 2005).
- Prevents lateral movement and widening of flood plain because of the eventual hardened bank line.
- Increases potential for channel degradation and lowering of the water table.

- Prevents bank erosion and subsequent transport of sediments downstream that could establish areas for establishing native vegetation.

- After the bank erosion has progressed to the riprap trench or windrow, then further lateral movement is prevented, which reduces the potential to widen the flood plain. Eliminates sediment supply from bank erosion after erosion has progressed to the predetermined alignment.

- A steep bank angle is on the outside of the bend as well as limited fish cover, except for spaces between riprap.

- Deeper, faster water flowing along the riprap than typically found in the natural channel. In some cases, bank line scour can create habitat that predators or RGSM can occupy.

4.2.3 Requirements

- Design guides for trench filled riprap are found in Bradley (1978), Brown (1985), Brown and Clyde (1989), and Richardson et al. (2001).

- Design guides for windrow riprap are found in Bradley (1978), Keown (1983), Brown and Clyde (1989), and Richardson et al. (2001).

- Complexity is low.

- Trench filled revetments and windrows should be constructed of well-graded, self-launching stone (USACE 1981) that is of adequate size. Size and gradation can be determined by using USACE (1990; 1991). If the riprap is well graded, then often, an underlying filter is not needed (Biedenharn et al. 1997).

- For trench filled revetments, the height of the stone section is generally one-half to one times the width (Biedenharn et al. 1997).

- Trench filled riprap can be constructed using a rectangular trench or a trench for a trapezoidal buried section. Trench filled riprap is best constructed on a slope of about 1:1 with a thickened toe section containing the launchable rock.

- Placing the stone at the lowest practical elevation constructed during low flows often can place the toe of the trench below the high-flow water surface elevation. This is the most advantageous placement because the launch distance is the shortest. A greater volume of stone is required for trench filled riprap because of nonuniform launching. A method to determine this volume is contained in Biedenharn et al. (1997) and USACE (1991).

- Material from the trench excavation can be used to raise the local height of the eroding bank to prevent nonuniform overtopping. This aids in more uniform launch rates.

- Windrows placed in a trapezoidal shape are best because this cross section supplies a steady supply of stones. A triangular shape is not desirable because the quantity of stone diminishes as the windrow is undercut.

- A geotechnical analysis is recommended to determine bank stability with the addition of the weight of a riprap trench or windrow.

- Trench or windrow riprap should be monitored after each high-flow event to determine if it is functioning properly. It may be necessary to add rock once undermining has occurred to ensure complete and uniform coverage of the bank line with rock.

- The level of reliability is high, provided that the riprap augmentation takes place postlaunching.

- Constructability issues include: access and ensuring bank stability during construction with heavy equipment. Stone should be added after the windrow launches on an “as-needed” basis until bank stabilization is complete. Site-specific conditions will determine how much additional stone is needed. Additional stone is needed because of nonuniformity of bank erosion and launch rates. The bank line may need some vegetation clearing for large equipment to construct the windrow or trench.

- Design flood generally is the discharge that flows over the banks so that launching riprap is not overtopped and the underlying soil eroded. The design flood is variable, depending on site conditions, level of infrastructure protection needed, and project authorization. Durability and design life depend on the design flood used. A 25-year event provides for an economical design life and a reasonable design flood. Design flood can range from the 2- to 100-year return period discharges.

- These methods have high durability and project life as long as supplemental riprap is added after launching.

4.3 Longitudinal Features – Deformable Bank Line and Thalweg Location

4.3.1 Deformable Stone Toe with Bioengineering and Bank Lowering

- The confidence level is Level 2 and Level 1 (riprap is relatively well understood with many methods, and the elevation of bank lowering, the rates of deformation, and necessary land area for erosion do not have a track record or field or lab data).

  Natural alluvial channel systems have dynamically stable planforms with gradual erosion and accretion of riverbanks (Miller and Skidmore 1998) while transporting the incoming sediment supply. Natural channel restoration or channel maintenance should strive to create a condition of sediment supply in balance with sediment capacity and mobile channel boundaries.

- Measures that rely on hardened banks preclude gradual channel mobility, and measures that rely exclusively upon soil bioengineering usually fail to achieve any natural bank stability (NRCS 1996; Watson et al. 1997) and cannot be used for protection of infrastructure. A deformable channel bank is one that allows channel stability accompanied by gradual bank line migration. Deformable bank lines are most applicable when re-establishing or preserving geomorphic processes and flood plain function are project objectives, and when there is some land availability between the eroding bank line and riverside infrastructure.

- This method involves stone toe protection, an internal gravel filter (if needed), soil lifts wrapped in biodegradable coir fabric or other bioengineering, and an aggressive revegetation plan (Miller and Hoitsma 1998). The stone toe protection in this method is designed to be moved by the flows after the vegetation is established and gradually becomes part of the bed material in the river as the bank deforms. The method also can be used in conjunction with overbank lowering when the channel is incised. This will increase flood plain connectivity and provide a large vegetated area through which the river may migrate, and it will achieve a condition where sediment supply is more in balance with sediment transport capacity. It is similar to the widening channel concept used to balance sediment transport with supply in some European rivers (Habersack and Piegay 2008). The vegetation in the lowered area will provide some bank stability by virtue of natural root structure, while allowing bank erosion and mobility.

- The soil lifts wrapped in biodegradable coir fabric provide a series of distinct soil lifts or terraces that are subsequently vegetated. The biodegradable coir fabric would have an expected life span of 3–5 years, over which time the vegetation would be firmly established. The coir fabric protects the soil lifts and vegetation plantings from erosion during high-flow events. The soil lifts wrapped in biodegradable coir fabric are called "fabric encapsulated soil" (FES).

- If the pretreated bank line is in an incised channel where the toe erosion is below the root zone of the riparian forest, then the lowered bank line area with new riparian zone vegetation would have a lower erosion rate than the pretreated bank line.

- The method began to be used in the 1990s, and there are limited field data and case studies.

- The objective of this method is to provide a stabilized bank using toe rock, which becomes mobile after vegetation has firmly established along the bank line. Once the riprap toe becomes mobile, the vegetation root structure provides for some bank stability, while still allowing bank erosion and channel migration.

- By constructing a low terrace that has high connectivity with the main channel, there will be lateral energy dissipation, which reduces main channel velocities and sediment transport capacity. Lower main channel velocity reduces bank line velocity and shear stress. Lowered sediment transport capacity can reduce or halt channel incision.

4.3.2 General Range of Application

- An example of deformable stone toe with bioengineering is the Santa Ana Project on the Middle Rio Grande. The bioengineering includes live willow plantings at various elevations within the FES bank line. In this case, there were two FES soil lifts constructed above a loose rock riprap toe section. The toe section was designed to become incorporated into the bed material load at about the 5- to 10-year flow event.

- The method has been used on Silver Bow Creek, Montana (Miller and Skidmore 1998); Sourdough Creek, Montana; Upper Truckee River, California; Raritan River, New Jersey; Western Run, Maryland; and Spring Creek, South Dakota (Miller and Hoitsma 1998).

- The method can be used on many rivers where more natural bank lines are desirable.

- Sediment supply from bank line erosion is eliminated until the bank becomes mobile. Once the bank line becomes mobile, sediment supply will be slightly increased, depending on the rate of bank erosion and the incoming sediment supply.

- Common modes of failure would be: toe rock erosion prior to the vegetation becoming firmly established in the FES, large die-off of planted vegetation, flanking, abrasion of the coir fabric by a substantial bed material load, and planting vegetation at an elevation along the bank line that is too low (where it would be subject to waterlogging and the vegetation will not grow) and placing the vegetation plantings too high (resulting in reduced root density above the toe of the bank and high future bank erosion rates) (Miller and Skidmore 1998).

- Countermeasures include: using large enough riprap with enough quantity that is well graded to launch into the scour hole and provide protection until the vegetation is firmly established, replanting vegetation that dies, providing flanking protection with tiebacks, using riprap that is erodible at lower frequency events, planting vegetation at the elevation where perennial vegetation grows along the riverbank, and planting vegetation between and through several FES soil lifts to establish vegetation at different elevations for maximum root density.

4.3.3 Advantages and Disadvantages

4.3.3.1 Advantages

- Use began in the 1990s (Miller and Skidmore 1998), and there are limited field applications and documentation; however, procedures for design of the riprap toe are well established.

- For cases where a flood plain surface is established as part of the project in an incised channel, the water surface elevation would be reduced as a result of increased channel width at high overbank flows. For cases where the flood plain surface remains unchanged, there should be no noticeable change in the water surface elevation unless a constriction or expansion is created in the main channel of more than 10% of the cross sectional area (Fischenich 2001).

- During flow events where the deformable stone toe remains stable, a limited amount of toe scour and general deepening of the main channel can occur depending on the bed material size, sediment transport capacity and supply, and channel hydraulics. Once the stone toe has mobilized, the bank line can begin to migrate, no additional toe scour would be anticipated, and the launching riprap even may reduce the scour depth. Thus, channel deepening and bank toe scour would be less than with methods that fix the bank long term because the bank line becomes mobile at larger peak flow events.

- Downvalley and lateral migration are halted until the bank line begins to deform; thus, the technique does not permanently fix the bank line location, and downvalley and lateral migration will still occur. Assuming that there is an active two-stage channel, it would be anticipated that, after the bank line toe rock is mobilized, the bank erosion rate would be decreased from historical levels because one of the functions of the vegetation in the two-stage channel or lowered flood plain is to provide bank stability above the erosion resistance of the pretreatment bank line while allowing some migration. If lateral migration extends once again close to riverside infrastructure, the relatively slow rate of migration will allow time to plan and design another bank protection scheme, if necessary.

- If flood plains are established behind the stone toe and vegetation is established and maintained until stone toe is removed, the potential exists for expansion of riparian vegetation.

- The lowered and deformable bank line could provide variable depth and velocity habitat during higher flow events, which would provide increased habitat complexity for RGSM.

4.3.3.2 Disadvantages

- A risk exists that the stone toe design event will be exceeded before vegetation is established. It depends upon the flood flow frequency postproject, as well as local bed and bank shear stresses. The lower the design flood frequency used to design the stone toe rock size, the higher the likelihood that toe erosion will occur prior to the vegetation being firmly established in the bank line. On the other hand, if the return period is increased for the design of the toe, then a risk exists that the toe may not deform for a lengthy period.

- Until the riprap toe protection is eroded away, the bank line is static, the channel may deepen and local scour occur, and the geomorphic response is similar to longitudinal stone toe with bioengineering and riprap revetments, although it is likely that the channel deepening and local scour will be less due to future bank line deformation.

- This method should not be used where high value infrastructure is near the eroding bank unless the channel can be relocated to provide sufficient land area for future channel migration. This method may require some additional easement area for which future bank erosion can safely occur.

- It is unknown what the rates of bank erosion will be for this method or if the lateral limits of migration lie within an acceptable lateral migration corridor, while providing protection to riverside infrastructure. As a result, future measures may be necessary to protect riverside infrastructure.

- The method has been applied to small streams with little or no reports of use on large rivers (Miller and Skidmore 1998). An exception is the Middle Rio Grande at the San Ana Pueblo. When tractive forces on the bank are greater than 1–1.5 pounds per square foot, or there are scour depths of more than 3–4 feet, the deformable bank line concept using coir fabric may not apply (Miller and Skidmore 1998).

- Application to larger rivers may involve using other materials and methods.

- Coir fabric may have limited longevity in rivers with a high bed material load, as there may be abrasion of the fabric, leading to failure (Miller and Skidmore 1998). Double fabric wraps may prevent this problem.

- For the short term (3–5 years), this method prevents lateral movement and widening of flood plain, assuming that the toe material design return period is not exceeded.

- For the short term, this method prevents bank erosion and subsequent transport of sediments downstream that could provide areas for establishing native vegetation.

- Potential exists to develop a scour pool along the stone toe until erosion occurs, which could be used by predators. Deep flows are nonideal habitat for the RGSM.

4.3.4 Requirements

- The development of the vegetated and deformable bank requires that the initial stone toe be stable to protect the bank from erosion to develop a foundation for the upper bank during establishing vegetation. Once vegetation is established, long-term bank stability with some deformation is provided by combining the stone toe and vegetation (Miller and Skidmore 1998).

- The stone toe for deformable bank lines should be constructed of well-graded, self-launching stone that is of adequate size. Size and gradation can be determined by using USACE (1990; 1991).

- Alternatively, the stone toe can be constructed of alluvial fill comprised of the largest bed material sizes in the stream and wrapped in coir fabric. This method requires construction in the dry and is, therefore, limited to cases where a cofferdam can be economically constructed. Construction of the stone toe using river gravel likely will be more erodible, after coir fabric degradation, than a stone toe using riprap, depending on the size of the riprap. Submerged toe construction using river gravel wrapped in biodegradable fabric offers initial immobility for the life of the fabric (e.g., 3–5 years) and eventual but gradual deformation after fabric degradation (Miller and Skidmore 1998).

Sizes within the toe range from the median sizes, which are transported at the 2- to 10-year events, and the largest sizes, which are transported at the 50-year event (Miller and Skidmore 1998). These sizes depend on the desired level of protection. In cases where higher bank deformation is desirable, the maximum size can be reduced, for example, to become mobile at the 10- to 15-year event.

- Design of the riprap toe is well established. The elevation of the top of the stone toe section is generally based on the elevation of depositional surfaces where vegetation is growing. Miller and Hoitsma (1998) recommend using the elevation where perennial vegetation usually grows. The width of the flood plain relative to potential channel movement has not been well established and would depend on local channel characteristics, valley geology, channel morphology, and amount of flow area increase needed to reduce sediment transport capacity to be in balance with supply.

- The lifespan of the biodegradable coir fabric depends on the amount of wetting and drying and exposure to sunlight, and it generally ranges from 3–5 years. During this period of time, the toe of the slope must remain stable, and the vegetation must grow to a sufficient size and density to provide future bank stability while allowing a natural rate of bank migration. The properties of bioengineered fabrics are documented by Hoitsma (1999).

  For incised channels, constructing a two-stage channel is advantageous to balance sediment transport supply with capacity. This also establishes an inset flood plain where erosion rates will be less than untreated areas. This is especially true where the bank height exceeds the riparian root depth, resulting in high bank erosion rates. The inset flood plain should be designed to balance sediment transport capacity with supply. See section 3.6 for more information on bank line lowering and two stage channel requirements.

- Vegetation should be species indigenous to the riparian zone and can be planted using the live staking method (Sotir and Fischenich 2007). Upper bank structures can be constructed using FES or other measures such as prevegetated mats, grown sod, live fascines, or wattles (Gray and Sotir 1996; Schiechtl and Stern 1994; Benthrup and Hoag 1998). Additional information on bioengineering applications is included in section 4.1.1.

- The amount of flood plain lowering can be analyzed using hydraulic modeling. The main channel should be connected to the flood plain at least above the bank-full discharge.

- The level of reliability can be great, provided that there is sufficient land available for lateral migration as the bank line deforms. Not suited for areas where the bank line has eroded near valuable infrastructure without channel relocation.

- The project life and design life can be great because the method allows geomorphic and flood plain processes.

- Level of installation complexity can be fairly high.

- Maintenance requirements include replanting vegetation that dies and potential riprap replacement should riprap erosion occur prior the vegetation becoming firmly established.

- Constructability issues include access, available land area to construct the toe, and bioengineering on the upper bank. If a cofferdam is being used, construction plans must include dewatering. If toe protection is constructed subaqueous, suitable equipment and construction timing during low flows would be important considerations.

4.3.5 Bioengineering

- The confidence level is Level 1 (because bioengineering does not have a well established track record without longitudinal stone toe installation).

- Vegetation has lowest erosion resistance of all available methods (Hey 1994).

- Plantings require time to establish, and bank protection is not immediate (NRCS 1996). Additional materials such as biodegradable fabrics can be used to provide temporary bank stabilization until vegetation becomes well established (Fischenich 2000).

- Few plants grow below the base level flow, except for their roots. Establishing plants to prevent undercutting of the bank due to toe scour is difficult (NRCS 1996); therefore, the use of living vegetation as a bank protection material is generally limited to the bank elevations above a base level of flow (Fischenich 2000). This base level of flow could be the mean annual water surface, bank-full elevation, or at the elevation of depositional bars and bank line surfaces where natural vegetation grows in the river system. Most bioengineering methods have some longitudinal toe protection component included (NRCS 1996; Fishenich 2000). There are examples of applying only bioengineering for bank stabilization for road side canals or other small channels where grass is used as an erosion resistance lining (Schiechtl and Stern 1994; Gray and Sotir 1996; Kilgore and Cotton 2005). In this case, information on the erosion resistance of various types of grass is available (Kilgore and Cotton 2005). Erosion resistance of various types of woody species is available (Schiechtl and Stern 1994) but not for cases where there is active bank toe scour (David Biedenharn, 2007, personal communication, Biedenharn Group).

- Vegetation can assist in bank stabilization by trapping sediment and increasing bank line flow resistance, thereby lowering near bank velocity (NRCS 1996). The boundary shear resistance to erosion is less than structural elements (NRCS 1996).

- This technique has the potential to increase the water surface elevation because of added bank roughness.

- The bank line location would not be permanently fixed, thereby allowing some downvalley and lateral bank erosion. It is unknown whether the channel would deepen and induce bank toe scour as a result of bioengineering.

- Because toe erosion is common in the Middle Rio Grande, bioengineering as a standalone method is not recommended for the Middle Rio Grande. In addition, many banks on the Middle Rio Grande are sandy and noncohesive, which further limits the applicability of bioengineering without toe protection. Therefore, no more research has been conducted into the geomorphic response, advantages and disadvantages, and requirements of bioengineering for bank protection purposes.

4.4 Transverse Features (Including the New Technologies Being Developed Jointly by Reclamation and Colorado State University)

- Transverse features are protection structures that extend into the stream channel and redirect flow so that the velocity and shear stress are reduced to nonerosive levels. The transverse features included in this maintenance plan are bendway weirs, spur dikes, vanes, J-hooks, trench filled bendway weirs, and large, woody debris.

- To minimize redundancy, advantages and disadvantages that apply to all transverse features are described at the beginning of this section. Aspects of advantages and disadvantages that apply to each method are discussed in each section.

- Bed stability is an essential consideration in any bank stabilization scheme; when there is system-wide channel degradation; a more comprehensive treatment plan may include grade stabilization (Biedenharn et al. 1997).

- Bendway weirs and vanes (or barbs) are similar with small but distinct differences. They each have a different effect upon the physical flow patterns. Vanes (or barbs) are built to bank height along the bank line and slope down such that the tip is inundated at most low flows. This sloping top redirects the flow away from the bank in the near bank region. Bendway weirs have a flat top positioned above the low water surface and below the bank-full water surface elevation; thus, there is a weir effect at low flows. The flow that is captured by the weir is all redirected to the center of the channel. At high flows, bendway weirs redirect the secondary currents, and this reduces the near bank high-flow velocity.

- In all transverse features, the rock used must be of suitable size and gradation to withstand the hydrodynamic forces of the flow.

4.4.1 General Advantages and Disadvantages

4.4.1.1 General Advantages

The general advantages of transverse features are:

- Little or no bank preparation is needed for construction. This reduces costs and reduces impacts to the riparian environments and, usually, allows overbank drainage and inundation levels to remain unchanged.

- Existing channel alignment and/or geometry can be modified.

- Transverse methods usually increase geotechnical bank stability by inducing sediment deposition near the bank, although this process may take a number of years to occur.

- Sediment deposition between the transverse features may not be desirable and may be mitigated by constructing notches (lowered areas in the transverse feature near the bank line) (Shields 1983a). No guidelines are given for the notch size.

4.4.1.2 General Disadvantages

The general disadvantages of transverse features are:

- If the mechanism of bank failure is geotechnical instability or erosion from bank line drainage, transverse methods do not immediately address these conditions, and bank failure could continue without another countermeasure.

- Transverse features change the flow alignment, channel geometry, and roughness so attention must be given to the river's morphological response.

- Some types of transverse features can be a safety hazard to recreation, and the esthetics may leave much to be desired, although subsequent vegetation growth often reduces the visual impact.

- Transverse features extend into the flow and cannot be constructed or maintained during high flows, and working in the river may be difficult. Because these structures redirect flow, they may be subject to severe hydraulic conditions during their service life and should be monitored and maintained so their function will remain intact.

- These methods may cause local sediment deposition between structures along the existing bank line and/or local bank scalloping if they are placed larger distances apart (Derrick 2002; McCullah and Gray 2005; NRCS 2007). This can be an advantage for developing variable depth and velocity habitats.

- Vanes, bendway weirs, and J-hooks may not provide bank protection sufficient to protect high value infrastructure located immediately adjacent to the protected bank. In this case, vanes, bendway weirs, and J-hooks can be combined with longitudinal stone or longitudinal bank lowering or relocating the channel away from the infrastructure. Spur dikes would provide sufficient bank protection.

