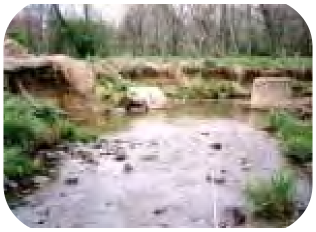
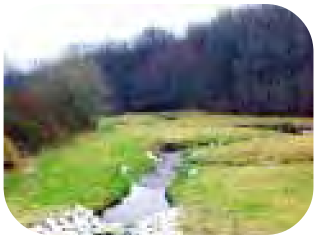
Urban Subwatershed Restoration Manual Series

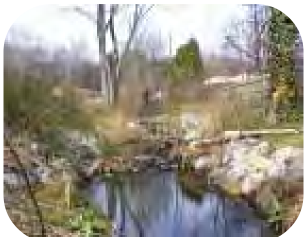
4

Urban Stream Repair Practices

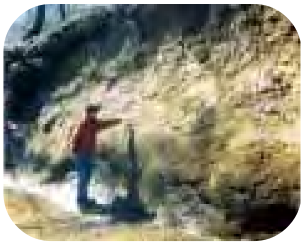
Version 1.0







November 2004



CENTER FOR
WATERSHED
PROTECTION

Manual 4

Urban Subwatershed Restoration Manual No. 4

URBAN STREAM REPAIR PRACTICES

Version 1.0

Prepared by:

Tom Schueler and Ken Brown
Center for Watershed Protection
8390 Main Street
Ellicott City, MD 21043
http://www.cwp.org
http://www.stormwatercenter.net

Prepared for:

Office of Water Management
U.S. Environmental Protection Agency
Washington, D.C.

November 2004

Foreword

The last decade has seen a great deal of interest and application in stream repair practices. Although many manuals and papers have been written on the topic, few have specifically focused on the unique challenges and constraints involved in repairing urban streams. This manual focuses on the methods to assess, design and construct stream repair practices in urban subwatersheds with 10% or more impervious cover typically containing streams from first to third order.

The manual addresses the full range of restoration objectives for urban streams, which can range from simple cleanups to the protection of threatened infrastructure and improved fish passage, geomorphic stability and biological diversity. A key theme of the manual is that subwatershed impervious cover directly or indirectly constrains the quality of urban streams and corridors and needs to be explicitly considered in all aspects of planning, assessment and design. As a result, we need to recognize that while some impairments in urban streams can be repaired, few streams can be fully restored in an ecological sense or possess the qualities they had prior to land development. We therefore use the term repair rather than restore to reflect the modest capability of our current practice to reverse the cumulative effects of watershed development, and to be cautious about over-engineering the natural and sometimes violent process of stream adjustment in urban watersheds.

We would like to acknowledge several individuals who showed us both the potential and limits of urban stream repair in various parts of the country, including: Michael P. Kelly, Civil Engineer, City of Austin, TX; Don Roseboom, formerly with Illinois Water Survey; my former colleague, John Galli, Metropolitan Washington Council of Governments; and many mid-Atlantic practitioners who graciously shared project data in an earlier Center study of stream repair practices. In addition, we want to thank our external reviewers who provided extremely useful comments and insights on a draft version of this manual. External reviewers included Dr. Derek Booth, former Director of the Center for Water and Watershed Studies (University of Washington); Dr. Greg Jennings, Interim Director of the Water Resources Research Institute (North Carolina State University); an anonymous hydraulic engineering expert; Dr. Mike Paul, stream ecologist (Howard University); and Tom Davenport (Region 5) and Robert Goo (Headquarters) of the U.S. Environmental Protection Agency.

The Center staff team that contributed to the manual included Ken Brown (currently of Loiederman Soltesz Associates, Inc.), Tiffany Wright, Paul Sturm, and Ted Brown. Special thanks are extended to Tiffany Wright for her able assistance in editing, proofing and helping producing this manual and to Karen Cappiella for her artwork. This manual was developed under a cooperative agreement with US EPA Office of Water CP-82981501. Thanks are extended to our EPA project officer, Robert Goo, for his patience, insights and flexibility during the two years it took to produce this manual series.

In closing, this manual is dedicated to my father, Robert L. Schueler, who passed away this summer as it was being finalized. His curiosity about urban streams, and his tireless dedication to protecting and restoring them inspired a generation of fisheries biologists and stream advocates, including myself.

Sincerely,

Tom Schueler
Director of Watershed Research and Practice
Center for Watershed Protection

About the Restoration Manual Series

This is the fourth manual in an 11 manual series that provides detailed guidance on how to repair urban watersheds. The entire series of manuals was written by the Center for Watershed Protection to organize the enormous amount of information needed to restore small urban watersheds into a format that can easily be accessed by watershed groups, municipal staff, environmental consultants and other users. The contents of the manuals are organized as follows.

Manual 1: An Integrated Approach to Restore Small Urban Watersheds

The first manual introduces the basic concepts and techniques of urban watershed restoration, and sets forth the overall framework we use to evaluate subwatershed restoration potential. The manual emphasizes how past subwatershed alterations must be understood in order to set realistic expectations for future restoration. Toward this end, the manual presents a simple subwatershed classification system to define expected stream impacts and restoration potential. Next, the manual defines seven broad groups of restoration practices, and describes where to look in the subwatershed to implement them. The manual concludes by presenting a condensed summary of a planning approach to craft effective subwatershed restoration plans.

Manual 2: Methods to Develop Restoration Plans for Small Urban Watersheds

The second manual contains detailed guidance on how to put together an effective plan to restore urban subwatersheds. The manual outlines a practical, step-by-step approach to develop, adopt and implement a subwatershed plan in your community. Within each step, the manual describes 32 different desktop analysis, field assessment, and stakeholder involvement methods used to make critical restoration management decisions.

The next seven manuals provide specific guidance on how to identify, design, and construct the seven major groups of watershed restoration practices. Each of these “practice” manuals describes the range of techniques used to implement each practice, and provides detailed guidance on subwatershed assessment methods to find, evaluate and rank candidate sites. In addition, each manual provides extensive references and links to other useful resources and websites to design better restoration practices. The seven manuals are organized as follows:

Manual 3: Storm Water Retrofit Practices

The third manual focuses on storm water retrofit practices that can capture and treat storm water runoff before it is delivered to the stream. The manual describes both off-site storage and on-site retrofit techniques that can be used to remove storm water pollutants, minimize channel erosion, and help restore stream hydrology. The manual then presents guidance on how to assess retrofit potential at the subwatershed level, including methods to conduct a retrofit inventory, assess candidate sites, screen for priority projects, and evaluate their expected cumulative benefit. The manual concludes by offering tips on retrofit design, permitting, construction, and maintenance considerations in a series of 17 retrofit profile sheets.

Manual 4: Urban Stream Repair Practices

The fourth manual concentrates on practices used to enhance the appearance, stability, structure, or function of urban streams. The manual offers guidance on three broad approaches to urban stream repair – stream cleanups, simple repairs, and more sophisticated comprehensive repair applications. The manual emphasizes the powerful and relentless forces at work in urban streams, which must always be carefully evaluated in design. Next, the manual presents guidance on how to set appropriate restoration goals for your stream, and how to choose the best combination of stream repair practices to meet them.

The manual also outlines methods to assess stream repair potential at the subwatershed level, including basic stream reach analysis, more detailed project investigations, and priority screenings. The manual concludes by offering practical advice to help design, permit, construct and maintain stream repair practices in a series of more than 30 profile sheets.

Manual 5: Riparian Management Practices

The fifth manual examines practices to restore the quality of forests and wetlands within the remaining stream corridor and/or flood plain. It begins by describing site preparation techniques that may be needed to make a site suitable for planting, and then profiles four planting techniques for the riparian zone, based on its intended management use. The manual presents several methods to assess riparian restoration potential at the subwatershed level, including basic stream corridor analysis, detailed site investigations, and screening factors to choose priority reforestation projects. The manual concludes by reviewing effective site preparation and planting techniques in a series of eight riparian management profile sheets.

Manual 6: Discharge Prevention Techniques

The sixth manual covers practices used to prevent the entry of sewage and other pollutant discharges into the stream from pipes and spills. The manual describes a variety of techniques to find, fix and prevent these discharges that can be caused by illicit sewage connections, illicit business connections, failing sewage lines, or industrial/transport spills. The manual also briefly presents desktop and field methods to assess the severity of illicit discharge problems in your subwatershed. Lastly, the manual profiles 12 different “forensic” methods to detect and fix illicit discharges.

Manual 7: Watershed Forestry Practices

The seventh manual reviews subwatershed practices that can improve the quality of upland pervious areas, which include techniques to reclaim land, revegetate upland areas, and restore natural area remnants. When broadly applied, these techniques can improve the capacity of these lands to absorb rainfall and sustain healthy plant growth and cover. This brief manual also outlines methods to assess the potential for these techniques at both the site and subwatershed scale.

Manual 8: Pollution Source Control Practices

Pollution source control practices reduce or prevent pollution from residential neighborhoods or storm water hotspots. Thus, the topic of the eighth manual is a wide range of stewardship and pollution prevention practices that can be employed in subwatersheds. The manual presents several methods to assess subwatershed pollution sources in order to develop and target education and/or enforcement efforts that can prevent or reduce polluting behaviors and operations. The manual outlines more than 100 different “carrot” and “stick” options that can be used for this purpose. Lastly, the manual presents profile sheets that describe 21 specific stewardship practices for residential neighborhoods, and 15 pollution prevention techniques for control of storm water hotspots.

Manual 9: Smart Watersheds: Municipal Programs

The ninth manual focuses on municipal programs that can directly support subwatershed restoration efforts. The five broad areas include improved street and storm drain maintenance practices, development/redevelopment standards, stewardship of public land, delivery of municipal stewardship services, and watershed education and enforcement. This last “practice” manual presents guidance on how municipalities can use these five programs to promote subwatershed restoration goals. The manual also contains a series of profile sheets that recommends specific techniques to implement effective municipal programs.

The series concludes with two user manuals that explain how to perform field assessments to discover subwatershed restoration potential in the stream corridor and upland areas.

Manual 10: The Unified Stream Assessment (USA): A User’s Manual

The Unified Stream Assessment (USA) is a rapid technique to locate and evaluate problems and restoration opportunities within the urban stream corridor. The tenth manual is a user’s guide that describes how to perform the USA, and interpret the data collected to determine the stream corridor restoration potential for your subwatershed.

Manual 11: The Unified Subwatershed and Site Reconnaissance (USSR): A User's Manual

The last manual examines pollution sources and restoration potential within upland areas of urban subwatersheds. The manual provides detailed guidance on how to perform each of its four components: the Neighborhood Source Assessment (NSA), Hotspot Site Investigation (HSI), Pervious Area Assessment (PAA) and the analysis of Streets and Storm Drains (SSD). Together, these rapid surveys help identify upland restoration projects and source control to consider when devising subwatershed restoration plans.

Individual manuals in the series are scheduled for delivery by 2006, and each will be initially available for free downloading, after which they can be ordered online or as hard copies from the Center for a nominal charge. Be sure to check our website, www.cwp.org, to find out when each manual will be available and how it can be accessed.

Table Of Contents

Stream Cleanup Practices

Simple Repair Practices

Comprehensive Stream Repair Applications

List of Tables

List of Figures

List of Acronyms and Abbreviations

The following list identifies acronyms and abbreviations that are frequently used in the manual.

B-IBI:	Benthic index of biotic integrity (measures health of aquatic insect community)
CM:	Channel modification assessment form of the Unified Stream Assessment (USA)
CMP:	Corrugated metal pipe
CSA:	Comparative subwatershed analysis
ECF:	Erosion control fabric
EPT:	Macroinvertebrate index that examines sensitive Ephemeroptera, Plecoptera, and Trichoptera taxa (mayflies, stoneflies and caddisflies, respectively)
ER:	Eroding bank impact assessment form of the USA
F-IBI:	Fish index of biotic integrity, a regional index based on 8 to 12 fish population metrics
GIS:	Geographic information system
IB:	Impacted buffer impact assessment form of the USA
L:	Sediment load
LWD:	Large woody debris
MI:	Miscellaneous impact assessment form of the USA
OT:	Storm water outfall impact assessment form of the USA
Q:	Discharge or flow
SVAP:	Stream Visual Assessment Protocol
RBP:	Rapid Bioassessment Protocol
RCH:	Reach characterization form of the USA
RCV:	Rock cross vane
RSAT:	Rapid Stream Assessment Technique
RVW:	Rock vortex weir
SC:	Stream crossing impact assessment form of the USA
TR:	Trash and debris impact assessment form of the USA
TRM:	Turf reinforcement mat
USA:	Unified Stream Assessment
UT:	Utility impact assessment form of the USA

Introduction

This manual assembles what is currently known about urban stream repair into a single volume. As a society, we have been “repairing” streams for hundreds of years, but rarely with the purpose of improving their quality or function. The practice of urban stream repair is relatively new; most of our experience has occurred in the last decade. Like any new field, urban stream repair is still evolving. Carpenter *et al*. (2003) observe that strong regional differences exist in both the practices and purposes of urban stream repair. This is not surprising, since initial efforts have been conducted independently by different professional disciplines to address diverse repair objectives. Some examples of the many different objectives driving current stream repair practice are listed below:

- Cleanup trash and improve the aesthetics of the stream
- Naturalize the stream corridor, particularly along greenways
- Create a recreational fishery in an urban setting
- Restore biological diversity in the stream community
- Promote fish passage for anadromous fish
- Achieve a more natural and stable stream channel design
- Promote bioengineering as a softer alternative to hard bank stabilization
- Daylight buried streams and restore channelized reaches
- Protect infrastructure threatened by bank erosion
- Improve downstream water quality by reducing erosion

While all of these objectives are important and legitimate in urban settings, only a few seek to actually repair stream conditions in an ecological sense. Indeed, full ecological restoration may be difficult or impossible to achieve in many urban streams, depending on the degree of cumulative subwatershed development. Consequently, we have elected to use the term “stream repair” throughout this manual to address the full range of urban stream objectives.

In addition, the scope of this manual is generally confined to practices installed within:

- Smaller streams ranging in size from first to third order
- Located within urban areas with at least 10% impervious cover
- Drained by distinct subwatersheds, which are less than ten square miles in area, and serve as the primary management unit for restoration
- As part of a broader, comprehensive plan that includes other stream corridor and upland watershed practices to meet subwatershed restoration objectives chosen by the community

This manual presents a comprehensive and unified approach toward urban stream repair, but it does not substitute for a sound design manual. Appendix A provides a comprehensive list of excellent on-line stream repair design references and resources.

Organization of the Manual

This manual is organized into four chapters. **Chapter 1** outlines the basics of stream repair, with a strong emphasis on the unique conditions encountered in urban streams, particularly in regard to how their geomorphology responds to upstream changes in hydrology and sediment transport. A broad group of progressively more ambitious urban stream repair goals is then discussed, with a focus on how both subwatershed impervious cover and upstream restoration practices influence their achievability. The chapter concludes by reviewing the range of available stream repair practices and presents some initial principles to guide stream repair in a larger subwatershed context.

Chapter 2 examines how stream repair potential can be systematically assessed at both the subwatershed and reach level. The chapter begins by outlining desktop methods to identify priority reaches in a subwatershed that have the greatest need or potential for stream repair and merit subsequent field investigation. The next section introduces the Unified Stream Assessment (USA) that documents impairments in the stream corridor, and identifies potential candidate sites for stream repair. Guidance is then provided on how to develop and rank initial concept designs for stream repair projects. The chapter concludes by describing five types of reach assessment studies that may be needed to support final design.

Chapter 3 presents the unique design context for urban stream repair practices, which requires careful analysis of upstream subwatershed conditions, dynamic factors within the project reach itself, and its connection to downstream receiving waters. The three urban stream contexts are described, with an emphasis on how each influences the design of individual urban stream repair practices. Guidance is then provided on how to select the most appropriate stream repair practices, given restoration objectives and conditions in the stream reach and subwatershed as a whole. The chapter concludes with tips on permitting, construction, maintenance, and monitoring that are critical to individual project success and the continued improvement of stream repair practices in general.

Chapter 4 provides individual profile sheets on 33 different stream repair practices. Each profile sheet describes each practice, and presents practical guidance on its feasibility, design, construction and maintenance. Each profile sheet also reports unit cost information (where available), and references regional and national manuals and design resources that can be accessed over the internet.

This manual should be read in the context of several others in the *Urban Subwatershed Restoration Manual* series, particularly:

- No. 1 Integrated Framework for Restoring Small Watersheds
- No. 3 Storm Water Retrofit Practices
- No. 5 Riparian Management Practices
- No. 10 Unified Stream Assessment: A User's Manual

Lastly, the vocabulary associated with the practice of stream repair draws from many different disciplines, such as fluvial geomorphology, fisheries biology, hydrology, hydraulic engineering and watershed management to name a few. Even within the same discipline, there often can be regional variation in terminology, particularly in regard to the names of individual repair practices. Some new terms are introduced in this manual to specifically address issues related to urban streams, when necessary. An extensive glossary is provided to clarify the meanings of the terms as they are specifically used in this manual, and the reader is encouraged to consult it frequently.

Chapter 1: Basics of Urban Stream Repair

This chapter introduces the basic concepts of urban stream repair. The first section reviews why urban streams are different from their natural counterparts, from a physical, hydrological, biological and water quality standpoint. The Impervious Cover Model (ICM) is then used to show how subwatershed impervious cover can be used to classify and manage urban streams. The next section reviews how the geomorphology of urban streams responds to upstream changes in hydrology and sediment transport, and discusses how channel evolution influences the design of stream repair practices.

The third section outlines a series of progressively more ambitious objectives that drive urban stream repair, and describes how both subwatershed impervious cover and upstream restoration practices influence their achievability. The fourth section reviews the range of available stream repair practices including stream cleanups, simple stream repairs, and more comprehensive repair applications. The chapter concludes by discussing general principles to consider when practicing stream repair in urban subwatersheds.

1.1 Why Urban Streams are Different

Recent research has dramatically illustrated how different urban streams are from their natural counterparts. These differences need to be clearly understood in order to design effective stream repair practices in urban subwatersheds. While there are many systems of stream classification (Rosgen, 1997, for example), the Impervious Cover Model is particularly useful to address the unique design context of urban streams (CWP, 2003).

Impervious cover is often used as a general index of the intensity of subwatershed development. The relationship between subwatershed impervious cover and stream quality indicators can be predicted by the ICM, based on hundreds of research studies on first to fourth order urban streams (Manual 1, Appendix A). The ICM predictions help diagnose the severity of urban stream impacts, set realistic goals for stream repair, and generally predict the forces and stresses within a given stream reach.

It is important to keep in mind that the ICM is a guide and not a guarantee. ICM predictions are general and may not apply to every stream in the ICM classification. Urban streams are notoriously variable in the sensitive and impacted categories, although variability is greatly reduced in the non-supporting and urban drainage categories. Factors such as gradient, stream order, stream type, age of subwatershed development, past land use, and current management practices can and will make some streams depart from its predictions.

The ICM classifies four types of urban streams, according to their current health and repair potential (Figure 1). The four types of streams include:

Sensitive streams have less than 10% subwatershed impervious cover and have the potential for “good” to “excellent” stream indicator scores, if the riparian corridor and the subwatershed as a whole are managed in a natural condition and proper farming, ranching or logging practices are applied. Even when sensitive streams do not attain high quality, they often have good to excellent potential for restoring channel stability and/or aquatic diversity depending on the type of stream repair practices used. Strictly speaking, sensitive streams are not the primary focus of this manual because they are not urban, although many of the same stream repair practices can also be applied to them. They are mentioned here because they represent the reference condition or benchmark against which the other three urban stream categories are measured.

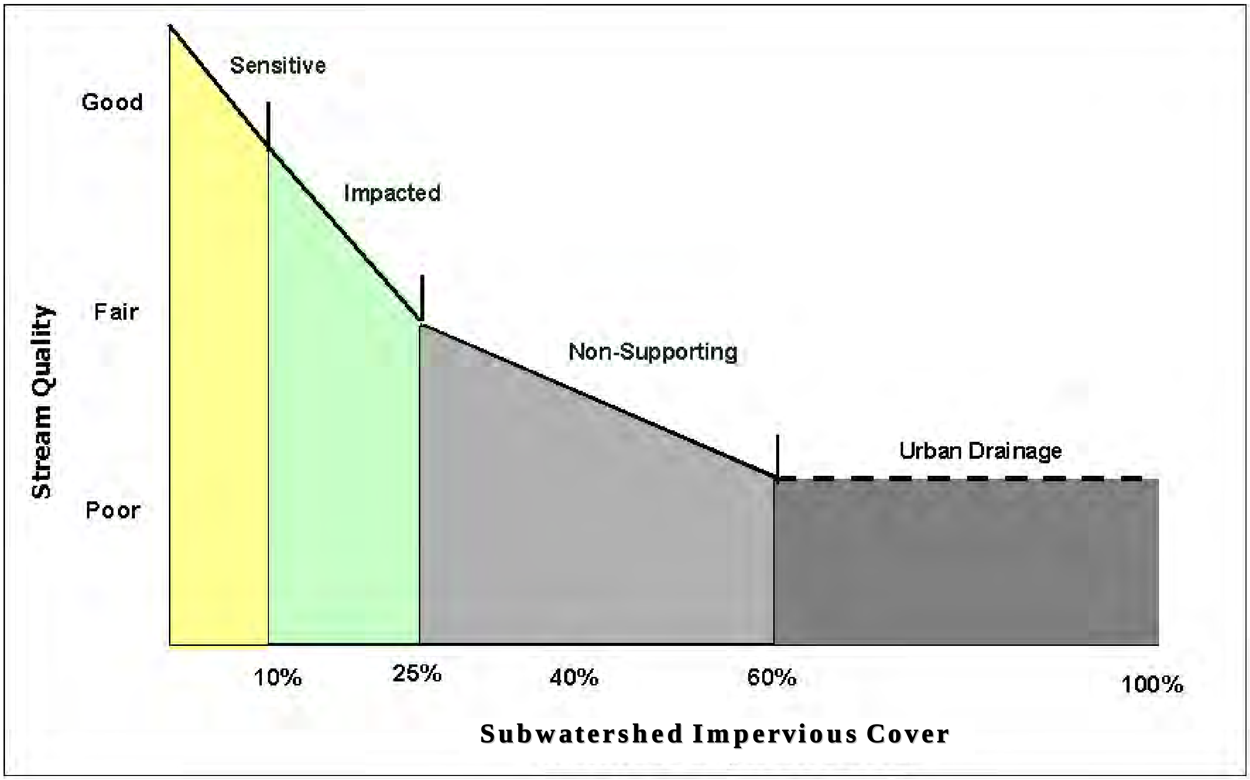


Figure 1: Impervious Cover Model Diagram

Impacted streams have between 10 and 25% subwatershed impervious cover, and show clear signs of declining stream health. Most indicators of stream health fall in the "fair" range, although some reaches may still be considered "good" (Table 1). Impacted streams often exhibit the greatest stream repair potential since they experience only moderate degradation, have an intact stream corridor, and usually have enough land available in the subwatershed to install upland restoration practices.

Non-supporting streams range between 25 and 60% subwatershed impervious cover and no longer support their designated uses, as defined by hydrology, channel stability habitat, water quality or biological indicators (Table 2). Subwatersheds at the lower end of the IC range (25 to 40% IC) may show promise for partial stream repair, but they are so dominated by hydrologic and water quality stresses that they normally cannot attain pre-development biological conditions. Under some circumstances, streams in the upper range of the non-supporting category (40 to 60% IC) may show some potential for partial biological restoration, but the primary repair strategies are to protect infrastructure, create more natural stream corridors and prevent bank erosion, or achieve other community objectives.

Urban drainage refers to streams or channels with subwatersheds that exceed 60% impervious cover and where the stream corridor has essentially been eliminated or physically altered so that it functions primarily as a conduit for flood waters. Water quality indicators are consistently poor, channels are highly unstable and habitat and aquatic diversity are very poor or are eliminated altogether (Table 3). The prospects to improve aquatic diversity within urban drainage are quite poor, although it may be possible to improve water quality conditions in the remaining stream corridor.

Table 1: Stream Indicator Predictions for Impacted Streams (<25% Subwatershed IC)

- 10 to 30 % of rainfall converted to storm water runoff
- Peak discharge for 100 year storm increased by factor of 1.1 to 1.5
- 1.5 to 3 bankfull flood events occur per year
- 60 to 90 % of stream network intact
- 50 to 70 % of riparian forest buffer intact
- 1 to 2 crossings per stream mile
- Channel cross-sectional area enlarges by factor of 1.5 to 2.5
- 2 to 5 times more annual sediment supply to stream during enlargement phase
- Stream habitat scores are fair, but variable
- 2 to 8 pieces of large woody debris (LWD) per 100 feet of stream (variable)
- Summer stream temperatures are 2 to 4 degrees F warmer
- Annual nutrient load 1.2 to 2 times higher than rural background
- Frequent bacterial standards violations during wet weather
- Acute toxicity to aquatic life is rare, chronic toxicity possible
- Bottom sediments enriched, but not contaminated; fish advisories uncommon
- Trash and debris load of 1 to 2 tons per square mile/yr
- Aquatic insect diversity rated as “fair” to “good” (B-IBI)
- Sensitive EPT taxa 40 to 50 % of reference
- Fish diversity rated as “fair” to “good” (F-IBI)
- Limited potential to support cold water fish species
- Stressed and simplified riparian plant community

Note: The full technical support for the ICM predictions can be found in Appendix A of Manual 1: *An Integrated Framework for Restoring Small Urban Watersheds*

Table 2: Stream Indicator Predictions for Non-Supporting Streams (25 to 60% Subwatershed IC)

- 25 to 60 % of rainfall converted to storm water runoff
- Peak Discharge for 100 year storm increase by factor of 1.5 to 2
- 3 to 7 bankfull flood events occur per year
- Only 25 to 60 % of original stream network intact
- Only 30 to 60 % of riparian forest buffer intact
- 2 to 10 crossings per stream mile
- Channel cross-sectional area enlarges by factor of 2.5 to 6
- 5 to 10 times more annual sediment supply to stream during enlargement phase
- Stream habitat scores consistently fair to poor
- Large woody debris scarce or absent
- Summer stream temperatures are 4 to 8 degrees F warmer
- Annual nutrient load 2 to 4 times higher than rural background
- Continuous bacterial standards violations during wet weather
- Moderate potential for acute toxicity to aquatic life during storms and spills
- Bottom sediments contaminated; fish advisories likely
- Trash and debris load of 2 to 5 tons per square mile/yr
- Aquatic insect diversity rated as “poor” (B-IBI)
- Sensitive EPT taxa 20 to 40% of reference
- Fish diversity rated as “poor” (F-IBI)
- Put and take trout or salmon only
- Riparian plant community dominated by invasive species

Note: The full technical support for the ICM predictions can be found in Appendix A of Manual 1: *An Integrated Framework for Restoring Small Urban Watersheds*

Table 3: Stream Indicator Predictions for Urban Drainage Streams (>60% Subwatershed IC)

- 60 to 90 % of rainfall converted to storm water runoff
- Increase in peak discharge of 100 year storm by a factor of 2 to 3
- 7 to 10 bankfull flood events occur per year
- Only 10 to 30% of original stream network intact
- Less than 30% of riparian forest buffer intact
- No streams left to cross
- Channel cross-sectional area enlarges by factor of 6 to 12 following adjustment
- Sediment supply to stream may decline
- Stream habitat absent or "poor"
- LWD absent
- Summer stream temperatures more than 8 degrees F warmer
- Annual nutrient load 4 to 6 times higher than rural background
- Continuous bacterial standards violations during dry and wet weather
- High potential for acute toxicity to aquatic life during dry and wet weather
- Bottom sediments contaminated; fish advisories common
- Trash and debris load of 5 to 10 tons per square mile/yr
- Aquatic insect diversity rated as "very poor" (B-IBI)
- Sensitive EPT taxa 0 to 20% of reference
- Fish diversity rated as "very poor" (F-IBI)
- No capacity to support trout or salmon
- Riparian plant community is isolated and degraded

Note: The full technical support for the ICM predictions can be found in Appendix A of Manual 1: *An Integrated Framework for Restoring Small Urban Watersheds*

1.2 Review of Urban Stream Geomorphology and Habitat Implications

Urban stream repair requires a thorough understanding of stream geomorphology. This section briefly reviews how urban streams are shaped by changes in hydrology and sediment load induced by upstream subwatershed development. Changes in urban stream geomorphology are fairly predictable and create a common pattern of stream habitat degradation that is the primary focus of stream repair.

Dynamics of Urban Stream Geomorphology

Natural stream channels are dynamic systems that are constantly adjusting in an attempt to maintain equilibrium with their flow regime and sediment load. Stream channels maintain equilibrium by changing their physical dimensions, expressed in terms of width, depth, sinuosity, and slope. In general, stream equilibrium is controlled by two dominant factors, storm flow (Q) and sediment load (L), as shown in Figure 2. A change in either factor will lead to the formation of new channel dimensions (Bovee, 1982; Harvey and Watson, 1986; Booth, 1990). The direction of these dimensional changes is, for the most part, predictable.

Subwatershed development initially causes sharp increases in both Q and L within stream channels, especially if it occurs without adequate storm water or sediment controls. As a result, subwatershed development sets in motion a series of predictable events that dramatically alters the physical dimensions of the stream (Morisawa and Laflure, 1979; Booth, 1990). Broadly speaking, urban stream channels respond to subwatershed development over time in three sequential phases:

- Phase 1: Initial Construction
- Phase 2: Active Channel Adjustment
- Phase 3: Eventual Adjustment to More Stable Channel Dimensions

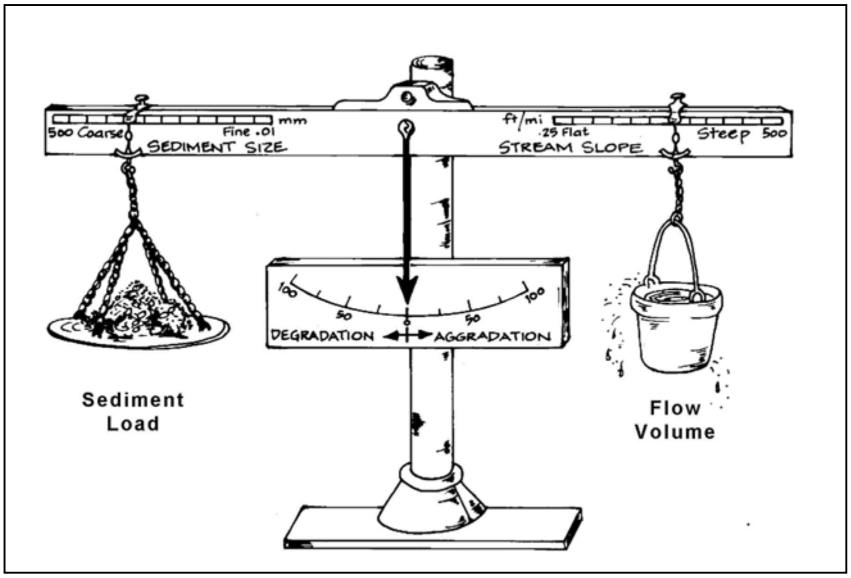


Figure 2: Schematic of Lane's Balance
Source: Lane, 1955

Phase 1: Initial Construction

The first phase of channel response begins during the construction phase of land development. If erosion and sediment controls are not effectively employed, land exposed during clearing and grading can erode and deliver large volumes of sediment to the stream during storms. Research has shown that uncontrolled construction sites can export 20 to 2000 times more sediment than other land uses (Dreher and Mertz-Erwin, 1991; Brown, 1998). Most headwater streams initially lack the capacity to transport the prodigious sediment load, which results in channel deposition. Excess sediment gradually accumulates in the channel, first filling pools and then depositing in runs and riffles. Sediment deposition gradually raises the elevation of the streambed, a process known as channel aggradation.

Aggradation is normally accompanied by widening, as the channel expands its cross-section to accommodate storm water flows, which have not diminished. Aggradation causes increases in the following stream channel dimensions during the initial construction phase:

- Meander wavelength
- Width to depth ratio
- Stream gradient

The result is a stream channel that is shallower, wider, and straighter than before (Bovee, 1982).

The hydraulically smoother, steeper, and straighter channel results in higher stream velocities as the channel adjusts to transport the increased sediment load. In extreme cases, where sediment load far outpaces the sediment transport capacity of urban streams, braiding may occur, forming several flow paths that meander within the channel.

The sediment deposition that occurs during the initial construction phase can significantly degrade urban stream habitat that supports aquatic life. In particular, silt, sand and other fine sediments fill the voids between larger gravels and cobbles in a process known as embedding, which eliminates habitat for aquatic insects and smothers fish spawning areas.

Urban channel response to initial construction can last for several years. In most cases, deposited sediments from the first phase are fully eroded by increased storm water flows in the next phase. It is important to note that the severity of the initial phase can be reduced if effective erosion and sediment control practices and stream buffers are applied to new construction sites.

Phase 2: Active Channel Adjustment

A second phase of urban channel response occurs when storm water flows sharply increase as a result of the combined effect of new impervious cover in the subwatershed (e.g., roads, parking areas, and driveways and buildings) and the installation of a more hydraulically-efficient storm water conveyance system to deliver runoff to the stream. Impervious cover generates considerably greater unit peak discharges for a given design rainfall event. Consequently, urban stream channels experience a greater frequency and magnitude of bankfull and sub-bankfull discharge events, compared to undeveloped streams. The severity of hydrologic alteration can be reduced if effective storm water controls are widely implemented in the subwatershed.

Increased storm water discharges provide urban streams much more power to transport sediment, and they quickly begin to erode sediments deposited during the initial phase of construction. Once the sediment is exhausted, the stream begins to erode its original bed and banks. Streams enlarge their cross-sectional area to respond to increased storm flows, and begin a phase of accelerated channel erosion, know as channel enlargement. Figure 3 shows an example of how an urban stream has enlarged in response to four decades of subwatershed development.

If an urban streambed is not sufficiently armored with immobile substrate materials such as bedrock, large cobbles, or boulders, the channel may begin downcutting, a process also known as incision (Booth, 1990; Booth and Henshaw, 2001; Hammer, 1972; MacRae and DeAndrea, 1999; Schumm, 1999; Caraco, 2000; and Rosgen, 1997). Incision is one of the most destructive alterations that can occur to an urban stream channel. Stream incision can occur in one of two ways. The first is a gradual lowering of the streambed in channels with mobile substrates, such as sand bed coastal plain streams. The second is a more active downcutting process that migrates in an upstream direction in cobble/gravel streams. The point in the channel profile where active downcutting occurs is referred to as a knickpoint. This knickpoint migrates in an

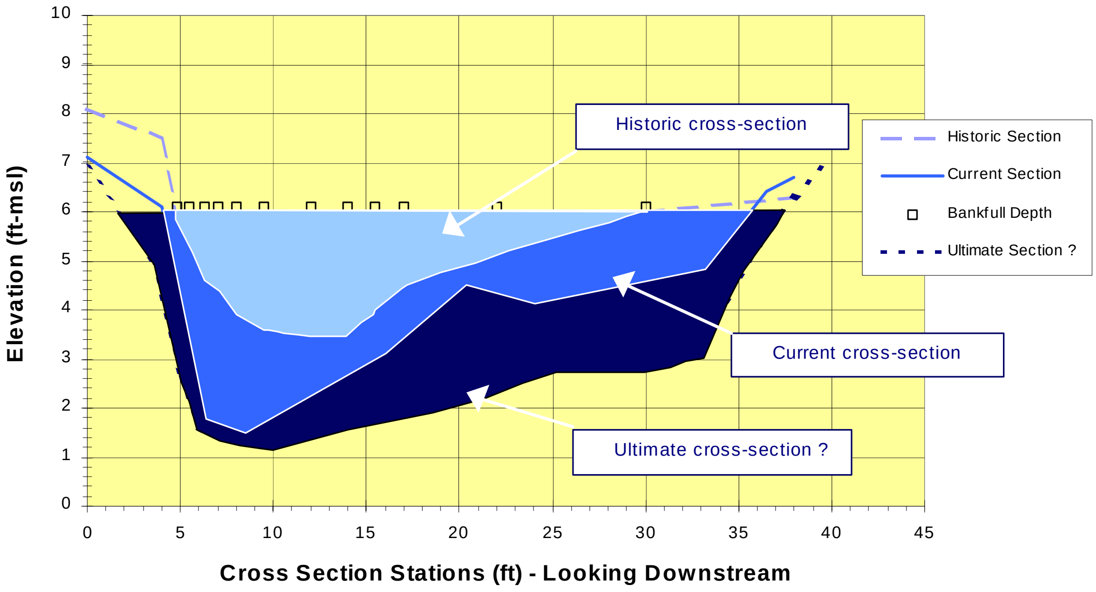


Figure 3: Watts Branch Stream Cross-Section

upstream direction until a new stable channel slope is achieved or it reaches a natural grade control such as bedrock, or an artificial control such as a dam or road culvert.

Channel incision reduces channel slope, and thereby reduce a stream's ability to transport sediments. The channel incision process is often extremely severe in urban headwater streams. The streambed may be only slightly lower in elevation at the location where the knickpoint initially forms. But as the knickpoint moves upstream toward the headwaters, its height relative to the original stream elevation continues to grow in height to achieve a new stable channel slope. For example, a modest reduction in stream gradient of only 0.1% carried upstream one mile above a knickpoint results in a drop in stream elevation of more than five feet at the head of the stream.

As urban streams incise, their banks become taller, more exposed, and less stable (Figure 4). Over time, the lowering of the stream bed elevation may cause the upper streambanks and floodplain to dry out, which in turn, causes deeply rooted riparian vegetation to be replaced by weakly rooted upland species, further weakening streambanks.

Over time, the unstable streambanks erode and the channel begins to widen. This process of channel enlargement can occur rapidly or over a period of decades and lead to urban stream channels that are much larger than that needed to convey predevelopment bankfull flows (Booth, 1990). Increases in channel cross-sectional area on the order of four to 12 times have been reported (Harvey and Watson, 1986), and appear to be partly related to the amount of impervious cover in the contributing subwatershed (Caraco, 2000). In addition, overbank floods that once left the channel to flow across the floodplain often become confined within the incised channel and exert extremely powerful hydraulic forces on the channel boundaries.

Stream incision does not occur in all urban streams subject to increased storm water runoff or decreased sediment loads. For example, streams that possess immobile or resistant bed materials (e.g., bedrock) have natural grade controls and respond by laterally eroding banks to enlarge their cross sectional area. Other urban stream reaches may possess artificial grade controls in the form of road culverts and utility crossings, which may reduce the extent of incision, unless they too are exposed, undercut and fail.

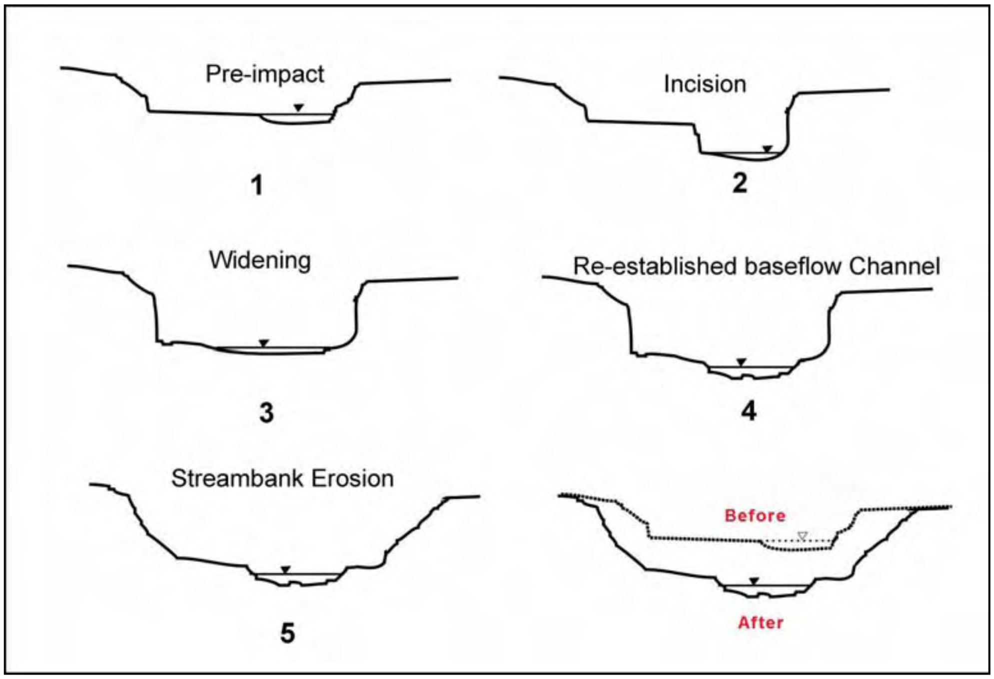


Figure 4: Channel Evolution: Progressive Stages of Channel Incision

Source: Schumm,1999

The process of channel enlargement in urban headwater streams often has far-reaching impacts to downstream receiving waters. The sediment yield produced by urban subwatersheds experiencing channel enlargement produces the majority of the streams annual sediment budget (Trimble, 1997; Dartiguenave *et al*., 1997; and Barton, 2003). While headwater streams are fairly efficient in this phase at transporting sediments downstream, they are ultimately deposited in low gradient and low velocity waters, such as tidal areas, reservoirs or rivers.

While incision is a dominant channel process in most urban streams, aggradation can and does occur in some reaches, particularly above crossings and channel constrictions, within extremely low gradient downstream reaches, and during both the initial phases of construction and active channel enlargement. In most cases, however, aggradation is a temporary phenomenon within the longer context of channel evolution in urban streams. Evidence of widespread aggradation in an urban stream network often signals that the adjustment process is just beginning or is too active to consider installing stream repair practices, except perhaps to protect vital infrastructure.

Phase 3: Eventual Adjustment to More Stable Channel Dimensions

Once the process of fully developing a subwatershed (known as buildout) is complete, urban streams begin the final phase of their geomorphic adjustment, gradually stabilizing with larger dimensions and a lower elevation. The time frame for this adjustment phase is estimated to be one to two decades for streams in the Pacific Northwest, according to recent research by Finkenbine *et al*. (2000) and Henshaw and Booth (2000). Studies in eastern streams indicate that it may take somewhat longer for urban streams to fully recover to a new equilibrium after subwatershed buildout (MacRae and DeAndrea, 1999). While more geomorphological research is needed to establish the exact time frame for this final phase of urban channel response, it is clear that a minimum of a few decades is probably needed to achieve a relatively stable channel geometry in most urban streams.

It is also important to note that buildout can take a few short years or many decades to play out, depending on the rate of new development, and subsequent infill and redevelopment. Consequently, most urban streams remain in the adjustment process for many decades.

The final phase of urban channel response is perhaps the best time to implement stream repairs, since the stream has had time to adjust to the altered flow regime, has relatively stable dimensions, and yet is missing many of the important physical and habitat features that contribute to stream quality.

Implications for Urban Stream Habitat

The three phases of urban stream channel response produce fairly predictable changes in the quality of urban stream habitat. After adjustment, the typical urban stream has some common habitat characteristics, as described below:

- The channel cross-section has enlarged considerably, whether by widening, downcutting or combination of both.

- The channel is entrenched and has more power to move sediments and bedload. Consequently, the stream has a high capacity to transport sediment, which continues as upstream sediment loads gradually diminish. Consequently, powerful hydraulic forces continue to work on bed and banks, particularly if the channel is confined or entrenched.

- Stream reaches tend to have steep and occasionally unstable streambanks that often have poor vegetative cover.

- The channel has a simplified habitat structure, typified by the loss of pools and riffles, and a shallow and poorly-defined low flow channel that wanders within a much larger and unstable stream channel.

- The adjacent stream corridor often lacks riparian forest cover, which often leads to stream warming that makes the channel unsuitable for cold-water organisms.

- The diversity of the aquatic community is "fair" to "poor," with many potential obstacles to recovery such as barriers that prevent re-colonization (e.g., crossings, interruptions and fish barriers, etc), and poor water quality.

- Carbon storage tends to be very low in urban streams, whether in the form of large woody debris or finer-grained organic matter (Paul, 2004). Leaf pack decay rates are higher due to physical fragmentation and stormflows. Since detrital processing is the major energy source for most streams, it is not clear how the lack of carbon influences biological productivity in urban streams.

The key theme of urban stream repair is that many different habitat impacts need to be "fixed" to mimic pre-development conditions within the adjusted older urban stream. This suggests that major improvements in biological and habitat response may be hard to come by in streams located in highly developed subwatersheds. The next section describes a range of different objectives to meet broader community, physical, and biological goals for restoring conditions in urban streams.

Important Caveat

While the preceding three-phase scenario is fairly typical of how many urban streams respond to upstream subwatershed development, it does not substitute for a detailed field assessment of current and past channel processes. The geomorphology of some urban streams can be strongly influenced by other alterations that often may accompany urban development such as in-stream gravel extraction, water diversions, historical land uses, and the construction or removal of dams and impoundments (Schumm, 1999; Kondolf, 1997; and Harding *et al*., 1998). In addition, the channel incision process is poorly understood for extremely low gradient urban streams, such as those found in the coastal plain.

1.3 Objectives of Stream Repair

This section reviews the range of stream repair objectives that can be pursued in urban subwatersheds. Communities can pursue at least nine progressively more difficult stream repair objectives, which fall into three broad goal categories:

- *Community Goals* - Improve stream amenities and safety: Objectives 1,2,3
- *Physical Goals* - Prevent bank erosion and improve channel stability: Objectives 4,5,8
- *Biological Goals* - Improve capacity of stream to support aquatic life: Objectives 6,7,9

Water quality improvement has traditionally not been a major goal for stream repair, it may be a necessary precondition for it. Stream repairs may have future potential to improve downstream water quality through enhanced nutrient reduction by stream uptake and assimilation, floodplain uptake and transformation, and reduced delivery of sediment and nutrients from bank erosion (DeWolfe *et al.*, 2004).

Communities may choose more than one stream repair objective to guide their subwatershed restoration efforts, but each one should be realistic and achievable. In most cases, the ability to achieve stream repair objectives is fundamentally constrained by subwatershed impervious cover. Booth (in press) has proposed a three-tier system for setting stream repair objectives based on impervious cover, and Table 4 expands on this system.

Several other factors should also be considered when choosing urban stream repair objectives for a subwatershed:

- Realistic potential for recovery or re-colonization of aquatic life
- Current channel process occurring in the reach
- Age of subwatershed development and the expected future channel evolution
- Existing physical constraints within the stream corridor, such as space, access, infrastructure, and management uses
- Projected future subwatershed development

Table 4: The ICM and the Ability to Meet Stream Repair Objectives

Stream Repair Objective	**Subwatershed Impervious Cover**			
	10 to 25%	**25 to 40%**	**40 to 60%**	**60 to 100%**
Cleanup Stream Corridor	●	●	⦿	⦿
Naturalize Stream Corridor	●	●	⦿	○
Protect Threatened Infrastructure	●	●	⦿	○
Prevent Bank Erosion	●	●	⦿	○
Expand/Reconnect Stream Network	●	●	⦿	○
Increase Fish Passage	●	⦿	○	×
Improve Fishery Habitat	●	⦿	○	×
Achieve Natural Channel Design	⦿	⦿	○	×
Recover Aquatic Diversity & Function	⦿	○	○	×

KEY
● Objective can normally be widely achieved across a subwatershed
⦿ Objective may be feasible, depending on individual reach characteristics
○ Objective can only be achieved in isolated reaches in the subwatershed
× Objective is generally not achievable in the subwatershed

Objective 1: Cleanup Stream Corridor

This stream repair objective is limited in scope: to improve the aesthetics of the stream and its corridor, and produce secondary benefits in terms of public education and community involvement. Public attitudes toward urban streams are profoundly influenced by aesthetic perceptions, and outrage over trash and debris has often been a powerful motivation for many citizens and activists to become concerned about urban stream quality. The primary practices applied to cleanup the stream corridor include routine stream cleanups, stream adoption programs, citizen hotline reporting and discharge and dumping prevention. Secondary practices include bank stabilization, reforestation and pollution source controls.

The goal is not necessarily to produce a natural stream, but rather one that is free of trash and debris, and safe and accessible for the public to interact as an urban water feature. The objective can generally be met in all streams in urban subwatersheds, except for enclosed or culverted channels.

Objective 2: Naturalize Stream Corridor

This stream repair objective seeks to create a more natural stream corridor within a managed setting, such as a park, greenway or "streamfront." Once again, the strategy is to create a more attractive stream and corridor for human use, and no specific biological or habitat endpoint is articulated. A naturalized stream corridor can be achieved in most impacted and non-supporting streams, and even some urban drainage, as long as adequate room is available in the corridor. The rationale for a more naturalized stream corridor is that it offers enhanced recreational or amenity values that will compel the public to support greater stream stewardship.

Bank stabilization and water quality improvement are often needed to make the stream accessible and safe for water contact recreation. Primary stream repair practices include both hard and soft bank stabilization, stream cleanup and adoption, and establishment of bank vegetation. In many cases, stream repairs are combined with riparian management, aggressive discharge prevention, upstream retrofits and pollution source controls.

Objective 3: Protect Threatened Infrastructure

This stream repair objective is limited but important -- to protect sewers, roads, underground utilities, bridges and other valuable community infrastructure from the consequences of urban stream erosion and enlargement. In some cases, a secondary objective is to prevent the loss of private property, but this is usually done on individual parcels or stream reaches. Both hard or soft bank stabilization practices are used to protect infrastructure and property from erosion, depending on stream size and available space in the stream corridor.

Soft bank stabilization practices are more natural, attractive and deformable, and are preferred if room is available and their somewhat higher risk of failure can be accepted. Additional stream repair practices such as culvert replacement/repair, grade control and upstream storage retrofits may also be needed to solve the underlying channel process that is causing the local erosion problem. Infrastructure protection can be applied to almost any urban stream, since it is usually the value and risk to infrastructure that drives this objective.

Objective 4: Prevent Additional Streambank Erosion

This stream repair objective seeks to reduce downstream sediment loads produced during the urban channel adjustment process. Eroding beds and banks can cause loss of property, destroy in-stream habitat, and contribute significant sediment and nutrient loads downstream.

While many communities have traditionally focused on individual problem reaches, this strategy seeks to systematically deal with bank and bed erosion problems across the headwater stream network by addressing the underlying channel processes that are causing it. Spot bank repairs, such as those done to protect infrastructure, work only at the point where they are installed, don't address the underlying cause of erosion, and have little downstream influence (indeed, spot repairs can actually exacerbate downstream problems).

The systematic approach to prevent bank erosion is typically applied during the adjustment phase when the greatest sediment loads are being produced. In many urban streams, this entails aggressive efforts to minimize channel incision, primarily by arresting the progress of advancing headcuts in the stream network. The strategy works best in impacted or non-supporting streams where room is available in the stream corridor.

The primary stream repair practices used include grade control and hard or soft bank stabilization practices, and in selected headwater streams, parallel pipe systems. Upstream storage retrofits may need to be constructed to provide channel protection volume to control the storm events creating channel instability. The design goal is to bring about the enlarged cross-section and controlled longitudinal elevations that the stream would eventually produce on its own.

Objective 5: Expand or Reconnect the Stream Network

This stream repair objective seeks to physically increase the length of surface streams in a subwatershed, and reduce the number of interruptions that restrict the movement of fish and aquatic life. This strategy is most effective in impacted streams and the lower portions of some non-supporting streams that still have adequate habitat and water quality conditions to support aquatic life. The primary practices used to meet the objective include stream daylighting, dechannelization, baseflow channel creation, and culvert modification. The basic strategy is to open up the stream network. Best results are normally achieved when the stream has already adjusted to upstream development.

Objective 6: Increase Fish Passage and Spawning Potential

This stream repair objective is slightly more ambitious than the preceding one and seeks to provide passage for migrating fish, such as salmon or other anadromous fish, into an urban subwatershed. It is often pursued when the subwatershed is located close to estuaries or lakes where fish runs once existed, particularly for impacted streams that may still have suitable upstream habitat conditions. The same stream repair practices used to expand or reconnect the stream network are employed along with in-stream habitat enhancement practices to increase the quality of newly opened spawning and rearing habitat. An urban stream is a notoriously poor environment for fish spawning, and biologists should always be consulted to determine the specific needs of the target fish species. For this reason, it may be necessary to apply other stream repairs and upland practices to meet this objective in non-supporting streams. Poor water quality, possible toxicity, stream warming, and other stresses make fish passage a questionable, and possibly unethical strategy in urban drainage.

Objective 7: Improve Fishery Habitat

This stream objective seeks to repair the stream so that it can maintain habitat conditions that support some kind of warm water, cool water, or cold water fishery. The fishery objective may be to maintain a self-sustaining fish population, or simply create conditions suitable for "put and take" fishing (e.g., annual restocking). The basic strategy is to recreate the many habitat features that are lost or simplified during the adjustment phase of an urban stream (e.g., pools, riffles, undercut banks, overhead cover, large woody debris and rearing areas).

Relatively stable stream habitat conditions are a prerequisite to meet this repair objective, so streambank erosion control or channel redesign are often needed (Objective 3 and 8). Next, a series of in-stream habitat, flow deflection and grade controls practices are installed in the urban channel to meet the basic habitat needs of the target fish species. In many cases, vegetation planting on both the streambank and riparian zone are also needed to support this objective. Often, upstream storage retrofits are installed to provide channel protection and pollutant reduction within the project reach.

Improving fishery habitat is generally an achievable strategy for most impacted streams, and the lower portions of some non-supporting streams, particularly if they have recovered from their adjustment phase, and have available room in the stream corridor. Pursuing fishery objectives during the active stage of urban stream channel adjustment is probably not a wise idea. In any event, it is extremely important to consult a fishery biologist to determine whether existing conditions would support recovery of the aquatic community.

Objective 8: Achieve Natural Channel Design

The objective of natural channel design is to create a new channel and floodplain that has the appropriate dimensions, pattern and profile that will be stable and in geomorphic equilibrium (i.e., the channel will not degrade or aggrade, and has the capacity to move current and future flows and sediment loads). More information on channel redesign can be found in Profile Sheet CR-32 (Chapter 4). Channel redesign often requires hard and soft bank stabilization, flow deflection, grade controls and other individual stream repair practices. The rationale behind this objective is that a natural channel design should be relatively stable and in equilibrium with the current flow and sediment regime, and therefore more sustainable in the long run.

Achieving a stable natural channel, however, can be a difficult and complex undertaking in most urban stream corridors. Many natural channel design methods developed in more rural streams need to be modified to reflect the altered hydrology and sediment transport conditions within highly urban streams. Quite simply, the predevelopment stream reference condition is no longer a stable or attainable goal. Instead, designers need to look to the channel geometry of urban streams that have adjusted to the new hydrologic and sediment transport conditions after the subwatershed has reached buildout. The most suitable location for natural channel design is in impacted streams that are expected to experience only moderate channel degradation, and have ample room in the stream corridor to create the expanded channel. It should also be kept in mind that a stable urban channel may not be hospitable to native aquatic life, if hydrologic, habitat, and water quality stresses are not controlled. In some cases, channel redesign can be coupled with upstream storage retrofits to provide more hydrologic control to the redesigned channel reach.

Objective 9: Recover Biological Diversity and Function

This represents perhaps the most ambitious stream repair objective since it seeks to recover biological diversity and ecological functions lost during the urbanization process, as measured by the diversity of fish, aquatic insects, and other organisms. As might be expected, such a challenging objective has been rarely attempted in urban streams, although some notable examples exist (Galli, 1999). The best prospects for success appear to be for impacted urban streams that have already adjusted to subwatershed development and still possess an intact stream corridor. In most cases, recovering diversity requires application of the full range of stream repair practices and many, if not all, of the upland practices, such as storm water retrofits, riparian management, discharge prevention, and pollution source controls.

Konrad (2003) notes that improvement of biological diversity in urban streams should still be considered an experiment, since it is not clear what hydrologic, water quality or habitat stresses are limiting diversity. In addition, the complex ecosystem functions that ultimately support biological diversity, such as carbon processing, nutrient uptake, and riparian interactions are poorly understood in urban streams (Paul and Meyer, 2001 and Paul, 2004).

1.4 The Range of Stream Repair Practices

Stream repairs refer to a large group of practices used to enhance the appearance, structure or function of urban streams. The practices range from routine stream clean-ups, simple stream repairs, all the way up to comprehensive repair applications. Stream repair practices are often combined with storm water retrofits and riparian management practices to meet subwatershed restoration objectives (Table 5). A list of 33 stream repair practices is presented in Table 6, and more detailed guidance on each can be found in Chapter 4.

Stream Cleanups

These practices involve regular pickup and disposal of trash, debris, litter, and rubble from the stream or its corridor, usually with volunteer help. While stream clean-ups are often cosmetic and temporary, they are extremely effective tools to involve and educate the public about urban stream degradation. In addition, public attitudes toward urban creeks are often influenced by the presence or absence of trash and debris. Lastly, well-organized and frequent stream cleanup programs can remove impressive quantities of trash and debris from the stream corridor, thus preventing its movement to downstream waters.

Table 5: Comparative Ability of Stream Repair Practices to Meet Objectives

Stream Repair Practice	Clean Stream Corridor	Naturalize Stream Corridor	Protect Infra-structure	Prevent Bank Erosion	Expand Stream Network	Increase Fish Passage	Improve Fishery Habitat	Achieve Natural Channel Design	Recover Diversity and Function
Stream Clean-up	●	⦿	⦿	○	○	○	○	○	⦿
Hard Bank Stabilization	○	⦿	●	●	●	○	⦿	⦿	⦿
Soft Bank Stabilization	○	⦿	●	●	●	⦿	●	●	●
Flow Deflection	○	⦿	○	⦿	⦿	⦿	●	⦿	●
Grade Control	○	⦿	●	●	⦿	●	⦿	●	●
In-stream Habitat Enhancement	○	⦿	⦿	⦿	⦿	●	●	⦿	●
Flow Diversion	○	⦿	○	⦿	●	○	⦿	⦿	⦿
Fish Barrier Removal	○	○	○	○	●	●	●	⦿	●
Comprehensive Applications	○	●	⦿	⦿	○	●	●	●	●
Storm Water Retrofits	⦿	○	⦿	●	⦿	○	●	●	●
Riparian Reforestation	⦿	●	○	●	●	⦿	●	●	●
Discharge Prevention	⦿	●	●	○	⦿	⦿	●	⦿	●
Pollution Source Controls	●	⦿	○	○	⦿	⦿	⦿	○	●
Watershed Forestry	⦿	⦿	○	●	⦿	⦿	●	●	●

Key ● = essential to meet objective ⦿ = supports the objective ○ = does not address objective

Table 6: List of Stream Repair Practices

Code	Practice
Stream Cleanups	
C-1	Stream Cleanups
C-2	Stream Adoption
Stream Repair Practices	
Hard Bank Stabilization	
R-3	Boulder Revetments
R-4	Rootwad Revetments
R-5	Imbricated Rip-rap
R-6	A-jacks
R-7	Live Cribwalls
Soft Bank Stabilization	
R-8	Streambank Shaping
R-9	Coir Fiber Logs
R-10	Erosion Control Fabrics
R-11	Soil Lifts
R-12	Live Stakes
R-13	Live Fascines
R-14	Brush Mattress
R-15	Vegetation Establishment
Flow Deflection Techniques	
R-16	Wing Deflectors
R-17	Log, Rock, and “J” Vanes
Grade Control	
R-18	Rock Vortex Weirs
R-19	Rock Cross Vanes
R-20	Step Pools
R-21	V-log Drops
In-stream Habitat Enhancement	
R-22	Lunkers
R-23	LWD Placement
R-24	Boulder Clusters
R-25	Baseflow Channel Creation
Flow Diversion	
R-26	Parallel Pipes
R-27	Stream Daylighting
Fish Barrier Removal	
R-28	Culvert Modification
R-29	Culvert Replacement and Removal
R-30	Devices to Pass Fish
Comprehensive Repair Applications	
CR-31	Combining Stream Repair Practices
CR-32	Channel Re-design
CR-33	De-channelization

Simple Stream Repair Practices

These diverse repair practices fix a specific stream problem at a defined point or stream reach. The primary goal may be to stabilize an eroding streambank, remove a fish barrier, daylight a storm water pipe, create in-stream fish habitat, or control channel incision. Stream repair practices are inherently limited by their in-stream location, which may result in the treatment of symptoms but not the underlying causes. Simple stream repairs generally do not involve channel re-design or relocation but instead work within the existing urban stream channel and corridor. In most cases, the repairs involve relatively minor adjustments to overall channel planform, profile or cross-section, and individual structures only minimally interact with each other.

Simple stream repairs are frequently installed in older urban subwatersheds where the stream channel has adjusted its grade and planform to altered urban flows, but it remains degraded. The basic strategy is to accommodate existing flow conditions and help the channel achieve greater stability. As a general rule, simple stream repairs require less extensive stream assessment data during design. And, while simple stream repairs have less potential for large-scale channel improvement, they offer a greater likelihood of success to solve the specific problem. In general, stream repair practices can be classified by their primary design objective:

Hard bank stabilization involves installation of structural bank protection practices to protect streambanks from further erosion or potential failure. Hard bank stabilization practices are used along stream reaches where eroding streambanks threaten private property or infrastructure and where available space or highly erosive flows are a constraint. Hard stabilization practices generally involve the use of rock, logs, or manufactured materials that are not deformable, and are intended to remain in place for decades.

Soft bank stabilization practices stabilize eroding streambanks through a combination of slope control, vegetation, and biodegradable fabrics that establish a stable but deformable bank over time. In many cases, live or dormant woody plant materials are the primary vegetative cover to stabilize eroding banks and improve stream habitat. Woody vegetation gradually develops extensive root systems that reinforce streambank soil structure and produce above-ground stems that reduce water velocity, promote sediment deposition and provide vegetative cover along streambanks. Most soft bank treatments are actually combinations of many individual practices applied together to create a stable bank, which may involve bank shaping, toe protection, erosion control fabrics, live stakes, and rapid vegetation establishment.

Grade control practices are designed to enhance vertical streambed control by providing "hard points" that are resistant to channel downcutting. Most grade controls are constructed of heavy boulders or logs that are firmly anchored into the bed and banks that help maintain the desired stream elevation. Grade controls are a particularly important repair practice for rapidly incising or degrading urban streams.

Flow deflection practices refer to structures placed within the stream channel to alter the direction of flow or concentrate flow within a portion of the channel. These practices generally utilize rock structures to deflect the flow away from eroding streambanks, concentrate flow in the center of a channel, redirect water in and out of meander bends, or enhance pool and riffle habitats.

In-stream habitat enhancement practices include a series of structures placed within urban stream channels to create pools, riffles, resting areas, undercut banks, overhead cover, and other features that improve the quality of fish habitat. Several stream repair practices are explicitly designed to create better fish habitat, such as boulder clusters, lunkers, large woody debris and baseflow channel creation. Other stream repair practices, such as flow deflectors, grade controls and imbricated riprap can also contribute to better fish habitat, but are primarily installed to address different stream repair objectives.

Flow diversion practices are highly engineered practices that modify storm water pipes to create new channels (daylighting) or bypass highly erosive storm water flows around a sensitive stream reach (parallel pipes), both of which are normally applied to smaller urban headwater streams.

Fish passage practices involve modification of existing structures or the placement of new structures to allow the upstream and downstream movement of fish along an urban stream channel, and are applied when historical or current fish survey data suggest that upstream spawning conditions are suitable.

Comprehensive Stream Repair Applications

These applications take a more sophisticated and comprehensive approach toward stream repair with the objective of attaining a more natural geometry and habitat structure for the stream channel that is consistent with its current hydrology and sediment transport dynamics. The ultimate objectives of comprehensive repair applications are to improve habitat conditions for aquatic life such as recovering trout or salmon populations, or to enhance warm-water fish diversity. To meet these objectives, comprehensive repair applications are frequently integrated with other restoration practices in the stream corridor and subwatershed. The three broad approaches to comprehensive stream repairs in this category include:

- Combinations of multiple stream repair practices
- Channel re-design
- De-channelization

The first application combines multiple stream repair practices that interact together to improve stream function, and involves only moderate changes to channel grade, cross-section or planform. The last two applications involve the creation or redesign of a new stable stream channel, in both planform and grade, along a formerly unstable reach. Comprehensive repair applications require a high degree of expertise from multiple disciplines, as well as extensive stream assessment and hydraulic modeling.

