VERMONT STANDARD RIVER MANAGEMENT PRINCIPLES AND PRACTICES:
Guidance for Managing Vermont's Rivers Based on Channel and Floodplain Function

(Edition 1.3)

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1.0 INTRODUCTION

- *Why is this document needed?*
- *Who should use the Standard Principles and Practices and when?*
- *How is this document organized for use by people with different levels of experience?*

1.1 Goals

The goals of this document are to:

- Support more effective flood recovery implementation;
- Improve the practice of river management; and
- Codify best river management practices in Vermont (Figure 1.1).

The following pages define practices and decision-making processes to assist state and federal agencies, municipalities, nonprofit organizations, and landowners with river management techniques that reduce future flood and erosion risks. This document is needed to break the cycle of flood recovery activities that leave post-flood river channels located near public infrastructure and private property more impacted and more vulnerable to damages from future flooding.

Codify Best Practices

Statewide hazard reduction and consistency for state and federal permitting and project support.

Improve River Management

Establish a consistent set of principles and practices based on the most current science and engineering for reduction of flood and erosion risk in Vermont over the long term.

Support Flood Recovery Implementation

Create guidance to assist the state and its municipalities with assessing and implementing flood recovery when a widespread flood takes place. Approaches will guide reconstruction or repair of public infrastructure and private property that reduces vulnerability to future flood and erosion hazards; recognize and accommodate the dynamics of rivers; meet regulatory requirements; and enhance eligibility for public funding.

Figure 1.1: Purpose of the principles and practices.

The methods presented below include the best principles and practices to maximize public safety and infrastructure protection while minimizing habitat impacts, maintaining water quality, mitigating future hazards, and controlling the cost of flood recovery activities. At the same time, the actions described here can meet the thresholds of State Performance Standards for stream alteration (VTANR, 2014). During flood recovery, emergency actions may not meet Performance Standards, but work in the channel must be conducted to meet them to the maximum extent possible. Flood recovery activities that protect public safety at one location may cause greater hazard at another location if not conducted appropriately.

This document compiles the most current river management practices based on the best available science and engineering methods to create consistent practice and language for risk reduction while maintaining river and floodplain function. Clarity is needed around effective river management methods during flood recovery, both during the chaos following large damaging events and in the calm of nonemergency river management activities at chronic problem locations where people and rivers come together. Common flood damages that require intervention that are addressed in this document include:

- Erosion of banks adjacent to houses and infrastructure;
- Erosion of road embankments;
- Channel movement across the river corridor;
- Riverbed downcutting that destabilizes banks, undermines structure foundations, exposes utility crossings, and vertically disconnects rivers from adjacent floodplains;
- Riverbed sediment buildup that can increase flood depths, initiate channel movement and avulsion, and lead to bank erosion;
- Riverbed filling with large woody debris that can increase flood depths, initiate channel movement and avulsion, and lead to bank erosion; and
- Bridge and culvert failure.

1.2 Document Organization

This document has been organized to allow users with different river management needs to access the material efficiently. The primary sections of the document include (Figure 1.2):

- Guiding Design Principles that include Principal River and Floodplain Functions and Design Objectives;
- Site Screening and Primary Problem Identification (Tier 1);
- Alternatives Analysis (Tier 2);
- River Management Standard Practices (Tier 3); and
- Essential Supporting Information (Tier 4).

Guiding Design Principles are provided for:

- Lateral channel stabilization;
- Vertical channel stabilization;
- Channel conveyance; and
- Stream crossings.

Each Guiding Design Principle contains **Design Objectives**[1] and **Design Considerations** to implement river management practices to reduce flood and erosion risks over the long term. The guidance is based on achieving **Principal River and Floodplain Functions** that define the scientific theory behind the practices and are the basis for the Performance Standards in the State of Vermont Stream Alteration Rules (2013)[2]. More than one Guiding Design Principle typically applies to a single practice or a related group of practices. An experienced user may primarily rely on the Guiding Design Principles to meet Rules (2013).

Site Screening and Primary Problem Identification in the *Tier 1* guidance is provided to move from observation of flood damages, such as road embankment erosion or culvert failure, to an understanding of the dominant channel processes that lead to damages. Understanding the changes that take place in the river channel is essential for selecting the proper corrective action.

The **Alternatives Analysis** that makes up *Tier 2* is important to identify the range of alternatives that will improve safety and protect property while meeting Design Objectives. Many emergency flood recovery actions that alleviate immediate hazards in the short term often result in increased risks to public safety and infrastructure and ecosystem impacts over the long term in the absence of an alternatives analysis. In most cases, a brief alternatives analysis will prevent this situation and may reduce overall recovery costs. Flow charts for the following six groups of river management practices have been created to support selection of the appropriate standard practices.

- Bank stabilization
- Bed stabilization
- Increase channel conveyance
- Channel realignment
- Floodplain restoration

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[1] The Design Principles for the bridge and culvert practices have specific Design Requirements in place of Design Objectives because the state has adopted numeric requirements for meeting the Equilibrium and Connectivity Performance Standards and obtaining an authorization for new and replacement crossing structures under the Vermont Stream Alteration General Permit.

[2] The two principal functions are Equilibrium and Connectivity, which have been set as the Performance Standards in Vermont's Rules to meet the statutory requirements for stream alterations.

- Increase hydraulic roughness

Standard Practices for Flood Recovery and River Management are detailed in *Tier 3*. Practice sheets have been created to help guide design of the preferred alternative(s), including conceptual design examples in a post-flood setting. A subset of practices has been selected for presentation to create design support tools for recommended practices that have been used in the state following recent floods and to meet the Design Objectives. Novel design methods for practices that reduce future flood risks are presented such as floodplain restoration. For previously well-documented practices, reference is made to existing design information to support implementation. The practices detailed in this guidance include:

- Placed riprap wall;
- Natural bed stabilization;
  - Install native channel sediment to elevate bed
- Grade control;
  - Weirs
  - Stone riffles
  - Stone strainers
  - Bed armoring
- Bench and flood chute restoration;
- Floodplain restoration;
- Remove sediment and woody debris filling channel/floodplain; and
  - Vertical stability
  - Channel realignment
  - Proactive sediment management plan
- Bridge/culvert replacement.
  - The geomorphic-engineering approach

Essential Supporting Information for design and implementation of the practices is contained in *Tier 4*. The information includes frequently referred to charts, figures, and equations for quick reference in technical appendices. The supporting information is located under separate cover as a companion to this document.

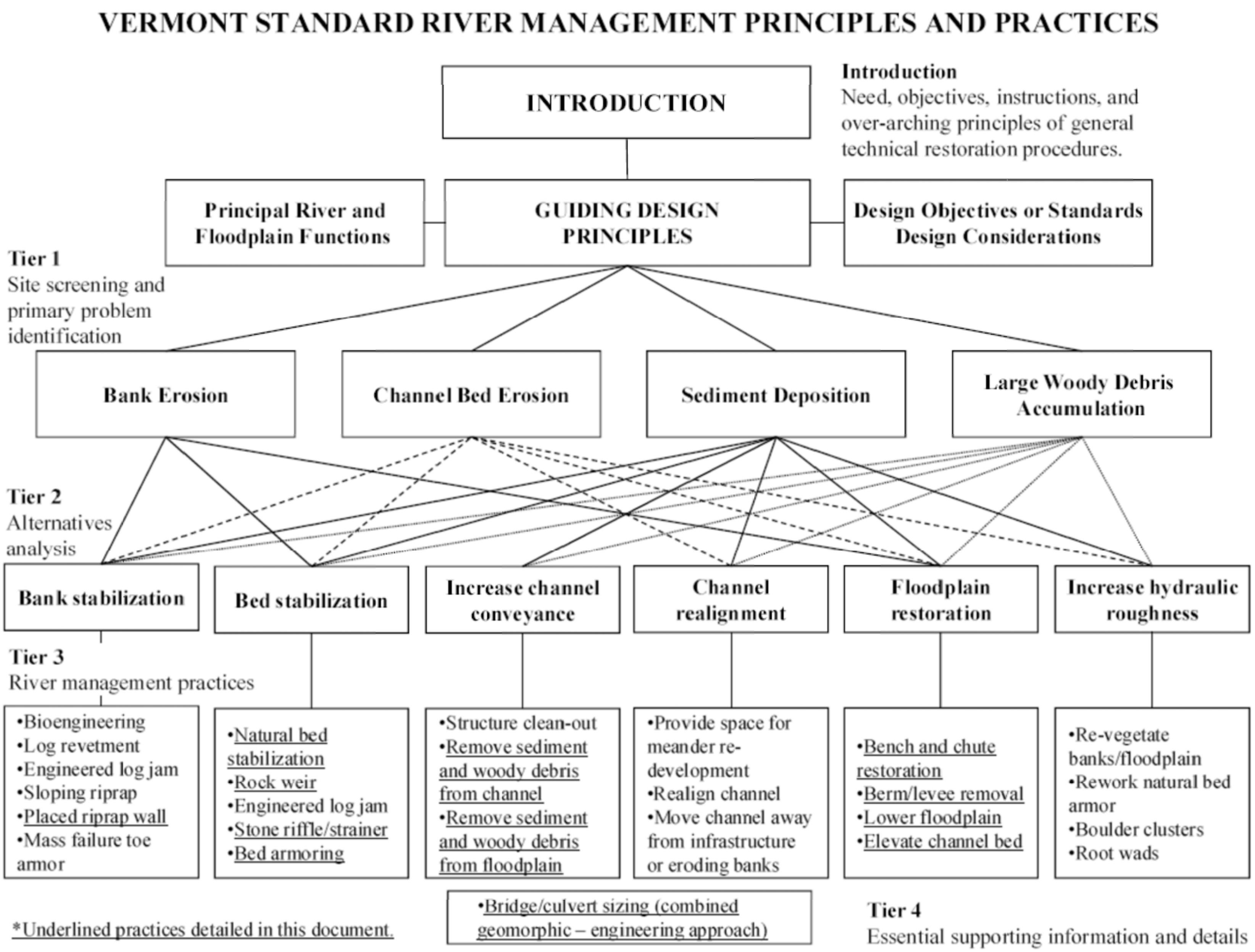


Figure 1.2: Document road map.

2.0 GUIDING DESIGN PRINCIPLES

- *What are the Design Objectives and Considerations for recommended channel management practices to guide alternatives analyses and design?*
- *What is the theory driving the use of the practices in this guidance and the basis of the State of Vermont Stream Alteration Rules (2013)?*

2.1 Introduction

Guiding Design Principles are provided for:

- Lateral channel stabilization;
- Vertical channel stabilization;
- Channel conveyance; and
- Stream crossings.

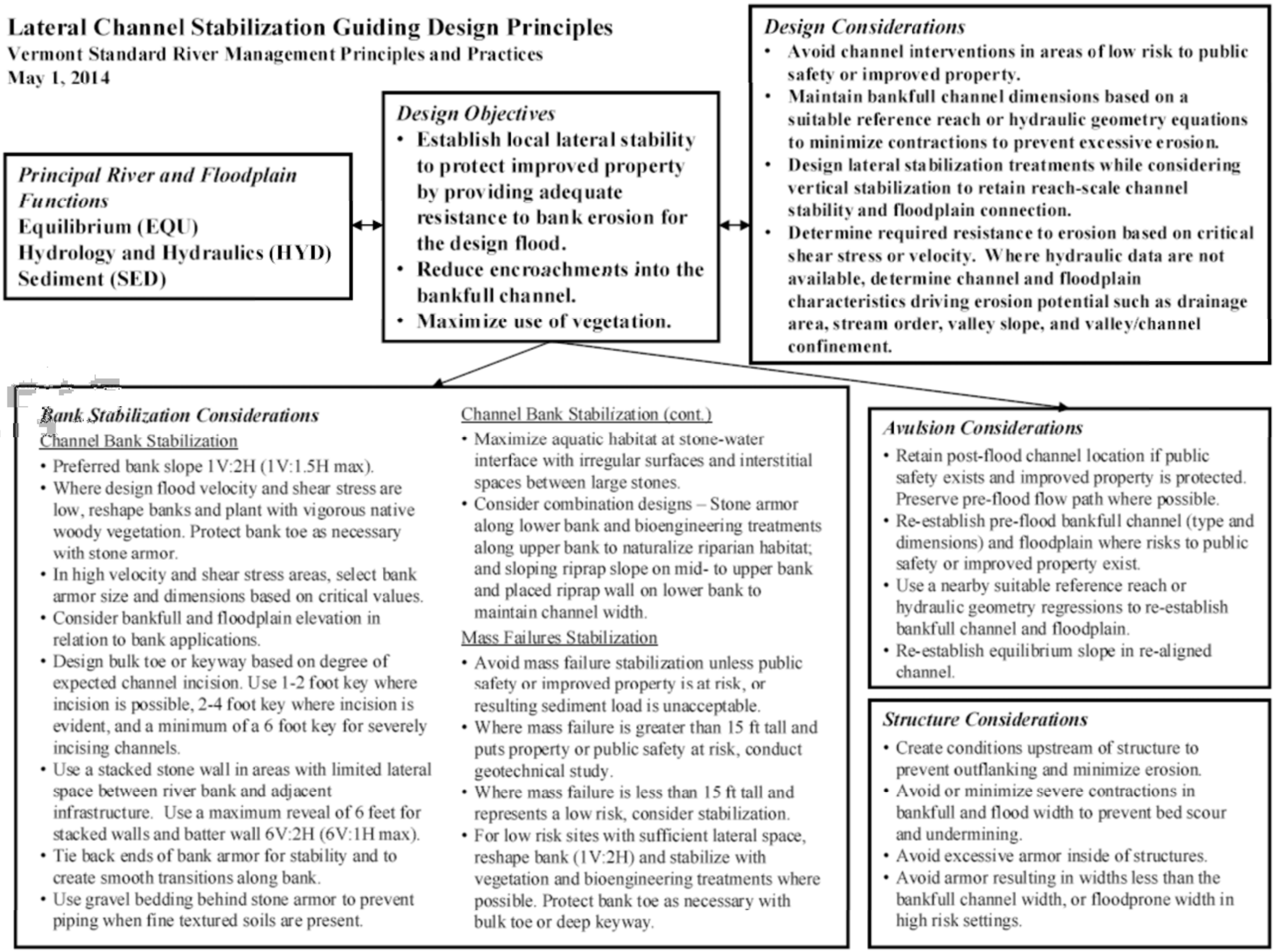
Each sheet contains Design Objectives, Design Considerations, and the applicable Principal River and Floodplain Functions (Figures 2.1, 2.2, 2.3, and 2.4). The principles and practices have been developed to support implementation of cost-effective channel management projects to reduce flood and erosion risks over the long term. More than one Guiding Design Principle typically applies to a single practice or related group of practices. An experienced user of this guidance may primarily rely on the Guiding Design Principles for practice design and to meet State of Vermont Stream Alteration Rules (2013). Some of the information summarized in the Guiding Design Principle is described in more detail as it pertains to practice design and implementation (see Section 5.0).

2.2 Design Objectives

The Design Objectives and Considerations are linked to river management methods that have been successfully used in Vermont during flood recovery and protection projects. This experience has worked its way into state rules and, thus, meeting the Design Objectives presented here will simplify project permitting.

The Vermont Stream Alteration Permit (VTANR, 2014) is based upon equilibrium and connectivity, two key Principal River and Floodplain Functions that are utilized by the state as Performance Standards to ensure that projects reduce flood and erosion risks, minimize impacts to fish and wildlife, protect the rights of riparian landowners, and protect outstanding waters. The Design Objectives presented here provide guidance to implement high-quality projects to meet Performance Standards and sustain Principal River and Floodplain Function.

An emphasis is placed on initial exploration of the do nothing alternative when considering river management. Work should be avoided if public safety and infrastructure are not at risk or if future flood risks are acceptable. Past flood recovery efforts that led to excessively costly projects, greater flood risks, severe impacts to habitat, and reduced water quality often got off course early by not considering the no-action alternative to limit work. Assessing existing conditions and identifying where work can be limited or even avoided is the first step following a flood.



Lateral Channel Stabilization Guiding Design Principles

Vermont Standard River Management Principles and Practices

May 1, 2014

Principal River and Floodplain Functions

Equilibrium (EQU)

Hydrology and Hydraulics (HYD)

Sediment (SED)

Design Objectives

- **Establish local lateral stability to protect improved property by providing adequate resistance to bank erosion for the design flood.**
- **Reduce encroachments into the bankfull channel.**
- **Maximize use of vegetation.**

Design Considerations

- **Avoid channel interventions in areas of low risk to public safety or improved property.**
- **Maintain bankfull channel dimensions based on a suitable reference reach or hydraulic geometry equations to minimize contractions to prevent excessive erosion.**
- **Design lateral stabilization treatments while considering vertical stabilization to retain reach-scale channel stability and floodplain connection.**
- **Determine required resistance to erosion based on critical shear stress or velocity. Where hydraulic data are not available, determine channel and floodplain characteristics driving erosion potential such as drainage area, stream order, valley slope, and valley/channel confinement.**

Bank Stabilization Considerations

Channel Bank Stabilization

- Preferred bank slope 1V:2H (1V:1.5H max).
- Where design flood velocity and shear stress are low, reshape banks and plant with vigorous native woody vegetation. Protect bank toe as necessary with stone armor.
- In high velocity and shear stress areas, select bank armor size and dimensions based on critical values.
- Consider bankfull and floodplain elevation in relation to bank applications.
- Design bulk toe or keyway based on degree of expected channel incision. Use 1-2 foot key where incision is possible, 2-4 foot key where incision is evident, and a minimum of a 6 foot key for severely incising channels.
- Use a stacked stone wall in areas with limited lateral space between river bank and adjacent infrastructure. Use a maximum reveal of 6 feet for stacked walls and batter wall 6V:2H (6V:1H max).
- Tie back ends of bank armor for stability and to create smooth transitions along bank.
- Use gravel bedding behind stone armor to prevent piping when fine textured soils are present.

Channel Bank Stabilization (cont.)

- Maximize aquatic habitat at stone-water interface with irregular surfaces and interstitial spaces between large stones.
- Consider combination designs – Stone armor along lower bank and bioengineering treatments along upper bank to naturalize riparian habitat; and sloping riprap slope on mid- to upper bank and placed riprap wall on lower bank to maintain channel width.

Mass Failures Stabilization

- Avoid mass failure stabilization unless public safety or improved property is at risk, or resulting sediment load is unacceptable.
- Where mass failure is greater than 15 ft tall and puts property or public safety at risk, conduct geotechnical study.
- Where mass failure is less than 15 ft tall and represents a low risk, consider stabilization.
- For low risk sites with sufficient lateral space, reshape bank (1V:2H) and stabilize with vegetation and bioengineering treatments where possible. Protect bank toe as necessary with bulk toe or deep keyway.

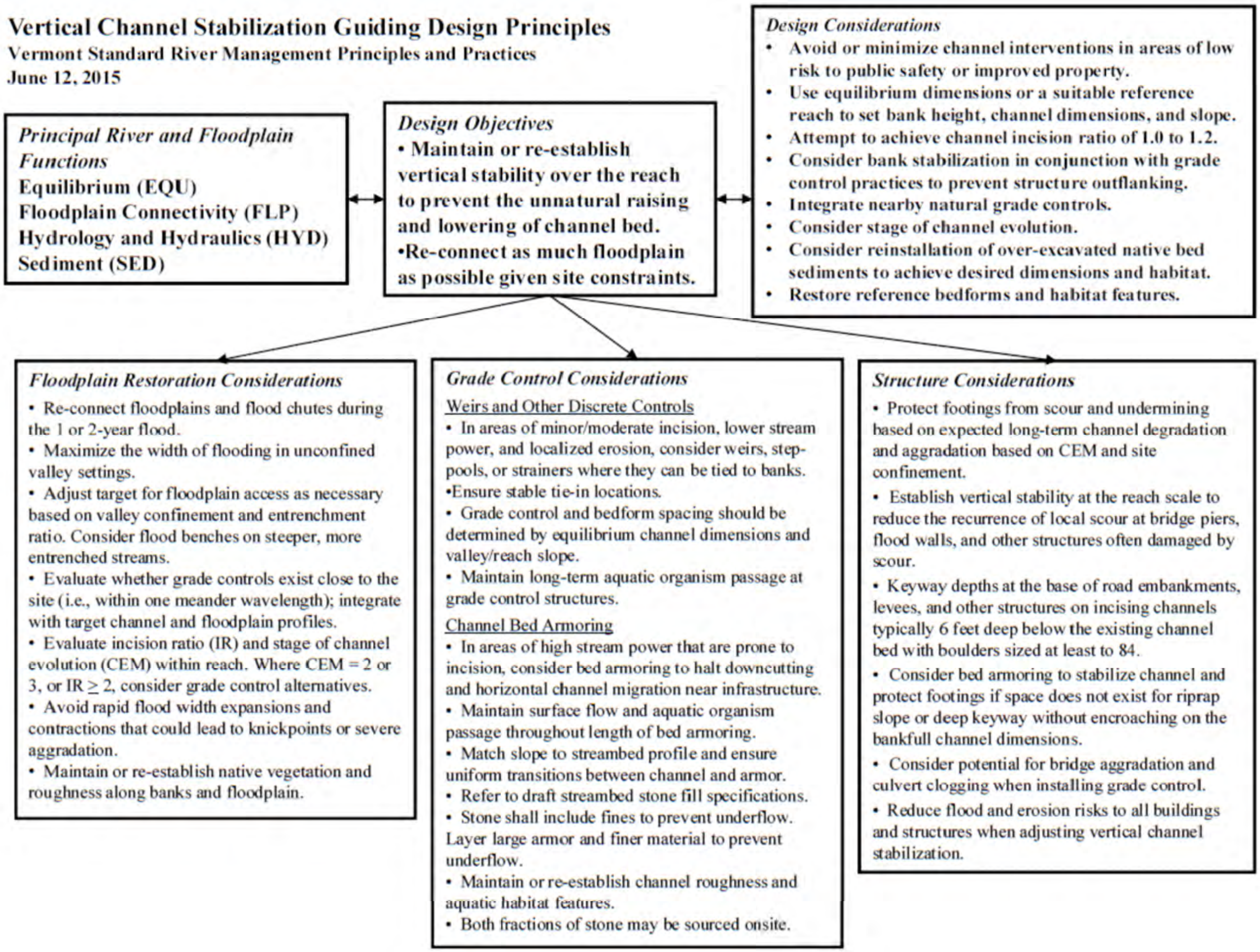
Avulsion Considerations

- Retain post-flood channel location if public safety exists and improved property is protected. Preserve pre-flood flow path where possible.
- Re-establish pre-flood bankfull channel (type and dimensions) and floodplain where risks to public safety or improved property exist.
- Use a nearby suitable reference reach or hydraulic geometry regressions to re-establish bankfull channel and floodplain.
- Re-establish equilibrium slope in re-aligned channel.

Structure Considerations

- Create conditions upstream of structure to prevent outflanking and minimize erosion.
- Avoid or minimize severe contractions in bankfull and flood width to prevent bed scour and undermining.
- Avoid excessive armor inside of structures.
- Avoid armor resulting in widths less than the bankfull channel width, or floodprone width in high risk settings.

Figure 2.1: Lateral channel stabilization.



Vertical Channel Stabilization Guiding Design Principles

Vermont Standard River Management Principles and Practices
June 12, 2015

Principal River and Floodplain Functions

Equilibrium (EQU)
Floodplain Connectivity (FLP)
Hydrology and Hydraulics (HYD)
Sediment (SED)

Design Objectives

- Maintain or re-establish vertical stability over the reach to prevent the unnatural raising and lowering of channel bed.
- Re-connect as much floodplain as possible given site constraints.

Design Considerations

- Avoid or minimize channel interventions in areas of low risk to public safety or improved property.
- Use equilibrium dimensions or a suitable reference reach to set bank height, channel dimensions, and slope.
- Attempt to achieve channel incision ratio of 1.0 to 1.2.
- Consider bank stabilization in conjunction with grade control practices to prevent structure outflanking.
- Integrate nearby natural grade controls.
- Consider stage of channel evolution.
- Consider reinstallation of over-excavated native bed sediments to achieve desired dimensions and habitat.
- Restore reference bedforms and habitat features.

Floodplain Restoration Considerations

- Re-connect floodplains and flood chutes during the 1 or 2-year flood.
- Maximize the width of flooding in unconfined valley settings.
- Adjust target for floodplain access as necessary based on valley confinement and entrenchment ratio. Consider flood benches on steeper, more entrenched streams.
- Evaluate whether grade controls exist close to the site (i.e., within one meander wavelength); integrate with target channel and floodplain profiles.
- Evaluate incision ratio (IR) and stage of channel evolution (CEM) within reach. Where CEM = 2 or 3, or IR $\geq$ 2, consider grade control alternatives.
- Avoid rapid flood width expansions and contractions that could lead to knickpoints or severe aggradation.
- Maintain or re-establish native vegetation and roughness along banks and floodplain.

Grade Control Considerations

Weirs and Other Discrete Controls

- In areas of minor/moderate incision, lower stream power, and localized erosion, consider weirs, step-pools, or strainers where they can be tied to banks.
- Ensure stable tie-in locations.
- Grade control and bedform spacing should be determined by equilibrium channel dimensions and valley/reach slope.
- Maintain long-term aquatic organism passage at grade control structures.

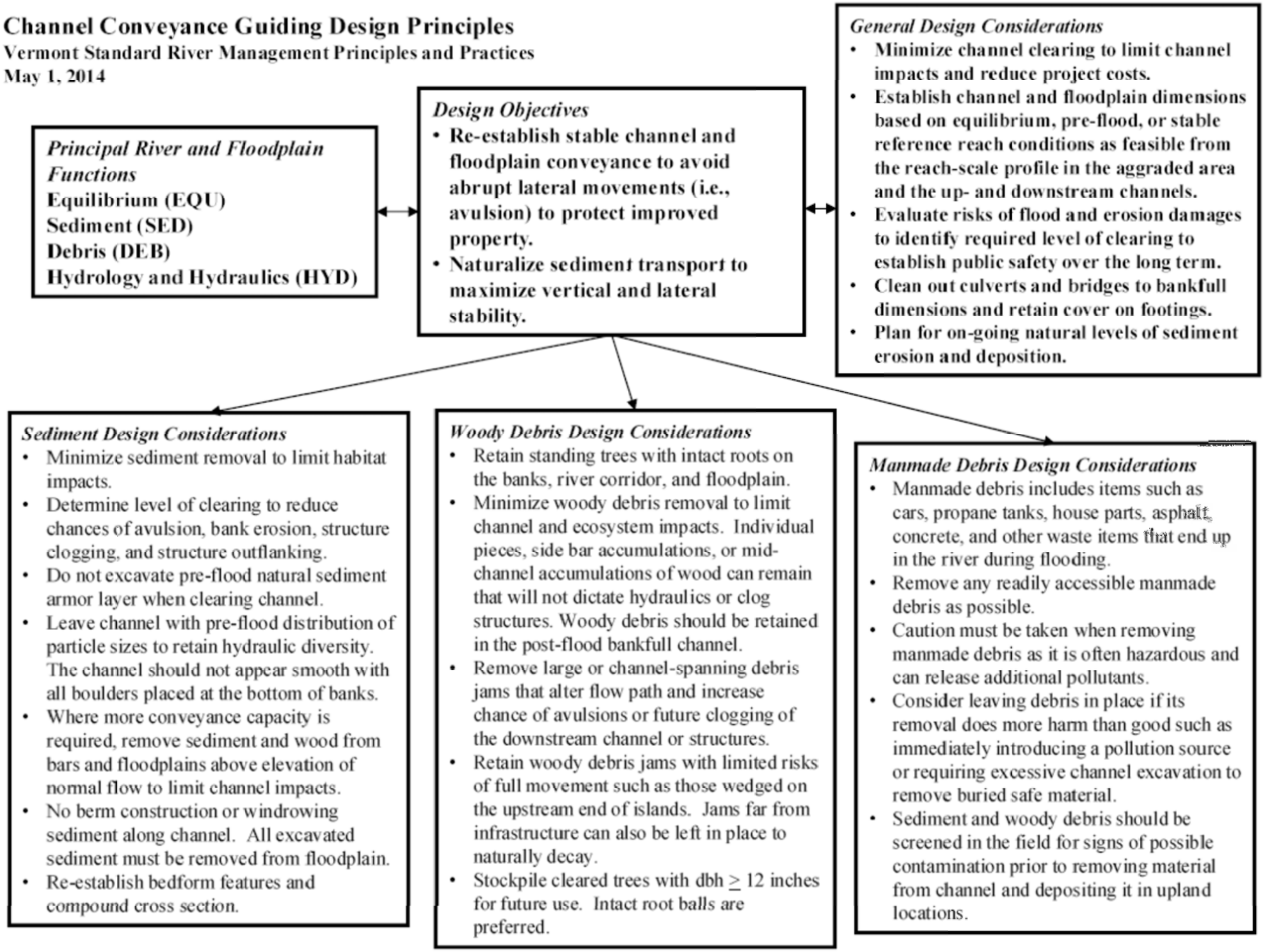
Channel Bed Armoring

- In areas of high stream power that are prone to incision, consider bed armoring to halt downcutting and horizontal channel migration near infrastructure.
- Maintain surface flow and aquatic organism passage throughout length of bed armoring.
- Match slope to streambed profile and ensure uniform transitions between channel and armor.
- Refer to draft streambed stone fill specifications.
- Stone shall include fines to prevent underflow. Layer large armor and finer material to prevent underflow.
- Maintain or re-establish channel roughness and aquatic habitat features.
- Both fractions of stone may be sourced onsite.

Structure Considerations

- Protect footings from scour and undermining based on expected long-term channel degradation and aggradation based on CEM and site confinement.
- Establish vertical stability at the reach scale to reduce the recurrence of local scour at bridge piers, flood walls, and other structures often damaged by scour.
- Keyway depths at the base of road embankments, levees, and other structures on incising channels typically 6 feet deep below the existing channel bed with boulders sized at least to 84.
- Consider bed armoring to stabilize channel and protect footings if space does not exist for riprap slope or deep keyway without encroaching on the bankfull channel dimensions.
- Consider potential for bridge aggradation and culvert clogging when installing grade control.
- Reduce flood and erosion risks to all buildings and structures when adjusting vertical channel stabilization.

Figure 2.2: Vertical channel stabilization.



Channel Conveyance Guiding Design Principles
Vermont Standard River Management Principles and Practices
May 1, 2014

Principal River and Floodplain Functions
Equilibrium (EQU)
Sediment (SED)
Debris (DEB)
Hydrology and Hydraulics (HYD)

Design Objectives
- **Re-establish stable channel and floodplain conveyance to avoid abrupt lateral movements (i.e., avulsion) to protect improved property.**
- **Naturalize sediment transport to maximize vertical and lateral stability.**

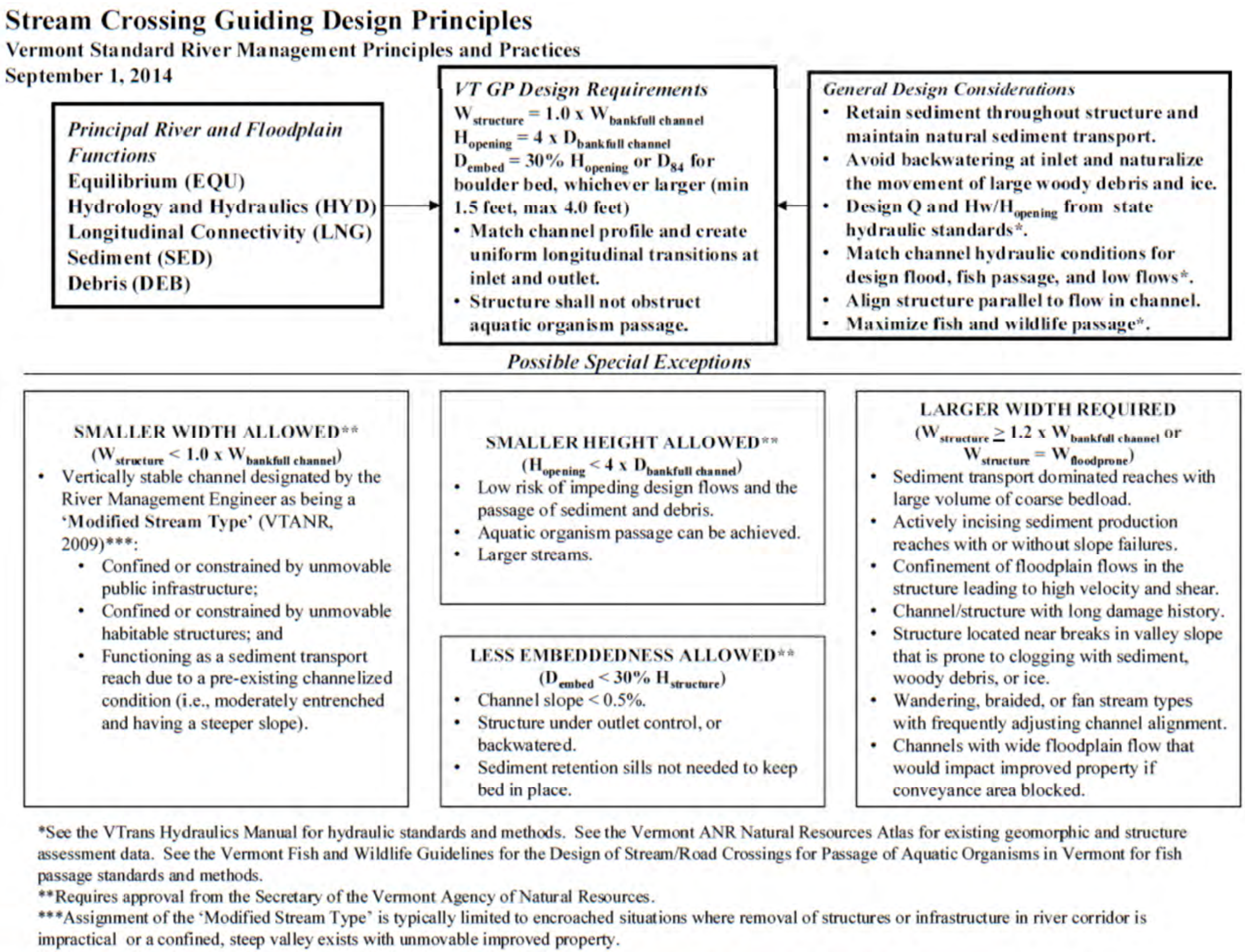
General Design Considerations
- **Minimize channel clearing to limit channel impacts and reduce project costs.**
- **Establish channel and floodplain dimensions based on equilibrium, pre-flood, or stable reference reach conditions as feasible from the reach-scale profile in the aggraded area and the up- and downstream channels.**
- **Evaluate risks of flood and erosion damages to identify required level of clearing to establish public safety over the long term.**
- **Clean out culverts and bridges to bankfull dimensions and retain cover on footings.**
- **Plan for on-going natural levels of sediment erosion and deposition.**

Sediment Design Considerations
- Minimize sediment removal to limit habitat impacts.
- Determine level of clearing to reduce chances of avulsion, bank erosion, structure clogging, and structure outflanking.
- Do not excavate pre-flood natural sediment armor layer when clearing channel.
- Leave channel with pre-flood distribution of particle sizes to retain hydraulic diversity. The channel should not appear smooth with all boulders placed at the bottom of banks.
- Where more conveyance capacity is required, remove sediment and wood from bars and floodplains above elevation of normal flow to limit channel impacts.
- No berm construction or windrowing sediment along channel. All excavated sediment must be removed from floodplain.
- Re-establish bedform features and compound cross section.

Woody Debris Design Considerations
- Retain standing trees with intact roots on the banks, river corridor, and floodplain.
- Minimize woody debris removal to limit channel and ecosystem impacts. Individual pieces, side bar accumulations, or mid-channel accumulations of wood can remain that will not dictate hydraulics or clog structures. Woody debris should be retained in the post-flood bankfull channel.
- Remove large or channel-spanning debris jams that alter flow path and increase chance of avulsions or future clogging of the downstream channel or structures.
- Retain woody debris jams with limited risks of full movement such as those wedged on the upstream end of islands. Jams far from infrastructure can also be left in place to naturally decay.
- Stockpile cleared trees with dbh $\geq$ 12 inches for future use. Intact root balls are preferred.

Manmade Debris Design Considerations
- Manmade debris includes items such as cars, propane tanks, house parts, asphalt, concrete, and other waste items that end up in the river during flooding.
- Remove any readily accessible manmade debris as possible.
- Caution must be taken when removing manmade debris as it is often hazardous and can release additional pollutants.
- Consider leaving debris in place if its removal does more harm than good such as immediately introducing a pollution source or requiring excessive channel excavation to remove buried safe material.
- Sediment and woody debris should be screened in the field for signs of possible contamination prior to removing material from channel and depositing it in upland locations.

Figure 2.3: Channel conveyance.



Stream Crossing Guiding Design Principles

Vermont Standard River Management Principles and Practices

September 1, 2014

Principal River and Floodplain Functions

Equilibrium (EQU)

Hydrology and Hydraulics (HYD)

Longitudinal Connectivity (LNG)

Sediment (SED)

Debris (DEB)

VT GP Design Requirements

$W_{structure} = 1.0 \times W_{bankfull\ channel}$

$H_{opening} = 4 \times D_{bankfull\ channel}$

$D_{embed} = 30\%\ H_{opening}$ or D_{84} for boulder bed, whichever larger (min 1.5 feet, max 4.0 feet)

- Match channel profile and create uniform longitudinal transitions at inlet and outlet.
- Structure shall not obstruct aquatic organism passage.

General Design Considerations

- Retain sediment throughout structure and maintain natural sediment transport.
- Avoid backwatering at inlet and naturalize the movement of large woody debris and ice.
- Design Q and $Hw/H_{opening}$ from state hydraulic standards*.
- Match channel hydraulic conditions for design flood, fish passage, and low flows*.
- Align structure parallel to flow in channel.
- Maximize fish and wildlife passage*.

Possible Special Exceptions

SMALLER WIDTH ALLOWED**

($W_{structure} < 1.0 \times W_{bankfull\ channel}$)

- Vertically stable channel designated by the River Management Engineer as being a 'Modified Stream Type' (VTANR, 2009)***:
  - Confined or constrained by unmovable public infrastructure;
  - Confined or constrained by unmovable habitable structures; and
  - Functioning as a sediment transport reach due to a pre-existing channelized condition (i.e., moderately entrenched and having a steeper slope).

SMALLER HEIGHT ALLOWED**

($H_{opening} < 4 \times D_{bankfull\ channel}$)

- Low risk of impeding design flows and the passage of sediment and debris.
- Aquatic organism passage can be achieved.
- Larger streams.

LESS EMBEDDEDNESS ALLOWED**

($D_{embed} < 30\%\ H_{structure}$)

- Channel slope < 0.5%.
- Structure under outlet control, or backwatered.
- Sediment retention sills not needed to keep bed in place.

LARGER WIDTH REQUIRED

($W_{structure} \geq 1.2 \times W_{bankfull\ channel}$ or $W_{structure} = W_{floodprone}$)

- Sediment transport dominated reaches with large volume of coarse bedload.
- Actively incising sediment production reaches with or without slope failures.
- Confinement of floodplain flows in the structure leading to high velocity and shear.
- Channel/structure with long damage history.
- Structure located near breaks in valley slope that is prone to clogging with sediment, woody debris, or ice.
- Wandering, braided, or fan stream types with frequently adjusting channel alignment.
- Channels with wide floodplain flow that would impact improved property if conveyance area blocked.

*See the VTrans Hydraulics Manual for hydraulic standards and methods. See the Vermont ANR Natural Resources Atlas for existing geomorphic and structure assessment data. See the Vermont Fish and Wildlife Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont for fish passage standards and methods.

**Requires approval from the Secretary of the Vermont Agency of Natural Resources.

***Assignment of the 'Modified Stream Type' is typically limited to encroached situations where removal of structures or infrastructure in river corridor is impractical or a confined, steep valley exists with unmovable improved property.

Figure 2.4: Stream crossing.

2.1 Principal River and Floodplain Functions

Principal River and Floodplain Functions (Figure 2.5) have been established for:

- Dynamic equilibrium (EQU);
- Hydrology and hydraulics (HYD);
- Sediment (SED);
- Debris (DEB);
- Floodplain connectivity (FLP); and
- Longitudinal connectivity (LNG).

These Principal Functions define the scientific theory behind the river management practices in this guidance and are the basis for the Performance Standards in the Vermont Stream Alteration Rules (2013).

2.1.1 Dynamic Equilibrium (EQU)

The primary principal river function in Vermont is dynamic equilibrium where channel shape (i.e., form) and natural function (i.e., processes) are maintained to achieve the most stable channel over the long term (Kline, 2011) (Appendix A). The theory of dynamic equilibrium is based on channels transporting a balance of sediment and water (Lane, 1955a). Channels in or near equilibrium are less likely to excessively erode or deposit sediment than channels far from equilibrium (i.e., disequilibrium).

Some channels such as bedrock-controlled gorges are always in equilibrium while others such as braided and wandering channel types can persist in a nonequilibrium, transient state for long periods of time following flooding and large changes to the channel (Church, 2002; Kleinhans and van den Berg, 2011). The further a channel is from dynamic equilibrium, the more unstable and risky the setting is, and river management typically becomes more complicated and expensive.

River management that maximizes, to the extent possible, the restoration and protection of natural channel stability should be performed because channels are not always in, or rapidly adjusting toward, equilibrium. The most stable state of a channel can only occur if space is provided for natural river processes such as erosion and deposition to take place. Valley and channel morphology, the presence of infrastructure that limits space for the river form and function to be naturally expressed, or changing precipitation patterns due to climate change can all keep a channel in a nonequilibrium state. The following Performance Standards are used depending on where the channel is relative to its equilibrium state.

- For channels in equilibrium, human activity cannot initiate vertical movement of the channel at the reach scale that would create a departure from equilibrium.
- For channels out of equilibrium, human activity cannot cause further departure in the dimensions and profile associated with its equilibrium form and its natural stream processes.
- For channels out of equilibrium, human activity cannot block the return of the predicted equilibrium state preventing future attainment of the most stable channel (unless defined as an emergency measure required to address a threat to life, public health, and safety or address the threat of severe damage to an improved property).

