ERDC/EL TR-03-4

Environmental Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Wetlands Regulatory Assistance Program

Effects of Riprap on Riverine and Riparian Ecosystems

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April 2003

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Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Preface

This report was authorized and funded by Headquarters, U.S. Army Corps of Engineers, as part of the Wetlands Regulatory Assistance Program (WRAP). HQUSACE representatives for this report are Mr. Charles Hess, Chief, Operations Division; Mr. Charles Stark, Acting Chief, Regulatory Branch; Mr. Mark Sudol, Chief, Regulatory Branch; Mr. Ted Rugiel, Regulatory Branch; and Ms. Katherine Trott, Senior headquarters Regulatory Program Manager. Mr. Robert L. Lazor, U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), was the WRAP Program Manager. General supervision of this effort was provided by Dr. Mike Passmore, Chief, Ecological Resources Branch; Dr. Dave Tazik, Chief, Ecosystem Evaluation and Engineering Division; and Dr. Edwin Theriot, Director, EL.

This report was prepared by Dr. Craig Fischenich, ERDC, EL. The assistance of Michael Waring, ERDC, EL (retired), and Michael Scuderi, U.S. Army Corps of Engineers, Seattle District, in compiling this list of references is gratefully acknowledged.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

This report should be cited as follows:

> Fischenich, J. C. (2003). "Effects of riprap on riverine and riparian ecosystems," ERDC/EL TR-03-4, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Executive Summary

Streambank stabilization affects many of the structural characteristics and functions of a stream. These impacts can be viewed as either adverse or beneficial, depending upon the perspective of the individual assigning values to the system. The prevailing philosophy in ecosystem management is that physical alterations of the structure and character of an ecosystem are most significant if they also impact process-based functions. A series of 15 river and riparian functions are presented in five categories, against which the impacts of riprap stabilization treatments are assessed.

Among the general categories, erosion control measures are most likely to impact morphological evolution, sediment processes, and habitat. They are least likely to impact the stream's hydrologic character and the chemical processes and pathways. Of the 15 specific functions, stream evolution, riparian succession, sedimentation processes, habitat, and biological community processes are most likely to be impacted.

Riprap is a material consisting of graded stone. The stone source may vary, but is typically blasted, grizzled, and screened at a quarry. This material can be used in a variety of ways to stabilize streambanks. Distinctions among various bank stabilization measures can be made on the basis of 1) how they work, 2) the materials used, 3) their geometry and position in the landscape, and (in some cases), 4) the character of stream system to which they are applied. Stabilization measures in four basic categories were evaluated for the likely impact to the basic functions.

Relative to the other categories of stabilization alternatives, *energy reduction* measures, which include a variety of techniques to lower the energy gradient of the stream, have the greatest potential impacts. Intermittent *flow deflection* structures that extend outward from the bank and force the higher velocities streamward generally have the least overall potential impact. *Slope stabilization* and *armor* measures, which include placing stone along the bank parallel to the flow, have intermediate impact potential.

Functions most likely to be impacted by stabilization measures include stream evolution processes, riparian succession, sedimentation processes, habitat, and biological community interactions. Those least likely to be impacted include the functions related to hydrologic balance and chemical and biological processes.

The nature and significance of the impacts depend upon the specific measure employed, and the characteristics of the stream system on which it is used.

Many of the impacts associated with erosion control measures are independent of the material used to accomplish the erosion control. Most of the impacts associated with an armor structure, for example, are the same regardless of whether the armor material is riprap, concrete, vegetation, or a synthetic product. Material-related impacts are generally associated with the habitat characteristics of the structure, and the influence of the structure on riparian vegetation.

The impacts associated with the use of riprap can be minimized by modification of structures used to provide for erosion control. When used as an armor material, riprap impacts can be minimized by reducing the height of the protection, by increasing the slope of the embankment, and by sizing the riprap in order to afford adequate habitat within the aquatic environment. Planting the interstices of a riprap revetment with woody vegetation can also reduce impacts. Similar modifications can be employed to minimize the impacts associated with riprap used as toe protection in a slope stabilization project.

Measures to reduce the impacts associated with flow deflection structures incorporating riprap include carefully locating the structures so as to minimize impacts to the riparian corridor, and modifying the structure design in order to generate desired habitat characteristics within the aquatic environment. Structure designs that result in diverse conditions or that restore or generate necessary habitat can have generally positive impacts. Some research suggests that the size and gradation of stone for both flow deflection and armor structures can be adjusted to reduce impacts.

Most impacts caused by energy reduction structures are related to the height of the structure. High structures significantly decrease the energy and water surface slope, induce sediment deposition upstream and scour downstream, and can present a barrier to the migration of aquatic organisms. These impacts can be minimized by replacing single structures with a series of low-head structures, and by incorporating structural modifications to improve sediment continuity and fish passage.

1 Overview

Riprap (graded stone or crushed rock) is the most common material used in the stabilization of streambanks and shorelines. The continued use of this material as fill has been challenged in many locations by resource agencies due to concern for potential environmental impacts. Moratoriums on the use of riprap have been established or are being pursued by the National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (USF&WS), and several State Environmental Quality offices. U.S. Army Corps of Engineer Districts currently invest considerable manpower interacting with applicants and resource agencies on this issue. These efforts are hampered by a number of factors including inconsistencies in the literature, differences among ecosystems, conflicting agency missions and directives, and insufficient knowledge. Lacking a sound procedure for the objective evaluation of potential impacts and given the ambiguous nature of the literature on the matter, decisions are often clouded by biased judgment.

To address this problem, research was initiated under the Wetlands Regulatory Assistance Program (WRAP) to develop guidelines for the evaluation of the environmental impacts and benefits of riprap. The first step in this research was the formulation of an annotated bibliography of related publications that could serve as a basis for regional and site-specific evaluations, and that characterizes the current state of knowledge on this subject.

This document presents the results of the literature review. Citations are presented in the following sections, with an annotation summarizing the study findings. Each citation is appended with one or more category numbers that indicate the major thrust of the reference, based on the following:

1. Methods of construction/engineering aspects.

2. General impact considerations.

3. Salmonid-specific impacts.

4. Salmonid habitat/life requisites.

5. Evaluation of riprap pros and cons.

6. Assessment methods for riprap and riverine habitat.

7. Case studies/literature review.

2 Impacts of Riprap

Riprap, or graded stone, has been used in a variety of ways to prevent streambank erosion in the United States for more than a century. Most of this work was unregulated and was executed prior to the recognition of the potential environmental impacts of such activities. Consequently, thousands of miles of stream have been stabilized with riprap, and it is clear that the nation's waters have been impacted.

Despite the pervasive and historic use of riprap for stabilizing streambanks, relatively little is known about the impacts of such activities. This is due in part to the narrow focus of previous impact studies, but is also attributable to the complexities of stream and riparian ecosystems. The interrelationships among the physical, chemical, biological, and socio/economic characteristics of these systems are not well understood, so a full accounting of potential impacts from fill projects involving riprap is yet to be formulated. However, public interest reviews and compliance with the guidelines for projects using riprap as fill require an objective and thorough investigation of impacts.

Summary of the Literature

The annotated bibliography to this report contains 103 citations addressing the impacts of riprap placed in a stream environment. A majority of these publications deal with the impacts of riprap upon habitat for fish species and, more specifically, for certain life stages of salmonids. Despite the limited focus of these previous efforts, there is no consensus on the impacts of riprap upon habitat for fish and other aquatic organisms, and the existing publications present conflicting evidence of the nature and degree of impacts.

Table 1 summarizes the findings presented in the literature with respect to the impacts of riprap upon aquatic organisms. Roughly an equivalent number of "adverse," "beneficial," and "no" impacts are cited by the studies. The impacts cited for coldwater fisheries are predominantly adverse, whereas impacts for warmwater organisms are overwhelmingly beneficial. Although a number of variables are involved, this general trend appears to be related to the character of the habitat afforded by the riprap relative to the habitat it replaces and the other habitat in nearby reaches. In most of the warmwater systems studied, coarse hard substrate was very limited, so the addition of riprap provided a habitat niche that was rapidly exploited by a number of species. In contrast, most of the coldwater systems studied had abundant hard substrate, and the riprap replaced some other habitat type (e.g. cut banks, overhanging vegetation, etc.) that may have been limited.

Table 1
Impacts of Riprap Upon Aquatic Organisms Cited in the Literature

	Impact			
Species/Life stage	**Adverse**	**None**	**Benefit**	**Reference**
Juvenile Chinook Salmon		X		California Department of Fish and Game (1983)
	X			Beamer and Henderson (1998)
	X			Michny and Deibel (1986)
	X			U.S. Fish and Wildlife Service (1992)
	X			Roper and Scarnecchia (1994)
Yearling Chinook Salmon		X		Ward et al. (1994)
Winter-Run Chinook Salmon	X			Ecos, Inc. (1991)
Coho Salmon	X			Beamer and Henderson (1998)
			X	House and Boehne (1986)
Juvenile Coho Salmon	X			Knudsen and Dilley (1987)
			X	Shirvell (1990)
Salmonid Habitat		X		Harvey and Watson (1988)
Juvenile Salmonid			X	Lister et al. (1995)

(Continued)

Table 1 (Concluded)

	Impact			
Species/Life stage	**Adverse**	**None**	**Benefit**	**Reference**
Salmon	X			*http://swr.ucsd.edu/fmd/citguide.htm*
	X			Buer et al. (1989)
Juvenile Steelhead Trout	X			Roper and Scarnecchia (1994)
		X		Ward et al. (1994)
	X			Knudsen and Dilley (1987)
			X	Shirvell (1990)
		X		Hamilton (1989)
Juvenile Brown Trout	X			Shuler, Nehring, and Fausch (1994)
Adult Brown Trout	X			Shuler, Nehring, and Fausch (1994)
Rainbow Trout		X		Beamer and Henderson (1998)
		X		Meyer and Griffith (1997)
Juvenile Cutthroat Trout	X			Knudsen and Dilley (1987)
Caddisflies			X	Dardeau, Killgore, and Miller (1995)
Midges			X	Dardeau, Killgore, and Miller (1995)
Mussels			X	Dardeau, Killgore, and Miller (1995)
Lithophils			X	Dardeau, Killgore, and Miller (1995)
Sturgeon			X	Dardeau, Killgore, and Miller (1995)
Paddlefish			X	Dardeau, Killgore, and Miller (1995)
Striped bass			X	Dardeau, Killgore, and Miller (1995)
Walleye			X	Dardeau, Killgore, and Miller (1995)
Blue Sucker			X	Dardeau, Killgore, and Miller (1995)
Flathead Catfish			X	Dardeau, Killgore, and Miller (1995)
Blue Catfish			X	Dardeau, Killgore, and Miller (1995)
Bluegill			X	Dardeau, Killgore, and Miller (1995)
Brook Silverside			X	Dardeau, Killgore, and Miller (1995)
Freshwater Drum			X	Dardeau, Killgore, and Miller (1995)
Larval Fishes	X			Li, Schreck, and Tubb (1984)

Several inconsistencies are evident in the literature. For example, of six authors studying the impacts of riprap upon juvenile steelhead trout, two concluded the impacts were adverse, two that they were beneficial, and two deemed the riprap to have no material impact upon habitat. Similarly inconsistent findings are evident for a number of the species studied. The different conclusions are likely attributable to several factors:

a. Differences in the physical character of the systems studied.

b. Differences in the study methods employed.

c. Differences in seasons studied.

d. Different preferences of life stages or subpopulations.

e. Influence from other species.

f. Bias.

g. Different size or configuration of the riprap.

h. Differences in the scale of the projects.

i. Different project ages.