Urban subwatersheds are an extremely challenging environment for comprehensive stream repair applications, given the dynamic changes in hydrology and sediment transport caused by upstream development. They are best applied in older urban subwatersheds where streams have had time to adjust to their altered flow regime. They may also be warranted in adjusting urban channels where long-term instability has serious consequences, sufficient stream corridor area is available, and designers can confidently anticipate future channel dimensions. Comprehensive repair applications require careful consideration of current and future storm discharges, floodplain elevations, infrastructure, encroachment, and erosion potential. While comprehensive applications use many of the same practices as simple repairs, they are installed in series and depend on each other for success, which greatly increases the complexity and risk inherent in their design.

1.5 Basic Principles of Stream Repair

The practice of urban stream repair is still evolving, but is gradually coalescing around some basic planning and design principles that can ensure more consistent and effective applications. A cardinal rule is that stream repairs should be designed by interdisciplinary teams that work together from project assessment through final construction. Four other key factors appear to greatly influence the success of urban stream repair, as follows:

- Unique nature of urban streams
- Importance of understanding subwatershed conditions
- Understanding the role of time in channel adjustment
- Choosing and designing repair practices that can withstand urban stream conditions

Unique nature of urban streams

Urban streams are different, and do not have any natural analogs or reference condition. Designers should abandon the notion of returning to predevelopment conditions, since many of the effects of subwatershed development cannot be fully mitigated. The focus instead should be on working with the urban stream and recognizing the unique stresses and adjustment processes they must experience.

In particular, designers should seek to understand the stressors that are actually limiting biological productivity in the stream. For example, the assumption that constructing stream habitat features will automatically lead to colonization by fish or aquatic insects may not always be warranted. Downstream interruptions, fish barriers, physical stresses, and poor water quality conditions may not support a diverse biological community in some urban subwatersheds.

Urban streams can never be solely managed as a natural system, but need to account for community needs and objectives, such as flood water elevations, sewers, bridges, crossings, recreation, and safety. In some cases, community objectives may take precedence over biological objectives.

Importance of Understanding Subwatershed Conditions

Urban stream repair cannot be isolated from its subwatershed context. Designers should thoroughly understand current and future subwatershed conditions, and recognize that the prospects for success are fundamentally constrained by the amount and age of subwatershed impervious cover. In this sense, a subwatershed assessment and screening process can identify individual reaches with the greatest potential for project success. A systematic approach to stream repair is preferable to selecting projects based on targets of opportunity or complaints.

Stream repair actually begins by trying to influence the subwatershed conditions that have altered predevelopment hydrology, sediment transport and habitat conditions. This can only be done by installing other practices in upland areas and the stream corridor. Key practices include:

- Storage and on-site storm water retrofit practices
- Watershed forestry practices
- Riparian reforestation practices
- Discharge prevention practices
- Pollution source control practices

The potential ability to treat a large fraction of the subwatershed with effective upstream practices is perhaps the only sustainable way to achieve actual restoration, as opposed to simple repair.

Understanding The Role Of Time In Channel Adjustment

The response of urban streams to upstream development is highly dynamic, and an understanding of past, current and future channel processes is critical to select the right time and practices to effect stream repairs.

Most urban streams are still actively adjusting their cross-section in response to past development. Consequently, designers should anticipate the future geometry of the channel reach and not base design on current dimensions. Most urban stream channels will become larger and more incised than they are now.

A useful place to start is to look at past stream “repairs” and engineering improvements installed in the urban stream network, including culverts, enclosures, armoring, crossings, and channelization. Designers should envision opportunities to connect stream reaches in good condition, open up the stream network, and retrofit failed or inappropriate bank stabilization and grade control practices installed in the past.

The ideal time to install stream repair practices is when the urban stream channel has fully adjusted to upstream development, and its enlarged dimensions are more or less stable. If the channel is still actively adjusting, no action is a perfectly acceptable repair strategy in subwatersheds, particularly if the stream repair project would result in significant clearing of existing streamside forest.

Extreme caution should be exercised if a subwatershed is still in the process of developing. Indeed, if future subwatershed IC is expected to increase by more than 25%, it may not be advisable to pursue stream repair objectives until the channel has had time to adjust and recover. Management efforts should be shifted to design better storm water practices, stream buffers, and forest conservation areas to mitigate the impact of future development.

Choose And Design Repair Practices That Can Withstand Urban Stream Conditions

Powerful forces are at work in urban streams, and stream repair practices must be designed to resist them. Experience and project failures have shown that designers should consider several factors when working in urban streams, as described in the box below.

DESIGN CONSIDERATIONS

- Any structure installed in the bed or banks can be expected to face future undermining, scour or outflanking during the urban channel adjustment process, and designers need to anticipate how to prevent failure as a result of vertical or lateral movement.
- Practices must be designed to effectively function over the entire range of urban stream flows, from baseflow all the way up to the maximum expected flow.
- Hydraulic modeling is often needed to estimate current and project future design flows and flow velocities that structures must withstand.
- Designers should be conservative when sizing rock and other material to remain immobile under maximum flow conditions.
- The effect of each practice on channel hydraulics, sediment transport channel and floodplain capacity, and fish passage should be thoroughly evaluated.
- Designers should seek to provide a stable active floodplain to dissipate streamflow energy during high flows.
- Designers should utlize flat, low profile structures when working in the channel that do not consume much of the cross-sectional area.
- Deformable streambank treatments should always be considered in wider portions of the stream corridor to allow the channel to naturally migrate.
- Bank toes are normally the most vulnerable area of both bank treatments and in-stream structures, so designers should carefully project the future depth of scour
- The ultimate vegetative condition of the streambank and riparian areas influences local bank dimensions. If these areas are managed in grass cover, they may produce a different bankfull width than if they are fully forested.
- Urban stream repair is still somewhat of an ongoing experiment, and every project should have some form of monitoring or inspection to determine what worked, what didn’t, and why.

Chapter 2: Assessing Stream Repair Potential at the Subwatershed and Reach Scale

This chapter examines how stream repair potential can be systematically assessed at both the subwatershed and reach level. The chapter begins by outlining the eight basic steps involved in stream repair assessment and design. The next section describes desktop methods to identify priority reaches in subwatersheds that have the greatest need or potential for stream repair, and merit subsequent field investigation. The third section introduces the Unified Stream Assessment (USA) that documents impairments in the stream corridor, identifies potential candidate sites for stream repair, and evaluates the overall repair potential within a subwatershed. The section also describes other stream assessment methods that can be used for the same purpose.

The fourth section presents guidance on how to develop initial concept plans for stream repairs within priority project reaches, and describes a process for screening concept designs to take forward for final assessment and design. The last section describes the range of reach assessment studies needed to support the final design of stream repair practices. More detailed design guidance on specific stream repair practices and stream conditions is provided in subsequent chapters.

2.1 Basic Steps in Stream Repair Design

Traditionally, most stream repair projects have been undertaken on an individual "problem" reach, in response to complaints, emergencies, or simple targets of opportunity. Such a scattershot approach to stream repair, however, is unlikely to deliver the maximum subwatershed benefit. This section describes a more systematic approach that evaluates all the streams within a given subwatershed to determine priority reaches with the greatest need or potential for stream repair. The eight basic steps of this subwatershed-based approach to stream repair are summarized below. (*Note that the section numbers in parentheses refer to the corresponding section of this manual where the steps are discussed in detail*.)

Step 1: Define the core objectives early in the subwatershed planning process to guide the scope and focus of stream repair projects (Section 1.3).

Step 2: Conduct desktop analyses to delineate and prioritize subwatersheds and stream reaches for subsequent field screening (Section 2.2).

Step 3: Conduct a rapid stream assessment such as the USA to identify specific impairments in the stream corridor and evaluate overall reach restoration potential (Section 2.3).

Step 4: Develop initial stream repair concept designs for priority reaches (Section 2.4).

Step 5: Prioritize potential reach projects based on feasibility, cost, subwatershed objectives and linkage with upland restoration practices (Section 2.4).

Step 6: Collect additional stream reach data and perform modeling analyses for priority projects, where needed, to determine the causes and mechanisms of impairment and the current stage of channel evolution needed for final design (Section 2.5).

Step 7: Develop final designs for stream repair projects, and assess their construction feasibility in the context of the overall subwatershed plan (Section 3.5).

Step 8: Construct the projects and conduct maintenance and monitoring to determine if they actually met their intended design objective (Section 3.6).

2.2 Desktop Factors to Consider in Stream Restoration

Urban stream repair potential can be initially assessed at the subwatershed level through simple desktop analyses that can quickly screen priority subwatersheds and/or stream reaches to target in subsequent assessment steps. The basic idea is to focus limited resources on the subwatersheds or project reaches with the best repair potential in the context of the overall goals and objectives for the watershed. The process begins with a comparative subwatershed analysis to screen for the priority subwatersheds or reaches.

Comparative Subwatershed Analysis

Quickly screening the most promising subwatersheds for stream repair is a relatively easy task, assuming basic Geographic Information System (GIS) layers are available. Table 7 presents some of the primary and supplemental GIS layers often used to assess stream repair potential in a comparative subwatershed analysis (CSA).

The first step in a CSA involves subdividing the watershed into subwatersheds, and carefully delineating their boundaries and stream reach segments. Next, important stream corridor and subwatershed screening factors are derived from GIS data, and are used to discriminate among all of the subwatersheds or project reaches. Common screening factors at the stream corridor level include channel density, stream corridor area, and number of stream crossings. Common subwatershed screening factors include the percentage of impervious cover, forest cover or public land in the subwatershed, and future retrofit or development potential. A complete list of potential stream repair screening factors is provided in Table 8, along with some supporting rationale.

Each screening factor can be weighted and analyzed in simple spreadsheet models to determine the comparative repair potential of a group of subwatersheds or stream reaches. Both the screening factors selected and their relative weights will be unique to each subwatershed, and should be customized to reflect local restoration goals. Priority subwatersheds or project reaches can then be easily selected based on their individual total scores. The priority areas selected based on the CSA are then investigated in the field in the next step. The GIS layers assembled for the CSA are rearranged to produce field maps to support survey teams.

Table 7: GIS Data Needs for Desktop Analysis of Stream Repair Potential

Primary	• Topography (5-ft resolution) for subwatershed delineation • Perennial stream network for stream density and corridor maps • Parcel or plat data to determine corridor ownership and age of development • Structures or land use to derive current subwatershed impervious cover • 100 year floodplain or other layer that defines the stream corridor • Forest cover, to determine % cover for corridor and subwatershed • Roads to determine crossings and stream access • Publicly owned land • Aerial photography
Helpful	• Zoning (to determine future subwatershed development potential) • Wetlands • Storm water outfalls • Sewer infrastructure
NOTE: Consult manuals 2 and 10 of the Urban Subwatershed Restoration Manual series for more guidance on desktop methods for subwatershed analysis	

Table 8: Desktop Screening Factors to Assess Subwatershed Stream Repair Potential

Primary	***Subwatershed Stream Density*** (stream miles/square mile) – This metric indicates how much of the urban stream network has been enclosed or altered in the past. A high stream density suggests more potentially suitable reaches for stream repair.
	Available Area in the Stream Corridor (acres/stream mile) – This metric provides a general indication of how much of the stream corridor is potentially available to install stream repair practices and related riparian reforestation practices. Subwatersheds with a high score have many more potential sites to work with.
	Road Crossings (crossings/stream mile) – This metric is an index of the amount of stream interruption within a subwatershed. Road culverts and other crossings are always potential fish barriers, and streams with many crossings may have major fish passage problems that may preclude some fishery recovery options.
	Current Subwatershed Impervious Cover (%) – As noted in Chapter 1, impervious cover (IC) is a powerful predictor of stream quality and restoration potential. Generally, subwatersheds with lower IC are better candidates for stream repair than ones with higher IC.
	Average Age of Subwatershed Development (years) -- This metric, which can be derived from plat or parcel data, provides a general indication of how much time stream channels have had to respond to past upstream subwatershed development. In general, older subwatersheds (30+ years) are better candidates than younger ones, since they may no longer be actively adjusting.
	Subwatershed Development Potential (% of subwatershed) – Subwatersheds with a high future development potential, as determined from zoning, are normally ranked lower because their stream channel network is expected to face increased storm water flows and sediment transport in the future.
	Density of Storm Water Management Ponds (Number/square mile) – This metric is a general index of both the current degree of storm water management and the future retrofit potential in the subwatershed. In general, a high density of ponds is preferred unless they have been built in the perennial stream network.
	Stream Corridor Forest Cover (% of stream corridor) – This metric can be hard to derive, but it is an index of the potential area available for riparian reforestation. Paradoxically, stream corridors with a low percentage of forest cover may be preferred since they have more opportunities for reforestation, better stream access, and require less clearing of existing mature forests during construction.
Supplemental	***Subwatershed Forest Cover*** (%) – Total forest cover can influence potential stream quality, and this metric ranks subwatersheds with extensive forest cover as having better prospects for ultimate restoration.
	Connection to Downstream Waters (Open or impeded) – This index is derived by looking at all crossings and barriers between the bottom of the subwatershed and the desired downstream receiving water (river, lake or estuary). Subwatersheds that are open to migration and/or re-colonization are preferred over subwatersheds where movement is partially or fully impeded by crossings, barriers, and dams.
	Stream Corridor in Public Ownership (%) - It is much easier to construct stream repairs on publicly owned or controlled land in the stream corridor, such as parks, greenways and floodplains. Subwatersheds with a high percentage of public corridor ownership are preferred.
	Fisheries Data (various) – Some regions have good data on current or historical fish populations, fish blockages or habitat quality. If available, fishery data should always be used for desktop screening, with subwatersheds possessing good/fair quality fishery data preferred over ones designated as poor.
	Citizen Concern (various) – Subwatersheds with an active watershed group, recreational users group or neighborhood association are normally ranked higher.

2.3 Assessing Stream Repair Potential with the USA

The USA is a continuous stream walk method that systematically evaluates impairments and identifies repair opportunities within the stream corridor of small watersheds (Table 9). The USA has undergone extensive field testing, and is a composite of many different stream assessment protocols. The USA is designed to rapidly collect basic information needed to assemble a manageable list of potential stream repair projects in the stream corridor. Only the basics of the USA are reviewed here, and only in the context of stream repair. A full user manual can be found in *Manual 10: Unified Stream Assessment: A User's Manual* (Kitchell and Schueler, 2004). The USA consists of nine stream corridor assessments: eight impact assessments and a single overall reach assessment. Impact assessments collect specific information at individual problem sites along the stream corridor, such as a storm water outfall, a severely eroded streambank, or a sanitary sewer overflow (Table 10). Reach assessments evaluate average conditions along the entire survey reach, where many impact sites are located. Each survey reach represents a relatively uniform set of conditions along the stream corridor and is used to characterize average bank stability, in-stream habitat, and riparian vegetation.

The reach assessment form (RCH) should be completed for every survey reach in a subwatershed. The RCH form can help screen stream repair opportunities by comparing reach conditions against those elsewhere in the subwatershed. The RCH assessment form can also derive several useful metrics to assess the feasibility of stream repair. For example, the back of the RCH form contains an overall index of stream habitat quality, which can be subdivided into stream and floodplain components. Other useful RCH data include reach accessibility, land ownership and wildlife utilization.

One advantage of the USA survey is that it can be customized to collect only the specific information desired for stream assessment. Table 11 indicates which specific impact and reach assessment forms should be used to collect data most relevant to local stream repair objectives.

It is always a good idea to allocate some office time to organize, map and interpret the wealth of USA data collected in the field. Simple maps of stream impacts or overall reach conditions are often quite helpful in assessing stream repair potential within the context of the larger subwatershed. An example map that portrays USA data is provided in Figure 5. Additional ideas on how to interpret USA data to develop better subwatershed restoration plans can be found in Manual 10.

Other Stream Assessment Techniques

The USA is one of many tools used to perform rapid stream assessment within a subwatershed; some alternative stream assessment tools are described in Table 12.

Table 9: Components of the Unified Stream Assessment (USA)
Impact assessments are site-specific and record data on condition and "restorability" at each problem site. Impact forms comprise an initial inventory of stream repair opportunities. The eight impact assessment forms are: Outfalls (OT)—*all storm water discharge pipes* Severe erosion (ER)—*bank sloughing, active widening or incision* Impacted buffer (IB)—*lack of natural vegetation, width* Utilities in the Stream Corridor (UT)—*leaking sewer, exposed pipes susceptible to damage* Trash and Debris in the Stream Corridor (TR)—*trash and illegal dumping* Stream Crossing (SC)—*culverts, dams, blockages* Channel Modification (CM)—*straightening, channelization, dredging, etc.* Miscellaneous (MI)—*unusual features or conditions*
The reach assessment form (RCH) characterizes the average physical conditions over the entire survey reach. The RCH assessment tracks individual problem sites and provides information used to compare reach quality throughout the entire stream corridor. Reach Assessment (RCH)—*average bank stability, in-stream habitat, riparian vegetation, flood plain connectivity, access, flow, and substrate over the entire reach.*

Table 10: Restoration Practices to Address Stream Corridor Problems

USA Form	Stream Corridor Problem Assessed	Potential Stream Repair Technique (Profile sheet numbers)*
OT	• Suspected illicit discharge • Enclosed stream channel • Outfall location • Outfall damage	• Discharge investigations (Manual 6) • Stream daylighting projects (R-27) • Storage retrofit below outfall (Manual 3) • Local stream repair/outfall stabilization
ER	• Nature and type of channel erosion • Severity of bank erosion • Threatened infrastructure	• Potential sites for hard and soft bank stabilization (R-3 to R-15) • Grade control practices (R-18 to R-21)
IB	• Encroachment in stream corridor • Condition of buffer vegetation • Width of the stream corridor	• Riparian reforestation (Manual 5) • Bufferscaping (Manual 8)
UT	• Sanitary sewer overflows • Leaking sewer pipes and manholes • Sewers crossing streams	• Hard bank stabilization for threatened infrastructure (R-3 to R-7) • Fish Barrier Removal (R-30) • Discharge Prevention Practices (Manual 6)
TR	• Trash/debris in the stream • Dumping in stream corridor	• Stream clean-up sites (C-1) • Stream adoption segments (C-2)
SC	• Fish barriers • Stream interruption • Potential runoff storage • Scour/erosion below crossing	• Fish barrier removal (R-30) • Culvert repair/replacement (R-28, R-29) • Upstream storage retrofit (Manual 3) • Local stream repair (R-3 to R-21)
CM	• Stream interruption • Channelization • Habitat degradation	• Baseflow channel creation (R-25) • Natural channel design (CR-32) • De-channelization (CR-33)
MI	• Wetlands and natural area remnants • Livestock access/hobby farms • Fish kills	• Riparian wetland restoration (Manual 5) • Exclusionary fencing, alternative water source • Discharge prevention (Manual 6)
RCH	• Average stream corridor habitat • Average streambank erosion • Disconnected floodplains • Floodplain encroachment • Restoration feasibility factors	• Tracks locations of potential stream repair practices for the project reach, assesses feasibility factors such as access, and summarizes average channel dimension and comparative habitat scores.

*The code in parentheses refers to the appropriate stream repair profile sheet in this manual. Manual numbers are as follows:

- Manual 3: Storm Water Retrofit Practices
- Manual 5: Riparian Management Practices
- Manual 6: Discharge Prevention Practices
- Manual 8: Pollution Source Control Practices

Table 11: USA Field Forms to Assess Different Stream Repair Objectives	
Stream Repair Objective	**USA Field Forms to Use**
Clean Up the Stream	TR: dumping sites, volume of trash, access, suitability for stream adoption OT: suspected illicit discharges UT: suspected sewage discharges
Naturalize Stream Corridor	IB: reforestation potential, available width, invasive plants ER: erosion severity, threat to infrastructure, erosion process RCH: overall reach conditions, wildlife utilization
Protect Threatened Infrastructure	ER: erosion threat to adjacent property OT: damage to storm water outfall SC: damage to existing culvert or road crossing UT: severity of threat to utility
Prevent Bank Erosion	ER: erosion severity, threat to infrastructure, erosion process, MI: location of knickpoints RCH: bank erosion severity, average bank dimensions, channel dynamics
Expand/Reconnect Stream Network	SC: crossing type and dimensions, blockage severity, removal options OT: stream daylighting opportunities CM: nature, length and severity of channelization, baseflow channel depth
Increase Fish Passage	SC: blockage severity, modification and removal options, drop in elevation CM: nature, length and severity of channelization, baseflow channel depth UT: whether utility crossing is potential fish barrier RCH: reach channel dynamics, upstream habitat quality, access
Improve Fishery Habitat	IB: available width, reforestation potential ER: bank erosion severity, channel dynamics RCH: substrate, shading, channel dimensions and dynamics, in-stream and floodplain habitat conditions, wetted perimeter, access
Achieve Natural Channel Design	IB: available width CM: adjacent corridor area SC: status of crossings grade controls UT: utility constraints in the corridor RCH: bank erosion severity, average bank dimensions, channel dynamics, construction access, floodplain width
Restore Aquatic Diversity and Function	ALL FORMS
Note: All USA field forms can be found in Manual 10	

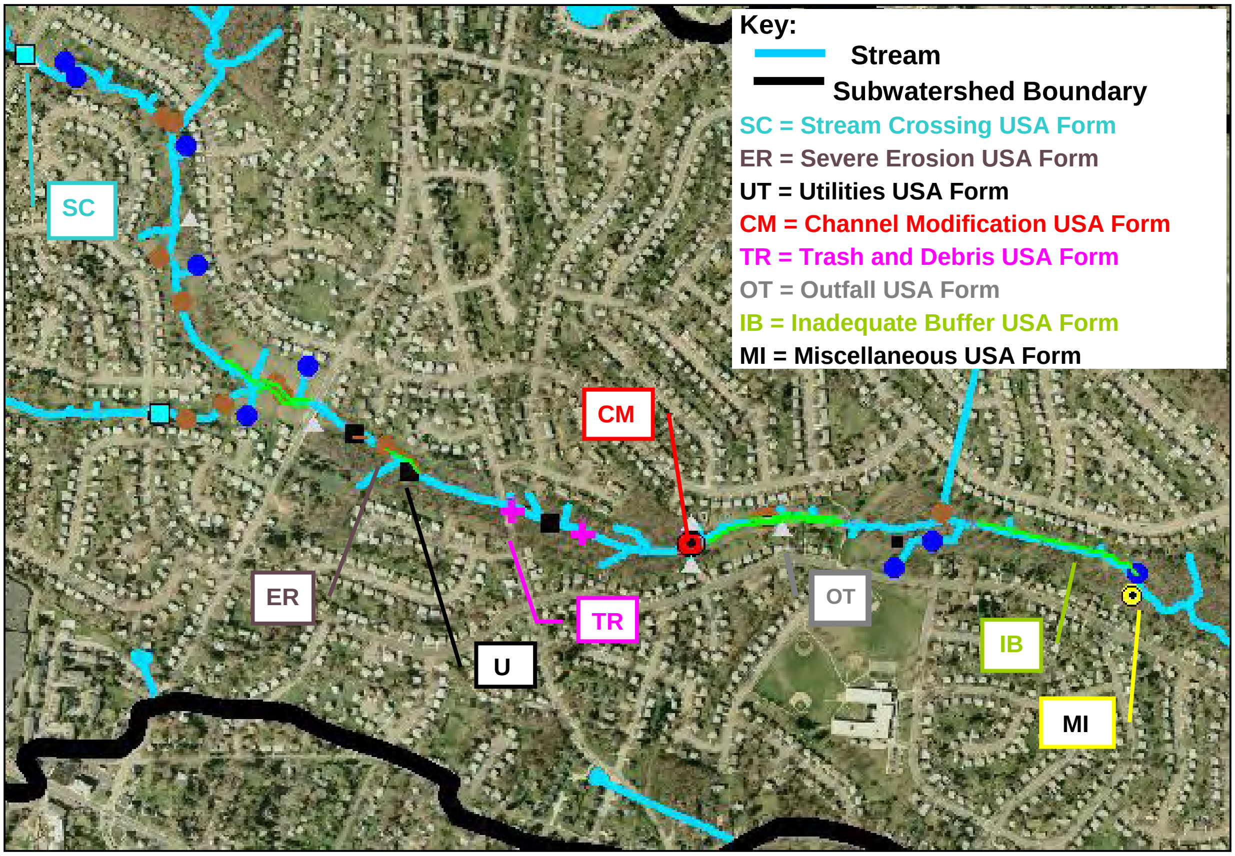


Figure 5: Map of USA Stream Repair Data

Table 12: Other Stream Assessment Tools
Numerous biological and physical assessment techniques have been developed to rapidly evaluate stream conditions. The Watershed Science Institute (2001) has prepared a summary of over 40 different assessment tools, which can be accessed at http://www.wcc.nrcs.usda.gov/ click on planning tools and scroll down to *Stream Corridor Inventory and Assessment Techniques.* Some other useful stream assessment tools include: • The *Stream Visual Assessment Protocol* (SVAP) is a physical assessment technique geared toward streams in rural subwatersheds with farming or ranching activity (USDA, 1998). The SVAP is generally conducted one on one with individual landowners, and focuses primarily on riparian management. Documentation on the SVAP can be accessed at: http://www.wcc.nrcs.usda.gov/wqam/wqam-docs.html. • Galli (1996) developed the *Rapid Stream Assessment Technique* (RSAT) to quickly assess streams in urbanized watersheds, with a focus on altered stream channel and riparian conditions. This protocol was originally developed for use in Piedmont streams. A PDF document describing RSAT can be downloaded at http://www.stormwatercenter.net • The *Rapid Bioassessment Protocols* (RBP) as part of a suite of tools for assessing streams and rivers developed by Barbour *et al*. (1999). The RBP habitat assessment component is frequently used to relate stream impairments found during biological sampling of aquatic insects or fish to observed stream channel and riparian conditions. The RBP habitat component has been developed and tested over wide range of watershed conditions and land uses. Information on RBP protocols can be found at http://www.epa.gov/owow/monitoring/rbp

2.4 Initial Project Concept Design and Subwatershed Screening

Most subwatersheds have many more potential stream repair projects than available resources for either design or construction. Thus, this step in the stream repair planning process involves two tasks to narrow down the choices to a manageable level. The first task involves rapid development of concept designs for stream repair projects within defined reaches that provide a general sense of the type or combination of practices applied, along with their cost and feasibility. The concepts should always be coupled with upstream retrofit practices that can address flow control and sediment transport. The second task consists of a ranking process to screen the best stream repair candidate projects to investigate further for more stream assessment and possible final design.

Developing Initial Concept Designs for Stream Repair Projects

Much of the initial concept design can be developed based on USA survey data and field observations, although in some cases, a second visit to a project reach may be needed to verify site information, collect more stream assessment data, and work up a more detailed design sketch. Basic information is recorded on a Stream Repair Investigation Form for each project reach. Figure 6 provides a sample, completed form. A blank version of the form can be found in Appendix B, which should be adapted to suit local conditions and stream repair objectives.

The initial concept design is intended to be a fairly rapid and organized description of the general approach to stream repair within a defined project reach, and is primarily used to determine whether the candidate project has enough merit to take it to the next stage of assessment and design. The initial concept design has four basic parts, as described below and shown in Figure 6:

Part A: Header Information Much of the information in this part of the form is simply copied from USA forms filled out earlier. The header section provides essential locational and organizational data, and should cross-reference any USA forms that were previously filled out for the project reach that may provide additional information to derive the concept design.

Part B: Feasibility Factors The front part of the form asks designers to assess and rate 11 key site factors that influence the feasibility of stream repairs within the project reach. The feasibility factors are subsequently used for screening purposes, and include:

- Land Ownership
- Available Riparian Corridor
- Corridor Vegetation
- Degradation Severity
- Upstream/Downstream Condition
- Construction Access to Stream
- Infrastructure Constraints
- Restoration Outcome Potential
- Upstream Age of Development
- Upstream Retrofit Potential
- Scope of Planned Repairs

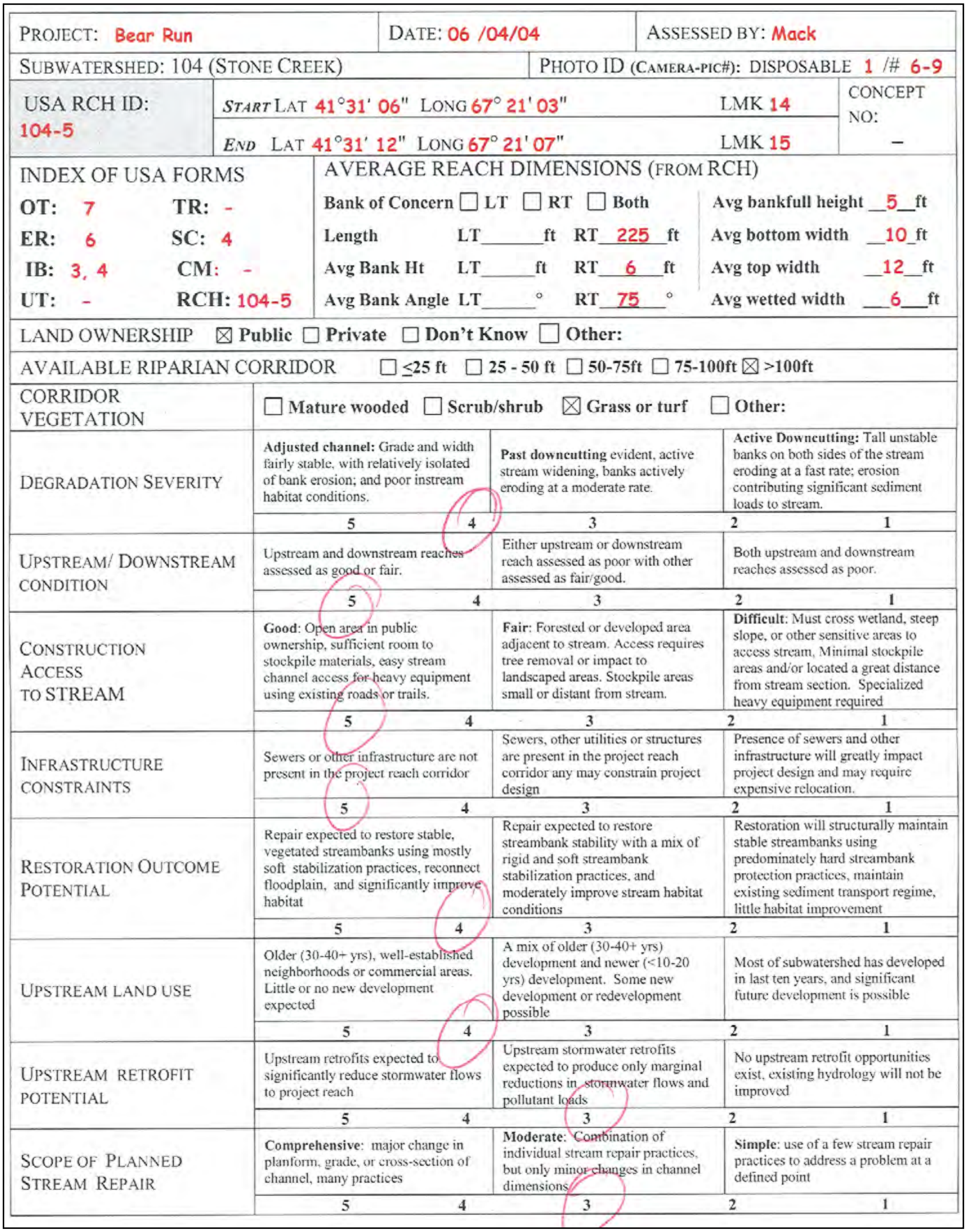
The form provides some narrative guidance on how to assess and rate each feasibility factor. If one or more factors suggest that a stream repair project is infeasible or impractical (e.g., uncooperative landowner and no construction access), then further work on the concept plan should be halted.

Part C. Concept Sketch and Proposed Stream Repair Practices The sketch is the heart of the initial concept plan, and should show the stream and corridor in plan view, along with the approximate locations of the general groups of stream repair practices that might be installed. At this point, specific recommendations about exact stream repair practice are not needed (since these decisions are made during final design, after detailed stream assessment data has been analyzed). The sketch should also show the limits of forest cover, potential access routes, and the general location of any sewers or utilities. Check boxes are provided next to the sketch to indicate the major stream repair groups that might be applied, along with the estimated number of structures or linear feet of practices proposed.

Part D. Comments, Special Studies/Permits and Cost Estimates The last part of the form provides a brief narrative of the overall stream repair strategy for the project reach, along with notations as to whether any additional monitoring studies or special permits or approvals are needed. The right hand panel provides space to calculate a planning level cost estimate for the project reach as a whole, using the practice dimensions indicated on the sketch multiplied by unit cost data provided in Chapter 3 of this manual. Normally, this last part of the concept design is worked up back in the office.

Screening Project Concepts to Take to Final Design

Once all of the initial concept plans have been developed, they need to be screened to choose priority stream repair projects to investigate further, and possibly take to final design. This is done in the same basic manner as the CSA described earlier. Common screening factors developed for each project reach are based on scores from the corresponding stream repair investigation forms. The final list and weighting of concept design screening factors depends to a great degree on the overall restoration objectives for the subwatershed. The scores for each project reach are then analyzed in a simple spreadsheet model to determine the best candidates to take to final design. A hypothetical example of subwatershed screening factors and their corresponding weights is provided in Table 13.



PROJECT: Bear Run	DATE: 06 /04/04	ASSESSED BY: Mack
SUBWATERSHED: 104 (STONE CREEK)		PHOTO ID (CAMERA-PIC#): DISPOSABLE 1 /# 6-9

USA RCH ID: 104-5	START LAT 41°31' 06" LONG 67° 21' 03" LMK 14 END LAT 41°31' 12" LONG 67° 21' 07" LMK 15	CONCEPT NO: –

INDEX OF USA FORMS

OT: 7 TR: -
ER: 6 SC: 4
IB: 3, 4 CM: -
UT: - RCH: 104-5

AVERAGE REACH DIMENSIONS (FROM RCH)

Bank of Concern ☐ LT ☐ RT ☐ Both
Length LT_____ft RT 225 ft
Avg Bank Ht LT_____ft RT 6 ft
Avg Bank Angle LT_____° RT 75 °
Avg bankfull height 5 ft
Avg bottom width 10 ft
Avg top width 12 ft
Avg wetted width 6 ft

LAND OWNERSHIP ☒ Public ☐ Private ☐ Don't Know ☐ Other:

AVAILABLE RIPARIAN CORRIDOR ☐ ≤25 ft ☐ 25 - 50 ft ☐ 50-75ft ☐ 75-100ft ☒ >100ft

CORRIDOR VEGETATION ☐ Mature wooded ☐ Scrub/shrub ☒ Grass or turf ☐ Other:

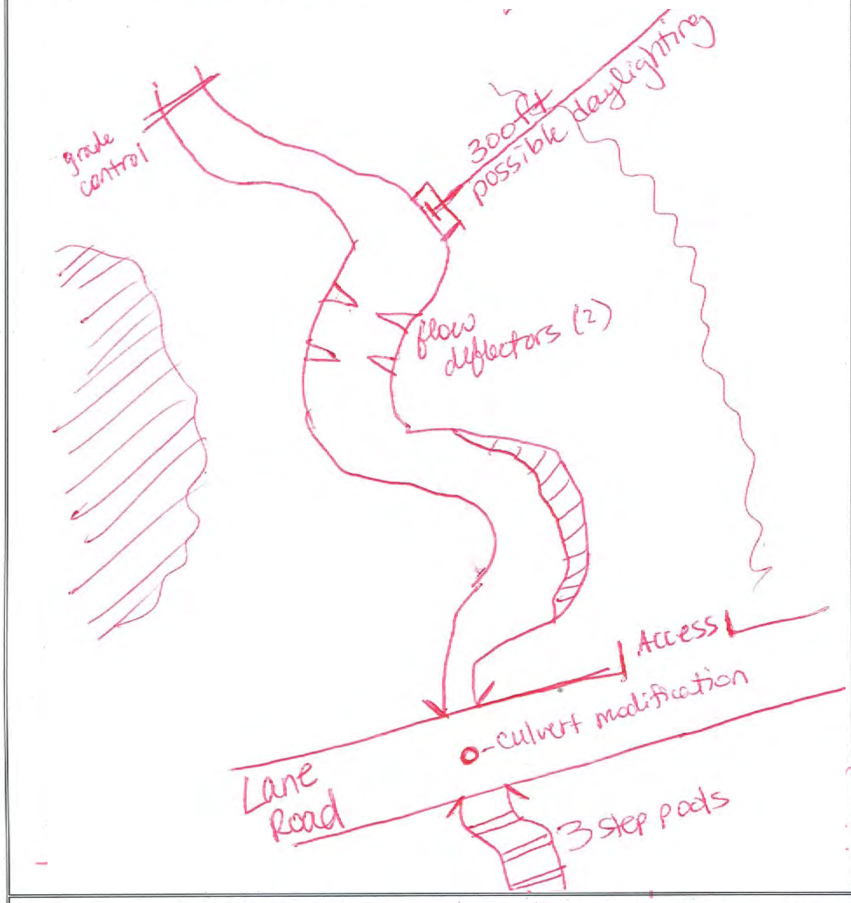
DEGRADATION SEVERITY	**Adjusted channel:** Grade and width fairly stable, with relatively isolated of bank erosion; and poor instream habitat conditions.	**Past downcutting** evident, active stream widening, banks actively eroding at a moderate rate.	**Active Downcutting:** Tall unstable banks on both sides of the stream eroding at a fast rate; erosion contributing significant sediment loads to stream.
	5 [✓ 4]	3	2 1
UPSTREAM/ DOWNSTREAM CONDITION	Upstream and downstream reaches assessed as good or fair.	Either upstream or downstream reach assessed as poor with other assessed as fair/good.	Both upstream and downstream reaches assessed as poor.
	[✓ 5] 4	3	2 1
CONSTRUCTION ACCESS TO STREAM	**Good:** Open area in public ownership, sufficient room to stockpile materials, easy stream channel access for heavy equipment using existing roads or trails.	**Fair:** Forested or developed area adjacent to stream. Access requires tree removal or impact to landscaped areas. Stockpile areas small or distant from stream.	**Difficult:** Must cross wetland, steep slope, or other sensitive areas to access stream. Minimal stockpile areas and/or located a great distance from stream section. Specialized heavy equipment required
	[✓ 5] 4	3	2 1
INFRASTRUCTURE CONSTRAINTS	Sewers or other infrastructure are not present in the project reach corridor	Sewers, other utilities or structures are present in the project reach corridor any may constrain project design	Presence of sewers and other infrastructure will greatly impact project design and may require expensive relocation.
	[✓ 5] 4	3	2 1
RESTORATION OUTCOME POTENTIAL	Repair expected to restore stable, vegetated streambanks using mostly soft stabilization practices, reconnect floodplain, and significantly improve habitat	Repair expected to restore streambank stability with a mix of rigid and soft streambank stabilization practices, and moderately improve stream habitat conditions	Restoration will structurally maintain stable streambanks using predominately hard streambank protection practices, maintain existing sediment transport regime, little habitat improvement
	5 [✓ 4]	3	2 1
UPSTREAM LAND USE	Older (30-40+ yrs), well-established neighborhoods or commercial areas. Little or no new development expected	A mix of older (30-40+ yrs) development and newer (<10-20 yrs) development. Some new development or redevelopment possible	Most of subwatershed has developed in last ten years, and significant future development is possible
	5 [✓ 4]	3	2 1
UPSTREAM RETROFIT POTENTIAL	Upstream retrofits expected to significantly reduce stormwater flows to project reach	Upstream stormwater retrofits expected to produce only marginal reductions in stormwater flows and pollutant loads	No upstream retrofit opportunities exist, existing hydrology will not be improved
	5 4	[✓ 3]	2 1
SCOPE OF PLANNED STREAM REPAIR	**Comprehensive:** major change in planform, grade, or cross-section of channel, many practices	**Moderate:** Combination of individual stream repair practices, but only minor changes in channel dimensions	**Simple:** use of a few stream repair practices to address a problem at a defined point
	5 4	[✓ 3]	2 1

Part A

Part B

Figure 6a: Stream Repair Investigation Form (front)

Concept Sketch: **Plan View of stream with approximate locations of stream repair practices**



PROPOSED STREAM REPAIR PRACTICES

☐ **A. Rigid Bank stabilization**
______ **linear feet**

☒ **B. Soft bank stabilization**
225 **linear feet**

☒ **C. Flow deflection**
2 **# of structures**

☒ **D. Grade control**
4 **# of structures**

☐ **E. Habitat structures**
______ **# of structures**

☒ **F. Flow diversion**
1 (300 ft) **# of structures**

☒ **G. Fish passage**
1 **# of structures**

☐ **H. Comprehensive**
______ **linear feet**

☒ **I. Other:**

reforestation 1200 feet long; 50 feet on each bank.

Part C

Comments on Project Design **(include any special supplemental design studies or permits needed)**

Major intent of project is to enable fish passage through culvert by creating step pools and to install a culvert modification at Lane Road to open up upstream areas. Some soft bank stabilization may be needed on the right bank and double wing deflectors are recommended to narrow baseflow channel and create riffles in widened sections near top. Possible daylighting of 36" storm water pipe could provide additional space

Further studies needed: longitudinal study above/below Lane Road; hydraulic analysis of current culvert capacity; fish studies; hydro/hydraulic modeling to assess daylighting feasibility.

Planning Level Cost Estimate

B: 225 X $30 = $6750

C: 2 X $1600 = $3200

D: 4 x $1600 = $6400

F: 1 @ $125/ft X 300 ft = $37500

G: 1 @ $10,000 = $10,000

I: reforestation 1.38 acres @ $4500/acre = $6,210

TOTAL COST (EXCLUSIVE OF DESIGN) = $70,060

Part D

Figure 6b: Stream Repair Investigation Form (back)

Table 13: Ranking Factors for Stream Repair Project Concepts

Stream Repair Screening Factors	Max Points
***Project cost*:** planning level cost estimate of total cost to install the stream repair practices over the length of project reach. Points are awarded based on the cost per project length, with more points given to projects with a lower cost per linear foot (lf). For example, 10 points might be awarded a project reach with an average cost less than $50/lf, 5 for $100/lf, and 1 if project costs exceed $200/lf	10
***Construction access*:** rates whether adequate construction access is available to get to the project reach, and if access roads or forest clearing are needed for stockpiling or heavy equipment access. Points are deducted for sites with poor access or that require significant clearing.	10
***Compatibility with subwatershed objectives*:** rates whether the project directly support the intended stream repair project objectives selected for the subwatershed. Points are deducted for projects that do not directly support objectives, or do so only indirectly.	10
***Linkage with other practices*:** stream repair projects that are combined with planned upstream retrofits or adjacent riparian reforestation projects are assigned more points, since these additional practices help contribute to project success.	10
***Land ownership*:** evaluates whether the project reach is on public land or private land. More points are awarded for project reaches located on public land, since costs to negotiate easements and maintenance conditions on private lands can be high. Points may also be deducted for public lands, if significant negotiation or long approval process is expected from the local or non-local agency.	10
***Stable or adjusted stream channel*:** rates the stability of the project reach, and whether it's enlarged but stable, or is actively adjusting. Points are deducted for project reaches that are still actively adjusting, since they often require additional design, more practices to be installed, and have a higher risk of project failure.	10
***Fisheries value*:** rates the degree to which a project supports local fishery objective, which may be a put and take trout stream, salmon rearing, warm water fishery, etc. Significant point deductions are made for project reaches that cannot support the local fishery objective because of water quality, inadequate habitat or physical stresses.	10
***Length of upstream habitat opened up*:** important screening factor for fish passage projects, which rates the relative length of quality upstream fish habitat potentially created as a result of the project.	5
***Demonstration value*:** added points are given to projects that demonstrate new or innovative stream repair practices, or are located in high visibility areas with high watershed education value.	5
***Community acceptance*:** community support or opposition can be a major feasibility factor in some urban stream repair projects, and is best scored by giving stakeholders or adjacent neighbors an opportunity to rank individual projects.	5
Special permits or studies: The need to secure special permits or approvals can jeopardize a project and certainly increase design costs. Points are deducted if wetlands are present, floodway elevations must be maintained or special design studies must be performed to support final design.	5
***Protection of threatened infrastructure*:** This is often an important screening factor for local agencies that want to minimize risk to existing infrastructure.	5
***Other factors*:** Other screening factors can include upstream/downstream habitat condition scores, recreational value, the scope of planned stream repair, and other factors important to the design team or stakeholder groups.	5
TOTAL POSSIBLE SCORE	100
Note: This is a hypothetical example only; the exact selection of screening factors and their relative weights should be determined by the design team and stakeholders to reflect the primary repair objectives chosen for the subwatershed.	

2.5 Detailed Reach Analysis to Support Final Design

Additional stream reach assessment data is usually needed to support the final design of stream repair practices. The amount and sophistication of reach assessment depends on whether the project is a simple stream repair, or part of a more comprehensive repair application, such as channel redesign, de-channelization or a combination of individual practices. In general, up to five different types of assessment data may be needed to support final design, including:

- Survey stream reach
- Determine dominant channel process
- Model future hydrology and sediment transport to the project reach
- Evaluate of recovery potential of aquatic community
- Assess stream corridor

This section describes each type of reach assessment, and provides reference to the methods and resources needed to conduct them.

Survey Stream Reach

Basic topographic surveys are essential to the design of nearly all stream repair practices, and consist of four inter-related reach surveys.

Substrate Surveys - A substrate analysis should always be performed for the streambed and the banks. The standard method involves pebble or particle counts to define the distribution frequency of particle sizes found on the streambed. The standard reference for pebble counts methods is Bundt and Abt (2001), with a concise summary also found in Doll *et al*. (2003). Pebble counts enable designers to classify the reach as having a pebble, cobble or boulder-sized streambed. If the streambed is composed of finer substrates, such as silt or sand, then a gradation analysis should be substituted for the pebble count. Methods for performing and interpreting gradation analyses can be found in Appendix D of Copeland *et. al* (2000). Substrate data is extremely important in design, as it suggests the size of particles that the dominant bed size transported under high flows, and indicates which kind of stream repair practices will be most suitable for the project reach.

B. Longitudinal Survey- A topographic survey looks at elevation or gradient changes within the project reach, and often extends further upstream or downstream. The survey begins by establishing a permanent benchmark in the stream corridor (such as a sewer manhole) and extends longitudinally down the stream channel. Typically, the survey uses a minimum of one-foot contour intervals and establishes the transects to be used in the cross-sectional survey.

The elevation of the streambed, water surface, bankfull elevation, top of bank, and terrace features are all tracked in a downstream direction. The difference between the streambed and water surface elevations are used to distinguish stream habitat features within the project reach, such as pools, riffles, as well as runs and glides. Data on the distribution of stream habitat types can provide useful clues as to missing habitat elements in the urban stream and the possible spacing of habitat forming structures (Newbury *et al*., 1998).

Longitudinal surveys may also map the grade along the thalweg, which is the deepest portion of flow in the channel, and will typically note the top and bottom elevations of riffles, bottom elevation of pools, glides, and runs. The locations of knickpoints, grade controls, culverts, and utility crossings should always be fixed on urban longitudinal surveys.

Longitudinal surveys also provide important clues as to the potential need for and optimal location for grade controls in urban stream reaches. Longitudinal profiles should be examined for over-steepened sections that may indicate the reach is experiencing channel incision or downcutting.

Cross-sectional Survey - This survey evaluates the cross-sectional dimensions of a stream channel taken at regular transects, including both riffles and pools, and is tied to the longitudinal survey. The number of transects depends on the length of the project reach and the complexity of the repair proposed, but a minimum of three should be taken. Perhaps the most important design parameter associated with the cross-section survey is the estimate of the bankfull elevation, which may not always be the top of bank in entrenched urban streams. Methods for estimating bankfull elevations can be found in Appendix A of Doll *et al*. (2003). Establishing an accurate bankfull elevation in rapidly adjusting streams can be difficult (Miller *et al*., 2001) and some professional judgment may need to be exercised. The bankfull elevation is critical in that it establishes the corresponding bankfull cross-section, discharge and velocity for the project reach, each of which is used in sizing and locating stream repair practices. Other key dimensions derived from the cross-section survey include the mean bankfull depth and width, the entrenchment ratio, and the angle and stability of banks.

<u>Planform Survey</u> - A planform survey evaluates the lateral extent and shape of the urban stream channel in the context of the valley it flows through and is typically developed by analyzing recent aerial photographs. The planform survey is used to establish the sinuosity of the channel, calculate various types of meander geometry, and locate bar features, thalweg, large woody debris, and other channel features. Rosgen (1997) is considered the standard reference for defining planform geometry variables.

Planform data is used to distinguish straight and meandering segments in the project reach, and to identify bank areas that are vulnerable to future erosion. If possible, recent and historical aerial photographs should be compared to yield clues as to how the channel has adjusted its pattern over time (or, as is the case with many urban streams, been altered, channelized, or otherwise “improved” in the past).

Determine the Dominant Channel Process

Stream surveys and field observations help define the dominant channel process that is currently occurring within the project reach, and the rate at which it is working. For most urban streams, the dominant channel process may be:

- Active channel incision, with upstream headcutting
- Channel incision, no widening (yet)
- Channel incision, widening occurring
- Channel incision and widening have occurred
- Widening but no channel incision (yet)
- Lateral instability with some in-stream deposition
- Aggradation with notable buildup of sediment in the channel
- Local streambank instability due to bank conditions
- Historical channel alteration such as channelization

Different segments of the project reach may experience different channel processes. Most urban streams can be expected to experience some degree of channel incision or widening in response to upstream development. A good understanding of channel process is extremely important to determine the underlying causes of stream impairments, develop a realistic stream repair strategy, and decide whether stream repairs should even be pursued. For example, many stream repair practices are not recommended in streams that are actively incising or widening.

The real trick in urban streams is to determine the next stage of channel evolution (i.e., to not only understand the channel process occurring now, but what it will be in the future). For some reaches, the future channel process can be inferred based on knowledge of subwatershed conditions, such as the amount of impervious cover or age of development, but in other cases, future conditions must be explicitly modeled.

Model Future Hydrology and Sediment Transport to Project Reach

Modeling of future hydrology and sediment transport is essential to support the design of comprehensive stream repair applications (CR-31 to CR-33), and may also be helpful for individual stream repair practices as well. Modeling requires excellent characterization data for both the subwatershed and the project reach to get accurate projections, and much of this input data is obtained from earlier surveys and desktop analyses.

The primary purpose of hydraulic modeling is to determine the future magnitude of discharge to the project reach, and define the corresponding forces exerted on the channel boundary. This design information is very important for urban streams, since it determines the shear stress and scour velocities to which the channel will be exposed. A series of hydrologic and hydraulic models can be used to derive stable channel dimensions and characteristics for existing and future conditions within the project reach. Typical output from the models include discharges and shear stresses over the full range of expected flow conditions (i.e., six month, one-year, 1.5 year, two-year, and 100-year storm events). Hydraulic modeling is particularly useful if stream repair is occurring at the same time as upstream retrofits are being designed, since it can explicitly incorporate any effects of changed hydrology on future channel dimensions. Modeling is also recommended when considerable subwatershed development has occurred or is expected to occur, since models can predict future increases in bankfull discharge and bank/bed shear stress.

Sediment transport modeling is an important (and frequently neglected) aspect of urban stream repair design. The key output is the average annual bed sediment load delivered to the project reach under current and future conditions. Simulation of sediment transport in urban subwatersheds, however, has been a complex and uncertain enterprise. The Corps of Engineers is currently developing the Sediment Impact Assessment Model (SIAM) that bridges the gap between models that compute sediment yield and models that simulate channel sediment transport. The SIAM will be linked with the widely-used hydraulic model, HEC-RAS, which should make it an easier and more powerful design tool (See Appendix A for more information on both models).

A full discussion of the use of modeling in urban stream repair design is outside the scope of this manual. Several useful summaries and references are available: Copeland *et al*., 2001; Miller *et al*., 2001; and HEC, 1997.

Evaluate Recovery Potential of Aquatic Community

It is regrettable that many urban stream repair projects are undertaken without first evaluating the recovery potential of the aquatic community. Urban streams are stressful environments for many organisms, and simply creating habitat features alone may not ensure that fish or other target species can be supported (see Impervious Cover Model in Manual 1, Appendix A). Therefore, it is a good idea to conduct habitat, biology and water quality surveys within the project reach to determine recovery potential, particularly if the design team is pursuing biological objectives for stream repair.

Numerous methods are available to assess stream habitat and flow conditions, and discern what features are impaired or limiting (Bovee, 1982 and Barbour *et al*., 1999). It is generally a good idea to supplement habitat surveys with fish shocking or aquatic insect sampling to document the diversity or abundance of the aquatic insect community. If the biological surveys indicate poor diversity or that fish are absent, it may be worth investigating whether water quality conditions are limiting.

In some cases, re-colonization of the aquatic community in the project reach is prevented by upstream or downstream barriers to fish migration (which may also explain the absence of certain fish species). Numerous methods are available to assess migration barriers within the urban stream network (see Profile Sheet R-30). Fish sampling in reference urban streams may then be needed to determine which fish species to reintroduce into the project reach once the barriers are removed (Galli, 1999).

Assess Stream Corridor

The last group of surveys evaluates conditions in the stream corridor to see whether they might constrain repair practices within the channel or banks. The floodplain and corridor in most urban streams can be highly constrained, and adequate room may not be available for all practices. Common corridor surveys include:

- Inventories of mature trees to save
- Soil tests and plant surveys to understand planting conditions
- Identification and management of invasive plant species
- Geotechnical suitability of bank soils
- Location of sewers and other infrastructure
- Confirmation of property line boundaries
- Modeling of floodplain elevations

Guidance on methods to perform these surveys is described in Manual 5, Riparian Management Practices. The exception is floodplain modeling, which often needs to be done to confirm that the 100-year floodplain elevations will not be increased as a result of project implementation, which must be established if the project is within a FEMA designated floodplain or floodway. A concise discussion of floodplain modeling methods is provided in Chapter 11 of Doll *et al*. (2003).

Chapter 3: Design Considerations for Individual Stream Repair Practices

This chapter focuses on the unique design context for urban stream repair, which requires careful analysis of upstream subwatershed factors, dynamic factors within the project reach itself, and its connection to downstream resource waters. The next three sections detail how subwatershed conditions, downstream waters and project reach dynamics influence the design of individual urban stream repair practices.

Guidance is then provided on how to select the most appropriate stream repair practices for a project reach, given stream repair objectives, and conditions in the stream reach and subwatershed as a whole. The chapter concludes with tips on project permitting, construction, maintenance and monitoring that are critical to project success and the continued improvement and evolution of stream repair practices in general.

Urban stream repair practices should be designed with three design contexts in mind:

- Upstream subwatershed factors
- Dynamics within the project reach
- Connection to downstream waters

The inter-relationship of the three design contexts is illustrated in Figure 7. An understanding of each design context helps predict spatial and temporal change in the project reach, and explains unique design factors that should be considered in urban stream repair.

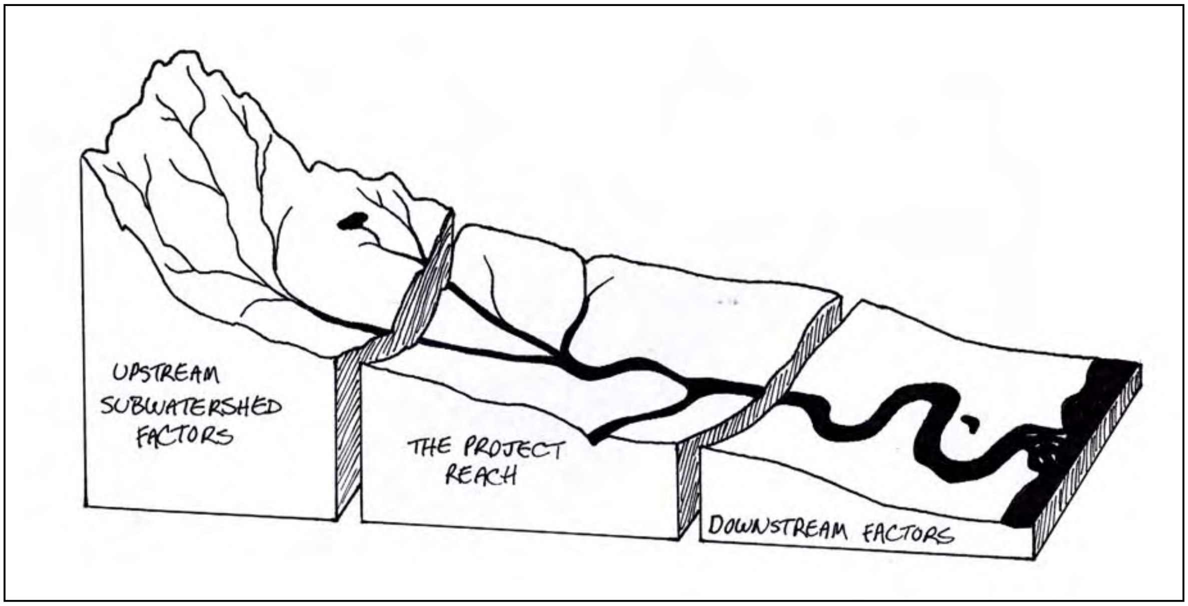


Figure 7: The design context for urban stream repair

3.1 Upstream Subwatershed Factors

Upstream subwatershed factors fundamentally determine the severity and timing of stream channel response and are a critical design context for urban stream repair. Upstream factors dictate current and future changes in discharge and sediment transport to the project reach and the probable direction of channel process and geometry. At least seven urban subwatershed factors should potentially be investigated to determine how they might influence discharge and sediment loading to the project reach. They include:

- Current impervious cover (IC)
- Expected IC at buildout
- Age of subwatershed development
- Future change in subwatershed forest cover
- Current storm water practice coverage
- Retrofit treatment potential
- Upstream channel modifications

Subwatershed factors should always be evaluated and/or modeled during comprehensive urban stream repair applications, and should be clearly understood even when designing simple stream repairs. Indeed, the purpose of subwatershed restoration is to try to control or manage one or more subwatershed factors so as to mitigate changes in hydrology/sediment transport caused by upstream development. The general effect that each subwatershed factor has on stream conditions and channel processes is outlined in Table 14.

In most cases, each subwatershed factor can be estimated using relatively simple desktop analyses. These estimates can then be input into hydrologic, hydraulic or sediment transport models to determine how changes in subwatershed factors will influence future bankfull design flows, maximum velocities on channel boundaries, and the expected stages of channel evolution.

Current Impervious Cover

The amount of current subwatershed impervious cover (IC) can be directly measured from aerial photos or estimated from GIS data or land use data. Current subwatershed IC determines the volume, rate, timing and quality of storm water runoff delivered to the project reach. As Caraco (2000) notes, subwatershed IC can predict the general degree of future channel enlargement in alluvial streams, as shown in Figure 8. Current subwatershed IC can be used to set realistic targets for stream repair, and generally predict how various indicators of stream quality will behave (see Impervious Cover Model discussion in Section 1.1).

Table 14: Influence of Subwatershed Factors on Reach Hydrology and Sediment Transport

Upstream Factor	Increase	Decrease
Discharge	• More subwatershed IC • Recent development • Channelization	• Upstream retrofits • Increased forest cover • Presence of storm water practices
Sediment Transport	• More subwatershed IC • New construction • Recent development	• Decades since buildout • Upstream impoundments • Increased riparian forest cover

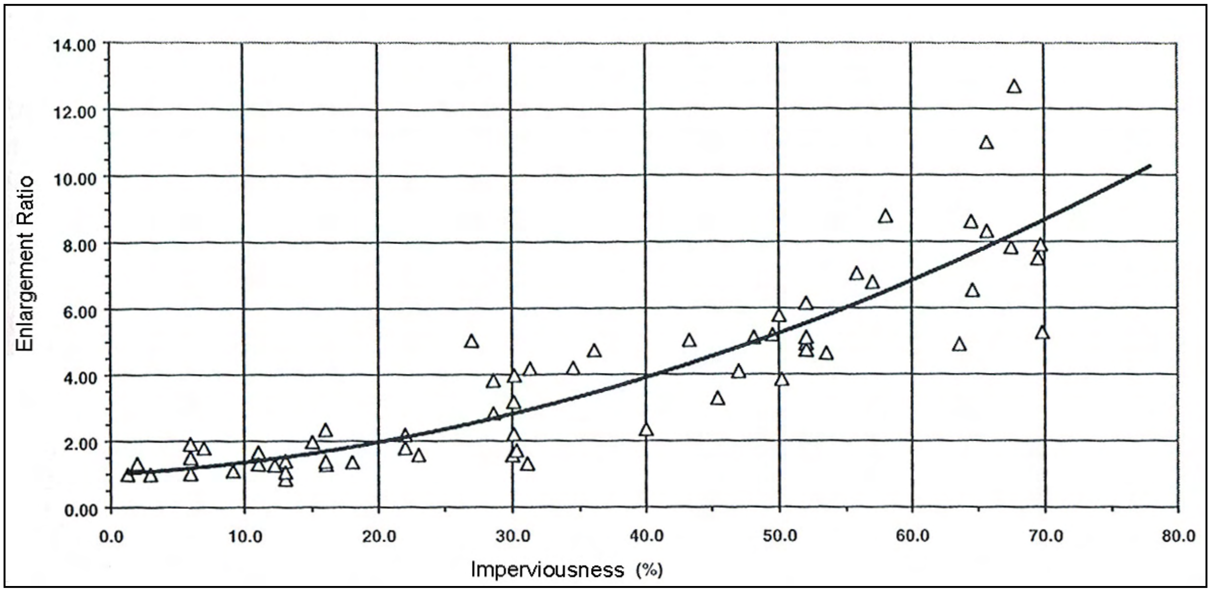


Figure 8: Relationship Between Ultimate Channel Enlargement and Impervious Cover

Source: MacRae and DeAndrea, 1999 and CWP 2001

Impervious Cover at Buildout

Many urban subwatersheds are not yet fully built out, so it is important to estimate or project the incremental amount IC that will be added in the future. Future IC can be estimated by analyzing current zoning maps and development forecasts for the subwatershed. A series of desktop techniques to project future changes in subwatershed IC are presented in Manual 7.

The magnitude and timing of additional subwatershed IC can greatly alter future channel conditions. For example, adding a large increment of IC to a subwatershed over a short period of time might cause an otherwise stable channel to become instable and trigger or extend the channel degradation phase. In addition, construction site runoff can sharply increase sediment loads in subwatersheds where extensive future development is expected.

If future subwatershed IC is expected to increase by more than 10%, then changes in channel dimensions and sediment loads should be explicitly accounted for during stream repair design. If the increase in subwatershed IC is greater than 25%, it may not be advisable to pursue stream repair objectives until the channel has had time to adjust and recover. Indeed, management efforts should probably be redirected toward designing better storm water practices, stream buffers and forest conservation areas to effectively control the impacts from future subwatershed development.

Age of Subwatershed Development

The age of development is an extremely important subwatershed factor, since it may take several decades to reach subwatershed buildout, and then several more for the channel to recover to a new equilibrium (see Section 1.2). The age of subwatershed development is expressed in terms of decades from buildout, which is defined here as the point in time when a subwatershed is not expected to experience any additional IC, beyond minor redevelopment. The average age of subwatershed IC can be hard to define precisely, but a general sense of age can be inferred from plat or parcel data, or through a simple drive-by neighborhood survey (see Neighborhood Source Assessment in *Manual 11*).

From a design standpoint, it is very important to know how close the subwatershed is to buildout, or how many decades have passed since it reached that point. Stream repairs are ideally undertaken after at least two or three decades have passed since subwatershed buildout. If the age of subwatershed development is less than two decades, or buildout has not yet occurred, designers should anticipate that channel dimensions and elevations will substantially change, and incorporate these changes into their stream repair designs.

Future Change in Subwatershed Forest Cover

Urban subwatersheds are a mosaic of forest, turf and impervious cover. Forest cover is the highest and best use of land in a subwatershed, when it comes to reducing storm water runoff. Forests act as a sponge for rainfall and produce very little runoff. The differences in runoff produced can be compared by looking at the differences generated by each of the three types of urban cover (Mostaghimi *et al*., 1994; Legg *et al*., 1996; Pitt, 1987; and Schueler, 1987).

Forest research has shown that less than 5% of rainfall is converted into runoff. Turf cover, on average, has a runoff coefficient twice as high as forest, although it tends to vary depending on the soil type, age and compaction of urban lawns (range: 0.05 to 0.25). As might be expected, nearly all the rain that lands on impervious cover is converted into storm water runoff.

The amount of forest cover can be quite variable in different urban subwatersheds and is quite dynamic over time, with potential large gains or losses in total forest cover possible within a few decades. For example, discharge to a project reach can increase sharply if large areas of forest are cleared for turf or converted into impervious cover. Conversely, discharge to a project reach can decline if extensive turf areas are reforested in the subwatershed. The tools and methods of watershed forestry are described in Manual 7, including a "leafout analysis" used to project future gains or losses in subwatershed forest cover.