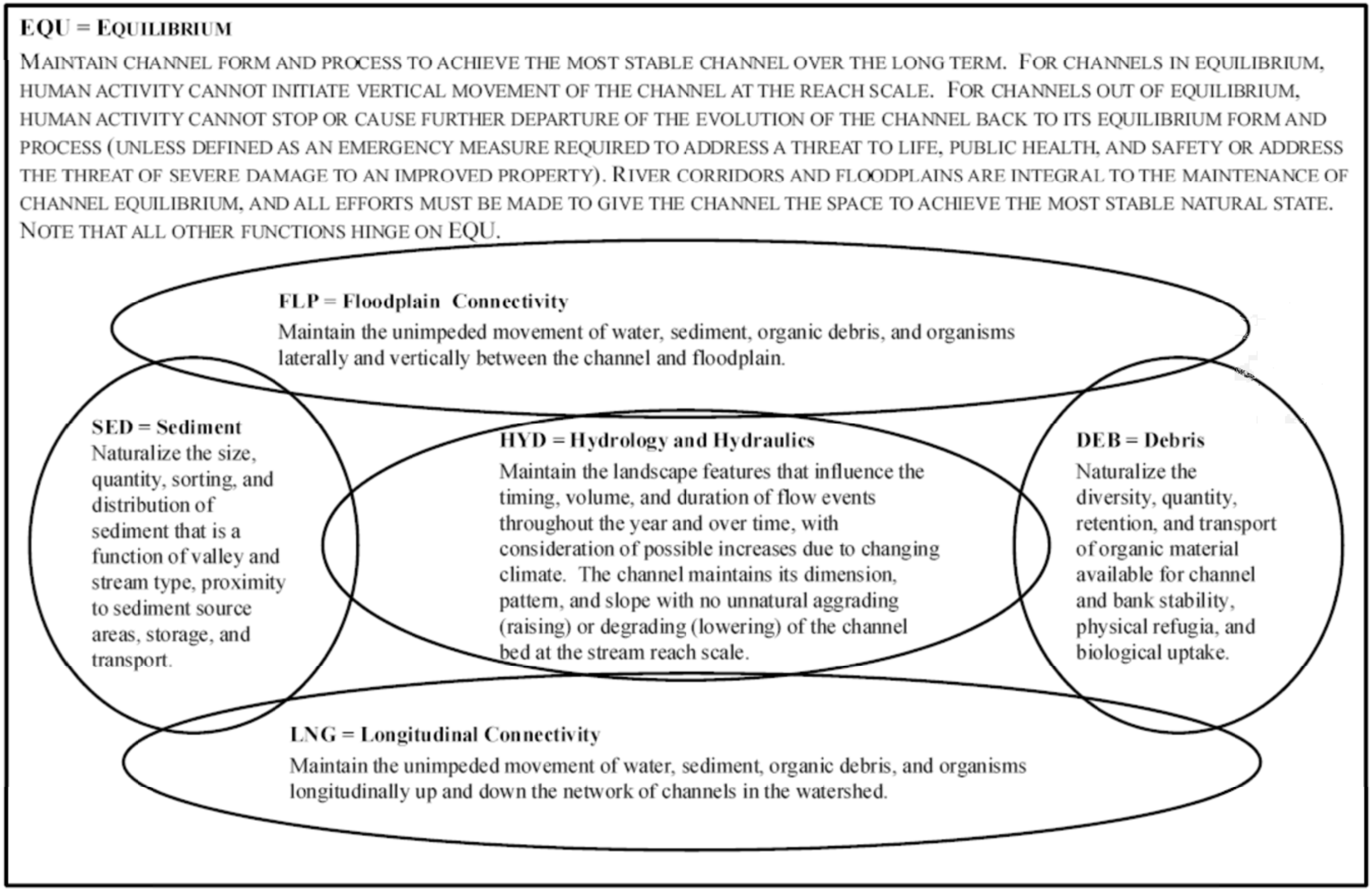
River corridors and floodplains are integral to the maintenance of channel equilibrium, and all efforts must be made to give the channel the space to achieve the most stable natural state. High-quality instream habitat is more abundant in stable channels, and dynamic equilibrium is essential for the long-term formation and maintenance of habitat features. All of the remaining Principal River and Floodplain Functions, and thus river management methods, hinge on maintaining or limiting departure from dynamic equilibrium.

2.1.2 Hydrology and Hydraulics (HYD)

The natural variability of the flow in the channel and floodplain is essential for establishing stable channels and good stream health (Richter et al., 1996). The channel and floodplain must be able to pass a wide range of flows that includes infrequent large floods, extreme thunderstorms that can produce decadal high flows, annual spring floods that just fill the channel, and extreme low flows.

Proper river management extends into the contributing watershed. The landscape features that influence the timing, volume, and duration of flow events throughout the year and over time must be maintained. Stream gauge records now confirm that both bankfull (Collins, 2009) and smaller floods (Armstrong et al., 2012) are getting larger and more frequent in the region due to changing climate and precipitation patterns.

Natural hydrology is essential for natural channel hydraulics (e.g., flow depth and velocity), allowing for the channel to maintain its dimension, pattern, and slope with no unnatural raising (i.e., aggrading) or lowering (i.e., degrading) of the channel bed at the reach scale.



EQU = EQUILIBRIUM

MAINTAIN CHANNEL FORM AND PROCESS TO ACHIEVE THE MOST STABLE CHANNEL OVER THE LONG TERM. FOR CHANNELS IN EQUILIBRIUM, HUMAN ACTIVITY CANNOT INITIATE VERTICAL MOVEMENT OF THE CHANNEL AT THE REACH SCALE. FOR CHANNELS OUT OF EQUILIBRIUM, HUMAN ACTIVITY CANNOT STOP OR CAUSE FURTHER DEPARTURE OF THE EVOLUTION OF THE CHANNEL BACK TO ITS EQUILIBRIUM FORM AND PROCESS (UNLESS DEFINED AS AN EMERGENCY MEASURE REQUIRED TO ADDRESS A THREAT TO LIFE, PUBLIC HEALTH, AND SAFETY OR ADDRESS THE THREAT OF SEVERE DAMAGE TO AN IMPROVED PROPERTY). RIVER CORRIDORS AND FLOODPLAINS ARE INTEGRAL TO THE MAINTENANCE OF CHANNEL EQUILIBRIUM, AND ALL EFFORTS MUST BE MADE TO GIVE THE CHANNEL THE SPACE TO ACHIEVE THE MOST STABLE NATURAL STATE. NOTE THAT ALL OTHER FUNCTIONS HINGE ON EQU.

FLP = Floodplain Connectivity

Maintain the unimpeded movement of water, sediment, organic debris, and organisms laterally and vertically between the channel and floodplain.

SED = Sediment

Naturalize the size, quantity, sorting, and distribution of sediment that is a function of valley and stream type, proximity to sediment source areas, storage, and transport.

HYD = Hydrology and Hydraulics

Maintain the landscape features that influence the timing, volume, and duration of flow events throughout the year and over time, with consideration of possible increases due to changing climate. The channel maintains its dimension, pattern, and slope with no unnatural aggrading (raising) or degrading (lowering) of the channel bed at the stream reach scale.

DEB = Debris

Naturalize the diversity, quantity, retention, and transport of organic material available for channel and bank stability, physical refugia, and biological uptake.

LNG = Longitudinal Connectivity

Maintain the unimpeded movement of water, sediment, organic debris, and organisms longitudinally up and down the network of channels in the watershed.

Figure 2.5: Principal river and floodplain functions.

2.1.3 Sediment (SED)

Sediment refers to the sand, gravel, cobble, and boulders that a river moves downstream. The natural sediment regime in a watershed leads to a predictable size, quantity, sorting, and distribution of sediment for particular valley and channel types. Managing rivers to enhance equilibrium requires a natural sediment budget to prevent excessive erosion or deposition. Sediment source, storage, and transport must be considered in the context of moving a channel toward long-term equilibrium. Changes to the natural sediment regime typically destabilize channels. An increased sediment supply due to mass failures of the valley wall or widespread bank erosion can result in increased sediment buildup that pushes flows laterally causing erosion and threats to nearby property. Sediment removal from the forces of a scouring flood or through mechanical dredging can lead to oversteepened erosion faces that move upstream (i.e., headcutting) destabilizing the bed and banks for many years.

2.1.4 Debris (DEB)

The generation, storage, and transport of woody debris from trees falling into a river influence channel equilibrium and stability and improves instream habitat (Brooks et al., 2006). For example, wood can create stable step-pools in steep mountain channels (Wohl and Merritt, 2008). Wood influences sediment storage, spacing of riffle-pool sequences, and vertical channel stability (Thompson, 1995).

Large woody debris forms physical holding locations for fish, and serves as the base of the aquatic food web (Allan, 1995). Wholesale woody debris removal following large floods to protect bridges, culverts, and other infrastructure removes an important mechanism for long-term channel bed and bank stability and future instream habitat structure. Effective river management must strike a balance between debris removal that can be problematic and debris that can remain in the channel and floodplain to perform beneficial functions. Consideration of the diversity, quantity, retention, and transport of organic material in conjunction with flow and sediment is an important aspect of proper channel management.

The level of risk created by post-flood woody debris accumulations should be assessed prior to removal (see Section 5.7 and Table 5.7-2).

2.1.5 Floodplain Connectivity (FLP)

Floodplains store flood waters, sediment, and nutrients thereby reducing flood risks and improving water quality (Leopold, 1994; Gurnell, 1997; Fischenich and Morrow, 2000; Noe and Hupp, 2005). Floodplains store more water, sediment, and debris during large floods compared to channels and thus are essential for limiting flood risks. As floodwaters spread out on floodplains, flow velocity decreases and reduces the risk of channel erosion. Floodplains also provide important habitat such as fish spawning grounds and wildlife travel corridors.

Traditional flood recovery activities that tend to channelize rivers work against floodplain connectivity to limit overbank flow and the deposition of sediment and debris in channels or floodplains. If storage of water, sediment, and debris is not allowed at any individual location, it forces some other location across the valley or downstream to receive more. A cycle of increasing flood and erosion risks outside of the active flood recovery area can take place leading to cascading consequences in the downstream river network.

The maintenance of the unimpeded movement of water, sediment, and organic debris across the channel and floodplain is essential to managing for equilibrium that naturally reduces flood risks. Recent flood recovery methods emphasize reconnecting available floodplain to reduce future flood risks. Floodplains differ in size and function based on their geomorphic setting (Nanson and Croke, 1992), and thus the size of reconnected floodplains can vary greatly. No matter their size, connected floodplains are important for flood risk reduction in most channels.

2.1.6 Longitudinal Connectivity (LNG)

The movement of water, sediment, organic debris, and organisms throughout a river system is essential for channel stability and for the aquatic ecosystem to function properly. A disruption by a dam or an undersized culvert can trap sediment and alter natural flow patterns that can destabilize long stretches of a channel (Kondolf, 1997; Jacobson et al., 2011). Changes to the river profile should be evaluated when changes are proposed to the channel or floodplain.

3.0 SITE SCREENING AND PRIMARY PROBLEM IDENTIFICATION (TIER 1)

- *Is erosion or deposition the dominant river process that led to the post-flood channel condition and associated structure failures?*
- *What observed damages and river channel conditions exist to illustrate the dominant process that takes place during flooding?*
- *What river management principles and practices are likely applicable to recover from damages considering the river channel conditions and dominant processes?*

3.1 Post-Flood Assessment

3.1.1 Objectives

The objectives of the post-flood assessment are:

- Identify erosion and deposition processes based on observed damages and post-flood channel conditions;
- Clarify and evaluate links between structure failures and river processes; and
- Determine the Guiding Design Principles that are applicable during flood recovery.

The post-flood assessment is essential for collecting information to begin planning and design of an effective recovery. Damages result from channel conditions and processes that must be understood to reduce future risks and the chances of reoccurring flood damages.

3.1.2 Methods

The post-flood assessment is typically conducted immediately after the flood and includes the following elements:

1. Site walk or windshield survey;
2. Field measurements;
3. Debrief with people who saw the flood firsthand; and
4. Home video/photograph review.

The site walk or windshield survey must extend beyond the immediate damage site and should typically be performed at the reach (~ 1 mile) scale. This distance allows observations of channel conditions that are likely influencing the project site or identification of project boundaries such as bedrock grade control in a channel that is downcutting. Photo-documentation and recording Global Positioning System (GPS) points of key damage sites, channel conditions, controlling channel features, and high water marks are typically performed during the site walk.

Some initial field measurements are commonly performed during the first site walk, and more data collection takes place during follow-up site visits. If substantial flood damages take place and recovery is to begin immediately with emergency protective measures, data collection would include items such as:

- Structures that are damaged and cannot be safely used;
- Depth of sediment and debris at bridges and culverts to be cleared;
- Lengths and priority of eroded banks to armor;
- Length of road embankment failure;
- Depth of new sediment deposits in the channel and floodplain; and
- Depth of new channel incision.

The initial data collection should include information that is adequate to allow the emergency response to begin immediately and provide an initial quantification of future recovery work.

As recovery work begins at the locations with immediate risks to safety and improved property, more detailed data collection often continues and typically includes:

- Refined initial measurements;
- Survey;
- Geomorphic assessment of the channel and floodplain;
- Disturbance footprint below ordinary high water;
- Length, surface area, and volume of fill to be placed; and
- Length, surface area, and volume of sediment, woody debris, and human debris to be removed.

Data collection needs vary based on the problem identification and flood recovery approach and can cover a wide range of variables and considerations for large damage sites with high risks (Appendix B).

Conversations about the flood often take place during the site walk as people who live and work along the river are out looking at damages. Discussions with people that observed the flood often reveal important information that can benefit flood recovery. Post-flood debriefing typically includes town staff and first responders in addition to riparian landowners.

Photographs and videos taken with mobile electronic devices by the public are common on the internet following large floods. This informal documentation can be useful for observing flood conditions and the nature of flood damages.

3.2 Primary Problem Identification

Flood damages ultimately arise from erosion and deposition of a river channel and floodplain. When a bridge or road embankment is destroyed, the solution to the problem and reduction of future flood risks have as much to do with river management as they do with building transportation facilities. Flood recovery must be linked to the river conditions and processes that led to the damages – the first and most important objective of the post-flood assessment.

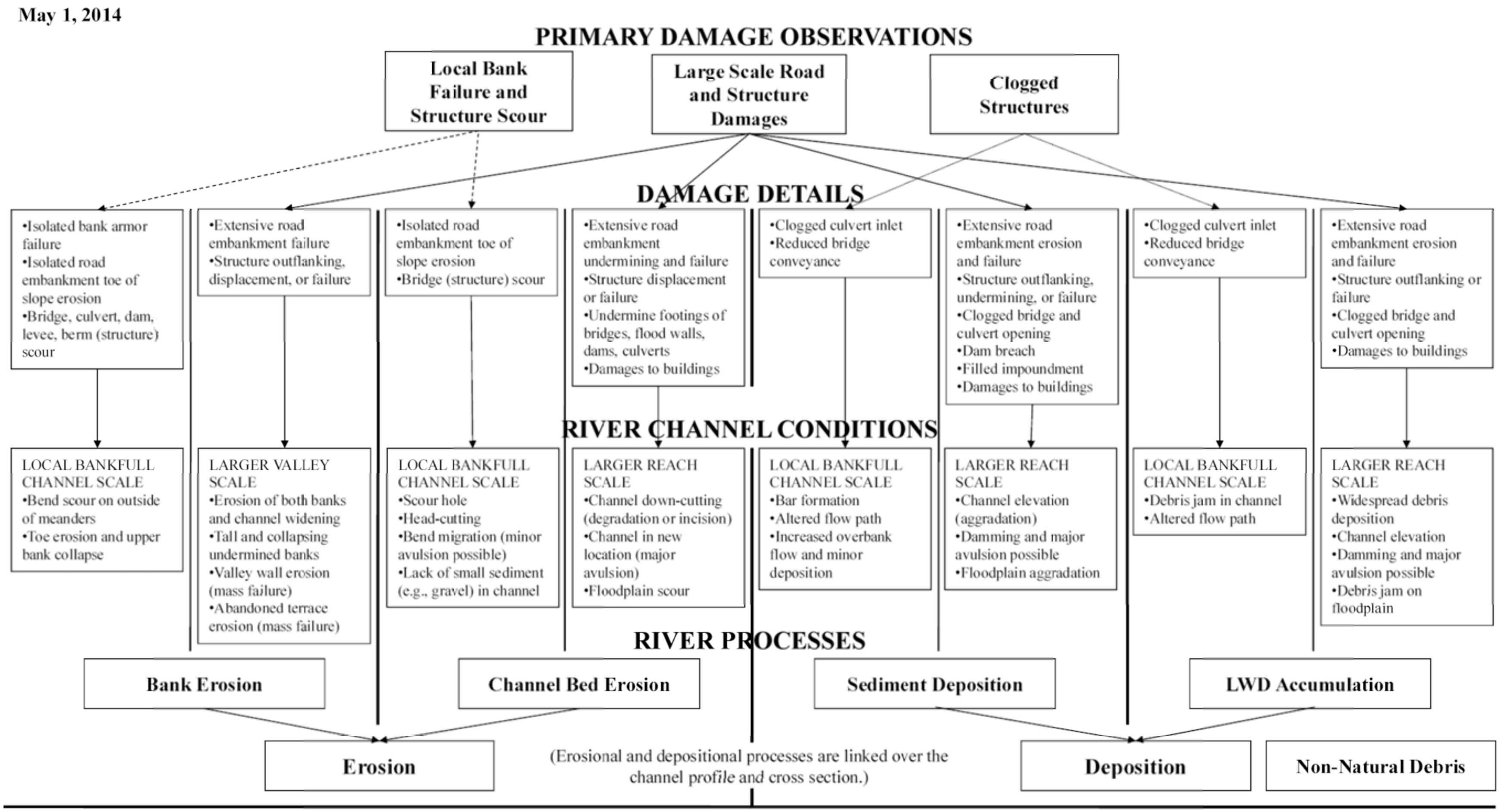
Observe and document the extent of damages, observe the conditions of the post-flood river channel, and determine if erosion, deposition, or both are taking place (Figure 3.1; Appendix C). Once the conditions of the river channel and floodplain are known and the dominant river process is understood, consideration of alternatives can take place to address channel change and prevent future damages. The link between damages and river form and process is essential to identify future risks based on the likelihood of river channel adjustment.

3.3 Scale of Damages, Assessment, and Recovery Work

3.3.1 Spatial Scale

The spatial scale of the damages, channel conditions, and dominant processes must be understood to properly assess and recover from floods. Important scales to consider include the site, reach (≤ 1 mile), river corridor (typically 1 to 5 miles), and watershed (Frissell et al., 1986; Steiger et al., 2005).

Most observations occur at a local site when looking at damages and structure failures. Successful river management requires linking the local scale to the reach where the channel and floodplain form and their dominant processes originate. Managing inundation at one location often leads to erosion at another location. Observations must therefore extend upstream and downstream of damage areas during the post-flood assessment for problem identification. For example, is observed scour only taking place at a bridge, or is it associated with channel incision at the reach scale? Is a channel avulsion part of a large-scale sediment deposition event? The answer to such fundamental questions of spatial scale will guide the alternatives analysis and dictate recovery methods.



APPLICABLE GUIDING DESIGN PRINCIPLES BASED ON DAMAGES (1 = MOST IMPORTANT)

Lateral	1	1	3	3	2	3	1	3
Vertical		2	1	1	1	2	2	1
Conveyance					4	1		2
Crossing	2	3	2	2	3	4	3	4

Figure 3.1: Observed damages, river channel conditions, and river process (see Appendix C for full-size chart).

River corridors are large areas up and down valleys where rivers flow and have flowed in the past, occupying the full width of the meanders (VTDEC, 2006a; Kline, 2010) (Figure 3.2 and Appendix D). Most flood damages take place in river corridors as channels naturally migrate across the valley (Kline, 2010). Dynamic equilibrium and channel evolution originate at the river corridor scale and, thus, the proper context for long-term river management to reduce future flood and erosions risks also begins at the river corridor scale.

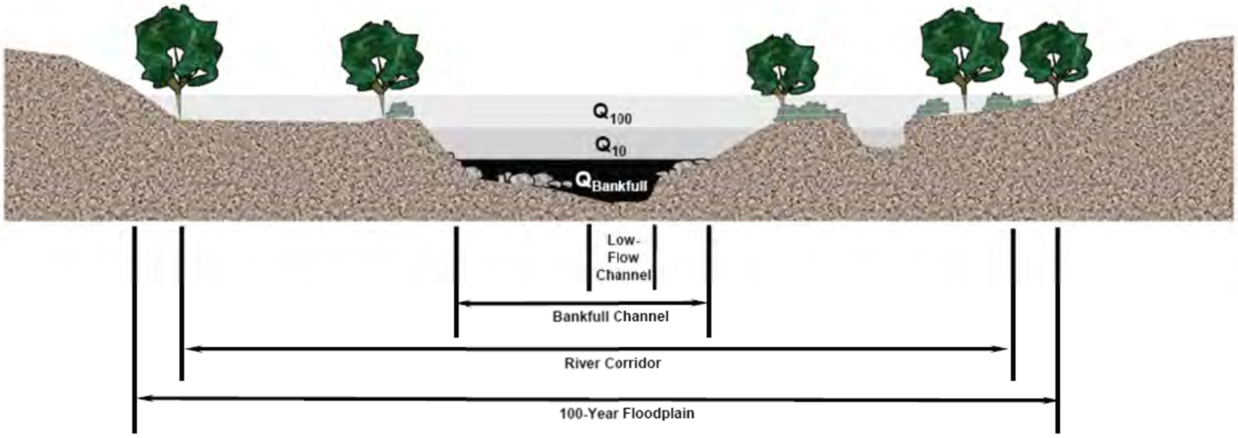


Figure 3.2: Cross section schematic.

Dynamic equilibrium (see section 2.1.1) where sediment and water are balanced in a stable channel form originates at the river corridor scale. This overarching principal river function must be linked to scales larger than the site where damages take place. The flood recovery alternatives analysis will progress in different directions if local damages are taking place in a river corridor that is in versus out of equilibrium.

Channels naturally evolve over time according to channel evolution models (Schumm et al., 1984; Simon, 1989; Rosgen et al., 2006). The evolving channel profile at the reach scale often contains several erosion faces (i.e., nickpoints) and downstream sediment aggradation areas (Appendix E). The stage of channel evolution establishes the expected current and future cross section shape and the likely stability of the cross section. Reach and corridor scale observations are required to determine the stage of channel evolution that is a critical input to flood recovery.

The watershed should be evaluated to determine if stressors at this largest scale are controlling river processes in the river corridor and local channel conditions. Although the watershed scale is typically too large for field evaluation to repair local flood damages, the alternatives analysis and design should be performed with some knowledge of the watershed context. In particular, watershed sediment regime and hydrology are essential for understanding the influence of river management activities. Future watershed conditions are also important to predict how a practice may control risks over the long term. Is watershed land use changing that will lead to higher flood flows and more sediment productions? Climate change is altering watershed hydrology that is leading to more floods (Collins, 2009; Armstrong et al., 2012).

3.3.2 Temporal Scale

The temporal context of flooding and damages is important to identify how vulnerable to damage a site is and the best approach to take to reduce the risk over the long term. How frequent do damages take place? How long since the last flood? The answer to these and other questions on timing must be considered in the alternatives analysis.

Flood flows have increased in the northeast United States since 1970, and thus current and future flows generated in the watershed must be considered for proper design (NMFS, 2011).

The timing of flood recovery is linked to the post-flood level of risk in the river corridor and often dictates whether temporary versus permanent work will take place. Flood recovery begins with restoring or protecting essential services as emergency work that can begin within hours or days of a flood. Such work can be the repair of a municipal water system, rebuilding roadways to isolated communities, and stabilizing raw banks immediately adjacent to vulnerable buildings. Depending on the size of the flood and nature of the damages, emergency protective work can last for months to reduce future or next flood threats.

Emergency protective work is often linked to a storm frequency such as eliminating threats for the 5-year flood (1990; FEMA, 2007). The decision on the level of future risk reduction is important for securing potential funding reimbursement and must be clearly justified and well documented. Both the varied nature of damages and recovery activities along with the observed increase in flood size and frequency over the past several decades complicate basing river management on a single storm event strictly linked to flood frequency. Multiple flood levels should be used to understand the range of risk reduction options in terms of costs and benefits to the affected property owners or communities. Flood recovery target levels should be reviewed with regulators and potential funders as early as possible to obtain an indication of the likelihood of funding reimbursement.

The time for alternatives analysis, design, and permitting is reduced after large floods and often mandates abbreviated engineering techniques to perform a large amount of work. Triaging sites based on risk, identifying a range of alternatives in the field, sketching designs in field notebooks, making initial quantity estimates, and developing a ballpark engineer's opinion of probable construction cost are required. During the fast pace of flood recovery, formal design is usually not possible prior to the start of construction; however, initial design and estimates must regularly be revisited for ongoing review and revisions as the immediate emergency subsides. The process of post-flood alternatives analysis and design is fast paced and adaptive.

3.4 Existing Information

3.4.1 River Corridor Plans

The gathering of existing information is important for all projects but is essential to post-flood assessment, alternatives analysis, and design given that time for data collection is typically very limited before design and construction begin. A Vermont River Corridor Plan (Kline, 2010) is a clearinghouse of information on the geomorphic nature of the channel and project recommendations for sound river management that were formulated when flooding was not taking place. The plans include some implementation details on flood risk reduction that may be directly useful to flood recovery. The project recommendations in the river corridor plans and methods in the river corridor documentation adhere to the same principles and practices described in this document. River corridor plans are available by contacting the Vermont Rivers Program (http://www.anr.state.vt.us/dec/waterq/rivers).

3.4.2 Stream Geomorphic Data

The Equilibrium Performance Standards and the principles and practices described here are based on the natural geomorphology of channels and floodplains. This information is required for post-flood assessment, alternatives analysis, and design. Without geomorphic data that describe the natural form and function of the river and floodplain, flood recovery can turn into guesswork that may or may not reduce future flood risks. Geomorphic data (VTANR, 2009) are available for many Vermont rivers and can be readily accessed on the Vermont Agency of Natural Resources Atlas website (http://anrmaps.vermont.gov/websites/anra). The atlas also contains information on assessed bridges and culverts. Data can be used for a wide range of purposes such as reviewing pre-flood baseline data for understanding changes and for initiating design of emergency protective measures immediately after flooding using past field data as a guide. If these data do not exist, some data collection will be needed to perform an alternatives analysis and complete design.

3.4.3 Town Resilience and Hazard Mitigation Plans

Towns can use river corridor plans, geomorphic data, and local experience to identify probable locations where a flood may result in damaging erosion and depositional processes. A resiliency element of a Town Plan (Act 16) can be used in a predisaster context to conduct alternatives analysis and get some degree of a prior agreement on how flood recovery practices will be pursued.

4.0 ALTERNATIVES ANALYSIS (TIER 2)

- *Do threats to life or property exist during the next flood that would require work?*
- *Can work be limited or avoided while still improving public safety, protecting infrastructure, reducing future flood risks, sustaining principal river and floodplain functions, maintaining habitat and water quality, and controlling recovery costs?*
- *What general type of management practices are typically considered for the observed damages, river channel conditions, and processes?*
- *What Design Objectives and Considerations apply to each specific river management practice that may be considered for implementation?*
- *What are the primary considerations for identifying the preferred alternative(s) to reduce flood and erosion risks?*

4.1 Introduction

The goal of the alternatives analysis is to select one or more cost-effective practices for design and implementation to *minimize threats to life or property now or during the next flood*. If a channel adjustment process is taking place or is likely to occur in the near future that threatens public safety or property, an alternatives analysis should be initiated. To facilitate the selection of preferred alternative(s), decision trees are provided for six groups of river management practices:

1. Bank stabilization;
2. Bed stabilization;
3. Floodplain reconnection;
4. Increase channel conveyance;
5. Channel realignment; and
6. Increase hydraulic roughness.

The questions listed below must be answered to define the threat, the physical setting (e.g., valley confinement and floodplain connectivity), and the potential for erosion and deposition in the channel to evaluate the range of possible practices and select the preferred alternative(s). This information is typically gathered during a site assessment, initial problem identification, and review of existing data (e.g., channel and floodplain geomorphology, the history of flood and erosion events, and hydraulic modeling). Effective use of the alternatives analysis sheets will be significantly aided with answers to these questions.

Implementing minimal emergency repairs is recommended to address the immediate threats, provide more time to perform an alternatives analysis, and design permanent repairs. Unless adequate data collection can take place and time exists to perform an alternatives analysis, permanent repairs that are done during the rapid emergency flood response often end up being counterproductive and increasing risks.

Refer to the applicable Design Objectives and Considerations when evaluating alternatives. The sizing of bridges and culverts is presented in the Design Principles (see Figure 2.4) and in Section 5.8 consistent with the requirements in the Vermont Stream Alteration General Permit to meet the Performance Standards established by the state in its rules.

4.2 Initial Project Questions

Do threats to life or property exist now or with the next flood?

NO – Consider the no-action alternative or the most deformable practice that will simulate a natural channel and allow natural channel and floodplain processes to take place.

YES – Implement practices with increasing rigidity appropriate to protect the value of the property. Keep in mind that the more rigid the practice for increased protection the more costly the practice, the more impacts to the channel and riparian lands, and the more permitting that is required.

What type of property is at risk to determine the required level of protection, acceptable project cost, and tolerable impacts?

Infrastructure, habitable structures, and other improved property – Utilities, town and state highways, homes, businesses, and factories that are essential to protect often require rigid practices that stabilize the banks and channel.

Other valued property – Outbuildings, moveable sheds, and farm fields may allow for deformable practices where flood and erosion risks are small and some flooding and erosion are tolerable.

Is property threatened by bank erosion where the channel moves laterally, or is the property in danger from damage where the stream or river could leave the existing channel and rapidly cut a new channel (i.e., avulse)?

Lateral erosion – Consider proximity of infrastructure or improved property to the eroding bank. Predict the rate of erosion based on hydraulics, sediment supply, and resistance of bank to erosion.

Avulsion – Consider potential future flow paths due to vertical and lateral changes in the channel in relation to the at-risk property location.

Is ample space available for the practice being considered?

NO – Avoid practices that encroach on the bankfull channel or isolate the floodplain. When protection of infrastructure or improved property must take place, minimize channel encroachment and design elements to dissipate stream energy to avoid additional flood and erosion risk.

YES – The practice fits on the bank or in the channel without encroaching on the equilibrium dimensions. Limiting encroachment is especially important in steep, narrow valley settings with high power where confinement often leads to erosion of the channel bed and collapse of bank stabilization practices due to undermining.

Is the valley confined or very broad?

Confined – Select practices that can resist excessive erosion of the bed and banks in narrow settings, especially if a portion of the naturally confined valley is occupied with infrastructure such as road embankments that increase confinement. Channel downcutting (i.e., incision), bank undermining, and bank erosion are common in confined settings.

Very broad – Very broad valley settings can be depositional areas where channels can fill with sediment, lose flood flow conveyance, and move laterally or avulse. Risks associated with sediment deposition and loss of conveyance are a concern where channel slope abruptly decreases and at confluence areas.

Can flood flows in the channel spill onto the floodplain?

NO – Lack of floodplain increases flood and erosion risks. Explore floodplain restoration practices to allow flows to spill onto the floodplain during small floods. Consider floodplain restoration with bank and bed stabilization practices for long-term risk reduction.

YES – Consider the flood relief elevation where flows spread onto the floodplain to guide practice design for more frequent floodplain activation, bank stabilization, bed stabilization, and structure improvements.

Do bedrock outcrops exist?

NO – Consider bed and bank stabilization practices, particularly in steep and confined settings.

YES – Consider locations of natural bedrock grade control on the channel bed and bedrock banks to understand whether stabilization is necessary and, if so, how the practice can tie into the existing features that provide resistance to erosion at the channel boundary.

Does the channel have high erosive energy (i.e., power)?

NO – Implement deformable practices as possible to achieve the desired level of property protection in less erosive settings.

YES – Implement practices with increasing level of rigidity to resist estimated or calculated shear stress to protect property. The combination of steep channel slope, confined channel setting, and 3rd to 4th order channels tends to produce the highest power and requires practices that are the most resistant to erosion and include hydraulic roughness elements. Practices in high-power settings should be coupled with creation or protection of upstream and downstream attenuation assets in the river corridor to reduce erosive force.

Is channel instability caused primarily by watershed-scale changes to hydrology or sediment transport?

NO – Implement preferred alternative(s).

YES – Implement preferred alternatives and initiate river corridor management (e.g., Kline, 2010) and watershed management to naturalize hydrology and sediment transport. If watershed stressors cannot be addressed in the near term, predict the magnitude of ongoing or increasing channel instability due to watershed conditions and consider them during the alternatives analysis and implementation to confirm practice durability.

4.3 Method

Having determined the river channel conditions and the adjustment processes associated with the observed damages, the river management practices that may be useful for recovery are selected (Figure 4.1). Keep the channel evolution stage and trajectory in mind while selecting alternatives to explore. For example, bank armoring alone is not likely to reduce erosion risks on a stream that is prone to downcutting and widening as the rock will be undermined.

An understanding of the Guiding Design Principles, including the Design Objectives, applicable to a range of river management practices will facilitate the alternatives analysis and design (Figure 4.2). Adherence to the principles will help identify alternatives that reduce future risks over the long term and will simplify project permitting since the recommended practices are based on the same Principal River and Floodplain Functions as those on which the Vermont Stream Alteration Rules are based.

The alternatives analysis decision trees are used to select one or more practices that appear to work for reduction of flood and erosion risks (Figures 4.3 to 4.8). The following questions are the entry point for the alternatives analysis trees.

Is there a threat to life or property now or with the next flood due to:

- **Bank erosion;**
- **Channel bed erosion;**
- **Floodplain disconnection;**
- **Loss of channel conveyance;**
- **The current channel location; or**
- **Loss of hydraulic roughness?**

The practices are generally organized by low to high impact from left to right across the alternatives analysis trees. The analysis begins with exploring the feasibility of the no-action alternative and moves on to more intrusive practices as the risks to infrastructure and habitable structures increase. Using a multidisciplinary team is ideal when the opportunity exists in order to address all considerations and properly carry out the alternatives analysis and design.

Once alternatives are selected for design, review the information about each practice in Section 5.0 or see the appropriate external design references (see Figure 4.2). Photographs, descriptions, notes on applicability, common mistakes, and estimated unit costs should be considered to decide if the selected practice is suitable to reduce flood and erosion risks at the project site. Several iterations between the alternatives analysis decision trees provided here, the practice information sheets in Section 5.0, and other references may be needed to finalize the selection of the preferred alternative(s). Reference to the supporting technical information in the appendices (under separate cover) may also be helpful to support decision-making and initiate design.

Legend
● = Primary Management Practice
○ = Secondary Management Practice

Observed River Channel Conditions and Adjustment Processes (From Tier 1)	Spatial Scale		River Management Practice Groups					
	Local Bankfull Scale	Reach or Valley Scale	Bank Stabilization	Bed Stabilization	Floodplain Restoration	Increase Channel Conveyance	Channel Realignment	Increase Hydraulic Roughness
BANK EROSION								
Bend scour on outside of meanders	x		●	○	○			○
Toe erosion and upper bank collapse	x		●	○	○			○
Erosion of both banks and channel widening		x	●	●	●			○
Tall and collapsing undermined banks		x	●	●	●		○	○
Valley wall erosion (mass failure)		x	●	○			○	○
Abandoned terrace erosion (mass failure)		x	●	○	○		○	○
CHANNEL BED EROSION								
Scour hole	x		○	●				
Head-cutting	x		○	●	○			○
Bend migration (minor avulsion possible)	x		○	●	●			○
Lack of small sediment (e.g., gravel) in channel	x			●	○			●
Channel down-cutting (degradation or incision)		x	●	●	●		○	●
Channel in new location (major avulsion)		x	●	●	●		●	●
Floodplain scour		x	●	●	●		○	●
SEDIMENT DEPOSITION								
Bar formation	x		●		○	○		
Altered flow path	x		●		●	○	○	○
Increased overbank flow and minor deposition	x		●		●	●		
Channel elevation (aggradation)		x	○	○	●	●		
Sediment damming and major avulsion possible		x	●	●	●	●	●	●
Floodplain aggradation		x	●	●	●	●	●	●
LWD ACCUMULATION								
Debris jam in channel	x		●		○	○		
Altered flow path	x		●		○	○	○	○
Widespread debris deposition		x	●	○	●	●		
Channel aggradation		x	○	○	●	●		
Damming and major avulsion possible		x	●	●	●	●	●	●
Debris jam on floodplain		x	●	●	●	●	●	●

Figure 4.1: Groups of river management practices that are applicable to river channel conditions and processes.

	Guiding Design Principles				Practice Design References‡	
River Management Practices Listed By Group§	Lateral	Vertical	Conveyance	Crossing*	Standard Practice Section	External Documents
BANK STABILIZATION						
Existing bank to remain in post flood location (no action)	√	√			4.3	
Create gentle slope on steep eroded banks	√					A, B
Bioengineering applications on bank	√					A, B, C, D, E, J, L, M, O
Root wad revetment	√					A, B, E, J, M, O
Engineered log jam	√	√				F, G, H
Stone toe of slope with vegetated upper bank	√				5.2	A, B, E, J
Sloped riprap bank	√	√			5.2	I, J, K, M, O
Placed riprap wall	√	√			5.2	I, L
Toe armor on mass failure	√	√			5.2	I, L
BED STABILIZATION						
Existing bed to remain (no action)	√	√			4.3	
Re-install native channel sediment to elevate bed	√	√	√		5.3	
Weirs and vanes	√	√			5.4	G, M, N, O
Stone strainers and riffles		√			5.4	G
Bed armoring	√	√	√		5.4	
FLOODPLAIN RESTORATION						
Existing floodplain to remain (no action)	√	√			4.3	
Flood chute restoration	√	√	√		5.5	G
Bench restoration	√	√	√		5.5	J, G
Floodplain restoration (remove berms, lower floodplain, raise bed)	√	√	√		5.6	G

Levels of protection, cost, and impacts increase with more rigid practices.

§Practices within each category are listed in order of increasing structural control. Passive practices provide the channel space and floodplain connection for processes to occur that are compatible with EQU now or in the future. More rigid practices have greater impacts to the channel and are most commonly used as emergency protective measures. Rigid practices should minimize departure from EQU to meet state Performance Standards.

*Crossing guidance will be required for other practices where a bridge or culvert exists.

‡Citations are listed at the bottom of the table on the next page and full reference information and internet access address are in the bibliography.

Figure 4.2: River management practices listed by group showing the applicable Guiding Design Principles and location of design information.

River Management Practices Listed By Group§	Guiding Design Principles				Practice Design References‡	
	Lateral	Vertical	Conveyance	Crossing*	Standard Practice Section	External Documents
CHANNEL REALIGNMENT						
Retain current channel alignment (*no* action)	√	√			4.3	
Allow space for meander re-development	√	√	√			Q, R
Re-align channel to pre-flood location	√	√			5.7	P
Move channel away from infrastructure or eroding banks	√	√	√		5.7	P
INCREASE CONVEYANCE						
No active channel work, plan for long-term erosion (no action)	√	√	√		4.3	S, T
Remove sediment and woody debris blocking bridges/culverts	√	√	√	√	5.7	S, T
Remove sediment and woody debris filling channel	√	√	√		5.7	S, T
Remove sediment and woody debris filling floodplain	√	√	√		5.7	S, T
INCREASE HYDRAULIC ROUGHNESS						
Preserve natural river bed armor stones		√	√			S, T
Retain sediment bars in channel	√	√	√			S, T
Re-vegetate banks	√					C, G
Re-vegetate floodplain	√	√				C, G
Re-install instream boulders		√	√			G, M
IMPROVE STRUCTURES						
Existing structures to remain (no action)	√	√	√	√		
Remove post-flood sediment levees along floodplain	√	√	√		5.7	G
Berm removal	√	√			5.6	G
Move berms/levees to back of historic floodplain	√	√	√		5.6	G
Bridge/culvert retrofit	√	√	√	√	5.8	
Bridge/culvert replacement	√	√	√	√	5.8	U, V
Dam removal	√	√	√	√		X, Y, Z

Citations
A. Eubanks and Meadows, 2002
B. Allen and Leech, 1997
C. Bentrup and Hoag, 1998
D. NWRPC, 2004
E. NRCS, 2007
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G. Cramer, 2012
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U. FHWA, 1985
V. Richardson and Davis, 1995
W. MacBroom and Schiff, 2013
X. Aadland, 2010
Y. EOEA, 2007
Z. AR, 1999

Figure 4.2 (continued): River management practices listed by group showing the applicable Guiding Design Principles and location of design information.

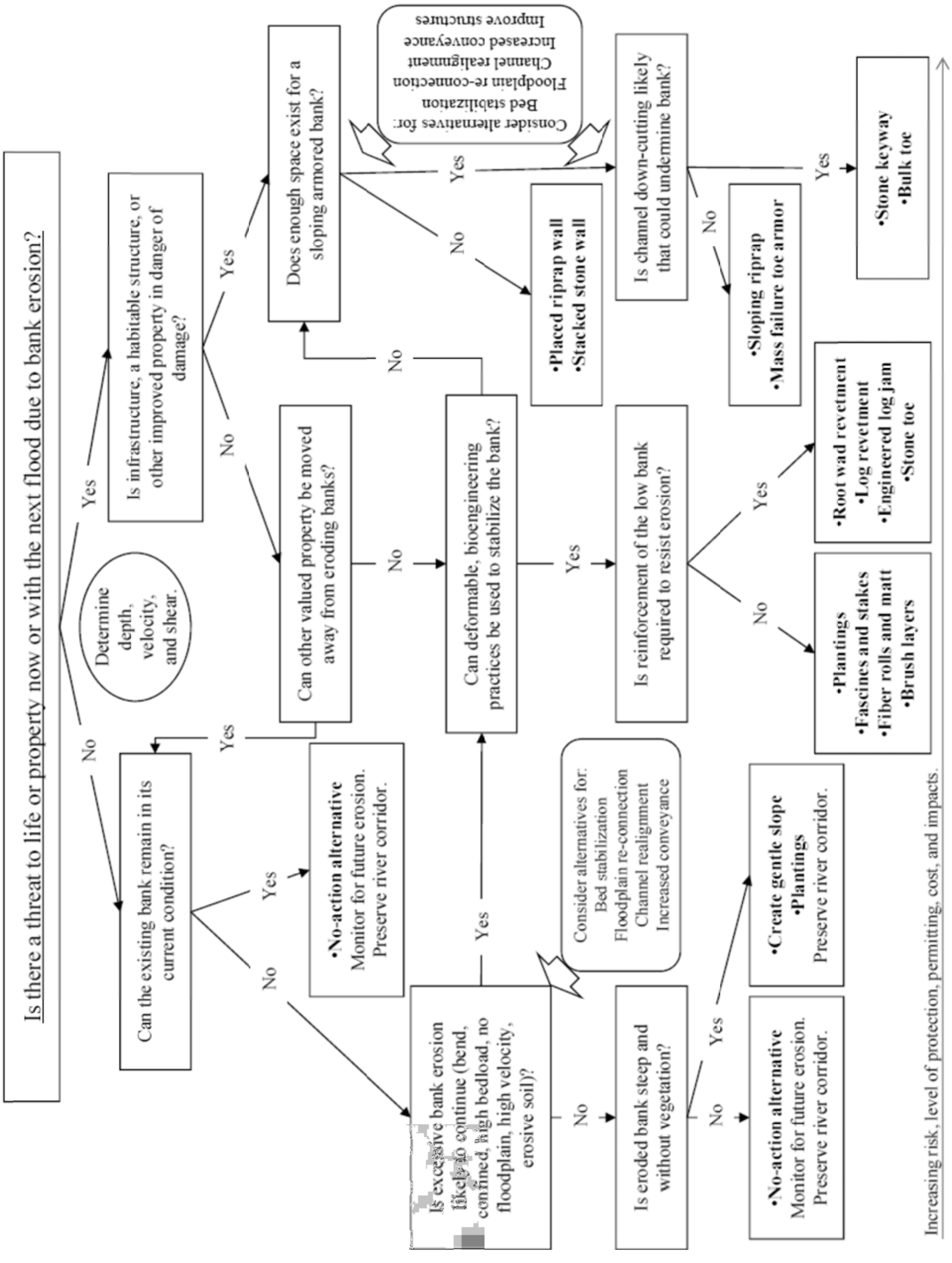


Figure 4.3: Bank erosion alternatives analysis decision tree.