Each of these factors influences the overall impact of riprap upon habitat for aquatic organisms, so study results tend to be highly empirical and should be extrapolated to other situations only with care. A thorough investigation of potential impacts from proposed riprap projects should include an assessment of the impacts cited in the literature, but must also include many factors in addition to the habitat impacts. Foremost among these are the potential impacts of the proposed work upon the processes and conditions that create and maintain the habitat, and that characterize the ecosystem.

Impacts Based Upon Function

Although their specific characteristics vary both spatially and temporally, all rivers support common *functions* – the physical, chemical, and biological components and processes that interact to form and maintain streams and riparian zones. The basic functions that rivers support have been divided into five categories:

a. Evolution through morphologic processes.

b. Maintenance of hydrologic balance.

c. Continuity of sediment processes.

d. Provision of habitat.

e. Maintenance of chemical processes and pathways.

Within each of these categories, three key functions have been identified (Table 2). It is important to note that not all functions will be of equal importance in every river, so interpretation of this framework will be required for each situation. In addition, other equally important functions may be identified for certain situations.

Table 2
Summary of Primary Functions

Morphologic Evolution	Hydrologic Balance	Sediment Continuity	Habitat Provision	Chemical Process & Pathways
Stream Evolution Processes	Surface Water Storage Processes (short & long-term)	Full Sedimentation Processes	Biological Communities and Processes	Water and Soil Quality Processes
Energy Processes	Surface/Subsurface Water Exchange Processes	Substrate and Structural Processes	Necessary Habitats for all Life Cycles	Chemical Processes and Nutrient Cycles
Riparian Succession	Hydrodynamic Character	Quality and Quantity of Sediments	Trophic Structures and Pathways	Landscape Pathways and Processes

The conditions and character of each river system, reach, site, or riparian corridor are a consequence of these functions, so the potential impacts to each should be evaluated when reviewing permit applications. It is helpful to determine which functions are currently limiting, are functioning inappropriately, or are acting as stressors, etc. to the system, because an impact may be either adverse or desirable, depending upon whether the change results in the degradation or the restoration of necessary functions or conditions. In evaluating relevant functions, it is also important to remain cognizant of the interrelated nature of the functions, namely that several functions have similar indicators and direct measures, and impacts to one are not necessarily independent of all others.

Streambank stabilization affects many of the structural characteristics and functions of a stream. The basic purpose of any stabilization project is to interrupt erosion processes where they are deemed to conflict with social needs or ecological requirements. These efforts also interrupt or affect other processes and alter the physical environment. Because of the strong interrelations among the structural components and functions of a stream/riparian system, a number of secondary and tertiary impacts are associated with bank stabilization measures.

Knowledge of the direct and ancillary impacts of stabilization can be used, for example, to select measures and develop a design that restores or enhances the structure or function of a degraded ecosystem. For example, erosion that results in the widening of a stream reach to the degree that sediment continuity, bed sediment character, and local hydrodynamics are adversely impacted can be compensated by stabilization measures that narrow the reach width to one that provides for the proper functioning of these conditions. If the stabilization measure also restores critical riparian and aquatic habitat, so much the better. But the selected measure may still impact other important processes such as channel evolution, riparian succession, and landscape pathways.

Few alterations to the structure or function of the environment are universally adverse or universally beneficial. Most measures benefit some components of the ecosystem at the expense of others. Thus, regulatory decisions must seek to optimize upon the likely outcomes by maximizing benefits and minimizing adverse impacts. This may involve “weighting” the functions, or considering them in the context of both short- and long-term impact.

The following sections present an overview of likely impacts from common bank stabilization practices. These impacts are based on the review of the materials summarized in the attached bibliography, along with extensive written works reviewed by the author and his experiences in research, design, construction, and monitoring thousands of bank stabilization structures. In this report, the term "impact" denotes a measurable change, without regard for the significance or value of the change. These changes or impacts are, by nature, very site-dependent; thus, generalizations provided herein may run contrary to some observations.

Stabilization measures composed of riprap are divided into four basic categories for presentation in this report. *Armor* techniques include the placement of riprap along the bank face to prevent erosion due to the shear force of the flowing water. *Flow deflection* structures extend outward from the bank, normal or angled to the flow, and function by forcing the higher velocity flows away from the bank for some distance downstream. *Slope stabilization* measures include placing large stone sections at the toe of the bank slope to resist translational or rotational failures. *Energy reduction* measures include a wide array of techniques that reduce the energy gradient of the stream and, thus, its ability to induce erosion.

Impacts on morphologic evolution

Morphologic evolution refers to the natural changes in stream characteristics, energy processes, and riparian succession that occur in healthy stream and riparian ecosystems. Stream lateral migration and riparian succession are necessary processes in maintaining appropriate energy levels in a system. They also promote diversity and ecological vigor by initiating change, which is important to long-term adaptation of ecosystems. Energy flow, predominately in the form of organic carbon, is governed by thermodynamics and aquatic chemical equilibrium. The ability of a stream to convert energy between its potential and kinetic forms through changes in physical features, hydraulic characteristics, and sediment transport processes is important in creating complex habitats generating heat for biochemical reactions, and reoxygenating flows. Stream and riparian management activities often impact this energy gradient. Impacts on morphologic evolution are summarized in Table 3.

Table 3 **Impacts on Morphologic Evolution**	
Category	**Impacts**
General	The only applicable generalization of the impacts of bank stabilization on morphological evolution through a project reach is that all stabilization measures are intended to prevent or reduce lateral stream migration. The extent to which this migration is reduced relative to "normal" bank migration for a particular system defines the degree of this impact.
Armor Techniques	In addition to preventing lateral migration (a form of channel evolution), armor techniques typically impact riparian succession processes. On systems with a high sediment load and where the slope of the revetment face is gentle, sediments may deposit in the interstices of the riprap and some succession processes may proceed, but these may differ substantially from those that would occur in the absence of the revetment. Armor layers of riprap seldom have a significant impact upon energy processes.
Deflection Techniques	Deflection techniques generally have more limited effects than armor structures upon succession processes because the bank between the structures is largely unaffected. However, sediment deposition between structures may lead to the establishment of uncharacteristic riparian complexes. Deflection structures, depending upon their size, can reduce or localize the kinetic energy in a system, leading to other related impacts.
Slope Stabilization Techniques	Slope stabilization techniques, in general, have impacts similar to those for armor techniques. They reduce channel evolution through migration, and can reduce most riparian succession processes unless they incorporate vegetation as a component of the slope stabilization. Even in that instance, large woody debris recruitment may be limited if the stabilization measure persists for a long period of time. Energy impacts are typically minor.
Energy Reduction Techniques	Energy reduction techniques generally reduce velocity, shear stress and stream power, converting kinetic energy to potential energy. Their impacts upon riparian succession processes and channel migration can be less significant than the impacts associated with other stabilization techniques, but energy reduction through the use of dams and weirs can significantly impact these functions as well.

Impacts on hydrologic balance

Stabilization practices can alter the hydrologic balance of a river reach in several ways. Examples include (1) increased storage by changing the resistance characteristics (either form or friction) of the reach or by altering the channel geometry (slope or cross section); (2) modifying surface/subsurface water exchange by creating a barrier to flow; and (3) modifying the hydrodynamic character by altering flow fields or through the creation of backwater conditions. These changes can be direct (e.g., adding a weir to change channel slope), or indirect (e.g., structures that may cause a sorting of bed materials, resulting in a coarser surface fraction with higher resistance). Variables that influence stabilization impacts upon hydrologic balance include 1) the materials (affect resistance, turbulence and porosity), 2) structure geometry and location (affect slope, degree of expansion or contraction, flow convergence or separation, and secondary currents), and 3) structure type. Impacts on hydrologic balance are summarized in Table 4.

Table 4 Impacts on Hydrologic Balance	
Category	**Impacts**
General	No generalization can be made on the impacts of bank stabilization using riprap on the hydrologic balance of a stream reach.
Armor Techniques	Riprap armor, in general, has little local or cumulative effect on water storage or exchange processes, and its impact upon hydrodynamics is generally associated with change in resistance. Exceptions may occur when the measure requires an alteration to the channel cross-sectional area. Impacts from resistance or cross section changes can be readily quantified through the application of the de Saint Venant Equations and resistance techniques. Expansions and contractions of less than 10 percent generally result in negligible impacts. Impacts from changes to resistance, which depend on the magnitude and length of the change, are greatest for streams with a width/depth ratio less than 20.
Deflection Techniques	Deflectors, which create form roughness and reduce the cross-sectional area of the channel, have the potential to increase water surface elevations, generate local scour, concentrate flows and generate backwater due to form roughness, impacting hydrodynamics and storage. Unfortunately, techniques to quantify these impacts are generally lacking. The impacts depend on the flow condition, character of the channel, and geometry of the deflector. Any deflector field that reduces channel width by more than 15 percent or cross section area more than 10 percent should be carefully reviewed.
Slope Stabilization Techniques	The impacts from slope stabilization techniques upon storage, water exchange, and hydrodynamics are similar to those for armoring techniques. Slope stabilization often employs vegetation, which can increase resistance relative to riprap.
Energy Reduction Techniques	Energy reduction techniques reduce kinetic energy, which is usually converted to potential energy in the form of increased water surface elevation. This increases storage, and generally reduces velocities in the backwater zone. During low-flow periods, the exchange of water between the surface and shallow groundwater may increase. Methods to quantify impacts to water surface elevations and velocities are straightforward, and generally consist of backwater analyses. Techniques to predict the impacts upon exchange can be complex, but this issue is typically of concern only for dams and very large weir structures.

Impacts on sediments

All stabilization structures and measures impact sedimentation processes. They reduce or eliminate sediment yield and tend to generate local scour, usually at the toe or immediately downstream. Sediment sorting and armoring tends to increase in stabilized reaches. Measures can affect local transport capacity by affecting resistance or channel geometry. The primary variables that influence sedimentation processes are the sediment yield, sediment characteristics, and the effects of the stabilization measure on velocity, stream power, and shear stress. Algorithms for computing erosion, deposition, and scour are often inaccurate and of limited value in assessing the true impacts and localized nature of these processes associated with bank stabilization. Impacts on sediments are summarized in Table 5.

Table 5 Impacts on Sediments	
Category	**Impacts**
General	All bank stabilization measures at least temporarily change sediment yield characteristics of a channel. Most cause local scour and many induce sediment deposition. These impacts tend to be temporary, though their results may persist for long periods of time, particularly in streams with armored beds and few tributaries.
Armor Techniques	Armoring techniques generally reduce local bank erosion but induce local scour. Scour usually occurs at the toe of the armor structure and extends into the stream about two to three times the scour depth. Algorithms to compute scour and sorting are notoriously poor, but provide some means of estimating the magnitude of the impacts. Armor techniques that use materials with high resistance values can also induce local sediment deposition, usually on and within the armor material.
Deflection Techniques	Flow deflection structures reduce sediment yield from the protected bank, and also alter the flow field, which, in turn, generates zones where both scour and deposition occur in close proximity. The overall impact on scour, deposition, and sediment movement varies greatly with the channel conditions and structure configuration, and the impacts of these structures on sediment processes and character require case-specific analyses.
Slope Stabilization Techniques	The impacts of slope stabilization measures on sediment processes and character are generally the same as those for armor techniques, and the differences are generally associated with different resistance values.
Energy Reduction Techniques	Techniques used to reduce energy within a stream have a significant impact on sediment transport, scour, and deposition. Grade control measures create backwater, increasing upstream depth and reducing velocity. Sediment transport capacity is reduced, and upstream stream reaches often have finer bed materials than those found in adjacent reaches, while substrates in downstream scour pools are generally coarser. Secondary channels blocked with chute closures may become backwater zones or wetlands, trapping fine sediments during flood events. Flows in the main channel may deepen, with a corresponding coarsening of the bed material and corresponding increase in sediment transport.

