Indiana Fluvial Erosion Hazard Mitigation Manual

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Cover Photographs:

Top: Yellow River near Knox, Indiana; Northern Moraine and Lake Region
(Photograph by CBBEL, taken October 11, 2016.)

Middle: West Fork White River near Centerton, Indiana; Central Till Plain Region
(Photograph by CBBEL, taken March 26, 2018.)

Bottom: West Fork Whitewater River near Brookville, Indiana; Southern Hills and Lowlands Region
(Photograph by CBBEL, taken March 11, 2017.)

PREFACE

This manual is directed to project engineers, technical professionals, and owners involved in the design and construction of fluvial erosion hazard mitigation projects, also referred to as bank stabilization or rehabilitation. The intent of this manual is to provide direction to experienced design professionals so that any modifications made to the stream maintain or improve the stability of the waterway and protect the interests of the owner.

The majority of information given in this document is general and provides many of the technical principles used throughout the country. The designer must be a suitably educated and trained professional that has experience in this field to properly apply these guidelines to the specifics of the site and the needs of the owner.

These guidelines were modeled after the following notable references on the same topic from state and federal organizations. Additional references are cited throughout the document:

Virginia Stream Restoration & Stabilization Best Management Practices Guide
Stream Corridor Restoration: Principles, Processes, and Practices - FISRWG
Channel Restoration Design for Meandering Rivers – USACE
Part 654 National Engineering Handbook: Stream Restoration Design – NRCS
A Function-Based Framework for Stream Assessment and Restoration – EPA

A team of 6 professionals, including 5 engineers from Christopher B. Burke Engineering, LLC (CBBEL) and a research scientist from the IUPUI Center for Earth and Environmental Science, contributed significant time to the development of this manual. These individuals are listed below:

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The Office of Community and Rural Affairs (OCRA) provided the funding for the project and the Indiana Silver Jackets oversaw the project; the support of these two organizations for this project and their long-term commitment to reducing the risk and impacts of fluvial erosion in Indiana are appreciated.

Stuart G. Walesh, Ph.D., P.E., Dist.M.ASCE, F.NSPE provided an external edit of the manual.

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EXECUTIVE SUMMARY

Fluvial erosion hazards (FEHs) are caused by the erosion of streambanks and floodplains during floods and are a significant concern in areas where human development and infrastructure are near natural waterways. The Indiana Silver Jackets hazard mitigation task force undertook the development of the FEH program for the State of Indiana. The purpose of the FEH program is to provide tools and guidance for FEH hazard planning and mitigation. To date, three phases have been completed in support of the FEH initiative that have developed a scientific body of data, tools, and methods. Phase 3 of the program includes the development of this document, a practical guide to mitigating FEHs in the State of Indiana.

A broad overview of the concepts of stream stability and fluvial geomorphology is provided to set the stage for the recommended analyses and design methodology for FEH mitigation. This summary is only intended to provide a generalized understanding of the topic and does not provide the depth of information necessary to educate oneself sufficiently to be a responsible designer of FEH mitigation projects. FEH mitigation projects should only be designed by qualified and experienced professionals.

The first step to addressing a FEH is the data gathering and problem identification phase. Truly understanding the root cause(s) of instability in a stream is the only way to address the issue in a sustainable way without negative impacts to adjacent stream reaches. Site and watershed assessments are included to provide important local- and regional-scale data. This information is used to determine if the primary cause(s) of the instability lie in the area providing runoff to the stream or within the stream itself. The process provides a wealth of information to practitioners about how the stream system functions. The information is used to educate stakeholders who then, with the guidance of the designer, assist in crafting and prioritizing a set of mitigation objectives.

Once the objectives for the project are set, additional analyses and calculations are completed to provide a baseline for assessing the impact and determining the details of potential improvements. The improvement considerations should include all aspects of stream function: hydrologic, hydraulic, geomorphic, physiochemical, and biological functions. Common methods and best management practices (BMPs) for addressing instabilities are provided and categorized as passive or active management strategies. Passive management strategies, which seek to modify the inputs of water and sediment into a stream, are discussed on the basis of agricultural and urban land uses. Active management strategies, which affect physical changes within the river corridor to improve stability, are provided with respect to the type of instability present in the stream. The methods and recommended BMPs have been selected based on their applicability to Indiana streams.

Practitioners must select and integrate the mitigation components necessary to meet the project objectives to the greatest extent that is both practicable and advisable. The anticipated performance of the alternatives, relative to the stated objectives, must be assessed. A number of practical considerations should then be evaluated to strengthen the ability of the project to be implemented with minimal difficulty. The stakeholders and designer then evaluate the proposed alternatives using the anticipated performance, with regard to social, environmental, and economic factors, to select an alternative.

Proper implementation, management, and maintenance are critical for the long-term success of a project. This document provides designers and stakeholders with the guidance necessary to implement both passive and active management strategies. The discussion includes explanation of the key components to project implementation and the need for an adaptive management strategy to complete post-construction monitoring and maintenance, which can promote the long-term success of FEH mitigation projects.

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GLOSSARY

The terms in this glossary were compiled from numerous sources. Some definitions have been modified for use within this report.

Active river management – Man-made adjustments within the riparian corridor meant to affect a positive change in the condition of the stream.

Adaptive management – An approach to management that addresses changing site and project conditions, as well as making revisions and refinements to ongoing management and operations actions based on new knowledge gained from monitoring project outcomes and results.

Aggradation – The process in which a steam's gradient is increased as a result of an increase in sediment deposition. This may occur as a result of an increase in relative sediment load or a decrease in relative flow.

Alluvial stream – Streams and channels that have bed and banks formed of material transported by the stream under present flow conditions; channels where the boundaries are altered in response to changes in discharge and sediment supply.

Bankfull channel – The natural waterway that contains the flow at and below the bankfull stage, also referred to as the active stream channel.

Bankfull discharge – The water discharge that completely fills the active channel just prior to overflow spilling onto the floodplain. The flow in the channel when the unimpeded water level is at the bankfull stage.

Bankfull stage – The elevation (or level) on a channel bank that defines incipient flooding.

Bankfull width – The width of the water surface in the active channel, measured at bankfull discharge and perpendicular to flow.

Bed material – The geologic materials found in the boundary—bed and banks—of a stream channel.

Bedload – Material transported by a stream through the processes of rolling, sliding, and saltation. Also, sediment particles that, when moved by the action of streamflow, are in frequent contact with the streambed.

Channel-forming discharge – The concept that for any alluvial stream, there exists a single discharge that, given enough time, would produce the width, depth, and slope equivalent to those produced by the natural distribution of flow in the stream. This discharge, therefore, dominates channel form and process.

Degradation – The process in which a stream's gradient is decreased as a result of an increase in flow and subsequent erosion/scouring and transportation of channel sediments from the stream bed. This may occur as a result of a decrease in relative sediment load or an increase in relative flow.

Deposition – The settling of material following a period of erosion and transportation, also referred to as sedimentation.

Drainage area – The land-surface area that contributes runoff to an identified point of interest, synonymous with 'contributing watershed'

Dynamic equilibrium – A condition where a stream experiences sediment continuity, in terms of both quantity and size of sediment transported, and the processes of bank erosion and channel migration occur only gradually, such that the shape, profile, and planform patterns remain similar over time. Also referred to as geomorphic equilibrium.

Effective discharge – The discharge responsible for the largest volume of sediment transport over a long period of record, as determined by statistical analysis of flow and sediment capacity/load; typically, in the range of a 1- to 3-year flood event, and in many settings has been shown to correspond to the bankfull discharge.

Erosion – The loosening and subsequent transportation of material by means of water, air, and/or gravity.

Floodplain – The flat area of land adjacent to a channel which, within the current climatic regime, has been constructed by processes associated with the stream, and is subject to recurring inundation.

Fluvial – Of, or pertaining to, rivers and streams. Also, the landforms, geologic deposits, and processes associated with the actions of flowing water.

Fluvial erosion hazard – The suite of risks to structures, property, and infrastructure elements that are brought about by the natural processes of stream-bank erosion and stream-channel meandering.

Geomorphology – The branch of geology that studies the landforms of the earth's surface and the processes that shape them.

Lateral migration – The process by which the channel banks of stream change horizontal location, resulting from erosion from the outer bank and deposition on the inner bank.

Meander – The naturally-occurring curves of a stream or river deviating from an otherwise linear course.

Meander belt width – The distance between lines drawn tangential to the extreme limits of fully developed meanders.

Passive river management – The use of watershed-based improvements to provide a benefit to the stability and/or health of the stream, or the non-structural removal of stressors within the riparian corridor.

Physiographic region – An area of common geologic materials, topographic character, and geomorphic history.

Point bar – The inner edge of a stream meander where deposition is continually occurring and sediments are deposited and stored within a fluvial system.

Project delivery method – A system used by an owner for organizing and financing design, construction, operations, and maintenance services for a project by entering into legal agreements with one or more entities.

Regional curves – Plots established to show the relations between drainage area and the bankfull-channel dimensions of width, mean depth, and cross-sectional area.

Riparian buffer – Any vegetated area located immediately adjacent to a stream that separates and protects the stream, and its associated habitat, from any alternative land uses. Benefits may include the decreased surface runoff from urban or agricultural areas and reduction of fluvial erosion hazards as a result of increased bank stability. Also referred to as the riparian corridor.

Rosgen channel classification – A system of describing river channels based on channel geometry, stream plan-view patterns, and streambed material.

Scour – Erosion of the channel boundary that results in a lowering of the boundary. Also, the process by which flow in the channel removes all surface vegetation.

Sediment – Any granular mineral or organic matter of any size in a stream channel, typically characterized as boulders, cobbles, gravel, sand, silt, or clay.

Sediment capacity – The maximum amount of sediment flow that can occur for a given water discharge in a stream reach; distinct from sediment load for streams that have a higher sediment capacity than what is delivered to the reach.

Sediment competence – The largest sediment size that can be mobilized by the discharge in a channel.

Sediment continuity – A state of equity in the inflow and outflow of sediment from a stream reach, whereby the volume of sediment deposited in or eroded from a reach during a given period of time is equal.

Sediment load – The total amount of sediment transported in a stream, whether in suspension in the water column (suspended load) or in contact with the bottom (bedload).

Sinuosity – The ratio of channel length divided by the straight-line valley length between two end points that define a channel reach. A measure used to describe the amount a channel meanders.

Stressor – A physical or transient condition that contributes to or causes a disruption in dynamic equilibrium.

Suspended load – Material transported by a stream that is held within the water column by turbulence and rarely comes into contact with the channel bed.

Threshold channel – A channel in which channel boundary material has no significant movement during the design flow. The term threshold is used because the channel geometry is designed so that applied forces from the flow are below the threshold for movement of the boundary material.

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CHAPTER 1 INTRODUCTION

While many stream restoration manuals and erosion control guides are available to provide guidance on streambank erosion methods, this document focuses on identifying, categorizing, and mitigating fluvial erosion hazards in the state of Indiana using current best management practices. The key to the approach outlined in this manual is understanding that managing streambank erosion requires knowledge of why the erosion is occurring. The manual assumes that the user has a basic understanding of fluvial geomorphology, general engineering concepts, and stream function to manage fluvial erosion so that fluvial erosion hazard mitigation minimizes adverse impacts to the stream itself as well as other assets within the stream corridor.

Figure 1-1: Typical Example of a Fluvial Erosion Hazard (IDHS)

This manual is a product of the Indiana Fluvial Erosion Hazard (FEH) Mitigation Program, a program developed by the Indiana Silver Jackets (ISJ) in response to flooding that occurred in Indiana in 2008. That flooding caused three fatalities, major transportation disruptions, damage to thousands of homes and businesses (as illustrated in Figure 1-1), damage to dozens of dams and flood-control structures, and damage to critical facilities, including utilities and two hospitals (Shipe, 2008; Morlock et al., 2008). As part of the state of Indiana's response to these losses, the ISJ suggested a series of related efforts to understand better both inundation hazards and erosion hazards. This manual is a continuation of that effort.

1.1 INDIANA FEH PROGRAM OVERVIEW

Damages resulting from inundation of flood waters can lead to substantial losses. Inundation damages are not the only flood-related hazard associated with rivers, streams, and floodplains. FEH, the hazard caused by the erosion of streambanks and floodplains during floods, also represents a significant concern in areas where human development and infrastructure are near natural waterways. To address this issue, the ISJ hazard mitigation task force undertook the development of the FEH program. The ISJ believes that the FEH program fills a critical gap in hazard planning and mitigation for Indiana and, therefore, needs to be a long-term effort.

> "…approximately one-third of the nation's streams experience severe erosion problems."
>
> *-NRC, 1999*

1.1.1 Fluvial Erosion Overview

In a 1999 report, the Federal Emergency Management Agency (FEMA) reported that in the U.S., "approximately one-third of the nation's streams experience severe erosion problems" (NRC, 1999). Total annual damage in stream reaches with severe erosion problems was estimated at $450 million (in 1998 dollars), with total annual treatment costs estimated to be more than $1 billion. Treatment costs may include, among others, costs for cleaning debris and sediment deposits from the channel after a flood; repairing or replacing bank armoring or other treatments designed to stabilize the channel; and damage to other superstructure elements intersecting with the channel, such as bridges, storm drain outlets, or buried utility lines.

Damage from fluvial erosion can be more serious than flood inundation damages in several ways. First, fluvial erosion can affect structures located outside, as well as inside, the regulatory floodplain, and elevating structures above the 100-year base flood elevation may not provide adequate protection from erosion damages. In addition, erosion cannot only damage a structure, it can completely remove the land underneath the structure, making it impossible to rebuild on the site. Finally, riverine erosion damage can occur not only during a single, large flood event, but may also occur during smaller, long-duration floods, or from the cumulative impacts of a series of small floods over a long time period.

Because of human activity, many streams have been significantly altered. This is especially true for streams located in or near urban areas, streams in areas of intensive agricultural activity, and streams along major transportation corridors. Such altered streams may be more vulnerable to damage from erosional and depositional processes (ASFPM, 2016).

1.1.2 Previous FEH Phases

To date, there have been three phases of the Indiana FEH Program. The first phase included development of science-based tools for identifying and assessing FEHs for stream reaches, FEH screening tools for identifying erosion concerns at bridge crossings, a series of educational presentations and workshops to educate the community, and some example FEH mitigation protocols. Phase 1 was carried out by a team consisting of the Indiana University-Purdue University Indianapolis (IUPUI) Center for Earth and Environmental Science (CEES), the Polis Center at IUPUI, and the U.S. Geological Survey (USGS). The results are published, as shown by Figure 1-2, in *Regional Bankfull-Channel Dimensions of Non-Urban Wadeable Streams in Indiana* (Robinson, 2013a).

Phase 2 of the FEH program builds on the science, tools, and methods developed in Phase 1. New tasks in Phase 2 included the development of regional scale maps showing potential FEH zones along Indiana streams and rivers. The maps are available from the Indiana Department of Natural Resources InDNRMaps Web Application (ISJ, 2018). Additional Phase 2 products included continued and expanded outreach and education activities; continued and expanded risk assessment activities such as enhancement of State and local multi-hazard mitigation plans; and development of new science-based tools to identify and document methods for measuring bank erosion rates and an erosion-monitoring network. Some of the results from Phase 2 are found in two USGS publications, *Channel Migration Rates of Selected Streams in Indiana* (Robinson, 2013b) and *Vulnerable Transportation and Utility Assets Near Actively Migrating Streams in Indiana* (Sperl, 2017)

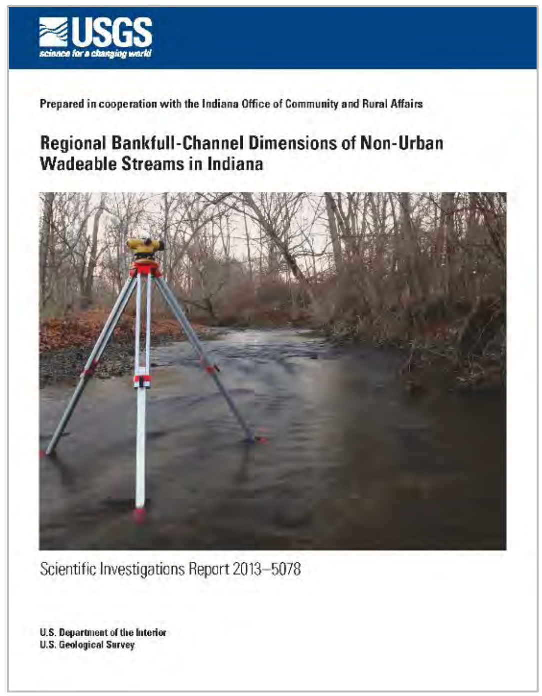

Figure 1-2: Regional Bankfull-Channel Dimensions of Non-Urban Wadeable Streams in Indiana
(Robinson, 2013a)

The message of Phase 2 was hazard avoidance. However, avoidance is not always an option. There are numerous areas around the state where historic buildings, infrastructure, and legacy problems require exploring and developing options for protecting structures and infrastructure while minimizing impacts to the stream system.

Phase 3 of the FEH program focuses on how to best mitigate the fluvial erosion hazard in areas where avoidance is not feasible, acceptable, or is cost prohibitive, and how to evaluate best methods for protecting structures and infrastructure, while striving to minimize impacts on the stream system. This manual is a product of that effort. The evaluation of erosion mitigation measures frequently will require engineering design and oversight. Therefore, the FEH Team for Phase 3 includes representatives from Christopher B. Burke Engineering, LLC (CBBEL) to confirm that the methods presented reflect best engineering practices. CBBEL staff have worked closely with the ISJ because of the firm's familiarity and work history with Indiana streams as well as their leadership role in the Association of State Floodplain Managers (ASFPM) and the Indiana Association for Floodplain and Stormwater Management (INAFSM).

1.2 PURPOSE AND OBJECTIVES

The primary goal of this document is to provide guidance for best practices to mitigate stream erosion in areas where it may lead to damage to property and infrastructure. The manual provides guidance for problem identification, study reach selection, alternative analysis, project implementation, monitoring and maintenance, and supporting documentation. That guidance will help design professionals make decisions that will minimize adverse impacts to the stream as well as other assets within the stream corridor.

1.3 DOCUMENT USE AND LIMITATIONS

This document is intended to be a guide to addressing stream erosion occurring along Indiana rivers and streams. It assumes the reader has knowledge of regional hydrology and geology, and a background in fluvial geomorphology and/or water resources engineering. Success requires the correct application of the techniques and methods described in this manual.

This document is not a guide to stream stabilization, rehabilitation, restoration or naturalization (hereafter referred to as stream restoration). A large body of literature defines stream restoration and the various methods and goals of stream restoration. This manual focuses on one aspect of stream restoration, managing streambank erosion where infrastructure and other assets might be threatened.

1.4 REFERENCES

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CHAPTER 2 FLUVIAL EROSION HAZARD CONCEPTS

Understanding the origination of the FEH program and steps taken to date lay the groundwork for further exploration of FEH concepts. Chapter 2 defines FEHs and the concept of stream stability and then discusses approaches to reducing FEHs.

2.1 DEFINITION

Not all fluvial erosion constitutes a FEH. A stream naturally meandering across a floodplain is not necessarily a hazard unless the meandering stream encounters some aspect of the built environment: a bridge, road, utility line, etc.

A common feature among most FEHs is they are constructed in a floodplain, an area that was shaped and formed by the river and will continue to be used by the river. The idea that a river will need room to move and adjust is not new. Many problems associated with building and development in floodplains have been discussed for decades (White, 1945; Dunne and Leopold, 1978). The discussion about erosion hazards is more recent; a white paper about the problems associated with FEHs and the continuing development of FEH programs around the country was recently released by the Association of State Floodplain Managers (ASFPM, 2016).

Though not all damage to the built environment in the floodplain is a result of erosion, it is commonly the significant cause of damage to infrastructure. In Indiana, over $10 billion in damages and 55 deaths have occurred since 1984, with major events in 2008 and 2013 disproportionately contributing to the total damages (NOAA, No date). A study by Morlock et al. found that the major flooding event in central Indiana in 2008 damaged “more than **650 roads, more than 60 bridges, approximately 100 culverts** (emphasis added), more than 100 dams and levees, and 56 water supply or wastewater-treatment facilities” (Indiana Office of Disaster Recovery, 2008). Note that the bold text highlights the infrastructure most frequently damaged or destroyed by fluvial erosion. One significant difference between the damage due to inundation and FEHs is that the erosion hazard frequently destroys the structure, or part of it as illustrated in Figure 2-1, during the flood event.

Figure 2-1: East Fork White River near Vallonia, Indiana
(IDHS, 2017)

2.2 STREAM STABILITY

Stream stability is a fundamental concept in fluvial geomorphology. There are many definitions, but one of the most frequently used is by Dave Rosgen, P.H., Ph.D.:

"*Stability is defined as a river or stream's ability in the present climate to transport the stream-flows and sediment of its watershed over time in such a manner that the channel maintains its dimension, pattern, and profile without either aggrading or degrading*" (Rosgen, 1996, 2001b).

In the above definition, aggradation is the raising of local channel bed elevation due to depositional processes and degradation is the lowering of local channel bed elevation because of channel incision processes.

Compare Rosgen's definition of channel stability with the Figure 2-2 illustration by Lane:

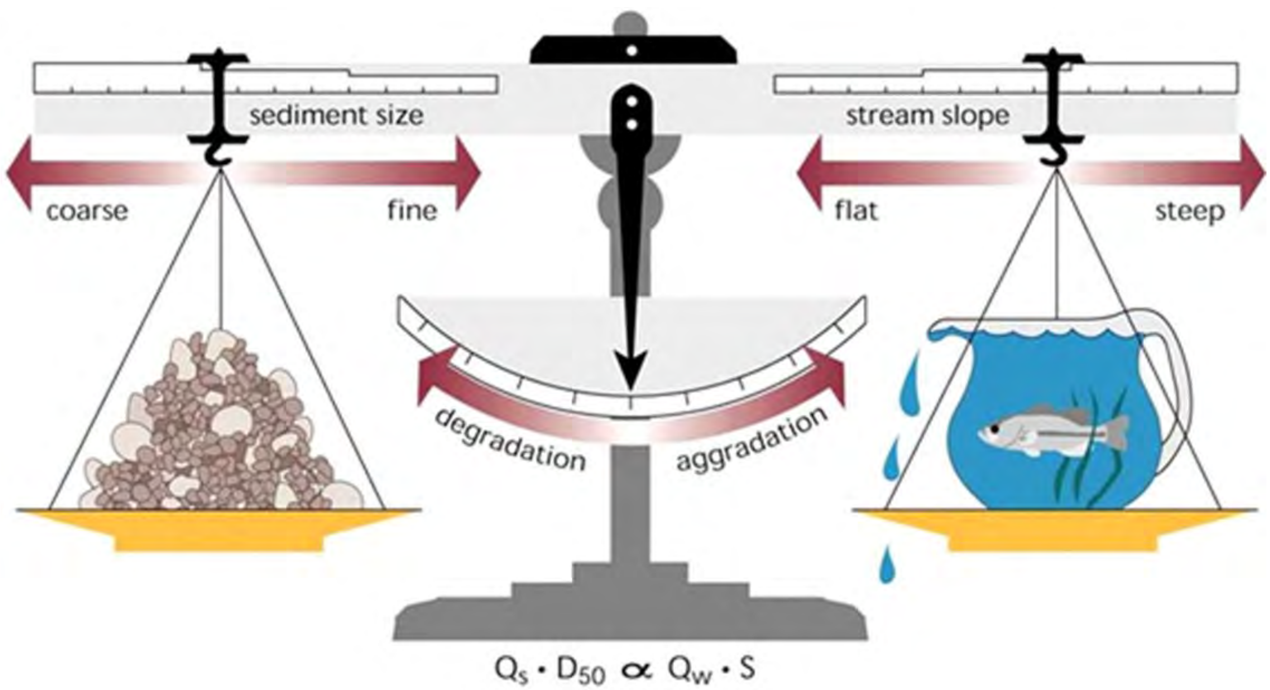

Figure 2-2: Lane's Balance
(USFWS, after Lane, 1955)

In Lane's diagram, sediment supply and size are shown on the left arm of the balance beam and stream flow and channel slope on the right arm. Lane's equation at the bottom of Figure 2-2 explains that the supply of sediment, and the mean grain size of the sediment (D_{50}), are proportional (or balanced) with the stream's discharge and slope. Note the similarity between Lane's equation and Rosgen's definition. Rosgen adds "in the present climate regime" to his definition; others will include climate in a statement about time. However, most definitions of channel stability share the fundamental concept of ability to transport sediment through a wide range of stream discharges without long-term changes to the channel. For a more complete discussion of "channel stability," see Rosgen 2001b.

Although not all fluvial erosion constitutes a FEH, a fluvial hazard often occurs because a building or some type of infrastructure is placed too close to a moving, or meandering, river or stream. While not all stream and river types meander, it is the dominate pattern (Leopold, 1994), and it is the pattern most common in FEHs. Meandering streams erode channel materials on the outer bend of the meander, and deposit on the inner portion of the meander, in what is often a very orderly pattern.

A stable meandering stream will demonstrate relationships between meander wavelength, channel width, and its radius of curvature. The sequence of erosion and deposition allows the stream to transport sediment, a primary function of the stream or river and a fluvial process often neglected in flood and hazard assessments. Because there are well-defined relationships between channel width, meander wavelength, and radius of curvature defining instability is frequently easier than defining stability in a channel. Meandering streams naturally erode which often causes confusion about how much a stream should be eroding, and whether it is eroding enough for concern.

The challenge for the practitioner trying to address a potential FEH is understanding when the stream system is stable, and the hazard is a result of a localized problem, and when the perceived hazard indicates a 'systemic' instability in the stream system. An instability is 'systemic' if the problem is pervasive in a substantial portion of a river system. The potential solutions for localized problems and systemic issues will likely be different.

The images in Figure 2-3 show a meander in the White River near Centerton, Indiana. Erosion of the outer bank is apparent in the two images, as is the growing deposition of sediment on the point bar, and the power line to the northwest provides a location reference. In these two images, the White River moved 290 feet in 5 years, or on average 58 feet per year (ft/yr). The challenge for fluvial hazard studies is often to determine whether the observed rate of erosion indicates that the stream or river is unstable. For example, in the case of the White River near Centerton, is the observed rate of erosion comparable to other nearby meanders?

Figure 2-3: White River near Centerton, Indiana

That question can be answered by looking at the river's planform and measuring meander migration rates, or in Indiana, by looking at the USGS publication *Recent (circa 1998-2011) Channel Migration Rates of Selected Streams in Indiana* (Robinson, 2013b). In that report, the Centerton meander in the above pictures is designated WHITER 47. From 1998 – 2012 that meander had a migration rate of 35.4 ft/yr. The two meanders upstream of that location had migration rates of < 1 ft/yr and the two meanders downstream of it had rates of 12.7 and 9.7 ft/yr. These data suggest that the Centerton meander had a meander rate much higher than any of the other meanders in that reach. Leopold and Rosgen noted in their field investigations that meandering, or lateral migration, rates from 3-4 times the average in a study area often indicate instability (Rosgen, personal comm. 2017). The data also suggest that the problem is a localized adjustment, because the meanders above and below the Centerton meander are moving less than would be predicted.

Another indicator of stream instability is found in the relationship between bankfull width and channel meander belt width. The relationship between meander wavelength, channel width, and its radius of curvature, and the relationship between channel bankfull width and meander belt width are critical to the Indiana FEH program. Earlier work on meandering rivers around the world documented that meandering, low-gradient, rivers tended to have a meander belt-width (MBW) ranging from 4 to 10 times the bankfull width of the channel (W_{bkf}), and that for most rivers the W_{bkf}/MBW ratio was near 6 (Williams, 1986). The measured

MBW on the Centerton meander in the 2010 image above was 2,500 feet, over 10 times the bankfull width of the channel at that location. Both the lateral migration rate and the MBW point to a localized problem with the Centerton meander.

Figure 2-4 below shows the importance of time, particularly with localized problems. The location of the channel banks in 2005 have been superimposed in blue on the 2017 aerial photography to show the adjustment of the Centerton meander. As can be seen in Figure 2-4, the MBW has returned to a condition that is closer to what is expected for a stable stream; however, the river still exhibits obvious signs of instability.

Figure 2-4: Comparison of White River Bank Locations for 2005 (blue) and 2017
(Google Earth)

2.3 APPROACH

The primary approach to reducing FEHs is avoidance. The state of Indiana, with guidance and support from the Vermont River Management Program, has led the nation in the mapping of regional FEH zones. The State produced maps for the 82 counties that had disaster declarations following the 2008 floods. Work on the remaining 10 counties is expected as funding becomes available.

The regional FEH zone maps are designed to serve as a resource for communities that would like to adopt FEH avoidance strategies. These maps enable individuals and communities to better recognize areas prone to natural stream-erosion processes and adopt strategies to avoid FEH-related risks. The regional FEH zone maps feature approximate setbacks for communities to better manage river corridors. The setbacks vary based on the stream's recent migration history (actively migrating or relatively stationary).

For actively migrating and relatively stationary streams, a GIS analysis algorithm generated bankfull width values for each stream segment using regional curves based on drainage area within each physiographic region in Indiana. For relatively stationary streams, the analysis used these values to create buffer zones of at least one bankfull width on each side (a total corridor width of 3 times bankfull width) or 100 feet on each side of the centerline, whichever is greater. For actively migrating streams, a total corridor width of 8 times bankfull width was generated using the algorithm, which was then manually edited and refined to reflect the local topography and evidence of prior stream migration.

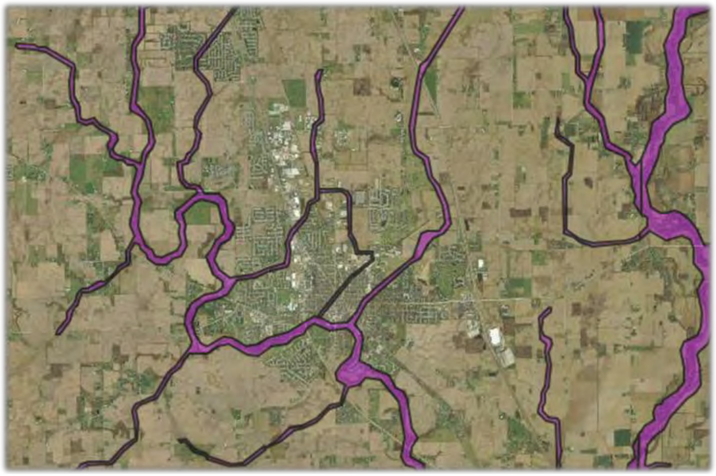

Figure 2-5: FEH Corridor Map
(ISJ, 2018)

The refined corridors were created at a map scale of approximately 1:10,000 to 1:15,000. The depicted areas, as illustrated in Figure 2-5, are not meant to be accurate beyond providing an approximate boundary of potential stream migration. These data are provided for informational purposes only and are not intended for use in project design or parcel-level site analyses. The proper evaluation of the FEH at a specific site requires a more detailed analysis of the local geology and fluvial mechanics.

Local counties and communities wishing to adopt these maps as the basis of their erosion hazard mitigation programs would need to establish guidelines and protocols to allow the acceptance of more detailed procedures and data than that used as part of the Indiana Silver Jackets erosion hazard mapping program. The Indiana FEH Regional Scale Maps are hosted by the Indiana Department of Natural Resources and are available at:

https://indnr.maps.arcgis.com/apps/webappviewer/index.html?id=43e7b307a0184c7c851b5068941e2e23

If avoidance is not possible, which is frequently the case with legacy issues, then the goal is to mitigate the hazard without simply transferring the problem upstream or downstream. Chapters 3 through 5 in this manual describe a recommended approach for assessing a potential issue, and case studies in Appendix 2 will describe the approach in practice.

2.4 REFERENCES

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CHAPTER 3 DATA GATHERING & PROBLEM IDENTIFICATION

3.1 INTRODUCTION

Quality data are critical to understanding the root cause of a problem. Inaccurate or insufficient data can lead to incorrect conclusions.

Collection of both local, reach-scale, and watershed-scale data is an important step to a full understanding of the study site's issues. Some sites may exhibit only local instability, others may be plagued with watershed-driven issues, and some may exhibit a combination. Each situation requires a different approach, which can be used only if the designer is aware of factors influencing the channel.

Avoid coming to a premature conclusion. Sometimes the practitioner should develop multiple working hypotheses throughout the data collection so as not to make conclusions based on one kind or set of data. Cast a wide net (collect all the data) and use multiple data points to corroborate the hypothesis that appears most likely to be true. The following sections describe the data collection and problem identification process.

3.2 SITE ASSESSMENT

A site assessment is necessary to foster a clear understanding of the problem(s) to be addressed and constraints on the solutions. Desktop analyses alone are not sufficient, despite high-resolution aerial imagery and topography. Though this information is often relatively current, the mere fact that an investigation is being completed is a sign that the stream is changing at an accelerated rate. This means that in the context of the project, the aerial imagery is usually out-of-date. Being physically present on a site allows for simultaneously assimilating many types of data, rather than looking at each dataset independently.

Though desktop analyses cannot provide a complete picture on their own, these analyses can aid in providing context for a site assessment. This foundational knowledge of the stream facilitates interpretation of the data during the site assessment.

The overall goal of a site assessment is to help identify reach-scale stressors and to develop a context for the potential improvements to the channel.

Many factors should be considered during the site assessment. The following sections provide guidance on the most important observations and analyses to be performed; however, specific site qualities and constraints should be considered to expand or exclude the site assessment components. The overall goal of a site assessment is to help identify reach-scale stressors and to develop a context for the potential improvements to the channel.

3.2.1 Reach Limits

In the course of planning a site assessment, identify a preliminary study reach. The study reach should extend beyond the impaired site, which includes any endangered structures, eroded banks adjacent and connected to an endangered structure, and adjacent [often steep] slopes that contribute runoff and/or groundwater, sediment, and/or woody debris. The study reach should extend sufficiently upstream and downstream to include observations of channel conditions that have an impact on the condition of the project site. Typically, the initial study reach should extend upstream and downstream of the site by 10 to 12 times the approximate bankfull width, for a minimum study reach length equivalent to 20 to 25 times the bankfull channel width (Rosgen, 1996). An approximate bankfull channel width can be determined preliminarily by using Indiana regional curves (Robinson, 2013a).

After completion of the site assessment, the study reach limits can be adjusted, as needed, based on a more thorough understanding of the contributing factors for the channel/bank instability. Figure 3-1 shows a schematic of the recommended preliminary reach limits.

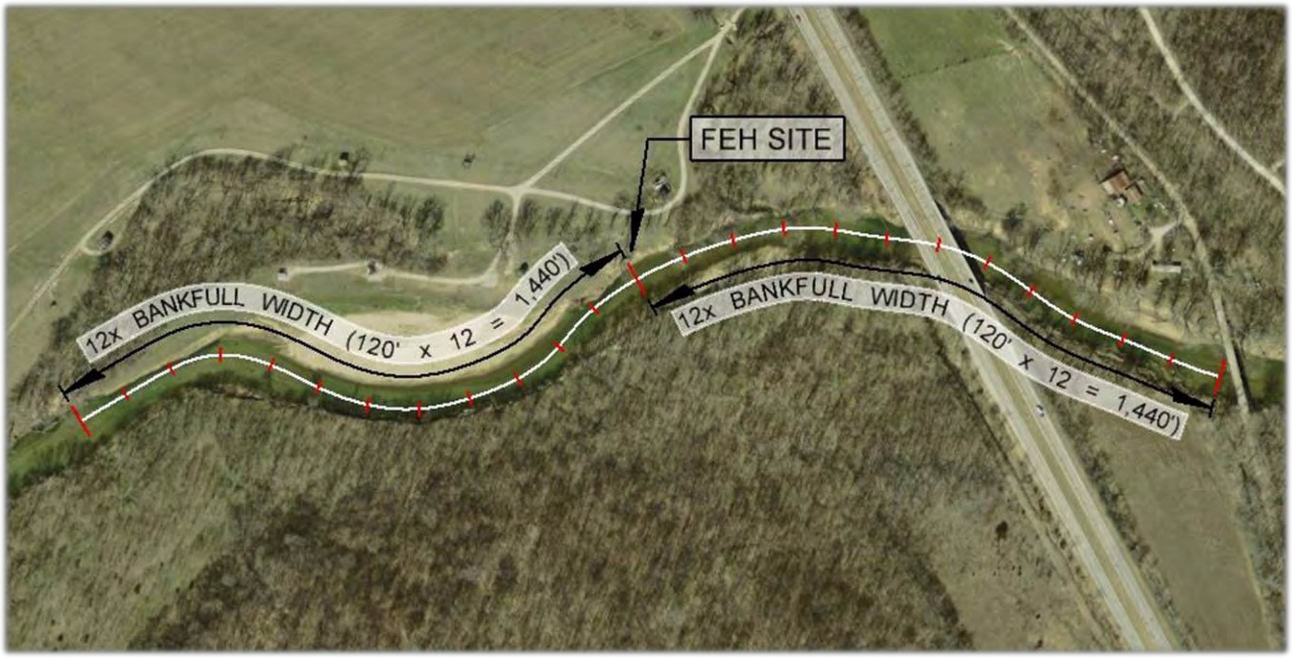

Figure 3-1: Preliminary Reach Limits Schematic

3.2.2 Risk to Infrastructure

One of the most frequent reasons for considering stream stabilization is a perceived threat to private or public infrastructure. Therefore, identify all locations where infrastructure is present along the study reach. Regardless of whether infrastructure is being threatened within the study reach, as shown in Figure 3-2, begin to consider ways to avoid or protect it when developing solutions. Infrastructure that is in danger of impairment due to fluvial instability is typically easier to identify. However, recognize that the stream in question may be a mobile stream that could eventually threaten infrastructure that at one time appeared to be a safe distance away. Also consider the potential future changes to the stream because of potential improvements. Since the improvements have not been developed and detailed at this stage, simply document the locations of utilities and infrastructure within the broader stream corridor.

Figure 3-2: Infrastructure at Risk due to a FEH
(Daily Herald, 2017)

The locations, type, and extent of some infrastructure may not always be apparent; as such, public utilities along the study reach should be located, at a minimum. If substantial private utilities are anticipated due to the location of significant above-ground private infrastructure, locating private utilities may also be warranted.

3.2.3 Habitat Quality and Availability

Habitat quality and availability are often good indicators of how impaired a stream is in terms of the hydrology, hydraulics, geomorphology, and water quality/chemistry. Harman and others developed a functional pyramid to illustrate how stream functions are interrelated and generally build on each other in a specific order, a functional hierarchy, and to define parameters that can be used to assess those functions (Harman et al, 2012). The functional pyramid, shown in Figure 3-3, helps demonstrate that if a stream has a robust, diverse, and situationally appropriate ecology, the stream is unlikely to be threatened. Similarly, if the availability and quality of habitat are poor and the flora and fauna are dominated by situationally inappropriate or invasive species, the stream is probably not functioning naturally on the other tiers of the pyramid.

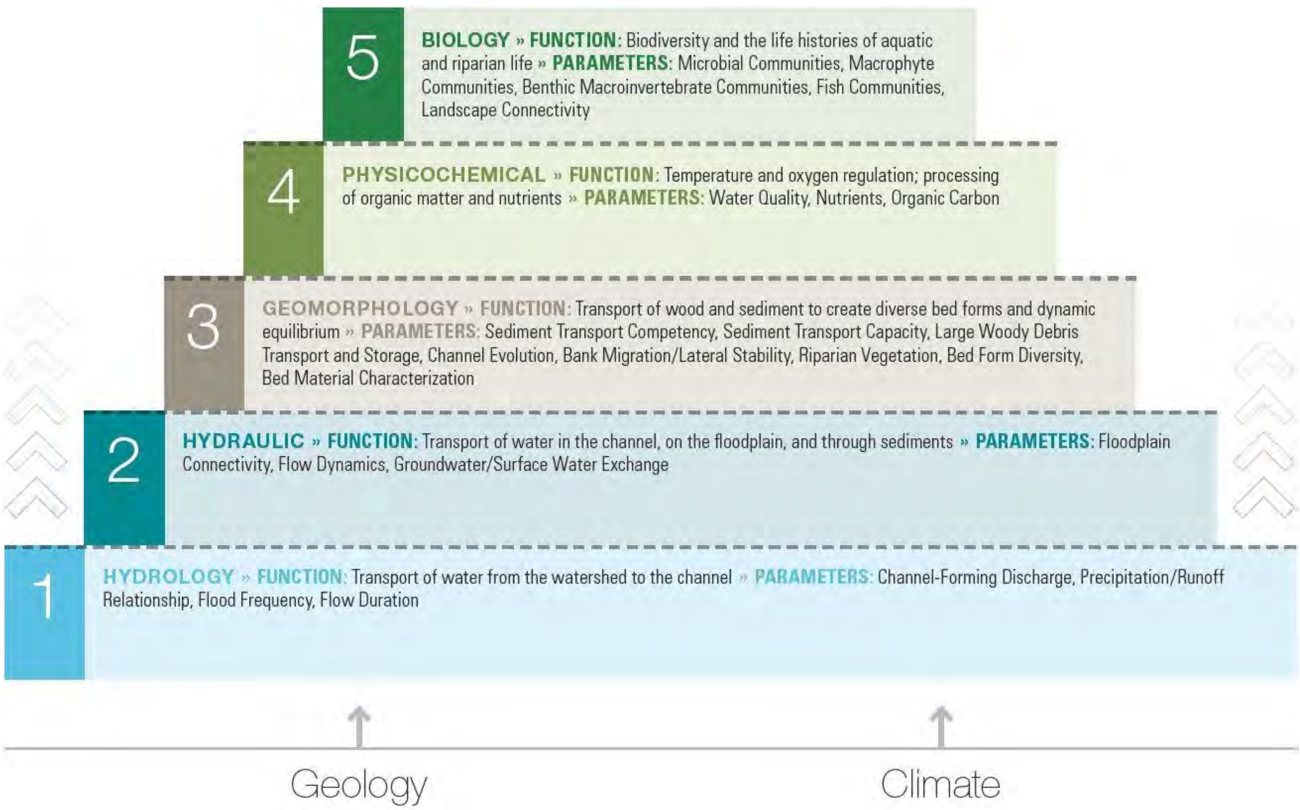

Figure 3-3: Stream Functions Pyramid
(Harman et al, 2012)

Figure 3-4: Collection of Field Data for QHEI

Document the quality and availability of habitat and diversity of flora and fauna to serve as an indicator of the level of impairment, as well as to establish as a baseline for future comparison. The comparison to post-project observations can determine how effective the project was at achieving the erosion mitigation objectives.

The most common method for completing the evaluation of instream habitat, as suggested by Figure 3-4, is use of the Qualitative Habitat Evaluation Index (QHEI). Additional evaluation of the riparian buffer area may be warranted if a FEH mitigation project may be implemented in the study reach.

3.2.4 Culturally & Historically Sensitive Areas

Throughout history, civilizations often developed next to a water source. For example, many of the largest cities in the United States are centered on major waterways or water bodies. This has a two-fold effect in terms of stream stability:

First, the presence of development and human activity near a stream increases the likelihood that the stream will be impaired in some fashion, thus increasing the probability that a stream will ‘need’ to be stabilized and/or restored.

Second, the frequency of near-water human occupation also increases the likelihood that historic or cultural artifacts are present along a stream or waterbody. The practitioner should consider the preservation of culturally or historically sensitive areas, as shown in Figure 3-5, during the assessment and improvement process.

Figure 3-5: Historical Artifacts along Waterways
(Brendan Fenerty)

A formal archeological investigation may not always be required from a regulatory or funding standpoint but may need consideration given knowledge of the adjacent area. Communication with the local historical society can provide insight about the likelihood of encountering cultural resources in or near the study reach. The proximity of other historically sensitive areas may provide a clue as to whether there may be artifacts and/or sites of interest within the study reach.

3.2.5 Site Constraints

Public and/or private infrastructure, as illustrated in Figure 3-6, as well as culturally and historically sensitive areas, may serve as constraints on the extent of the potential improvements to the stream. Environmentally sensitive areas, difficult topography, buildings, watershed connectivity, and property ownership may also present constraints on the potential improvements to the stream.

Figure 3-6: Difficult Site Access
(Hamilton County, 2017)

Identify all site constraints during the data gathering and site assessment phase to allow for prudent consideration of the project extent when considering improvements. Consider not proceeding with the project if site constraints cannot be relocated or avoided without compromising the proposed stream improvements. Chapter 5 provides additional detail about dealing with site constraints. Without concrete knowledge of site constraints in the beginning stages of the project, the quality of the ultimate design may be compromised.

Identification of site constraints may also provide insight into the final extent of the study reach. If a site constraint can only be accommodated by extending the study reach, that must be known prior to the completion of the site assessment to allow the project team to collect the necessary data.

Identification and cross-referencing of parcel information to determine ownership for access and maintenance or for obtaining construction rights are crucial and should be completed prior to scheduling the site assessment. Typically, the necessary information is available on the County Assessor's GIS platform.

Prior to visiting the study reach, use high-resolution topography to examine watershed connectivity and potentially difficult topography. Exercise caution when assessing potentially difficult topography, prior to visiting the site, because a good sense of scale is often missing when viewing detailed information from a wide perspective. Confirm, during the site visit to the study reach, the tentative conclusions developed during the initial desktop analysis of the topography.

3.2.6 Channel Processes

Determining the root cause of the instabilities observed in a channel requires understanding the processes currently occurring in the channel, as well as the processes that should be occurring in an equivalent natural and healthy channel. Channel processes can be broken into four major categories, each of which can then be broken down into at least 2 subcategories, as described below:

Hydrologic and Hydraulic Processes: Hydrologic processes, as illustrated in Figure 3-7, refer to how much water flows to the stream, how it enters the stream both spatially and temporally, when it enters the stream (seasonally), and how often the stream experiences flow. Hydrologic processes form the base of the stream function pyramid (Figure 3-3) and are influenced by geology and climate.

High-resolution topography and statistical analysis of data from stream flow gages (when one is available within a reasonable distance to the project site) can provide most of the information listed above. Topographic data can be analyzed to identify how flow accumulates and enters the channel, whether by flowing directly down the channel bank or flowing into the channel via tributaries.