4.4.2 General Application

Common channel response for the application of transverse features:

- Transverse features deflect flow away from the bank line, thereby altering the secondary currents and flow fields in the bendway. Therefore, they have more substantial local impacts than do bank line armoring techniques. The amount of flow that is deflected away from the bank line varies with each method and local site conditions. It generally is assumed that the length of effects is about one-half meander wavelength up and downstream for meandering streams and about four channel widths downstream and one to two widths upstream for a braided stream" (Fishenich 2001).

- The thalweg moves away from the bank line (Johnson et al. 2001).

- The following is a conceptual hypothesis without supporting data. With the thalweg being moved out away from the bank line and interruption of the secondary currents, the maximum velocity location is more towards the center of the channel. This could increase the velocity in the center of the crossing or riffle and result in mining bed material from the crossing or riffle.

- Transverse features have the potential to raise the water surface because of the reduced cross sectional area. Encroaching upon the channel width with transverse features often results in deepening of the main channel and local scour. These methods induce additional local scour at the toe of the structure and downstream for "about two to three times the scour depth" (Fischenich 2000).

- When the cross sectional area is reduced, the velocity often increases. In addition to disrupting secondary currents, these methods generate eddies, increase turbulence, and create velocity shear zones.

- These structures generate form roughness, and because they significantly alter the flow field, zones of scour and deposition can occur in close proximity. The scour and depositional patterns depend on the orientation, planform, channel type, bed material characteristics, amount of sediment transport, etc.

- The scour and deposition, and zones of high and low velocity in close proximity, create variable depth and velocity habitat. This creates greater environmental benefits than riprap revetments or longitudinal stone toe (Shields et al. 1995). Greater edge or shoreline length is created (McCullah and Gray 2005).

- As with bank stabilization methods, these techniques reduce local bank erosion, while inducing local channel deepening and local bank toe scour, while generally having a minor effect upon sediment transport (Fishenich 2000). The width-to-depth ratio can decrease. If there is a large increase in flow resistance, sediment transport capacity can be reduced.

- Fixing the bank line location with transverse features can diminish lateral and downvalley migration and have the same upstream and downstream morphological effect as bank line features described in section 4.1.1. In channel conditions where the sediment supply from bank erosion is a significant part of the total sediment load, there could be increased or accelerated bed and bank erosion downstream (Fischenich 2001).

- The response may be deepening of the channel as long as the bank remains fixed. If any of these methods are flanked, large riprap may remain in the channel for a time with the scour hole on the downstream side.

- Bank scalloping between transverse features is a common occurrence and can lead to failure. Some bank retreat between structures is likely to occur before a stable bank is achieved by vegetation growth and/or sediment deposition.

- Long-term bank protection is best provided with bendway weirs, vanes, and J-hooks if significant sediment deposition occurs that vegetates into a dense riparian zone (McCullah and Gray 2005).

4.4.3 General Requirements

Common requirements for the application of transverse features:

- Riprap should be of sufficient size to remain in place during high flows.

- Key length can be estimated using the method reported by McCullah and Gray (2005).

- Scour can be predicted using methods found in Przedwojski et al. (1995) and Kuhnle et al. (1999; 2002).

4.4.4 General Benefits

Riparian benefits common to transverse features:

- Area between features would be subject to sediment deposition and overbank flooding, which promote the development of riparian vegetation.

- Backwater or slack water areas could become established between features that are conducive to riparian development. These benefits may be realized before sediment deposition occurs that fills the area between features.

Aquatic benefits common to transverse features:

- Vanes and other intermittent structures such as transverse features (bendway weirs, spur dikes, rootwads, engineered log jams, etc.) provide greater habitat than longitudinal bank line features (Shields et al. 1995; Brown 2000).
- Variable depth and velocity habitat is created, including deep pools at the tips of the transverse features. Slack water areas also can exist between structures. These slack water areas may become partially or completely filled with sediment. These shallow, low velocity areas could be utilized by RGSM.
- Local scour could provide habitat diversity and refugia habitat during low-flow periods.

4.4.5 General Effects

Riparian effects common to transverse features:

- Primary channel may be subject to degradation, reducing overbank flooding in the future, and lowering the overall water table.
- Reduces the river's potential for lateral movement and establishment of multiple age classes of vegetation.

Aquatic effects common to transverse features:

- Channel deepening and tip scour can locally lower the riverbed.
- Can create deep scour pools that could be used by predators of RGSM.

4.4.6 Bendway Weirs

- The confidence level is between:
  - Level 2 has limited design criteria with limited lab data
  - Level 1 because there are no design or test data
- Bendway weirs are features that extend from the bank out into the flow. They have horizontal crests that are submerged at high flows and are angled upstream.
- Bendway weirs are designed to control and redirect currents though a bend and immediately downstream from the bend. Their purpose is thalweg

management (to move, realign, or relocate the river thalweg through the weir field and downstream). This reduces near bank velocity by redirecting the current. Some bank scalloping may occur between weirs; it is difficult to predict.

- Weirs disrupt the secondary currents that occur in bends during high flows and redirect high-flow currents towards the center of the channel and away from the bank, thereby reducing or eliminating bank line erosion (Derrick 1997b).

- Bendway weirs differ from spurs and vanes (barbs) in that they capture the flow field and redirect flows away from the bank (Derrick 1997b). This is accomplished throughout the bendway usually with a minimum of five structures in the weir field. Bendway weirs are intended to function when overtopped, while spur dikes and vanes deflect flow and are meant to be overtopped near the tips and not near the bank line.

- Bendway weirs were originally developed by the USACE to increase channel width in bends on the Mississippi River to improve navigation and increase channel depths to reduce dredging costs (Biedenharn et al. 1997).

- Since the original development, bendway weirs have been applied to small stream applications as a streambank protection measure.

4.4.6.1 General Range of Application

- The range of application is very large, from small streams where the main purpose is bank protection, up to large rivers, such as the Mississippi River, where the main purpose was creating a wider and deeper shipping channel (Biedenharn et al. 1997).

- Lagasse et al. (1997) report that bendway weirs are used for bank protection at highway bridge crossings on braided or meandering rivers with small to medium radius bends and for channels up to 150 feet wide in the States of Colorado, Idaho, Illinois, Missouri, Montana, Oregon, and Washington. They also note that there is “limited but successful field experience using bendway weirs/stream barbs as stream instability countermeasures.” (Success has been realized; however, the number of reported installations is limited.)

- Bendway weirs can erode away in sand and gravel bed channels due to undermining and subsidence. This situation can be addressed by placing either a gravel filter or fabric filter underneath the stone weir. Self-launching stones are the simplest method to stabilize the weir toe as scour holes form.

- Derrick (1997b) has documented weir conditions that can lead to additional bank erosion problems. If the weirs are angled incorrectly and are too long and high near the downstream end of the bend, there can be a large amount of flow over the point bar that could impinge against the downstream bank. Since the success of the weir field depends on entrance angle, the entrance conditions in relationship to the stream reach must be stable. If the flow direction changes due to upstream channel migration, the flow patterns may not be suitable to reduce the near bank velocity and shear stress, and the bendway weir and bank will erode away (Chester Watson, 2007, personal communication, Biedenharn Group, LLC, Vicksburg, MS).

- There must be sufficient riparian buffer zone between the actively eroding bank line and the structures to be protected because scalloping may occur between the weirs (Derrick 2002).

4.4.6.2 Partial List of Rivers Where Bendway Weirs Have Been Employed

- Channels in Mississippi (Thorne et al. 2003).

- Buckeye Creek, California, and the Blue River in Kansas (McCullah and Gray 2005).

- Reported to be used at highway bridge river crossings in seven States in the United States (Lagasse et al. 2001a).

4.4.6.3 Advantages and Disadvantages

4.4.6.3.1 Advantages

- Flows can be redirected throughout the weir field and in the downstream channel.

- Weirs function best under high-flow and high energy conditions (Derrick 1997a).

- The channel along the outer bank can become a zone of low velocity where sediment can deposit.

- Aquatic habitat is improved because the bendway weirs create variable depth and velocity conditions and, possibly, bank scalloping.

- Weirs can be installed after other methods of bank protection are installed (such as longitudinal features) to improve their performance and habitat value.

- Bendway weirs are known to "create geometrically complex water"/ riverbank boundary conditions that provide variable velocity and depth conditions, which improves fish habitat. Woody debris can accumulate on weirs, adding fish cover (McCullah and Gray 2005).

- The habitat benefits are the same as transverse features or flow deflection techniques discussed above. In addition, there is a greater tendency for scallops to develop between structures, which could create nursery habitat. This method also has the potential to create the most variable depth and velocity habitat.

4.4.6.3.2 Disadvantages

- Bendway weirs are not recommended in narrow streams (less than 50 feet wide).

- They have not been used in high velocity and high gradient streams. The meaning of high velocity and high gradient relative to channel morphology has not been defined. There must be sufficient space between the bank line structures that need to be protected and the weirs so that as bank scalloping occurs, the bank structures will remain protected (Derrick 2002).[1]

- Regular monitoring and maintenance are required for the weirs to remain functioning during their service life.

- The redirective effects of bendway weirs on the flow field are limited in cobble and gravel bed streams due to the erosion resistance of the bed material (McCullah and Gray 2005). Weir stones would tend to launch into the downstream scour hole much more readily in a sand bed channel than in cobble or gravel bed streams.

- Can create scour pools that could be used by RGSM predators.

4.4.6.4 Requirements

- A review of current design guidelines is found in HEC-23 (Lagasse et al. 2001a). No systematic quantitative design method currently exists for length, angle, width, and spacing for various channel conditions.

- No information has been reported on estimating scour for bendway weir installations. Currently, there are no design guidelines to determine the depth and size of the scour hole from bendway weirs. Design guidelines exist for spur dikes (Kuhnle et al. 1999; Kuhlne et al. 2002). Adding some rock to the structure to launch into the scour hole is advised (McCullah and Gray 2005).

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[1] Reclamation and Colorado State University are jointly doing research work to develop design guidelines for the spacing and geometric configurations for various channel conditions to better define the caution given in the previous two bullets.

- Bendway weirs should be constructed throughout the bendway because the success of bendway weirs depends on the flow conditions at the upstream end of the bend.

- Lengths typically range from one-third to one-half of the channel width, with some lengths being 20% of the channel width. Weir length is based on how far from the eroding bank the thalweg should be moved and how erodible the point bar is (Derrick 1997a). Lagasse et al. (2001) state that weirs longer than one-third of the stream width can alter channel patterns and, possibly, cause erosion of the opposite bank. Spacing varies from 1.5 to 3.5 times the length (Lagasse et al. 2001).

- Bendway weirs are pointed upstream. Crest orientation angle for bendway weirs is between 10–20 degrees from the bend radii. Crest width usually varies from 2–3 times the maximum riprap stone size (D_{100}) or wider if more launchable rock is desired. If equipment is needed to construct the bendway weirs from the weir top, there must be enough width to permit safe equipment access. Weir spacing is about 1.5 times their length. Spacing decreases as the bend radius decreases, so the bendway weirs become less economical for low-radii bends (McCullah and Gray 2005). The values of the bend radii, or R_C/W (where R_C is the centerline radius of curvature, and W is channel top width), for which they become less economical, have not been reported.

- The only cost data available is from McCullah and Gray (2005), who report that bendway weirs on the Missouri River cost about $65–$236 per foot of structure.

- Appraisal-level cost estimates that reflect the situation on the Middle Rio Grande should be made.

4.4.7 Spur Dikes (Groins, Hard Points, L Dikes, and T Dikes)

- The confidence level is Level 2.

- Spur dikes are a series of individual structures that are placed transverse to the flow projecting from the riverbank with a horizontal crest, usually at the elevation of the top of bank or design flow water surface elevation.

- Spurs deflect flow away from the bank, reducing the near bank velocity and, thus, preventing erosion of the bank in critical areas.

- Spurs also can be used to reduce the channel width and induce sediment deposition along the bank line between individual spur dikes.

- Spur dikes generally are constructed with a downstream angle.
- Hard points are short spur dikes (Biedenharn et al. 1997).that add roughness and localized bank stability.
- Increased bank protection can occur over time as sediment continues to deposit.
- Generally used to halt meander migration.
- Can be used to narrow channels that are overly wide and create deeper main channel.

  L-head, “hockey stick,” or T-head added to the spur tip can move scour away from the dike (Biedenharn et al. 1997). In cases of tight river bends, the spur dike can contain a longitudinal dike, in an L or T shape, off of the spur dike tip to effectively reduce the number of dikes required. This is a Middle Rio Grande observation, and no specific or general design guidance is given for this application).

4.4.7.1 General Range of Application

- The most common use of spur dikes is in shallow, wide streams with moderate to high suspended sediment load. The shallow depth reduces the height of the structures needed, while the wide channel provides opportunity for the channel alignment and geometry to adjust to the presence of the spur dikes (Biedenharn et al. 1997).
- Spur dikes often are used on large rivers to increase channel depth and improve channel alignment and stabilization of the banks (McCullah and Gray 2005).
- Spur dikes can be used on smaller, higher gradient streams with slightly tighter spacing than on smaller gradient streams (WDFW 2003).
- Spur dikes can be used on rivers where establishing riparian vegetation is a high priority. Once the sediment deposits occur between spur dikes, natural vegetation occurs, which could be supplemented by plantings later.
- Channel capacity at high flow can decrease initially, depending on the level of flow restriction caused by the spurs. The channel usually adjusts by forming a deeper, narrower cross section (McCullah and Gray 2005). The extent of the local adjustment cannot be predicted with reliability (Biedenharn et al. 1997).

- Lagasse et al. (2001a) report that spur dikes are widely used at highway bridge crossings for braided or meandering rivers with long radius bends that are wide or moderately wide.

- In a report by Thorne et al. (2003), spur dikes had the most success for relatively long radius bends with a wide range of outer bank shear intensities in eight streams in Mississippi. R_c/W values were greater than about 3.

- The most common causes of spur failure are undermining due to scour at the tips and flanking by the river (bank erosion around and behind the structure). Providing scour protection in the form of self-launching and/or a wider crest width reduces undermining failure potential. Keying the structure into the bank can provide protection from outflanking (McCullah and Gray 2005).

- A secondary cause of spur failure is the entrance angle changing due to upstream channel migration, resulting in a larger flow entrance angle with concurrent larger amounts of velocity and scour (Chester Watson, 2006, personal communication, Biedenharn Group, LLC, Vicksburg, MS). A countermeasure for this situation can be adding additional rock to launch into the scour hole in addition to the amount necessary to launch into the estimated scour pool as a safety factor.

4.4.7.2 Partial List of Rivers Where Spur Dikes Have Been Employed

- Channels in Mississippi (Thorne et al. 2003).

- Sulphur Creek, Redding, California; Keogh River in British Columbia; and Little Blue River, Kansas (McCullah, and Gray 2005).

- Reported as widely used at highway bridge river crossings in the United States (Lagasse et al. 2001a).

4.4.7.3 Advantages and Disadvantages

4.4.7.3.1 Advantages

- Spur dikes modify the channel alignment.

- Spur dikes can provide erosion protection for riverside structures.

- Sediment deposition between spur dikes can provide areas for new vegetation growth and areas that are inundated with low velocity and low depth.

- An incremental construction approach can be used.

- By being transverse into the flow, they offer the opportunity to include a wide variety of environmental features, including establishing woody vegetation on the sediment deposits between spur dikes (Biedenharn et al. 1997).

- When sediment deposits between spurs along the bank line, then bank line erosion protection can be accomplished cheaper than with riprap revetments. By moving the location of scour away from the bank line, partial failure of the spurs can be repaired before damage occurs to the riverside infrastructure.

- Provide a downstream scour hole (zone of large depth), shallow depth upstream of and downstream from the spur dikes, and zones of fast and slow velocity (i.e., variable depth and velocity), although subsequent sediment deposits may be detrimental to shallow water habitat.

- In terms of aquatic habitat, spurs usually provide more habitat than continuous riprap features (Shields et al. 1995.

- Can be lower cost than riprap revetments for shallower rivers.

- Can result in a deeper, narrower channel (Biedenharn et al. 1997), which is an advantage if this is part of the project purpose.

- There is a greater tendency for sediment deposition between spur dikes than the other transverse features. This can be an advantage if this is part of the project purpose.

4.4.7.3.2 Disadvantages

- For deep channels, spurs may cost more than riprap revetments due to the large volume of rock required to construct a high structure (Biedenharn et al. 1997).

- There may be some erosion between spurs (bank scalloping) and can only be used in applications where the additional bank erosion between spurs is acceptable for project purposes.

- Channel capacity may be reduced initially (Biedenharn et al. 1997).

- Channel usually adjusts to form a wider, deeper mid-channel section and a narrower overall cross section. The extent of this adjustment cannot always be predicted with great reliability (Biedenharn et al. 1997).

- The bank line remains in a fixed location after construction, resulting in an interruption of fluvial geomorphic processes.

- No formal and widely tested design methods currently exist.

- Spur dikes are usually used on outer banks along long radius bends. As the bend radius decreases, the spacing decreases, and the necessary number of dikes soon reaches a number where the method is no longer cost effective (McCullah and Gray 2005).

- Spur dikes modify the channel alignment and provide a downstream scour hole. They completely block the flow up to bank height or design discharge since they have horizontal tops. The flow field is most altered with this technique, resulting in deeper and larger scour hole development than other transverse methods.

- Can result in a deeper, narrower channel (Biedenharn et al. 1997). In some situations, a deeper channel can result in a coarsening of bed material. This can be a disadvantage if it results in undesirable habitat conditions for RGSM.

- Can create deep scour pools that could be used by RGSM predators.

4.4.7.4 Requirements

- A review of current design guidelines is found in HEC-23 (Lagasse et al. 2001a), HEC-20 (Lagasse et al. 2001b), and NRCS (2007). No systematic quantitative design method currently exists for crest length, angle, width, and spur spacing for various channel conditions.

- Limits of protection can extend between bend inflection points. The core of maximum velocity follows the thalweg at low flows and can shorten its path by cutting across the point bar at high flows. The region of maximum scour and bank erosion is observed to be located in the downstream part of the bend. Therefore, the protection may not need to extend to the upstream inflection point between bends.

- Lengths typically range from less than 20% of the bank-full channel width to about one-third the channel width. Spacing varies from 1.5 to 3.5 times the length (Lagasse et al. 2001).

- Crest orientation angle generally varies from perpendicular to the approach flow to being angled upstream 75 degrees. Crest width usually varies from 2-3 times the maximum riprap stone size (D_{100}) or wider if more launchable rock is desired (McCullah and Gray 2005). If the spur dikes cannot be constructed from the bank line, then the width will need to be sufficient for safe equipment access.

- Ranges of entrance angles are not always reported in the literature for successful installations. More review of the literature is needed to determine the entrance angles of successful installations.

- Scour can be predicted using Przedwojski et al. (1995) and Kuhnle et al. (1999 and 2002).

- The only cost data available are from McCullah and Gray (2005), who report that spurs typically cost about the same as riprap revetments. On the Missouri River, they cost about $65–$236 per foot of structure. Spur dikes can be cheaper than riprap, in some cases, depending on site conditions. An estimate to compare the cost of spur dikes with the cost of riprap revetments should be made at each site.

4.4.8 Vanes or Barbs

- The confidence level is between:
  - Level 2 because there are limited design criteria.
  - Level 1 because there are very little test data that can be used as a basis for design.

- Vanes, also known as barbs, are discontinuous, transverse structures angled into the flow. They can be used for bank protection, as well as for providing variable depth and velocity habitat.

- Instream tips are usually low enough to be overtopped by nearly all flows; the crest slopes upward generally to the bank-full stage elevation at the bank.

- They are angled upstream to redirect overtopping flows away from the protected bank.

- Vanes redirect flow and reduce local bank erosion, while providing a downstream scour hole. Flow redirection causes the velocity and shear stress along the bank to decrease, while creating a secondary circulation cell that transfers energy to the center of the channel (Fischenich 2000), creating a new thalweg location.

- Some sediment deposition may occur upstream of and downstream from the structures, resulting from the redirected flows. In situations where sediment deposition occurs between the structures, additional bank protection can develop over time.

- In cases where sediment deposition occurs between structures, bank protection can be provided cheaper than riprap revetments.

- The redirection of flow reduces the velocity and shear stress along the bank, while creating a secondary circulation cell that transfers high velocity away from the bank (Fischenich 2001). This provides toe protection and reduces or arrests bank erosion.

- Vanes have a scour pool near the tip and can create variable depth and velocity conditions that benefit aquatic habitat.

4.4.8.1 General Range of Application

- Vanes can be used on rivers where establishing riparian vegetation is a high priority. Once the sediment deposits occur between vanes, natural vegetation occurs, which could be supplemented by plantings later.

- It is suggested that vanes only be used in channels with a width-to-depth ratio of 12 or greater (Maryland 2000).