Impacts on habitat

All stabilization measures affect the local habitat conditions in a reach. Riprap provides a substrate that generally differs from the parent material of the channel boundary, so offers a different habitat condition. In addition, the stabilization structure may alter the channel geometry, flow field, riparian vegetation conditions, or a host of other habitat elements. The net effect of these changes varies by species, life stage, season, flow condition, age, and the extent of coverage or structure size. Riprap can create preferential habitat for some organisms at the expense of others, and can upset one or more entire guilds or trophic levels in the system. Impacts on habitat are summarized in Table 6. The literature identified in the annotated bibliography presents a more detailed discussion of specific habitat impacts.

Table 6 Impacts on Habitat Provision	
Category	**Impacts**
General	Bank stabilization measures directly affect habitat by altering the character of the substrate and riparian/aquatic associations. Indirect impacts are usually related to alterations in the flow field, shifts in population dynamics, and pathway modifications.
Armor Techniques	Armor techniques utilizing riprap favor species that use interstitial voids of the rocks for shelter or cover. This can, in turn, result in population shifts, changes in predation, and other biological community impacts. The addition of riprap usually results in an increase in macroinvertebrate biomass and density. Most revetments result in a reduction of streamside vegetation, so riparian flora and fauna are often adversely impacted.
Deflection Techniques	Deflection techniques generally have only limited effects on habitat for riparian flora and fauna, and the interstices of the stone are not generally used to the same degree as are those in revetments. Macroinvertebrate colonization is comparable to that for stone in armor layers. The predominant influence of deflection structures on habitat is related to the diverse patterns of scour and deposition located near the deflector fields.
Slope Stabilization Techniques	The habitat impacts associated with slope stabilization techniques are similar to those for revetments, except that those measures that include vegetation as a key component of the slope stabilization generally have lower impacts on riparian flora and fauna than do revetments. Migration reduction may eliminate island habitats.
Energy Reduction Techniques	Energy reduction techniques can significantly affect habitat. Weir structures generate backwater conditions that alter the flow field, promote fine sediment deposition, increase flow depth, increase the wetted perimeter of the channel, and alter the adjacent riparian community composition. Immediately downstream of these structures, deep but concentrated scour holes typically form, creating habitat niches with deep pools and coarse substrates. Organisms often concentrate in these areas – leading to increased stress and competition. Other energy reduction measures such as channel blocks can accelerate sedimentation processes and eliminate backwater rearing areas.

Impacts on chemical and biological processes

Stream channels and their associated riparian zones help maintain soil and water quality and support important chemical processes and nutrient cycles necessary to perpetuate the long-term health of the physical and biological properties of these areas. Stream and riparian systems occupy unique landscape positions that are critical to the survival of many plant and animal species, and provide longitudinal connectivity that allows for biotic and abiotic energy pathways that link ecological processes and communities. They can also serve as important barriers, and buffers to plant and animal migration. Finally, these ecologically diverse areas often provide critical source and sink areas for maintaining population equilibrium of some plant and animal species, especially during large-scale disturbances that affect large portions of habitat. Stabilization measures generally affect these functions only indirectly. Impacts on chemical processes and pathways are summarized in Table 7.

Table 7
Impacts on Chemical Processes and Pathways

Category	Impacts
General	No generalizations can be made regarding the impacts of riprap upon soil and water quality, nutrient cycling, and the provision of pathways.
Armor Techniques	Revetments constructed of riprap generally have only minor impacts upon water quality. Long reaches of continuous riprap armor can increase stream temperatures due to solar radiation, and can diminish nutrient loading because of the elimination of riparian vegetation, but these impacts are likewise generally minor. Large amounts of limestone used as riprap can raise the pH of a stream, but such increases are also generally very slight. Revetments do, however, often serve as a barrier between the aquatic and terrestrial ecosystem, restricting biotic movement between these zones and potentially increasing predation.
Deflection Techniques	Flow deflection structures constructed of riprap generally have no influence upon soil quality or nutrient dynamics. When placed in a configuration that results in the formation of a deep thalweg, however, they can alter the low-flow pathway along the stream channel and can serve to reduce temperatures in the stream because of the increased depth and velocity.
Slope Stabilization Techniques	The impacts of slope stabilization measures upon chemical processes and pathways are essentially the same as those for an armor layer, except nutrient dynamics are less affected in slope stabilization projects when vegetation is used to stabilize the upper slopes.
Energy Reduction Techniques	Energy reduction techniques such as weirs, closures, and vanes can impact several important chemical processes and pathways. Because these measures often decrease velocity, the potential for elevated stream temperatures and reduced oxygen levels exists, particularly for low gradient systems. Increases in surface area and wetted perimeter provide more soil/water and air/water contact, so chemical processes that occur at these interfaces often increase. Weir structures often present a barrier to biotic movement along the channel, and can affect the formation and breakup of ice cover.

3 Avoidance and Minimization of Impacts

Numerous large- and small-scale negative ecological impacts are associated with riprap bank stabilization structures, and construction of structures may cause severe damage to riparian and instream habitats. Alternatives to stabilization with structures using riprap may be available, and should be evaluated. Design features can often be incorporated into riprap structures that will minimize the impacts to the functions listed in the previous section, and steps may be taken to minimize impacts from construction.

Despite all evidence to the contrary, the perception persists that ecologically healthy streams and riparian corridors are stable. In truth, dynamic processes such as erosion, deposition, flooding, and drought occur in healthy streams, and are critical for maintaining pathways and establishing new habitats. Even in *pristine* systems, it is common to find that 10 to 50 percent of the banks are actively eroding, and the process of erosion is important to the ecological health of most systems (Figure 1). Thus, the first consideration in any permit application review involving the use of riprap should be the necessity of providing any erosion control.

Most streambank stabilization efforts are intended to protect infrastructure or other important investments, and deference must be given to these concerns when weighing public interest.

Successful streambank stabilization is based upon more than an understanding of the problem and the identification of techniques capable of addressing the problem. It is also based on understanding the interaction of the problem and proposed solutions with other ecosystem components, both locally and beyond the project's boundaries, and over varied temporal scales.

Figure 1. Some erosion is necessary for proper ecological function and the creation of new habitats such as nesting sites and spawning gravels

Comparison of Techniques

The selected technique should be the one that successfully stabilizes the system with the minimum impact to the functions listed in the preceding section of this report. To be successful, methods used to control erosion must address the underlying cause of the bank loss. Banks fail in one of four ways:

a. Hydraulic forces remove erodible bed or bank material.

b. Geotechnical instabilities result in bank failures.

c. Mechanical actions cause a reduction in the strength of the bank.

d. A combination of the above factors causes failure.

Fischenich and Allen (2000) present details of each of these mechanisms of bank loss, and list appropriate stabilization measures for each.

Table 8 summarizes the relative impacts of bank stabilization techniques upon each of the 15 functions. Among categories of stabilization measures, a clear distinction can be made only for the energy reduction techniques, which have the greatest impact on the full range of ecosystem functions. These are the only suitable techniques to address erosion caused by channel incision, but for other causal mechanisms, techniques from the other categories may be preferable.

Table 8 suggests that stabilization efforts generally have a greater impact on morphological evolution, sediment continuity, and habitat than on hydrologic balance and chemical processes. Moreover, the greatest impacts are likely to be associated with channel evolution, riparian succession, and sedimentation processes, so these should be a focal point of any assessment.

Within each of the stabilization categories, a number of different techniques can be employed. For example, a bank can be effectively armored using a revetment made of riprap, concrete, pavement blocks, rubble, or other material, or it can be armored with vegetation, erosion control fabrics, or other means. Many of the impacts associated with each category are independent of the specific technique. For example, ALL armor techniques affect stream evolution, energy processes, surface water storage, and hydrodynamic character in essentially the same manner. In most instances, the differences among the techniques relate to the materials and design details, rather than to the overall performance of the structure.

Thus, the use of riprap as a *material* should be assessed in addition to an evaluation of the overall structure type. Differences in material type primarily affect habitat, but can also influence groundwater exchange, movement of organisms, and many of the chemical and nutrient processes. The ramifications to habitat of adding riprap are often mixed – benefiting some species at the expense of others. The impacts to habitat and to other functions from the use of riprap as a material, and as a function of the characteristics of the structure itself, are addressed in the following section. The relative impacts of erosion control methods on stream and riparian functions are compared in Table 8. A variety of armor techniques are shown in Figure 2.

Table 8
Relative Impact of Erosion Control Methods on Stream and Riparian Functions (Scaled 1 to 10 with 1 Representing the Most Severe Impact)

Function	Armor Techniques	Flow Deflection	Slope Stabilization	Energy Reduction	Average	Rank
Morphologic Evolution						
Stream Evolution Processes	3	6	3	7	4.75	1
Energy Processes	9	6	9	4	7.00	9
Riparian Succession	3	6	4	6	4.75	2
Hydrologic Balance						
Surface Water Storage Processes	10	8	10	5	8.25	14
Surface/Subsurface Water Exchange	10	10	10	7	9.25	15
Hydrodynamic Character	10	7	10	4	7.75	12
Sediment Continuity						
Full Sedimentation Processes	5	5	5	4	4.75	3
Substrate and Structural Processes	8	5	7	5	6.25	6
Quality and Quantity of Sediments	7	7	7	6	6.75	8
Habitat Provision						
Biological Communities and Processes	6	5	7	5	5.75	5
Necessary Habitats for all Life Cycles	6	5	6	5	5.50	4
Trophic Structures and Pathways	8	9	8	6	7.75	13
Chemical Processes &Pathways						
Water and Soil Quality Processes	8	9	7	5	7.25	11
Chemical Processes & Nutrient Cycles	7	9	7	5	7.00	10
Landscape Pathways and Processes	4	9	5	9	6.75	7
Average	6.9	7.1	7.0	5.5		
Rank	2	4	3	1		

Figure 2. Impacts from each of these armor techniques are largely the same - most of the differences are associated with the direct habitat afforded by each material

Stone Size

The size of the stone used in riprap revetments or other riprap structures must meet certain requirements for stability, or it will be susceptible to failure. However, the gradation and size of the stones can influence the local habitat by virtue of the sizes of the interstitial spaces. In some situations, the spaces provided by large or poorly graded stone may provide greater habitat than a riprap sized strictly for the design hydraulic condition.

The size of the stone used in a riprap mix is determined by the stream's energy environment. Wave energy and boat wakes sometimes dictate this size, but it is usually determined on the basis of the stream velocity and depth at the design discharge. The design condition should represent the most adverse condition likely to occur on the stream, but this is not typically the largest flood. Generally, some intermediate discharge in the 2- to 10-year return frequency exerts the greatest force against riprap and is selected as the design discharge.