Current Storm Water Practice Coverage

The hydrological effects of subwatershed IC can be mitigated to some extent by upstream storm water management practices, such as ponds, wetlands, and bioretention. Consequently, it is helpful to know what fraction of total subwatershed area is treated by storm water practices, and to get a general sense of their primary hydrological design objectives (e.g., flood control, peak shaving, water quality and/or groundwater recharge). It can be difficult to get a precise estimate for storm water coverage, but a general estimate can be derived by consulting local agency storm water files to find the number, type and location of storm water practices that have been installed in the subwatershed. It can also be generally assumed that no effective storm water practices exist if the average age of subwatershed development exceeds 15 years.

The presence of a high density of storm water practices in a subwatershed does not always imply that they are controlling the hydrological events that are influencing stream channel processes. Indeed, some storm water ponds designed for two year peak shaving may actually exacerbate downstream channel erosion by extending the duration of time that channels are exposed to erosive current velocities (MacRae and DeAndrea, 1999). Only storm water practices that are explicitly designed to provide water quality control and detain moderate storm events (e.g., 0.5 to 1.0 year design storms) are likely to exert meaningful hydrologic control on urban streams.

Retrofit Treatment Potential

If a high density of storm water practices does exist in a subwatershed, it may be possible to significantly alter the hydrologic regime through systematic retrofitting to provide storage volume adequate for channel protection. Retrofit treatment potential is normally determined by conducting a retrofit inventory to investigate whether enough storage and on-site retrofits can be implemented upstream. For stream repair purposes, retrofits are primarily sized to detain excessive bankfull and subbankfull flows, and to a lesser degree, remove pollutants from storm water runoff. More details on the subwatershed retrofitting process can be found in *Manual 3: Storm Water Retrofit Practices*.

Designers should model the hydrologic effect of upstream retrofits on comprehensive stream repair applications, since they should sharply reduce both discharge and sediment loads to the project reach. In general, retrofit potential is modeled based on the percent of subwatershed area effectively treated by retrofits.

Upstream Channel Modifications

The stream network should always be investigated to determine if any upstream channel modifications could influence the design of stream repairs in the project reach. The three major modifications include:

- Upstream dams and impoundments
- Channelization and bank armoring
- Channel constrictions such as crossings and bridges

Upstream dams and impoundments may exert some hydrologic control, and also act as sediment traps, eliminating downstream bedload movement and reducing suspended sediment levels. Consequently, they create "hungry streams" whose excess sediment transport capacity often leads to further channel degradation (Kondolf, 1997). Channelization locally increases channel slope and reduces channel roughness, thereby increasing the erosive power exerted on unprotected downstream reaches. Lastly, upstream channel constrictions, such as crossings, culverts, and bridges create upstream grade controls, areas of aggradation, and inadvertent control of bankfull and/or overbank flood events.

3.2 Dynamics Within the Project Reach

The second design context for urban stream repair is the project reach itself. At least nine dynamic factors come into play within the project reach and are outlined below:

- Dominant channel process
- Channel Planform
- Longitudinal profile
- Channel cross-section
- Streambed
- Streambanks
- Adjacent Stream Corridor
- Water quality
- Stream Baseflow

Dominant Channel Process

Perhaps the most important design assessment in urban stream repair is determining the dominant channel process occurring within the project reach, and whether it is still adjusting. Channel processes in urban streams can include:

- Aggradation
- Degradation
- Downcutting/incision
- Headcutting
- Widening
- Stable, but enlarged

Some of the key definitions and field indicators of channel processes are provided in Table 15. In addition, subwatershed factors should also be analyzed to understand the future direction of channel evolution (see Section 3.1).

Channel evolution refers to the stages by which the cross-sectional geometry of an incising stream changes over time, including initial incision, channel enlargement, and subsequent aggradation to a new and potentially stable final cross-section. The processes occur as channels adjust to reach a new equilibrium between available sediment and flow volumes.

Table 15: Features Used to Determine Current Channel Process

Process	Definition	Geomorphic Evidence
Aggradation	The geologic process by which a streambed's elevation is raised by the deposition of additional material transported from upstream (opposite of degradation)	• Mid-channel bars • Embedded riffles • Siltation in pools • Accretion on point bars • Deposition in the overbank zone
Degradation	The removal of streambed materials caused by the erosional force of water flow that results in a lowering of the bed elevation throughout the reach (opposite of aggradation)	• Deepened or "entrenched" stream bed • Cut face on bar forms • Headcutting and knickpoint migration • Suspended armor layer in bank • Terrace cut through older bar material • Exposed sanitary or storm sewers
Downcutting (or incision)	Deepening of stream channel cross section resulting from process of degradation	• Tall banks (may see stratification) • Disconnection from floodplain • May occur if widening prohibited
Headcutting	The erosion of the channel bed, progressing in an upstream direction	• Knickpoints • Defined or pronounced drops in elevation (mini waterfalls) • Abnormally steeped channel segments
Widening	Increased width of stream channel cross section resulting from degradation process	• Falling/leaning trees • Scour on both banks through riffle • Exposed tree roots; fracture lines along top of bank • Exposed infrastructure
Stable, but Enlarged	Channel in balance between aggrading and degrading forces	• Enlarged channel • Wetted perimeter does not extend over stream width • Poorly defined low flow channel • Entrenched or confined channel

Adapted from WSAHGP (2002) and other sources

The current channel process strongly influences the timing and feasibility of individual stream repair practices. For example, many stream repair practices are not recommended in actively incising or widening urban channels (see comparative matrix in Section 3.4). If the stream channel is actively adjusting, stream repairs may fail or create an imbalance that renews or exacerbates erosion and/or deposition. Older urban streams, on the other hand, have had time to adjust to subwatershed development and can normally accommodate a wide range of stream repair practices, with relatively low risk of failure.

A thorough understanding of the direction and rate of channel evolution is essential for any comprehensive stream repair application, since the project must conform to the ultimate size and shape of the channel that will be stable. Channel evolution should also be accounted for in the design of simple stream repair practices.

Channel Planform

Planform describes the characteristics of urban stream channels when viewed from a map or aerial photo, and is expressed in terms of pattern, sinuosity, and meander attributes. Figure 9 illustrates the planform of an actively adjusting urban stream in Maryland. Channel planform can be used to classify streams, evaluate channel processes, and design the pattern for the stream (Rosgen, 1996). Methods for performing planform surveys were described in the last chapter, but the design implications are briefly reviewed here.

Most streams are sinuous in nature, although urban streams may have been artificially straightened by past channelization and other drainage "improvements." Sinuosity is the ratio of the stream channel length, as measured in the thalweg from the top of the reach to the bottom. Meanders refer to the sinuosity of a stream reach

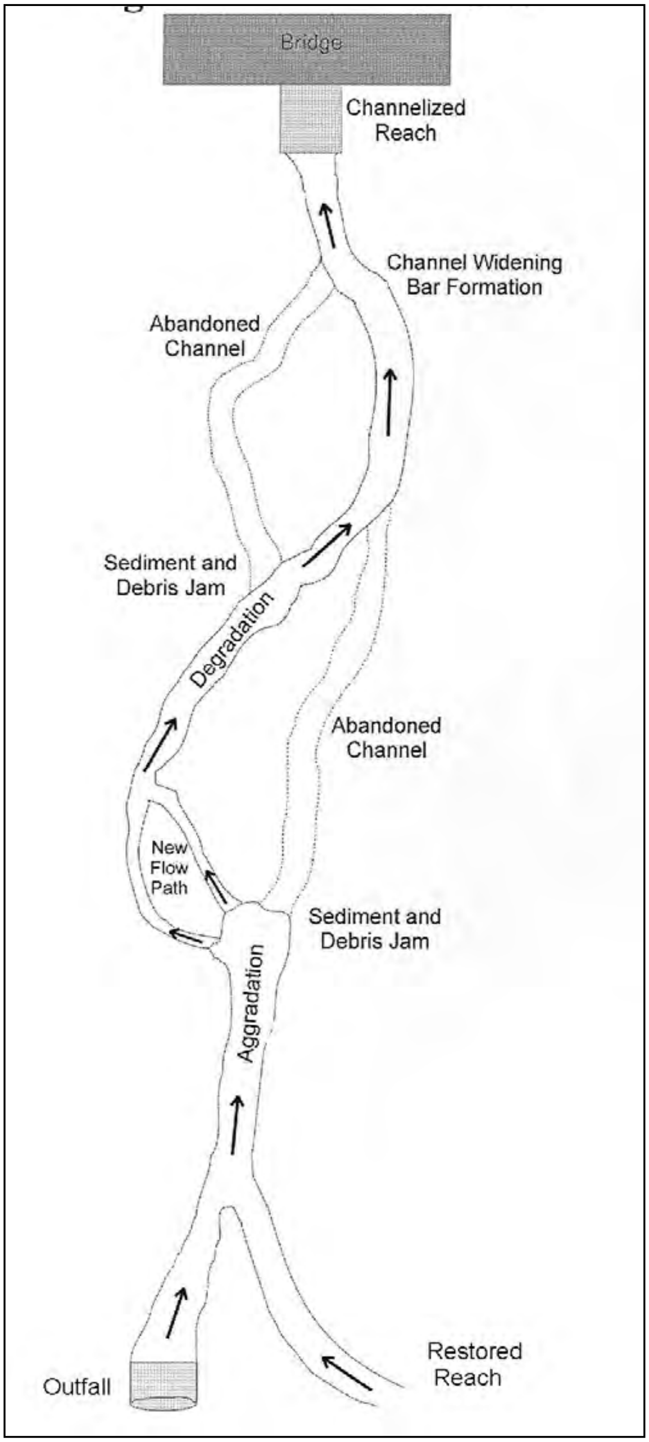


Figure 9: Planform for Bens Run in Reisterstown, MD

when viewed in planform. A stream is considered meandering if its length is 1.5 times greater than the valley through which it passes. Meander bends are the sweeping curves as a stream swings from one side of the floodplain to the other. The outside of the meander bend is a common area of bank erosion, whereas the inside of the bend is normally associated with deposition. A point bar is a common deposition feature usually found on the side opposite the concave bank of a meander bend that serves to move bedload from one meander to the next.

Many stream repair practices do not alter the planform of the urban stream, but planform does influence where and how repair practices should be located in the stream. Some stream repairs work best in meander bends, whereas others work better in straight reaches (See Section 3.4). Stream planform is an important design factor in most comprehensive stream repair applications, and more discussion is provided in Profile Sheets CR-31 to CR-33. A recurring design problem involves how much meandering can be accommodated given encroachment and lack of space in the urban stream corridor. Often, infrastructure and the confined nature of the urban stream corridor make it difficult to achieve the desired planform.

Longitudinal Profile

The longitudinal profile is a survey of the elevation of the streambed, water surface, and streambank height along the project reach. The nature and methods involved in a planform survey were previously described in Section 2.5. A key urban stream design variable is stream gradient, which is the slope of the channel bed, expressed as a percentage of the drop in elevation in a reach divided by the total length of a stream reach. Some examples of stream gradient profiles are illustrated in Figure 10.

The longitudinal profile should always be examined to determine if knickpoints are present in the project reach. Knickpoints are significant changes in streambed elevation, are caused by channel incision, and indicate dynamic channel processes at work. Knickpoints are an excellent indicator of active channel erosion, and their

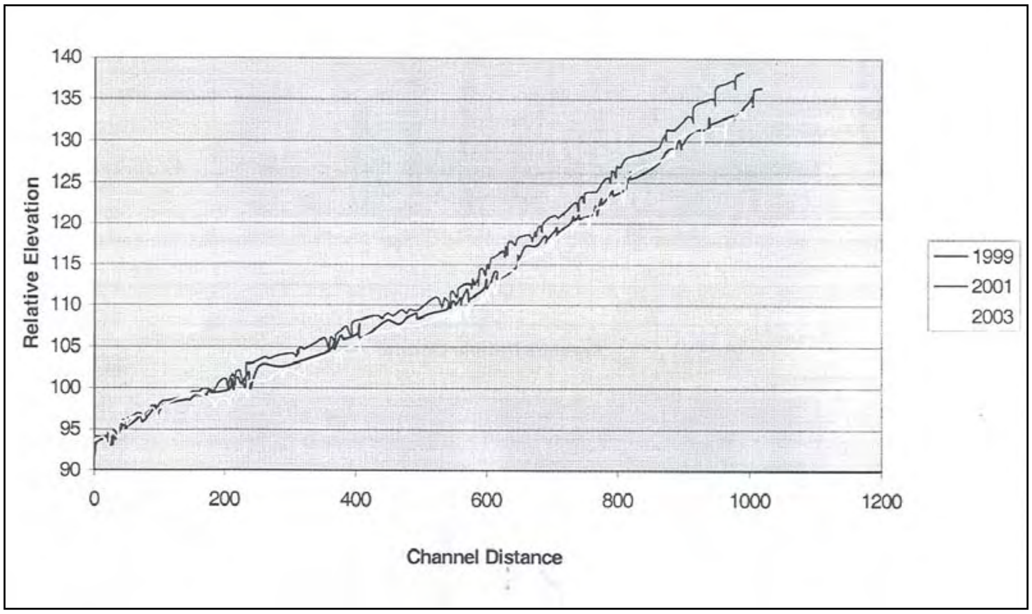


Figure 10: Examples of Stream Gradient Profiles in Seattle Stream Repair Projects
Source: UCMT, 2004

presence often suggests the need to install grade controls to prevent them from moving into the project reach. From a design standpoint, channel gradient can affect the feasibility of individual stream repair practices. For example, some stream repair practices are not recommended in extremely high or low gradient streams (see comparative matrix in Section 3.4).

Channel Cross-Section

The key design elements associated with the channel cross-section are illustrated in Figure 11. The most important design element is the elevation of bankfull discharge, which may not always be the top of bank in entrenched urban streams. The bankfull elevation is critical in that it establishes the corresponding bankfull cross-section area, discharge and velocity for the project reach, each of which is used to size and locate stream repair practices.

The current channel cross-section of most urban streams can be expected to enlarge, unless several decades have passed since subwatershed buildout. As noted earlier, urban streams can increase their cross-sectional area by a factor of two to 12, depending on the degree of subwatershed IC. Therefore, the real design issue is the manner by which the cross-section will enlarge--whether by incising, widening or both. Any structure installed in the bed or bank can be expected to either experience scouring or outflanking, depending on the direction of enlargement. If large increases in subwatershed IC have recently occurred or are projected in the future, then designers should make sure that cross-sectional dimensions are based on future conditions and not current ones.

Rosgen (1997) outlines four design strategies to deal with incising urban streams. In simple terms, the basic strategies are to raise the water, lower the bridge, expand the channel or armor the sides.

Strategy 1 establishes the bankfull stage at its historical floodplain elevation by filling in and stabilizing an existing channel (e.g., raising the water).

Strategy 2 creates a new floodplain and stream pattern with the streambed remaining at present elevation by removing floodplain soils (e.g., lower the bridge).

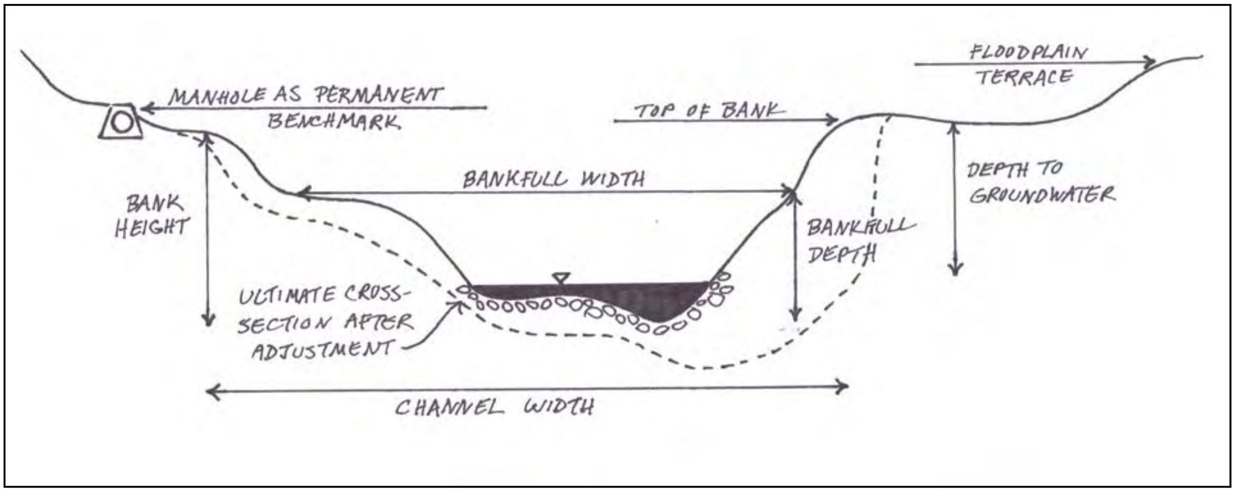


Figure 11: Typical Urban Stream Cross-Section

Strategy 3 maintains the existing streambed elevation but creates a stable channel cross-section within a narrow floodplain (e.g., expand the channel).

Strategy 4 maintains both the existing streambed elevation and channel cross-section but stabilizes existing banks in place with hard bank stabilization practices (e.g., armoring the sides).

Rosgen (1997) indicates that the first two strategies are preferable from the standpoint of natural channel design, although they may not always be practical or cost-effective in highly constrained urban stream corridors.

Streambed

Several design parameters are of interest on the streambed, including the dominant bedload material, depth of scour, and habitat suitability for aquatic insects.

Bedload is the portion of stream sediment load not in suspension, and it consists of relatively coarse sediments that are transported by jumping, sliding or rolling on or near the streambed. Stream reaches normally have a dominant size class of bed material, which may consist of sand, gravel, cobbles, and boulders. The dominant bedload material often influences the feasibility of individual stream repair practices. For example, many stream repair practices are limited to pebble or cobble substrates, and may not work well in sand-bed or boulder streams (see comparative matrix in Section 3.4).

Erosion occurs when the hydraulic forces in the flow exceed the resisting forces of the channel boundary. The amount of erosion is a function of the relative magnitude of the shear stress and duration over which it occurs. The interaction of flow and boundary materials within urban channels is imperfectly understood, although some models and formulas give approximate estimates (Copeland *et al*., 2001).

From a design standpoint, a threshold or permissible current velocity exists that will not cause erosion at the channel boundary (Table 16). Erosion thresholds for bedload materials such as silt and sand are quite low, generally about 2.5 feet per second (fps). Critical erosive velocities for pebble and cobble substrates are higher (3 to 12 fps), with boulder substrates being even higher (12 to 18 fps).

Hydrologic and hydraulic models, such as HEC-RAS (HEC, 1997), can be used to forecast current velocities and shear stress within the channel cross-section for design storm events, such as the one-, two-, 10- or 100-year frequency rainfall event. The designer can then

Table 16: Permissible Velocity for Selected Bed and Bank Materials
Source: Fischenich, 2001a

Boundary Category	Boundary Type	Permissible Velocity (fps)
Soils	Fine Colloidal Sand	1.5
	Sandy loam (noncolloidal)	1.75
	Alluvial silt (noncolloidal)	2
	Silty loam (noncolloidal)	1.75 - 2.25
	Firm loam	2.5
	Fine gravels	2.5
	Stiff clay	3 - 4.5
	Alluvial silt (colloidal)	3.75
	Graded loam to cobbles	3.75
	Graded silts to cobbles	4
	Shales and hardpan	6
Gravel/cobble	1-in	2.5 - 5
	2-in.	3 - 6
	6-in.	4 - 7.5
	12-in.	5.5 - 12
Vegetation	Class A turf	6 - 8
	Class B turf	4 - 7
	Class C turf	3.5
Degradable Erosion Control Fabrics (ECF)	Jute net	1 - 2.5
	Straw with net	1 - 3
	Coconut fiber with net	3 - 4
Rip-rap rock	6 – in. d_{50}	5 - 10
	9 – in. d_{50}	7 - 11
	12 – in. d_{50}	10 - 13
	18 – in. d_{50}	12 - 16
	24 – in. d_{50}	14 - 18
Bioengineering methods	Coir roll	8
	Vegetated coir mat	9.5
	Live brush mattress (initial)	4
	Live brush mattress (grown)	12
	Live fascine	6 - 8
	Live willow stakes	3 -10
Hard surfacing	Gabions	14 - 19
	Concrete	>18

compare the computed velocity against the permissible velocity for various surfaces and materials provided in Table 17. A factor of safety should be added to account for the fact that erosion may occur in parts of the channel at flow velocities less than the permissible velocity.

In a relatively straight stream reach, shear stress and current velocity are maximized at the center of the channel. Secondary currents can form in meander bends that can exert even higher stresses focused on the outside of the bend, which can be much higher than a straight reach. In addition, stream obstructions such as tree snags, boulders, mid-channel bars, resistant outcrops, and stream repair practices create zones of higher and lower current velocities, and these differences should be accounted for during design.

Many urban stream repair practices involve placement of structures on the streambed and/or anchored to the banks. Designers should ensure that structures or materials placed in the channel or banks will be stable over the full range of flow velocities and shear stresses expected during the design life of the project. In most cases, structures need to be composed of extremely large, flat and heavy rocks or boulders.

Another key design parameter is the expected depth of scour, which is an estimate of how deep scour erosion will occur below the current streambed elevation, as a result of an upstream stream repair practice or future channel incision. Techniques for estimating the depth of scour are presented in Castro and Sampson (2001) and Copeland *et al*. (2001). The depth of scour should be calculated in streams that have highly mobile bed sediments or high bedload transport rates to make sure scour will not undermine stream repair practices or cause further bank instability.

The last streambed factor to consider is aquatic insect habitat potential, which is helpful to know if biological objectives are being pursued in urban stream repair projects. Aquatic insects form the base of the food chain in forested headwater streams, so it is important to determine if the project reach has suitable habitat quality to support a diverse community. Aquatic insect habitat potential can be directly assessed by sampling aquatic insect diversity or inferred from streambed habitat parameters such as bed material and embeddedness (Barbour *et al*., 1999).

Streambanks

Since most urban stream repairs involve some form of bank stabilization, it is important to evaluate several streambank design parameters. Figure 12 illustrates the location of key streambank design parameters moving vertically from the bottom of the streambed up to the top of bank. Streambank design parameters help determine whether hard or soft stabilization practices should be used in the project reach, and the specific combination of individual repair practices to apply.

The lowest point of interest for bank design is actually below the streambed invert and is known as the depth of potential scour. This important design parameter examines how deeply scour erosion will occur below the current streambed elevation, as a result of future channel incision or an upstream stream repair. The next point of interest is the streambank toe, which is the break in slope at the foot of a bank where it meets the streambed and where erosional forces are usually the greatest.

The toe protection zone is operationally defined as extending from the lower limit of perennial vegetation down to the expected depth of scour. The most common form of erosion in urban streams is toe erosion, which occurs when the streambank is undermined at the toe followed by the subsequent collapse or slumping of overlying soil layers. Consequently, most urban bank stabilization practices require some form of protection at the vulnerable toe.

The next significant elevation is the lower limit of perennial vegetation on the streambank that can still support growth of perennial plants. In urban streams, a vertical gap often exists between the normal baseflow elevation and the lower bank. This elevation defines the lower limits of the streambank planting zone, which is suitable for growing perennial woody vegetation. The upper limit of the streambank planting zone extends up to the top of bank and can extend into the floodplain.

The final point of interest is the top of the bank, which acts as the transition point between the stream and its floodplain. In stable channels, the top of bank is associated with the discharge that occurs on an average frequency of about 1.5 to 2 years. The bankfull discharge represents the channel forming discharge and results in a well-established bench at the "bankfull stage" in stable channels. Most urban channels experience flows at or above the bankfull stage many times each year. In many urban streams, however incision has progressed to the point that the channel has become entrenched (i.e., bankfull elevation is lower than top of bank). Thus, the top of bank may or may not actually represent the bankfull discharge elevation in urban streams.

Other notable design parameters include streambank height and angle, and the cohesiveness of bank soils, each of which is needed to evaluate overall bank stability within the project reach. Several useful bank stability assessment methods have recently been developed to guide design, including Rosgen (2001), Doyle *et al*. (2000), Patterson *et al*. (1999), and Copeland *et al*. (2001).

The last bank design issue is whether deformable streambanks make sense within the project reach. Deformable streambanks employ soft bank stabilization practices and are free to change their dimensions over time to respond to upstream changes in hydrology and sediment

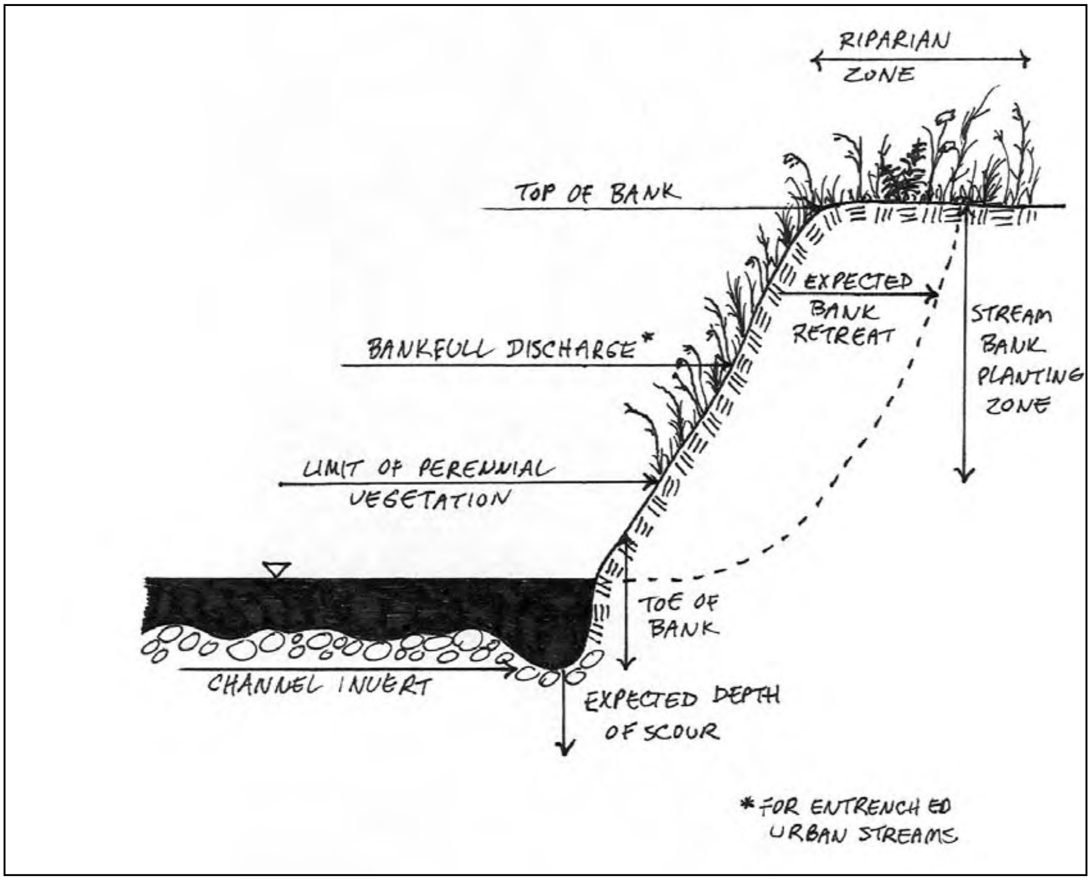


Figure 12: Key Design Parameters on Urban Streambanks

transport (Miller and Skidmore, 2000). Deformable banks are allowed to erode over time at rates that are controlled by natural processes but checked by bank vegetation. In general, deformable banks are stable once vegetation becomes fully established, although they are susceptible to natural erosion processes.

The decision to go with deformable banks is usually made by looking at the expected velocities at the toe of the bank, and determining whether soils reinforced by vegetation can withstand them without eroding. Permissible velocities for various bank surface treatments are provided in Table 18. In a relatively straight stream reach, the current velocity on the banks is about 80% of the maximum velocity in the center of the streambed [extending about a third of the way up the bank (Chow, 1959)].

The last key design issue to consider on urban streambanks is the expected retreat of bank due to channel enlargement. While it is currently impossible to predict the exact number of feet that the bank will retreat as a result of future enlargement, it is probable that the current bank will move away from the stream during its adjustment phase. This retreat has obvious consequences for the design of stream repair practices, since most are anchored or keyed into the current bank. If practices are not extended well into the bank, they will likely experience scour or outflanking in the future. Designers should carefully consider how the practices might fail during bank retreat, and take steps to protect their most vulnerable points. The most vulnerable point is generally where the upstream end of the practice joins the current bank, and these should be keyed far as possible into the bank, and armored with rock to resist erosion.

Adjacent Stream Corridor

The urban stream corridor is the width of available land extending outward from either streambank that is suitable for potential stream repair or reforestation projects. The outer boundary of the corridor is usually fixed by structures, utilities, impervious surfaces and/or unwilling landowners that restrict or prevent the natural use of the corridor (Figure 13).

Often, field inspections and analysis of infrastructure maps are needed to accurately define the available urban stream corridor. More guidance on managing the urban stream corridor can be found in Manual 5 *Riparian Management Practices*. In general, six factors influence the

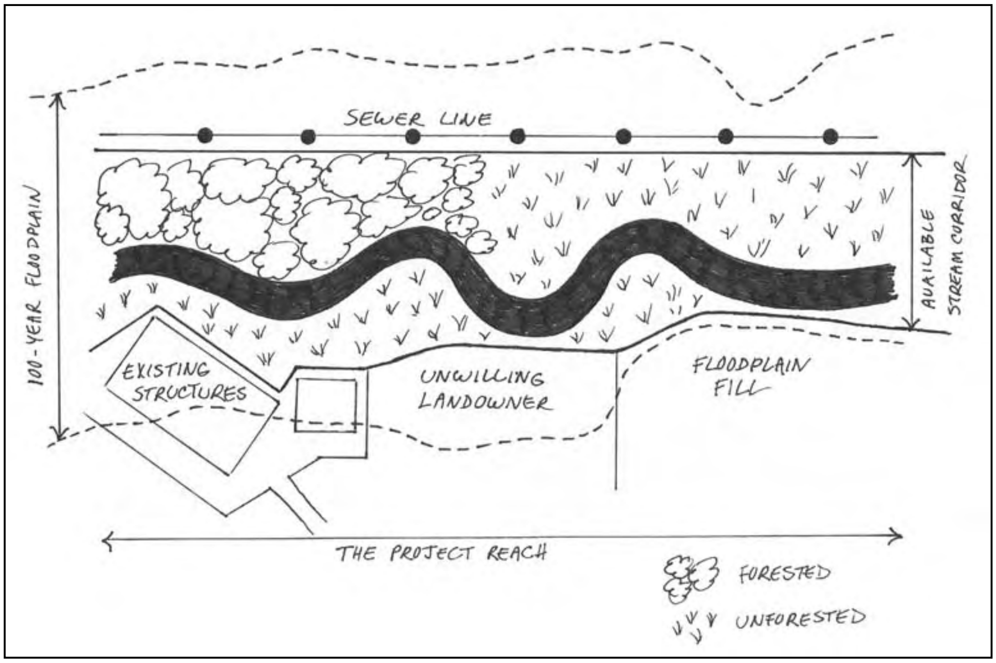


Figure 13: Design Factors to Consider in the Stream Corridor

design of stream repair practices within the adjacent stream corridor:

- Access
- Available Room
- Riparian Vegetation
- Floodplain Connectedness
- Riparian Planting Conditions
- Floodplain Capacity

Access and available room are always key feasibility constraints for stream repair projects. In most cases, heavy construction equipment must be able to reach the stream and banks, and stockpiling areas and access roads must be cleared. In addition, most stream repair practices need to be well anchored into the bank, and some bank treatments may extend more than 30 feet outward from the channel. The relative space and access needs for individual stream repair practices are compared in Section 3.4.

Most urban stream corridors lack a quality riparian forest. The riparian fragments that do remain are often isolated and have little or no connection with each other. Urban corridors are also susceptible to invasions of non-native plant species, or are mowed and maintained as turf (Figure 14). From a design standpoint, the type and quality of riparian cover can strongly influence channel dimensions. For example, bankfull widths are often significantly wider for urban streams with forest riparian cover compared to turf (Friedman *et al*., 1996; Hession, 2001; Zimmerman *et al*., 1967; and Sweeney, 1992). Consequently, designers should adjust their assumptions about channel geometry if they also intend to reforest the riparian area as part of a stream repair project.

Another stream corridor design issue is whether the stream channel is still connected to the floodplain. One of the consequences of channel incision is that the streambed's elevation is lowered in relation to the floodplain. Floodplain plant communities in entrenched urban stream corridors often suffer from "hydrological drought" such that they are disconnected from the water table and periodic inundation that they are specifically adapted for (Groffman *et al*., 2003). Many soft bank stabilization practices utilize woody riparian vegetation whose roots must reach the water table to survive and provide their reinforcement function. Consequently, designers should always evaluate floodplain connection and estimate the vertical distance from the floodplain down to the stream and associated water table.

Nearly all stream repair practices require some form of vegetative stabilization. An urban stream corridor, however, can be a difficult growing environment for many plant species. In addition to hydrologic drought, plants are subject to potential scour from storm water runoff, human disturbance, encroachment, invasive plants, and overbrowsing by deer and beaver (Brush and Zipperer, 2002; UMCT,

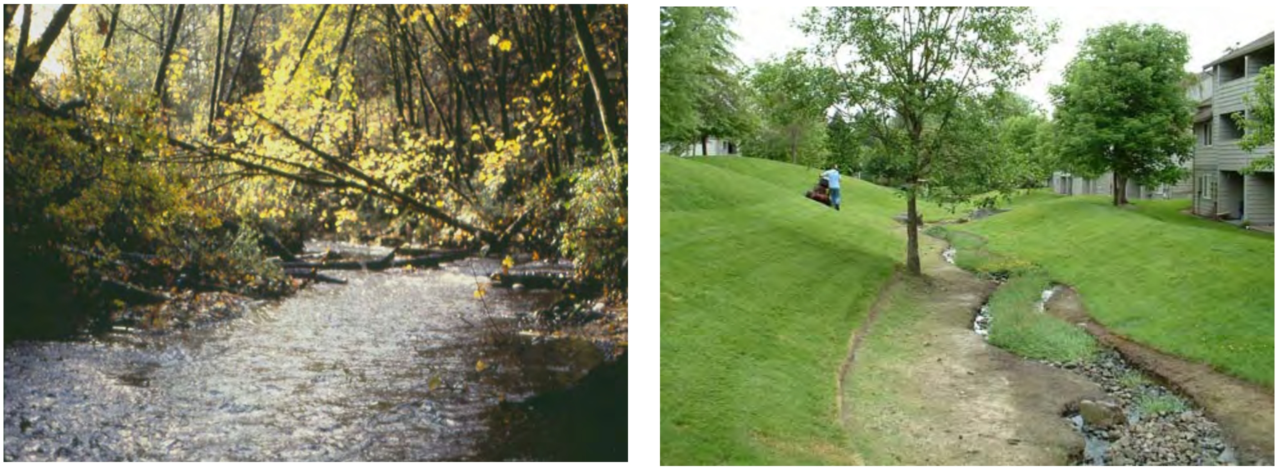


Figure 14: Comparison of Forested (left) and Unforested Urban Riparian Areas

2004; and Kwon, 1999). Designers should account for each of these factors as they develop planting plans, and should generally expect more mortality and slower growth rates for plantings in the urban stream corridor, compared to rural areas.

The last design issue in the adjacent stream corridor is the capacity of the existing floodplain to handle floodwaters. The natural floodplain is the flat or nearly flat lowland bordering a stream that is periodically inundated by water during extreme flood events. Most urban floodplains have experienced some degree of encroachment and may no longer be able to handle large floods without damages. Operationally, the urban floodplain is defined as the area inundated during the 100-year storm event. The area of inundation expands in both a vertical and lateral direction in response to higher peak flooding discharge rates generated by subwatershed development.

In many communities, the urban floodplain has historically been an attractive place to build. In order to protect buildings from floods, landowners have incrementally modified the floodplain by filling sections with earth to provide a higher platform for buildings. While floodplain filling provides local relief, it also sharply reduces the capacity of the floodplain and exacerbates downstream flooding problems. In addition, undersized bridges or culverts that cross the floodplain often reduce its capacity to handle floodwaters. As a result, many urban floodplains are expanding at the same time they are losing floodplain capacity due to encroachment.

Therefore, the effect of urban stream repair projects on floodplain capacity usually needs to be assessed. Normally, models are used to document whether the 100-year floodplain elevation will change as a result of project implementation. Such modeling is generally required if the stream repair project is located within a FEMA designated floodplain or floodway. A concise discussion of floodplain modeling methods is provided in Chapter 11 of Doll *et al*. (2003).

Water Quality

Designers may wish to assess dry weather water quality conditions within the project reach to ensure they are suitable for recovery of aquatic life or water contact recreation. Depending on the stream repair objective, the most common water quality parameters to check are dissolved oxygen, summer water temperature and bacteria.

Dissolved oxygen (DO) and summer water temperatures are measured to determine the fishery potential of urban streams. DO is typically sampled in pools and streambed pore waters during the summer months to evaluate the quality of pool and spawning habitats for fish. Horner *et al*. (1997) found that intragravel DO is an important factor for salmon spawning, and that it declined in response to increasing subwatershed IC.

Summer stream temperatures should be measured if salmon or trout recovery is the urban stream repair objective. Stream warming is a common phenomenon in urban streams, and it has been shown to increase in proportion to subwatershed IC (Galli, 1990). Cool or cold water is essential for trout and salmon, and many urban headwater streams cannot meet this important habitat requirement unless they are spring-fed.

Dry-weather bacteria levels should be sampled if the stream repair objective involves attracting people to the stream to engage in water contact recreation. If high bacteria levels are encountered during dry weather, the upstream network may need to be investigated for illicit discharges or sewer overflows. More information on techniques to find, fix and prevent bacteria problems in urban subwatersheds can be found in Brown *et al.* (2004) and Schueler (1999).

Regrettably, no simple or easy test exists to measure potential toxicity in urban streams, although research and project experience indicates that fish in urban streams can suffer from chronic or acute toxicity at higher levels of subwatershed impervious cover (UCT, 2004; Crunkilton *et al*., 1996; Newbury *et al*., 1998;

and Weber and Bannerman, 2004). The exact mode of toxicity is probably different in every urban stream and may be caused by storm water runoff, contaminated bed sediments, spills, leaks, or illicit discharges. It is prudent to assume that urban drainage will experience some degree of aquatic life toxicity, and will have limited capacity to support the recovery of the aquatic community.

Monitoring of water quality levels during storm water runoff events is seldom needed to support stream repair design. Abundant data is available to characterize pollutant levels in urban storm water runoff, with the most recent summary to be found in Pitt *et al*. (2003), and Table A-1 of *Manual 1: An Integrated Framework to Restore Small Urban Watersheds.*

Stream Baseflow

The quantity and depth of baseflow is often an important design parameter within the project reach, and should be directly measured during the driest season of the year. Baseflow is expressed as both a rate (cubic feet per second) and a depth (inches at the deepest point in an average run or riffle within the project reach). Both the rate and depth of flow are of considerable interest from the standpoint of fish habitat quality and passage (Bovee, 1982). For example, an urban stream that dries up seasonally supports much less fish habitat than a stream that can sustain perennial flows throughout the year. Similarly, an urban stream that has an extremely shallow depth of flow may restrict fish passage, unless a deeper and more confined baseflow channel is created (see Profile Sheet R-25).

The rate and depth of baseflow is an important feasibility parameter for many stream repairs practices, such as imbricated rip-rap, coir fiber logs, lunkers, flow deflection practices, stream daylighting, parallel pipes, culvert modification or replacement, fish passage devices, and all comprehensive stream repair applications.

3.3 Downstream Factors

Downstream factors below the project reach provide the last important design context for urban stream repair (Figure 15). Several downstream factors ultimately control the incision and re-colonization potential within the project reach.

Downstream channel gradient is often determined as part of the longitudinal survey for the project reach (see Section 2.5). The key design issue is whether any downstream knickpoints exist that could migrate upstream and cause further channel degradation in the project reach. It is a good practice to look for knickpoints by walking the downstream reach until a natural or artificial grade control is encountered.

The second key downstream factor is the degree to which the project reach is connected to downstream resource waters, such as a river, natural lake or estuary. Some kind of downstream corridor remains in all but the most extensively developed subwatersheds, if for no other reason than because it is usually too expensive to totally enclose them in pipes. The corridor that remains, however, is usually very interrupted (i.e., frequently crossed, culverted, channelized, impounded, ditched, enclosed, armored or otherwise encroached upon). Any of these interruptions to the stream or its corridor can restrict or eliminate connections to downstream resource waters, which greatly reduces re-colonization potential by fish, aquatic insects and wildlife. Downstream fish barriers always merit investigation, and are created when a dam, road or utility crossing, or elevated culvert prevents fish from migrating up to the project reach.

The last important downstream factor to consider is the designated use of the downstream receiving waters, and whether they are meeting water quality standards. The regulatory status of downstream receiving waters can be quickly assessed by checking the State 303(d) list, which identifies waters that are not attaining water quality standards.

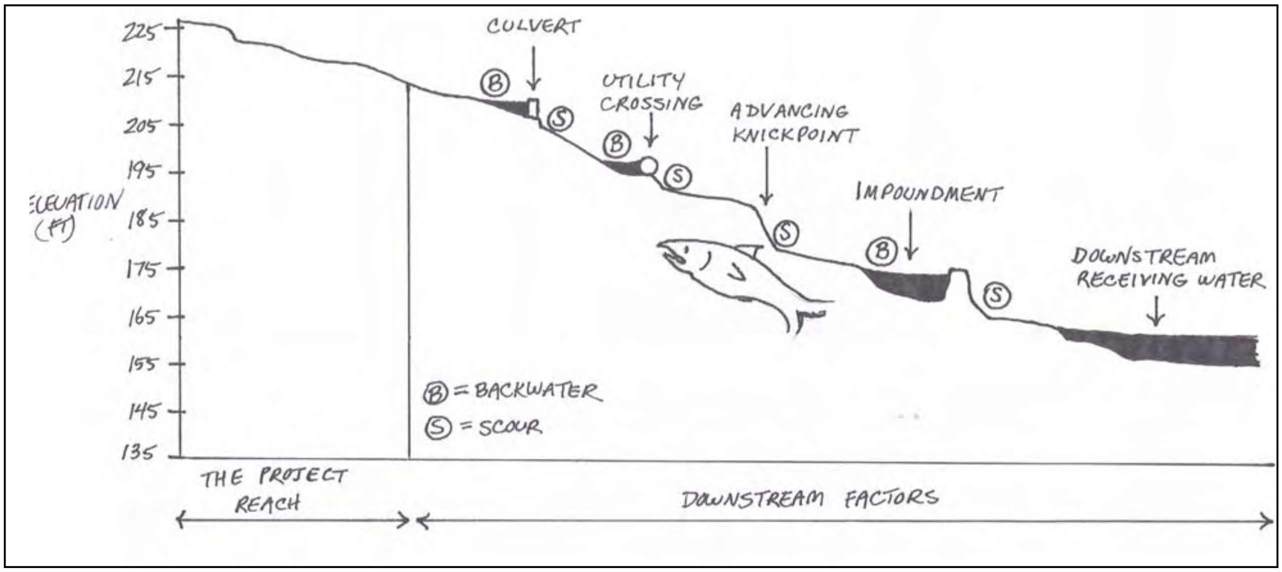


Figure 15: Important Downstream Factors to Consider in Design

3.4 Choosing the Best Stream Repair Practices

This section provides comparative information to assist designers in choosing from the many stream repair practices that can potentially be used in urban streams. Each of the 33 different stream repair practices are compared in four different matrices, based on its:

- Ability to meet specific stream repair design objectives (Table 17)
- Suitability for prevailing urban stream conditions (Table 18)
- Relative feasibility and cost factors (Table 19)
- Capacity to create different stream habitat features (Table 20)

These matrices are provided to allow general comparison among practices, but the individual profile sheets presented in the next chapter should be consulted to get more details on the strengths and limitations of each stream repair practice.

Table 17: Comparative Ability of Stream Repair Practices to Meet Design Objectives

Repair Practice	Naturalize Stream Corridor	Protect Infrastr-ucture	Prevent Bank Erosion	Expand Stream Network	Improve Fish Passage	Improve Fishery Habitat	Natural Channel Design	Restore Biological Diversity
Hard Bank Stabilization Practices								
Boulder Revetments	⦿	●	●	○	×	×	○	×
Rootwad Revetments	○	●	●	○	×	⦿	⦿	⦿
Imbricated Rip-Rap	⦿	●	●	○	×	⦿	○	○
A-Jacks	⦿	⦿	●	○	×	×	○	○
Live Cribwalls	○	⦿	●	○	×	×	○	○
Soft Bank Stabilization Practices								
Streambank Shaping	⦿	⦿	●	○	×	○	●	⦿
Coir Fiber Logs	○	○	●	○	×	○	●	⦿
Erosion Control Fabrics	○	●	●	○	×	×	●	⦿
Soil Lifts	⦿	●	●	○	×	○	●	⦿
Live Stakes	⦿	⦿	●	○	×	○	●	⦿
Live Fascines	○	⦿	●	○	×	○	⦿	⦿
Brush Mattresses	○	⦿	●	○	×	○	⦿	⦿
Vegetation Establishment	●	●	●	○	×	⦿	●	●
Flow Deflection Practices								
Wing Deflectors	⦿	×	×	×	○	●	⦿	●
Rock or Log Vanes	⦿	⦿	⦿	×	×	●	⦿	⦿
Grade Control Practices								
Rock Vortex Weirs	⦿	⦿	⦿	○	○	●	●	⦿
Rock Cross Vanes	⦿	⦿	⦿	○	○	⦿	⦿	⦿
Step Pools	⦿	⦿	⦿	⦿	⦿	○	⦿	⦿
V-Log Drops	⦿	⦿	⦿	○	○	⦿	⦿	⦿
In-stream Habitat Practices								
Lunkers	○	×	×	×	○	●	○	⦿
LWD Placement	○	○	⦿	×	○	●	⦿	●
Boulder Clusters	○	×	×	×	○	●	○	⦿
Baseflow Enhancement	○	×	×	⦿	⦿	●	⦿	⦿
Flow Diversion Practices								
Parallel Pipes	×	×	⦿	×	×	○	×	○
Stream Daylighting	⦿	×	×	●	⦿	⦿	⦿	⦿
Fish Passage Practices								
Culvert Modification	○	×	×	●	●	⦿	○	⦿
Culvert Replacement	○	●	×	●	●	⦿	○	⦿
Devices to Pass Fish	○	×	×	●	●	⦿	○	⦿
Comprehensive Repair Applications								
Combinations	●	●	●	●	●	●	●	●
Channel Redesign	⦿	○	●	⦿	⦿	⦿	●	●
De-Channelization	⦿	○	⦿	●	●	●	●	●

Key ● primary practice to meet design objective
⦿ supplemental practice to achieve design objective
○ occasionally used to meet design objective
× rarely used to meet design objective

Table 18: Comparative Suitability of Stream Repair Practices For Different Stream Conditions

Repair Practice	Adjusted Reach	Actively Incising	Lateral Adjust-ment	Aggrading	Bed Material	Meander(M) or Straight (S)	Stream Order	Stream Gradient
Hard Bank Stabilization Practices								
Boulder Revetments	Y	No #	Y	No	b,c,g	M or S	all	all
Rootwad Revetments	Y	No #	No	No	b,c,g	M	2,3,4	all
Imbricated Rip-Rap	Y	No #	Y	No	b,c,g	M or S	all	M/H
A-Jacks	Y	No #	Y	No	b,c,g	M or S	1, 2	L,M
Live Cribwalls	Y	No #	No	Y	b,c,g	M or S	all	L,M
Soft Bank Stabilization Practices								
Streambank Shaping		Y	No *	No	c,g,s	M or S	all	L,M*
Coir Fiber Logs	Y	No	No *	Y	c,g,s	M or S	1,2	L,M
Erosion Control Fabrics	Y	N/a	N/a	Y	n/a	M or S	all	all
Soil Lifts	Y	No #	Y	Y	c,g,sl	M or S	2,3,4	all
Live Stakes	Y		Y	Y	n/a	M or S	all	all
Live Fascines	Y	No #	Y	Y	n/a	M or S	all	all
Brush Mattresses	Y	No #	Y	Y	n/a	S	all	all
Vegetation Establishment	Y		Y	Y	n/a	M or S	all	all
Flow Deflection Practices								
Wing Deflectors		No #	No *	No	c.g	S	2,3,4	L,M
Rock or Log Vanes	Y	No #	Yes	No	c,g	M or S	all	L,M
Grade Control Practices								
Rock Vortex Weirs	Y	Y	No *	Yes	c,g	S	all	L,M
Rock Cross Vanes	Y	Y	No *	No	c,g	S or M	all	L,M
Step Pools	Y	Y	No	No	c,g	S	2,3,4	M,H
V-Log Drops	Y	Y	No	No	c,g	S	2,3,4	L,M
In-stream Habitat Practices								
Lunkers	Y	No #	No	No	c,g	M	2,3,4	L,M
LWD Placement		Y	Y	Y	s,c,g	S	2,3,4	All
Boulder Clusters	Y	No #	No	No	c,g,b	S	2,3,4	M,H
Baseflow Enhancement		No #	No	No	c,g	S	2,3,4	L,M
Flow Diversion Practices								
Parallel Pipes	No	Y#	?	No	c,g	S	1	M,H
Stream Daylighting	N/a	Y#	n/a	Y		S	1,2	M,H
Fish Passage Practices								
Culvert Modification	Y	Y #	Y	depends	b,c,g	S	all	L,M
Culvert Replacement	Y		Y	Y	b,c,g	S	all	L,M
Devices to Pass Fish	Y	Y #	Y	No	b,c,g	S	all	M,H
Comprehensive Applications								
Combinations	Y	Y	Y	Y	all	M or S	all	all
Channel Redesign		No	No *	Y	all	M or S	2,3,4	all
De-Channelization	Y	No	No *	n/a	all	M or S	2,3,4	L,M

Key: n/a = not applicable; # = if grade control and toe protection are also provided; * only if adequate toe protection provided
s= sand, c=cobble, g= gravel, b= boulder substrate;
1=first order, 2 = second order, 3 = third order, 4 = fourth order;
L= low gradient, M= medium gradient, H= high gradient

Table 19: Comparative Feasibility and Cost of Stream Repair Practices

Repair Practice	Heavy Equipment Access	Corridor Room	Forest Impact	Fish Study	Unit Cost	Feasibility Notes
Hard Bank Stabilization Practices						
Boulder Revetments	Y	M	BC	No	$20 to 40 per lf	noncohesive soils
Rootwad Revetments	Y	M	BC	No	$10 to 100 per lf	recreational use
Imbricated Rip-Rap	Y	M	BC	No	$60 to 90 per lf	non-deformable
A-Jacks	No	M	BC	No	$65 to 85 per lf	toe protection only
Live Cribwalls	Y	M	BC	No	$250 to 300 per lf	slope failure
Soft Bank Stabilization Practices						
Streambank Shaping	Y	M	BC	No	varies	need toe protection
Coir Fiber Logs	No	L	None	No	$8 to 30 per lf	2 to 5 year lifespan
Erosion Control Fabrics	No	n/a	BC	No	$1 to 5 per sy	woven/non-woven
Soil Lifts	Y	L	BC	No	$12 to 30 per lf- f	need toe protection
Live Stakes	No	L	FS	No	$1 to 3 per stake	reach water table
Live Fascines	No	L	FS	No	$ 5 to 22 per lf	sunlight
Brush Mattresses	No	L	FS	No	$ 30 to 50 per lf	toe protection
Vegetation Establish.	No	M	FS	No	varies	invasive species
Flow Deflection Practices						
Wing Deflectors	Y	L	AC	No	$400 to 800 each	rock size
Rock or Log Vanes	Y	L	AC	No	$ 400 to 1400 each	outflanking
Grade Control Practices						
Rock Vortex Weirs	Y	L	AC	Y	$1200 to $2100 each	high failure rate
Rock Cross Vanes	Y	L	AC	No	$1200 to $1700 each	outflanking
Step Pools	Y	L	AC	No	$2000 to $6000 each	head drop
V-Log Drops	No	L	AC	No	$800 to $2600 each	armoring
In-stream Habitat Practices						
Lunkers	Y	M	BC	Y	$45 to 60 per lf	bedload transport
LWD Placement	Y	L	AC	Y	$20 to 40 per lf	orientation
Boulder Clusters	Y	L	AC	Y	$60 to 250 each	rock size
Baseflow Enhancement	Y	L	AC	Y	varies	bedload transport
Flow Diversion Practices						
Parallel Pipes	Y	H	BC/RC	No	$50 to 300 per lf	available head
Stream Daylighting	Y	H	RC	No	$100 to 300 per lf	overburden depth
Fish Passage Practices						
Culvert Modification	Y	n/a	No	Y	varies	needs of target fish species
Culvert Replacement	Y	n/a	No	Y	varies	
Devices to Pass Fish	Y	n/a	No	Y	varies	
Comprehensive Applications						
Combinations	Y	M	BC	Y	varies	varies
Channel Redesign	Y	H	BC/RC	Y	varies	incision
De-Channelization	Y	H	BC/RC	Y	varies	utilities

Key: Y = yes; n/a = not applicable
L= 0 to 10 feet of corridor needed, M= 10 to 30 feet needed, H = more than 30 feet of corridor needed
BC= bank clearing, AC= clearing for stream access, RC= significant clearing of riparian areas
FS=requires full sun for establishment
lf= linear feet; sy= square yard; lf-f= linear feet per one foot tall lift

Table 20: Comparative Habitat Features Created by Stream Repair Practices

Repair Practice	Pool	Riffle	Under-cut Banks	Overhead Cover	Resting & Rearing	Fish Passage	Deepen/ Confine Baseflow	Protect Banks
Hard Bank Stabilization Practices								
Boulder Revetments	○	×	○	×	×	×	○	●
Rootwad Revetments	×	×	⦿	●	⦿	×	○	●
Imbricated Rip-Rap	×	×	●	○	⦿	×	○	●
A-Jacks	×	×	○	○	×	×	×	●
Live Cribwalls	×	×	×	⦿	×	×	×	●
Soft Bank Stabilization Practices								
Streambank Shaping	×	×	×	⦿	×	×	×	●
Coir Fiber Logs	×	×	○	●	×	×	×	⦿
Erosion Control Fabrics	×	×	×	×	×	×	×	⦿
Soil Lifts	×	×	⦿	×	×	×	○	●
Live Stakes	×	×	×	●	×	×	×	●
Live Fascines	×	×	×	●	×	×	×	●
Brush Mattresses	×	×	×	●	×	×	×	●
Vegetation Establish.	×	×	×	●	×	×	×	●
Flow Deflection Practices								
Wing Deflectors	●	●	×	×	⦿	×	●	○
Rock or Log Vanes	●	●	×	×	⦿	×	⦿	⦿
Grade Control Practices								
Rock Vortex Weirs	●	●	×	×	●	⦿	⦿	○
Rock Cross Vanes	⦿	●	×	×	⦿	⦿	⦿	○
Step Pools	●	×	×	×	⦿	●	×	○
V-Log Drops	●	⦿	×	×	⦿	⦿	⦿	○
In-stream Habitat Practices								
Lunkers	×	×	●	⦿	●	×	⦿	×
LWD Placement	⦿	⦿	⦿	●	●	×	⦿	⦿
Boulder Clusters	○	○	○	×	●	×	○	×
Baseflow Enhancement	×	⦿	○	×	⦿	⦿	●	×
Flow Diversion Practices								
Parallel Pipes	preserve existing stream habitat features							
Stream Daylighting	habitat features must be added to new channel							
Fish Passage Practices								
Culvert Modification	×	○	×	×	⦿	●	○	×
Culvert Replacement	×	×	×	×	⦿	●	⦿	×
Devices to Pass Fish	○	×	×	×	⦿	●	×	×
Comprehensive Applications								
Combinations	●	●	●	●	●	●	●	●
Channel Redesign	●	●	●	●	●	⦿	●	●
De-Channelization	⦿	●	⦿	●	●	⦿	●	●

Key ● primary practice to create habitat feature
⦿ supplemental practice to create habitat feature
○ may slightly enhance the habitat feature
× does not create habitat feature

3.5 Permitting and Construction Issues

This section briefly touches on key construction and contracting issues that relate to effective installation of stream repair projects. A much more extensive discussion can be found in KST (2002), which presents practical tips to navigate through the permitting, contracting, and construction minefields encountered when working in streams.

The first major task is to secure the permits and approvals from local, state, and federal agencies needed to allow work to begin. Multiple permits are usually needed for most stream repair projects and can include:

- 401 water quality certification
- 404 wetland permits
- State waterway construction permits
- Federal and state fish and wildlife approvals
- Local forest conservation or buffer ordinances
- Local erosion and sediment control permit
- Local or state floodplain management
- Landowner approval

The specific combination of permits needed for stream repair projects varies from state to state, and designer should check with both the state environmental quality and natural resource agencies to determine the submittal requirements and review process. The permitting process for stream repair projects can be long and complex, and several weeks of time should be allocated in the design budget to prepare permit submittals and handle interagency coordination.

Given the multiple agencies involved, it is often a good idea to host a pre-application meeting at the project site to discuss the concept design and resolve any issues before proceeding to final design. Pre-application meetings can identify potential permitting problems and familiarize reviewers with the project site.

Designers and contractors must work closely together to ensure proper stream repair practice installation. The trend in recent years is to contract with an experienced design/build firm that can handle the project from initial assessment to final construction.

Erosion and sediment control is an extremely important element of stream repair design, permitting and construction. Keeping sediment out of the stream while working on its bed and banks is challenging, and requires many specialized methods and practices, such as water diversions, pump-arounds, sandbagging, cofferdams, dewatering, temporary stabilization, construction staging and temporary stockpiling. Indeed, the cost for specialized sediment and erosion control often accounts for as much as a third of the total budget for many stream repair projects.

Most state and local agencies set extensive permit conditions and restrictions for working in the stream or on its banks, and have established construction windows at various times of the year where in-stream construction is prohibited. Permitting agencies also routinely limit the extent of disturbance in the riparian zone, and specify an extensive sequence of construction that is fundamentally driven by erosion and sediment control considerations.

Useful guidelines for dealing with erosion and sediment control while working in streams can be found in MWMA (2000), KST (2002), Doll *et al*. (2003) and VA DCR (2004), and some general principles are summarized in Table 21. One of the key findings from Brown's (2000) comprehensive assessment of urban stream repair projects is that practices seldom fail, but designers and contractors frequently do.

Table 21: Erosion And Sediment Control Considerations for Urban Stream Repair Projects

- Most states have extensive windows during the year when in-stream construction is prohibited to protect fish spawning.
- As much work as possible should be done from the bank, and the amount of time and extent of disturbance in the channel should be limited.
- Some practices are best installed by using excavating equipment within the stream itself, which can protect riparian vegetation. Equipment can enter the stream at a controlled access point, and then retreat up the bank slope to properly key structures into the bank.
- Begin stream repair work upstream and proceed in a downstream direction.
- Avoid the use of silt fence along the streambank edge as it will be in the way and is not very practical.
- Clearing of the riparian corridor should be minimized, and include only the immediate project area, the most direct access and haul roads possible, and any needed staging or stockpile areas. Clearly flag any wetland areas to prevent encroachment. Clearing of large trees in the riparian corridor should be avoided to the greatest extent possible, and any trees that are cut down should be recycled into the stream repair project (rootwads, large woody debris or mulch).
- All exposed bank slopes should be immediately stabilized using annual rye grain and erosion control fabrics (See Profile Sheets R-10 and R-15).
- When constructing practices that span the entire channel, temporary sandbag barriers should be installed above and below the daily worksite, and a diversion pump used to bypass upstream flows around the disturbed work area.
- If practice construction involves less than half of the channel width, a temporary sandbag barrier can be used to isolate the work area from the rest of the stream. A dewatering pump may be needed to decant turbid water from the work area into the floodplain.

Failure of stream repair practices was normally caused by one of three factors:

- Practices were installed that were not suited to current channel conditions (most frequently when urban streams were actively adjusting or enlarging).
- Practices were improperly installed (usually at the wrong elevation, or too close together)
- Practices were part of a poor overall project design

Pre-construction meetings should be held with designers, contractors and permitting agencies to go over stream repair objectives and implementation. Designers should always supervise the installation of stream and bank practices, make sure elevations are correct, and prepare an “as-built” plan after construction is completed. The profile sheets in Chapter 4 contain detailed guidance on the construction sequence for individual stream repair practices, as well as tips on effective installation.

3.6 Project Maintenance and Evaluation

This section briefly describes issues related to the maintenance and evaluation of stream repair practices. Most stream repair practices should require relatively little maintenance after the first few years after construction, if they have been properly designed and installed. The real critical maintenance period is the first year or two after installation, when the structures are adjusting to the stream and vegetation is becoming established.

Stream repair projects should always be inspected after large storms to see if the design assumptions in the office actually worked in the field. The maintenance and inspection requirements for individual stream repair practices can be found in the profile sheets provided in Chapter 4.

Construction contracts should contain contingency items so that contractors can adjust practices in the first year, and maintain vegetation over the first two growing seasons. This is particularly important for soft bank stabilization and comprehensive repair applications that rely on vegetation to reinforce the bank. The first few years are often difficult, and designers should plan on giving plants and woody vegetation a helping hand during this period. Numerous projects have reported poor initial plant survival, relatively slow growth rates of woody vegetation, and takeover of invasive plants in the urban streambank planting zones. Profile Sheet R-15 provides practical tips to rapidly establish vegetation in the streambank planting zone and associated riparian areas.

Urban stream repair is still somewhat of an experimental practice and long-term monitoring is critical to the continued improvement and evolution of practices. Regrettably, the performance of most urban stream repair projects installed in the past has not been evaluated. Much of the information on the performance of urban stream repair practices has been anecdotal, or inferred from larger river projects (Frissel and Nawa, 1992).

Several recent studies, however, have shed more light on how different practices have performed in meeting various urban stream repair objectives. Brown (2000) conducted the most extensive study, sampling more than 450 individual stream repair practices in Maryland and Illinois. Galli (1999) reported on the long-term response of fish and aquatic insects to a comprehensive restoration application in Sligo Creek, Maryland. Other notable assessments of urban stream repair projects include Booth *et al*. (2001, large woody debris); Jennings and Harman (2000, rootwads and vanes); UCMT (2004, various practices); and Newbury *et al*. (1998, lunkers, A-jacks and rock weirs).

While it may not be possible to intensively monitor every stream repair practice over the long run, a project information archive should be prepared for every stream repair project that enables others to assess the project in the future. At a minimum, the project archive should consist of:

- Clearly stated design objectives
- As-built drawing
- Monumented channel surveys (cross-sectional, longitudinal)
- Before and after photographs
- Planting plans, including species, coverage and any post-installation care
- Exact locations of any fish or aquatic insect monitoring
- All stream and subwatershed assessment data used to develop the design

If budgets allow for monitoring, several excellent approaches have been developed to evaluate the performance of stream repair projects (Doll *et al*., 2003; KST, 2002; Brown, 2000; FISWRG, 1998; and Goldsmith *et al*., 1998).

Monitoring is strongly recommended for urban stream repair projects that are explicitly designed to meet fishery objectives. Fixed sentinel stations should be established within the project reach to sample fish population trends and/or aquatic insect diversity over time. Roni *et al*. (2003) notes that it is extremely hard to detect or measure biological response to stream repairs in the short term and provides some useful guidance on fish monitoring protocols. In addition, trends in key subwatershed factors such as percent IC and FC should be tracked over time.

Chapter 4: Stream Repair Practices Profile Sheets

This chapter provides profile sheets for 33 different stream repair practices. Each profile sheet generally describes the repair practice, along with design schematics and photos of what it looks like in the field. Each sheet then describes the nature of any stream habitat feature created by the practice. The feasibility of the practice is assessed in terms of the stream types where it works best and the channel processes where it should be avoided. The bulk of each sheet is devoted to practical guidance on design, construction and maintenance, with specific reference to unique urban stream considerations reviewed in preceding chapters.

Each profile sheet also reports unit cost information, where available, for developing initial planning-level cost estimates for concept designs. The unit cost data for each practice was derived as the average of up to four independent sources (MD (2), NC, and WA). Each profile sheet concludes with a handful of design and construction specifications drawn from state, regional, national or international sources. These design resources, which can be accessed over the internet, were selected to provide geographic balance across the country.