- Lagasse et al. (1997) report that vanes (barbs) are used for bank protection at highway bridge crossings on braided or meandering rivers with small to medium radius bends and for channels up to 150 feet wide in the States of Colorado, Idaho, Illinois, Missouri, Montana, Oregon, and Washington. They also note that there is "limited but successful field experience using bendway weirs/stream barbs as stream instability countermeasures." (Success has been realized; however, the number of reported installations is limited.)

- Vanes can be positioned in a channel to initiate meander development or migration for habitat purposes (McCullah and Gray 2005).

- The most common causes of vane failure are undermining due to scour and flanking by the river (bank erosion around and behind the structure). Providing scour protection in the form of self-launching and/or a wider crest width reduces undermining failure potential. Providing additional downstream footers also can be used as a countermeasure. Keying the structure into the bank can provide protection from outflanking.

- Vanes can fail if the spacing is too great, causing excessive bank scalloping to occur (NRCS 2007).

- A secondary cause of vane failure is the entrance angle changing due to upstream channel migration, resulting in a larger flow entrance angle with concurrent larger amounts of velocity and scour. Countermeasure for this situation can be upstream bend stabilization and adding additional rock as a safety factor, to launch into the scour hole in addition to the amount necessary to launch into the estimated scour pool as a safety factor. Accept that upstream bend migration may occur and that the vanes may need to be repositioned in the flow.

- If the angle does not redirect flow sufficiently, further bank erosion can occur downstream from the structures.

- Improper van angle and height can redirect flow into unintended places, creating further bank erosion downstream from the structures (Johnson et al. 2001).

- Some failures are related to seepage under and around the structures. Proper footer placement and, in some cases, additional deeper footer rocks are a countermeasure for this failure mode.

4.4.8.2 Partial List of Rivers Where Vanes or Barbs Have Been Employed

- San Vacinte Creek in California (McCullah and Gray 2005).

- Ninnescah River, Kansas (McCullah and Gray 2005).

- Snake River in Idaho.

- John Day River Basin.

- Lower Blanco in Colorado and Bitteroot River in Montana (Rosgen 2006).

4.4.8.3 Advantages and Disadvantages

4.4.8.3.1 Advantages

- Vanes can be used to reduce streambank erosion and modify flow direction and local scour, while gaining environmental benefits.

- Where sufficient sediment supply exists, sediment deposition between vanes can be used to provide locations for vegetation plantings and natural vegetation reestablishment, thus increasing bank stability.

- Redirecting the flow to the center of the channel can create (by increasing the shear stress in the center of the channel) a stable width-to-depth ratio, maintain channel capacity, and maintain sediment transport capacity (Rosgen 2006).

- Vanes require less rock than riprap for a similar length of bank.

- The thalweg moves away from the bank line (Johnson et al. 2001).

- The habitat benefits are the same as given above in section 4.4.4.

4.4.8.3.2 Disadvantages

- The low volume of rock near the tip of the vanes may result in reduced flow redirection due to the rock launching into a scour hole.
- Bank scalloping between vanes is a common occurrence and can lead to vane failure.
- Long-term bank protection is best provided with vanes if significant sediment deposition occurs that vegetates into a dense riparian zone (McCullah and Gray 2005). A common long-term maintenance activity for vanes is adding riprap to the vane tip.
- No formal and widely tested design methods currently exist.
- The habitat effects are the same as given above in the transverse features section.

4.4.8.4 Requirements

- No systematic quantitative design method currently exists for crest length, angle, width, spacing, orientation, or vertical angle for various channel conditions.
- Limits of protection can extend between bend inflection points. The core of maximum velocity follows the thalweg at low flows and can shorten its path by cutting across a point bar at high flows. The region of maximum scour and bank erosion is observed in the downstream part of the bend. Therefore, the protection may not need to extend to the upstream inflection point between bends.
- Lengths typically range from 25–33% of the bank-full width (Maryland 2000; Brown 2000); spacing is about twice the channel width (Johnson et al. 2001; Maryland 2000).
- The crest is oriented upstream 20–30 degrees from the bank line tangent (Johnson et al. 2001). Crest slope is created with the tip being inundated at most flows and sloping up to the bank-full stage elevation, and it should generally be between 3–7%. It is recommended that vanes be constructed with self-launching stones to stabilize the scour hole, thus preventing additional tip erosion. More rock can be added to the width where large amounts of scour are anticipated, but no guidelines are given.
- Ranges of entrance angles have not been found in the available literature on successful installations.

- Rock vanes extending one-third of the bank-full width into the channel and oriented upstream between 20–30 degrees have been shown to move the thalweg an average of 20% bank-full width away from the eroding bank (Johnson et al. 2001).

- Key length can be estimated using the method reported by McCullah and Gray (2005).

- The only cost data available are from McCullah and Gray (2005), who report that vanes typically cost about half of the amount of installing riprap on the bank.

- Appraisal-level cost estimates that reflect the situation on the Middle Rio Grande should be made.

4.4.9 J-Hooks

- The confidence level is between:
    - Level 1 because J-hooks do not have a track record and have few literature citations.
    - Level 2 because the vane part of the J-hook has some design guidelines.

- J-hooks are vanes with a tip placed in a downstream pointing "J" configuration. The "J" tip is partially embedded in the riverbed, so it is submerged during low flows. J-hooks are discontinuous, transverse structures angled into the flow that redirect the flow from eroding banks.

- The crest slopes upward from near the riverbed elevation to generally the bank-full stage elevation at the bank line.

- The "J" tip is intended to produce additional instream habitat by creating a scour pool downstream from the "J" tip, especially in gravel to cobble substrates (McCullah and Gray 2005).

- The vane portion of the J-hook is angled upstream to redirect overtopping flows away from the protected bank.

- Some sediment deposition may occur upstream of and downstream from the structures resulting from the redirected flows. In situations where sediment deposition occurs between the structures, additional bank protection can occur over time.

- In cases where sediment deposition occurs between structures, bank protection can be provided cheaper than riprap revetments.

- Vanes with J-hooks redirect flows away from eroding banks and are the same as vanes with an added downstream pointing "J" configuration. The "J" part of the tip is often embedded in the streambed, so they are inundated at low flows (McCullah and Gray 2005).

- The added feature is that the "J" creates an additional scour hole and can produce a riffle downstream (McCullah and Gray 2005). The J-hook scour hole is larger, wider, and deeper than created by vane structures alone.

- Vanes redirect flow and reduce local bank erosion, while providing a downstream scour hole. Flow redirection causes the velocity and shear stress along the bank to decrease, while creating a secondary circulation cell that transfers energy to the center of the channel (Fischenich 2000), creating a new thalweg location. This provides toe protection and reduces or arrests bank erosion.

- The "J" tip further enhances the scour pool near the tip and creates variable depth and velocity conditions, providing more potential aquatic habitat than vanes without "J" tips.

4.4.9.1 General Range of Application

- J-hooks can be used on rivers where establishing riparian vegetation is a high priority. Once the sediment deposits occur between vanes part of the J-hook, natural vegetation grows. This vegetation could be supplemented by plantings later.

- It is suggested that they only be used in channels with a width-to-depth ratio of 12 or greater (Maryland 2000).

- J-hooks should not be used in streams with highly mobile substrate or bedrock channels (Maryland 2000).

- Lagasse et al. (1997) do not report the use of J-hooks at highway bridge crossings.

- The most common causes of J-hook failure are undermining due to scour at the tips and flanking by the river (bank erosion around and behind the structure). Providing scour protection in the form of footers is necessary to prevent the downstream scour hole from undermining the rock forming the "J" tip. Keying the structure into the bank can provide protection from outflanking.

- If the angle does not redirect the flow sufficiently, further bank erosion can occur downstream from the structures.

- Riprap that is not large enough to remain in place during high flows can also contribute to failure.

4.4.9.2 Partial List of Rivers Where J-Hooks Have Been Employed

- Manatawny Creek in Pennsylvania (McCullah and Gray 2005).
- Lower Blanco in Colorado and Bitteroot River in Montana (Rosgen 2006).

4.4.9.3 Advantages and Disadvantages

4.4.9.3.1 Advantages

- J-hooks can be used to reduce streambank erosion and modify flow direction and local scour, while gaining environmental benefits.
- Where sufficient sediment supply exists, sediment deposition between J-hooks can be used to provide locations for vegetation plantings and natural vegetation re-establishment, thus increasing bank stability. Generally, the sediment load may not be sufficient to deposit along the bank and maintain the scour pool depth downstream from the “J” tip.
- Redirecting the flow to the center of the channel can create a stable width-to-depth ratio (by increasing the shear stress in the center of the channel), maintain channel capacity, and maintain sediment transport capacity (Rosgen 2006).
- J-hook installation does not require extensive bank reshaping, and most equipment can work from the bank top, reducing bank and bank top disturbance.
- J-hooks require more rock than vanes and less than riprap for a similar length of bank.
- The thalweg moves away from the bank line (Johnson et al. 2001).
- Habitat benefits are the same as transverse features or flow deflection techniques above. Additional pool habitat is created by the J-hook in the center third of the channel. This scour pool provides nursery habitat and some bed stability. The created pool by the J-hook provides a longer, wider, and deeper pool than the pool created by a vane structure.

4.4.9.3.2 Disadvantages

- The method generally should be used in rivers with coarser sediments in the gravel and cobble size range (Maryland 2000). The “J” tip can become filled with sediment in finer-grained channels such as sand bed and fine gravels.

- If the bank line becomes stable, it will remain in a fixed location after construction, resulting in an interruption of fluvial geomorphic processes.

- The channel response is not likely to be a deeper channel overall because the "J" tip will create a grade control in the bed if constructed to the opposite bank point bar or opposite bank. If the J-hooks are flanked, then large riprap may remain in the channel for a time. Eventually, it is likely that the large riprap will migrate into the downstream scour hole.

- Construction of the "J" tip requires working in the river channel and excavating the riverbed to embed the tip into the riverbed. This may or may not be a disadvantage depending on the size of the river channel and the receptivity of regulatory agencies to equipment working in the riverbed.

- The scour hole may not develop unless constructed, or it may be filled or obliterated in rivers that transport higher amounts of gravel and cobble size material.

- Periodic maintenance is likely due to the presence of the "J" tip being near the riverbed elevation and being subject to bed elevation changes and sediment transport and deposition.

- No formal and widely tested design method currently exists.

- The habitat effects are the same as given above in the transverse features section 4.4.4. Some potential for predators using the pool habitat.

- Deposition of sediment close to bank line would be beneficial to RGSM.

4.4.9.4 Requirements

- No systematic quantitative design method currently exists for crest length, angle, width, spacing, orientation, or vertical angle for various channel conditions. Rosgen (2006) has design relationships and criteria that need to be confirmed or replaced with design criteria based on flume experiments or numerical simulations.

- Rock vanes extending one-third bank-full width into the channel and oriented upstream between 20 and 300 have been shown to move the thalweg an average of 20% of the bank-full width away from the eroding bank (Johnson et al. 2001).

- Limits of protection can extend between bend inflection points. The core of maximum velocity follows the thalweg at low flows and can shorten its path by cutting across a point bar at high flows. The region of maximum scour and bank erosion are observed in the downstream part of the bend. Therefore, the protection may not need to extend to the upstream inflection point between bends.

- Lengths typically range from 25–33% of the bank-full width (Maryland 2000; Brown 2000); spacing is about twice the channel width (Johnson et al. 2001; Maryland 2000).

- The crest is oriented upstream of the tangent to the bank line at an angle ranging from 20–30 degrees (Johnson et al. 2001). Crest slope is created with the tip being inundated at most flows and sloping up to the bank-full stage elevation and should generally be between 3–7%. It is recommended that vanes be constructed with self-launching stones to stabilize the scour hole, thus preventing additional tip erosion. More rock can be added to the width, where large amounts of scour are anticipated but no guidelines are given.

- Ranges of entrance angles are not always reported in the literature for successful installations. More literature review is warranted to find out the entrance angles of successful installations.

- Scour cannot be predicted using any available methods.

- A common long-term maintenance activity for vanes is adding riprap to the vane tip.

- Key length can be estimated using the method reported by McCullah and Gray (2005).

- The only cost data available are from McCullah and Gray (2005), who report that J-hooks typically cost about half as much as installing riprap on the bank. The cost data from McCullah and Gray (2005) are the same for vanes and J-hooks. The cost for J-hooks would be more than for vanes because of the increased cost of constructing the “J” part in the riverbed.

4.4.10 Trench Filled Bendway Weirs

- The confidence level is Level 1.

- Trench filled bendway weirs are stone features extending transverse to the anticipated future flow direction and are buried in excavated trenches behind the riverbank. The river erodes to the predetermined weir locations, and the erosion resistant weir tips would become exposed. The trench bottom elevation usually will be below the high-flow water surface elevation and above the low-flow water surface elevation. Bendway weir stones would launch from the bottom of the trench to the thalweg elevation. After launching, additional rock would need to be added and the weir tips reshaped to provide the same hydraulic effect as typical bendway weir installations. It is intended that bank erosion would continue to the root of each weir and that during and after the bank erosion process (and with additional rock placement and reshaping), the bendway weirs would be sufficiently stable so that the effects on the flow described in Section 4.4.6 ,"Bendway Weirs," would be realized.

- Since bendway weirs are intended to capture the flow field and redirect flows away from the bank throughout the bendway (with usually a minimum of five bendway weirs) (Derrick 1997b), it is intended that bank erosion could occur throughout the bendway (bank line scalloping).

- Bendway weirs constructed in trenches provide a less intrusive construction technique when compared with bendway weirs constructed into the flow.

This is an experimental technique applied to the Middle Rio Grande. No data or reports are available about the performance, construction methods, advantages, and disadvantages. The installations on the Middle Rio Grande have not experienced sufficient bank erosion at this time to expose the bendway weir tips. The information in this section is conceptual, qualitative, and is based upon experience and judgment.

4.4.10.1 General Range of Application

- This method has not been applied at any known location other than the Middle Rio Grande. On the Middle Rio Grande, the method has not been tested because erosion has not yet exposed the bendway weirs.

- The potential range of application, common modes of failures, and countermeasures for trench filled bendway weirs are likely the same as for bendway weirs as given in sections 4.6 and 4.4.6, respectively.

- It is envisioned that common failure modes would be the trench excavation causing bank instability as a result of vegetation disturbance, inadequate size and quantity of launchable rock in the weirs, installation in a river reach that is degrading or has contraction scour (McCullah and Gray 2005), tip scour, and rock instability during launching. Common failure modes after bank erosion is largely completed would be undermining and subsidence of the stones.

- Increasing stone size and the quantity of rock to launch to the channel thalweg would be a useful countermeasure. In addition, adding stones to the weirs throughout the bank erosion process would increase bendway weir stability and counteract continued undermining and subsidence of the weir stones. Self-launching stones are the simplest method to stabilize the weir toe as scour holes form.

- Failure also could occur if the bank erosion does not occur simultaneously between weirs. This could lead to a situation where some weirs have large flow concentrations, causing additional tip scour which could be greater than nontrench filled bendway weirs. Countermeasure for this occurrence would be adding supplemental stones to the weirs.

- During the bank erosion processes, the bendway weirs could become exposed to various lengths through time. During this process, there may be concentrated flow along the bendway weir tips, which would create more scour than typically experienced by bendway weirs constructed in flowing water. A countermeasure to this condition could be using larger stones and increased self-launching rock volume.

- It is possible that the exposed tips of some trench filled bendway weirs may erode completely away due to the concentration of hydraulic forces. Reducing bank erosion to the planned location may best be accomplished by reconstructing the weirs at the design locations.

- The level of protection is not well defined because this is an experimental application of bendway weirs.

- The local, temporal, and spatial river responses would be similar to those found in sections 4.4.6 and 4.2 for bendway weirs and trench filled riprap revetments, respectively. In addition, during the bank erosion phase of the project, there would be additional local sediment supply from bank erosion.

4.4.10.2 Advantages and Disadvantages

4.4.10.2.1 Advantages

- Assuming that erosion of the bank line continues and the bendway weirs remain in place during active bank erosion, then the riverbank line may be stabilized along a predetermined alignment.

- Any trench filled method can be applied during high-flow events if there is an emergency situation.

- Erosion of the bank line can continue to occur until erosion exposes the trench filled bendway weirs.

- Avoids in-water construction and bank shaping.

- Advantages of trench filled bendway weirs, after bank erosion has occurred, are similar to bendway weirs given in sections 4.4.6.

- The habitat benefits are the same as given above in the transverse features and bendway weir sections.

- Additional local scour pool habitat may be created during the bank erosion process after the bendway weir tips are exposed.

4.4.10.2.2 Disadvantages

- Long-term performance is an unknown, and this method is not recommended where critical infrastructure is near the actively eroding bank line.

- The bank line will continue to erode until erosion exposes the trench filled bendway weirs.

- The erosion and function of the bendway weirs would not be as effective during the bank erosion process, and significant erosion of the bendway weirs may occur.

- Disadvantages of trench filled bendway weirs are given in section 4.6.6.

- Conceptually, the exposed portion of the trench filled bendway weirs may halt bank erosion before the planned alignment is achieved. Under these conditions, there may be higher flow concentrations along the exposed part of the bendway weirs. This could subject the trench filled bendway weirs to larger hydraulic forces than under the usual bendway weir installation.

- The habitat effects of trench filled bendway weirs are given in sections 4.4 and 4.4.6. Predators could use the pool habitat.

4.4.10.3 Requirements

- Riprap sizes and the estimated tip scour would need to be increased beyond the usual bendway weir applications because, during the erosion process, the bendway weir tips will be exposed to larger hydraulic forces than the usual bendway weir application. The amount of increase is unknown.

- The planview layout of the trench filled bendway weirs could be the same as the usual application of bendway weirs. The spacing may need to be closer together to reduce the effects of increased concentration of hydraulic forces on the weirs than usual applications.

- No design guidelines exist for the application of trench filled bendway weirs. The limited bendway weir design guidelines, found in section 4.4.6, should be consulted to develop design concepts that can be applied to trench filled bendway weirs.

- The level of reliability is unknown, but it is anticipated to be less than for bendway weir applications.

- It is likely that additional maintenance (e.g., replacing stones undermined due to scour) would be required beyond the usual bendway weir installations to counteract the effects of the increased concentration of hydraulic forces at the tips.

Potential construction considerations include:

- Trench filled bendway weirs can be constructed using a rectangular or trapezoidal trench.

- Placing the stone at the lowest practical elevation constructed during low flows can often place the toe of the trench below the high-flow water surface elevation. This is the most advantageous placement because the launch distance is the shortest. A greater volume of stone is required for trench filled riprap because of nonuniform launching. The method used for trench filled riprap (Biedenharn et al. 1997 and USACE 1991) should be consulted to develop concepts of how much additional riprap may be required.

- Material from the trench excavation can be used to raise the local height of the eroding bank to prevent nonuniform overtopping. This aids in more uniform launch rates.

- Trench filled bendway weirs should be monitored after each high-flow event to determine if they are functioning properly. It may be necessary to add supplemental rock once bank erosion has been initiated to ensure the integrity of the bendway weirs.

- Constructability issues include: access and ensuring bank stability during construction with heavy equipment; additionally, stone should be added on an “as-needed” basis until the desired level of bank stabilization is complete. Site-specific conditions will determine how much additional stone is needed. Additional stone is needed because of nonuniformity of bank erosion and launch rates at the bendway weir tips. The bank line may need some vegetation clearing for large equipment to construct the windrow or trench.

- Design flood generally is the discharge that flows over the banks so that launching riprap is not overtopped and the underlying soil eroded. The design flood is variable depending on site conditions, level of infrastructure protection needed, and project authorization. Durability and design life depend on the design flood used. A 25-year event provides an economical design life and a reasonable design flood. Design flood can range from the 2- to 100-year return period discharges.

4.4.11 Large Woody Debris

- The confidence level is Level 2 because there are some design guides available, but there are limited test data.

- There is considerable evidence and documentation that the presence of LWD has a positive influence on stream structure and habitat by primarily providing in stream cover and pool formation (McCullah and Gray 2005). LWD structures are often termed “engineered logjams” and are used to deflect flows, retain gravels, and create complex hydraulics (WDFW 2003; McCullah and Gray 2005).

- A realistic lifespan for the wood itself is 5–15 years (Sylte and Fischenich 2000); however, several factors influence the longevity of the wood that include:

    - Tree species: avoid using hardwood species such as cottonwood or alder, which can decay rapidly.

    - Conifers, such as fir and pine, are moderately long lasting, while oak, cypress, redwood, and cedar last the longest.

    - Frequent wetting and drying can increase decomposition, while submerged wood can last indefinitely (Sylte and Fischenich 2000).

- Because the available LWD wood source on the Middle Rio Grande is cottonwood, which has a low lifespan of about 5 years or less and decays rapidly, LWD is not recommended for bank stabilization actions on the Middle Rio Grande. Therefore, no more research has been conducted into the geomorphic response, advantages and disadvantages, and requirements of LWD for bank protection purposes. However, LWD provides valuable habitat as described below.