Stone size and thickness should be sufficient to withstand conditions during this design discharge, and may include some factor of safety. A failed riprap structure is generally more environmentally damaging than one that performs its stabilization function properly, so it is important that the riprap be properly sized. Guidance for riprap in streamflow applications is found in EM-1110-2-1601, "Hydraulic Design of Flood Control Channels," and the equation for determining stone size is:

$$D_{30} = S_f C_s C_v C_T d \left[\left(\frac{g_w}{g_s - g_w} \right)^{\frac{1}{2}} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5}$$

where

D_{30} = riprap size of which 30 percent (by weight) is finer, m
S_f = safety factor, unitless
C_s = stability coefficient for incipient failure, unitless
C_v = vertical velocity distribution coefficient, unitless
C_T = blanket thickness coefficient, unitless
D = local depth of flow, m
g_w = unit weight of water, N/m^3
g_s = unit weight of stone, N/m^3
V = local depth-averaged velocity, m/s
g = gravitational constant, m/s^2
K_1 = side slope correction factor, unitless

Riprap thickness for most streambank protection projects is the greater of $1.0D_{100}$(max) or $1.5D_{50}$(max) and the blanket thickness coefficient (C_T) can be taken as 1.0. For riprap of this thickness and having a uniformity coefficient (D_{85}/D_{15}) between 1.7 and 5.2, the stability coefficient for incipient failure (C_s) can be estimated as:

C_s = 0.30 for angular rock
C_s = 0.375 for rounded rock

The value for the vertical velocity distribution coefficient (C_v) should be:

C_v = 1.0 for straight channels or inside of bends
C_v = 1.25 downstream of concrete channels
C_v = 1.25 at end of dikes
C_v = 1.283 - 0.2log(R/W) for outside of bends (or 1.0 for R/W > 26)

where:

R = centerline radius of bend, m
W = water surface width at upstream end of bend, m

For bank protection, $V = V_{SS}$ where V_{SS} is the depth-averaged velocity at 20 percent of the slope length up from the toe. A minimum safety factor (S_f) of 1.1 should be used. Recommended side slope correction factors (K_1) based upon slope are:

Slope	1V:1.5H	1V:2H	1V:3H	1V:4H or flatter
K_1	0.71	0.88	0.98	1.0

Revetment Dimensions

The dimensions of revetments should be sufficient to provide the necessary degree of protection without overkill. The longitudinal extent of protection required for a particular bank protection scheme is highly dependent on local site conditions. In general, the revetment should be continuous for a distance greater than the length that is impacted by channel-flow forces severe enough to cause dislodging and/or transport of bank material. Although this is a vague criterion, it demands serious consideration. A common criterion suggests an upstream distance of 1.0 channel width and a downstream distance of 1.5 channel widths from the area subject to erosion, but these values must be adjusted to adapt to the conditions at each site.

The design height of a riprap installation should be set at the minimum necessary elevation, plus some allowance for freeboard. The "necessary" elevation depends upon the energy of the stream, the size of the riprap, the channel planform, and the bank angle. In general, the force exerted upon riprap by the flow decreases almost linearly from its maximum near the bed to a value of zero at the water surface. Most stabilization projects use riprap up to an elevation much higher than is needed to afford adequate stabilization (Figure 3). Although barren soils are easily eroded, a simple cover of vegetation is usually adequate to protect against shear stresses up to about 2 psf. This equates to a depth of more than 6 ft below the water surface on a stream with a 0.5-percent slope. Freeboard is provided to ensure the desired degree of protection considering uncertainties. The amount of freeboard cannot be fixed by a single, widely applicable formula but, rather, depends upon the degree of analytical certainty and acceptable risk.

Figure 3. Common problems include setting the riprap elevation higher than needed and not extending the protection far enough downstream

The undermining of revetment toe protection has been identified as one of the primary mechanisms of riprap revetment failure. In the design of bank protection, estimates of the depth of scour are needed so that the protective layer is placed sufficiently low in the streambed to prevent undermining. The ultimate depth of scour must consider channel degradation as well as natural scour and fill processes.

When designing a riprap section to stabilize a streambank, the designer accounts for scour in one of two ways: 1) by excavation to the maximum scour depth and placing the stone section to this elevation, or 2) by increasing the volume of material in the toe section to provide a launching apron that will fill and armor the scour hole. Preference should usually be given to option (2) because of ease of construction and lower cost, and because of environmental impacts associated with excavation of the streambed.

Typical riprap bank stabilization structures are very uniform and lack the irregularities needed to provide velocity refugia for fishes or other aquatic organisms. There are, however, many design features that can be incorporated into riprap structures to improve habitat value, including the following:

a. Using larger-than-normal stone to increase size of interstitial spaces and thus increase amount of velocity refugia and cover for fishes.

b. Adding spur dikes to the structure. These features are built perpendicular to current extending from the toe toward the channel (Figure 4).

c. Adding fish groins (i.e., ridges of riprap running from the top bank to the toe of the structure) (Shields et al. 1995).

d. Incorporating indentations into the riprap structure.

e. Placing large boulders (1 to 1.5 m in diameter) along the toe of the structure.

f. Filling interstitial spaces with gravel so that the structure can serve as spawning habitat for salmonid fishes.

These features, except the last one, are designed to maximize eddies and velocity refuges for fishes and other aquatic organisms. However, they also have the potential to increase flow resistance and trap ice and debris, and thus reduce channel capacity and increase flood hazard of a stream.

Deflection Structure Design

Flow deflection structures extend into the stream channel, and redirect part of the flow so that hydraulic forces at the channel boundary are reduced to a non-erosive level. They include a variety of measures that differ somewhat in configuration and function and fall under names such as: groins, dikes, retards, bendway weirs, and vanes.

Figure 4. Incorporating irregular alignments, features such as spurs, and other habitat measures into a revetment can significantly improve habitat benefits

Although channel capacity at high flow is decreased initially with these structures, the channel will usually adjust by forming a deeper, though narrower, cross section and the ultimate effect may even be an increase in capacity. However, the extent of the adjustment cannot always be reliably predicted, even with physical or numerical models. Dikes and retards may be a safety hazard if the stream is used for recreation, and the esthetics often leave much to be desired, although vegetative growth lessens the impact in most regions.

Little or no bank preparation is involved for deflection structures. This reduces cost and riparian environmental impacts, simplifies the acquisition of rights-of-way, eliminates material disposal problems, and usually allows existing overbank drainage patterns to remain undisturbed. Existing channel alignment and geometry can be modified, although the changes may not always be beneficial or predictable. Indirect approaches usually increase geotechnical bank stability by causing deposition at the bank toe, although this process is not immediate enough or positive enough in all cases.

These structures offer the opportunity for incorporating a wide variety of environmental features. They can be designed to generate scour holes and may thus improve aquatic and terrestrial habitat by increasing diversity (Figure 5), although sometimes at the expense of shallow-water habitat. Conversely, they can be designed to trap sediments and create shallow-water areas near the streambank. In arid areas, the reduction of water surface area during low flows decreases evaporation, which is usually considered a benefit.

Figure 5. Flow deflection structures can create diverse habitats

An incidental effect of these two techniques might be to increase energy loss in bends at low flow, through both the modification of channel shape and the roughness introduced by the structures themselves. This would be beneficial on many streams, especially channelized ones that have suffered a lowering of flowlines with detrimental effects on aquatic habitat, riverside facilities, and the water table. A bend would in effect act as a very long grade control structure, without interfering with the natural flow of the stream, or if the structures are submerged below navigation depth, without interfering with navigation.

The principal design considerations for flow deflection structures are the structure length, height, orientation (angle to the bank), spacing and the type of material used for its construction. Unfortunately, little guidance is available for most of these parameters. The optimum height of flow deflection structures depends on the objectives of the project, the nature of the erosion at the site and the general channel geometry. Structures intended to generate a low-flow channel, disrupt secondary currents, protect against toe erosion, or placed along a straight reach generally need not be placed high above the bed of the stream. Many designers try to match the relative elevations of natural point bar features under these circumstances. On tight bends, or where the erosion occurs along the entire bank face, the structures generally need to be higher. They are commonly constructed with a top that slopes from nearly the top of the bank to only a fraction of the flow depth (about 20 percent) at the toe. In cases where impacts to the water surface elevation during flood flows are a concern, a balance between the structure length and height must be sought. Sand and gravel-bed streams that scour and adjust to the placement of deflectors can generally accommodate a flow blockage of only about 15 percent without experiencing impacts to the water surface profile.

Structure length is almost always determined with the objective of providing a desirable flowline for the thalweg and bank. When the structures are intended to trap sediments and promote the development of bars, natural bars on the stream can be used as a guide to help determine the necessary structure length. Structure lengths exceeding 30 percent of the channel width generally require more detailed analyses.

Spacing of deflection structures (groins, barbs, hardpoints) is generally based on the length of the structure and the width of the channel. This is one of the few parameters for which acceptable design guidelines exist. Table 9 presents guidelines found in the literature. These guidelines are intended to address the minimum necessary spacing to provide adequate stabilization.

The most contentious issue with respect to flow deflection structures seems to be the appropriate orientation. Some argue that the only effective orientation is upstream (and they may even identify a specific angle), while others point out that for every upstream-angled structure, a dozen have been constructed perpendicular to the flow or angled downstream and have worked effectively for decades. Simply put, this is an intractable issue at this point. Additional research is needed to define the limits of application and to formulate the appropriate guidance.

Incorporation of Vegetation

Live plants can be incorporated into a riprap structure to enhance its habitat and aesthetic value (Figure 6). Live staking (i.e., planting live woody vegetation) of the riprap interstices is common, and root wads can be incorporated into a riprap structure. The woody vegetation enhances the habitat value of the structure, and as an added benefit, it can also increase bank stability and reduce chances of structure failure. In areas where aesthetics are especially important, the stone above the normal high water level can be covered with soil and planted in grasses.

Table 9
Recommended Groin Spacing (S) as a Function of Groin Length (L) and Stream Width (B) (from Fischenich and Allen (2000))

Author	Spacing S/L	Spacing S/B	Type of Bank	Remarks
United Nations(1953)	1		Concave	General practice
	2-2.5		Convex	General practice
Ahmad (1951)	4.29		Straight	
	<2.5		Curves	
Joglekar (1971)	2~2.5			Upstream groins
U.S. Army (1984a)	2			Mississippi River
Mathes (1956)	1.5			
Strom (1962)	3-5			
Acheson (1968)	3-4			Varies depending on curvature and stream slope
Altunin (1962)	4		Straight	$\alpha > 75°$
	3			for $0.005 \leq I \leq 0.01$
	2			for $I \geq 0.01$
Richardson et al. (1975)	2-6			For bank protection
	3-4			T- head groins for navigation channels
	1.5-2			Deep channel for navigation
Mamak (1956)	2-3	1		
Macura (1966)		0.5	Concave	
		5/4	Convex	
		3/4-1	Straight	
Jansen et al. (1979)		1-2		In constricted rivers
		0.5-1		
Blench et al. (1976)	3.5			
Copeland (1983)	> 3		Concave	
Akantisz et al. (1989)		0.9-1		For ϕ = 45°-50° R/B = 8- 13.5
				For ϕ = 55° R/B = 8
				For ϕ = 55° R/B = 13.5
Kovacs et al. (1976)	1-2			Danube River
Mohan and Agraval (1979)	5			Submerged groins of height one-third the depth
Maza Alvarez (1989)	5.1- 6.3		Straight	Sloping-crested groins for bank
	2.5- 4		Curves	Protection

Figure 6. A combination of riprap in the toe section and woody vegetation on the upper banks often affords the best combination of stabilization and environmental benefits

Cuttings (live stakes) are the most beneficial means of adding vegetation to riprap structures. Cuttings should be prepared from woody plants that root adventitiously (e.g. Salix spp.), obtained from as near the site as possible, and should be free from obvious signs of diseases. To root effectively, cuttings must have good soil/stem contact, which can be difficult to achieve in many riprap structures, and must be placed to a depth sufficient to access groundwater during drought (Figure 7).