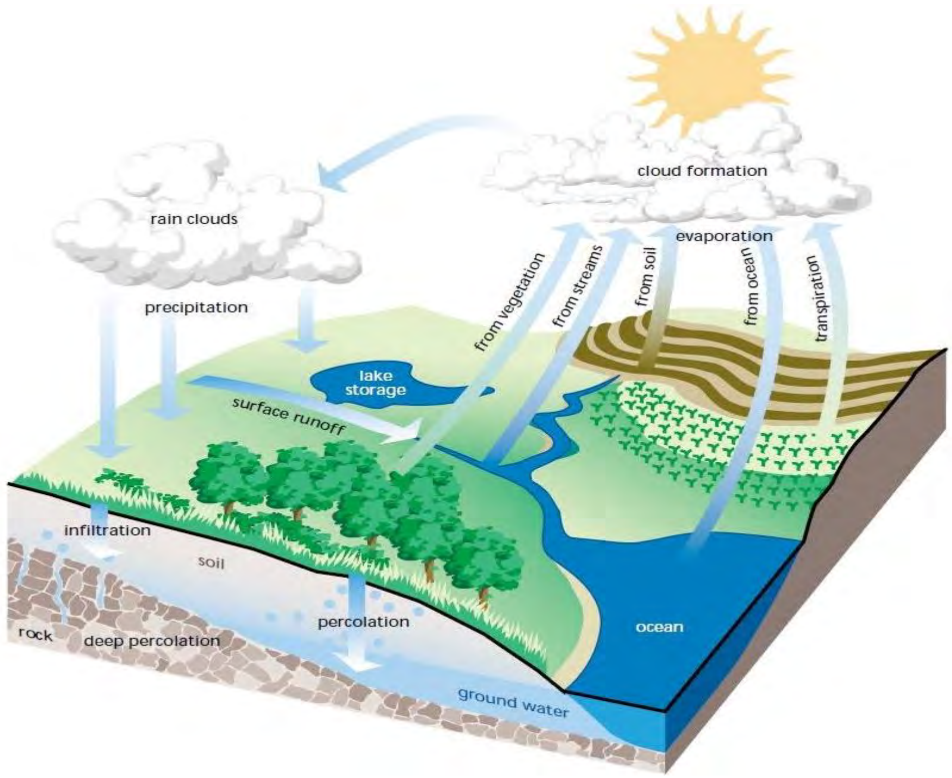

Figure 3-7: The Hydrologic Cycle

(FISRWG, 2001)

Where gage data are not available, analysis of nearby gages, regional flow-frequency estimation techniques, or hydrologic modeling can be used to approximate the hydrologic response of the watershed contributing to the study reach. The most commonly used hydrologic analysis methods are included in the Indiana Department of Natural Resources Indiana Peak Discharge Determination System (IPDDS) (INDR, 2013). The IPDDS can be used to determine peak flow rates; if other or more detailed hydrologic information is needed to understand fully the processes that are occurring in the study reach, a more sophisticated approach will be necessary. Exercise great care when synthesizing data or extrapolating from indirect information sources. At minimum, conduct a sensitivity analysis to determine the impact of the assumptions used on the results of the analysis.

Analysis of average daily flow can provide information relative to how much flow enters the stream and when it enters the channel (seasonally). Trends measured across multiple years can help to identify disruptions or abrupt changes in the quantity and seasonal timing of the flow in the stream. Analysis of the trend in peak annual flow rates can help isolate the frequency of intense storms. Finally, analyze hourly flow rates to highlight smaller time-scale components of hydrology such as how runoff occurs during a single event, whether the watershed is typically very quick-responding or not, and the typical duration of runoff events for the given stream. Though analysis of gage and topographic information will provide most of the hydrologic channel processes information, site observations are important for identifying how the flow enters the channel and how it affects the channel.

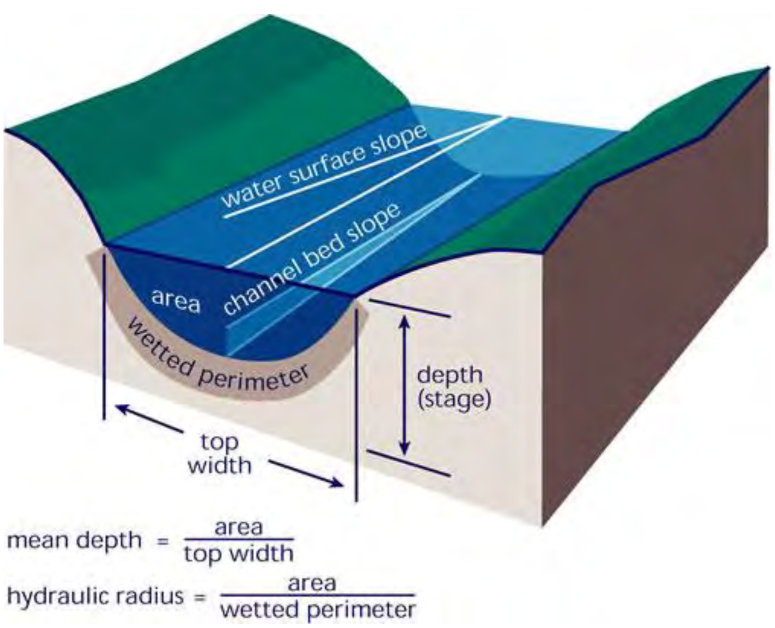

Figure 3-8: Open-Channel Hydraulics
(http://www.coolgeography.co.uk)

Hydraulic processes in the channel refer to the relationship between flow, depth, velocity, and shear stress. This set of relationships is determined by the channel geometry, as shown in Figure 3-8, and, in part, by the channel hydrology, as indicated in Figure 3-3. These factors provide information about the frequency and duration of stream flow for certain portions of the channel that may impact what types of materials form the channel boundary at various depths. Perhaps, more importantly, these relationships provide insight to the ability of the channel to transport not only water, but sediment and woody materials. However, the discussion of sediment and wood transport is more appropriately classified as a geomorphic process.

Channel geometry must be accurately defined by both cross-sectional and longitudinal profiles. High-resolution topography can provide an excellent information source for certain portions of the channel valley; however, specific field measurements should be taken to supplement and confirm remotely-sensed data.

Hydraulic processes are most often analyzed using a hydraulic model of the stream. Depending on the location, extent, and configuration of the study reach, some hydraulic models may be more appropriate for the given application. The practitioner should pay close attention to the assumptions being made in the model so that the situation does not violate, or serve as a poor example of, the assumed condition. The most notable assumptions to question are the existence of a steady flow-rate that does not change appreciably in a relatively short period, and the existence of one-dimensional flow. If one or both assumptions do not apply to the given situation, an unsteady-state or two-dimensional model, like that shown in Figure 3-9, should be considered to more accurately describe the hydraulic processes occurring under various flow conditions.

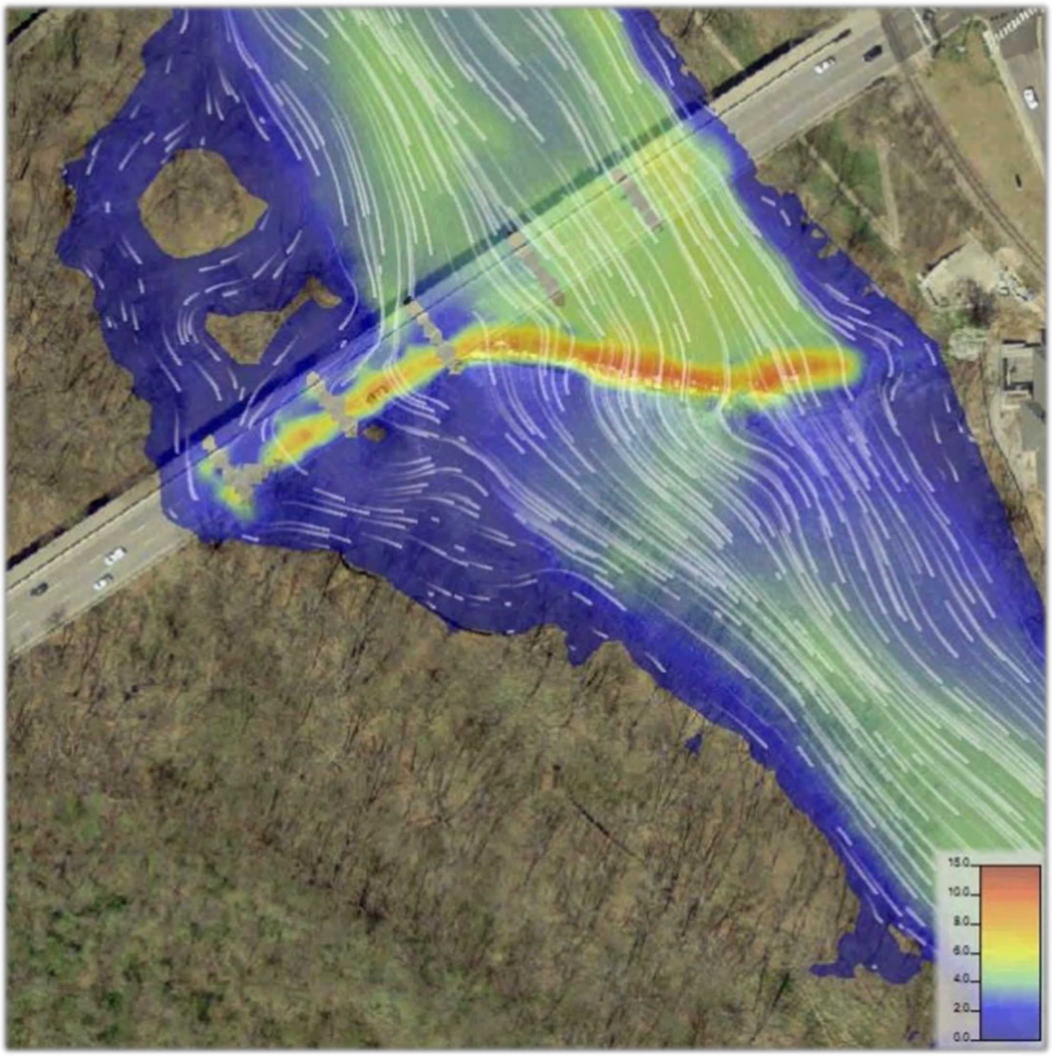

Figure 3-9: Two-dimensional Model Output for East Fork White River
(Color denotes velocity magnitude; white streaks denote flow paths)

Geomorphic Processes: The processes in this category relate to the formation of the channel itself. Geomorphic processes are driven by the hydrologic and hydraulic processes described above, as shown in Figure 3-3 by the materials forming the channel, both in terms of earth materials and vegetation. These processes explain how the alluvial features in channel valley affect the formation of the channel and how the cross-sectional and longitudinal shape of the channel change over time. These processes are most notably characterized by the sediment conveyed through the channel, including the material type, origin, size, and quantity.

Geomorphic processes are most readily identified by investigating signs of sediment transport. Sediment transport involves two linked components, erosion from one location that results in sedimentation at another location. Where excessive erosion occurs, excessive sedimentation will likely follow. Active sediment transport most often manifests in the following observable ways, each of which is illustrated in Figure 3-10:

1. Scour near the bottom of the channel bank - High channel velocity/shear stress regularly prevents the growth of vegetation and removes the surficial material at the bottom of the channel bank.
2. Cantilevered banks - Severe bank scour can result in cantilevered banks. These banks are rarely stable and are typically observed only when dense vegetation above the scour line prevents immediate bank failure.
3. Mass bank failures - Not all mass bank failures are primarily caused by erosion of the toe of the bank. Some mass failures are the result of simple geotechnical instability of the bank slope, given the bank's shape and material composition. Mass bank failures are most frequent along streams that are migrating laterally.
4. Large (relative to the stream size) unvegetated sediment bars - Unvegetated sediment bars provide evidence that erosion and deposition are occurring, and that they are also occurring frequently enough to prevent the growth of annual vegetation.
5. Lateral channel migration - Not all mass bank failures are caused by erosion, but all laterally migrating channels are experiencing erosion. Signs of lateral migration are most evident at the study reach when infrastructure is nearby, but can also be identified by examining aerial photography.

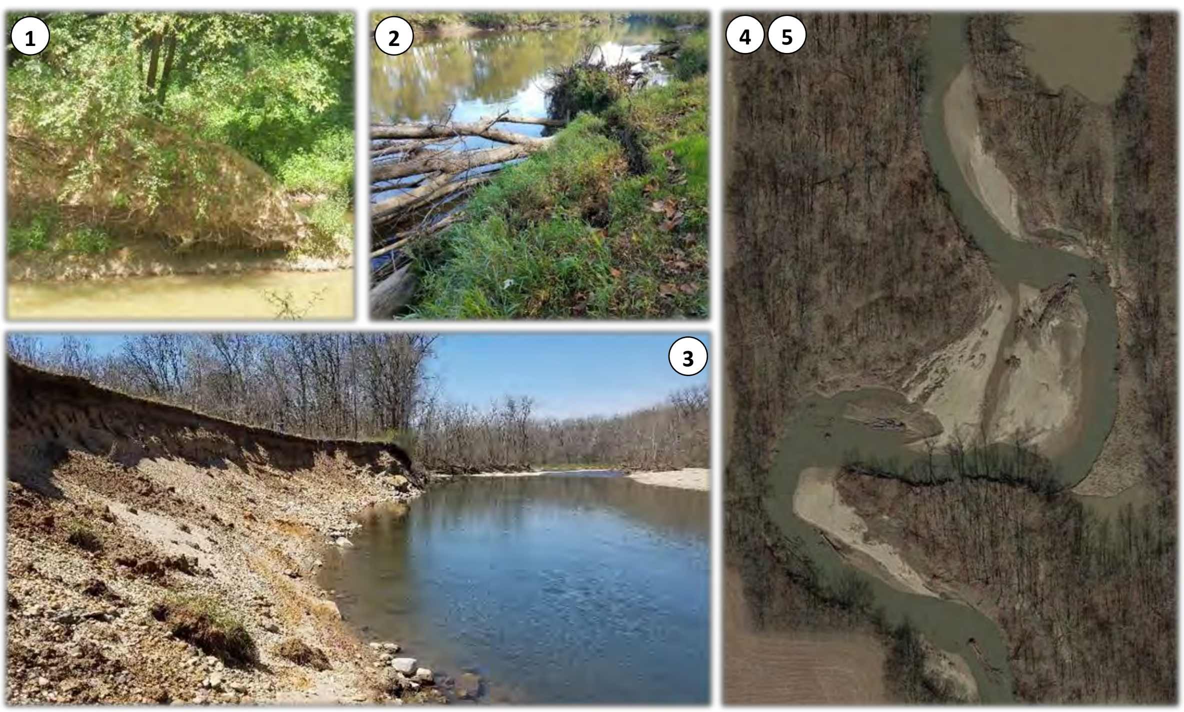

Figure 3-10: Signs of Active Sediment Transport

(1) Wabash River, near Lafayette, IN (2) White River, Morgan Co, IN (3) Sugar Creek, Crawfordsville, IN (4 & 5) White Lick Creek, near Mooresville, IN

A major component to understanding the geomorphic processes that are occurring is obtaining detailed information relative to the materials forming the channel boundary. Analyses of sediment samples from the channel bed, channel banks, and sediment deposits or bars are critical. Without this information, a realistic analysis of the sediment transport in the stream is highly improbable. Various methods can be used to obtain sediment samples from the channel boundary, including the Wolman pebble count and sediment cores from deposits (see Rosgen, 1996, 2009; Bunte and Abt, 2001).

Figure 3-11: Suspended Sediment Sampling
(USGS, 2016)

In addition to taking sediment samples from the channel boundary, investigators can take observed suspended sediment samples, as shown in Figure 3-11, and bed load samples to determine how much sediment is moving through the stream. The sampling method must be matched to the type of stream and the size of transported sediment.

The investigation of hydraulic processes typically includes a significant data gathering effort in terms of the channel geometry. Consideration of geomorphic processes should be made during the channel geometry data collection process to make note of bankfull indicators to help identify the bankfull elevation/depth, width, and, after processing the data, the bankfull flow area. Channel geometry parameters must be accurate because many components of stream stabilization and restoration rely on them.

Furthermore, practitioners need to identify and understand the stream type, which is being considered, on a reach-scale. The stream type, or classification, must be considered when evaluating stability/instability and the applicability of potential mitigation measures. Various stream classification methods are available; however, the Rosgen stream classification system shown in Figure 3-12 is the most widely used.

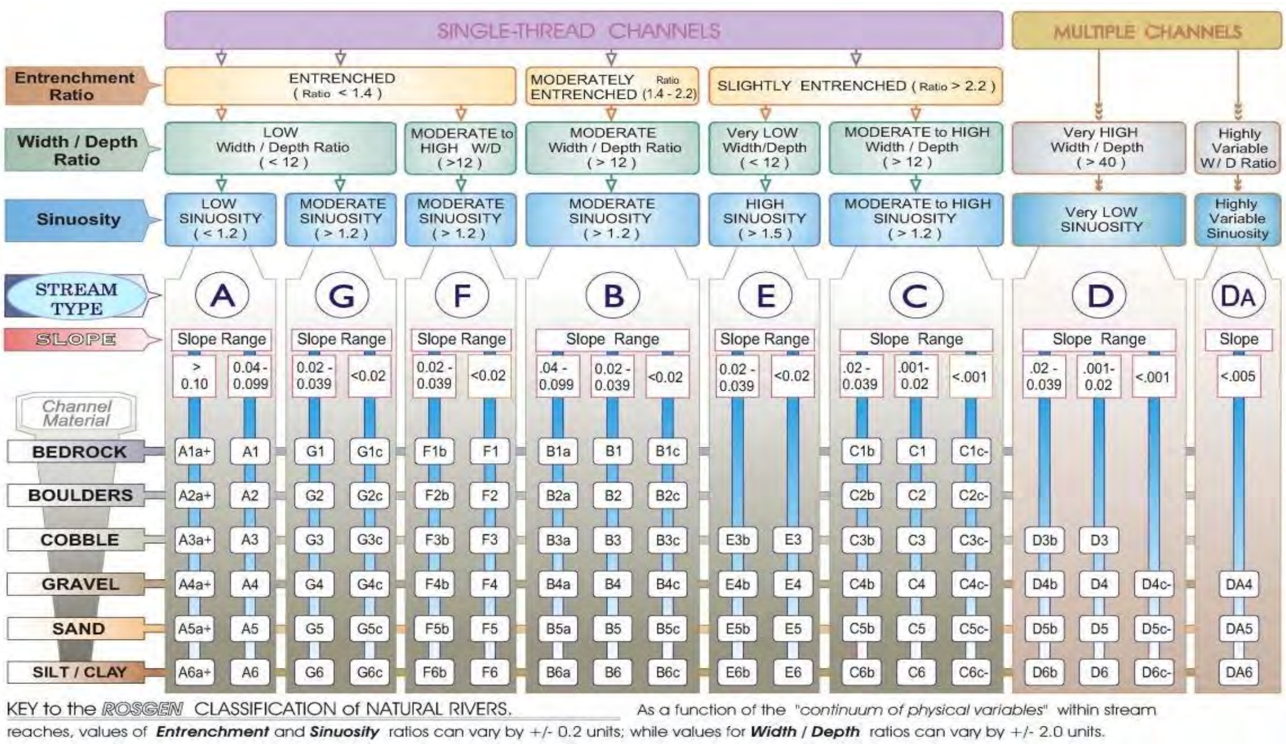

Figure 3-12: Rosgen Stream Classification System
(Rosgen, 1994)

Chemical Processes: Soil and water chemistry can greatly affect the condition of the channel. Given unfavorable chemistry, the channel boundary may not support vegetation, which may allow for a greater amount of sediment transport, and preclusion of suitable habitat.

Therefore, the practitioner should conduct water quality sampling to establish a baseline water chemistry for the stream. Many types of tests can be performed; however, the most common tests are for the following parameters: total suspended solids, dissolved solids, turbidity, dissolved oxygen, nitrogen, phosphorus, heavy metals, fecal coliform, E. coli, pH, water temperature, biological oxygen demand, and chemical oxygen demand.

Biological Processes: The plants and animals present in a stream, as illustrated in Figure 3-13, are important because they impact and/or are impacted by the condition of the stream. Consider the entire lifecycle of the plants and animals that live within the stream to identify what functions are being impaired and by what instabilities in the stream. Evaluate use of the stream by animals and humans to identify if the use(s) are impaired by stream instabilities and to assess how stream use may be a contributing factor to the instabilities.

Figure 3-13: Flora/Fauna Inventory
(Landcare Research)

Careful visual observation of plants and animals present in the stream during the site assessment can inform decision-making. However, local nature groups are often helpful in more fully understanding the animal life in proximity of the stream.

3.2.7 Reach-scale Stressors

Document and examine the findings from the site assessment, as suggested in Table 3-1, to help determine what factors appear to be contributing to the channel instability. Information gathered during a site assessment may seem unimportant when considered only in the context of the study reach; however, additional insights from the watershed assessment may suggest a greater importance. As a result, maintain an impartial view of the working hypothesis until all the information has been assimilated.

Note sources of instability that are isolated to the study reach, or a portion thereof, as reach-scale stressors for future consideration in the development of an erosion hazard mitigation plan. Also, identify channel instabilities that are pervasive throughout the channel, even beyond the study reach, as systemic issues. Due to the widespread nature of systemic instabilities, a watershed assessment as discussed in Section 3.3 may become necessary, as well as consideration of passive management strategies discussed later in Section 4.4.

Table 3-1: Example Identification Worksheet for Reach-scale Stressors

Stressor No.	Reach Location	Stressor Type	Stressor Description	Systemic / Local	Acute / Chronic	Apparent Severity
1	Reach 'A'	Natural	Scour at bank toe	Local	Acute	Moderate
2	Reach 'B'	Human Influenced	Floodplain fill	Local	Chronic	Severe
3	Reach 'C'	Human Influenced	Lack of riparian corridor	Systemic	Chronic	Moderate
4	…					

3.3 WATERSHED ASSESSMENT

In many situations, instabilities in a channel reach are not caused by disturbances to or the composition of the channel in the immediate vicinity of the project site, but instead are caused by inputs coming into the reach in terms of water, sediment, and/or woody material. Problems arising from the watershed are often referred to as systemic because the origin cannot be identified as a distinct location and the problems are widespread.

The watershed assessment is the counterpart to the site assessment and provides a more thorough understanding of stream hydrology as a system. Watershed assessment also identifies watershed-scale stressors and helps to understand the limitations of what can be done within the study reach to combat the issues.

The components of a watershed assessment link to the hydrology of the stream and focus most heavily on how the hydrology has changed naturally or anthropomorphically. Significant changes in the hydrology of a stream often lead to widespread, systemic instability as the characteristics of the stream are modified by the change in the amount of hydrodynamic energy entering the stream.

3.3.1 Land Use Types and Practices

Significant alteration of land use types and/or practices, like illustrated in Figure 3-14, can have a dramatic effect on both the volume of runoff and the rapidity of runoff accumulation. Increasing intensity of land use often causes a reduction in the infiltration capacity of the soil, either by excessive soil compaction or because of the soil surface being covered with more impervious material. Land use alteration also typically results in a more efficiently draining surface. The ground surface is graded more evenly to provide more consistent, reliable conveyance of surface runoff to avoid water ponding in areas and the land becoming unusable during or shortly after wet-weather events. This results in an overall increase in the rate of runoff accumulation and eventually a greater flow rate in the channel.

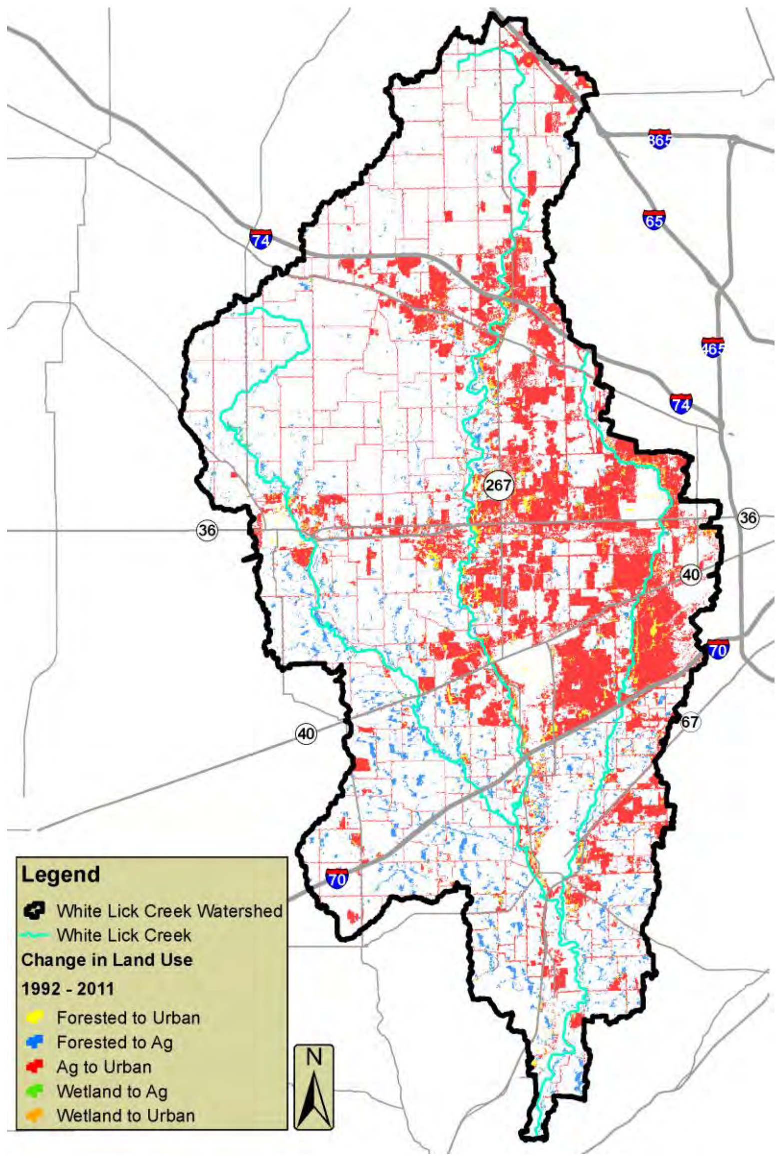

Figure 3-14: Land Use Change in White Lick Creek

Changes in the hydrology of the stream often create an imbalance in the system; however, land use changes can also affect the system by resulting in substantial changes in the amount of sediment supplied to the stream by the watershed itself. All watersheds supply sediment to the stream network, even naturally functioning and pristine watersheds. Changes to the land uses and/or the distribution of land uses, both spatially and in terms of the quantity of each land use type, as shown in Figure 3-15, can result in significant changes to the watershed sediment yield by closing off a source of sediment or creating a new source of sediment. For instance, the installation of large impervious areas eliminates the potential that the ground surface will experience erosion, thus all but eliminating the supply of sediment for urbanized areas. Likewise, a forested area generally contributes a very small amount of sediment to a stream, but if the forest is cleared and used for agricultural purposes and soil conservation practices are not used, there may be a significant rise in the amount of sediment being detached and entering the stream.

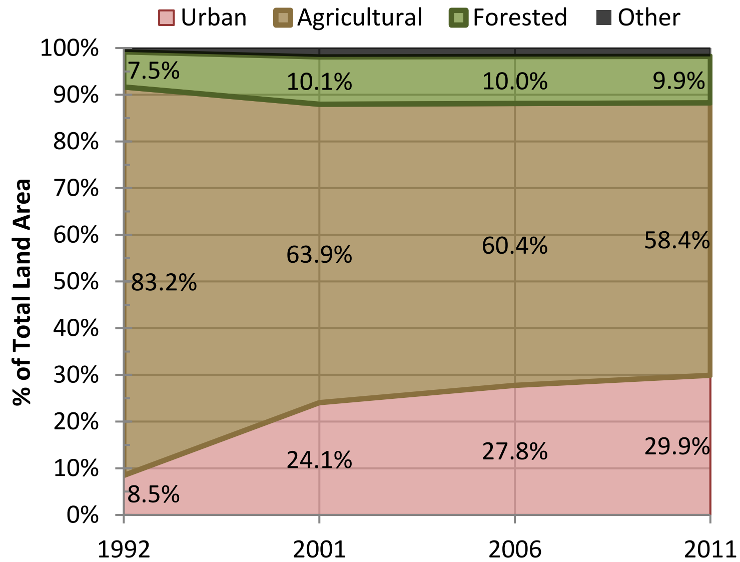

Figure 3-15: Land Use Change Trend in White Lick Creek

Use long-term land use trends to identify dramatic shifts in the types and quantities of land uses within the watershed; they can hint at the root cause of channel instabilities and/or to corroborate an existing hypothesis. An efficient method of determining changes in the quantity of types of land use, as well as the spatial distribution of those land use types, is to compare National Land Cover Dataset (Homer et al., 2015) information for various years to identify major trends. Though this analysis is largely qualitative, it can suggest the trend in watershed sediment yield.

Figure 3-16: Agricultural Erosion Directly into Stream
(Indiana University, 2018)

Types of management practices are especially important in agricultural areas due to the large amount of disturbed land surface. Poor management strategies can allow for directly connected pathways, as illustrated in Figure 3-16, between a cultivated field and the stream network. Proper soil conservation will prevent the majority of the detached sediment from leaving the fields. Though the soil may be displaced, it is retained in the upland portions of the watershed and does not pass into the stream network.

As indicated, land management practices in agricultural areas can significantly impact stream health. Simply viewing aerial photography of the agricultural areas will typically result in an uninformed conclusion because it is based on a single day in a single year. The Natural Resource Conservation Service (NRCS) is heavily involved in improving land management practices and offers incentives to the agricultural industry to promote responsible practices. As a result, the NRCS will likely have far more accurate and up-to-date information relative to land use practices and may be consulted to gain a better understanding of prevalent land use practices being implemented in the watershed.

Soil detachment and delivery to the stream network relate to both the land use type and land management practices. Several methods are available for determining an approximate sediment yield from a watershed; however, one must be conscious of the limitations of the type of analysis being completed. Older methods, such as the Revised Universal Soil Loss Equation, have been adapted to perform in the current age of computer-intensive analysis, resulting in spatially distributed assessments of sediment yield. Newer and more robust methods of determining spatially distributed estimates of soil detachment, sediment deposition prior to entry into the stream, and sediment contribution to the stream are being developed; however, these methods are not yet widely used. These newer methods and their associated models can provide valuable insight into how much and where sediment might be coming from in the watershed, but caution must be used as these models are often very sensitive to user input. In large watershed assessments, sediment monitoring should be in place for several years prior to developing an FEH mitigation design.

3.3.2 Rainfall Trends

Changes in the quantity of total rainfall and/or intensity of rainfall events, as illustrated in Figure ***3-17***, can have a significant impact on the quantity of flow, as well as the types of events experienced by the system. Rainfall information may be evaluated in several ways to provide different information on various aspects of storm events including the gross volume of water and the intensity of the storms, as well as the frequency and seasonality.

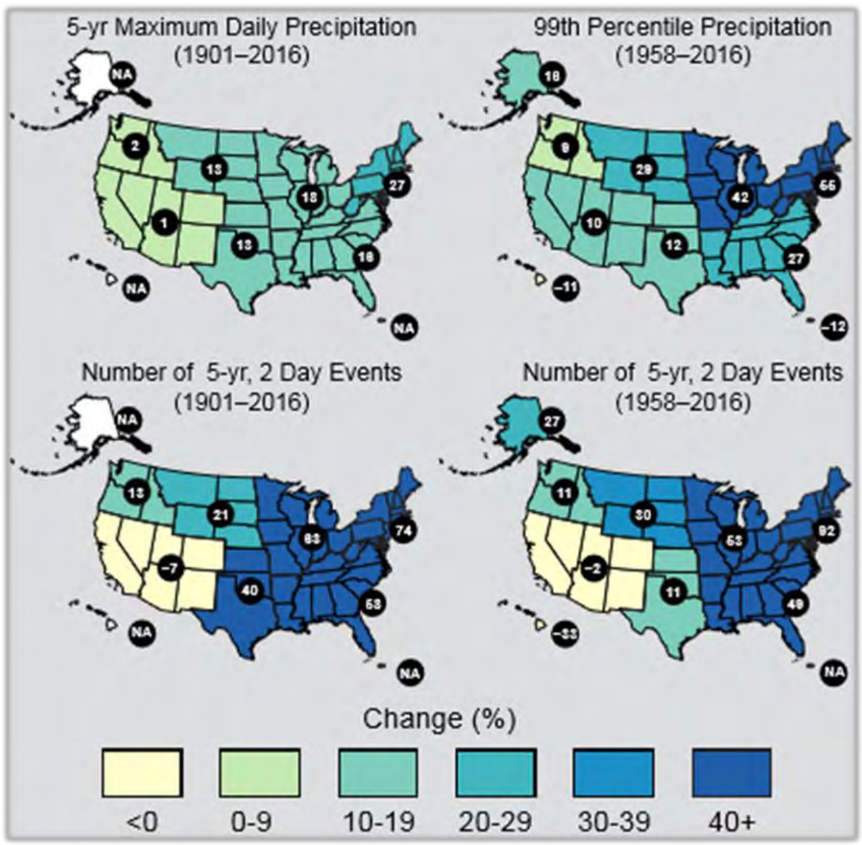

Figure** 3-17**: Observed Change in Heavy Precipitation
(CSSR, 2017)

Total rainfall volume (in inches) is provided by the annual rainfall depth. An analysis of annual rainfall depths identifies trends in rainfall volume, which can be compared to trends in the volume of runoff to identify changes in the amount of runoff generated per inch of rainfall.

The frequency of intense rainfall events is more relevant to erosion potential than annual average precipitation. Investigation of rainfall depth over various durations helps assess trends in rainfall intensity. Intense rainfall events cause flashier, more erosive flows in streams. This analysis may suggest changes in the frequency of such storms, but should be cross-referenced with the frequency of high daily flow rates to confirm the hypothesis. General trends can rarely be determined from one weather station; an analysis usually requires a network of stations.

Rainfall seasonality plays a key role in habitat creation. Understanding rainfall seasonality also helps to determine optimal times for constructing improvements in the stream. An investigation of weekly and/or monthly rainfall depths helps to assess changes in the consistency of flow events in each season and throughout the year. A shift in the seasonality of rainfall, and thus flow events, may disrupt spawning cycles and germination of some plant communities.

3.3.3 Upstream Drainage Efficiency

Drainage improvements within a stream network often result in reduced flooding of upstream areas because of the higher flow capacity of the stream, which reduces the storage of floodwaters in what were once floodplain areas. Flow passes more quickly because of increased channel capacity, which alters the hydrology of the downstream reaches of the stream network. An increase in the drainage efficiency of headwater or simply upstream areas can take on several forms.

The construction of drainage channels and/or the existence of widespread agricultural tiling can contribute to substantial increases in the downstream flow rates in the stream channel due to the more rapid conveyance of flow from watershed areas into the channel. The National Hydrography Dataset includes information about the origin of the channels identified in the geospatial information. This analysis merely provides a qualitative result but can be used in conjunction with flow gage data to support a hypothesis.

In addition to increasing flow rates, agricultural drainage tiling can result in a larger volume of runoff entering the stream. Rather than allowing much of the rainfall that infiltrates the soil to enter the groundwater supply, a tiled agricultural field will direct much of the infiltrated rainfall into the channel as runoff. Knowledge of the agricultural drainage tiling in a watershed can provide multiple benefits to the practitioner. First, the identification of extensively tiled areas can be flagged as potential problem areas for stream stability issues. Figure 3-18 shows an example of drainage modification in the Kankakee River watershed in northwestern Indiana. Second, tile drainage information provides a better understanding of the watershed hydrology and may assist in achieving a better calibration of watershed hydrologic models.

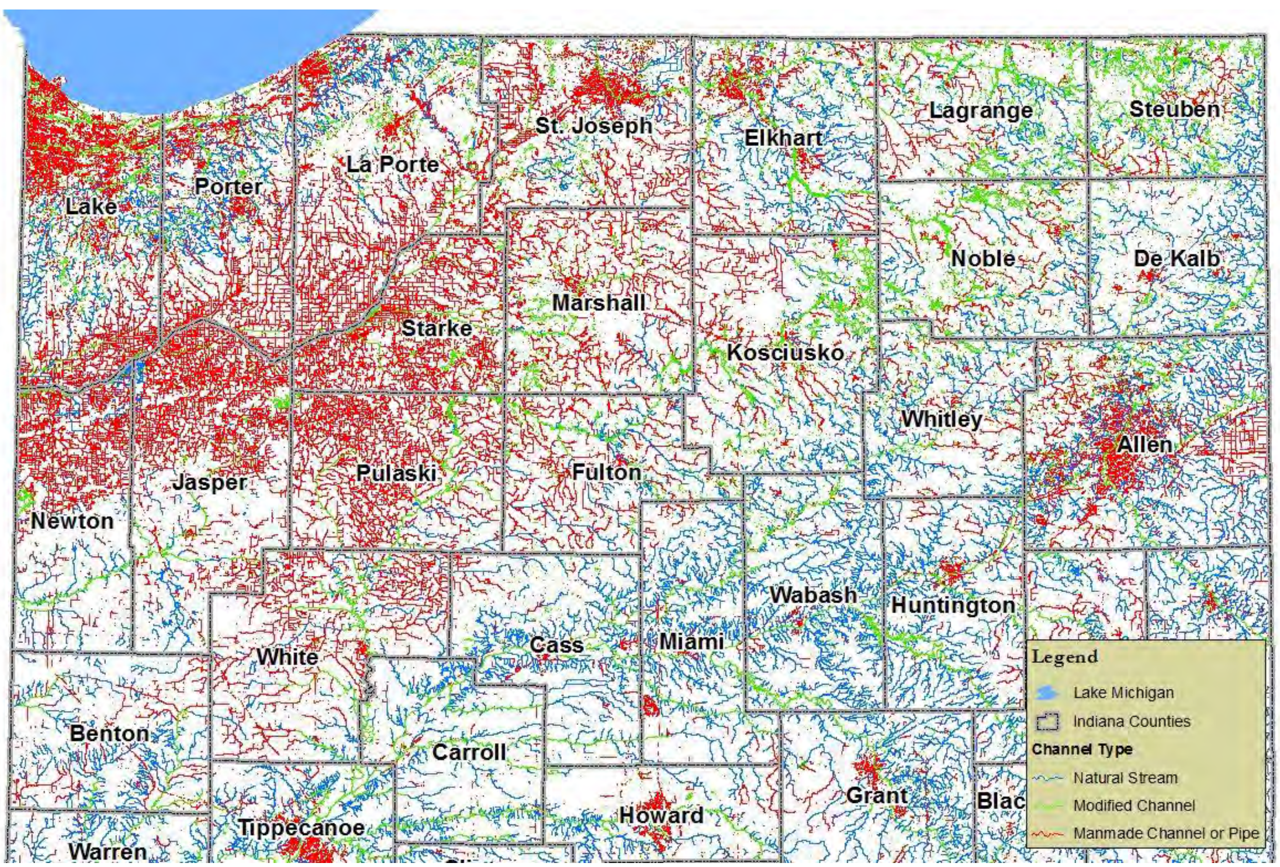

Figure 3-18: Increased Drainage Density

Many watersheds have pockets of land that do not often contribute runoff to the main watercourse because of hummocky topography, as shown in Figure 3-19. If previously non-contributing drainage areas are artificially drained by construction of drainage channels, tiling, or pumping, the flow rates and volume of runoff conveyed by the channel are obviously increased. This results in a higher potential for sediment transport. Examination of watershed topography and known subsurface drainage systems help identify non-contributing areas.

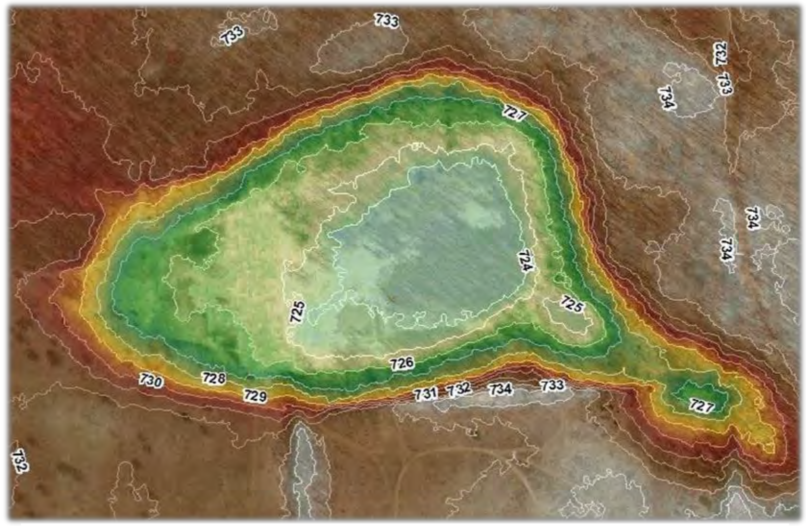

Figure 3-19: Non-contributing Drainage Area

3.3.4 Watershed-scale Stressors

The findings from the watershed assessment should be documented, as suggested in Table 3-2, and the information examined to determine what factors appear to be contributing to the channel instability. The very nature of watershed-scale stressors makes the use of site-specific projects impractical in many cases. Because watershed-scale stressors are frequently systemic issues, practitioners should often consider passive management strategies, as discussed in Section 4.4.

Table 3-2: Example Identification Worksheet for Watershed-scale Stressors

Stressor No.	Sub-watershed Name	Stressor Type	Stressor Description	Systemic / Local	Acute / Chronic	Apparent Severity
1	Muddy Fork	Human Influenced	Poor ag soil conservation practices	Local	Acute	Moderate
2	Sand Creek	Natural	Highly erodible, steep terrain	Systemic	Chronic	Severe
3	Industrial Drain	Human Influenced	Intense urban development	Local	Chronic	Moderate
4	…					

3.4 INITIAL STAKEHOLDER INPUT

Although this manual is first and foremost a technical manual, the importance of non-technical factors, such as stakeholder input, cannot be overlooked. There are several ways to engage the public. A stakeholder group can help gain public input and/or a larger public engagement effort can be undertaken using public meetings, surveys, training seminars, websites, etc. Including all stakeholders and the public's input in the FEH mitigation process will promote a more holistic project that works to achieve multiple goals. Involving the appropriate parties earns acceptance from key groups in the community, increasing the prospect that the selected erosion mitigation components will be socially acceptable.

An organized set of guidelines for the decision-making process, project objectives, and identifying/acknowledging constraints and limitations on the FEH mitigation project must be established at the beginning of the project to avoid confusion and/or confrontation during the project. While this manual does not provide exhaustive guidance for stakeholder engagement, the following sections provide a brief overview of the major factors to be considered when seeking stakeholder input.

3.4.1 Stakeholders

Stakeholders for the project consist of all parties impacted by the completion or absence of a FEH mitigation effort, either in direct or indirect contact with the identified preliminary study reach. Stakeholders included in the erosion mitigation process may include, as illustrated in Figure 3-20: the design team, property owners, adjacent property owners, public officials, regulators, environmental and public interest groups, and potentially other private citizens.

A well-formed set of stakeholders would be inclusive of all individuals and groups that have financial, social, environmental, and technical stakes in the project. The group should be diverse in that multiple viewpoints will be represented to promote a holistic and constructively critical review of the project throughout the process.

Figure 3-20: Potential Stakeholders

3.4.2 Decision-making Process

Prior to reaching a point where a decision needs to be made, establish the decision-making entity, whether it is an individual or an advisory group that will have the final say on matters. For the purpose of promoting stakeholder buy-in throughout the FEH mitigation process, the decision-making entity should focus on gaining consensus, rather than making strong declarations and unilateral decisions.

No matter the type of decision making entity, the process for coming to a decision should be transparent enough to build confidence in the process from the stakeholders. Transparency can often be achieved by formulating and publicizing the specific decision-making process in advance so that the stakeholders can see how considerations will be made fairly and in line with the values of the stakeholders and the general community. An effective method for communicating the key values weighed in the decision-making process is to create a process that shows how decisions will identify what is important and accentuate the desired outcomes of the stakeholders.

3.4.3 Project Objectives

Identify, at the beginning of the project, the idealized conditions that would result from the project in terms of drainage function, aesthetics, recreational uses, environmental components, educational benefits, and maintenance requirements. Remember that many stakeholders will not have a technical understanding of the issues in the stream. For communication purposes, consider discussing the stakeholder's project objectives in layman's terms to avoid confusion and differing understandings of the complex nature of streams. The main goal of this portion of the initial stakeholder meeting is to determine what the public/private citizens want the project to achieve.

A representative from the design team performing the site and watershed assessments should be included in the process of cataloging the project objectives during the initial stakeholder meeting to avoid miscommunication later in the project. The design team is responsible for translating the desired outcomes specified by the stakeholders into specific, measurable, and obtainable technical objectives.

The design team representative should inform the stakeholders when a stated objective may be counter to the overall health of the stream. Base the guidance on the information and knowledge of the stream gained through the site and watershed assessment phases. The design team representative can also clarify how the stated objectives may interact, particularly if some of the objectives would result in conflicting erosion mitigation components. Continue the discussion and debate until arriving at a clear set of desired outcomes for use by the design team to develop an FEH mitigation design.

3.4.4 Additional Constraints and Limitations

Physical constraints and limitations for technical reasons should have been preliminarily identified during the site assessment. However, recognize that stakeholders may be aware of additional constraints that were not obvious or could not be identified during the initial investigation. Stakeholders may also place additional constraints or limitations on the project based on non-technical reasons that must be considered when developing the FEH mitigation design.

3.5 FLUIVAL EROSION HAZARD MITIGATION OBJECTIVES

The erosion mitigation objectives should represent the desired outcomes conveyed by the project stakeholders. The difference between the desired outcomes and erosion mitigation objectives should primarily be specificity and technical details.

3.5.1 Impairments/Stressors

Prior to creating a list of detailed technical objectives, create a list of the problems that must be addressed by the FEH mitigation design. The impairments and stressors on the stream reach and watershed should be listed and described to help focus the development of the technical objectives. Identify the degree of impairment or departure from the desired condition. Group the impairments and stressors into local-scale or watershed-scale issues.

3.5.2 Mitigation Objectives and Desired Stream Functions

Create a list of mitigation objectives and desired stream functions, like that shown in Table 3-3, based on the desired outcomes stated by the stakeholders. Each objective should note the technical requirements for achieving the desired outcome. Provide specific metrics to measure success for each technical requirement.