    - LWD could be incorporated into projects as a habitat enhancement feature but not as a primary material for constructing structural measures.

- LWD, constructed from cottonwood, would have short-term habitat benefits and should be considered for its environmental value.

- LWD can provide habitat complexity, cover, variable depth and velocity, and slackwater areas, which are important components of naturally occurring good aquatic habitat. However, use of LWD by RGSM is not known.

- LWD structures are intended to replicate natural conditions.

- LWD can be used to enhance outer bank protection treatments such as riprap revetments and longitudinal stone toe.

Chapter 5. Cross Channel (River Spanning) Features

5.1 Grade Control

- Four different types of grade control structures are suggested for potential application for the Middle Rio Grande:
  - Deformable riffles.
  - Rock sills.
  - Riprap grade control (with or without upstream seepage control).
  - Gradient restoration facilities (GRF).

  All of these are considered loose rock structures, without grout or concrete. Information on other grade control structures can be found in Nielson et al. (1991) and Watson et al. (2005).
- This section contains information on method objectives, general range of application, common modes of failure and countermeasures, level of protection, advantages and disadvantages, and requirements that are common to all four types of grade control structures considered applicable to the Middle Rio Grande.
- The objective of cross channel or river spanning features is to control the channel bed elevation or grade, create pool habitat, or use for water diversion structures. Owing to many reaches of the Middle Rio Grande experiencing incision, the primary focus of cross channel structures would be slowing or halting channel incision or raising the riverbed. Grade control features are used in cases where channel incision has or will cause excessive lateral migration and undermining of levees and riverside infrastructure (Bravard et al. 1999).

5.1.1 General Range of Application

- Many incised channels have excessive unit stream power, which can be reduced by lowering the gradient or increasing channel width. Grade controls reduce the gradient by controlling the bed elevation and dissipating energy in discrete steps (Bravard et al. 1999).
- Grade control structures involve installation of a variety of immobile and partially mobile hard structures in the riverbed to raise the riverbed or

maintain its current elevation. These structures can be designed and constructed of a variety of types of loose rock, sheet pile, concrete, and combinations of these materials. Some form of local bank protection or tiebacks may be needed to prevent outflanking by the river.

- These structures physically control the downward cutting of the riverbed in one local reach (Bravard et al. 1999) upstream of the structure. These structures do not halt continued channel bed lowering downstream from the structures or the increased shear stress caused by channel confinement, (e.g., channel narrowing by degradation and vegetation growth, levees, bridge crossings, roads, etc.).

- In some cases, aquatic and riparian habitat can be improved by raising the riverbed and halting continued downward cutting of the bed (Bravard et al. 1999).

- Where the bed of the river is degrading or incising, bank stabilization features can fail unless the incision is addressed simultaneously (Biedenharn et al. 1997). Addressing incision includes options such as grade controls, channel widening, channel lengthening, and sufficient launchable riprap in thickened rock toes for bank stabilization measures.

- Grade controls can be considered high or low. There is no general agreement on what is considered a high or a low grade control or checkdam. Mendrop and Little (1997) classified Mississippi checkdams over 6 feet as “high” and those less than 6 feet as “low.” Often, “low” refers to structures less than 3 feet high. Loose rock structures are most effective when the drop height is less than 2 or 3 feet (Watson et al. 2005; NRCS 2007). Grade control structures (i.e., GRFs) on the Middle Rio Grande between Angostura Diversion Dam and Highway 550 bridge at Bernalillo, New Mexico, were constructed with about a 2-foot drop height with a long, low downstream apron for fish passage. Apron lengths were 400 or 500 feet resulting in apron slopes of 0.005 or 0.004, respectively.

- A series of loose rock structures is often placed in close succession, effectively providing a greater drop height than a single structure (NRCS 2007). The structures should be spaced so that the channel degradation does not undermine adjoining grade control structures.

- In general, high weirs have more downstream scour and also may prevent upstream fish migration (Bravard et al. 1999).

- Low weirs have a smaller drop and have reduced scour potential, reduced risk of failure, less severe consequences in the event of failure, and improved potential for fish passage. A series of low weirs may be preferable to one high weir (Haltiner et al, 1996).

- Instead of grade control structures, an armored bed has been used on small streams in Germany, which will resist entrainment, thus preventing incision (Kern 1997)

- The grade control structures' lifespan, number, and spacing should be accounted for in the design.

- The location of grade control structures, the number, and spacing depend on accurate estimates of dynamic equilibrium bed slopes and the occurrence of future channel degradation.

- Grade control may reduce the tendency for lateral channel migration by reducing channel incision, especially in cases where it may be possible to maintain the bed elevation above the root zone of the adjacent riparian forest. In some situations, the channel may be actively migrating, and grade control structures will need flanking protection (Bravard et al. 1999).

- These methods raise the upstream water surface elevation, at least during low flows, depending on the height of the structure. The upstream velocity is reduced, and upstream secondary current may be disrupted by inundation. Low head structures may not raise the water surface during peak flows.

- These methods can enhance bank stability by stabilizing the bed elevation, thereby potentially reducing the length of bank line that has unstable heights (Watson and Biedenharn 1999).

- The length of the affected reach of river can be the greatest for these methods, when compared to other methods in this appendix, due to raising the water surface, decreasing channel velocity, upstream sediment deposition, and, potentially, downstream degradation.

- Common failure modes include entrainment of the riprap (nonmobile grade control structure), downstream scour, flanking, and upstream sediment storage coupled with downstream sediment deficiency, leading to channel degradation. Countermeasures include adequate riprap sizing, downstream scour protection, and flanking protection via tiebacks or upstream bank stabilization (Watson et al. 2004). The best flanking protection is an upstream stable straight approach (NRCS 2007). Flanking protection should be added to the project as described below. The upstream channel still may need stabilization even in the case of a stable, straight, upstream approach.

Countermeasures for sediment transport include using a series of smaller structures instead of one large structure, which stores more sediment, thereby depleting downstream sediment supply. A series of multiple low drops would have negligible effect on sediment transport (NRCS 2007).

- The level of protection provided for passage of peak flows and to prevent bank erosion towards riverside infrastructure can range from medium to high depending on the grade control type, spacing, and height.

5.1.2 General Advantages and Disadvantages

5.1.2.1 General Advantages

- Prevents continued incision.
- Raises the bed and water surface elevation for structures constructed above the existing bed, improves flood plain connectivity (Brookes 1996), and balances the long-term sediment transport capacity with supply.
- Prevents channel degradation that leads to damage to riverside infrastructure.
- Improves channel stability.
- Improves bank stability while preventing oversteepened banks that lead to severe mass failures of both streambanks.
- Maintains or prevents lowering of the ground water table (Watson et al. 2005; NRCS 2007).
- Gradient control features should reduce channel degradation upstream of the feature, promoting overbank flooding and raising the water table, which are conducive to riparian establishment and development.
- Increased upstream water levels (except for peak flows) likely would increase riparian vegetative health.
- By preventing future upstream local degradation the current level of floodplain connectivity can continue.
- Lower apron slopes can meet fish passage flow velocity requirements (Bestgan et al. 2003).

5.1.2.2 General Disadvantages

- Fluvial processes of bed elevation changes over time are diminished; in some cases (particularly high structures); sediment transport may be out of balance between upstream storage and downstream reduced sediment load; and without special design features, fish passage can be disrupted. Channel widening, increasing flood plain connectivity (bank lowering or two-stage channels) and increasing the channel length all accomplish bringing sediment transport capacity more in balance with supply without structures (Watson et al. 2005; NRCS 2007).

- Downstream channel degradation could occur to a degree that the water table is lowered, reducing water availability to riparian vegetation.

- There is the potential for fish passage issues at very low river depths. During high flows, the velocities may be excessively high for RGSM. Steeper apron slopes may restrict fish movement (Bestgan et al. 2003). Several long, low slope aprons have been constructed on the San Ana Pueblo but without reported fish passage data.

- Guidelines for spacing and siting grade control structures are given in Bravard et al. (1999), Biedenharn and Hubbard (2001), Watson et al. (2005), and NRCS (2007).

- Design guidelines for grade control structures for most types are found in Watson et al. (1999), Watson et al. (2005), and NCRS (2007).

- Riprap sizing can be determined using the methods contained in Watson et al. (2005). NRCS (2007) also summarizes five methods for designing rock size. For fully submerged conditions, USACE (1994) is recommended, along with the method found in Lagasse et al. (2001). Of the five methods in NRCS (2007), the USACE (1994) method provides the most conservative, based on size for design and based on unit discharge (NRCS 2007). Additional design methods are available (Frizell, et al., 1998)

- For a series of structures (regardless of the type), the hydraulic spacing should be determined based on the hydraulics and sediment deposition patterns of the downstream grade control. Mussetter (1982) and Beidenharn and Hubbard (2001), provide a method for the optimum spacing based on the length of deposition above the structure.

- One of the most important factors is determining the equilibrium sediment slope upstream of the structure (Bravard et al. 1999). This will be a function of the incoming sediment concentration, load, and size; channel characteristics (slope, width, depth, roughness, etc.); and the hydraulic effect of the structure. Methods to estimate the upstream equilibrium channel slope are given in Biedenharn and Hubbard (2001) and include regime analysis, tractive force, minimum permissible velocity, and sediment transport modeling. Incipient motion criteria also can be used (Pemberton and Lara 1984; Yang 1996; Reclamation 2006).

- The crest should be keyed into both banks to prevent flanking. These can be riprap-filled trenches or sheet pile walls, which extend to the greater of either the top bank elevation or the 2-year flood plain (NRCS 2007). Shields et al. (1999) recognized that flanking protection needs to be beyond the 2-year flood plain and recommend that a 25-year or, in some cases, a 100-year event would be needed. In this case, on the Middle Rio Grande, it would be useful to extend them further than the 2-year event water surface elevation because the 2-year flood plain is the current bank in many locations. Without a key beyond the current bank line, the structure would be easily flanked. Flanking protection is often placed into the banks a distance to protect against channel migration, the same distance as past meander bend locations, or to some natural nonerodible surface or geologic formation. The distance flanking protection provided can also depend on maintenance capability. Where maintenance capability is readily available, flanking protection can be less than where very little future maintenance capability exists. Site adjustments would need to be made by evaluating migration potential for each structure.

- Some grade control structures are constructed at intervals of naturally formed riffles, or about every 5–7 bank-full widths, with weir crest elevations that do not cause backwater at bank-full flow (Newbury and Gaboury 1993; Watson et al. 2004). Shields (1996) provides criteria for spacing of low stone weirs.

- Multiple low head drop structures:
  - Usually can be designed and constructed for less cost.
  - Have less adverse impacts to fish passage.
  - Have less potential for morphological impacts.
  - Do not alter flow and sediment transport.
  - Have a limited impact upon bank stability.
  - Have increased difficulty in determining appropriate spacing and siting.
  - Have more construction access than single structures.
  - May not be high enough to reconnect the channel with the flood plain (NRCS 2007).

- There can be an effect on sediment transport, scour, and deposition, depending on the structure height, incoming sediment load, and size and channel characteristics (slope, width, depth, roughness, etc.). Sediment is deposited in the upstream reach and is generally finer than sediment found in adjoining reaches (Fischenich 2000). However, this depends on the sizes of bed sediments and the rate of sediment transport and supply in the upstream reach. Sediment can deposit upstream of these structures, even without a rise in the water surface during high-flow events. Downstream scour pools generally develop. In some cases, particularly with higher head structures, sediment may be trapped upstream in sufficient quantities relative to the sediment supply that downstream degradation occurs (Fischenich 2000). As the upstream channel adjusts over time, the reach upstream of the structure fills with sediment, and sediment continuity may be re-established. A series of smaller grade control structures reduces the effect upon channel morphology and sediment transport. Multiple low drops will not cause significant effect on flow and sediment transport (NRCS 2007). For low head drops, the reach upstream of the grade control should approach the dynamic equilibrium slope, depth, width, and velocity of the upstream river reaches. A series of structures may trap enough sediment to consider placing additional downstream structures to protect against induced degradation (NRCS 2007). Modeling the sediment with several different types of grade control spacing will help ensure that there is a balance between supply and transport of water and sediment (Watson and Biedenharn 1999). SRH-1D can be used for this purpose.

- Conventional wisdom indicates that these low head weirs act essentially as broad-crested weirs at low flow, are submerged by high flows, and have little effect on the water surface elevation. Measurements made by Walker et al. (2002) showed that riffle style grade controls (low head) have an effect on head loss during high flows, which affects flood elevations and sediment transport.

- Downstream local scour estimates should be made using guides such as Pemberton and Lara (1984). Countermeasures include excavating and placing riprap to the estimated scour depth or design rock that launches into the scour hole during peak flows.

- The level of reliability of river spanning loose rock structures depends on the design flood, riprap sizing, safety factor, scour estimates, etc. Reliability can be high.

- Durability of loose rock structures can also be high, and with at least a 25-year peak flow flood used for the design flood, they will have a long project life.

- Potential constructability issues include cofferdam design and construction, access, and ensuring even distribution of riprap material gradation.

- Level of complexity for implementation is moderate to high due to cofferdam susceptibility to failure at high flows.

- Maintenance requirements may include replacement of dislodged rock periodically, additional installations of flanking countermeasures (such as bank stabilization), and additional flanking distance.

5.1.3 Deformable Riffles

- The confidence level is Level 1. Deformable riffles are a new, untested concept.
- The goals of the methods are:
    - Establish a channel with a stable grade.
    - Allow some vertical channel bed movement.
    - Enrich sediment supply by adding a small amount of gravel/small cobble bed material load.
- This method would be cheaper to install and more environmentally acceptable than traditional loose rock grade control structures.
- The deformable riffles would be more natural than traditional grade control.
- The concept, in part, combines features of the rock sill method of Whittaker and Jaeggi (1986), reported by Watson and Biedenharn (1999), and the trench fill grade control structure reported by Watson and Biedenharn (1999), while supplying some gravel/small cobble size bed material to the river system. The *c*oncept is also similar to placing an armored bed in small streams used in Germany, which will resist entrainment, thus preventing incision (Kern, 1997). .
- The Whittaker and Jaeggi (1986) concept is to place rock sills directly on the streambed to act as a hard point to resist entrainment within a degradational river zone, while deforming as the channel establishes small pools between each sill.
- The trench fill grade control concept presented by Watson and Biedenharn (1999) consists of excavating a trench across the streambed, which is filled with rock. In this method, there should be sufficient nonerodible rock to resist general channel degradation, as well as any additional local scour. The riprap would deform into the downstream scour hole.
- In the conceptual deformable riffle method, a trench would be constructed across the channel and filled with material that would be stable during most flows, while becoming slightly mobile during less frequent high-flow events, to provide a small amount of sediment enrichment. The trenches

also would extend in the longitudinal downstream direction the length of typical stable riffles and with a stable riffle slope.

- The riffles would be constructed using larger particle sizes than found in typical stable riffles on the Middle Rio Grande. These riffles are assumed to be erodible at higher flows. Fluvial entrainment of the deformable riffles would be estimated to take place between 5- and 10-year peak flow events. The gradation of imported riprap also would contain sizes less than the median size, which would be mobile at the 2-year event. Riffles would be spaced at about five to seven river widths apart. Each riffle would contain a supply of material, enough to be mobilized during several 5- to 10-year events; thus, a small amount of gravel/cobble size material would be supplied to the river during each event. Also, during each 5- to 10-year event, a small amount of erosion of the riffles would occur.

- On the River Skerne, it was anticipated that erosion of the riffle would transport riffle material and create a downstream riffle. However, it did not occur, even though the downstream slope steepened from an 8:1 to a 4:1. Smaller rock sizes were observed to be eroded away. In this case, the riffle was designed to be about 0.6 meter high and remain stable during flood stage (Vivash and Murphy 1999).

- These riffles would be constructed in a channel that is in the process of converting from a wide, sand bedded, low-flow braided channel to a single-thread, slightly sinuous channel, but prior to full conversion, while sand sizes are still in the bed. The method would be most effective for cases where the banks are stable in the current alignment. As finer grained sand particles are mined from the bed, the bed at each riffle location would remain about the same elevation initially. Mining of the sand bed material also would form longitudinal pools between each constructed riffle. During each succeeding 5- to 10-year event, the bed would become lower by the small amount of riffle erosion. Because pools would form between each riffle, with the alignment kept the same, it would be anticipated that the transported riffle material would deposit immediately downstream from the riffle in each pool. Keeping the current alignment would mean that point bars and deep pools with strong secondary currents would not form. At a conceptual level, this should prevent larger particles, eroded from the upstream riffle, from transporting to the next downstream riffle. Rather, they would be deposited in the downstream pool. Thus, a stable grade can be achieved.

- Benefits to these types of structures are that they provide grade stabilization while supplying gravel/cobble size material to the bed, and they could be constructed more economically than traditional grade control because smaller sizes would be used in each riffle.

- Fish passage would be preserved during low flows because the installed rock sizes would be constructed with slopes typical of current riffles, which allow fish passage.

5.1.3.1 General Range of Application

- The general range of application for this method has not been documented because it is a new concept.
- A riffle was constructed on the River Skern, UK (Vivash and Murphy 1999) with a sloping downstream apron extending to the pool.
- Channel spanning stone structures offer the most robust performance with habitat benefits for incised channels, while constricting the low-flow channel (Shields et al. 1999).
- Common modes of failure, which be conceptualized at this time, are:
    - Flanking.
    - Excessive erosion of the deformable riffle and/or removal by fluvial entrainment.
    - Undermining by excess downstream degradation and scour.
    - Ensuring fish passage is also a requirement.
- Countermeasures, which are conceptualized at this time, are:
    - Install in straight reaches or provide upstream bank protection.
    - Appropriate sizing of riffle bed material.
    - Design and construct enough riffles and/or tie into natural or other manmade bed controls to ensure adequate protection against excessive downstream degradation and construct at riffle slope to prevent downstream scour.
    - Construct enough riffles at riffle slope; see section 5.1.1.
- At larger flow events, the riprap would become mobile and transport downstream. The downstream transport would be into the next pool. The advantage of these types of structures is that, once the structures become mobile, the upstream effect of raising the water surface during low flows and sediment deposition are reduced. The downstream potential effects of short-term reduction in sediment supply and downstream scour also are reduced.

Newberry type riffles are intended to replace pool and riffle habitat lost due to channelization or other types of channel alterations (Newbury and Gaboury 1993).

5.1.3.2 Advantages and Disadvantages

5.1.3.2.1 Advantages

- Provides for grade control and bank stability and helps river remain in current alignment, thus reducing the number of future priority sites as a result of lateral channel migration.
- Provides for fish passage, while allowing the development of a relatively constant grade with some sediment enrichment of sizes, which will contribute to the long-term channel stability.
- Habitat benefits are the same as grade control above. RGSM could be guided to fish passage areas. RGSM seek and follow laminar or low velocity flow areas (boundary layer) when moving upstream (Bestgen et al. 2003).
- In concept, this would be less costly than traditional grade stabilization.
- These structures would be economical to design and build.

5.1.3.2.2 Disadvantages

- This is a new conceptual method that has not been used yet.
- May be difficult to select proper bed sediment sizes for the deformable riffles.
- Limited to low level of hydraulic drop, probably 1 foot or so. There is the potential for displaced riprap due to seepage flows.
- The channel will continue to degrade or incise, although at a slower rate.
- Habitat effects are the same as grade control above. Potential for fish passage issues at low flows, and there could be high local velocities.
- Construction impacts on RGSM habitat could be high but mitigated by using cofferdams.

5.1.3.2.3 Requirements

- The rock sill design concept and the trench fill riprap grade control structure guidelines are contained in Watson and Biedenharn (1999), Watson et al. (2005), and NRCS (2007).

- Design guidelines for siting and spacing grade control structures of this type are found in Newbury and Gaboury (1993). Design methods, specifically for deformable riffles, do not exist.

- A critical element of this method is the selection of the riprap material for the deformable grade control trench fill structures. Riprap material would be designed to be stable up to about the 5- to 10-year return interval peak flow.

- NRCS (2007) gives an example of how the final thalweg profile is affected by the structures.

- The rock sill crest and downstream slope would have a low V-shape cross section to concentrate flows into the center of the deformable riffle. This increases flow depth during low-flow periods in the center of the riffle.

5.1.4 Rock Sills

- The confidence level is Level 2.

- The Whittaker and Jaeggi (1986) concept of rock sills is to place rock directly on the streambed to act as a hard point that resists entrainment within a degradational river zone (Watson et al. 2005). This differs from the deformable riffle because rock sills are intended to be constructed of immobile stones, while deformable riffles have smaller stones that become entrained during certain high-flow events.

- The rock sills would deform as the channel establishes small pools and scour between each sill. Often, a hydraulic drop can form as sill rocks launch into the downstream scour hole.

- The rock sills would be spaced so that the degradation between structures does not undermine the next upstream sill.