Woody cuttings or posts can be placed through many riprap sections using a stinger mounted on an excavator. The stinger creates a pilot hole into which the cutting is inserted. A newly patented procedure, shown in Figure 7, allows the installation through riprap of plants that are encapsulated with soil. This greatly improves survival, as a lack of soil contact within the riprap section is a leading cause of mortality for plants installed with a conventional stinger.

Figure 7. Conventional stinger application (left) and new stinger design (right) that uses soil-encapsulated plants (center) for insertion into riprap sections

Grade Control

Low-head stone weirs (LHSW) are boulder structures that extend across the entire bed of a stream channel, and have an effective height of less than 3 ft (see Figure 8). The structures are primarily used to:

a. Prevent streambed degradation.

b. Reduce the energy slope to control erosion.

c. Create backwater for reliable water surface elevations.

d. Increase aquatic habitat diversity.

Unlike traditional grade control structures, which can adversely impact fish passage, habitat, recreation, and other environmental functions, LHSW are designed to provide stabilization and riffle and pool habitat, reoxygenate water, establish desired substrate characteristics, improve local bank stability, and enhance habitat diversity and visual appeal.

LHSW structures are flexible in that their design characteristics can be altered to achieve specific objectives and to address unique site characteristics. All LHSW structures are designed to remain stable under the full range of anticipated flow conditions, and to permit fish passage.

Figure 8. Low-head stone weir on the North Fork of the White River, Colorado

All LHSW structures obstruct the flow, creating a backwater area upstream that, at least temporarily, serves as a pool and reduces upstream erosion. Most concentrate the energy losses in a scour hole or dissipation basin immediately downstream of the structure. They can be designed to arrest bed degradation, or can have virtually no effect upon this phenomenon. The extent to which these and other characteristics are manifested depends upon the structure dimensions, shape and orientation, material, and the character of the stream.

A common configuration for conventional LHSW structures is a V-shaped structure with the apex pointing upstream, a depressed central region to serve as a low-flow notch, and boulders or riprap as a foundation with the ends keyed well into the banks. The dimensions can be varied for effect, but the structure height is commonly set at about the bankfull elevation at the banks, and is generally 0-2 ft above the bed at the apex.

The V-shape is intended to concentrate flows in the central portion of the channel and minimize the velocity gradient near the banks. The friction generated by the water flowing over the weir crest causes the streamlines to “bend” approximately perpendicular to the crest alignment. This phenomenon only persists for a narrow range of flow depths (generally less than one fifth the structure height), so on an LHSW with a sloping crest, the effect varies with discharge.

Construction

Construction methods used to place revetments should be carefully reviewed to ensure that they do not contribute to environmental degradation. Construction of a typical riprap structure requires extensive use of heavy equipment, and steps should be taken to minimize damage to riparian vegetation and instream habitats. Movement of construction materials should be planned to minimize impacts to riparian vegetation outside the area of interest.

When possible, riprap placement should be conducted so as to preserve existing trees along the bank that are not in danger of windthrow or toppling (Figure 9). Equipment operation on the upper banks should be regulated to minimize soil compaction in the riparian zone, which leads to plant mortality.

The common methods of riprap placement are hand placing; machine placing, such as from a skip, dragline, or some form of bucket; and dumping from trucks and spreading by bulldozer. Hand placement produces the best riprap revetment, but it is the most expensive method except when labor is unusually cheap. Steeper side slopes can be used with hand-placed riprap than with other placing methods. Where steep slopes are unavoidable (when channel widths are constricted by existing bridge openings or other structures, and when rights-of-way are costly), hand placement should be considered. In the machine placement method, sufficiently small increments of stone should be released as close to their final positions as practical. Rehandling or dragging operations to smooth the revetment surface tend to result in segregation and breakage of stone, and can result in a rough revetment surface. Stone should not be dropped from an excessive height as this may result in the same undesirable conditions. Riprap placement by dumping and spreading is the least desirable method, as a large amount of segregation and breakage can occur. In some cases, it may be economical to increase the layer thickness and stone size somewhat to offset the shortcomings of this placement method.

Timing of construction is important when managing for certain impacts. Construction activities should generally be avoided when they will disrupt spawning or nesting activities of nearby sensitive species. Designs that incorporate vegetation may require that the installation occur during the dormant season. Construction activities should generally be abandoned when flows are sufficient to heighten the risk of catastrophic failure.

Figure 9. Careful placement of riprap can allow the preservation of mature trees along the banks and avoid impacts associated with their removal

4 Summary

Riprap usually refers to natural stone (i.e., cobbles, boulders, or broken stone), used for shoreline, streambank, or streambed armoring for erosion control. It has many advantages over other bank protection techniques including:

a. Low cost compared to other bank protection techniques.

b. Relatively simple construction with no special equipment or construction techniques necessary.

c. Easily repaired by adding stone to damaged areas.

d. Vegetation can often grow between the rocks, increasing stability of the bank and improving habitat value of the structure.

e. Riprap structures are flexible and are not impaired or weakened by settling or other minor adjustments.

When stone is readily available, riprap is one of the most economically effective bank stabilization techniques. There are numerous large- and small-scale negative ecological impacts associated with riprap bank stabilization structures, and construction of structures often results in severe damage to riparian and instream habitats.

Conversely, riprap structures also have ecological benefits and can even be used specifically to improve the quality of riverine habitat. Stabilizing stream channels with riprap can reduce sediment loads, improve water quality, and allow reestablishment of riparian vegetation. Stone used in riprap structures provides hard substrate habitat that can be important in some sand bed streams where it might be limited, and spaces between riprap stones provide velocity refuge and cover for aquatic invertebrates and small fishes.

Generally, streams with healthy riparian vegetation communities and the habitat features associated with such communities (shade, relatively stable undercut banks, large woody debris, etc.) will be harmed ecologically from the addition of riprap structures. On the other hand, habitat may be improved on streams where natural hard substrate is rare or lacking. Additionally, systems with excessive erosion due to anthropogenic causes are most likely to benefit ecologically from riprap.

Careful planning can minimize impacts due to construction, and design features can often be incorporated into riprap structures that will improve their habitat value. Although severe ecological impacts are often associated with riprap, it is still one of the most ecologically and aesthetically desirable techniques for erosion control and under certain conditions can be ecologically desirable.

The evidence presented in the literature strongly suggests that the impacts from riprap are very site-specific. The influence of riprap upon habitat even for a specific life stage of a given species depends upon the character of the system in which the riprap is placed, so care should be exercised in extrapolating habitat assessments from one system to another.

5 Annotated Bibliography[1]

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Abt, S. R., Watson, C. C., Fischenich, J. C., and Peters, M. R. (1995). "Bank stabilization and habitat aspects of low-flow channels," *Land & Water, The Journal of the International Erosion Control Association*, January/February 1995, 10-13.
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(This study paired natural and "Hydromodified" [riprap or other human-induced modification] over an 80-mile river length. No riprap or rubble was found in the natural banks, but woody cover was found in some of the hydromodified banks and tended to increase over time following modification. The amount of wood cover had a significant positive correlation with abundance of juvenile Chinook and coho salmon. There was also evidence that rainbow trout show a preference for riprap (but not rubble) and some woody cover, suggesting that they may not be adversely affected by hydromodification as long as the rocks are not too large). 3

[1] Each citation is appended with one or more of the following category numbers that indicate the major thrust of the reference:

1. Methods of construction/engineering aspects.
2. General impact considerations.
3. Salmonid-specific impacts.
4. Salmonid habitat/life requisites.
5. Evaluation of riprap pros and cons.
6. Assessment methods for riprap and riverine habitat.
7. Case studies/literature review.

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(The stone dikes of the lower Mississippi River have been shown to be high-quality environment for macroinvertebrates requiring a hard substrate. Average macroinvertebrate density of the stone dike substrate was 102,485 organisms/m^2 as opposed to an average of 865 organisms/m^2 from natural substrates.) 2,5

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(This study developed a habitat quality index (HQI) for predicting trout standing crop in Wyoming streams. Eroding banks and stream velocity were two of nine habitat attributes that were used to develop a stream rating. Higher percentages of eroding banks and lower water velocities contributed to lower overall ratings. The HQI could be modified for other species.) 4,6

Binns, N. A. (1986). "Stabilizing eroding stream banks in Wyoming," Wyoming Game and Fish Department, Cheyenne, WY.
(This guidebook summarizes some key principles of river mechanics and details bank stabilization methods used on Wyoming streams. The structures and techniques have been successfully used to stabilize eroding banks on a wide variety of Wyoming streams.) 1,7

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(This is an ongoing study that focuses on changes in bank erosion, bank composition, river length, depth, width, sinuosity, and floodplain deposition. Completed studies indicate that bank protection and dams have significantly affected the river habitat; reduction of salmon spawning gravel from freshly eroded banks was of special concern. While both the dams and riprap were implicated, it appears that the major causal effect was reduced erosion rates from lower flows associated with dam construction). 2,3

Burke, T. D., and Robinson, J. W. (1979). "River structure modifications to provide habitat diversity." *A national workshop on mitigating losses of fish and wildlife habitats.* General Technical Report RM-65, Colorado State University, 556-561.
(Discussion of beneficial and detrimental effects of Missouri River Bank Stabilization and Navigation Project and description of structure modifications used to improve fish and wildlife habitats, flood carrying capacity, and control of accretions. Methods include notched, rootless, and low elevation structures.) 1,2,5

Cabalka, D., and Trotti, J. (1996). "The grass-lined channel," *Erosion Control* 3-6, 42-50.
(Grass-lined channels (GLC's) provide a welcome alternative to conventional riprap and cast-in-place concrete linings. GLC's employ vegetation alone or in concert with other materials to cover the subgrade defining the shape of the channel.) 1

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(This study attempted to assess the potential impacts of bank protection measures on spawning, rearing, and food sources of Chinook salmon. Although no statistical difference was found between riprap and cutback areas with respect to total quantity of primary food organisms, the variability of the data was very high. Riprap areas contained only one third the number of salmon as the cutback areas. Additional studies were recommended to assess the impacts of bank protection on spawning gravels.) 3,4,7

Chamberlain, F. W., and Meyers, M. S. (1995). "A case study of the use of riprap in Rochester, Minnesota," *River, coastal and shoreline protection: Erosion control using riprap and armourstone*. John Wiley & Sons Ltd., 591-605.
(This paper presents a case study of the use of riprap for an ongoing flood control project. Primary concerns of safety, cost-effectiveness, reliability, and efficiency are addressed, along with considerations for the environmental and social aspects of the design. Design details and construction procedures are presented and discussed.) 1,2,7

Dardeau, E. A., Jr., Killgore, K. J., Jr., and Miller, A. C. (1995). "Using riprap to create or improve riverine habitat." *River, coastal and shoreline protection: Erosion control using riprap and armourstone.* John Wiley & Sons Ltd., 609-620.
(A general overview of the use of riprap is provided. Benefits include slowing or halting bank erosion thereby allowing recovery of natural vegetation, providing hard substrate for invertebrates [especially in alluvial systems], and increasing fish habitat for various life stages of many different fish species. Significant recommendations include specifying well-graded and sized riprap for each project, avoiding the use of riprap in areas of high sediment deposition, and monitoring the effectiveness of the riprap placement through quantification of changes in population and species composition.) 2,5