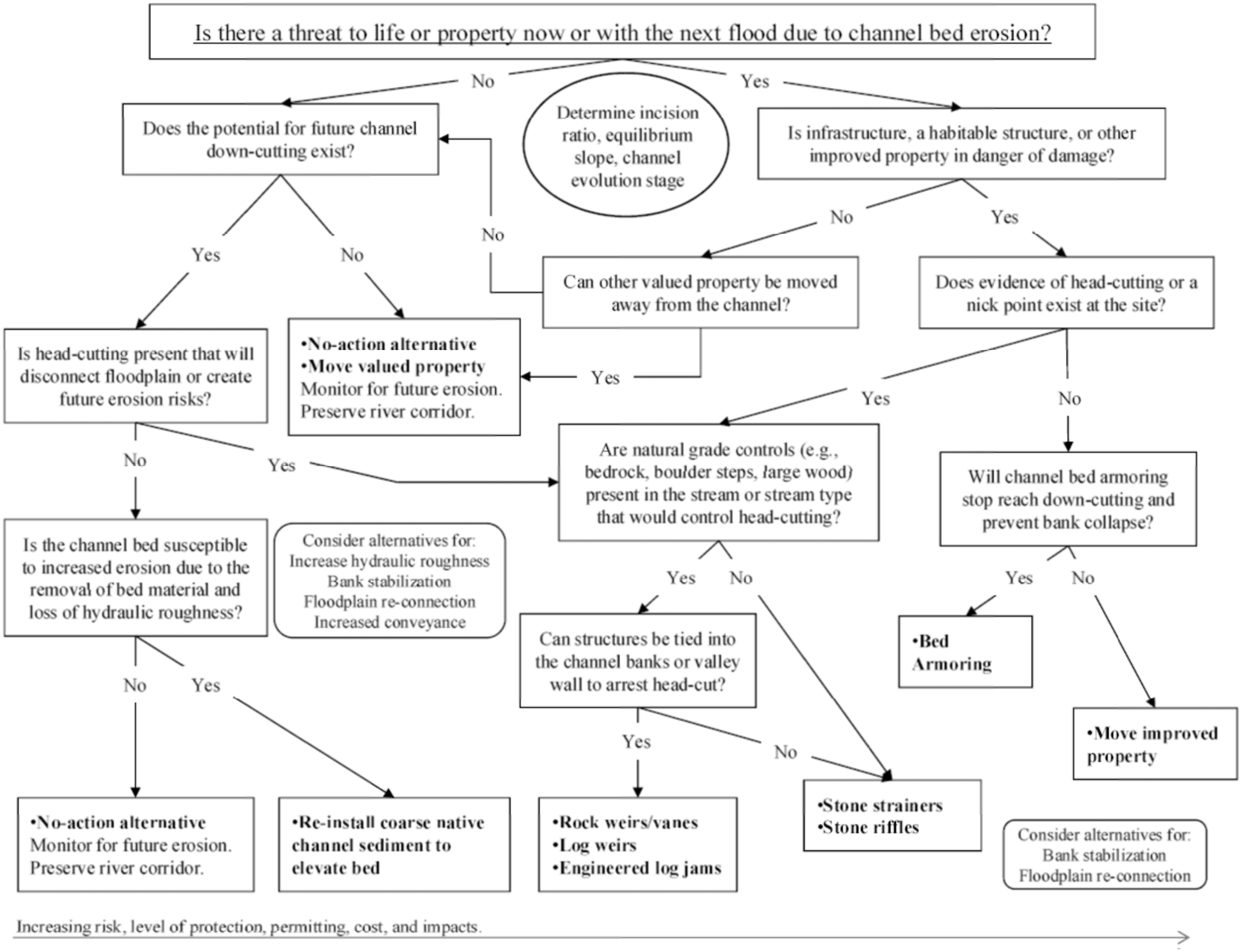


Figure 4.4: Bed erosion alternatives analysis decision tree.

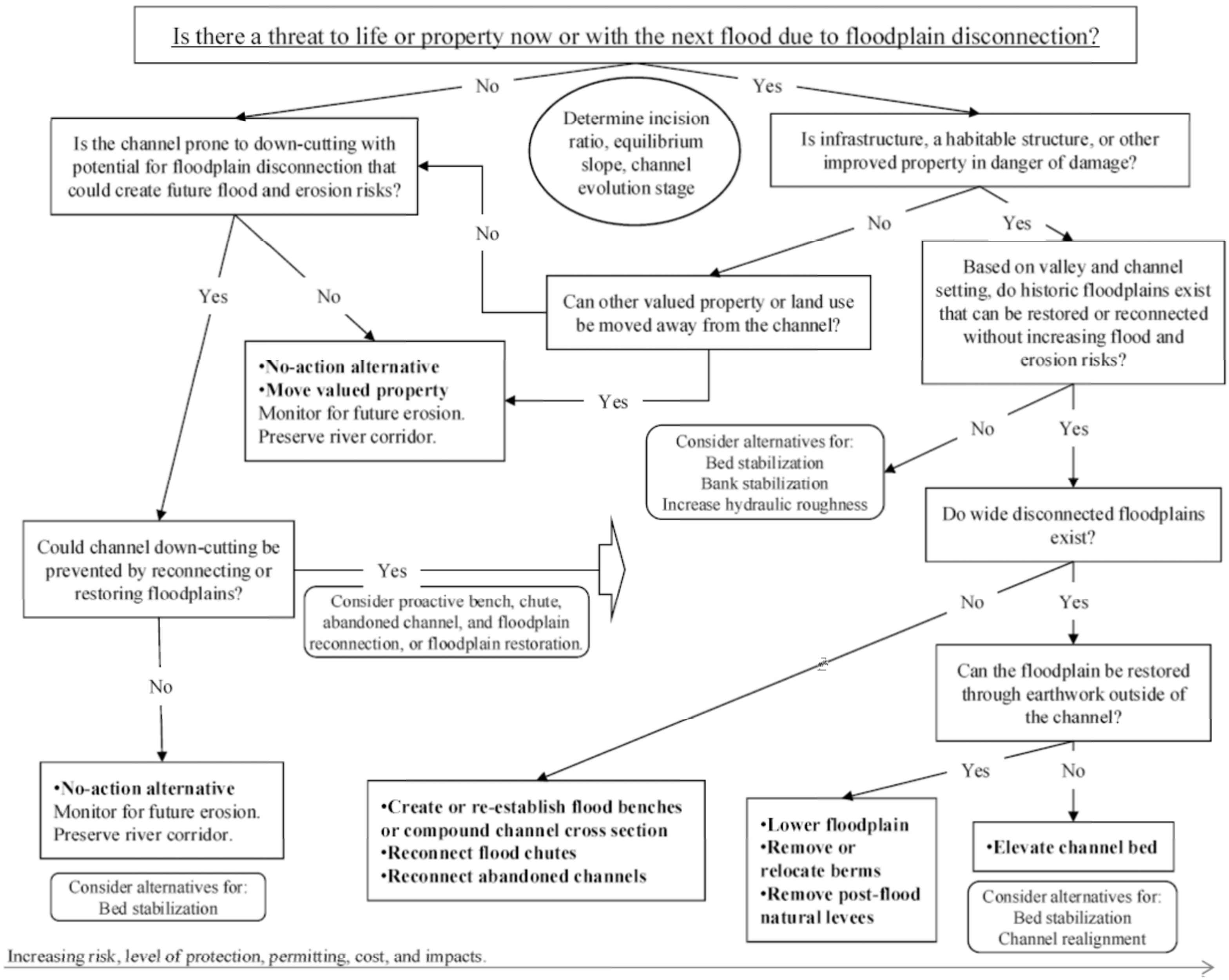


Figure 4.5: Floodplain disconnection alternatives analysis decision tree.

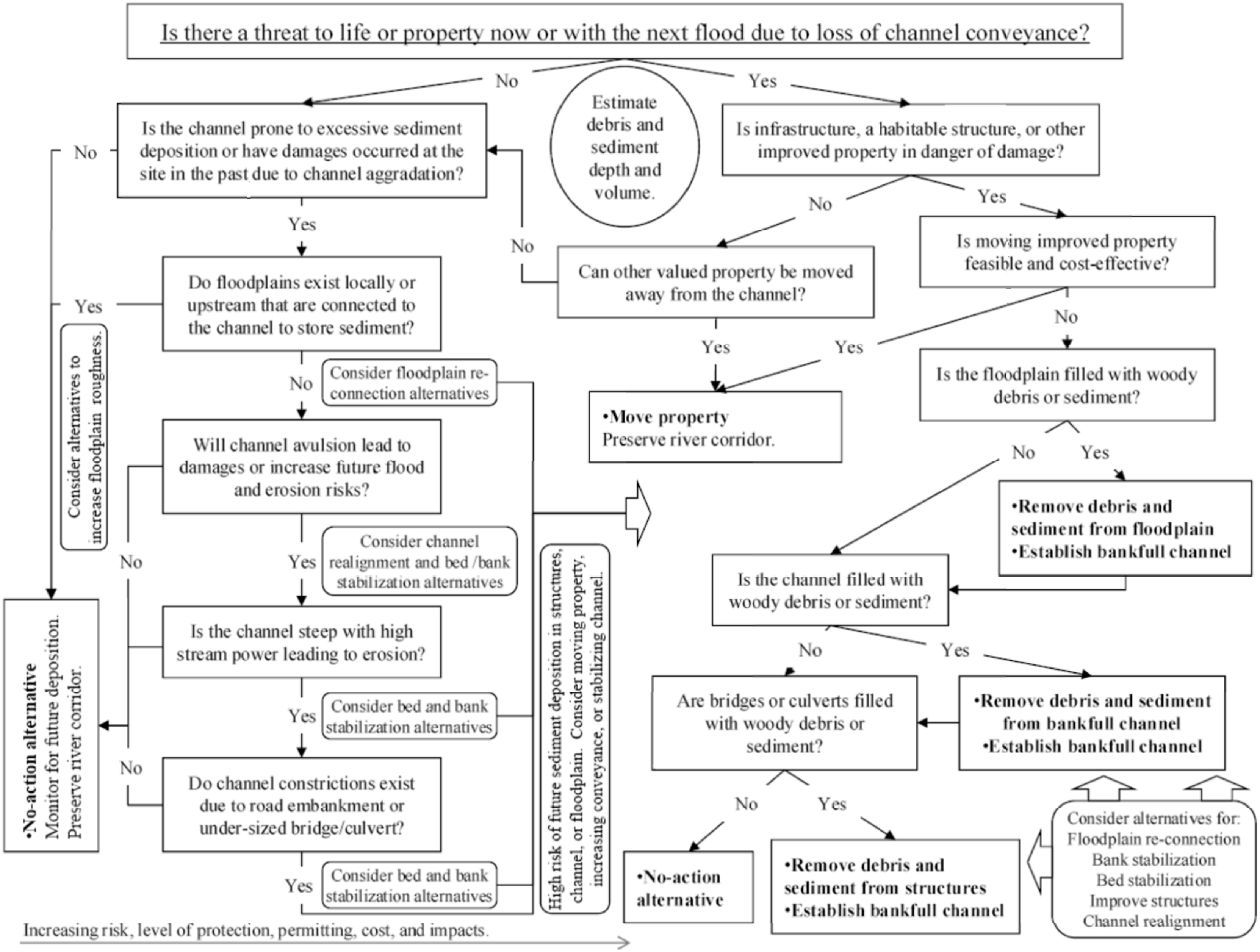


Figure 4.6: Loss of channel conveyance alternatives analysis decision tree.

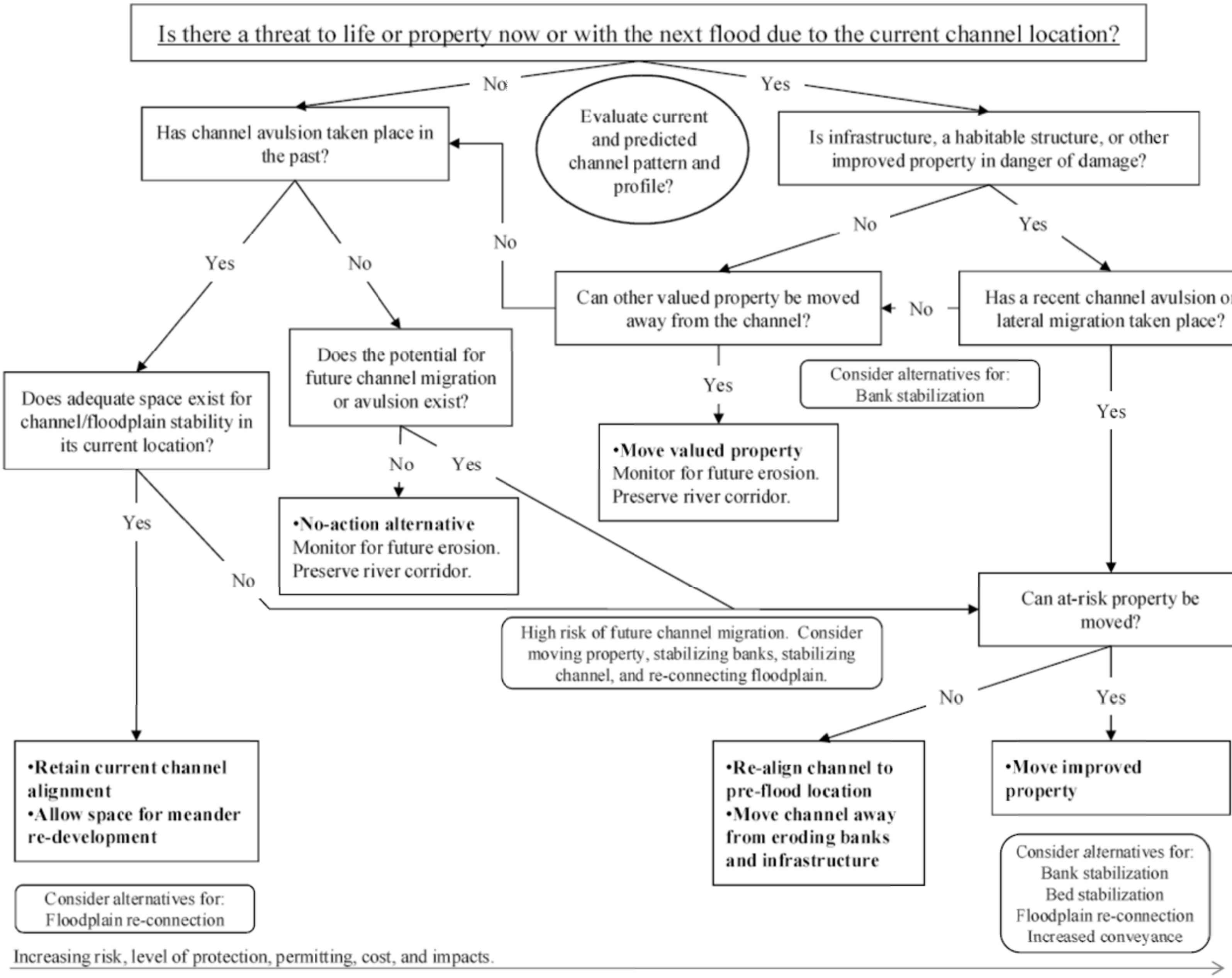


Figure 4.7: Channel misalignment alternatives analysis decision tree.

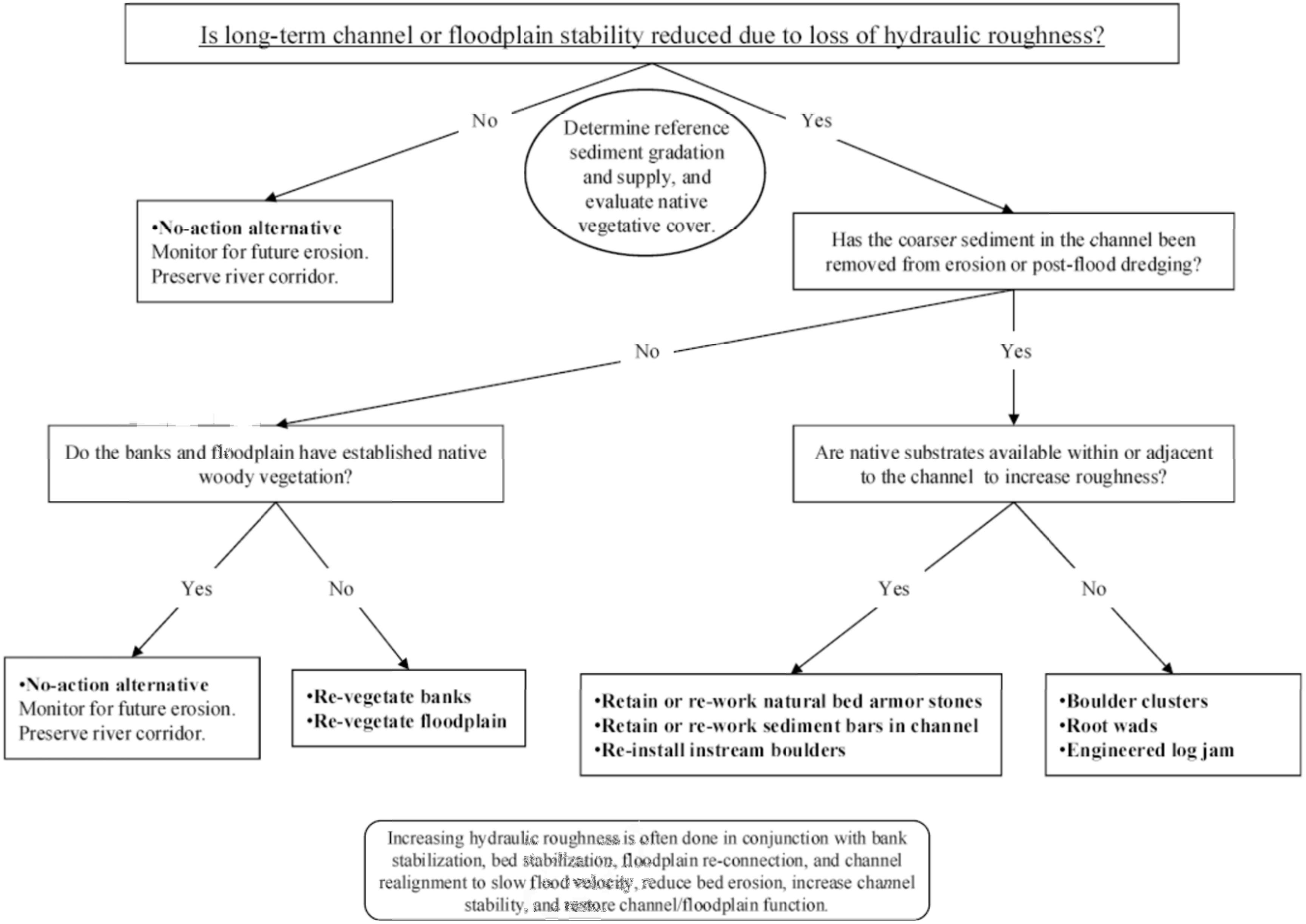


Figure 4.8: Loss of channel roughness alternatives analysis decision tree.

5.0 VERMONT STANDARD RIVER MANAGEMENT PRACTICES (TIER 3)

- *What are the preferred practices for flood recovery to minimize future risks?*
- *What are post-flood design and implementation approaches?*
- *What are the common design variations of river and floodplain practices that can be used for varying site conditions?*
- *What are the common constraints to practice implementation and how can they be overcome?*
- *What are the most common mistakes that must be avoided?*
- *What practices are prohibited by law and why?*
- *What practices are limited by law, and when should these be considered?*
- *What is the preferred timing of practices to avoid creating new or exacerbating existing hazards in relation to a flood event?*
- *What jurisdictions are involved in flood recovery for permitting and potential funding?*
- *To whom shall I turn for help with alternatives analysis and design?*

5.1 Introduction

The following seven practices are described below:

1. Placed riprap wall;
2. Natural bed stabilization;
    - Reinstall native channel sediment to elevate bed
3. Grade control;
    - Weirs
    - Stone riffles
    - Stone strainers
    - Bed armoring
4. Bench and flood chute restoration;
5. Floodplain restoration;
6. Remove sediment and woody debris filling channel/floodplain; and
    - Vertical stability
    - Channel realignment
    - Proactive sediment management plan
7. Bridge/culvert replacement.
    - The geomorphic-engineering approach

Each section mostly stands alone so that it can be used individually to guide design. Reference is made to supporting information in the technical appendices (Tier 4) under separate cover.

Each practice sheet contains the following sections:

- Description
    - Includes annotated photographs
- Application
    - Proper use
    - Meeting the Design Objectives
    - Limitations
    - Geomorphic context
    - Habitat maintenance
    - Common mistakes
    - Compatibility with emergency temporary repairs and timing of implementation
- Site Work Constraints
- Primary Design Elements
    - Design checklist
- Costs
    - Unit ballpark cost
    - Funding reimbursement requirements
- Permitting
- Construction
    - Constructability
    - Temporary construction controls
    - Access
- Conceptual Design Plans/Details
- Summary of Supporting Design Information in Appendices
- Possible Companion Practices
- Similar Practices

5.2 PLACED RIPRAP WALL

Placed Riprap Wall Design

Assessment
- Location, length, width, and height of bank erosion
- Adjacent land use and property
- Risk of continued erosion and damages

Design
- Rock type and sizing
- Wall location and alignment
- Keyway thickness and depth
- Height and slope
- Bedding
- Revegetation

DESCRIPTION

The placed riprap wall is rigid bank stabilization to protect infrastructure, buildings, and unmovable improved property in a confined channel setting where sloping stone riprap transitions to a nearly vertical wall at the edge of the channel (Figure 5.2-1). This practice is used where space does not exist for the more common uniformly sloping riprap. The placed riprap wall is also referred to as riprap with stone toe wall, imbricated riprap, stone armor, and riprap.

Figure 5.2-1: Placed riprap wall on the North Branch of the Hoosic River along Route 100 in Stamford, Vermont installed following Tropical Storm Irene where the roadway embankment and surface were eroded. (Source: Milone & MacBroom, Inc., 11/8/2012)

APPLICATION

Proper Use

The placed riprap wall is often the least-cost alternative for bank stabilization in confined settings with infrastructure prone to repeat erosion damages such as narrow road corridors. The practice is more expensive than vegetative approaches yet is more resistant to erosion in high power settings such as steep channels and 3rd and 4th order streams that tend to have the ability to do the most erosion during floods (Knighton, 1999). Placed riprap walls installed in river corridors that are more than 25% filled with a road embankment are likely to experience strong scouring flows during flooding.

A traditional sloping riprap application is commonly used where the proposed slope repair will not encroach on the bankfull channel dimensions (see Figure 4.3). Many of the design considerations below for the placed riprap wall also apply to the more common sloping riprap bank armor. For further information, refer to existing riprap design guidelines (see sloping riprap bank, Figure 4.2).

Meeting the Design Objectives

- Create lateral channel stability while retaining target channel bankfull width in confined settings and reducing fill compared to common uniformly sloping riprap.
- Set keyway invert elevation based on history of channel downcutting to maximize wall and vertical channel stability. Link to other vertical channel stability practices at sites with excessive bed erosion.
- Return native boulders to riverbed often located in bank to offset historic channel downcutting, improve floodplain access, increase channel roughness, decrease energy grade, reduce flood velocity, and improve instream habitat.
- Establish low or flood benches where possible to lower flood velocities and reduce future erosion risks.

Limitations

- Introduction of non-native stone to riverbank.
- Difficult to re-establish bank vegetation.
- Sourcing large angular or blocky rock can be difficult and expensive.
- Installation requires more skill by machine operator to construct wall, transitions, and tie-backs. Building a placed riprap wall can take longer than installing a traditional riprap application and is thus more costly.
- Geotechnical analysis is typically required for taller slopes where the height of the wall is larger than 6 feet and in areas dominated by silts and clays.

Geomorphic Context

The placed riprap wall is most commonly applied along small to moderate-sized mountain streams in narrow river corridors, particularly those with roadways located next to the stream. Applications typically occur along 4th order (Strahler, 1952) or smaller channels in the middle or upper watershed. Larger channels often have space for uniformly sloping riprap (USACE, 1994; Lagasse et al., 2009; FHWA, 2012b) and thus a wall is not needed. Placed riprap walls are typically applied on step-pool, riffle-pool, and plane bed channel types (VTANR, 2009).

Floodplains are often narrow in the smaller mountain channels where a placed riprap wall may be installed and typically take the form of flood benches at the base of valley walls. These benches are important flood relief mechanisms in narrow river corridors, and use of the placed riprap wall allows for these small floodplain areas to be maintained or expanded.

The placed riprap wall is often placed in excessively confined settings along road embankments and, thus, channel bed and bank erosion and channel downcutting are typical. The narrow channels tend to transport sediment during floods, yet sediment deposition can take place upstream of narrow valley locations such as bedrock cuts, undersized bridges and culverts, and upstream of large meander bends. Flows tend to be variable in mountain channels, with extreme low flows in summer, where much of the flow can take place within the coarse riverbed. Flow in steep mountain channels can be extremely high during intense mountain storms, rain on snow thaw floods, ice out, or large regional storms such as nor'easters and tropical storms.

An important consideration in narrow corridors filled with improved property is the extent that the channel wants to move across its valley. Floods confirm that the present location of many single-thread meandering channels is really a single snapshot of a wandering stream (Church, 2002) that moves across the valley during extreme flood events primarily in response to large loads of sediment and debris moving through the system. The location of the placed riprap wall should maximize the space for the channel to wander in these settings.

Habitat Maintenance

- Limit impacts to downstream habitat by working from the edge of channel and isolating the main flow away from the base of wall.
- Improve aquatic habitat at the stone-water interface with the intentional arrangement of stone at the base of the wall.
- Replace cobbles and boulders to roughen the streambed in post-flood setting.
- Reduce need for repeat bank and channel work.

Common Mistakes

- Rock size too small.
- Wall not thick enough in all dimensions to resist flood flows.
- Base of wall located too far from bank closing off river channel.
- Rocks protruding out from wall that will be knocked off during flooding.

- Voids in large riprap not filled.
- Wall height too tall.
- Keyway located too shallow in high erosion areas.

Compatibility with Emergency Temporary Repairs and Timing of Implementation

- In confined setting where repeat damages have occurred, consider implementing the placed riprap wall during emergency repairs as encroachment with uniformly sloping, undersized stone riprap creates a false sense of protection and can often increase the risk of damages during the next flood.
- After a flood damages a road next to a stream channel with tall banks, there is an opportunity for less costly construction access to the stream because the area will already be accessed to repair the road.
- Less fill will need to be excavated during construction if the project is implemented following erosion of the embankment.
- Working in a channel that has been naturally disturbed from flooding immediately after the event will minimize the length of time required for the stream ecosystem to recover.
- The extent of flooding in the area and state will influence the length of time road closures are tolerable for implementing the placed riprap wall. One-lane traffic is required for emergency vehicles. Off-road haul units may be required where only a single lane exists following flooding.

SITE WORK CONSTRAINTS

The extent of damages and what is exposed to future damages often dictate the pace that work is completed. The reclamation and protection of vital public infrastructure against lateral channel migration will take precedence over most site constraints. A rush often takes place to reopen critical regional roadways, yet this fast work pace can lead to the need to redesign and reconstruct the same project in the future. Taking a short amount of time to follow the principles and practices presented here, such as by confirming the use of proper rock size and retaining the bankfull channel width, will limit the need for future repair work and ultimately decrease the project duration.

Work in cities or villages may be constrained by complex access, high traffic volume, the presence of abundant utilities, and reduced work hours compared to rural settings. Work in rural areas can likely proceed at a faster pace due to fewer obstacles.

PRIMARY DESIGN ELEMENTS

Rock Type and Sizing

Large angular to blocky rock should be used for stacking to create the placed riprap wall. Rock sizing must be performed to ensure that the wall will resist erosion due to the design flood flow velocity and geotechnical forces. The typical approach to sizing rock is to choose a size that has a larger critical velocity (e.g., Fischenich, 2001) (Appendix F) than the measured or calculated velocity in the channel when movement is expected. Rock sizing based on velocity must account for the expected velocity distribution in the channel such as where velocity is highest on the outside of a meander bend.

Flood history and geomorphic condition of the channel must be considered to properly size rock. In steep, confined channels, large rock is often required to provide adequate resistance to bank erosion. Standard rock size guidance (e.g., Table 5.2-1) may need to be replaced with modified large riprap specifications (Appendix G) in erosion-prone areas or with a more in-depth analysis (FHWA, 1983; Kilgore and Cotton, 2005). Notes should be included on design plans along with the specified rock for riprap to guide proper installation (Appendix H).

Table 5.2-1: VTrans Standard Rock Sizing (Source: VTrans, 2014)

Fill Type	Median rock size, range (inches)	Velocity (fps)
I	4, 1 – 12	≤ 6
II	12, 2 – 36	6 – 12
III	16, 3 – 48	12 – 14
IV	20, 3 – 60	14 – 16

One of the common methods to estimate rock size is the Isbash Method (1963) (Figure 5.2-2).

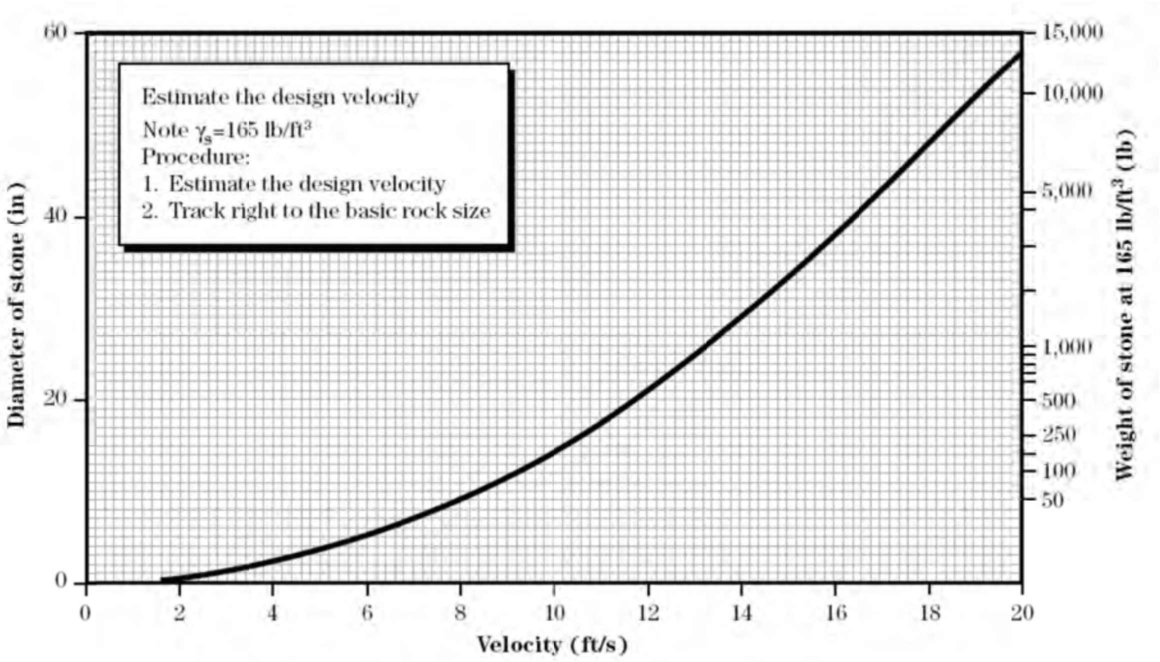


Figure 5.2-2: Rock sizing based on the Isbash curve. (Isbash, 1963; NRCS, 2007a)

Rock sizing is also performed based on the calculated or modeled shear stress during the design flow. $\tau_c = \tau_c^* (1.65)\, \gamma_w\, D50$ where τ_c^* is the Shield's Parameter that is 0.6 for normal material and 0.06 to 0.1 for dense material with a mixed grain size.

Rock sizing should be linked to the vertical location of the bankfull channel and floodplain. Size can often be reduced once the elevation of the floodplain is reached as flows can spread out and slow down (see plans below).

For emergency situations where immediate stabilization of a bank is necessary for protection of critical infrastructure and public safety, an on-site identification of the size of rock that remained immobile in the channel during the flood is an acceptable estimation of the size of rock needed for stabilization.

Riprap Wall Location

The toe of the riprap wall on the face closest to the channel must be properly located in the field to retain at least the target bankfull channel width. Paint marks, flagging, or offsets should be used to set the toe location during construction.

Armor Depth

The toe of the riprap wall can be established by a rock keyway (i.e., rock in a trench below the channel bed), a bulk toe (i.e., thicker volume of rock fill on the channel bed surface), or by bed armoring when full bed stabilization is required (see Section 5.4). A bulk toe is used where adequate lateral space exists for a wider rock application without encroaching on the bankfull channel width and where the channel is not likely to deeply incise. A keyway integrates well with a placed riprap wall and tends to lead to less encroachment than a bulk toe. Although bed armoring is more costly and can lead to larger temporary construction impacts to the channel, this approach can minimize lateral encroachment and is therefore an important alternative to consider in confined, high-power settings.

The depth of a keyway should be placed below the current elevation of the lowest point in the channel bed (i.e., thalweg) to protect the wall from undermining. Keyway depths below the channel bottom shall be determined from the current amount of channel incision, the stage of channel evolution (CEM) (Appendix E), and the anticipated channel change (Table 5.2-2). For braided and wandering dynamic channel types prone to sediment deposition and avulsion, keyway depths should be at least 4 feet deep.

Table 5.2-2: Keyway Depths Based on Channel Incision and Evolution

Depth (feet)	Incision Ratio	CEM Stage	Predicted Channel Change
1-2	1.0 – 1.2	I, V	Constant or aggrading
2-4	1.2 – 1.4	II, III, IV	Moderate incision
4-6	1.4 – 1.6	II, III, IV	Moderate to severe incision
>6	>1.6	II, III	Severe incision or entrenchment

Keyway depth should also be determined based on the position of the project site in the channel alignment. Scour depth estimates based on multiples of bankfull depth can be used to confirm proposed keyway depths (TAC, 2001) (Table 5.2-3). Scour is typically at its highest at the outside of meander bends and, thus, keyways should be deepest on bends.

Table 5.2-3: Predicted Scour (or Keyway) Depth Based on Location in Channel Alignment (Source: TAC, 2001)

Depth (Multiple of $D_{bankfull}$)	**Channel Alignment Location**
1.25	Straight
1.5	Moderate bend
1.75	Severe bend
2.0	Abrupt right-angle turn
3.5	Sub-surface sill

In narrow, confined channels where little space may exist for a bulk toe or keyway, the placed riprap wall can be tied into bed armoring to maintain the bankfull channel dimensions and limit the potential for channel downcutting (see Section 5.4).

Wall Height

The height of the riprap wall must be set with consideration of the elevation of the bankfull channel and floodplain and to keep the wall structurally stable. A maximum wall height of 6 to 8 feet is recommended unless a geotechnical analysis is performed that confirms a taller wall will remain stable during flooding.

Side Slopes

The maximum slope of the face of the wall (i.e., batter) on the placed riprap wall is 1H:6V. A more gentle batter of 2H:6V is common. Rocks should be placed on the wall without protrusions so that high flows will not dislodge any single elements. The target slope of the sloping riprap above the wall is 2H:1V, with a maximum of 1.5H:1V. Sloping riprap bank protection is often installed with a slope of 3H:1V.

Bedding

Granular bedding (Appendix I) is recommended behind the placed riprap wall and riprap slope to prevent fine material from piping through the crevices in the large rock. Smaller riprap should also be used to fill voids in the larger stones. The thickness of the bedding is typically at least 6 inches. Filter fabric may be used where the banks consist of silts and clays. Fabric underlayments on steeper banks can lead to failure of the riprap due to loss of friction and, thus, granular bedding is preferred.

Revegetation

Vegetation should be installed on the banks as much as possible to help stabilize the ground surface, locally filter runoff, and enhance near-bank habitat in the channel. Stockpiled grubbing material can be placed on the riprap slope leading down to the stone wall and seeded to establish perennial vegetation. Shrubs and trees can be planted in the joints of the riprap in areas where taller vegetation is acceptable (Appendix J).

COSTS

The ballpark cost of installed placed riprap wall per linear foot is $550. This cost is primarily controlled by the availability and proximity of large rock to build the base of the wall. The labor for construction of the placed riprap wall is higher than for a uniformly sloping riprap application due to the required placement of more of the rocks.

Thorough documentation is required when seeking reimbursement from funding agencies. Information and applications should be filed prior to construction in nonemergency scenarios. After-the-fact submissions must take place in emergency situations.

- GPS the perimeter of the application to get the length and footprint.
- Record the design volume of rock called for and typical cross section.
- Identify the amount of fill removed from the channel.
- Note what property the placed riprap wall is protecting.
- Is the installation a repair of a previous riprap installation?
- Has the bank been moved back, or does it exist in its original location?
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or immediately after work if emergency.
    - Federal Emergency Management Agency (FEMA)
    - Natural Resources Conservation Service (NRCS)
    - United States Army Corps of Engineers (USACE)
    - Vermont Agency of Natural Resources (VTANR)
    - Vermont Agency of Transportation (VTrans)
    - Municipality
- Document how the project meets applicable State Performance Standards and permit requirements.

PERMITTING

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
    - Quantify length, area, and volume of disturbance below ordinary high water (OHW) (Appendix K)
    - Identify reporting category
    - Contact Vermont Field Office
- Vermont Stream Alteration Permit
    - Meet Performance Standards as identified above
    - Identify reporting category
    - Contact river management engineer
- Local Zoning Permit
    - Contact Town Administrator for reporting needs

CONSTRUCTION

Constructability

Experience in constructing the placed riprap wall is growing as the application is common on recent flood damage sites. Large machinery and a good supply of large rock are needed for proper and efficient construction. Closure of a single lane of traffic is often required, and sites with taller road embankments may require removal and replacement of a travel lane to establish a work platform at the proper height to reach the bottom of the keyway.

Temporary Construction Controls

Water control is the primary challenge when building the placed riprap wall since work is taking place at the edge of the active channel, and the keyway typically extends below the bottom of the channel. The work area where the base of the wall is to be located is often isolated from the main flow by placing excavated gravel and cobble from the bank, edge of channel, or recent dredge spoils in the area to form an elevated work platform. The platform allows the machinery to remain off the channel bed most of the time and to isolate turbid water in the keyway hole from the main flow.

Project demarcation fence is typically not needed where lane closures are taking place as access to the work area is impossible. Demarcation fencing is needed in any location that the public could come in contact with the placed riprap wall work area, staging locations, or stockpiles. Silt fencing may be required around stockpile areas to control the movement of fine sediment during construction. Refer to the VTrans Construction Specifications (VTrans, 2011) for guidelines on locating and identifying staging and stockpiling areas.

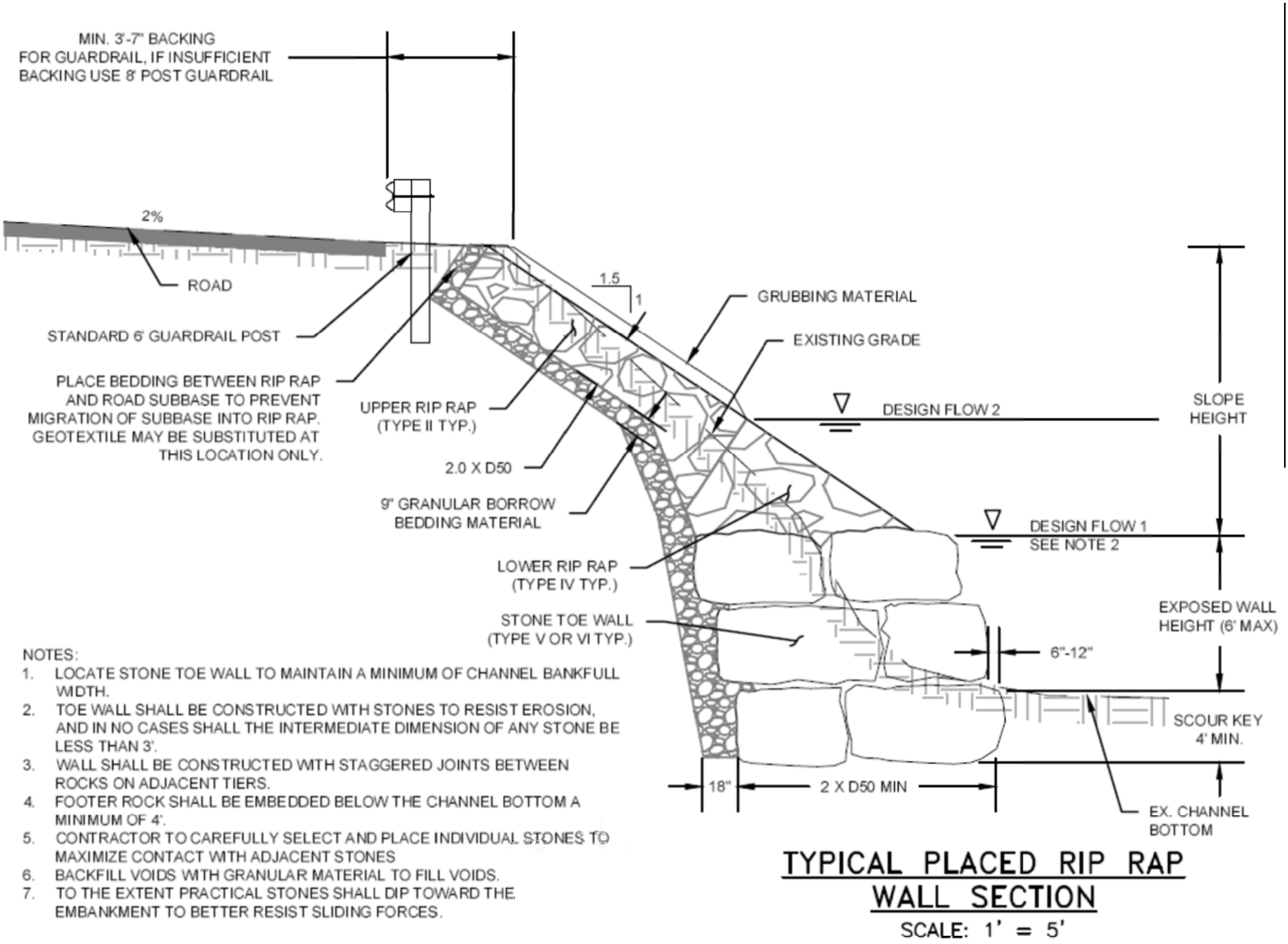
Access

Access to build the placed riprap wall is often made from state or municipal roads. Ownership of proposed access locations must be verified by reviewing roadway right-of-way mapping and local parcel mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access must take place across private land, agreements with the landowners are common. Access agreements typically include discussions or notes about returning the land to the original condition following the project. Planting of the upper bank with perennials, shrubs, and trees may be requested to naturalize the site following the construction work.

For larger projects or those likely requiring frequent future maintenance, easements can be drafted to allow periodic access for specified work such as flood damage repair or sediment management.