The reader may also want to consult the matrices presented in Section 3.5 to see how individual stream repair practices compare with respect to design objective, stream suitability, site feasibility and habitat features created.

A directory of the stream repair profile sheets is provided below.

<u>Profile Sheet Page</u>

Stream Cleanup Practices

Simple Stream Repair Practices

Comprehensive Stream Repair Applications

C-1

Stream Cleanups

STREAM CLEANUPS

Description

Stream cleanups are a simple practice to enhance the appearance of a stream corridor by removing unsightly trash, litter and debris. In some cases, mechanical equipment is needed to remove large quantities of rubble, appliance and trash that have been illegally dumped in the stream or its corridor. Cleanups make the stream a more attractive place for anglers, canoers, hikers and landowners. In some cases, stream cleanups can prevent pollutants from being released, if drums, tires, appliances, medical waste or other potentially hazardous materials are present (Figure 1).

Typically, stream cleanups are accomplished using volunteers from the community or schools that are led by a local watershed group and/or supported by municipal agencies. Stream cleanups have great value in educating volunteers and increasing community awareness about watershed restoration, and are also an effective recruiting tool for local watershed groups. Repeated stream cleanups can often make a real difference in the appearance of impacted and non-supporting streams, but may not always be able to keep up with the severe trash and debris loads experienced in urban drainage streams. In addition, the volume of illegal dumping in the corridor of urban drainage subwatersheds tends to be much higher.

Feasibility

The Trash and Debris (TR) form of the Unified Stream Assessment is an excellent tool to use when choosing potential cleanup sites in a subwatershed, as it pinpoints locations of greatest trash accumulation along the entire stream corridor, and evaluates accessibility and other factors (Manual 10). Several feasibility factors should be considered when scouting potential stream cleanup sites. The first factor is access, which usually means finding a bridge, road crossing or easement that makes it possible to reach the stream. Next, safety should be considered. Stream corridors with steep slopes, steep eroding banks, or overgrown thorny vegetation can all pose access problems. Third, an adjacent trash stockpiling area is needed to temporarily store trash and debris collected until it can be removed a few days later. This usually means finding a nearby parking lot or roadside area accessible by a dump or garbage truck. The fourth factor is the water quality of the stream itself. The main concern here is skin contact with bacteria and pathogens. It can generally be assumed that if the cleanup site is located in a non-supporting or urban drainage subwatershed, dry weather stream flows may contain bacteria. In these situations, plastic gloves, waterproof waders and other protective equipment should always be worn (Figure 2). Stream cleanups can be done in all kinds of urban subwatersheds, but are most effective in impacted and non-supporting streams.

http://www.saveourstreams.org/

Figure 1: Example of potentially hazardous materials and conditions in an urban stream

Figure 2: Stream cleanup effort in an urban Maryland stream

Implementation

Implementing a cleanup entails three steps: planning and organizing, conducting the cleanup, and performing follow-up activities.

Planning a Cleanup - Planning and organizing are the most time-consuming component of a successful stream cleanups, and several details should be considered for a smooth effort, including:

- Selecting an appropriate site(s)
- Choosing the cleanup date, and a rain date
- Assessing safety needs at the site
- Recruiting volunteers and organizing teams
- Acquiring landowner permission
- Arranging for trash hauling
- Buying supplies
- Publicizing the cleanup event

Choosing and publicizing the stream cleanup date should be done months in advance to provide ample time for volunteers and workers to include it in their busy schedules. Stream cleanups should be scheduled to avoid poor weather conditions, such as extreme heat or cold, rainy periods that might cause flooding, and snow. Good scheduling can reduce the risk of a low turnout or cancellation of the cleanup due to poor weather. Typically late spring or early fall is the best season to schedule stream cleanups in most regions of the country.

Safety is an essential responsibility for the cleanup organizer, and potential risks should be thoroughly evaluated. Since volunteers will be handling trash and debris and be in and around water, they may be susceptible to injury. The following safety factors should be evaluated:

Clothing – Advise volunteers to wear thick pants, sturdy shoes/boots, and gloves

First Aid Kit – A good first aid kit should be provided, along with someone who has training in its use. The kit should contain items to address common outdoor injuries (e.g., bee stings, cuts, poison ivy, and ankle sprains)

Stockpile Sites – These sites should be marked with orange warning cones or flags to alert pedestrians and traffic

Daily weather reports - Forecasts should be consulted to be aware of potentially threatening weather events, such as thunderstorms

Safety plan – This plan should show the nearest phone and list important emergency phone numbers and the closest medical center

Water – Stream cleanups can be strenuous, so make sure ample water is available to volunteers to prevent dehydration

Liability Waiver – Make sure volunteers sign liability forms and provide medical information about allergies and medications

Cleanup organizers should organize recruits into teams of six to eight to work in specific areas of the stream. Each team should be assigned a team leader that has scouted the stream reach and knows where debris should be stockpiled.

Parents or guardians must give written permission if minors wish to participate in the stream cleanup. This should include an emergency phone contact and permission to administer medical care. Organizers should consider requiring a minimum age for volunteers.

Arrangements for removing trash and debris should be made in advance with the local public works department. It is also helpful to coordinate with local recycling centers on how to recycle materials collected during the cleanup (e.g., plastics, aluminum, glass).

The length of the stream cleanup determines how many supplies are needed. For example, a small project may only require a borrowed truck, while a larger project may require use of a large dump truck. Typical supplies needed for a stream cleanup include: trash bags, waders, plastic gloves, refreshments, shovels, wheelbarrows, t-shirts, first aid kits, and other equipment (Kumble and Bernstein, 1991). For larger projects, the cost of trash removal and hauling debris should be taken into consideration.

Organizers should notify local newspapers, and radio and television stations about the cleanup, with an emphasis on progress made, the watershed restoration effort, and recognition of volunteers.

The Cleanup - Cleanups are typically done in a single day. All trash and debris collected during the cleanup should be organized into piles of recyclables (e.g., plastic, glass, aluminum, etc.) and non-recyclable garbage. Municipal recycling and trash removal agencies should coordinate trash hauling. It is helpful to track the amount and type of garbage collected during the cleanup. Also, try to plan some kind of stream education event to educate volunteers on the larger watershed restoration effort. Before and after photographs help document how much was accomplished (Figure 3). Finally, thank all who participated in the cleanup effort or contributed in some way to the project.

After the cleanup, the site should be monitored to determine the source of the trash, and efforts to continue trash pick-up should be made. Summaries of the type and volume of trash collected should be reported to the press and local agencies.


http://www.saveourstreams.org

Figure 3: Trash removed during a stream cleanup

Costs - The overall cost of a stream cleanup is highly dependent on the amount of donated supplies and services. Trash and debris hauling and landfill disposal fees can be significant, although most municipal agencies are usually happy to provide them for free. Donation of services, corporate sponsors, waiving of fees, and the use of publicly-owned equipment can reduce cleanup costs. Most cleanups use volunteer labor, but organizers must supply equipment, such as hand tools, waders and safety equipment (e.g., gloves, goggles, etc.). Efforts should be made to obtain these materials as donations or at a reduced cost. Additional costs include volunteer appreciation materials, disposable cameras, film and developing, refreshments for volunteers, promotional materials, printing costs, and educational materials.

Further Resources

Stream cleanup guidance from U.S. Environmental Protection Agency http://www.epa.gov/adopt/patch/html/streambeach.html

Water Action Volunteers. *Stream and River Cleanup*. http://clean-water.uwex.edu/wav/river/cleanup.pdf

National River Cleanup http://www.nationalrivercleanup.com

C-2

Stream Cleanups

STREAM ADOPTION

Description

A stream adoption program encourages individual citizens to become involved in the assessment, monitoring and stewardship for specific urban stream reaches. Stream adoption is normally organized as a volunteer program, in which participants "adopt" an urban stream segment to routinely clean up trash, perform monitoring, report water quality violations and implement smaller stream repair and stewardship projects (Figure 1). Volunteers become the eyes and ears for the stream and act as the primary caretaker of an individual stream segment within a subwatershed. The goal is to walk and assess the stream segment during every season of the year.

Stream adoption is best done in impacted and non-supporting watersheds. The extensive enclosure and interruption that occurs in urban drainage subwatersheds makes them very difficult to adopt. Stream adopters play a very important role in reporting problems in the subwatersheds, including dumping, sanitary sewer overflows, fish kills, erosion and sediment control violations, spills, and illegal discharges. In addition, they can play a valuable role in providing direct retail homeowner education.

Feasibility

Stream adoption programs can be difficult to implement in urban watersheds if access is poor to the stream network. Access may be restricted by fences, commercial and industrial uses, overgrown vegetation, or because streams are enclosed or culverted. Urban stream adoption has unique cleanup and safety issues and is typically more complex compared to rural streams.

Figure 1: Advertising of a local adopt-a-stream program

Implementation

Implementing a stream adoption program involves many tasks to recruit, train and retain a large number of volunteers across a subwatershed. These tasks include identifying viable stream reaches to adopt, recruiting and training volunteers, and providing incentives for those volunteers to continue their stewardship activities.

Watershed Delineation and Stream Selection – Watershed delineation is used to find stream reaches that are practical for volunteers to adopt and manage. This is usually done after the stream network in a subwatershed has been systematically walked using the Unified Stream Assessment (USA) technique (Manual 10). Generally, all "walkable" streams in a subwatershed are open for adoption, but these should be divided into smaller, more manageable units for actual adoption. According to Zielinski (2004), "adopted" reaches should meet the following criteria:

- Be about 1,000 to 2,000 feet long
- Have at least one easy access point to the stream from a road or open area
- Be located between major road crossings or major land use changes (include culvert with downstream section)
- Major confluences should be used as breaks between reaches
- Have public access along at least one side of the floodplain

Once streams reaches are identified, it is helpful to give each one a unique subwatershed address. Using a simple stream address system allows organizers to create less cluttered maps and reduces potential confusion among volunteers.

Once all adoptable reaches have been identified, a map of the stream reach should be generated, depicting watershed boundaries, roads, structures, streams, parks, neighborhoods, landmarks and adoption sections. This map can be printed in brochure format and distributed throughout the watershed (map on one side, program details on the other). The watershed address should also be posted on the watershed organization's website. Volunteers can then choose which reaches they would like to adopt by looking at the maps.

Designing the Program and Recruiting Volunteers – Zielinski (2004) interviewed adopt-a-stream programs around the country and presents some tips to design effective programs in Table 1. The critical element of any program is to recruit, train and retain volunteers. While individuals choose to volunteer for many reasons, it seems that satisfaction goes hand-in-hand with recognition as the motivation to practice stewardship. Incentives are benefits that entice individuals to participate in an activity and may include, but are not limited to:

- Improve the quality of life in the community
- Have fun
- Take the first steps of environmental activism
- Acquire new skills
- Fulfill the community service requirements for a club, school, church
- Make new friends and network
- Contribute to a cause that is important to them

Table 1: Tips on Developing an Effective Stream Adoption Program (from Zielinski, 2004)

- Provide progressive levels of stream adoption to meet the different skills and interests of the volunteer pool. For example, one stream watch program has five different levels of adoption: *stream cleaners* that monitor trash levels in the corridor, *stream walkers* that perform a visual survey of stream problems, *stream watchers* that regularly conduct the USA on each reach, *bug pickers* that collect aquatic insect data at fixed stations, and *snapshot samplers* that collect regular grab samples to characterize water quality.
- Educate potential volunteers about water quality issues to get them interested in volunteering.
- Recruit volunteers through newsletters, newspaper ads, websites, flyers, and word-of-mouth
- Make adoption fun, educational and family-oriented
- Continuously recruit and train new volunteers, and develop an updated contact database. Try to outreach to volunteers at least five times a year
- Conduct regular “hands on” training workshops for both new and existing volunteers
- Choose previously tested and standardized monitoring methods and develop quality control plans
- Assign some local technical staff to support field activities and be liaison to the volunteers
- Continuously monitor volunteer satisfaction and modify program to maintain it at a high level
- Provide direct and timely response when volunteers discover water quality problems
- Work with volunteers to implement small-scale stream repair projects within adopted stream segments
- Address potential liability issues with standard waiver forms and safety training
- Use a newsletter or website to regularly communicate with volunteers and get data out to the public

Since many other volunteer opportunities exist, and residents have many other competing demands on their time, it is important to recognize the meaningful contribution that volunteers make in the community. Many low-cost options to encourage and recognize volunteers include:

- A recognition event: dinner, lunch, or other gathering
- Awards
- Certificates
- Drawings for prizes
- Gift Certificates to restaurants
- Gifts of photos of the watershed
- Most hours of service
- Number of years of service
- Outstanding service
- Recognition at regularly scheduled events
- Thank you letters and other acknowledgements
- T-shirts
- Volunteer of the month/year

The selection of incentives and recognition should reflect the nature of the expected volunteers or organizations. For example, volunteer groups composed of college students will be motivated by different incentives and benefits than one comprised mostly of elderly or adolescent volunteers.

Monitoring the Adopted Stream - Stream adoption programs can collect volunteer monitoring data. Monitoring may include water quality testing, habitat and aquatic insect sampling, pH, outfall testing, and physical stream assessments (Figure 2). The monitoring frequency for stream assessments can range from one to five times per year, depending on the type of assessment. This data should be incorporated into a database so that trends in the stream can be tracked. This information helps the stream managers and volunteers better understand the state of the streams and subwatershed.

Reporting Water Quality Violations – A major role of a stream adopter is to act as the eyes and ears or the stream and report problems. The stream adopter should be trained to identify, document, and quickly report any of the following: dumping, fish kills, erosion and sediment control violations, suspicious outfalls, sanitary sewer overflows, buffer encroachment, illicit discharges, or other water quality violations.

Other Roles – Stream adopters can play many roles in other stewardship activities. They can monitor trash levels along the stream and its corridor and arrange regular stream cleanups (Profile Sheet C-1). In addition, they can be the "retail" watershed education distributor in the subwatershed to civic groups, garden clubs, and neighborhood associations.

Cost – The costs to organize and implement a stream adoption program is typically moderate, depending on whether or not paid staff are needed to administer the program. According to Zielinski (2004), the annual cost to adopt a mile of stream ranges from $200 to $1,000. If paid staff are needed, annual costs can run from $5,000 to $10,000 per subwatershed, not including plans to secure sponsors, assemble outreach materials, or acquire monitoring and cleanup equipment and database systems. It is important to note that much of the monitoring and cleanup equipment can be donated by local businesses and institutions.

Figure 2: Aquatic insect sampling

Further Resources

Many states, communities or watershed organizations have developed stream adoption or citizen monitoring program to involve citizens in stream assessment. The goals and methods of adoption programs can differ considerably (Zielinski, 2004). The following list of resources is not meant to be exhaustive, but provides good examples of national organizations and regional programs that may be helpful.

Adopt-a-Stream http://www.adopt-a-stream.org, including a Teachers guide:
http://www.adopt-a-stream.org/about_the_teachers_guides.html

Izaak Walton League http://www.iwla.org/

Streamkeepers
http://www.streamkeeper.org/tools

Assabet River Stream Watch Program (MA)
http://assabetriver.org/streamwatch/

Delaware Stream Watch
http://www.delawarenaturesociety.org/streamwatch.htm

Huron River Watershed Council Adopt-a-Stream (MI)
http://comnet.org/local/orgs/hrwc/adopt/adopt.htm

Maryland Stream Waders
http://www.dnr.state.md.us/streams/mbss/waders2.html

This also has excellent volunteer stream monitoring manual:
http://dnrweb.dnr.state.md.us/download/bays/streams/2002waders.pdf

North Carolina Stream Watch
http://www.ee.enr/state.nc.us/

Adopt-a-Stream Programs
http://www.fws.gov/r5cneafp/adopt2.htm
(Atlantic)

http://www.wdfw.wa.gov/outreach/education/salclass.htm (Pacific)

R-3

Stream Repair: Hard Bank Stabilization

BOULDER REVETMENT

Description

A boulder revetment is a stream repair practice used to stabilize eroding streambanks. The revetment consists of a series of boulders placed in varying configurations along an eroding streambank to prevent erosion at the toe and in some cases, the middle and upper streambank zone (Figure 1).

Habitat Features Created – Boulder revetments have only a limited potential to enhance stream habitat. As most boulder revetments are made of irregularly shaped boulders, there is limited potential to create void space below the water surface. Boulder revetments have a more indirect role in habitat enhancement by reducing streambank erosion and subsequent sediment influx to the stream.

Feasibility

The toe of the streambank is the most erosion prone area of an urban stream, with the lowest third of the bank experiencing the greatest erosive forces. Erosion at the toe of the streambank often results in failure of the entire bank, which greatly increases sediment delivery to the stream. Boulder revetments help protect vulnerable streambanks in situations where softer bioengineering practices are not practical because of high flow velocities and shear stress.

Boulder revetments are an effective bank stabilization method when the cause of bank failure is toe erosion, bank scouring, or urban stream enlargement. Boulder revetments are not recommended for streambanks that are failing due to active downcutting (i.e., stream degradation). In these situations, revetments can be undermined as the streambed drops, unless the underlying grade control problem is addressed.

Boulder revetments often serve as the foundation for bank shaping and other bioengineering measures on the middle and upper banks (Figure 2). Boulder revetments can provide complete bank protection on smaller streams with bank heights of less than two feet.

Boulder revetments are a hard and non-deformable practice that prevents the normal processes of lateral channel adjustment and meander migration from occurring.

Figure 1: Boulder revetment along a meander in an urban park

Figure 2: Boulder revetment with willow plantings along an urban stream

As such, their use should be confined to the outer edges of the meander corridor to protect valley side slopes and terraces from further erosion. Deformable bioengineering practices are generally preferred within the meander corridor, where feasible (Figure 3). Over-reliance on boulder revetments in an urban stream may simply transfer future channel adjustments to upstream and downstream areas that are presently stable.

If the bank substrate is composed of sandy, silty or organic materials, scour may cause the revetment to settle or fail. Designers should ensure that the stream substrate can support the weight of the revetment and that the revetment extends below the potential depth of scour (Figure 4). Boulder revetments require good access for heavy equipment, and a staging area to stockpile boulders and equipment. Additional construction costs are incurred when the staging area is distant from the bank repair site, and smaller, lighter equipment is needed to access the site.

Implementation

Most boulder revetments consist of a course of footer boulders and one or two courses of revetment boulders. Figure 5 depicts double boulder and large boulder revetment configurations. Unlike imbricated rip-rap revetments, boulder revetments are not intended to be self-supporting walls, and may use smaller, less blocky boulders. The size of the boulders should be set so they will not move during flow velocities expected for the 50 or 100-year flood level. Boulder revetments are suitable on straight reaches or meander curves, as long as the potential depth of scour is accounted for. Use of native rock is recommended where practical. Bright white or off-colored stone may not be aesthetically pleasing in regions where native stone is dark.

Another design variation is the deformable toe revetment. This new streambank treatment is designed to be stable for the time it takes to establish streambank vegetation, after which the boulders are allowed to move. Deformable toe revetment designs use boulder sizes that will be stable for more frequent design floods (5- to 10-year return frequency) and wrap them in biodegradable erosion control fabrics. The fabric ensures that the boulders will be stable for the life of the fabrics (about 2 to 5 years), which gives enough time for vegetation to take hold. At that time, the streambank is allowed to laterally adjust and the meander can migrate.

At times, a single row of three to four foot diameter boulders may be used to create a revetment. When large boulders are used, it is important that they be entrenched deeply enough to prevent channel scour from dislodging them. Otherwise, the construction of a large boulder revetment is very similar to single and double boulder revetments, minus the footer stones.

Construction – A single boulder revetment is created by first excavating a trench below the invert of the stream and extending it along the toe of the eroding streambank. Filter cloth is

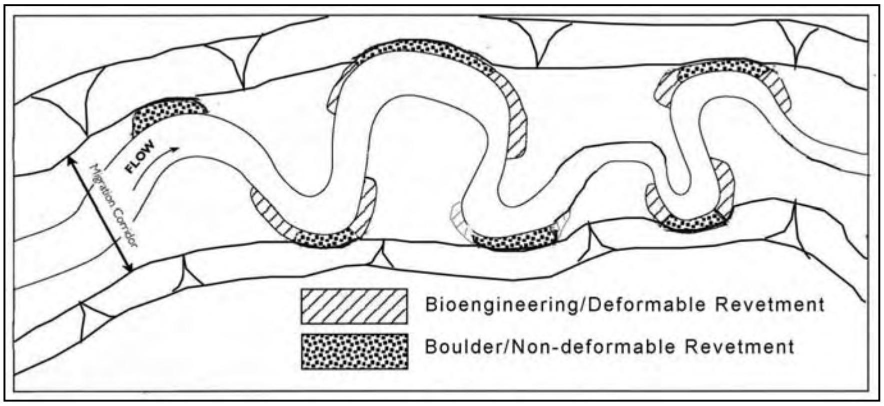


Figure 3: Appropriate use of deformable (soft) and non-deformable (hard) bank protection practices
Source: Miller and Skidmore, 2000

Figure 4: Boulder revetment failure due to toe scour

then placed in the trench and extended up the streambank. A series of large flat/rectangular boulders are then placed in the trench as footers. The bottom of the footer boulders must be below the expected depth of scour. Once the footer boulders have been installed, revetment boulders are placed on top. If protection is needed higher on the bank, a second course of stones may be placed on top of the first, forming a double boulder revetment. The face of the revetment should be made as rough as possible to decrease current velocities on the streambank. The revetment should generally extend at least one-third of the streambank height to protect the most erosion prone area. Once the revetment is installed, the upper streambank should be graded and shaped to transition into the top of the revetment. Streambed vegetation and erosion control mats are then installed on exposed soils.

Other streambank stabilization practices are often placed above the boulder revetment. Soil lifts and bioengineering practices are often combined with toe revetments to protect the upper streambank. In these cases, the boulder revetment should extend to a height above which vigorous perennial vegetation can survive.

Maintenance/Monitoring – Initially, inspections of the boulder revetment should be undertaken after the first few large storms to ensure that the boulders are stable and upper bank plantings are surviving. Once this has been confirmed, annual inspections are warranted. No special maintenance is needed for boulder revetments, except for occasional replacement of dead/dying vegetation.

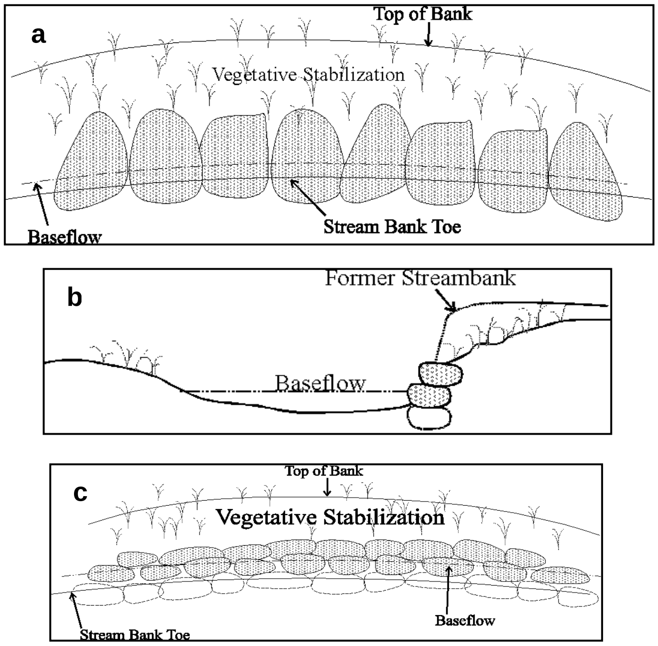


Figure 5: (a) Large boulder revetment, (b) Profile of boulder revetment, (c) Plan view of boulder revetment

Cost – The unit cost to install a single boulder revetment ranges from $20 to $40 per linear foot of eroding streambank. Cost for boulder revetments increases when double layer treatments are used and additional treatments are needed on the upper bank.

Further Resources

Washington State Integrated Streambank Protection Guidelines (2002)
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf (roughened rock toes)

Maryland Guidelines to Waterway Construction (2000)
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-11.pdf

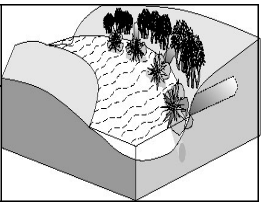
NRCS Engineering Field Handbook - Chapter 16 Streambank and Shoreline Protection
http://www.nrcs.usda.gov/technical/ENG/efh.html

Ohio Stream Management Guide
http://www.ohiodnr.com/water/pubs/fs_st/streamsfs.htm

R-4

Stream Repair: Hard Bank Stabilization

ROOTWAD REVETMENT



Description

A rootwad is the lower trunk and root fan of a large tree. Rootwad revetments are a stream repair practice intended to stabilize eroding streambanks. Individual rootwads are installed in series along meander bends to protect the streambank from erosion. A rootwad revetment can consist of just one or two rootwads, or more than 20, depending on the size of the stream. The root mass of the rootwads reduces current velocities along the streambank, which helps minimize erosion.

Habitat Features Created – Rootwad revetments have moderate potential to enhance in-stream habitat by providing overhead cover and resting areas for fish along meander bends.

Feasibility

Rootwads have emerged as both a common and reliable practice to protect streambanks along meander bends (Figure 1). While more complicated to design and install than traditional, hard bank protection practices, rootwad revetments offer several advantages. Rootwads are cost effective, if rootwad material can be obtained on site or locally. Rootwad revetments are also deformable in the long term (5-15 years) and can create substantial aquatic habitat.

These advantages come with a somewhat higher risk of failure and certain limitations on where rootwads are appropriate. Rootwads work best along streams that are not expected to experience severe channel incision. In some larger streams, rootwads may pose a safety hazard to boaters and their application may not be advisable in streams that can be paddled or experience heavy recreational use. Rootwads must also be combined with bank shaping and vegetative stabilization in order to prevent erosion and soil loss between individual rootwads (Figure 2). Without effective upper bank stabilization, rootwads are prone to failure.

Regional Considerations – In arid or semi-arid regions, availability of rootwads may be limited. In addition, ice can damage/dislodge rootwads during spring melt in colder climates.

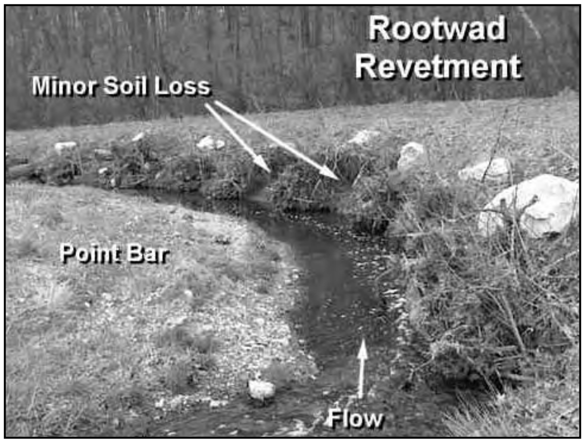


Figure 1: Well-constructed rootwad revetment installed along a small piedmont stream

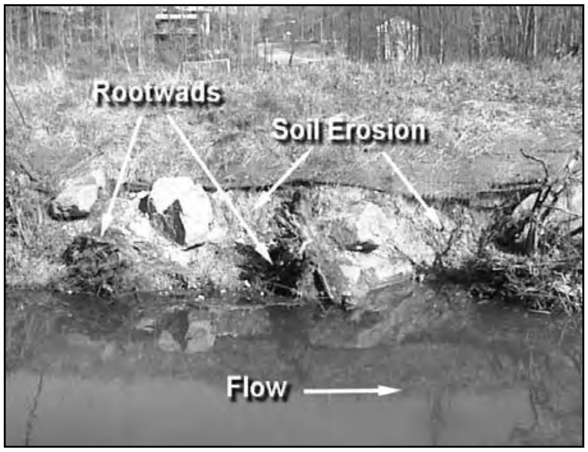


Figure 2: Soil erosion due to a lack of vegetation along a rootwad revetment

Rootwad revetments are recommended to stabilize meander bends along streams in older urban watersheds that have had time to adjust their geometry (e.g., radius, cross section and grade) to altered hydrology and are no longer rapidly adjusting (Figure 3). Since rootwads are fixed, they cannot adjust to rapid geomorphic change, and are prone to failure when major vertical and/or horizontal channel adjustments occur.

Rootwad revetments may work on meander bends that have not fully adjusted or are newly adjusted, but they have a much higher potential to fail under these conditions (Figure 4). Using rootwads in stream channels that are still adjusting can also cause erosion and channel instability upstream or downstream. When rootwads are used in these situations, designers should carefully predict the direction and dimensions of expected stream channel adjustments (i.e., design the meander bend to expected future dimensions and not just the current ones).

Figure 3: Stable rootwad revetment along an urban stream

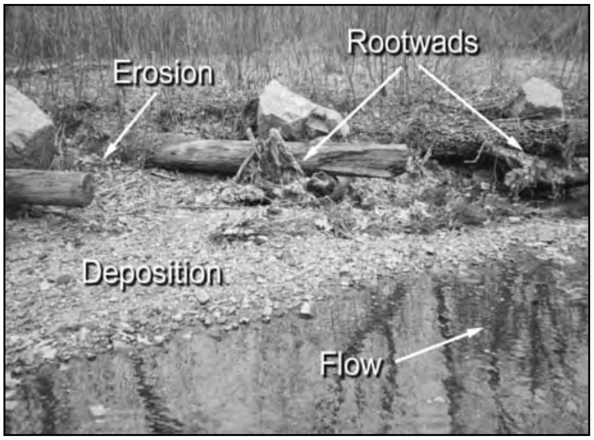


Figure 4: Rootwad revetment installed on an adjusting stream reach

Rootwads should not be installed in highly entrenched channels (i.e., deeply incised). Storm flows that exceed the height of the rootwad fan must be able to flow to an overbank floodplain area to dissipate the energy of the current. Floodwaters can erode the area above and behind the rootwad revetment with the potential to scour the rootwads out from above and behind (Figure 5).

Implementation

Individual rootwads are not intended to armor the streambank, but rather to deflect the thalweg away from the streambank. Spacing of the rootwads along the revetment and the orientation of the root fans to the flow are critical to this deflection. The key design parameter for rootwads is the diameter of the root fan, which should extend from the maximum depth of scour on the streambed up to the bankfull height of the bank. Doll *et al*. (2003) recommend that the tree trunk above the wad should have a diameter of ten to 24 inches, and the trunk should be at least 10 to 15 feet long to extend into the bank.

Root fans of individual rootwads should be oriented perpendicular to the current (± 15 degrees) at the installation point along the meander bend (Figure 6). Individual rootwads should be spaced so that the current deflected by one rootwad will not hit the streambank before encountering the next downstream rootwad. As a general spacing rule, rootwads should be placed no more than three to four times the distance the root fan extends out from the streambank. This rule is appropriate on streams where the ratio of the radius of the meander curve to the channel top width (Rc/W) is 3.0 or greater. When this ratio approaches 2.5, individual rootwads are no longer effective at deflecting flows and must essentially be touching to protect the streambank (Sylte and Fischenich, 2000). At this density, the revetment is essentially “root-rap” and other hard bank stabilization practices may be more appropriate (e.g., R-3, R-5).

Figure 5: Failed rootwad revetment along a confined meander

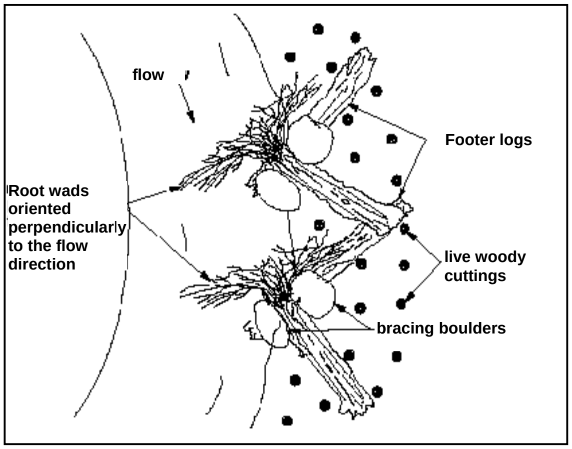


Figure 6: Plan view of rootwad revetment

Generally, the trunk of each rootwad should be at least 10-15 feet long with 75% of the length embedded in the streambank. The rootwad fan width should extend from the maximum expected depth of scour to near the bankfull height. This height can be difficult to achieve in many highly entrenched urban streams. Rootwads can be interlocked or stacked to achieve the necessary height, but care must be taken to make sure the arrangement is stable.

According to Harman *et al*. (2001), rootwads cannot be installed too low, but can fail if installed too high above the stream invert. In addition, at least half of the rootwad fan should extend below the normal baseflow water elevation to maximize habitat value.

Construction – Rootwad construction begins at the downstream end of the revetment. Harman *et al*. (2001) describe two basic methods for rootwad construction— drivepoint and trenching. The drivepoint method uses a track hoe with a hydraulic thumb to insert the sharpened rootwad directly into the bank without trenching. The drivepoint method is considered by Harman *et al*. (2001) to be more cost effective, and involves the least soil disturbance. The trenching method is described below.

First, excavate a trench in the streambank for the first footer log. This trench should be roughly perpendicular to the desired orientation of the rootwad. The footer trench should be excavated so that two-thirds of the footer log will extend into the streambank and at a depth to allow the root fan to extend down to the maximum depth of scour.

After the first footer trench has been excavated, dig a second trench for the rootwad that is perpendicular to the footer trench. The rootwad trench should be excavated so that two-thirds of the trunk will extend into the streambank and to a depth that will allow the rootwad to sit roughly level on top of the footer log. Install the footer and rootwad. The trunk of the rootwad should rest firmly on the footer log so that the root fan faces into the current at the desired orientation. Where rootwads are closely spaced, an upstream rootwad trunk can be placed on top of the downstream footer log. After installing the footer and rootwad, place large rocks on the top and sides of the rootwad trunk, behind the footer log, to hold it in place. Once the rootwad is installed, backfill the trenches with compacted rock/fill. This process continues until all rootwads have been installed.

After all of the rootwads are installed, the top of the streambank should be graded to transition into the rootwads. Stabilize the streambank with a combination of erosion control fabric and vegetation. Transplanted shrubs and trees are preferable to provide dense live root mass for long-term bank stabilization. If transplants are not available, then brush mattresses or live fascines may be used to provide bank protection.

Generally, the gap between the rootwads is considered the weakest point along the entire revetment and requires vigorous revegetation to minimize any soil loss.

Maintenance/Monitoring – It is important to closely monitor plantings around rootwads since scour can cause premature failure if vegetative stability is not achieved. The installation should be inspected after each significant storm during the first two growing seasons. Any loss of plant materials should be immediately addressed. Once plantings are well established, rootwads can be inspected annually (Figure 7).

Cost – Costs to install a rootwad revetment depend on whether there is an on-site source of rootwads or they must be brought in from off-site. Good designers will often scavenge log material during clearing of access roads or from nearby construction sites. Unit costs for rootwads obtained on-site range from $50 to $330 each, whereas unit costs to install a rootwad obtained off-site range from $250 to over $600 each.

Further Resources

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-10.pdf

Rootwad Composites for Streambank Erosion Control and Fish Habitat Enhancement
http://www.wes.army.mil/el/emrrp/pdf/sr21.pdf

Stream Restoration- A Natural Channel Design Handbook, Chapter 8.1
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

Ontario Stream Rehabilitation Manual
http://www.ontariostreams.on.ca/OSRM/toc.htm

Figure 7: Root-rapping in Pacific Northwest

R-5

Stream Repair: Hard Bank Stabilization

IMBRICATED RIP-RAP

Description

Imbricated rip-rap is a stream repair practice that provides hard bank stabilization and consists of large boulders arranged as interlocking blocks along the streambank toe. Imbricated rip-rap is a structural solution to stabilize high streambanks from erosion where it is not possible to shape the streambank to a stable angle or apply other deformable measures (Figure 1).

Habitat Features Created – Although imbricated rip-rap is a hard streambank stabilization practice, it can provide habitat enhancement in the form of gaps beneath the water surface between the revetment stones, which provide overhead cover and refuge areas for fish.

Feasibility

Imbricated rip-rap is often used along entrenched streams with severe instability that cannot be mitigated by other techniques because of space and infrastructure constraints. Imbricated rip-rap should only be used where continued bank failure would result in the loss of property or infrastructure, or massive sediment movement into the stream (e.g., slope failure), and where no other bank stabilization practices are feasible. Also, if the bed substrate is composed of sandy, organic or silty materials, it may not support the weight of the revetment. In these cases, additional foundation materials may be required.

Figure 1: Imbricated rip-rap revetment protecting utility infrastructure

Imbricated rip-rap is a non-deformable practice that eliminates the ability of the stream to adjust laterally in response to changing flow and sediment transport conditions. Extensive use of imbricated rip-rap may simply shift where these natural adjustments occur upstream or downstream of the practice. Imbricated rip-rap makes sense when streambank instability is the result of stream channel processes, such as toe erosion, channel scour, meander migration and lateral adjustment. If streambank failure is caused by slope instability or mass wasting unrelated to stream channel processes, these upland problems must be corrected prior to installation.

In addition, imbricated rip-rap is <u>not</u> recommended for urban stream channels that are experiencing or expected to undergo vertical degradation or incision. In any case, footer stones must be installed below the depth of the expected scour. Imbricated rip-rap should be used in tandem with grade control practices, if there is potential for vertical channel degradation.

Implementation

Rock size determines the maximum height of the revetment. In general, the height of the revetment should not exceed three times the long axis of the average rock or 10 feet, whichever is less. Filter fabric and/or a graded gravel filter should be installed between the revetment and the existing streambank surface to prevent soil piping.

Imbricated rip-rap can be close to vertical but should be sloped back slightly for stability (i.e., 1H:6V). This practice requires large boulders that are generally flat or rectangular in shape so that they can be stacked securely and with structural integrity. The structural properties of imbricated rip-rap make it one of the few practices that can be installed along near vertical streambanks. The boulders should be sized so that they will remain stable at the expected current velocity of the design flood event, and footer boulders located below the expected depth of future scour. Methods to estimate stable rock size and the depth of the scour can be found in Copeland *et al*. (2001).

Construction – Imbricated rip-rap is installed in the same general manner as a boulder revetment but can rise to protect the full height of the streambank (Figure 2). In other cases, imbricated rip-rap is used to protect the bottom half of the bank, with the upper bank laid back and vegetatively stabilized. The first step in the construction sequence is to grade the streambank to the desired slope. After the streambank is graded to the desired angle, a trench should be cut along the toe of the bank for the footer stones. The depth of the footer trench should allow stones to extend down to below the expected depth of scour. More than one course of footer rocks may be needed for the foundation. A layer of geotextile fabric is then laid from the top of the streambank down into the footer trench, to prevent the loss of streambank soils through the revetment.

Individual footer stones are placed on top of the filter cloth in the trench. The largest stones should be placed lowest within the revetment. Once the first course of footer stones is in place, the remaining trench can be backfilled with smaller rip-rap as toe protection. A key design element of imbricated rip-rap is the spacing of the first layer of revetment blocks, which should be separated by a gap of 12 to 18 inches.

Gaps beneath the water surface serve as overhead cover and refuge for fish (Figure 3). Succeeding courses are stacked with staggered joints between each course. Free draining gravel should be backfilled between the revetment stones and the filter fabric as each course is laid. The process is continued until the desired wall height is reached. The existing top of the bank is then laid back into the imbricated rip-rap wall and stabilized with vegetation (Figure 4).

Maintenance/Monitoring – Imbricated riprap should be inspected for structural integrity monthly for the first six months, or after any large storm events during the first year, with annual inspections thereafter.

Cost – Reported unit cost for imbricated rip-rap ranges from $60 to $90 per linear foot, with higher costs for greater bank heights stabilized.

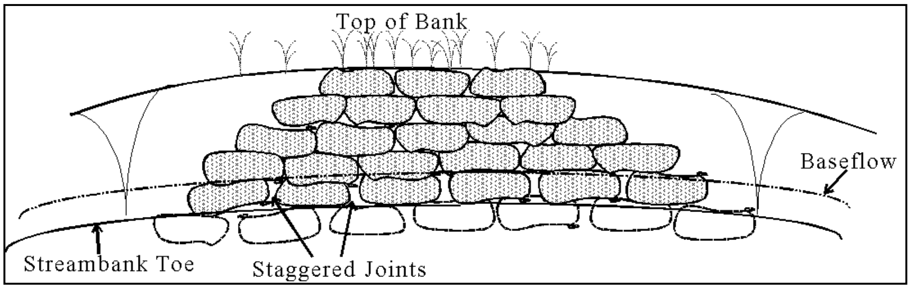


Figure 2: Longitudinal view of an imbricated rip-rap revetment

Figure 3: Spacing between the first course of revetment stones

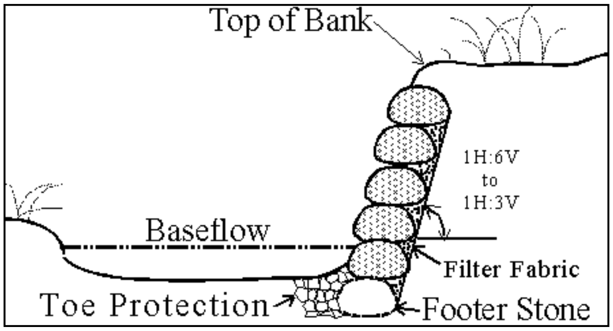


Figure 4: Cross-section view of imbricated rip-rap revetment

Further Resources

Maryland Guidelines to Waterway Construction (includes standard details for imbricated riprap)

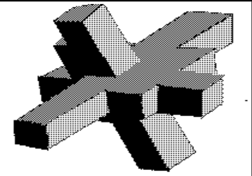
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-2.pdf

Virginia Stream Restoration and Stabilization Best Management Practices Guide
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

R-6

Stream Repair: Hard Bank Stabilization

A-JACKS



Description

A-jacks are a stream repair practice used to protect the toe of eroding streambanks consisting of six-armed or star-shaped cement structures that are commercially produced. Each arm of the A-jack is approximately two feet long. A-jacks were originally designed as much larger structures for use as breakwaters along shorelines and have been adapted for use as toe protection for urban stream repair. Individual A-jacks are stacked and interconnected to form a revetment along the eroding toe of a streambank (Figure 1). A-jacks are normally combined with streambank shaping (R-8), coir logs (R-9), erosion control fabrics (R-10), live stakes (R-12) or vegetative establishment (R-15) to provide effective bank stabilization.

Habitat Features Created – A-jacks have minor potential to improve streambank habitat by creating a stable streambank toe and reducing streambank erosion.

Feasibility

A-jacks provide hard toe protection and must be combined with other streambank protection measures to stabilize the middle and upper streambank. A-jacks are two-piece modular structures that are assembled at the bank repair site. Each piece weighs about 40 pounds, which makes them fairly easy to assemble and place by hand. A-jacks are suitable for use as toe protection in both straight reaches and meander bends along urban streams. They should be used with care on rapidly degrading streams, as downcutting of the stream channel may cause undercutting and failure. To date, A-jacks have been used primarily in the Midwest, but there appear to be no fundamental constraints to their use in other regions of the country.

A-jacks work best along streambanks that have cohesive soils. Sandy and other non-cohesive soils will require packing the voids in the structures with coir fiber matting to prevent soil loss through the A-jacks.

Figure 1: A-jacks installed beneath coir fiber logs

Implementation

An A-jacks revetment is designed much in the same way as a boulder revetment (R-3). Each A-jack interconnects with adjacent ones creating a hard, stable structure. They can be stacked in multiple tiers to achieve the desired height and width (Figure 2). Key design factors include entrenching the toe below the expected depth of scour and creating a stable upper bank treatment.

Construction –A-jacks are typically shipped on pallets and then assembled at the bank repair site. The streambank should be excavated back and a trench dug along the toe of the streambank as deep as the expected depth of scour. Individual A-jacks are placed in the trench to form an interconnected row. Multiple interconnected rows can be installed to achieve the desired width of the revetment. Once the lowermost row or tier is formed, additional A-jacks can be stacked atop the first to achieve the desired revetment height. Once installed, the voids in the structure can be packed with coir fiber matting or erosion control fabrics to prevent soil loss. When the desired revetment height is reached, the A-jacks revetment is backfilled with a mixture of soil and rock. An appropriate upper streambank treatment is then applied to restore the full height of the streambank

Maintenance/Monitoring –The A-jacks themselves do not require much maintenance, but the upper streambank treatment should be regularly inspected to make sure it is stable and vegetated.

Cost - The cost to install an A-jacks toe revetment typically ranges from $65 to $85 a linear foot depending on the number of rows or tiers installed along the bank.

Further Resources

A well-illustrated example of A-Jacks construction is provided in Chapter 5 of the *Field Manual of Urban Stream Restoration* (Newbury *et al*., 1998), which can be obtained from the Conservation Technology Information Center website http://www.ctic.purdue.edu/

Armortec, Inc. (manufacturer)
http://armortec.com/products/products.htm

Virginia Stream Restoration and Stabilization Best Management Practices Guide (interlocking concrete jacks)
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

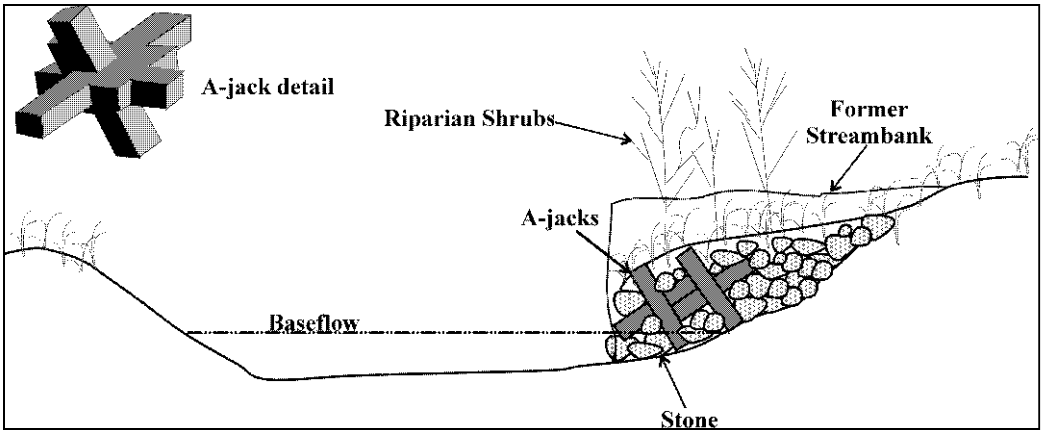
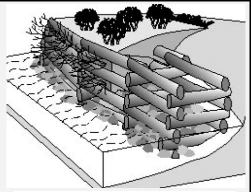


Figure 2: Cross-section view of an A-jacks revetment

R-7

Stream Repair: Hard Bank Stabilization

LIVE CRIBWALLS



Description

Live cribwalls stabilize eroding streambanks and consist of a timber frame retaining wall constructed along the streambank that incorporates live vegetation (Figure 1). The cribwall is formed by an interlocking, tiered arrangement of untreated logs that is backfilled with soil and rocks. Gaps between tiers allow room for plantings of woody vegetation, which serve both functional and aesthetic purposes. As the logs decompose over time, root structures of the woody vegetation provide structural support for the eroding bank.

Habitat Features Created: Live cribwalls do not directly enhance in-stream habitat, but can enhance riparian habitat by creating overhanging bank vegetation and reducing streambank erosion.

Feasibility

Log cribwalls are usually constructed along eroding streambanks with steep slopes where private property or infrastructure is threatened and space is not available to re-grade the streambank to a stable angle. Live cribwalls are considered to be a more visually appealing alternative to imbricated rip-rap. Live cribwalls are frequently used in banks where toe erosion has caused mass failure of streambank soil. Since live cribwalls are a hard bank protection stabilization, they prevent normal channel and meander migration and may transfer these processes upstream or downstream. Live cribwalls are not permanent and will degrade over several decades. They are not recommended for rapidly degrading or incising urban streams. Design of live cribwalls must consider the potential for lateral soil movement or mass wasting (e.g., landslides, slope instability, soil limitations), and a licensed geotechnical engineer should be consulted if there are serious concerns about slope failure.

Implementation

A live cribwall essentially functions as a retaining wall and should be designed to resist geotechnical forces such as sliding, overturning and bearing failure (Figure 2). The design team should include qualified geotechnical engineers to address safety and structural issues. The design of the cribwall should not appreciably narrow the stream cross-section, which can cause increased current velocities and scour along the toe of the cribwall.

Live cribwalls are constructed from logs that range in diameter from six to 18 inches. The size and species of wood used for a cribwall depends on the strength of the wood, its resistance to rot, the desired height of the cribwall, and local stream hydraulics.

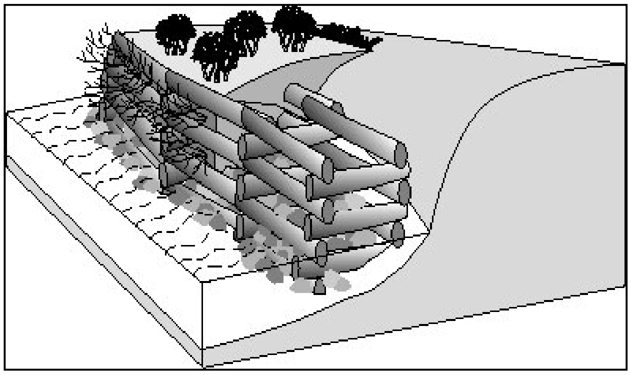


Figure 1: Schematic of an installed live cribwall

(Source: FISRWG, 1998)

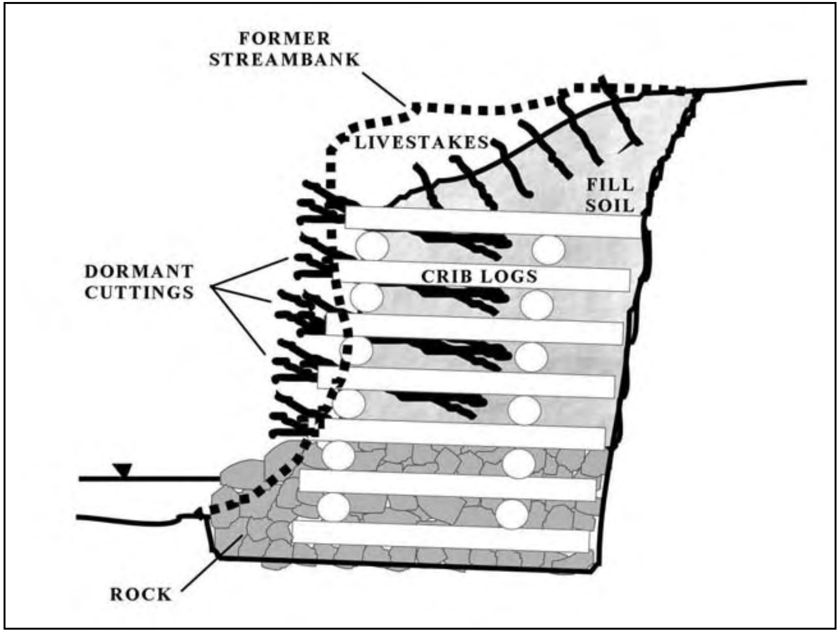


Figure 2: Cross-section of a live cribwall

One of the most important cribwall design considerations is protection of the toe of the eroding bank. Live cribwalls must extend below the expected depth of scour and be armored with large rock. The transition between the live cribwall and downstream banks should be smooth to minimize erosion potential during high flow events. The lifespan of cribwalls depends on the structural elements (e.g., logs and fasteners) used in construction. The logs used to construct the cribwall should be resistant to rot; fasteners (e.g., spikes, lag bolts) should be of sufficient strength and made of galvanized metal; and the backfill material should be designed to stay in place and support living plant materials. Retention of backfill in the cribwall structure may require the use of erosion control fabrics to hold finer soil particles in place.

Growing conditions are often harsh in the gaps along the cribwall, making it difficult to establish vigorous vegetative cover. The backfilled soil should be amended with organic matter or other soil amendments to provide plant nutrients, and native riparian plant species should be selected. Supplemental irrigation may also be needed in the first few months after installation.

The timing of cribwall construction is also an important consideration. Construction should occur during periods of low stream flow to make dewatering easier and minimize siltation of the stream, and planting should be scheduled for the early spring or fall in most regions of the country.

Construction - Construction begins with the excavation of the eroded streambank where the cribwall is to be installed. The excavation should extend down below the expected depth of scour of the streambed. The first layer of the "crib" is installed in the excavated area and backfilled with rock. The outside toe of the cribwall should be protected with large rock to resist scour. The long logs that are placed parallel to the stream are referred to as "stretchers," while the shorter logs placed perpendicular to the channel are called "headers." The number and spacing of headers depends on the structural requirements of the cribwall.

The largest and most rot resistant logs should be placed near the bottom of the cribwall. Once the cribwall rises above the elevation where perennial vegetation can survive, backfill should consist of finer soil, capable of supporting plant growth. Dormant woody plantings are then incorporated into the gaps between each tier of logs. Once the desired height is reached, the upper streambank should also be graded into the cribwall and revegetated. Lastly, upstream and downstream ends of the cribwall should be smoothly transitioned into the existing streambank and planted.

Monitoring/Maintenance – Frequent inspection of vegetative survival and cribwall integrity should occur during the first growing season. Vegetation establishment may require supplemental irrigation, weeding, and replacement of dead/dying vegetation. Once plantings are firmly established, monitoring of log members, anchors, and vegetation should be conducted annually. Inspections should include digital photos of cribwall to document the condition of the logs and the health of the vegetation. Maintenance of cribwalls may involve repair of log members, anchors, and adjacent streambank areas.

Cost - Construction costs for a log cribwall include excavation, installation of the log structure, backfill and the planting of vegetation. Typical unit costs range from $250 to $350 per linear foot of bank protected. Costs are greatly affected by availability of log materials, labor rates, and the desired height of the cribwall.

Further Resources

Standard details for log cribwalls can be found at the following online resources*:*

Washington State Integrated Streambank Protection Guidelines (log cribwalls)
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-9.pdf

Water Related Best Management Practices (BMPs) in the Landscape - Stream System Protection, Restoration, and Reestablishment
http://www.wcc.nrcs.usda.gov/watershed/UrbanBMPs/pdf/streams/bank/livecribwall.pdf

Engineering Field Handbook - Chapter 16: Streambank and Shoreline Protection
http://www.nrcs.usda.gov/technical/ENG/efh.html

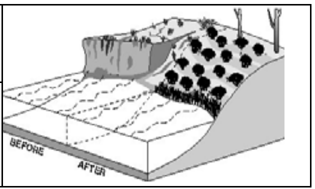
Ontario Stream Rehabilitation Manual (Live Cribwalls)
http://www.ontariostreams.on.ca/OSRM/toc.htm

Ohio Stream Management Guides (Live Cribwalls)
http://www.ohiodnr.com/water/pubs/fs_st/streamsfs.htm

R-8

Stream Repair: Soft Bank Stabilization

STREAMBANK SHAPING



Description

Streambank shaping is a stream repair practice used to achieve a more stable bank slope. It consists of changing the contours of an eroding streambank without changing the streambank toe or the planform of the stream. Streambank shaping can be used as a stand-alone practice when streambank instability is the primary cause of bank failure, or it can be combined with toe protection practices when toe erosion or channel degradation are causing the bank to erode.

Habitat Features Created - Streambank shaping does not directly enhance in-stream habitat, but can reduce fine sediments delivered to the stream.

Feasibility

As a stand-alone practice, streambank shaping can be applied to urban streams that are incised but have relatively stable longitudinal slope and channel width. Incised streams are often in the process of creating a new floodplain at a lower elevation in the stream channel, and have tall, vertical, and unstable streambanks, which far exceed the root zones of riparian vegetation. In other cases, riparian vegetation has been removed by grazing or mowing, making the banks prone to failure. If the streambank toe is not actively eroding, streambank shaping in combination with riparian plantings may be sufficient to restore streambank stability (Figure 1). In these cases, designers simply remove bank material that will likely be eroded in the future and transported downstream. Careful streambank shaping helps an urban stream adjust its cross-section to the increased hydrology produced by upstream watershed development.

If toe erosion is the primary cause of bank failure, additional hard streambank treatments, such as boulder revetments, coir logs or A-jacks, need to be installed to protect the toe before bank shaping can begin (Figure 2).

The bank angles and channel dimensions of urban streams often depend on stream classification and regional stream geometry (Rosgen, 1997). The type of soil and vegetation at the streambank also dictate stable streambank angles. Also, the potential increase in channel cross-section may improve the capacity of the channel to pass floodwaters. Adequate room must be available within the stream corridor to lay the bank back to a stable angle. Constraints such as trails, utilities and other infrastructure in the corridor should be carefully evaluated.

Implementation

The feasibility of streambank shaping as a stand-alone practice requires a thorough assessment of channel cross-section and planform. The existing and future channel cross-section should be stable and show no evidence of active enlargement or degradation. Some planform or lateral adjustment is allowable, if it occurs within the meander corridor. However, if the lateral adjustment is expected to extend outside the meander corridor and erode valley side slopes or infrastructure, other bank protection measures should be substituted. It is also important to note that streambank shaping alone will not arrest active widening or degradation of the stream

Figure 1: Streambank shaping along an urban midwest stream

Figure 2: Streambank shaping in combination with boulder revetment and rock vortex weirs

Therefore, designers need to carefully analyze the stream reach to determine the rate of toe erosion and whether the streambed is actively cutting down. Useful evidence to confirm slow toe erosion rates is build up of failed upper bank sediment along the toe. Conversely, fallen upper bank sediments tend to be quickly transported downstream from actively eroding toes.

A longitudinal gradient field survey may be needed to determine if the stream is actively downcutting. The most notable indicator of downcutting is the presence of a knickpoint below the streambank shaping site. Knick points migrate upstream and are a strong indicator of active streambed degradation. Absence of sediment deposits or bars in the stream channel may also indicate excessive channel erosion and potential bed degradation. If fallen upper bank material is present along the streambank toe and there is no evidence of active bed degradation, then shaping and re-vegetating the streambanks alone may restore bank stability. This is often the case along older urban streams where the channel has adjusted to altered hydrology and the process of channel adjustment has slowed.

Additional toe protection and grade control practices may be needed if the field assessment indicates active toe erosion and/or bed degradation are occurring. Shaping of the upper streambank can begin once other stream repair practices have addressed these problems (Figure 3).

Streambank shaping is something of an art. Designers should examine urban reference streams with stable vegetated streambanks to get an idea of locally appropriate streambank angles and vegetation types. Hydraulic analysis can be helpful to determine the type of bank material that can withstand the shear stress produced by bankfull discharges. Fischenich (2001a) has developed useful equations to determine bank stability of different bank materials based on the velocity of projected flows.

The grading plan should clearly specify where and at what angle the streambank is to be graded, the limits of grading and disturbance, and specifications for re-vegetation. Streambank shaping can generate large volumes of excess soil that need to be removed from the project area. Adequate access to the streambank shaping for dump trucks and heavy equipment may be needed.

Construction –The limits of grading and disturbance should be clearly marked in the field, and the designer should be present at the site during all grading operations. The success of streambank shaping is highly dependent on the skills of the heavy equipment operators. The designer and equipment operators must clearly understand each other and the project’s

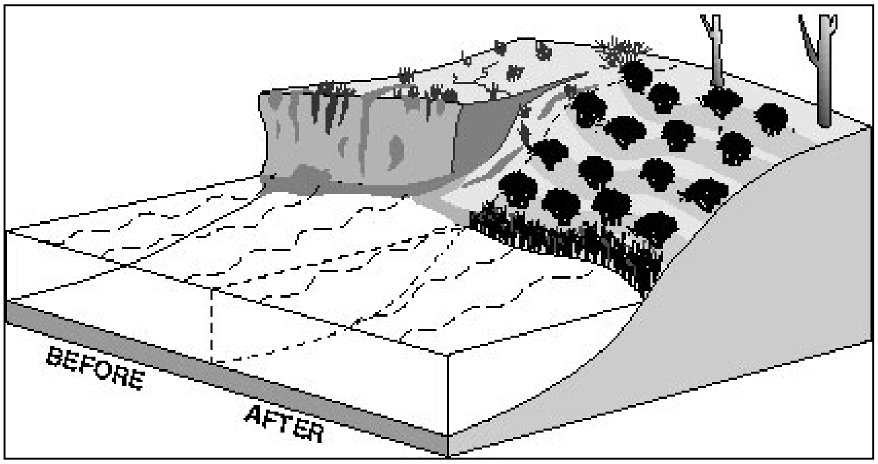


Figure 3: Before and after a streambank shaping project
Source: FISWRG, 1998

objectives. Erosion control practices should be installed along the toe of the streambank, prior to any grading. When grading is complete, streambanks should be re-vegetated with native trees, shrubs and ground cover, in accordance with the revegetation plan (see Profile Sheet R-15).

Hydro-seeding is the most efficient means to quickly establish a ground cover on relatively flat floodplain areas disturbed during construction operations. The newly shaped streambank, however, should be seeded by hand or mechanically seeded, with the seed tamped or rolled to ensure good soil contact. Erosion control fabric should be applied to lower bank areas exposed to streamflow (i.e., coir fiber, jute, straw). Additional planting can then be installed in accordance with the revegetation plans.

Maintenance/Monitoring – Newly-shaped streambanks should be monitored frequently during the first two weeks to ensure that adequate moisture is available for seed germination and growth. If not, supplemental watering must be provided. The streambanks should be inspected after the first significant storm event for erosion and soil loss. Any erosion should be immediately repaired.

Cost – The cost of streambank shaping depends on the volume of soil removed, and associated hauling and disposal costs. Typical grading costs can run from $5.00 to $15.00 per cubic yard. Project costs increase when the project site requires specialized equipment, access is difficult, or if sediment disposal sites are distant. In addition to grading costs, designers should consider revegetation and erosion control costs. Seeding costs can range from $0.16 to $1.65 (specialized seed mixes) per square yard. Erosion control fabric costs range from $3.00 to $10.00 per square yard, installed.

Further Resources

Useful guidance and specifications for bank shaping can be found at the following online resources:

Washington State Integrated Streambank Protection Guidelines.
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf (Bank Reshaping)

Stream Corridor Restoration: Principles, Processes, and Practices
http://www.usda.gov/stream_restoration/PDFFILES/APPENDIX.pdf

Water Related Best Management Practices in the Landscape - Stream System Protection, Restoration, and Reestablishment
http://abe.msstate.edu/csd/NRCS-BMPs/pdf/streams/bank/bankshaping.pdf

R-9

Stream Repair: Soft Bank Stabilization

COIR FIBER LOGS

Description

Coir fiber logs are a stream repair practice that provides toe protection for small urban streambanks. They are commercially made, biodegradable, erosion control products and go by many trade names, such as Biologs™, Koirlog™, BioD-rolls™, and Fiberschines. Coir fiber logs consist of tightly bound cylinders of coconut fiber (coir) held together by coir fiber netting. They are typically one foot in diameter and 10 to 20 feet long, although other lengths and diameters are available. Coir fiber logs are installed along the toe of the streambank to provide short-term deformable protection of the streambank toe The fiber log decays in two to five years, but roots from colonizing vegetation gradually replace the coir fiber and provide vegetative stabilization at the toe. Stream sediments deposited in the log also provide a good medium for plant growth. Coir fiber logs are an excellent method to provide short-term toe protection in streams where toe scour is not severe and riparian conditions are conducive to rapid plant growth (Figures 1 and 2).

Habitat Features Created – Coir fiber logs enhance habitat by stabilizing the streambank toe and fostering the growth of overhanging vegetation.

Feasibility

Coir fiber logs are placed along the toe of the streambank to provide an erosion-resistant planting medium for riparian vegetation. They are most appropriate for smaller, low gradient urban streams that are not rapidly incising or laterally adjusting. The logs are installed near the stream invert so they become saturated with water, which allows vegetation to be planted directly within them. Coir fiber logs appear natural and unobtrusive, and gradually decompose over a 2 to 5 year period, leaving the roots of colonizing vegetation to secure the toe of the streambank (Miller *et al*., 1998). Individual logs are relatively lightweight (e.g., a 10-foot roll weighs about 75 pounds), and can be installed with a minimum of site disturbance.