Derrick, D. L. (1997). "Harland Creek bank stabilization demonstration project," *Land and Water* 41-5, 22-25.
(Bendway weir, willow post, and longitudinal peaked stone toe protection bank protection methodologies were successfully applied to 14 eroding bends of a stream. Results show satisfactory project performance, with most reaches appearing stable and maturing quickly.) 1

Ecos, Inc. (1991). "Biological data report regarding Sacramento River Bank Protection Project impacts on winter-run chinook salmon," Report to U.S. Army Engineer District, Sacramento (Delivery Order No. 14, DACW05-88-D-0058).
(The purposes of this report were to 1] determine if the project will have adverse impacts on the winter run, 2] describe alternative mitigation measures that could be used in the project, and 3] identify cumulative effects of the project. Preliminary data indicated four to twelve times the density of salmon at natural banks as opposed to revetted banks. Degradation of rearing habitat is probably most attributable to reduced instream and overwater cover associated with loss of riparian vegetation and bank modification. While natural bank conservation is the preferred method for construction site review, it was recognized that an equitable balance between habitat and flood control protection must often be achieved. Six mitigation strategies and five bank protection methods are reviewed). 1,2,3,4,5

Field, J. J. (1997). "Channel modifications along an artificially constructed channel designed to provide salmon habitat." *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision.* 822-827.
(Channel modifications along an artificially relocated reach of Schell Creek near Ferndale, WA damaged 68 percent of the 59 habitat improvement structures placed in the channel. Damage resulted from channel aggradation, bed erosion, and bank scour. All of the damage occurred in the first year during three bank-full or near-bank-full flows. Future attempts at stream location should allot time for the channel to reach a quasi-equilibrium condition before placing habitat structures in the channel. Evaluation of stream enhancement projects is critical if past mistakes are to be avoided in future projects.) 1,2

Fischenich, J. C. (1990). "Cumulative impacts analysis of a midwest fluvial system." *Proceedings, 1990 ASCE Hydraulic Engineering Conference.* San Diego, CA.
(Summarizes an analysis of the cumulative impacts of bank stabilization activities along 314 miles of the Platte River in Nebraska. The study defines limits of bank stabilization actions before causing impacts to sediment transport, bed level, and water surface elevation.) 2

Fischenich, J. C. (1991). "In-stream fish habitat improvement using structural measures: A case study on the South Platte River in Colorado." *Proceedings of the ASCE 24th Annual Water Resources Conference*. St. Paul, MN.
(Presents designs and analyses for eight streambank and instream erosion control measures and their impacts upon aquatic biota.) 1,2

Fischenich, J. C. (1994). "Design criteria for in-stream and streambank environmental features." *Proceedings of the 1994 ASCE National Conference on Hydraulic Engineering*. Buffalo, NY.
(Provides guidelines for the design of erosion control features so that environmental benefits and stability are optimized.) 1

Fischenich, J. C. (2002). "Impacts of riprap on aquatic and riparian ecosystems." In preparation, U.S. Army Engineer Research and Development Center, Wetlands Regulatory Assistance Program, Vicksburg, MS.
(Assesses the impacts of riprap in absolute terms and relative to other stabilization measures. The basis for assessment is a suite of 15 stream functions organized into categories of system dynamics, hydrologic character, sedimentation processes, biological support, and water quality.) 2, 5, 7

Fischenich, J. C., and Theriot, R. (1998). "Integrating new technologies into stream restoration." *Proceedings, Special Meeting of the Society of Ecological Engineering.* Paris, France, August 1998.
(Characterizes the state of knowledge in stream restoration, lists ongoing research efforts in the United States, and identifies future research needs). 7

Fischenich, C. J., and Allen, H. H. (2000). "Protocol for design of stream and floodplain restoration projects." *Association of State Wetland Managers Wetlands '99" Conference.* Annapolis, MD, October 25-27, 1999.
(Proposes a means for evaluating an impacted stream system to ascertain the cause, and a sequence of efforts to establish the appropriate restoration strategy. Focuses on stream instabilities.) 6

Frissell, C. A., Liss, W. J., Warren, C. E., and Hurley, M. D. (1986). "A hierarchical framework for stream habitat classification: Viewing streams in a watershed context," *Environ. Manage.* 10, 199-214.
(A general approach for classifying streams within the watersheds that surround them is articulated in this article. The framework provides a perspective that should allow a more systematic interpretation or description of watershed/individual stream relationships.) 6

Georgia Soil & Water conservation Commission. (1994). "Guidelines for streambank restoration."
(This manual was published to help owners of streamside property understand how to prevent and correct simple streambank erosion problems utilizing live plant material, structural measures, or a combination of both. The techniques described in this manual are intended for small stream systems with uncomplicated erosion problems.) 1,6

Goff, K. (1999). "Designer linings," *Erosion Control* 6-5, 58-65.
(The indiscriminate use of riprap to prevent scour and erosion, the lining of once-vegetated riverbanks with concrete, and too many locks, levees, and dams are perceived by most to be undesirable vestiges of past environmental folly. Therefore, it is time to reassess our traditional approaches to waterway stabilization and develop a systematic approach to the problem of streambank erosion. Combining armor-type protection with softer, bioengineered techniques is proving to be a viable approach to many embankment stabilization problems. In fact, the effectiveness of armoring techniques is improved when vegetation is included in stabilization projects.) 1,5

Gore, J. A., and Shields, F. D., Jr. (1995). "Can large rivers be restored," *BioScience* 45-3, 142-152.
(Although restoration of large rivers to a pristine condition is probably not practical, there is considerable potential for rehabilitation; that is, the partial restoration of riverine habitats and ecosystems. Renewal of physical and biological interactions between the main channel, backwaters, and floodplains is central to the rehabilitation of large rivers.) 7

Gore, J. A., and Hamilton, S. W. (1996). "Comparison of flow-related habitat evaluations downstream of low-head weirs on small and large fluvial ecosystems," *Regulated Rivers: Research & Management* 12, 459-469.
(The focus of within-channel restoration is the placement and construction of instream habitat structures to enhance the capture of organic detritus and aufwuchs, as well as colonization by macroinvertebrate and fish species. These instream structures also modify local hydraulic conditions to present preferred habitat to benthic invertebrates.) 1,2

Gorman, O. T., and Karr, J. R. (1978). "Habitat structure and stream fish communities," *Ecology*, 59-3, 507-515.
(Increasing community and habitat diversity followed stream-order gradients. Natural streams supported fish communities of high species diversity, which were seasonally more stable than the lower-diversity communities of modified streams. After disturbances such as channelization, seasonal peaks in species diversity attain levels typical of undisturbed streams.) 2

Haltiner, J. (1995). "Environmentally sensitive approaches to river channel management." *River, coastal and shoreline protection: Erosion control using riprap and armourstone.* John Wiley & Sons Ltd., 545-556. (Traditional engineering approaches to river channel erosion and flood hazards have focused on single-purpose, structurally intensive solutions such as monolithic riprap or concrete-lined channels, and drop structures. While often successful in reducing erosion, they provide little or no environmental, aesthetic, or recreational value. However, biotechnical approaches integrating riprap or other structural measures with vegetation provide a range of bank and channel stabilization methods consistent with a multi-objective approach.) 1

Hamilton, J. B. (1989). "Response of juvenile steelhead to instream deflectors in a high gradient stream." *Practical approaches to riparian resources management.* R. E. Gresswell, B. A. Barton, and J. L. Kershner, eds. American Fisheries Society, Montana Chapter, Bethesda, Maryland, 149-157. (This study examined the effects in high gradient streams of boulder/rock triangular wing deflectors on juvenile steelhead populations and stream channel characteristics. It was found that population increases did not occur in the high-gradient streams, whereas similar habitat improvements in low-gradient streams had been reported to show population increases. The author includes a literature review showing type of structure, population response, and gradient.) 1,3

Harvey, M. D., and Watson, C. C. (1988). "Effects of bank revetment on Sacramento River, California." Proceedings of the California Riparian Systems Conference Held in Davis, California on September 22-24, 1988: Protection, Management, and Restoration for the 1990's. USDA Forest Service Gen. Tech. Rep. PSW-110, 47-50.
(This study found that revetment of individual bends in the study area did not affect salmonid habitat adversely. It did not prevent the re-entrainment of point bar gravels or cause a coarsening of the point bar sediments. As long as an upstream source of gravel exists, then gravel recruitment from point bars will at least partially mitigate the loss of gravel sources on revetted banks). 3,5

Hemphill, C., Fischenich, J. C., Redigan, J. (1999). "Bioengineered streambank stabilization methods to reduce costs and improve habitat." *ASCE Int. Water Resources Engineering Conference, Seattle, WA*. August 8-11, 1999.
(This paper describes the use of bioengineering techniques on the Sauquoit River in New York. Emphasizes the benefits of selected techniques versus conventional flood channel design and stabilization.) 5,7

Henderson, J. E., and Shields, F. D., Jr. (1984). "Environmental features for streambank protection projects," Technical Report E-84-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
(This report provides guidance for incorporating environmental considerations into streambank protection projects. Each feature is discussed in terms of concept, the purpose or use of the feature, environmental considerations, limitations to use of the feature, performance history, and cost.) 1,7

Henderson, J. E. (1986). "Environmental designs for streambank protection projects," *Water Resources Bulletin* 22-4, 549-558.
(Adverse environmental impacts have been minimized and existing habitat and aesthetics have been enhanced through the development of new, innovative designs or modifications to existing designs and through use of construction and maintenance practices that promote habitat and aesthetics. Vegetation is most effective for bank protection when used in combination with structural components.) 1,2

Henszey, R. J., Wesche, T. A., and Skinner, Q. D. (1989). "Evaluation of the state-of-the-art streambank stabilization," Wyoming Department of Environmental Quality, Cheyenne, WY.
(This report reviews the current literature on streambank stabilization techniques, and compiles a state-of-the-art streambank stabilization bibliography. Classical treatments such as riprap, gabions, and tree revetments are included, but primary emphasis is on the characteristics and requirement of plant species suitable for bank revegetation in the semiarid western United States.) 1,2,5,7

House, R. A., and Boehne, P. L. (1986). "Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon," *North American Journal of Fisheries Management* 6, 38-46.
(Differences between a young-alder stream section logged and cleared of large debris 20 years ago and a mature mixed-conifer section unlogged and containing large amounts of large woody debris were studied. Stream enhancement techniques were used to simulate large woody debris in the logged alder section to try to increase salmonid use. Large woody debris in the channel caused the development of secondary channels, meanders, pools, and undercut banks in the unlogged, mature-conifer stream section. Salmonid biomass was significantly greater in the mature-conifer than the young-alder section prior to stream enhancement. After enhancement, no significant difference was found. The study revealed that structure is most likely a more important factor than shade in governing a stream's capacity for producing salmonids.) 4,5

Inoue, M., and Nakano, S. (1999). "Habitat structure along channel-unit sequences for juvenile salmon: A subunit-based analysis of in-stream landscapes," *Freshwater Biology* 42, 597-608.
(This study examined habitat structure and habitat use by juvenile masu salmon in small streams in Northern Hokkaido, Japan. Results of the study suggest that habitat value should be determined not only by the habitat itself, but also by the characteristics of adjacent habitats. To that end, the use of the habitat by the fish should be studied in the context of the total in-stream landscape.) 4,6