Table 3-3: Example List of Mitigation Objectives and Desired Stream Functions

Desired Stream Function	Priority
Stabilize the streambank adjacent to the infrastructure for events up to the 100-year event	1
Improve sediment continuity through the reach to prevent excessive sedimentation in periods of low flow	2
Improve the flood conveyance capacity of the channel and terrace to ≥ 50-year event	3
Improvements should be aesthetically pleasing and blend in with the upstream and downstream reaches	4
Improvements should require minimal periodic maintenance (such as mowing or spraying)	5
Provide habitat for smallmouth bass	6
Provide irrigation for local farm fields	7
Serve as outdoor science-lab for local schools	8
Public kayak course	9

Note that some of the desired outcomes from the stakeholders may not be features that were once present in the stream or would naturally develop in the stream of concern. The design team is responsible for identifying these irregularities and communicating with the stakeholders to fully inform them of the issue. If the desired outcome will lead to detrimental impact to the stream, the design team should advise stakeholders and work to exclude those features from the FEH mitigation design.

3.5.3 Prioritization of Mitigation Objectives

Not all the desired outcomes provided by the stakeholders may be achievable due to technical issues, lack of sufficient finances, political issues, protection of specific environmental/cultural/historical areas, or other spatial constraints. To maximize the success of the project, prioritize the list of erosion mitigation objectives based on the decision-making process created by the stakeholders, while also keeping in mind which objectives are most influential and readily achieved.

3.5.4 Social Acceptance

If a concerted public outreach effort was conducted, as suggested by Figure 3-21, the social acceptance of the project should be quite high. If the project has both positive and negative effects, consider the social acceptability of the negative impacts. Transparency and communication of the negative impacts to all stakeholders, particularly those being negatively impacted, are paramount. Consider alternatives that have lesser negative impacts or mitigate the negative impacts for the affected party and discuss them with the stakeholders. If portions of the project are found to be socially unacceptable, those components should be considered for elimination so that they do not result in compromising the effectiveness of the remainder of the project.

Figure 3-21: Public Outreach Meeting
(MakProSVC)

3.5.5 Environmental Impacts

Streams are environmentally sensitive features that require careful handing to avoid detrimental impact to the stream ecology. Streams often intertwine with other environmentally sensitive areas that may or may not be impacted by the FEH mitigation design. If the sensitive areas are regulated by federal, state, or local entities, environmental impacts will be considered during the permitting process as well as during the design process. Consider the possibility of reducing or eliminating negative environmental impacts throughout the FEH mitigation design development.

3.5.6 Management and Maintenance

The characteristics of streams adjust over time as the inputs change. As a result, and as illustrated in Figure 3-22, an FEH mitigation site will likely require some maintenance, particularly in the early years of existence, because bioengineering methods increase in resilience over time.

In addition to the natural adjustment of streams over time, the FEH mitigation design may include components for public recreation/use that will require intermittent or continuous maintenance and/or management. Take efforts during the FEH mitigation design process to minimize these costs to the extent practicable.

Figure 3-22: Minimizing Maintenance through Conservation Areas
(EMH&T)

3.6 ADDITIONAL INFORMATION NEEDS

Perform the site and watershed assessment phases before the specific erosion mitigation objectives are established so the practitioner can inform the decisions of stakeholders and to get a sense of the system's problems and stressors and the level of impairment of the stream. Details of the stated erosion mitigation objectives may require additional site data collection or additional research of watershed-scale factors all in the interest of prudent FEH mitigation design development. Examples of potential additional information needs include more in-depth geotechnical analysis, more extensive detailed site survey information, and wetland delineation.

3.7 REFERENCES

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CHAPTER 4 ANALYSIS AND DESIGN

4.1 INTRODUCTION

Identifying a stream as unstable or unhealthy does not provide enough detail to determine the potential causes of the instability, nor does it allow for development of a design to stabilize the streambank. The various analyses discussed in Chapter 3 provide metrics to determine areas of poor stream health within the assessment reach, that will be addressed by the design, and to help quantify the severity of the impairment.

The analyses can also more clearly define how the stream functions. Knowledge of the stream's processes can lead to more nuanced mitigation measures that reduce the susceptibility to potential failure or poor performance.

Designers can also gain a better understanding of how successful a project is likely to be by completing the various analyses for the pre- and post-project conditions to determine if the designed project components will be adequate under a range of conditions and flows. Understanding the likely performance of mitigation measures included in a design helps identify potential areas of weakness in the design that can then be adjusted to reduce further the potential for poor performance.

View the stream as a system throughout the problem identification and design phases to avoid inadvertently causing instability elsewhere in the system. Consider each level of analysis within the broader context of the stream system. The effects of adjustments to the stream are not limited to one variable, but all variables through the many complex relationships involved in open channel flow and sediment transport.

View the stream as a system throughout the problem identification and design phases to avoid inadvertently causing instability elsewhere in the system.

4.2 ANALYSIS EXTENT

Adjust the extent of the study reach from the default length of 20 to 25 times the bankfull width based on reach specific factors. Geology, stream type, land use, hydrography, and access are the most common factors that may expand or reduce the extent of the study area.

The complex physical landscape of Indiana ranges from recently deglaciated terrains in the central and northern parts of the state to much older glaciated or non-glaciated areas in the southern part of the state. The bedrock exposed at or near the surface (see Figure 4-1) dips gently to the west and the rocks exposed at the surface vary from erosion-resistant sandstone in the western part of the state to very erodible carbonate rocks in the east.

The impact of the varied geology is significant and must be considered when trying to assess stream stability and function. For example, the West Fork of the White River flows through formerly glaciated areas where, the surficial geology is outwash sand and gravel and the river is unconfined, into areas that are bedrock-bound and the river is confined. Erosional patterns differ in the two areas and care should be taken to not infer that what is stable in one portion of the river would be stable in another part of the river. These geologic boundaries are abrupt and affect many Indiana stream systems.

Figure 4-1: Exposed Bedrock in Southern Indiana
(Cave Country Canoes)

Sometimes the change in geologic boundaries [and other factors] will also result in a change in stream type. The stream type must be taken into account when considering whether the upstream and downstream end of the default study reach of the stream are stable. However, rapid identification of stream types for study reach determination requires that the investigator is familiar enough with stream types to understand what may be causing the changes in the stream (Harrelson, et al. 1994; Rosgen, 1996). Ideally, a study reach terminates where the stream type transitions from one type to another. A study reach can span multiple stream types and all stream types should be considered during the analysis. Comparisons of observed channel dimensions versus expected dimensions and potential treatment methods should be evaluated with respect to stream type.

Ideally, a study reach terminates where the stream type transitions from one type to another. A study reach can span multiple stream types and all stream types should be considered during the analysis.

Stream type and planform can also vary across areas with different land uses. A standard example of the effect of land use changes in Indiana on stream channel dimensions occurs when the stream flows from a forested area into an area dominated by row-crop agriculture. If the riparian buffer is absent or limited in the agricultural area, the stream will often become much more mobile laterally. The increasing sediment load as the river moves across the floodplain triggers a feedback loop that can result in significant departure from expected channel parameters. Like geologic boundaries, these land use boundaries can be very abrupt and the changes in stream behavior significant.

Finally, access is one other challenge in adjusting a study reach, as suggested by Figure 4-2. Access to a stream can vary with the size of the stream, state and local jurisdiction, and questions about private ownership. If a private landowner will not allow access to their property, a study reach may need to be relocated. Err on the side of caution and always ask before looking at a stream where land ownership is unknown.

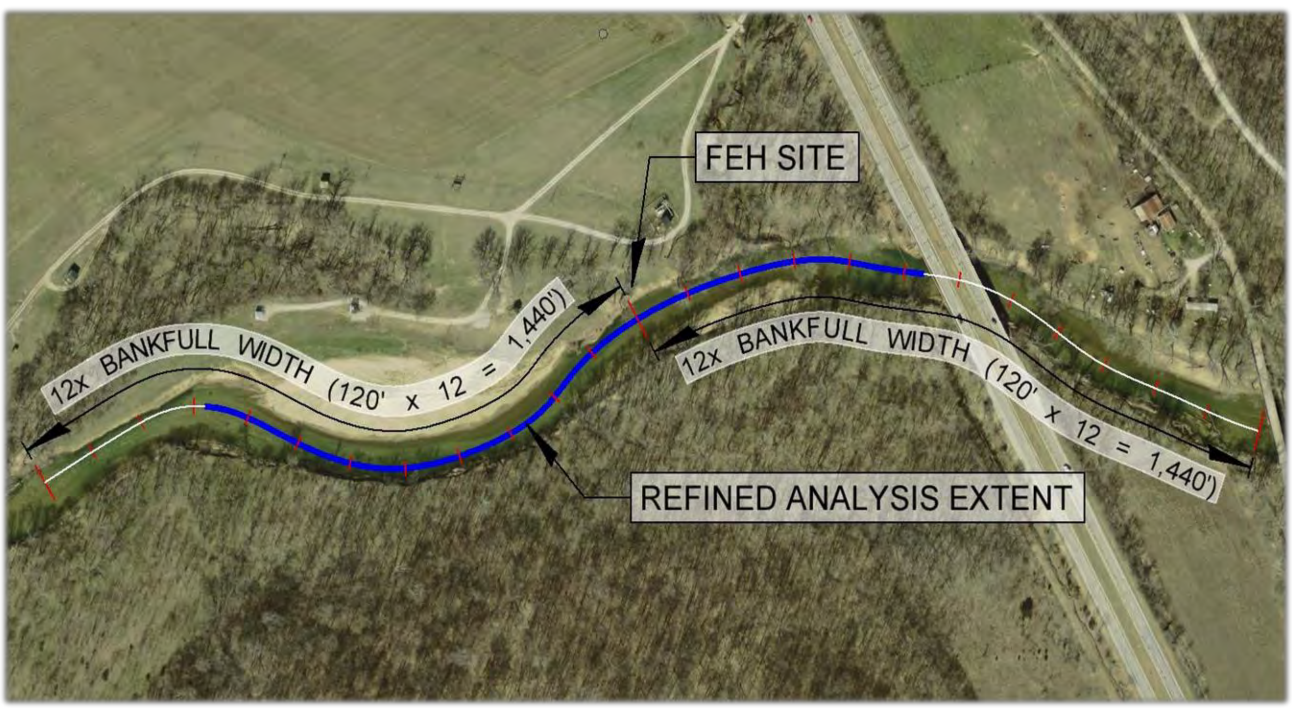


Figure 4-2: Preliminary Study Reach Limits vs. Refined Analysis Extent

4.3 ANALYSIS METHODS

The following sections describe a combination of both analytical and form-based analysis methods. The methods included in the sections provide a list of analyses options -- not a list of analyses that must be completed for every project. River systems experiencing unusual or extraordinarily high levels of instability may require additional analyses that are not discussed in this document. Please consult the references for additional sources. Similarly, a simpler river system with straightforward issues may not require much analysis to arrive at design solutions. The individual determining the course of the study and/or design must have a robust background in geomorphology and be able to provide the necessary resources and skills to produce a successful project.

4.3.1 Channel-Forming Flow

The channel-forming flow is commonly defined as the "single discharge that, given enough time, would produce the width, depth, and slope equivalent to those produced by the natural flow in the stream" (USDA, 2007). In reality, no single flow rate is solely responsible for the shape of a channel, particularly alluvial channels. Rather, "the natural spectrum and sequence of flow events are largely responsible for regulating this balance over time and molding dynamically stable channel forms through sediment erosion, transportation, and deposition" (Soar and Thorne, 2001).

Practitioners and academics alike have sought to use a single flow rate to represent the complexity of stream hydrology and form adjustment, largely due to the difficulty in simulating the dynamic processes. As a result, many of the analysis methods used require a single, representative flow rate. Many terms are used to describe the channel-forming flow, all of which have slight variations and differences as described in the USACE Channel Restoration Design for Meandering Rivers (Soar and Thorne, 2001) and Part 654 of the National Engineering Handbook (USDA, 2007). This document primarily uses the term 'bankfull' to describe the channel-forming flow.

Figure 4-3: Alluvial Stream Before and After a Flooding Event

As illustrated in Figure 4-3, alluvial channels present a situation where erosion, sediment transport, and deposition occur in sufficient amounts to adjust and reshape the stream. When designing a streambank stabilization project in an alluvial channel, determine a representative flow rate or discharge on which the design will be founded. According to channel-forming flow theory, by designing the streambank stabilization project to be stable during the channel-forming flow, the channel should remain stable in the long-term (Soar and Thorne, 2001). The channel will likely be somewhat depositional during flow lower than the channel forming flow and will likely experience some erosion at flows above the channel-forming flow. However, the theory assumes that these are counterbalancing and not appreciable over the long-term. A prudent design will consider stream conditions during flow above and below the channel-forming flow to confirm that anticipated erosion and sedimentation should not be excessive or destabilizing. If a channel is to remain an alluvial channel, it must not be armored or protected against all erosion and sedimentation because some erosion and sedimentation must be allowed for the channel to truly be and function as an alluvial stream.

Several methods are available for determining channel-forming flow. The flow rate most commonly used in Indiana is the bankfull discharge, or the discharge that can be associated with the water in the channel reaching bankfull stage. Bankfull stage, as shown in Figure 4-4, is the level in the stream where the flow reaches the 'first flat', or insipient floodplain, and is identified by physical markers in the stream (Robinson, 2013).

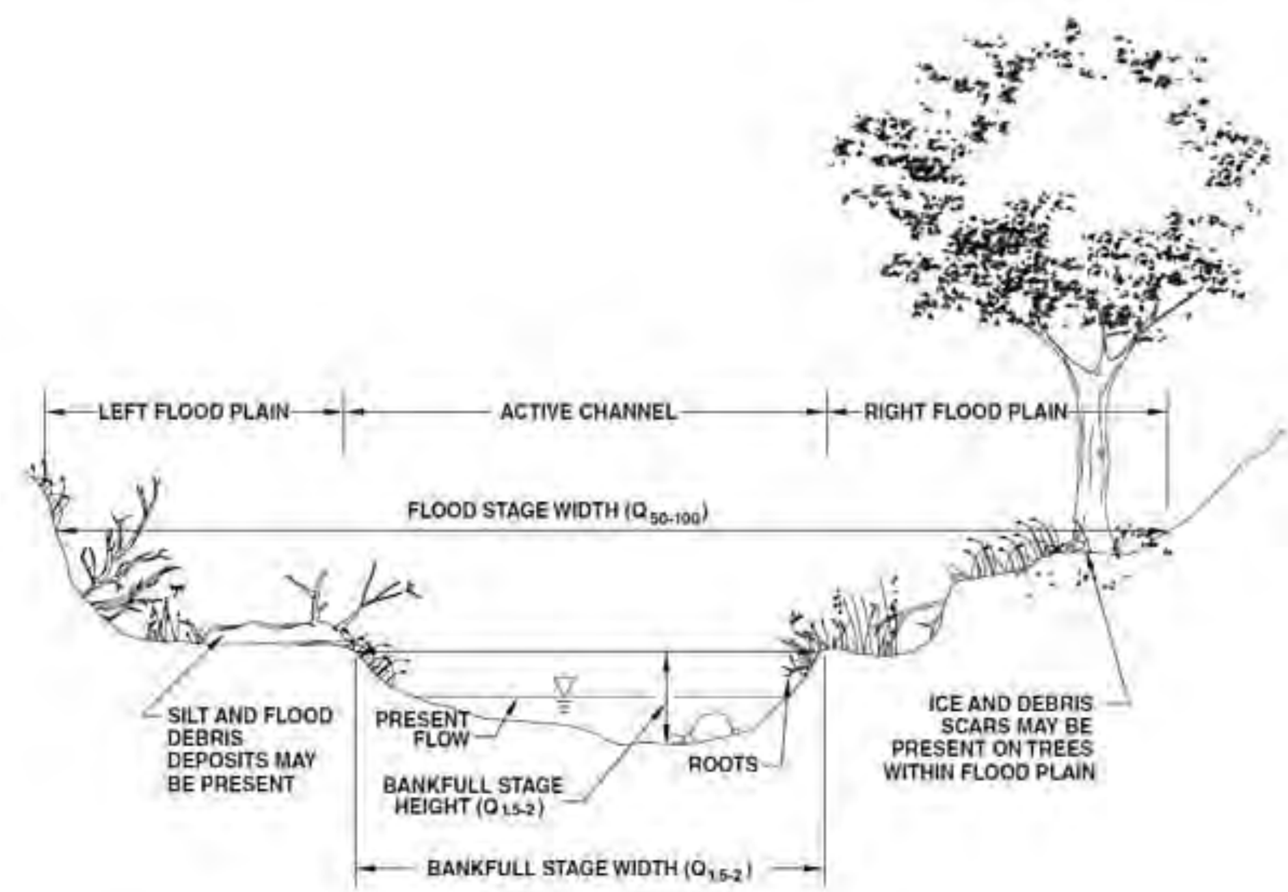


Figure 4-4: Channel Cross-section with Bankfull Indicators
(USDA)

The 'effective discharge', or the flow rate that is statistically responsible for the most sediment transport in a given year, can also be used as a surrogate for the channel-forming flow and is determined by an analytical process, rather than a form-based process like the bankfull discharge. A thorough description of the methods used in determining both the bankfull discharge and effective discharge, as illustrated in Figure 4-5, is provided in the National Engineering Handbook (USDA, 2007).

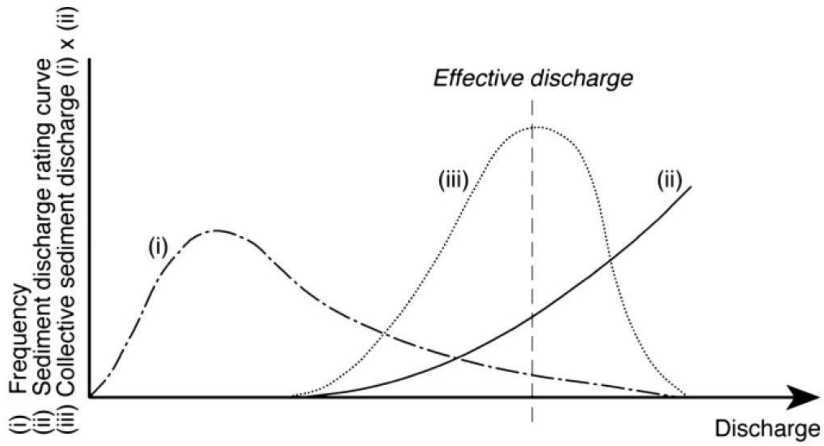


Figure 4-5: Effective Discharge Determination
(Soar and Thorne, 2001)

Additionally, if a stream gage is in or near the study reach, a statistical analysis, as suggested by Figure 4-6, can be completed to determine a recurrence interval approximation of the bankfull discharge, typically the 1.5-year return interval ($Q_{1.5}$) flow rate (Leopold, 1994). If a stream gage is not near the study reach, the StreamStats regression-based discharge determination for a point along a stream could be used. When utilizing the regression-based approximation provided by StreamStats, apply at least one additional method of determining the channel forming discharge for confirmation. The use of the bankfull or effective discharge is much preferred because these methods are most well-suited for a detailed, site-specific analysis.

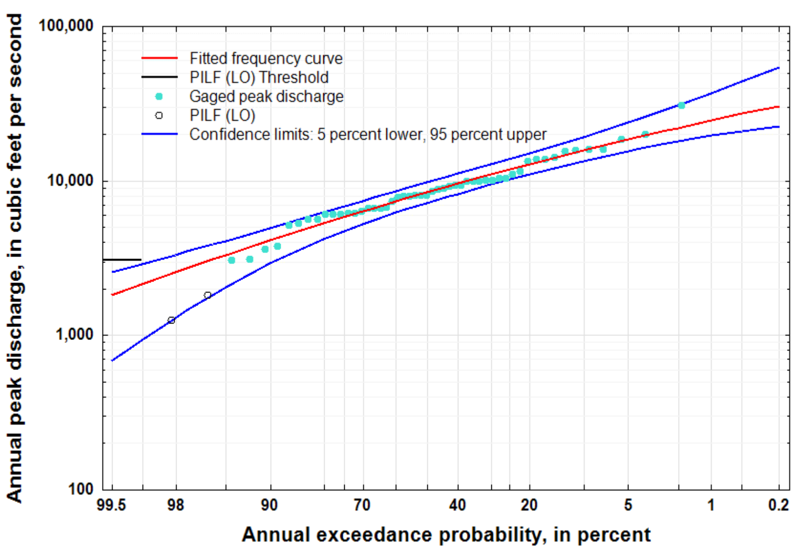


Figure 4-6: Statistical Analysis of USGS Gage Data using B-17C

Use multiple methods (including analytical and form-based) to determine the channel-forming flow to be used as the design discharge. If the various methods do not result in a similar flow rate, investigate further to determine why there is disagreement and to decide if one or more of the methods is expected to be a poor predictor for the specific stream. The issue of a method of discharge determination serving as a poor predictor of the channel-forming flow is especially relevant when attempting to determine the bankfull discharge in an incised and/or degraded stream reach. Bankfull indicators are frequently absent or difficult to distinguish in the field due to the lack of a floodplain, severe bank instability, or general poor condition of the channel. Additional discharge determination methods must be used in situations where a portion of or the entirety of the study reach is degraded and no stable reaches exist in the immediate vicinity of the study reach. Forcing the determination of the bankfull stage in a degraded reach will likely lead to a poor discharge selection, which will could severely decrease the quality of the eventual design.

Figure 4-7: Natural and Artificial Threshold Channels
(Top: Dreams Time, Bottom: Clean Water Iowa)

The recommendation to use multiple channel forming discharge determination methods is not limited to alluvial channels, but also to ‘threshold’ channels. ‘Threshold’ channels, as shown in Figure 4-7, are channel segments or entire streams that are either naturally or artificially armored so that they remain static/unchanged regardless of the flow, sediment, and wood inputs. This type of channel can also be referred to as an ‘erosion resistant’, ‘rigid boundary’, or ‘static’ channel, among other names. Threshold channels do not experience meaningful amounts of erosion due to the resilience of the channel bed and banks.

Artificially created threshold channels (or channels intended to be threshold channels) are protected by manmade materials or large, quarried stone and are relatively common, particularly in urban areas. Naturally occurring threshold channels may be formed of bedrock, stone large enough to prevent mobilization, or particularly dense and robust vegetation. Naturally occurring threshold channels exist in Indiana, and those that do are often in series with alluvial reaches. This produces the situation where the flow entering the threshold reach downstream of an alluvial reach contains sediment that may or may not be deposited in the threshold reach. The deposition or lack thereof may affect the function of the stream reach, particularly the biological function. Consider a range of flows to promote a more holistic design that prevents or reduces negative impacts.

Stable alluvial streams change when subjected to a range of flows and the health of the stream depends on a consistent regime of flow magnitude, timing, duration, etc. These various flow events are referred to as ‘maintenance’ flows that induce natural processes in the stream that can affect the physical, chemical, and biological function of the stream. An analysis should consider the full range of maintenance flows to determine if the conditions for the designed FEH mitigation measures will support the natural processes necessary to produce a stable and healthy stream reach.

The entirety of the flow history through a given reach affects and has shaped the channel characteristics, according to channel-forming flow theory (Soar and Thorne, 2001). For the channel-forming flow to remain [and have always been] a single value, the distribution of flow magnitude, frequency, and duration must be consistent through time (known as “stationarity”). Recent weather and flow condition trends suggest that more intense events are occurring more frequently. This presents a problem for practitioners. Should the channel-forming flow be determined without consideration of recent changes in the flow regime? Should the channel-forming flow assume that the trends continue or worsen? The practitioner should complete the analysis with the information available while recognizing that more extreme future flow conditions are neither a foregone conclusion nor a fallacy. The potential impact of more extreme flow conditions should be determined and considered.

The practitioner should complete the analysis with the information available while recognizing that more extreme future flow conditions are neither a foregone conclusion nor a fallacy.

4.3.2 Sediment Continuity

Sediment continuity is a primary requirement for a stable alluvial channel. Sediment continuity requires that the amount of sediment entering a reach equals the amount of sediment leaving the reach. The sediment that enters may not be the same particles that leave the reach, but the quantity and distribution of sizes must be the same for the channel to remain stable over the long-term. As suggested by Figure 4-8, analysis of sediment continuity includes the determination of the mass flux of sediment into a stream reach, the addition/loss of sediment within the reach, and the mass flux of sediment leaving the reach. These values are used to determine how the characteristics of the stream might change (e.g. aggrade, degrade, and/or laterally migrate). Specific methods for estimating sediment supply from the watershed and upstream reaches, the anticipated amount of sediment erosion/deposition within the reach, and the sediment capacity of the stream reach are covered in the National Engineering Handbook (USDA, 2007), Applied River Morphology (Rosgen, 1996), WARSSS (Rosgen, 2006), and Channel Restoration Design for Meandering Rivers (Soar and Thorne, 2001), among others. Alluvial channel design is not likely to result in a stable channel if sediment continuity is not considered. Changes to the sediment supply and discharge from a reach should be expected to affect natural adjustments to the channel width, depth, roughness, grain size, slope, potential and severity of scour, and the ability to store sediment (Montgomery and Buffington, 1997).

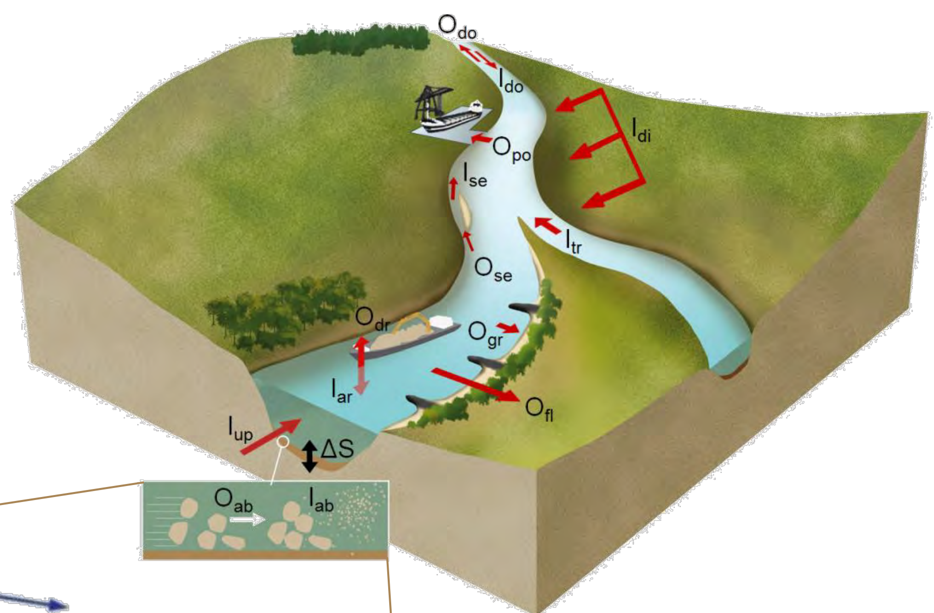
LEGEND

I = Sediment Inflow to System

O = Sediment Outflow from System

Subscripts

do = downstream
po = ports/harbors
se = side-channel erosion
tr = tributary
dr = dredging
ar = anthropogenic sources
up = upstream reach
fl = floodplain
ab = active boundary abrasion
di = diffuse sources
gr = groyne field (spur dykes)



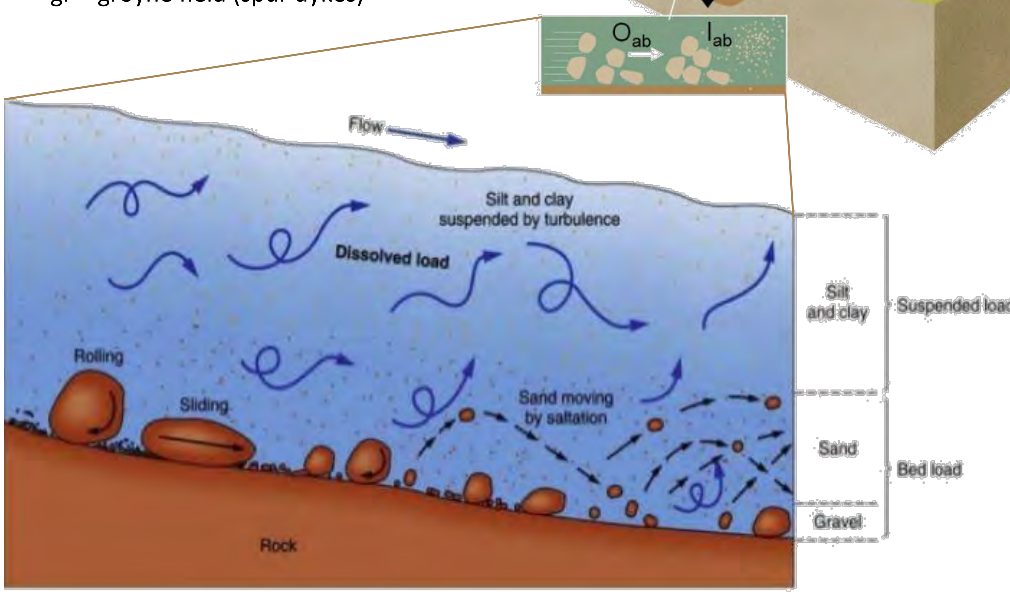


Figure 4-8: Sediment Transport through a River System
(Adapted from the International Commission for the Hydrology of the Rhine Basin [above]
Little Geological Consulting [below])

Many stabilization projects have armored Indiana streams to artificially produce threshold streams. These exceptionally erosion-resistant channels can produce acute discontinuities in sediment supply and transport by changing the characteristics of the flow and/or reducing the supply of sediment to the stream. Consideration of sediment continuity in threshold channels is similarly important to make sure that the upstream and downstream extent of the project (and the study reach in general) has an acceptably close balance between sediment capacity and sediment supply to prevent severe degradation, as shown in Figure 4-9, or aggradation of upstream or downstream reaches.

Man-made threshold channels have the potential to create acute discontinuities; however, other potential situations can produce the same effect. Naturally occurring log-jams/debris jams, manmade dams, active and abandoned gravel pits/quarries, dredged channels, over-widened channels, and other natural and anthropogenic features can cause abrupt changes in the sediment concentration in the flow by either dramatically reducing/increasing the sediment capacity of the reach or preventing sediment contribution to the flow. Consider the potential for these features to affect the study reach in the process of establishing the root cause of instability as well as in determining the components of a potential design.

Figure 4-9: Erosion Downstream of a Threshold Channel
(Ecological Landscape Alliance, 2018)

4.3.3 'Stable' Channel Geometry

The first, and potentially most important, step in understanding the characteristics of a 'stable' channel is to differentiate between the terms 'stable' and 'static'. Alluvial streams, by definition, have bed and banks, and floodplain formed of material transported by the stream under present flow conditions that readily exchange material between the inflowing sediment load and the bed and banks of the channel (USDA, 2007), and thus change over time. Many definitions of 'stable' channels have been crafted, with similar major themes being shared by most. Rosgen provides a concise description, noting that stream stability can be characterized as: "The ability of a stream, over time, in the present climate, to transport the flows and sediment from its watershed in such a manner that the stream maintains its dimension, pattern, and profile without aggrading or degrading" (Rosgen, 1996).

> *Stream stability can be characterized as: "The ability of a stream, over time, in the present climate, to transport the flows and sediment from its watershed in such a manner that the stream maintains its dimension, pattern, and profile without aggrading or degrading"* (Rosgen, 1996).

To more fully understand stream stability, couple stability with the concept of dynamic equilibrium. Dynamic equilibrium refers to the constant and often minute adjustments made to a stream to bring about a state of balance between the forces acting on the channel, which are dependent on the input of flow, sediment, and wood, and the ability of the channel materials to resist that change. Viewed over a reasonable period (generally ~50 years), a stream that is near a state of dynamic equilibrium will appear to be 'stable'.

Assess sediment capacity and sediment competence to promote appropriate selection of channel dimensions and materials. Sediment capacity should be considered for the entire range of flows that may occur in the channel to make sure that sediment continuity is maintained (or nearly so) for both small and large events. Ignoring sediment continuity for small events can lead to a long and slow degradation or aggradation process.

In contrast, ignoring larger events can lead to more acute and catastrophic aggradation or degradation (Rosgen, 2007, 2009; Soar and Thorne, 2001). Sediment competence is also important to consider when trying to understand whether the channel should be expected to self-armor as smaller, more mobile sediments are carried away by the flow, leaving behind larger, immovable material. Similarly, if the channel is composed of too much small diameter, more erodible material, the channel may be subject to degradation during larger flow events.

The stability of the existing channel geometry can be assessed using analytical or form-based methods. Consider using sediment transport equations applicable to the stream characteristics being examined to determine sediment competence and capacity for a given cross-section of the reach. Complete the analysis over the range of flows anticipated for the channel to determine whether the channel will experience erosion or deposition in a significant amount at any flow rate. The sediment transport equation analysis must be accompanied by an evaluation of the sediment supply to the reach, ideally with observed data.

Evaluate form-based channel stability by comparing the channel dimensions and geometric ratios to a reference reach that is naturally stable or to regional equations developed from a collection of stable reference reaches. The assumption is that by providing the appropriate channel shape, the channel will be able to convey the flow and sediment without appreciable change. Careful selection of a reference reach is required for this approach (Rosgen, 1996).

Stable channel geometry must be determined for a FEH mitigation design.

Stable channel geometry must be determined for a FEH mitigation design. The design process is very similar to the analysis process and can be completed using analytical or form-based methods. A thorough explanation of analytical methods for determining stable channel geometry is provided in Channel Restoration Design for Meandering Rivers (Soar and Thorne, 2001). The Natural Channel Design methodology developed by Dave Rosgen is provided in Chapter 11 of the National Engineering Handbook (USDA, 2007), Applied River Morphology (Rosgen, 1996), and WARSSS (Rosgen, 2009).

4.3.4 Scour

Scour refers to the erosion of material along the boundary of a channel. Scour is also sometimes used to describe the degradational process in a stream. Distinguish between scour and long-term or systemic erosion issues, such as widespread degradation, aggradation, or excessive lateral migration. Here we use the term scour to describe localized erosion from a streambed or bank because of an imbalance between the erosive force and erosion resistance of the channel boundary or lining. The imbalance can be caused by the presence of a bridge, culvert, meander bend, constriction, debris, etc. that typically results in a local acceleration of the flow that increases the erosive potential of the stream (USDA, 2007).

The National Engineering Handbook provides a schematic example of several types of scour, as shown in Figure 4-10, and direction on the calculations required to compute scour depths associated with several types of natural and manmade channel features (USDA, 2007).

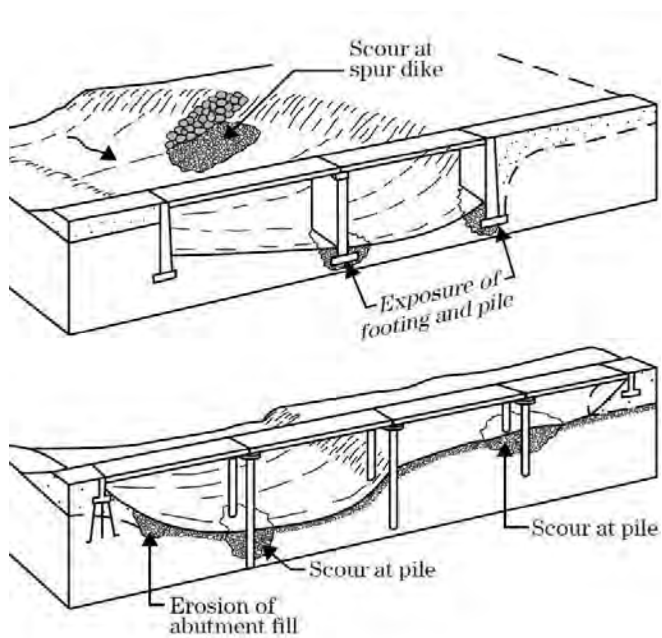


Figure 4-10: Examples of Local Scour
(USDA, 2007)

Scour calculations are a critical component of any stream restoration or stabilization project. Alluvial channel design must consider scour to confirm the adequacy of channel dimensions or the appropriateness of components that cannot tolerate scour. Adjust the design to account for the potential lowering of bed elevations adjacent to channel banks, as well as adjacent and in-stream structures.

Threshold channel design processes should also include scour calculations to determine the impact of potential component failure. Proper threshold channel design will prevent scour from occurring. However, when dealing with particularly important structures such as public infrastructure, try to envision the potential failure of a portion of the improvements that could result from events that exceed the design storm event. Furthermore, consider where over-design may be warranted to be doubly confident of adequate performance when the analyses used to produce the input for channel armoring are based on less-than-ideal quality data or simplified analysis methods. A discussion of the scour analyses methods used during the USGS bridge scour assessment in Indiana is available at the Indiana FEH website (http://feh.iupui.edu/)

4.3.5 Habitat Quality & Availability

The health of a stream, and thus stability, is not limited to sediment continuity or flow conditions. The biological and physiochemical components to stream health can directly affect the stability of the stream, as well as the surrounding ecosystems. Figure 4-11 illustrates a healthy stream environment.

Assess the quality and quantity of habitat, flora, and fauna present within the project area to establish the base condition. The most common method for evaluating instream habitat is a QHEI study. Additional evaluation of the riparian buffer area can be completed using several methods, such as the Proper Functioning Condition (Prichard et al., 1998), NRCS Rapid Visual Assessment Protocol, and the EPA Rapid Bioassessment Protocol (Barbour et al., 1998).

Identify the potential hindrances to healthy flora/fauna communities. Allelopathic vegetation can prevent the development of adequate vegetative cover and natural reinforcement of the channel banks. Human and agricultural activities can also diminish or destroy the integrity of the riparian buffer. Catalogue the type, locations, extent, and severity of the negative influences.

Figure 4-11: Healthy Riparian Corridor
(Umeå University, 2018)

4.3.6 Introducing Stream Function

Indiana is promoting a greater understanding of the overall health of natural channels and waterways, which in turn has led to an increased interest in assessing stream function. The environmental components (chemical and biological) of stream health are being considered more often and in greater detail than historically. The reintroduction or addition of stream function to local waterways may be desirable as interest in producing fully functional and healthy streams increases.

Figure 4-12: Reintroduction of Native Vegetation
(USFWS, 2018)

Recognize the difference between reintroducing and adding stream function. Reintroducing stream function refers to recreating a condition or flora and fauna population that once existed in the stream. Reintroduction, as illustrated in Figure 4-12, is often motivated by the loss of a specific condition that allows a process to occur or to support the habitat necessary to sustain the flora and fauna population. Adding function refers to producing a condition that previously did not exist but has now become desirable and possible. Both conditions have the potential to produce the desired result, but they can also result in unintended consequences detrimental to another population or characteristic of the channel.

Approach adding a function with considerable caution because changing conditions may make local or native species and habitats less sustainable than invasive types. The addition of a non-native, invasive species (see Figure 4-13) should not be considered as many cases can be cited to highlight the potentially devastating effects (e.g., zebra mussel, Asian bush honeysuckle, Asian carp, kudzu, etc.). When considering adding or re-introducing a stream function, base it on the entire function of the stream. As discussed in Chapter 3, Harman et al. produced a detailed function-based assessment strategy, which is condensed into the stream functions pyramid shown in Figure 3-3 (Harman et al., 2012). A Functions-based Framework for Stream Assessment and Restoration Projects (Harmon et al., 2012) provides a comprehensive discussion of the relationships between the levels of the pyramid and how stream functions interact.

The sustainability of stream function not currently present needs to be considered with respect to the current hydrogeologic conditions. Avoid introducing a stream function that requires regular maintenance. Make stakeholders aware of the need to maintain a requested function and the efforts required to do so. Eliminate from consideration stream functions that require flow conditions (magnitude, frequency, duration, etc.) that do not exist because eventual failure or inability to establish the function will undoubtedly occur.

The features and processes necessary to create and maintain function must be well understood to determine if stream improvements can be designed to produce the required conditions. Conduct hydrologic and hydraulic analyses to confirm that the required flow conditions can be expected to occur at sufficient frequency to keep the function sustainable. The analyses can also help to identify hindrances to establishment/maintenance of an added or re-introduced function.

Figure 4-13: Invasive Species
(Top: Missouri Dept. of Conservation, 2017)
(Middle: Purdue Ext. Entomology, 2018)
(Bottom: Circle of Blue, 2016)

4.4 PASSIVE RIVER MANAGEMENT

Passive management refers to enacting improvements outside of the stream corridor (i.e., watershed-based improvements) to provide a benefit to the stability and/or health of the stream, or the non-structural removal of impairments to the stream corridor itself.

Typically, passive management strategies include modifications to land use practices, augmentation of site-specific stormwater management best management practices, and pollution reduction efforts. Management strategies can take the form of adding beneficial components and/or removing detrimental features or activities. In Indiana, the types of management strategies that can be employed depend on whether the current land use is agricultural or urban.

In principle, passive management strategies are more appropriate for addressing systemic issues, or situations where active management is not an option due to property ownership or other project feasibility limitations.

4.4.1 Agricultural Land Management

Approximately two-thirds of the land area in Indiana is currently used for agricultural purposes. See Figure 4-14 for the spatial distribution of agricultural land use in Indiana. The predominance of agricultural land in many watersheds theoretically makes passive management strategies a particularly effective method when employed consistently. The most common impairments to the health of a given stream are related to land use practices that prevent or reduce the efficiency of infiltration of stormwater runoff, livestock management, and the introduction of significant amounts of nutrients into the system.

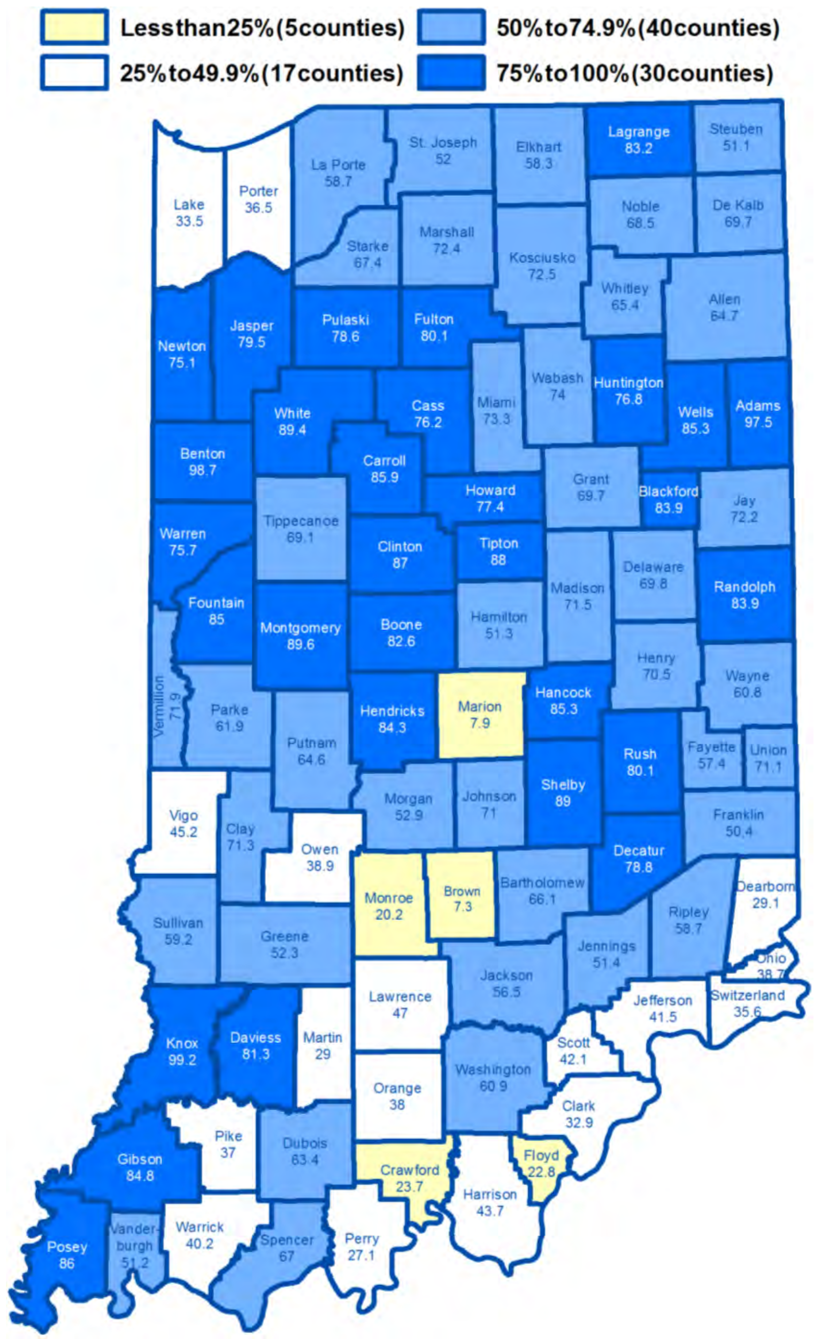


Figure 4-14: Indiana Agricultural Land Use by County
(USDA, 2012)

Land Cover & Tillage

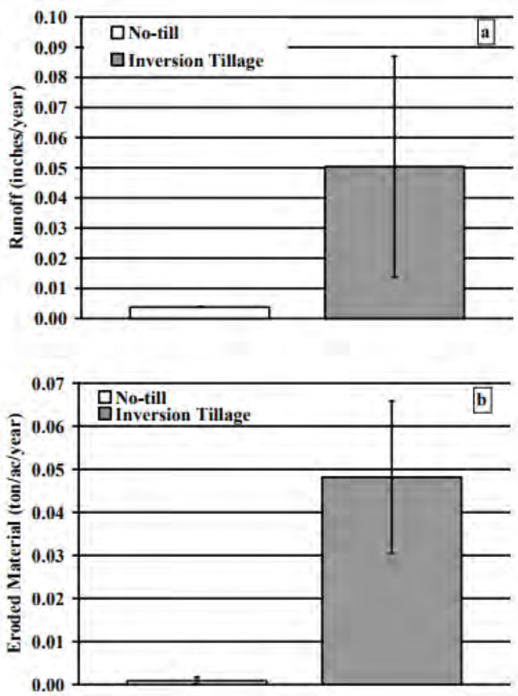


Figure 4-15: Runoff and Erosion from No-till and Inversion Tillage
(Williams et al., 2009)

The type of ground cover is one of the most influential components to the hydrologic response of a watershed because it affects both the rate and volume of runoff produced by a given storm. Land uses that either prevent runoff infiltration or reduce soil permeability typically negatively impact stream stability by increasing peak flow rates, as well as producing more runoff more often. Vegetative cover can also help armor a stream by stabilizing soil particles that would otherwise eventually make their way into the stream.