CONCEPTUAL DESIGN PLANS/DETAILS



NOTES:

1. LOCATE STONE TOE WALL TO MAINTAIN A MINIMUM OF CHANNEL BANKFULL WIDTH.
2. TOE WALL SHALL BE CONSTRUCTED WITH STONES TO RESIST EROSION, AND IN NO CASES SHALL THE INTERMEDIATE DIMENSION OF ANY STONE BE LESS THAN 3'.
3. WALL SHALL BE CONSTRUCTED WITH STAGGERED JOINTS BETWEEN ROCKS ON ADJACENT TIERS.
4. FOOTER ROCK SHALL BE EMBEDDED BELOW THE CHANNEL BOTTOM A MINIMUM OF 4'.
5. CONTRACTOR TO CAREFULLY SELECT AND PLACE INDIVIDUAL STONES TO MAXIMIZE CONTACT WITH ADJACENT STONES
6. BACKFILL VOIDS WITH GRANULAR MATERIAL TO FILL VOIDS.
7. TO THE EXTENT PRACTICAL STONES SHALL DIP TOWARD THE EMBANKMENT TO BETTER RESIST SLIDING FORCES.

Figure 5.2-3: Placed riprap wall typical detail. (Source: Dubois & King and Milone & MacBroom, Inc., 5/1/2014)

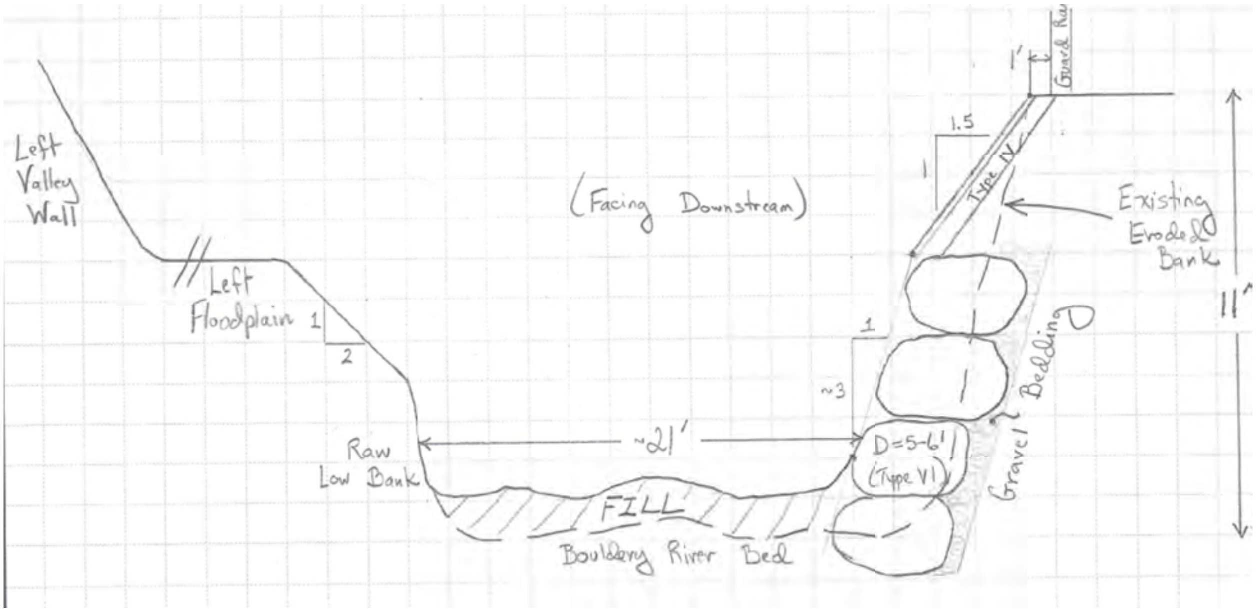


Figure 5.2-4: Placed riprap wall design sketch showing large stone placement in confined setting up to floodplain elevation and then smaller stone in wider flow setting. (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental Associates, 7/30/2012)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- Critical velocity and shear stress (Appendix F)
- Modified large-rock specifications (G)
- Riprap design notes (H)
- Riprap granular bedding (I)
- Joint plantings for riprap (J)
- Ordinary high water (K)
- Channel evolution model (E)

POSSIBLE COMPANION PRACTICES

- Transition placed riprap wall sections into traditional sloping bank armor and keyway as channel widens and target channel width can be met without use of placed riprap wall.
- Natural bed stabilization (Section 5.3)
- Grade control (Section 5.4)
- Flood bench and chute restoration (Section 5.5)
- Floodplain restoration (Section 5.6)

SIMILAR PRACTICES

- Riprap Sloped Bank – Common method used when ample space exists for traditional sloped application without encroaching on the bankfull channel. Refer to existing guidelines for common methods (e.g., FHWA, 1989; NRCS, 2004).

Stacked Stone Wall – Blocky rock wall with staggered joints, stringers running longitudinally down wall, and tie back rocks running from face of wall into the slope behind the wall. The finished wall acts like a single structure with rock faces that are more uniform and smooth than a placed riprap wall (Figure 5.2-5).

Figure 5.2-5: Stacked stone wall under construction on Stony Clove Creek in the Catskill Mountains, Chichester, New York. (Source: Milone & MacBroom, Inc., 7/16/2012)

Pin Wall – A stacked stone wall with vertical drilled holes through the wall elements and rebar reinforcing pins placed in the holes to add strength to the structure. The pin wall will typically remain in place longer than the stacked stone wall.

5.3 NATURAL BED STABILIZATION

DESCRIPTION

Natural Bed Stabilization Design

Assessment

- Longitudinal profile
- Geomorphic stream type
- Bankfull width and depth
- Equilibrium sediment slope
- Pattern (i.e., meandering, braided, wandering)
- Roughness elements
- Intact natural bed armor layer
- Incision ratio
- Channel evolution

Elevate and Roughen Channel Bed

- Upstream and downstream limits and target channel slope
- Length, width, and depth of the channel to be elevated with native substrate
- Volume of sediment to be reinstalled
- Volume and gradation of sediment available along channel margins and in floodplain

Elevating the channel bed is performed to reduce risk by moving the channel closer to its equilibrium by installation of available river sediment. Natural bed stabilization is commonly used:

1. When historic flood recovery work resulted in excessive coarse sediment removal from the channel;
2. When natural bed armor was stripped from the channel due to excessive stream power during a flood;
3. In a channel that has cut down and is disconnected from its floodplain; and
4. When historic berms are being removed to restore floodplain connection.

In locations where habitable structures or infrastructure exist and channel incision is severe, natural bed stabilization alone is not likely to reduce flood risks, and a more rigid grade control practice will be needed (Section 5.4). Sediment removal is likely needed rather than natural bed stabilization to restore channel conveyance in highly depositional areas.

Natural bed stabilization by installing sediment reduces the instability of the lower bank associated with channel downcutting; widens the cross section flow area and reduces flood velocity; and restores connection to floodplains in an incised channel. This practice involves raising the channel bed and making the profile more uniform, reconnecting adjacent floodplains or flood benches, and increasing hydraulic roughness (i.e., decreasing the energy grade) (Figure 5.3-1). Natural bed stabilization is performed by installing river sediment or quarried materials, or by importing boulders to roughen the channel bed. River sediments may often be found adjacent to a stream in the dredged materials used to form berms and windrows. Elevating and roughening the bed can reduce the threat of vertical and lateral channel instability by moving a sediment-starved channel closer to its equilibrium. Natural bed stabilization is desired over more aggressive bed stabilization approaches when possible as it returns the texture and composition of the native bed and bedforms for less cost.

APPLICATION

Proper Use

Natural bed stabilization is commonly implemented in conjunction with other river management practices such as berm removal, floodplain restoration, bank stabilization, and bed stabilization.

This practice is appropriate for channels that have been stripped of coarse sediment by erosion during a flood or overexcavation during flood recovery. Where past flood recovery efforts resulted in the channel being dredged too deeply, a loss of hydraulic roughness takes place that leads to greater flood vulnerability for infrastructure along rivers.

Figure 5.3-1: (A) Straightened and windrowed channel on Pinney Hollow Brook along VT Route 100-A in Plymouth, Vermont following Tropical Storm Irene. (Source: Milone & MacBroom, Inc., September, 2011) (B) Completed placed riprap wall and natural stabilization of bed to increase bankfull width and cross-sectional area. (Source: Fitzgerald Environmental, October, 2013)

Meeting the Design Objectives

- Use equilibrium dimensions or a suitable reference reach to set bank height, channel dimensions, and slope.
- Restore reference bedforms and habitat features.
- Maintain or re-establish vertical stability over the reach to prevent the unnatural raising and lowering of the channel bed.
- Reconnect as much floodplain as possible given site constraints.
- Create uniform slope transitions in and out of the bed stabilization area.
- Restore reference hydraulic roughness in channel.
- Avoid or minimize channel interventions in areas of low risk to public safety or improved property.

Limitations

- Reintroduction of sediment results in a temporary impact to channel bed and aquatic habitat as some fine sedimentation is often unavoidable.
- Where bed sediments were previously dredged and removed, there may be insufficient local native materials to elevate bed.
- Requires frequent construction oversight to ensure that profile and bedforms are shaped according to plans.
- Not feasible for areas of severe channel incision or high deposition rates.

Geomorphic Context

Natural bed stabilization is typically applied along small to moderately sized rivers within narrow to confined river valleys in conjunction with other practices where past disturbances have taken place. The ultimate goal of installing sediment to stabilize the channel bed is to move the channel towards its dynamic equilibrium (Lane, 1955a) where sediment is lacking relative to the power of the channel due to the flow and watershed position.

Excessive removal of channel sediments after a flood may impact the natural bed armor (see Figure 5.7-2). If the armor layer is unknowingly removed during sediment removal following a large deposition event, the activity will often lead to vertical instability. Design of natural bed stabilization treatments requires an understanding of the existing condition of natural bed armor in the reach.

Habitat Maintenance

- Conduct bed and bank stabilization concurrently to limit machinery disturbance to channel.
- Limit reinstallation of fine-textured substrates alone (i.e., only sands and silts) to elevate bed to avoid fine sedimentation of channel.
- Avoid or limit disturbance to riparian vegetation where bed materials were windrowed along banks.
- Place largest cobbles and boulders (e.g., >12 inches) in the channel to naturalize habitat features.
- Include root wads in the stone fill to add shelter and diversity.

Common Mistakes

- Creating abrupt changes in the longitudinal profile that may form nickpoints or headcuts during future floods.
- Creating abrupt bed transitions around bridges, culverts, and other in-stream structures.
- Raking windrowed material too aggressively and cutting into pre-flood bank.
- Uneven dispersal of native sediments along channel cross-sectional area (Figure 5.3-2).
- Removing only a portion of the windrowed material and leaving berms in place that prevent floodplain access where no habitable structures or infrastructure exist.
- Not considering stream power and longitudinal profile to know if more aggressive grade control treatment is needed in vertically unstable channels.

Figure 5.3-2: Schematic of reinstallation of native bed materials including preferred (left), acceptable (middle), and incorrect (right).

Compatibility with Emergency Temporary Repairs and Timing of Implementation

- Reinstallation of native channel sediment is common as part of the permanent repairs (e.g., bank stabilization), and these practices should be done concurrently to minimize repeat channel disturbance.
- Working in a channel that has been naturally disturbed from flooding immediately after the event will minimize the length of time required for the ecosystem to recover.

SITE WORK CONSTRAINTS

When natural bed stabilization is planned as a follow-up to temporary emergency repair work, the primary site constraint is whether the work can be coupled with other stabilization work at the site. Often this practice is completed in tandem with bank stabilization work along roadways. In this case, federal emergency recovery funding may cover the costs of natural bed stabilization since it reduces the vulnerability of nearby infrastructure. If natural bed stabilization is not associated with flood recovery funding, other state and federal grant funding may have fewer conditions on reimbursement of costs.

Since natural bed stabilization often involves excavation along riverbanks, it is important to secure property owner permission before the work is completed. Any work involving disturbance on private property requires permission in advance of the work.

Weather can also impact natural bed stabilization practices. High water complicates access to river channels. Deposited and windrowed sediment can freeze in place during winter complicating excavation.

PRIMARY DESIGN ELEMENTS

Identify Upstream and Downstream Project Limits

The first design step involves walking the project site to determine the upstream and downstream limits of the bed stabilization area (Figure 5.3-3) and its relation to other stabilization practices. Note any abrupt changes in bankfull channel width, bed profile and form, sediment gradation, and dredged material windrowed along the adjacent banks and floodplain.

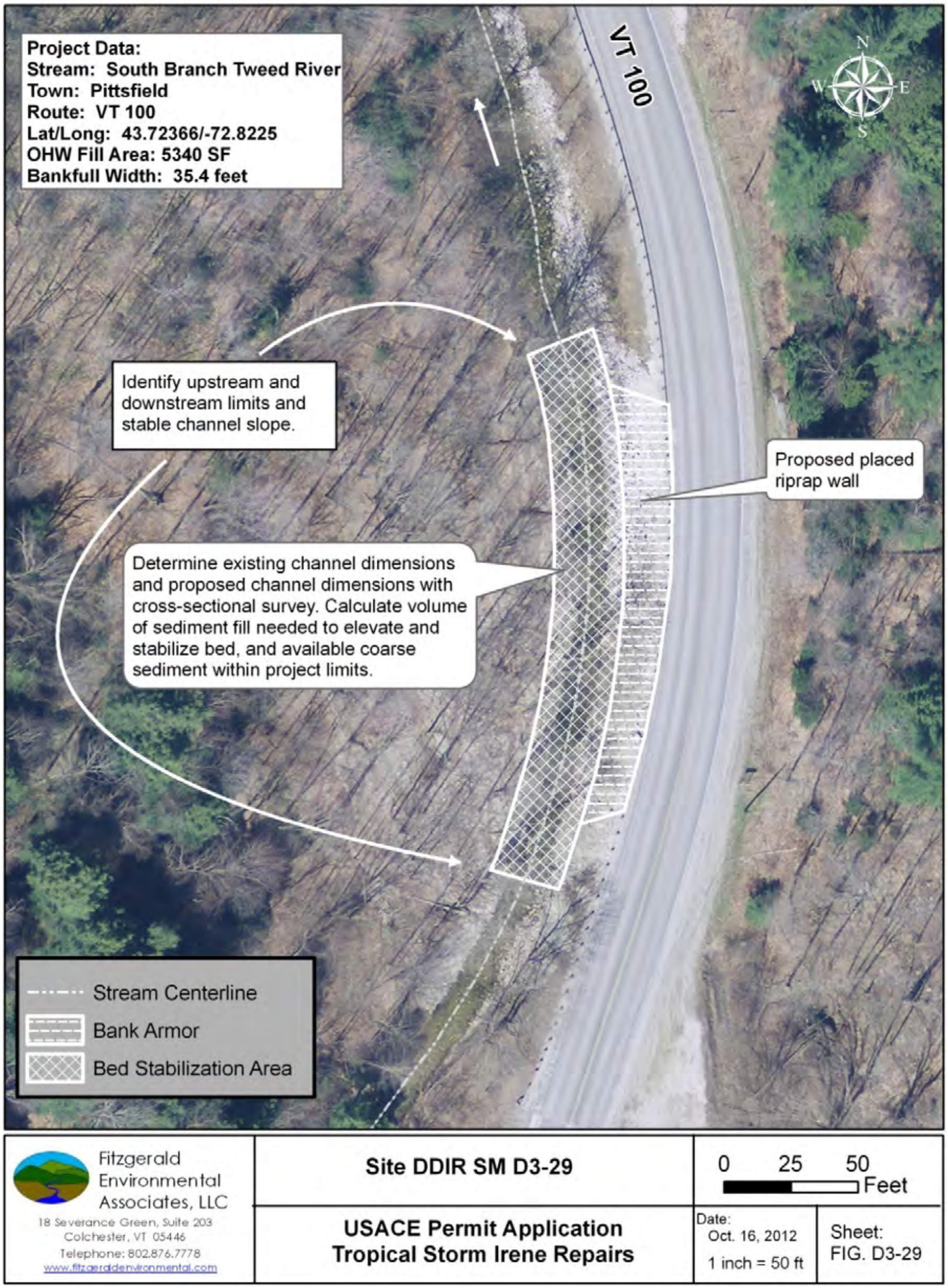


Figure 5.3-3: Bed stabilization area and proposed placed riprap wall on South Branch of Tweed River and VT Route 100 in Pittsfield, Vermont. (Source: Fitzgerald Environmental, October, 2012)

Determine Equilibrium Channel Slope and Dimensions

Determine the stable channel slope and reference cross-sectional dimensions using past geomorphic field data if available, hydraulic geometry regression equations (VTDEC, 2006c) (Appendix L), Light Detection and Ranging (LiDAR) data if available, and current field measurements. If the natural bed stabilization area overlaps with another practice, determine the extents of each implementation area to estimate sediment cut and fill volumes.

Survey of Existing Channel/Floodplain Dimensions and Slope

Use basic survey equipment (e.g., automatic level or hand level) to measure the profile and cross section that best represent the project site. If channel or embankment geometry varies within the project area, survey multiple channel cross sections as needed. Survey the longitudinal profile of the channel within the stabilization area and beyond the project limits to adequately characterize the channel slope upstream and downstream. Calculate the existing incision ratio (VTANR, 2009) to evaluate the degree of floodplain connectivity and compare with pre-flood incision ratio if data is available.

Quantify Locally Available Sediment Volume and Gradation

Probe coarse sediment deposits on channel margins, berms, and floodplain that are available to elevate and stabilize the channel bed. Estimate sediment gradation while probing. Note that flood benches and other floodplain features may have been buried if there was dredging and windrowing of excavated material (Figure 5.3-4). Attempt to locate the pre-flood bank and floodplain profiles during the field assessment. A test pit or exploratory trench may be needed.

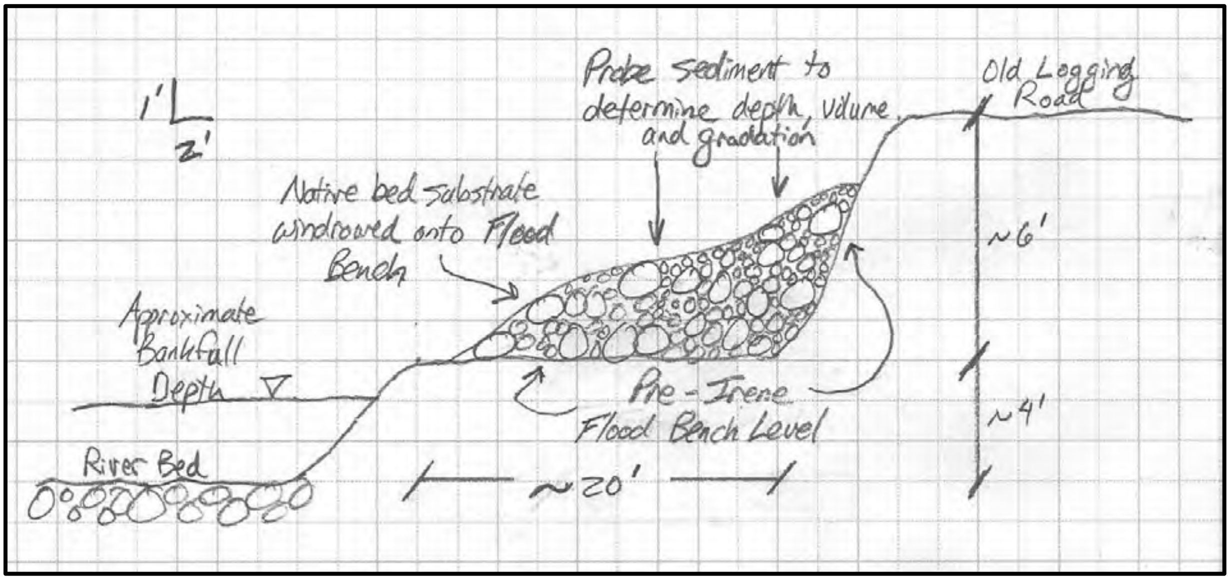


Figure 5.3-4: Profile of windrowed material along the Pinney Hollow Brook and VT Route 100-A in Bridgewater, Vermont following Tropical Storm. (Source: Fitzgerald Environmental, August, 2012)

Using the cross-sectional survey and the estimated deposit depths, determine the volume of the available sediment to elevate the channel bed. Multiply the cross-sectional area by the length of the deposit to calculate the volume.

Channel Fill Recommendations

Compare the existing cross-sectional dimensions with the proposed dimensions that best meet the desired stable channel characteristics given the site constraints. If a bank stabilization treatment is also taking place, incorporate the proposed changes in channel dimensions into the bed elevation design (see Figure 5.3-6). Determine the volume of sediment fill required to raise the bed to the desired elevation and compare with the volume of coarse sediment available on site. The following design considerations should be evaluated to identify an appropriate bed elevation and profile to stabilize the channel, reduce flood vulnerability, and improve aquatic habitat.

- Maximize the bankfull channel width. In moderate gradient, high bedload channels with a tendency for a wandering or braided planform, maximize floodprone width also.
- Compare the existing and proposed channel incision ratios and maximize access to adjacent floodplains and flood benches (Figure 5.3-5).
- While maximizing floodplain access, consider adjacent property and infrastructure to ensure no increase in risk due to fill.
- Carefully excavate deposits over floodplains and benches while leaving a veneer of the sediment deposit over the existing profile to minimize ground disturbance.
- Place the largest boulders in the channel to encourage development of natural bedforms and habitat features.
- If adequate materials are not available on site to elevate the bed, off-site borrow may be used but should be consistent in gradation and texture to the native channel substrate. Alternatively, boulders large enough to remain in place during moderate floods (e.g., 10-year flood) may be used to help establish the future profile of the bed by encouraging the recruitment of bedload sediments.

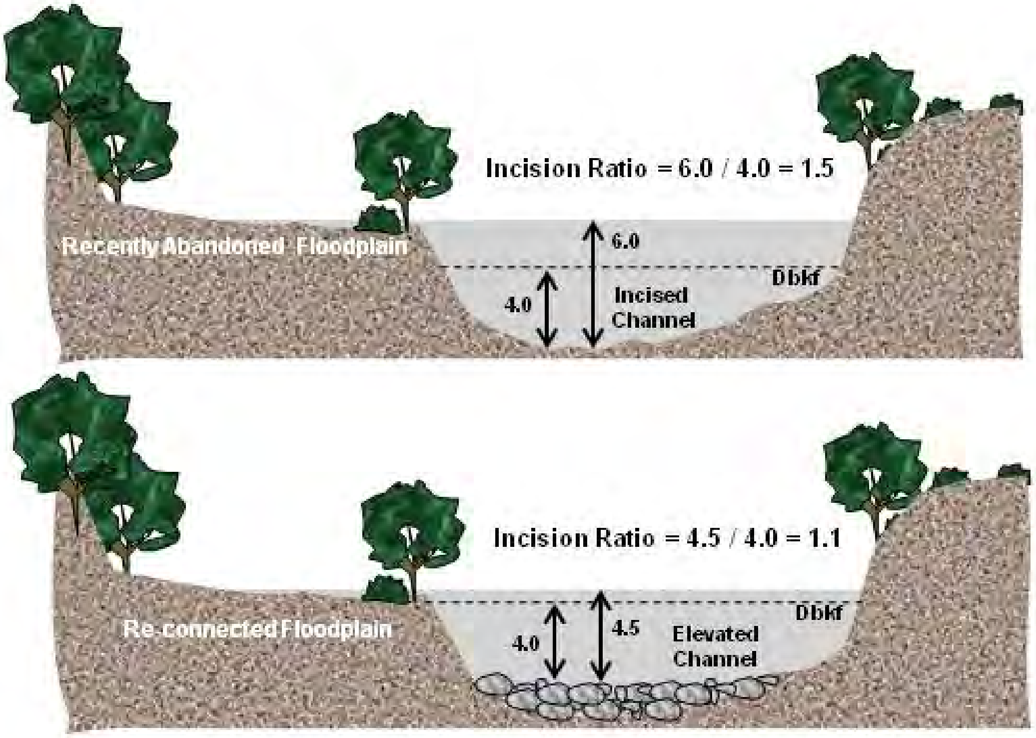


Figure 5.3-5: Schematic of increased floodplain access and subsequent increase in cross-sectional flow area resulting from an elevated channel bed. Channel incision is reduced by decreasing the ratio between overbank flow depth and bankfull depth (Dbkf). (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental)

COSTS

The ballpark cost of general excavation (appropriate for estimating costs of reinstallation of native sediment) is $10 per cubic yard for large quantities of material (e.g., >5,000 cubic yards). The price typically ranges from $6.50 to $14.80 per cubic yard based on past flood recovery experience in the state and from average work rates along the state highway system (VTrans, 2009).

Thorough documentation is required when seeking reimbursement from funding agencies. Information and applications should be filed prior to construction in nonemergency scenarios. After-the-fact submissions must take place in emergency situations.

- GPS the perimeter of the work area and document footprint, widths, and length of channel affected by work.
- Photograph the post-flood conditions and compare to pre-flood photographs and site information.
- Document pre-flood versus post-flood incision ratio.

- Establish several sediment depth estimates across the deposit cross sections.
- Quantify the amount of sediment to be moved or removed from the banks, benches, or floodplain.
- Quantify the amount of sediment or rock to be installed in the channel and the area of application.
- Document other stabilization practices being completed in conjunction with natural bed stabilization.
- Document private property ownership and all permissions obtained to complete work.
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or during emergency work.
    - FEMA
    - NRCS
    - USACE
    - VTANR
    - VTrans
    - Municipality
- Document how the project meets applicable State Performance Standards and permit requirements.

PERMITTING

This practice will require state and federal environmental permits. Although this remedial practice uses native materials to stabilize the channel, it does not fit well within the current stream and wetland regulatory framework as it results in fill below ordinary high water (OHW; Appendix K). Permits will be needed from VTDEC (2014) and the U.S. Army Corps of Engineers (2012) if the work results in fill that exceeds the jurisdictional thresholds. Planning for permits well in advance of the work is recommended as the process may take many months during busy review periods.

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
    - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
    - Identify reporting category
    - Contact Vermont Field Office
- Vermont Stream Alteration Permit
    - Meet Performance Standards as identified above
    - Identify reporting category
    - Contact river management engineer
- Local Zoning Permit
    - Contact Town Administrator for reporting needs

CONSTRUCTION

Constructability

The methods summarized in this practice to naturally stabilize the channel bed will be new to most people involved with the assessment, design, construction, permitting, and funding of this work. Many designers and construction contractors have experience with instream structures such as rock weirs; however, the practice of reinstalling dredged material after a flood is not as common.

Probe and rake the sediment deposits with the teeth on the excavator bucket as work progresses to prevent overexcavation. Construction oversight is needed, particularly when nearing the target sediment removal depth on the bank or the pre-flood bank surface to prevent overexcavation. Be sure that the:

- Final longitudinal profile of the channel is consistent with design;
- Gradation of sediment used to fill the channel does not result in excessive fine sedimentation of the channel bed; and
- Excavation of windrowed materials along banks is done to minimize impact to the pre-flood ground surface.

Since most of the work to stabilize the bed takes place in the channel and along the banks, road closures are only needed if the practice is being completed in conjunction with a bank stabilization treatment that requires lane closures (e.g., placed riprap wall).

Temporary Construction Controls

Since natural bed stabilization involves disturbance of a large portion of the channel bed, this work should always be completed during low flow periods to limit downstream sedimentation and allow for proper visibility to successfully complete the work. During reinstallation of native bed sediments, water control is often not practical as the work is taking place across the entire channel cross section. If temporary water control is needed in a portion of the channel, berms made of native sediment deposits can be used to guide water out of the work areas.

Some degree of fine sedimentation is unavoidable during this practice even if the material being reinstalled is mostly coarse grained. A series of check dams and sediment trap pools can be used during instream work to capture fine sediment and control downstream turbidity. Check dams can be made from sediment, sand bags, or jersey barriers. Several check dams and pools can be placed downstream of the work area. The pools should be periodically cleaned out as work takes place.

Access

Access to stabilize stream beds is typically made from state or municipal roads. Ownership of proposed access locations must be verified by reviewing roadway right-of-way mapping and local parcel mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access must take place across private land, agreements with the landowners are common. Access agreements typically include discussions or notes about returning the land to the original condition following the project. Planting of the upper bank with perennials, shrubs, and trees may be requested to naturalize the site following the construction work.

For larger projects or those likely requiring frequent future maintenance, easements can be drafted to allow periodic access for specified work such as flood damage repair or sediment management.

CONCEPTUAL DESIGN PLANS/DETAILS

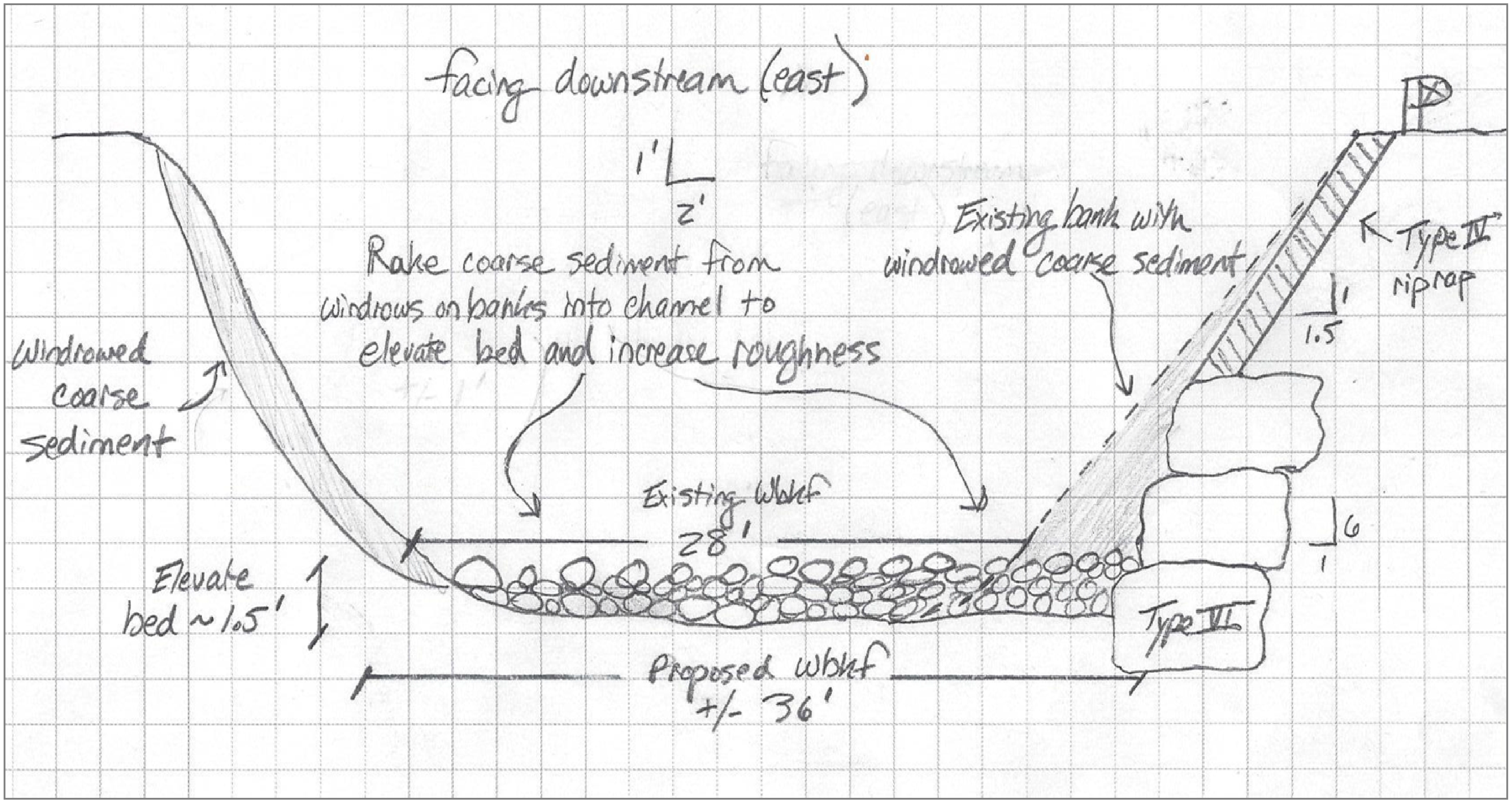
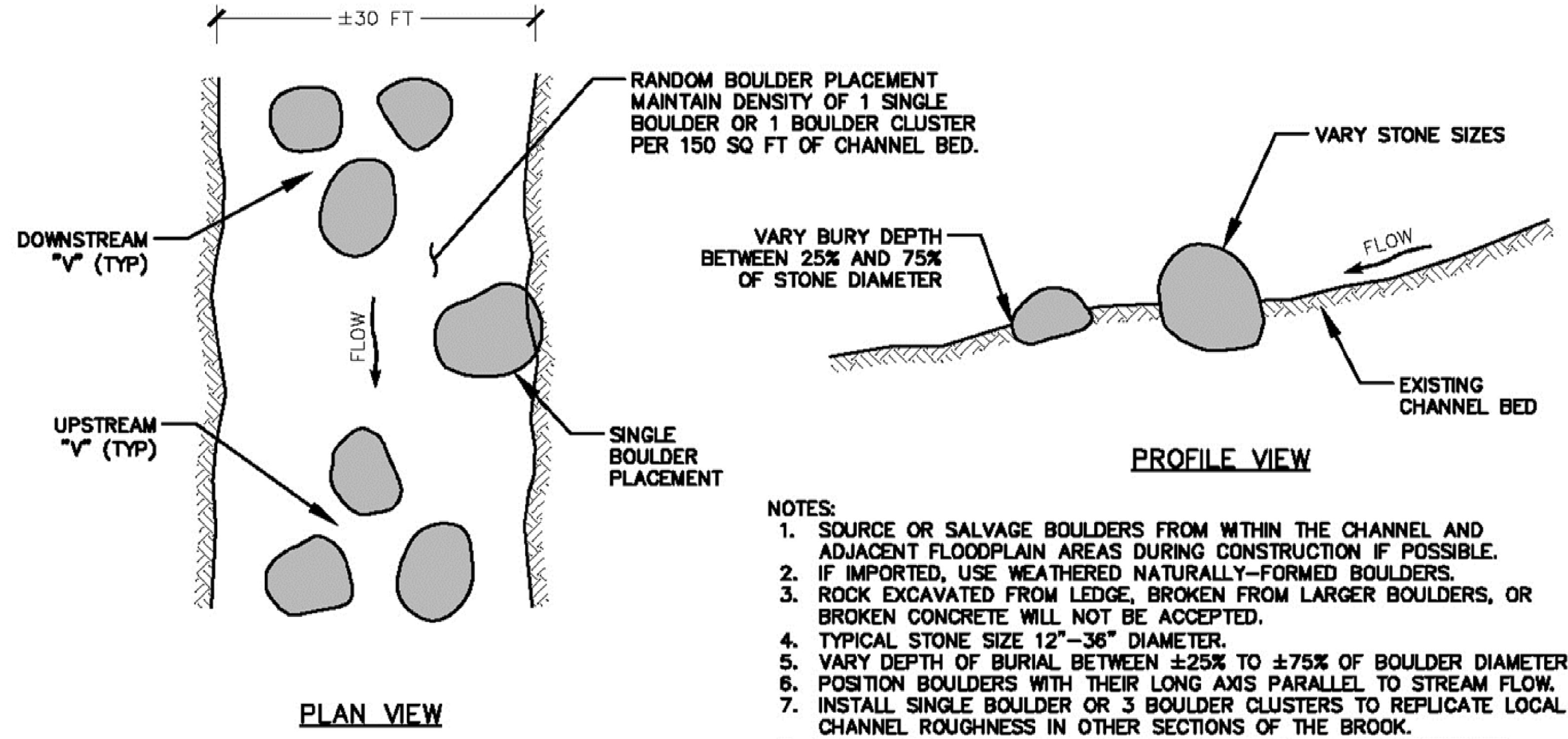


Figure 5.3-6: Design plans to elevate and roughen channel bed using native coarse sediment along channel banks in Bridgewater, VT. (Source: Fitzgerald Environmental and Milone & MacBroom, Inc.)



NOTES:

1. SOURCE OR SALVAGE BOULDERS FROM WITHIN THE CHANNEL AND ADJACENT FLOODPLAIN AREAS DURING CONSTRUCTION IF POSSIBLE.
2. IF IMPORTED, USE WEATHERED NATURALLY-FORMED BOULDERS.
3. ROCK EXCAVATED FROM LEDGE, BROKEN FROM LARGER BOULDERS, OR BROKEN CONCRETE WILL NOT BE ACCEPTED.
4. TYPICAL STONE SIZE 12"–36" DIAMETER.
5. VARY DEPTH OF BURIAL BETWEEN ±25% TO ±75% OF BOULDER DIAMETER.
6. POSITION BOULDERS WITH THEIR LONG AXIS PARALLEL TO STREAM FLOW.
7. INSTALL SINGLE BOULDER OR 3 BOULDER CLUSTERS TO REPLICATE LOCAL CHANNEL ROUGHNESS IN OTHER SECTIONS OF THE BROOK.
8. FINISHED ELEVATION AND PLACEMENT OF BOULDERS IS SUBJECT TO APPROVAL IN THE FIELD BY PROJECT ENGINEER.
9. SEE TECHNICAL SPECIFICATIONS FOR ADDITIONAL INFORMATION.

ROUGHENED CHANNEL / RANDOM BOULDER PLACEMENT

NOT TO SCALE

Figure 5.3-7: Design plans to install boulders and improve aquatic habitat on Great Brook in Plainfield, Vermont. (Source: Milone & MacBroom, Inc.)

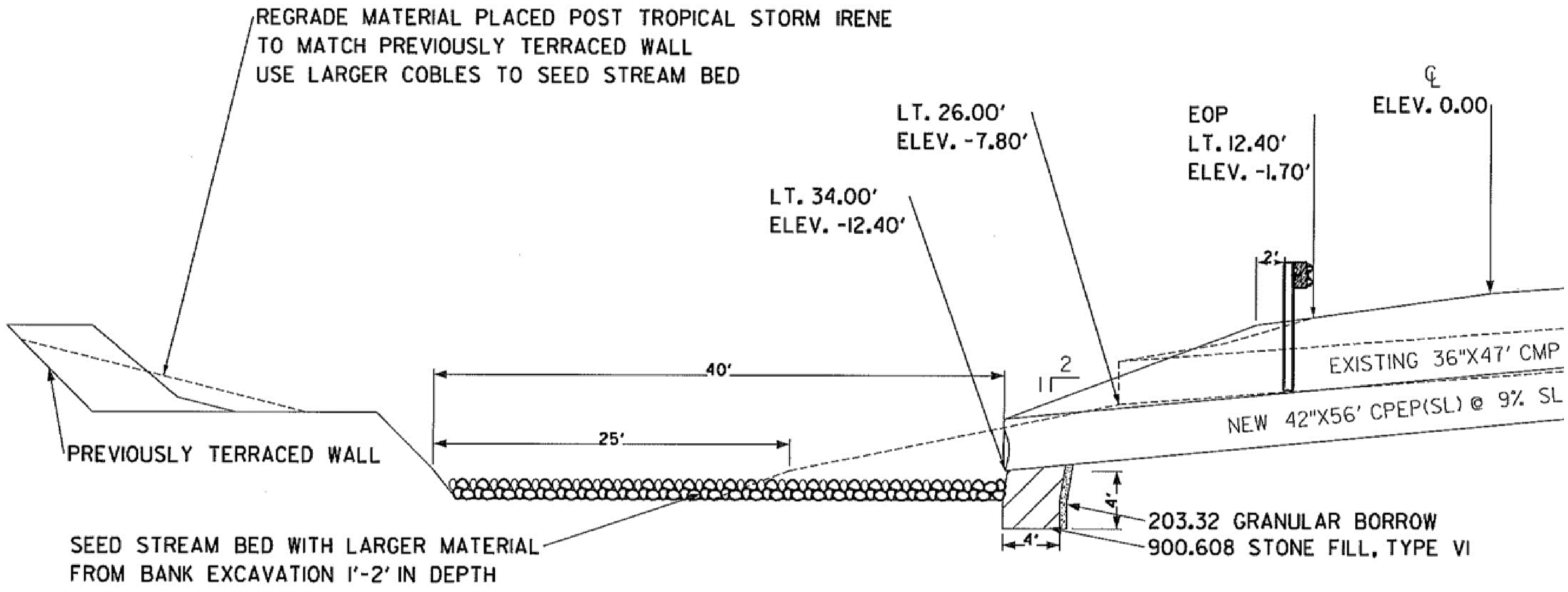


Figure 5.3-8: Design plans to elevate and roughen channel bed using native coarse sediment along channel banks in Bridgewater, Vermont. (Source: VTrans District 3)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- Ordinary high water (Appendix K)
- Avoid excavating the stream channel too deep (Kline, 2012a) (U)
- Linking damages to dominant stream processes (C)
- Vermont hydraulic geometry regression equations (HGR) (VTDEC, 2006c) (L)
- Channel evolution model (E)
- Equilibrium slope for the size of sediment (T)
- Meandering, braided, or wandering channel pattern (R)
- Floodprone width (Q)

POSSIBLE COMPANION PRACTICES

- Placed riprap wall or traditional bank armor (Section 5.2)
- Grade control (Section 5.4)
- Bench or flood chute restoration (Section 5.5)

SIMILAR PRACTICES

- Floodplain restoration by raising channel elevation (Section 5.6)

5.4 GRADE CONTROL

DESCRIPTION

Installation of grade control is performed to control channel downcutting; reduce instability of the lower bank; widen the cross section flow area to reduce flood velocity; and restore connection to floodplains in an incised channel. This practice involves the construction of channel slope control features such as stone riffles, strainers, and weirs that are analogous to installing a new riffle or step bed feature. Grade control may also be achieved using log check dams (USFS, 1992) or engineered log jams (Brooks et al., 2006; SEPA, 2006). The extreme version of grade control is the reach-scale armoring of the bed by installing large rock and preferably reinstalling a native riverbed over the large rock.

Grade Control Design

Assessment

- Longitudinal profile
- Geomorphic stream type
- Bankfull width and depth
- Incision ratio
- Channel evolution

Design

- Upstream and downstream limits
- Channel profile
- Bed elevation and floodplain access
- Bankfull and floodplain dimensions
- Channel and floodplain hydraulics
- Structure spacing and dimensions (strainers, riffles, and weirs)
- Rock type and sizing
- Construction sequence and reinstallation of native river sediment for bed armor

Artificial channel bed grade control with rock is an invasive practice reserved for areas of moderate to severe vertical channel instability. Grade control is commonly applied to protect infrastructure prone to flood and erosion damages; where embankment instability caused by undermining of the low bank can be addressed more effectively in the channel; and where critical infrastructure such as a sewer line crosses a river channel. This practice can effectively reduce impacts to water quality and aquatic habitat associated with excessive channel incision that leads to export of high sediment and nutrient loads. Grade control is also used to limit channel downcutting and improve aquatic habitat in dam removal projects and to increase tailwater elevations downstream of perched culverts to improve aquatic organism passage.

APPLICATION

Proper Use

The primary objective of grade control is to re-establish vertical channel stability to protect nearby structures or infrastructure from erosion damages (Figure 5.5-1). The channel bed is stabilized by increasing the resistance to the forces driving sediment transport.

Bed armoring is reserved for the most severe areas of bed instability when other treatments cannot reduce flood risks to adjacent infrastructure. Stone riffles, strainers, or weirs are more discrete practices that may be used in a post-flood response to stabilize the channel in areas prone to moderate incision due to a river corridor constriction such as a roadway. Riffles, strainers, and weirs elevate and roughen the bed to encourage the recruitment of bedload sediments in future channel-forming floods.

In areas with low to moderate channel incision, natural bed stabilization (Section 5.3) may provide adequate vertical control while grade control is needed in areas of moderate to high incision. Grade control changes the slope of the channel at a point or over a reach that in turn changes future sediment transport and stream power. Natural bed stabilization, on the other hand, primarily resets the channel bed to its pre-flood condition yet does not change the long-term sediment dynamics. In other words, grade control changes channel process while natural bed stabilization changes channel form.