5.1.4.1 General Range of Application

- Best used in a channel where the degradation or incision will be lower than 2–3 feet between structures.

- A series of low sills have been used successfully on rivers in Europe (Jaeggi and Zarn 1999). There has been some storage of sediment upstream of each sill. The specific channel conditions for successful application are not reported.

5.1.4.2 Advantages and Disadvantages

5.1.4.2.1 Advantages

- This method is economical to design.
- Rock sills are relatively easy to construct.
- There are limited environmental impacts.
- There is generally fish passage for many species.
- When spaced properly with adequate scour protection, rock sills can provide variable depth and velocity habitat.
- Habitat benefits are the same as grade controls above.

5.1.4.2.2 Disadvantages

- Generally limited to drop heights of 2–3 feet. Because these structures are placed directly on the existing bed elevation, a drop height of 1 foot may be most appropriate.
- Structures can easily fail where they are spaced too far apart, leading to a condition of excessive degradation between structures (NRCS 2007).
- Seepage flows through the hyporheic zone can potentially lead to rock displacement.
- Not suitable where rapid bed degradation is likely or where scour depths adjacent to the toe will be greater than the toe height of the structure (McCullah and Gray 2005).
- Habitat effects are the same as grades control above. Rock could provide cover for predators of RGSM.

5.1.4.3 Requirements

- The rock sill design concept general guidelines are contained in Watson and Biedenharn (1999), Watson et al. (2005), and NRCS (2007). Design guidelines for the siting and spacing of grade control structures of this type can be found in these references and the work by Newbury and Gaboury (1993) and Biedenharn and Hubbard (2001). Spacing may be based on natural riffle locations (Newbury and Gaboury 1993) or on degradation potential and dynamic equilibrium conditions (Biedenharn and Hubbard 2001).
- The structures must be spaced close enough that channel degradation above one does not undermine the upstream structure (NRCS 2007).

- A critical element of this method is the selection of the riprap material for the rock sill to remain stable and launch into the downstream scour hole without additional downstream migration. Additional downstream migration would erode the newly formed sill toe.

- The riprap could extend to the pool (Vivash and Murphy 1999), or could extend long enough to provide the riprap volume to fill the future scour hole with an additional amount of riprap as a safety factor.

- An example of the final thalweg profile and structure location is given in NRCS (2007).

- The rock sill crest and downstream slope would have a low V-shape cross section to concentrate flows into the center of the deformable riffle. This increases flow depth during low-flow periods in the center of the riffle.

5.1.5 Riprap Grade Control With or Without Upstream Seepage Control

- The confidence level is Level 2.

- Riprap grade control structures can be constructed by excavating a trench across the streambed that is filled with rock. The structure is flexible in that, as the channel degrades and downstream scour occurs, a portion of the riprap in the trench will launch.

- If seepage is an issue, particularly for fish passage at low flows, an upstream impervious layer of fill material or a sheet pile wall can be constructed.

- The trench fill grade control structure generally is constructed with the riprap at the existing grade of the riverbed so that the structure halts upstream degradation (Biedenharn et al. 1997) but does not raise the riverbed.

- These structures also can be designed and constructed to raise the bed of the river and low-flow water surface. This configuration would be with an upstream adverse approach slope of 4:1 and a downstream slope that is sufficiently flat to allow fish passage. Often, the downstream slope is constructed at 20:1. These types of structures are referred to as "Newbury" riffles (Newbury and Gaboury 1993). In the Midwestern States of the United States, more gradual slopes have been used (Newbury et al. 1999). The bank-full or higher flow discharge water surface elevation remains unchanged by these low head structures.

- Newbury riffles usually are not constructed with a cutoff wall but can be sealed upstream with smaller particles or grout.

- Weirs with crests that make an angle with the bank also can be used to reduce erosion on the outside of meander bends by modifying flow similar to bendway weirs or vanes (McCullah and Gray 2005).

- A third type of riprap grade control structure is the "Chevron Weir" rock ramp (Wittler et al. 1996, and Wittler, 1996). Chevron weirs have an upstream pointing curved weir with a downstream rock ramp. They are similar to the Newbury riffle but with a curved weir crest.

5.1.5.1 General Range of Application

- Applicable for drop heights of less than 2–3 feet.

- For Newbury riffles, guidelines exist for cobble bed streams (Newbury and Gaboury 1993) and gravel bed material sizes (Newbury et al. 1999). These structures have been used where improvement to the depth and number of pools is desired. The method would potentially require some modification for application to a sand bed or sand and gravel bed situation. Used on Canadian streams (Newbury and Gaboury 1993) and on an urban stream in the United States (Newbury et al. 1999). Installations have taken place on the East Fork of Mill Creek in Butler County, Ohio; the South Branch of the Waukegan River in Waukengan, Illinois; and on Mink Creek in British Columbia (McCullah and Gray 2005).

- A similar design for a sand bed stream is described by Tate (1988). Chevron weirs were used on Muddy Creek in Montana for hydraulic heights from 2–3 feet (Wittler et al. 1996).

- The level of protection can be high with properly designed and constructed trench filled riprap or Newbury riffles.

5.1.5.2 Advantages and Disadvantages

5.1.5.2.1 Advantages

- Newbury riffles usually are used to improve fish habitat and not for erosion control; however, a series of well-designed Newbury riffles can counteract mild channel incision (McCullah and Gray 2005).

- The steep upstream slope and much flatter downstream slope create a bed profile similar to natural riffles (McCullah and Gray 2005).

- This method is economical to design.

- They are relatively easy to construct.

- There are limited environmental impacts, and there is generally fish passage for species found in most gravel bed streams. They have been used in streams with salmon and walleye (Newbury and Gaboury 1993).

- When they are spaced apart properly and have adequate scour protection, they can provide variable depth and velocity habitat.

- When water cutoff is used, these structures eliminate seepage problems and potential for rock displacement.

5.1.5.2.2 Disadvantages

- The launched riprap in the trench filled grade control structure could assume the downstream slope near the angle of repose, or at least a fairly steep angle. This most likely would limit fish passage of small minnow such as RGSM (Bestgen et al. 2003).

- Newbury riffles are not usually constructed with seepage cutoff walls. This could be a disadvantage in channels with water withdrawals or during low flows because low flows may mostly pass through the rock in the structure, potentially limiting fish passage.

- Generally limited to drop heights of 2–3 feet because these structures are placed directly on the existing bed elevation.

- Structures can easily fail where they are spaced too far apart, leading to a condition of excessive degradation between structures (NRCS 2007).

- Headcuts more than 3 feet high usually result in failure of this type of structure unless there is a well-protected stilling basin or deeply embedded stone toes or keys (McCullah and Gray 2005).

- Seepage flows through the hyporheic zone can potentially lead to rock displacement without seepage cutoff.

- More complex design is required than rock sills.

- Higher construction costs than rock sills.

- Not suitable where rapid bed degradation is likely or where scour depths adjacent to the toe will be greater than the toe height of the structure (McCullah and Gray 2005).

5.1.5.3 Requirements

- The trench fill grade control structure design concept general guidelines are contained in Watson and Biedenharn (1999), Watson et al. (2005), and

NRCS (2007). Guidelines for the Newbury riffle are found in Newbury and Gaboury (1993) and Newbury et al. (1999). Design guidelines also are given in Brookes and Shields (1996).

Design guidelines for the siting and spacing of grade control structures of this type can be found in the above references and the work by Newbury and Gaboury (1993) based upon riffle spacing. Siting and spacing guidelines that account for dynamic equilibrium bed slopes in degrading rivers are found in Biedenharn and Hubbard (2001). The structures must be spaced close enough that channel degradation above one does not undermine the upstream structure (NRCS 2007). Design criteria for low-head stone structures also can be found in Rice et al. (1996) and Robinson et al. (1998), who present design equations based on tests of steep, rock-lined channels. These methods can be adapted for weir designs by treating the downstream face of the weir as a steep chute.

- A critical element of this method is the selection of the riprap material size for the rock sill to remain stable and launch into the downstream scour hole without additional downstream migration. Additional downstream migration would erode the newly formed toe. Another critical design component is to ensure that there is enough rock volume in the trench to resist general bed degradation and local scour at the structure (Watson et al. 2005).

- The trench fill grade control or Newbury riffle crest and downstream slope would have a low V-shape cross section to concentrate flows into the center of the channel. This increases flow depth during low-flow periods in the center of the riffle.

- The amount of seepage and whether or not seepage cutoff is necessary can be a key design component depending on the hydrology and fish passage needs. The upstream slope of the riffle can be sealed with smaller particle material or grout.

- Weirs placed in sand bed channels are often undermined or flanked. Undermining may be addressed by excavating a key trench into the stream bed or using sheet pile (McCullah and Gray 2005).

5.1.6. Gradient Restoration Facilities

- The confidence level is between:

    - Level 3 because there are reliable design criteria and documentation.

    - Level 2 because there is not much documentation on fish passage.

- GRFs are low to medium head, loose rock, grade control structures with a long, low slope downstream apron to facilitate fish passage such as the RGSM.

- GRFs consist of a structure that fixes the upstream bed elevation with a sheet pile wall, a sheet pile wall with a concrete cap, or a stable, grouted riprap section. The downstream location of the structure is also often fixed by a sheet pile wall. Scour protection riprap is added to protect the downstream sheet pile wall from downstream scour.

- The upstream cutoff prevents seepage through the structure. Seepage flows can contribute to rock displacement and reduce flow depth during low flows so that fish passage is not possible. The downstream sheet pile wall is to prevent downstream migration of the riprap and for seepage control. Special consideration should be made to ensure fish passage over the downstream riprap in the event of downstream degradation. GRFs are designed to replicate long, low slope riffles and raise the riverbed up, control the grade, and improve flood plain connectivity.

- The design is similar to the Newbury riffles (with the addition of the sheet pile walls, with a 5:1 upstream slope). The downstream slope used on the Middle Rio Grande ranged from 200:1 to 250:1.

- These low head structures can raise the water surface during low flows and are submerged during higher flows. When sediment deposits upstream, the water surface can be permanently raised.

5.1.6.1 General Range of Application

- These structures are intended to be used for rivers where there are high bed load transport rates and for cases where very low apron slopes are needed for fish passage.

- Because they contain sheet pile walls for seepage control and to keep the riprap in place, they can be used on rivers with a wide range of channel characteristics.

- These types of structures have been used on the Middle Rio Grande between Angostura Diversion Dam and Highway 550 bridge at Bernalillo, New Mexico, and on the Sacramento River.

- Common modes of failure would be: riprap entrainment, filter failure, flanking, seepage around the sheet pile walls that could hinder low-flow fish passage, downstream scour, and downstream degradation.

- Countermeasures would be: ensuring that riprap and underlying filters are properly sized; tiebacks are long, adequate enough, and evenly spaced for multiple structures to prevent flanking; sheet pile walls are designed to minimize seepage downstream; essential scour protection is adequate; toe of the structure is embedded so that there is only a very small change of energy slope when flows transition between the structure and the downstream river channel; and sufficient structures or other means to limit downstream degradation.

- The level of protection against future channel incision is high upstream of the structures.

5.1.6.2 Advantages and Disadvantages

5.1.6.2.1 Advantages

- Controls the grade and has a long, low downstream slope for passage of small fish.

- Raises the channel bed for greater flood plain connectivity and ground water storage.

- Cutoff walls provide for maximum seepage protection and provide for maximum flow depth during low-flow periods.

- The upstream steeper slope and the very low downstream slope can replicate riverbed riffle pool features on relatively low gradient rivers such as the Middle Rio Grande and the Sacramento.

- The structure location remains constant during the design life.

- Bed elevation remains constant during the design life; thus, the flood carrying capacity can be accurately estimated.

- Can have large drop heights up to about 6 feet (NRCS 2007).

- Habitat benefits are the same as grade control above.

5.1.6.2.2 Disadvantages

- Most complex design of all cross channel structures.

- Highest construction costs of any cross channel structures included in this appendix.

- Not suitable where rapid or extensive future bed degradation is likely or where there will be large scour depths. Future downstream bed degradation, unless it is controlled, could cause the structure to obstruct fish passage.

- Flanking countermeasures will need to be included in the structure so that, over the long lifespan, the structure remains intact (Brookes 1988).

- Bed elevation is held constant during the design life, eliminating natural bed elevation changes during high and low-flow events and during extended wet or dry cycles. This interrupts naturally occurring bed level fluctuations over time.

- High drop heights have more potential for obstruction of fish passage without low slope downstream apron.

- Habitat effects are the same as grade control above.

5.1.6.3 Requirements

- Specific guidelines for GRF do not exist. The design must include structure height, siting, upstream channel approach alignment, upstream migration and/or flanking countermeasures, bank geotechnical evaluation, riprap sizing, determining apron slope, downstream scour protection, distance the downstream apron is placed below the current bed elevation for a smooth downstream transition, bank protection throughout the structure length, sheet pile length for seepage, and downstream scour protection. Design concepts and general guidelines such as found in Watson and Biedenharn (1999), Watson et al. (2005), and NRCS (2007) are useful. Design guidelines for the siting and spacing of grade control structures of this type can be found in these references and the work by Newbury and Gaboury (1993). Guidelines for the Newbury riffle are found in Newbury and Gaboury (1993) and Newbury et al. (1999). Guidelines for rock ramps can be found in Mooney et al. (2007).

- A critical element of this method is the selection of the riprap material for the rock apron to remain stable and launch into the downstream scour hole without additional downstream migration. Additional downstream degradation could erode the scour hole and create fish passage issues.

- The GRF rock sill crest and downstream slope would have a low V-shape cross section to concentrate flows into the center of the channel during low flows. This increases flow depth during low-flow periods in the center of the riffle.

- The structures must be spaced close enough that channel degradation above one does not undermine the upstream structure (NRCS 2007).

5.2 Low Head Stone Weirs

Most of the material in this section is summarized from Holmquist-Johnson, 2007) Some of the materials on geomorphic response, range of application, construction issues, maintenance, and level of complexity were added to complete the methods outline with a similar level of information as all other sections).

- The confidence level is between:
  - Level 2 because there are limited design criteria.
  - Level 1 because of the lack of field or lab test data and few literature citations.
- River spanning loose rock structures can be used to provide sufficient head for irrigation diversion, permit fish passage over barriers, protect banks, stabilize degrading channels, activate side channels, reconnect flood plains, and create in-channel habitat.
- These structures are called by a variety of names including U-, A-, V-, and W- weirs. These structures share the common characteristics of: (1) loose rock construction materials (individually placed or dumped rocks); (2) generally spanning the width of the river channel; and (3) causing an abrupt change in the water surface elevation at low flows.
- Functionality is often measured by a structure's ability to maintain upstream water surface elevation during low flows and/or downstream pool depths and to remain stable under a complete range of flows. Cross channel structures generally are composed of a few very large boulders that play a key role in the stability and function of the step or drop and are commonly constructed in a broad U-shape, with the apex of the weir pointing upstream. The curvature of the weir tends to align the flow towards the center of the downstream pool. This alignment of flow into the downstream pool has two important effects:
  1. Helps maintain the downstream scour hole (Rosgen 2006).
  2. Can prevent flow from being directed towards the outer banks and, therefore, limits bank erosion (figure 5-1).

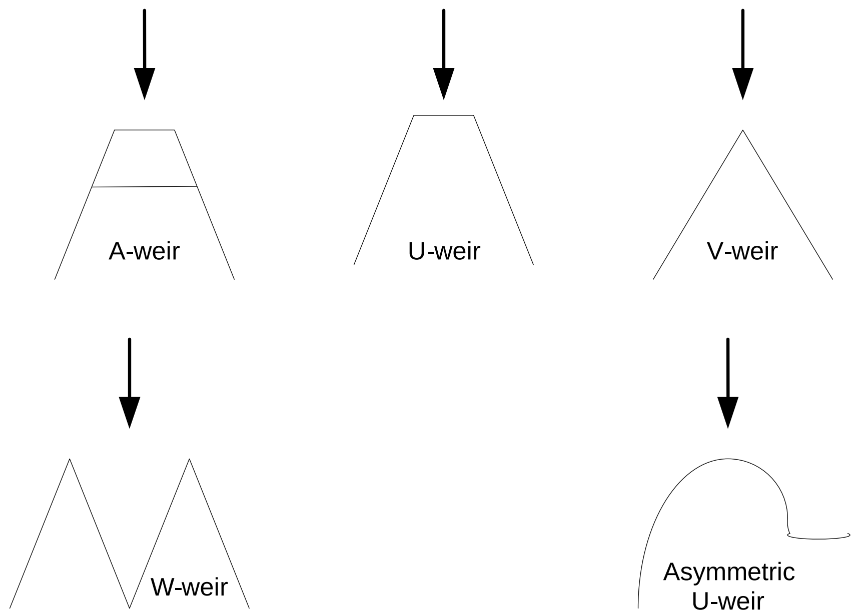

Figure 5-1. Plan view depiction of weir structure types (rows indicate direction of flow).

5.2.1 General Range of Application

- Rock weirs can be used in steep slope river conditions and in bends.
- Common failure modes (Mooney et al. 2007) are:
    1. Growth of scour pool.
    2. Weir stones sliding or rolling into scour hole.
    3. Sediment filling or burying the structure.
    4. General bank migration/flanking
    5. Piping through the arm resulting in flanking.
    6. Piping underneath header rock.
- Structural failure can result in: disruption of service, expensive repairs, repeated maintenance costs, and failure to meet biological and geomorphic requirements.
- Common countermeasures are in the process of being developed. Conceptually, countermeasures would include:

1. Installing multiple footer rocks.
2. Lining the scour hole with non-erodible riprap material.
3. Increasing flanking protection.
4. Providing upstream bank protection to halt channel migration, and bank line piping.
5. Sealing the structure with river bed material to prevent piping underneath the header rock.
6. A double row of footer boulders, for pool scour protection, and longitudinal boulder bank protection to prevent flanking (rather than a key).
7. A row of boulders at the downstream end of the scour pool was used on the Blue River to ensure stability (Bill Fullerton, 2008, personal communication, Vice President, Tetra Tech EMI).

- Undetermined countermeasures and design criteria are proposed for development in cases where sediment fills and buries the structure.
- Overbank tie-in also provides increased stability and resistance against bank migration, resulting in flanking of the structure.
- Additional countermeasures related to structure geometry, geomorphic location, and structure material/construction are currently being investigated.
- From a morphologic standpoint, alluvial channels with slopes below 1% may consist of sandy substrates where rock structures may not remain in place but, rather, sink into the bed. Cross channel rock structures are inappropriate in aggrading reaches, and caution should be exercised when installing in laterally dynamic channels with the potential for migration or avulsion that could bypass the structure. Additional or more extensive flanking countermeasures likely would be needed in this situation. In channels with a great amount of lateral dynamics, other methods may be more appropriate after a thorough geomorphic investigation is completed.
- During low flows, there is an abrupt change in water surface elevation through the structures. Generally, the structures have portions constructed above the existing bed and create a backwater effect at low flows. Since these are porous and three-dimensional structures, standard backwater analysis methods cannot be readily applied. Analysis guidelines and criteria for using one-dimensional backwater analysis currently are being developed. Generally these structures do not raise the water surface during high flows.
- Often, these structures are used in conjunction with another bank protection method to provide habitat enhancement or to redirect the low-flow channel

(thalweg) away from eroding bank lines (WDFW 2003). In addition, there is some interruption of secondary currents and relocation of the zone of maximum velocity towards the center of the channel (Rosgen 2006). Riffle installations generally would not change the thalweg location.

- The velocity upstream during low flows is decreased, while local downstream velocities increase above natural conditions through the pool zone. The velocities in the structure are complex and three-dimensional.

- For structures that are constructed from tightly spaced rocks (still porous), sediment does not transport between stones; thus, there will be some upstream sediment deposition. Downstream pool scour results from flow acceleration through the structure. The scour and depositional patterns depend on the orientation, structure characteristics, channel planform, channel type, bed material characteristics, amount of sediment transport, etc. Locally, the material scoured from the structure pool zone can deposit downstream from the weir and form a tailout or riffle (WDFW 2003).

- Once the upstream channel has deposited and the scour hole and tailout have formed, sediment transport continuity may be re-established through the reach as adjusted by local slope and grain sorting. How sediment is transported through these structures and the effect upon channel morphology are not documented in the literature.

- Information on the length of effects could not be located at this time. Conceptually, the length of effects upstream would be the length of deposition for the channel to reach a new equilibrium slope and the back water zone. The downstream length of effect could be the location where the elevation of any tailout sediment deposits reach a new dynamic equilibrium elevation, slope, and grain size.

- These structures could potentially be used as the inlet and outlet of side channels to increase local velocity, thereby reducing sediment deposition. This could improve the sustainability of side channels.

- The size and location of downstream pool zones vary with these structures, as does the sediment deposits just upstream of the weir. Beyond the immediate vicinity of the structures, they have essentially the same geomorphic river response as other grade control structures.