Jackson, W. L., and Van Haveren, B. P. (1984) "Design for a stable channel in coarse alluvium for riparian zone restoration," *Water Resources Bulletin* 20-5, 695-703.
(Geomorphic, hydraulic, and hydrologic principles are applied in the design of a stable stream channel for a badly disturbed portion of Badger Creek, Colorado, and its associated riparian and meadow complexes. Gabion controls are recommended to help reduce the chance of lateral migration of the newly constructed channel. Controls are designed to allow for some vertical adjustment of the channel bed following increased bank stability due to revegetation.) 1

Jungwirth, M., Moog, O., and Muhar, S. (1993). "Effects of river bed restructuring on fish and benthos of a fifth order stream, Melk, Austria," *Regulated Rivers, Research and Management*, xx, 195-204.
(Studies conducted on 15 sections of seven different epipotamal streams established the impact of riverbed structures on fish communities. Reduced spatial heterogeneity due to river straightening resulted in decreasing numbers of fish species, stock density, and biomass. The variance of maximum depths used as a measure of habitat structure showed a highly significant correlation with the number and diversity of fish species.) 2

Karouna, N. (1991). "Stream restoration and bio-engineering techniques." *Restoring our home river: Water quality and habitat in the Anacostia*. College Park, MD.
(This paper is a comprehensive summary of structural methods that can be used to stabilize eroding streambanks and improve aquatic habitat within degraded urban stream systems. Many of the basic techniques were derived from work traditionally associated with the restoration of undeveloped watersheds.) 1

Keown, M. P. (1983). "Stream bank protection guidelines," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
(Streambank protection is a complex subject. There are no engineering manuals available with construction plans for bank protection projects that are guaranteed to work. However, this pamphlet provides general information needed to develop a systematic plan of action for solving a streambank protection problem.) 6

Klingeman, P. C. (1984). "Evaluating hydrologic needs for design of stream habitat modification structures." *Proceedings of the Pacific Northwest Stream Habitat Workshop, Arcata, CA*.
(This paper describes the needs and uses of basic hydrologic, hydraulic, and geomorphic information for designing stream habitat modification structures. Also, common types of stream habitat modification structures are described.) 1,6

Knudsen, E. E., and Dilley, S. J. (1987). "Effects of riprap bank reinforcement on juvenile salmonids in four western Washington streams," *North American Journal of Fisheries Management* 7, 351-356.
(Construction of riprap bank reinforcement, rather than the actual riprap itself, resulted in significant short-term negative effects. These effects increased as the severity of habitat alteration increased, and decreased as stream and fish size increased.) 1,3

Kondolf, G. M. (2000). "Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals," *Restoration Ecology* 8, 48-56.
(Stream restoration projects to improve habitat for anadromous salmonids must be justified on the basis of geomorphology as well as biology. At the watershed scale, the geomorphic setting should be addressed by specifying changes in the flow regime or sediment yield; at the reach scale, geomorphic setting and process should be addressed by indicating the basis for design channel form and dimensions, calculating the frequency of bed mobilization, and assessing existing gravel quality for spawning. Provisions should be made for post-project performance evaluation.) 6

Li, H. W., Schreck, C. B., and Tubb, R. A. (1984). "Comparison of habitats near spur dikes, continuous revetments, and natural banks for larval, juvenile, and adult fishes of the Willamette River," Final Technical Completion Report, Project Number G864-05.
(Natural banks afford the best habitat for resident fishes on the mid-Willamette River because of their structural diversity. Spur dikes contain a greater diversity of habitats than continuous revetments in terms of velocities, depths, and cover. Spur dikes were intermediate between natural banks and revetments for species richness and densities of juvenile and larval fish. The number of species of adult fishes were similar in both spur dikes and continuous revetments, and greater for natural banks.) 4,7

Lisle, T. E. (1986). "Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, Northwestern California," *Geological Society of America Bulletin* 97, 999-1011.
(This study showed how large obstructions and bedrock bends might affect the channel of a gravel-bed stream. The author states that the formation of bars and pools that is inherent in many gravel channels can thus be enhanced by using flow structures set up around large obstructions and bends formed of resistant materials.) 1

Lister, D. B., Beniston, R. J., Kellerhals, R., and Miles, M. (1995) "Rock size affects juvenile salmonid use of stream bank riprap," *River, Coastal and Shoreline Protection* 621-632.
(Assessment of habitat alteration included comparisons of juvenile salmonid densities along banks of large and small riprap, and natural cobble-boulder material. Densities were found to be greater along large riprap than small riprap banks. Placing large boulders along the toe of the bank appeared to increase rearing densities.) 1,4

Long, K. S., Nestler, J. M., Fischenich, J. C. (1997). "Survey of habitat-related channel features and structures in tailwaters," Technical Report EL-97-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
(Summarizes a survey of instream and streambank features placed in tailwater reaches below reservoirs. Focuses on the impacts of the features to velocity and depth.) 2,7

Meyer, K. A., and Griffith, J. S. (1997). "Effects of cobble-boulder substrate configuration on winter residency of juvenile rainbow trout," *North American Journal of Fisheries Management* 17, 77-84.
(Cobble-boulder substrates were arranged in four different configurations to assess winter habitat use by rainbow trout (*Oncorhynchyus mykiss)*. As the configuration was changed to create more concealment cover, the number of fish remaining in the enclosures increased significantly, even though the quantity of substrate remained unchanged. The results demonstrate the importance of the configuration of cobble-boulder substrate in determining its suitability as winter cover for rainbow trout.) 3,4

Michny, R., and Deibel, R. (1986). "Sacramento River Chico Landing to Red Bluff Project juvenile salmon study," Report prepared for U.S. Army Engineer District, Sacramento.
(This study was conducted to determine (1) the effect that rock revetment has on juvenile Chinook salmon, and (2) the usefulness of specific slope and substrate modifications, in lieu of standard revetment, as salmon rearing habitat. Salmon abundance was higher and more stable in the natural bank habitat. The revetted banks had the lowest abundance; the abundance of fish in the rearing bench habitat was higher than revetted areas, but also varied more). 3

Morrow, J. V., Jr., and Fischenich, J. C. (1999). "Habitat requirements for freshwater fish," Technical Note SR-99-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
(With very few exceptions, stream restoration projects will have consequences for fish communities and the user groups associated with those communities. An organism's habitat must contain all the physical, chemical, and biological features needed for that organism to complete its life cycle. For fishes, this may include a variety of parameters such as water temperature regimes, pH, amount and type of cover, substrate type, turbidity, depth, water velocity, inorganic nutrient levels, and accessibility to migration routes. Habitat quality affects health of individual fishes, fish populations, and communities, and changes in habitat will usually result in changes to the species composition of a fish community. This technical note characterizes fish habitat and habitat requirements and preferences. It is designed to help water resource managers who may have little or no training in fishery science to better understand problems associated with freshwater fish habitat.) 2,6

Northcutt, G. (1998). "Hybrid structures turn hard armor green," *Erosion Control*, 5-7, 46-55.
(A new breed of structures blurs the distinction between hard armor and soft vegetative solutions. These hybrid solutions result in landscape features with natural-looking appearances that camouflage the structural integrity engineered into them.) 1

Nunnally, N. R., and Sotir, R. B. (1994). "Soil bioengineering for streambank protection," *Erosion* 1-5, 38-44.
(Streambank protection and stabilization measures work either by reducing the force of flowing water, by increasing the resistance of the bank to erosion, or by some combination of the two. Soil bioengineering systems are natural in appearance; they provide shade, overhanging cover, and organic debris for aquatic ecosystems; and they provide good riparian habitat.) 2,5

Pastorok, R. A., MacDonald, A., Sampson, J. R., Wilber, P., Yozzo, D. J., and Titre, J. P. (1997). "An ecological decision framework for environmental restoration projects," *Ecological Engineering* 9, 89-107.
(Ecosystem restoration projects require planning and monitoring, yet projects completed thus far have been planned on an ad hoc, consensus basis and are virtually ignored after revegetation at the site is complete. A process was developed to integrate a fundamental understanding of ecological principles into the existing project planning framework used by the U. S. Army Corps of Engineers in their growing role in restoration of aquatic habitats, but it should be applied to terrestrial habitats as well.) 6

Roper, B. B., Konnoff, D., Heller, D., and Wieman, K. (1998). "Durability of Pacific Northwest instream structures following floods," *North American Journal of Fisheries Management* 18, 686-693.
(The durability of 3,946 instream structures in 94 streams that had floods with return intervals exceeding 5 years was assessed. Overall structure durability was high. The higher magnitude of flood events resulted in reduced durability. Stream order also affected structure durability.) 6,7

Roper, B. B., and Scarnecchia, D. L. (1994). "Summer distribution of and habitat use by Chinook salmon and steelhead within a major basin of the South Umpqua River, Oregon," *Transactions of the American Fisheries Society*. 123, 298-308.
(Basin-wide summer habitat use by juvenile Chinook salmon and steelhead was determined through a combination of established stream habitat assessment methods. It was suggested that high stream temperatures in the lower reaches, habitat preferences of each species, and the interaction between the two species may have influenced the distribution and abundance of both species. The densities of the species varied substantially over the reaches, suggesting that habitat studies on streams with variable habitat and patchy fish distributions should be conducted over much larger areas of a basin than has typically been the case in past studies.) 4,6

Rosgen, D. L. (1997). “A geomorphological approach to restoration of incised rivers.” *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. 12-29.
(Geomorphologic concepts are described as integrated into incised river restoration projects. A range of restoration design concepts are presented, including returning the stream to its original elevation and reconnecting floodplains, widening the belt width to construct a new channel at the existing elevation, changing stream types, and stabilizing the existing incised channel in place.) 1

Schmetterling, D. A., and Pierce, R. W. (1999). “Success of instream habitat structures after a 50-year flood in Gold Creek, Montana,” *Restoration Ecology* 7-4, 369-375.
(In this study, 66 structures made of natural materials (rock and wood) were constructed that resulted in 61 new pools in an attempt to restore salmonid habitat. Following an estimated 50-year recurrence interval flood, 55 (85 percent) of the structures remained intact and stable.) 1,4

Shields, F. D., Jr. (1991). “Woody vegetation and riprap stability along the Sacramento River mile 84.5-119,” *Water Resources Bulletin* 27-3, 527-536.
(Stability of vegetated and bare riprap revetments along a Sacramento River reach during the flood of record was assessed. Damage rates for revetments supporting woody vegetation tended to be lower than for unvegetated revetments of the same age located on banks of similar curvature.) 6

Shields, F. D., Jr., and Hoover, J. J. (1991). “Effects of channel restabilization on habitat diversity, Twentymile Creek, Mississippi,” *Regulated Rivers: Research & Management* 6, 163-181.
(Twentymile Creek was channelized prior to 1910, in 1938, and in 1966. Straightening and enlargement in 1966 resulted in channel instability, rapid bed degradation, and cross-section enlargement. Grade control structures and various types of streambank protection were constructed along the channel in the early 80's to restore stability. This paper studies the effects of restabilization of Twentymile Creek on aquatic habitats.) 7