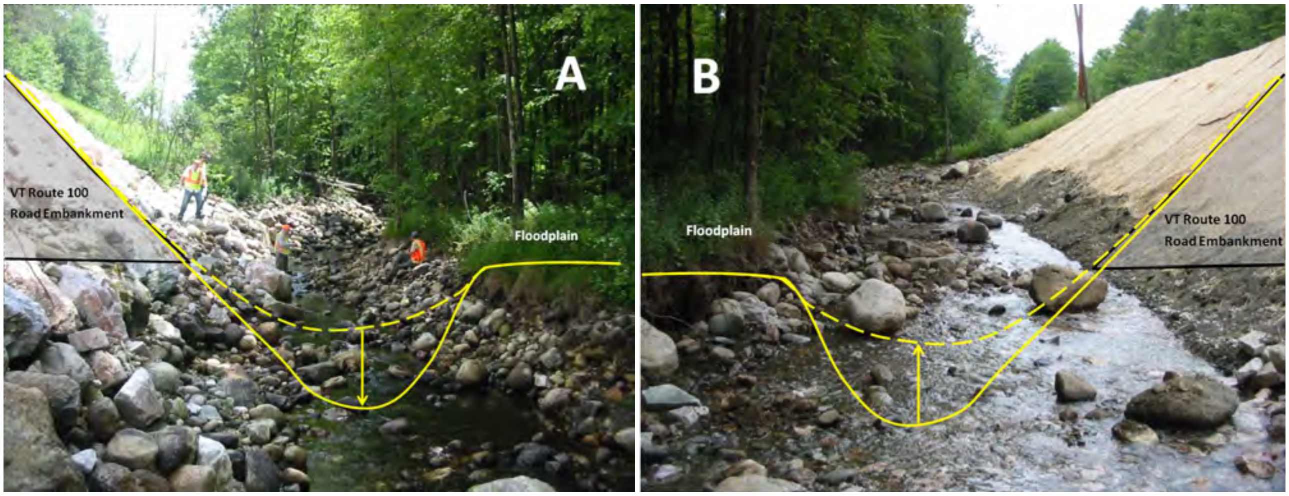


Figure 5.4-1: (A) Incised channel downstream of a headcut on the South Branch Tweed River (looking upstream) in Killington along VT Route 100. (Source: Milone & MacBroom, Inc., July, 2012) Toe of armored road embankment was unstable and susceptible to undermining following bed erosion during Tropical Storm Irene. (B) Completed bed armoring (looking downstream) with native bed sediments reinstalled over top of armoring. (Source: Fitzgerald Environmental, August, 2013)

Meeting the Design Objectives

- Maintain or re-establish vertical stability over the reach to prevent the unnatural downcutting of the channel bed.
- Reconnect as much floodplain as possible (i.e., target incision ratio = 1.0 – 1.2) given site constraints.
- Use equilibrium dimensions from a suitable reference reach of hydraulic geometry regression equations to set bed elevation relative to bank height, channel dimensions, slope, and spacing of grade control structures and bedforms.
- Use stone riffles and weirs in areas of moderate stream power and susceptibility to property damage.
- Use bed armoring in areas of high stream power prone to incision and likely property damage. Specify the reinstallation of native river sediment over bed armoring to

naturalize aquatic habitat and allow for aquatic organism passage immediately after construction when time allows.
- Create uniform slope transitions in and out of the bed stabilization area.
- If present, integrate natural grade control features into grade control design.
- Ensure stable tie-in locations in the banks for weirs and riffles.
- Restore reference hydraulic roughness, bedforms, and habitat features in channel as much as possible.
- Maintain long-term aquatic organism passage for all grade control practices.

Limitations

- Requires introduction of non-native stone into riverbed.
- Bed armoring may require a large volume of rock armor.
- Weirs and bed armoring can be outflanked if unstable channel banks are left unprotected.
- Instream work disturbs the channel, and reinstallation of native bed material results in a temporary impact to channel bed and aquatic habitat as sedimentation is unavoidable.
- Requires construction oversight to ensure channel profile and bedforms are shaped according to plans.
- Stone riffles and weirs may not be feasible in areas of high stream power and severe channel incision.
- Adjacent infrastructure or steep banks may limit bank tie-in locations.
- Grade control practices such as weirs could become a block to aquatic organism passage if not properly matched to downstream channel slope or if channel downcutting occurs.
- Bed armoring could fragment aquatic habitat if water flows under the coarse rock.

Geomorphic Context

Rivers are most stable when the channel's resistance to erosion is equivalent to the erosive forces acting on it during floods (Lane, 1955b). When sediment transport capacity during high flow events exceeds the resistance of the bed and banks, the channel is eroded and can become vertically and laterally unstable. While bed and bank erosion are natural river processes that vary in a watershed (e.g., with location, hydrology, and sediment transport), human encroachments in river corridors tend to exacerbate erosion particularly in reaches that have high natural rates of erosion and stream power.

Past experience with flood damage in Vermont and follow-up research have confirmed the theory that the sediment transfer zone of the watershed (Schumm, 1977) is where stream power is highest along the channel network (Knighton, 1999). Therefore, the greatest potential for bed and bank erosion and channel incision exists in the mid watershed. In Vermont, these midwatershed zones tend to coincide with increasing infrastructure in the river corridor and floodplain. As headwater channels transition into mid-order reaches in semi-confined to narrow valley settings (VTANR, 2009), the valley width increases enough to allow road embankments and other development to be situated along the edge of the corridor. In these developed settings, some degree of fill and encroachment within the corridor and floodplain is common to elevate and protect infrastructure. Naturally high stream power is increased by the constrictions resulting in increased flood and erosion risks. The effect of incremental river corridor encroachment on stream power may not be evident until a large flood energizes the river and floodplain enough to cause extensive erosion along the corridor and valley walls.

The severity of channel downcutting is also a function of whether natural grade controls exist in the river reach. Mid-order mountain reaches with frequent or continuous river corridor encroachments and lack of natural grade controls are the most vulnerable to severe channel incision. These areas often require artificial grade control following large floods to mitigate long-term incision and protect adjacent infrastructure.

Excessive removal of channel sediments after a flood may lead to the unknown removal of the natural bed armor that decreases vertical stability (see Figure 5.7-2). Design of grade control treatments requires an understanding of the existing condition of natural bed armor in the reach so that the installed features can tie into or replace removed sections of the natural bed armor layer.

Habitat Maintenance

- Conduct bed and bank stabilization concurrently to limit machinery disturbance to the channel.
- Reinstall native sediments over bed armoring, re-establish a compound channel cross section, and rebuild natural bed roughness.
- Stockpile and reinstall native boulders with diameter larger than 12 inches in the channel to naturalize habitat features and maintain hydraulic roughness.
- Ensure adequate aquatic organism passage at grade control installations.
- Control potential sedimentation of the channel during construction.
- Avoid or limit disturbance to riparian vegetation during construction access.

Common Mistakes

- Not considering stream power to determine which grade control practice is most appropriate.
- Use of undersized rocks for weirs that are susceptible to erosion during flooding.
- Not providing proper bank and bed tie-in for weirs and riffles.
- Improper spacing of stone weirs and riffles.
- Bed armor depth is too shallow and susceptible to undermining.
- Unstable banks are left unprotected with potential for the channel to roll off and outflank armoring (Figure 5.4-2).
- The transition between bed armoring and the channel bed is too steep at downstream limits creating abrupt changes in the longitudinal profile that may block aquatic organism passage or form upstream travelling erosion faces (i.e., headcuts) in future floods (Figure 5.4-2 and 5.4-3).
- Uneven dispersal of native sediments along channel cross-sectional area (see Figure 5.3-2).

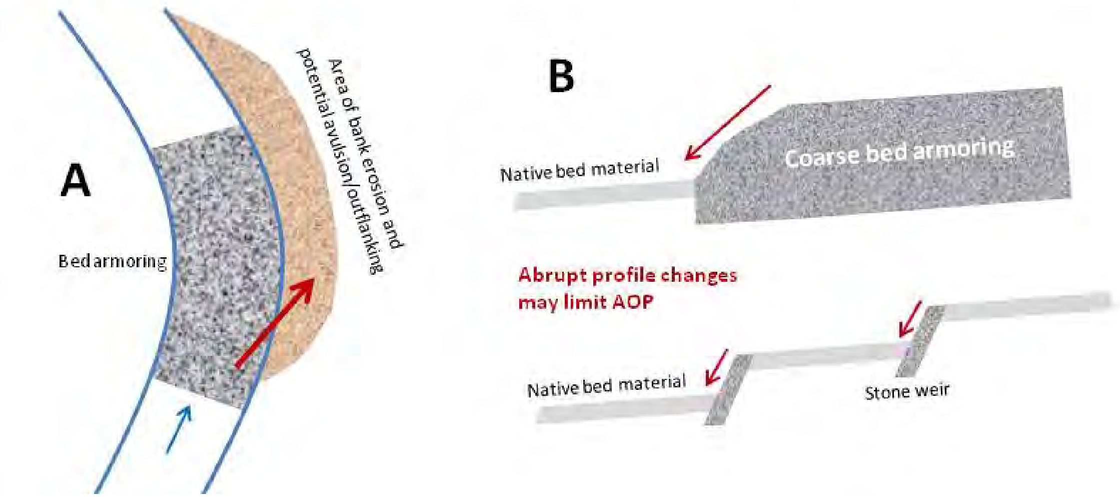


Figure 5.4-2: Schematic of common mistakes in grade control practice. (A) Plan view of unstable banks along bed armoring that are vulnerable to channel avulsion or outflanking. (B) Profiles of transitions from bed armoring or stone weirs that are too steep or tall (at arrows) and may block aquatic organism passage.

Figure 5.4-3: Photograph of steep, abrupt transition from bed armoring to native channel bed at the downstream end of emergency bed armoring on the Sleepers River in Danville, Vermont. (Source: Fitzgerald Environmental, 2013)

Compatibility with Emergency Temporary Repairs and Timing of Implementation

RIFFLES, STRAINERS, AND WEIRS

- Installation of stone riffles or strainers are compatible with an emergency setting to re-establish vertical stability in a moderately incised setting that requires less rock armor and instream machine time than bed armoring. Using installed bed features to control the future channel grade is often a cost-effective approach to reducing flood risks.
- Tying stone weirs and riffles into adjacent banks will be easier during emergency repair work as the eroded bed and banks are being stabilized.
- Working in a channel that has been naturally disturbed from flooding immediately after the event will minimize the length of time required for the ecosystem to recover.

BED ARMORING

- Bed armoring may be performed as an emergency temporary repair in the post-flood setting by dumping large stone in an incised channel where erosion damages are high, and structures and infrastructure are prone to next flood damages. This approach leads to habitat impacts and reduced aquatic organism passage due to large rock filling the channel and flow travelling through the voids (i.e., underflow). Emergency bed armoring is reserved for locations where rapid recovery of a roadway or building requires filling of an eroded channel bed. Sediment transport may fill in the voids in the stone bed armor and prevent underflow, but it is likely that further repair work will be required to restore habitat, restore fish passage, and ensure bed stabilization.
- Layering sand, gravel, and cobble in alternating layers with the rock bed armor that can rapidly be performed in an emergency setting to limit underflow and habitat impacts.
- Bed armoring in an emergency setting is often performed to stabilize an undermined bank next to a building or a road embankment so the restored armor slope can be founded on a stable base. A bulk rock toe could be created during the emergency road reconstruction, and then the rest of the bed could be armored after the roadway is completed to allow more time to properly install armor and sediment so underflow does not take place. The bed armor is then tied into the bulk toe without disturbing the road embankment.
- Bed armoring is also performed in the nonemergency situation in confined, high-power river settings where repeat flood damages have occurred to stabilize the bed and banks over the long term by changing sediment transport dynamics.

SITE WORK CONSTRAINTS

During emergency recovery work, proper installation of grade control practices may be constrained or slowed by a lack of suitable material, experienced contractors, and technical oversight assistance. Bed armoring often requires a large volume of large rock (i.e., Type IV or larger riprap) (VTrans, 2014) that can be limited in supply during a widespread flood recovery. Machine operators in the post-flood setting need proper technical guidance and on-site instruction to ensure the Performance Standards and design elements are met.

Since grade control involves access and often excavation along riverbanks, it is important to secure property permission before the work is started.

Weather can impede the installation of grade control practices. Construction of grade control must be performed in the dry or in low-water conditions so that the work area is visible. Coarse sediment deposited from the flood can be used to direct water and create work platforms. A coffer dam made of sandbags, concrete bock, or sheeting may be used to control water. For projects where work must take place in the dry, pumping flow around the work site into a dewatering basin on the floodplain is commonly used.

The work window in river channels is typically July to October.

PRIMARY DESIGN ELEMENTS

Identify Upstream and Downstream Project Limits

The first design step involves walking the project site to determine the upstream and downstream limits of the required bed stabilization area. Document how the proposed grade control will stabilize the channel bed and relate to any existing natural grade control or other proposed bed or bank stabilization practices. Note any abrupt changes in bankfull channel width, bed profile, sediment gradation, and bank instability.

The upstream limit of bed armoring often extends upstream to an erosion face (i.e., a nickpoint) that typically is located where the channel is less confined. The top of the erosion front can be used to determine the top elevation of the bed armoring. The downstream limit of bed armoring should be located where the lateral confinement of the channel decreases. This approach to determining the limits of bed armoring creates uniform velocity (and energy grade) transitions into and out of the bed armoring area.

Channel Profile

Determine the reach slope using field survey measurements, past geomorphic assessment data, and LiDAR data. Plot the longitudinal profile of the reach upstream and downstream of the site to determine a range of possible target slopes in the project area. The reach slope and profile through the project area are used for setting the bed elevation (see Figure 5.4-7).

Bed Elevation and Floodplain Access

Ultimately, the bed elevation should be set to match the reach slope as closely as possible and to maximize floodplain access without putting adjacent infrastructure at risk. Where channels have cut down and have incision ratios greater than 1.5 and a channel evolution stage of II or III (VTANR, 2009), the bed may need to be raised to improve floodplain access. Vertical relief between the channel and floodplain surface should be set to allow floodplain inundation once every 1 to 2 years where possible. The target incision ratio is 1.0 to 1.2 for natural floodplain access (Figure 5.4-4). The proposed elevation of grade control structures or bed armoring should also be considered in conjunction with any required bank stabilization so that an adequate foundation for a stable lower bank is formed.

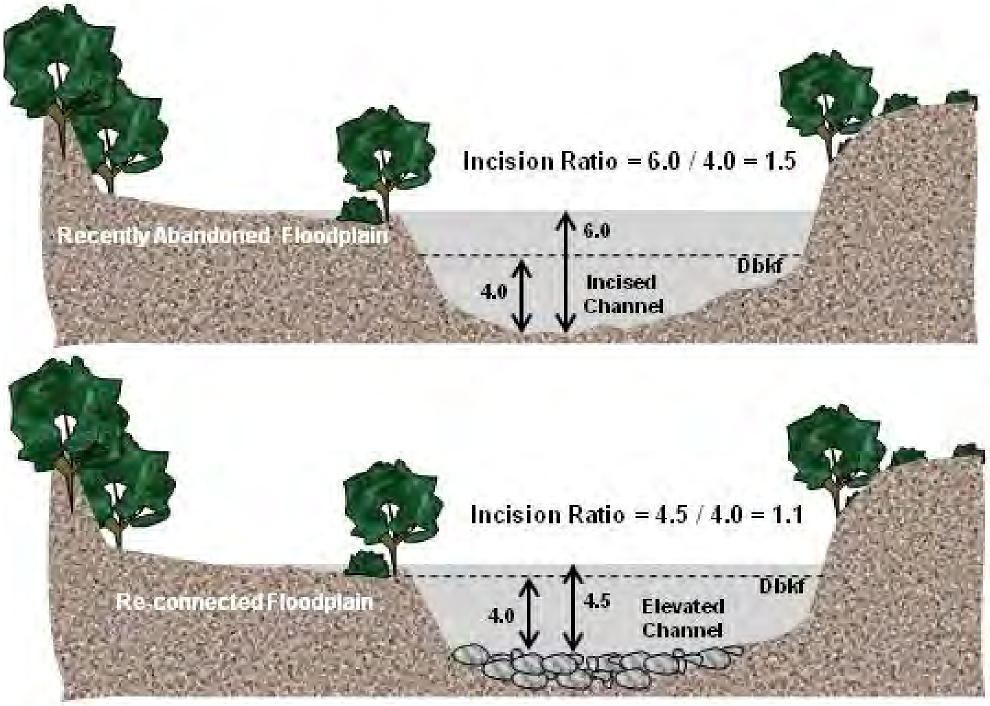


Figure 5.4-4: Schematic of increased floodplain access resulting from an elevated channel bed. Channel incision is reduced by decreasing the ratio between overbank flow depth and bankfull depth (Dbkf). (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental)

The increase in bed elevation of a grade control practice will depend on site-specific conditions such as the height of a headcut that has moved through the site and the level of channel incision. Generally, a proposed bed elevation increase of 1 to 2 feet will be performed with a weir, riffle, or strainer. For larger proposed bed increases, multiple structures may be used. In high-risk settings where the channel has cut down more than 5 feet, bed armoring is typically prescribed. Bed armoring applications can extend up to a depth of 10 feet if that is needed to create a uniform channel profile to limit erosion risks where adjacent infrastructure is vulnerable.

Grade Control Transitions

Transitions from grade control treatments to the natural river channel at upstream and downstream project limits require careful design. Key design elements include:

- Maintain uniform profile transitions in and out of the project area;
- Tie the profile into natural grade control that may exist near the site;
- Tie the profile into a natural bed armor layer if one exists;
- Taper bed armoring into the downstream channel at a maximum slope of 5% to 10%; and

- For bed armoring, maintain full thickness in the downstream taper section when natural grade control or bed armor are absent.

Bankfull and Floodplain Dimensions

Determine the reference bankfull channel dimensions by field measurement, past geomorphic assessment data, or Vermont hydraulic geometry regression equations (VTDEC, 2006c) (Appendix L) and compare with existing channel dimensions. Use survey equipment (e.g., level or total station) to record channel cross sections across the project site. Survey an adequate number of sections to characterize the variability across the site.

Calculate the existing width-to-depth ratio, entrenchment ratio, and incision ratio (VTANR, 2009) to evaluate the degree of floodplain connectivity and departure from reference conditions. Compare measurements to reference reach measurements or pre-flood incision ratio if data are available. Bankfull channel and floodplain ratios provide a reference point for evaluating how proposed changes in the bed elevation and channel profile using grade control structures will affect cross-sectional geometry and floodprone width.

Weir and Riffle Spacing

Channel slope dictates where bedform features such as steps and riffles form and remain stable on natural channels. Stone riffles and weirs should be spaced along the channel profile based on the channel slope and bankfull width. Rosgen (2012) provides empirical guidance for spacing of pools, riffles, and steps based on channel slope (Figure 5.4-5). On riffle-pool channels with slopes less than 2%, bedform spacing is typically five to seven times the bankfull channel width for reference habitat conditions (MMI, 2008). This is the target spacing when multiple riffles or strainers are installed for grade control. On step-pool channels with slopes larger than 3%, spacing is typically two to four times the bankfull channel width.

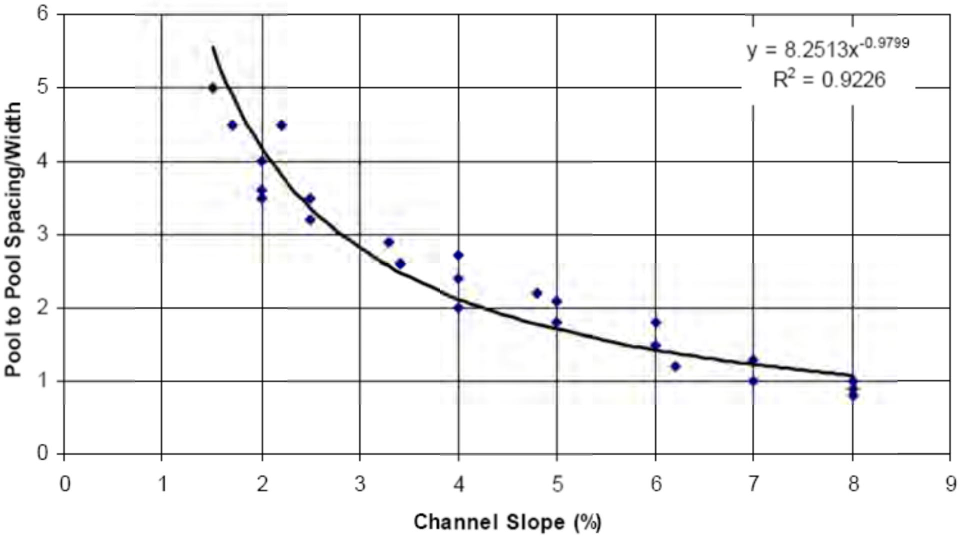


Figure 5.4-5: Ratio of pool spacing to bankfull width as a function of channel slope. (Source: Rosgen, 2001)

Weir and Riffle Structure Dimensions

The riffle, strainer, or weir dimensions should match nearby reference riffles or steps as much as possible. Make observations of the typical width and height of the features. Document the slope of the channel approaching and leaving riffles or steps. Identify the sediment gradation of riffles. Some key design elements include:

Cross Section

- Match cross-sectional width and height of nearby reference steps or riffles;
- Create concave features in cross section that generally connect maximum bankfull depth at the bank and the proposed grade in the center of the channel;
- Tie structure into banks a minimum of 5 feet;

Profile

- Match longitudinal slope of nearby reference steps or riffles;
- Avoid abrupt changes in channel profile;
- Set slope to 1% to 3% unless site-specific river conditions call for a shallower or steeper bed; and
- Create uniform transitions between bed and grade control structure.

Rock Sizing

Rock sizing must be performed to ensure that the grade control structures will resist erosion due to the design flood flow velocity and resultant shear stress. At a minimum, bed armoring and key stones for weirs and riffles should be mostly immobile and have a diameter larger than the 84th percentile particle size (D84) in the channel. The D84 is determined from a pebble count (Wolman, 1954) or past geomorphic assessment.

The typical approach to sizing rock is to choose a size that has a larger critical velocity (e.g., Fischenich, 2001) when movement is expected than the measured or calculated velocity in the channel. Flood history and geomorphic condition of the channel must be considered to properly size rock. In steep, confined channels where flood damages have taken place, large rock is often required to provide adequate resistance to bank erosion. Standard rock size guidance (e.g., Table 5.4-1) may need to be replaced with modified large riprap specifications (Appendix G) in erosion-prone areas or with a more in-depth analysis (FHWA, 1983; Kilgore and Cotton, 2005).

Table 5.4-1: VTrans Standard Rock Sizing (Source: VTrans, 2014)

Fill Type	**Median rock size, range (inches)**	**Velocity (fps)**
I	4, 1 – 12	≤ 6
II	12, 2 – 36	6 – 12
III	16, 3 – 48	12 – 14
IV	20, 3 – 60	14 – 16

One of the more popular methods to estimate rock size is the Isbash Method (1963) (Figure 5.4-6).

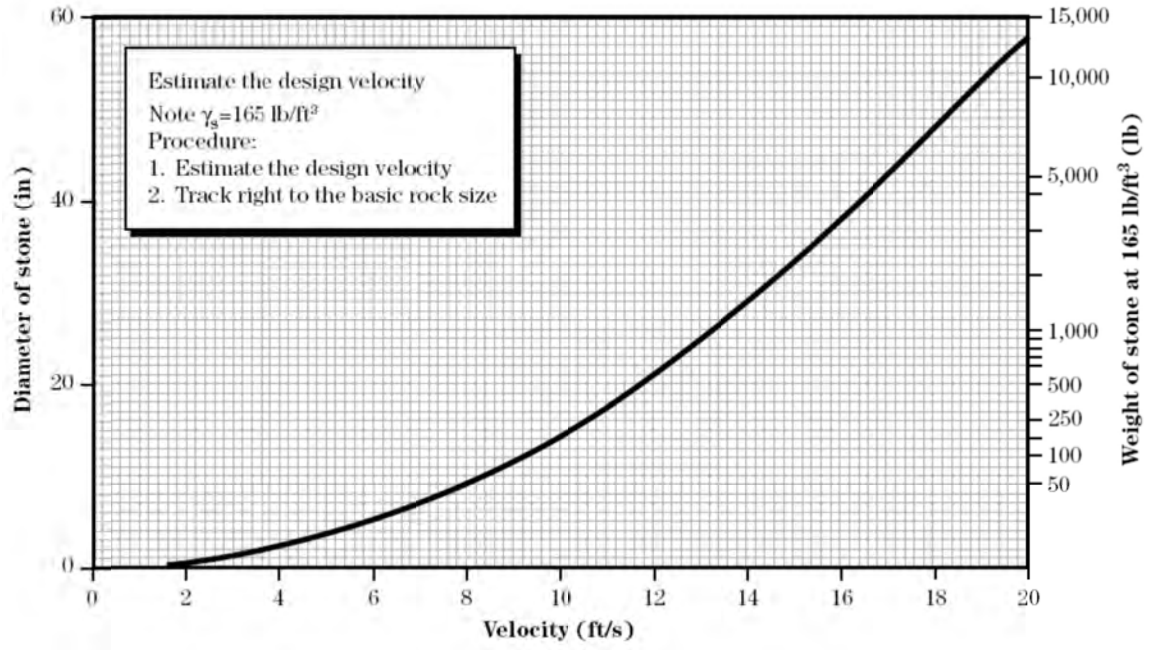


Figure 5.4-6: Rock sizing based on the Isbash curve. (Source: Isbash, 1963; NRCS, 2007a)

Rock sizing is also performed based on the calculated or modeled shear stress during the design flow. $\tau_c = \tau_c^* (1.65) \gamma_w D50$ where τ_c^* is the Shield's Parameter that is 0.6 for normal material and 0.06 to 0.1 for dense material with a mixed grain size.

Rock Type

Stone Riffles and Strainers

Natural river rock is preferred over angular rock for stone riffles and strainers to naturalize instream habitat. If material is not available on site, round river rock should be imported. If round river rock is not available, blocky or angular rock may be used but should be placed in the channel to mimic riffle bed features. Stone strainers are strictly an accumulation of larger boulder material placed in the bed while stone riffles should be constructed with a gradation that matches nearby natural riffles as closely as possible. Larger foundation stones that are immobile during the design flood are placed at various locations to tie the structure to the bed (see Figures 5.4-13 and 5.4-14). Foundation stones may be angular as they will be buried in the channel bed. Install dominant riffle particles consistent with the median particle size (D50) at nearby riffles observed upstream or downstream of the project site. These stones should be round to mimic natural habitat. Finally, round, smaller grain sizes based on natural bed gradation are used to fill voids.

Weirs

Large blocky or angular rock is typically used for weirs to lock the rocks together and properly secure the structure in the bed and banks. Weir rocks should have relatively uniform dimensions to allow for stacking and linking across the channel. Weirs consist of foundation stones and upper courses of stone.

Bed Armor Performance Standards, Design Guidance, Construction Considerations, and Sample Sequence of Work

1. Performance Standards
    a. Halt channel downcutting.
    b. Halt horizontal channel migration threatening infrastructure and unmovable habitable buildings. (Avoid horizontal channel migration along opposite bank of threatened infrastructure.)
    c. Provide aquatic organism passage and continuous surface flow.
    d. Create final channel dimensions and cross sections similar to adjacent channel reaches.
2. Design Considerations
    a. Match slope to streambed profile and ensure uniform transitions from the natural stream bed to the project area.
    b. Restore the channel bankfull width, to the greatest extent possible, to address major discontinuities with adjacent reaches.
    c. Create or promote the development of a low-flow channel similar to and connected to adjacent reaches.
    d. Maintain or re-establish channel roughness and aquatic habitat features similar to those of adjacent reaches with matching post-project flow velocities.
    e. Assess sediment load and transport regimen of upstream and downstream channel reaches.
    f. Ensure compatibility between bed armor depth, key depth, and configuration of adjacent slope armor (if present).
    g. Ensure that elevating the channel profile will not increase inundation risk to adjacent infrastructure.
3. Material Specifications
    a. Refer to the draft streambed stone fill specification (Appendix M).
    b. Stone shall be well graded material including fine sediments such as sand and fine gravel to fill voids and prevent underflow.
    c. Both fractions of stone may be sourced onsite using native river sediment if possible and with approval from ANR.
4. Construction Considerations
    a. Insure that material of both large (armor) and small (void fill) size fractions are onsite for construction.

    b. Fine material shall be layered with the large sediment fraction class and mechanically worked into voids to prevent underflow.
    c. Hydraulic flushing of the material may be used to enhance void filling.
    d. Streambed infill material shall not be compacted.
    e. Conduct work in a manner that limits tracking over placed material.
    f. Water and sediment control measures are required to minimize sediment discharges to surface water.
5. Construction Sequence
    a. Excavate existing native river sediment to the depth that the bottom of the rock is to be placed within the designated bed armoring area. Stockpile the excavated river sediment on the banks or floodplain for reuse.
    b. Install bed armoring in excavated riverbed with layers of armor and fines to fill voids. The elevation of the top of the bed armoring should be 1.5 to 2.0 feet below final bed elevation to allow space for installation of the native riverbed on top of the armor.
    c. Confirm proper armor elevations with construction survey.
    d. Reinstall excavated river sediment (and other previously dredged river sediment) within and over bed armoring. Work material into voids in larger bed armoring with teeth on excavator bucket or by jetting water over material. Once complete, water should flow on top of the armored riverbed surface and the channel should be fish passable.
    e. Establish a compound channel cross section with a low-flow channel and benches that mimic the adjacent channel cross section.
    f. The final bed should have a mix of particle sizes and a hydraulic roughness consistent with upstream and downstream reaches.
    g. The project should be monitored by a qualified river engineer to be sure flow is on top of the installed bed armor and habitat is not fragmented. If underflow is taking place, install more fine sediments such as sand into the voids of larger rocks.

Hydraulics

The pace of the repair work will determine the amount of time available for design. If grade control is taking place during emergency repair work, a basic uniform flow calculation to estimate flood velocity using the Manning's Equation and to estimate shear stress is recommended (Chow, 1959; Chanson, 2004). Estimates of flood flow rates can be obtained from regression equations (Olson, 2002) on the USGS *StreamStats* website (http://water.usgs.gov/osw/streamstats/Vermont.html).

If more time is available for design, more detailed hydrology and hydraulic modeling is recommended for large projects and those with high risk due to site setting. The analysis can include:

- A prediction of flood flows based on USGS stream gauge statistics, hydrologic modeling such as HEC-HMS (USACE, 2001), or regression estimates;
- A hydraulic model such as HEC-RAS (USACE, 2010) to analyze flood depth, velocity, profiles, shear stress, and stream power; and
- A comparison of existing versus proposed hydraulics to see changes in flood depth with proposed grade control.

The hydraulic model is useful for stone sizing and to confirm that raising the channel bed will not increase flood risks to adjacent property.

COSTS

Installation costs of bed armoring will vary depending on the size of the project, the required rock size, river access, haul distance from the rock source, and haul distance from the fill disposal area. The ballpark cost of installed large stone armor is $40 to $50 per cubic yard.

The construction costs for stone riffles and weirs will vary depending on the size of the feature, the availability of rock, site access, and whether the structures are being completed in conjunction with other stabilization work. For a moderately sized mountain river in Vermont (40-50 feet wide), one stone riffle or weir may cost $5,000 to $10,000 to construct. Actual costs will vary depending on site-specific river conditions (e.g., size, access, etc.), the number of structures to be constructed, and the availability of stone.

Thorough documentation is required when seeking reimbursement from funding agencies. Information and applications should be filed prior to construction in nonemergency scenarios. After-the-fact submissions must take place in emergency situations.

- GPS the perimeter of the work area and document footprint, widths, and length of channel affected by work.
- Photograph the post-flood conditions and compare to pre-flood photographs and site information.
- Document pre-flood versus post-flood incision ratio in the channel.
- Quantify the amount of sediment or rock to be installed in the channel and the amount of material to excavate.
- Document other stabilization practices being completed in conjunction with grade control.
- Document private property ownership and all permissions obtained to complete work.
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or during emergency work.
    - FEMA
    - NRCS

  - USACE
  - VTANR
  - VTrans
  - Municipality
- Document how the project meets applicable State Performance Standards and permit requirements.

PERMITTING

This practice will require state and federal environmental permits. Permits will be needed from VTDEC (2014) and the U.S. Army Corps of Engineers (2012) if the work results in fill that exceeds the jurisdictional thresholds. Planning for permits well in advance of the work is recommended as the process may take many months during busy review periods.

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
  - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
  - Identify reporting category
  - Contact Vermont Field Office
- Vermont Stream Alteration Permit
  - Meet Performance Standards as identified above
  - Identify reporting category
  - Contact river management engineer
- Local Zoning Permit
  - Contact Town Administrator for reporting needs

CONSTRUCTION

Constructability

Many designers and construction contractors have experience with instream structures such as stone weirs to control the grade of a stream. Other structures such as riffles and strainers are less common even though they use the same construction approach. Some initial discussions may be needed to explain the similarities and differences between weirs, riffles, and strainers.

Since stone riffles, strainers, and weirs are discrete features that need to remain stable to achieve vertical channel stability, construction oversight of tie-in locations is critical. Bed armoring has less potential for failure since the treatment is continuous across the channel bed, but tie-in locations at the boundaries of the application must be carefully considered to avoid decreasing connectivity along the channel bed profile.

In general, construction oversight is needed for grade control to ensure that the following elements are done properly:

- Final longitudinal profile of channel is consistent with design to ensure vertical stability;
- Rock sizes are large enough;
- Installations are properly tied in to banks and bed;
- Adjacent bank erosion is stabilized; and
- Aquatic organism passage is maintained.

Since most of the work to stabilize the bed takes place in the channel and along the banks, road closures are only needed if the practice is being completed in conjunction with a bank stabilization treatment that requires lane closures. Some traffic control may be required where dump trucks or haul units enter and leave the site with imported rock or exported sediment.

Temporary Construction Controls

Since grade control practices involve disturbance to a large portion of the channel bed, this work should always be completed during low flow periods to limit downstream sedimentation and allow for proper visibility to successfully complete the work. During reinstallation of native bed sediments, working in the dry is often not practical as the work is taking place across the entire channel cross section. If temporary water control is needed in a portion of the channel, berms or work platforms made of native sediment deposits can be used to guide water out of the work area. Bladders that can be filled with water can be used to direct water away from the work area for larger projects.

Some degree of fine sedimentation may be unavoidable during instream work, particularly when native bed materials are being reinstalled over bed armoring. A series of gravel dams and sediment trap pools can be used during instream work to capture fine sediment and control downstream turbidity. Check dams can be made from sediment, sandbags, or jersey barriers. Several check dams and pools can be placed downstream of the work area. The pools should be periodically cleaned out as work takes place.

Access

Access to stabilize channel beds is typically made from state or municipal roads. Ownership of proposed access locations must be verified by reviewing roadway right-of-way mapping and local parcel mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access must take place across private land, agreements with the landowners are common. Access agreements typically include discussions or notes about returning the land to the original condition following the project. Planting of the upper bank with perennials, shrubs, and trees may be requested to naturalize the site following the construction work.

For larger projects or those likely requiring frequent future maintenance, easements can be sought to allow periodic access for specified work such as flood damage repair or sediment management.

CONCEPTUAL DESIGN PLANS/DETAILS

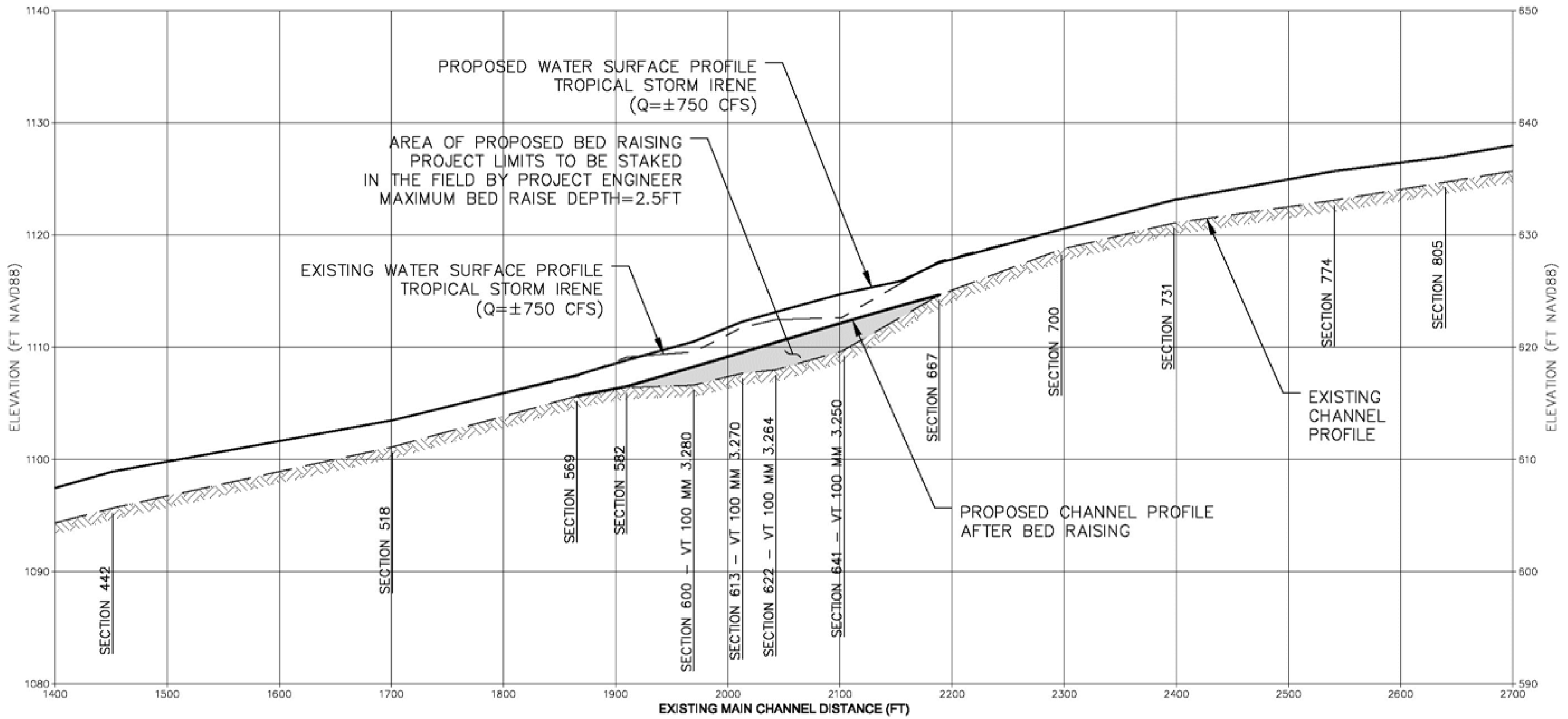


Figure 5.4-7: Longitudinal profile showing bed armor location to elevate scoured portion of the channel bed (shaded area) on South Branch Tweed River in Killington, Vermont along VT Route 100. (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental)

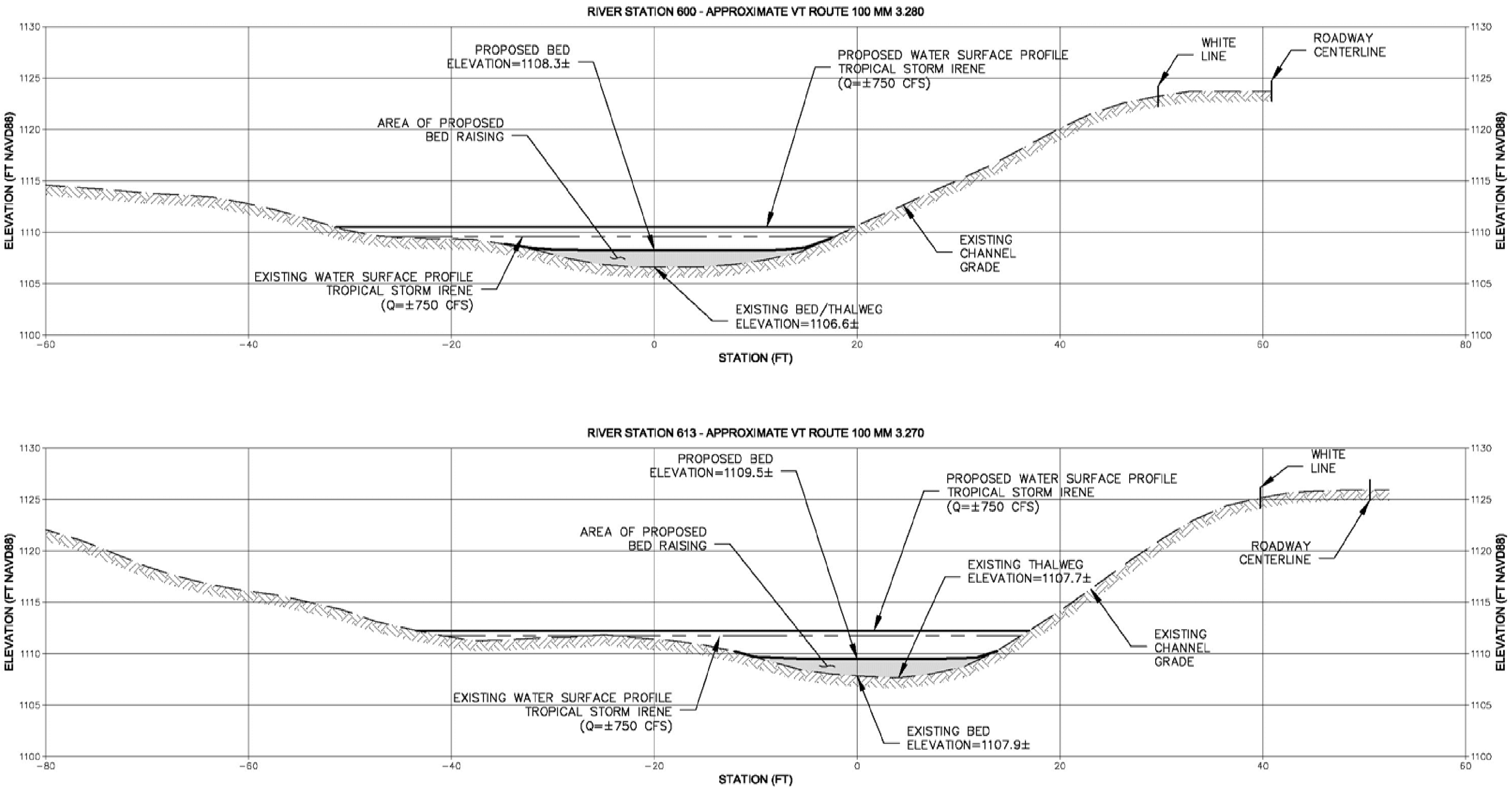
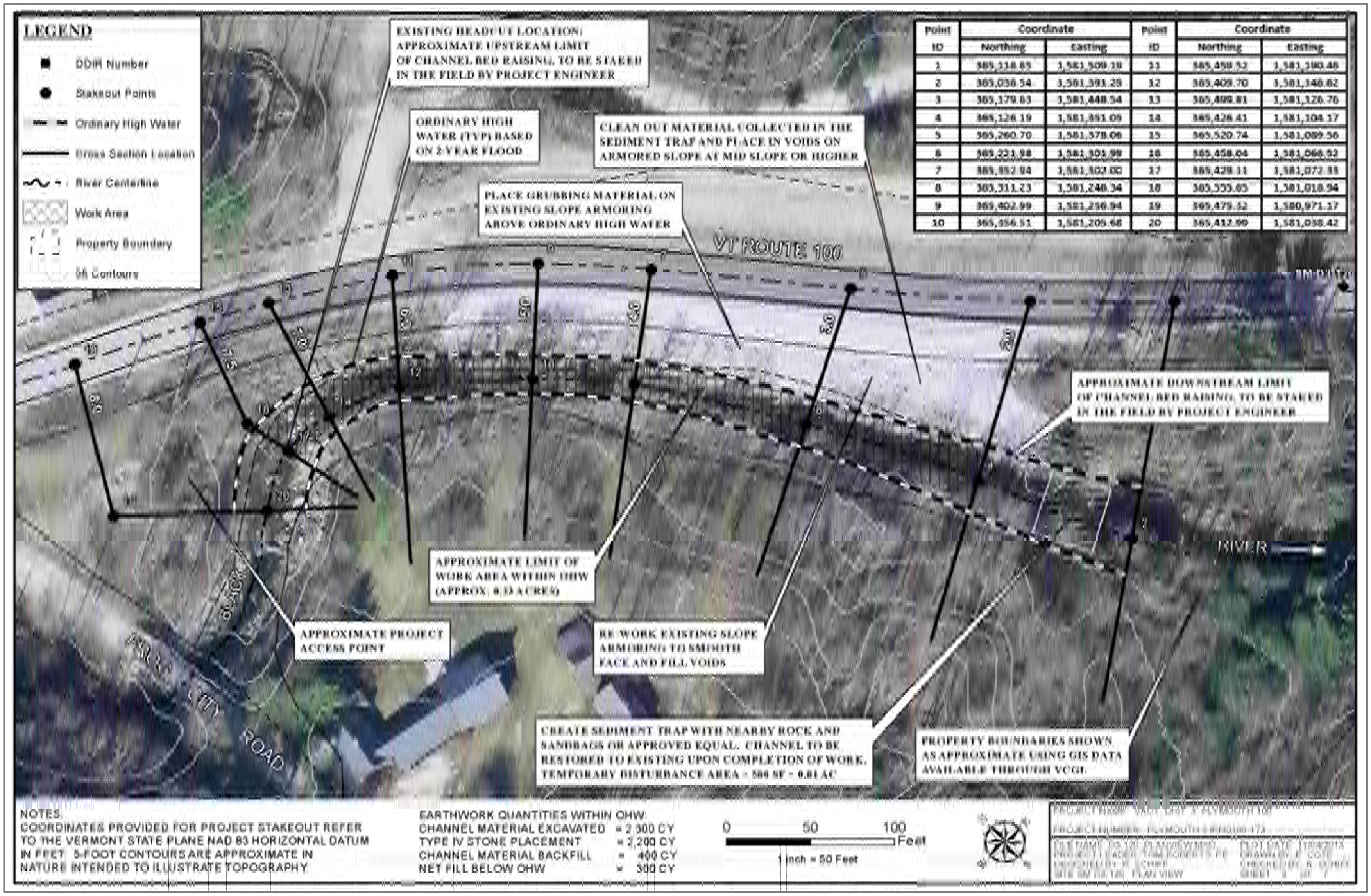


Figure 5.4-8: Cross sections showing bed armor application to elevate channel bed (shaded area) on South Branch Tweed River in Killington, Vermont along VT Route 100. (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental)



EXISTING HEADCUT LOCATION; APPROXIMATE UPSTREAM LIMIT OF CHANNEL BED RAISING, TO BE STAKED IN THE FIELD BY PROJECT ENGINEER

ORDINARY HIGH WATER (TYP) BASED ON 2 YEAR FLOOD

CLEAN OUT MATERIAL COLLECTED IN THE SEDIMENT TRAP AND PLACE IN VOIDS ON ARMORED SLOPE AT MID SLOPE OR HIGHER

PLACE GRUBBING MATERIAL ON EXISTING SLOPE ARMORING ABOVE ORDINARY HIGH WATER

APPROXIMATE DOWNSTREAM LIMIT OF CHANNEL BED RAISING, TO BE STAKED IN THE FIELD BY PROJECT ENGINEER

APPROXIMATE LIMIT OF WORK AREA WITHIN OHW (APPROX. 0.33 ACRES)

APPROXIMATE PROJECT ACCESS POINT

RE-WORK EXISTING SLOPE ARMORING TO SMOOTH FACE AND FILL VOIDS

CREATE SEDIMENT TRAP WITH NEARBY ROCK AND SANDBAGS OR APPROVED EQUAL. CHANNEL TO BE RESTORED TO EXISTING UPON COMPLETION OF WORK. TEMPORARY DISTURBANCE AREA - 500 SF - 0.01 AC

PROPERTY BOUNDARIES SHOWN AS APPROXIMATE USING GIS DATA AVAILABLE THROUGH VCGI.