The use of cover crops and/or no-till practices can effectively reduce the amount of soil compaction and increase the infiltration capacity of the soils. A USDA study of the impact of using no-till versus conventional tillage suggests that conventional tillage can reduce infiltration capacity by 90% and make sediment contribution ten times greater than a no-till field, as shown in Figure 4-15 (Williams et al., 2009).

Best management practices (BMPs) applied over agricultural surfaces improve infiltration and soil stabilization. The more common conservation BMPs used in cultivated fields in Indiana are as follows:

- No till and/or cover crops
- Buffer and/or filter strips
- Vegetated swales
- Dry dams

Grazing

Livestock can indirectly and directly affect stream condition through soil compaction, bank shearing, decimation of vegetation, and/or severing roots of riparian vegetation, which are needed for plant survival and bank stability (Behnke and Raleigh, 1978). Livestock waste can also serve as a concentrated source of nutrients or pollutants when deposited directly in the stream, thus harming water quality more than if the waste is deposited on upland surfaces and is largely retained in place.

Understanding the relationship between vegetation and channel stability helps plan and design grazing management strategies that are compatible with riparian area maintenance or restoration, as illustrated in Figure 4-16. Of similar importance is recognizing that the condition and management of the associated uplands can directly affect conditions in the riparian area. Change in upland management should not be to the detriment of the riparian area and vice versa.

Grazing practices should reflect consideration of both livestock production and natural resource management. Grazing plans should consider growing seasons of the vegetation along the channel to avoid long-term impacts to vegetation that provides bank protection. Sensitive areas and/or grazing areas that are currently not intended to be active should be quarantined to prevent overgrazing.

Figure 4-16: Grazing Strategy Considerations and Relationships
(USDA, 2004)

Soil Compaction

Heavy equipment used to cultivate crops in agricultural fields tend to be rubber-tired and impart high ground loads that result in soil compaction. The compression of and damage to the soil structure reduces the infiltration capacity of the soil during storm events. Even shallow tillage of the soil will repair the compaction induced by heavy equipment (Williams et al., 2009).

Tillage has been the most common method for eliminating soil compaction; however, tillage can lead to increased surface erosion, and in many cases can eventually lead to decreased infiltration capacity. Alternative means of reducing or preventing soil compaction have been researched by the University of Minnesota and the University of Nebraska. Figure 4-17 (DeJong-Hughes et al., 2001) illustrates the concept of controlled traffic to reduce the area of the field subjected to surface compaction. Controlled traffic was cited as the most effective means of reducing surface compaction because as much as 90% of soil compaction occurs during the first pass of a piece of equipment.

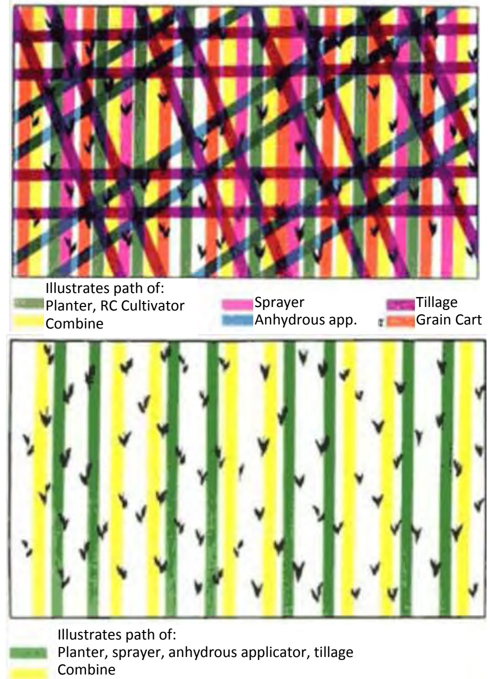


Figure 4-17: Unmanaged vs. Controlled Equipment Paths
(DeJong-Hughes et al., 2001)

Drainage

Arguably, the most problematic agricultural practice occurring in Indiana is the installation of extensive tile drainage systems, like that illustrated in Figure 4-18. The intent of the tile drainage is to decrease the probability of crop loss due to extended periods of ponding and soil saturation. Tile drains raise several issues for stream stability.

1. Tile drains collect infiltrated runoff that would otherwise be stored as groundwater. The collection of runoff in this manner and its ultimate discharge into the stream significantly increases the overall volume of runoff.
2. Tile drains collect groundwater that may have eventually reached the stream through groundwater flow; however, the drains dramatically reduce the amount of time it takes for the runoff to reach the stream, significantly increasing the rate of the runoff.
3. Tile drains reduce soil moisture during times of drought, as well as times of wet weather. Decreased drought resistance negatively affects crop production and can increase the potential for surface erosion due to a lack of plant vigor.

In most cases, drainage improvements have an overall negative impact on the stability of a stream. However, this does not mean that drainage improvements cannot occur in a more environmentally sensitive way. Subtle adjustments to field topography or outlet control structures can prevent ponding areas without dramatically decreasing the amount of time it takes the runoff to reach the stream.

Figure 4-18: Extensive Tile Drainage

Nutrients

Fertilizers used in agriculture (nitrogen and phosphorus) often degrade stream water quality. Excessive amounts of these chemicals in streams can lead to hypoxia, or a lack of available oxygen for aquatic flora and fauna, as illustrated in Figure 4-19 using Lake Erie. High nutrient levels and hypoxia may produce algae blooms (green areas) that can also be hazardous to humans, pets, and livestock.

Full coverage application and over-application are two key contributing factors to excessive nutrient loading in streams. Innovative technological solutions to help reduce nutrient loading have been developed. Precision soil testing and GPS-aided fertilizer application have been trialed and are beginning to gain acceptance. These methods reduce application rates, lower operational costs for farmers, and decrease water quality issues in the receiving streams. Additional methods that help to reduce nutrient loading in streams are no-spray buffer zones, filter strips, crop rotation, and appropriately applied natural fertilizers.

Figure 4-19: Hypoxia in Lake Erie
(NASA, 2012)

4.4.2 Urban Stormwater Runoff

Indiana cities and towns cover approximately 11-percent of the state, making urban land use the third most common type in Indiana behind agricultural (62%) and forested (23%) (Homer, 2011). Urban areas may cover a much smaller percentage of the state than agricultural lands, but the potential impact of urban areas is far greater on a per-acre basis due to the presence of significant amounts of impervious surfaces (2.6% of the Indiana land area).

Asphalt, concrete, rooftops, graveled areas, and compacted soils cause very low infiltration rates, leading to much higher runoff rates per acre. The typically severely modified urban landscapes promote efficient drainage, resulting in the almost absolute loss of watershed storage. Revisions to the topography eliminate or severely diminish the surface ponding that was present prior to development. The combination of decreased infiltration and loss of surface storage increases runoff rates and volumes as illustrated, respectively, in Figure 4-20 and Figure 4-21.

Furthermore, urban water quality suffers because of the introduction of hydrocarbons from automobiles and asphalt. Water temperatures are also elevated as the hard surfaces, primarily asphalt and concrete, retain the sun's heat and transfer it to the runoff during storm events. The hydrocarbons and increased water temperatures decrease dissolved oxygen levels in the streams, hindering the flora and fauna.

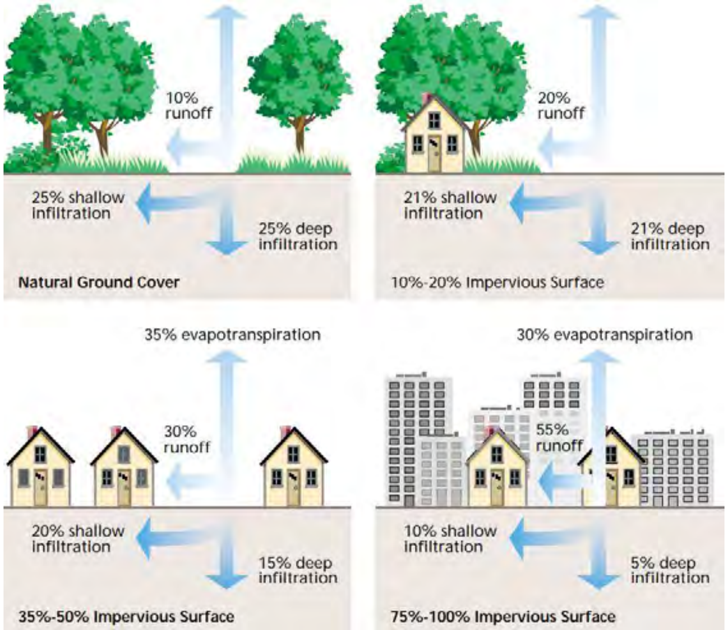


Figure 4-20: Effects of Urbanization on Runoff
(FISRWG, 2001)

Understanding how urbanization impacts waterways and how to combat the detrimental effects has improved over time. Older development infrastructure typically does not include management of increased runoff volume, intensity, and pollutant loads. Newer developments are commonly required to address all three issues. Implementation of urban stormwater BMPs can be beneficial to a stream, whether they are implemented in preventive or retroactive modes; however, the implementation style can affect the types of BMPs that are practical and effective.

Green Infrastructure

In domino fashion, reduced infiltration and loss of watershed storage increases runoff rates which, in turn, increases stream flow which, in turn, increases a stream's sediment capacity and competence. The increased capacity for erosion can lead to downcutting, lateral migration, or general bank scour, depending on the quality and erosion resistance of the channel banks and bed.

Use of stormwater detention or retention reduces the rate of runoff by temporarily storing a portion of the runoff; however, storage alone does little to recover the infiltration that is lost due to increased impervious cover. Conventional stormwater management typically includes detention/retention as the primary method for managing the hydrologic response of the site. Creating developable space requires that some areas drain very efficiently. Even with the inclusion of undisturbed area, the additional runoff volume and elevated flow rates must be absorbed to allow the post-development hydrograph to resemble the pre-project condition. Stormwater detention/retention can usually allow for the timing and peak of the event to be similar to pre-project conditions; however, the increased volume of runoff often causes off-peak, elevated flow rates to occur for a much longer duration.

Green infrastructure is an alternative to the conventional pipe to pond stormwater management approach commonly used in urban areas. This method uses the natural characteristics of soil and vegetation to capture and treat stormwater runoff where, or close to where, it falls. The green approach can be applied at a regional, neighborhood, and site scale to mitigate stormwater problems and mimic the natural hydrologic response that existed before land development occurred (OCRA, 2015). Green infrastructure includes low impact development practices, better site design, and source-control engineered methods to mitigate stormwater-related impacts such as flooding and pollution carried by runoff (OCRA, 2015).

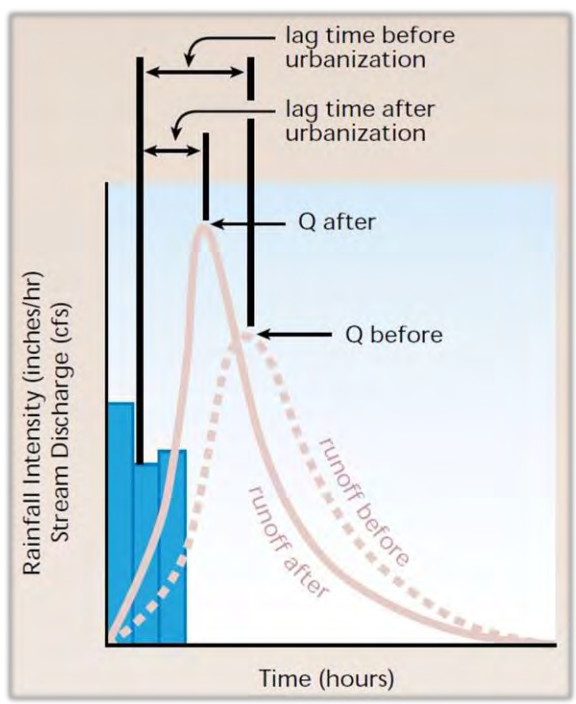


Figure 4-21: Effects of Urbanization on Hydrology
(FISRWG, 2001)

While many sources offer an abundance of guidance for the implementation of green infrastructure in site development and redevelopment, the most relevant source of information in Indiana is the Green Infrastructure Curriculum and Training Program produced by the Office of Community and Rural Affairs (OCRA). The following list presents some of the more popular methods in Indiana that should be considered as potential passive management strategies:

- Minimize disturbance
- Utilize cluster-type development
- Underground and surface detention basins
- Level spreaders
- Permeable pavement/pavers
- Curb cuts and/or turnouts
- Rainwater harvesting
- Infiltration basins and trenches
- Extended detention
- Bioswales
- Tree/planter boxes
- Constructed wetlands
- Bioretention/rain gardens
- Green/blue roofs

<u>Pollutants of Concern</u>

High concentrations of pollutants in stormwater runoff can severely diminish or preclude the ability of flora/fauna to function properly in a stream. Pollutants may be toxic to flora/fauna or simply deplete the dissolved oxygen required to sustain aquatic life. Many of the pollutants that typically cause these issues accumulate after being carried from impervious surfaces by runoff. The primary pollutants of concern for Indiana waterways are:

- Nitrogen
- Phosphorus
- Hydrocarbons
- Suspended & Dissolved Solids
- Fecal Coliform/Strep
- *E. coli*

First, determine the specific pollutants that are impacting the study reach and then determine the portions of the watershed, as suggested by Figure 4-22, that may be causing the pollution. Identification of the problem areas enables targeted watershed management strategies to reduce the pollutant loading. Baseline water quality sampling should be performed at the site to cover the full range of potential pollutants.

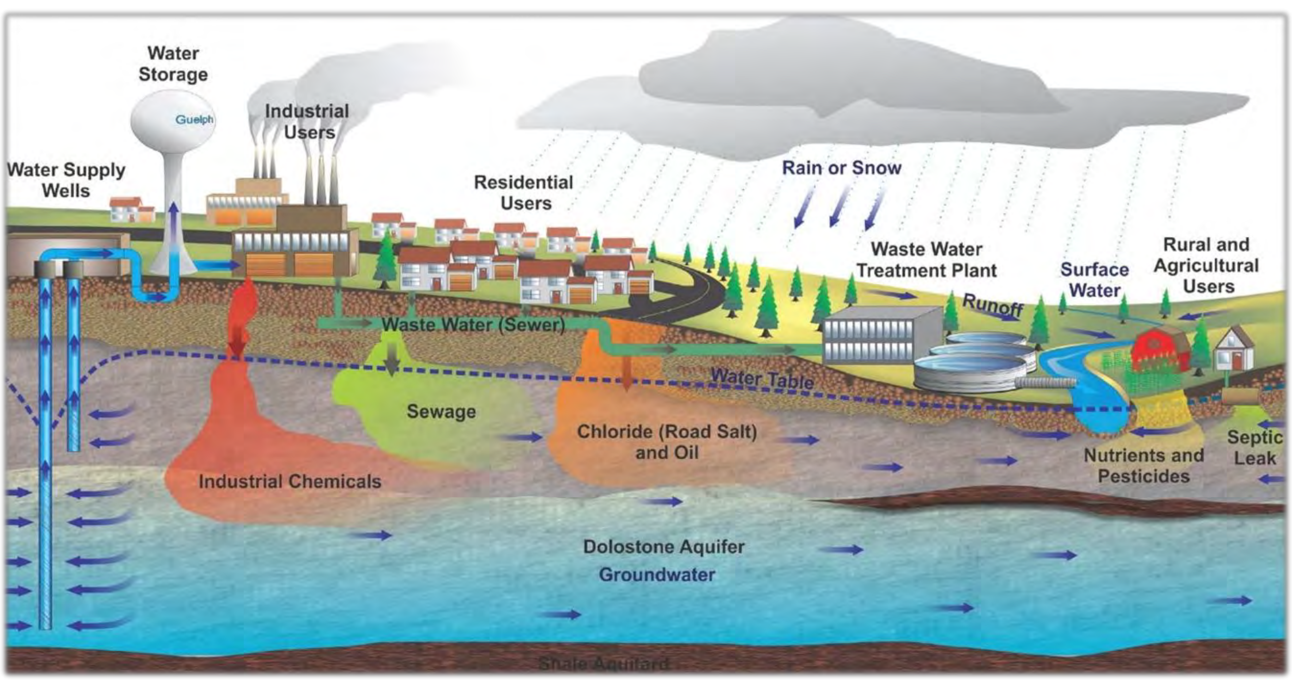


Figure 4-22: Pollutant Transport through Urban Environment
(Institute for Groundwater Research)

Many of the methods used to help reduce increased surface runoff volume and intensity also help to reduce pollutant loading. Urban areas may require additional treatment methods to eliminate hydrocarbons and other chemical compounds. Bioswales, rain gardens (Figure 4-23), and other green infrastructure methods can help to treat the 'first flush' through biological uptake; however, more intensive or mechanical treatments may be required to eliminate litter and more problematic chemical compounds.

Figure 4-23: Rain Garden Treating 'First Flush'
(American Academy of Engineers and Scientists, 2015)

4.5 ACTIVE RIVER MANAGEMENT

Active river management refers to man-made adjustments within the stream corridor, most commonly within the bankfull channel. Typically, these adjustments address some form of physical instability, either vertical or lateral; however, improvements can also be for water quality or habitat enhancement purposes. Use active river management measures only when restoration objectives cannot be achieved by passive management measures. Inappropriate or inadequate use of active river management carries with it the risk of exacerbating or inciting stream instability. Take care to ensure that the modifications made within the stream corridor will not negatively affect areas outside of the project reach.

4.5.1 Vertical Stability

Unstable alluvial streams often have cross-sectional, planform, and/or grade changes that are accelerated and distinguishable over the short-term. The most commonly cited indicator of stream instability is bank failure, as illustrated in Figure 4-24, which can be caused by a number of processes. Channel incision, a form of vertical instability, often causes bank failure.

Figure 4-24: Channel Experiencing Degradation via a Headcut
(Pitchfork Ranch, 2017)

Vertical channel instability takes the form of aggradation or degradation. Aggradation occurs when the upstream reaches convey more sediment than the downstream channel can transport and excess sediment is deposited in the channel, resulting in an increasing bed elevation. Degradation occurs when the opposite situation exists; the downstream channel can transport more sediment than the upstream reaches provide. The channel cannot have a rigid channel bottom for a degradational trend to develop. If a rigid bottom exists, the channel will not readily degrade, but rather laterally migrate. Aggradation and degradation are often related, so that where there is one, there will be the other.

Schumm's channel evolution model, which was later amended by Simon and is shown in Figure 4-25, illustrates the processes and relationship between aggradation and degradation. Note that the upstream over-steepened reach identified in the profile at the bottom of Figure 4-25 is undergoing a degradational process and the downstream area is experiencing aggradation. Classes IV and V of the channel evolution model accurately show that if a channel lacks vertical stability, lateral stability cannot be achieved. The reverse can also be true. Lateral instability (not necessarily caused by vertical instability) in upstream reaches of a stream may incite vertical instability (aggradation) downstream, only if the influx of sediment exceeds the transport capacity of a given reach.

Vertical instability is one of the most difficult types of instability to correct, because it is often related to a system-wide lack of equilibrium. In many situations, the most plausible means of establishing vertical stability is to do nothing and allow the wave of incision to propagate through the system. This propagation will establish a new channel profile that reflects more recent changes in the flow regime and channel characteristics. Several methods of active river management that can be implemented, when allowing the channel to adjust naturally are not acceptable. Acceptable options include floodplain reattachment, grade control structures, and bed armoring, each of which is discussed below.

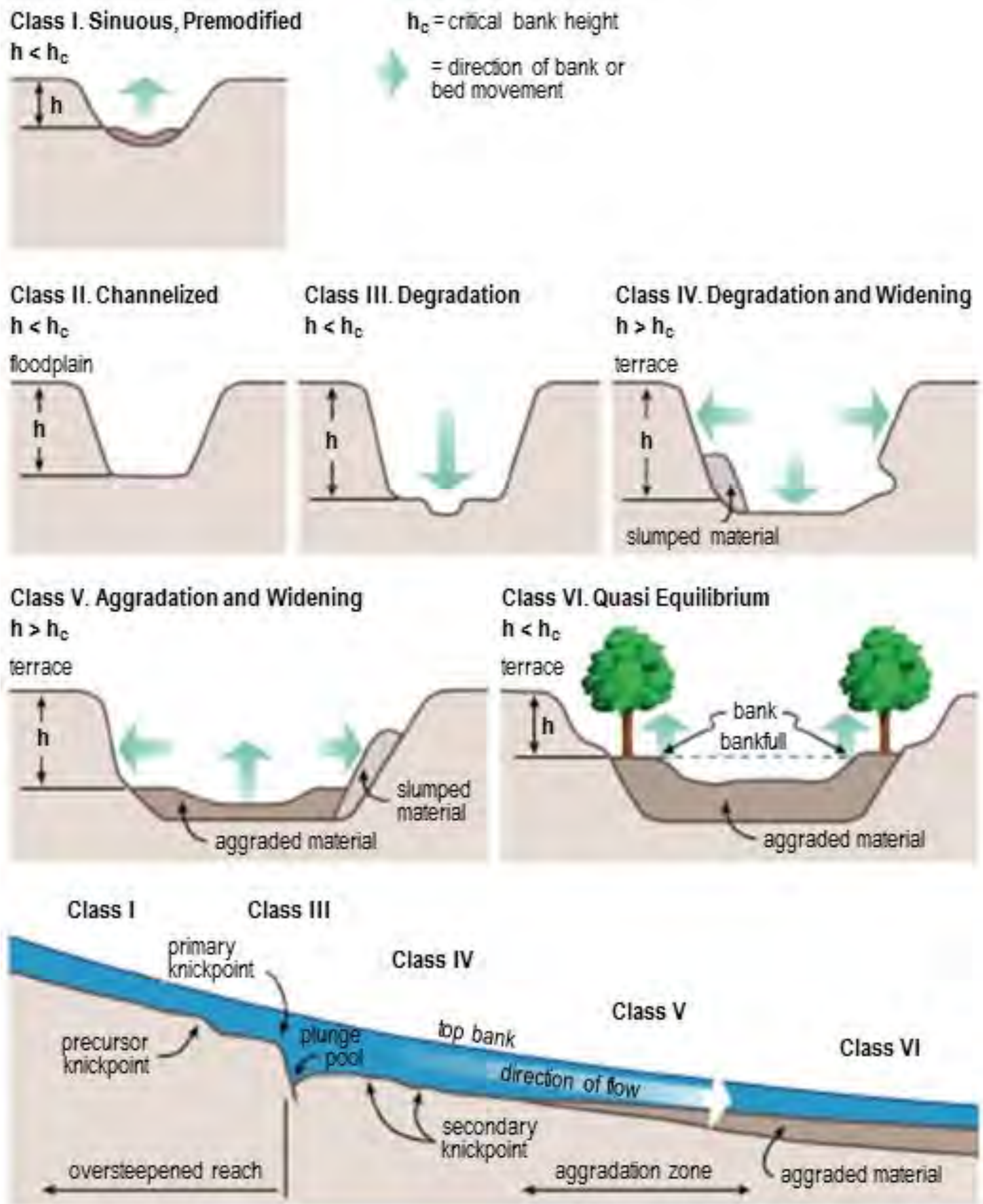


Figure 4-25: Channel Evolution Model
(Schumm et al. after USACE)

Floodplain Reattachment

Channel incision, as shown in the first part of Figure 4-26, can cause the floodplain to detach from the bankfull channel. Floodplain detachment may also result from construction of earthen berms and or levees. The detachment further decreases the stability of the channel, because the excessive amount of energy present in flood flows (flows larger than bankfull discharge) cannot be readily dissipated by the increased roughness and flow conveyance provided by overbank floodplain areas. The lack of energy dissipation then increases the stress on and erosion of the channel bed.

Floodplain reattachment refers to the process of adjusting the channel geometry such that flood flows begin to spill out over a floodplain area. The floodplain area must be sufficient to help dissipate enough energy during high flows so that excessive degradation is prevented, and the channel profile is consistent over time, neither aggrading nor degrading.

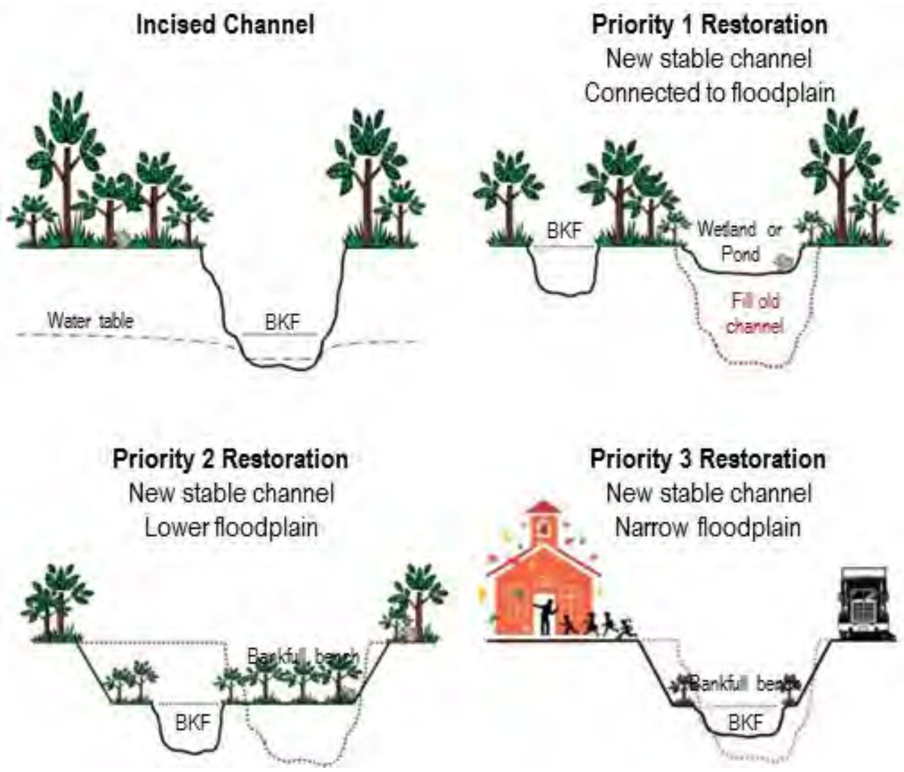


Figure 4-26: Floodplain Reattachment
(NCSU, 2017)

Floodplains can be reattached by several methods, some of which are illustrated in Figure 4-26. Removal of previously constructed berms or levees, that effectively cut off floodplain areas, offers a simple way of reattaching floodplains. However, rarely is removal alone enough to effectively reestablish floodplain connectivity due to prior channel incision (i.e., bankfull elevation is not as high as the floodplain surface elevation). In such cases, channel relocation or grade control structures may be necessary.

Relocation of a portion of the channel or increasing the length of the channel (i.e., adding more sinuosity) can help to elevate the channel bed to previous levels and allow activation of the existing floodplain surface during flood flows.

Floodplain reattachment can be beneficial beyond improving vertical stability. The energy dissipation achieved by an effective floodplain helps to reduce bank scour, lateral migration, and the sediment load. Floodplains also store sediment and large woody material mobilized by large events. Close connectivity to the bankfull channel also makes these areas rich habitat for flora and fauna species prone to riparian areas.

Address the following additional concerns when considering floodplain reattachment:

1. **Floodplain re-abandonment:** Reattachment of floodplain areas that do not sufficiently adjust the erosive potential of the stream will continue the pattern of incision causing re-abandonment of the floodplain. Additionally, if channel relocation or lengthening is not completed in such a way that the channel gradient is established at the equilibrium slope (e.g., grade control structure), the channel will probably aggrade or degrade

2. **Land disturbance and impact to sensitive areas:** Relocation of or adjustments to significant portions of the channel, or channel gradient, can result in the loss of beneficial use (in terms of floodplain functions) for a potentially large amount of land. Furthermore, substantial adjustments to the function or geometry of a channel will likely impact an appreciable amount of environmentally sensitive areas that may or may not currently be active habitat for riparian or aquatic species.
3. **Impacts to BFE (Base Flood Elevation):** Raising the bed elevation to previous levels through channel relocation, channel lengthening, or use of grade control structures, will have an impact on the water surface elevation during flooding events. The Base Flood Elevation (BFE), the water surface elevation associated with the 1% annual exceedance chance flood, is of particular interest due to the regulatory and insurance-based implications. Practitioners must understand the flooding risk posed by the improvements required to reattach the floodplain.

Table 4-1 (presented at the end of Chapter 4) provides guidance about the methods and design process involved with floodplain reattachment as well as other mitigation measures discussed in the remainder of this section.

Grade Control Structures

Over-steepening of a reach, as indicated in Class I through Class III of the Schumm's channel evolution model (Figure 4-25), commonly causes channel degradation. The physical slope of the channel is the most important factor in whether or not a reach is over-steepened; however, the stable slope, referred to as the equilibrium slope, also depends on the flow regime. The equilibrium slope for a channel can change if the flow regime changes; this is evidenced in the down cutting of streams receiving runoff from watersheds being heavily urbanized. The equilibrium slope for a channel is that slope where the channel is expected to neither aggrade nor degrade with the current flow regime.

Grade control structures, like that shown in Figure 4-27, offer an artificial means of forcing the equilibrium slope to exist in a channel. Rigid structures, introduced into the channel to fix specific points along the profile at ideal elevations, produce the equilibrium slope, on average. Various types of construction methods can be used to create grade control structures. They can be formed of loose rock of sufficient size such that channel flow cannot move them, or be rigid structures made of concrete or steel sheet piling. Select the type of grade control and appurtenant structures on a case-by-case basis.

Figure 4-27: Grade Control Structure
(USACE)

Guidance on the process of determining the equilibrium slope for a channel and designing grade control structure(s) for a stream reach is referenced in Table 4-1.

Grade control structures can be particularly difficult to implement successfully. The creation of a hardened point in a channel that is otherwise potentially mobile requires careful consideration. Therefore, thoroughly address the following design concerns:

1. **Flanking:** Structures that are not well thought out or tied into the surroundings adequately will likely suffer from flanking. Flanking occurs when the channel simply flows around the structure, effectively eliminating the planned benefit. Designers must assure that the structure is adequately tied-in and function under the full range of flows anticipated for the reach.

2. **Flow direction:** The placement of a structure across the entire bankfull channel will change the alignment of the flow passing through the reach. Carefully consider and analyze the situation to determine the most appropriate alignment of the structure to avoid directing flow in a manner that will cause future instability. Two-dimensional hydraulic modeling may be warranted if the structure is significantly taller than 20% of the flow depth in the channel.
3. **Safety:** Grade control structures are, in essence, one or more low-head dams in a series. Consider the possible formation of a hydraulic roller on the downstream side of each grade control structures and, if any roller is of problematic size, revise the design to eliminate it. Evaluate the safety of the structure for recreational users under all flow rates and incorporate signage where warranted.
4. **Habitat/Fish passage:** Establishment of a vertical discontinuity in the stream may form a barrier for the passage of fish and other aquatic species. Therefore, include design details and environmentally sensitive components, such as fish ladders and/or chutes, to promote the biological health of the stream corridor. Furthermore, the installation of toe protection causes impacts to the portion of the channel below the Ordinary High-Water Mark (OHWM). Those impacts can be a detriment to the in-stream habitat and cause a more intensive permitting process. Use the smallest footprint practicable to minimize impacts.

Bed Armoring

Channel degradation can be a local or a systemic issue. Gradually lowering bed elevations through a significant portion (or the entirety of) a stream is clear evidence of a systemic issue. Stable stream segments on the upstream and downstream side of a knickpoint (see Figure 4-24 and Figure 4-25) indicate a local vertical instability. Approach local and systemic vertical instability differently, particularly when bed armoring is to be used. Use bed armoring only when a local vertical instability is present.

Bed armoring, as illustrated in Figure 4-28, is the process of increasing the erosion resistance to a degree that prevents erosion for the entire range of flows that may pass through the channel. Essentially, bed armoring creates a threshold channel for a short stretch to eliminate the local instability. Armoring does not necessarily require the installation of stone or concrete, just any material, flexible or rigid, that will prevent erosion.

Figure 4-28: Riprap Bed Armoring

Bed armoring can be achieved using adequately sized loose stone, as shown in Figure 4-28; concrete; and articulated concrete block mats. Turf reinforcement can even be an effective means of bed armoring in intermittent streams. Consider other project objectives when selecting an armoring method to provide the most benefits possible.

As discussed in Section 4.3.2, creating a segment of threshold channel can be detrimental to downstream reaches if not done properly. Table 4-1 provides relevant guidance documents for designing a threshold channel. Address the following concerns during design:

1. **Tie-in location & downstream scour:** Extend the armor beyond the immediate extent of the knickpoint to a location where the energy from the steep slope will be sufficiently dissipated so as not to induce scour immediately downstream of the hardened section. In determining the upstream extent, consider scour due to flow acceleration.
2. **Flanking:** The prevention of channel degradation does not necessarily preclude lateral migration. The design must account for or prevent lateral migration of the channel through the armored reach.
3. **Habitat:** Unfortunately, significant modification or replacement of the channel substrate can eliminate macroinvertebrate habitat. Where possible, design armoring to help maintain, to the extent practicable, the existing habitat. Limiting impacts below the OHWM will also help to reduce permitting complexity.

4.5.2 Lateral Stability

Lateral migration in channels tends to follow a relatively predictable pattern. Streams migrate at meander bends. As the flow passes around the bend, the water nearest the outside bank moves faster than the water near the inside of the meander bend. The flow is often oriented at an angle pointed slightly toward the outside bank. Higher flow velocity, flow direction, and erodibility of the bank material result in the bank being gradually eaten away by the flow. The geometry of the bend and location of the erosion cause meanders to migrate outward and down-valley, a process depicted in Figure 4-29. Figure 4-29 also shows a phenomenon that often occurs along highly mobile streams, the development of oxbow lakes. As the channel migrates laterally, the meanders tend to become elongated and have sharper bends. The path of least resistance for

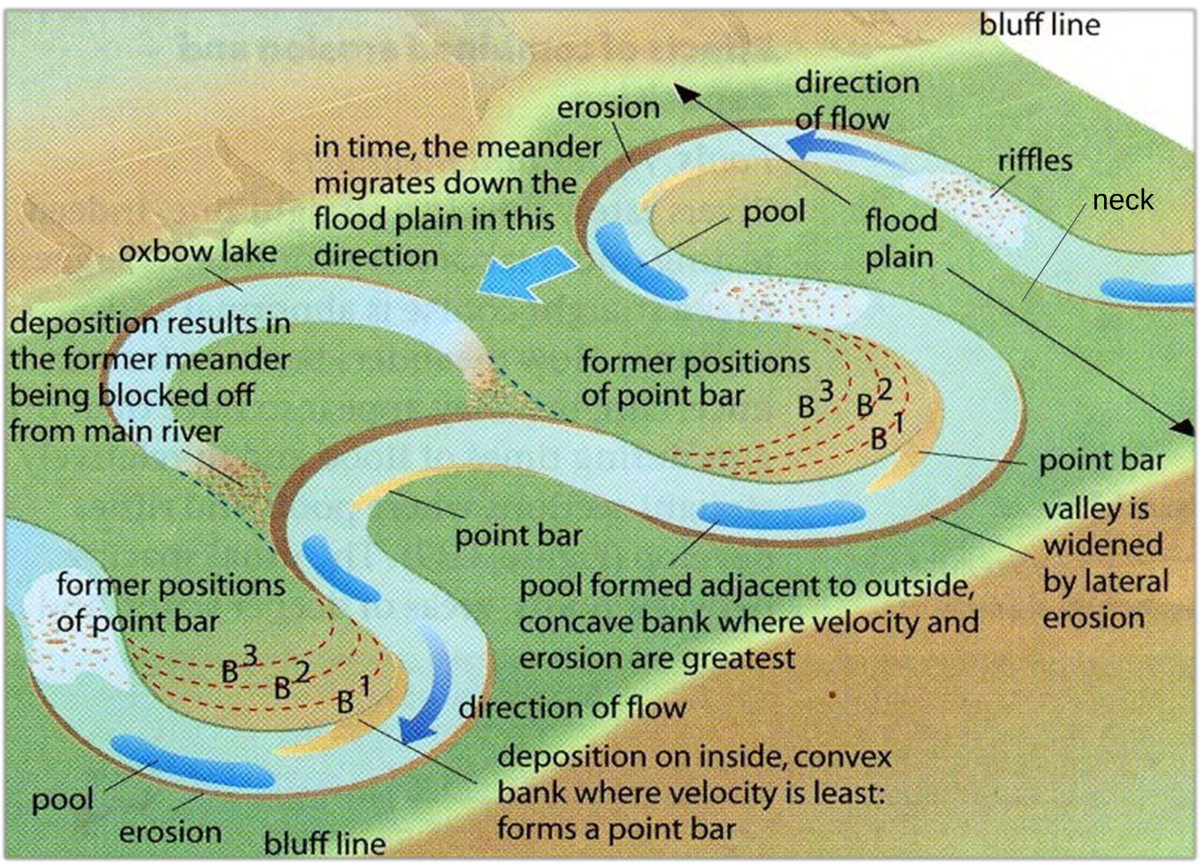


Figure 4-29: Typical Stream Meander Geometry and Progression
(geographyiseasy.wordpress.com)

the water begins to form a secondary channel that cuts off the previous point of the meander bend; this process is commonly started by a large flow event that cuts the initial cutoff chute. The cutoff chute is then repeatedly activated and enlarged, eventually becoming the primary channel, and abandoning the previous bend location, leaving behind an oxbow lake.

The likelihood of a meander bend being cutoff is affected by many things but can generally be simplified to the following statement: a meander bend will experience cutoff when the energy required to move the water along the current channel is greater than the energy required for the water to pass over the neck of the meander (see Figure 4-29) for a long enough period of time for the cutoff chute to enlarge and become the primary flow path. A cutoff becomes more likely as the meander bend becomes sharper, the channel length from the upstream side of the neck to the downstream side of the neck becomes longer, and the thickness of the neck decreases, particularly if the neck is composed of erodible material.

Lateral migration can appear to be the instability in a channel; however, in certain situations lateral migration is only a symptom of the instability. In some cases, increased lateral migration may occur as river adjusts to changes that occurred during a large flood. Sediment and debris may force the channel outside of its normal meander belt width. Channel degradation can instigate geotechnical instability of the channel banks (i.e., the bank height and/or angle exceeds critical values). Carefully distinguish between natural [albeit accelerated] lateral migration and bank failures resulting from vertical instability. Improvements implemented to stop lateral migration in a vertically unstable channel will likely be short-lived.

Several methods are used to slow or prevent lateral migration; generally, the methods can be classified as ‘resistive’ or ‘redirective’. ‘Resistive’ measures increase the erosion resistance of the channel boundary by establishing a higher threshold for erosive forces or by dissipating the near-bank erosive energy. ‘Redirective’ techniques relocate the high-energy flow path in the stream to a location further from the channel bank. The following sections provide summaries of the four most common methods for mitigating lateral migration.

Toe Protection

Toe protection, such as that shown in Figure 4-30, is often a critical component of channel improvements; it helps establish a geotechnically stable embankment under a range of conditions. Streambanks often experience slope failures when the toe is eroded. Toe reinforcement is imperative in situations where the stream is vertically unstable and is experiencing degradation; however, toe protection is also needed even when vertical stability is present because of the potential for bank scour.

Figure 4-30: Toe Protection – Toe Wood

Many types of toe protection can be implemented; examples of different types of toe protection are listed in Table 4-1. Pay special attention to the following details when designing toe protection measures:

1. **Bed Scour –** The bed elevation of an alluvial channel is not constant, even in vertically stable streams. The bed elevation typically lowers during the beginning and middle of an erosive event and increases (often to an elevation near pre-event conditions) during the latter portion of an event, as the flow rate and sediment transport capacity increase and decrease. Scour protection measures must extend to an elevation below the anticipated scour depth to be effective. Careful consideration of the maximum anticipated scour is critical, particularly so for streams that exhibit long-term degradational trends.
2. **Upstream and Downstream Tie-in –** The location where the scour protection measures begin and end must be well thought out. Design the end configuration and/or extent so that the integrity of the bank improvements is not compromised by potential failure of the adjacent banks.
3. **Impacts below OHWM –** Installation of toe protection impacts the portion of the channel below the Ordinary High-Water Mark (OHWM). The magnitude of the impacts can adversely affect in-stream habitat and cause the permitting process to be more intensive. Seek the smallest footprint practicable to minimize impacts.
4. **Non-reliance on Vegetation –** Install toe protection in a portion of the channel that is frequently or completely inundated by the flow in the channel. Vegetative toe reinforcement rarely works because few types of vegetation can establish and persist under such wet conditions. Use the lowest elevation where dense vegetation appears to exist in the channel prior to improvements as a guide for determining where vegetative reinforcement, above that elevation, is likely to be successful.
5. **Drainage Layer –** Most bank protection and toe protection treatments are more effective when they incorporate a drainage layer to reduce the duration of embankment saturation after storm events and to prevent the destabilizing build-up of pressure from groundwater flow. Drainage layers can and should also be used to serve as a filter between the finer-grained soils in the streambank and the coarser material often used for toe protection.

Bank Armoring

Bank armoring, as illustrated in Figure 4-31, involves increasing the erosion resistance of the bank sufficiently to prevent any erosion from occurring. Bank armoring can reduce or prevent bank scour (the loss of surficial material without compromising the geotechnical stability of the bank) as well as control lateral migration. The intensity of the treatment is typically greater when protecting a bank from lateral migration as opposed to scour.

Introduction of armoring immediately impacts the sediment continuity of a reach. It reduces the sediment supply because the sediment previously sourced from the bank is now kept in place. Removal of that source of sediment can result in an increase in erosion in downstream areas, which may or may not be problematic. Carefully consider the sediment continuity of a reach of an actively meandering stream prior to employing extensive bank armoring improvements. If bank armoring must be used to protect critical infrastructure, consider augmentation of the channel geometry as needed to promote sediment continuity.

Figure 4-31: Bank Armoring

Inclusion of toe protection (see earlier discussion) is often an important component of an overall bank armoring plan as the establishment of a stable toe is necessary (in most cases) to maintain a geotechnically stable slope. Geotechnically unstable slopes may experience shallow failures that destroy the integrity of the bank armoring.

Bank armoring strategies can employ synthetic or more natural materials and methods. Table 4-1 lists examples of different types of bank armoring. Pay special attention to the following details when designing bank armoring measures:

1. **Upstream and Downstream Tie-in –** The location where the bank armoring begins and ends is an important detail and is dependent on the intent of the bank armoring. Bank armoring for scour prevention may only need to extend to the limits of the area experiencing scour. In contrast, armoring to prevent meander migration may need to extend well beyond the eroded area. In either scenario, the treatment(s) must be integrated with the existing bank in such a way that erosive flows will not compromise the extremities of the armoring system.
2. **Toe Protection –** The inclusion of toe protection to prevent the geotechnical instability of the slope is often critical for the long-term integrity of the improvements. Inadequate toe protection can and often does lead to failure of the bank improvements.
3. **Flanking –** Design bank armoring improvements as a part of the overall stream. Carefully consider how flow moves through the reach during various conditions because high-flows may flank (or flow behind/around) the treatment(s). Adequate tie-in on all sides of the treatment is paramount where the improvements cannot extend above the highest flow elevation.
4. **Drainage Layer –** Most bank protection and toe protection treatments are more effective when they include a drainage layer to reduce the duration of embankment saturation after storm events and to prevent the destabilizing build-up of pressure from groundwater flow. Drainage layers can and should also be used to serve as a filter between the finer-grained soils in the streambank and the coarser material often used for toe protection.

Flow Redirection

Poorly directed flow can exacerbate erosion problems in a stream since a larger amount of energy is absorbed by the bank material to both slow and turn the flow. This energy absorption can lead to significant erosion. Flow eddies are also common where flow is not well-aligned with the channel bank, leading to turbulence and flow separation that causes erosion.

First understand why the flow is poorly directed. In many cases, a small-scale disturbance, such as a fallen tree, sloughed bank, logjam, etc. causes the poorly aligned flow. In these situations, take the less-invasive approach -- simply remove the disturbance. Examples of reasons to employ more invasive flow redirection techniques, such as that shown in Figure 4-32, include poorly aligned flow resulting from the meander geometry of a channel, poorly aligned bridge piers, and problematic structure foundations.

Figure 4-32: Flow Redirection – Rock Vanes
(City of Golden Valley, 2018)

The use of flow redirection treatments is more appropriate for larger streams where armoring is not feasible. Flow redirection structures are typically quite large relative to the stream size. Larger streams allow for the use of structures of sufficient size without catastrophically reducing the flow capacity of the channel.

Table 4-1 lists examples of different types of flow redirection methods. Give special attention to the following details when designing flow redirection structures:

1. **Consideration of a Range of Flows –** Simulate the anticipated redirected flow vectors under various flow conditions to determine if the structure will appropriately redirect flow without detrimental effects to downstream areas.
2. **Bank Tie-in –** Tie structures into the bank in a way that will maintain structure integrity. In many situations, this will include extending the treatment to the bankfull elevation at the channel bank. Embedment into the bank (or other protection measures) will prevent minor scour above the structure and flanking.
3. **Materials and Structure Longevity –** Flow redirection structures are typically made from stone or logs. Stone materials should be sized such that they are not mobile during the desired range of operation. Flows exceeding the maximum flow considered may cause the material to begin to migrate, reducing the functionality and longevity of the structure. Design wooden materials such that they are either perpetually submerged or submerged often enough to prevent the material from drying because the material will rot if wetting-drying cycles are common.
4. **Scour Considerations –** Flow redirection structures must account for scour to prevent undermining and loss of structure stability. Most types of flow redirection structures extend into the channel and are either cantilevered from the bank or supported by the channel bed. The stability of cantilevered structures depends, in part, on bank material at the toe of the slope being able to resist erosion.
5. **Habitat –** Flow redirection structures are typically large enough and can be shaped so that aquatic habitat can be incorporated easily into the design without adding expense. Consideration of types of species that could benefit from added habitat will influence the details of the construction. Minimize impacts below the OHWM to reduce complexity as well as mitigation requirements for permitting.