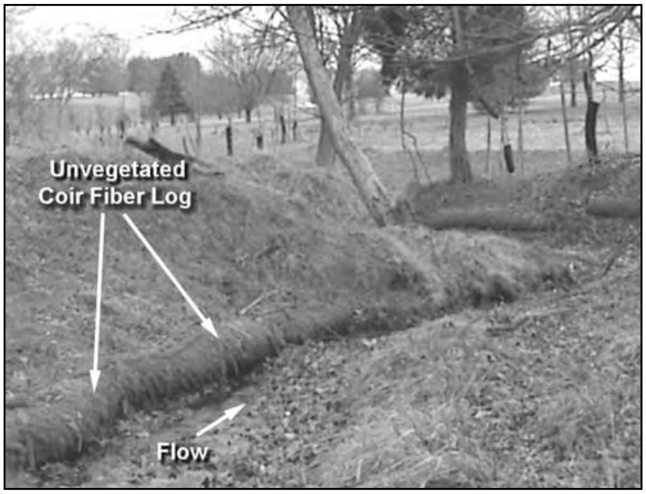


Figure 1: Coir fiber log prior to plant installation

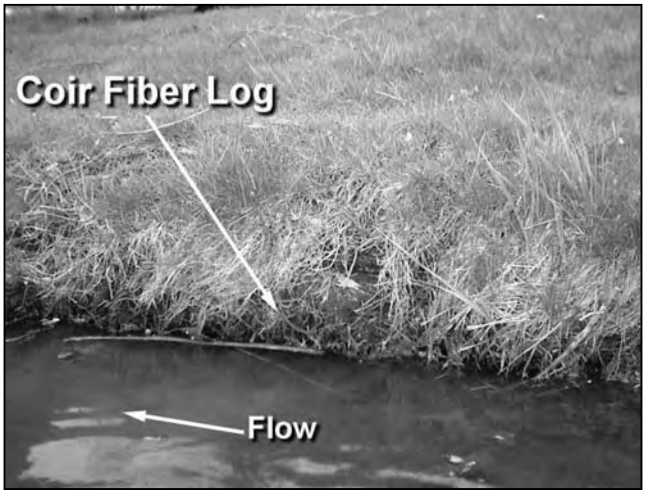


Figure 2: Vegetated coir fiber log installed along a low gradient stream

Coir fiber logs have very limited ability to prevent significant streambank toe scour. In streams that have the potential for significant scour, alternative streambank toe protection techniques should be used (Figure 3). Coir fiber rolls are also not recommended for actively degrading channels. In addition, coir fiber logs require sufficient sunlight to enable the growth of colonizing plants.

Implementation

Coir fiber rolls are installed by excavating a three to four-inch deep trench along the toe of the streambank. The coir fiber log is then placed in the trench so that the bottom and back of the log are in contact with the stream substrate and the toe of the streambank, respectively. Best plant survival occurs when the log is installed so that its top is above the baseflow level of the stream or the lower level of perennial vegetation, whichever is higher (Figure 4). If water depth is greater than log height, two fiber logs can be stacked so that the upper log is suitable for planting. Each successive length of log must be placed end to end with the next, using coir fiber or synthetic rope. The upstream end of the coir fiber log should always be inserted, or "keyed," three to five feet into the streambank to prevent dislocation.

Once the coir fiber logs are placed in the stream, they can absorb up to 10 times their weight in water, which makes repositioning them difficult. Notched hardwood stakes are used to secure coir fiber logs and are partially driven into the substrate along the sides of the log at intervals specified by the manufacturer. Coir or nylon twine is woven between and around the notches of each stake, which is then driven flush with the top of the coir fiber log to firmly secure it to the streambed. The streambank above the coir fiber log can then be graded or laid back to the top of the log and stabilized with appropriate vegetation.

If erosion control fabric is needed to hold the upper bank, it should extend to the toe of the coir fiber log to provide a smooth and secure transition. Coir fiber logs can also be used in combination with mattresses and other upper streambank bioengineering practices (e.g., brush mattresses, live fascines, bank shaping). Planting of live rooted materials in the coir fiber logs should be delayed for at least a month to allow stream sediments to infiltrate the coir fiber in order to improve plant vigor and survival.

Maintenance/Monitoring – Coir fiber log installations should be inspected after the first significant storm to ensure that they are securely fastened to the streambed and bank. Once planted, vegetation should be checked periodically during the first growing season, and dead/dying plant materials should be replaced. The installations should also be inspected after the log decays to ensure that rooted vegetation can hold the bank.

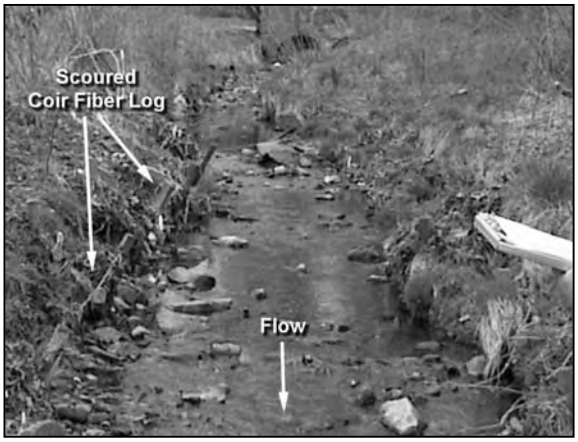


Figure 3: Coir fiber log has decayed without vegetative stabilization

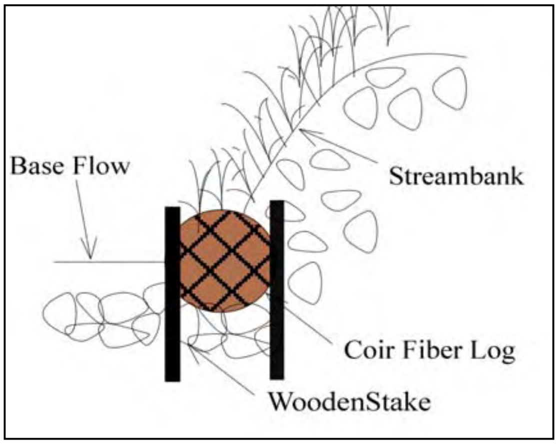


Figure 4: Cross-section view of coir fiber log installation

Cost – Reported unit costs to install coir fiber logs range $8.00 to $30.00 per linear foot, depending on the log diameter selected. Average costs are about $15.00 per linear foot.

Further Resources

Several design specifications for coir fiber logs can be accessed from the following websites:

Washington State Integrated Streambank Protection Guidelines
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf (Coir Logs)

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-6.pdf

The Practical Streambank Bioengineering Guide for Arid and Semi-Arid Intermountain West
http://plant-materials.nrcs.usda.gov/pubs/idpmcpustguid-appA.pdf (fiberschines)

Coir Geotextile Roll and Wetland Plants for Streambank Erosion Control
http://www.wes.army.mil/el/emrrp/tnotes.html

Virginia Stream Restoration and Stabilization Best Management Practices Guide (natural fiber rolls)
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

R-10

Stream Repair: Soft Bank Stabilization

EROSION CONTROL FABRICS

Description

Erosion control fabrics (ECF) are a repair technique applied to prevent soil erosion, reinforce soil structure, and help establish vegetation on newly graded or shaped streambanks. The fabrics come in a variety of weights and types ranging from open weave netting to dense non-woven mats (Figure 1). Many of these fabrics are made of biodegradable materials, such as coconut husk fiber (coir), jute or straw, while others incorporate synthetic reinforcing materials, which may not biodegrade. The most resilient ECF is known as turf reinforcement mat (TRM). These mats are made entirely of non-biodegradable materials and essentially become a permanent installation. TRMs are generally used to stabilize drainageways and conveyance channels, but have limited application for urban stream repair.

Feasibility

ECFs that are made of straw and jute may be suitable for upland slopes and floodplains, but are generally not resilient enough to protect streambanks exposed to flowing water (Fischenich, 2001a). Biodegradable coir fiber and reinforced coir fiber fabrics are recommended for most streambank applications.

Some manufacturers specify that coir ECFs can be installed on slopes as steep as 1H:1V, but this only applied to upland slopes not exposed to flowing water. Coir ECFs are generally recommended on streambank slopes of 2H:1V or gentler. The proper streambank slope is a function of the streambank protection practices employed, soil type, and exposure to erosive stream flows.

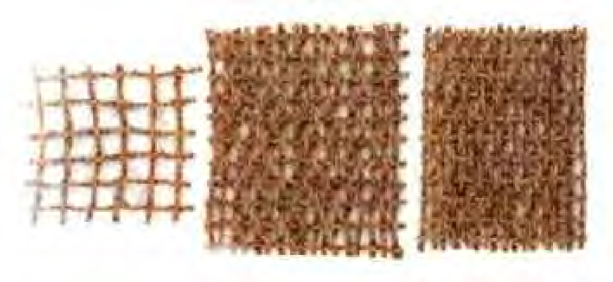


Figure 1: Three different ECF weave types

Biodegradable coir fabrics are classified into two basic categories:

Non-woven blankets consist of coir fibers that are sandwiched between natural or biodegradable netting. Non-woven blankets are very effective at preventing the loss of fine soil particles but do not have the tensile strength of woven fabrics. These fabrics have an average expected lifespan of one to two years in the field.

Woven fabrics consist of coir yarns that are woven into fabric/netting with a wide range of mesh sizes. They can be tightly woven (similar to burlap), or have a more open weave netting. Woven fabrics are commonly used for streambank erosion control applications. Designers need to consider the mesh size of the weave and the thickness of the yarn when selecting the type of woven fabric needed for the project. The high tensile strength of woven fabrics provides excellent reinforcement for streambank slopes and offers an average lifespan of one to four years in the field.

Designers should keep in mind that the manufacturer's estimates of the useful product life should only be used to compare different products and may not always represent the actual lifespan of the product installed at a streambank stabilization site. Numerous real-world factors determine how long ECFs will persist, including exposure to ultraviolet radiation (sunlight), microbial decay, humidity, vegetative cover, sediment deposition, alternating cycles of wetting and drying, sediment movement/scour, human or animal foot traffic, and wildlife damage (Miller *et al*., 1998). Fabrics can decay at highly variable rates even within the same project reach.

ECFs are used to temporarily stabilize and reinforce soil on newly graded streambanks until vegetation can become established. On larger, higher gradient streams, ECFs are generally applied to the upper streambank portion to enable perennial/woody vegetation to grow. The lower portion of the streambank is seldom an appropriate area for ECFs and is usually reserved for more structural streambank toe protection measures (e.g., boulder revetments, rootwad revetments, A-jacks). On smaller, lower gradient streams, where vegetation and roots may be sufficient to stabilize both the upper and lower streambanks, ECF are often combined with softer bioengineering treatments, such as live fascines and coir fiber logs to protect the entire streambank. Combinations of woven and non-woven ECFs are also used to construct soil lifts (see Profile Sheet R-11).

Five key questions need to be answered when choosing the most appropriate ECF for streambank application:

> *Should the ECF be biodegradable, non-biodegradable, or a combination of both?* Many ECF incorporate synthetic reinforcing materials (threads or mesh). Synthetic reinforcing materials increases the longevity and strength of coir fiber fabrics, but the product will persist for many years and the netting may pose a hazard to wildlife.
>
> *How long can you wait until vegetation is established?* Biodegradable materials are intended to temporarily stabilize and reinforce soils until vegetation is established that can replace these functions. The goal in most applications will be to rapidly establish a vigorous cover before the bank will be exposed to erosive storm flows. Stronger fabrics, with tighter weaves, provide greater insurance that the ECF will last until the vegetation can take over. Fabric strength is defined by the manufacturer and is usually expressed in grams per square meter of fabric.
>
> *How cohesive are streambank soils?* Sandy or fine-grained soils with low cohesion often require a more robust fabric, reinforced fabric, a tighter fabric weave, or a combination of woven and non-woven fabrics. Conversely, more cohesive bank soils, such as silts and clays, may not require as strong an ECF.
>
> *How frequently will the streambank be exposed to erosive conditions?* ECF can provide significant protection to newly constructed streambanks but may fail if they experience frequent floods. Designers should analyze the likely flow conditions expected at the site and select the appropriate grade of ECF.
>
> *To what climatic factors will the ECF be exposed?* Designers should anticipate the climatic factors that influence the longevity of fabrics, such as the length of the growing season, solar exposure, drought, wet seasons, ice flows and freeze-thaw conditions.

Implementation

For most installations, the perimeter of the ECF and any seams parallel to stream flow are staked in trenches that are then backfilled with soil/rock. The interior area of the fabric is staked or pinned at intervals across the face of the slope. Seeding of the streambank must be completed before ECF installation. Supplemental plantings of live stakes, bare root cuttings, or container grown stock can be installed through the fabric, taking care not to jeopardize the integrity of the fabric (Figure 2).

Most ECFs are available in rolls of various widths and lengths. Wider ECF rolls often have seams that can become weak points in certain streambank applications. The design should specify whether seams are acceptable, and if so, what orientation they should have in relation to the streambank. The fabric can be applied in a parallel or perpendicular orientation to the stream. A parallel orientation is recommended when the streambank height is less than the

Figure 2: Biodegradable coir fabric with live stakes

width of the fabric, since it minimizes the number of overlapping connections that are parallel to streamflow. If the streambank height is greater than the width of the ECF roll, the fabric can be placed either perpendicular or parallel to the flow. A perpendicular orientation increases the number of overlapping seams, while a parallel orientation will require the parallel seams to be secured in a trench (Figure 3).

Construction - There are many different ways to employ ECF for streambank stabilization, but a typical installation sequence is provided below. Seed should be applied and lightly compacted into the soil prior to ECF installation. Next, a six to 12 inch deep trench is dug around the perimeter of the ECF installation area, and the fabric is laid out, leaving enough extra fabric to secure in the trenches. Normally, ECF is rolled out downstream to upstream directions. If multiple rolls are needed, the upstream fabric must be overlapped or shingled over the downstream fabric with an overlap of at least two feet.

Once the fabric has been laid out, wedge-shaped stakes are used to secure the fabric to the bottom of the trenches and the trenches are backfilled with a mixture of soil and rock. It is important that the fabric lay tight and smooth to the soil surface. If toe protection practice is used, ECF should be secured along the fabric's lower edge under and behind the toe protection (e.g., boulder revetment, coir fiber log, or fascine). The interior portion of the ECF is secured to the slope with pins or stakes, according to the manufacturer's specifications. The upstream end of the ECF fabric and any transitions between the fabric and toe protection practices are always potential weak points, and special care should be taken to adequately secure them.

Maintenance/Monitoring – ECF installation and the seeding/plantings should be inspected frequently during the first growing season and after significant storm events. Inspections should examine whether stakes and trenches continue to securely hold the fabric in place. Any tears in the ECF or soil erosion should be repaired immediately. Seeding/plantings may require supplemental watering or irrigation during the first growing season to ensure survival.

Cost – Reported unit cost for ECF ranges from one to five dollars per square yard, installed, with the variation based on the type of fabric selected.

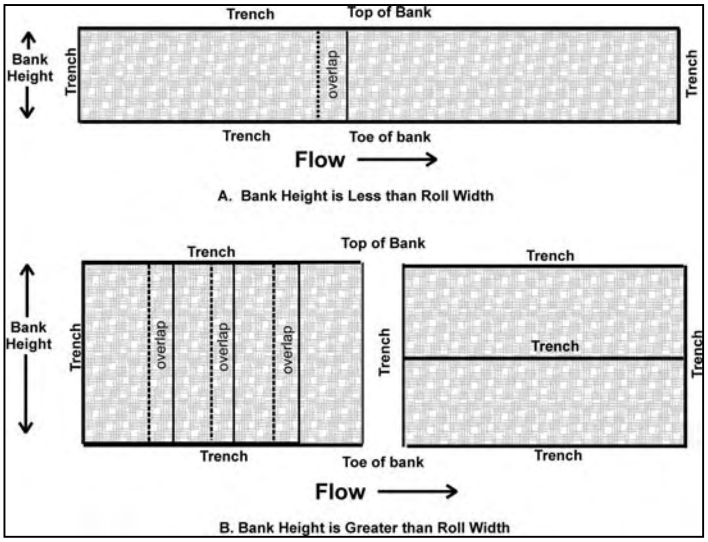


Figure 3: Erosion control fabric installation

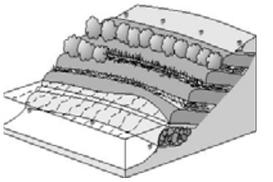
Further Resources

Some guidance on the proper selection and installation of erosion control fabrics can be accessed at the following websites:

Washington State Integrated Streambank Protection Guidelines
http://www.wa.gov/wdfw/hab/ahg/ispg_app_h_plantingconsid.pdf and
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf (manufactured retention systems)

The Practical Streambank Bioengineering Guide - Arid and Semi-Arid Intermountain West
http://plant-materials.nrcs.usda.gov/pubs/idpmcpustguid-appA.pdf (erosion control fabric)

Natural Resources Conservation Service. Streambank and Shoreline Erosion. Chapter 16
http://www.nrcs.usda.gov/technical/ENG/efh.html

R-11	Stream Repair: Soft Bank Stabilization	
	SOIL LIFTS	

Description

Soil lifts are a stream repair technique used to reconstruct a streambank using successive layers of soil wrapped or encapsulated within erosion control fabric. They are also known as reinforced soil, vegetated geogrids, or fabric-encapsulated soil. Each lift forms a terrace that sits atop the lift beneath it (Figure 1). The streambank soil and the height of the reconstructed streambank determine the number and height of the lifts. Vegetative cover is then established on the surface of each lift by one of three methods, direct seeding beneath the ECF, rooting plants directly through the lifts, or placing dormant cutting along the face of the lifts.

Habitat Features Created – Soil lifts indirectly enhance stream habitat through the creation of a stable streambank toe and reduced sedimentation from streambank erosion.

Figure 1: Soil lifts

Feasibility

Soil lifts are used to stabilize urban streambanks where structurally sound but deformable treatment is desired. Soil lifts avoid the potential drawbacks of traditional hard bank stabilization practices, such as boulder revetments. When used in combination with an effective toe protection technique, soil lifts can immediately stabilize streambanks and ultimately provide deformable vegetative stabilization over the long term. Soil lifts are a versatile streambank stabilization technique since they can reconstruct streambanks with slopes as steep as 1H:1V and banks as tall as 30 feet. Various types of ECF are available to encapsulate lifts (e.g., biodegradable, synthetic, woven, and non-woven). The choice of which ECF to use depends on streambank soils, the degree of protection required, and the potential for future erosion (see Profile Sheet R-10).

Soil lifts are applicable in most regions of the country, but plant materials used to provide vegetative stabilization should be adapted to local conditions.

Soil lifts must be combined with grade controls and toe protection in actively degrading streams. Streambank toe protection may not be needed to protect soil lifts on aggrading streams. In addition, the soils contained within the lifts must have sufficient fertility and texture to support plant growth, unless soil amendments are provided.

Implementation

A system of soil lifts typically consists of four components, as shown in Figure 2.

1. Toe protection
2. Gravel filter drain
3. Soil lifts
4. Vegetation

1. Toe Protection - Designers should first determine the potential depth of scour and then select an effective toe protection treatment to keep the lower streambank stable. Scour at the streambank toe will quickly undermine soil lifts further up the bank. As a general rule, toe protection should extend from the maximum expected depth of scour in the streambed up to the level of perennial vegetation on the streambank.

Streambank toe protection can be designed in two ways. The first is to design the toe so that it is essentially immobile at any flow (non-deformable). The second is to design the toe so that it is immobile until vegetative cover is established, but then becomes mobile during high flows thereafter (deformable). A deformable streambank toe allows natural channel migration to occur in the stream corridor, whereas a non-deformable hard toe prevents the stream from adjusting over time as watershed conditions change (Miller and Skidmore, 2000). Non-deformable structures are generally recommended when infrastructure and/or private property are significantly threatened by erosion.

Deformable streambank toe protection usually consists of rock wrapped within ECF that is sized to become mobile during the 10 to 25 year design storm flow event. The fabric helps reinforce and immobilize the rock at high flows until upper bank vegetation is established. At that point, the streambank toe will again be mobile and deformable.

2. Gravel Filter Drain - A gravel filter drain is a layer of gravel, installed beneath or behind the soil lifts that extend down to the streambank toe. The gravel filter drain allows water to drain out of the streambank and prevents high pore water pressure during rapid drawdown events common in urban watersheds. Rapid drawdown occurs when floodwaters recede rapidly, leaving saturated streambanks susceptible to slope failure.

3. Soil Lifts - Individual lifts can range from 0.5 to 1.5 feet high (Figure 2). The bank soil type to be encapsulated and the height of the streambank will determine the number and height of each soil lift. Nutrient poor, sandy soils can be problematic since they are unstable and seldom support dense or vigorous vegetation. When these soils are encountered, soil lifts should be amended with topsoil, compost or other soil amendments. Normally, a soil lift is encapsulated by two layers of coir fiber fabric; an outer layer of ECF netting reinforces the lift, while an inner layer of non-woven coir fiber is used to prevent loss of fine soil particles from within the lift.

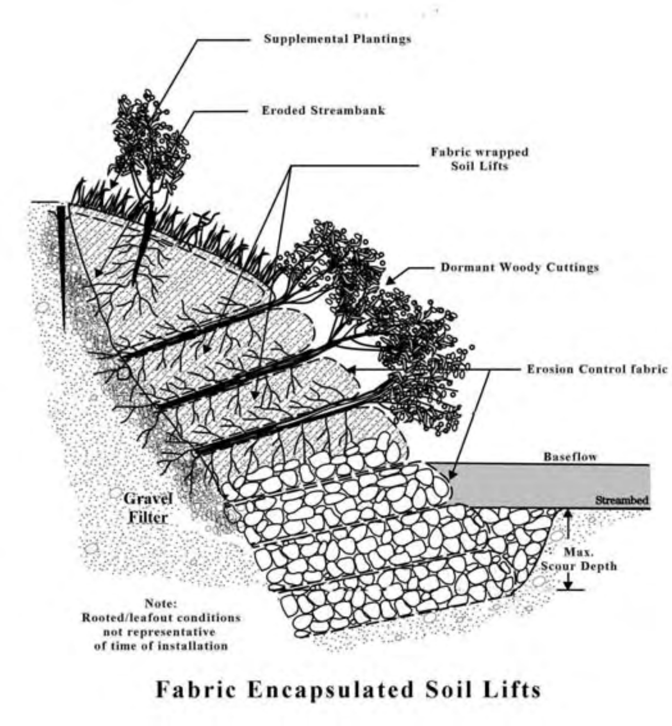


Figure 2: Cross-section of a streambank constructed of soil lifts
(Source: USDA NRCS)

4. Aggressive Revegetation – As the ECF degrades, the roots of the vegetation will provide structural reinforcement of the streambank. Consequently, an aggressive plan is needed to establish vegetative cover that accounts for soil fertility and moisture conditions (see Profile Sheet R-15). Seeding of native grasses beneath the ECF is recommended to provide initial rapid ground cover. Dormant cuttings of native riparian shrubs are often placed horizontally between each successive soil lift (using the same plant materials that are used for brush mattresses or live fascines, see Profile Sheets R-13 and R-14). Horizontal dormant plantings should be arranged at two to five cuttings per foot with the butt (basal) ends extending to the back of the excavated trench. They should be placed so that 75% of the cutting is covered by the next overlying soil lift. Care should be taken not to jeopardize the integrity of the ECF during planting operations. Species selected should generally mimic the native riparian community.

Construction – The construction of streambank soil lifts is a complicated undertaking and requires an experienced construction supervisor and crew. The steps below simply outline the process and should not be considered exhaustive.

1. Excavate a trench for the toe protection.
2. Install toe protection treatment.
3. Place a layer(s) of ECF over the toe protection and leave enough length channelward to wrap over the compacted soil of the lift. Top and bottom edges of fabric should be embedded a minimum of three feet.
4. Place soil on the fabric and compact.
5. Seed the compacted soil where it will be exposed to sunlight.
6. Wrap the fabric tightly over the compacted soil and stake the fabric at the back of the lift. Make sure that the upstream and downstream ends of the lift transition smoothly and are secure keyed into the existing streambank.
7. Place a layer of dormant cuttings on top of the lift and spread some topsoil over them.
8. Place another layer(s) of ECF on top of the cuttings and repeat steps 4 through 7 until the desired bank height is reached.
9. Transition the existing streambank into the uppermost soil lift, re-vegetate disturbed areas and install any supplemental plantings.

Maintenance/Monitoring – Monthly inspections should be made during the first growing season to ensure adequate vegetative establishment. Inspections may indicate the need for supplemental watering/irrigation, re-seeding, or the replacement of dead/dying plant materials. When properly constructed, soil lifts should not generally require much long-term maintenance.

Cost – Not much standardized cost data has been reported for soil lifts, because each application is often unique. Available unit costs for a one-foot tall soil lift ranges from $12 to $30 per linear foot.

Further Resources

The following resources can be consulted for more detail on the design and construction of soil lifts:

Washington State Integrated Streambank Protection Guidelines (soil reinforcement)
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

Engineering Field Handbook - Streambank and Shoreline Protection (vegetated geogrids)
http://www.nrcs.usda.gov/technical/ENG/efh.html

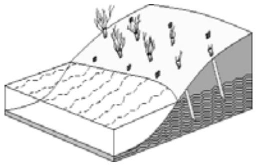
Stream Corridor Restoration: Principles, Processes, and Practices (vegetated geogrids)
http://www.usda.gov/stream_restoration/PDFFILES/APPENDIX.pdf

Virginia Stream Restoration and Stabilization Best Management Practices Guide (live soil lifts)
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

R-12

Stream Repair: Soft Bank Stabilization

LIVE STAKES



Description

Live stakes are a bioengineering technique used to stabilize eroding streambanks. Also known as dormant woody cuttings or pole plantings, live stakes consist of dormant, unrooted cuttings of riparian tree and shrub species that are installed in streambanks (Figure 1). As the stakes take root and grow, they provide vegetative cover and improve streambank stability. The roots of planted live stakes help stabilize the streambank by reinforcing and binding soil particles together and by extracting excess soil moisture. Live stakes can also improve and extend the performance of both hard and soft streambank stabilization practices.

Habitat Features Created – While live stakes do not directly enhance in-stream habitat, they do create stable vegetated streambanks, which delivers less sediment to the stream, and provide overhanging vegetation.

Feasibility

Live stakes are a cost effective technique to vegetate and reinforce unstable streambanks, especially when used in combination with other toe protection treatments for the lower streambank. Live stakes can be used as a stand-alone practice for wide, shallow urban streams that experience low to moderate toe erosion and have poor bank vegetation. Live stakes are also effective on aggrading streams, since they promote sediment deposition and stabilize bar formations. They are not generally recommended as a bank treatment for actively degrading streams.

Live stakes can be installed during any season, but greater success is achieved if they are installed close to the beginning of the growing season (e.g., early spring). Designers should remember that live stakes will not provide full bank protection for at least one growing season until the stakes develop a vigorous root system.

Plant materials should be acquired from local sources and adapted to the local climate. Planting times should take into account regional conditions, such as possible ice damage, flooding, high water table, and herbivory. In addition, survival rates for live stakes are generally higher in humid climates, compared to arid or semi-arid regions.

Implementation

Adequate moisture, soil fertility and sunlight must be available for live stakes to grow. In particular, designers should check to see whether the stakes will reach the water table, which can be many feet below the bank surface in many urban streams. Also, streambank erosion rates need to be relatively low so that live stakes have enough time to take root and grow.

Figure 1: Live stake

Live stakes can be purchased from a native plant materials supplier, or harvested during the dormant season from local stands of vegetation exhibiting little or no evidence of disease or insect infestation. Typical tree and shrub species used for live stakes include various species of willows (*Salix spp*.) and cottonwood (*Populus spp*.), and more rarely, alders (*Alnus spp*.). Each of these common riparian species root easily from cuttings and have fibrous root systems that are ideal for reinforcing soils.

A study of live stake survival found tree-type willows had lower survival rates compared to shrub-type willows (Zierke and Hoag, 1995). Tree-type willows and cottonwoods may initially develop with multiple stems, but over time, some stems will exert dominance and a single or multi-trunk tree will develop. Over time, large trees can shade out other plants that stabilize the streambank, ultimately reducing their stability. The multiple stems and spreading nature of shrub-type species, on the other hand, make them better candidates to reinforce and stabilize streambank soils. Tree-type willows and cottonwoods are best planted at the top of the bank or in the floodplain.

In general, harvested cuttings should have a minimum diameter of one inch and preferably exceed 1-1/2 inches. Figure 2 depicts the results of live stake survival in terms of length and diameter of cuttings. The recommended cutting diameter depends on the tree or shrub species selected. For example, stems from some shrub-form alders and willows never grow more than one to two inches in diameter, whereas tree-form willows and cottonwood cuttings can easily be three to four inches diameter. These larger diameter cuttings are often referred to as “pole plantings,” and are generally four to six feet long and may require a mechanical auger to install (Hoag and Ogle, 1994).

Live stakes need to be long enough so that about two-thirds of the stake is below ground, with one to three lateral buds extending above the ground. Each stake should be tall enough so that it will not be shaded or overgrown by adjacent vegetation, and deep enough to reach the water table in the summer months, particularly in drier climates. Generally, 1-1/2 inch diameter cuttings should be at least two to three feet long, while three to four inch cuttings should be four to six feet long.

Terminal buds should be removed when cuttings are harvested, and all side branches should be cut off flush with the stake. Lateral buds should be preserved. Cuttings should be bundled and transported to the planting site for immediate installation or stored for later use; stored cuttings

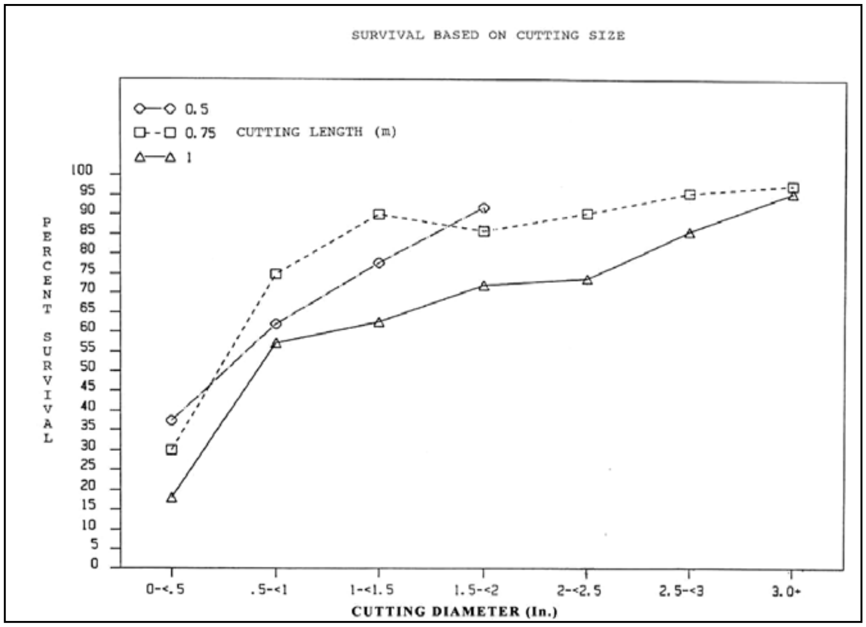


Figure 2: Live stake survival in terms of length and diameter

Source: Zierke and Hoag, 1995

must be kept in a cool, dark environment (32-35° F). Prior to storage, the terminal ends of stored cuttings should be dipped in a 50/50 mixture of white latex paint and water, to prevent desiccation during storage and allow easy identification of the terminal end during installation.

Hoag and Short (1992) evaluated four methods to plant live stakes. Direct insertion by hand was found to be the most successful method, followed closely by the use of a hand auger or a planting bar. Direct insertion using hammers tended to shatter the tops of the cutting, even when a rubber cap was used to absorb some of the force generated by the sledgehammer, and is not recommended as a planting method. The most important factor in live stake survival is close contact between the surface of the cutting and soil. Fertilizers and soil amendments were not found to increase stake survival. In fact, Hoag and Short (1992) reported establishment rates for untreated live stakes that were as good or better than live stakes treated with fertilizers and/or soil amendments.

Hoag and Short also evaluated whether fresh or stored cuttings fared better in field trials. They found no significant difference in planting success between cuttings that were harvested in the dormant season and stored in a cooler until summer, and fresh cutting harvested the day before planting. However, fresh cuttings may not be as tolerant to adverse site conditions, such as hot temperatures, low moisture, and insect infestations. Stored cuttings also have the advantage of providing more flexibility in regards to scheduling harvesting, site preparation, and planting operations. Cuttings can be stored for extended periods of time (e.g., six months) without much decrease in sprouting success.

Construction - Cuttings should be soaked in water for a few days to initiate root growth before planting. Live stakes can be pushed directly into the bank by hand at streambanks with soft soil. A metal bar, soil probe, or auger may be needed to drill a pilot hole for live stakes planted in denser streambanks. The planting tool used should have a diameter that is slightly smaller than the live stakes to ensure adequate contact between the stake and the soil. Stakes should be driven into the pilot holes with a dead-hammer, taking care not to damage the stakes. Driving stakes without a pilot holes is not recommended.

Live stake cuttings should be placed in the streambank in a random pattern with a density of about two to five cuttings per square yard, depending on the species. Different planting techniques are used if live stakes are used in combination with other streambank stabilization practices (see Profile Sheets R-3, R-6, and R-8 through R-11).

Several factors contribute to live stake mortality, with desiccation of the stakes before and after installation the most common one. Failure to reach the summer water table and poor contact between the cutting and soil can also cause poor survival (Zierke and Hoag, 1995).

Maintenance/Monitoring – Live stakes should be inspected frequently during the first two growing seasons to check for survival and loss of integrity due to bank erosion. Live stakes that fail to root and grow should be replaced. Once live stakes are established, they require little maintenance.

Cost – The unit cost to install a single live stake ranges from one to three dollars, depending on the cost/availability of plant materials and labor rates. Use of locally harvested plant materials and volunteer labor can greatly reduce live stake installation costs.

Further Resources

Additional guidance on the use of live stakes in streambank stabilization can be accessed at the following websites:

The Practical Streambank Bioengineering Guide - Arid and Semi-Arid Intermountain West (pole plantings)
http://plant-materials.nrcs.usda.gov/pubs/idpmcpustguid-appA.pdf

Maryland Guidelines to Waterway Construction (live stakes)
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-4.pdf

Washington State Integrated Streambank Protection Guidelines (woody plantings)
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

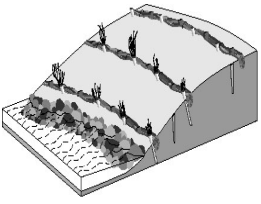
NRCS Engineering Field Handbook: Stream and Shoreline Protection
http://www.rnrcs.usda.gov/technical/ENG/efh.html

Ontario Stream Rehabilitation Manual (live stakes)
http://www.ontariostreams.on.ca/OSRM/toc.htm

R-13

Stream Repair: Soft Bank Stabilization

LIVE FASCINES



Description

Live fascines are a bioengineering technique used to stabilize eroding streambanks that consists of bundled dormant cuttings of willow, alder or poplar branches bound with either wire or twine. A typical fascine is about eight to ten feet long and six to ten inches in diameter, although they can be fashioned to almost any length and diameter needed to protect the eroding streambank site.

Fascines may be used as a toe protection technique along low gradient streams where erosion potential is low. In streams with higher erosion potential, fascines are restricted to higher portions of the streambank, and are located above or behind more resistant toe protection techniques, such as rootwad or boulder revetments (Figure 1).

Habitat Features Created - Live fascines do not directly enhance in-stream habitat, but do create a stable streambank with overhanging vegetation.

The typical application places fascines in shallow trenches along the streambank that is parallel to the stream. When installed correctly, dormant cuttings will quickly root and grow, adding structural stability and vegetative protection to the streambank, and preventing down slope erosion and rill formation. On taller streambanks, two or more parallel rows of fascines may be installed to stabilize the streambank. Live fascines will also provide several years of physical protection to the streambank since the dense bundles add roughness that dissipates the energy of erosive flows.

Live fascines utilize dormant cuttings that are harvested during the non-growing season and then installed early in the next growing season. Specific guidance on harvesting of dormant cuttings is provided in Profile Sheet R-12.

Feasibility

Live fascines alone cannot stabilize streambanks experiencing severe erosion, and should not be installed below the elevation where flow conditions prevent the establishment of perennial vegetation on the bank. Most riparian shrub species used in fascines require full or partial sun and are not suited to heavily-shaded stream corridors.

Regional Considerations – Woody species used for fascines should be obtained from local sources that are best adapted to local growing conditions. The Natural Resources Conservation Service Plant Materials Program offers excellent guidance on the regional suitability of various woody plants and the best times of year to install

Figure 1: Fascines installed behind a boulder revetment

fascines and can be found in the *Further Resources* section.

Implementation

When fascines are harvested, no more than one-third of the stem should be cut from any individual shrub. Terminal buds should be removed from the branches to promote lateral bud growth. Stem cuttings should be at least one-half inch in diameter, measured at the base of the stem. To ensure rooting success, cuttings should be harvested in late fall or winter and refrigerated until needed in spring.

Fascines are normally assembled by bundling a mix of branch sizes into eight to ten foot lengths that are roughly six to ten inches in diameter (although almost any length or diameter can be assembled to meet project needs). Bundles should be secured with twine or wire every 18 inches along their length.

Fascines should be placed in pond or stream water for several days before installation to initiate root growth.

Construction - Fascines should be installed as low on the streambank as practical, but they should not be submerged. On longer bank slopes, multiple rows of parallel fascines can be installed up the streambank, but only if soil moisture along the upper bank can support growth. On banks where conditions are drier, or in arid or semi-arid regions, live stakes that can reach down to the summer water table are a better alternative.

Individual fascines are installed in a shallow trench that is excavated parallel to the streambank. The trench should be deep enough so that two-thirds of each fascine lies below the soil surface. The fascines should overlap each other by one to two feet. The excavated soil should then be tamped down into the fascine filling the voids between cuttings to the greatest degree possible. Fascines should be secured with stakes (e.g., diagonally cut 2x4s) driven through the fascines at three to four foot intervals. Stakes should also be driven through the overlaps between fascines (Figure 2).

More often than not, fascines are installed above more robust toe protection measures, such as boulder revetments, coir fiber log, A-jacks, or lunkers (Figure 3). When installing fascines immediately above an A-jack or boulder revetment, place the erosion control fabric between the revetment and the fascine to ensure that soil is not lost through the revetment.

One of the preferred fascine applications is to install them immediately behind coir fiber logs along lower gradient streams. The coir fiber logs ensure protection and offer an excellent rooting medium for the fascines. As the coir fiber logs disintegrate over time, the roots of the cuttings will grow to replace them.

Maintenance/Monitoring - Little or no maintenance is required once fascines are established. Fascines should be inspected during the first growing season to ensure that they are still secure, and have adequate soil cover and moisture.

Cost – Reported unit cost for installation of live fascines ranges from $5 to $22 per linear foot, depending on the availability and cost of cuttings and local labor rates.

Figure 2: Fascines installed along a streambank

Figure 3: Fascines installed behind a coir fiber roll

Further Resources

Many regional and national references can be consulted on the design and installation of live fascines:

The Practical Streambank Bioengineering Guide Arid and Semi-Arid Intermountain West
(fascines or willow wattles)
http://plant-materials.nrcs.usda.gov/pubs/idpmcpustguid-appA.pdf

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-5.pdf

Washington State Integrated Streambank Protection Guidelines (woody plantings)
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

USDA-NRCS Jamie L. Whitten Plant Materials Center
http://plant-materials.nrcs.usda.gov/mspmc/

The Natural Resources Conservation Service Plant Materials Program
http://plant-materials.nrcs.usda.gov/

Ohio Stream Management Guide (live fascines)
http://www.ohiodnr.com/water/pubs/fs_st/stfs14.pdf

Natural Resources Conservation Service. Engineering Field Manual. Stream and Shoreline Protection
http://www.nrcs.usda.gov/technical/ENG/efh.html

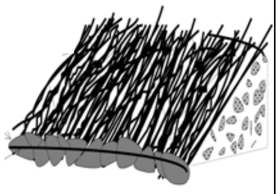
Live and Inert Fascine Streambank Erosion Control
http://www.wes.army.mil/el/emrrp/tnotes.html

Ontario Stream Rehabilitation Manual
(fascines)
http://www.ontariostreams.on.ca/OSRM/toc.htm

R-14

Stream Repair: Soft Bank Stabilization

BRUSH MATTRESSES



Description

Brush mattresses are used to stabilize eroding streambanks and consist of a layer or thick mat of dormant cuttings of riparian woody species placed directly on the streambank and secured by wire and stakes (Figure 1). The purpose of a brush mattress is to create immediate structural streambank protection that will root and grow over time into permanent vegetative stabilization.

Habitat Features Created – Brush mattresses indirectly enhance stream habitat by creating a more stable streambank that reduces sediment delivered to the stream.

Applications

Brush mattresses utilize dormant branch cuttings that are typically 1/2 to 1-1/2 inches in diameter and four to eight feet long. The ideal bank slope for brush mattresses is 3H:1V, although some have been effectively installed on slopes as steep as 2H:1V that possess cohesive soils and adequate soil moisture. Brush mattresses are a few inches to a foot thick and are placed along the streambank perpendicular to stream flow. Larger streams usually require a thick mattress. Dormant cuttings must be placed in direct contact with bank soil in order to take root and grow. The lowest portion of the mattress is buried in a trench and protected by a toe practice, such as coir fiber log, live fascine, or boulder revetment. The mattress is secured to the streambank by stakes with wire connecting the stakes in a grid pattern. Soil is tamped down into the cuttings to fill void spaces and ensure good soil/cutting contact before the mattress is secured. Brush mattresses provide an immediate structural protection to the streambank, with long-term protection provided by the growth of the dormant cuttings. Since brush mattresses utilize dormant cuttings, they must be installed during the non-growing season, usually in early spring.

Figure 1: Brush mattress

Brush mattresses can be assembled and installed using only hand tools, unless major streambank shaping is needed. As a result, mattresses are ideal for stream reaches with limited access for heavy equipment. Adequate soil moisture is essential for plant growth. Mattresses are not recommended for shaded streambanks or reaches with beaver activity. Brush mattresses are also not recommended for lower banks within meander bends or in streams that are rapidly incising.

Regional Considerations - Plant species and planting times used for brush mattresses should be appropriate for the local climate and conditions. Brush mattresses require moderate to high soil moisture conditions at the soil surface. Consequently, they may not be feasible in arid/semi-arid climates where soil moisture is lacking, unless supplemental irrigation/watering is provided.

Implementation

The first step in the construction sequence for brush mattresses is to grade the streambank to an appropriate angle (ideally 3H:1V or gentler; 2H:1V maximum). If the streambank needs no grading, woody debris/litter should be removed from the bank surface to allow the mattress full contact with the soil. Next, an 8-12 inch trench is excavated behind the toe protection practice (e.g., live fascine, coir fiber log, boulder revetment) to help ensure adequate soil moisture and contact for rooting and growth.

The mattress sections are then placed along the streambank perpendicular to the stream flow, with the bottom ends of the cuttings laid in the trench. Layers of cuttings should continue to be placed until the streambank is barely visible. The normal depth of the mattress is four to 12 inches. Thicker mattresses are needed when streams carry large amounts of debris, ice, or sediment at higher flows (Figure 2).

Once the cuttings are in place, two to three foot stakes are partially driven into the brush mattress on three to four foot centers. Stakes can be purchased or made from diagonally cut 2 x 4 lumber, but should have a groove or notch to securely attach the wire. Ten to 12 gauge bailing wire is used to connect the stakes, first horizontally and then diagonally to form a grid pattern. The wire should be wrapped around each stake so that if a wire breaks between two stakes, the remaining connections will not fail.

Loose soils should be tamped into the mattress to fill void space and ensure good soil contact. After this is done, the stakes can be fully driven in to tightly press the mattress against the streambank. When finished, only the top portion of the brush mattress should be visible, with the rest hidden by soil. The upstream end of the mattress should be checked to ensure that it is tightly secured to the streambank and will not be undermined during high flows. Rock or logs may be needed as additional protection.

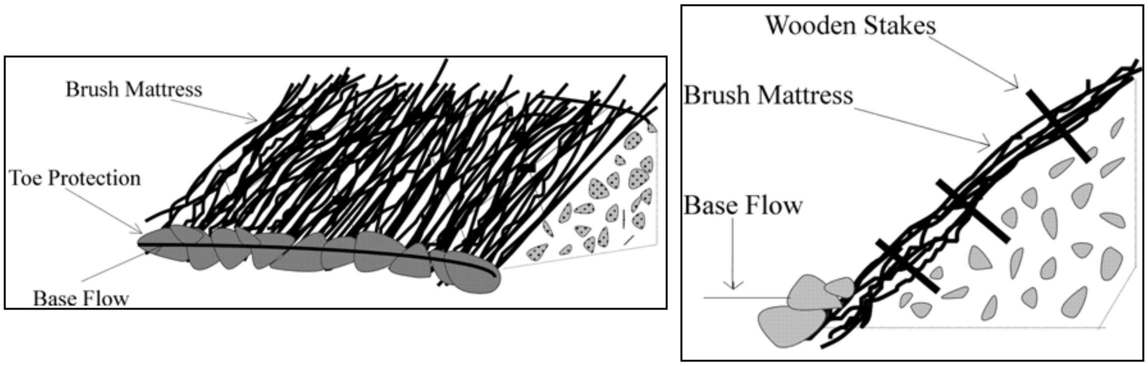


Figure 2: Brush mattress schematic (left) and cross-section (right)

Maintenance/Monitoring – Frequent inspections should be made during the first growing season to check plant growth and make sure the brush mattress is secure. If low soil moisture is encountered, supplemental watering or irrigation should be provided immediately. After woody cuttings become established, little maintenance is required.

Cost – Reported unit costs for installed brush mattresses range from $30 to $50 per linear foot and depend upon labor rates and the availability of dormant plant material.

Further Resources

The following resources can be consulted for more information on the design and installation of live fascines.

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec2-8.pdf

The Practical Streambank Bioengineering Guide - Arid and Semi-Arid Intermountain West (Brush Mattress)
http://plant-materials.nrcs.usda.gov/pubs/idpmcpustguid-appA.pdf

Washington State Integrated Streambank Protection Guidelines (woody plantings)http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

Engineering Field Handbook - *Chapter 16 Streambank and Shoreline Protection* (Brush Mattress)
http://www.nrcs.usda.gov/technical/ENG/efh.html

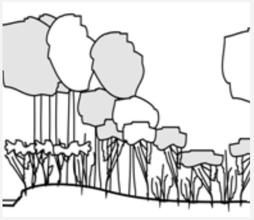
Brush Mattresses for Streambank Erosion Control
http://www.wes.army.mil/el/emrrp/tnotes.html

Ontario Stream Rehabilitation Manual
http://www.ontariostreams.on.ca/OSRM/toc.htm

R-15

Stream Repair: Soft Bank Stabilization

VEGETATION ESTABLISHMENT



Description

Establishing vigorous vegetative cover is a critical element of streambank stabilization. The streambank planting zone extends from the lower limit of perennial vegetation up to the top of the bank, and is periodically subject to inundation by erosive storm flows. The lower limit of perennial vegetation is controlled by more frequent, higher velocity storm flows. Perennial vegetation may survive down to the baseflow elevation of undeveloped streams. In urban streams, however, frequent storm flows and fluctuating water levels often create a vertical gap between the baseflow elevation and the lower limit of perennial vegetation. The gap is subject to erosion and usually stabilized with a toe protection practice. While plants themselves may not survive in the lower bank area, extended roots of herbaceous and woody plants may help stabilize the toe, as long as current velocities during storms are not severe.

Along small headwater streams with low streambanks, the entire streambank planting zone may only be a few feet wide and tall. By contrast, the planting zone may extend from ten to 30 feet in larger streams, supporting several different plant communities based on the frequency of inundation, soil type and bank angle. Practices for the streambank planting zone are distinguished from those of the riparian planting zone, which extends from the top of bank and across the stream corridor. Site preparation and planting practices for the riparian zone are described in Profile Sheets SP-1 to SP-4 and F-5 to F-8, contained in Manual 5.

Habitat Features Created - Streambank plantings can provide multiple benefits, including stream shading, a source of leaf litter and large woody debris, flood attenuation, pollutant removal, and wildlife habitat.

Application

There are two general phases to establish streambank vegetation. The first phase seeks to rapidly seed the exposed streambank to establish cover to prevent erosion and ensure streambank stability. Biodegradable erosion control fabrics (ECF) are often used to reinforce the soil until the grass seed germinates (see Profile Sheet R-10). Seed used for rapid bank stabilization consists of a mixture of native riparian grasses and fast germinating annual grass species. Annual rye grain is often used along streambanks since it can be seeded in the fall, winter or spring and will provide good stability. Annual grasses will not persist after the first season, allowing perennial species to take over. Make sure to avoid seeding perennial rye grass. The second phase seeks to establish woody vegetation on upper portions of the bank. The deeper roots of trees and shrubs consolidate bank soils and prevent erosion. Either dormant cuttings or live materials can be used to establish woody vegetation.

Dormant cuttings, such as live stakes and fascines (Profile Sheets R-12 and R-13) are typically planted at the same time as the ECF is installed. The planting of bare root or container grown plants is usually delayed until grasses have initially stabilized streambank soils. Live plant materials are much more expensive than seed and there is a greater chance of live plant survival once initial soil stabilization is achieved. In addition, cutting the ECF to install live plant materials disturbs the integrity of the fabric and should be avoided until a vigorous grass cover has been established.

The installation of live stakes, fascines, and erosion control fabrics are described in Profile Sheets R-10, R-12, R-13, and R-14. The remainder of this profile sheet focuses on how to establish native woody vegetation after the streambank is stabilized.

Dormant plant materials must be installed either before or very early in the growing season. Live plants also have a longer planting window and can be planted throughout the growing season in most locations, although supplemental watering may be required. Plantings should mimic the natural vegetation found along the streambank, with the goal of achieving a mature, self-sustaining plant community.

Implementation

The characteristics of the streambank influence density, location and species of vegetation planted. Often, coarser sediments (i.e., sands, small gravel) are deposited close to the stream channel, whereas finer silts and clays are deposited further away from the stream. This tends to form low, natural levees along the top of the streambank. As a result, the streambank planting zone often has the driest and sandiest soils, with soil conditions becoming wetter with increasing distance from the stream (Figure 1). Upland species often become established along the top of the streambank with riparian or wetland species occurring lower down along the streambank.

A planting plan should be developed for every streambank stabilization project that contains the following minimum elements:

- Planting schedule
- Planting material handling and storage guidelines
- Site preparation requirements
- Project maintenance and monitoring schedule
- Number, location and bank elevation of plant species to be installed
- Location of vegetation to be preserved and sensitive resource areas
- Access points to the site

Plant Species – A diverse mix of plant species should be chosen that is typical of species found along streams in the region. Important plant characteristics include tolerance of inundation and drought, growth form (i.e., grass, herb, shrub, tree), rate of growth, resistance to disease, and benefit to wildlife. Plants species should be appropriate for local climate and rainfall, as well as site conditions such as soils, sun exposure and moisture. The *Further Resources* section has several websites that offer helpful guidance on plant selection.

Plant Materials - Planting materials can include seed, bare root, and container grown stock. Each type of plant material has advantages and disadvantages (Table 1). Plants should be grown locally or obtained from a local source to ensure adaptation to local conditions. If purchased, inspect the plant materials upon arrival to ensure

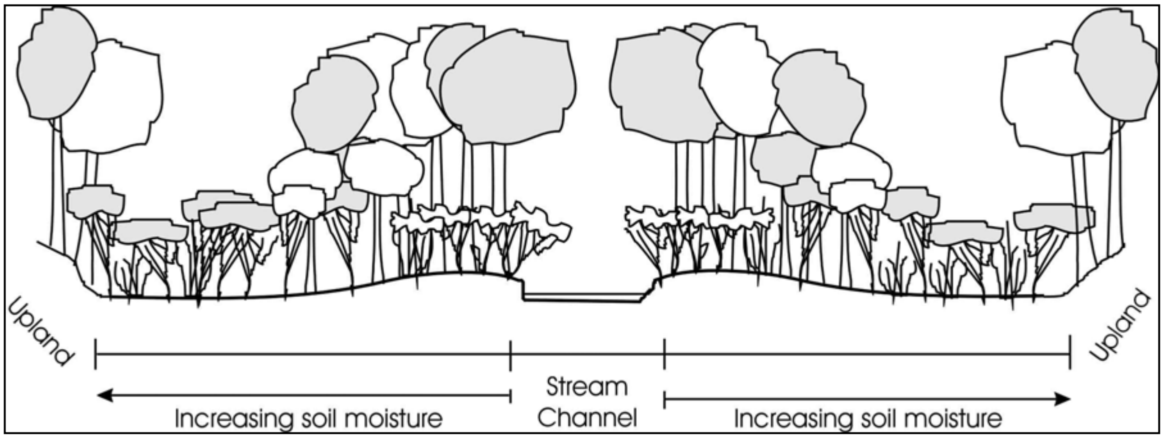


Figure 1: Soil moisture gradient along a stream corridor

Type of Plant Material	Advantages	Disadvantages
Seeds	• Most inexpensive	• Low survival rates • Slowest to establish
Bare root	• Inexpensive • Readily available	• Low survival rates • Slow to establish • Limited planting window • High maintenance
Container-grown trees and shrubs (one to seven gallons)	• Can out compete invasives • Low maintenance • High survival rates • Quick to establish	• Limited availability • Moderate to high cost • Limited availability

viability. Plant materials may require storage for a period of time between delivery and installation. Storage conditions prior to installation must be appropriate for each type of plant material and should be specified on the planting plan. The planting density should be based on individual species requirements, but should be clustered or grouped, where possible.

Maintenance – Maintenance requirements may include supplemental watering during establishment, weed/invasive species control, replacement of dead/diseased materials, and supplemental plantings. Indeed, designers should plan and budget for extensive maintenance of the streambank planting zone during the first several growing seasons after installation.

Special Considerations – The streambank planting zone can be a difficult environment to produce the desired vegetative community. Many practitioners have reported poor plant survival or competition from invasive plants at many urban streambank vegetation sites (UCMT, 2004, Brown, 2000). Some special maintenance considerations for the urban streambank planting zone are offered below:

Invasive Plant Species - Invasive plant species are commonly found in urban riparian areas and may quickly out compete newly-planted native species if they are not effectively controlled. In many cases, soil disturbance and light exposure during stream repair construction create optimal conditions for invasive species to invade the site. Even if invasive plants are removed from the planting site, seeds from adjacent land can soon re-infest the site. Methods to control invasive species include mechanical removal, herbicides, and biological controls (See Profile Sheet SP-2 in Manual 5). From a design standpoint, the best planting strategy is to rapidly create dense and vigorous woody vegetation that can shade out invasives, and to plan and budget for invasive plant removal should this strategy fail.

Beavers - Beavers can cause damage to existing or newly planted trees in riparian areas by flooding or removing tree bark (Kwon, 1999). If beavers are present in the project reach, several options can prevent damage to trees:

- Deer Repellent: The unpleasant odor may drive beavers to move to a new site
- Tree Guards: A three-foot tall collar of hardware cloth or heavy wire mesh can be installed around the base of newly planted trees. While it limits damage to bark, it may be too expensive to use for a long streambank planting area.
- Water level control devices: Install a pipe under the beaver dam to drain the pond (Kwon, 1999)
- Trapping and relocation

Deer - Deer often browse on newly installed vegetation, and can cause extensive plant mortality when deer populations are high in the urban stream corridors. A common indicator of overbrowsing is a prominent browse line, where no green vegetation exists within four to five feet of the ground. Several options exist to prevent deer as well as some rodents from damaging newly planted materials:

- Deer repellent
- Deer-resistant species – select and plant tree species that are unpalatable to deer
- Fencing – install a ten-foot tall wire fence around entire planting area; effective but expensive
- Population control methods
- Tree shelters – plastic tubes are an effective method to protect trees from deer browsing

Entrenched Streams and the Water Table – Channel incision in many urban streams creates entrenched channels with steep and tall banks. Riparian vegetation in these streams is disconnected from the water table and more upland species are favored (Groffman *et al.*, 2003). Thus, even though plants in the upper bank zone are close to the stream, they may experience poor soil moisture conditions, and grow more slowly or have poor survival rates. In some cases, irrigation may be needed to initially sustain fast rates of growth for woody vegetation. Streambank irrigation techniques are described in Fischenich (2001b).

Further Resources

The following resources present guidance on selecting the most appropriate plant species and practices for the streambank planting zone:

USDA Plants Database
http://plants.usda.gov/cgi_bin/topics.cgi?earl=fact_sheet.cgi

Lady Bird Johnson Native Plant Guide
www.enature.com/guides/select_lbjnative.asp

USDA Plant Hardiness Zone Map
http://www.usna.usda.gov/Hardzone/ushzmap.html

NRCS Plant Materials Program
http://plant-materials.nrcs.usda/gov/

Tennessee Valley Authority Banks and Buffer Software
http://www.tva.gov/river/landandshore/stabilization/websites/htm

Maryland Riparian Forest Buffer Design and Establishment Guidelines
http://www.agnr.umd.edu/MCE/Publications/publication.cfm?ID=13

NRCS Engineering Field Manual Stream and Shoreline Protection
http://www.nrcs.usda.gov/technical/ENG/efh.html

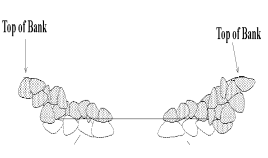
Landscaping Considerations for Urban Stream Restoration Projects
http://www.wes.army.mil/el/emrrp/tnotes.html

California Salmonid Stream Habitat Restoration Manual, Part XI: Riparian Habitat Restoration
http://www.dfg.ca.gov/nafwb/manual.html

R-16

Stream Repair: Flow Deflection Techniques

WING DEFLECTORS



Description

Wing deflectors are a stream repair practice used to redirect or concentrate flow in a stream. They consist of low-profile triangular structures that extend out from the streambanks toward the center of the stream, with the widest portion of the triangle anchored into the streambank. Double wing deflectors concentrate stream flow to narrow and deepen the baseflow channel. Single wing deflectors redirect or deflect flows to promote the formation of undercut banks on the opposite streambank or to increase sinuosity.

Habitat Features Created – Wing deflectors have significant habitat enhancement potential. Double wing deflectors enhance in-stream habitat by forming pools, narrowing and deepening of the baseflow channel, and enhancing riffles. Single wing deflectors enhance habitat by creating channel sinuosity and undercut banks.

Feasibility

Application - Wing deflectors can be placed singly or opposite each other (i.e., double wing deflector). Double wing deflectors work much like rock cross vanes to narrow and deepen the baseflow channel, create downstream pool habitat, and reduce streambank erosion (Figure 1). Wing deflectors can be constructed as a rock-filled log frame or constructed entirely of large rock. In urban streams, wing deflectors are usually constructed with large, flat rocks that do not obstruct flow. Single wing deflectors can be placed on alternating sides of the channel to promote sinuosity. Alternatively, double wing deflectors can be placed five to seven channel widths apart to simulate the natural pool/riffle sequence of streams. Single wing deflectors should be used with extreme care in urban streams since they may force flows toward the opposite bank and cause additional streambank erosion. Wing deflectors are not recommended for streams that are actively degrading or adjusting their planform. Deflectors work best in urban streams that have already undergone extensive channel widening and have shallow, poorly defined baseflow channels. Good stream

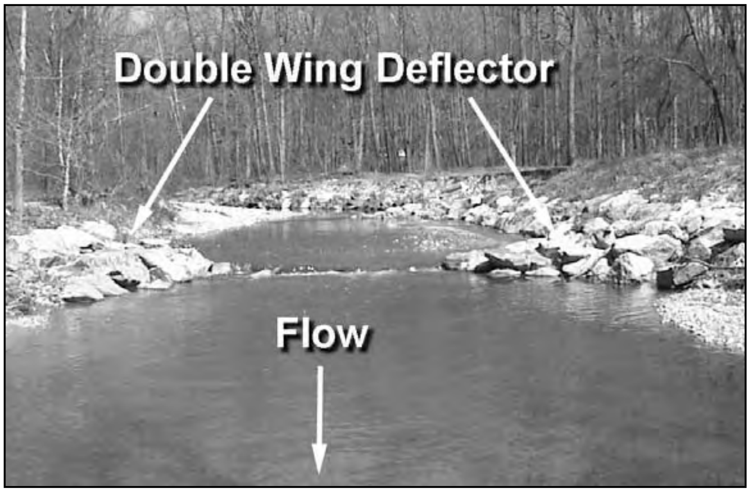


Figure 1: Example of double wing deflector

access is required for heavy equipment and rock stockpiling. Wing deflectors are not suitable for high gradient streams that have boulder or bedrock substrates (and minimal bedload transport).

Implementation

Wing deflector design depends on the size of the stream. On smaller streams, a single log frame filled with rock may be sufficient, whereas a second tier of logs is needed on moderate sized streams. On larger streams, the deflector is often made entirely of large rock. In all cases, the logs or rocks must extend down below the expected future scour depth. Figure 2 illustrates deflector designs.

Wing deflectors are normally a low-profile structure that does not extend up to the bankfull elevation of the streambank, although large rock is needed to armor the zone where the deflector and the streambank meet. In general, wing deflectors grade down to the channel invert and extend about a fourth to a third of the way across the channel. The exact distance the deflector extends into the stream channel depends upon the specific application. When two wing deflectors are installed opposite each other they should reduce the width of the baseflow channel by one-half or less, depending on the stage of channel adjustment.

Newbury *et al.* (1998) has developed a deflector design modification that recreates riffle sequences often missing in urban streams, which can be found in the *Further Resources* section.

Construction – The construction sequence for wing deflectors begins with the excavation of a trench at a 30-40 degree angle to the streambank, five to ten feet into the streambank, and extending below the expected depth of scour in the stream. The upstream log should be laid into the trench and fixed in place using three-foot long rebar (1/2 to 5/8 inches in diameter). The last six inches of rebar should be bent over the log pointing downstream. The trench for the downstream log should be dug at a 90-degree angle to the upstream log and also extending five to ten feet into the streambank. When a second tier of logs is to be used, the second logs should be placed over the first log and both logs should be pinned into the streambed. Once the frame has been constructed, the deflector should be backfilled with large rock that will be immobile during the expected life of the structure (approximately 20 years).

Most wing deflectors used in urban streams are constructed entirely from large rocks. The basic construction sequence, however, remains much the same, with large footer boulders replacing the logs within the trenches.

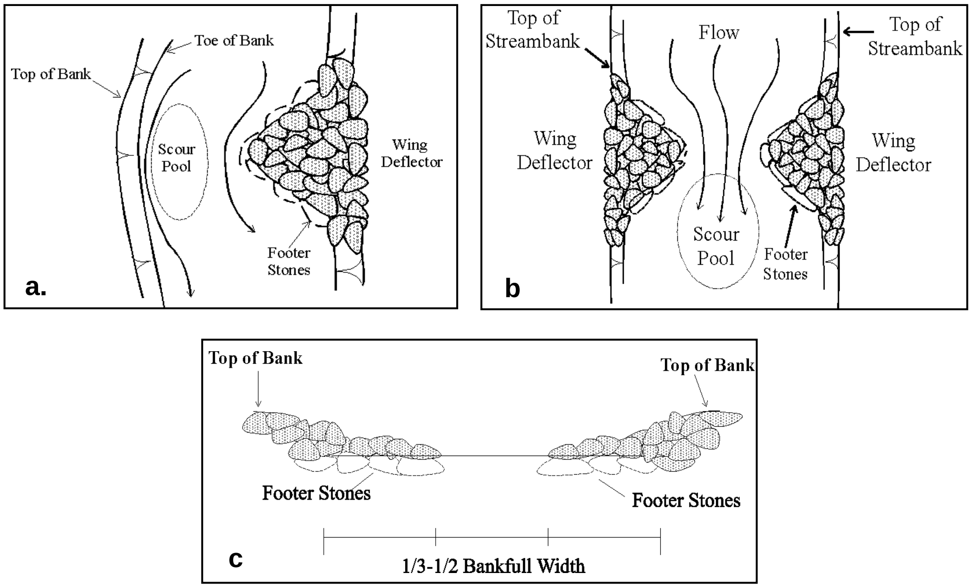


Figure 2: (a) Plan view of single wing deflector, (b) Plan view of double wing reflector, (c) Cross-section of double wing reflector

Maintenance/Monitoring – Deflectors should be inspected after large storm events during the first year and annually after that. Any movement or loss of rock from the deflector should be immediately repaired.

Cost – Only one source reported unit cost data for wing deflectors, with an estimated installation cost of about $400 per deflector (or $800 for a double wing deflector).