Point ID	Coordinate		Point ID	Coordinate	
	Northing	Easting		Northing	Easting
1	365,118.85	1,581,509.19	11	365,459.52	1,581,190.48
2	365,036.54	1,581,391.29	12	365,409.70	1,581,148.62
3	365,179.63	1,581,448.54	13	365,499.81	1,581,126.76
4	365,126.19	1,581,391.05	14	365,426.41	1,581,104.17
5	365,260.70	1,581,378.06	15	365,520.74	1,581,089.56
6	365,221.98	1,581,301.99	16	365,458.04	1,581,066.52
7	365,352.94	1,581,302.00	17	365,429.11	1,581,072.33
8	365,311.23	1,581,240.34	18	365,555.65	1,581,018.94
9	365,402.99	1,581,256.94	19	365,475.52	1,580,971.17
10	365,356.51	1,581,205.68	20	365,412.99	1,581,038.42

NOTES:
COORDINATES PROVIDED FOR PROJECT STAKEOUT REFER TO THE VERMONT STATE PLANE NAD 83 HORIZONTAL DATUM IN FEET. 5-FOOT CONTOURS ARE APPROXIMATE IN NATURE INTENDED TO ILLUSTRATE TOPOGRAPHY.

EARTHWORK QUANTITIES WITHIN OHW:

CHANNEL MATERIAL EXCAVATED	= 2,300 CY
TYPE IV STONE PLACEMENT	= 2,200 CY
CHANNEL MATERIAL BACKFILL	= 400 CY
NET FILL BELOW OHW	= 300 CY

Figure 5.4-9: Design plan showing bed armor location and layout to elevate channel bed on Black River in Plymouth, Vermont along VT Route 100. (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental)

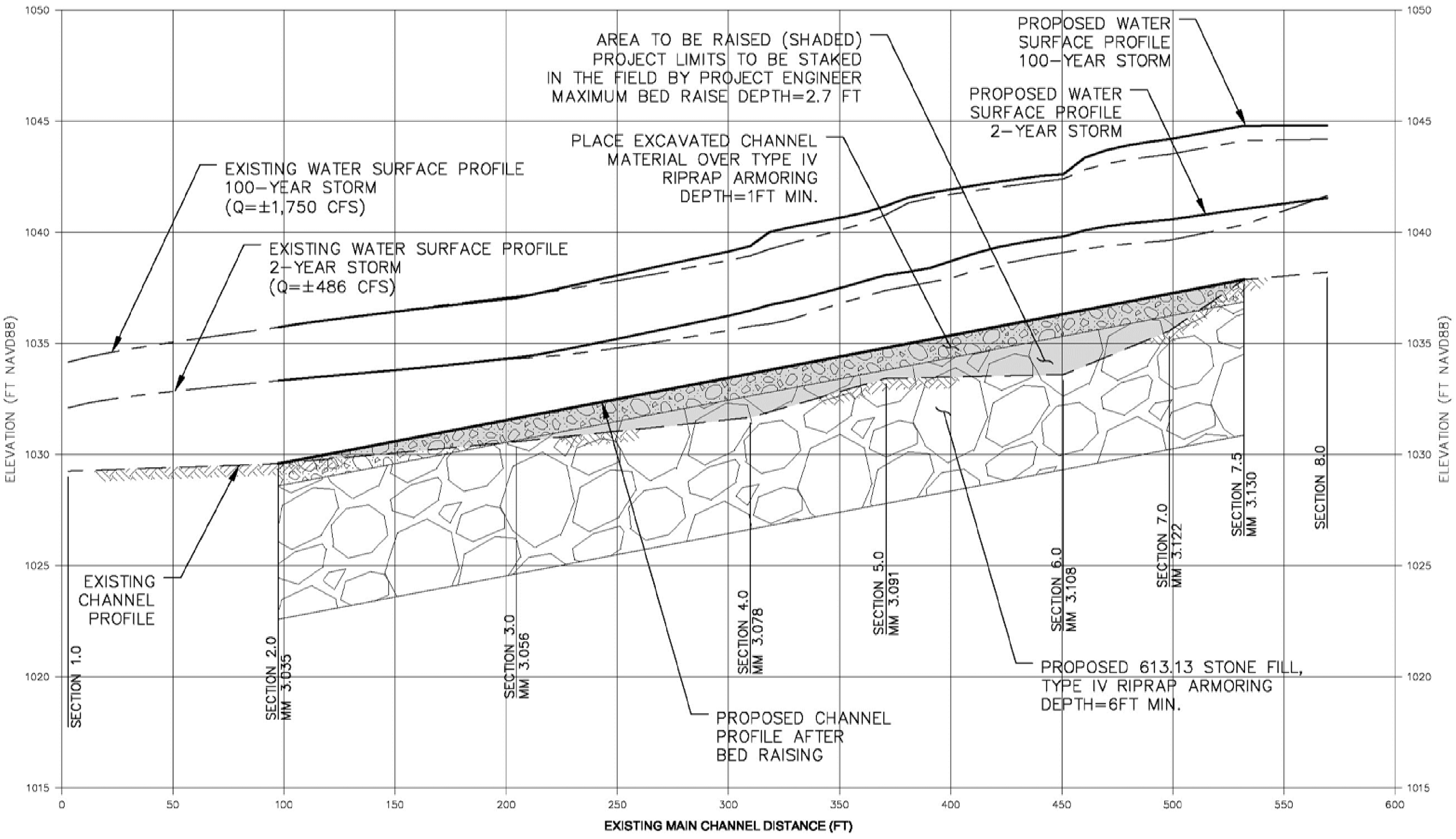


Figure 5.4-10: Longitudinal profile of bed armoring to elevate channel bed on Black River in Plymouth, Vermont along VT Route 100. (Source: Milone & MacBroom, Inc. and Fitzgerald Environmental)

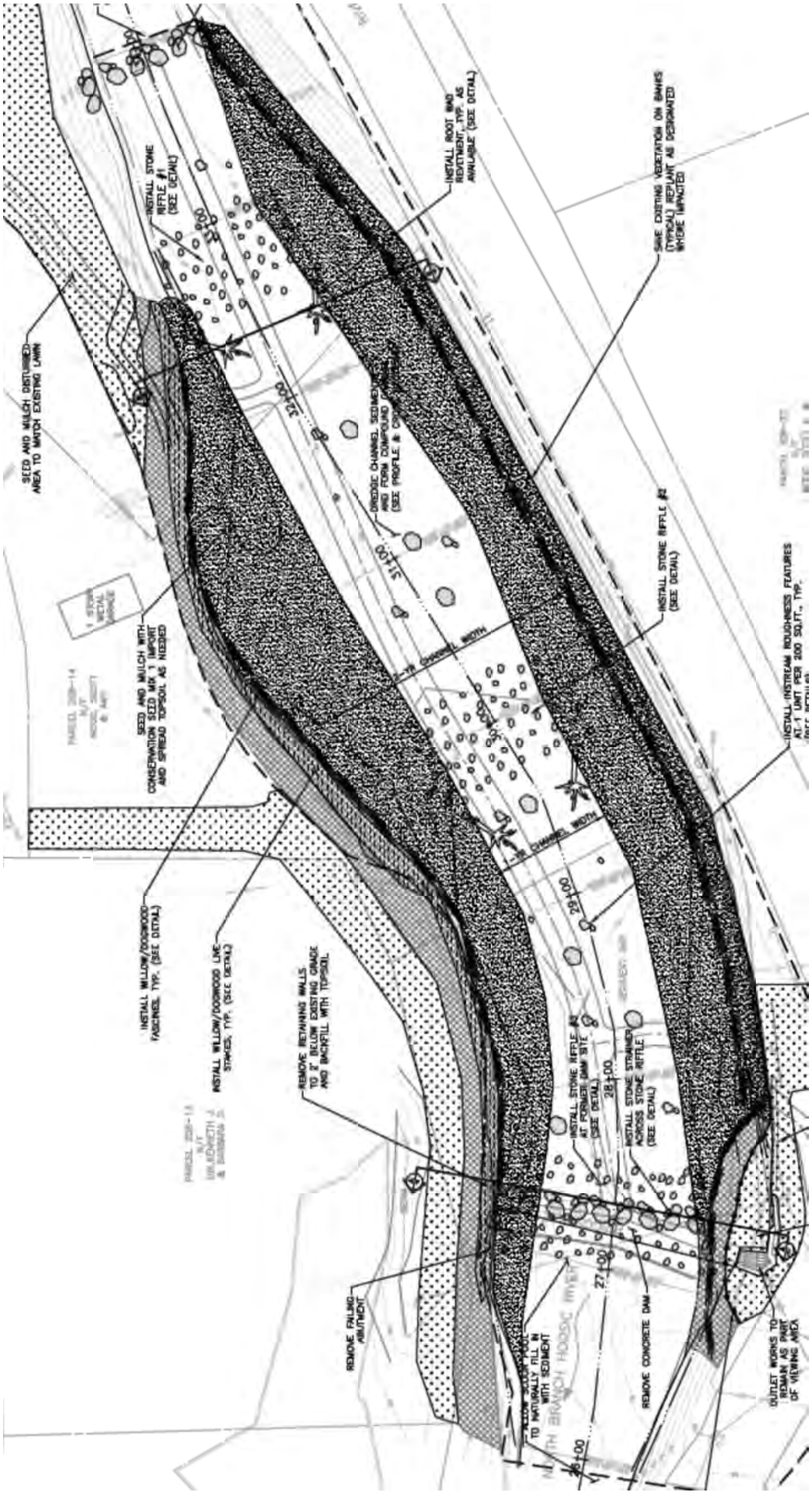


Figure 5.4-11: Grade control plan using stone strainers and riffles. (Source: Milone & MacBroom, Inc.)

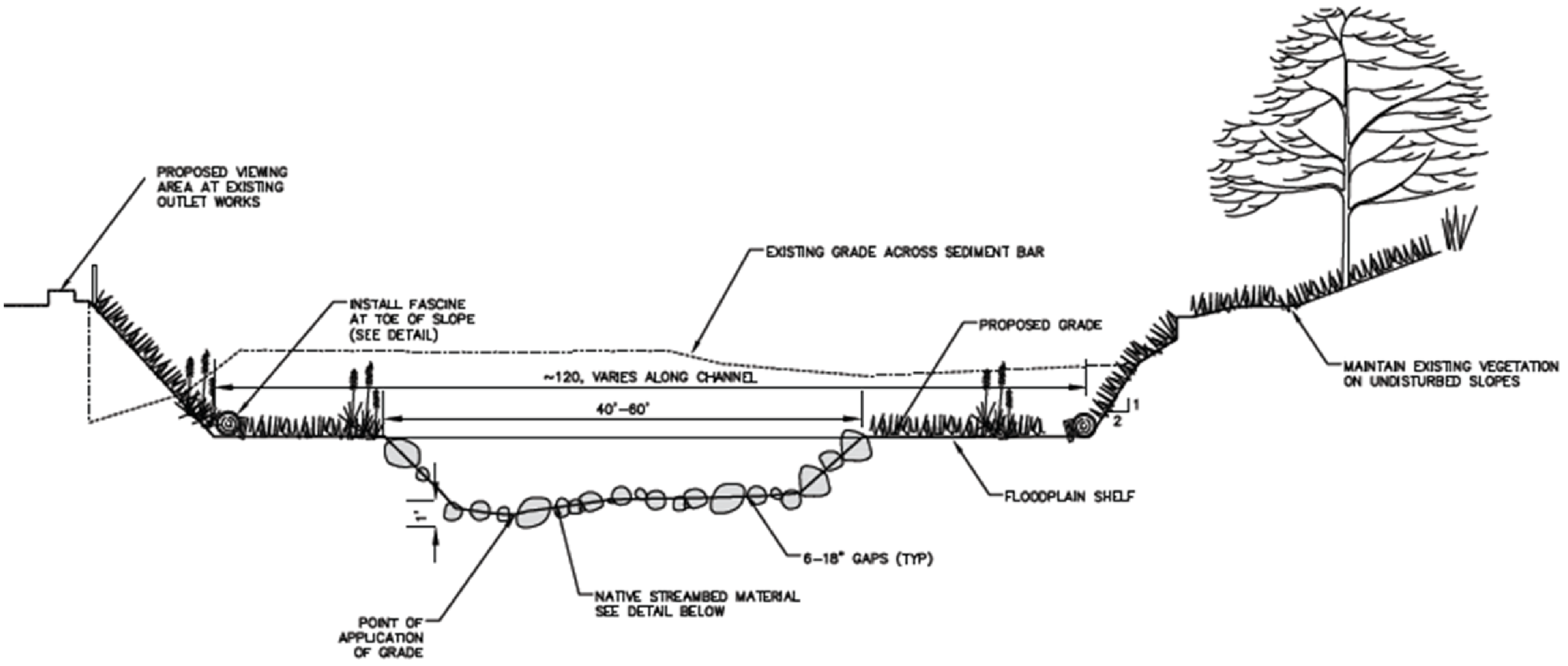
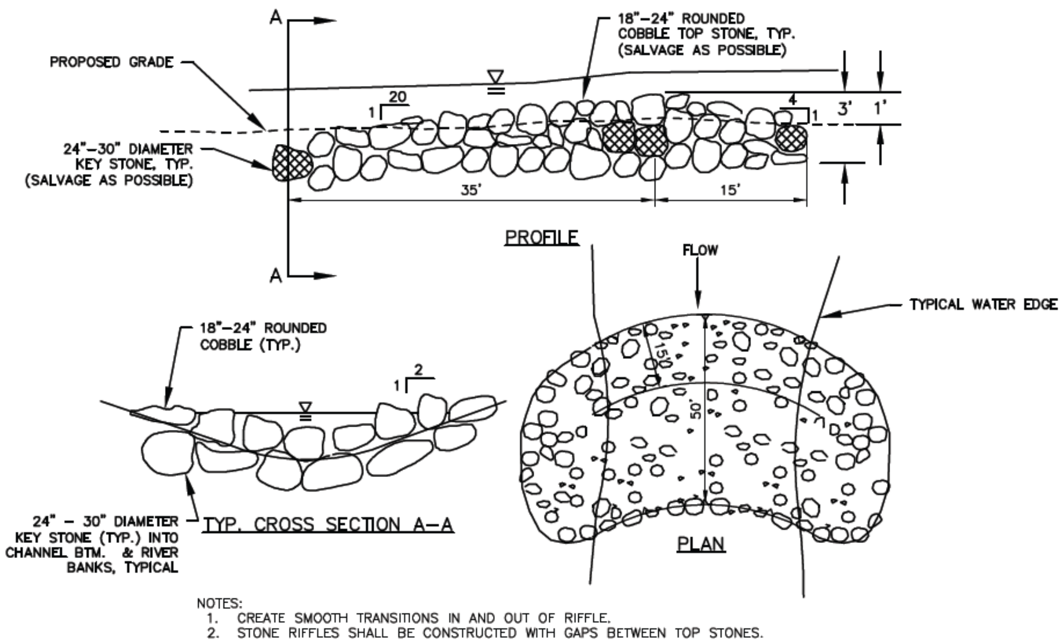
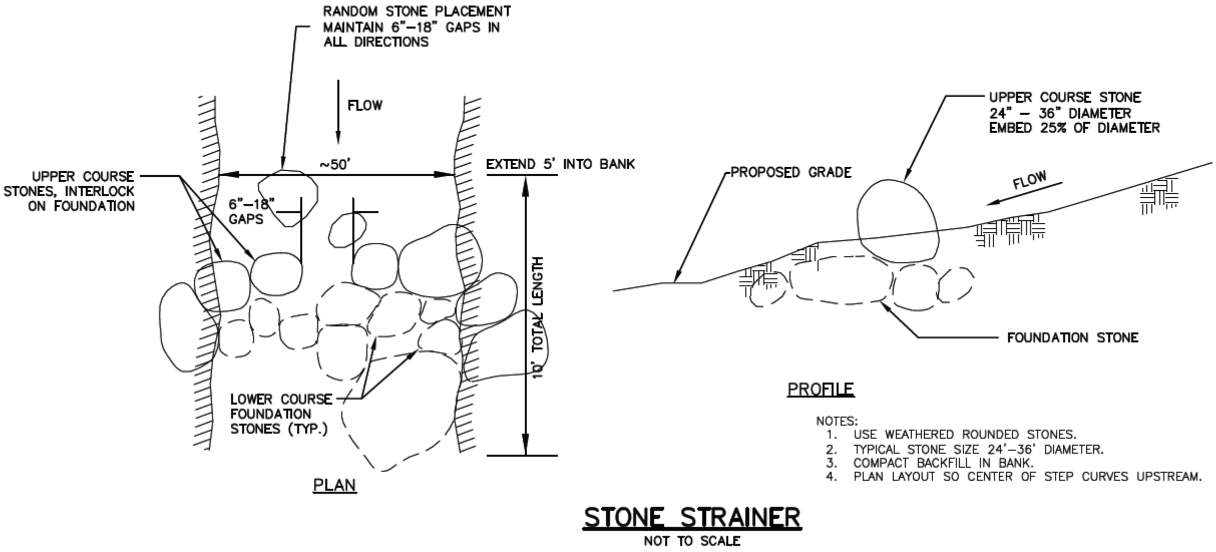


Figure 5.4-12: Stone strainer cross-section view used for grade control. (Source: Milone & MacBroom, Inc.)



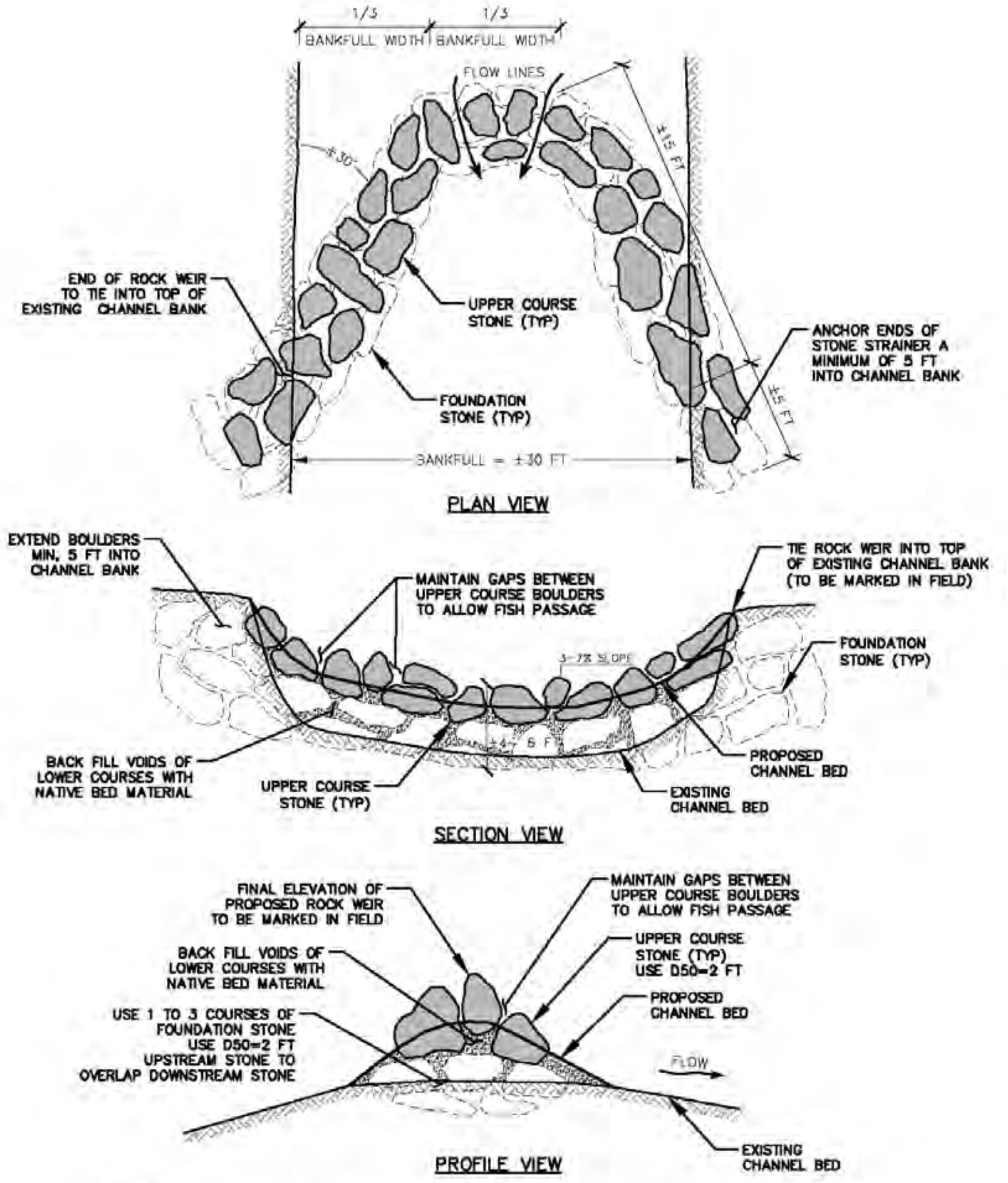
NOTES:
1. CREATE SMOOTH TRANSITIONS IN AND OUT OF RIFFLE.
2. STONE RIFFLES SHALL BE CONSTRUCTED WITH GAPS BETWEEN TOP STONES.

Figure 5.4-13: Stone riffle design detail for grade control following dam removal. (Source: Milone & MacBroom, Inc.)



NOTES:
1. USE WEATHERED ROUNDED STONES.
2. TYPICAL STONE SIZE 24'–36' DIAMETER.
3. COMPACT BACKFILL IN BANK.
4. PLAN LAYOUT SO CENTER OF STEP CURVES UPSTREAM.

Figure 5.4-14: Stone strainer design detail for grade control following dam removal. (Source: Milone & MacBroom, Inc.)



NOTES:

1. SOURCE OR SALVAGE UPPER COURSE BOULDERS FROM WITHIN THE CHANNEL AND ADJACENT FLOODPLAIN AREAS DURING CONSTRUCTION IF POSSIBLE. IF IMPORTED, USE WEATHERED NATURALLY-FORMED BOULDERS FOR UPPER COURSE.
2. USE ANGULAR BOULDERS, RIPRAP, OR BROKEN LEDGE FOR FOUNDATION STONES TO INTERLOCK TOGETHER. OVERLAP UPSTREAM STONES OVER DOWNSTREAM STONES.
3. PLACE UPPER COURSE STONES SUCH THAT THEY INTERLOCK WITH FOUNDATION STONES.
4. FINISHED ELEVATION AND PLACEMENT OF BOULDERS WILL BE DETERMINED IN THE FIELD BY PROJECT ENGINEER.
5. ADJUSTMENT OF FINAL LOCATION AND PLACEMENT OF UPPER COURSE STONES MAY BE REQUIRED AT THE DIRECTION OF THE PROJECT ENGINEER.
6. SEE TECHNICAL SPECIFICATIONS FOR ADDITIONAL INFORMATION

ROCK WEIR

NOT TO SCALE

Figure 5.4-15: Rock weir design detail to improve aquatic organism passage at a perched culvert on Great Brook in Plainfield, Vermont. (Source: Milone & MacBroom, Inc.)

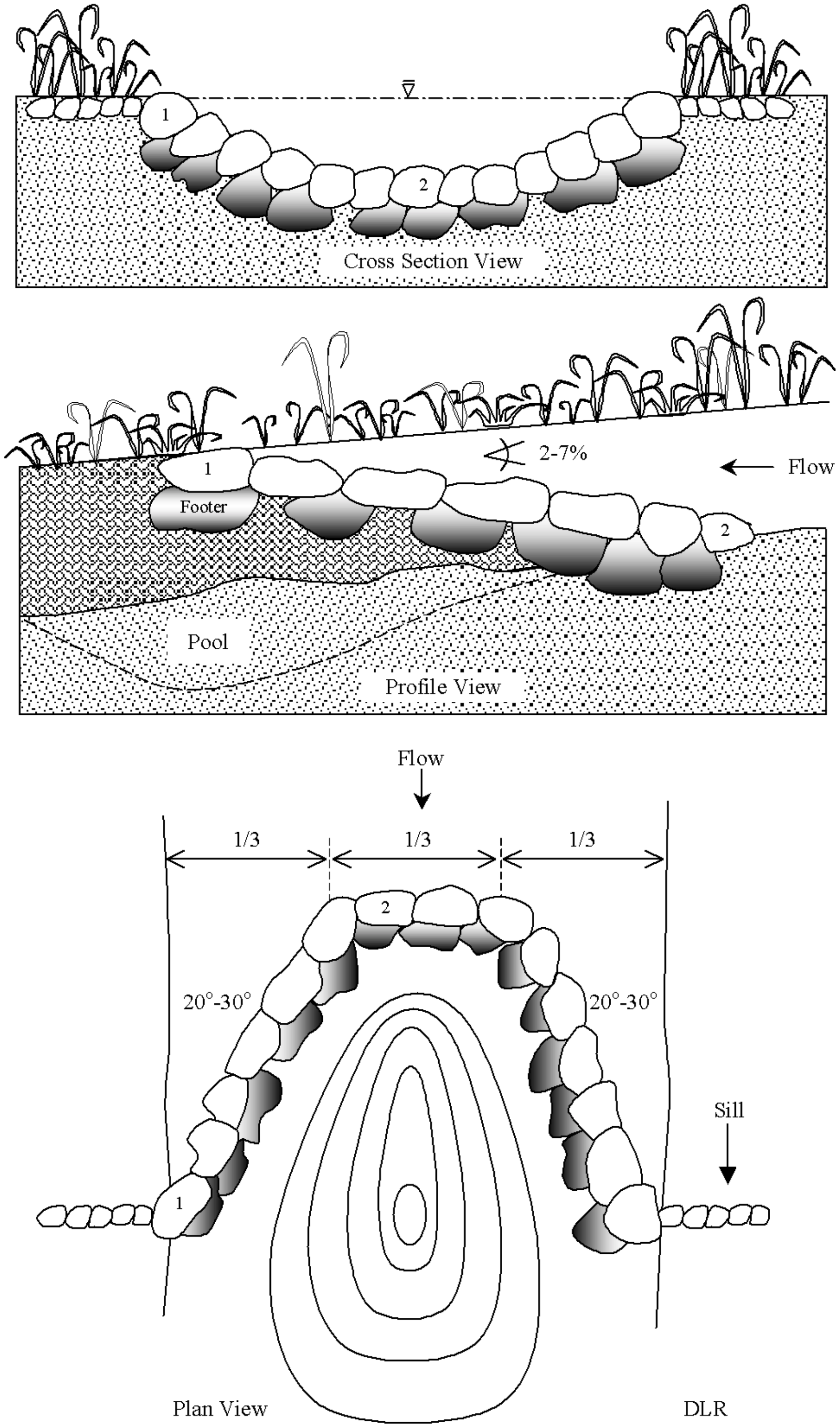
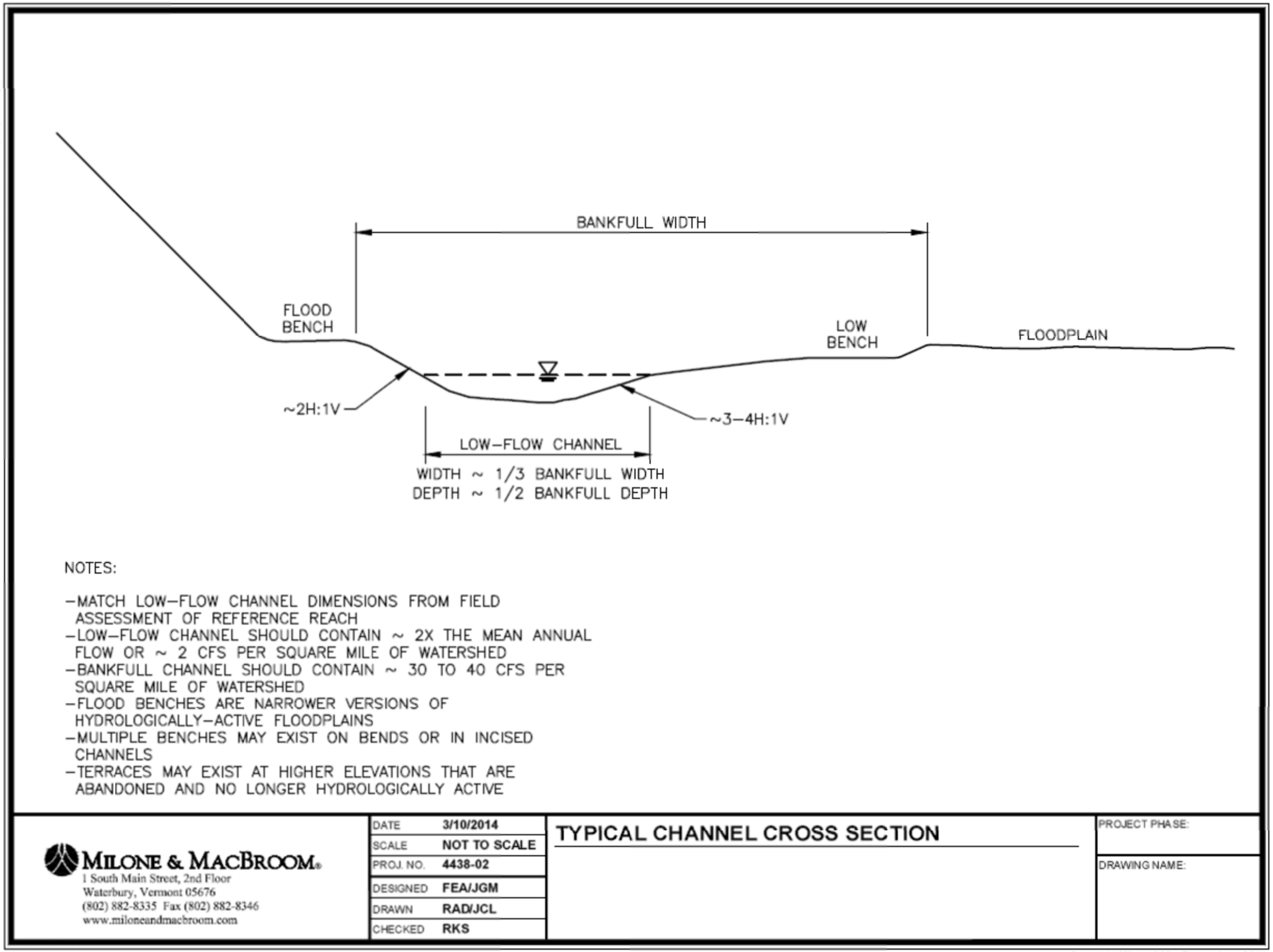


Figure 5.4-16: Conceptual section, profile and plan of grade control weir. (Source: Rosgen, 2001)



NOTES:

- –MATCH LOW–FLOW CHANNEL DIMENSIONS FROM FIELD ASSESSMENT OF REFERENCE REACH
- –LOW–FLOW CHANNEL SHOULD CONTAIN ~ 2X THE MEAN ANNUAL FLOW OR ~ 2 CFS PER SQUARE MILE OF WATERSHED
- –BANKFULL CHANNEL SHOULD CONTAIN ~ 30 TO 40 CFS PER SQUARE MILE OF WATERSHED
- –FLOOD BENCHES ARE NARROWER VERSIONS OF HYDROLOGICALLY–ACTIVE FLOODPLAINS
- –MULTIPLE BENCHES MAY EXIST ON BENDS OR IN INCISED CHANNELS
- –TERRACES MAY EXIST AT HIGHER ELEVATIONS THAT ARE ABANDONED AND NO LONGER HYDROLOGICALLY ACTIVE

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TYPICAL CHANNEL CROSS SECTION

PROJECT PHASE:

DRAWING NAME:

Figure 5.4-17: Channel compound cross section. (Source: Fitzgerald Environmental and Milone & MacBroom, Inc.)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- Vermont hydraulic geometry regression equations (HGR) (VTDEC, 2006c) (Appendix L)
- Modified large-riprap specifications (G)
- Channel evolution model (E)
- Equilibrium slope for the size of sediment (T)
- Linking damages to dominant stream processes (C)

POSSIBLE COMPANION PRACTICES

- Placed riprap wall or traditional bank armor (Section 5.2)
- Bench and flood chute restoration (Section 5.5)

SIMILAR PRACTICES

- Natural bed stabilization (Section 5.3)

5.5 BENCH AND FLOOD CHUTE RESTORATION

DESCRIPTION

Bench and Flood Chute Restoration

Assessment
- Reference bench or chute dimensions
- Incision ratio
- Stage of channel evolution

Bench Design
- Bench width, elevation, and length
- Bench lateral and longitudinal slope
- Lateral and vertical stabilization measures if required
- Excavation volume

Chute Design
- Chute dimensions
- Entrance elevation
- Chute longitudinal slope
- Lateral and vertical stabilization measures if required

Forming benches and reconnecting flood chutes is analogous to floodplain restoration but at a smaller scale. Benches are low-lying areas in or immediately adjacent to a channel. Depending on their elevation and width, benches can be used to form low-flow channels, re-establish the bankfull channel, or provide additional overbank flood area (Table 5.5-1; Figure 5.5-1).

Bench restoration is performed by adjusting the shape of the channel cross section typically by berm removal, removal of dredge spoils, removal of past bank armoring that encroaches in the channel (Figure 5.5-2), or lowering the elevation of a disconnected historic floodplain. Bench restoration is commonly performed in conjunction with other practices that include bank stabilization, placed riprap wall, natural bed raising, installation of grade control, and channel restoration following sediment removal.

Table 5.5-1: Types of Benches

Type	**Inundation Level**	**Purpose**
Low Bench	<Q1.5	Create bedforms and bars, and sediment transport in channel. Maintain instream habitat. Form low-flow channel.
Flood Bench	Q1.5 to Q10	Increased flood and sediment conveyance and storage areas, especially in confined settings.

Flood chutes are flood flow paths that cut off a meander bend during high water or when the channel is clogged with sediment and debris (VTANR, 2009). Restoration of a flood chute has the potential to spread floodwaters and allow additional space for sediment and debris deposition. By providing multiple flow paths and a combined wider flow area, reconnecting chutes can lower flood velocity and reduce erosion risks. Caution must be taken when considering flood chute reconnection to be sure flood and erosion risks are not increased by inducing sudden channel erosion (i.e., avulsion) in unwanted areas. Flood chute restoration that increases the frequency of inundation is performed by lowering the chute entrance (Figure 5.5-3) or raising the channel bed at the chute entrance.

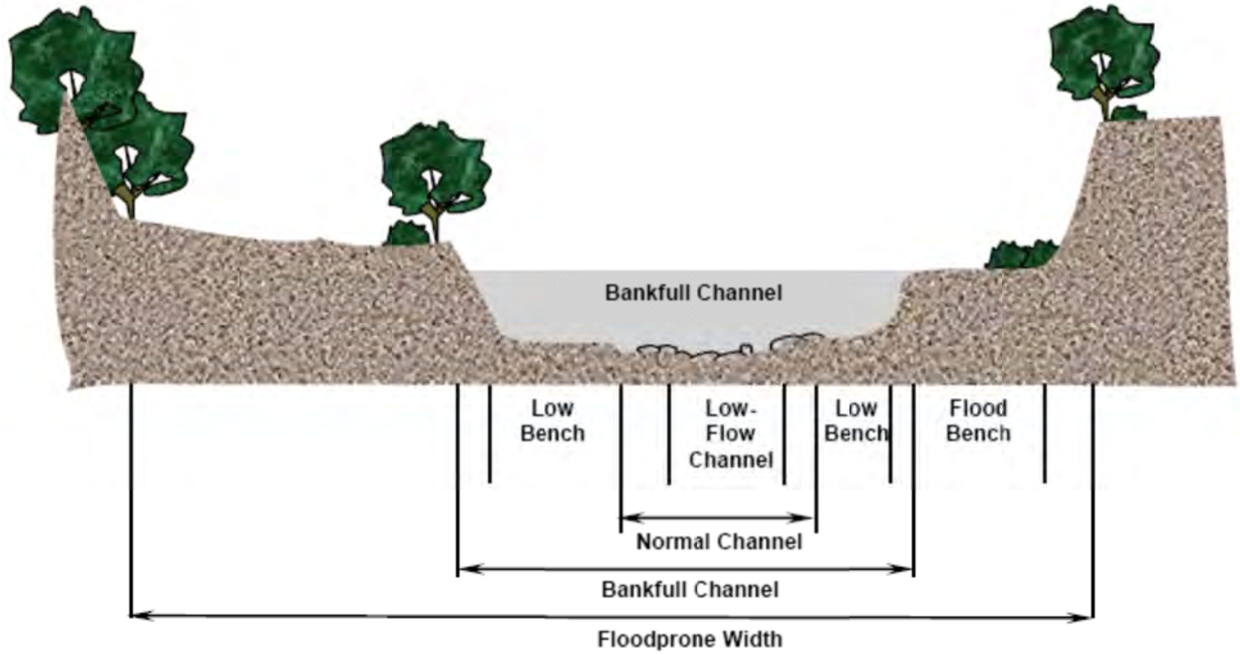


Figure 5.5-1: Schematic showing the benches and a compound channel cross section.

Figure 5.5-2: (A) Photograph of floodplain fill following emergency bank stabilization and road repair along the Tweed River in Killington, Vermont. (B) Photograph of the restored low bench after removal of the post-flood fill following permanent repairs. (Source: Milone & MacBroom, Inc., 2012)

Figure 5.5-3: Reconnected flood chute on the Middlebury River in Ripton, Vermont to divert high floodwaters away from property and infrastructure. (Source: Milone & MacBroom, Inc. 2010)

The risk reduction benefits of a functioning floodplain can be provided by restoring smaller floodprone features such as flood benches and flood chutes within or adjacent to the bankfull channel. In general, the more connected the channel is to floodplain features the lower the risks of damages in the river corridor due to erosion or deposition. Project experience shows that bench and chute restoration have the potential to reform the bankfull channel and double or even triple the flood width during small floods in confined settings. Low and flood benches can be used to reduce toe erosion along road embankments and reduce bank erosion adjacent to buildings.

(Also referred to as floodplain restoration, floodplain reconnection, floodplain recovery, flood benches (all types), benching, and chute reconnection)

APPLICATION

Proper Use

The objectives of bench and flood chute restoration are to provide more space for the river to spread out to reduce the erosive power of the river during smaller floods. The upgradient edge of a low bench is typically the toe of the bank that forms the bankfull channel and, thus, a low bench forms the bankfull channel. Benches improve habitat and sediment transport. Space is provided by restoring flood benches and flood chutes for sediment and debris storage. This practice is recommended wherever opportunity arises due to benefits of risk reduction and habitat improvement and should take place in conjunction with all other river management activities.