5.2.2 Advantages and Disadvantages

5.2.2.1 Advantages

- Low construction and maintenance costs.
- Creates fish cover and resting pools (Rosgen 2006; McCullah and Gray 2005).
- There is great variety between the various types of structures, and they can be deformable.
- They create a more natural appearance than many other structure types (Rosgen 2006).
- They can maintain appropriate width-to-depth ratio (Rosgen 2006), provided that flanking or bank piping does not occur.
- Conceptually, a series of structures can dissipate energy and reduce degradation.
- Gradient control features should reduce channel degradation upstream of the feature, promoting overbank flooding and raising the water table, which are conducive to riparian establishment and development.
- Backwater areas or high-flow channels could become established upstream, raising ground water levels that maintain existing riparian vegetation.
- Habitat benefits are the same as grade control above. Can provide pool habitat. Interstices through rocks could provide fish passage at most flows.

5.2.2.2 Disadvantages

- Potential bed and bank destabilization.
- Potential boating safety hazard.
- Inappropriate in sandy and other fine-grained streams and on bedrock streams (McCullah and Gray 2005). Header and footer rocks can be held into place on bedrock streams by pins or grout.
- Greater uncertainty of long-term durability. These structures appear to be susceptible to rock dislodgement and flanking as a result of small geomorphic changes in the channel.

- When there are high sediment loads, high excess shear stress in channels adjusting their planform, and easily eroded banks, these structures often are eroded away by flows (Miller and Kochel 2009).

- Limited and temporary downstream channel degradation could occur to a degree that the water table is lowered, reducing water availability to riparian vegetation.

- Not useful for controlling erosion in channels that are rapidly incising (McCullah and Gray 2005).

- Not recommended for channels that have well developed pool-riffle systems (Maryland 2000).

- Habitat effects are the same as grade control above. Could restrict fish passage, but interstices through rock could provide fish passage at most flows. Predators may occupy the pools.

5.2.3 Requirements

- Vertical drop height, lateral constriction, size of rock material, scour, pool geometry, and construction methods are common design considerations for these structures.

  When constructing these structures for fish passage, the drop height and pool dimensions must be constructed to meet local agency fish passage criteria. For channel stabilization purposes, the drop height will reflect the elevation loss that must be accommodated to stabilize the channel, while meeting the low-drop criteria. The specific type of structure constructed is usually determined by the channel width, slope, bank-full depth, and vertical drop height. In general, channel widths greater than 100 feet tend to use W-weirs to span the river width and minimize structure length. Channel widths less than 100 feet typically use U-, A-, and V-weirs, depending on the total elevation drop that is required within the channel and the intended function of the structure (water diversion, fish passage, habitat diversity, grade control, etc.).

- The size of rocks used must be large enough to simultaneously resist movement as well as create the desired hydraulic conditions. Definitive design criteria for sizing the rocks comprising the structures are very limited, indicating that the size of the rocks is determined more by the available rock dimensions than by channel hydraulics. To determine the size of rocks for construction of manmade structures, Thomas et al., (2000) suggest using the USACE “steep slope riprap design” method (USACE 1991). The method by Simons and Senturk (1992) for sizing individual stones based on a force balance also has been used to size stones for these weirs. Scour downstream from hydraulic structures increases the depth locally and creates hydraulic diversity. The formation of a scour pool also can undermine the rocks, comprising the structure. Continued scour pool formation and rolling of the rocks into the scour hole can lead to failure of the structure. To prevent partial or full loss of the structure, the structure foundation should be embedded to a depth greater than the anticipated scour.

- Literature on constructed rock weir design lacks quantitative information on predicting scour. While specific scour predictions for constructed rock weirs are not evident, predictions for scour depth immediately downstream from vertical drop structures provide some guidance.

- One of the most important concepts to emerge from fish passage literature reviews is the need to adapt basic designs to fit each site-specific situation (geomorphology, flow regime, biological community). A cookie cutter approach is unlikely to be effective. It is also essential to work closely with local biologists who are knowledgeable of the fish species in the river where fish passage is to be provided.

- The best basic primer on designing natural channels is contained in the book *Fish Migration and Fish Bypasses*, by Jungwirth et al. (1998). Another useful reference is *An Illustrative Handbook on Nature-Like Fishways* (Wildman et al. 2005). This handbook provides an excellent definition of terms and presents 28 cases that illustrate many of the nature-like fishways already constructed. A good deal of literature is available on the relatively recent trend toward designing more natural appearing fish passage structures. Much of the early work started in Europe in the 1980s. In the United States, the eastern seaboard has been the center of most natural fish passage projects. There is scant information on design criteria for natural passage structures. This concept is a relatively new endeavor. However, there is abundant literature available in the form of case studies. One particular article provides an excellent review of ichthyomechanics and the hydraulics of fishways (Katopodis 1992). This provides a basic understanding of the design considerations for fishways, which can be readily adapted to natural fish passage structures.

- One of the most important concepts that should be considered is that multiple species and multiple life stages need to be accommodated when designing fish passage structures, particularly in an era when many resident species (nonmigratory) are listed as threatened, endangered, or species of concern. Additionally, many resident species are of high value for sporting or commercial purposes. Land management agencies are increasingly managing for biodiversity and are placing emphasis on protecting a wide range of aquatic species.

- The most fundamental aspect of planning any fish passage structure is consideration of the species to be passed. Detailed knowledge of the movement, time of spawning and swimming, and leaping abilities of each species, as well as any other behavioral traits applicable to passage are ideally incorporated into the planning and design of a fish passage structure. This information is rarely available especially for nonsalmonid species. The lack of information is compensated for by mimicking, to the degree possible, the slope, morphology, and hydraulic conditions of streams in which the fish community is found (Parasiewicz et al. 1998).

- Ultimately, this is limited to local fish passage criteria (drop height, velocity, flow depth, structure length, etc).

- Criteria for using a W-weir for controlling local pier scour at a bridge crossing were developed by Johnson et al. (2001).

- Costs vary from site to site depending on expertise and availability of labor and materials. The selection of a design event balances the present cost of constructing more resilient structures versus the cost, effort, and likelihood of replacing or repairing weaker structures if a larger flow event occurs.

- Hydrology drives the hydraulic forces that may result in failure of a structure. A design only protects against flows up to a predetermined magnitude. Protecting against larger flow events requires more expensive materials in larger quantities. Smaller, less resilient structures requiring more frequent repairs may result in lower economic costs. Risk analysis can assist managers in making judgment calls by providing economic costs. Social, regulatory, or habitat perspectives may outweigh costs. In such cases, the economic analysis shows the expense associated with these values based decisions.

- If these structures are used to promote pool and riffle habitat, the spacing should generally average five to seven channel widths to emulate natural conditions, while a regular spacing should be avoided (Brookes 1988).

- At high flows, these structures create form roughness, which must be accounted for to estimate high-flow water surface elevations.

- The following design questionnaire presents some organization for determining the applicability of cross channel rock weirs:

    1. Is the existing or planned velocity, depth, or amount of cover undesirable?

    2. Is the channel stable in profile?

3. Are the banks stable?

4. Is the required rock diameter available?

5. Is the predicted scour pool acceptable?

6. Are the predicted local depth and velocity conditions desirable?

Chapter 6: Conservation Easements

- The confidence level is Level 2.

- Conservation easements are land agreements that prevent development from occurring and allow the river to erode through the area as part of fluvial processes. Conservation easements also preserve the riparian zone in its current state and future states as determined by fluvial processes and flood plain connectivity.

- Rivers as corridors of riparian forests and ecosystems and the need for corridor conservations are being promoted (Karr et al. 2000).

- Conservation easements may, or may not, involve infrastructure relocation or setback. See chapter 2 for more information on infrastructure relocation or setback.

- Similar to infrastructure relocation or setback, it may be possible to use conservation easements as an opportunity for the river to access historical flood plain areas.

6.1 General Range of Application

- Conservations easements are being used on many rivers in the United States, Canada, and Europe to preserve lands for habitat purposes, river migration corridors, flood plains, and a meander belt (Karr et al. 2000; Brookes 1988).

- Conservation easements should protect, as much as possible, naturally functioning native fish and aquatic communities and ecosystems (Karr et al. 2000).

6.2 Advantages and Disadvantages

6.2.1 Advantages

- Providing land for the river migration corridor reduces or eliminates the need for other bank stabilization or river maintenance works to protect riverside infrastructure.

- Reduces infrastructure protection requirements and preserves riparian areas and allows more natural river movement (i.e., erosion and deposition).

- There are no direct effects upon the main channel river characteristics, which can be an advantage or disadvantage depending on the situation.

- If project lands are involved or the landowner is willing, then conservation easements may allow the river the greatest flexibility to adjust its hydraulic geometry and to migrate laterally as determined by channel processes.

- Allows more natural river movement and promotes greater area of undisturbed habitat, which could provide habitat for RGSM.

6.2.2 Disadvantages

- Few landowners may actually be interested in allowing their land use to change to provide lands for conservation easements and eventual lateral river migration.

- A review of Middle Rio Grande Project authorization and Reclamation authorization would need to be accomplished to determine if this method is viable.

- Site selection is critical. Site may not be suitable for riparian establishment or development. Site should have river dynamics.

- Habitat effects would be similar to infrastructure relocation or setback.

6.3 Requirements

- Types of potential locations are riparian areas that are privately owned adjacent to the river, which would provide opportunity without much, if any, land use change.

- Locations where there are willing landowners regardless of the current land use.

- It would be useful to identify areas or reaches where the most benefit would be realized by conservation easements.

- Protection measures through conservation easements are all too often put into place after a site or species is seriously endangered, so protection measures are taken on an emergency basis (Karr et al. 2000). Protection would be best served if accomplished in a more proactive manner.

- Sites where there will be future channel dynamics provide the opportunity for establishing new riparian forest communities. These areas include low-lying surfaces that provide aquatic edge habitat and variable depth and velocity habitat during high flows.

- Ideally, conservation easements would be large enough to preserve a full complement of native species and geomorphic processes (Karr et al. 2000).

Chapter 7: Change Sediment Supply

- Knowledge about sediment supply, transfer, transport, and deposition is a prerequisite to developing sustainable river maintenance and restoration (Sear 1996). In particular, the sustainability of river channel strategies and methods is dependent on the relationship of supply and sediment transport capacity.

- Balancing sediment supply with capacity often involves watershed and land use changes, all of which are outside congressional authorization in the Flood Control Acts of 1948 and 1950.

- Sediment transport and supply vary with discharge over time and in space within a river network. Understanding these changes is essential.

- Where the river system is sediment supply limited, the result is generally channel incision, bank erosion, and, possibly, a channel pattern change from a low-flow, braided sand channel with shifting sand substrate to a single-thread, mildly sinuous channel with a coarser bed. In general, the channel width decreases, channel depth increases, local slope decreases, and sinuosity increases. The addition of sediment supply can stabilize and even reverse these tendencies. This method strives to reinstate a sediment process, rather than limiting the effects of a sediment imbalance (Bravard et al. 1999).

- Where a river system has more sediment supply than sediment transport capacity, channel aggradation will occur. In general, aggradation results in the channel width increasing, channel depth decreasing, local slope increasing, and sinuosity decreasing (Schumm 1977), and in decreased channel and flood capacity. Flood capacity can also be reduced by sediment berms forming along the channel banks (Schumm 2005). Reduction of sediment supply can slow or reverse these trends.

- In this section are two methods that address: (1) where increased sediment supply is needed (i.e., incisional reaches with possible channel pattern change) and (2) where decreased sediment supply is needed (i.e., reduce aggradation).

- While the general channel response is known, there is uncertainty about the effects of various amounts of sediment augmentation or removal, and adaptive management should be an integral part of these methods.

7.1 Sediment Augmentation (Sand Sizes)

- The confidence level is between:
  - Level 2 because there are examples of the beneficial effects of adding sediment supply to rivers.
  - Level 1 because the Middle Rio Grande is such a nonequilibrium river that changes in sediment supply could have large effects.
- Where the river system is sediment supply limited and where the channel is incising, narrowing, and the bed material size is changing from sand to gravel, the channel can convert from a wide sand bed, low-flow braided channel to a single-thread, slightly sinuous, gravel-bedded channel. The slightly sinuous channel migrates laterally into levees or other riverside infrastructure, resulting in the development of river maintenance sites. In this channel situation, reintroduction of increased sediment supply could halt narrowing, incision, and channel conversion.
- Adding sediment to the river also may result in sand deposits in pools, erosion of gravel riffles, decreased depth, and increased width-to-depth ratio (Jackson and Beschta 1984).
- The timing, magnitude, and locations of sediment reintroduction are key elements of a successful sediment augmentation project.

7.1.1 General Range of Application

- There are numerous examples of gravel augmentation projects for habitat improvement. Several rivers in Europe have gravel augmentation programs (Yrjana 1998; Bravard et al. 1999).
- Trinity River has sediment added to build bars for habitat improvement (Lisa Fotherby, 2008, personal communication, Interior, Reclamation, TSC, Sedimentation and River Hydraulics Group, Denver Federal Center, Denver CO).
- Gravel augmentation programs are underway on the Green River in Washington and the Yuba River in California (Bill Fullerton, 2008, personal communication, Vice President, Tetra Tech EMI.).
- Bedload has been increased on the Russian River in the United States (Bravard et al. 1999).

- Sources of sediment include the upstream watershed, the flood plain via lateral migration, upstream reservoir sediment deposits, and artificial input (Bravard et al. 1999).

- Dormant landslides are being rejuvenated to increase bed material load supply to the Drome River in Europe (Yrjana 1998).

7.1.2 Advantages and Disadvantages

7.1.2.1 Advantages

- The root cause of the current channel instability and lateral migration into riverside infrastructure in many reaches of the Middle Rio Grande is bed level lowering and bed sediment size becoming coarser (caused in part by reduced sediment supply from upstream reservoirs and water shed changes in the tributaries). Adding sediment supply to the system would address the root cause of the river being supply limited and reduce or eliminate further channel incision, narrowing, and the resulting lateral migration.

- There are two schools of thought: (1) adding sediment may not reverse channel conversion in reaches where it has already occurred, and (2) adding sand sediment load to a gravel sand bed channel with pools and riffles would result in filling the pools, reducing riffle stability, reducing form roughness, creating increased width to depth ratio, and increasing the slope as in the laboratory physical model study reported by Jackson and Beschta (1984).

- Based on the qualitative relationship developed by Schumm (1977), an assessment can be made of channel response to the addition of sediment. Using these relationships for the case of increased sediment load, the slope should increase, depth decrease, and particle size decrease (at least during low-flow events); the width would either not change or widen; the width-to-depth ratio would increase; and sinuosity may remain the same or decrease.

- Adding sediment to the river may reduce the number of future river maintenance sites, thereby potentially reducing the need for future in-channel work.

- Additional sediment allows for the establishment of river bars and terraces that are conducive to establishing and developing riparian areas.

- Augmentation of sediments would reduce channel degradation.

- Increasing the sediment supply would increase the potential for overbank flooding, raise the water table, establish river bars and islands, and develop exposed areas suitable for establishing riparian vegetation.

- Increases likelihood of variable depth and velocity habitat with shifting sand substrate.

7.1.2.2 Disadvantages

- Careful monitoring of the timing, amount and the location of sediment reintroduction would be necessary to ensure that the amount of sediment introduced does not produce an aggrading channel with the associated loss of high-flow channel capacity within the current levee system.

- Once a sediment augmentation project has begun, the need may be perpetual for the long term. If the augmentation were to start and then later be discontinued, the river channel would again revert back to the condition prior to beginning augmentation.

- Locating perpetual sources of sediment may be difficult depending on the annual amount (see several conceptual alternatives given below in sections 7.1.3 and 7.1.4).

- No significant adverse effects upon the riparian forest from this method.

- The RGSM habitat may be affected locally at the sediment augmentation sites. The method and timing of sediment augmentation would need to be carefully planned to avoid impacts locally to RGSM due to vastly increased local sediment loads.

7.1.3 Sources of Sediment for Augmentation Within Middle Rio Grande Project Authority

- Bank lowering would involve clearing vegetation, excavating bank material, and placing the excavated material in the river to be transported downstream during high flows. Bank lowering could also provide opportunities to increase flood plain connectivity.

- Bar/island clearing and/or lowering would involve vegetation clearing and excavating bar or island material and placing the excavated material in the river to be transported downstream during high flows. Bar/island clearing and lowering also could provide additional flood plain connectivity if the current bar/island elevation is outside of the flood plain inundated every 1–3 years.

- Island destabilization involves clearing vegetation and root plowing the island, thus loosening sediment for removal by high flows. This source would be practical if the elevation of the top of the island was low enough in the incising river to be inundated frequently with erosive flow velocities.

- Bank destabilization involves clearing vegetation and root plowing the bar, thus loosening sediment for removal by high flows. This source would be practical if the elevation of the top of the bar was low enough in the incising river to be inundated frequently with erosive flow velocities.

7.1.4 Sources of Sediment for Outside of Middle Rio Grande Project Authority

- Sediment bypass through upstream USACE reservoirs would potentially involve a slurry pipeline from the reservoir deltas to a location immediately downstream from the dam. Potential dams are Cochiti and Jemez. Jemez is already a flow through dam for most flow conditions; however, some sediment is stored during events where water is ponded behind the dam.

- Arroyo bank destabilization could be used to increase sediment supplies from tributaries of the Middle Rio Grande. This activity could involve destabilizing the bed and banks with mechanical equipment.

7.1.5 Requirements

- Sediment supply to replace the existing mined amount of sediment is planned as the strategy on the Platte River. This amount of sediment augmentation was determined by sediment transport modeling (Reclamation and U.S. Fish and Wildlife Service 2006).

- Sediment modeling, experimental field and/or laboratory applications with monitoring, and model calibration would be needed to determine the appropriate sediment augmentation amounts based on potential temporal and spatial channel responses.

- The amount of sediment to be added could be the same as is currently being mined from the bed, which would halt channel incision; thus, no additional sediment would reach Elephant Butte Reservoir Delta. Alternatively, this also could be the amount necessary to partially restore past channel average depths and width to depth ratio.

- Sediment sources sustainability would need to be addressed. Sediment bypass through upstream reservoirs would be a sustainable sediment source. Another method to develop sustainability would be using sediment stored in the current riverside flood plain or terraces to create a channel that would be in dynamic equilibrium with the current sediment supply without future augmentation. Specifically, the method would:

  (1) Begin at the most upstream extent practical and proceed downstream.

(2) Mechanically widen the main channel and lower riverbanks to create a two-stage channel.

(3) Create dimensions of the mechanically widened main channel and two-stage channel that result in a balance between sediment supply (current lower sediment supply upstream of any augmentation actions) and transport capacity.

(4) Place the excavated material in the river channel to increase sediment supply.

The annual length of the excavation to create the wider two-stage channel would be the volume necessary to supply the river with the amount currently being mined from the bed, thus preventing future downstream channel degradation. The amount also could be a larger amount if additional benefits were identified such as those shown by Jackson and Beschta (1984).

- The volume chosen to be supplied to the downstream reaches must be transportable downstream from the sediment supply reach. The amount of material that can be transported from the augmentation site would be the maximum that can be supplied to the downstream river under this alternative.

- Range of cost for this method will be determined at a later time.

7.2 Natural or Constructed Sediment Basins

- The confidence level is between:

  - Level 2 because there are examples of the beneficial effects of decreasing the sediment supply to rivers.

  - Level 1 because the Middle Rio Grande is such a nonequilibrium river that changes in sediment supply could have large effects.

- The reduction of sediment supply can reverse downstream aggradational trends by "controlling sediment delivery to a downstream channel and to localize sediment accumulation" (Sear 1996). The objective of this method is to reduce downstream aggradation, promote sediment storage at strategic locations, and reduce dredging costs to maintain a channel through the delta of Elephant Butte Reservoir.

- The method can include features such as constructed settling basins and initiating channel relocation to deposit sediment over most of the valley floor or topographic low areas.

- Settling basins create a wider, lower velocity channel condition, which initiates sediment deposition. Basins eventually fill with sediment, requiring local dredging and disposal of sediment or relocating the basin to another area that is conducive to sediment storage.

- Relocating the channel periodically across the available valley floor results in a more uniform deposition of sediment.

- Both constructed settling basins and initiating channel relocation decrease the downstream sediment supply by providing upstream storage locations.

- The delta of Elephant Butte Reservoir and the channel upstream past San Antonio to the mouth of Arroyo de las Cañas is the reach where the sediment supply exceeds transport capacity. Dredging operations are needed to maintain a surface water connection between the river and Elephant Butte Reservoir because sediment deposition can completely fill the river channel. In addition, channel capacity is reduced as the channel bed rises. Channel aggradation is anticipated to continue in this reach.

- Controlling excess sediment at its source in the watershed is generally the most sustainable action (Sear 1996). Initiating changes in the watershed is outside of Reclamation's congressional authority from the Flood Control Acts of 1948 and 1950.