Further Resources

Specifications and construction guidance for deflectors can be found in the following resources:

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-5.pdf

Ontario Stream Rehabilitation Manual (wing deflectors)
http://www.ontariostreams.on.ca/OSRM/toc.htm

Ohio Stream Management Guides (deflectors)
http://www.ohiodnr.com/water/pubs/fs_st/streamsfs.htm

A well illustrated application of the Newbury riffle design variation can be found in Chapter 3 of *The Field Manual of Urban Stream Restoration* (Newbury *et al*., 1998), which can be obtained from Conservation Technology Information Center website
http://www.ctic.purdue.edu/

R-17

Stream Repair: Flow Deflection Techniques

LOG, ROCK AND J-ROCK VANES

Description

Vanes are a stream repair practice used to redirect flow in urban streams. They consist of a linear rock or log structure that extends out from the streambank and points upstream. The purpose of vanes is to reduce erosion along the streambank toe by redirecting stream flow toward the center of the stream channel. They are generally used in urban streams where toe erosion and scour is the dominant erosion process (Figure 1).

J-rock vanes are a simple variation on the rock vane, which extends outward from the streambank as an upstream pointing "J" that acts to enhance downstream scour pool formation.

Habitat Features Created - Rock, log and J-rock vanes enhance stream habitat by creating downstream scour pools, narrowing and deepening of the baseflow channel, and enhancing riffle habitat.

Feasibility

Vanes are a useful practice for both small and large streams with low to moderate bedload transport (Figure 2). Vanes are less effective in high gradient streams and in streams with highly mobile, fine substrates (e.g., sand bed streams). Vanes are effective along both straight reaches and meander bends.

Vanes are not recommended for urban streams that are actively degrading or incising. Vanes are more suitable for urban streams that are undergoing channel widening and are experiencing lateral instability. Other streambank protection techniques should be considered for streams with immobile bed materials (e.g., bedrock or boulders).

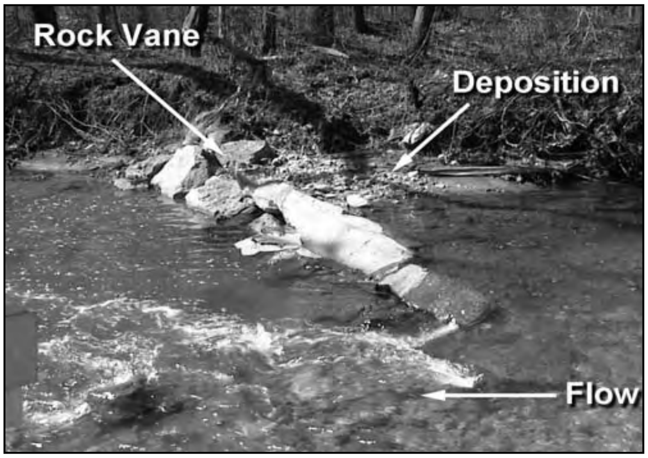


Figure 1: Example of rock vane

Figure 2: Log vane structure providing in-stream habitat and streambank stability

Implementation

Rock and log vanes grade from the bankfull elevation of the streambank down to the stream channel invert. Vanes generally extend into the stream about one-fourth to one-third the bankfull width and point upstream at a 20 to 30 degree angle (Figure 3).

Harman *et al.* (2001) recommends that vanes have no more than a 2-7% slope from the bankfull elevation to the stream invert in smaller streams of the southern piedmont. Vanes should be carefully located so as not to produce additional bank erosion on the upstream side where they join the bank, where eddy scour can often be a problem. Also, stream flow should not be permitted to outflank the vane and cause further bank erosion problems. Vanes should extend two to four rock lengths into the bank (rock vane) or one-third of the log length (log vane) to prevent erosion during overbank flows. Large rocks should also be used to stabilize the area where the log enters the streambank. Rocks or boulders used to construct the vane should be sized to be immobile at the bankfull discharge, and should be rectangular or flat in shape. Jennings and Harman (2001) suggest that larger boulders (40” x 24” x 18”) work best in many North Carolina streams.

Construction - Rock vanes are constructed by excavating a trench in the streambed below the expected depth of scour. Footer boulders are placed in the trench touching end to end. It is extremely important to prevent gaps between boulders that allow streamflow to pass through the structure (Jennings and Harman, 2001). Vane stones are then placed on top of the footer boulders in a staggered fashion (i.e., over two adjacent footer boulders and skewed slightly upstream of the footer boulders), once again taking care to make the joints between boulders as tight as possible. As the vane is built out and slopes down from the bank, the last footer stones may become unnecessary, as the vane stones can be placed in the trench and extend up to achieve the desired elevation. A vane may consist of two tiers of stone in small to medium sized streams, or fashioned into a triangular cross section to withstand higher flows on large streams (Figure 4). Geotextile liners should be placed upstream of the vane to prevent piping of fine sediments between rocks.

Log vanes are constructed in much the same way. The first step is to excavate a trench in the streambed, below the expected depth of scour. Two logs are usually required, one embedded in the substrate and the other placed on top of it and fixed to the other with rebar (Figure 5). In

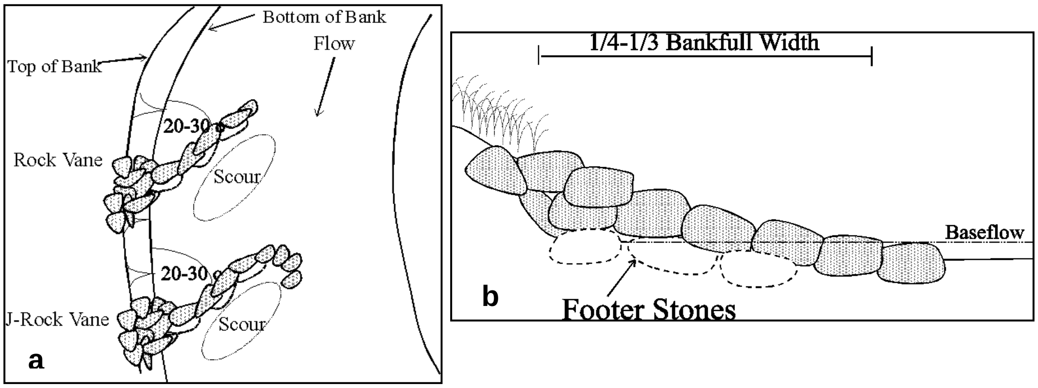


Figure 3: Plan view of rock vanes (a); Cross-section view of a rock vane (b)

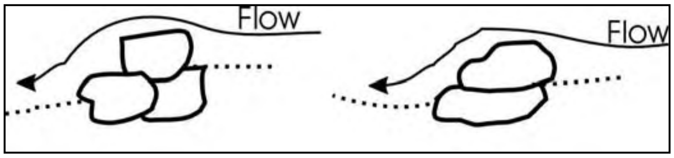


Figure 4: Cutaway views of rock vane

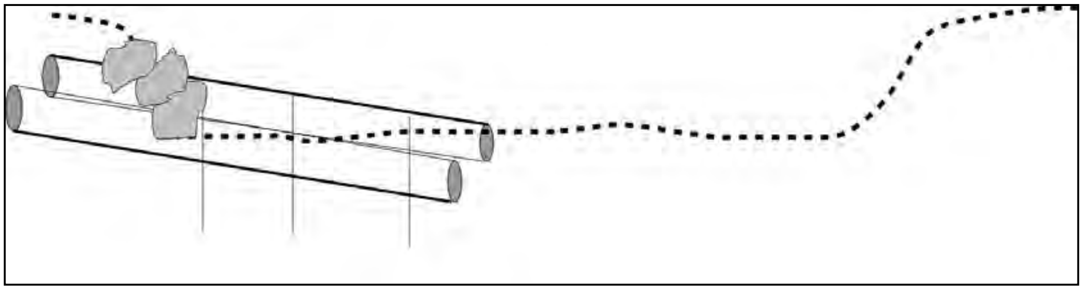


Figure 5: Cross-section view of log vane

smaller streams, vanes can be formed with a single large diameter log (18-24").

Maintenance/Monitoring – Vanes should be inspected after large storms during the first year to check for stability. The most common problem is erosion at the point where the vane joins the streambank, and any outflanking should be repaired immediately.

Costs – Reported unit costs for log vanes range from $400 to $1,200 each. The unit cost to install a rock vane ranges from $400 to $1,400 each.

Further Resources

Several online resources can be consulted for more information on rock vanes**:**

Maryland Guidelines to Waterway Construction (J-rock vanes, rock vanes, and log vanes)
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-4.pdf
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-3.pdf
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-2.pdf

North Carolina Stream Restoration: A Natural Channel Design Handbook
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

Ontario Stream Rehabilitation Manual (low-stage weirs)
http://www.ontariostreams.on.ca/OSRM/toc.htm

Virginia Stream Restoration and Stabilization Best Management Practices Guide (rock and J-rock vanes)
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

Washington State Integrated Streambank Protection Guidelines (barbs, pg. 6-23)
http://wdfw.wa.gov/hab/ahg/ispg_chap06_all.pdf

R-18

Stream Repair: Grade Control

ROCK VORTEX WEIR

Description

Rock vortex weirs (RVW), also known as porous weirs, are an in-stream structure designed to provide grade control in smaller streams and create a diversity of flow velocities. The advantage of RVW is that it can accomplish these functions while still maintaining bedload transport and fish passage, which not many other grade controls can do. Thus, the key RVW design feature is the separation distance between individual weir stones that allows sediment to move and fish to pass (Figure 1a).

In plan view, the weir arches upstream, with the wings angling downstream and extending into the streambank up to the bankfull elevation (Figure 1b). During baseflow, water flows around and between the weir stones, creating a diversity of flow velocities and depths that allow fish to pass. During higher flows, water rises over the weir stones to form a scour pool below the structure while allowing bed load to pass through. Properly built RVWs should not cause upstream sediment deposition or streambank erosion on the flanks of the weir. As a grade control, the RVW can prevent further channel incision, thereby reducing upstream bank erosion.

Habitat Features Created - Rock vortex weirs have a moderate potential to enhance in-stream habitat. When correctly located and constructed, RVW can create habitat by forming downstream scour pools and increasing the diversity of flow velocity above and within the structure.

Feasibility

RVWs are typically used to concentrate flow in the center of straight stream reaches near the downstream end of a riffle section. The upstream tip of the weir should be located one to two channel widths downstream of the crossover of the thalweg, and should be placed in locations where pools would naturally form. During baseflow, interaction of the stream and rocks creates different flow velocities, while during higher flows, a scour pool is created below the structure (Figure 2).

Rock vortex weirs can also direct flow into or out of a meander bend, by shifting the apex of the weir slightly toward one bank or the other. RVWs will not usually protect banks that are actively eroding because of rapid drawdown or mass slope failure.

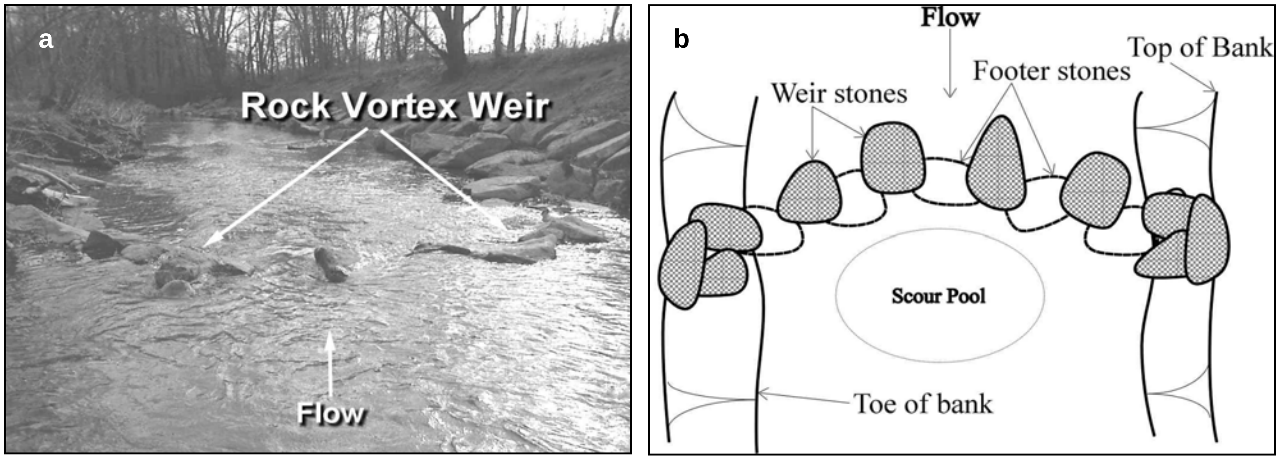


Figure 1: Well designed RVW in a stream along the Atlantic coastal plain (a); Schematic of RVW (b)

RVWs can be used in series to dissipate energy along incising streams and reduce grade changes in urban streams subject to increased storm water flows. A single RVW can accommodate a grade change of about six to ten inches, measured upstream and downstream of the structure, depending on stream flow and the size of weir rocks. RVWs tend to be more effective in preventing future grade adjustments than repairing past grade adjustments. If more substantial grade control is needed, a step pool or similar structure may be more appropriate. In larger streams, RVWs can only function as grade control if the weir rocks are large enough to remain fixed during high flows.

Several practitioners have reported a high incidence of failure for RVW in urban settings due to uncertainties in design and construction (Brown, 2000 and Jennings, 2004). The Rock Cross Vane (RCV) described in profile sheet R-19 appears to be a much more stable structure that performs the same function and may be a preferable alternative.

RVWs are most appropriate in cobble/gravel streams with gradients less than 3% and moderate bedload transport. If higher bedload transport is anticipated, it is important to ensure that the footer stones are anchored well below the maximum depth of scour. RVWs are not recommended for sand bed streams.

RVW construction requires good access to the stream for heavy equipment and adequate room to stockpile materials. Dewatering, flow diversions, or cofferdams may be needed during construction.

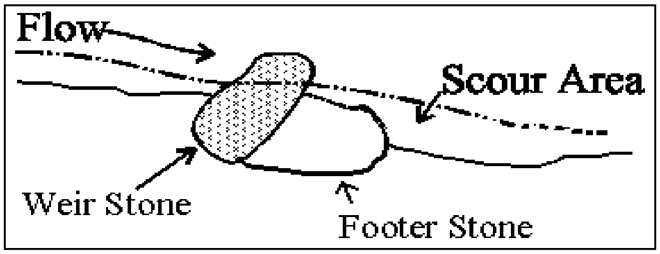


Figure 2: Profile view of RVW

Implementation

The basic design of the RVW requires a separation distance between weir stones of about 1/3 to 1/2 the average weir stone diameter. In addition, weir stones should not rise above the stream channel invert by more than 10-15% of the expected bankfull height. (Figure 3). Failure to meet these two criteria will reduce the available stream cross-section, and lead to streambank erosion, dislodgement of the RVW, and/or increased sediment deposition upstream. Rock weirs are typically installed in a series if the project goal is to promote fish passage or provide grade control. The relative height of each weir is a very important design parameter when RVWs are installed in series. In general, the slope between successive weir crests should not be flatter than the pre-project water surface slope during low flows. The top of the footer stones should be located at the channel invert to allow for sediment transport and fish passage. For fish passage, RVW spacing depends on slope, length and depth of backwater created, and the desired flow depth needed downstream (Castro and Sampson, 2001). For grade control, RVWs should be placed no closer than the elevation change above and below the structure divided by the channel slope. As an example, a six-inch high weir in a stream with a two percent gradient will have a minimum spacing of 25 feet (i.e., 0.5/0.02).

Footer stones should extend down at least as far as the expected depth of scour (Figure 4). If a scour analysis cannot be done in the field, expected scour depth can be estimated using the Castro and Sampson equation.

For **gravel or cobble** bed streams:

(1) Scour Depth = 2.5*h

For **sand** bed stream:

(2) Scour = 3 to 3.5*h

where h = height of exposed rock relative to bed elevation

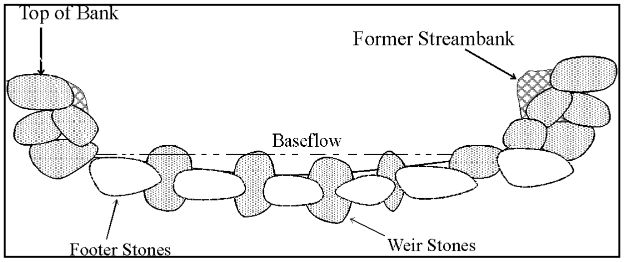


Figure 3: Cross-section of RVW

If scour depths are too great, designers should consider decreasing weir height. Higher weirs cause greater flow convergence, and thus greater scour depths.

Construction - Weir rock shapes should be angular to sub-rounded. In general, the smallest dimension of an individual rock should not be less than one-third of its largest dimension. Large rock, defined as greater than two feet in diameter, is less expensive by weight and takes less time to install.

The largest rocks should be used in the exposed weir section. Rock sizing depends on the size of the stream, maximum depth of flow, planform, entrenchment, and ice and debris loading. Guidance on rock sizing can be found in Copeland *et al*. (2001) and NRCS (1996).

Rock weirs should be constructed during low flow conditions to minimize stream disturbance. RVW construction usually requires work within the stream channel, which may require flow diversions to partially or fully dewater the channel at the installation site. Rock should never be dumped, but rather carefully placed to ensure that each rock is interlocked and stable. The designer or an experienced inspector should always be present to supervise weir installation.

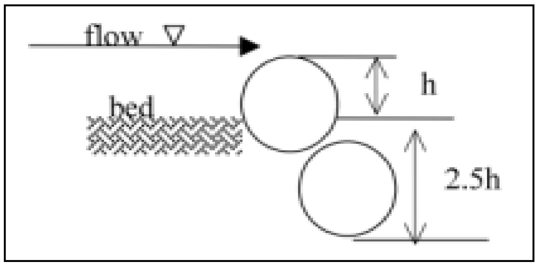


Figure 4: Schematic of scour depth parameters

Source: Castro and Sampson, 2001

The sequence of construction for a RVW starts with the placement of a foundation of large stones in a trench excavated along the stream bottom. The exact size of the foundation stones depends on the size of the stream and the expected high flows, but materials should be sized to be immobile at least during a 50-year flow event. Additional stones are then placed in the trench behind and against the footer stones so that they extend up to the desired weir height elevation. As mentioned earlier, a separation distance of at least 1/3 to 1/2 of the average rock width should be maintained between individual rocks. The position and placement of rock is critical to the stability of the RVW, and often more than one stone may need to be tried before a stable placement is achieved. Additional rock should be placed to ensure that high flows do not outflank the structure at the point where weir legs are anchored into the streambanks. Geotextile liners should be placed upstream and beneath the weir to prevent piping of fine sediments between rocks.

Rosgen (1997) developed the original design for RVWs, and subsequent field experience in many urban stream settings reinforces the need to closely follow weir design criteria. The main objective of an RVW is to avoid creating backwater conditions and disrupting sediment transport processes. This can only be accomplished if the separation distance criteria are met, and the rocks are not extended higher than 10-15% of the bankfull stage elevation (Figure 5). Brown (2000) investigated many urban RVWs, and found many were constructed with weir rocks spaced too close together and extended too high above the channel invert. As a consequence, these RVWs greatly reduced local channel cross-sectional area, which in turn caused the weir to be outflanked (scouring around the sides of the structure), lose their structural integrity, and cause upstream sediment deposition (Figure 6).

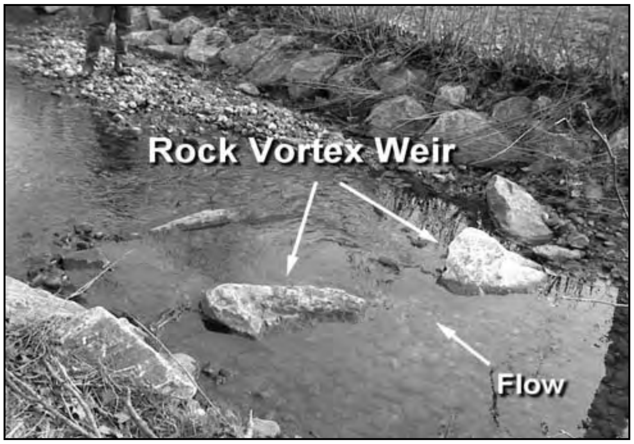


Figure 5: RVW with proper rock spacing

Maintenance/Monitoring – Each RVW should be inspected after the first significant storm event, as some initial rock movement will usually occur. Unless the rock movement impairs the function of the structure, no maintenance is necessary. When properly constructed, RVWs generally require little long-term maintenance.

Cost – Reported unit costs to install a single RVW range from $1,200 to $2,100. These costs do not reflect design, access, mobilization, demobilization or additional channel dewatering costs that may be required as part of a larger stream repair project.

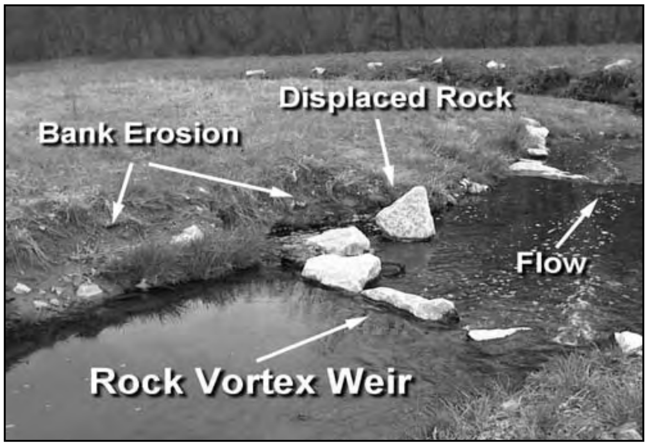


Figure 6: RVW with Rocks Spaced Too Closely

Further Resources

Additional design specifications and information concerning rock vortex weirs can be found in the following references:

Washington State Integrated Streambank Protection Guidelines.
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

Castro and Sampson, 2001 Technical Note No. 13 - Design of Rock Weirs
http://www.id.nrcs.usda.gov/technical/engineering/

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-7.pdf

Virginia Stream Restoration and Stabilization Best Management Practices Guide
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

R-19

Stream Repair: Grade Control

ROCK CROSS VANE

Description

A rock cross vane (RCV) is similar to the rock vortex weir, but differs in that the rocks barely extend above the stream invert. The RCV consists of a rock sill located perpendicular to stream flow that is situated at the invert elevation of the stream channel (Figure 1). The two arms of the sill extend downstream, rising in elevation until they meet the streambank at bankfull height. The low profile of a RCV makes it less vulnerable to scouring and upstream sediment deposition. The RCV is generally used to provide grade control, narrow the baseflow channel, and reduce local bank erosion. RCVs are often located at the top and bottom of meander bends to establish invert elevations for pool/riffle formation (Figure 2).

Habitat Features Created – Rock cross vanes have a modest potential to enhance in-stream habitat through the maintenance of stream grade and the enhancement of riffle habitats.

Feasibility

RCVs are most appropriate in low to moderate gradient cobble or gravel bed streams and should be avoided in sand-bed streams. While RCVs provide grade control, they generally cannot stop a significant knickpoint from migrating upstream. In these situations, a step pool or other hard grade control structure may be needed. Construction requires access by heavy equipment and adequate room to stockpile materials. Construction may also require dewatering, flow diversion, or cofferdams.

Implementation

RCVs consist of a low weir section with two adjacent arms extending downstream into the streambanks that rise to bankfull elevation of the stream (Figure 3). Care must be taken to ensure that the arms are keyed far enough into the streambanks to prevent outflanking during high flows.

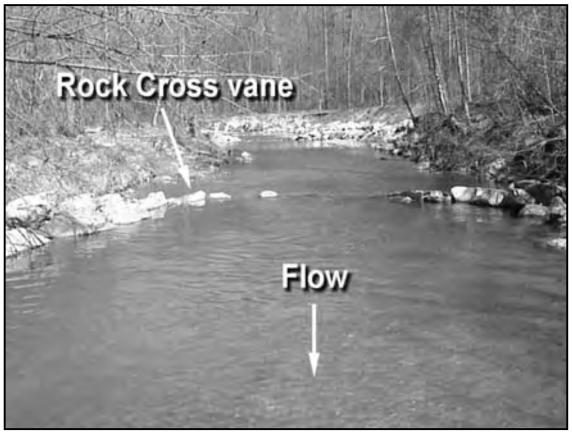


Figure 1: A well designed rock cross vane

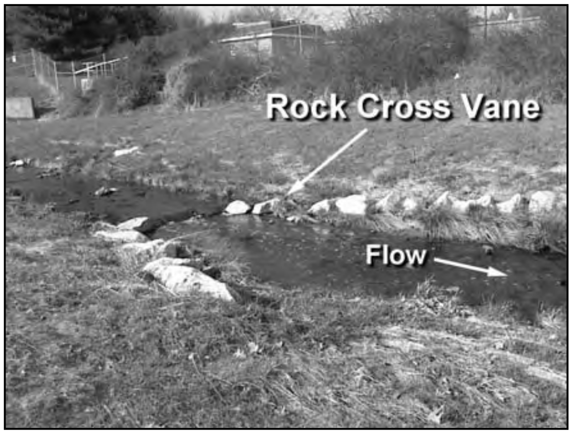


Figure 2: A rock cross vane used to establish stream invert

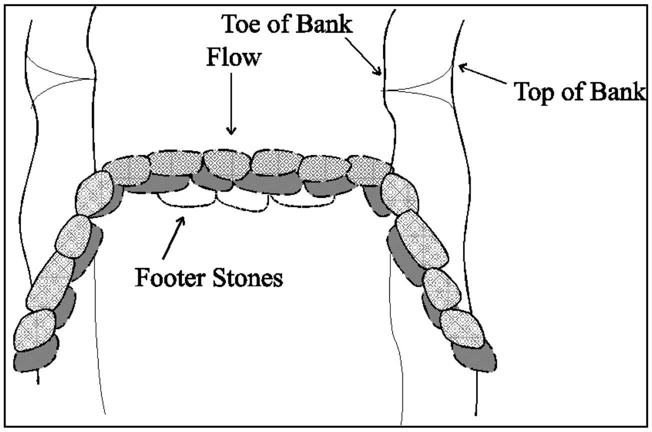


Figure 3: Plan view of a rock cross vane

Construction – RCVs are constructed of large angular rocks that are typically two to three feet in diameter. Each rock must be heavy enough to remain immobile during the highest flows expected for the streambed.

The sequence of construction starts with a rock sill that is formed by excavating a trench perpendicular to stream flow in the center third or half of the stream. As a general rule, the trench should be two or three times deeper than the rocks are high (depending on the number of rock footer courses) and just wide enough to accommodate the rocks. Large, flat rectangular rocks are then placed end to end in the trench so that they are touching each other. One or two stone footer courses are usually used, depending on the width of the channel and the erosive capacity of the stream (Figure 4). Once the first footer course is installed, the trench is then extended upstream of the course so that a second layer of rocks can be placed in a shingle formation (e.g., half on the streambed and half of the rock overlapping rock course).
The trench needs to be extended the entire width of the bankfull channel in the form of an inverted “U” with the arms at a 20 to 30 degree angle to the streambank. The U-shaped trench is then extended upstream once again, and a third set of rocks is placed so that it overlaps the second course. Once again, a shingle pattern is used such that about a third of each rock is on the streambeds and two-thirds overlaps (See Figure 3 above). The tops should be even or slightly above the desired stream invert within the baseflow channel of the stream (Note: only two courses of rock may be needed in smaller streams).

The RCV’s arms should rise to bankfull elevation and be anchored several feet into the streambank to prevent outflanking. The number of courses and the size of the stone will depend on the size of the stream, the potential for scouring, and the type of stream substrate (Castro and Sampson, 2001). Geotextile liners should be placed upstream of the vane to prevent fine sediments from piping through the rock structure.

Maintenance/Monitoring - If the RCV is properly constructed, little maintenance is needed. Each RCV should be inspected after the first large storm event to check for rock movement, and after the first growing season to check for adequate vegetative stabilization along the streambanks.

Cost - Average unit costs to install a single RCV range from $1,200 to $1,700, although they can increase to $4,000 to $5,000 in wider streams. These were derived from four different sources and do not reflect costs related to design, project access, mobilization and complex flow diversion or dewatering techniques during construction.

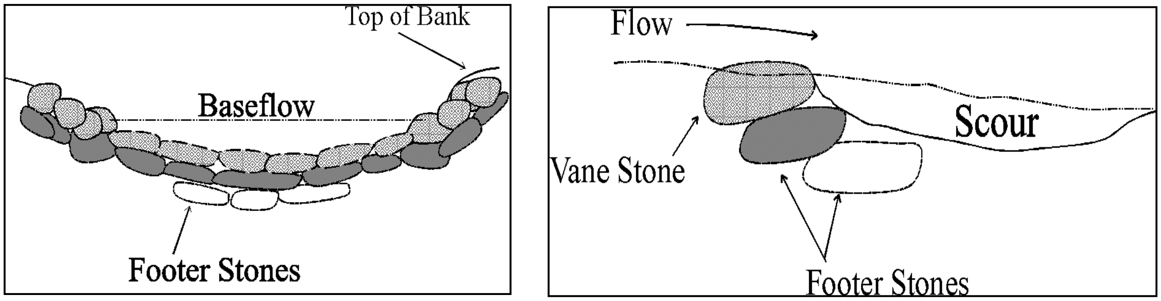


Figure 4: RCV profile (a) and Cross-section (b)

Further Resources

Additional guidance on design and construction of rock cross vanes can be found in the following sources:

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-8.pdf

North Carolina Stream Restoration: A Natural Channel Design Handbook (rock cross vane)
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

Design of Stream Barbs (Technical Note 12)
http://www.id.nrcs.usda.gov/technical/engineering/

R-20

Stream Repair: Grade Control

STEP POOLS

Description

Step pools are stream repair practices that consist of a series of low elevation weirs and pools that dissipate stream energy along degraded or incising stream reaches. They are often used where a large knickpoint has formed and is migrating headward, or in channels that have incised below a culvert or storm water outfall. They are generally made of very large rocks that alternate between short steep drops and longer low gradient pools. In larger streams, step pools may also be constructed using sheet piles or poured concrete. The number of steps and overall length of the pools is governed by the longitudinal elevation change that needs to be controlled.

Habitat Features Created - Step pools enhance stream habitat by improving upstream fish passage.

Feasibility

Step pools are often used to reconnect urban stream reaches that are separated by large drops in channel elevation, such as road crossings. Step pools are a useful practice to arrest the further upstream migration of knickpoints (Figure 1). The most significant drawback to step pools is that they can create a permanent fish barrier if improperly designed.

Step pools located in cobble or gravel streams must allow bedload to easily pass through the structure, or else the deposition of bedload will reduce the capacity and the habitat value of individual pools. If the stream has highly erodible banks, measures must be taken to ensure that flows will not outflank the step pool. The sides of the weirs should extend at least four times the diameter of the biggest rock into the streambank. The use of step pools is not advised in stream channels that are laterally unstable.

If step pools are designed to reestablish fish passage below a crossing, then the height of each drop and the depth of each pool must be designed to allow resident and migratory fish species to pass. A drop of one foot may be negotiable for adult trout and salmon but may not allow the passage of less athletic or juvenile fish. A drop of six inches or less between pools is recommended for non-salmonid and juvenile fish. The depth of each pool also plays a role in helping fish negotiate the structure. Shallow

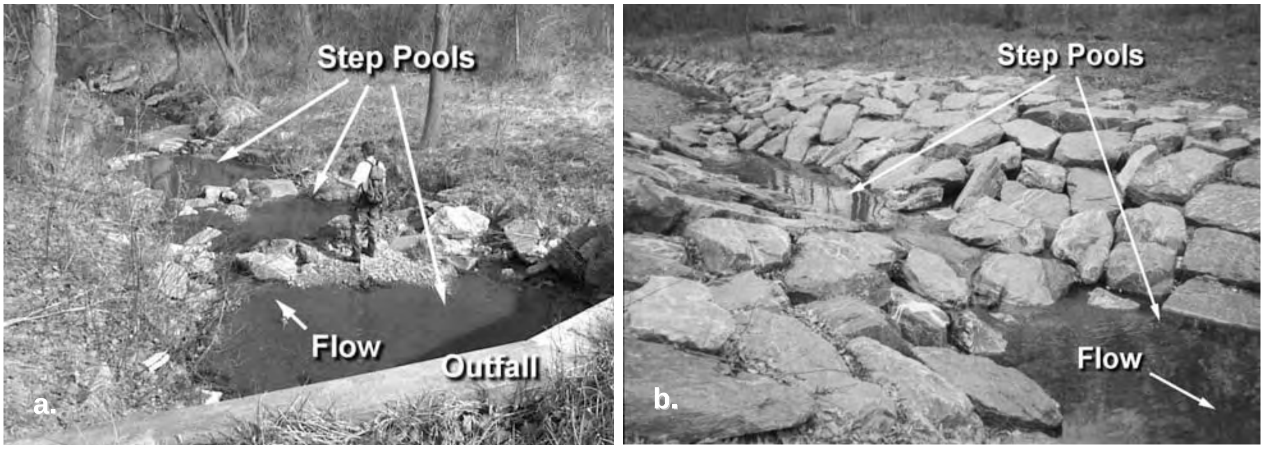


Figure 1: A series of steep pools below a road culvert (a); A series of step pools used to halt knick point migration (b).

pools (less than six inches) do not give fish enough momentum to pass the drop section. More guidance on fish passage requirements can be found in Profile Sheets R-28 through R-30.

Implementation

The most important design elements for step pools are that the structure must be stable at all flows, rocks must be large enough to be essentially immobile, and the drops should be low enough to allow fish to pass upstream.

In order to prevent the establishment of a fish barrier, each step above the pools should be no more than one foot high and the pools should be deep enough to allow fish sufficient room to maneuver. For non-salmonid species, the maximum drop may need to be less than six inches.

The ratio of steepness is often used as a design parameter to create effective natural step pool morphology. The ratio of steepness is defined as the average value of the step height over step length, divided by channel slope (S) above and below the step pool. For most step pools, the ratio of steepness should be in the range of 1 to 2.

Equation: $1 \leq [(H/L)_{ave}/S] \leq 2$

The weirs used in a step pool should point upstream, in the same manner as a rock vortex weir. The weir should also slope towards the center of the stream. This will ensure that flows are not directed towards the streambanks at high flows. The weir stones should be spaced close together with the low point of the weir concentrating the flow of water to the next pool (Figure 2).

Streambanks must be fully armored to prevent high flows from outflanking the step pools. Some sediment will be deposited in step pools, but higher flows will generally scour the pools and transport sediments deposited during low flow periods.

Construction – More extensive details on the sequence of construction for step pools can be found in the design manuals listed in the *Further Resources* section. In general, step rocks should be placed over footer rocks so that each rock rests equally on two underlying footer rocks, and be slightly offset in an upstream direction. Footer rocks should extend below the potential scour hole depth. To determine the estimated scour depth, use the equation provided for rock vortex weirs (see Profile Sheet R-18).

Maintenance/Monitoring – If step pools are properly constructed, little maintenance is required. Flow over each weir should be periodically checked to insure that fish passage is maintained. Smaller rocks may also need to be realigned to permit dry weather flow to cross the weirs. Lastly, the condition of vegetation used to stabilize banks should be checked during the first growing season to ensure that it is adequately stabilizing the banks.

Cost – Reported unit costs to install individual step pool structures range from $2,000 to over $6,000, with much of the variation due to stream width. Total costs depend on the number of step pools required to handle the elevation change. Dewatering and stream diversion can significantly add to construction costs and is not included in unit costs provided.

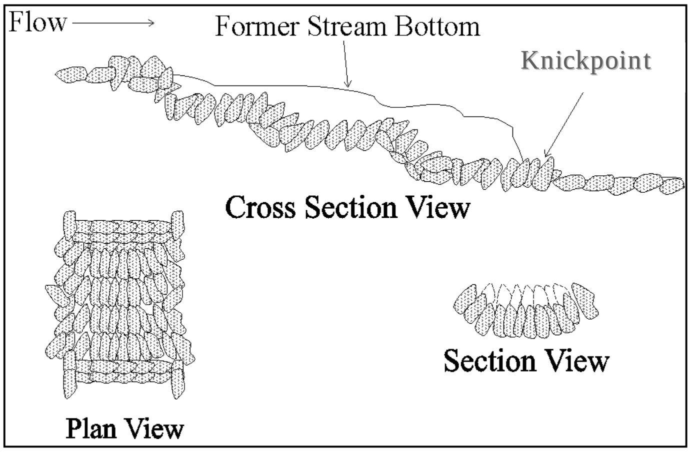


Figure 2: Various design views of step pools

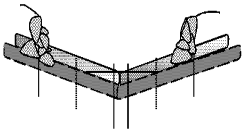
Further Resources

Design and construction guidance for step pools can be found in the following:

Washington State Integrated Streambank Protection Guidelines (drop structures)
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-9.pdf

Virginia Stream Restoration and Stabilization Best Management Practices Guide
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

R-21	Stream Repair: Grade Control **V-LOG DROPS**	

Description

A V-log drop is a stream repair practice used to provide grade control in urban streams. It consists of two logs joined at an angle with its apex pointing upstream. The apex is installed at or below the invert of the streambed. The arms extend downstream and gradually rise to join with each streambank. The V-log drop functions in the same manner as a rock cross vane, concentrating the flow in the center of the stream channel, promoting downstream pool formation, and reducing upstream bank erosion caused by channel incision.

Habitat Features Created – The V-log drop has a significant potential to enhance habitat through the maintenance of stream grade and the creation of downstream scour pools.

Feasibility

V-log drops are most appropriate on smaller streams that have mobile bed sediments (e.g., cobble or gravel), and are less effective on streams with highly mobile bed sediments (e.g., sand bed streams). V-log drops are not recommended for streams that have a high gradient, are actively degrading, or have a boulder or bedrock substrate. V-log drops are not likely to obstruct fish passage because the low point of the structure is located at or below the stream invert.

In many ways, V-log drops mimic the effect of large woody debris (LWD) in streams. Indeed, log drops are most appropriate in streams where LWD was historically a major stream habitat element but is currently missing. Urban streams tend to lack LWD (CWP, 2003). V-log drops also offer a more natural alternative to boulder structures. In most cases, logs can be obtained from tree clearing for access roads or nearby construction sites. Lastly, installation of V-log drops can sometimes be installed without heavy equipment access, although a backhoe will make the job faster.

Implementation

The most important design parameter for the V-log drop is the diameter of the log in relation to the size of the stream. Logs that are eight to ten inches in diameter can be used for small, first order streams, while one to two foot diameter logs are needed for second and third order streams. In larger streams, each arm may be formed by stacking two logs to prevent undermining by scour. Designers should always estimate the potential depth of scour, and make sure the structure does not obstruct much of the channel cross-section.

Each log must be long enough so that one third of its total length is anchored in the streambank. Each leg of the V should extend up to the bankfull elevation. If this is not possible, large rock should be placed over and around the logs to armour them and prevent scour during larger storms. Figure 1 illustrates typical design details for a V-log drop structure.

Construction – Each log should be cut to length so that they will join at the center of the stream. Each log extends downstream and rises at a five to 15 degree angle, heading into the streambank. At least one-third of the log's length should be securely anchored in the streambank. The angle of the V can vary from 75 to 105 degrees depending on stream width. A wider angle is appropriate for third order streams, while first order streams should have an angle of 90 degrees or less. The angle that the logs rise from the streambed up to the streambank should not exceed 10 to 15%.

Maintenance/Monitoring – V-log drops should be inspected after significant storm events during the first year. The frequency of inspection after the first year depends on the risks and costs should the structure fail. If failure of the structure will not result in damage to public infrastructure, private property, or stream impacts, then an annual inspection may be all that is needed. Quarterly inspections may be warranted if these conditions exist at the site.

Costs – The unit cost to install a single V-log drop structure ranges from $800 to $2600.

Further Resources

Basic design and construction specifications for V-log drop structures can be accessed at:

Washington State Integrated Streambank Protection Guidelines.
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

Virginia Stream Restoration and Stabilization Best Management Practices Guide
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

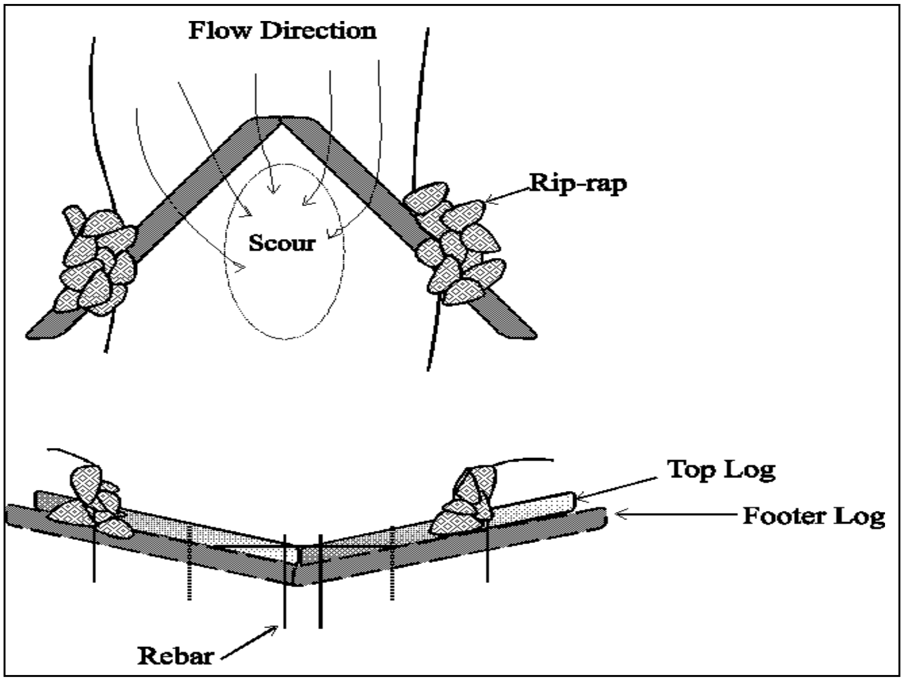


Figure 1: V-log drop design

R-22

Stream Repair: In-stream Habitat Enhancement

LUNKERS

Description

Lunkers are a stream repair practice used to provide undercut bank habitat and streambank toe protection along meander bends. Originally developed for trout stream enhancement in Wisconsin, the term lunker is an acronym for "little underwater neighborhood keepers for rheotactic salmonids" (Hunter, 1991). They consist of wooden, crib-like structures that are installed below the water surface along the toe of meander bends (Figure 1). Each lunker is constructed of horizontal wooden planks separated by vertical spacers to form a crib-like box. In recent years, some lunkers have been constructed from recycled plastic materials, which reduce the potential rot/decay issue.

Habitat Features Created - Lunkers have a significant potential to enhance fish habitat and refuge areas by creating overhead cover and undercut streambanks.

Feasibility

Lunkers are located below the low flow water surface on the outside of meander bends so that they will receive enough current to flush out sediment. Lunkers are not suitable for straight reaches or the inside of meander bends because these areas are subject to sediment deposition. Lunkers work best in medium to large urban streams with cobble/gravel substrates and where there is some potential for a recreational fishery. They are not recommended for rapidly incising or degrading streams. Lunkers are often combined with bioengineering or other streambank stabilization practices to protect the upper streambank and have been successfully installed throughout the country. Lunkers are not appropriate for streams that are laterally unstable or have high bedload transport rates. Excavation of the streambank and installation of the lunkers requires access by heavy equipment.

Figure 1: Assembled lunkers prior to installation
Source: Minnesota DOT

Implementation

Lunkers are modular, wooden or plastic structures four to eight feet in length, three to four feet wide and 12 to 18 inches tall. Individual lunker structures are pre-assembled off-site and transported to the site for installation. Each module is installed sequentially along a meander bend and secured to the streambed with half-inch rebar. The lunkers are installed so that their top elevation remains just below the low flow water elevation. Lunkers must be kept below the water surface, since repeated wetting and drying will cause rapid deterioration of wood. During installation, the streambank must be excavated back the full width of the lunker (three to four feet). After installation, appropriately sized rock is placed on top of the structure as additional toe protection, and the streambank backfilled with soil, shaped and revegetated (Figure 2).

Construction – Individual lunkers are constructed of rough-cut two-inch thick hardwood or cedar lumber. A single 8’x 4’x 18” lunker will require eight 4’ x 1’ x 2” boards, six – 8’ x 1’ x 2” boards, and eight 10” sections of 8”x 8” posts or logs for use as spacers. Each lunker requires approximately 80 board feet of lumber. The structures are created by first nailing two spacers to a four foot board, one spacer at the end of the board (front of the structure) and the other about three feet back. The second board is nailed to the opposite end of the spacers. Construct four of these units. Space these units two feet apart and nail two-eight foot boards to them, connecting the units at the spacers. These boards form the bottom of the structure. Flip the structure over and nail four 8-foot boards flush to each other to cover the top of the structure. Drill half- inch holes from top to bottom through the spacers. The process is repeated until the required number of lunkers is constructed.

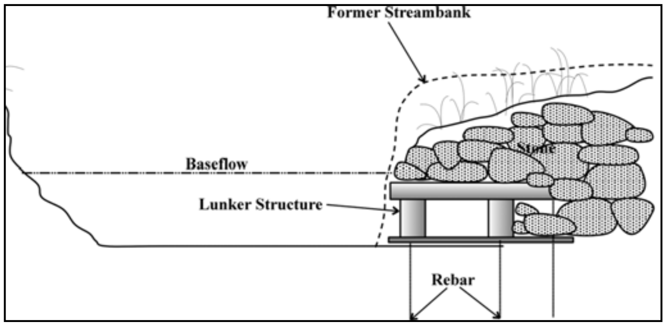


Figure 2: Cross-section of a lunker

The streambank should be graded back to the width of the lunkers. The depth of excavation should allow the top of the lunkers to lie just below the water surface (Figure 3).

Rock should be placed on the top front edge of the lunker that is of sufficient size to protect the toe during high flows. The streambank should then be backfilled with soil and shaped to achieve a stable slope. If conditions warrant, erosion control fabric should be laid as part of the backfilling procedure. The last step involves planting appropriate plant materials to stabilize the streambank.

Maintenance/Monitoring – Lunker installation should be monitored frequently during the first year. The lunkers themselves do not require maintenance, although wooden lunkers should be periodically inspected to check for rot/decay and sediment deposition. Replace dead/dying plant materials on the upper streambank to ensure stability. The anticipated life expectancy of a lunker is 10 to 15 years.

Cost – Reported unit costs to install a single eight-foot lunker range from $360 to $500.

Figure 3: Newly installed lunkers
Source: Vernon County, MI LWCD

Further Resources

More information on the design and construction of lunkers can be accessed from the following sources:

Field Manual of Urban Stream Restoration available for purchase from Conservation Technology Information Center
http://www.ctic.purdue.edu/CTIC/Catalog/UrbanManagement.html

Ontario's Stream Rehabilitation Manual (lunkers)
http://www.ontariostreams.on.ca/OSRM/toc.htm

Stream Corridor Restoration: Principles, Processes, and Practices (lunkers)
http://www.usda.gov/stream_restoration/PDFFILES/APPENDIX.pdf

R-23

Stream Repair: In-stream Habitat Enhancement

LARGE WOODY DEBRIS

Description

The introduction of large woody debris (LWD) is a relatively new stream repair practice designed to provide complex in-stream habitat enhancement. The practice has also been adapted to provide bank protection and grade control on larger streams. LWD consists of large tree limbs, trunks, and root wads that are installed within the channel to interact with stream flow and alter local channel morphology. LWD creates in-stream habitat for fish and aquatic insects, provides areas of temporary in-stream sediment storage (e.g., gravel bars), and increases the overall structural complexity of the channel. Rootwad revetments are another form of LWD placement along meander bends (see Profile Sheet R-5).

Riparian forests naturally supply LWD to streams in undisturbed subwatersheds, and LWD is often a major structural habitat component of headwater streams. Urban streams often lack LWD because of direct removal, loss of streamside forests, and wash-out by elevated storm flows (Horner *et al*., 1997 and Fox *et al*., 2003). The decline in LWD in urban streams can lead to channel scouring, loss of pools, changes in streambed morphology, and an overall loss of in-stream habitat (Figure 1).

In recent years, introduction of new LWD has been investigated as an urban stream repair practice, particularly in the Pacific Northwest (Nichols and Sprague, 2003; Abbe *et al*., 2003; Larson *et al*., 2002; Hildebrand, 1998; Shields *et al*., 2001; Booth *et al*., 2001). Initial efforts consisted of installing large individual logs and rootwads along the stream channel. The current practice has evolved to create composite structures of many different sizes and layers of individual LWD pieces. These structures are called “engineered log jams” and are anchored or cabled to the bank, or assembled together into a single heavy unit that will remain immobile during high flows (Abbe *et al*., 2003 and Shields *et al*., 2001).

Habitat Features Created – Large woody debris is a major in-stream habitat component in forested regions and creates overhead cover, resting areas for fish, scour pools, and more complex stream velocity patterns (Figure 2).

Feasibility

Several factors must be considered before using LWD as an urban stream repair practice. First, a good understanding of current channel evolution and hydraulics is needed before re-introducing LWD since it can alter existing flow conditions and local stream morphology. Second, designers need to select the appropriate size, density and orientation of LWD for the stream channel. If LWD is too small, it will be easily moved by the stream and cause debris jams and blockages at downstream culverts and road crossings. The best approach is to examine natural reference streams of the same size to determine the size,

Figure 1: Large woody debris in a coastal plain stream

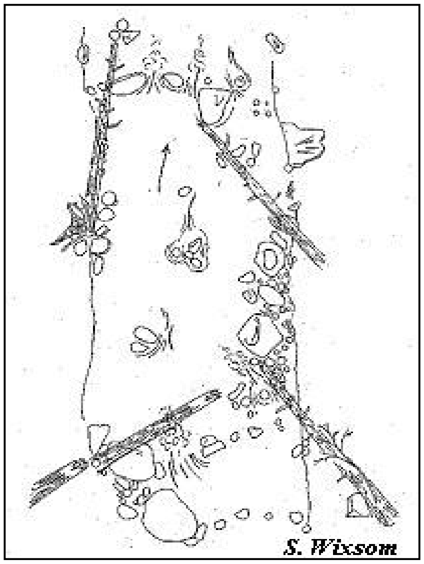


Figure 2: Typical assortment of large woody debris
Source: Ohio DNR, 2001

length, and diameter of LWD that naturally occurs. In addition, the overall density of LWD in reference reaches should also be evaluated (Fox *et al*., 2003). Good designs attempt to replicate LWD conditions in reference streams, while at the same time recognizing that urban streams are subject to greater current velocities, and LWD may need to be anchored. Lastly, poorly oriented LWD can deflect or alter flows and cause negative impacts to the channel and bank, so designers should carefully analyze how the LWD will interact with the flow.

Placement of LWD in highly confined or entrenched urban streams should be done with extreme care. If these streams currently experience routine flooding problems, debris jams, or culvert blockages, or have adjacent infrastructure, LWD placement is not recommended. Also, adding LWD makes little sense in regions of the country that do not have forested riparian areas, or where LWD is not an important structural component of natural streams.

Implementation

To date, the majority of design guidance involving LWD relates to its use on larger stream and rivers. The use of LWD in first and second order streams is a relatively new undertaking and limited design guidance or standard details are yet available.

Hildebrand *et al*. (1998) found that log length played a significant role in the stability of LWD. Logs that were shorter than the average channel width were much more likely to move than logs that were 1.5 to 2 times longer than the average channel width. Orientation also appears to play a role in log stability. Logs that are perpendicular or angled to the flow are more stable than logs that are parallel to the flow. Logs that are placed as ramps act in the same manner as log vanes (i.e., anchored on the bank and extending down into the channel in an upstream direction) caused the pool scour both up and downstream of the ramp log.

Bethel and Neal (2003) reported that logs without rootwads tended to move farther than logs with rootwads attached. Regardless of its size or orientation, LWD should never obstruct more than 10% of the cross-sectional area of an urban stream channel.

Another design consideration is whether the LWD should be anchored to the streambank. LWD can be anchored rigidly in place, either by embedding it in the streambank or armoring it with boulders. Alternatively, LWD can be tethered or cabled to the streambank, thus allowing some movement during high flow conditions. Larson *et al*. (2002) reports that anchored LWD did not move in Puget Sound streams, and created scour pools, increased sediment retention, and had some effect on grade control. Lastly, the weight of heavy LWD pieces may be great enough to hold it in place in smaller streams, with the expectation that some LWD may move during high flows (Figure 3).

The most recent trend has been the installation of engineered log jams that are composite structure of many types of LWD pieces used to provide grade control and/or bank protection.

Shields *et al*. (2001) describes interlocking LWD structures of more than a dozen large logs effectively protected incising sand-bed streams in Mississippi, with each LWD structure protecting about 60 feet of eroding bank. Abbe *et al*. (2003) presents a design concept for composite LWD structures that has large rootwad segments providing the basic foundation, medium sized logs stacked in an interlocking crib, and the smallest LWD pieces racked within the crib structure. The large mass of composite LWD structures generally remains immobile during bankfull floods, although their sheer size renders them infeasible for first and second order streams.

Construction – Construction guidelines for the placement of LWD in small streams are rare. Heavy equipment access is needed to deliver the LWD to the stream and a backhoe or similar equipment is needed to manipulate it into place. In small urban streams, smaller pieces of LWD may be installed by hand.

Maintenance/Monitoring - Unless cables are used as a mechanical anchor, LWD placements do not require maintenance, although some failure or movement of LWD has been reported on larger streams (Frissel and Nawa, 1992). Every effort should be made to document before and after treatment conditions to increase understanding about the performance and longevity of this experimental repair practice. The number, size, location and orientation of the installed LWD should be recorded and annual surveys made to document movement, habitat enhancement, sediment storage, and changes to channel morphology. Biological sampling should be conducted before and after LWD placement to document changes in fish and macroinvertebrate populations.

Cost – Due to the limited number of projects and the varied sizes of materials and installation methods, general cost data is not available. Slaney and Zaldokas (1997) report an average cost of $20-$40 per linear foot for LWD placement projects in Western Canada. The cost for materials and installation of a single rootwad obtained from off-site sources that is part of a rootwad revetment ranges from $250 to $600. This would be an adequate planning level cost per installed piece of LWD.

Further Resources

As noted earlier, not much design and construction guidance is available on LWD placement for smaller urban streams. It is expected that standard LWD details will be developed to solve specific urban stream repair design objectives in the next several years. The references cited in this profile sheet should be consulted for design ideas drawn from larger stream and river applications.

Washington State Integrated Streambank Protection Guidelines
http://www.wa.gov/wdfw/hab/ahg/ispg_chap06_all.pdf

California Salmonid Stream Habitat Restoration Manual (large woody debris)
http://www.dfg.ca.gov/nafwb/manual.html

Incorporation of Large Wood into Engineering Structures. Engineering Note 15
http://www.id.nrcs.usda.gov/technical/engineering/

Ontario Stream Rehabilitation Manual (woody debris management)
http://www.ontariostreams.on.ca/OSRM/toc.htm

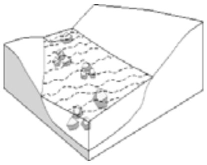
Figure 3: Large woody debris anchored on the streambank

Source: Washington State Department of the Environment

R-24

Stream Repair: In-stream Habitat Enhancement

BOULDER CLUSTERS



Description

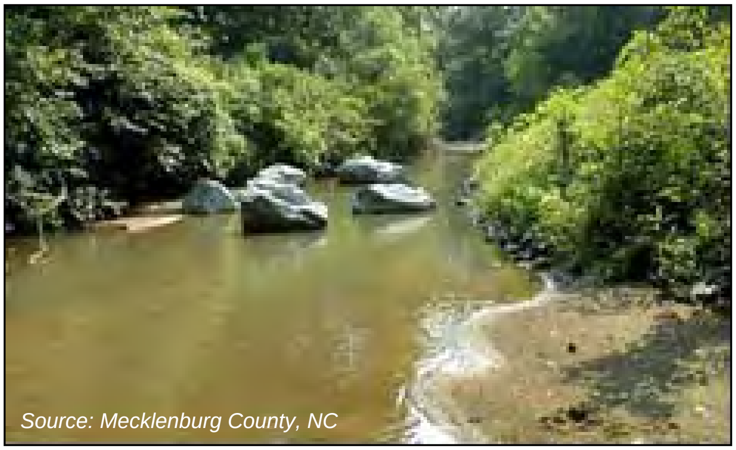
Boulder clusters are a stream repair practice that helps create better in-stream fish habitat. They consist of large rocks placed in clusters near the center of the stream that create small scour pools, eddies and areas of turbulent flow. Boulder clusters are used in medium to large streams where fish habitat diversity is comparatively low but has the potential to improve (Figure 1).

Habitat Features Created - Boulder clusters have a moderate potential to enhance in-stream fish habitat by creating a diversity of flows, small scour pools, and resting areas for fish.

Feasibility

Boulder clusters are most appropriate in urban streams that have cobble/gravel substrates, are dominated by shallow run and riffle habitat, and have few pools. For best effect, boulder clusters should only be applied in streams that are stable in terms of their grade and planform. Boulder clusters should be avoided in braided and sand bed streams, and have limited value in low gradient streams. Also, if boulders are not a natural element of the stream, large woody debris or log structures are more suitable practices to improve fish habitat.

Boulder clusters make the most sense in streams that have low fish habitat diversity but have good potential for habitat improvement. Fish sampling should be conducted early in the planning process to determine density and abundance of the current fish population, and whether passage is impeded by fish barriers. Other potentially limiting factors, such as water quality, baseflow, and stream temperature should also be assessed to determine feasibility. Boulder clusters require good access to the stream for heavy equipment.



Source: Mecklenburg County, NC

Figure 1: Boulder cluster installed in a stream

Implementation

The design of boulder clusters is based on the size, number, location and configuration of boulders within the stream reach. Boulders should be heavy enough to withstand current velocities expected during bankfull and even higher flood events. Copeland *et al*. (2001) provides guidance on hydraulic modeling to determine boulder sizing. Designers can also look at the size of stable boulders present in similar urban stream reaches to determine appropriate boulder size. In most second or third order urban streams, boulders in the two to three foot diameter size class are often needed.

Triangular groups of three to five boulders appear to be the most effective design. The boulders should be separated by about one boulder diameter, and boulders should not lie in the wake of an upstream boulder. Downstream boulders should be placed at the edge of the turbulent flow created by the next upstream boulder (Figure 2). In general, boulder clusters should occupy less than ten percent of the bankfull cross sectional area. Boulders should not be placed so that they deflect flows or increase current velocity at the streambank. Lastly, designers should avoid placing boulder clusters where they may impact or alter existing habitat features, such as riffles.

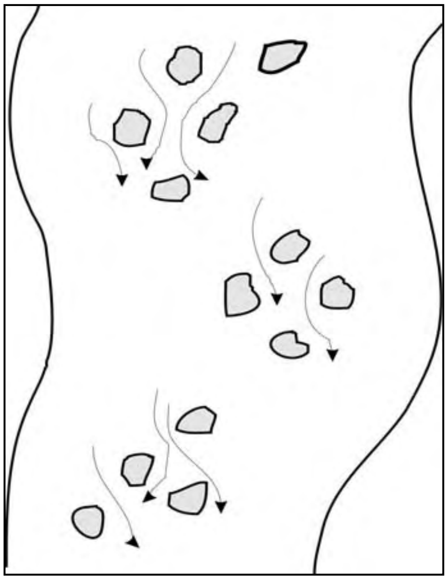


Figure 2: Boulder cluster design schematic

Construction: Boulders should not be "dumped" into the stream, but placed with a backhoe or other suitable heavy equipment. The boulders should be placed in shallow trenches or holes that are about one quarter of the diameter of the boulder so that they remain immobile over the long-term.

Maintenance/Monitoring: Boulder clusters require minimal maintenance and monitoring, although they should be checked annually for movement. Boulders that are observed to have moved do not necessarily require relocation, unless they are causing channel instability or streambank erosion problems. Follow-up fish sampling is recommended to determine how effective boulder clusters in creating habitat.

Cost: Reported unit costs to install boulder clusters range from $60 to $250 per boulder and are influenced by the size of boulders used and ease of access to the stream.

Further Resources

Additional guidance on design and installation of boulder clusters can be accessed from the following online resources:

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/sec3-1.pdf

Boulder Clusters
http://www.wes.army.mil/el/emrrp/pdf/sr11.pdf

Stream Corridor Restoration: Principles, Processes, and Practices (boulder clusters)
http://www.usda.gov/stream_restoration/PDFFILES/APPENDIX.pdf

Ohio Stream Management Guides (eddy rocks)
http://www.ohiodnr.com/water/pubs/fs_st/streamsfs.htm

R-25

Stream Repair: In-stream Habitat Enhancement

BASEFLOW CHANNEL CREATION

Description

This stream repair practice is used to create a confined baseflow channel within an enlarged urban stream. The creation of a stable baseflow channel is accomplished by installing a series of stream repair practices to concentrate or deflect flows toward the center of the stream channel. Common practices used for this purpose include rock and log vanes (Profile Sheet R-17), double wing deflectors (R-16), “V” log drops (R-21), rock vortex weirs (R-18), rock cross vanes (R-19), large woody debris (R-23) and cut off sills and linear deflectors (discussed later).

Urban stream channels tend to enlarge as impervious cover increases. As stream channels enlarge, baseflow occupies a smaller portion of the overall channel (Figure 1). This often results in an overly-wide baseflow channel dominated by shallow run and riffle habitat and a lack of pools. In these channels, the baseflow channel or thalweg tends to migrate back and forth across the channel bottom, shifting course after each storm event recedes (Figure 2). The constant disruption and shallow depth of the baseflow channel can reduce or eliminate habitat for fish and aquatic insects. The goal of baseflow channel creation is to narrow and deepen the baseflow channel in order to create adequate flow depth and velocity to support aquatic life.

The lack of physical habitat within the baseflow channel is only one of a large number of stressors affecting urban streams. Creation of a stable baseflow channel is best undertaken in conjunction with a comprehensive approach to subwatershed restoration. In particular, storm water management retrofits that reduce the frequency and volume of storm flows can also help create a stable baseflow channel.

Feasibility

Baseflow channel creation is most effective in medium to large urban streams with mobile cobble/gravel substrates that have finished enlarging their cross-section. The practice is far less effective in streams that have immobile substrates, such as bedrock or large boulders. In sand bed or braided streams, the naturally shifting nature of the streambed limits the ability to create a stable baseflow channel. Also, baseflow channel creation should be avoided in actively degrading or enlarging urban streams, since it is difficult to create stable features in these rapidly adjusting streams. Baseflow tends to naturally concentrate along the outside of meander bends, even in degraded urban streams.

Figure 1: Example of urban stream channel enlargement

Figure 2: Wide shallow baseflow typical along urban streams

As such, baseflow channel creation is most applicable along straighter run and riffle sections where flows tend to spread thinly across the stream. Streams in older urban watersheds often have had enough time to adjust their geometry to altered urban hydrology (e.g., radii, cross section and grade) and are often good candidates for baseflow channel creation.

Implementation

The basic design combines a series of stream repair practices within the stream reach to achieve a narrower, deeper, and better-defined baseflow channel. The deepest part of the baseflow channel is known as the thalweg, and it tends to wander back and forth across the streambed, depending on the sinuosity of the channel. Designers should carefully analyze the existing stream channel to determine the optimal flow path for the new baseflow channel. Individual practices should be spaced sufficiently apart so they do not impair the effectiveness of the next upstream or downstream practice. Special emphasis is placed on cut-off sills and linear deflectors, which are described below:

Cut-off sills are a series of low rock sills that extend out from the streambank at a 20 to 30 degree angle pointing upstream (Figure 3). The purpose of a cut-off sill is to promote sediment deposition and bar formation along the margins of the stream channel, thereby defining a narrower baseflow channel. The rocks that comprise the cut-off sill do not extend very far above the streambed, and are best used in streams with relatively high bedload movement and can also help stabilize lateral bars.

Linear deflectors consist of a series of cut-off sills that are connected by a line of rock or boulders constructed parallel to the streambank (Figure 4). The cells formed behind the linear deflector are then backfilled with sediment, gravel or rock, or allowed to gradually fill up over time through bedload deposition. The net effect is to narrow, deepen and better define the baseflow channel in enlarged urban streams with relatively high bedload movement (Figure 5). Designers should carefully consider the placement of the linear deflector in relation to the opposite streambank. If it is placed too closely, it can cause further erosion of the opposite bank. If the opposite bank is currently or potentially unstable, bank stabilization measures should be installed.

Other stream repair practices that can be used to promote a narrower and deeper baseflow channel are illustrated in Figure 6.