Meeting the Design Objectives

- Bench and flood chute restoration meet all of the Performance Standards based on the nature of the practice that provides more space for river processes to take place. The following design principles for lateral, vertical, and conveyance apply.
    - Form a low-flow channel and establish bankfull channel dimensions.
    - Restore as much floodprone area as possible given site constraints.
    - Benches should be designed to inundate annually or up to once in 10 years depending on their location and function.
    - Flood chutes should be designed to inundate once in 1, 2, 5, or 10 years depending on site conditions.
    - Avoid rapid flood width expansions and contractions that could lead to excessive erosion or aggradation.
    - Maintain or re-establish native vegetation and roughness in benches and chutes.
    - Consider the stage of channel evolution.
    - Evaluate avulsion potential when reconnecting flood chutes.
    - Plan for future sediment deposition.
    - Remove excavated material from floodplain.
    - Retain standing trees.

Limitations

- Permanent infrastructure that exists in the river corridor often limits the potential for restoring flood benches and flood chutes.
- Protection from flood and erosion is often required on the upgradient side of restored flood benches to protect remaining infrastructure.
- A suitable sediment disposal area that meets local, state, and federal regulations is required.
- River channels in an active state of incision may require bed stabilization in conjunction with flood bench and flood chute restoration.

Geomorphic Context

Bench restoration is analogous to naturalizing the expected compound cross section in channels where several flood levels and widths exist (see Figure 5.5-1). Compound cross sections are the most common shape on meandering channel types such as riffle-pool and also exist on other channel types such as plane bed and step-pool (VTANR, 2009). Bench restoration is commonly used to reverse past encroachments that can minimize futures risks and improve habitat (see Table 5.5-1).

Floodplains serve the essential function of storing floodwaters and deposited sediment. Benches and chutes store less than larger floodplains yet, in confined valley settings where space is limited, the restoration of a flood bench or flood chute can create enough space to reduce flood and erosion risks. Evaluation of the width of the river corridor (Appendices N and D), bankfull channel, benches, and low-flow channel will help guide bench and chute restoration.

The incision ratio is an indication of the vertical connectivity between a channel and floodplain that results from the current level of channel downcutting. The ratio identifies which features will be inundated during a bankfull flood. The incision ratio is the height of the recently developed (or abandoned) floodplain divided by the maximum bankfull depth (VTANR, 2009) (Appendix O). The ratio identifies which floodprone features will be inundated during a flood based on elevation. An incision ratio of 1.0 to 1.2 indicates that the bankfull flow can access the floodplain while a larger ratio indicates that the floodplain is only accessed by larger floods. Evaluation of the existing and proposed incision ratio takes place when designing the elevation for a flood bench and flood chute restoration.

Channel evolution (Appendix E) provides a prediction of the future form of the channel and floodplain and the likelihood of change. For example, stages I and V tend to be a stable channel and floodplain setting, while stages II, III, and IV tend to be more dynamic where the channel has cut down and is in various stages of building a new floodplain at a lower elevation (Schumm, 1977; FISRWG, 1998). The stage of evolution should be known when restoring bench or flood chute to know if the channel will tend to move laterally or be stable after the project is constructed.

Habitat Maintenance

- Control potential sedimentation of the channel during construction.
- Revegetate benches where fine sediment and organic soils exist. Coarse sediment areas on low benches or the bottom of chutes that are inundated several times a year may not revegetate.
- Retain standing trees and deposits of large woody debris in bench and chute areas to form riparian habitat.

Common Mistakes

- Setting the elevation of the bench or chute too high that reduces inundation frequency and retains confined flows.
- Setting the elevation of the bench or chute too low that could induce channel movement or sudden avulsion during a flood.
- Creating abrupt transitions in floodprone width upstream and downstream of the new bench or chute.
- Inadequate protection of remaining infrastructure at the back edge of the restored bench.
- Not considering channel evolution stage to know if the channel will tend to move into the newly created floodprone features.

Compatibility with Emergency Temporary Repairs and Timing of Implementation

- Large floods can widen confined channels naturally restoring flood benches. If space exists to allow the new bench to remain, these features can be incorporated into flood recovery to reduce project costs and future risks.

- Large sediment deposition events may reconnect historic flood chutes. As with benches, these features can be incorporated into flood recovery work since they reduce future risks.

SITE WORK CONSTRAINTS

The primary site constraint to flood bench and flood chute restoration is property that is located adjacent to the channel in the river corridor. Both lateral and vertical stabilization techniques are usually required to protect property next to the new flood benches or chutes that are prone to flooding.

Permission from landowners is typically required in order to perform flood bench or flood chute restoration. Outreach is often needed to review the benefits of widening the floodprone area and the proposed design. Ultimately, an agreement is needed with the landowner to leave the land in the post-flood widened state or to widen the floodprone area to a certain location on the land.

Channel and bank excavation take place during bench and flood chute restoration, so a suitable place to put the material is needed. The sediment waste area must be out of the FEMA floodplain and the Agency of Natural Resources (ANR) river corridor. No wetlands can be filled. Cultural resources cannot be impacted. Trucking of sediment is a large part of the project cost, so the closer the waste area to the floodplain restoration site the lower the project cost. Geographic Information System (GIS) mapping and the Vermont ANR Natural Resources Atlas (http://anrmaps.vermont.gov/websites/anra/) can be used to perform an initial review of potential sediment waste areas.

Bench and flood chute restoration take place in or immediately next to the river channel and require work in the bankfull channel and below the ordinary high water line (Appendix K). The work window in river channels is typically July to October. Low bench restoration should be performed during low flow periods when no rain is taking place since these features are designed to inundate regularly. If bench or chute inundation does take place during construction, temporary erosion control blankets can be used to reduce erosion and sedimentation where fine-textured sediment exists.

PRIMARY DESIGN ELEMENTS

Width

Bench width is a primary design element since it determines the extent of flow or future flooding. The target bench width is typically on the order of 10 to 100 feet and should be based on a reference bench width obtained by a combination of field observation and geomorphic assessment. Width will likely vary between low and flood benches. A reference cross section through a non-encroached portion of the river corridor can be used to determine how wide benches should be. Flood benches often are installed adjacent to existing infrastructure in combination with lateral stabilization to protect the infrastructure. Hydraulic geometry regression equations (HGRs) that provide a relationship between drainage area and bankfull channel width (VTANR, 2009) (Appendix L) can be used for approximate design of benches.

If the flood chute is utilizing a historic flow path, the channel width may remain the same. If the width needs to be adjusted, the bankfull channel width is the maximum width of the chute.

Length

The length of bench restoration can vary and is largely a function of available space. Flood chute restoration length is determined by the length of the existing historic chute. The chute alignment typically follows the historic alignment. If the alignment needs to be determined because the chute is partially or completely filled in, the pattern of the main river channel and identification of overland flow paths can be used to help restore the chute. The layout of the chute cannot increase risks to any property. Past aerial photographs and maps that show historic flow paths of the channel and flood chute are helpful for chute restoration layout.

Elevation

Properly selecting the elevation of a bench or flood chute is critical to reducing future flood and erosion risks. Low benches that are located at the back edge of the bankfull channel are typically set to inundate one to four times each year. Flood benches are typically inundated during the bankfull or larger flood (see Figure 5.5-1). The flood bench elevation can be set higher for less inundation in locations where unmovable property exists adjacent to the bankfull channel and where hydraulic and sediment transport analyses show that flood and erosion risks are not increased.

Benching in channels with nearby development is often performed in conjunction with lateral bank and vertical bed stabilization. If a bench is created on both sides of a channel with nearby floodprone property, the bench furthest from the property is typically set approximately 1 foot lower than the bench near the property to encourage the river to move away from the property.

The elevation of the entrance to a flood chute determines how frequently floodwaters will enter the chute. Chute inundation frequency can range widely yet typically is set at one time in 2 years to one time in 10 years. The chute entrance elevation and dimensions are set to convey a certain amount of flow relative to the flow in the channel to lower local flood levels. The elevation of surrounding property such as a house or a roadway that is prone to flooding is often considered when setting the entrance elevation to a flood chute so that water flows down the flood chute before it would inundate the improved property.

The tolerance for the channel to occupy the chute in the future via avulsion is considered when setting the entrance elevation. In a river corridor with unmovable property that is subject to erosion hazards, the chute entrance may be placed high (e.g., to inundate during the 10-year flood and larger) to reduce the likelihood of avulsion. In a setting where avulsion is acceptable and flood and erosion risks are low, a bankfull chute that inundates once every year or two may be desired.

Slope

A restored bench should slope toward the river channel slightly (0.25% to 0.50%). The bench should also slope down-valley approximately matching the slope of the river channel. The slope of a flood chute is typically similar to or a little steeper than the main river channel. The slope of the chute is the elevation difference between the upstream and downstream locations where the chute joins the channel divided by the length of the chute. The design slope of a chute is often predetermined based on an existing historic flow path that is going to be restored.

Surface

In most settings, a deformable surface that can be changed during the next flood will be suitable on a restored bench or flood chute. However, when structures or infrastructure exist in the river corridor and flood risks remain high, a rigid surface may be desired on a flood bench or chute to prevent excessive erosion. Creation of a flood bench with a stone armor surface would be suitable through a bridge or along a road embankment where the floodplain remains filled. The rigid bench surface would allow some flood flows to spread out while also providing for some vertical resistance to erosion. The entrance to a flood chute may also be armored in dynamic channel settings to reduce the likelihood of outflanking and avulsion. A rigid bench or chute may be considered in combination or in place of a deep stone key to reduce the chance of erosion and undermining.

Lateral and Vertical Stabilization

Bench and flood chute restoration in confined settings with development in the river corridor typically includes bank stabilization to protect adjacent property. Fill in the floodplain that appears to be protecting adjacent property actually increases flood and erosion risks since the fill narrows the channel and floodplain (i.e., the "floodplain paradox") (Figure 5.5-4). The floodplain fill confines flows increasing velocity that leads to more erosion and channel downcutting. If the floodplain were wider and lower, it would inundate more frequently, so flows would spread out, velocity would be lower, and erosion potential would be lower. Infrastructure protection projects should include restoration of flood benches and flood chutes since these practices reduce future flood and erosion risks.

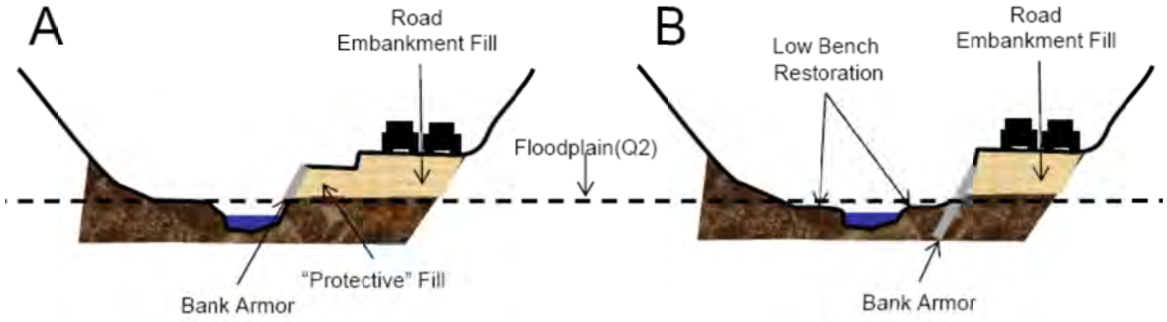


Figure 5.5-4: Schematic of a "floodplain paradox" where the appearance of protective fill (A) actually increases flood and erosion risks. Risk of damages is reduced when flood flows can spread out and access restored benches (B). Stone armoring protecting infrastructure is designed to withstand the highest shear stress for the design flood. (Source: Milone & MacBroom, Inc.)

Grade control may also be required to achieve lateral stability to prevent undermining of the banks (see Section 5.4).

Channel Evolution

Channel evolution (Appendix E) must be considered for bench and flood chute restoration. Channel widening, lateral channel movement, and floodplain formation for channel evolution stages II, III, and IV should be anticipated and included in the design. A channel in these more dynamic stages is more likely to avulse and occupy a restored flood chute than a channel in the more stable sages (I and V).

Excavation Volume

Once the bench or flood chute restoration design has been established, calculate the volume of sediment that is occupying the proposed excavation areas. Approximate survey methods with a laser range finder or a level and rod are usually acceptable to quantify small projects. Survey is needed for larger projects.

COSTS

The ballpark cost to excavate a bench or flood chute and haul the material to an area just outside of the floodplain is $8 to $10 per cubic yard. As the length of the haul increases, $75 to $150 per hour of truck time will have to be added to the project cost.

With FEMA and other federal and state regulatory agencies acknowledging the flood risk reduction benefits of functioning floodplains, the potential to fund bench and flood chute restoration projects through grants is increasing. Thorough documentation of the design will increase the chances of receiving funding to implement the project. Information and applications should be filed prior to construction in nonemergency scenarios. After-the-fact submissions may be required in emergency situations if a bench or flood chute is restored as part of a flood recovery effort.

- GPS the perimeter of the restoration area to show the footprint, widths, and length.
- Quantify the volume of fill to be removed. In a flood recovery setting, the state of the floodplain after the flood and anticipated after construction should be documented.
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or as emergency work progresses.
  - FEMA
  - NRCS
  - USACE
  - VTANR
  - VTrans
  - Municipality
- Document how the project meets applicable State Performance Standards and permit requirements.

Permitting

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
    - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
    - Identify reporting category
    - Contact Vermont Field Office
- Vermont Stream Alteration Permit
    - Meet Performance Standards as identified above
    - Identify reporting category
    - Contact river management engineer
- Local Zoning Permit
    - Contact Town Administrator for reporting needs

CONSTRUCTION

Constructability

Bench and flood chute restoration projects are straightforward from a constructability point of view and have a high likelihood of successfully reducing flood risks. As soon as the effective flow area is increased, the risks for inundation and erosion decrease.

Temporary Construction Controls

Project demarcation fencing is needed in any location that the public could come in contact with at the project site, staging locations, stockpiles, or waste disposal areas. Refer to the VTrans Construction Specifications (VTrans, 2011) for guidelines on locating and identifying staging and stockpiling areas.

Sediment and erosion controls are typically applied only as disturbance takes place near the riverbank. The Vermont Low Risk Site Handbook For Erosion Prevention and Sediment Control (VTDEC, 2006b) is commonly used in conjunction with field-based decisions for maintaining sediment and erosion controls at the construction site.

Work is performed only during low flow, and temporary elevated work platforms made of pushed up coarse material are often used to guide water out of work areas and create a platform for machinery. Machine crossings can be made with built-up sediment. Culverts can be used to create dry crossings. A series of check dams and sediment trap pools can be used during in-channel work to capture fine sediment and control downstream turbidity. Several check dams and pools can be placed downstream of the work area, and the pools should be periodically cleaned out as work takes place. Water control may not be needed during flood bench and flood chute restoration projects since much of the work can take place outside of the channel.

Access

Access to restore benches and flood chutes is typically made from private drives, state highways, or municipal roads. Ownership of the proposed access locations must be verified by conversations with landowners or by reviewing local parcel mapping and roadway right-of-way mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access is proposed across private land, agreements with the landowners are common. Access agreements typically include discussions or notes about returning the land to the original condition following the project.

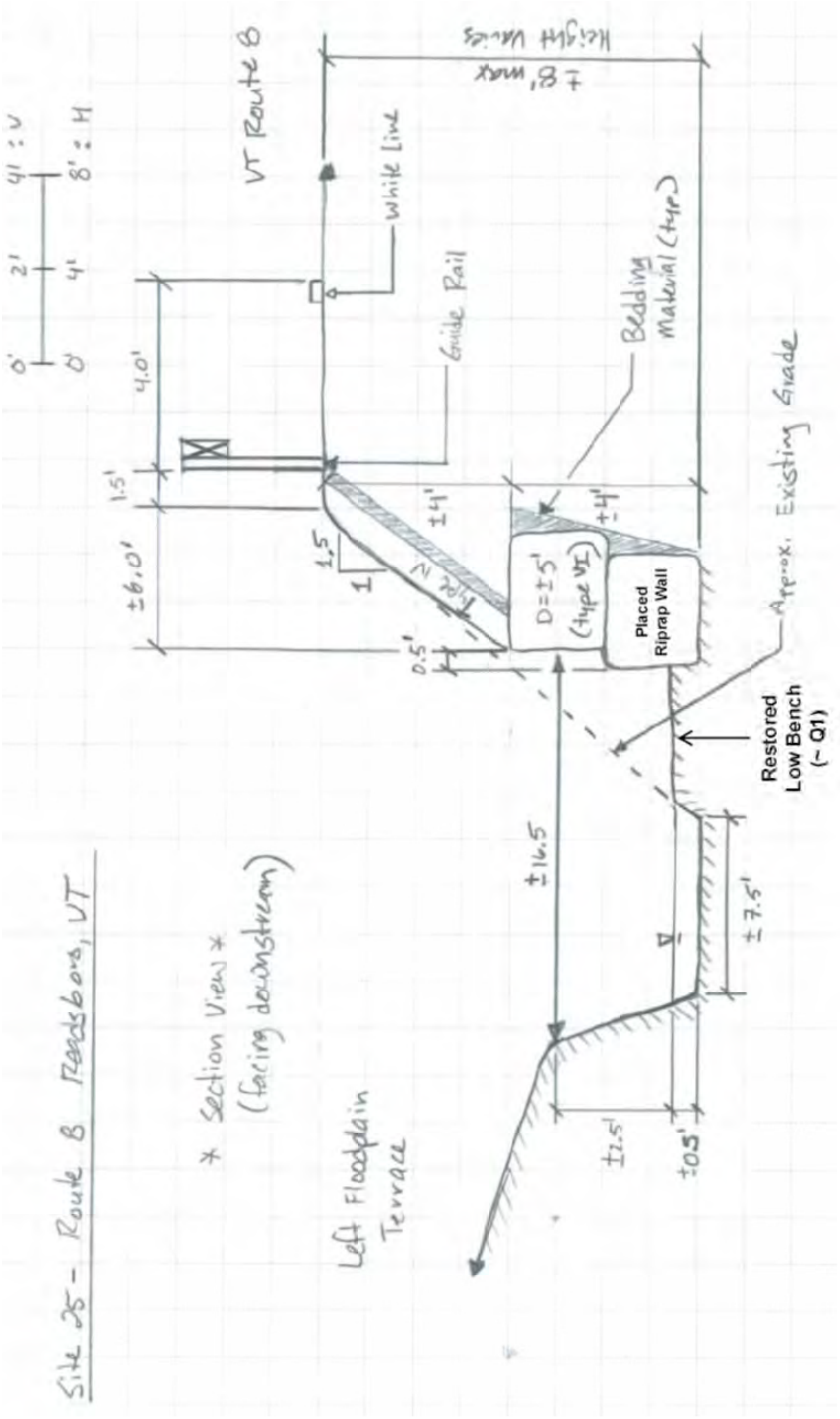


Figure 5.5-5: Sketch plan of a low bench restoration in conjunction with a placed riprap wall. The bench was designed to inundate three or four times a year to reduce flood velocities and erosion risks to the adjacent roadway (Source: Milone & MacBroom, Inc.).

Figure 5.5-6: Photograph of restored low bench in conjunction with a placed riprap wall. (Source: Milone & MacBroom, Inc.). In a natural setting, the bench would form on the inside of the meander bend such as that associated with a point bar on a riffle-pool channel. The bench was left on the outside bend for this road protection project to properly narrow the channel to the reference bankfull width and reduce the channel work by leaving the work platform of native sediment in place. Migration of the channel thalweg toward the outside of the bend is anticipated over time.

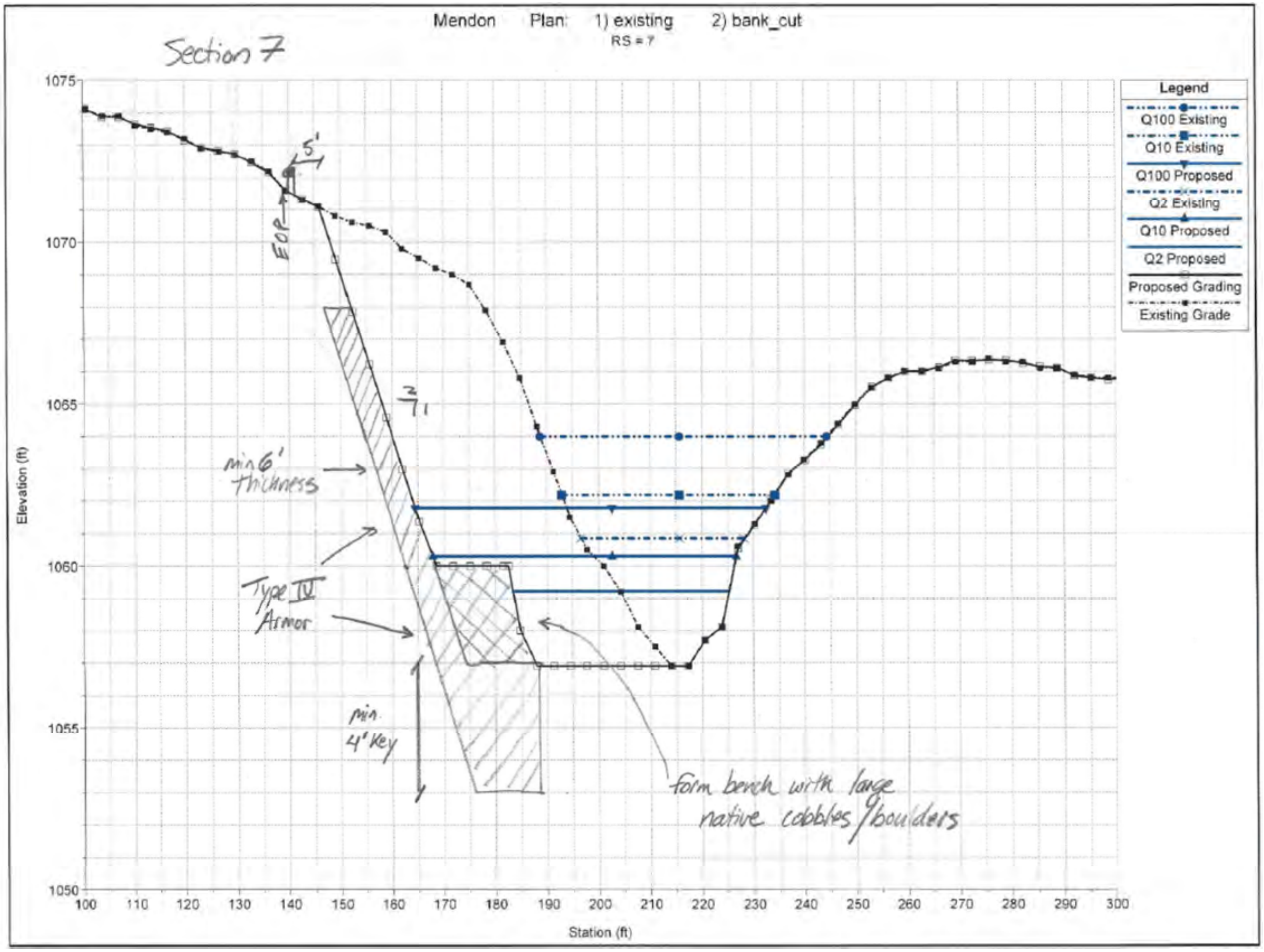


Figure 5.5-7: Hydraulic model cross section showing restoration of a flood bench and reduction of flood levels. (Source: Fitzgerald Environmental, 2013)

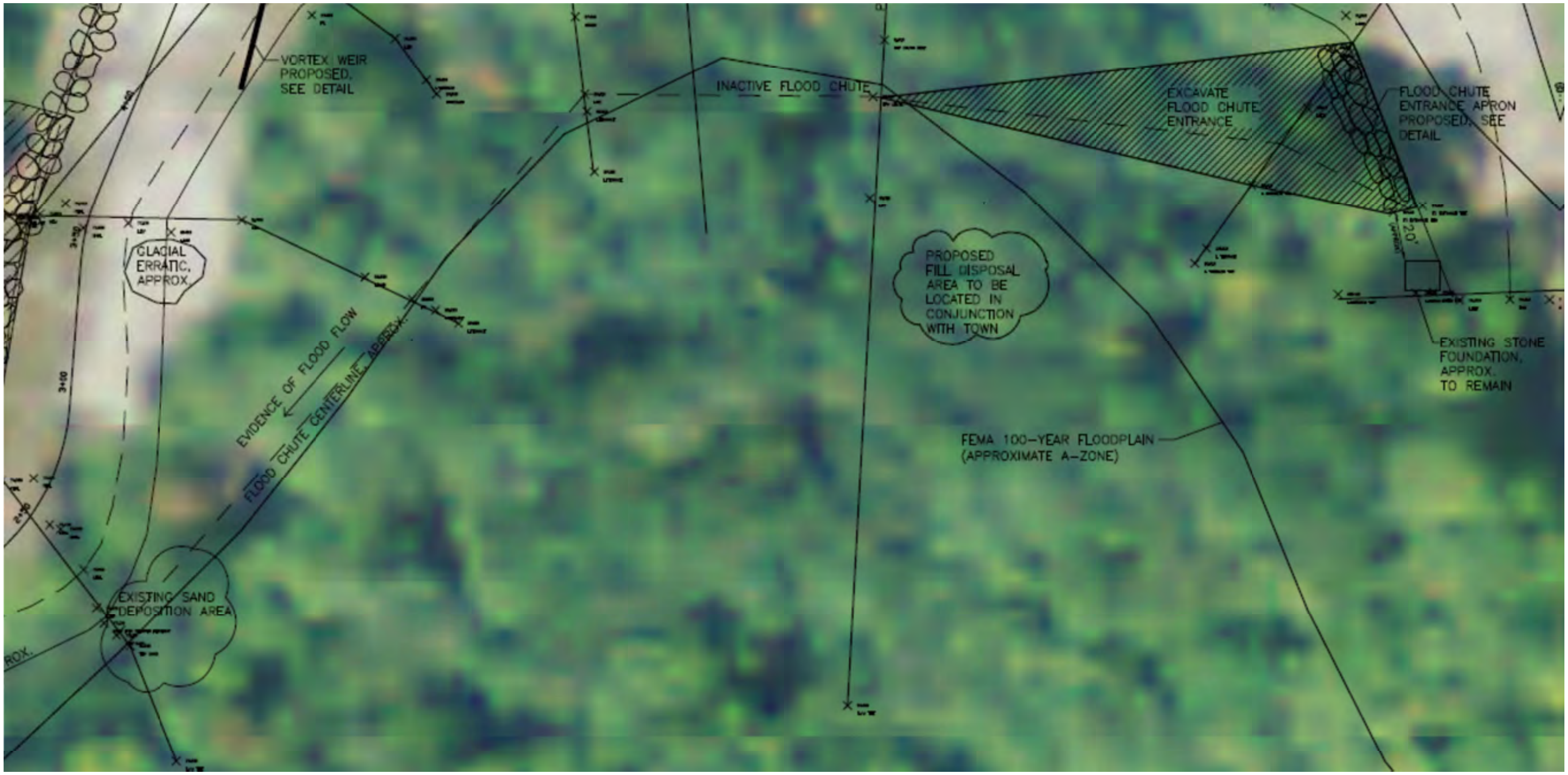
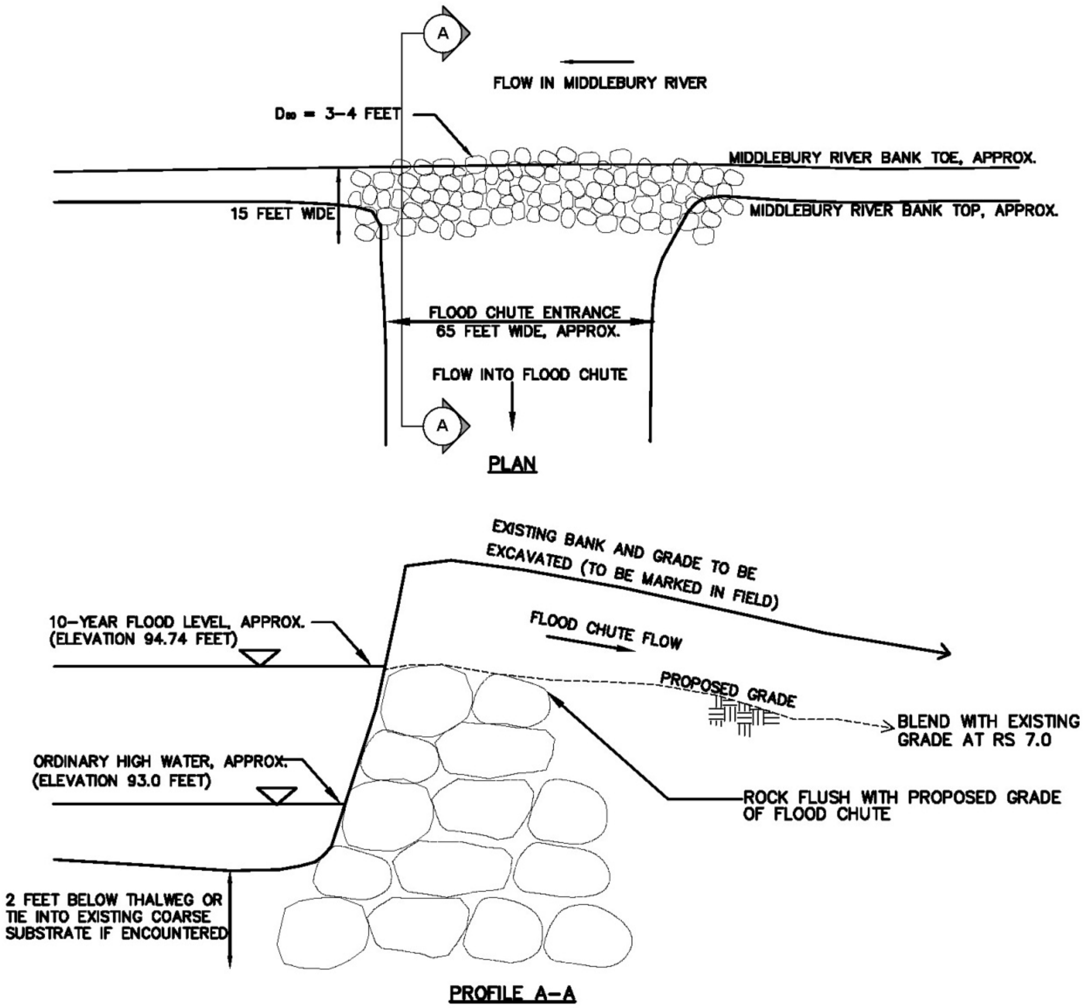


Figure 5.5-8: Flood chute restoration plan on the Middlebury River in Ripton, Vermont showing proposed excavation at a historic chute entrance. (Source: Milone & MacBroom, Inc.)

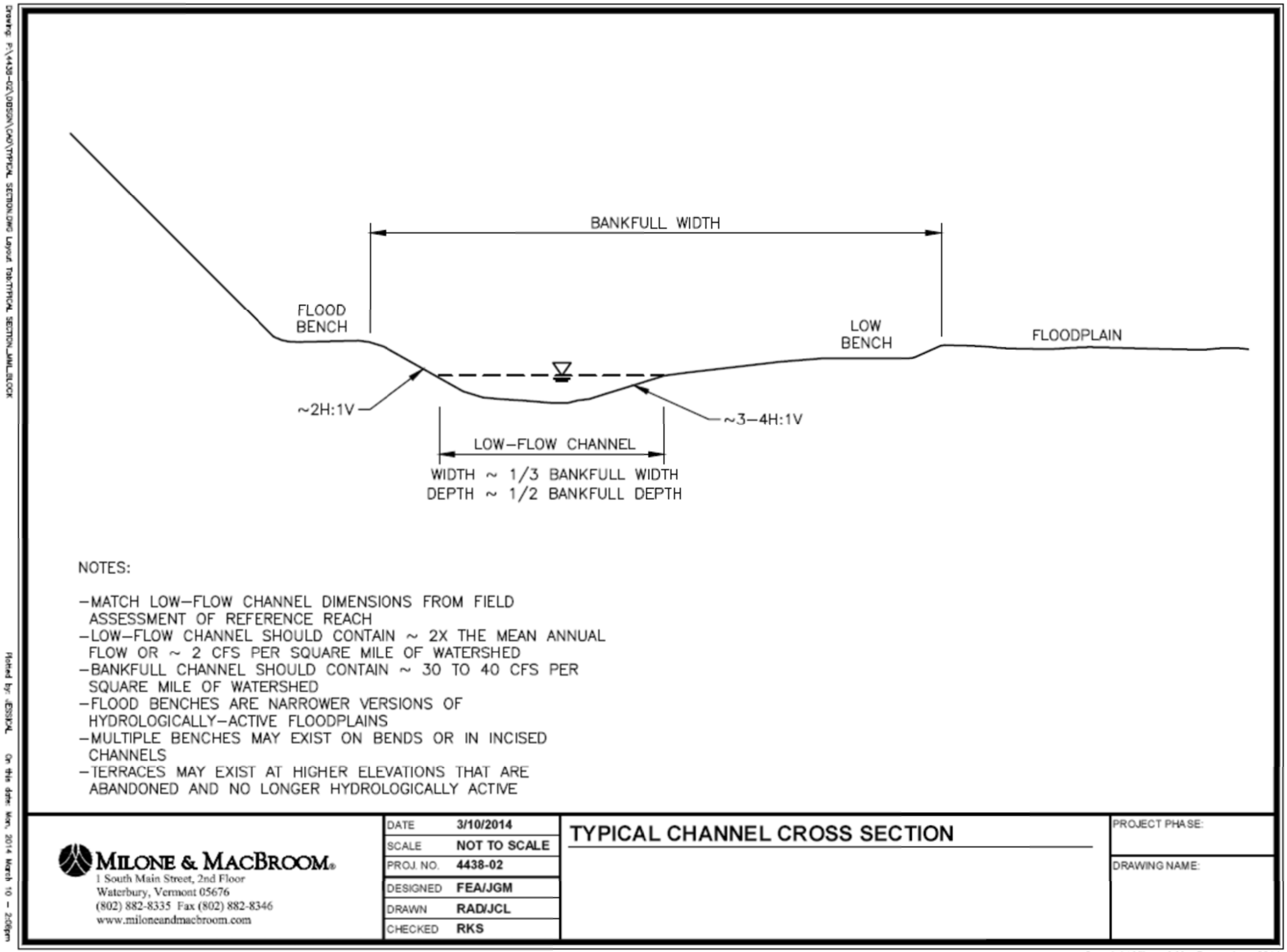


PROPOSED FLOOD CHUTE RECONNECTION NOTES
VOLUME OF PROPOSED EXCAVATION = 657 CUBIC YARDS
AVERAGE EXCAVATION DEPTH = 4.2 FEET
APPROXIMATE DISTURBED AREA = 0.1 ACRES
ENTRANCE APRON LENGTH = 65 FEET
ENTRANCE APRON THICKNESS = 15 FEET
ENTRANCE APRON DEPTH = 8 FEET
ENTRANCE APRON ROCK VOLUME = 290 CUBIC YARDS
ROCK VOLUME BELOW ORDINARY HIGH WATER REPLACES
BANK MATERIAL FOR INCREASED VOLUME OF 0 CUBIC YARDS

FLOOD CHUTE RECONNECTION

NOT TO SCALE

Figure 5.5-9: Flood chute restoration entrance detail showing access at the 10-year flood level and armoring to protect the entrance from scour and avulsion on the Middlebury River. (Source: Milone & MacBroom, Inc.)



NOTES:

- MATCH LOW–FLOW CHANNEL DIMENSIONS FROM FIELD ASSESSMENT OF REFERENCE REACH
- LOW–FLOW CHANNEL SHOULD CONTAIN ~ 2X THE MEAN ANNUAL FLOW OR ~ 2 CFS PER SQUARE MILE OF WATERSHED
- BANKFULL CHANNEL SHOULD CONTAIN ~ 30 TO 40 CFS PER SQUARE MILE OF WATERSHED
- FLOOD BENCHES ARE NARROWER VERSIONS OF HYDROLOGICALLY–ACTIVE FLOODPLAINS
- MULTIPLE BENCHES MAY EXIST ON BENDS OR IN INCISED CHANNELS
- TERRACES MAY EXIST AT HIGHER ELEVATIONS THAT ARE ABANDONED AND NO LONGER HYDROLOGICALLY ACTIVE

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TYPICAL CHANNEL CROSS SECTION

PROJECT PHASE:

DRAWING NAME:

Figure 5.5-10: Typical channel compound cross section. (Source: Fitzgerald Environmental and Milone & MacBroom, Inc.)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- River corridor delineation (Appendix D)
- River corridor sketch (N)
- Incision ratio (O)
- Channel evolution model (E)
- Ordinary high water line (K)
- Vermont HGR (VTANR, 2009) (L)

POSSIBLE COMPANION PRACTICES

- Placed riprap wall or traditional bank armor at back edge of floodplain (Section 5.2)
- Vertical bed stabilization (Sections 5.3 and 5.4)
- Floodplain restoration (Section 5.5)

SIMILAR PRACTICES

- Floodplain restoration (Section 5.6)

5.6 FLOODPLAIN RESTORATION

DESCRIPTION

Floodplain Restoration

Assessment

- Reference floodplain dimensions
- Confinement ratio
- Channel-floodplain connectivity
  - Entrenchment ratio
  - Incision ratio
- Stage of channel evolution
- Floodplain power setting
- Channel pattern

Design

- Floodplain width, elevation, and length
- Change in channel-floodplain connectivity
- Floodplain slope
- Lateral and vertical stabilization measures if required
- Excavation volume

Floodplain restoration improves the connection between a river channel and adjacent lands that were once prone to regular flooding but no longer are. This practice reduces flood and erosion risks by providing space in the valley for water, sediment, debris, and ice to be stored. Over long periods of time (e.g., 50 to 100 years), sediment and debris may be eroded from floodplains and transported downstream to another floodplain or the basin outlet. The presence of a floodplain allows floodwaters to spread out and move slower that reduces erosion hazards. Floodplain restoration is performed by:

- Removing a berm adjacent to a river channel that allows floodwaters to spill onto the recently abandoned floodplain (Figure 5.6-1);
- Removing historic dredge spoils from past flood events (Figure 5.6-2);
- Removing a natural post-flood sediment levee deposit on the edge of the river channel that allows floodwaters to spill onto the recently abandoned floodplain;
- Lowering the elevation of the floodplain (Figure 5.6-3);
- Raising the elevation of the channel bed such as through natural bed stabilization or bed armoring; and
- Creating a new channel in the floodplain with some filling of the historic channel.

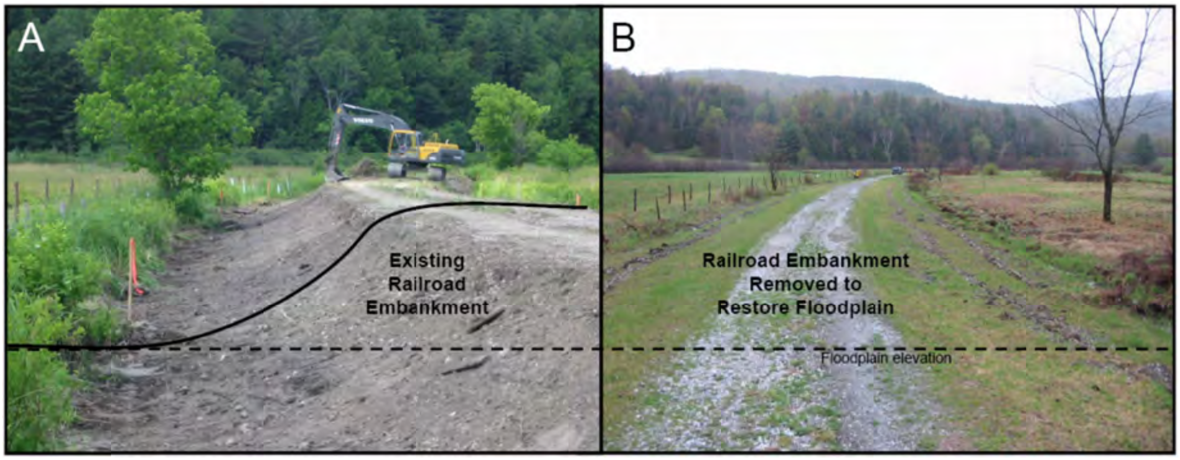


Figure 5.6-1: (A) Photograph of a former railroad embankment (with vegetation removed) that is isolating half of the natural floodplain width along Black Creek in Fletcher, Vermont. (B) Photograph of the restored floodplain after removal of the railroad embankment. (Source: Milone & MacBroom, Inc., 2007)

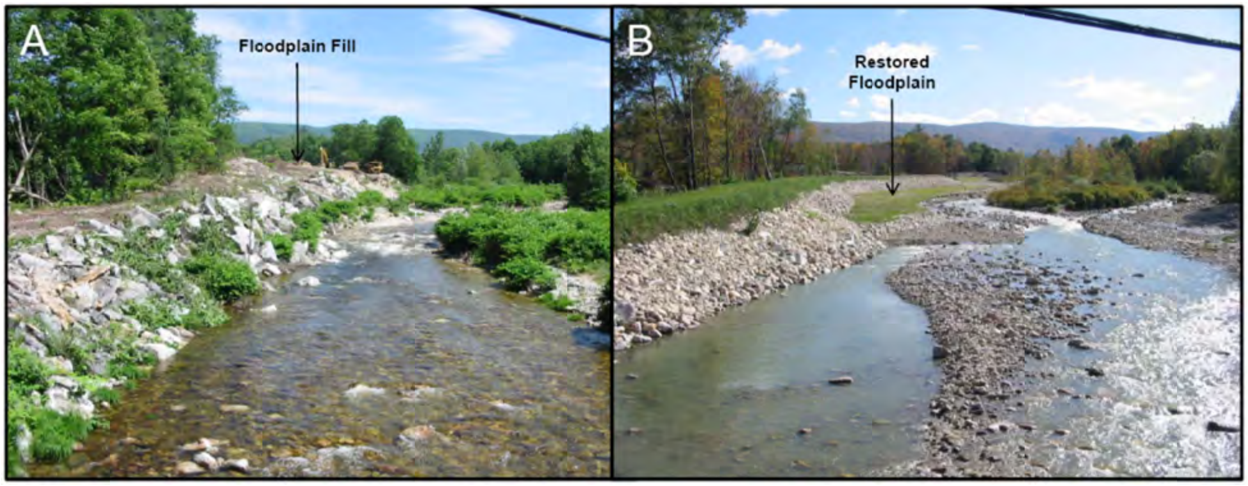


Figure 5.6-2: (A) Photograph of historic dredge spoils filling the floodplain along the Roaring Branch in Bennington, Vermont. (B) Photograph of the restored floodplain after removal of the floodplain fill. (Source: Milone & MacBroom, Inc.)

Figure 5.6-3: Floodplain restoration along Wanzer Brook in Fairfield, Vermont by lowering the elevation of the floodplain (between the dotted and solid line). (Source: S. Jaquith, VTANR)

Berm and natural levee removal is the most cost-effective method for floodplain restoration since the amount of restored floodplain area per excavated material is high. Removal of berms and levees often takes place when the opportunity arises to remove a historic encroachment due to a change in land use or ownership in the historic floodplain. Lowering the elevation of the floodplain typically occurs when an alternatives analysis identifies a specific location that would reduce risks if reconnected to the channel. Raising of the channel bed to restore floodplain, sometimes explicitly referred to as floodplain reconnection, is typically performed in conjunction with vertical bed stabilization to both improve resistance to channel downcutting and spreading flows out on the floodplain to reduce the mechanism of downcutting.