- The range of application, benefits, characteristics, advantages and disadvantages, and requirements for relocation channels in the delta of Elephant Butte Reservoir is covered in chapter 3, section 3. Land will not be included in this section. The range of application, advantages and disadvantages, and requirements of settling basins are included in this section.

7.2.1 General Range of Application

- Settling basins or some form of sediment removal has been used for nearly all water diversions. "Only diversions from large storage reservoirs formed by dams" and from "low flows in mountain streams are free of sediment" (Raudkivi 1993). Therefore, every other type of diverted water generally has some sediment requiring removal.

- Settling basins have been used virtually all over the world for diverted water sediment removal.

- Sediment "traps" (Sear 1996) have been used in rivers in the UK. Sand traps and a silt trap in a gravel bed stream are documented for rivers in Denmark and the UK, respectively (Sear 1996).

- Locally upstream of the settling basins, there could be sediment deposition, especially if the basins fill. This could possibly result in upstream aggradation.

- Downstream, the channel could narrow, aggradation may slow, or aggradation could be reversed. In general, downstream from settling basins, the channel width would decrease, the depth increase, the slope decrease, and sinuosity increase (Schumm 1977; Schumm 2005) as a result of decreased sediment load.

7.2.2 Advantages and Disadvantages

7.2.2.1 Advantages

- The root cause of the loss of flood control capacity and channel connectivity to the pool of Elephant Butte Reservoir is that the sediment supply exceeds the capacity of the channel to transport it. Decreasing sediment supply would address the root cause of the river having an overabundance of sediment supply.

- Localizing sediment accumulation could potentially reduce the spatial distance over which dredging and sediment removal would need to occur.

- Downstream from the settling basins, the channel capacity would increase.

- Abandoned settling basins could become new riparian zones.

7.2.2.2 Disadvantages

- Relocating settling basins would be frequent with the large sediment loads of the Middle Rio Grande.

- Given the wide range of flow and sediment loads in the river, it would be difficult to establish settling basins that would accumulate sediments under all flow conditions.

- Careful monitoring of the amount of sediment removed would be necessary to ensure that the amount of sediment deposited does not produce an excessively degrading channel downstream leading to excess bank erosion.

- Once settling basins are used, there will be a continued need for them in the foreseeable future. (However, the ongoing dredging program is also continuing in the foreseeable future to connect the river to the reservoir pool, maintain channel capacity, and maintain valley drainage).

- At some time in the future, currently available areas for sediment accumulation will be filled with sediment, and other areas will need to be located.

- More uniform width, depth, and velocity. Limited amount of low or no velocity habitat. Low amount of cover. Reduces braiding and distributary channels and, thus, provides less opportunity for riparian growth. Lowers ground water table and reduces the size of river bars. This decreases habitat complexity for RGSM.

7.2.3 Requirements

- Settling basins must be long enough and have enough change in cross sectional area to enable sediment to settle before flow leaves the basin. The basin size must be adequate to store sediments, which will deposit.

- The design of the inlet and outlet should minimize turbulence (Raudkivi 1993) and achieve an evenly distributed flow through the basin. A triangular basin design with a narrow inlet and wide outlet was used successfully by Bondurant et al. (1975). They found that the optimum pond design also has a sloping bottom decreasing in depth towards the outlet.

- The velocity in the basin must be less than the threshold of movement for the sediment sizes, which are planned to be removed from the flow so that the design sediment sizes settle within the basin.

- Chen (1975) produced curves that relate the basin surface area and flow rate to the trap efficiency of various sediment sizes.

- Various design methods are available. The method used by Reclamation is found in a guide by Randle (1984), based upon the publication by Pemberton and Lara (1971). Design methods are also contained in Raudkivi (1993), Ranga Raju et. al. (1999), Lawrence et al. (2001), and Ranga Raju and Kothyari (2004).

- Typical basins on diversion canals have a lower operational discharge range than a river channel and often operate with a single adjustable or static outlet, which functions over the operational range of flows. The Rio Grande has a wide range of flow and sediment concentration. The concept of using settling basins may need to be altered for sediment deposition to occur over this wide range of conditions. Thus, a single basin and outlet works would not likely provide settling conditions for all flows. There could be multiple basins, a larger basin for higher flows, and smaller basins for low flows. Having multiple basins would allow outlet works for each that could be designed to pass the desired range of flows, while providing the water surface elevation, so that a suitably large, cross sectional area would be created and sediment could deposit. Alternatively, the basins could be designed to provide sediment deposition during high-flow events, while sediment may pass through during low-flow events. This would provide sediment deposition during conditions when most of the sediment is being transported. The large volumes of sediment would be costly to remove; thus, the concept of moving the basins to different locations within the valley may be advantageous when compared to the construction and maintenance costs of a basin in a static location. These temporary basins could be formed using earthen berms and simple outlet works constructed of riprap material to be stable over an operational life of a few years.

- Basins should be designed for the wide range of flows normally found in this reach and to accommodate flood events. Given the situation where the settling basins would need to be moved regularly, designing for a large event may not be as important as for methods with fixed features. One criterion for determining the design event would be to estimate the flood that would largely fill the downstream channel with sediment should the basin fail to accumulate sediment. The design life should be based on optimizing the cost of establishing new basins, the settling effectiveness through time, and the time to fill the basin to the point where sediment deposition is compromised.

- The method is reliable with the proper basin size for the flow rate and sediment load.

- Basin relocation would be a continuous need.

Chapter 8: Habitat Improvement and Mitigation

8.1 Introduction

- At all river maintenance sites on the Middle Rio Grande, there will be methods used and/or features added so that there is a net positive habitat benefit.

- Methods that provide for a net positive habitat benefit or rehabilitate a desirable channel process should be used wherever possible. When site conditions or other factors, such as landowner receptivity, limit using more desirable methods, habitat features should be added to provide a net positive habitat benefit. The purpose of this section is to include a review of available habitat improvement and mitigation methods that can be used on projects, in conjunction with other methods, to provide a net positive habitat benefit.

- Some of the habitat improvement methods are methods that have both habitat and river maintenance benefits. These methods are included in the preceding sections, and references to the applicable sections will be included.

8.2 General Design Considerations

- General design considerations are found in Shields (1983a, 1983b), Wesche (1985), Brookes (1988), and Miller et al. (2000). For the Middle Rio Grande, many of these items are currently underway, planned for the future, or have been done. They are given here for general information.

General design considerations are:

- Determine desired habitat characteristics and assess channel stability and channel processes through a feasibility study.

- Determine habitat deficiencies relative to preferred habitat conditions for parameters such as depths, velocities, substrates, cover, food source, and the types of channel processes that would promote desirable conditions over a potentially longer term than individual features, etc.

- Determine the location of features based on habitat requirements.

- Determine the type of features based on physical effects, velocity, bed sediments, economics, and estimated sustainability.

- In relation to the size of features, determine the discharge when desired effects would best be realized.

- Investigate the hydraulic effects of features. For example, are structures acting as roughness elements, or to what extent do features promote scour holes, including their size and depth?

- Consider effects on sediment transport. In some cases where sediment processes are known to be significant, specific multidimensional sediment modeling may be appropriate.

- Selection of materials and feature design. Methods may need to include measures to prevent undesirable bed and bank erosion or deposition, flanking, undercutting, etc.

- Adding roughness elements to channels has been shown to improve habitat for salmonids (Brookes 1988) and many fish species (Wesche 1985). These roughness elements include boulders and woody debris, which change the local hydraulics, creating scour and grain sorting, along with variable depth and velocity habitat. Roughness elements have been shown to be applicable to channels that are relatively stable and have gravel bed material size (Brookes 1988).

- Habitat improvement features add complexity to the system, which is generally beneficial to the establishment and development of riparian vegetation.

- Clearing or removing native riparian vegetation that, as a result of constructing the features, would be adverse.

- These features increase variable depth and velocity habitat, flood plain connectivity, and sediment deposition areas to provide development of the riparian zone. Created side channels, backwaters, and terraces are beneficial to RGSM.

8.3 Rootwads

- The confidence level is Level 2.

  In the literature, there were publications giving information on rootwad revetments (McCullah and Gray 2005), rootwad and log composite revetments (Sylte and Fischenich 2000), and large wood and log jams (Saldi-Caromile et al. 2004). This item is for rootwad placement for habitat purposes. The portion of the available literature that applies to rootwads for habitat purposes is used in this section.

- Rootwads are trees placed into the banks or bed of the channel with the root mass or root ball placed in the flow.

- Rootwads provide some flow redirection; and, if placed close together, they can move the current line away from the bank, reducing bank erosion (McCullah and Gray 2005).

- The purpose of potential rootwad installations on the Middle Rio Grande would be to create additional habitat value such as local scour pools, substrate sorting when the bed is gravel, and create variable velocity habitat (McCullah and Gray 2005; Sylte and Fischenich 2000).

- Rootwads often are used as a composite with other logs to form an erosion resistant, continuous, interlocking wood material lining the bank line (McCullah and Gray 2005; Sylte and Fischenich 2000). In the context of use on the Middle Rio Grande, the available specie is cottonwood trees, which have a rapid decay rate with a lifespan of about 5 years when subject to repeated wetting and drying. Thus, cottonwood trees do not lend themselves for use as rootwad composites for bank protection.

8.3.1 General Range of Application

- Rootwads can be used successfully on many types of rivers.

- These methods are considered to be more natural habitat features where there is large wood in the stream (McCullah and Gray 2005).

- Where the banks of the river are comprised of uniform sands, rootwads have limited application (Sylte and Fischenich 2000) due to bank instability.

- Rootwads are often embedded in an excavated trench in the bank line. The excavated material placed on top of the rootwad trunk serves as ballast to offset buoyancy and drag forces on the rootwads. The face of the excavated trench along the bank line is subject to fluvial erosion during high riverflows. This is especially a concern when the soil material is sandy and does not have binding clay or larger erosion resistant particles. This situation was observed at the Santa Clara rootwad revetment project.

- Erosion of the face of the trench can be overcome by placing small riprap or cobble bed material to armor the bank. Placement of the rootwads on the inside of bends or in transition reaches also will reduce the erosion potential of the trench face. Anchors such as deadman or cabling to boulders can also be used to keep the rootwad in position should trench or limited bank erosion occur (Saldi-Caromile et al. 2004).

- Habitat value is localized and is present as long as the rootwad is functional, remains in position, and the bank line does not erode and outflank the rootwad.

8.3.1.1 Advantages and Disadvantages

8.3.1.1.1 Advantages

- Rootwads tend to provide increased flow resistance along the bank line and dissipate energy (Maryland 2000).
- Can trap and retain sediment (McCullah and Gray 2005).
- Can cause scour at high flows.
- Create turbulence that moves the location of the main current away from the bank line on the outside of the bendway (Sylte and Fischenich 2000).
- Can induce bed material sorting (Sylte and Fischenich 2000).
- Adds complexity to the river, and variable depth and velocity conditions can be created. Some potential for creating areas of sediment deposition (depending upon specific placement), which is generally beneficial to the establishment and development of riparian vegetation.
- Can provide structure and habitat for RGSM. Isolated pools are often maintained in scour pools caused by rootwads. This can serve as refugia habitat for silvery minnow during low-flow periods.

8.3.1.1.2 Disadvantages

- For banks that have less than 15% silt or clay, bank erosion may occur around the rootwads (Sylte and Fischenich 2000).
- Requirements (length, width, number, spacing, orientation, entrance conditions, etc.) cost and benefits.
- Methods to design rootwads to withstand rootwad buoyancy drag force, and frictional resisting forces are found in Saldi-Caromile et al. (2004).
- Saldi-Caromile et al. (2004) include various types of anchors for large wood, which also apply to rootwads.

- If large wood or rootwads are used to improve the habitat of a riprap revetment, the size of the rock should be increased because the rootwad increases turbulence and can redirect the flow, increasing the shear stress on the rock (Saldi-Caromile et al. 2004).
- When placed along the bank line, rootwads are oriented upstream so that the force of the flow pushes the tree trunk and root ball into the bank. The angle is as much as about 15 degrees towards the bank. In some situations, such as a crossing or riffle zone, rootwads can be angled 90 degrees with the bank.
- Rootwads provide the maximum habitat value when the root ball extends from the bank-full elevation to the maximum scour depth. About three-fourths of the rootwad should be embedded into the bank after anticipated scour has occurred. Durability and project life depend on the anchoring or ballast size and tree species. Cottonwood trees have short life expectancy relative to other tree species.
- Generally, rootwads are designed for the channel forming or bank-full discharge.
- Maintenance may include adjusting anchors or replacing eroded material from the face of trenches.
- Ranges of cost will be determined at a later time.

8.4 Log Jams/Large Woody Debris

- The confidence level is Level 2.
- Log jams and LWD structures are made from felled trees and may be used to redirect, deflect, or dissipate erosive flows.
- LWD also can be used to enhance the effectiveness and mitigate for the impacts of other treatments such as riprap revetments, longitudinal stone toes, and transverse features (WDFW 2003).
- LWD can be used to enhance the creation of side channels by forming medial bars with a pool downstream from the LWD (Saldi-Caromile et al. 2004).
- Create and maintain variable depth and velocity habitat through scour.

8.4.1 General Range of Application

- LWD structures have been used throughout the United States and Canada on sand bed channels (Shields et al. 2004) and gravel bed rivers of all sizes (McCullah and Gray 2005).

- Common modes of failure are inadequate ballast, , structural weight, or inadequate anchoring.

- Countermeasures are large ballast and adequate anchors with a minimum safety factor of 2.0 when conditions may present a risk to life or infrastructure. Lower factors of safety are appropriate for enhancement projects in remote areas. Safety factors can be determined using a force balance such as NRCS.

8.4.2 Advantages and Disadvantages

8.4.2.1 Advantages

- Provide economical habitat improvements.

- Promote side channel formation and maintenance (Fischenich and Morrow 2000; Saldi-Caromile et al. 2004).

- LWD tends to increase flow resistance and dissipate energy (McCullah and Gray 2005).

- Create areas of low velocity and overhead cover (Fischenich and Morrow 2000).

- Some of the morphological responses are noted by Fischenich and Morrow (2000):
    - Create pools.
    - Generate scour and substrate sorting and complexity.
    - Increase depths in shallow reaches.
    - Promote bar formation and induce sediment deposition.

- Morphological response would be localized to the immediate vicinity of the features.

- LWD can be engineered, designed, and anchored so that it will pass design flows and resist erosive forces, while providing habitat benefits.

- Provides short-term habitat value. LWD can add structure and cover for fish including downstream slack water areas. Can create variable depth and velocity habitat providing for habitat diversity in areas with monotypic flow patterns and refugia habitat during low flows. Could establish new sediment deposition areas where new riparian vegetation could grow. Downstream sediment deposition can create variable depth and velocity habitat.

8.4.2.2. Disadvantages

Wood, subject to repeated wetting and drying, will decay; a realistic lifespan for the wood itself is 5–15 years. Cottonwood found on the Middle Rio Grande has a lifespan on the low end of the typical life time (Sylte and Fischenich 2000) of around 5 years. Wood that is continuously wet can last many decades.

- Frequent wetting and drying will increase decomposition rate (Sylte and Fischenich 2000).
- Can be damaged by beavers (McCullah and Gray 2005).
- Can lead to the establishment of new medial islands or bars, which could be detrimental if a narrowing trend currently exists in the channel.
- Scour pools may provide refuge for predatory fishes.

8.4.3 Requirements

- Design and placement methods are found in Saldi-Caromile et al. (2004), Abbe et al. (1997), D'Aoust and Millar (2000), and Shields et al. (2004).
- LWD must be keyed in, partially embedded, anchored, or have ballast to remain stable during passage of design flows.
- Reliability for providing habitat is high.
- Complexity is relatively low.
- Durability and project life depend on the anchoring or ballast size and tree species. Cottonwood trees have low life expectancy relative to other tree species.
- Generally, LWD is designed for the channel forming or bank-full discharge.
- Maintenance of LWD generally consists of realignment or removal of moved pieces following large storm events or replacing or adjusting anchoring hardware (McCullah and Gray 2005).

8.5 Island and Bank Clearing/Destabilization

See section 2.4.3 above.

8.6 High-Flow Side Channels (Perennial, High Flow, and Oxbows)

See section 2.4.5 above.

8.7 Longitudinal Bank Lowering

See section 2.4.6 above.

8.8 Boulder Groupings

- The confidence level is Level 2.
- Boulder groupings are strategically placed, large, immobile boulders, and groupings of boulders placed within a channel to increase or restore structural complexity and variable depth and velocity habitat (Saldi-Caromile et al. 2004). If the channel lacks these features, adding boulder groupings can be an effective and simple way to improve aquatic habitat.
- This method provides immediate benefits of cover and refuge from high velocity. High-flow events interacting with boulder groupings create and maintain downstream scour pools and provide bed sorting. The presence of variable velocity locations provides habitat for many species (Fischenich and Seal 2000).
- Large boulders are placed individually, in clusters, or in groups to improve habitat.
- Flow separation around the boulders leads to the formation of eddies or vortices in their wake, thus locally increasing downstream turbulence (Fischenich and Seal 2000).
- Scour is generated downstream from each structure, creating pockets of deeper water. In gravel bed channels, the bed material in the pocket pools is coarsened, which adds to the physical diversity of a stream reach.

8.8.1 General Range of Application

- Boulder placements have been used successfully throughout North America to enhance fish habitat (Saldi-Caromile et al. 2004).

- This method has been used mostly in channels where the natural roughness elements, such as wood and boulders, have been removed or where the channel has been straightened and habitat diversity, such as cover, variable depth and velocity, and refuge areas has been lost (Saldi-Caromile et al. 2004).

- Common modes of failure include being buried by sediment in aggradational reaches, becoming ineffective or abandoned when channels shift alignment, sinking into each boulder's scour hole in sand bed channels (McCullah and Gray 2005), and accelerating bank erosion when placed near eroding or unstable banks.

- Countermeasures to ameliorate these potential failure modes include: application in reaches that are near dynamic equilibrium and are not actively aggrading, reaches that have high lateral migration, using only on gravel or cobble bed rivers, and place far enough away from banks to avoid additional bank erosion. Bed material size should be coarser than medium gravel or about 50 millimeters (McCullah and Gray 2005).

- Best used in reaches where there is a dominance of riffle habitat over pools, avoid pools and slow runs (Fischenich and Seal 2000), and velocity should exceed 4 feet per second at bank-full flow (Fischenich and Seal 2000).

- Should be used in reaches where fish populations are habitat limited (McCullah and Gray 2005).

- When the channel bed material is fine enough, scour can occur, creating variable depth and velocity habitat and bed material sizes. Boulders can create local scour (pools) and velocity shear zones; variable depth, velocity, and bed material sizes; best use in coarse gravel or larger bed material settings where long riffles dominate (McCullah and Gray 2005).

- Sand bed streams or unstable reaches should be avoided (Fischenich and Seal 2000). In fine grained gravel beds, the scour hole size would be larger than in coarser gravel or cobble beds. Boulders can dislodge into the downstream scour hole if it is large enough, and flows will re-create another downstream scour hole. This process can lead to continued movement of boulders through time.

- Effects are localized to the immediate vicinity of the boulders when they are placed in riffle dominated reaches, away from banks (outside the wake zone), and cover less than 10% of the bank-full cross sectional area (Fischenich and Seal 2000).

8.8.2 Advantages and Disadvantages

8.8.2.1 Advantages

- Works well in river reaches where there are not locally available roughness elements.

- Boulder groupings can be used to add aquatic benefits to a wide range of channel maintenance methods.

- Boulder groupings are simple, natural-looking features that add visual diversity and habitat to degraded and uniform reaches.

- Consequences of failure are generally slight.

- Creates variable depth and velocity conditions, with slack water areas on the downstream from boulders. Benefits to RGSM will depend upon microhabitat features such as proximity to shoreline, depth, and velocities.

8.8.2.2 Disadvantages

- The shape of a boulder cluster can be short term if the boulders become mobile during frequent storm events.

- Boulder groupings do not provide benefits when placed in depositional zones where they will be become buried in sediment.

- Boulders installed in sand bed channels tend to sink into their own scour holes due to their size and rapid development.

- If the channel is laterally dynamic, placed boulders may be abandoned as the channel shifts and migrates.

8.8.3 Requirements

- Recommendations on boulder placements, boulder stability, the number, configuration, and location are provided in Flosi et al. (1998), Fischenich and Seal (2000), and McCullah and Gray (2005).

- Boulders should be sized to be immobile at the design flow. There are two different reports on the magnitude of the design flow. Design flows generally range between the 50- and 100-year flow. Saldi-Caromile et al.

(2004) recommend these high flows so that boulder groupings are not deformable and to minimize risk. On the other hand, Fischenich and Seal (2000) recommend using the bank-full discharge. It is recommended that the engineer determine the design flow based on local site conditions; the type, value, and location of riverside infrastructure; project goals; etc. Higher value infrastructure and higher habitat needs would suggest a larger return period flow to size riprap with.