Construction and Maintenance - The construction sequence and maintenance requirements for baseflow channel creation are based on the component stream repair practices used to narrow and confine the channel. Consult the appropriate stream repair profile sheet for more details, including double wing deflectors (R-16), rock vanes (R-17), rock vortex weirs (R-18), rock cross vanes (R-19), V-log drops (R-21) and large woody debris (R-23).

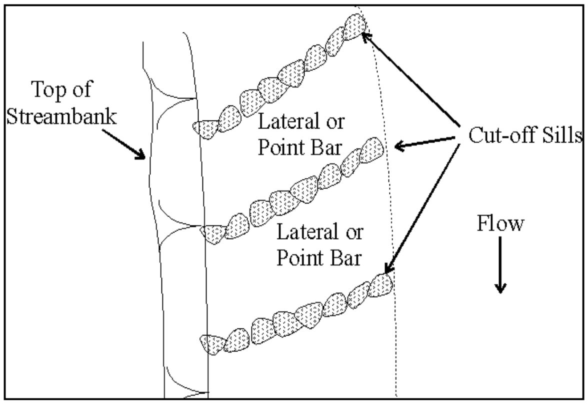


Figure 3: Plan View of cut-off sill

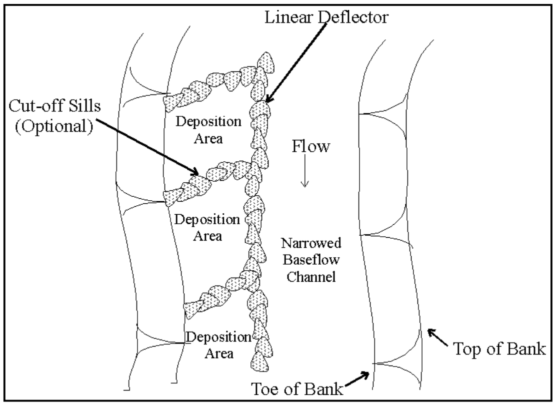


Figure 4: Plan View of linear deflectors

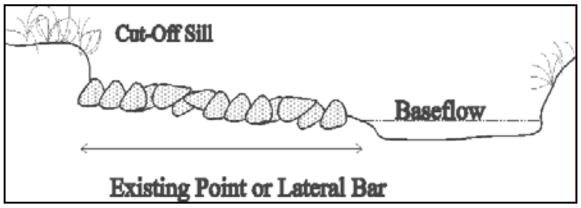


Figure 5: Section view of cut-off sill

Cost – The cost to create baseflow channels depends on the type and combination of stream repair practices used and the desired length of the baseflow channel. Refer to individual profile sheets for the component stream repair practices for unit cost information.

Further Resources

Rehabilitation of Aquatic Habitats in Warm Water Streams Damaged by Channel Incision in Mississippi.
http://www.sedlab.olemiss.edu/wqe_unit/topashaw/rehabilitation_aquatic_habitats.pdf

Design of Low Flow Channels
http://www.wes.army.mil/el/emrrp/tnotes.html

Virginia Stream Restoration and Stabilization Best Management Practices Guide (cut off sills)
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

Figure 6: Other Stream repair practices that can promote baseflow channel creation include: (a) Double wing deflectors; (b) Rock cross vane; (c) Rock vane; (d) Rock vortex weir; and (e) Large woody debris

R-26

Stream Repair: Flow Diversion

PARALLEL PIPES

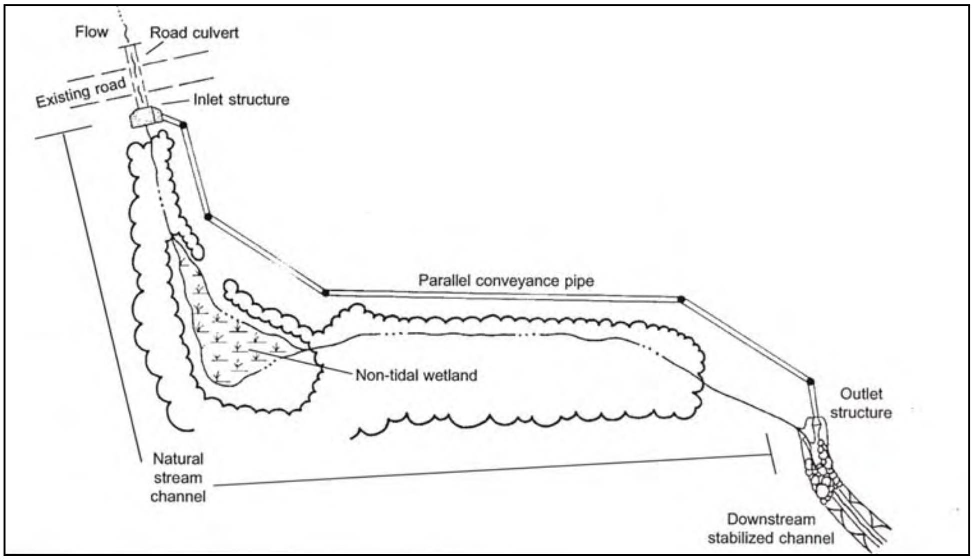
Description

This stream repair practice is typically installed to bypass excessive storm water flows to prevent erosion and habitat degradation in small headwater streams. Parallel pipe systems convey storm flows around sensitive stream reaches or wetland areas before eventually discharging at a more stable downstream location (Figure 1). A flow splitter is used to direct baseflow and small storm flows to the existing stream channel and bypass the moderate storm flows through the pipes that would otherwise cause channel erosion. Large storm events (e.g. flows greater than the two-year design flood) overtop the splitter and are conveyed along the channel and its floodplain.

Feasibility

Parallel pipe systems are most appropriate for smaller first order streams where moderate storms events can be bypassed within reasonable pipe sizes (e.g., less than 54”) and where control structures are reasonably small and will not impede fish passage. Parallel pipes are not recommended in headwater streams with high bedload movement or organic debris loading, unless explicitly designed to avoid clogging. Parallel pipes are normally installed during initial subwatershed development, before the channel has begun the adjustment process. They should be used with caution in incising streams, and only if grade controls are installed downstream of the project reach. Few parallel pipe systems have been installed in cold climate regions, where ice buildup might impair the diversion of snowmelt during the winter months. Lastly, parallel pipe systems are generally applied to straight stream reaches, as opposed to sinuous or meandering ones.

Parallel pipe systems are installed for many reasons. Typical applications include protection of sensitive portions of natural stream channels to convey storm water runoff to a downstream storage retrofit practice, or to stabilize “blown-out” channels as part of a comprehensive stream repair application. Parallel pipe systems are best utilized in highly urban subwatersheds where streams face excessive current velocities, upstream storm water retrofits are not feasible or practical, and bank stabilization with rip-rap is



not desired. In addition, parallel pipe construction disrupts the stream less than comprehensive stream repair applications (although it results in extensive clearing in the stream corridor).

Parallel pipe system intake structures can be installed in several locations within the urban drainage network, including:

- Existing or planned storm water outfalls
- Within an existing or planned conventional storm drain manhole
- Immediately downstream of a road culvert
- Within the stream channel itself

Site Constraints and Permits – The feasibility of parallel pipes are normally constrained by available head (the drop in elevation from the inlet structure and the outlet, which should be evaluated by an experienced storm water engineer). Parallel pipe construction involves in-stream work and usually requires several different regulatory permits (e.g., Section 401 water quality certification, waterway construction permits, Section 404 permits).

Implementation

A parallel pipe system consists of an inlet structure (flow splitter), a conveyance pipe or open channel, and an outlet or discharge structure. The inlet structure is usually cast-in-place concrete and located at an upstream control point. It consists of a flow-capturing structure, a low-flow orifice or weir, a low stage weir for diversion of storm flows, an outlet pipe for the parallel conveyance system, and an overflow weir for high-flow events discharging back into the natural channel. Large riprap is usually required to guard against erosion at the control structure. The actual “parallel pipe” consists of a reinforced concrete pipe. The outlet channel or stilling basin should be stabilized and designed to safely convey stormflows to the receiving water. Large riprap or other suitable energy dissipation technique should be employed immediately below the outlet, but should be as short as possible and designed to return to the natural conditions quickly.

It is important to keep in mind that parallel pipes can generally be applied at relatively small diameter outfall pipes with small contributing watershed areas (25 to 400 acres). Consequently, the size and length of streams that can be protected is usually very small (Table 1). Generally, only a few hundred to a few thousand feet of first order stream can be protected by a parallel pipe system. Therefore, the stream reach to be protected should have excellent habitat or spawning potential for the desired fish species.

Parallel pipe systems require extensive hydraulic and hydrologic modeling to split the correct flow volumes away from the stream. A suggested modeling approach is outlined in Table 2. The basic approach is to divert the flows from 85% of the one-year design storm event and the two-year design storm event in the parallel pipe, and let smaller and larger flows pass through the channel (Claytor, 1996).

The following considerations are important to keep in mind when designing parallel pipe systems:

- Keep parallel pipe out of forested stream buffer, where possible
- Locate mature trees prior to laying out parallel pipe alignment
- Locate control structure to minimize secondary environmental impacts
- Reforest parallel pipe rights-of-way after construction
- Use appropriately designed trash rack depending on litter/debris supply of watershed
- Consider potential for a fish migration barrier and mitigate where possible

Table 1: What You Can Learn About a Pipe in the Field

Pipe Diameter (inches)	Area (sq. feet)	Maximum Discharge (cfs)	Average Velocity (fps)	Drainage Area (acres)
6	0.3	1	4	0.1 to 1
12	0.8	3	6	1 to 2
24	3.4	25	10	2 to 5
36	7.1	90	12	5 to 25
48	12.6	150	14	25 to 100
60	19	350	18	100 to 200

For pipes flowing full, with 1% slope.
Note: all drainage areas are very approximate

Table 2: Parallel Pipe Design Approach

1. Identify the stream reach to be protected
2. Field locate the control structure (detailed topography necessary)
3. Compute peak discharges for storm events
    - Design discharge for diversion (use depth for which 85% of all annual rainfall events are less than or equal to)
    - Large storm(s) for overflow weir (e.g., 10 to 100 year frequency event)
4. Field measure or compute baseflow discharge (one cfs per square mile)*
5. Calculate hydraulic characteristics of control structure
    - Use weir flow/orifice flow equations for baseflow
    - Use Federal Highway Administration culvert charts or computer model for parallel pipe inlet flow condition
    - Use weir flow equation for high stage overflow
    - Use hydraulic model (e.g., HEC-RAS) for downstream tailwater analysis
    - Designer must recognize hydraulic losses at control structure intake
6. Compute required pipe size for parallel pipe system to pass design storm (use open channel flow equations, e.g., Manning's.)
7. Check hydraulic gradient for parallel pipe system under high flow conditions (usually 10 to 100 year storm)
8. Compute required outlet channel size (length and geometry)

** Rule of thumb for Mid-Atlantic region; Source: Claytor, 1996*

Construction - Construction of a parallel pipe system is not significantly different from construction of a conventional storm drain. However, extra attention must be given to the temporary flow diversions during construction of the control structure, for both baseflow and storm flows. It is also extremely important to have good quality control during weir and orifice construction, as slight errors can divert substantial amounts of water to the wrong location. A pre-construction meeting is imperative, and frequent inspections by the design engineer should be incorporated into the bidding specifications. The control structure formwork should be field surveyed prior to pouring concrete to ensure that proper elevations and dimensions have been achieved.

Maintenance - One of the primary concerns about parallel pipe systems is the susceptibility of the inlet structure to clogging (Figure 2). Accumulated trash, woody debris and sediment can all potentially clog low flow openings and thus deprive the stream of necessary baseflow. A good solution is to provide a stilling basin immediately up-stream of the control structure, and employ a hooded low-flow orifice with a minimum diameter of three inches. Trash racks and hooded openings may require cleaning on a more frequent basis. Stilling basins may require dredging every two to three years. The actual pipe system requires little maintenance as long as the intake does not clog and the system was designed and constructed properly.

Parallel pipe systems have been used extensively in suburban Montgomery County, Maryland since the late 1980s and informal inspections indicate that they are protecting headwater stream channels. Several systems that are more than five years old experienced persistent clogging at the inflow structure. The intake and outlet structures should be inspected at least twice a year and after major rainfall events to check for clogging. Continued monitoring and review of design criteria are necessary to ensure that the practice is a reliable, long-term stream protection measure.

Cost - Parallel pipe systems can provide an alternative to structural stabilization of small headwater stream channels to protect high quality fishery or spawning habitat. However, once the drainage area becomes reasonably large, and pipe sizes exceed 54 inches, structural stabilization may be more cost effective. Furthermore, it is important to realize that parallel pipes are not water quality treatment practices and do not attenuate storm water runoff. If these systems are poorly designed, many of the problems they are designed to correct are simply moved downstream. Some planning level cost estimates for parallel pipe systems, as a function of pipe diameter, are printed in Table 3.

Figure 2: Parallel pipe inflow structure

Table 3: Parallel Pipe Construction Cost Data

Pipe size (RCP)[1]	Maximum drainage area (acres)[2]	Capacity (cfs)[3]	Construction costs (per linear foot)[4]
24”	40	22.6	$50
36”	130	66.7	$95
48”	300	143.6	$130
60”	570	260.4	$200
72”	1,000	423.4	$300

[1] Standard pipe sizes are for reinforced concrete
[2] Maximum drainage area is based on single family residential land use (i.e., one-half acre lots)
[3] Capacity is based on Manning’s equation for reinforced concrete pipe at a 1.0% slope or steeper
[4] Construction costs include installation, exclusive of control structure costs, and are based on approximate average installation costs for the Mid-Atlantic region from 1990 to 1994, updated to 2004, and adjusted for inflation

Further Resources

Not much design guidance has been published on parallel pipe systems to date, with the standard reference provided below:

Claytor, R. 1996. *Parallel Pipe Systems as a Stream Protection Technique.* Article 150 in “Watershed Protection Techniques.” Available from Center for Watershed Protection. http://www.cwp.org/

R-27

Stream Repair: Flow Diversion

STREAM DAYLIGHTING

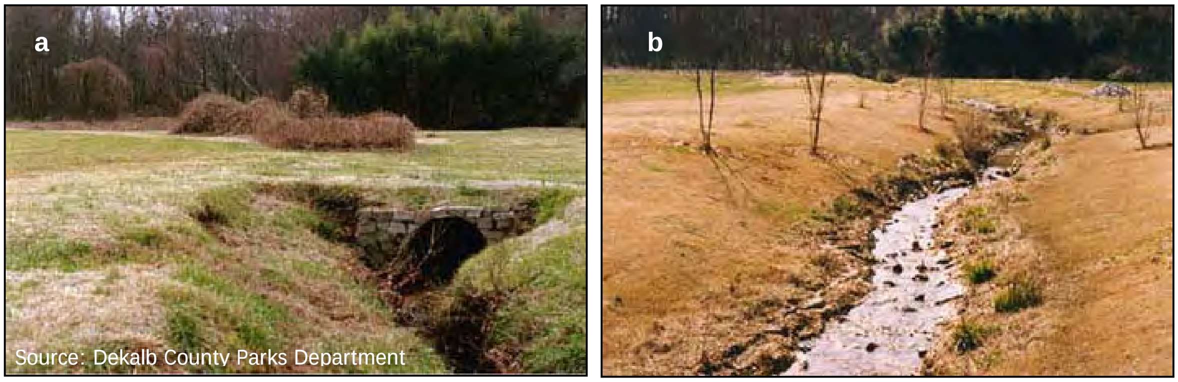
Description

Daylighting is a stream repair practice that opens up and extends the network of headwater streams in a subwatershed. It consists of unearthing and re-establishing surface streams that had been enclosed in the past by pipes or culverts (Figure 1). Many miles of headwater stream channels have been enclosed in pipes and culverts in urban subwatersheds across the country. Many of these streams were enclosed to eliminate the floodplain, create more buildable land, or simply because that was the way things were done. Only in the past decade has the value of headwater streams been recognized and many communities have pursued daylighting to expand length and visibility of their urban streams.

Three possible outcomes can occur when a new stream is created by daylighting.

Naturalized Stream: This daylighting outcome seeks to establish a stable stream channel that conveys baseflow, stormflow, and floods in a “natural” manner. Natural is defined here as having natural streambanks, a stable streambed, and “normal” stream geometry, although some stream repair practices may be needed to achieve this condition. The principles of channel redesign or de-channelization are used to design the new stream (see Profile Sheets CR-32 and CR-33). This outcome can be hard to accomplish at many daylighting sites since it requires more land and lower impervious cover in the contributing subwatersheds. These daylighted streams can be considered analogous to impacted streams (Resh, 1995).

Channelized Stream: In this daylighting outcome, upstream discharges are so powerful that active erosion can only be prevented by hardening the newly exposed stream channel. Hard bank stabilization practices are installed to protect the banks and grade controls are applied to keep the bed from incising. The new stream can still look attractive, contain some aquatic habitat features, have a natural riparian zone, and is expected to have the same general qualities as non-supporting streams.



Source: Dekalb County Parks Department

Figure 1: Stream channel daylighting – Before (a) and After (b)

Artificial Stream: In these settings, a narrow stream corridor and high impervious cover in the contributing watershed produce too much storm water to maintain a stable channel. Thus, the new streams must be highly armored and employ a non-erodible liner or substrate to protect the bed from erosion. In some cases, parallel pipe systems are installed to bypass higher flows from the channel, as well (see Profile Sheet R-26). Consequently, the armored stream primarily functions as a landscaping feature or "stream front" and has the same basic stream quality as urban drainage. They may still have significant value in raising public awareness about the plight of buried streams.

Feasibility

What makes a storm water outfall a good candidate for stream daylighting? This is an important question since scores of storm water outfalls are present in most urban subwatersheds. The best candidates for daylighting can be determined using the OT form during the Unified Stream Assessment (Manual 10). Several factors are important to assessing whether daylighting is feasible at a particular outfall, including:

Connection with Existing Stream Network - Outfalls are preferred if they are directly connected to the existing perennial stream network and expand the length of the stream corridor.

Outfall Pipe Diameter - The most cost-effective outfall pipe candidates typically range from 24 to 60 inches in diameter, which normally drain catchments ranging from 25 to 400 acres, depending on the degree of upstream development. Smaller outfall pipe diameters normally drain such a small drainage area that they cannot support perennial flow, and larger diameter pipes may be too expensive or constrained to daylight. Short lengths of large diameter pipes or culverts that "interrupt" two healthy reaches of perennial streams should always be investigated for daylighting. Profile Sheet R-29 should be consulted for methods to daylight these systems.

Presence of Perennial Flow - Outfall pipes should have some dry weather flow during most of the year. It is important to make sure that the flow from the pipe is truly derived from groundwater and not produced by an illicit discharge from an upland pollution source. For some simple tests to make this call, consult Brown *et al*., (2004).

Distance of Unobstructed Pipe - The greater the distance that a storm water pipe travels underground without any surface obstructions the better. One should "follow the manholes" to determine if there is a clear line of sight over the storm drain right of way. Look for surface and underground obstructions that would make excavation impractical, such as buildings, roads, utilities, mature forests or other land uses.

Width of Drainage Easement or Right-of-Way - Most enclosed storm drains have an aboveground drainage easement or right of way that allows a municipality access to repair the pipes. The width of the right of way corridor is an important daylighting design parameter, as it governs how much space will be available for the planform of the new channel.

Depth of Overburden - The depth of soil or overburden above the storm drain pipe is also an important feasibility factor for daylighting. If the pipe is buried deep underground, the large amount of excavation and off-site hauling and disposal of overburden may render the site infeasible.

Invert of Outfall in Relation to Stream - The distance in vertical elevation between the stream and invert of the outfall pipe should be estimated. In many urban streams, channel incision has created a significant vertical drop from location of the original storm water outfall. Even a drop as small as a few feet between the outfall and the stream means that the new stream gradient will be extremely steep, and may require extensive grade controls.

The benefits of stream daylighting extend beyond the creation of a surface stream. If the pipe or culvert was undersized, daylighting can prevent collapse and localized flooding problems. Daylighting can also increase the capacity of the drainage system to convey floodwaters. Lastly, daylighting can connect two perennial stream reaches and thus eliminate a barrier to fish migration.

Implementation

The process of stream daylighting begins with hydrological modeling of the existing pipe system and its contributing subwatershed. The modeling goal is to project the range of flows, current velocities, and shear stresses that the exposed channel is likely to face in the future. The next step is to repeat the hydrologic modeling, given the new cross sectional area, gradient and roughness of the new open channel, based on realistic dimensions for the site. The model results largely determine whether a naturalized, channelized or artificial stream is possible at the site.

If the pipe can be effectively daylighted, the designer must then determine the suite of stream repair practices needed to maintain a stable channel. While the specific combination of practices will be unique for each site, designers should always investigate two critical points. The first is the point where the old outfall discharges to the newly daylighted stream; the second is the confluence of the daylighted stream and the existing stream network. Armoring and grade controls should always be evaluated at these two points. Designers should also consider how to recycle or safely dispose of any concrete rubble or corrugated metal pipe removed as part of the daylighting operation.

An important part of daylighting design is active neighborhood consultation. Both the public and some agencies may feel that exposing a piped stream may lead to flooding, safety problems, or nuisance conditions. Adjacent residents may fear their property values will diminish, the stream will pose a danger to their children, or it will breed mosquitoes, weeds or pests. Often, the reluctance of neighborhoods and property owners may be harder to overcome than physical constraints. Early consultation and education is important to obtain community support for daylighting.

Cost – The cost of daylighting urban streams can range from $100 to $300 per linear foot, depending on the diameter of the pipe and the desired daylighting outcome.

Further Resources

While stream daylighting has become a popular stream repair strategy, no standard design and construction details or references have yet been published, although several useful summaries of individual projects have been produced, as shown below.

Daylighting: New Life for Buried Streams
http://www.rmi.org/images/other/Water/W00-32_Daylighting.pdf

3 Rivers 2nd Nature Stream Restoration and Daylighting Program.
http://3r2n.cfa.cmu.edu/Year2/maps/aquatic/daylighting/

R-28

Stream Repair: Fish Passage Practices

CULVERT MODIFICATION

Description

Culverts are a common feature of the interrupted urban stream. This stream repair practice modifies existing culverts that are acting as barriers to upstream migration of resident and/or anadromous fish. Culvert modification is performed when culvert repair/replacement is impractical or prohibitively expensive (see Profile Sheet R-29). The basic objectives of culvert modification are to increase the depth of flow within the culvert, reduce current velocities, and reduce the vertical drop between the culvert and the downstream reach.

Three approaches are often combined together in the same culvert to promote fish passage:

Installation of **baffles** within the culvert. Baffles are structures that are placed perpendicularly or diagonally to the flow within the culvert to provide resting areas for fish, concentrate water and reduce current velocities. Baffles are generally made of metal and contain notches or openings that aid in fish passage (Figure 1).

Creation of a **low flow channel** within the existing culvert by concentrating baseflow within a confined portion of the bottom of a culvert to ensure an adequate depth or volume of water to allow fish passage. They are particularly useful in flat bottom culverts that disperse flows creating extremely shallow flow depths that can be a fish barrier. Low flow channels are created either by excavating a channel through the culvert or by narrowing a section of the channel (essentially creating a channel within a channel).

Use of **downstream grade controls** to raise the elevation of the streambed so that backwater from the last grade control reaches above the culvert invert at low flow. Grade controls, such as rock vortex weirs, rock cross vanes, step pools and V-log drops (Profile Sheets R-18 through R-21) create backwater that alleviates the vertical drop and reduces current velocities below the culvert.

Culvert modifications are generally designed to pass certain target fish species under prescribed flow conditions, and may not pass all species found within the urban stream fish community.

http://fisheries.fws.gov/FWSMA/fishpassage/FPPrgs/R3/R3 GrandPortage.htm

Figure 1: Baffle Step Pool Structure

It is important to understand how culverts shape the dynamics of urban streams to determine how to modify a particular culvert. To begin, most culverts are under-sized in urban subwatersheds. They were originally designed with enough cross-sectional area to pass the flows from the design flood (usually based on the 10-, 25- or 100-year design storm). Over time, however, additional subwatershed development produces much higher floods for the same design storm. As a result, some culverts act as a hydraulic control during floods, backing water upstream and depositing sediments, which further reduce the capacity of the culvert.

At the same time, culverts often act as a downstream grade control, stopping the migration of knickpoints advancing upstream. While this is helpful in arresting bank erosion locally, it also produces a plunge pool or vertical drop downstream of the culvert that can become a significant fish barrier.

Feasibility

Culvert modification can be an effective method to create fish passage, although the benefit may not always be permanent, due to the potential for clogging and sediment deposition observed in urban streams (WDFW, 2003). Table 1 summarizes the factors that may influence the choice of which combination of culvert modification techniques to use. The use of grade control structures has the potential to improve fish passage with fewer chances for clogging, and it may be possible to design grade control structures to pass a broader array of fish species (Figure 2).

Culvert modification in urban subwatersheds presumes that upstream conditions are adequate to support the habitat and water quality needs of the target fish species, which may not always exist in non-supporting and urban drainage streams (see Chapter 1).

Therefore, fishery biologists should always analyze upstream conditions before commencing design. In addition, interrupted urban streams often have multiple fish barriers, so it is useful to comprehensively assess the entire stream network below proposed culvert modification site to determine whether fish are being stopped by a prior barrier. A subwatershed approach to fish passage prioritizes the most important barriers to modify first, with priority going to culverts that will open up the greatest length of quality fishery or spawning habitat. The city of Portland has developed a useful method to prioritize fish barrier projects in urban subwatersheds, which can be found in the *Further Resources* section.

Regional Considerations - The swimming speed and jumping ability of target fish species are an important regional design consideration. For example, salmonids have different physiological abilities than herring, shad or rockfish, and culvert design should reflect those differences. The flow regime during the spawning season can also differ regionally.

Table 1: Culvert Modification Techniques

Technique	Maintenance (Low to High)	Hydrologic Study required	Channel Gradient	Cost
Baffles	High	Yes	Moderate up to 3.5%	Medium
Low flow channel	Medium	Yes	Moderate up to 3.5%	High
Grade control structures	Medium	Yes, helpful	Low to Moderate	Medium

Implementation

Figure 2: Use of a series of grade control structures downstream of a culvert

Culvert modification can sometimes achieve the same goals as culvert replacement and at a lower cost. A number of factors should be considered when making the decision (Table 2). The foremost concern when modifying culverts is the potential loss of hydraulic capacity within the culvert, which is often already limited within urban culverts. Further reductions in its cross-sectional area to promote fish access could potentially affect the hydraulic integrity of the culvert.

The first step in culvert modification design is to model the peak flows being delivered to the culvert over a range of design storm events, which requires an accurate understanding of current land use in the upstream subwatershed.

Next, hydraulic models are used to assess the condition of the existing culvert to pass these flows safely. It is also extremely important to verify the cross-sectional area of the culvert and the entrance and exit channels in the field, as these dimensions often change considerably over time because of localized erosion and sediment deposition.

If the hydraulic modeling indicates the existing culvert is unable to pass the required peak discharges, the culvert should be considered a strong candidate for replacement or repair (see Profile Sheet R-29). If, on the other hand, the culvert is determined to have adequate capacity, a second set of hydraulic model runs is performed to confirm whether reductions in cross-sectional area due to proposed modifications will maintain adequate capacity through the culvert. Hegberg *et al.* (2001) describes several design equations and modeling tools for analyzing fish passage at culverts. Other design references are provided in the *Further Resources* section.

Table 2: Design Considerations for Culvert Modification

Technique	Design Considerations
Baffles	• Goal is to pass a certain target species of fish • Requires considerable hydrology and hydraulics modeling • Need to be concerned about the baffles effect on culvert capacity
Low Flow Channel	• Goal is to pass a certain species of fish though a good low flow channel may also pass other species • Can be used in tandem with baffles • Requires hydrology and hydraulics modeling
Grade Control Structures	• Goal is to raise the elevation of the stream downstream of the culvert to backwater the culvert • Grade control structures are the preferred method to retrofit a culvert • Does not significantly affect culvert capacity

Construction – Key construction factors include scheduling construction for non-critical times of the year to avoid harm to the fishery. All excavation for low-flow channels and downstream grade controls should follow strict guidelines for sediment control, including diversions, bypasses, dewatering and sand bags (MWMA, 2000). Silt-laden water should always be filtered or infiltrated before it is returned to the stream. Pumps or flow-through devices can also be used to maintain downstream baseflow during construction operations.

Maintenance – Annual maintenance should always be conducted in advance of fish migration periods to ensure successful fish passage. Modified culverts should be inspected for clogging, and any sediment deposition and woody debris removed.

Cost – The cost of culvert modification is very site-specific and depends on the size, length and vertical drop of the culvert. Comparative costs of the three modification techniques are provided in Table 1. In addition, culvert modification is often associated with significant ongoing maintenance and monitoring costs.

Further Resources

City of Portland Fish Barrier Prioritization Method
http://www.trans.ci.portland.or.us/

Washington Design of Road Culverts for Fish Passage
http://www.wa.gov/wdfw/hab/engineer/cm/

U.S. Fish and Wildlife Service fish passage website
http://fisheries.fws.gov/FWSMA/fishpassage/

Massachusetts River and Stream Crossing Standards Technical Guidelines
http://www.umass.edu/umext/nrec/pdf_files/guidelines_river_stream_crossings.pdf

British Columbia Fish-Stream Crossing Guidebook
http://www.for.gov.bc.ca.tasb/legsregs/fpc/FPCGUIDE/GuideTOC.htm

California Salmonid Stream Habitat Restoration Manual
http://www.dfg.ca.gov/nafwb/manual.html
Oregon Aquatic Habitat Restoration and Enhancement Guide
http://www.oweb.state.or.us/publications/habguide99.shtml

R-29

Stream Repair: Fish Passage Practices

CULVERT REPLACEMENT OR REMOVAL

Description

This stream repair practice replaces or removes culverts that are migration barriers for resident and/or anadromous fish. Many urban culverts are under-sized, and lack the capacity to pass flows from the design flood for which they were originally designed. Undersized culverts act as a hydraulic control during floods, backing water upstream and depositing sediments, which can further reduce the capacity of the culvert. Consequently, many urban culverts are good candidates for replacement in order to protect roads and other infrastructure from damage. During the replacement process, culvert design is changed to promote better fish passage.

The basic approach is replace under-sized culverts with new ones that have a much greater cross-sectional area, and are placed at or below the current invert of the streambed. At the same time, a series of grade controls are installed downstream to raise the elevation of the streambed so that backwater from the last grade control reaches above the culvert invert at low flow (See Profile sheets R-18 to R-21).

Five basic design options are available to replace or remove culverts:

1. *Zero Slope Culverts* - This design conveys water through the culvert without a change in slope, which slows current velocities so that fish can pass.

2. *Bridge Replacement Design* – This design spans the stream and provides enough cross-sectional area to pass floods and allow for a natural stream bottom under the bridge (Figure 1).

3. *Embedded Culverts*: In this design, the replacement culvert is over-sized and installed about six inches to a foot below the current invert of the streambed at the crossing point. This allows an adequate depth of water through the culvert, as well as the placement of a few inches of natural stream substrate on the bottom of the pipe (Figure 2).

4. *Bottomless Culverts*: This culvert design utilizes a concrete or CMP arch over the stream to allow it to pass under as naturally as possible. Like the embedded design, the cross-sectional area of the bottomless culvert is over-sized. Since the natural grade is maintained, sediment can be transported and fish passage maintained.

Figure 1: Bridge (right) used for culvert replacement on the Manistee River, MI

5. Permanent Removal - This design simply removes the culvert, and is a practical option if the culvert is no longer needed, such as when the existing crossing has been superceded by a new crossing (Figure 3).

In general, the preferred culvert replacement method is to create a system as similar to the native stream as possible. Fish have evolved in their native surroundings, and systems that attempt to mimic those conditions tend to work better for fish. Excellent guidance on preferred methods for design and assessment for culvert replacement can be found in the *Further Resources* section.

Source: US Fish and Wildlife Service

Figure 2: Channel simulation – embedded culvert Orchid Lake, Alaska

http://fisheries.fws.gov/FWSMA/fishpassage/FPPrgs/R7/R7DuckCreek.htm

Figure 3: Culvert removal in Duck Creek, Alaska

Feasibility

Culvert replacement is the preferred long-term technique to promote fish passage because culvert modifications and fish passage devices only provide temporary benefits, do not pass all fish species and requires frequent maintenance. Culvert replacement is a particularly attractive option in many urban subwatersheds because much of the aging and under-sized culverts will need to be replaced to prevent flood damage and protect other infrastructure. As aging culverts are replaced, serious consideration should be given to fish passage design, if fish still could potentially use the stream reach. Table 1 summarizes the key factors that may influence the selection of culvert replacement design.

Culvert replacement may not always be feasible or appropriate at all road crossings. Culvert modification (Profile Sheet R-28) may achieve the same goals as replacement and at less cost. Modifications should always be investigated, especially when replacement is problematic (e.g., road closure on a major highway with few alternative routes). In other instances, the goal of fish passage in general may not be appropriate. For example, the ability of the target fish species to successfully utilize habitat and reproduce in the upstream section should be investigated, particularly if it is located in a non-supporting or urban drainage subwatershed. Another important consideration is the amount of spawning habitat that would open up as a result of a particular culvert replacement. A subwatershed approach toward fish passage is needed to identify the most critical barriers. Replacing two culverts in order to open up five miles of quality habitat makes more sense than replacing 12 culverts to open up one mile of quality habitat. A useful subwatershed prioritization scheme for culvert replacement used in Portland, OR can be found in the *Further Resources* Section.

Several design considerations should be considered when choosing a culvert replacement technique, as shown in Table 2.

Construction - Once a culvert replacement design is selected, it should be analyzed for its engineering and hydraulic properties (e.g., load-bearing strength, expected depth of scour, armoring, and flood capacity), and on optimal sequence of construction developed. Stringent erosion and sediment control practices should be used during construction operations (e.g., silt fences, sandbags, dewatering and pumping—See Profile Sheet 28) and construction should only be scheduled during non-critical times of the year for fish.

Maintenance/ Monitoring- Fish monitoring should be conducted in the subwatershed to determine where existing fish barriers are located, and whether a barrier actually exists at the culvert replacement site. The new culvert should be inspected at the onset of spawning season to ensure that it is free of sediment deposition, debris jams or organic matter. Lastly, post-replacement fish monitoring is advised to determine whether the replacement worked as designed.

Table 1: Culvert Fish Barrier Replacement Techniques

Technique	Maintenance (Low to High)	Hydrologic Study Required?	Channel Gradient	Pass all Species?	Cost
Zero slope design	Medium	No	Low to moderate (less than 3%)	Yes	Med-High
Bridge	Low	Yes	Low to High	Yes	Highest
Embedded culvert	Medium/High Smaller are more prone to maintenance	Yes	Moderate to High (up to 6%) Moderate to High channel length	Yes	High
Bottomless culvert	Low	Yes	Low to Moderate/High	Yes	High
Permanent removal	Low	No	Any	Yes	Med

Table 2: Design Considerations for Replacement Techniques

Technique	Design Considerations
Zero Slope Culvert	• Goal is to have zero slope in the culvert (culvert is essentially a pool) • It generally results in a slight over design • The diameter of the culvert >1.25 times the channel bed width • The outlet should be countersunk
Bridge	• Goal is to achieve a natural stream configuration with some accommodation for a floodplain • Ideally the span should be wide enough to construct without a wing wall on the upstream side
Embedded Culvert	• Goal is to achieve a semi- natural stream within a culvert • Use of natural channel substrate in the culvert
Bottomless Culvert	• Goal is to achieve a natural stream with native stream bed materials • Footers and geology are important (care should be taken if considering such a design on unconsolidated materials)
Permanent Removal	• There may be a gap in elevation created when a culvert is removed. Step pools may be needed to provide passage through the elevation change

Further Resources

Several excellent resources can be easily accessed to help assess and design culvert replacements projects in urban subwatersheds, including the following:

City of Portland Salmon Reach Screening Guidance
http://www.trans.ci.portland.or.us/

Oregon Department of Fish and Wildlife: Guidelines and Criteria for Stream – Road Crossings
http://www.dfw.state.or.us/ODFWhtml/InfoCntrFish/Management/stream_road.htm

Assessment Procedures for Identifying Barriers to Aquatic Organism Passage at Road-Stream Crossings
http://www.stream.fs.fed.us/publications/PDFs/NIAP.pdf

Washington Design of Road Culverts for Fish Passage
http://www.wa.gov/wdfw/hab/engineer/cm/

U.S. Fish and Wildlife Service fish passage website:
http://fisheries.fws.gov/FWSMA/fishpassage/

Massachusetts River and Stream Crossing Standards- Technical Guidelines.
http://www.umass.edu/umext/nrec/pdf_files/guidelines_river_stream_crossings.pdf

British Columbia Fish-Stream Crossing Guide
http://www.for.gov.bc.ca/tasb/legsregs/fpc/FPCGUIDE/Guidetoc.htm

R-30

Stream Repair: Fish Passage Practices

DEVICES TO PASS FISH

Description

These stream repair practices are used to pass fish over an urban stream barrier that cannot be removed, such as a dam or sewer crossing. This discussion is restricted to devices that can be used on small dams and obstructions located on smaller order streams. In general, these devices are not designed to pass fish of all species and ages, and can be expensive to design, construct and maintain.

Three primary devices to pass fish include:

Vertical slot fishway is a structure that consists of a linear metal ramp that has a series of baffles with vertical slots to enable fish passage (Figure 1). The fishway is installed at a slope between 10 and 20% and has the ability to accommodate and to remain operational over a wide range of flow events.

Figure 1: Vertical slot fishway
Source:
http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/004/y2785e/y2785e03.htm

Denil fish passage (a.k.a. Alaskan Steep pass) is a similar structure that contains baffles installed at 45 degree angles and acts to slow currents facing fish. The structure is made of aluminum and can be installed at relatively steep slopes (20-33%). The denil structure is relatively light and portable, if needed (Figure 2).

Figure 2: Alaskan Steep pass fish passage structure
Source: MD DNR, 2003

Pool and weir system is a manufactured fish passage structure that consists of vertical slots that act as weirs and slow velocities to enable fish to swim or leap over the weir structure. The shape of the weir can be notched or rounded. The slope of the pool and weir system depends on the swimming and leaping abilities of the target fish species (Figure 3).

Figure 3: Pool and weir system on the Dordogne River (France)
Source:
http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/004/y2785e/y2785e03.htm

Feasibility

Each fish passage device can be an effective way to promote fish passage over in-stream crossings and small dams, although removal is preferred as a permanent solution. Fish passage devices have the potential to clog and may be limited by the wide range of flows experienced in urban streams. Frequent maintenance is often needed to ensure success of these devices (WDFW, 2003). One of the primary factors in determining which device to use is the operational flow range needed to pass fish. If the structure needs to pass fish under a wide range of flow conditions, vertical slot fishways are preferred (Clay, 1995). If the stream's flow regime is less variable, the other two devices may be suitable. Table 1 summarizes the key factors that may influence the choice of fish passage device to overcome a small fish barrier.

Fishery biologists should be consulted on the swimming speed and jumping ability of the local target fish species that the device is intended to pass. Fish passage devices are generally designed to pass certain target fish species under prescribed flow conditions. As such, they may not pass all native fish species found within the urban stream fish community.

The use of fishways in urban streams presumes that upstream habitat and water quality conditions can support the target fish species. Suitable habitat conditions may not always exist in non-supporting and urban drainage streams, given their altered hydrology, degraded habitat and poor water quality. Therefore, fishery biologists should always analyze upstream conditions before commencing design. In addition, interrupted urban streams often have multiple dams and crossings, so it is very important to comprehensively assess the stream network below proposed fishways to determine if migrating or resident fish are being stopped by a prior series of obstructions.

Thus, it is important to take a watershed approach to fish passage design and prioritize which barriers are the most important to modify first. In general, the objective in urban subwatersheds is to select the project or series of projects that opens up the greatest length of quality fisheries or spawning habitats.

Implementation

Several design factors need to be considered when designing fishways on urban streams. First, fishway design and installation should be conducted by a team of fishery biologists, hydraulic engineers and experienced contractors. Second, urban streams often experience reduced baseflow during dry weather, yet experience much higher flows during larger storms. Consequently, designers need to accurately estimate the range of expected discharges and current velocities that the fish passage device will likely encounter during critical fish passage periods. Hydrologic modeling is needed to characterize these conditions and help choose the most appropriate fish passage device. Third, designers will normally need to provide additional anchoring and/or armoring to protect the fish passage device in most urban streams.

Table 1: Comparison of Fish Passage Devices

Technique	Maintenance (Low – High)	Hydrologic Study required	Slope of the Practice	Operational flow range
Vertical Slot Fishway	High	Yes	10-20%	Wide range (Over 6 feet)
Denil Fish Passage Structure	High	Yes	20-33%	Relatively constant (Up to 5-6 feet)
Pool and Weir System	High	Yes	~ 20%	Relatively constant

Adapted from Clay (1995)

The design team should also clearly understand the target fish speeds and the minimum swimming, jumping and bursting speeds that the fishway must achieve. Excellent data has been developed for many important species, which can be found on the U.S. Fish and Wildlife fish passage website provided in the *Further Resources* section. Lastly, designers should carefully analyze both the entrance and exit of the fishway in the context of the urban stream. For example, it is important to create “attraction water” at the entrance to the fishway so that the target fish know where to start (deeper pool with white water). Designers should also consider how they will protect the exit of the fishway from clogging and sediment deposition.

Maintenance and Monitoring -The entire stream network in the subwatershed should initially be assessed to determine where existing fish barriers are located. Fish monitoring should also be performed to determine if the device is actually working and if juvenile fish can pass through or over the structure in sufficient numbers. For example, if the device allows adult fish to pass upstream but does not permit juvenile fish to migrate back downstream, the ultimate goal of successful fish passage will not be realized. The device should be inspected for clogging, sediment deposition and woody debris during every fish migration period. Any material within the device should be promptly removed.

Further Resources

More information on the assessment and design of fishways can be accessed from the following online sources:

Washington Design of Road Culverts for Fish Passage.
http://www.wa.gov/wdfw/hab/engineer/cm/

U.S. Fish and Wildlife Service fish passage website:
http://fisheries.fws.gov/FWSMA/fishpassage/

U.S. Forest Service methods to analyze fish barriers:
http://www.stream.fs.fed.us/publications/PDFs/NIAP.pdf

CR-31

Comprehensive Stream Repair Applications

COMBINATIONS OF SIMPLE PRACTICES

Description

Combinations of individual stream repair practices are frequently required to achieve specific restoration objectives without making major changes to the planform of the urban stream channel. The comprehensive approach is distinctly more limited in scope than either channel re-design (CR-32) or de-channelization (CR-33), since it does not involve the complete re-construction of the stream channel. The designer works with existing stream channel morphology, making relatively minor changes to its grade, cross-section and planform to achieve the intended design objective. Generally, this approach works best in older urban stream channels that have achieved some measure of channel stability in terms of grade and planform, but still have specific habitat or fishery impairments. Combinations of simple practices should be used with caution on actively adjusting streams that have not yet evolved into a more stable morphology.

Several examples of this approach have been utilized across the country (Galli, 1999; Goldsmith *et al*., 1998; and Gustav, 1994), and a typical layout is presented in Figure 1. Table 1 presents guidance on how individual stream repair practices can be combined together to achieve specific restoration objectives. It should be kept in mind that no two urban stream situations are exactly alike, and each project should be deigned based upon local stream assessment studies and analysis of subwatershed conditions. The combination approach should always be integrated with other subwatershed and stream corridor practices such as storm water retrofits, riparian management, discharge prevention and pollution source controls, as shown in Table 2.

Implementation

When stream repair practices are combined, each individual practice should be evaluated in relationship to other upstream or downstream practices so they effectively work together as a system. Locating practices haphazardly or too densely may cause individual practices to interfere with each other, and jeopardize the project as a whole.

Most combination projects require extensive stream and subwatershed data to support the design process (see Chapter 2). It is generally recommended that an interdisciplinary team of geomorphologists, engineers, hydrologists, biologists and surveyors design the project. The following information is generally required to support design:

- Determination of current channel adjustment process
- Hydraulic modeling of shear stress on bed and banks
- Expected depth of scour for the bed and banks
- Accurate mapping of all infrastructure and utilities within and adjacent to the stream channel
- A detailed topographic survey of the stream including longitudinal and cross-sectional profiles of the project reach, and adjacent upstream and downstream reaches
- Streambed material sizes and distribution
- Geotechnical data for streambank soils and a plant inventory
- Rock sizing calculations so that structures remain immobile during design flows
- Fish, habitat and/or passage surveys, if biological restoration objectives are pursued

Designers should always anticipate future increases in channel cross-sectional area and decreases in channel elevation, if significant development has recently occurred or is projected to occur in the upstream subwatershed. Failure to account for future increases in storm flows and sediment loads may lead to the failure of individual stream repair practices, and possibly the entire project (Brown, 2000).

A large number of potential combinations of stream repair practices exist, but the final selections should be assessed in terms of their primary intended function. For example, the need for grade control should be established before selecting a specific grade control practice. Once the design need for a practice type is established, the most appropriate stream repair practice(s) can be selected using the comparative matrices presented in Chapter 3.

Adjacent practices should then be analyzed for possible negative interactions. For example, hard bank stabilization practices may increase downstream flow velocities during storm events, which may warrant further grade control practices, even if they were not originally deemed necessary. Flow deflection practices

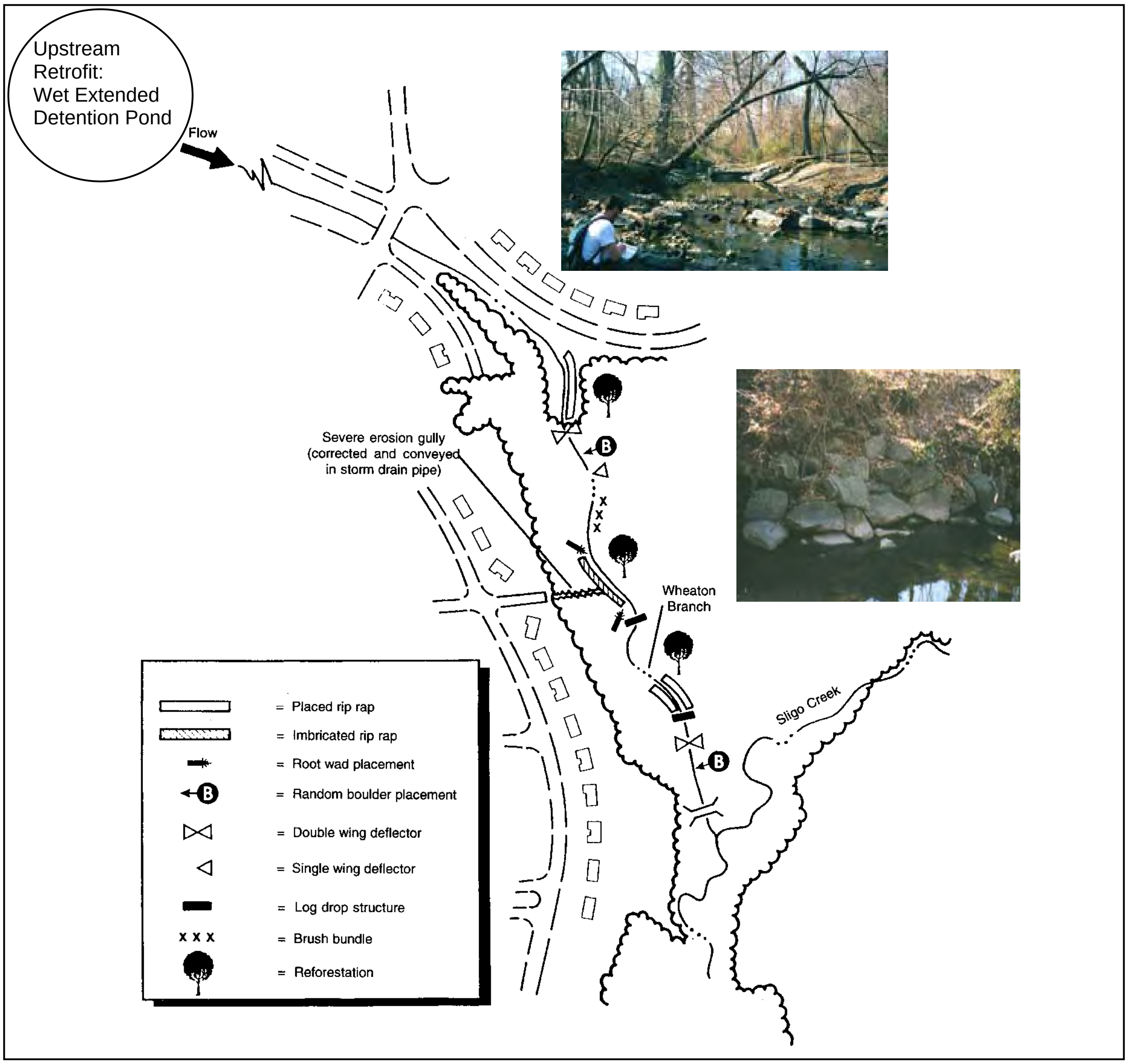


Figure 1: Example of Combination of Stream Repair Practices: Wheaton Branch, MD

may increase erosion on the opposite bank, making bank stabilization necessary. Each practice also has a zone of influence on the channel both up and downstream. Placing practices too close together may impair overall project function (Brown, 2000).

Table 1: Combinations of Individual Stream Repair Practices to Meet Design Objectives

Repair Practice	Naturalize stream corridor	Protect infra-structure	Prevent bank erosion	Expand stream network	Improve fish passage	Improve fishery habitat	Natural channel design	Recover biological diversity
Hard Bank Stabilization Practices								
Boulder revetments	⦿	●	●	○	×	×	○	×
Rootwad revetments	○	●	●	○	×	⦿	⦿	⦿
Imbricated rip-rap	⦿	●	●	○	×	⦿	○	○
A-jacks	⦿	⦿	●	○	×	×	○	○
Live cribwalls	○	⦿	●	○	×	×	○	○
Soft Bank Stabilization Practices								
Streambank shaping	⦿	⦿	●	○	×	○	●	⦿
Coir fiber logs	○	○	●	○	×	○	●	⦿
Erosion control fabrics	○	●	●	○	×	×	●	⦿
Soil lifts	⦿	●	●	○	×	○	●	⦿
Live stakes	⦿	⦿	●	○	×	○	●	⦿
Live fascines	○	⦿	●	○	×	○	⦿	⦿
Brush mattresses	○	⦿	●	○	×	○	⦿	⦿
Vegetation establishment	●	●	●	○	×	⦿	●	●
Flow Deflection Practices								
Wing deflectors	⦿	×	×	×	○	●	⦿	●
Rock or Log Vanes	⦿	⦿	⦿	×	×	●	⦿	⦿
Grade Control Practices								
Rock vortex weirs	⦿	⦿	⦿	○	○	●	●	⦿
Rock cross vanes	⦿	⦿	⦿	○	○	⦿	⦿	⦿
Step pools	⦿	⦿	⦿	⦿	⦿	○	⦿	⦿
V-log drops	⦿	⦿	⦿	○	○	⦿	⦿	⦿
In-stream Habitat Practices								
Lunkers	○	×	×	×	○	●	○	⦿
LWD placement	○	○	⦿	×	○	●	⦿	●
Boulder clusters	○	×	×	×	○	●	○	⦿
Baseflow enhancement	○	×	×	⦿	⦿	●	⦿	⦿
Flow Diversion Practices								
Parallel pipes	×	×	⦿	×	×	○	×	○
Stream daylighting	⦿	×	×	●	⦿	⦿	⦿	⦿
Fish Passage Practices								
Culvert modification	○	×	×	●	●	⦿	○	⦿
Culvert replacement	○	●	×	●	●	⦿	○	⦿
Devices to pass fish	○	×	×	●	●	⦿	○	⦿
Comprehensive Repair Applications								
Combinations	●	●	●	●	●	●	●	●
Channel Redesign	⦿	○	●	⦿	⦿	⦿	●	●
De-Channelization	⦿	○	⦿	●	●	●	●	●

Key ● *primary practice to meet design objective*
⦿ *supplemental practice to achieve design objective*
○ *occasionally used to meet design objective*
× *rarely used to meet design objective*

Table 2: Other Subwatershed Practices that Support Specific Stream Repair Objectives

Stream Repair Practice	Naturalize stream corridor	Protect infra-structure	Prevent bank erosion	Expand stream network	Increase fish passage	Improve fishery habitat	Achieve natural channel design	Recover diversity and function
Storm Water Retrofits	○	⦿	●	⦿	○	●	●	●
Riparian Reforestation	●	○	●	●	⦿	●	●	●
Discharge Prevention	●	●	○	⦿	⦿	●	⦿	●
Pollution Source Controls	⦿	○	⦿	⦿	⦿	⦿	⦿	●
Watershed Forestry	⦿	○	●	⦿	⦿	●	●	●

Key: ● *essential to meet objective*
⦿ *useful in meeting objective*
○ *rarely used to meet objective*

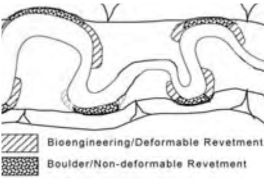
Further Resources

To date, there has been no published material to guide designers on how to effectively combine stream repair practices to meet the desired subwatershed objectives. Often, the selection, location, and interaction of stream repair practices are a matter of profession judgment and prior experience.

CR-32

Comprehensive Stream Repair Applications

CHANNEL RE-DESIGN



Description

Channel re-design is a comprehensive stream repair application that alters the dimensions, pattern and profile of an unstable channel in order to create a new channel that will not aggrade or degrade, given its projected hydrologic regime and sediment load. The geometry and dimensions of the new channel are designed based on a reference stream reach, regional hydraulic geometry curves, hydraulic modeling, or a combination of all three methods. Channel re-design is warranted when an urban stream channel has been altered to the point that a stable channel condition cannot be achieved through the application of individual stream repair practices, and the natural evolution of stable channel dimensions is not likely to occur for an extended period of time.

Stream channels are dynamic systems that constantly adjust to maintain equilibrium with their flow regime and sediment load. Stream channels adjust by changing their physical dimensions of grade, planform or cross-sectional area. Stream equilibrium or stability is controlled by two dominant factors, sediment load (L) and hydrology (Q). A change in either factor will lead to the formation of new channel dimensions. Urban subwatersheds face major changes in hydrology and sediment loads that can create unstable streams.

Feasibility

Since channel re-design seeks to predict new stable channel dimensions, it requires a thorough understanding of urban fluvial geomorphology, as well as current and future subwatershed conditions. These conditions include past alterations to the stream network, storm water runoff, flood conveyance, existing infrastructure, and land use. Undertaking a channel redesign project without fully understanding future channel evolution or upstream subwatershed conditions can lead to greater channel instability and project failure.

Implementation

Skidmore *et al.* (2002) categorize three basic approaches to natural channel design - analog, derived and computed. Each of the three approaches has advantages and limitations in the context of urban streams, as described below.

The analog approach utilizes a reference reach as the primary basis for channel design. In general, the reference reach should have the same drainage area, land use, landform, and soil as the project reach, and the designer seeks to replicate the same channel geometry within the project reach (Rosgen, 1998, Harrelson *et al.*, 1994). While the analog approach works well in subwatersheds, which are lightly developed (e.g. less than 10% IC), it has questionable value in more urban subwatersheds. The basic problem is that an urban reference stream will generally be in just as a bad a shape as the project reach (i.e., stable channel dimensions may not be supported by subwatershed conditions). As Brown (2000) notes, urban reference streams should be based on the ultimate enlarged channel dimensions that are stable for the maximum level of future impervious cover in the subwatershed. In practical terms, this means that urban channels that have had several decades to fully adjust and recover from subwatershed buildout should be considered the true reference condition for urban streams.

The derived approach takes an empirical approach to channel design, and is based on sampling many reference reaches within the same physiographic region to derive regional curves or ranges for channel geometry.

Designers then use the curves to define width/depth ratios, planform, bankfull height and other channel dimensions, given their local estimate of the bankfull discharge for the project reach. Several excellent regional hydraulic geometry curves have recently been published (McCandless and Everett, 2002; VWQD, 2000; Harman *et al*., 2000), but not all regions of the country have them. The drawback of the derived approach is that reference reaches sampled are rarely urban, and thus may not behave in the same hydrologic manner. In addition, Miller and Skidmore (2000) note that it is difficult to accurately estimate bankfull discharge in urban streams that are actively adjusting. These limitations suggest that designers should be careful when extrapolating channel geometry from regional curves when subwatershed IC has changed or is predicted to change in the future.

The computed approach to channel redesign uses hydrology, hydraulic and sediment transport models based on fluvial and hydraulic principles to derive stable channel dimensions and characteristics for existing and future conditions within the project reach. This modeling approach is generally recommended for most urban streams, although it should be checked with the channel geometry estimates obtained from the analog or derived approach. The modeling approach is particularly useful if channel redesign is occurring at the same time as upstream retrofits are being designed, since it can explicitly incorporate any effects of changed hydrology on future channel dimensions. The modeling approach is also recommended when considerable subwatershed development has occurred or expected to occur, since models can predict future increases in bankfull discharge and bank/bed shear stress. The weakness of the computed approach is that current models generally cannot reliably predict current or future planform for the project channel. This level of design information is best obtained from the analog or derived approach.

The specific combination of permits needed for stream repair projects varies from state to state, and designers should check with both the state environmental quality and natural resource agency to determine the submittal requirements and review process.

The permitting process for stream repair projects can be long and complex, and several weeks of time should be allocated in the design budget to prepare permit submittals and handle interagency coordination.

Excellent guidance on the various approaches to urban channel design are highlighted in the *Further Resources* section at the end of this profile sheet, but a few general observations on the design and construction process are provided below.

Channel redesign requires extensive stream and subwatershed data collection before the design process can actually begin, and is best conducted by an interdisciplinary team composed of geomorphologists, engineers, hydrologists, biologists and surveyors. The following information is generally required for urban streams:

- Current and future subwatershed land use
- Hydrologic modeling of current and future storm flows
- Accurate mapping of the storm drain network and outfalls in the project area
- Accurate mapping of all infrastructure and utilities within and adjacent to the stream channel
- A detailed topographic survey of the stream corridor including the longitudinal profile of the stream, stream planform, and cross-sections. Survey data should include upstream and downstream reaches
- An assessment of streambed material sizes and distribution
- Profiles of streambank materials at the cross-sections
- An assessment of current channel adjustment processes (e.g., degradation, aggradation, lateral migration, etc.)
- An assessment of biological condition

From this information, a reasonable picture should be developed of the stream channel and corridor, the surrounding land use, and watershed conditions. Urban subwatersheds can present many problems for natural channel design and early recognition of these problems can prevent costly mistakes later.

The four primary design elements of channel redesign are planform, grade, cross section, and flow. *Planform* is the shape of the channel looking down on it from above, *grade* is the steepness or slope of the channel, and the *cross-section* is the area within the channel between opposite streambanks. Flow is the discharge conveyed through the channel for design storms of various recurrence intervals (e.g., one, two, ten and 100 years).

The power of flowing water provides the energy to transport sediments and determines the overall planform, grade and cross section of the channel. Accurate prediction of storm flows is critical to proper design of the other three elements. Channel adjustments occur when the flow is not in balance with the sediment load. This imbalance can result in either too little energy to transport sediment (aggradation) or excess energy to transport sediment (degradation). The grade, planform and cross section of a properly designed channel will convey storm flows and sediment loads and not result in degradation or aggradation within the project reach.

In urban streams, it is extremely important to project how current and future subwatershed conditions will influence flow or sediment loads delivered to the project reach. In addition, the effect of changes in flow and sediment transport from the channel redesign reach on downstream reaches should also be analyzed during the design process.

Channel redesign projects should be analyzed for sediment transport continuity of the bed material load. This is normally done for the channel-forming discharge during preliminary design. During final design, the average annual bed material load should be computed and compared to the inflowing sediment load to determine long-term channel stability. Anticipated changes in future discharge and/or sediment loads should also be explicitly modeled. In addition, the bed material load should be modeled under a defined flood event to predict how it will perform (e.g., the 10- or 25-year recurrence interval flood). Guidance for performing sediment transport analyses can be found in Copeland *et al*. (2001). The Sediment Impact Assessment Model (SIAM), currently under development by the Corps of Engineers, will enable HEC-RAS users to directly perform these analyses, and predict sediment transport impacts through the entire channel network.

The design process is iterative. While designers can alter the planform, grade, and cross section of the newly designed channel, they often have little or no control over the flow or incoming sediment load, unless upstream retrofits are planned. Consequently, flow and sediment loads normally dictate the initial design of the new channel, along with composition of the channel bed and bank materials and the geomorphic setting. The initial channel design is then analyzed for stability against a range of flow conditions. Additional analysis for scour and shear stress along the newly designed channel are made to determine streambed and bank stability. These analyses generally lead to alterations in the design until a stable channel evolves. The designer must then specify the types of streambank practices required to meet streambed and bank stability requirements and maintain planform and grade dimensions. These include streambank toe, mid, and upper bank treatments; the number and elevations of grade control practices; and the type and density of streambank vegetation. On top of this, designers must also account for existing infrastructure, flood conveyance, and connections to the upstream and downstream reaches.

Construction - Once a design is adopted, it must be assessed for constructability and a sequence of construction written. KST (2000) presents a useful and practical review of the construction, permitting and contracting issues associated with natural channel design. The urban stream corridor often creates numerous obstacles for natural channel design since it entails wholesale reconstruction of a channel within the context of extensive infrastructure. For example, timing of channel redesign should be coordinated with any planned replacements or upgrades to sewers, road culverts and bridges within the project reach. In some cases, it may be necessary to relocate utilities that are in conflict with the newly designed stream channel. Construction of the new channel will need to consider the separate design and approval processes for these projects, and alter construction timetables accordingly.

Construction of the new channel requires direct access roads that have sufficient load bearing capacity to support heavy earth moving equipment. Alternatively, specialized equipment can be specified to minimize access clearing, which can greatly increase construction costs. Depending on the scope of the redesign project, large areas may be needed to stockpile construction materials and equipment. In addition, most urban channel redesign project generate large volumes of fill material that must be transported off-site. The cost of disposing excess fill material is often a major element of the overall project budget.

The method of channel construction will dictate certain construction considerations. If the new channel can be constructed adjacent to the current channel, leaving the existing channel to convey flows, dewatering and erosion/sediment control issues can be easily addressed. If the new designed channel needs to be constructed within the existing channel, dewatering methods and erosion controls can be significant project expenditures.

Dewatering techniques and in-stream sediment controls are needed during the construction of the newly designed channel. Dewatering can be accomplished by pumping stream flow around the project area or by diverting water into a temporary conveyance channel or pipe. Cofferdams can also be used to isolate portions of larger urban channels while working. The dewatering techniques should have enough capacity to convey expected high storm flows during the construction process. The risks of inundation must be accounted for and may include construction delays, damage to equipment and downstream sediment movement. Sediment control practices should also be installed to stabilize all disturbed areas outside of the channel, and maintained throughout the construction process.

Costs - Project costs for channel redesign are very site -specific. In general, planning estimates for the cost of constructing of a newly designed channel can range from $100 to $300 per linear foot. Project design costs generally account for another 10 to 20% of the construction cost. The planning estimate does not include any additional costs for utility relocations, bridge/culvert replacement, fill removal, land acquisition, or permitting.

Monitoring/Maintenance - The complicated nature of channel redesign projects requires careful monitoring. The new stream channel should be surveyed immediately after completion to ensure that its dimensions adhere to the original design specifications. Vegetation and channel stability should be inspected after major storms during the first year, and vegetation and bank erosion problems should be immediately repaired. Long-term monitoring should be part of the overall channel redesign plan, with permanent cross-sections established to track channel dimensions over the long term and identify problems before they pose a threat to the stability of the channel (see Section 3.6).

Further Resources

North Carolina Stream Restoration: a natural channel design handbook
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

Washington State Integrated Streambank Protection Guidelines
http://www.wa.gov/wdfw/hab/ahg/ispgdoc.htm

Stream Corridor Restoration: Principles, Processes, and Practices
http://www.usda.gov/stream_restoration

Hydraulic Design of Stream Restoration Projects
http://libweb.wes.army.mil/uhtbin/hyperion/CHL-TR-01-28.pdf

Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/mgwc.pdf

Pennsylvania Natural Stream Channel Design Handbook
http://www.canaanvi.org/nscdguidelines/

CR-33

Comprehensive Stream Repair Applications

DE-CHANNELIZATION

Description

Stream channelization historically involved straightening and sometimes hardening stream channels to increase conveyance capacity, eliminate floodplains, and drain wetlands. The historic goal of stream channelization projects has been to contain all flows within the channel and move the water downstream as quickly as possible. Stream de-channelization is the practice of returning a stream channel to as natural a condition as possible, given current constraints, while creating a stable, non-erosive channel.