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1995) "Rehabilitation of watersheds with incising channels," *Water Resources Bulletin* 31-6, 971-982.
(Rehabilitation measures, which are selected and laid out using a subjective integration of hydraulic and geotechnical stability analyses, include grade controls, bank protection, and small reservoirs. Aquatic habitat studies indicate that stone-protected stilling basins below grade-control weirs and habitats associated with drop popes and stone spur dikes are assets to erosion-damaged streams.) 2,7

Shields, F. D., Jr., Bowie, A. J., and Cooper, C. M. (1995). "Control of streambank erosion due to bed degradation with vegetation and structure," *Water Resources Bulletin* 31-3, 475-489.
(Combinations of vegetation and structure were applied to control streambank erosion along incised stream channels in northwest Mississippi. Tested configurations included eroding banks protected by vegetation alone, vegetation with structural toe protection, vegetation planted on regraded banks, and vegetation planted on regraded banks with toe protection. Designs involving riprap toe protection in the form of a longitudinal dike and woody vegetation appeared to be most cost-effective.) 1,2

Shields, F. D., Jr., Cooper, C. M., and Knight, S. S. (1995). "Experiment in stream restoration," *Journal of Hydraulic Engineering* 121-6, 494-502.
(Aquatic habitats in a deeply incised sand-bed channel were modified by adding stone and planting dormant willow posts. Restoration structures were designed as complements to existing channel stabilization works. Fish numbers tripled, median fish size increased by 50 percent, and the number of species increased from 14 to 19.) 1,2

Shields, F. D., Jr., Cooper, C. M., and Testa, S., III. (1995). "Towards greener riprap: Environmental considerations from microscale to macroscale." *River, coastal and shoreline protection using riprap and armourstone*. John Wiley and Sons, Ltd., 558-573.
(Effects of riprap on riverine fish and macroinvertebrate habitats are strongly related to spatial scale. At the microscale (median stone diameter squared), riprap supports dense, diverse populations of macroinvertebrates that compare favorably to natural conditions. At the mesoscale (square of the channel width), hydraulic conditions created by the riprap can be either beneficial or detrimental to habitat quality; numerous citations support both views. Macroscale (reach) effects of riprap stabilization of the planform on the bed material size and cross-section shape have not been clearly established for all stabilized river systems. Studies were conducted on the Willamette and Sacramento Rivers regarding suggestions that extensive bank protection might reduce the gravel supply enough to impact gravel-spawning species.) 2,3,5,7

Shields, F. D., Jr., and Cooper, C. M. (1997). "Stream habitat restoration using spurs added to stone toe protection," *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. 667-672.
(Longitudinal stone toe is one of the most reliable and economically attractive approaches for stabilizing eroding banks in incised channels. However, aquatic habitat provided by stone toe is inferior to that provided by spur dikes. Results indicated that spur addition resulted in modest increases in base flow, stony bank line, water width and pool habitat availability, but had only local effects on depth.) 1

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1997). "Rehabilitation of warmwater stream ecosystems following channel incision," *Ecological Engineering* 8, 93-116.
(A case study of two streams damaged by channel straightening and incision is presented. One stream was stabilized by using a metal sheetpiling weir and dormant willow post planting, while the other was treated with a stone weir, stone toe bank protection, and willow sprout planting.) 7

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1998). "Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi," *Hydrobiologia* 382, 63-86.
(A study of incised warmwater stream rehabilitation was conducted to develop and demonstrate techniques that would be economically feasible for integration with more orthodox, extensively employed watershed stabilization techniques. During the study, two reaches were modified by adding woody vegetation and stone structure to rehabilitate habitats degraded by erosion and channelization. These experiments suggest that major gains in stream ecosystem rehabilitation can be made through relatively modest but well-designed efforts to modify degraded physical habitats.) 1,2,5

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1998). "Addition of spurs to stone toe protection for warmwater fish habitat rehabilitation," *Journal of the American Water Resources Association* 34-6, 1427-1436.
(Longitudinal stone toe is one of the most reliable and economically attractive approaches for stabilizing eroding banks in incised channels. However, aquatic habitat provided by stone toe is inferior to that provided by spur dikes. Test designs were performed that combined features of stone toe and spurs. Overall results indicated that spur addition resulted in modest increases in base flow stony bank line, water width, and pool habitat availability, but had only local effects on depth.) 1,5

Shirvell, C. S. (1990). "Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) cover habitat under varying streamflows," *Canadian Journal of Fisheries and Aquatic Science* 47, 852-861.
(The effect of abundance and position of rootwads on their function as cover habitat for juvenile salmonids was investigated, primarily in relation to stream flow. Results of the study show that rootwads can provide both shelter and protection simultaneously for fish with different motives. It was suggested that the fish were not selecting positions because of an affinity for the rootwads themselves, but rather for the conditions caused by the rootwads.) 3,4,6

Shuler, S. W., Nehring, R. B., and Fausch, K. D. (1994). "Diel habitat selection by brown trout in the Rio Grande River, Colorado, after placement of boulder structures," *North American Journal of Fisheries Management* 14-1, 99-111.
(Brown trout distribution and microhabitat use were measured in 10 study sections on the Rio Grande River, Colorado, where three types of structures make from large boulders had previously been placed. On average, 65 percent of the adult brown trout and 69 percent of the juvenile brown trout observed were holding positions near structures.) 4

Sotir, R. B., and Nunnally, N. R. (1995). "Use of riprap in soil bioengineering stream bank protection." *River, coastal and shoreline protection: Erosion control using riprap and armourstone*. John Wiley & Sons Ltd., 577-589. (Streambank protection systems that incorporate woody vegetation provide additional benefits over those that do not. Soil bioengineering employs woody vegetation as the major structural component in streambank protection designs. Although in some applications adequate protection against erosion can be provided by vegetation systems alone, most applications require the use of some rock in conjunction with vegetation to prevent damage to the system that would impair its effectiveness or reduce its environmental benefit.) 1,5 *http://www.sotir.com/pubs/publist/riprap/riprap.html*

Sotir, R. B. (1998). "Soil bioengineering takes root," *Civil Engineering* July, 50-53.
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(Abundance of rainbow trout in relation to characteristics of pockets created by boulders was studied in Fall River, southeastern Idaho. Results showed that maximum water depth and pocket surface area were both positive factors affecting trout density.) 4

Thorne, C. R., Reed, S., and Doornkamp, J. C. (1996). "A procedure for assessing river bank erosion problems and solution," R&D Report 28, National Rivers Authority, Almondsbury, Bristol BS12 4UD.
(The purpose of this report is to provide operational level guidance on the management of riverbank erosion problems for individuals concerned with flood defense, land drainage, local drainage, local planning, recreation, conservation, and navigation. Where a structural solution that involves physically protecting the bank is appropriate, there is now a wide range of designs and materials that may be used. These range from hard engineering materials to softer materials and combinations of the two.) 6

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http://swr.ucsd.edu/fmd/citguide.htm

(This link is to A Citizen's Guide to the 4(d) Rule for Threatened Salmon and Steelhead on the West Coast, published by the National Marine Fisheries Service Northwest and Southwest Regions, June 20, 2000. Provides information on compliance with the Endangered Species Act with reference to salmonids. Also provides links for additional information at the Federal and local levels.)

http://www.4sos.org/

(Provides sources of information and links to additional information for stream restoration and salmonid-specific issues. Primarily layman/activist oriented.)

http://www.cityofbellevue.org/utilities/shorezone/potential.htm

(The Utilities Department for the City of Bellevue, Washington published the Final Report on Effects of Shorezone Development - Potential Impacts of Shoreline Development. This particular site discusses the potential impacts of various types of shoreline development. It contains links to fish ecology, conclusions, and the Utilities homepage.)

http://nepa.eh.doe.gov/eis/eis-0265/Table_of_Contents.htm

(This link is to the Table of Contents page for the Bonneville Power Administration Watershed Management Program Final Environmental Impact Statement [DOE/EIS-0265].)

http://www.americanrivers.org/

(The AmericanRivers home page is primarily a layman-oriented site for obtaining information on, and becoming active in, a number of river issues nationwide, including the Columbia and Snake River systems. The "Tools and Additional Links" button provides access to both scientific and popular literature.)

http://www.epa.gov/OWOW/NPS/MMGI/Chapter6/ch6-2a.html

(This is Chapter 6 of the EPA Office of Water manual. This contains information on channelization and channel modification measures, including a discussion of riprap. Also contains links to other areas of interest on non-point source issues.)

http://www.epa.gov/OWOW/NPS/urbanize/report.html

(EPA Office of Water site with information on the hydrologic impacts associated with the urbanization of streams. Provides a literature cited section.)

http://www.state.ak.us/adfg/habitat/geninfo/webpage/liepitz.htm

(Executive summary of "An Assessment of the Cumulative Impacts of Development and Human Uses on Fish Habitat in the Kenai River" by Gary S. Liepitz. The purpose of the study was to identify and evaluate the cumulative impacts of development on Kenai River fish habitat.)

http://www.epa.gov/owow/estuaries/coastlines/spring98/rockbarb.html

(This site provides information from the EPA Office of Water on the use of rock barbs for enhancing fish habitat and water quality in the Tillamook Bay watershed. It provides a good "how-to" discussion of the use and construction of barbs in conjunction with riprap and vegetation. A discussion of pros and cons is provided.)

http://www.critfc.org/handbook/Bibliography.html

(The link is to a bibliography produced by the Columbia River Inter-Tribal Fish Commission. Many titles refer to salmonids, habitat, impacts, riparian and stream enhancements, etc. The home page of the Commission can also be accessed from this site.)

http://www.ijc.org/boards/wqb/hab_summ.html

(Provides extended abstracts for a number of presentations from the Habitat Session of the Practical and Cost-Effective Watershed Management Conference, Livonia, Michigan, May 3, 1996. Streambank stabilization, sediment control, and habitat enhancement are included among the topics.)

REPORT DOCUMENTATION PAGE						*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
April 2003

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Effects of Riprap on Riverine and Riparian Ecosystems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
J. Craig Fischenich

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Environmental Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/EL TR-03-4

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Riprap (graded stone or crushed rock) is the most common material used in the stabilization of streambanks and shorelines. The continued use of this material as fill has been challenged in many locations by resource agencies due to concern for potential environmental impacts. U.S. Army Corps of Engineer Districts currently invest considerable manpower "interacting" with applicants and resource agencies on this issue. These efforts are hampered by a number of factors including inconsistencies in the literature, differences among ecosystems, conflicting agency missions and directives, and insufficient knowledge. Lacking a sound procedure for the objective evaluation of potential impacts and given the ambiguous nature of the literature on the matter, decisions are often clouded by biased judgment.

To address this problem, research was initiated under the Wetlands Regulatory Assistance Program (WRAP) to develop guidelines for the evaluation of the environmental impacts and benefits of riprap. The first step in this research was the formulation of an annotated bibliography of related publications that could serve as a basis for regional and site-specific evaluations, and that characterizes the current state of knowledge on this subject.

(Continued)

15. SUBJECT TERMS

Ecosystem
Riparian ecosystem
Riparian functions
Riprap
Riverine ecosystems
Streambank stabilization

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		60	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

14. (Concluded).

This document presents the results of the literature review. Citations are presented in the following sections, with an annotation summarizing the study findings. In addition to the annotation, each citation is appended with one or more category numbers that indicate the major thrust of the reference, based on the following:

1. Methods of construction/engineering aspects.
2. General impact considerations.
3. Salmonid-specific impacts.
4. Salmonid habitat/life requisites.
5. Evaluation of riprap pros and cons.
6. Assessment methods for riprap and riverine habitat.
7. Case studies/literature review.