- Typical patterns of boulder placement can be found in Saldi-Caromile et al. (2004) and Johnson and Stypula (1993).

- Boulders and boulder groupings are most effective when located in straight, low gradient riffles that are less than 0.5 to 1% slope (Saldi-Caromile et al. 2004).

- Should be used in gravel and cobble bed streams with bed sizes greater than medium gravel or about 50 millimeters. They are not recommended for sand bed channels (Fischenich and Seal 2000; Saldi-Caromile et al. 2004).

- Boulders and boulder groupings have high reliability. There is a large degree of uncertainty in boulder placement design and performance but low risk of boulders being transported far downstream.

- Federal Highway Administration (1979), as cited in Saldi-Caromile et al. (2004), recommends that a maximum flow blockage as a result of boulders should be less than one-fifth of the low-flow capacity. This maximum area blocked by boulders should be reduced if the stream channel is less than 3%. Fischenich and Seal (2000) recommend that boulders block less than 10% of the flow area at bank-full discharge.

- It is recommended that boulders be fully submerged during bank-full flow (Saldi-Caromile et al. 2004).

- Construction has low complexity and requires excavating receiving holes for the boulders and equipment to place the boulders.

- Placement in braded or unstable sections, or the upper end of riffles, should be avoided (Fischenich and Seal 2000).

- To maximize the benefits of boulders during low flows, they should be concentrated near the channel thalweg (Fishenich and Seal 2000) but away from either bank. Placement should be avoided that will deflect flows toward erodible banks (McCullah and Gray 2005).

- Fischenich and Seal (2000) recommend placing three to five boulders in a triangular configuration in staggered groups or clusters along the riffle or shallow run. To maximize turbulence and scour, they further recommend placing boulders about 1 diameter apart.

8.9 Riparian Vegetation Establishment

- The confidence level is Level 2.
- Riparian zones include the active flood plain and adjacent plant communities that are affected by the river system.
- Riparian zones provide shade, fine and large woody material, nutrients, near bank cover, organic and inorganic debris, insects, and wildlife habitat (Saldi-Caromile et al. 2004).
- This method includes active restoration involving manipulation of the landscape, such as grading and planting to accelerate recovery.
- Riparian restoration is most effective when areas are protected from land use activities that degrade the riparian forest. Flood plain connectivity also often requires altered streamflow or channel modifications.
- Vegetated flood plains reduce floodflow velocities, reduce main channel scour, and encourage sediment deposition in the flood plain.
- Sediment deposition is encouraged by increasing hydraulic roughness created in flood plain areas by dense stands of woody vegetation. Velocity also is reduced, and the high flow water surface is increased for the same reason.
- Frequently inundated areas of the channel will often recolonize with native vegetation species.
- If riparian vegetation is above the mean high water mark, there would be no effects upon upstream and downstream river reaches.

8.9.1 General Range of Application

- All except the driest southwest ephemeral rivers have a riparian zone and can benefit from riparian vegetation establishment.
- Common modes of failure for planting include grazing, lack of flood plain connectivity, inability of roots to reach the water table, or plants that are inundated by flows in excess of their tolerance and die.
- Many projects on the Middle Rio Grande exist where vegetation planting has been successful. At the Bernalillo site, the flood plain was revegetated. At

the Santa Ana Project, a deformable bank line was installed with a lowered terrace to create a flood plain. The deformable bank line and lowered terrace were planted with native tree species.

8.9.2 Advantages and Disadvantages

8.9.2.1 Advantages

- Can be used to restore flood plain areas where natural revegetation would not occur due to low flood plain connectivity.
- Can be used to accelerate riparian zone recovery for areas with flood plain connectivity.

8.9.2.2 Disadvantages

- Plantings can have a large mortality rate when the roots do not have contact with the ground water table.
- Plantings can have a large mortality rate if they are planted at an elevation that is too low for the flows and are excessively inundated.

8.9.3 Requirements

- Accelerating revegetation consists of selecting appropriate plant species for the management area and introducing them in a manner that allows them to properly grow.
- The design and implementation of riparian zone restoration and management is given in Saldi-Caromile et al. (2004).
- Riparian zones are best established in reaches where there will be periodic inundation of the establishing vegetation areas.
- Riparian zones will be healthy, in the long term, when coupled with bank line migration, which erodes portions of the riparian forest while creating new vegetation growth areas on depositional surfaces in the river channel. Eroded portions could provide for more overbanking, which is beneficial to RGSM.
- Guidelines for planning riparian restoration in the Southwest can be found at <http://www.nm.nrcs.usda.gov/news/publications/riparian.pdf> and <http://www.nm.nrcs.usda.gov/news/publications/dormant-willow-planting.pdf> (NRCS nda and NRCS ndb) (accessed March 27, 2012).

8.10 Bank Line Embayments

- The confidence level is Level 1.

- The physical characteristics of the Middle Rio Grande channel have changed significantly, especially since the closure of Cochiti Dam. As a result of reduced sediment loads, the main channel in many reaches has incised, which has "isolated flood plain habitat during years with reduced runoff discharge" (Porter and Massong 2005a).

  Bank line embayments (Reclamation 2005) simulate historical channel features and flood plain habitat types that were frequently inundated. Their intended purpose is to retain drifting RGSM eggs and fry (Porter and Massong 2004). They also attract "free-swimming fish" (Massong et al. 2004) and "provide rearing habitat and enhanced food supplies for developing RGSM larvae" (Reclamation 2005).

- Bank line embayments have several different names including shelves, scallops, inlets, and backwater areas.

- Natural bank line embayments can occur on arroyo fans and at the confluences of flood control channels; however, there are only a few locations where bank line embayments occur naturally. Given their importance as a habitat feature (Porter and Massong 2004; Tetra Tech EMI 2004; Reclamation 2005), more frequent availability of these types of habitat would be beneficial These habitat features are excavated into banks at a range of elevations that allows riverflows to enter during high-flow events such as spring runoff and summer thunderstorms. They are excavated into the bank lines with sufficient width and distance into to bank, to provide a drift zone or slack water area of very low velocity for RGSM habitat, while allowing inflow and outflow at the inlet mouth. The drift zone is the inundated area with "un-measurable low water velocity that occurs farther back in the inlet" (Massong et al. 2004). These features exchange water with the main channel across the bank line, rather than an inlet and outlet, as in the case of high-flow side channels (Tetra Tech EMI 2004). These features generally have a sloping bed surface that can be inundated at a variety of discharges during which RGSM spawning occurs. Discharges at which the invert is wetted can range from 500–1,000 cfs (Bauer 2005). A common range of wetting discharges can also be 1,500–2,500 cfs (Amy Porter, 2008, personal communication, Biologist, Interior, Reclamation, Albuquerque Area Office).

- Willows can also be planted (willow swales) in the excavated areas.

- Inlets, scallops, and shelves each have the same basic purpose with different planview dimensions. Previously, these features also were called backwater ponds when constructed on the downstream side of bars.

- Inlets are constructed into the bank line and can be perpendicular or have a slight angle upstream and downstream relative to the bank line. They are generally constructed one to two excavator buckets wide. They are excavated into the bank several buckets deep, up to 20 feet long or more, depending on local topography and whether the area is readily available for excavated material disposal. They are constructed with a sloping bottom elevation so that there is a variety of depth for a range of discharges.

- Scallops are also features excavated into the bank line, but they have more of a curved shape, are generally excavated a shorter distance into the bank line than inlets, and are usually longer along the riverbank.

- Shelves are areas excavated in a more longitudinal direction along the bank lines that are inundated at high flows and provide a flooded surface. They are often excavated around the mouths of inlets (Porter and Massong 2005a). Shelves can be combined with inlets (Massong et al. 2004).

- Shelves combined with inlets can also contain small rock berms placed perpendicular to the bank line, which slows the water velocity, promoting upstream and downstream sediment deposition simultaneously, and providing for lower velocity and less sedimentation at the inlet. The berms can be placed upstream of the inlet and at an angle to the bank line near the upstream side of the inlet to guide flow into the inlet. The sediment deposition adjacent to berms is envisioned to provide variable elevation surfaces over time (Massong et al. 2004) and could potentially increase RGSM egg retention rates.

8.10.1 General Range of Application

- Most applicable where there is a lack of backwaters; channel features that produce complex eddy currents and that generate near-zero flows. Under these conditions, semibouyant eggs spawned from RGSM can suffer from excessive downstream drift (Tetra Tech EMI 2004).

- The general range of application beyond the Middle Rio Grande is unknown.

- The most common mode of failure is sedimentation.

- Countermeasures to sediment deposition include re-excavation or relocation of the embayments.

- These structures are small enough that they would not affect existing river morphological processes.

8.10.2 Advantages and Disadvantages

8.10.2.1 Advantages

- They have been shown to have a positive effect upon aquatic habitat because they attract a variety of fish species and "retain silvery minnow eggs" (Massong et al. 2004).

- Relatively low cost and low level of effort to construct and maintain; therefore, as they fill with sediment, they can easily be reconstructed or the sediment can be removed.

- Creates habitat types that are no longer readily available. Flooding during high waterflows can increase available RGSM nursery habitat areas.

- Can increase likelihood of native vegetation growth.

8.10.2.2 Disadvantages

- Inlets, scallops, shelf, and backwater areas can be sediment depositional zones that reduce the effectiveness of egg and larval retention. The length of life can be low due to these sediment deposits.

- These are experimental features, and there are limited examples of the dimensions and conditions under which they function the best.

- While they do fill with sediment, they are relatively inexpensive and easy to construct, so they could be either maintained or constructed in new locations on a regular basis.

- For some conditions, sedimentation at the mouth area of constructed inlets "can fill rapidly creating a disconnected drift zone within the inlet" (Massong et al. 2004). This could potentially create RGSM egg and larval stranding.

8.10.3 Requirements

- General information about the requirements of bank line embayments is given in Massong et al. (2004).

- Conceptual drawings of inlets and shelves are found in Massong et al. (2004). Typical dimensions are not shown on these drawings. For example, the width and length (distance into the bank) necessary for inlets to provide a suitable drift zone are not shown for various river velocities and bank line locations. This is a promising method, which has improved egg retention; thus, more information on these issues through more extensive and systematic design, construction, and postconstruction monitoring would be very useful.

- This could provide quality nursery habitat for RGSM due to:

  1. A drift zone for retaining eggs and larvae out of the current.
  2. Sufficient depth and area for rearing RGSM larvae
  3. The appropriate elevation to be inundated at minimal flows during spring runoff
  4. The capacity to remain inundated for 1 to 6 weeks to support larval growth prior to returning to the river (Massong et al. 2004)

  The shelf inlet should be connected to the river, with a shelf slope that allows a variety of depths to occur through a range of discharges above 1,500–2,500 cfs (Massong et al. 2004). Shelves, inlets, and scallops have also been excavated to depths that allow inundation to begin at 500 cfs.

- Some vegetation on the shelf can help provide reduced flow velocities for egg and larval retention (Massong et al. 2004).

- Rectangular shape directs currents into and out of the inlet (Massong et al. 2004).

- Locating shelves and inlets on point bar or islands where they can be connected to riverflows and convey surface water helps provide flows to flush fine sediments (Massong et al. 2004).

- At riverside drain outfalls, construct inlets so that they connect to the outflow channels. The outfalls can be widened to promote shelf development and to slow the outflow waters to create a slower water environment (Massong et al. 2004).

- Level of reliability is relatively high because there is documentation of positive effects for egg retention and larvae usage (Massong et al. 2004).

- Constructability issues include access and locating suitable areas to deposit excavated material. Potentially, the riparian forest would be disturbed for equipment access.

- These features readily fill with sediment and, thus, have high maintenance requirements and low design/project life without sediment removal.

- The level of complexity for implementation and maintenance is low. These are relatively simple features; excavation is the main construction component.

8.11 Jetty Removal

- The confidence level is Level 1.

8.11.1 History and Function of Kelner Jetties

- Jetties were installed on the Middle Rio Grande nearly continuously along the riverbanks from Bernalillo, New Mexico, south to Highway 60 bridge over the river near Bernardo, New Mexico. Their original purpose was for bank protection and to establish a new bank line a safe distance away from the levee or other infrastructure. Jetties were used to establish a 600-foot-wide river channel from Bernalillo to Isleta Diversion Dam and a 550-foot-wide river channel from Isleta Diversion Dam south to Highway 60 bridge.

- Jetties are comprised of three 16-foot-long, 4-inch by 4-inch by ¼-inch steel angles. The three angles are bolted together at their midpoints. They form a set of three perpendicular angles held into place by lacing wire at 15-inch intervals. They are linked together in a line with ½- to ¾-inch wire rope (cable). The cables extend in a continuous line through adjoining jetty units, and each jetty is connected at each end to a tieback line of jetties. The cable linking jetties together is a double line with cable clamps used to connect cables around each jetty unit. In addition to the tiebacks at each end, the tieback lines are also spaced throughout the field, generally about 250 feet apart. At the end of each tieback line, the cable is connected to a standard creosoted, 8-foot railroad tie buried 3 to 5 feet in the ground. When the jetties are installed on a bend where there is a large current angle with the bank line, two front lines are used (USACE 1953).

- They were most often installed in the exiting river channel by Reclamation to establish the new bank line and channel widths via sediment deposition (Carlson and Enger 1956; Lagasse 1980). They function in this setting as follows. As flow passes through the front lines, the velocity is reduced, resulting in deposition of sediment in and behind the front lines. As the flow continues downstream on the land side of the front lines, the velocity increases. Upon flowing through the tieback lines, the velocity is reduced. The spacing of tieback lines was determined to ensure that the velocity remained slower behind the front line than in the river channel. Waters recirculating back to the river carry less sediment than the riverflows; thus, the water flowing into the jetty field deposits sediment, and flows recirculating to the river could carry additional sediment. This resulted in sediment being deposited in the jetties, and the slightly clearer water recirculating back to river channel picks up sediment from the riverbed, providing a slight scouring action in the river. Over time, a new bank line is established via sediment deposition and has the opportunity to become vegetated. The time for the bank line to develop depends on hydrology and sediment supply and can be within a few years.

- The objective of jetty installations was to establish a new bank line, narrow the river, and provide bank and levee protection.

- Jetties were also put in the Rio Grande during flood stages to protect the spoil levees prior to the construction of Cochiti Dam.

- Cochiti Dam, with its sediment trapping capability, altered the river processes so that new jetty installations no longer met their historic purpose. Many jetty fields became undercut and sank into the riverbed as channel degradation processes ensued.

8.11.2 Jetty Removal

- Environmental interests have become increasingly important on the Middle Rio Grande in about the last decade. There has been a documented decline in the environmental condition of the river and its bosque (Crawford et al. 1993). Part of the decline has been attributed to the bank lines being fixed in place by jetty jacks.

- There are many views held by various persons and agencies regarding the objectives and benefits of jetty jack removal.

- One view is that jetty jack removal is an important part of restoring river function, and that jetty removal would allow active bank erosion, provide additional sediment supply, and reconnect the river to its flood plain (Grassel 2002).

- Another view is that jetty jack removal creates more opportunities for recreation and native vegetation plantings, particularly within the Rio Grande State Park (Grassel 2002).

- A third view is that the jetty removal should be accompanied by “nonnative phreatophyte replacement” to maintain water delivery efficiency and reduce consumptive use. Further, jetty removal is viewed as creating a wider channel, thus decreasing water delivery (Grassel 2002).

- A fourth view is that the jetties still provide bank and levee protection, and only those not needed for levee protection should be removed.

- The method includes complete jetty removal or cutting them off at the ground level and placing a berm over the top. Complete removal could be accomplished by pulling them out with equipment or excavating around them prior to removal.

- Reconnection to the flood plain would be beneficial to RGSM.

8.11.3 General Range of Application

- Jetties function best in moderately sinuous and sediment-laden rivers such as the Arkansas and the Middle Rio Grande before Cochiti Dam (Grassel 2002). In addition, in rivers that are sediment laden, jetties function the best for establishing new bank lines when the channel is relatively shallow and wide with a sandbed. The Middle Rio Grande prior to the closure of Cochiti Dam had ideal conditions for this method to be effective.

- Jetties have also been used on rivers such as the Purgatorie River near Higbee, Colorado; Arkansas River, Arkansas; Cimarron River, Kansas; and on rivers in Nebraska (USACE 1953).

- Jetty removal can be accomplished on any river where they are installed.

- Jetty removal has taken place on the Middle Rio Grande in the Santa Ana Pueblo, the Los Lunas Project, and various other locations including in the Rio Grande State Park.

- The local and special geomorphic response is variable. At some restoration project sites, the historic overbank is no longer inundated by peak flows. Lowering the overbank to re-establish a connected flood plain can be a project objective. This necessitated jetty removal. In this case, the major effect is bank lowering. Jetty removal would conceptually result in the bank being more erodible, resulting in channel widening, lateral migration, or both. For the situation where jetties are removed from an existing bank line, the existing bosque forest will stabilize the bank unless there is active bank toe erosion and/or the riverbed has degraded below the root zone. In these cases, jetty removal would result in less bank stability, potentially resulting in channel widening, lateral migration, or both. When channel incision and subsequent lateral migration occur in a channel with reduced sand bed material load, the bank line beneath jetties can erode rendering them ineffective for bank protection.

8.11.4 Advantages and Disadvantages

8.11.4.1 Advantages

- Can result in lateral migration or channel widening, which would potentially restore some of the river processes.
- Can enable flood plains to be reconnected (potentially with some bank lowering or bed raising).
- Is aesthetic for recreational areas.
- Has a relatively low cost.

8.11.4.2 Disadvantages

- Jetty removal may not initiate flood plain reconnection if the channel is already incised.
- Banks could become destabilized, leading to levee erosion.

8.11.5 Requirements

- The method requires large equipment capable of excavating around jetties and lifting them out, or lifting them out without excavation.
- Removal from the site and disposal of metal jetty parts are necessary.
- Removal may, or may not, result in bank line migration, channel widening, or flood plain connection. Additional actions may be necessary if these are project objectives.
- Construction (removal) issues include:
    1. Jetties may be entangled with large woody debris and require multiple pieces of equipment for removal.
    2. In some cases, cutting the jetties and leaving part of the angle iron in place may be the only way for removal to be accomplished.
    3. If the jetties are in the water and the bank has eroded behind them, equipment with a long enough reach and capacity is needed for removal.
    4. Excavation may be required in cases where lifting the jetties out is not possible.
- The complexity of implementation is medium.

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Unique Terms

The analysis approach is discussed in section 4.1 of the main report, Middle Rio Grande River Maintenance Program Comprehensive Plan and Guide.

Evaluation Factors. For this analysis, we rated strategy implementation effects by the attribute of three evaluation factor for each suitable strategy in each reach:

- Engineering Effectiveness Evaluation Factor (as scored by the Attributes for Strategy Performance and River Maintenance Function)
- Ecosystem Function Evaluation Factor (as scored by the attributes for the SWFL and RGSM)
- Economic Evaluation Factor

Goals. Goals are outcome statements that describe desired conditions on the Middle Rio Grande. The updated goals are:

- Support Channel Sustainability
- Protect Riverside Infrastructure and Resources
- Be Ecosystem Compatible
- Provide Effective Water Delivery

Planform Stages. See appendix C, section C1.4.1.3, for a description of the Middle Rio Grande Planform Evolution Model. For further clarification, please refer to Mesong et al. 2010. The planform stages progress from Stage 1–3 on a common pathway; Stages A4–A6 are aggrading conditions, and Stages M4–M8 are migrating conditions. The planform stages, as listed in the previous described order, are as follows:

- Stage 1 (Mobile sand-bed channel)
- Stage 2 (Vegetating bar channel)
- Stage 3 (Main channel with side channels)
- Stage A4 (Aggrading single channel)
- Stage A5 (Aggrading plugged channel)
- Stage A6 (Aggrading avulsed channel)
- Stage M4 (Narrow single channel)
- Stage M5 (Sinuous thalweg channel)
- Stage M6 (Migrating bend channel)

- Stage M7 (Migrating with cutoff channel)
- Stage M8 (Cutoff is now main channel)

Reach Characteristics. Reach characteristics are overall assessments of the existing conditions of the reach to provide information used in prioritizing reaches and in rating the strategy effects by reach. Reach characteristics are:

- Channel Instability Reach Characteristic
- Water Delivery Impact Reach Characteristic
- Infrastructure, Public Health, and Safety Reach Characteristic
- Habitat Value and Need Reach Characteristic (as reflected by southwestern willow flycatcher [SWFL] and Rio Grande silvery minnow [RGSM])

Strategies: Strategies are the basic approaches to achieving the goals on a reach-wide basis, and methods are the means to implement those strategies. The variety of river management practices considered for implementation on the Middle Rio Grande is grouped into six basic strategies:

- Promote Elevation Stability
- Promote Alignment Stability
- Reconstruct and Maintain Channel Capacity
- Increase Available Area to the River
- Rehabilitate Channel and Flood Plain
- Manage Sediment