Channelization can range from simple straightening meanders and removing woody debris all the way up to replacing streams with concrete lined channels. Straightening of meanders and the removal of woody debris has been a common practice in agricultural areas, which effectively increases the slope of the stream and reduces channel roughness (Figure 1). In turn, this leads to greater stream velocities, more erosive power, channel enlargement, and habitat impairment.

Channelization of urban streams often involves replacement with hardened concrete channels, which prevents potential channel erosion and enlargement caused by the straightening, but which results in the complete loss of in-stream habitat (Figure 2). In addition, un-channelized downstream reaches can become severely degraded as the highly erosive storm flows delivered from the channelized reaches cause more channel erosion and enlargement on unprotected channels.

De-channelization practices can range from increasing the sinuosity of a straightened reach to removing a concrete channel and reconstructing a completely new “naturalized” channel. The extent of de-channelization that can be undertaken is primarily limited by stream corridor constraints such as adjacent land use, infrastructure, and flood conveyance needs, and are similar to those involved in daylighting a fully enclosed stream (see Profile Sheet R-27). Like daylighting, de-channelization can affect stream reaches both above and below the project site. Slower-moving flows in a de-channelized reach may increase flooding upstream, if

Figure 1: A Typical Channelized Agricultural Stream
Source U.S. EPA

Figure 2: A Typical Channelized Urban Stream

adequate flood conveyance capacity is not provided in the project reach. Changes in sediment transport through the de-channelized reach can also alter erosion and deposition patterns, for better or worse, in downstream reaches. Careful hydrologic, hydraulic, and sediment transport modeling of the dechannelized reach and upstream and downstream sections is needed.

Feasibility

Channelized streams are found in nearly all urban subwatersheds, but are particularly numerous in non-supporting and urban drainage subwatersheds. The location of channel modifications can be tracked in a subwatershed using the CM form of the Unified Stream Assessment (Manual 10), which is then used to develop a list of candidate sites for de-channelization projects.

De-channelization projects can be challenging in the urban subwatershed for several reasons. First, the cross-section of the new channel will almost always need to be greater than the channel that it replaces. This means that more of the stream corridor will be needed to make room for the new channel. Second, the slope of the new channel will generally be less than the channel it replaces, which means that the new channel will have a planform with more meanders. Again, more stream corridor area will be needed to allow the channel to migrate to its new planform. Space is always at a premium in the urban stream corridor, since prior encroachment, floodplain expansion and sewer construction all constrain its available width.

The third key challenge is to safely convey floodwaters through the new channels and downstream reaches. Most urban stream corridors are used for flood conveyance, so designers must satisfy both floodplain regulators and downstream property owners that there will be no increase in flood elevations or bank erosion as a result of the project.

The fourth challenge in urban de-channelization is the time factor. Many urban streams may take many decades to fully adjust to the changes in stream hydrology and sediment caused by past subwatershed development. If a de-channelization project is undertaken before upstream and downstream reaches have fully adjusted, additional channel enlargement should be anticipated, and grade controls must be employed upstream and downstream of the project to prevent further down cutting. All four challenges can be overcome if a wide stream corridor is present and careful geomorphic and hydrologic analyses are conducted.

Implementation

De-channelization involves the same process as channel re-design (see Profile Sheet CR-32). The design is somewhat more complex, however, given the physical alterations of the channel and stream corridor constraints. For example, the floodplain is likely to have been filled and graded and may no longer be at the appropriate elevation to store floodwater. Extensive excavation is often required to reestablish the current elevations for floodplain and the new stream channel (Figure 3).

The actual geometry used to create the dimensions of the new channel should follow the principles of natural channel design, to the extent practicable (see Profile Sheet S-32). Natural channel design seeks to create a channel with dimensions, patterns and a profile that will not aggrade or degrade, and can effectively move both sediment and water. Excellent guidance on natural channel design methods can be found in Doll *et al.* (2003) and Miller *et al.*(2001).

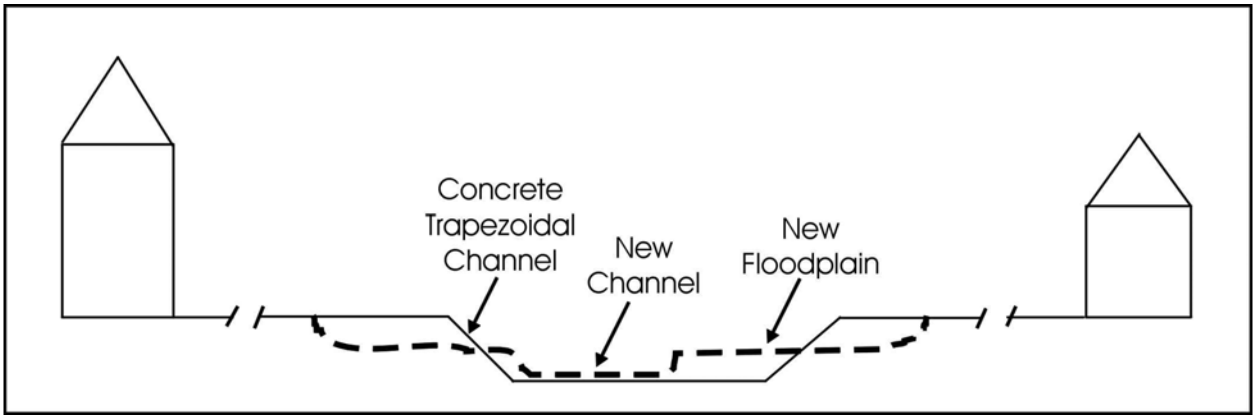


Figure 3: Excavation of Floodplain

Since de-channelization normally involves flattening of channel slope (thereby decreasing sediment transport capacity), there is some risk of aggradation if the new channel cannot carry the incoming sediment load. Therefore, de-channelization projects should be evaluated for sediment transport continuity of the bedload. This is normally done for the channel-forming discharge during preliminary design.

During final design, the average annual bed material load should be computed and compared to the inflowing sediment load to determine long-term channel stability. Anticipated changes in future discharge and/or sediment loads should also be explicitly modeled. In addition, the bed material load should be modeled under a defined flood event to predict how it will perform (e.g., the 10 or 25-year recurrence interval flood). Guidance for performing sediment transport analyses can be found in Copeland *et al.* 2001).

Many different stream repair practices can be used to form and stabilize the new channel including upstream and downstream grade controls (R-18 to 21), hard bank stabilization at meander toes (R-3 to R-7), bank shaping or soil lifts (R-8 and R-11), bank re-vegetation (R-15), baseflow channel creation (R-25). In addition, in-stream habitat enhancements (R-22 to R-24) and flow deflectors (R-16 and R-17) may also be used, depending on the project objectives.

Urban de-channelization projects involve many design challenges, including the:

Expected longitudinal, cross-sectional and planform geometry for a "natural" stream of the same size, bedload and gradient - This is initially estimated using the Rosgen stream classification system or regional curves.

Width of the available stream corridor - This is the maximum width from the bank of the channelized reach outward on both sides. Care should be taken to identify any underground utilities, such as sewer lines, which are typically constructed next to the channelized stream. In addition, the width of the stream corridor may be further restricted by other competing uses such as parks, recreation, tree protection, and drainage easements.

Gradient of the new and old channels - The slope of the existing channel is likely to be greater than the new channel. The new slope will determine the type of bank stabilization needed to protect the meanders (e.g., hard or soft) as well as the need for grade controls.

Connection to the floodplain - Most channelized streams no longer have a direct connection to the floodplain (i.e., most flood waters remain within the channel). Therefore, careful hydrologic analyses need to be conducted to determine how to reconnect the new channel to the floodplain. Often, this will entail excavating the floodplain to a new lower level (see Figure 3). If this needs to be done, soil borings are needed to confirm the nature of these soils (e.g., whether they need to be de-watered, are contaminated, or are suitable for hauling off-site).

Utility Relocation - The extensive network of utilities often found within stream corridors should be ground-truthed. In some cases, it may be necessary to relocate utilities that conflict with the newly designed stream channel. The timing of the project should be coordinated with any planned replacement or upgrades of sewers, road culverts or bridges within the project area.

Construction – The construction sequence for de-channelization projects can be fairly complex, as it involves wholesale reconstruction of a stream channel. An important consideration is how baseflow and storm flow will be conveyed during the construction phase. In the case of concrete channels, removal of the concrete at the start of construction may require extensive dewatering efforts and the installation of a temporary channel liner (e.g., geotextile material).

The channel liner is intended to prevent erosion of the newly exposed channel soils before the new stable channel is created. Ideally, as much of the new channel should be constructed prior to the removal of the existing channel, so storm flows can pass unimpeded through the existing concrete channel during storm events and eliminate the need for costly dewatering. Once the new channel is constructed, the existing concrete channel can then be breached (Figure 4).

Maintenance/Monitoring - The complex nature of de-channelization projects requires close monitoring upon completion. The stream channel should be surveyed after completion to ensure that all dimensions adhere to the design specifications. This survey data should then be used to monitor any changes in channel dimensions over time. Frequent inspections of vegetation and channel stability should be made after storm events during the first year. Any dead or diseased vegetation should be replaced and areas of bank erosion repaired immediately. As de-channelization projects can have an effect on upstream and downstream reaches, these areas should also be inspected annually.

In addition to frequent project inspection, long-term monitoring should be part of the overall project plan. Permanent cross-sections should be established to track channel adjustments over time and identify problems before they pose a threat to the stability of the new channel.

Cost – Project costs are highly project specific. The unit cost to construct a newly designed channel typically ranges from $100 to $300 per linear foot, with design costs adding another 10 to 20% to the overall cost. These unit costs exclude the cost to relocate utilities, replace bridges or culverts, acquire land, or remove the rubble from the old concrete channel, each of which can be quite significant if needed.

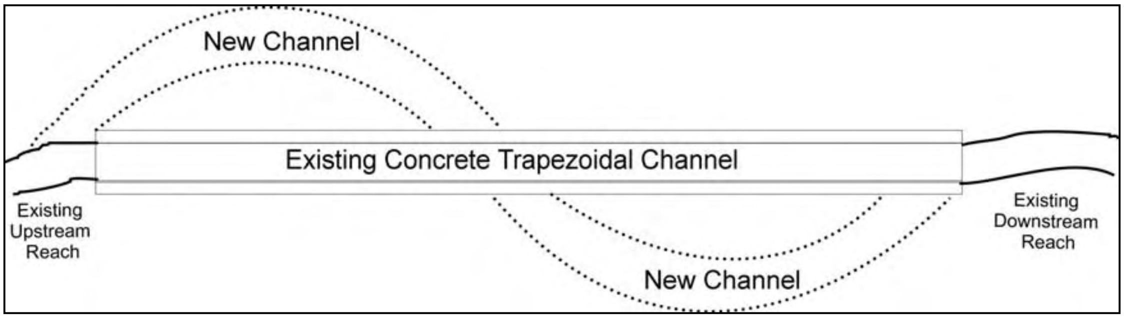


Figure 4: Schematic for Constructing a New Channel with the Existing Channel Left in Place

Further Resources

Additional resources on design and construction of de-channelization projects can be found in the following online resources:

Washington State Integrated Streambank Protection Guidelines
http://www.wa.gov/wdfw/hab/ahg/ispgdoc.htm

Stream Corridor Restoration: Principles, Processes and Practices Federal Interagency Stream Restoration Working Group
http://www.usda.gov/stream_restoration/

Hydraulic Design of Stream Restoration Projects
http://libweb.wes.army.mil/uhtbin/hyperion/CHL-TR-01-28.pdf

The Maryland Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/document/wetlandswaterways/mgwc.pdf

North Carolina Stream Restoration: A Natural Channel Design Handbook
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

References

Abbe, T., G. Press, D. Montgomery, and K. Fetherston. 2003. Integrating engineered log jam technology into river rehabilitation In *Restoration of Puget Sound Rivers* pp. 422-482. D. Montgomery, S. Bolton, D. Booth and L. Wall, editors. University of Washington Press. Seattle, WA.

Barbour, M., J. Gerritsen, B. Snyder and J. Stribling. 1999. *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish*. 2nd Edition. EPA 841-B-99-002. U.S. EPA Office of Water. Washington, D.C.

Barton, C. 2003. Applications of a sediment budget to assist urban stream restoration. *Watershed Review* 1(2): 4. Center for Water and Watershed Studies. University of Washington, Seattle, WA.

Bethel J. and K. Neal 2003. Stream enhancement projects: a King County perspective. in *Restoration of Puget Sound Rivers* pp. 394-421. D. Montgomery, S. Bolton, D. Booth and L. Wall editors. University of Washington Press. Seattle, WA.

Biederharn, D. C. Elliot and C. Watson. 1997. The WES stream investigation and streambank stabilization handbook. U.S. Army Corps of Engineers. Waterways Experiment Station. Vicksburg, MI.

Bledsoe, B. 2001. Relationships of stream response to hydrologic changes. *Linking Stormwater BMP Designs and Performance to Receiving Water Impacts Mitigation* Proceedings. Snowmass, CO. Engineering Research Foundation.

Booth, D. 1990. Stream channel incision following drainage basin urbanization. *Water Resources Bulletin.* 26(3): 407-417. American Water Works Association.

Booth, D. and C. Jackson. 1997. Urbanization and aquatic systems: degradation thresholds, stormwater detention and the limits of mitigation. *Journal of American Water Resources Association* 33(5):1077-1090.

Booth, D. and P. Henshaw. 2001. Rates of channel erosion in small urban streams. *Water Science and Application* 2:17-38.

Booth, D., J. Karr, S. Schauman, C, Konrad, S. Morley, M. Larson, and S. Burges. *In Press.* Reviving urban streams – land use, hydrology, biology, and human behavior. *Journal of American Water Resources Association.*

Booth, D., J. Karr, S. Schauman, C. Konrad, S. Morley, M. Larson, P. Henshaw, E. Nelson and S. Burges. 2001. *Urban stream rehabilitation in the Pacific Northwest*. Final Report EPA Grant No. R82-5284-010. University of Washington, Seattle, WA.

Bovee, K. 1982. *A guide to stream habitat analysis using the instream flow incremental methodology*. U.S. Department of Interior. Fish and Wildlife Service. Office of Biological Services. FWS/OBS-82/26.

British Columbia Ministry of Forests (BCMF). 2002. *Fish-stream Crossing Guidebook.* Forest practices code of British Columbia. Vancouver, BC.

Brown, E., D. Caraco and R. Pitt. 2004. Illicit discharge detection and elimination- a guidance manual for program development and technical assessments. Center for Watershed Protection and the University of Alabama. Ellicott City, MD.

Brown, K. 2000. *Urban stream restoration practices: an initial assessment*. Center for Watershed Protection. Ellicott City, MD.

Brown, W. 1998. The limits of settling. *Watershed Protection Techniques*. 2(3): 429-433.

Brush, G. and W. Zipperer. 2002. A comparison of exotic and non-exotic plant populations in the Gwynns Falls riparian corridor. Unpublished Data. Baltimore Ecosystem Study. Long Term Ecological Research Site. Baltimore, MD.

Bundt, K. and S. Abt. 2001. Sampling surface and subsurface particle size distributions in wadable gravel and cobble bed streams for analyses in sediment transport, hydraulics and streambed monitoring. USDA Forest Service. Rocky Mountain Research Station. RMRS-GTR-74.

Caraco, D. 2000. The dynamics of urban stream channel enlargement. *Watershed Protection Techniques* 3(3): 729-734. Center for Watershed Protection. Ellicott City, MD.

Carpenter, D., L. Slate, J. Schwartz, S. Sinha, K. Brennan and J. McBroom. 2003. Regional preferences and accepted practices in urban stream restoration--an overview of case studies.

Castro, J. and R. Sampson. 2001. *Design of rock weirs*. Engineering Technical Note 13. USDA National Resources Conservation Service. Boise, ID.

Center for Sustainable Design (CSD). 1999. Water related best management practices in the landscape – stream system protection, restoration, and reestablishment. Mississippi State University. Vicksburg, MS.

Center for Watershed Protection (CWP). 2003. The impacts of impervious cover on aquatic systems. *Watershed Protection Research Monograph No. 1*. Center for Watershed Protection. Ellicott City, MD. 142 pp.

Chow, V. 1959. *Open channel hydraulics*. McGraw Hill, Inc. New York, NY.

Clay, C. 1995. *Design of fishways and other fish facilities*. 2nd edition. CRC Press. Boca Raton, FL.

Claytor, R. 1996. Parallel pipe systems as a stream protection practice. *Watershed Protection Techniques* 1(4): 198-202.

Copeland, R., D. McComas, C. Thorne, P. Soar, M. Jonas and J. Fripp. 2001. *Hydraulic design of stream restoration projects.* U.S. Army Corps of Engineers, Engineer Research and Development Center. ERDC-CHL-TR-01-28.

Couch, C. 1997. Fish dynamics in urban streams near Atlanta, Georgia. *Watershed Protection Technique*s. 2(4): 511-514.

Crunkilton, R., J. Kleist, J. Ramcheck, W. DeVita and D. Villeneuve. 1996. Assessment of the response of aquatic organisms to long-term *In Situ* Exposures Of Urban Runoff. *Effects of Watershed Development and Management on Aquatic Ecosystems.* Roesner, L., editor. *Proceedings of the ASCE Conference*. Snowbird, UT.

Dartiguenave, C., I. Lille and D. Maidment. 1997. *Water Quality Master Planning for Austin, T*X. CRWR Online Report 97-6.

Dreher, D. and L. Mertz-Erwin. 1991. Effectiveness of urban soil erosion and sediment control programs in Northeastern Illinois. Northeastern Illinois Planning Commission. Chicago, IL.

DeWolfe, M., W. Hession and M. Watzin. 2004. Sediment and phosphorus loads from streambank erosion in Vermont, USA. In *Critical Transitions in Water and Environmental Resources Management.* G. Sehlke, D. Hayes and D. Stevens, editors, American Society of Civil Engineers. Reston, VA.

Doll, B., G. Grabow, K. Hall, J. Halley, W. Harman, G. Jennings and D. Wise. 2003. *Stream Restoration-- A Natural Channel Design Handbook.* North Carolina State University. Raleigh, NC. 140 pp.

Doyle, M, C. Rich, J. Harbor and A. Spacie. 2000. Examining the impacts of urbanization on streams using indicators of geomorphic stability. *Physical Geography* 21:155-181.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. *Stream Corridor Restoration: Principles, Processes, And Practices*. National Technical Information Service. Springfield, VA.

Finkenbine, J., J. Atwater and D. Mavinic. 2000. Stream health after urbanization. *Journal of the American Water Resources Association* 36(5): 1149-1160.

Fischenich, C. 1999. *Glossary of Stream Restoration Terms*. U.S. Army Corps of Engineers. Ecosystem Management and Restoration Research Program. ERDC-TN-EMRRP-SR-01.

Fischenich, C. 2001a. *Stability Thresholds For Stream Restoration Materials*. U.S. Army Corps of Engineers. Ecosystem Management and Restoration Research Program. ERDC-TN-EMRRP-SR-29.

Fischenich, C. 2001b. *Irrigation Systems For Establishing Riparian Vegetation.* Ecosystem Management Research Program. U.S. Army Engineer Research and Development Center. Vicksburg, MS.

Fischenich, C. 2002. *Design Of Low Flow Channels.* EMRPP Technical Note. U.S. Army Corps of Engineers. Research and Development Center, Vicksburg, MS. TN-EMRRP-SR-19.

Fischenich, C. and H. Allen. 2000. *Stream Management*. Water Operations Technical Support Program. U.S. Army Corps of Engineers. Engineer Research and Development Center. ERDC/EL SR-W-00-1.

Fischenich, C. and R. Seal. 2000. *Boulder Clusters*. U.S. Army Corps of Engineers. Ecosystem Management and Restoration Research Program. ERDC-TN-EMRRP-SR-11.

Flossi, G., S. Down, J. Hopelain, M. Bird, R. Corey and B. Collins. 1998. *California Salmonid Stream Habitat Restoration Manual*. Inland Fisheries Division. California Department of Fish and Game. Sacramento, CA.

Fox, M., S. Bolton and L. Conquest. 2003. Reference conditions for instream wood in Western Washington. in *Restoration of Puget Sound Rivers*. Montgomery, Bolton, Booth and Wall, editors. University of Washington Press. Seattle, WA.

Friedman, J., W. Osterkamp and W. Lewis. 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. *Geomorphology.* 14: 341-351.

Frissel, C. and R. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. *North American Journal of Fisheries Managemen*t. 12: 182-197.

Galli, J. 1990. *Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practice*s. Metropolitan Washington Council of Governments. Washington, D.C.

Galli, J. 1999. Monitoring the effectiveness of urban retrofit BMPs and stream restoration projects. In *Proceedings of National Conference on Retrofit Opportunities for Water Resource Protection in Urban Environments*. U.S. EPA/625/R-99/002.

Galli, J.1996. *Final Technical Memorandum: Rapid Stream Assessment Technique (RSAT) Field Methods*. Department of Environmental Programs, Metropolitan Washington Council of Governments. Washington, D.C.

Goldsmith, W., K. Barret, M. Larson and W.Lattrell. 1998. Urban channel restoration: design and monitoring. *Proceedings of Conference on Wetlands Engineering and River Restoration*. American Society of Civil Engineers. Reston, VA.

Gray, D. and R. Sotir. 1996. *Biotechnical and Soil Bioengineering: A Practical Guide for Erosion Control*. John Wiley and Sons. New York, NY.

Gray, D. and R. Sotir. 1996. *Biotechnical Stabilization of Steepened Slopes.* Transportation Research Board. Washington, D.C.

Groffman, P., D. Bain, L. Band, K. Belt, G. Brush, J. Grove, R. Pouyat, I. Yesilonis and W. Zipperer. 2003. Down by the riverside: urban riparian ecology. *Frontiers in Ecology and Environment*. Ecological Society of America. 1(6): 98-104

Gustav, P. 1994. Maintaining fish habitat in urban streams. *Water Environment Technology*. 48: 53

Hammer, T. 1972. Stream channel enlargement due to urbanization. *Water Resources Research* 8(6): 1530-1540.

Harding, J., E. Benfield, P. Bolstad, G. Helman and E. Jones. 1998. Stream biodiversity: the ghost of land use past. *Proceedings National Academy of Science*. 95: 14843-14847.

Harman, G. Jennings, K. Tweedy, J. Buck and D. Taylor. 2001. Lessons learned from designing and constructing instream structures. In *Proceedings of ASCE Wetlands and River Restoration Conference*. Reno, NV.

Harman, W., D. Wise, A. Walker, R. Morris, M. Cantrell, M. Clemmons, G. Jennings, D. Clinton, and J. Patterson. 2000. Bankfull regional curves for North Carolina mountain streams in *Proc. AWRA Conf. Water Resources in Extreme Environments*. Anchorage, AK. D. Kane, editor. pp. 185-190. Middleburg, VA. American Water Resources Association.

Harrelson, C., C. Rawlins, and J. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field technique. General Technical Report RM-245. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. Fort Collins, CO.

Harvey, M. and C. Watson. 1986. Fluvial processes and morphological thresholds in incised channel restoration. *Water Resources Bulletin* 22(3): 359-368.

Hegberg, C., S. Jacobs, A. Schlindwein and S. Cohen. 2001. Natural fish passage structures in urban streams: Part 2: Hydraulic design and analysis. *Proceedings International Conference on Ecology and Transportation.*

Henshaw, P. and D. Booth. 2000. Natural restabilization of stream channels in urban watersheds. *Journal of the American Water Resources Association*. 36(6): 1219-1236.

Hession, W. 2001. Riparian forest and urban hydrology influences on stream channel morphology: implications for restoration. *Proceedings of World Water and Environmental Resources Congress*. D. Phelps and G. Sehlke, editors. Orlando, FL.

Hildebrand, R., A. Lemly, C. Dolloff and K. Harpster. 1998. Design considerations for large woody debris placement in stream enhancement projects. *North American Journal of Fisheries Management*. 18:161-167.

Hoag, J. and D. Ogle. 1994. The stinger—a tool to plant un-rooted hardwood cuttings of willow and cottonwood species for riparian or shoreline erosion control or rehabilitation. Technical Note 6. USDA-NRCS Aberdeen Plant Materials Center. Aberdeen, ID.

Hoag, J. and H. Short. 1992. *Use of willow and cottonwood cuttings for vegetating shorelines and riparian areas*. Riparian Wetland Project Information Series No. 3 .USDA-NRCS Aberdeen Plant Materials Center. Note 1081 Aberdeen, ID.

Hoitsma, T. 1996. Innovations in rooted willow cuttings. *Wetland Journal* 8(3): 17-20.

Horner, R., D. Booth, A. Azous, and C. May. 1997. Watershed determinants of ecosystem functioning. in *Effects of Watershed Development and Management on Aquatic Ecosystem*s. *Proceedings of the ASCE Conference*. L. Roesner, editor. Snowbird, UT.

Hunter, C. 1991. *Better trout habitat-a guide to stream restoration and management*. Island Press, Washington, D.C.

Hunter, M. and C. Thrush. 2002. Restoring Denver area streams and gulches. *Proceedings 9th International Conference on Urban Drainage*. Portland, Oregon.

Hydrologic Engineering Center (HEC). 1997. *HEC-RAS version 2.0 users manual*. U.S. Army Corps of Engineers. Davis, CA.

Jackson, S. 2003. River and stream crossing standards – technical guidelines. University of Massachuesetts Cooperative Extension. Amherst, MA.

Jennings, G. 2004. Personal communication. Professor, Biological and Agricultural Engineering. North Carolina State University. Comments dated 21 September, 2004.

Jennings, G. and W. Harman. 2000. Stream corridor restoration experiences in North Carolina. ASAE Paper 002012, ASAE Annual International meeting. Milwaukee, WI. St Joseph, MI. American Society of Agricultural Engineering.

Keystone Stream Team (KST). 2002. Guidelines for natural stream channel design for Pennsylvania waterways. Alliance for the Chesapeake Bay, Baltimore, MD.

King County Department of Public Works (KCDPW). 1993. Guidelines for bank stabilization projects in the riverine environment of King County. Surface Water Management Division. Seattle, WA

Kondolf, G. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management*. 21(4): 533-551.

Konrad, C. 2003. Opportunities and constraints for urban stream rehabilitation. in *Restoration of Puget Sound Rivers* pp. 292-317. D. Montgomery, S. Bolton, D. Booth and L. Wall, editors. University of Washington Press. Seattle, WA.

Kumble, P. and G. Bernstein. 1991. Small habitat improvement projects: checklist and matrix. *Anacostia Watershed Restoration Sourcebook*. Metropolitan Washington Council of Governments. Washington, D.C.

Kwon, H. 1999. The return of the beaver. *Watershed Protection Techniques*. 2(3): 405-410.

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. American Society of Civil Engineering. *Proceeding 81*. Paper 745. pp. 1-17.

Larson, M., D. Booth and S. Morley. 2002. Effectiveness of large woody debris in stream rehabilitation projects in urban basins. *Ecological Engineering*.

Legg, A, R. Bannerman and J. Panuska. 1996. Variation in the relation of rainfall to runoff from residential lawns in Madison, WI. *USGS Water Resources Investigation Report 96-4194*.

Leopold, L., G. Wolman, and J. Miller, 1964. *Fluvial processes in geomorphology*. W.H. Freeman & Sons. San Francisco. CA.

MacRae, C. 1996. Experience from morphological research on Canadian streams: is control of the two-year frequency runoff event the best basis for stream channel protection? *Effects of Watershed Development and Management on Aquatic Ecosystems. Proceedings of the ASCE Conference*. L. Roesner, editor. Snowbird, UT.

MacRae, C. and M. DeAndrea. 1999. Assessing the impact of urbanization on channel morphology. *Proceeding Second International Conference on Natural Channel Systems*. Niagra Falls, OT.

Maryland Water Management Administration. (MWMA). 2000. *Maryland guidelines for waterway construction.* Maryland Department of Environment. Baltimore, MD.

McCandless, T. and R. Everett. 2002. *Maryland stream survey: bankfull discharge and channel characteristics of streams in the piedmont hydrologic region*. U.S. Fish and Wildlife Service. Chesapeake Bay Field Office. CBFO-S02-01. Annapolis, MD.

Meyer, J. and C. Couch. 2000. *Influences of watershed land use on stream ecosystem structure and functio*n. NCERQA Grant Final Report. University of Georgia. Athens, GA.

Miller, D. 1997. Fabric-encapsulated soil method for riverbank stabilization. *Geotechnical Fabric Report*. 15(1): 48-53.

Miller, D. and P. Skidmore. 2000. Application of deformable stream bank concepts to natural channel design. *Water Resources Engineering.* 98:441-446.

Miller, D. P. Skidmore and D. White. 2001. *White paper - channel design*. Prepared for Washington Departments of Fish and Wildlife, Ecology, and Transportation, Olympia, WA.

Miller, D., T. Hoitsma and D. White. 1998. Degradation rates of woven coir fabric under field conditions. in *Proceedings ASCE Wetland Rivers Restoration Conference.* Denver, CO.

Morisawa, M. and R. Laflure. 1979. Hydraulic geometry, stream equilibrium and urbanization. In *Adjustments of the Fluvial System: Proceedings Tenth Annual Geomorphology Symposium*. Binghamton, NY.

Mostaghimi, T., M, Wynn, J. Frazee, P. McClelland, R. Shaffer and W. Aust. 1994. Effects of forest harvesting best management practices on surface water quality in the Virginia coastal plain

National Resources Conservation Service (NRCS). 1995. Chapter 18: Soil bioengineering for upland slope protection and erosion reduction. *Engineering Field Book*. Washington, D.C.

National Resources Conservation Service (NRCS). 1996. Chapter 16: Streambank and shoreline protection. *Engineering Field Book.* Washington, D.C.

National Resources Conservation Service, Plant Materials Center (NRCS-PMC). 1998. The practical streambank bioengineering guide - users guide for natural streambank stabilization in the arid and semi-arid Great Basin and Intermountain West. Aberdeen, ID.

Newbury R. and M. Gaboury. 1993. *Stream Analysis and Fish Habitat Design: A Field Manual*. Newbury Hydraulics Ltd. Gibsons, British Columbia, Canada.

Newbury, R., M. Gaboury, and D. Roseboom.1998. *Field Manual of Urban Stream Restoration*. Illinois Water Survey and Region 5 U.S. EPA. Chicago, IL.

Nichols, R. and S. Sprague. 2003. Use of long-line cabled logs for streambank rehabilitation. In *Restoration of Puget Sound Rivers* pp. 422-442. D. Montgomery, S. Bolton, D. Booth and L. Wall, editors. University of Washington Press. Seattle, WA.

North Carolina Department of Environment and Natural Resources (NCDENR). 2001. *Guidelines for Riparian Buffer Restoration*. Raleigh, NC.

Ohio Department of Natural Resources (DNR). 2002. Stream management fact sheets – *Large Woody Debris*. Columbus, OH.

Oregon Cooperative Extension Service (OCES). 2000. Stream*A*Syst - a tool to help examine stream conditions on your property. Corvallis, OR.

Palone, R. and A. Todd. 1997. *Chesapeake Bay Riparian Handbook - a Guide for Establishing and Maintaining Riparian Forest Buffers*. USDA Forest Service NA-TP-02-97. Radnor, PA.

Patterson, J., D. Clinton, W. Harman, G. Jennings, and L. State. 1999. Development of streambank erodibility relationships for North Carolina streams. in *Wildland Hydrology, Proc. AWRA Specialty Conf*. Bozeman, MT. D. Olson and J. Potyondy, editors. pp 117-123. American Water Resources Association, Middleburg, VA.

Paul, M. 2004. *Personal communication*. Stream ecologist. Howard University. Urban stream ecology research lecture. February 21, 2004.

Paul, M. and J. Meyer. 2001. Streams in the urban landscape. *Annual Review of Ecology and Systematics.* 32: 33-65.

Pinkham, R. 2000. *Daylighting: New Life for Buried Streams*. Rocky Mountain Institute. Snowmass, CO.

Pitt, R. 1987. Small storm urban flow and particulate washoff contribution to outfall discharge. PhD dissertation. University of Wisconsin, Madison. Madison, WI.

Pitt, R., A. Maestre and R. Morquecho. 2003. *National stormwater quality database* (NSQD). University of Alabama and Center for Watershed Protection. Tuscaloosa, AL.

Resh, V. 1995. Stream daylighting in a Berkeley, California creek. *Watershed Protection Techniques*. 1(4): 184-187.

Riley, A. 1998. *Restoring streams in cities.* Island Press. Washington, D.C.

Rinaldi, M. and P. Johnson. 1997. Stream meander restoration. *Journal of American Water Resources Association*. 33: 855-856.

Roni, P., M. Liermann and A. Steel. 2003. Monitoring and evaluating fish response to instream restoration. In *Restoration of Puget Sound Rivers.* pp 394-421. D. Montgomery, S. Bolton, D. Booth and L. Wall editors. University of Washington Press. Seattle, WA.

Rosgen, D. 1996. *Applied River Morphology*. Wildland Hydrology. Pogosa Springs, CO.

Rosgen, D. 1993. Applied fluvial geomorphology: a training manual - short course. Wildland Hydrology, Inc. Pagosa Springs, CO.

Rosgen, D. 1997. A geomorphological approach to restoration of incised rivers. in *Proceedings of the conference on management of landscapes disturbed by channel incision*. S. Wang, E. Langendoen and F. Shields, editors. University of Mississippi, Oxford, MS.

Rosgen, D. 1998. *The reference reach field book.* Wildland Hydrology. Pagosa Springs, CO.

Rosgen, D. 2001. A stream channel stability assessment methodology. In *Proceedings of the Seventh International Sedimentation Conference.* Reno, NV March 25-29.

Schueler, T. 1987. Controlling urban runoff. A practical manual for planning and designing urban best management practices. Metropolitan Washington Council of Governments. Washington, D.C.

Schueler, T. 1999. Microbes and urban watersheds. *Watershed Protection Techniques*. 3(1): 551-596.

Schumm, S. 1999. Causes and controls of channel incision. In *Incised River Channels—processes, forms, engineering and management*. pp. 19-34. S. Darby and A. Simon, editors. John Wiley & Sons. New York, NY.

Schumm, S. M. Harvey and C. Watson. 1984. *Incised Channels: Morphology, Dynamics and Control*. Water Resources Publications. Littleton, CO.

Shields, F., N. Morin and C. Cooper. 2001. Design of large woody debris structures for channel rehabilitation. *Proceedings Seventh Federal Interagency Sedimentation Conference.* USDA ARS. National Sedimentation Laboratory. Oxford, MI

Skidmore, P. D. Shields, M. Doyle and D. Miller. 2002. A categorization of approaches to natural channel design. *Proceedings ASCE Conference on Wetlands and River Restoration.* Reno NV.

Slaney, P. and D. Zaldokas. 1997. Fish habitat rehabilitation procedures. *Watershed Restoration Technical Circular No. 9.* Ministry of Environment, Land and Parks. Vancouver, BC.

Sotir, R. 1998. Case histories in soil bioengineering stream bank protection. *Water Resources Engineering*. 98(1): 334-339.

Sweeney, B. 1992. Streamside forests and the physical, chemical and trophic characteristics of piedmont streams in eastern North America. *Water Science Technology*. 26: 2653-2673.

Sylte, T. and C. Fischenich. 2000. *Rootwad composites for streambank erosion control and fish habitat enhancement.* U.S. Army Corps of Engineers. Ecosystem Management and Restoration Research Program. ERDC-TN-EMRRP-SR-21.

Trimble, S. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science*. 278: 1442-1444.

United States Department of Agriculture (USDA). 1998. *Stream Visual Assessment Protocol*. USDA Natural Resource Conservation Service, National Water and Climate Center Technical Note 99-1.

University of Toronto. 2000. *Ontario's Stream Rehabilitation Manual*. Canadian Digital Collection Program. Ontario, Canada.

Urban Creek Monitoring Team (UCMT). 2004. Creek rehabilitation projects: three year monitoring results for projects constructed in 2000. Seattle Public Utilities. Seattle, WA.

Vermont Water Quality Division. (VWQD). 2000. *Vermont Regional Hydraulic Geometry Curves*. Vermont Dept. of Environmental Conservation. Waterbury, VT.

Virginia Department of Conservation and Recreation (VA DCR) 2004. *Virginia Stream Restoration and Stabilization Best Management Practice Guide*. Richmond, VA.

Wahab, A. 2002. Stream restoration in Fanno and Tryon Creek watersheds in Portland. *Proceedings Northwest Stream Restoration Design Symposium*. Stevenson, WA.

Wang, L., J. Lyons, P. Kanehl and R. Bannerman. 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Managemen*t. 28(2): 255-266.

Washington Department of Fish and Wildlife. 2003. *Design of road culverts for fish passage*. Habitat and Lands Program. Environmental Engineering Division. Olympia, WA.

Washington State Aquatic Habitat Guidelines Program (WSAHGP). 2002. *Integrated streambank protection guidelines*. Washington Departments of Fish and Wildlife, Ecology, and Transportation. Olympia, WA.

Watershed Science Institute (WSI). 2001. Stream corridor inventory and assessment techniques. Technical report. U.S. Department of Agriculture. Natural Resources Conservation Service.

Watson, C., S. Abt and D. Derrick. 1997. Willow post bank stabilization. *Journal American Water Resources Association.* 32(2): 293-300.

Weber, D. and R. Bannerman. 2004. Relationship between impervious surfaces within a watershed and measures of reproduction in fathead minnows. *Hydrobiologia.* 525:215-228.

Zierke, M. and C. Hoag. 1995. Collection, establishment, and evaluation of unrooted woody cuttings to obtain performance tested ecotypes of native willows and cottonwoods. *Riparian Wetland Project Information Series No. 5*. USDA-NRCS Aberdeen Plant Materials Center. Pub 3251. Aberdeen, ID.

Zielinski, J. 2004. Developing and implementing a stream watch program. Center for Watershed Protection. Prepared for Baltimore County Department of Environmental Protection and Resource Management. Ellicott City, MD.

Zimmerman, R., J. Goodlet and G. Coner. 1967. The influence of vegetation on channel form in small streams. pp. 255-275 in *International Association of Scientific Hydrology*. *Publication No. 75: Symposium on River Morphology*.

Glossary

This glossary defines some of the technical terms used throughout this manual and was derived from several sources including Fischenich (1999); Brown, (2000); Miller *et al.* (2001); and WSAHGP (2002). Definitions have been adapted and supplemented in some cases to directly address their urban stream context.

A-jacks: pre-fabricated interlocking concrete structures used to protect the toe of an eroding bank.

Aggradation: the process by which a streambed is raised in elevation by the deposition of sediment transported from upstream (opposite of degradation). In urban streams, aggradation occurs when the channel is supplied with more sediment load than it is capable of transporting.

Alluvial stream: streams that have erodible boundaries and are free to adjust their dimensions, plan form and gradient in response to changes in slope, sediment transport, and discharge.

Anadromous: fish that are born in freshwater, migrate to and live a portion of their life cycle in estuarine or marine environments, and return to freshwater to reproduce. Examples include salmon, shad, herring and rockfish.

Armoring: a natural process where an erosion-resistant layer of relatively large particles is established on the surface of the streambed through removal of finer particles. A properly armored streambed generally resists movement of bed material at discharges up to ¾ of bankfull depth. Also, refers to the process of protecting the bank or a stream repair practice with rip-rap or boulders to prevent localized erosion.

Bankfull: the full capacity of the stream channel up to the top of bank on either side, which acts as the transition point between the stream and floodplain.

Bankfull discharge: the stream discharge corresponding to the water stage that first overtops the banks of stable alluvial stream channels. In many streams, the discharge occurs on an average frequency of about 1.5 to 2 years.

Bank shaping: a stream repair practice that achieves a more stable bank slope and a greater bankfull cross-section by laying back and contouring an eroding streambank. Bank shaping is rarely used as a stand-alone practice in urban streams, and is usually combined with toe protection and other bioengineering treatments.

Baseflow channel creation: a combination of stream repair practices used to create a confined and deeper baseflow channel or thalweg in an enlarged urban stream channel.

Bedload: the portion of a stream's sediment load that is not in suspension, consisting of coarse sediments that are transported by jumping, sliding or rolling on or near the streambed.

Bed material: the dominant size class of sediment material found on the streambed for a particular stream reach, as determined from counts of the material in the field. The five classes of bed material assessed in this manual are sand, gravel, cobbles, boulders and bedrock.

Buildout: is the point in time in which further development activity ceases in a subwatershed, and it attains its maximum degree of IC. In reality, most subwatersheds continue to experience minor redevelopment and infill development after buildout

Braided channel: stream that has flow in several channels, which successively meet and divide. Braiding occurs when the sediment load is too great to be transported by a single channel.

Boulder clusters: stream repair practice that creates in-stream fish habitat by installing groups of large boulders near the center of the stream to create small scour pools, eddies, and areas of turbulent flow.

Brush mattress: streambank stabilization technique that uses a mattress-like covering of living woody plant cuttings that will ultimately grow into the bank to provide long-term vegetative stability.

Channelization: historical practice of straightening of streams to increase their capacity to move floodwaters through the reach.

Channel enlargement: progressive increase in the cross-sectional area of the bankfull channel in urban streams induced by the increase in the frequency and magnitude of bankfull flooding caused by upstream development.

Channel evolution: stages by which the cross-sectional geometry of an incising stream change over time, including initial incision, channel enlargement, and subsequent aggradation to a new and potentially stable final cross-section. The channel evolution process can take several decades in urban watersheds, and is a critical factor in stream repair design.

Channel redesign: comprehensive stream repair practice that seeks to create a new channel with dimensions, pattern and profile that will not aggrade or degrade over time, and can effectively move both sediment and water. The new geometry for the channel is based on hydraulic and sediment transport modeling and is maintained using a series of stream repair practices.

Cohesive soils: bank soils that have natural resistance to being pulled apart or being eroded.

Coir: biodegradable coconut fiber used as deformable toe protection treatment or as an erosion control fabric to reinforce exposed or newly-shaped bank soils.

Cribwall: a structure built of logs laid horizontally and separated by smaller wooden spacers used to protect eroding streambanks. The structure is backfilled with soil and rocks, and may be planted with live cutting (live cribwall).

Cross-section: transect of a stream taken at a right angle to its flow.

Culvert: an enclosed pipe or concrete box structure used as a conduit for stream flow beneath a road or other type of stream crossing. Culverts are frequently found in urban streams and can act as both a grade control and a potential barrier to fish migration.

Daylighting: stream repair practice that unearths and re-establishes surface streams that had been historically enclosed in large diameter storm water pipes or extended culverts.

De-channelization: a comprehensive stream repair practice that creates a stable and non-erosive channel in urban stream reaches that were channelized in the past, and in some cases, hardened with concrete. The new channel generally has less channel gradient, more channel roughness and a more sinuous or meandering planform within the urban stream corridor.

Degradation: the removal of streambed materials caused by the erosional force of water that results in the lowering of the bed elevation through a stream reach (opposite of aggradation). Many urban streams experience degradation as a result of increased storm water flows produced by upstream development.

Deformable: streambanks and/or boundaries that are free to change their dimensions over time to respond to upstream changes in hydrology and sediment transport. Deformable banks are allowed to erode over time at rates that are controlled by natural processes but checked by bank vegetation.

Depth of scour: important design parameter for many urban stream repair practices that examines how far scour erosion will occur below the current streambed elevation, as a result of the placement of a stream repair practice upstream, or as a result of future channel incision.

Design life: the expected longevity of a stream repair practice under normal field conditions

Discharge: the rate of flow in a stream at a fixed cross-section, expressed in volume per unit time, normally as cubic feet per second. Discharge is the product of the mean velocity and the cross-sectional area of flow.

Discharge prevention practices: methods used to detect and fix chronic discharges of sewage and other pollutants in urban subwatersheds. Examples include failing septic systems, sanitary sewer overflows, sewer leaks, and illicit discharges from industrial and other generating land uses.

Dormant cuttings: un-rooted stems of live trees and shrubs harvested from riparian areas that are stored under controlled conditions and used in a variety of bioengineering and planting practices to stabilize eroding urban streambanks.

Downcutting: deepening of urban stream channel cross-section over time as a result of channel degradation caused by upstream development, and typified by tall, unstable banks, channel entrenchment, and disconnection from the floodplain.

Embeddedness: degree to which larger particles in the streambed (gravel, cobble or boulders) are surrounded by or covered with fine sediments, expressed as the percentage of large particle class covered by fine sediments. Urban streams can be highly embedded which reduces habitat for aquatic insects.

Engineered log jam: constructed collections of large woody debris that redirect stream flow away from eroding banks.

Erosion control fabric (ECF): stream repair practice to prevent soil erosion, reinforce soil structure and enable vegetation to become established on newly graded or shaped streambanks. Fabrics are often composed of biodegradable materials such as coir or jute that break down within a few years.

Fascine: a long bundle of live woody plant cuttings that are bound together and secured to the bank to stabilize eroding streambanks.

Fish barrier: an obstacle in a stream such as a dam, crossing, or elevated culvert that prevents upstream or downstream movement by fish.

Floodplain: any flat or nearly flat lowland bordering a stream that is periodically inundated by water during floods.

Flow deflection practices: stream repair practices that concentrate or redirect flow in an enlarged urban stream to create a desired channel feature, such as a riffle or meandering thalweg.

Flow diversion practices: engineered stream repair practices that modify storm water pipes to create new channels (daylighting) or bypass erosive storm flows around a sensitive stream reach (parallel pipes), normally applied to smaller urban headwater streams.

Footers: bottom boulders or logs that are placed within a trench below the streambed, which serve as the structural foundation for an in-stream repair practice and must extend below the estimated depth of scour expected for the streambed.

Grade controls: Hard points in the bed of a stream channel, which hold a set elevation in the longitudinal profile and are resistant to erosion and headcut migration. Grade controls can be natural features, such as rock outcrops, or manmade features such as culverts and other stream crossings. Several stream repair practices can be installed in the stream to provide grade control to prevent channel incision.

Gradient: the slope of a stream channel bed, expressed as a percentage in the drop in elevation in a reach divided by the total length of a stream reach.

Hard bank stabilization: use of hard stabilization treatments to fix a bank or meander bend in the same place over time. Examples include boulder and rootwad revetments and other erosion-resistant, non-deformable materials used to protect threatened infrastructure or property in the urban stream corridor.

Headcut or knickpoint: The erosion of the channel bed, progressing in an upstream direction, manifested by pronounced drops in stream elevation or abnormally steepened channel segments.

Imbricated rip-rap: hard bank stabilization practice consisting of large boulders arranged in interlocking blocks along the streambank, which have gaps between footer boulders that create fish habitat in the submerged portion of flow.

Impacted stream (subwatershed): an urban stream that has a subwatershed containing from 10 to 25% impervious cover, which are often the best candidates for stream repair. Physical, hydrological, biological and water quality indicators for these streams are typically in the "fair" range, according to the Impervious Cover Model.

Impervious cover: Impermeable man-made surfaces such as rooftops, parking lots and roads that prevent infiltration of rainfall and increase the volume of storm water runoff in a subwatershed. The percentage of impervious cover in a subwatershed can be used to classify and manage urban streams, according to the Impervious Cover Model.

Impervious cover model (ICM): model used to classify and manage urban streams based on the amount of impervious cover found in their contributing subwatersheds. The ICM classifies four types of urban streams: sensitive, impacted, non-supporting and urban drainage, each of which has a unique stream repair potential and subwatershed management strategy.

Incised channel: a stream channel that has deepened and become disconnected from its floodplain. Incision is common in urban streams experiencing increases in storm water discharge.

Incision: the deepening or entrenchment in a channel cross-section as a result of the process of degradation.

In-stream habitat enhancement: stream repair practices that improve fish habitat conditions in urban streams by creating features such as pools, riffles, resting areas, undercut banks or overhead cover.

Invert: the elevation of the deepest portion of the stream at a fixed point along the stream, or the elevation of the bottom of an outfall pipe.

Knickpoint: See *Headcut*

Large woody debris (LWD): pieces of wood in contact with the stream channel that are longer than 10 feet and at least six inches in diameter (larger streams), or at least three feet long and six inches in diameter (headwater streams). LWD is an important habitat and structural element of natural streams, and several stream repair practices use log jams to mimic this habitat element.

Limit of perennial vegetation: the lowermost elevation of the streambank that can support growth of perennial plants. In urban streams, a vertical gap often exists between the normal baseflow water elevation and the lower bank due to the scour and inundation caused by frequent storm water flooding.

Live stakes: dormant cuttings of woody species such as willows and cottonwoods that are used in bioengineering treatments to stabilize eroding streambanks. The cuttings are either directly inserted into the streambank, or arranged in bundles or mats. Over time, the cuttings sprout and their vigorous root structures help stabilize the bank and provide roughness.

Longitudinal profile: a survey of the streambed elevation through a reach that also may include flow depths, bed materials and current velocity.

Lunkers: stream repair practice that provides undercut bank habitat and streambank toe protection along meander bends. Lunkers are constructed of horizontal wooden planks separated by internal spacers that create a crib-like structure underneath the streambank toe.

Meander: the winding appearance of a stream reach when viewed in plan form. A stream is considered meandering if its length is greater than 1.5 times that of the valley through which it passes.

Meander bend: the sinuous curve as a stream swings from one side of the floodplain to the other. The outside of the meander bend is a common area of bank erosion, whereas the inside of the bend is normally associated with deposition.

Meander width: measure of the projected distance between outer banks of two successive meanders in a stream reach.

Non-supporting stream (subwatershed): an urban stream that contains 25 to 60% impervious cover in its contributing subwatershed, and typically has fair to poor stream indicator scores, according to the ICM. These streams have only modest stream repair potential.

Outflanking: the process by which a stream repair practice fails because of scour occurring at the point where the practice joins the bank. The risk of outflanking is high for most urban stream repair practices due to higher current velocities and the enlargement of the stream channel during the adjustment phase. Outflanking also occurs when stream repair practices reduce the available cross-sectional area of a channel, which forces stream flows to work against the toe of the bank

Parallel pipes: stream repair practice installed to bypass erosive storm flows to prevent channel erosion and habitat degradation in small urban headwater streams. This flow diversion practice splits flows at an upstream control structure, and directs them into large storm water pipes down the stream corridor to a more stable downstream location. Baseflow and larger floods are not bypassed.

Permissible velocity: the maximum mean flow velocity within a channel that will not cause erosion of the channel boundary.

Plan form: characteristics of a stream channel when viewed from a map or aerial photo, which are expressed in terms of the pattern, sinuosity, and individual meander attributes of the channel such as amplitude, wavelength and radius of curvature.

Point bar: A stream deposition feature usually found on the side opposite the concave bank that helps move bedload from one meander to the next.

Pool-riffle ratio: The ratio of the length of pools to the length of riffles within a given stream reach.

Reach: a specified length of a stream with the same geomorphological characteristics.

Revetment: armoring of the bank with an erosion-resistant material such as boulders, rocks or rootwads.

Riffle: a stream feature in which water flow is more shallow and rapid than the reaches above and below it; most natural streams have an alternating sequence of pools and riffles.

Rip-rap: rock with a uniform size or weight used to stabilize streambanks from erosion or create in-stream habitat structures.

Rock vortex weir (RVW): stream repair practice consisting of a low profile structure of loosely consolidated boulders that spans the width of a channel to provide grade control, enhance riffles and create a downstream scour pool. The porous design allows bedload sediments and migrating fish to pass more easily.

Rock Cross Vane (RCV): variation of a rock vortex weir used to provide grade control, narrow the baseflow channel, and reduce local bank erosion. The vane is formed by two arms of boulders that are angled upstream, extending from the bank to the stream invert in the center of the channel.

Rootwad: the root mass of a large tree trunk often used for bank protection or to anchor large woody debris.

Scour: the process of removing material from the bed or banks of a stream through the erosive action of flowing water.

Scour pool: an area of deeper water in the stream caused by the scouring action of water that occurs downstream of channel obstructions or along meander bends. Several stream repair practices are designed to create scour pools in urban channels to create habitat and dissipate stream energy.

Shear stress: a measure of the erosive force acting on the stream channel boundary, expressed as force per unit area (lbs/square foot). In the channel, shear stress is created by water flowing parallel to the boundaries of the channel bank. On the channel bank, shear stress is a combined function of the flow velocity and the shape of the bend and bank cross-section.

Sinuosity: the ratio of the stream channel length, measured in the thalweg from the top of the reach to the bottom.

Soft bank stabilization: bioengineering practices used to stabilize eroding streambanks that rely on vegetation, slope control and biodegradable fabrics to establish a stable but deformable bank over time.

Soil lifts: soft streambank stabilization practice that uses layers of soil that are wrapped or encapsulated within woven erosion control fabrics. Each successive layer or lift is used to build up the bank. The lifts are designed to provide deformable bank stabilization until vegetative growth planted within the lifts can anchor the bank.

Stream order: a hydrologic system of stream classification. Each small, un-branched tributary is a first order stream, and when two first order streams join, they form a second order stream. A third order stream is formed by the confluence of two second-order streams, and so forth.

Stream interruption: the fragmentation of the urban stream network into isolated reaches through the progressive construction of crossings, culverts, dams, channel modification and other engineering "improvements".

Streambank planting zone: a zone on the streambank that is suitable for establishing perennial woody vegetation, extending from the lower limit of perennial vegetation near the streambank toe up to the top of bank or floodplain.

Streambank toe: the break in slope at the foot of a bank where it meets the streambed and where bank erosional forces are usually the greatest.

Stream corridor: the width of available land extending outward from either streambank that is suitable for potential stream repair projects. The outer boundary of the corridor is determined by the presence of structures, utilities or impervious surfaces that restrict or prevent the natural use of the corridor.

Step pools: stream repair practice used to provide grade control and promote fish passage that consists of a series of low elevation weirs and pools that dissipate stream energy along degrading or incising stream channels.

Storm water outfall: the point at which a concrete or corrugated metal storm drain pipe discharges to a stream or floodplain. Storm drain pipes are used to convey excess runoff underground, and come in a wide range of diameters, based on the area, impervious cover and drainage pattern of the upstream catchment. Storm water outfalls are important locations to investigate within the urban stream corridor, since they may contain illicit discharges, produce local scour, and provide potential opportunities for daylighting and storm water retrofitting.

Storm water retrofits: construction of upstream ponds, wetlands and bioretention practices to capture, store and treat storm water runoff to improve hydrologic and water quality conditions to a downstream reach.

Subwatershed: small urban watersheds with a drainage area of less than 10 square miles that are the primary unit for the analysis, design and implementation of stream repair and other restoration practices.

Thalweg: the longitudinal line of deepest water within a stream channel.

Toe: the base area of a streambank where erosive forces are greatest, extending from the upper limit of perennial vegetation to the stream invert.

Toe erosion: the erosion of the streambank or bed caused by the undermining of the toe and subsequent gravity collapse or slumping of overlying layers.

Urban drainage (subwatersheds): streams that have more than 60% impervious cover in their contributing subwatersheds, and have "poor" to "very poor" stream indicators in the few remaining surface reaches that have not been enclosed by storm water pipes or culverts. These streams seldom have much potential for stream repair, although they remain targets for pollution reduction.

V-log drop structure: stream repair practice used to provide grade control in urban streams consisting of two logs joined at an angle with the apex pointing upstream. The “V” that is formed concentrates flow in the center of the stream, creates downstream scour pools, and maintains grade control.

Vanes: stream repair practices consisting of a linear rock or log structure extending out from the streambank and pointing upstream. Vanes are primarily used in urban streams to reduce erosion along the streambank toe, and can create some in-stream habitat features.

Watershed forestry: systematic efforts to manage and increase the total amount of forest cover within an urban subwatershed so as to incrementally reduce the generation of storm water runoff and pollutant loadings. Efforts include forest conservation practices to minimize future forest loss and maximize future forest gains through strategic reforestation efforts on both public and privately-owned land.

Wing deflectors: stream repair practice consisting of a low profile pyramid-shaped stone structure used to concentrate or redirect flow. Single or double deflectors can be installed, and are used to concentrate baseflow channels, create riffles, or make the thalweg more sinuous.

Appendix A: Internet Resources for Urban Stream Repair

General Resources

Stream Corridor Restoration: principles, processes and practices
Federal Interagency Stream Restoration Working Group
http://www.usda.gov/stream_restoration/

North Carolina Stream Restoration Institute
http://www.ncsu.edu/sri/

Stream Systems Technology Center
http://www.stream.fs.fed.us

Urban Streams Restoration Program
http:/www.dpla.water.ca.gov/environment/habitat/stream/usrp.html

Stream*A*Syst
http://www.agcomm.ads.orst.edu/agcomwebfile/edmat/html/em/em8761/em8761.html

Ecosystem Management and Restoration Research Program
Stream Restoration Technical Notes
http://www.wes.army.mil/el/emrrp/tnotes.html

NRCS Watershed Science Institute
Various guidance
http://www.wsi.nrcs.usda.gov/products/stream.html

NRCS Engineering Field Book
Chapters 16 and 18
http://www.nrcs.usda.gov/technical/ENG/efh.html/

US FWS Fish Passage Website
Http://fisheries.fws.gov/FWSMA/fishpassage/

Stream Repair Practice Manuals

British Columbia

Fish-stream Crossing Guidebook
http://www.for.gov.bc.ca.tasb/legsregs/fpc/FPCGUIDE/guideTOC.htm

California

Salmonid Stream Habitat Restoration Manual
http://www.dfg.ca.gov/nafwb/manual.html

Illinois

Field Manual of Urban Stream Restoration available for purchase from Conservation Technology Information Center
http://www.ctic.purdue.edu/CTIC/Catalog/UrbanManagement.html

Maryland

Guidelines to Waterway Construction
http://www.mde.state.md.us/assets/documents/wetlandswaterways

Massachusetts

River and Stream Crossing Standards: Technical Guidelines
http://www.umass.edu/umext/nrec/pdf_files/guidelines_river_stream_crossings.pdf

North Carolina

Stream Restoration: A Natural Channel Design Handbook
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

Ohio

Stream Management Guides
http://www.ohiodnr.com/water/pubs/fs_st/streamsfs.htm

Ontario

Stream Rehabilitation Manual
http://www.ontariostreams.on.ca/OSRM/toc.htm

Oregon

Aquatic Habitat Restoration and Enhancement Guide
http://www.oweb.state.or.us/publications/habguide99.shtml

Guidelines and Criteria for Stream-Road Crossings
http://www.dfw.state.or.us/ODFWhtml/InfoCntrFish/Management/stream_road.htm

Pennsylvania

Guidelines for Natural Stream Channel Design for Pennsylvania Waterways
http://www.canaanvi/org/nscdguidelines/

Vermont

Stream Geomorphic Assessment Protocols
http://www.vtwaterquality.org/rivers/htm/rv_geoassesspro.htm

Virginia

Stream Restoration and Stabilization Best Management Practices Guide
http://www.dcra/state/va.us/sw/docs/streamguide.pdf

Washington

Integrated Streambank Protection Guidelines
http://www.wa.gov/wdfw/hab/ahg/

Design of Road Culverts for Fish Passage
http://www.wa.gov/wdfw/hab/engineer/cm/

Models and Other Design Resources

US Army Corps of Engineers
Hydraulic Design of Stream Restoration Projects
http://libweb.wes.army.mil/uhtbin/hyperion/CHL-TR-01-28.pdf

HEC_RAS and other Hydraulic Models
http://www.hec.usace.army.mil/publications/pub_download.html

Sediment Impact Analysis Model
http://www.wes.army.mil/rsm/pubs/pdfs/rsm-tn-11.pdf

Geomorphic assessment and channel design
http://www.wes.army.mil/rsm/pubs/pdfs/rsm-tn-12.pdf

Various Stream Classification and Assessment Methods
Wildland Hydrology Consultants
http://www.wildlandhydrology.com/

Assessment Procedures for Identifying Barriers to Aquatic Organism Passage at Road-Stream Crossings
http://www.stream.fed.us/publications/PDFs/NIAP.pdf

Appendix B: Stream Repair Investigation Form

PROJECT:	**DATE:** _____/_____/_____	**ASSESSED BY:**
SUBWATERSHED:	**PHOTO ID** (Camera-Pic#): /#	

USA RCH ID:

START **LAT** ____°____'____" **LONG** ____°____'____" **LMK** _____

END **LAT** ____°____'____" **LONG** ____°____'____" **LMK** _____

CONCEPT NO:

INDEX OF USA FORMS

OT: TR:
ER: SC:
IB: CM:
UT: RCH:

AVERAGE REACH DIMENSIONS (from RCH**)**

BANK OF CONCERN ☐ LT ☐ RT ☐ Both
Length LT_______ft RT________ft
Avg Bank Ht LT______ft RT________ft
Avg Bank Angle LT_____° RT_____°

Avg bankfull height ______ft
Avg bottom width _______ft
Avg top width _______ft
Avg wetted width _______ft

Land ownership ☐ Public ☐ Private ☐ Don't Know ☐ Other:

Available riparian corridor ☐ ≤25 ft ☐ 26 - 50 ft ☐ 51-75ft ☐ 76-100ft ☐ >100ft

CORRIDOR VEGETATION ☐ Mature wooded ☐ Scrub/shrub ☐ Grass or turf ☐ Other:

Degradation severity	**Adjusted channel**: Grade and width fairly stable, with relatively isolated of bank erosion; and poor instream habitat conditions.	**Past downcutting** evident, active stream widening, banks actively eroding at a moderate rate.	**Active Downcutting:** Tall unstable banks on both sides of the stream eroding at a fast rate; erosion contributing significant sediment loads to stream.
	5 4	3	2 1
Upstream/Downstream condition	Upstream and downstream reaches assessed as good or fair.	Either upstream or downstream reach assessed as poor with other assessed as fair/good.	Both upstream and downstream reaches assessed as poor.
	5 4	3	2 1
Construction access to stream	**Good:** Open area in public ownership, sufficient room to stockpile materials, easy stream channel access for heavy equipment using existing roads or trails.	**Fair:** Forested or developed area adjacent to stream. Access requires tree removal or impact to landscaped areas. Stockpile areas small or distant from stream.	**Difficult:** Must cross wetland, steep slope, or other sensitive areas to access stream, Minimal stockpile areas and/or located a great distance from stream section. Specialized heavy equipment required
	5 4	3	2 1
Infrastructure constraints	Sewers or other infrastructure are **not** present in the project reach corridor	Sewers, other utilities or structures are present in the project reach corridor any may constrain project design	Presence of sewers and other infrastructure will greatly impact project design and may require expensive relocation.
	5 4	3	2 1
Restoration Outcome Potential	Repair expected to restore stable, vegetated streambanks using mostly soft stabilization practices, reconnect floodplain, and significantly improve habitat	Repair expected to restore streambank stability with a mix of rigid and soft streambank stabilization practices, and moderately improve stream habitat conditions	Restoration will structurally maintain stable streambanks using predominately hard streambank protection practices, maintain existing sediment transport regime, little habitat improvement
	5 4	3	2 1
Upstream land use	Older (30-40+ yrs), well-established neighborhoods or commercial areas. Little or no new development expected	A mix of older (30-40+ yrs) development and newer (<10-20 yrs) development. Some new development or redevelopment possible	Most of subwatershed has developed in last ten years, and significant future development is possible
	5 4	3	2 1
Upstream retrofit potential	Upstream retrofits expected to significantly reduce stormwater flows to project reach	Upstream stormwater retrofits expected to produce only marginal reductions in stormwater flows and pollutant loads	No upstream retrofit opportunities exist, existing hydrology will not be improved
	5 4	3	2 1
Scope of planned stream repair	**Comprehensive:** major change in planform, grade, or cross-section of channel, many practices	**Moderate**: Combination of individual stream repair practices, but only minor changes in channel dimensions	**Simple**: use of a few stream repair practices to address a problem at a defined point
	5 4	3	2 1

Concept Sketch: Plan View of stream with approximate locations of stream repair practices	**PROPOSED STREAM REPAIR PRACTICES** ☐ A. Rigid Bank stabilization ______________linear feet ☐ B. Soft bank stabilization ______________ linear feet ☐ C. Flow deflection ____________# of structures ☐ D. Grade control ____________# of structures ☐ E. Habitat structures ____________# of structures ☐ F. Flow diversion ____________# of structures ☐ G. Fish passage ____________# of structures ☐ H. Comprehensive ______________ linear feet ☐ I. Other:
Comments on Project Design (include any special supplemental design studies or permits needed)	**Planning Level Cost Estimate**