<u>**Channel Augmentation**</u>

Natural unmanaged streams will tend toward an equilibrium state. However, a natural stream will change significantly during its life cycle before reaching a stable condition. Channel augmentation seeks to put the channel on a more agreeable trajectory or accelerate its evolution while reducing the potential for causing instability in adjacent areas. Channel augmentation refers to reshaping the channel within the flood prone area, as illustrated in Figure 4-33. The adjustments to the channel may alter the planform and the relationships between width, depth, hydraulic radius, etc.

Figure 4-33: Channel Augmentation along Dry Run Diversion in Indianapolis, Indiana
(Left: Pre-Project, Right: After Channel Augmentation)

The changes made to the channel geometry should establish or more closely resemble 'stable' channel geometry, or the shape and planform of the channel that will allow for sediment continuity through the project reach. The USGS StreamStats platform provides estimates of stable channel geometry (Robinson, 2013) that can be used as an initial approximation; final details of the adjustments should be evaluated to confirm sediment continuity. Base the type and magnitude of the channel adjustments on the changes necessary to reestablish a more stable condition rather than reshaping the channel for reasons other than stream health.

Channel augmentation can be used to prevent the need for flow redirection in smaller streams, as well as to establish a relationship between erosion potential and erosion resistance that effectively limits detrimental scour. Table 4-1 provides for channel geometry adjustment. Additional design concerns are:

1. **Disturbance to Sensitive Areas –** The adjustment of a large portion of the channel inherently involves significant earth moving and disturbance to the existing channel and potentially the floodplain. Minimize the amount of disturbance to environmentally sensitive areas.
2. **Removal & Reestablishment of Vegetation –** Extensive earth moving also includes removing the vast majority, or all, of the vegetation within the footprint of the project. Vegetation is often a critical component to the erosion resistance of a channel. Destruction of this natural 'armor' leaves the channel at extreme risk of erosion immediately following the completion of earth-moving activities. Extreme efforts are often warranted to quickly reestablish vegetation to reduce the risk of catastrophic failure of the recently constructed improvements.
3. **Scour Considerations –** Channel adjustments must consider scour to prevent the failure of recently re-shaped channel banks. Consider additional reinforcement of the channel bed or toe of the channel bank; however, the channel augmentation ideally addresses the scour issue.
4. **Upstream and Downstream Tie-in –** Channel re-shaping must extend to a well-suited transition that allows the flow to move smoothly from an unaltered reach into the improved reach. Be sure to establish continuity for bankfull and floodplain surfaces and flow paths to maintain channel performance for larger events.
5. **Habitat –** The partial or complete re-shaping of the channel often disturbs a significant amount of habitat; however, the opportunity for incorporating habitat improvements is similarly plentiful.

4.5.3 Habitat Improvements

Habitat and aquatic life fall into the top level of the functional pyramid (Harman et al., 2012), suggesting that for these components of a stream to succeed, the hydrologic, hydraulic, geomorphologic, and physiochemical function of the stream must be in order. Proper stream function will produce the maintenance flows required for sediment rejuvenation, spawning, rearing, and migration, all while maintaining the quality of water at a level that will support both the habitat and colonizing species.

<u>Water Quality Improvement</u>

Water quality can have a significant impact on the overall success of a project. Nutrients, turbidity, and other pollutants affect the development and quality of habitat.

Methods for improving water quality, like those illustrated in Figure 4-34, can be divided into watershed-based methods, which seek to reduce or eliminate the introduction of the pollutant, and site-specific methods used to capture or metabolize the pollutant. Table 4-1 provides types of methods and references for their design. Additional design considerations are:

Figure 4-34: Water Quality Improvements
Left: Watershed-wide buffer strips, Right: Site-specific rain garden

1. **Sustainability and Maintenance Requirements –** Treatment method(s) must be sustainable and require little-to-no maintenance for the effect to be long-lasting. Design water quality features so that they provide the intended benefit for the life of the project.
2. **Integration with Project Components –** Incorporate water quality features with other channel improvement features, where possible, especially if the implementation creates no additional cost.

<u>Habitat Rejuvenation</u>

Sediment transport, which is a natural function of many streams, enables the base of the aquatic food chain to thrive. Sediment transport through a system rejuvenates the channel bed, as suggested by Figure 4-35, sorting the bed material and creating prime habitat for macroinvertebrates in the interstices.

Figure 4-35: Sediment Rejuvenation

Habitat rejuvenation is not a treatment method that is added to the channel, but a result of a properly designed channel. The following channel design considerations will promote adequate habitat rejuvenation:

1. **Sediment Competence –** Flow passing through the stream must be capable of mobilizing the bed material. Bed material grain size distribution and flow rates in the channel are realistically not under the designer's control in alluvial streams; as a result, the ability to mobilize the sediment must be achieved by carefully shaping the channel to produce a sufficient amount of bedload under certain conditions.
2. **Frequency and Timing of Maintenance Flows –** Base the desired timing and frequency of sediment rejuvenation on the types of species intended to colonize or continue to exist within the project reach. Consider specific timing for spawning, rearing, and migration.

Constructed Habitat

Features that create habitat, such as the structure and vegetation as illustrated in Figure 4-36, also improve channel stability. Improvement or introduction of habitat also enhances the overall function of the stream. Table 4-1 provides methods for introducing or reintroducing habitat where it once existed and recolonizing a stream. Give careful consideration to the following design details for appropriately adding habitat to a stream:

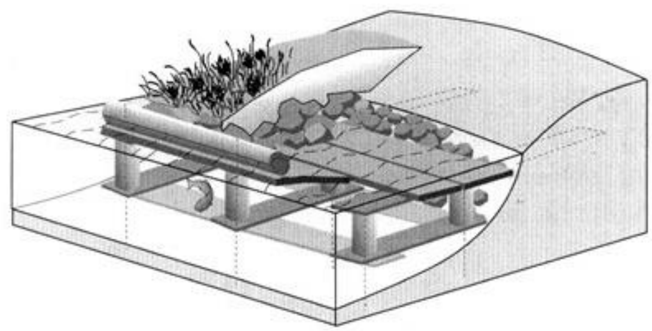


Figure 4-36: Constructed Habitat – Lunker Structure
(Environmentally Sensitive Streambank Stabilization, 2014)

1. **Appropriateness of Introduction –** Only incorporate habitat improvements into the types of streams where the habitat is known to exist and thrive. Some types of habitat simply do not exist naturally in certain stream types. Explain to stakeholders why a particular habitat (or the colonizing species) may or may not be appropriate for the stream.
2. **Potential Impact to Existing Habitats –** The introduction of a new habitat and colonizing species may have a detrimental impact to existing habitats and/or species. Consider the advantages and disadvantages of new habit introduction in terms of the health of the overall stream. Avoid adding habitat or colonizing species that will reduce channel stability.
3. **Population Available to Utilize Habitat –** Habitat may be useful to more than one species; however, some habitat is very specialized or may be not well-suited for the existing species in the stream. Determine the availability of the desired species and its ability to colonize and maintain a population prior to finalizing habit design.
4. **Diversity of Habitat --** Habitat diversity is important in most systems because an ecosystem dominated by a single species is unlikely to be a healthy one. Constructing an appropriate diversity of habitats promotes species diversity necessary for an ecosystem to thrive and support the food chain in a sustainable manner.
5. **Controlling Invasive Species –** Do not use invasive species to create habitat. Introduction of invasive species can result in uncontrollable system dominance because the native species are likely not well-suited to compete. Successful introduction of a desirable habitat or species may require the elimination of an invasive species.

Table 4-1: BMP Technical Reference Information

No.	Mitigation Measure	Primary Category	Secondary Category	Design Reference*
1.1.1	Rock W-weirs	Grade Control Structures	Flow Redirection	https://www.wou.edu/las/physci/taylor/g407/restoration/WA_Dept_Forestory_2004_Porous_Weirs.pdf
1.1.2	Step-pools (Boulder / Stone)	Grade Control Structures	Floodplain Reattachment	https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Step%20Pool.pdf
1.1.3	Log drops and V-log drops	Grade Control Structures	Floodplain Reattachment	https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf
1.1.4	Newbury Riffle	Grade Control Structures	Bed Armoring	http://www.salixaec.com/streambanks.html
1.2.1	Toe wood	Toe Protection	Habitat Improvements	Christopher B. Burke Engineering, LLC (adapted from Wildland Hydrology)
1.2.2	Rock-toe revetments	Toe Protection		Christopher B. Burke Engineering, LLC (adapted from Federal Highway Administration)
1.2.3	Interlocking concrete jacks	Toe Protection		https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf
1.2.4	Boulder revetments	Toe Protection	Bank Armoring	https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf
1.3.1	Branch layering	Bank Armoring		https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf
1.3.2	Natural fiber rolls (Vegetated / Unvegetated)	Bank Armoring		http://www.adfg.alaska.gov/index.cfm?adfg=streambankprotection.coir
1.3.3	Brush mattresses	Bank Armoring	Channel Augmentation	https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf
1.3.4	Gabion baskets (Vegetated / Unvegetated)	Bank Armoring	Toe Protection	https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf
1.3.5	Gabion mattresses	Bank Armoring	Bed Armoring	http://www.salixaec.com/streambanks.html
1.3.6	Live stakes	Bank Armoring	Habitat Improvements	https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf

Table 4-1: BMP Technical Reference Information (Continued)

No.	Mitigation Measure	Primary Category	Secondary Category	Design Reference*
1.3.7	Live fascines	Bank Armoring	Habitat Improvements	https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf
1.3.8	Live soil lifts	Bank Armoring	Channel Augmentation	Christopher B. Burke Engineering, LLC (adapted from ESENSS)
1.3.9	Natural fiber matting / TRM / Erosion control blanket	Bank Armoring		https://nagreen.com/sites/default/files/2017-05/Channel%20Installation%205-4-17.pdf https://nagreen.com/sites/default/files/2017-05/DOT%20System%20Guide%205-4-17.pdf
1.3.10	Riprap bank armoring	Bank Armoring		Christopher B. Burke Engineering, LLC (adapted from Federal Highway Administration)
1.3.11	Articulating concrete blocks	Bank Armoring		http://www.salixaec.com/streambanks.html
1.4.1	Rock cross-vanes	Flow Redirection	Grade Control Structures	https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Rock%20Cross%20Vane.pdf
1.4.2	J-hook vanes	Flow Redirection	Grade Control Structures	https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/J-hook%20Vane.pdf
1.4.3	Rock vanes	Flow Redirection		https://www.researchgate.net/figure/17-Rock-vane-plan-and-cross-sections-not-to-scale_fig15_273447279
1.4.4	Log vanes	Flow Redirection		https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Log%20Vane.pdf
1.5.1	Constructed riffle-pool series	Channel Augmentation	Habitat Improvements	http://charlottenc.gov/Engineering/Bids/Special%20Provisions/Generic%20Details/Water%20Quality/02-In-Stream%20Structures/03-Variable%20Constructed%20Riffle/03-VARIABLE%20CONSTRUCTED%20RIFFLE-PDF.pdf
1.5.2	Bank regrading/shaping	Channel Augmentation	Flow Redirection	Christopher B. Burke Engineering, LLC (adapted from ESENSS)
1.5.3	Cut-off sills	Channel Augmentation	Floodplain Reattachment	https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf
1.5.4	Boulder clusters	Channel Augmentation	Habitat Improvements	http://charlottenc.gov/Engineering/Bids/Special%20Provisions/Generic%20Details/Water%20Quality/02-In-Stream%20Structures/02-Boulder%20Cluster%20Turbulent%20Riffle/02-BOULDER%20CLUSTER%20TURBULENT%20RIFFLE-PDF.pdf

* Copies of BMP Fact Sheets are provided in Appendix 1

4.6 IMPLEMENTATION CONSIDERATIONS

Truly successful projects are carefully conceived, designed, planned, implemented, and maintained. Beginning with, and exemplified by project leaders, participants attend to a full array of details and stay focused from the initial concept to the expected end of the design life and beyond.

4.6.1 Project Delivery Method

For publicly bid or procured projects, two primary methods are available for taking a FEH mitigation project from an idea to finished product.

Design-Bid-Build

The Design-Bid-Build project delivery method, as shown in Figure 4-37, is the most common method in Indiana. It is a familiar process for most owner entities and is sometimes required by the owner's internal processes, by the funding source, or by public law. The Design-Bid-Build process involves three sequential phases: design by a designer, a bidding phase to select a contractor, and a construction phase. The designer and contractor are directly contracted to the owner, and not to one another. The advantages and disadvantages of this project delivery method are as follows (DBIA, 2015):

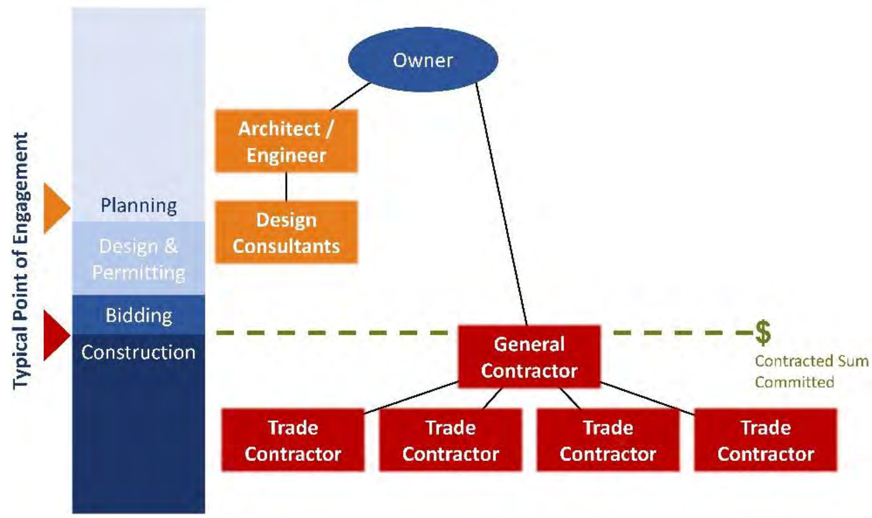


Figure 4-37: Design-Bid-Build Project Delivery
(After DBIA, 2015)

Advantages

1. Widely applicable, well-understood, and well-established
2. Complies with bidding laws for public work
3. Allows for qualifications-based selection of designer
4. Owner retains control as both the designer and contractor are employed by the owner

Disadvantages

1. Longer process because each successive phase must be completed prior to the next phase
2. Generally higher construction cost as contractors are exposed to more risk
3. Delayed understanding of project cost
4. Low-bid award may result in quality and quality control issues during construction
5. Change orders during the project due to natural changes in the geometry of channel between the time design was completed and construction starts, constructability issues, as well as design errors/omissions

Design-Build

The Design-Build project delivery method, as illustrated in Figure 4-38, provides an alternative to the traditional procurement method. The owner is contracted to a single entity that will complete the design and construction of the project. The entity may be either a single organization or a joint organization. Joint organizations may be designer-led or contractor-led, with the other party being a subcontractor to the lead organization. Other configurations exist; however, the ones mentioned here are the most relevant for FEH mitigation work. The advantages and disadvantages of the design-build process are as follows (DBIA, 2015):

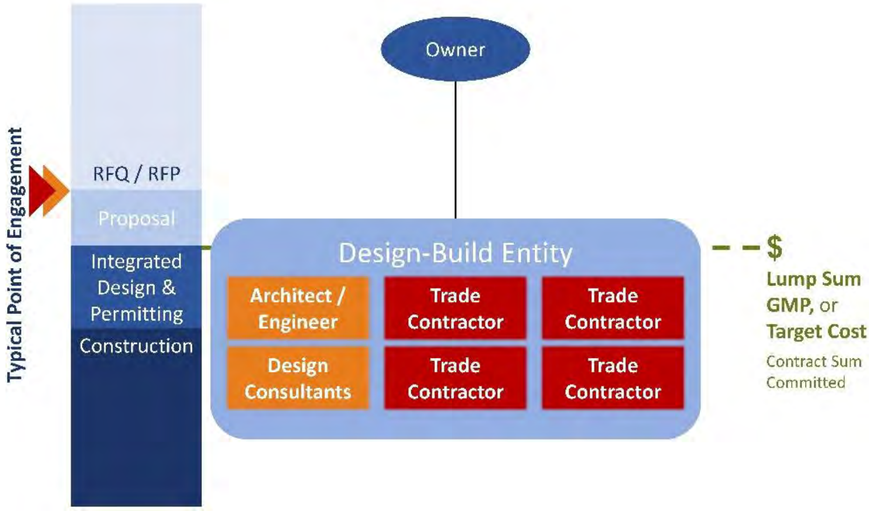


Figure 4-38: Design-Build Project Delivery
(After DBIA, 2015)

Advantages

1. Allows for qualifications-based selection for the designer and contractor team
2. Avoids adversarial relationship since a single entity is responsible for the completion of the project
3. Change orders are typically limited to owner-requested changes
4. Generally lower costs because value engineering and constructability issues are sorted out during the design process
5. Shorter project schedule as the design and construction phases often overlap partially or entirely
6. Earlier understanding of project costs due to collaborative design
7. Ability to adapt to natural changes in channel geometry during the design and construction phases

Disadvantages

1. Owner maintains less control of design details, because dealing with inconsistencies and issues is often the responsibility of the design-builder
2. Less familiarity state-wide
3. Owner must be capable and willing to place emphasis on qualifications of the designer-builder team over cost (low bid); this often requires a shift in mindset

4.6.2 Constructability & Timing

Constructability and timing heavily influence the quality and vulnerability of a project. For example, projects that incorporate vegetation as a key erosion mitigation measure are particularly susceptible to erosion immediately after construction is completed because the vegetation is not adequately established and the root mass has not developed sufficiently to reinforce the structure of the soil. Design considerations for constructability and timing are as follows:

1. **Availability of Materials –** The availability of materials (or lack thereof) affects the types of treatments that can be incorporated into a project. Lack of available materials, primarily vegetation types and/or stone materials, is a good indicator that those treatments may not be particularly well-suited for a 'natural' channel design approach project. Absence of such treatment materials in the area of the stream suggests that the method is inappropriate for the stream.

2. **Design Applicability to Physiographic Region –** Some treatment methods are more applicable to streams that are in arid regions vs. tropical/temperate regions, steep vs. very mild slopes, ephemeral vs. perennial streams, etc. Treatments tailored to suit a specific physiographic region may not be applicable in other physiographic regions. When considering using a new treatment in one area, determine if that treatment has been used in a similar setting.
3. **Contractor Experience/Expertise –** Some treatment methods are more common in certain physiographic regions. Particularly complicated or detailed treatments, as illustrated by Figure 4-39, require an experienced contractor familiar with the construction method(s) or significant training on the method for a contractor lacking experience. If experienced contractors cannot be found to install an intricate treatment, consider an alternative treatment. In essence, it is more important to have a high-quality installation of an acceptable treatment rather than a mediocre installation of the optimal treatment.
4. **Complexity/Practicability of Construction Process –** Simpler designs are typically better because they are easier to construct well; however, some projects require more complex designs due to outside constraints or unique problems in the stream. The designer should consider every step in the contemplated construction process to assure that each treatment feature is constructible without causing instability in the stream or becoming unstable during construction.

Figure 4-39: Contractor Experience with Complicated Treatments

5. **Allowance for Inclement Weather –** Working in streams presents an exceptionally challenging situation when inclement weather occurs. Considerations for inclement weather should include (at a minimum): lag time between when rainfall starts and water levels reach an unacceptable high stage, temporary means of securing recently placed [yet unfinished] materials for structures, and protection of open excavations.
6. **Ability to Establish Vegetation –** The timing of the project relative to the growing season(s) for temporary and permanent vegetation is critical to early project stability. Projects should be designed and permitted such that construction (particularly revegetation) can occur within the ideal seasonal window.
7. **Project Flexibility and Contingency Plans –** Imagine what might go wrong during a project and, where feasible, design flexibility into the project to reduce the probability of failure during project implementation. Thoroughly understand and communicate where the design must not be changed and, in contrast, where there is room for adjustment. Set the stage for quick resolution of issues when working in streams during seasons with inclement weather.

Figure 4-40: Poor Vegetation Establishment Due to Unfavorable, Cold Weather
(Yellow River, Knox, IN)

4.6.3 Site Access

Early on in the design process, identify a quality access route to the project site. Without adequate site access, a project cannot be built. Address the following access-related factors during the design process:

1. **Legality of Access –** Confirm the legal right to access the site along the planned route if the site is not accessible across public property, the private property of the client, or an easement that allows for reconstruction or construction access. Regulated drain easements may not be sufficient for project work because they limit access only for maintenance of the drain.
2. **Sufficiency of Size –** The site access route must accommodate the size and weight of the construction equipment and material delivery vehicles without creating unsafe conditions or excessive deterioration.
3. **Permitting Impacts –** Configure the site access route to minimize adverse impacts to environmentally sensitive areas. Where such impacts cannot be avoided, incorporate or require protective matting or other preventive measures.

4.6.4 Environmental Impact

Typically, the purpose of a stream restoration or stabilization project is enhancing the overall environmental state of the stream by improving one or more levels on the functional pyramid. Accordingly, negatively impacting an environmentally sensitive area as part of a project is counter-productive, unless avoiding the area will detrimentally affect the project integrity or prevent accomplishing critical project objectives. Incorporate the following considerations into the design process to, as suggested by Figure 4-41, minimize its environmental impact:

1. **Minimize Disturbance –** Minimizing the overall project disturbance area is the most effective means of reducing the environmental impact of a project; it can also help to reduce the cost and permitting difficulty, particularly if environmentally sensitive areas will be left undisturbed.
2. **Incorporate Mitigation for Disturbed Areas –** Weave mitigation features into the project layout if early coordination with the agencies identifies the potential need for environmental mitigation. Using on-site mitigation reduces cost by eliminating the need for an off-site mitigation project, while keeping the environmental benefits on the site.

Figure 4-41: Minimizing Environmental Impact
(City of Golden Valley, 2018)

3. **Adjust Details to Provide Environmental Benefit –** Design details can be adjusted to be more environmentally beneficial by selecting, where possible, native species and naturally-based materials.

4.6.5 Anticipated Longevity

The effectiveness of the proposed solutions is important; however, all designs have a limit to the durability and longevity of the structures and materials. Collaboratively select the desired project life design with those targets in mind. Consider the following factors when determining project life, developing the design concept, and selecting project materials:

1. **Correlate Project Purpose with Longevity –** Match project longevity with the project's remedial or preventive intent. As illustrated in Figure 4-42, select a long lifespan for projects aimed at improving long-term stability. Design short-term improvements, or projects needed to begin a process but not necessarily perpetuate the process, so that they reach their functional life shortly after the process is expected to be established. Manufactured materials and overly robust designs can provide excessive project lifespans and may cause unnecessarily high construction costs.

Figure 4-42: Robust Materials Protecting Critical Infrastructure
(Bean Creek, Indianapolis, IN)

2. **Consideration of the Stream as Dynamic System –** Alluvial streams should, by definition, transport at least a portion of the material that forms the channel. Constraining a particularly dynamic system too firmly or for too long may initiate instability in adjacent reaches or pave the way for catastrophic failure of the improvement due to differing boundary conditions for the channel (e.g., changed meander locations leading to flanking).
3. **Material Considerations –** Select materials used to construct the treatments to be consistent with the necessary lifespan for each component. For example, erosion control blankets used on a short-term basis to help establish permanent vegetation should be temporary, with the material degrading shortly thereafter.

4.6.6 Project Cost

Project cost is often a major factor in stakeholder decisions. Consider the overall cost of the project (design, construction, maintenance, and decommissioning, if applicable) during all phases of the design, not only after the design is completed. Evaluate the following topics to help control project costs:

1. **Project Delivery Method –** The project delivery method, or the entities and contractual relationships that exist to bring the project from problem definition, through design and construction, and to the finished product, can have a significant impact on the overall cost of the project. More traditional project delivery methods, such as Design-Bid-Build, place the project risk heavily on one entity, resulting in high contingency costs. More progressive, risk-sharing contractual relationships can be advantageous from a project cost and schedule perspective.
2. **Alternative Materials –** The cost of materials is often a significant component of the overall project cost. Consider alternative materials, that provide the same level of service, as an effective means of reducing the project cost without diminishing project quality. Furthermore, evaluate products that have a slightly lower level of service where the design can tolerate minor decreases in material specifications. Consider the topics discussed in Sections 4.6.4 and 4.6.5 as they relate to potential alternative materials.

3. **Value Engineering –** Value engineering, as illustrated in Figure 4-43, is an effective means to reduce the construction cost after completion of the preliminary design. Value engineering solutions conceived by the design team and experienced contractors should be considered. Value engineering often involves material substitutes that may or may not increase the risk of complications during and after construction. The designer must carefully consider each value engineering proposal to prevent compromising project stability, longevity, and ability to meet other stated project objectives.

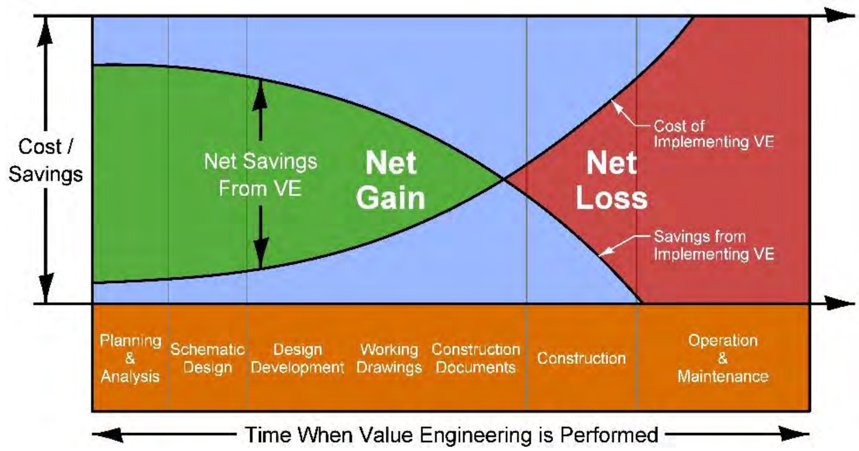


Figure 4-43: Potential Savings from Value Engineering
(Whole Building Design Guide)

4. **Scope Reduction –** Project scope, most often the physical length, can sometimes be adjusted to reduce the magnitude of the project and proportionally reduce the project cost. The ability to reduce the project scope will depend on how and where the project can be tied-into existing features without compromising project integrity.
5. **Prioritization of Key Project Components –** When considering cost reduction proposals, base them on prioritization of the quality of the key project components relative to the other components. Reducing the quality of the key features may transfer stress to other project components that may or may not be adequately suited for the changed conditions. The project budget should similarly prioritize the key components (i.e., spend money on what matters and eliminate/downgrade ancillary components).

4.6.7 Social Acceptability

In some ways, the success of a project has nothing to do with whether or not the project accomplishes the technical objectives. Project success, from a social perspective, depends on how the project is perceived. If a project is socially unacceptable because of cost or impact to cultural, social, or environmental resources, the project will likely be perceived as a failure, despite its technical success. Conversely, a favorable opinion of a project by society can be forgiving for some amount of minor failures in meeting the technical objectives. Consider the following ways to promote a positive societal opinion/view of an evolving project:

1. **Engage Community Proactively –** A sound understanding of the priorities of stakeholders and other interested parties is the most important aspect of improving social acceptance of a project. Proactively collaborate with affected community and leaders to understand their key concerns, as suggested by Figure 4-44, and objectives, which will lead to more informed decision making during the design process.
2. **Community Education –** Educating the community about fluvial problems and project objectives – how the project will solve the problems -- can foster a greater understanding and buy-in from locals. Understanding what is being done, why it is happening, and how it is going to be done will reduce negative feedback or other problems before, during, and after construction.

Figure 4-44: Awareness of Social Issues

3. **Sensitivity to Community Concerns in Project Design –** In many situations, expect a few hot-button issues to arise with a particular group or property owner. Some examples: protection of existing trees, wetlands, or other environmental features; positive/negative views about the types of materials that are to be used; construction methods or disturbance to the public; fears of increased flooding or destabilization of adjacent stream reaches; and/or preservation of cultural features. Promote greater project acceptance by identifying the issues and being sensitive to them, as much as possible, without compromising project objectives.

4.6.8 Management/Maintenance Considerations

Project maintenance is a necessity for many projects, especially in the early phases of a project that is largely bioengineered, to correct minor issues until the vegetation is fully established. Maintenance or more intensive management of a project site may not be allowable from an objectives standpoint or because of a specific prohibition in an environmental permit. Address the following maintenance considerations during the design process:

Project maintenance is a necessity for many projects, especially in the early phases of a project that is largely bioengineered, to correct minor issues until the vegetation is fully established.

1. **Sustainability for Maintenance Funding –** The cost of initial or on-going maintenance is often unaccounted for in a project and, therefore, is frequently neglected. During the design process, proactively address the availability and sustainability of maintenance funding. The project should be designed to minimize or eliminate the amount and/or cost of maintenance where no maintenance funding is likely to be available; this may increase the initial project cost, but will promote a higher level of long-term integrity.
2. **Project Performance without Maintenance –** Anticipate project performance assuming no preventive maintenance. Adjust the design where a lack of maintenance could lead to project failure or where key project objectives will not be met.
3. **Impact on Project Longevity –** Lack of maintenance, as illustrated in Figure 4-45, will likely have a detrimental impact on the longevity of the project. Communicate the anticipated adverse effect on project longevity to the owner and determine if the result is acceptable. If the anticipated life span does not meet client expectations, secure additional funding or perform a less maintenance-intensive design.

Figure 4-45: Lack of **Management/Maintenance**

4.6.9 Natural Variability

When modifying a natural system, minimize disturbance. Natural systems are diverse, incorporate some diversity into a design to blend in with the original channel features. Adding natural variability to a project can also improve the function by diversifying the treatments/features so that one negative influence on the project reach does not detrimentally affect the entire project. Consider the following ways to account for natural variability:

1. **Avoiding 'Sterile' Designs –** Straight channels with a single consistent type of channel bank are not natural, do not look natural, and do not function as a natural channel. Projects that incorporate only

one type of treatment, while robust, are not likely to address physiochemical and biologic project objectives. Even projects that have little available space can have small features that add some variability.

2. **Physical Constraints on Variability –** Some projects have spatial, geologic, and/or environmental constraints that essentially prevent planform variability. Consider adding variability by using multiple plant species for vegetative reinforcement, or small in-channel features. Incorporating mitigation features, such as fish habitat or live stakes, into the design can provide some variability in the project while also adding environmental value and potentially addressing the mitigation need.
3. **Mimicking Variability of Local Natural Areas –** Note**,** and consider during design, the types and magnitude of the natural system in the project vicinity. Assess the naturally occurring variability in a natural, yet similar setting. This assessment will provide a starting point for adding diversity to the project in a manner that is both effective and consistent with the locale, as illustrated in Figure 4-46.

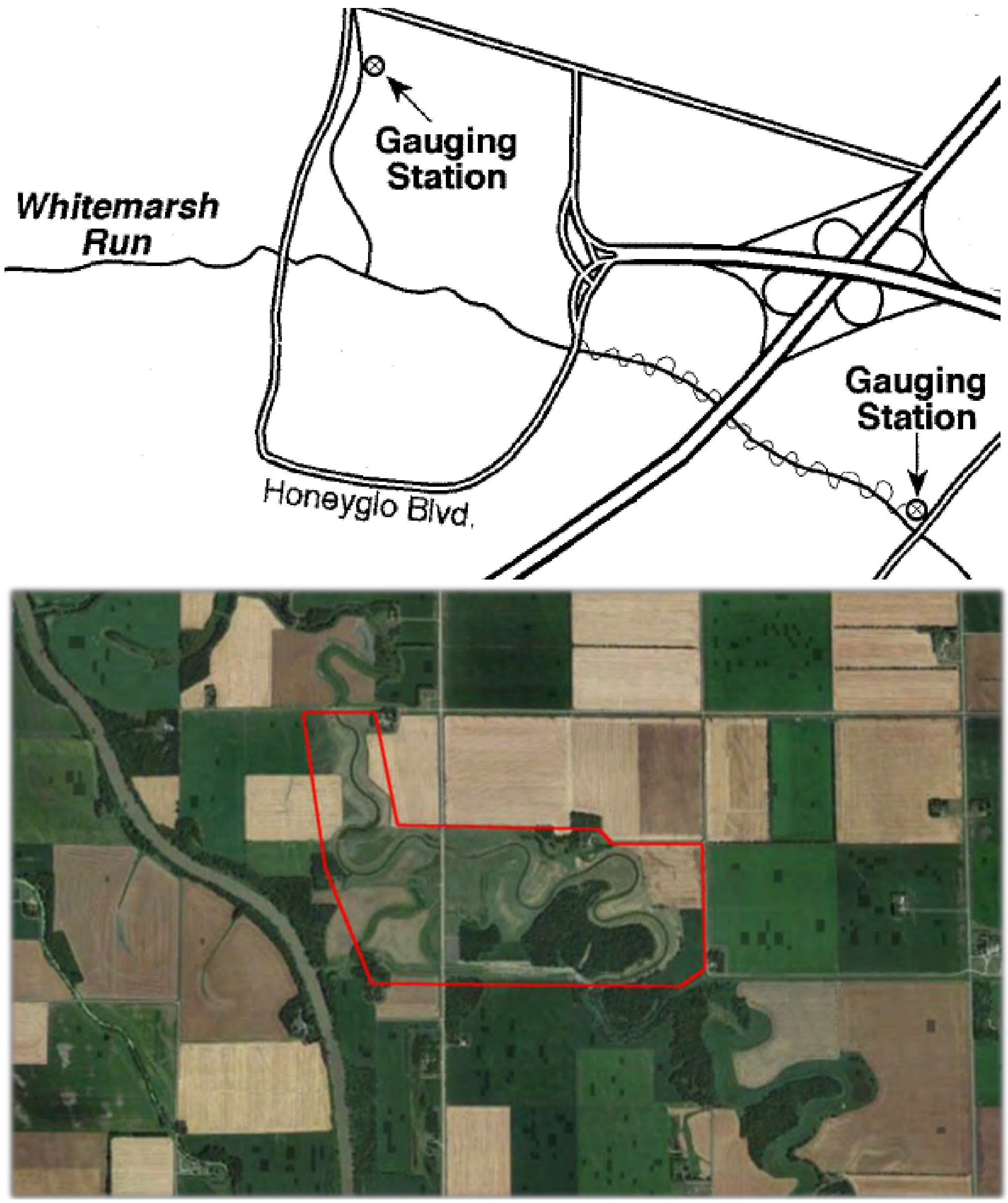


Figure 4-46: Appropriate and Inappropriate Variability
(Top: Sinuosity inconsistent with surrounding reaches, [Soar and Thorne, 2001])
(Bottom: Project nearly indistinguishable from natural reaches, [Google Earth, 2015])

4.7 ANTICIPATED RESTORATION DESIGN PERFORMANCE

Complete the relevant analyses discussed in Section 4.2 for the proposed condition to confirm that the anticipated improvements will meet the restoration or stabilization objectives. Adjust the proposed measures to improve feature and overall project performance where project objectives are not met or where the project does not adequately address the implementation considerations discussed in Section 4.6.

Identify specific impracticable project objectives during the design process, confirm them while evaluating the proposed project performance, and communicate about them to stakeholders with a thorough explanation of why the objective cannot be met and/or how meeting the objective may compromise the rest of the project.

4.8 SELECTION OF ALTERNATIVES

Select the alternative, or combination of improvements if multiple treatments have been considered, that best meets the restoration or stabilization objectives. Use the criteria established in Chapter 3 and the results of the analysis and evaluation of performance in Section 4.7.

Carefully consider stakeholder restoration or stabilization objectives and priorities based on the criteria established in Chapter 3. Select alternative or combination of improvements that best meets the objectives based on the evaluation of anticipated performance discussed in Section 4.7.

As a general note, naturally functioning streams are inherently more stable and resilient than altered stream systems. Selecting an alternative that most closely follows the natural channel design principles is expected to be more successful, resilient, and cost effective in the long run.

The determination of which alternative should be selected can be a complex decision when many factors must be considered. A Triple Bottom Line (TBL) analysis is an effective tool for helping to pragmatically select the best alternative. Table 4-2 is an example of a TBL score sheet.

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Table 4-2: Example Triple Bottom Line Decision Matrix for Project Selection

Alternative Name, Treatment Type, or Other Project Metric	**Cumulative Score (15)**	**ECONOMIC**				**SOCIAL**					**ENVIRONMENTAL**				
		Capital Cost	**Lifecycle O&M Cost**	**Shared Funding**	Score (5)	**Widespread Benefit (# of properties)**	**Reduce Flooding Drainage Problems**	**Benefit to Public Health & Safety**	**Benefit to Quality of Life**	Score (5)	**Level of Protection for Threatened Features**	**Impact to Adjacent Stream Reaches**	**Restore/ Protect Floodplain Function**	**Improve/ Protect Stream Habitat**	Score (5)
	Weighting Factor=	*0.45*	*0.20*	*0.35*	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*1.00*	*0.40*	*0.30*	*0.20*	*0.10*	*1.00*
	0=	*> $10M*	*very high*	*none*		*0*	*none*	*none*	*none*		*added risk*	*significant (-)*	*no change*	*no change*	
	1=	*>$5M <$10M*	*high*	*100% Owner*		*1-10*	*limited*	*limited*	*limited*		*no change*	*minor (-)*	*limited*	*limited*	
	2=	*>$1M <$5M*	*mod-high*	*75% Owner*		*11-30*	*limited-mod*	*limited-mod*	*limited-mod*		*minimal*	*no change*	*limited-mod*	*limited-mod*	
	3=	*>$500K <$1M*	*moderate*	*50% Owner*		*31-100*	*moderate*	*moderate*	*moderate*		*moderate*	*minor (+)*	*moderate*	*moderate*	
	4=	*>$100K <$500K*	*low-mod*	*75% Other*		*101-300*	*mod-high*	*mod-high*	*mod-high*		*high*	*moderate (+)*	*mod-high*	*mod-high*	
	5=	*<$100K*	*low*	*100% Other*		*300+*	*high*	*high*	*high*		*robust*	*significant (+)*	*high*	*high*	
Alternative 1 / Treatment 1	**8**	0	3	3	1.7	5	4	2	3	3.5	4	0	4	4	2.8
Alternative 2 / Treatment 2	**10**	3	3	4	3.4	5	5	0	3	3.3	5	1	3	1	3.0
Alternative 3 / Treatment 3	**6**	4	0	4	3.2	2	0	1	3	1.5	3	0	0	3	1.5

In the example shown above:

- Alternative 1 performs best in social perspectives but does not adequately address economic or environmental objectives and priorities.
- Alternative 3 performs reasonably well in the economic aspects of the project but fails to meet social and environmental objectives.
- Alternative 2 performs reasonably well for all three perspectives. Note that Alternative 2 does not provide the highest score in each category, but it has the highest cumulative score suggesting that Alternative 2 is the most appropriate project to select.

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4.9 DESIGN DOCUMENTS

Once an alternative is selected, development of design documents begins in earnest. Design documents include construction drawings and technical specifications which, together, convey the project's design intent.

The accuracy of the existing condition information shown on the drawings is important. Poor detail or insufficient accuracy can prevent features from being constructed in line with the original design intent. This is particularly important at the project's tie-in locations to prevent abrupt transitions that compromise project integrity. Accuracy of existing condition data also influences accurate bank heights for stability analysis, quantities for earthwork balance and costs, and streamlining channel alignment.

Provide sufficient detail in construction drawings to convey adequately the critical components of each treatment used in the mitigation design. Clearly show dimensions, configurations, and treatment components on the drawings in a way that allows the contractor to construct the features resulting from the analysis. Where the installation process is critical, provide phased details to clarify the process. Don't over-detail the construction drawings because this invites the opportunity for conflicting information and increases overall project cost.

Construction drawings should account for flexibility in the design to accommodate lower-than-desired existing condition data quality and to accommodate changing conditions in rapidly changing systems. Identify, with notes and details, areas of flexibility and show how the contractor is to account for variability.

Accompany the construction drawings with technical specifications that provide clarification and supplementary details to the drawings about the materials and construction processes to be used. Designers should be mindful of the practical limitations of construction when identifying construction tolerances and testing requirements. Furthermore, designers should view and create the specifications and drawings as a combined set of information to prevent conflicting requirements and promote complete descriptions of design features.

The design documents should be developed and released according to the project delivery method requirements. For Design-Build projects, this means that not all construction details will be completed prior to document release. Carefully note changed conditions to prevent construction issues.

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CHAPTER 5 PROJECT IMPLEMENTATION

5.1 INTRODUCTION

Much of what makes a fluvial erosion hazard (FEH) mitigation project successful has little to do with the design calculations. Thorough attention to the project concept and its implementation determine a project's success. Proper implementation, management, and maintenance are critical for the long-term success of a project.

Much of what makes a fluvial erosion hazard (FEH) mitigation project successful has little to do with the design calculations… Proper implementation, management, and maintenance are critical for the long-term success of a project.

Implementation of passive and active management practices requires different approaches. However, both entail thorough consideration of the necessary steps including design, funding, permitting, construction, management, and maintenance.

5.2 IMPLEMENTATION OF PASSIVE MANAGEMENT PRACTICES

Implementation of passive, in contrast with active, management practices can be more difficult because the entire watershed is not typically owned by one entity and implementation typically necessitates that mitigation measures occur over a large area to be effective. Most passive management strategies involve the preservation and protection of sensitive areas, thereby often requiring the forfeiture of the use of privately owned property. The difficulty lies in obtaining the willing cooperation and agreement of multiple landowners.

This challenge makes identification and prioritization of treatment areas a critical component of implementing passive management practices. If passive mitigation is not compelled by regulatory agencies, incentive-based programs can improve landowners' willingness to participate.

5.2.1 Programs for Facilitating Implementation

The primary source of incentive-based programs, as suggested by Figure 5-1, is the U.S. Department of Agriculture's Natural Resource Conservation Service (NRCS). The NRCS can fund the installation of many agriculture-based best management practices (BMPs), or the NRCS can compensate the landowner for being a part of the program. A full listing of the available programs is available on the NRCS website at https://www.nrcs.usda.gov/wps/portal/nrcs/in/programs.

Figure 5-1: USDA-NRCS Program Enrollment

Other non-governmental organizations, such as The Nature Conservancy (TNC), also have programs aimed at improving the stability and health of Indiana stream and watersheds. For more information about TNC initiatives, contact the main field office at (317) 951-8818.

Wetland and tree mitigation required by regulatory permits for projects can also serve as passive management treatments. The requirements involved with each type of mitigation are dependent on the agency requiring the mitigation.

5.2.2 Duration of Participation & Deed Restriction

The required duration of participation for NRCS incentive-based programs and TNC initiatives vary and should be confirmed with the respective organizations. The duration and limitations on how the dedicated land can be used vary and may not produce the lasting effect required for the improvement of the system stability.

Mitigation efforts required by regulatory permits are typically enforced in perpetuity by deed restrictions on the mitigation sites. Deed restrictions serve as a reliable means of affecting long-term change in the watershed.

5.3 IMPLEMENTATION OF ACTIVE RIVER MANAGEMENT PRACTICES

5.3.1 Funding

Lack of sufficient funding is a common reason why FEH mitigation projects are not implemented. Without an adequate funding source, the design, permitting, construction, and maintenance cease at one point or another in the process. Funding must be secured for the entirety of the implementation process, including post-construction management and maintenance. Consider project cancellation, or an alternative project, where funding is not adequate to see the project through its intended design life.

> Avoid projects with incomplete funding or projects that are severely scope-reduced due to budget issues because these projects have a much higher probability of failure.

Securing funding early in the problem-identification phase is an effective means of improving the likelihood of successful implementation, as designs can be more readily adjusted to match the construction and maintenance costs with available funds. Exercise caution when determining the anticipated amount of funding needed prior to completing a sufficiently detailed analysis and design. Consider allowances for unknown or unanticipated complications. If initial funding estimates are considerably lower than that required by the final design, finishing the project and having the ability to maintain the improvements may be impossible. Avoid projects with incomplete funding or projects that are severely scope-reduced due to budget issues, because these projects have a much higher probability of failure.

Designers and project coordinators should be aware of additional requirements that may be attached to certain funding sources. These requirements can affect the design, construction, and maintenance phases by requiring specific or additional documentation and reporting. Examples of such requirements include: restrictions on sourcing of construction materials, wage rates, signage requirements, maintenance restrictions, and replacement requirements for projects that may later impact the implemented features.

5.3.2 Regulatory Permitting Requirements

The impact of the regulatory permitting process on the overall success of project can be significant. Successful permitting accounts for the time required for permit submittal and reviews, the requirements of government entities, and the incorporation of potential mitigation. Promote project success by considering the following factors during the permitting process:

1. **Establish Jurisdictional Entities –** To permit a project successfully, first determine which entities have jurisdiction. Maintain a knowledge base about current regulations for the applicable types of projects. Complicated projects may require additional assistance from a knowledgeable and experienced firm. Inquiring about regulatory requirements from local and regional government bodies can also be beneficial.
2. **Early Coordination with Agencies –** Early coordination with the regulatory agencies having jurisdiction helps to identify the key aspects of the project that need to be clearly addressed in the permit submittals, as well as identifying the potential need for environmental mitigation. Establishing a cooperative relationship with the agencies improves the permitting process.

3. **Incorporation of Mitigation Requirements –** The potential need for environmental mitigation, identified during early coordination with the agencies, can be used to determine how best to incorporate the mitigation requirements into the project. Acquisition and design of off-site mitigation can be costly and does not replace the environmental benefit in the same location. Confirm, with the regulatory agency requiring the mitigation, the full extent of the mitigation measures required to make a project 'self-mitigating.'

Inclusion of regulatory agency permit conditions will often be required to satisfy project objectives. Coordinating with local authorities and conservation groups for assistance with enforcing the permit conditions can help reduce the likelihood of drastic changes occurring at the site over the duration of the monitoring and maintenance process.

During the planning phase, account for government agency jurisdictions with regard to project scale and location. For example, notification of a local drainage and/or stormwater board may be required if the project site comes within a county regulated drain easement (typically 75 feet on each side of a county regulated drain in Indiana). County regulated drains can range from small ditches to significant streams. Any work or infrastructure within a regulated drainage easement will require obtaining a permit from the local drainage and/or stormwater board.

Most Common State & Federal Permits Required for a Project

IDEM Rule 5
IDNR Construction in a Floodway
IDEM 401 Water Quality Certification
USACE 404 Dredge and Fill Permit

The next level of regulatory agencies to consider in Indiana are the Indiana Department of Environmental Management (IDEM) and Indiana Department of Natural Resources (IDNR). IDEM requires a Construction Site Run-off general permit (Rule 5) for all projects that result in the disturbance of one acre or more of total land area. This permit submittal includes a Notice of Intent and construction plan. IDEM requires submittal of a Section 401 Water Quality Certification (WQC) Regional General Permit form for any projects that result in impacts below ordinary high water (OHW). For projects that impact more than 300 feet of waterway and/or 0.1-acre of wetland, IDEM requires an Individual Permit. The 401 WQC is a component of a federal permit reviewed by the U.S. Army Corps of Engineers (USACE).

In addition to a 401 WQC permit, most projects require a Section 404 Dredge and Fill Permit from USACE. Section 404 of the Clean Water Act regulates what dredged and fill materials are discharged into U.S. waterways. IDEM coordinates the 404 permit reviews by the USACE but has an independent jurisdiction over most isolated sites in the state. For projects that are largely 'stream restoration' projects, a Nationwide 27 permit may be applicable in lieu of the USACE 404 permit. The designer should contact both IDEM and USACE to determine the impact of a given project site and the specific permitting options and requirements.

The IDNR regulatory divisions most commonly involved with this type of work include the Division of Water and the Division of Fish and Wildlife. Projects located in the floodway require the submittal of a Construction in a Floodway Permit application to the Division of Water. The Division uses this application to assess the impacts to the effective cross-sectional area at the site as well as impacts to upstream and downstream areas. The approval process can take several months depending on the project type and level of detail required for the permit. The Division of Fish and Wildlife oversees the mitigation or maintenance of vegetation and biological growth along regulated waterways and wetlands. Most projects require a five-year monitoring period for stream mitigation depending on existing conditions such as stability, erosion, vegetation growth, and bare areas. The visit frequency for the required monitoring is two times per year during the growing season. All conditions are documented and reevaluated for continued mitigation and maintenance.

5.3.3 Communication during Construction

Construction of mitigation treatments is as important as the selection of the treatments during the design. The level of attention to detail required from a contractor during construction can vary based on the improvements included in the project. The more intricate the treatments, the more attention to detail is required. Having a contractor with sufficient experience and expertise is critical, especially for detailed and/or complex work.

Figure 5-2: Pre-construction Meeting between Contractor and Designer

Designs must be well-communicated, as suggested by the pre-construction meeting shown in Figure 5-2, to be well-constructed. The communication of the design happens in several different ways. The type and style of communication with the contractor will vary based on the project delivery method; however, several necessary components are universally true:

1. Clearly convey the design intent with drawings, specifications, and verbal instruction
2. Verbally and visually identify critical details, elevations, and configurations
3. Discuss preferences and areas of flexibility
4. Address differing conditions, omissions, errors, and potential conflicts as soon as they are discovered. Carefully consider the contractor's abilities and the project details when deciding how to move forward

5.4 POST-CONSTRUCTION ACTIVITIES: ADAPTIVE MANAGEMENT

The completion of construction does not signify the end of a FEH mitigation project; it merely identifies an important milestone. Prudent post-construction activities include monitoring and maintenance, if required. Physical adjustments to streams from mitigation projects will always elicit a response after construction is finished, sometimes small, sometimes large. An adaptive management strategy is most effective to account for the changing nature of streams when considering monitoring and maintenance activities. As conditions change, monitoring and maintenance requirements will likely require change to be fully effective.

> FEH mitigation projects are generally most vulnerable immediately following construction, particularly when bio-engineering methods are used.

FEH mitigation projects are generally most vulnerable immediately following construction, particularly when bio-engineering methods are used. A transition period exists where the newly constructed/modified reach becomes a mature, stable reach as the stream adjusts and permanent vegetation is established. Accordingly, for most projects anticipate strategies for short-term observation and implementation of corrective measures. Certain projects, particularly those that include a significant amount of mitigation, may also require a long-term approach to ensure continued performance over time. Regardless of a project's short-term or long-term need, neglecting proper monitoring and maintenance practices jeopardizes the desired project outcomes. Establishing and executing a monitoring and maintenance plan as part of an adaptive management strategy for a project increases the likelihood of meeting the project objectives over time.

5.4.1 Plan Objectives and Approach

Post-construction monitoring strategies are established to track how the stream adjusts to the construction of the project, to determine if project goals are met, and to identify appropriate maintenance practices to ensure a project's continued success. Complete a project-specific monitoring and maintenance plan during the design phase in accordance with the established project goals. Outline strategies for how and when to perform monitoring and maintenance, as well as who is responsible for each activity. Although each plan is unique, the outline should generally aim to determine the following:

1) Proper performance of in-stream structures and stabilization measures
2) Changes in channel morphology
3) Response by ecological/biological resources

The physical, chemical, and biological measurements necessary to make these determinations will guide planned or emergency maintenance activities. In addition, the plan should identify possible funding sources, if not already allocated, to assure sufficient funding will be available for the required frequency and duration of monitoring and for repair efforts.

5.4.2 Monitoring

Monitoring is necessary to determine if the stream is responding to the project in the anticipated manner and to assure that potential negative adjustments are corrected before severe or catastrophic failure. Monitoring is used to determine if all restoration objectives are achieved, and to determine what (if any) improvements can be made to the treatments for future projects. Monitoring is also a frequent requirement of regulatory permits for projects that impact aquatic and/or riparian habitat.

Clear and measurable goals are essential to an effective and useful monitoring plan. Monitoring activities should provide for the collection of specific information and data types (as suggested by Figure 5-3) that appropriately document physical, chemical, and biological conditions of at the site. An outline of monitoring activities should be developed which includes observational requirements that will allow for all project objectives to be periodically evaluated.

Figure 5-3: Post-construction Collection of Field Data

Physical parameters include, but are not limited to, cross-sectional geometry, longitudinal profile, and streambed and bank composition. Chemical parameters may include total suspended solids, dissolved solids, turbidity, dissolved oxygen, nitrogen, phosphorus, heavy metals, fecal coliform, E. coli, pH, water temperature, biological oxygen demand, and chemical oxygen demand. Monitor plants, fish, and/or other invertebrates in the biological study of the stream to determine the quantity, health, and diversity of the various species. Depending on the budget and required level of effort for post-construction activities, the type and quantity will vary in performance detail and routine. For additional details and insights concerning post-construction monitoring, refer to A Functions-based Framework for Stream Assessment and Restoration Projects (Harman et al., 2012), *A Natural Design Handbook* (NCSU, 2017), the National Engineering Handbook Part 654 (USDA, 2007), and Stream Corridor Restoration Principles, Processes, and Practices (FISRWG, 2001).

The timing, frequency, and duration of monitoring are also important to consider and will vary from project to project. Because many of the parameters that may be monitored are seasonally affected, identify seasonally adjusted targets in the project objectives phase so that monitoring observations will be made in appropriate seasons. The frequency of monitoring should be often enough so that observations will allow for adjustments or corrective action to prevent poor project performance in one area from detrimentally affecting other portions of the project site. If set by regulatory permit conditions, the monitoring duration can be as long as 10 years. However, strive to base the project monitoring duration on the ability of the project to function (in the manner intended) as a self-sustaining part of the system. Monitoring duration, frequency, and timing are some of the key components of the 'adaptive' nature of the management strategy. As conditions in the stream change, the monitoring requirements may need to change to understand fully how the project is performing and be able to anticipate potentially negative channel responses.

As conditions in the stream change, the monitoring requirements may need to change to understand fully how the project is performing and be able to anticipate potentially negative channel response.

Several monitoring techniques exist and can be categorized for most common uses in high effort or in low effort situations (See Chapter 6 of Stream Corridor Restoration Principles, Processes, and Practices, FISRWG, 2001). Sometimes monitoring can be as simple as an owner representative or local conservation group volunteering to take periodic photographs of the site. More involved monitoring methods may be necessary depending on the magnitude of the project. In some cases, measurements and/or calculations obtained or reviewed by a professional engineer or biologist may be necessary to determine if the project is performing as intended. Additional details of the stream response to various conditions may even need to be observed through video footage of certain areas of the project site. Video footage may be acquired from a stationary point or using a drone outfitted with the necessary sensors, as illustrated in Figure 5-4.

Figure 5-4: Post-construction Monitoring with Unmanned Aerial Vehicles
(Rees Aerials, 2018)

Regardless of the data collection method, the data should be collected in a systematic format that illustrates the project site conditions over time. Photos should be taken in every site visit and cataloged appropriately, and maintenance recommendations must be made and revised after each visit. Routine review of the collected data by the appropriate personnel will promote timely and prudent decisions on necessary adjustments to monitoring protocols or the need for maintenance activities.

5.4.3 Maintenance

In the context of FEH mitigation projects, maintenance refers to the repair of unavoidable or unanticipated damage or to make corrective adjustments to underperforming components of the FEH mitigation project. Unless maintenance funding is secured in perpetuity, maintenance should only include those activities necessary for the success of the project; maintenance for FEH mitigation projects is not intended to preserve a manicured site condition.

Maintenance activities are frequently required shortly after construction to address minor settlement of structures and filled embankments, failed or inadequate vegetation, and to repair minor erosion that may have occurred due to a lack of sufficiently established vegetation. Don't view these issues as project failures, but rather an unavoidable nuisance in dynamic systems. In fact, for all designs, other than those intended to be threshold channel designs, not having to make adjustments after a significant event would be very unusual and a sign of a potential issue.

Maintenance requirements should diminish after the initial establishment of vegetation, after which only point maintenance activities should be performed as necessary based on the results of monitoring efforts relative to project objectives. The passage of time, severe flooding, or changed upstream or downstream conditions may present the need for corrective action or adjustment of the mitigation measures to improve the overall project performance. However, the adjustments should not typically include dramatic changes or reconstruction of the project. Maintenance needs may also include the removal of unwanted or invasive species that would otherwise diminish the ability of the mitigation measures to meet the project objectives.

The frequency and duration of project maintenance will depend on the types of treatments used, the requirements of regulatory permits, and the dynamism of the system. Regardless of the regulatory requirements, continue maintenance activities informed by project monitoring until the project site is self-sustaining.

5.4.4 Final Inspection and Termination of Post-Construction Management

The project may undergo several cycles of monitoring, corrective maintenance, and monitoring to confirm the adequacy of the maintenance activity. Throughout the process, maintain the adaptive quality of the management strategy to accommodate changing conditions outside of the project site, allowing the project to become gradually more resilient and self-sustaining.

Once monitoring results suggest the project is self-sustaining, complete a final inspection and evaluation of the project site to confirm the conclusions. Evaluate results of the final inspection against project objectives and share the results, at a formal meeting, with all stakeholders involved in the original conception and project design.

At the conclusion of the meeting, the stakeholders should come to an agreement as to whether or not the project is self-sustaining and meets the project objectives. Monitoring and maintenance activities involved with project objectives can then be reduced or terminated for nature-based projects that are deemed to be self-sustaining and successful. Long-term monitoring and maintenance may be required for projects utilizing engineered materials that have a limited design life or require replenishing.

5.5 REFERENCES

Harman, W. and R. Starr, 2011. Natural Channel Design Review Checklist. U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, Annapolis, MD.

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APPENDIX 1 BMP FACT SHEETS

APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

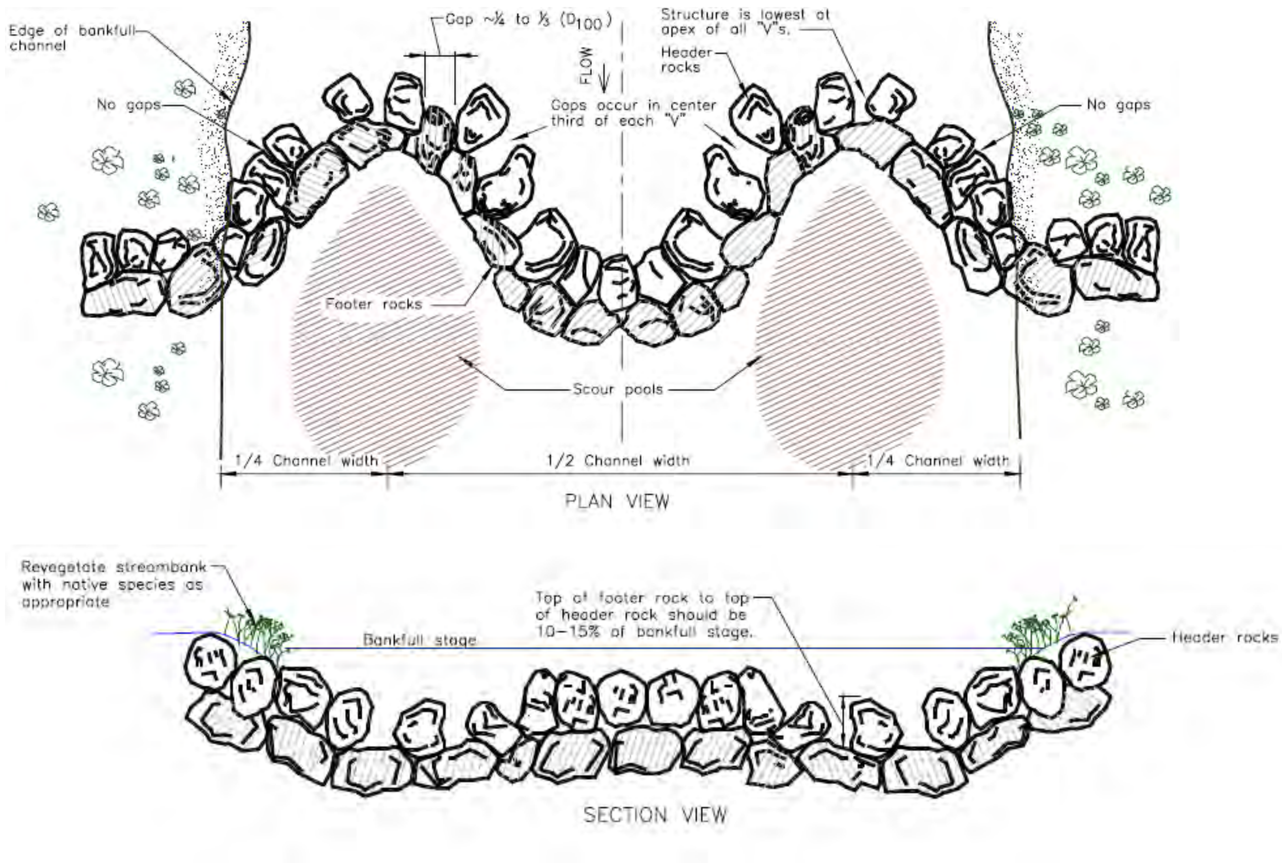
1.1 GRADE CONTROL MEASURES

Grade control measures artificially fix a point in the channel profile to prevent head-cutting or channel degradation of the channel upstream of the structure. Grade control structures can also be used to establish the equilibrium slope for the channel; rigid grade control structures are constructed at specified points to force the desired slope. Examples of grade control measures include, but are not limited to, rock w-weirs, step-pools (boulder/stone), log drops and v-log drops, and Newbury riffles.

Reference Chapter 4.5.1 for more information regarding grade control and Table 4-1 for BMP technical reference information.

APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

1.1.1 Rock W-Weirs



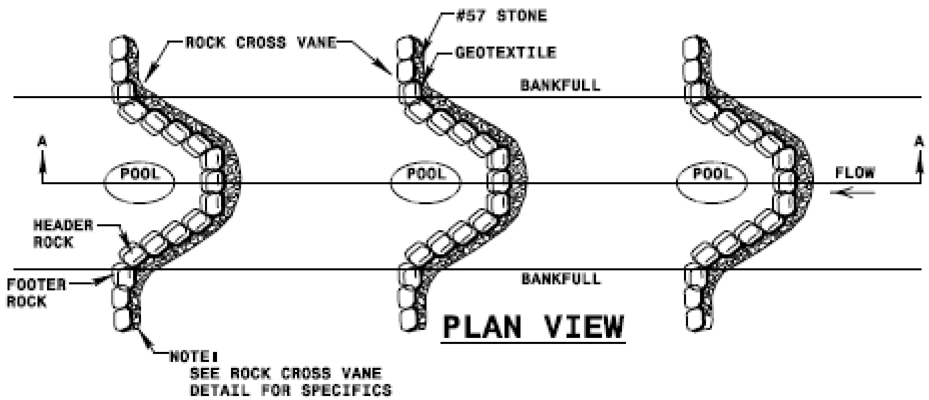
Notes:

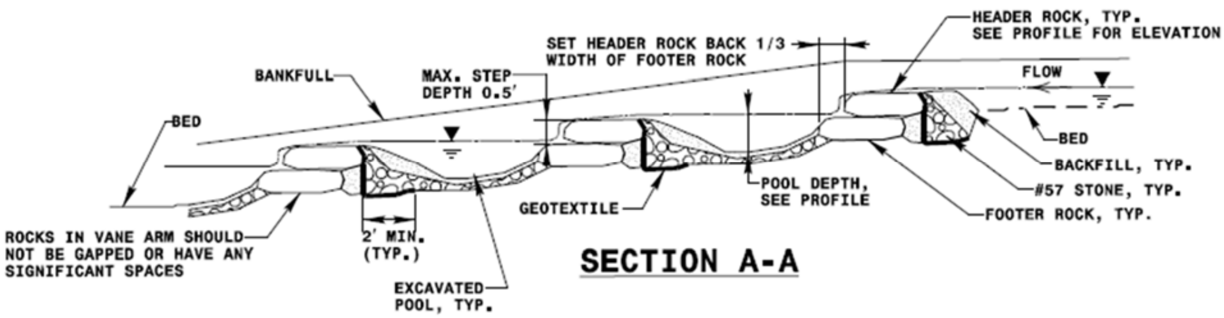
1. Conceptual view has been exaggerated to illustrate the relative elevation of structure features.
2. "W" weir is essentially two cross-vane weirs placed side-by-side.
3. Center of structure should be higher than apex elevation, but lower than elevation along banks.
4. Pool depths should be 2 to 3 times bankfull depth, or as identified by designer from reference reach.
5. Header and footer stones should be at least twice the diameter of the smallest non-mobile particle size for the maximum design flow event. Boulder/stone diameter should be evaluated as the geometric mean of the a-, b-, and c-axes. Designer shall size footer stones to allow for practicable, stable stacking of material.
6. "W" weirs can also be used to help improve the alignment of flow or redirect flow away from an area that is being protected. When realigning flow with a "W" weir, the structure is not installed perpendicular to the channel banks, but 'pointing' in the desired direction of flow. Excessive departure from a perpendicular alignment should be avoided. If the amount of desired redirection exceeds # degrees, the use of multiple "W" weirs to more gradually turn the flow should be considered.

Source:

"Porous Weirs "W" Weir Conceptual Design." Figure 2. Stream Habitat Restoration Guidelines 2004. Washington State Aquatic Habitat Guidelines Program. Accessed August 2018. <https://www.wou.edu/las/physci/taylor/g407/restoration/WA_Dept_Forestory_2004_Porous_Weirs.pdf>

1.1.2 Step-pools (boulder/stone)





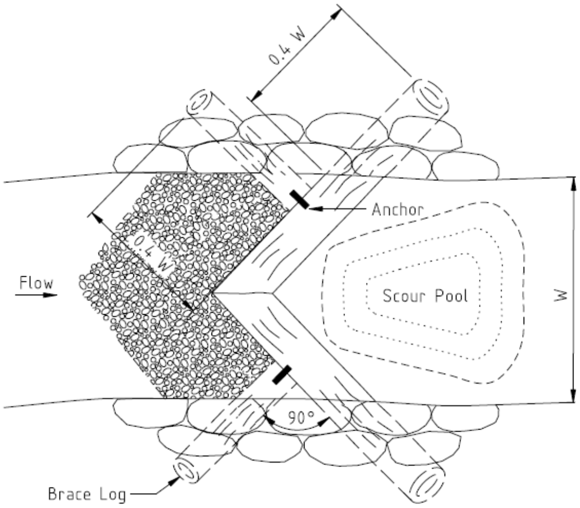
Notes:

1. Steps to be short, frequent, and closely spaced.
2. Pool spacing shall be inversely proportional to stream slope, and directly proportional to bankfull width.
3. Pool depths at bankfull elevation shall be typically 2 to 3 times deeper than step depths at bankfull elevation, or as identified by designer from reference reach.
4. Footer boulders should be placed without gaps in order to adequately support the boulders at the head of steps during high energy/high flow events and to reduce the potential for piping of backfill material through the face of the structure.
5. Rock vane backfill to consist of #57 stone (¾" to 1 ½").
6. Header and footer stones should be at least twice the diameter of the smallest non-mobile particle size for the maximum design flow event. Boulder/stone diameter should be evaluated as the geometric mean of the a-, b-, and c-axes. Designer shall size footer stones to allow for practicable, stable stacking of material.
7. Step-pool structures can be useful in helping to reconnect abandoned floodplains. Typically, to reconnect a floodplain area, the downstream end of the project will require a steeper channel slope than the pre-project condition. Step-pool structures can help establish that slope in a reliably stable manner.

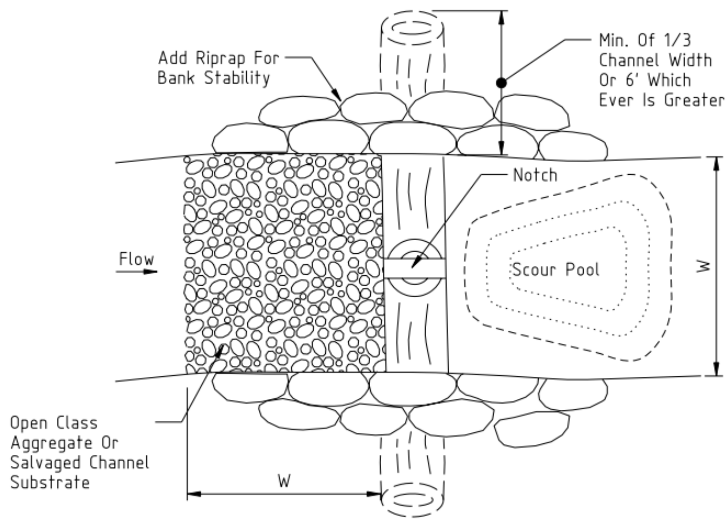
Source:

"Step Pool Detail." North Carolina Department of Transportation Environmental Compliance. Accessed August 2018. <https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Step%20Pool.pdf>

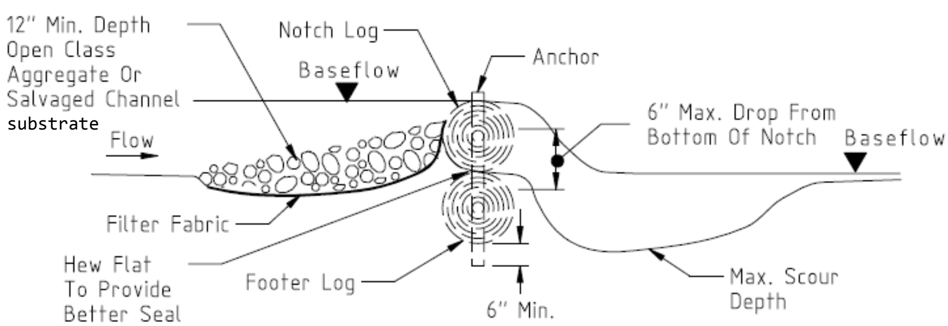
1.1.3 Log Drop Structures



PLAN



PLAN



PROFILE

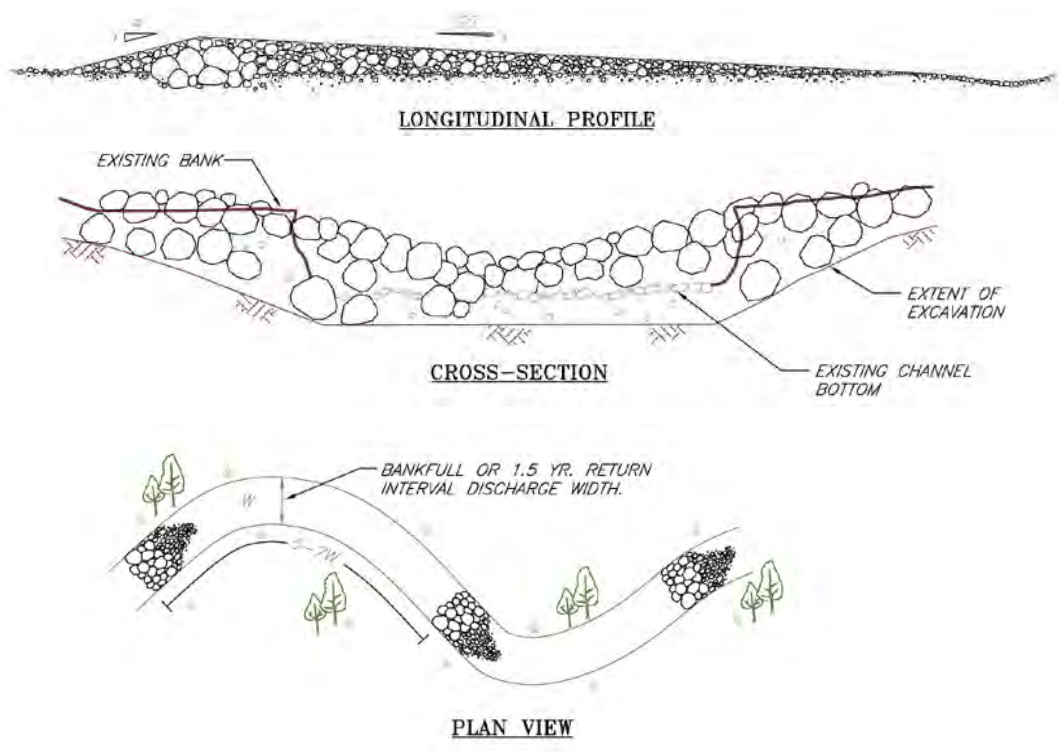
Notes:

1. Structures are typically used in high gradient (>3% slope), relatively small streams and can be constructed in series to provide grade control. As stream size increases, use of v-log drop is recommended.
2. Excessive drop height and log width can impede fish passage.
3. Footer logs should extend into the banks 0.4 times the bankfull width (W).
4. Notched drop log should be placed on top of footer log with notch centered in channel.
5. For V-Log drops, brace logs should be anchored upstream of drop logs at a 90-degree angle.
6. Extend filter fabric above top of notch and brace logs and key into the bank.
7. Log drops can be useful in helping to reconnect abandoned floodplains. Typically, to reconnect a floodplain area, the downstream end of the project will require a steeper channel slope than the pre-project condition. Log drops can help establish that slope in a reliably stable manner.
8. Middle of v-log drop shall be lowered relative to the landward ends by 6 inches.

Source:

"V Log Drops." The Virginia Stream Restoration & Stabilization Best Management Practice Guide. Department of Conservation and Recreation Division of Soil and Water Conservation. Accessed August 2018. <https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf>

1.1.4 Newbury Riffle



Notes:

1. Spacing is typically 5-7 times the bankfull channel width.
2. Riffle crests and downstream surfaces should be V-shaped to direct the flow towards the channel centerline to reduce bank scour at the riffle site and maintain depth in the center of the downstream pool.
3. Banks should be protected from the channel centerline up to top bank.
4. A geotextile should be used underneath the stone to prevent leaching of finer substrate material.
5. Post-construction monitoring of Newbury riffles is highly recommended to ensure that erosion and sedimentation processes do not negate habitat benefits.
6. Riffles are not suitable for reaches where rapid bed degradation (lowering) is likely, or where scour depths adjacent to the toe will be greater than the height of the toe.
7. Use in small to medium, gravel/cobble streams. Applications to streams with beds containing significant amounts of material finer than gravel should be done with great care.
8. Riffles should not be placed in extremely sluggish or stagnant reaches or those with baseflow depths much greater than 2 ft.
9. Stone for the structure should be well-graded and properly sized.

Source:

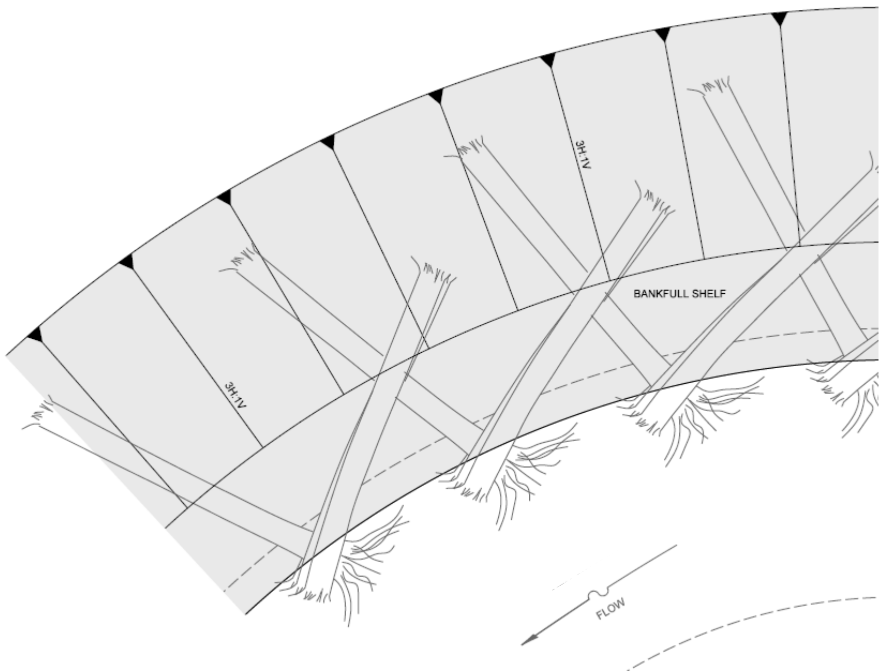
"Newbury Rock Riffles." Environmentally Sensitive Streambank Stabilization Manual. National Cooperative Highways Research Program Project 24-19 by Salix Applied Earthcare. <http://www.salixaec.com/streambanks.html>

1.2 TOE PROTECTION MEASURES

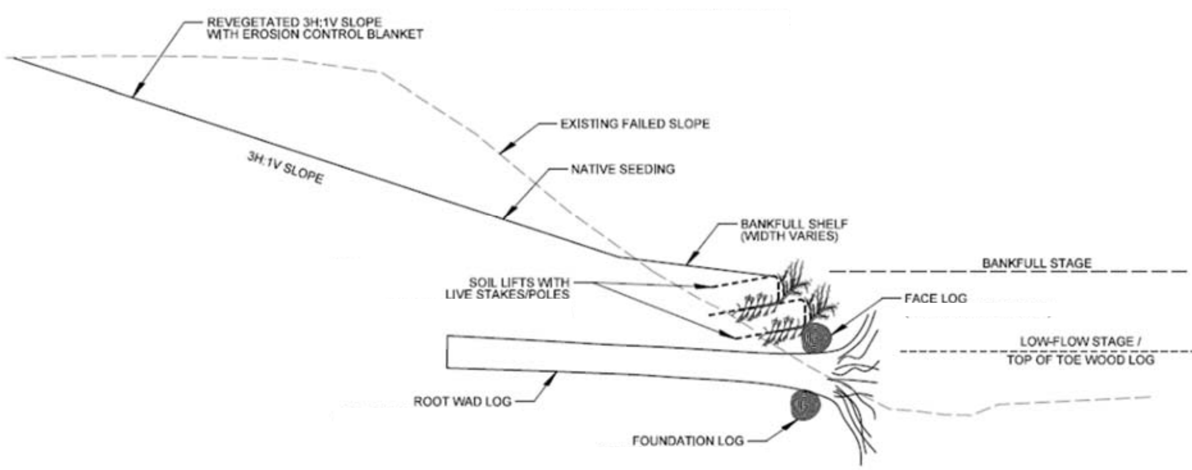
Toe protection measures are critical for addressing slope instabilities under various conditions. Toe protection reinforces the slope regardless of the vertical stability condition by reducing the likelihood of low-bank scour. Examples of toe protection measures include, but are not limited to, toe wood, rock-toe revetments, interlocking concrete jacks, boulder revetments, and sheet pile/h-pile walls.

Reference Chapter 4.5.2 for more information regarding toe protection and Table 4-1 BMP Technical Reference Information.

1.2.1 Toe Wood



PLAN VIEW - TOE WOOD AND SOIL LIFTS



TYPICAL SECTION - TOE WOOD DETAIL

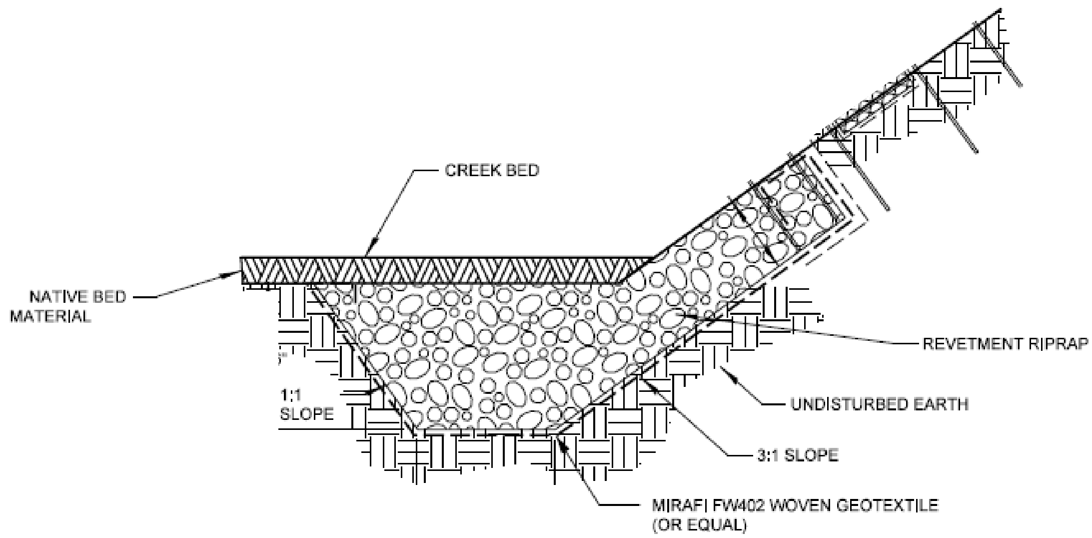
Notes:

1. Foundation logs shall face the downstream direction at an angle to the bank between 20-30 degrees.
2. Approximately 20% of the foundation log shall be exposed with the remaining portion embedded in bank and counter-buttressed by other logs and fill material.
3. Foundation logs shall be backfilled with native material and small woody debris prior to placement of toe wood.
4. Toe wood shall be cantilevered over foundation logs with root fan extended out past the foundation log and oriented perpendicular to the direction of flow.
5. Non-woven geotextile shall be placed on top of root wad logs, prior to placing face logs and backfill material.
6. Face logs shall be embedded into the bank and placed over toe wood and adjacent to the root fan.

Source:

Notes and detail prepared by Christopher B. Burke Engineering, LLC, adapted from Wildland Hydrology

1.2.2 Rock-Toe Revetments



Notes:

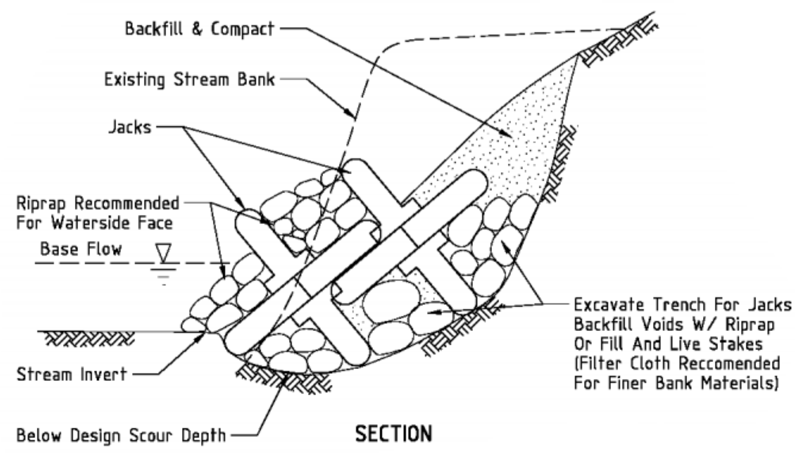
1. Rock-toe dimensions shall be determined by designer based on anticipated scour depth and the elevation of Ordinary High-Water Mark.
2. Slope matting, if present, shall be placed into rock-toe trench to produce a continuously protected transition between the two measures.
3. Stone toe protection shall extend downward to the maximum scour depth for the design event.
4. Minimum stone thickness shall be twice the D_{50}.

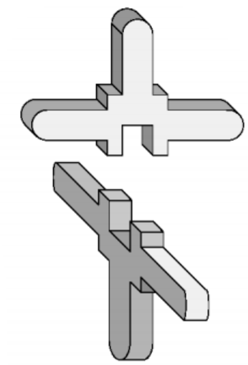
Source:

Notes and detail prepared by Christopher B. Burke Engineering, LLC, adapted from National Cooperative Highway Research Program Report 568 “Riprap Design Criteria, Recommended Specifications, and Quality Control” Figure C4.9. Accessed August 2018.
<http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_568.pdf>

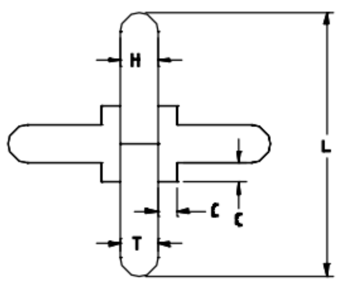
APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

1.2.3 Interlocking Concrete Jacks





Jacks Formed By Sliding Two Identical Sections Together



Interlocking Concrete Jacks	L(in)	T(in)	H(in)	C(in)	Vol(ft³)	Wt(lbs)
AJ-24	24	3.36	3.68	1.84	0.56	78
AJ-36	36	5.52	5.52	2.76	1.89	265
AJ-48	48	7.36	7.36	368	4.49	629

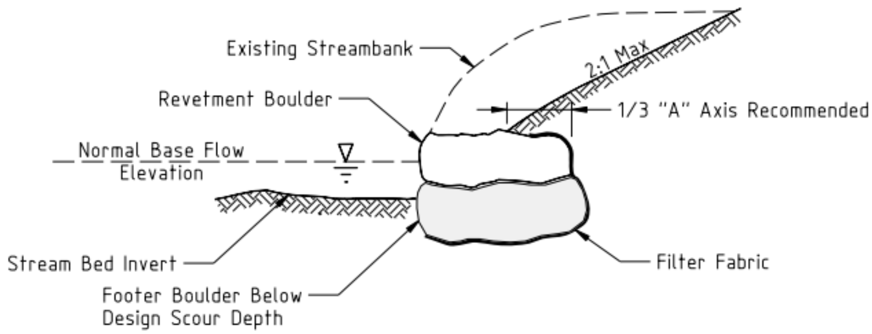
Notes:

1. Choose size and number of tiers of Interlocking Concrete Jacks to ensure they can withstand expected flow conditions and that the bottom-most Interlocking Concrete Jack is below the design scour depth and the top-most is above the normal baseflow elevation.
2. If riprap is used to fill voids, choose a class with a D_{50} that is at least 1/3 the arm length of the Interlocking Concrete Jack.
3. On small streams and silty banks, a filter fabric can be used between rows and behind Interlocking Concrete Jacks to prevent removal of soils and pumping of fines.

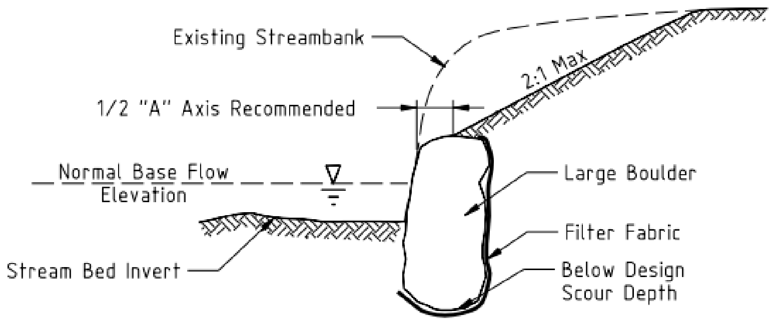
Source:

"Interlocking Concrete Jacks." The Virginia Stream Restoration & Stabilization Best Management Practice Guide. Department of Conservation and Recreation Division of Soil and Water Conservation. Accessed August 2018.
<https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf>

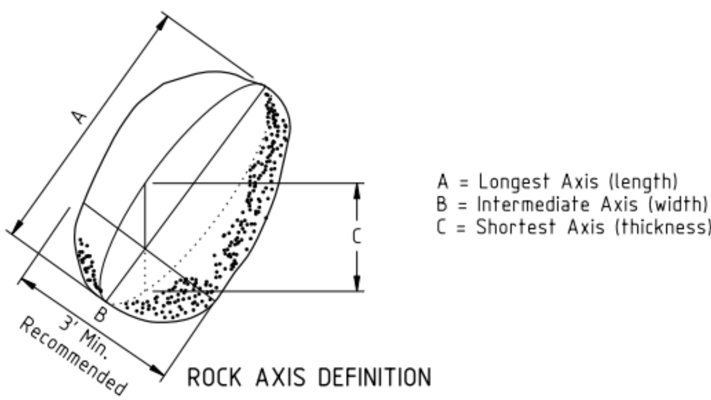
1.2.4 Boulder Revetments



SECTION - DOUBLE BOULDER REVETMENT



SECTION - LARGE BOULDER REVETMENT



ROCK AXIS DEFINITION

Notes:

1. Boulder revetments should extend vertically into the stream bed below the design scour depth.
2. Boulders should be sized to withstand expected near-bank velocities and shear stresses.
3. Boulders shall be stacked [and chinked] in such a way as to remain stable when backfilled.

Source:

"Boulder Revetments." The Virginia Stream Restoration & Stabilization Best Management Practice Guide. Department of Conservation and Recreation Division of Soil and Water Conservation. Accessed August 2018.
<https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf>

1.3 BANK ARMORING MEASURES

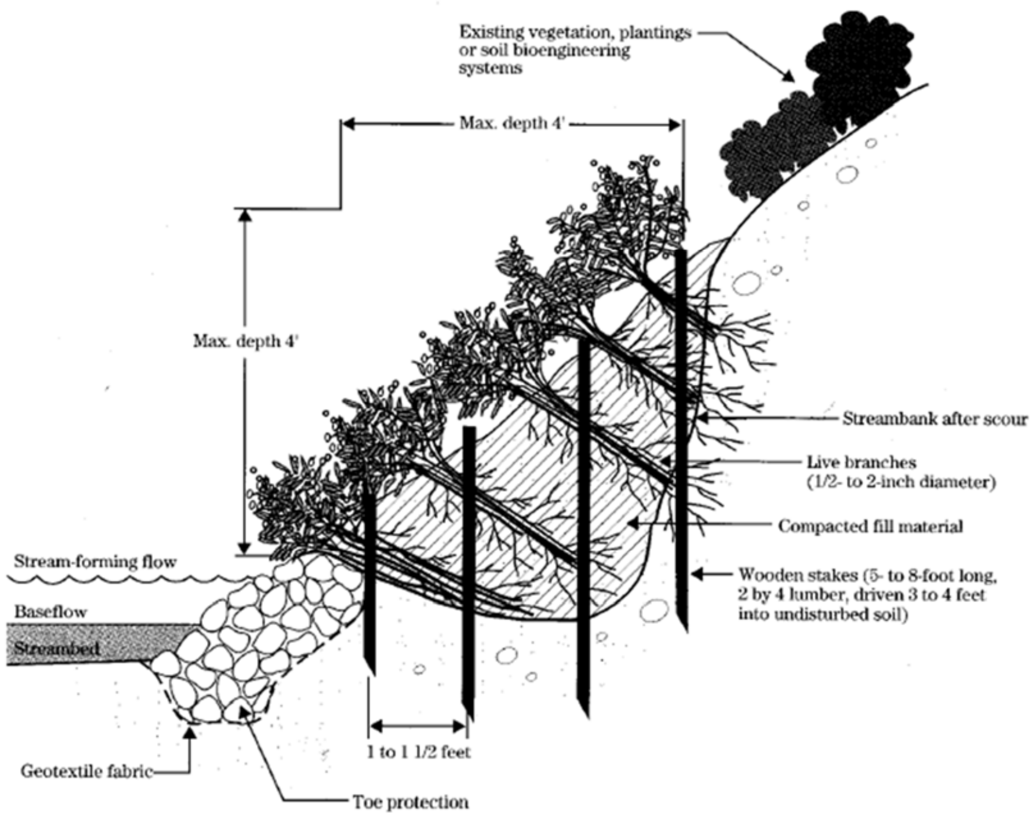
Bank armoring measures use both natural and synthetic materials to prevent bank scour as well as lateral migration by increasing the erosion resistance of the channel bank. Toe protection is often incorporated into the bank armor treatment to maintain slope stability. Examples of bank armoring measures include, but are not limited to, branch layering, natural fiber rolls, brush mattresses, vegetated gabion baskets, gabion mattresses, live stakes, live fascines, live soil lifts, natural fiber/turf reinforcement matting, riprap, and articulated concrete blocks.

Several bank armoring methods can be applied to the bed of the channel to serve as bed armoring measures. Gabion mattresses, riprap, and articulated concrete blocks are capable of providing adequate bed armoring protection in an unvegetated state. Turf reinforcement matting can provide bed armoring in ephemeral streams.

Reference Chapter 4.5.2 for more information regarding bank armoring and Table 4-1 for BMP technical reference information.

APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

1.3.1 Branch Layering



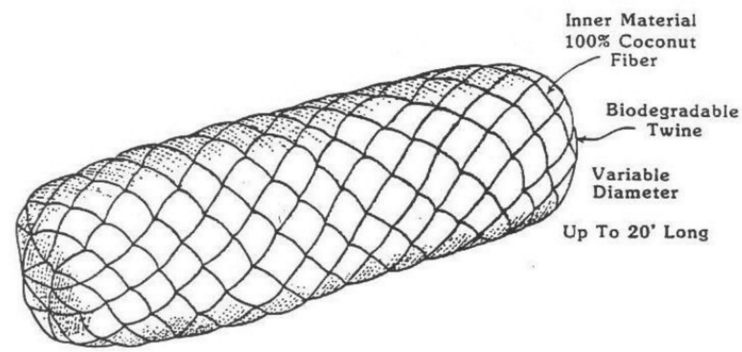
Notes:

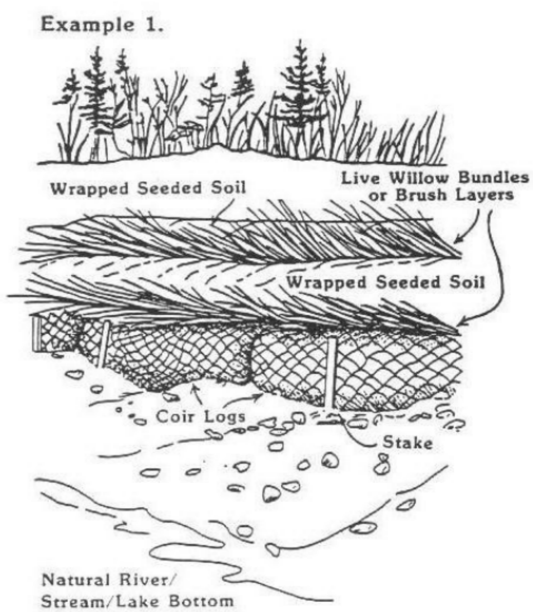
1. Branch layering provides immediate bank reinforcement and is most effective when bank repair dimensions range from 2’ to 4’ in height and depth.
2. Branches should be long enough to extend from the face of slope through the repair area.
3. Branches should be installed above the bankfull depth and flush with the slope to prevent scour.
4. Basal ends of branches should be installed lower and at the back of the repair area and should be very near to or in the vadose zone.

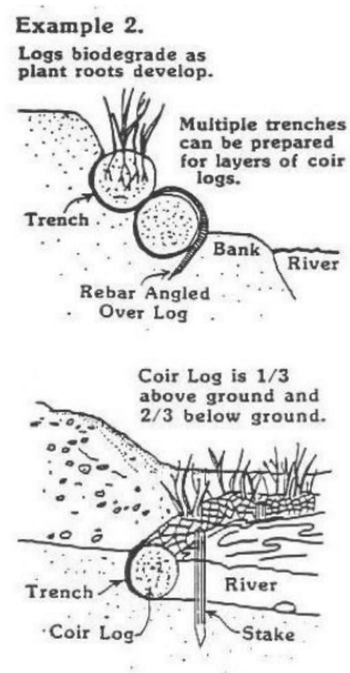
Source:

“Branchpacking.” Figure 8. Streambank and Shoreline Protection Manual 2002. Lake County Stormwater Management Commission. Accessed August 2018. <https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf>

1.3.2 Natural Fiber Rolls







Notes:

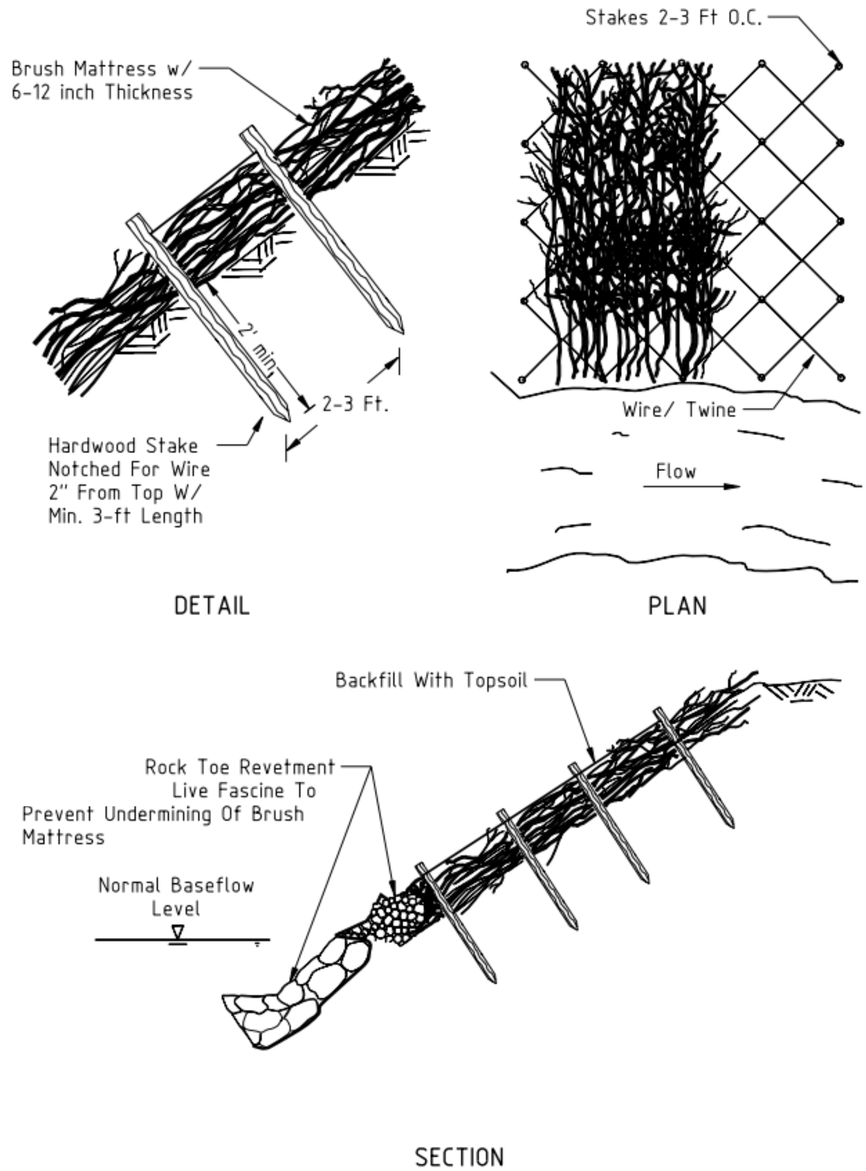
1. Install coir log during periods of dry riverbed or isolate area. Coir logs should not be utilized below the Ordinary High-Water Mark.
2. Secure log with wooden or live stakes driven through coir log mesh and driven into earth. Stake log into place and secure logs to stakes by cross-lacing biodegradable twine between wooden stakes on either side of each log.
3. Tie adjacent log together with biodegradable twine.
4. Compact soil around logs.
5. Secure the upstream and downstream ends by positioning coir logs so they transition smoothly into a stabilized bank.

Source:

"Protection Techniques: Coir Logs". Streambank Revegetation and protection: A Guide for Alaska. Alaska Department of Fish and Game. Accessed August 2018. <http://www.adfg.alaska.gov/index.cfm?adfg=streambankprotection.coir>

APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

1.3.3 Brush Mattresses



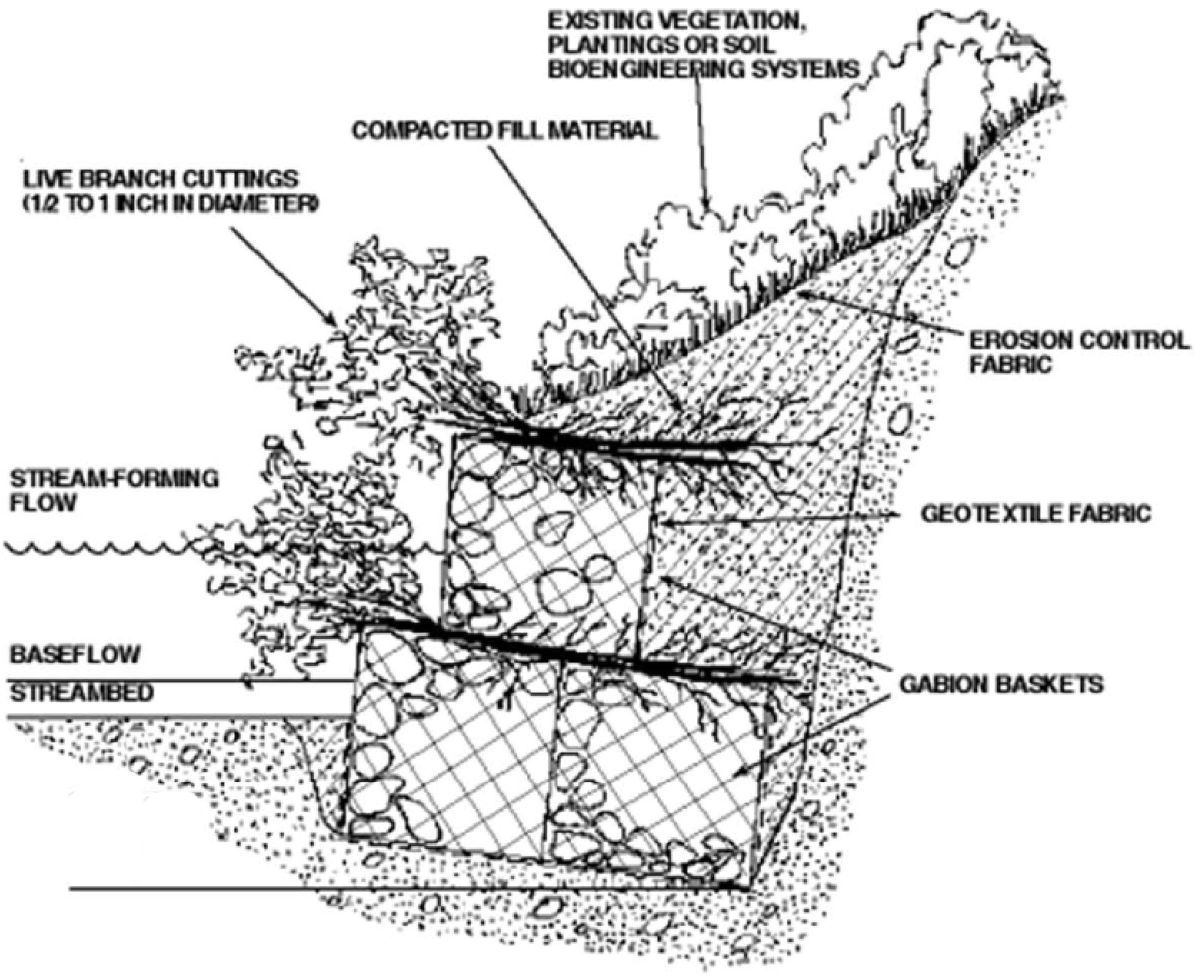
Notes:

1. Brush mattresses should only be installed during the dormant season. This is the period after leaf drop in the fall and before bud break in the spring.
2. Soak the live branches for a minimum of 24 hours before planting. Soaking for 5-7 days is considered ideal and should promote establishment.
3. Drains or geotextiles may be required if there is a potential for seepage under the brush mattress.
4. Brush mattresses must be designed and constructed to withstand the near bank shear stresses and velocities that impact the streambank.
5. Brush mattresses should achieve approximately 80% coverage of the area of application. The contract documents should include a guarantee/warranty regarding proper handling and installation of the live branches to promote survival and growth of the brush mattresses.
6. The contract documents should include a guarantee/warranty regarding percent survivability of the live branches for a minimum of 1 - 3 years after installation.
7. Brush mattresses should only be installed in areas low enough along the bank to have significant wet periods and easy access to groundwater.

Source:

"Brush Mattresses." The Virginia Stream Restoration & Stabilization Best Management Practice Guide. Department of Conservation and Recreation Division of Soil and Water Conservation. Accessed August 2018. <https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf>

1.3.4 Gabion Baskets (Vegetated/Unvegetated)



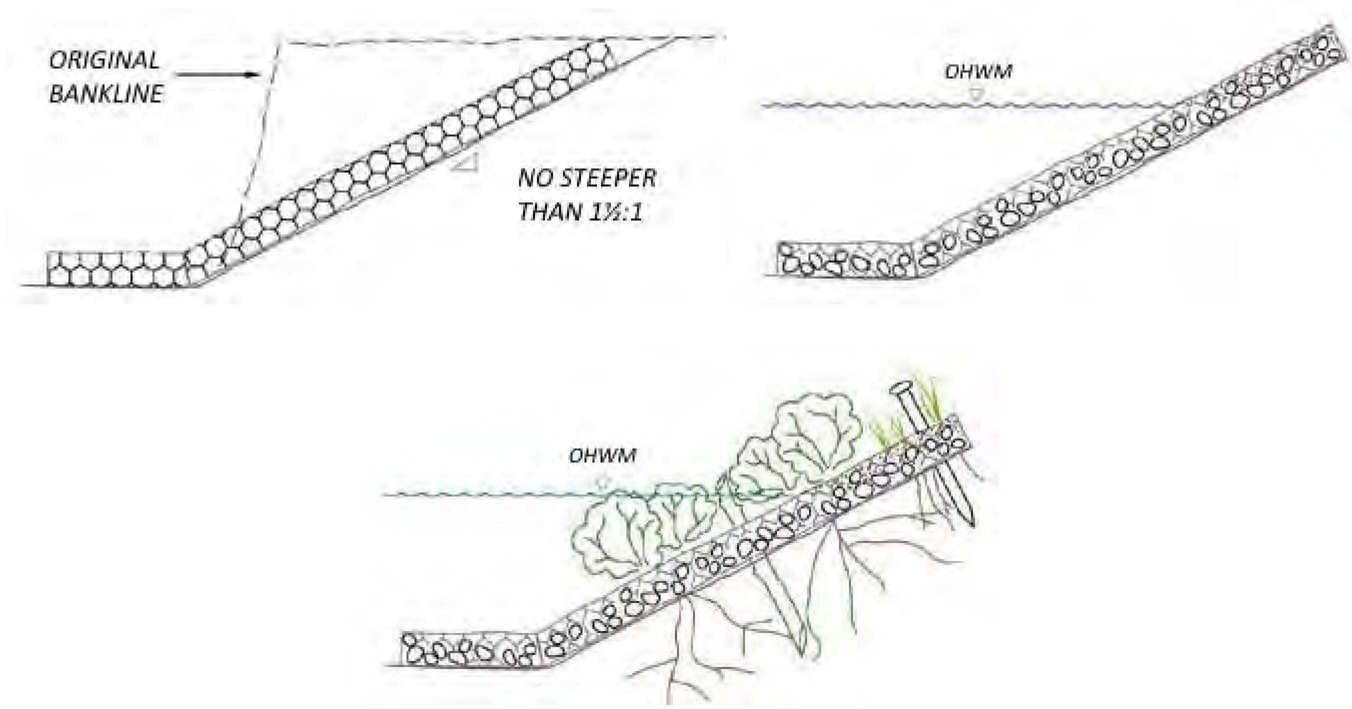
Notes:

1. Effective where the bank slope is or must be steep (typically greater than 1:5H:1V and requires structural support).
2. Appropriate at the base of a slope where a low wall may be required to stabilize the toe of the slope and reduce its steepness.
3. Where gabions are designed as a structural unit, the effects of uplift, overturning, and sliding must be analyzed in a manner similar to that for gravity type structures.
4. A drainage layer should be used behind the gabion baskets to reduce the lateral earth pressure.

Source:

"Rock Gabions." Figure 15. Streambank and Shoreline Protection Manual 2002. Lake County Stormwater Management Commission. Accessed August 2018. <https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf>

1.3.5 Gabion Mattresses



Gabion mattresses shown in bank installation. Stream bed installation uses the same installation/design techniques to cover and protect the stream bed. Stream bed applications should also extend to just above the OHWM.

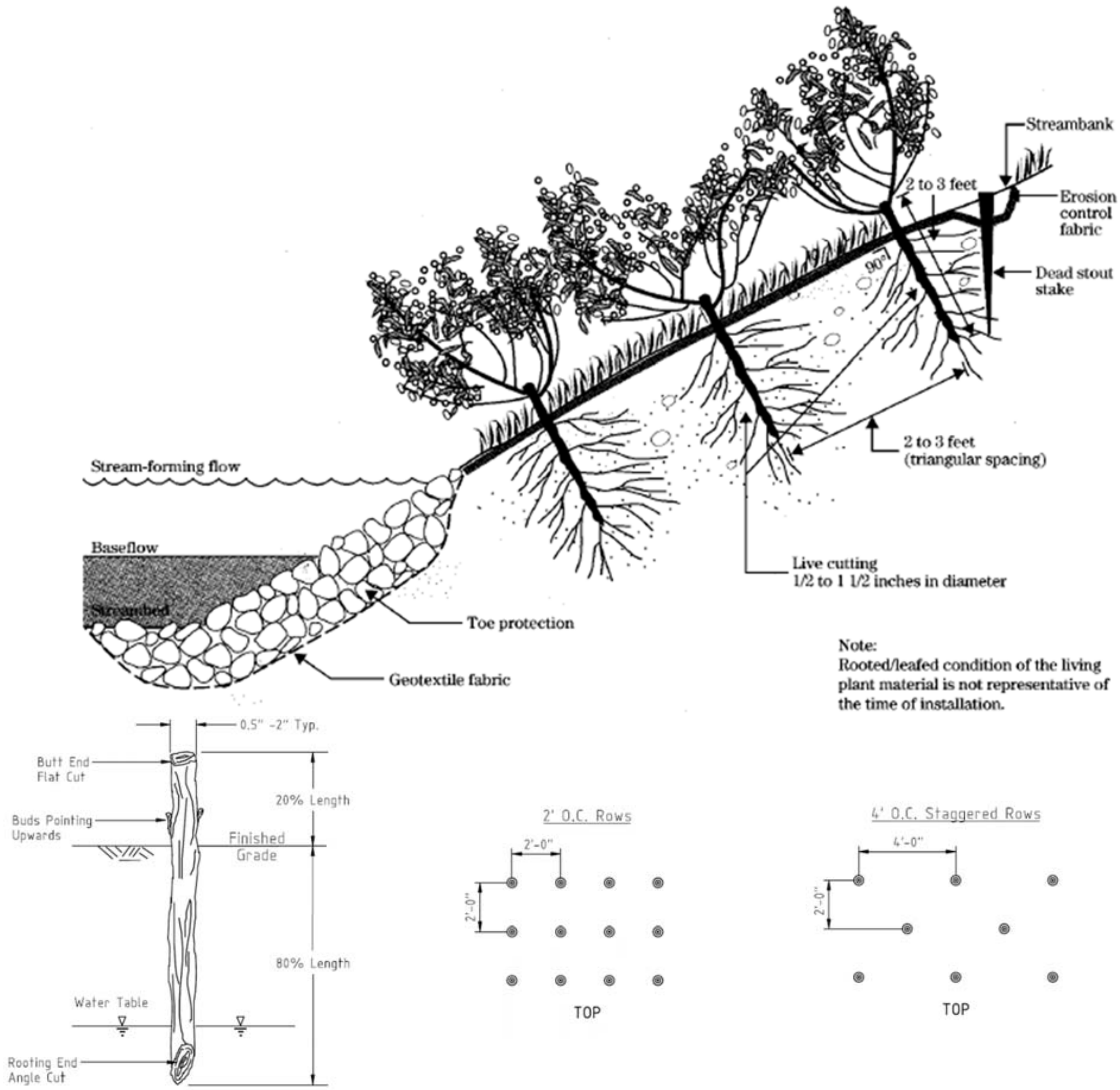
Notes:

1. Reshape the channel to the desired final grade and assemble gabion mattress baskets.
2. Fill baskets with rock, and, if desired topsoil above the high-water line. Close basket lid and lace the lid to the basket edges with wire or hog rings.
3. Insert live stakes using a pilot bar, if necessary. Drive them in deep enough that they can access the vadose zone. If topsoil has been added, seed and mulch.
4. Continuous, well-located transitions should be designed where bank armoring is used above the gabion mattress to provide seamless protection and prevent flanking.
5. Can be placed as a continuous mattress for slope protection. Slopes steeper than 2H:1V should be analyzed for slope stability.
6. Gabions used as mattresses should be a minimum of 9 inches thick for stream velocities of up to 9 feet per second. Increase the thickness to a minimum of 1.5 feet for velocities of 10 to 14 feet per second.
7.

Source:

“Vegetated Gabion Mattress.” Environmentally Sensitive Streambank Stabilization Manual. National Cooperative Highways Research Program Project 24-19 by Salix Applied Earthcare. < http://www.salixaec.com/streambanks.html>

1.3.6 Live Stakes



Notes:

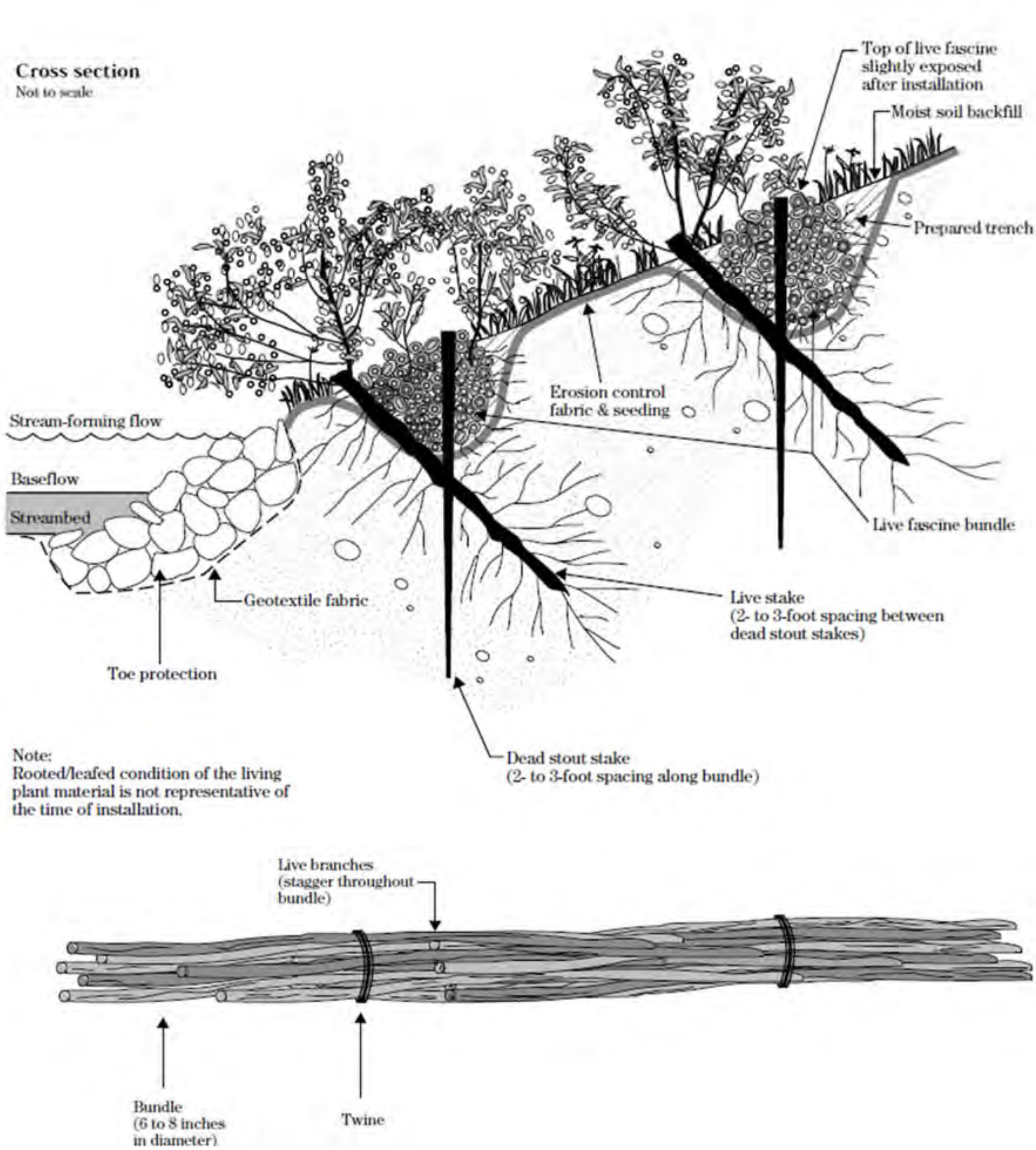
1. Do not use in areas where near-bank shear stress exceeds 2 lb/ft^2 or velocities exceed 5-10 fps.
2. Stake lengths should be long enough to reach soil suitable for rooting when used with other practices. Typically, 2-3' long. The rooting end should be very near to or within the vadose zone.
3. Select species to match site conditions, including shading, flood and drought tolerances, and aesthetics.
4. Live stakes must be installed after leaf drop in the fall and before bud break in the spring.
5. Stakes that are splintered, split or broken during installation must be replaced.
6. Store live stakes in a cool, shaded location in damp peat moss, sand, wrapped in newspaper in ventilated plastic bags, or in burlap sacks and topsoil for a maximum 128 of 48 hours. If live branches cannot be installed within 48 hours of delivery, then they shall be stored in a cooler between 33 and 40 degree Fahrenheit in one of the moist mediums listed above. Live branches shall remain moist at all times before planting.
7. After installation, cleanly cut exposed stake to approximately 3" in length. Cut at slight angle.

Source:

"Live Stakes." Figure 1. Streambank and Shoreline Protection Manual 2002. Lake County Stormwater Management Commission. Accessed August 2018. <https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf>

"Live Stakes." The Virginia Stream Restoration & Stabilization Best Management Practice Guide. Department of Conservation and Recreation Division of Soil and Water Conservation. Accessed August 2018. <https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf>

1.3.7 Live Fascines



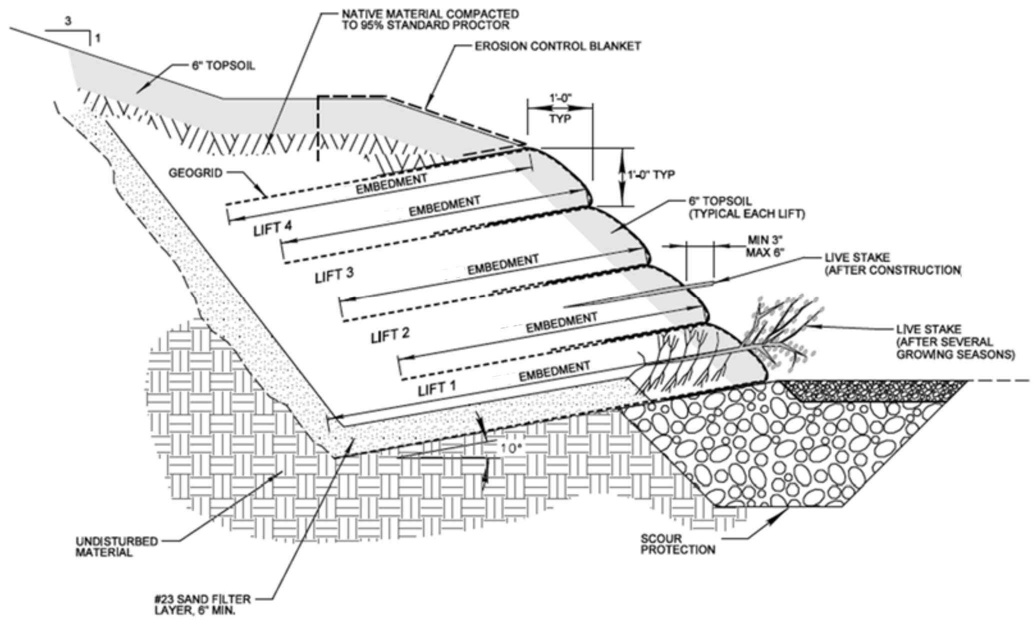
Notes:

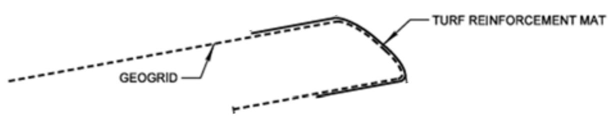
1. Live fascines should be installed above bankfull discharge.
2. Cuttings tied together to form live fascine bundles normally vary in length from 5 to 10 feet or longer, depending on site conditions and limitations in handling. The complete bundles should be 6 to 8 inches in diameter, with all of the growing tips oriented in the same directions. Stagger the cuttings in the bundles so that tops are evenly distributed throughout the length of the uniformly sized live fascine.
3. Live fascine bundles should be installed in a trench approximately 10 inches wide and 10 inches deep.
4. Dead stout stakes should be 2.5 feet long and driven directly through live fascine bundle.

Source:

"Live Fascines." Figure 2. Streambank and Shoreline Protection Manual 2002. Lake County Stormwater Management Commission. Accessed August 2018. <https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf>

1.3.8 Live Soil Lifts





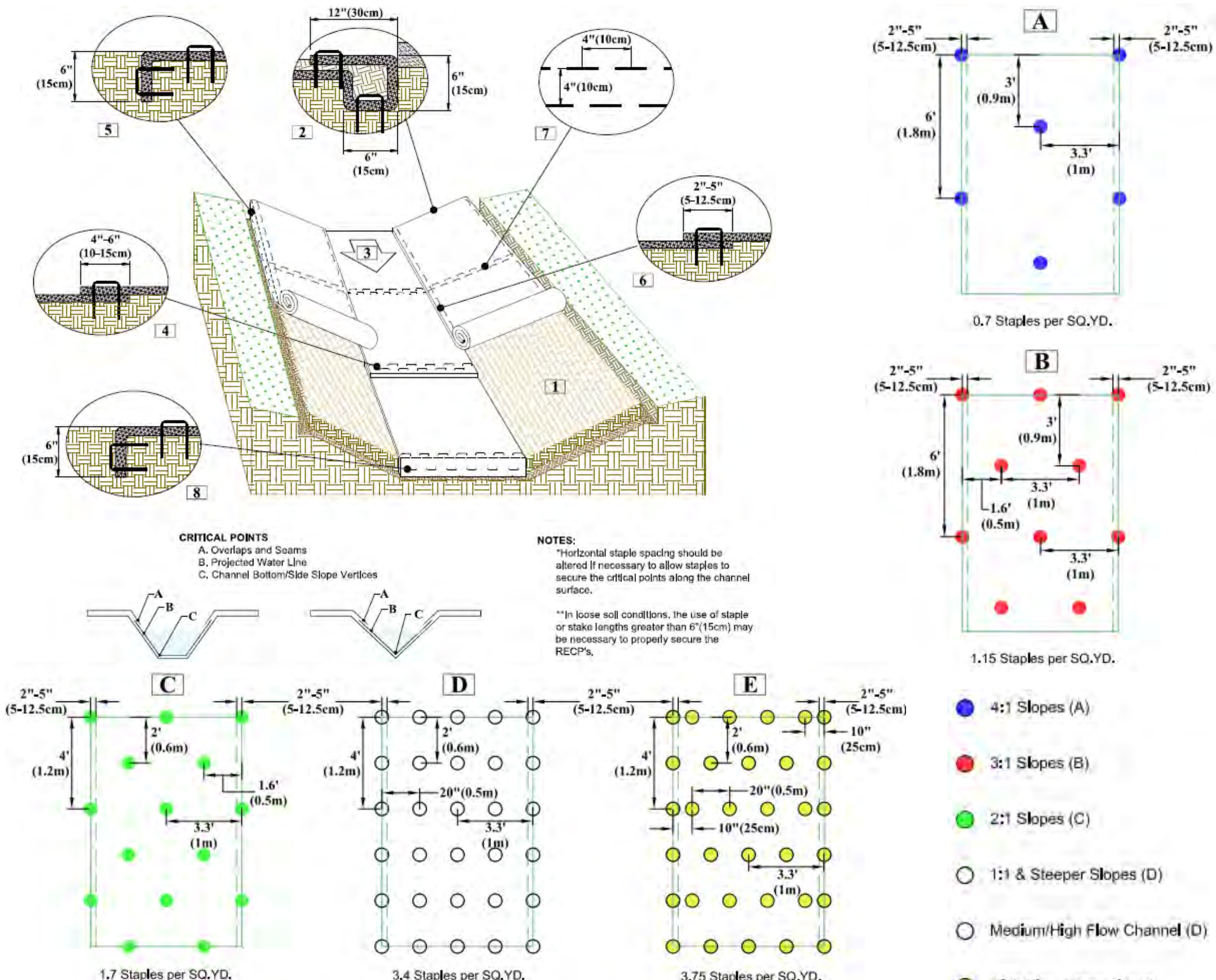
Notes:

1. Geogrid to be included as required by slope stability analysis. Slopes not requiring geogrid may use coir netting or turf reinforcement mat as the reinforcement/wrap layer in the soil lifts.
2. Live poles should be used in place of live stakes when soil lift installation occurs during the dormant season. Live poles installed in vegetated, mechanically stabilized earth slopes are to be installed while constructing the lifts, between one lift and the subsequent lift.
3. Turf reinforcement mat and geogrid products and embedment lengths to be determined by designer. Typical embedment lengths are ± 6 feet.

Source:

Notes and detail prepared by Christopher B. Burke Engineering, LLC, adapted from ESENSS

1.3.9 Natural Fiber Matting / Turf Reinforcement Mat / Erosion Control Blanket



Notes:

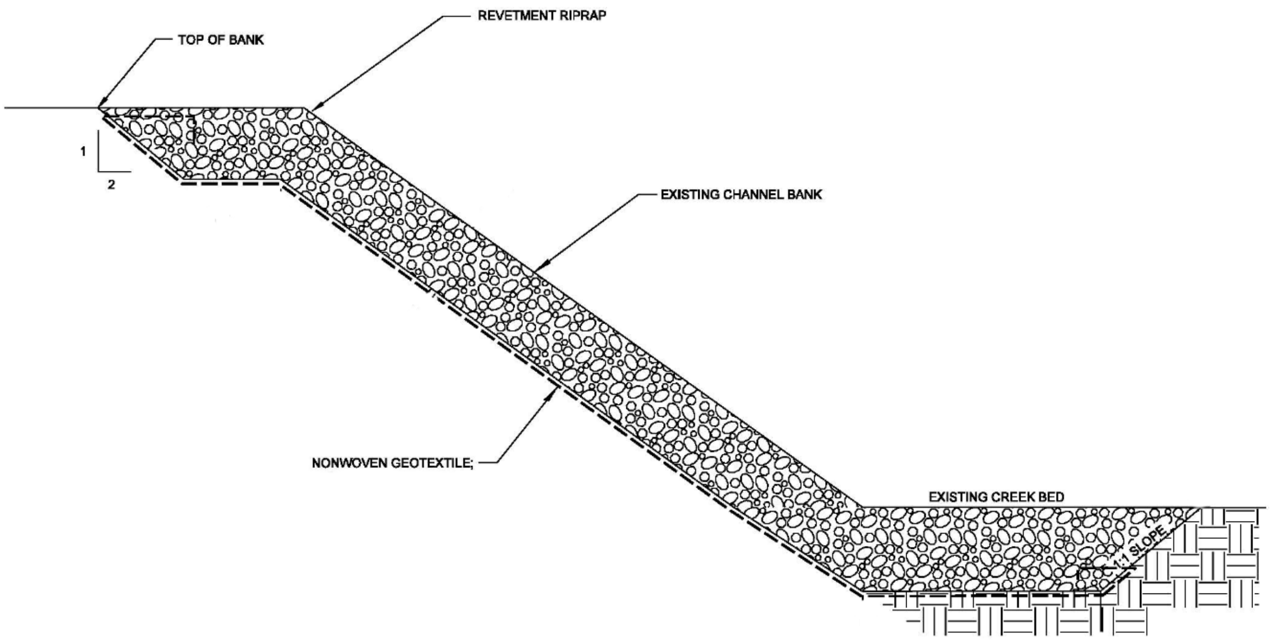
1. Prepare soil before installing rolled erosion control products (RECPs), including any necessary application of lime, fertilizer, and seed.
2. Begin at the top of the channel by anchoring the RECPs in a 6"(15cm) deep X 6"(15cm) wide trench with approximately 12"(30cm) of RECPs extended beyond the up-slope portion of the trench. Use mat at the channel/culvert outlet as supplemental scour protection as needed. Anchor the RECPs with a row of staples/stakes approximately 12"(30cm) apart in the bottom of the trench. Backfill and compact the trench after stapling. Apply seed to the compacted soil and fold the remaining 12"(30cm) portion of RECPs back over the seed and compacted soil. Secure RECPs over compacted soil with a row of staples/stakes spaced approximately 12" apart across the width of the RECPs.
3. Roll center RECPs in direction of water flow in bottom of channel. RECPs will unroll with appropriate side against the soil surface. All RECPs must be securely fastened to soil surface by placing staples/stakes in appropriate locations as shown in the staple pattern guide.
4. Place consecutive RECPs end-over-end (Shingle style) with a 4"-6" overlap. Use a double row of staples staggered 4" apart and 4" on center to secure RECPs.
5. Full length edge of RECPs at top of side slopes must be anchored with a row of staples/stakes approximately 12"(30cm) apart in a 6"(15cm) deep X 6"(15cm) wide trench. Backfill and compact the trench after stapling.
6. Adjacent RECPs must be overlapped approximately 2"-5" (5-12.5cm) (Depending on RECPs type) and stapled.
7. In high flow channel applications, a staple check slot is recommended at 30 to 40-foot (9 -12m) intervals. Use a double row of staples staggered 4"(10cm) apart and 4"(10cm) on center over entire width of the channel.
8. The terminal end of the RECPs must be anchored with a row of staples/stakes approximately 12" (30cm) apart in a 6"(15cm) deep X 6"(15cm) wide trench. Backfill and compact the trench after stapling.
9. Refer to manufacturer product-specific staple patterns

Source:

"Channel Installation Guide." Erosion Control Installation Details. North American Green. <https://nagreen.com/sites/default/files/2017-05/Channel%20Installation%205-4-17.pdf>

"RECP Staple/Stake Fastening Patterns." Erosion Control Installation Details. North American Green. <https://nagreen.com/sites/default/files/2017-05/DOT%20System%20Guide%205-4-17.pdf>

1.3.10 Riprap Bank Armoring



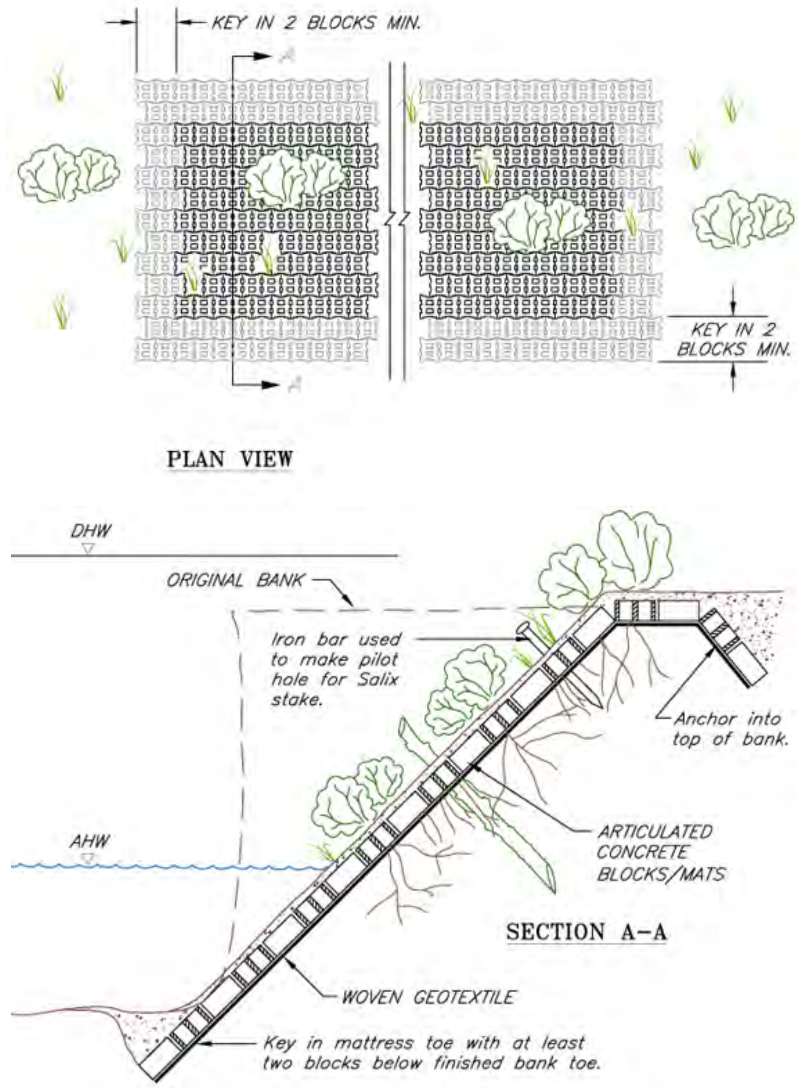
Notes:

1. Areas on which nonwoven geotextile fabric and riprap are to be placed shall be cleared of any brush, trees, stumps, debris, or other unsuitable material and graded as specified by designer.
2. Riprap shall be installed immediately after placing geotextile, being careful not to damage the fabric, using a method that will prevent segregation of stone sizes.
3. Riprap shall be well-distributed and free from pockets of small stones and clusters of large stones. Fill holes or open spots as necessary.
4. Riprap depth shall be measured perpendicular to the existing grade and be at least twice the riprap D_{50}. The riprap shall extent across the stream bed for a distance greater than or equal to the maximum scour depth during the design event.
5. Riprap-protected slopes should not be steeper than 2H:1V.

Source:

Notes and detail prepared by Christopher B. Burke Engineering, LLC, adapted from National Cooperative Highway Research Program Report 568 “Riprap Design Criteria, Recommended Specifications, and Quality Control” Figure C4.9. Accessed August 2018.
<http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_568.pdf>

1.3.11 Articulating Concrete Blocks



Notes:

1. The designer should consider hydraulic lift, drag, and impact when designing ACBs.
2. Select specific type/model of ACBs based on anticipated stream conditions and the results of full-scale product testing.
3. The protected slope must be geotechnically stable prior to placement of surface protection. ACB installations should not be placed on slopes which are steeper than the natural angle of repose of the soil.
4. Grading beneath the block and fabric is critical to establishing an acceptable finished profile of the ACBs.
5. A filter layers is required under the ACBs. The function of the filter is critical, as it must retain the soil in place while letting water pass through without clogging.
6. After the ACB installation is complete, the open cell voids or joints between the ACB units are filled with granular material or soil.
7. If vegetation is required, hydraulic seeding or mulching to establish commonly used grasses and plants. In applications subject to continually flowing water, solid units should be used below the normal waterline or the voids of hollow units should be filled with adequately sized gravel.
8. Installation methods depend on whether the ACB product being used is classified as cabled or as non-cabled.

Source:

"Articulated Concrete Blocks/Mats." Environmentally Sensitive Streambank Stabilization Manual. National Cooperative Highways Research Program Project 24-19 by Salix Applied Earthcare. < http://www.salixaec.com/streambanks.html>

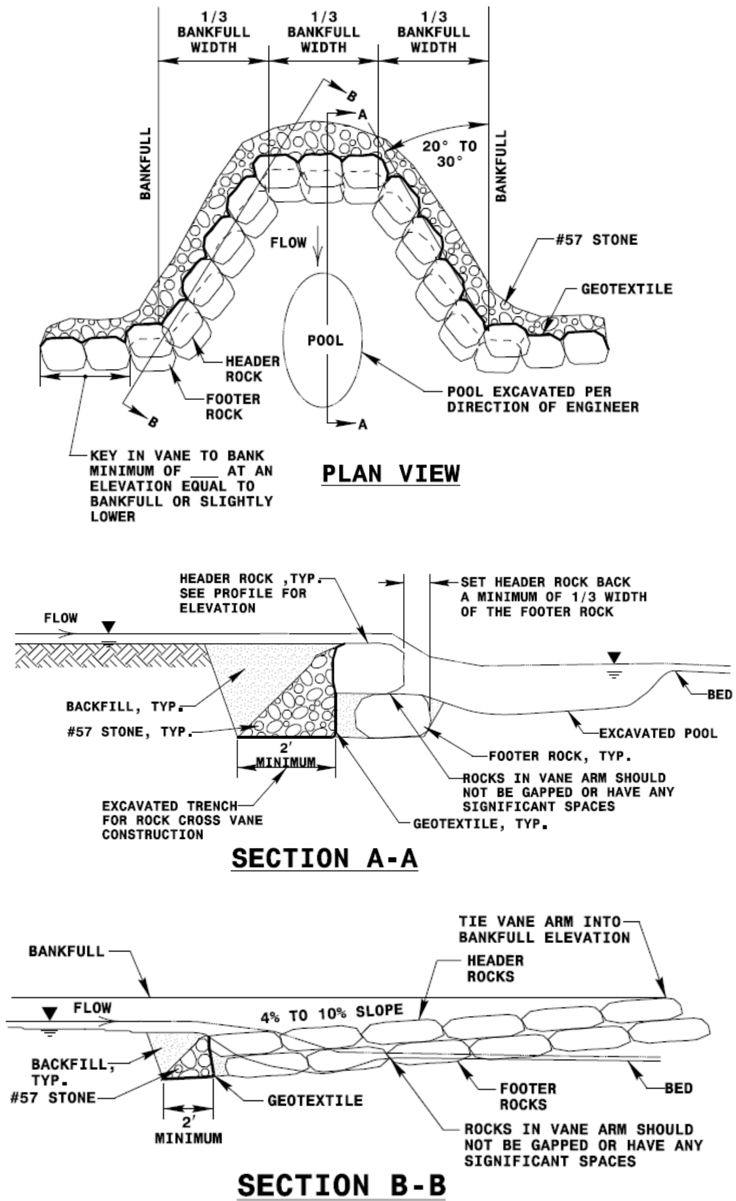
1.4 FLOW REDIRECTION MEASURES

Flow redirection measures involve addressing poorly aligned streams. These treatments direct flow away from the streambank, bridge pier or abutment, or other critical infrastructure in order to reduce erosion. Flow redirection measures are typically used on large streams where armoring is likely infeasible. As such, these measures can be large relative to the size of the stream. Examples of flow redirection measures include, but not limited to, rock cross-vanes, rock vanes, j-hook vanes, and log vanes.

Reference Chapter 4.5.2 for more information regarding flow redirection and Table 4-1 for BMP technical reference information.

APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

1.4.1 Rock Cross-Vanes



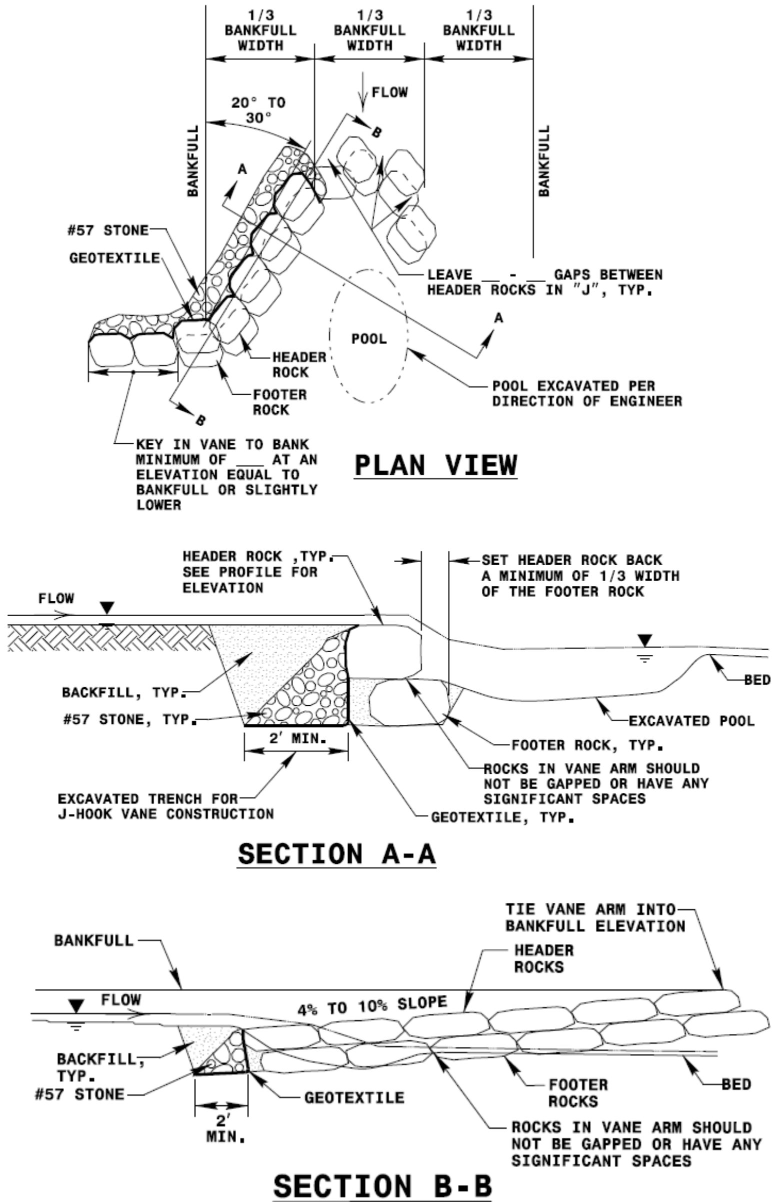
Notes

1. Pool depth should be 2 to 3 times bankfull depth, or as identified by designer from reference reach. Deepest part of pool to be in line with where vane arm ties into bankfull stage. Do not excavate pool too close to footer boulders.
2. Class "A" stone (2" to 6") can be used to reduce voids between headers and footers. #57 stone (¾"to 1 ½") can be used to backfill vane.
3. Compact backfill to extent possible or at the direction of the engineer.
4. Designer to determine vane key in length at the bank based on anticipated scour depth.
5. Header and footer stones should be at least twice the diameter of the smallest non-mobile particle size for the maximum design flow event. Boulder/stone diameter should be evaluated as the geometric mean of the a-, b-, and c-axes. Designer shall size footer stones to allow for practicable, stable stacking of material.
6. When realigning flow with a cross-vane, the structure is not installed perpendicular to the channel banks, but 'pointing' in the desired direction of flow. Excessive departure from a perpendicular alignment should be avoided. If the amount of desired redirection exceeds # degrees, the use of multiple cross-vanes to more gradually turn the flow should be considered.

Source:

"Rock Cross Vane Detail." North Carolina Department of Transportation Environmental Compliance. Accessed August 2018. <https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Rock%20Cross%20Vane.pdf>

1.4.2 J-Hook Vanes



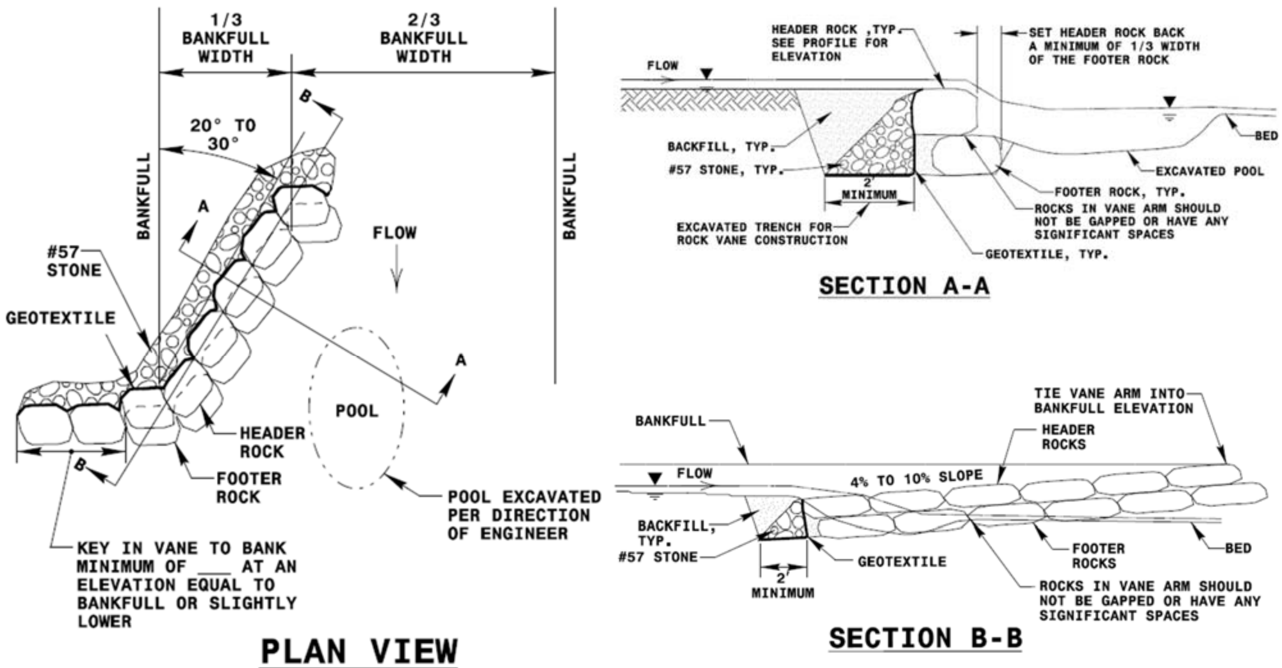
Notes:

1. Pool depth should be 2 to 3 times bankfull depth, or as identified by designer from reference reach. Deepest part of pool to be in line with where vane arm ties into bankfull. Do not excavate pool too close to footer boulders.
2. Class "A" stone (2" to 6") can be used to reduce voids between headers and footers. #57 stone (¾"to 1 ½") can be used to backfill vane.
3. Compact backfill to extent possible or at the direction of the engineer.
4. Designer to determine vane key in length at the bank based on anticipated scour depth.
5. Header and footer stones should be at least twice the diameter of the smallest non-mobile particle size for the maximum design flow event. Boulder/stone diameter should be evaluated as the geometric mean of the a-, b-, and c-axes. Designer shall size footer stones to allow for practicable, stable stacking of material.
6. When realigning flow with a J-hook, the structure is not installed perpendicular to the channel banks, but 'pointing' in the desired direction of flow. Excessive departure from a perpendicular alignment should be avoided. If the amount of desired redirection exceeds # degrees, the use of multiple J-hooks to more gradually turn the flow should be considered.

Source:

"J-Hook Vane Detail." North Carolina Department of Transportation Environmental Compliance. Accessed August 2018. <https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/J-hook%20Vane.pdf>

1.4.3 Rock Vane



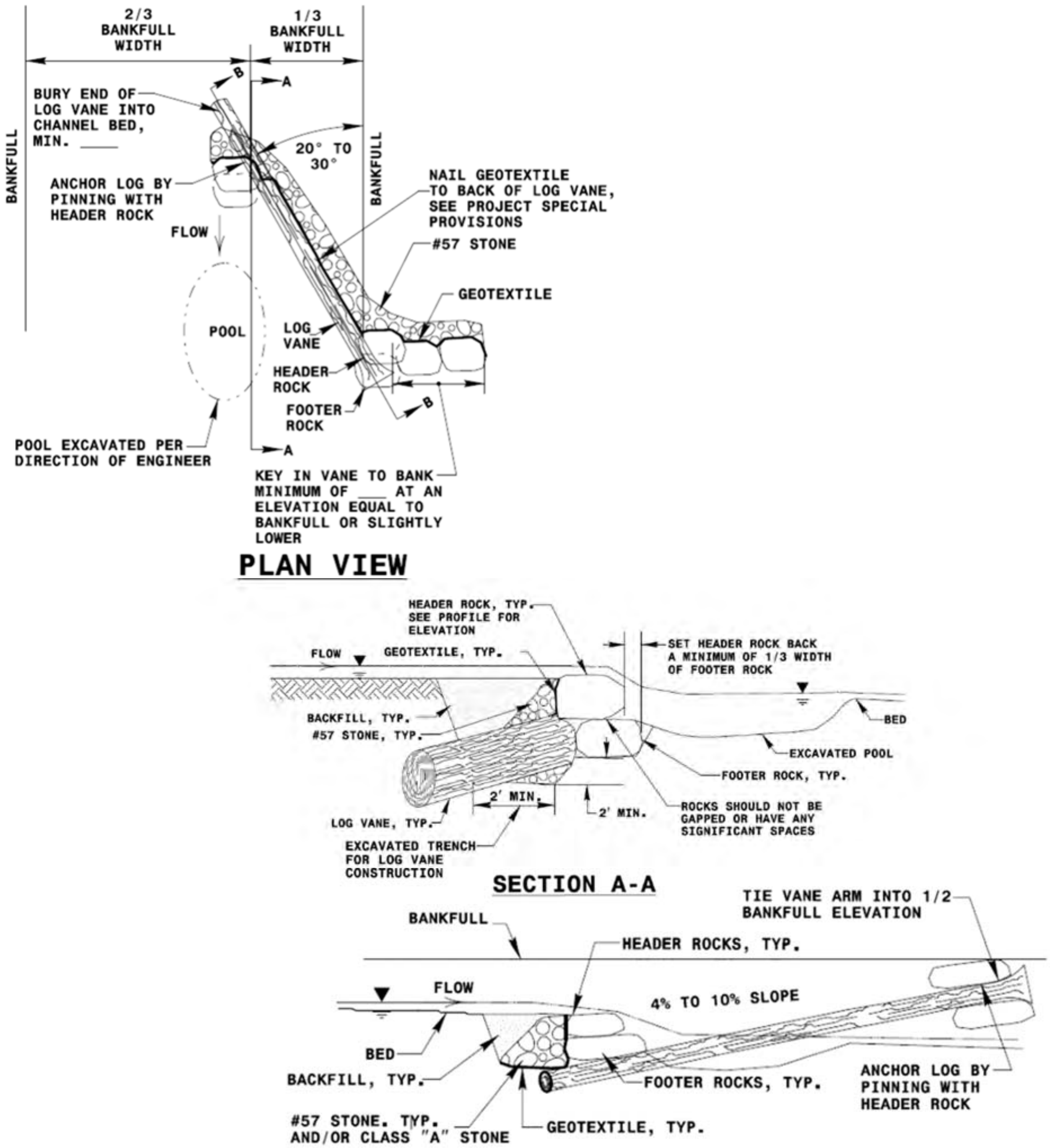
Notes:

1. Pool depth should be 2 to 3 times bankfull depth, or as identified by designer from reference reach. Deepest part of pool to be in line where vane arm ties into bankfull. Do not excavate pool too close to footer boulders.
2. Class “A” stone (2” to 6”) can be used to reduce voids between headers and footers. #57 stone (¾”to 1 ½”) can be used to backfill vane.
3. Compact backfill to extent possible or at the direction of the engineer.
4. Header and footer stones should be at least twice the diameter of the smallest non-mobile particle size for the maximum design flow event. Boulder/stone diameter should be evaluated as the geometric mean of the a-, b-, and c-axes. Designer shall size footer stones to allow for practicable, stable stacking of material.
5. Designer to determine vane key in length at the bank based on anticipated scour depth.

Source:

“Rock Vane Detail.” North Carolina Department of Transportation Environmental Compliance. Accessed August 2018. <https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Rock%20Vane.pdf>

1.4.4 Log Vane



Notes:

1. Pool depth should be 2 to 3 times bankfull depth, or as identified by designer from reference reach. Deepest part of pool to be in line with where vane arm ties into bankfull. Do not excavate pool too close to footer boulders.
2. 2" to 6" stone and /or #57 stone (¾"to 1 ½") can be used to reduce voids between headers and footers.
3. Compact backfill to extent possible or at the direction of the engineer.
4. Header and footer stones should be at least twice the diameter of the smallest non-mobile particle size for the maximum design flow event. Boulder/stone diameter should be evaluated as the geometric mean of the a-, b-, and c-axes. Designer shall size footer stones to allow for practicable, stable stacking of material.
5. Designer to determine log vane embedment depth and vane key in length at the bank based on anticipated scour depth.

Source:

"Log Vane Detail." North Carolina Department of Transportation Environmental Compliance. Accessed August 2018. <https://connect.ncdot.gov/resources/Environmental/Details%20and%20Special%20Provisions/Log%20Vane.pdf>

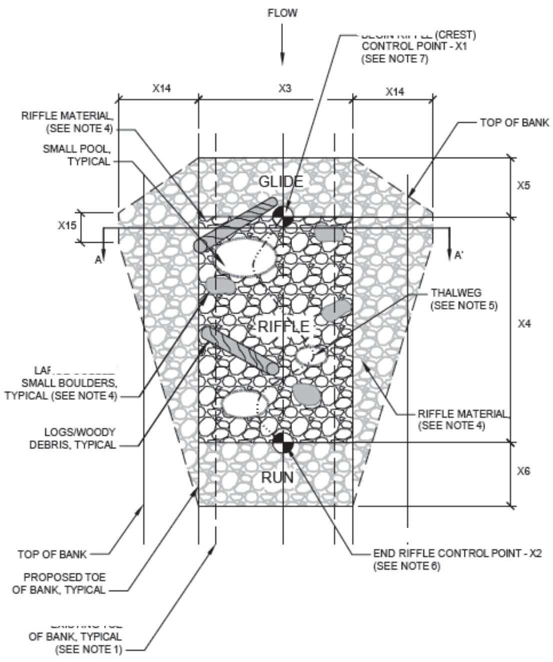
1.5 CHANNEL AUGMENTATION MEASURES

Channel augmentation measures involve adjustments to the channel geometry to promote a more stable condition. Often, these measures result in the advancement of the channel evolution process of the stream, allowing for sediment continuity. Examples of channel augmentation measures include, but are not limited to, bank regrading/shaping, constructed riffle-pool series, lateral cut-off sills, and boulder clusters.

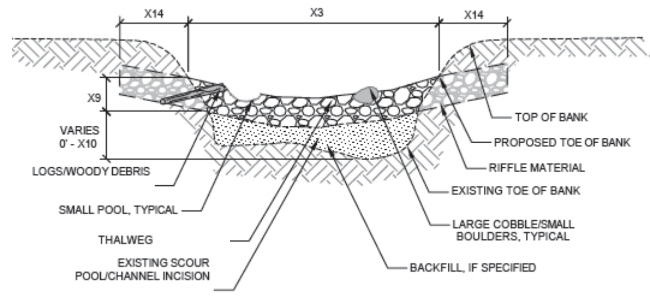
Reference Chapter 4.5.2 for more information regarding channel augmentation and Table 4-1 for BMP technical reference information.

APPENDIX 1: BEST MANAGEMENT PRACTICES– FACT SHEETS

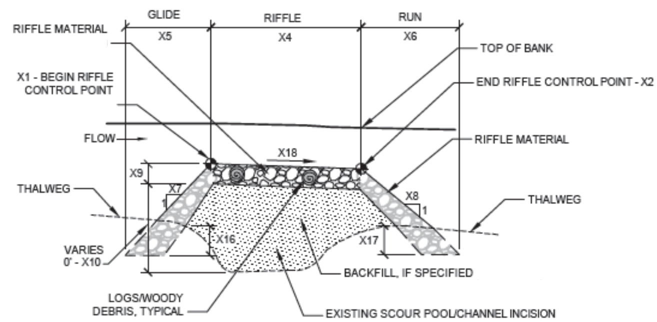
1.5.1 Constructed Riffle-Pool Series



PLAN VIEW



CROSS SECTION A-A'



PROFILE

Notes:

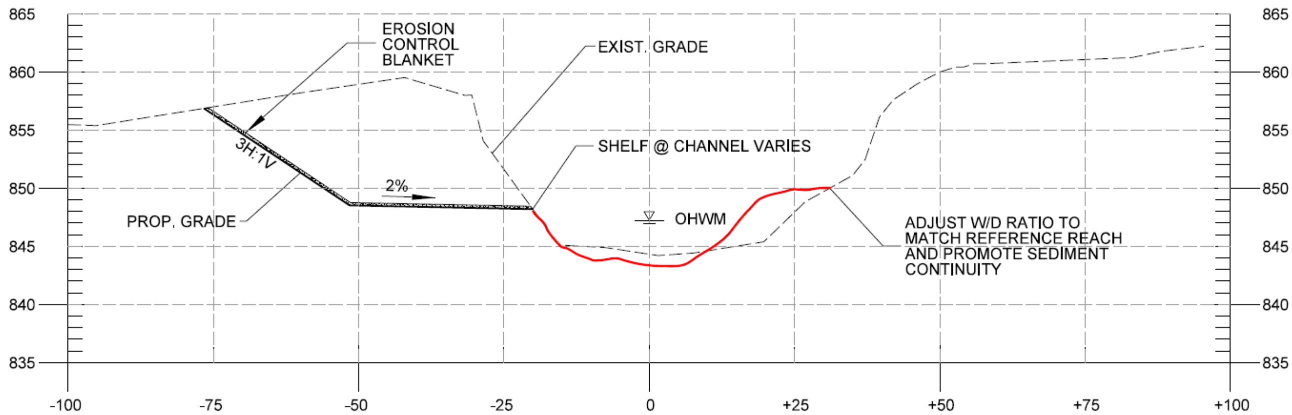
1. Backfill material, if needed to establish a riffle, sub-pavement, and/or to raise the channel bed due to scour/incision, shall be coarse, granular material with type, size, and gradation, if applicable, specified by the designer. Backfill shall be placed such that the addition of the specified thickness of riffle material shall achieve the designated grades.
2. Riffle material shall be comprised of rocks and wood, as appropriate for the stream type. The rock material shall be of a type, size, and gradation as specified by the designer to be mobile or non-mobile as the conditions in the channel warrant (i.e.- clean-water discharge environment, high bedload system, etc.). Rock riffle material may be excavated, stockpiled, and re-used from abandoned channel sections. If riffle material is not harvested from abandoned channel sections, rock riffle material shall be slightly rounded, "river-type" rock, unless other rock characteristics are appropriate for the channel. Logs, woody debris, and boulders shall be included with the rock material as specified by the designer.
3. The placement of backfill and/or riffle material shall be done in a manner to create a smooth profile, with no abrupt 'jump' (transition) between the upstream pool-glide and the riffle, and likewise no abrupt 'drop' (transition) between the riffle and the downstream run-pool. The finished cross section of the riffle material shall generally match the shape and dimensions shown on the riffle typical section with some variability of the thalweg location as a result of the logs and boulders.
4. The constructed riffle shall be keyed in to the streambanks and/or bed as designated by the designer. The 'key' shall extend beyond the toe of bank at the beginning (crest) of the riffle. Where preservation of existing streambank vegetation is a priority, a 'key' may not be used (or the dimensions may be adjusted) to limit disturbance.

DIMENSION (VALUES TO BE PROVIDED BY DESIGNER)		
VARIABLE	TYPICAL UNIT	DESCRIPTION
X1	FT. (NAVD)	BEGIN RIFFLE CONTROL POINT ELEVATION
X2	FT. (NAVD)	END RIFFLE CONTROL POINT ELEVATION
X3	FT.	RIFFLE WIDTH
X4	FT.	RIFFLE LENGTH
X5	FT.	GLIDE (POOL-TO-RIFFLE TRANSITION) LENGTH
X6	FT.	RUN (RIFFLE-TO-POOL TRANSITION) LENGTH
X7	NONE	GLIDE SLOPE RATIO (HORIZONTAL COMPONENT)
X8	NONE	RUN SLOPE RATIO (HORIZONTAL COMPONENT)
X9	IN. OR FT.	RIFFLE MATERIAL THICKNESS (DEPTH)
X10	IN. OR FT.	BACKFILL OR SUBPAVEMENT THICKNESS (DEPTH), IF SPECIFIED
X11	IN.	D50 OF ROCK RIFFLE MATERIAL
X12	IN. OR FT.	BOULDER RIFFLE MATERIAL DIAMETER
X13	IN.	LOG RIFFLE MATERIAL DIAMETER
X14	FT.	RIFFLE KEY WIDTH
X15	FT.	RIFFLE KEY LENGTH
X16	IN. OR FT.	GLIDE KEY DEPTH
X17	IN. OR FT.	RUN KEY DEPTH
X18	% OR FT. PER FT.	RIFFLE SLOPE

Source:

"Variable Constructed Riffle." City of Charlotte Engineering & Property Management. Accessed August 2018. <http://charlottenc.gov/Engineering/Bids/Special%20Provisions/Generic%20Details/Water%20Quality/02-In-Stream%20Structures/03-Variable%20Constructed%20Riffle/03-VARIABLE%20CONSTRUCTED%20RIFFLE-PDF.pdf>

1.5.2 Bank Regrading/Shaping



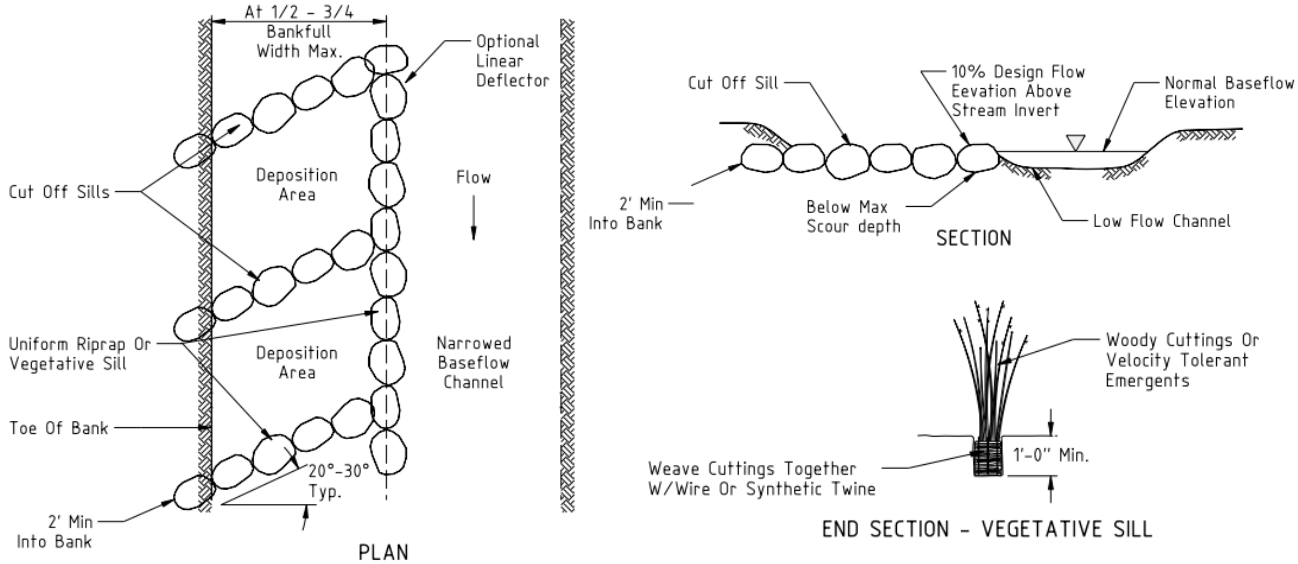
Notes:

1. Adjustments to the bankfull channel geometry to be established by the designer based on dimensionless ratios from a stable reference reach.
2. When bankfull channel adjustments are not necessary, disturbance within the existing channel should be minimized in order to limit impacts to environmentally sensitive areas.
3. Incised channels should have a bankfull shelf excavated, where possible. The proposed slope from the bankfull shelf to the top of the existing bank shall be evaluated by performing a slope stability analysis of the project area. The width of the bankfull shelf should be established based on available area, flow velocity reduction needs during flooding conditions, and flood risk reduction objectives.
4. Newly established bank slopes shall be seeded and blanketed as identified by the designer to promote quick establishment of vegetation and reduce the risk for erosion.
5. Additional armor in the channel and at the toe of slope may be warranted to prevent scour, particularly when no bankfull channel revisions are made.
6. The limits of bank regrading/shaping shall extend upstream and downstream, as identified by the designer, to points on the existing bank that provide a smooth transition for the flow between unimproved and improved banks.
7. The designer should attempt incorporate improvements to existing habitat to offset the impacts of the bank regrading/shaping.

Source:

Notes and detail prepared by Christopher B. Burke Engineering, LLC

1.5.3 Cut-off Sills



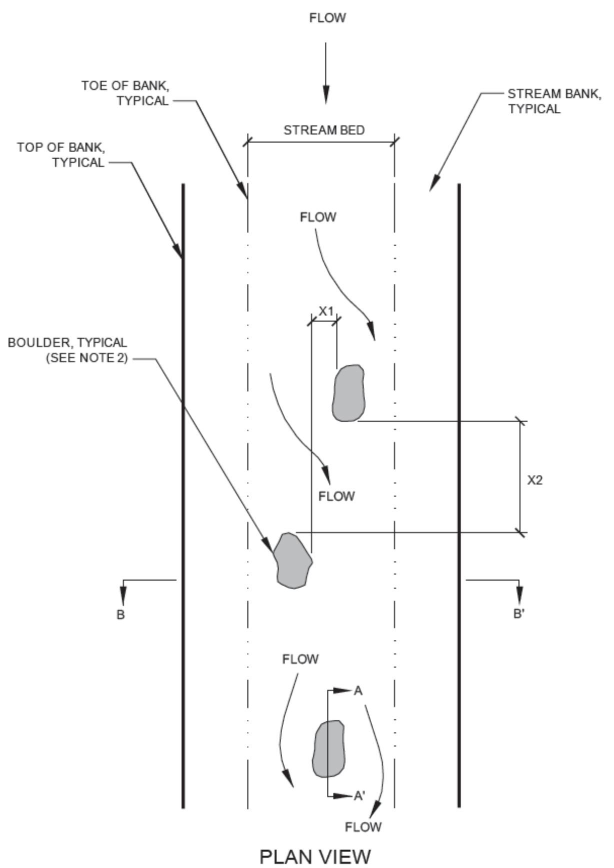
Notes:

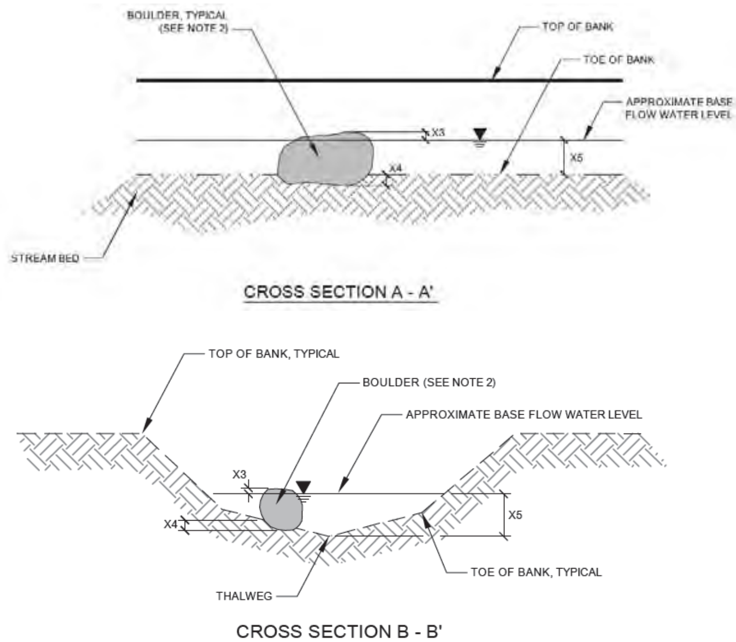
1. Cut-off sills should only be used in relatively small channels. See rock vanes for larger streams.
2. The designer should complete a scour depth analysis and ensure that all sill rocks are placed at a depth below the design scour depth.
3. No more than 6 inches of the sill should be above the normal baseflow level.
4. The terminal end of the sill should not extend into the channel further than 1/2 to 3/4 of the bankfull channel width.
5. Sills should be placed at a downstream angle that does not exceed 20 to 30 degrees with the streambank. The greater the flow velocity, the smaller the angle of deflection.
6. Extend the sill a minimum of 2 foot into the streambank.
7. Require an inspection of the rock material before it is placed. Rock size and shape requirements are specific. Inappropriate material must be removed or structural failure may occur.
8. Reinforce the bank opposite of a cut-off sill as necessary to avoid scour and erosion from the newly concentrated flow and to ensure bank stability.

Source:

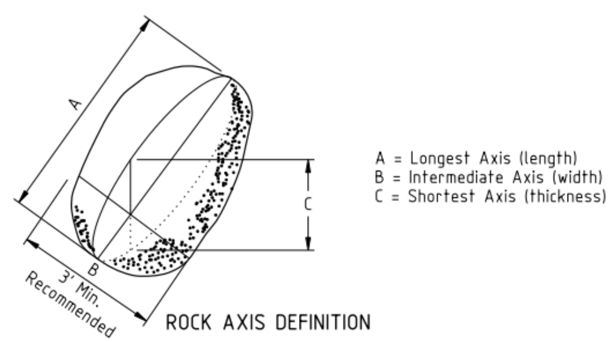
"Cut Off Sills." The Virginia Stream Restoration & Stabilization Best Management Practice Guide. Department of Conservation and Recreation Division of Soil and Water Conservation. Accessed August 2018. <https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/BMPGuide.pdf>

1.5.4 Boulder Clusters





DIMENSION (VALUES TO BE PROVIDED BY DESIGNER)		
VARIABLE	TYPICAL UNIT	DESCRIPTION
X1	IN. OR FT.	MINIMUM LATERAL DISTANCE BETWEEN BOULDERS
X2	IN. OR FT.	MINIMUM LONGITUDINAL DISTANCE BETWEEN BOULDERS
X3	IN. OR FT.	HEIGHT OF EXPOSED BOULDER SURFACE ABOVE/BELOW BASEFLOW
X4	IN. OR FT.	MINIMUM DEPTH OF BOULDER EMBEDMENT
X5	IN. OR FT.	APPROXIMATE DEPTH OF BASEFLOW
X6	IN. OR FT.	BOULDER LENGTH
X7	IN. OR FT.	BOULDER WIDTH
X8	IN. OR FT.	BOULDER THICKNESS



Notes:

1. Boulder cluster(s) shall be installed in glide/riffle (straight) channel sections only, with the tops of the boulders set very near or below the normal (base flow) water surface.
2. Boulder cluster(s) shall be constructed with boulders with A-, B-, and C-axis dimensions (length, width, and depth [thickness]) as specified by the designer.
3. Placement dimensions of the boulders relate to the boulder dimensions. The designer shall specify all dimensions in the detail:
   a. The placement of adjacent boulders shall not block the straight, downstream flow vectors in the channel. Thus, the minimum lateral distance between the boulders shall be at least one-half of the measurement of the laterally-placed axis of the boulder.
   b. Boulders shall be spaced about 1/3 of the bankfull channel width apart and no more than twice the maximum axis measurement of the boulders apart.
   c. The boulders shall be embedded into the stream bottom a minimum depth equaling one-third of the boulder thickness.
4. No more than 3 inches of the boulder should be exposed above baseflow. If the boulder cluster is installed in dry conditions, adjustments to the boulder protrusion above the base flow water surface may be required once flow resumes.

Source:

"Boulder Cluster." City of Charlotte Engineering & Property Management. Accessed August 2018. <http://charlottenc.gov/Engineering/Bids/Special%20Provisions/Generic%20Details/Water%20Quality/02-In-Stream%20Structures/02-Boulder%20Cluster%20Turbulent%20Riffle/02-BOULDER%20CLUSTER%20TURBULENT%20RIFFLE-PDF.pdf>

APPENDIX 2 FEH MITIGATION CASE STUDIES

BEAN CREEK – DESIGN OF A THRESHOLD CHANNEL REACH

Bean Creek – April 2016

Located in Garfield Park near the City of Indianapolis' south side, a portion of Bean Creek has experienced observable erosion since 2000. In 2014, a large storm event caused catastrophic erosion that undermined a 48" diameter sanitary sewer interceptor pipe which crosses the stream. Severe bank erosion adjacent to the pipe also resulted from this event. The sanitary sewer utility responded immediately following the event, temporarily protecting the pipe while a designed solution could be provided.

The design objective was to stabilize the stream, thus protecting the critical infrastructure, while enhancing the natural environment. As a result of the complex flow situation near the sanitary sewer interceptor, a 2-dimension flow model was developed. This model accounted for the project reach being just upstream of the confluence of Bean Creek and Pleasant Run and the sanitary sewer interceptor's skewed crossing. The results from the model were used to guide the selection and design of mitigation measures, which focused on creating a threshold channel section at the pipe crossing while maintaining or improving flow capacity and sediment continuity. As such, a combination of streambank stabilization techniques was used to address the project objectives.

The design objective was to stabilize the stream, thus protecting the critical infrastructure, while enhancing the natural environment

- **Grade Control -** A Newbury Riffle was constructed to protect the sanitary sewer from future undermining while allowing for fish passage, even in low-flow conditions. The orientation of the Newbury Riffle was also designed to improve the alignment of the flow.
- **Toe Protection -** A riprap toe was utilized to prevent failure of bank improvements due to scour.
- **Bank Armoring -** A high-performance turf reinforcement mat, live stakes, and soil lifts were used to armor the channel banks.
- **Channel Augmentation -** The bank angle on both sides of the channel was reduced to improve geotechnical stability and increase the flow area of the channel. A high-flow shelf was excavated on the north (right) side of the channel to increase flow capacity and to correct poor flow alignment

The design for these stabilization measures was completed in May 2016. A contractor was selected, and the work was completed in March 2017.

Bean Creek – May 2017

APPENDIX 2: FEH MITIGATION CASE STUDIES

SUGAR CREEK – A HIGH BANK SCENARIO

Slope retreat over the past 20 years has resulted in the closing of a portion of Wayne Avenue and the loss of several homes adjacent to Sugar Creek in Crawfordsville, Indiana. Based on the United States Geological Survey (USGS) publication *Channel Migration Rates of Selected Streams in Indiana*, Sugar Creek was identified as an actively migrating stream with a 75th percentile channel-migration rate of 6.4 feet/year. Considering this rate of migration with the high bank on which Wayne Avenue sits, it is evident this location has and will continue to experience a high erosion potential.

Sugar Creek – April 2017

The City of Crawfordsville recognized the existing instability and sought to determine its primary cause and the feasibility of stabilizing the slope. Initial desk-top analyses of aerial imagery and LiDAR topography suggested that while the top of bank was retreating, the toe of slope has remained stationary for some time. Field observations of nearby apparent stable banks revealed vegetated slopes with a lower angle of repose. As such, the slope near Wayne Avenue is expected to continue adjusting [reducing the bank angle] unless corrective measures are implemented to stabilize the slope.

Conceptual FEH mitigation measures, such as reducing the bank slope and/or reinforcing the slope were considered; however, these solutions currently prove to be cost-prohibitive and impracticable due to the embankment height. Thus, current and planned mitigation activities will include ongoing monitoring of the slope condition and relocation/removal of at risk infrastructure and homes. The City continues to monitor the Wayne Avenue area and is now investigating other areas along Sugar Creek that may present the same problem.

Sugar Creek – April 2017

Considering this rate of migration with the high bank on which Wayne Avenue sits, it is evident this location has and will continue to experience a high erosion potential… conceptual FEH mitigation measures were considered; however, these solutions currently prove to be cost-prohibitive and impracticable due to the embankment height. Property acquisition and the removal of structures were recommended to reduce the risk posed by the FEH.

APPENDIX 2: FEH MITIGATION CASE STUDIES

YELLOW RIVER – SYSTEM ASSESSMENT

The Yellow River is a major tributary to the Kankakee River and once part of the Grand Kankakee Marsh, a 500,000-acre marsh complex considered the second largest wetland in the conterminous United States. The Everglades is the only larger wetland area. With a contributing watershed that encompasses 435 square-miles, spanning 6 counties, the Yellow River watershed has a long history of channelization and has been identified as the primary source of sediment into the Kankakee River. Due to concerns from downstream counties as well as the State of Illinois, Starke County and the Kankakee River Basin Commission (KRBC) decided to investigate the true source of the sediment and how to reduce the sediment load passing downstream into the Kankakee River.

… the Yellow River watershed has a long history of channelization and has been identified as the primary source of sediment into the Kankakee River.

In 2014, an assessment was carried out to identify sediment sources and reduce erosion and sediment input into the Yellow River. Field assessments were conducted from the Yellow River headwaters in St. Joseph County to its confluence with the Kankakee River in Starke County. Field assessment observations were then compared to data from the United States Geological Survey (USGS) stream gages with continuous suspended sediment monitors. The findings of the system assessment revealed that one of the primary sources of sediment was from the channel banks throughout a 12-mile reach of the stream, not the Marshall County portion of the watershed, as was previously assumed. These findings resulted in a series of recommended mitigation measures for distinct parts of the Yellow River watershed. Colors referred to for the stream reaches correspond with the map below. In the upstream portion of the watershed (blue) soil health practices are recommended to reduce the movement of sediment from the agricultural field into the stream. In the historically stable portion of the Yellow River downstream from Plymouth (green) the workplan recommends monitoring to ensure that the stable portion of the river remains stable. In the eastern part of Starke County (red) the highly unstable banks need stabilization and floodplain reattachment using toe wood and channel augmentation. In the aggrading downstream portion of the river the plan recommended modifying the channelized stream to a more stable width [narrower] and depth dimensions (purple).

Yellow River System Assessment Channel Morphologic Zones – August 2015

APPENDIX 2: FEH MITIGATION CASE STUDIES

YELLOW RIVER – IMPLEMENTING MITIGATION MEASURES

Building upon the system assessment completed in 2015, a reach of the Yellow River through Starke County was targeted for implementation of mitigation measures. Located approximately 1,000 feet upstream of the State Road 23 bridge, the project site consisted of approximately 1,800 feet of streambank stabilization. The measures implemented accounted for fine-grained, cohesionless soils and addressed channel alignment, incision, and a disconnected floodplain. The following design considerations were applied:

Yellow River Pre-Construction – October 2016

Channel Alignment & Augmentation

- Increased radius of curvature
- Continuous bench at bankfull stage
- Bench placed on inside of meander bend
- Reduced bank angle above bench

Scour Protection/Flow Redirection

- Stabilized bottom of slope with toe wood
- Redirected flow at outside meander bend
- Included live stakes/poles to increase low bank roughness and resistance to erosion

Yellow River During Construction – October 2017

Ultimately, a combination of stabilization techniques was designed for the project area including a cross-vane, j-hook, toe wood, and benching. The design was completed in July 2017 with construction being completed in March 2018. The project allowed the channel to maintain a mobile bed while constraining bank erosion to the point bars on the inside of the meander bends. The revision of the bankfull channel dimensions helped to promote more effective sediment transport. The reduction of bank erosion and increased effectiveness of bed transport processed is anticipated to improve sediment continuity through the reach.

Yellow River Post-Construction – August 2018
(Left: toe wood and laid-back slopes; Right: Cross-vane)

APPENDIX 2: FEH MITIGATION CASE STUDIES

BIG WALNUT CREEK – FEH MITIGATION STUDY

Big Walnut Creek is a major tributary to the Eel River with a contributing drainage area of 326 square-miles. Channel instability and migration has historically been an issue with Big Walnut Creek from the confluence with the Eel River in Clay County, extending upstream through Putnam County. The issues are particularly troublesome near a wellfield just south of Highway 40 near Brazil, Indiana. A FEH mitigation study was completed to evaluate the channel and watershed characteristics, analyze the physical processes at work, identify the stressors leading to the instabilities, and to determine what, if any, mitigation measures are warranted for the wellfield area.

Big Walnut Creek Flood Condition - May 2017

Nearly 60% of the bed material is expected to be mobilized during events as frequent as the 1-year event…

The FEH mitigation study included three phases of investigation to determine the root causes of the instability: site assessment, watershed-scale assessment, and reach-scale assessment. The assessments determined five major factors that have led to the current channel instability and migration issues:

- **Highly mobile channel material –** Nearly 60% of the bed material is expected to be mobilized during events as frequent as the 1-year event, which prevents stability-improving vegetation from establishing.
- **Local hydrology –** An overflow path in the northern overbank area allows erosive flows to pass through the wellfield and causes the flow to be poorly aligned at the FEH location.
- **Sediment 'sinks' –** A gravel pit has been captured downstream of the assessment reach. Channel incision and further destabilization is anticipated if no remedial actions are taken.
- **Channel incision and inadequate floodplain –** The channel is incised and has poor connection to the geomorphic floodplain. The confinement of the flow prevents dissipation of erosive energy during events greater than or equal to the bankfull flow.
- **Increased flow rates and flow volume –** A dramatic increase in the volume of runoff and the peak annual flow rate has occurred over the last 40 years. The increases are thought to be the result of increased agricultural drainage and climate change.

Big Walnut Creek Post Flood Condition
May 2017

Improvements at the FEH location were not immediately necessary since the observed bank migration rate was relatively low and a modest distance separated the stream and nearest wellhead. A monitoring program was recommended to evaluate the bank migration and level of instability in Big Walnut Creek near the gravel pit. Short-term strategies for mitigating the FEH at the wellfield included toe protection, reducing the bank slope, and improving the erosion resistance in the overflow path. Long-term solutions were complicated by the captured gravel pit downstream from the site and required additional evaluation.

APPENDIX 2: FEH MITIGATION CASE STUDIES

WHITE LICK CREEK – FEH MITIGATION STUDY

A FEH mitigation study of White Lick Creek was completed to identify the root causes of the erosion observed near Old State Road 267 and evaluate the ability to mitigate the FEH. White Lick Creek, a major tributary to the West Fork White River, has a contributing watershed of 291 square miles at the FEH site and includes the western portion of the Indianapolis Metropolitan Area (Brownsburg, Avon, Plainfield, Danville, and Pittsboro). The mitigation study characterized the stability of the stream, identified existing stressors that led to the instability present, and evaluated proposed improvements.

White Lick Creek – May 2017

The FEH mitigation study made extensive use of previous studies, most notably a system assessment completed in 2015. An additional site assessment was completed to compliment the watershed-scale and reach-scale assessments from the previous study. The following four major factors were determined to be the most responsible for the current channel instability and migration issues: highly mobile channel material, sediment ‘sinks’, channel incision and inadequate floodplain storage, and increased flow rates and flow volume.

White Lick Creek – May 2017

The results of the FEH mitigation study suggested that the system-wide issues have been present historically, were worsened by urban development and climate change, and are likely to persist regardless of the potential site-specific correction of a problem. However, Old State Road 267 serves as critical infrastructure to Plainfield and was recommended to be protected against damage from fluvial erosion. Monitoring the channel conditions at the FEH site and near the downstream gravel pits was noted as a critical component to mitigating future instability.

Passive and active management strategies were considered as part of the assessment. Applicable passive measures included more conservative and environmentally friendly urban watershed management practices that could reverse the impact of past development activities. Toe wood was recommended as a proven mitigation technique to reinforce the toe, adjust the bankfull dimensions of the channel, and create floodplain benches.

The results of the FEH mitigation study suggested that the system-wide issues have been present historically, were worsened by urban development and climate change, and are likely to persist regardless of the potential site-specific correction of a problem.

APPENDIX 2: FEH MITIGATION CASE STUDIES

EAGLE CREEK – FEH MITIGATION STUDY

Eagle Creek Dam Spillway – June 2018

A system assessment was completed to evaluate options for reducing the risk of ongoing slope failure along the existing levee system downstream of Eagle Creek Reservoir in Indianapolis, IN. The headwaters of Eagle Creek are located in the northwest portion of Hamilton County and flow generally south through Boone and Marion Counties to its confluence with the White River on the west side of Indianapolis. Upstream of the reservoir, the Eagle Creek corridor is primarily agricultural, transitioning to urban as it approaches the Marion County border. The assessment reach was located downstream of the reservoir, where much of Eagle Creek is leveed.

The original purpose of the assessment was to determine the existing charateristics of the channel and watershed, identify the root causes of the existing instabilities, and determine what, if any, mitigation strategies are warranted and applicable. The scope of the assessment was curtailed due to the artificial hydrologic regime and sediment barrier imposed by the Eagle Creek Dam. Previous stuides were reviewed and analysis of available data was completed to determine the severity of the systemic issues. The most significant factors affecting the stability of the channel through the assessment reach are as follows:

> Passive mitigation measures are typically best for addressing the type of systemic issues present in Eagle Creek; however, the dam heavily dampens the inputs from the watershed, which negates positive changes in the watershed.

- Artificial hydrology and sediment barrier caused by Eagle Creek Dam
- Channel incision and inadequate floodplain

FEH Site along Eagle Creek – September 2018

A combination of FEH mitigation measures will be necessary to maintain the integrity of the levee system, a critical flood control structure for the City of Indianapolis. Recommended improvements along the channel banks include reinforcing the toe and adjustment of the upper bank to create a more stable slope. Passive mitigation measures are typically best for addressing the type of systemic issues present in Eagle Creek; however, the dam heavily dampens the inputs from the watershed, which will negate potential positive changes in the watershed.

Once the improvements have been constructed, the condition of the reconstructed bank at the site should be monitored on an annual basis, and/or after significant flooding events addressing damaged banks or migrating stream as soon as possible.