In most locations, some or all of the historic floodplain is isolated from the channel due to: floodplain filling to elevate a building or road embankment; floodplain filling to install flood protection measures (e.g., dams, berms, and levees); or channel downcutting (i.e., incision). In general, the more connected the channel is to its floodplain the lower the risks of damages in the river corridor due to erosion or deposition. With public infrastructure, homes, and businesses located on many valley bottoms, restoration of the full historic floodplain may not be possible. The benefits of a functioning floodplain can still be provided by restoring part of a historic floodplain.

Floodplain restoration has the important social consequence of resetting land use expectations next to river channels that are subject to flooding. When a floodplain is restored to reduce flood risks, it is understood that the floodplain exists for river processes to take place. The restored floodplain may be compatible with farming and recreational uses with the understanding that large pulses of water, sediment, debris, and ice will likely fill the floodplain every few years, and the river channel may move across the floodplain during a large flood.

Floodplain restoration is growing in popularity as it is a nonstructural, cost-effective method to reduce future flood risks over the long term. FEMA now considers an annual benefit of $37,493 per acre of riparian lands per year for ecosystem services such as flood hazard reduction, erosion control, and recreation (FEMA, 2013a, b). A recent study in Pierce County, Washington showed that the monetary value of a functioning floodplain for services such as avoiding flood damages is $32 million to $433 million over a 50-year period (EE, 2013).

(Also referred to as floodplain reconnection, floodplain recovery, and levee setback)

APPLICATION

Proper Use

The objectives of floodplain restoration are to provide more space for the river to spread out on the valley floor, reduce the erosive power of the river during flood, provide space for sediment and debris storage as floods recede, and allow for nutrient uptake by floodplain vegetation. This practice is recommended wherever possible due to benefits of risk reduction, habitat improvement, and water quality protection. Floodplain restoration can take place opportunistically as property along rivers becomes available or based on a river corridor plan to restore and conserve areas to reduce the likelihood of future downstream damages.

Restored floodplains are often 1 acre or larger while reconnection of flood benches and flood chutes (Section 5.5) typically takes place over smaller areas.

Meeting the Design Objectives

- Floodplain restoration meets all of the Performance Standards by providing more space for river processes to take place. The following design principles for lateral, vertical, and conveyance apply.
    - Restore as much floodplain as possible given site constraints. Maximize the width of flooding in unconfined valley settings.
    - Re-establish floodplain dimensions based on reference conditions in the river corridor and valley.
    - Target channel incision ratio is 1.0 to 1.2.
    - Restore floodplains to inundate during the 1- or 2-year flood.
    - Avoid rapid flood width expansions and contractions that could lead to severe erosion or aggradation.
    - Maintain or re-establish native vegetation and roughness along banks and floodplain.
    - Consider stage of channel evolution.
    - Plan for future sediment deposition to reduce channel incision maintaining floodplain access as much as possible.
    - Move structures and infrastructure out of floodplain as possible.
    - Remove excavated material from floodplain.
    - Retain standing trees as possible.

Limitations

- Permanent infrastructure that exists in the floodplain often limits the extent of floodplain restoration.
- Protection from flood and erosion is typically required on the upgradient side of the floodplain to protect remaining infrastructure.
- Large and costly excavation projects.
- Large sediment disposal areas that meet local, state, and federal regulations are required for construction.
- Floodplain restoration can be in conflict with anticipated land uses and can be perceived as a loss of useful land.

Geomorphic Context

The size of floodplains naturally varies across a watershed. Floodplains tend to be larger in transport and deposition zones in the mid and lower watershed than in source zones in the upper watershed (Schumm, 1977). In the upper watershed, floodplains may consist of narrow zones where coarse woody debris and sediment are contributed to the river channel. Lower in the watershed broader floodplains that can store large amounts of water and sediment during flood are more common (Smith et al., 2008).

The confinement ratio, the width of the valley divided by the bankfull width of the channel, indicates the extent that a river can adjust its planform over geologic timescales and the extent that a river depends on a hydrologically active floodplain to dissipate energy. A confinement ratio larger than 6 indicates a broad valley setting where an alluvial river should be connected to a large floodplain. A ratio less than 4 indicates a narrow valley setting where a channel may or may not be connected to a smaller floodplain (VTANR, 2009). The level of confinement often guides planning for floodplain restoration.

The entrenchment ratio quantifies the lateral extent that a large flood can spread out on the floodplain. The entrenchment ratio is the floodprone width (the width at a stage twice the maximum bankfull depth) divided by the bankfull channel width. The entrenchment ratio describes the morphology of the valley floor and indicates if a wide or narrow floodplain would naturally exist. Channels with high entrenchment ratios (>2.0) should have broad floodplains while channels in confining valleys with low entrenchment ratios (< 1.4) have small floodplains. Entrenchment ratio can be used in conjunction with the confinement ratio (and the incision ratio, see below) to plan for and design floodplain restoration.

The incision ratio is an indication of the vertical connectivity between a channel and floodplain that results from the current level of channel downcutting. The incision ratio is the height of the recently developed (or abandoned) floodplain divided by the maximum bankfull depth. The ratio identifies which features will be inundated during a bankfull flood. An incision ratio of 1.0 to 1.2 indicates that the bankfull flow can access the floodplain while a larger ratio indicates that the floodplain is only accessed by larger floods. The presence of berms and natural sediment levees elevates the incision ratio by isolating the floodplain from the channel (Appendix O). Careful evaluation of the existing and proposed incision ratio takes place when designing the elevation for a floodplain restoration.

Channel evolution (Appendix E) provides a prediction of the future form of the channel and floodplain and the likelihood of change. For example, stages I and V tend to be a stable channel and floodplain condition. Floodplain restoration typically is performed in stages II, III, and IV where the channel has cut down and is in various stages of building a new floodplain at a lower elevation. Lowering of the floodplain is analogous to accelerating the channel evolution process in a controlled way. An important advantage of active floodplain restoration is the capture of sediment that would otherwise flow downstream into receiving waters.

Floodplains serve the essential function of storing floodwaters and deposited sediment. In most settings the storage volume on floodplains is much larger than in the channel so these features are important for reducing flood and erosion risks. Floodplains experience hydraulic and sediment transport dynamics just as river channels do. Higher energy floodplains in steep and narrow valley settings may be prone to scour while moderate power floodplains such as along braided channel systems can experience both scour and deposition (Nanson and Croke, 1992) (Appendix P). The power (i.e., or ability to do work or erosion) of the floodplain flow should be estimated to predict how much erosion or deposition is anticipated on a restored floodplain during a flood.

Habitat Maintenance

- Channel work will typically not be required, so instream habitat impacts can be avoided.
- Control potential sedimentation of the channel near the riverbank during construction.
- Revegetate the floodplain where fine sediment and organic soils exist. Coarse sediment areas in the low floodplain that are inundated several times a year are often not revegetated.
- Retain standing trees and deposits of large woody debris in the floodplain to form riparian habitat.
- Creation of ephemeral backwater habitats can be included during a floodplain restoration.

Common Mistakes

- Setting the floodplain elevation too high that reduces inundation frequency and some confined flood flows persist.
- Setting the floodplain too low that results in excessive floodplain power and possible channel avulsion.
- Not creating sufficient floodplain roughness to dissipate floodplain flow power.
- Not considering ongoing channel incision that may continue despite floodplain restoration and result in abandonment of the restored floodplain.
- Creating abrupt transitions in floodprone width above and below the floodplain restoration area.
- Inadequate protection of remaining infrastructure at the back edge of the restored floodplain.
- Not considering floodplain power to know if erosion or deposition is likely to change the restored floodplain in the future.

Compatibility with Emergency Temporary Repairs and Timing of Implementation

- By damaging floodprone infrastructure and eroding large amounts of sediment, large floods can naturally reconnect channels to historic floodplains. If the opportunity exists, floodplain restoration can be incorporated into flood recovery that will reduce recovery costs and future risks.
- Floodplain restoration is not commonly performed as emergency repairs unless a phased project is already in place or the floodplain is opened up during the flood.

SITE WORK CONSTRAINTS

The primary site constraint to floodplain restoration is the surrounding infrastructure that typically is located within a portion of the historic floodplain. The extent of the restored floodplain is often limited by the need to protect remaining property from damages. If floodplain restoration is to take place near existing infrastructure, both lateral and vertical stabilization techniques are usually required to protect property adjacent to the new floodplain.

Permission from one or more landowners is typically required in order to perform floodplain restoration. Past views of floodplain restoration were dominated by the belief that providing space for the river was not a good use of the land. With a long history of extensive damages in floodplains and the growing recognition of the risk reduction benefits of a naturally functioning floodplain, this practice is now socially more acceptable. Nevertheless, floodplain restoration often requires project outreach prior to design to reach agreements with landowners of what the floodplain restoration will look like. These agreements can include land donations, an easement donation, land purchase, purchase of a river corridor easement, and barter of land for construction services or fill.

Floodplain restoration can require large excavation volumes, so a suitable place to put the material is needed. The sediment waste area must be out of the FEMA-regulated floodplain and the ANR River Corridor. No wetlands can be filled. Cultural resources cannot be impacted. Trucking of sediment is a large part of the project cost, so the closer the waste area to the floodplain restoration site the lower the project cost. GIS mapping and the Vermont ANR Natural Resources Atlas (http://anrmaps.vermont.gov/websites/anra/) can be used to perform an initial review of potential sediment waste areas. Disposal and processing of materials at waste sites can create large amounts of dust and noise and, therefore, adjacent landowners should be contacted about the proposed work, and an agreement needs to be made about allowable work hours.

Floodplain restoration is typically performed in nonemergency settings. Given the large cost of the projects, phasing is common to allow for a full project to incrementally be built as funding is obtained. With FEMA now recognizing the monetary benefits of functioning floodplains, larger amounts of money may be available to complete larger projects in the future.

Weather can impede floodplain restoration. Although lowering of the floodplain is suitable winter work since it generally takes place away from river channels, frozen ground lengthens the time to perform excavation. If winter work is to be performed, winter site stabilization and revegetation in spring are required. Wet weather that leads to high flows complicates work on floodplains, especially where portions have been lowered to restore their connection to the river channel. Floodplain restoration should be performed during low water when no flow reaches the floodplain.

PRIMARY DESIGN ELEMENTS

The design elements for floodplain restoration include width, elevation, length, slope, stabilization measures, channel evolution stage, channel pattern, and excavation volume. Width and elevation are often considered together to identify the target elevation of the channel bed and floodplain surface relative to the floodprone width (Appendix Q).

Floodplain Width

Floodplain width is a primary design element for floodplain restoration since it determines the lateral extent of future flooding. The target floodplain width can be on the order of hundreds to thousands of feet and should be based on a reference floodplain width obtained by a combination of field observation, geomorphic assessment, and GIS mapping. Floodplain width on braided and alluvial fan channels should typically be as wide as possible until unmovable property exists. In settings that are naturally more confined, a reference cross section through a nonencroached portion of the valley can be used to understand how wide the floodplain should be. The width of the floodplain is typically set to one of the following:

- Full width of the reference floodplain;
- Partial width of the reference floodplain in the geomorphic-based river corridor (Appendices N and D) where the channel is most likely to meander;
- Partial width of the reference floodplain if unmovable property exists;
- Partial width of the reference floodplain to store water and sediment for a selected design storm; and
- Partial width of the reference floodplain set at the floodprone width (Appendix Q).

For partial width floodplain restoration, an analysis to verify that the selected floodplain width will reduce flood and erosion risks should be performed. Field observations, computations, hydraulic modeling, and sediment transport analysis of the existing and proposed floodplain and channel can be used to predict changes.

Floodplain and Channel Elevation

Properly selecting the floodplain elevation relative to the channel elevation is critical to reducing future flood and erosion risks. Vertical relief between the channel and floodplain surface should be set to allow floodplain inundation once every 1 to 2 years where possible. The target incision ratio is 1.0 to 1.2 for natural floodplain access (Figure 5.6-4). The incision ratio must explicitly be evaluated and designed for each method of floodplain restoration.

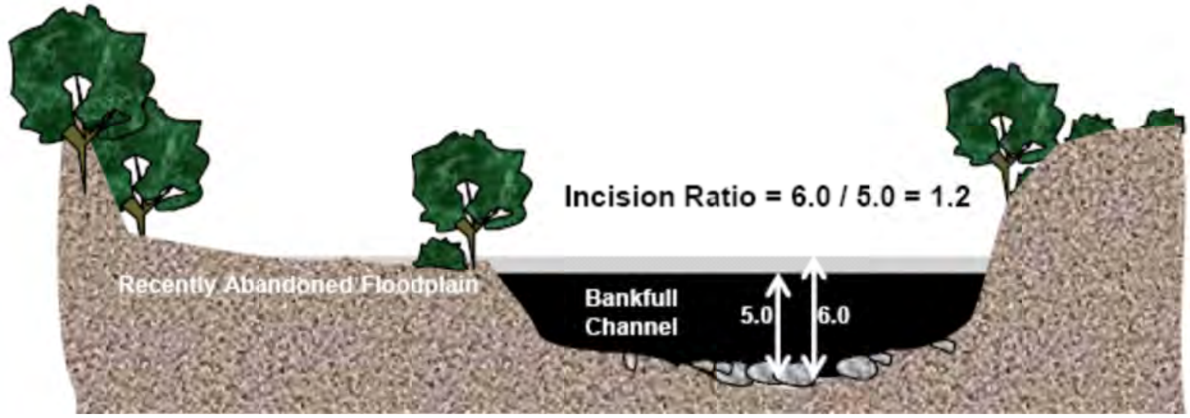


Figure 5.6-4: Schematic of target incision ratio for floodplain restoration. (Source: Milone & MacBroom, Inc.)

Higher incision ratios mean a channel and floodplain are less connected and downstream flood risks remain due to confined high velocity flows during a flood. When restoration of a portion of a floodplain that contains unmovable infrastructure such as a road embankment takes place, the floodplain elevation may have to be set at higher than natural levels (e.g., the 10-year flood). Hydraulic modeling and sediment transport analysis are needed to verify that this compromise both protects infrastructure and reduces future flood risks.

Floodplain Length

The length of floodplain restoration projects is often determined by using the available space around remaining infrastructure and improved property. The length of restored floodplains can vary widely based on site conditions.

Floodplain Slope

The restored floodplain should slope toward the river channel slightly (0.25% to 1%). The floodplain should also slope down-valley approximately matching the slope of the river channel.

Lateral and Vertical Stabilization

Floodplain restoration, particularly in confined settings, typically includes bank stabilization at the upgradient or back edge of the floodplain to protect adjacent property. When an option exists for where to place lateral stabilization practices, locate them immediately adjacent to existing infrastructure and design the elements to resist the highest instantaneous shear stress that occurs during the design flood (Figure 5.6-5). This approach allows for the widest possible floodplain with the existing infrastructure in place.

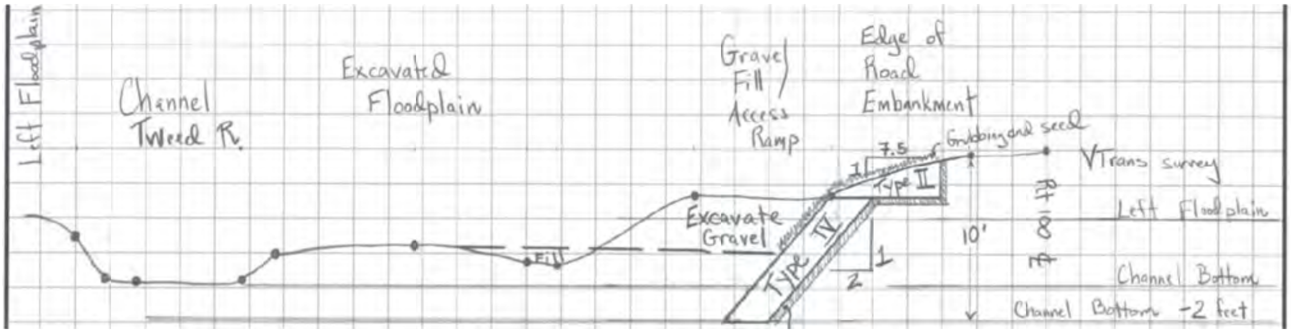


Figure 5.6-5: Sketch plan showing placement of road embankment armor along Vermont Route 100 rather than along dredged gravel. (Source: Milone & MacBroom, Inc.)

Placing lateral stabilization practices such as stone armoring along a road embankment rather than in the floodplain with adjacent fill reduces flood and erosion risks. Fill in the floodplain that appears to be protecting adjacent property actually increases flood and erosion risks since the fill narrows the channel and floodplain (i.e., the "floodplain paradox") (Figure 5.6-6). The floodplain fill confines flows increasing velocity that leads to more erosion and channel downcutting. If the floodplain were wider and lower, it would inundate more frequently, so flows would spread out, velocity would be lower, and erosion potential would be lower.

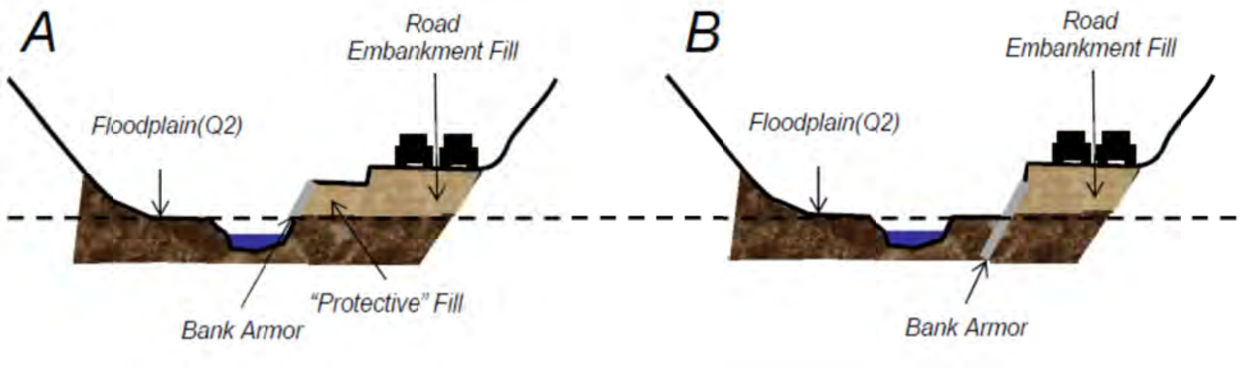


Figure 5.6-6: Schematic of a "floodplain paradox" where the appearance of protective fill (A) actually increases flood and erosion risks. Risk of damages is reduced when flood flows can spread out and access restored floodplains (B). Stone armoring protecting infrastructure is designed to withstand the highest shear stress for the design flood. (Source: Milone & MacBroom, Inc.)

Where channel evolution stage is II or III or where incision ration is larger than 2 after floodplain restoration, vertical bed stabilization (Sections 5.3 and 5.4) may be required to maintain floodplain connection over the long term. Vertical stability may also be required for lateral stability to prevent undermining of the banks.

Channel Evolution

Channel evolution (Appendix E) must be considered with floodplain dimensions and incision ratio to properly design a floodplain restoration. Plan for anticipated channel widening, lateral channel movement, and floodplain formation for channel evolution stages II, III, and IV.

Channel Pattern

Channel pattern determined from a geomorphic assessment or nearby reference reaches is an important consideration for floodplain restoration. Identify what the channel will look like in the floodplains – single thread with a consistent width or multithread with a large and varying width. With the knowledge of the channel slope and (mean annual or bankfull) discharge it is possible to predict if a meandering single thread, braided multi-thread, or wandering channel exists (Leopold and Wolman, 1957; Church, 2002) (Appendix R).

Excavation Volume

Once the floodplain restoration width, elevation, and length have been established, calculate the volume of sediment that is occupying the proposed excavation area in the floodplain. Survey is typically performed to design and determine volumes for a floodplain restoration project. Approximate methods with a laser range finder or a level and rod may be acceptable to quantify work.

COSTS

The ballpark cost of excavation of fill from a floodplain and a haul to an area just outside of the floodplain is $8 per cubic yard for large quantities of material (e.g., >5,000 cubic yards). The cost to remove a berm in the middle of a floodplain with a local haul is $2.86 to $5.00 per cubic yard. The price can range from $2.86 to $10 per cubic yard based on past floodplain restoration experience in the state. The cost of excavation on floodplains with local hauling of material is similar to the average cost in the state for common earth excavation of $5.85 (VTrans, 2009). As the length of the haul increases, $75 to $150 per hour of truck time will have to be added to the project cost.

With EFMA and other federal and state regulatory agencies acknowledging the flood risk reduction benefits of functioning floodplains, the potential to fund floodplain restoration projects through grants is increasing. Thorough documentation of the design will increase the chances of receiving funding to implement the project. Information and applications should be filed prior to construction in nonemergency scenarios. After-the-fact submissions may be required in emergency situations if a floodplain is to be restored as part of a flood recovery effort.

- GPS the perimeter of the floodplain restoration area to show the footprint, widths, and length.
- Quantify the volume of fill to be removed from the floodplain or placed in the channel. In a flood recovery setting, the state of the floodplain after the flood and anticipated after construction should be documented.
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or as emergency work progresses.
    - FEMA
    - NRCS
    - USACE
    - VTANR
    - VTrans
    - Municipality
- Document how the project meets applicable State Performance Standards and permit requirements.

PERMITTING

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
    - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
    - Identify reporting category
    - Contact Vermont Field Office
- Vermont Stream Alteration Permit
    - Meet Performance Standards as identified above
    - Identify reporting category
    - Contact river management engineer
- Local Zoning Permit
    - Contact Town Administrator for reporting needs

CONSTRUCTION

Constructability

Floodplain restoration projects are straightforward from a constructability point of view and have a high likelihood of successfully reducing flood risks over the long term since the practice does not rely on structural elements to properly function. As soon as the floodplain is widened and lowered, the risks for inundation and erosion decrease.

Floodplain restoration that takes place by removal of berms or lowering floodplains tends to be low-risk construction activities since work is taking place outside of the river channel. When floodplain restoration takes place by elevating the riverbed, the impacts of the project increase since work is mostly taking place in the river channel.

Temporary Construction Controls

Project demarcation fencing is needed in any location that the public could come in contact with at the floodplain restoration project site, staging locations, stockpiles, or waste disposal areas. Refer to the VTrans Construction Specifications (VTrans, 2011) for guidelines on locating and identifying staging and stockpiling areas.

Given the linear nature of floodplain restoration projects, sediment and erosion controls are typically applied only as disturbance takes place close to a flow path in the floodplain, an actively flowing drainage ditch, or near the riverbank. In most cases, the flat vegetated land in the floodplain limits the potential for sediment migration from the construction site. The Vermont Low Risk Site Handbook For Erosion Prevention and Sediment Control (VTDEC, 2006b) is commonly used in conjunction with field-based decisions for maintaining sediment and erosion controls at the construction site. If floodplain inundation does take place during construction, temporary erosion control blankets can be used in the low floodplain with fine sediment and soils to reduce erosion and sedimentation.

Water control is typically not needed during floodplain restoration projects as work tends to take place outside of the channel. If water control is needed for work in or near the channel, work is performed only during low flow, and temporary elevated work platforms made of pushed up coarse material are often used to guide water out of work areas and create a platform for machinery. Machine crossings can be made with built-up sediment. Culverts can be used to create dry crossings. A series of check dams and sediment trap pools can be used during in-channel work to capture fine sediment and control downstream turbidity. Several check dams and pools can be placed downstream of the work area, and the pools should be periodically cleaned out as work takes place.

Access

Access to restore floodplains is typically made from private drives, state highways, or municipal roads. Ownership of the proposed access locations must be verified by conversations with landowners or by reviewing local parcel mapping and roadway right-of-way mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access is proposed across private land, agreements with the landowners are common. Access agreements typically include discussions or notes about returning the land to the original condition following the project.

For floodplains where large amounts of sediment deposition are anticipated in the future, easements can be drafted to allow for access following a flood for specified work such as sediment removal.

CONCEPTUAL DESIGN PLANS/DETAILS

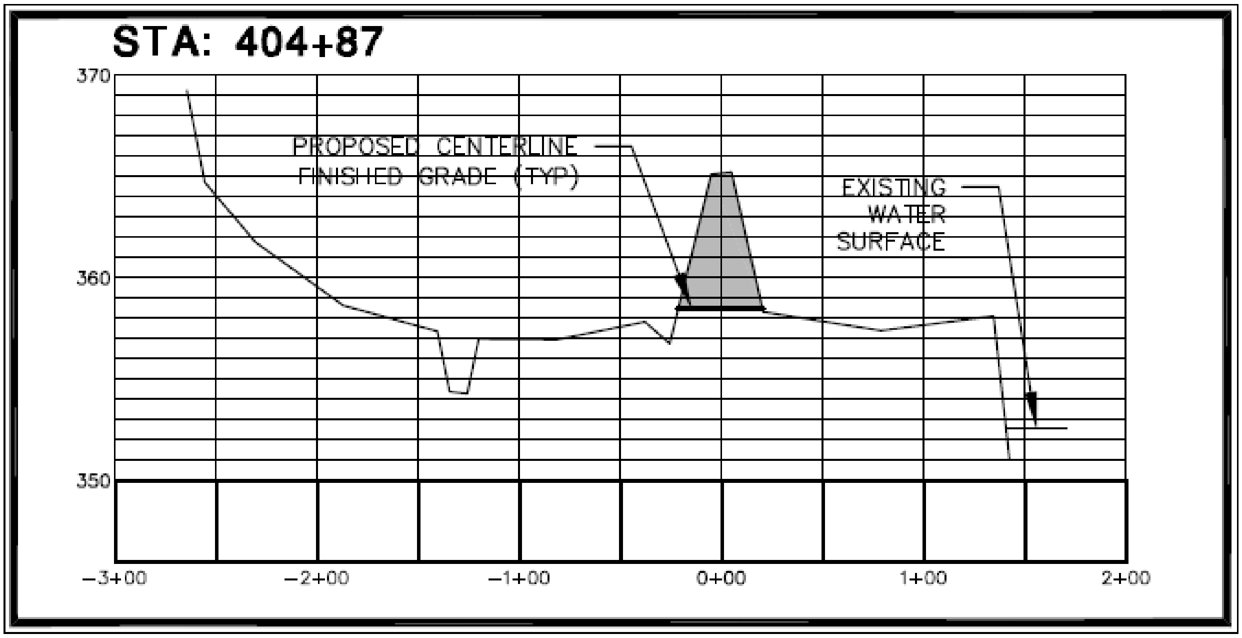


Figure 5.6-7: Cross section of railroad embankment removal to restore floodplain. (Source: Milone & MacBroom, Inc.)

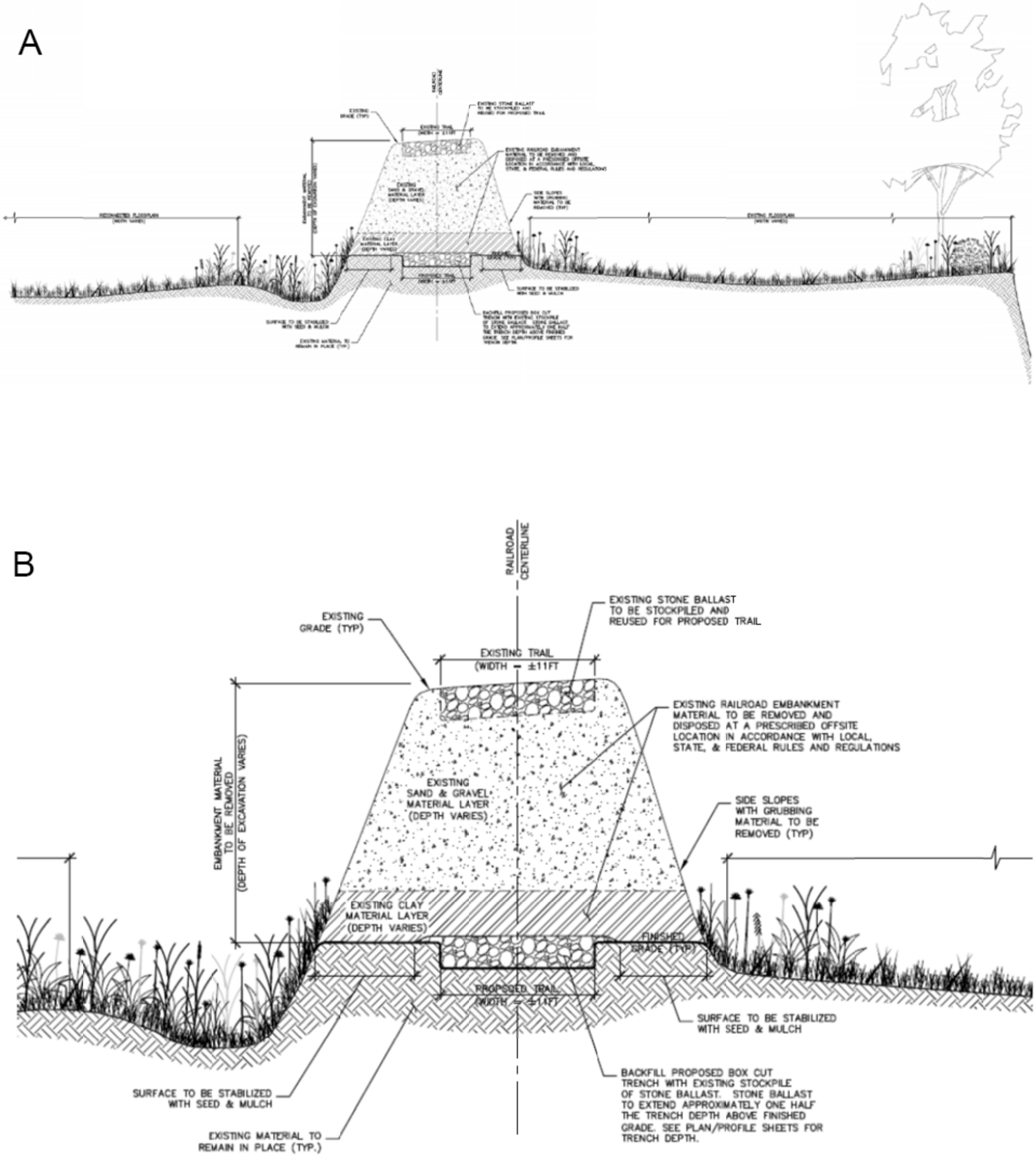


Figure 5.6-8: Typical section full size (A) and zoom (B) showing floodplain restoration by removal of a railroad embankment. (Source: Milone & MacBroom, Inc.)

Figure 5.6-9: Floodplain restoration plan for project (A) and first phases (B) showing removal of fill and bermed sediment spoils (diagonal hatch), relocation of flood protection to back of floodplain (gray), fill disposal area (cross hatch). (Source: Milone & MacBroom, Inc.)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- Incision ratio (Appendix O)
- Channel evolution model (E)
- Floodplain power (Nanson and Croke, 1992) (P)
- River corridor delineation (D)
- River corridor sketch (N)
- Floodprone width (Q)
- Meandering, braided, or wandering channel pattern (R)

POSSIBLE COMPANION PRACTICES

- Placed riprap wall or traditional bank armor at back edge of floodplain (Section 5.2)
- Vertical bed stabilization (Sections 5.3 and 5.4)

SIMILAR PRACTICES

- Flood bench and chute reconnection (Section 5.5)

5.7 REMOVAL OF SEDIMENT AND WOODY DEBRIS

DESCRIPTION

Removal of sediment and woody debris is performed to increase conveyance for water, sediment, woody debris, and ice during the next flood to protect infrastructure, buildings, and unmovable improved property where vertical instability and risk of rapid channel migration (i.e., avulsion) exist. Common scenarios for removal of sediment and woody debris include clogged bridges and culverts, filled channels and floodplains, and avulsed channels. Removal of sediment and woody debris typically includes re-establishment of the bankfull channel and floodplain, vertical stability, and a safe channel alignment (Figure 5.7-1). In extreme cases where excessive sediment deposition is a frequent event that leads to recurring flood damages, proactive sediment management plans may be established to keep flood risks low.
(Also referred to as dredging, gravel mining, structure and channel cleanout)

Sediment Removal Design
Assessment
- Location, length, width, and depth of the sediment deposit

Channel
- Geomorphic stream type
- Bankfull width and depth (and removal volume)
- Alignment
- Slope transitions
- Equilibrium sediment slope
- Pattern (i.e., meandering, braided, wandering)
- Roughness elements
- Intact natural bed armor layer
- Incision ratio
- Geomorphic evolution

Floodplain
- Width and length (and removal volume)
- Elevation relative to channel

Woody Debris Removal Design
Assessment
- Location and size (i.e., single, cluster, channel-spanning jam) of woody debris
- High-risk woody debris requiring removal

APPLICATION

Proper Use

The objective of sediment and woody debris removal is to increase the conveyance capacity of the channel and floodplain to allow the next flood to safely pass. This practice has historically been improperly implemented and, thus, attention to the design details is needed to achieve the desired risk reductions. This practice is typically implemented in high-risk settings where other alternatives will not reduce risks. This practice is sometimes implemented in conjunction with floodplain restoration or replacing an undersized structure to allow for higher conveyance of sediment and debris in the future.

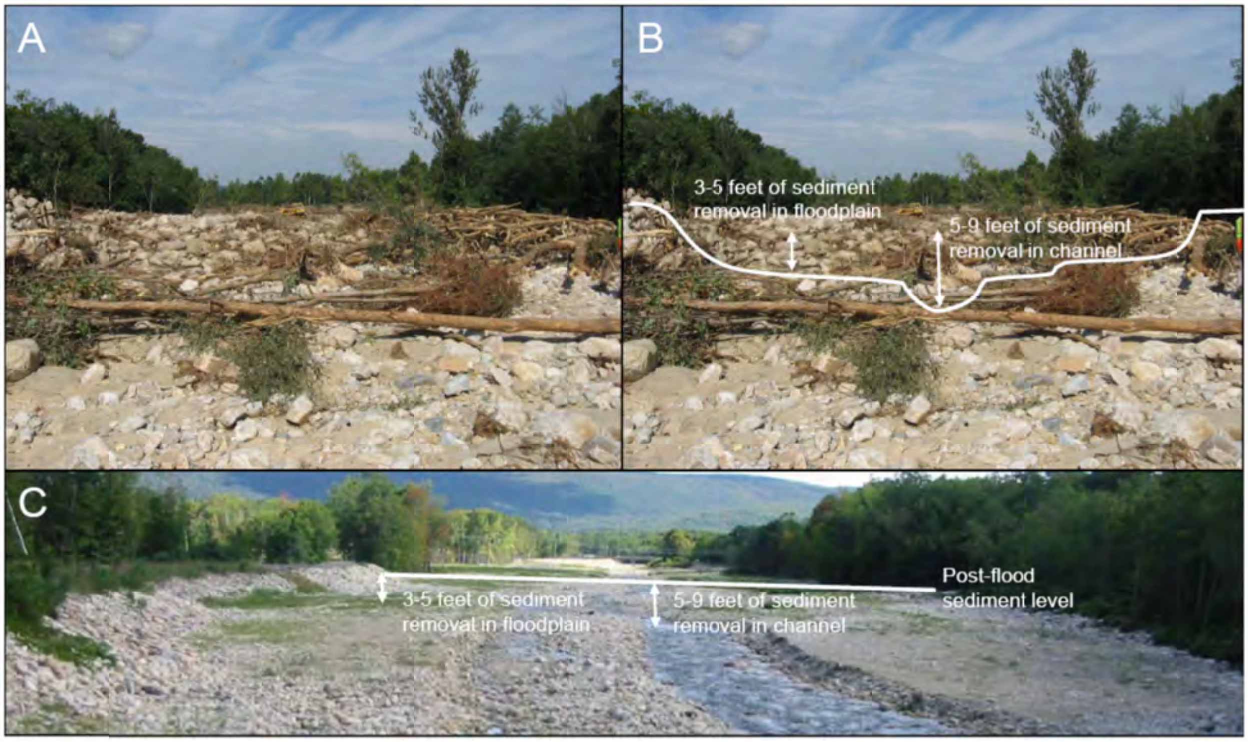


Figure 5.7-1: (A) Filled channel and floodplain on the Roaring Branch in Bennington, Vermont following Tropical Storm Irene where deposits were up to 9 feet tall. (Source: Milone & MacBroom, Inc., 9/1/2011) (B) Schematic showing amount of sediment and woody debris removal. (C) Completed sediment removal. (Source: Milone & MacBroom, Inc., 9/20/2012)

Meeting the Design Objectives

- Sediment
    - Re-establish channel and floodplain dimensions based on equilibrium, pre-flood, or stable reference reach conditions.
    - Allow for deposition to reduce channel incision increasing floodplain access as much as possible.
    - Create uniform slope transitions in and out of the sediment removal area.
    - Move property away from the channel if possible; otherwise, move the channel away from at-risk property.
    - Plan for ongoing levels of natural sediment erosion and deposition.
    - Remove excavated material from floodplain.
    - Maintain hydraulic roughness in final channel.
    - Minimize the removal of sediment.
- Woody Debris
    - Retain standing trees and those with attached root systems.
    - Only remove woody debris that alters flow path, increases risk of avulsion, and could clog downstream bridges and culverts.
    - Minimize the removal of woody debris.

Limitations

- Sediment Removal
    - Increases impact to channel habitat beyond that from the flood that will lengthen the ecosystem recovery time.
    - Removes material that would otherwise be transported through the system as part of the natural sediment load that stabilizes the bed and banks.
    - Eliminates bed features and homogenizes the channel.
    - Often creates an upstream erosion face that leads to headcutting and long-term destabilization of the upstream reach and increased sediment delivery and deposition in the sediment removal reach.
- Woody Debris Removal
    - Decreases channel and floodplain roughness that can lead to higher flood velocity and more erosion.
    - Removes large wood inputs to channel that form shelter and that break down over time forming part of the food base of the aquatic ecosystem.

Geomorphic Context

Removal of sediment and woody debris is most commonly required on channel types that are prone to excessive sediment deposition such as braided channels (stream type D, Rosgen and Silvey, 1996), on or near alluvial fans (NRC, 1996), and wandering channels (Church, 2002; Kleinhans and van den Berg, 2011). Material may need to be removed from single-thread channels such as riffle-pool or plane bed streams (VTANR, 2009) following large floods when deposition has reduced the space for conveyance during the next flood. Sediment removal from single-thread channels will typically involve smaller volumes of material and take place less frequently than on multithread deposition-prone channels.

Excessive deposition may take place upstream of undersized bridges and culverts, and this condition tends to warrant a more localized removal of material. A narrow river corridor and valley could create a deposition-prone channel setting that may lead to consideration of local removal of sediment or woody debris if property is at risk. Excessive deposition is common where smaller (i.e., 1st, 2nd and 3rd order) tributary channels meet larger rivers and at slope transitions. Undersized bridges or culverts in these areas tend to catch sediment and fill the channel during large floods. These slope transition areas usually require post-flood sediment and debris removal to maintain flow in the channel and conveyance through the structures.

Sediment transport can create a natural armor layer in the channel bed that is located at or near the surface of the pre-flood channel bed (Figure 5.7-2). The substrate in the armor layer is larger than the rest of the channel and is created by sorting of the substrate over varying flows. For example, the armor layer could be cobble in a channel dominated by gravel and sand. This armor layer helps control the vertical position of the channel bed. The armor layer is often unknowingly removed during sediment removal following a large deposition event that leads to a substantial decrease in channel stability. The natural armor layer must be left intact during sediment removal following floods.

Floodplains serve the essential function of storing floodwaters and deposited sediment. In most settings, the storage volume on floodplains is much larger than in the channel, so these features are important for reducing flood and erosion risks. When removing sediment and woody debris, it is important to understand the dynamics on the floodplain just like in the channel. Is the floodplain prone to erosion or deposition (Nanson and Croke, 1992)? The power (i.e., or ability to do work or erosion) of the floodplain should be estimated, calculated ($\Omega = \gamma QS$), or modeled to understand if the deposited material is likely to transport downstream during future floods.

Following large deposition events, the channel can avulse to a new location or roll off the accumulated material in the center of the channel, slide to the edges of the channel, and severely erode the riverbanks. Plans should be established to move critical infrastructure in repeat damage areas for flood risk reduction. If property is in the way that cannot be moved, then channel realignment should take place. The goal of realignment is to move the channel away from the eroding banks or toward the pre-flood location that is consistent with the channel's predicted pattern and evolution.

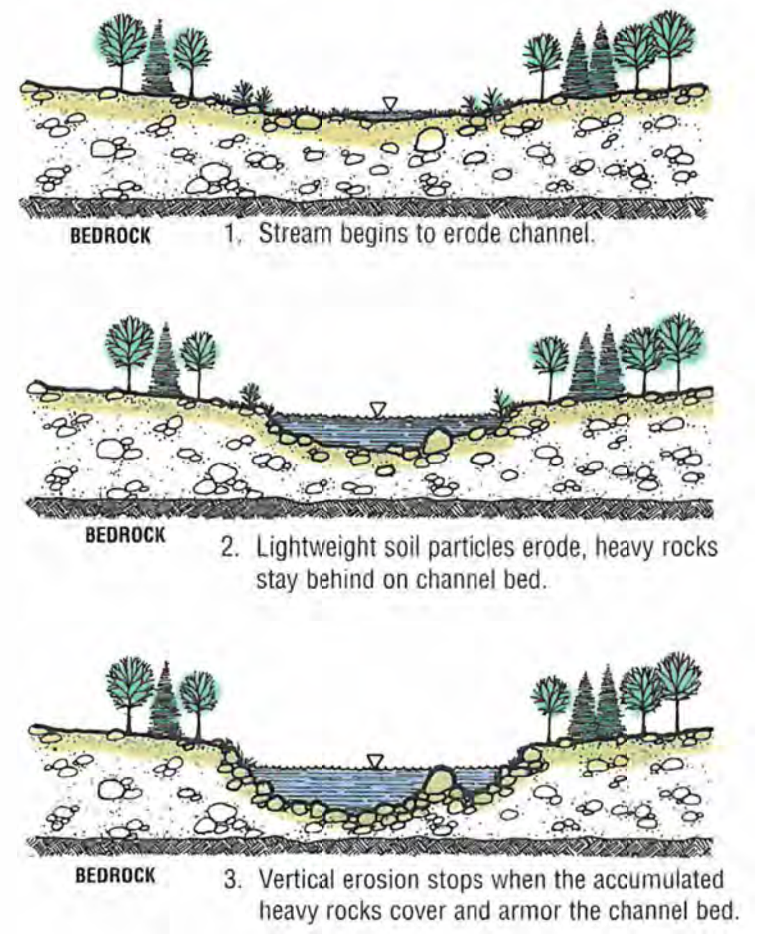


Figure 5.7-2: Natural channel bed armoring through preferential removal of fine particles by flow. (Source: MacBroom, 1998)

Rivers are continually moving water and sediment downstream. Observations and modeling of sediment transport indicate that following large deposition events successive smaller floods will transport material downstream. An understanding of the anticipated movement and downstream distribution of large sediment deposits is the best way to understand how much, if any, material needs to be taken out of the channel to reduce current and future flood risks. Controlling the amount of sediment and woody debris removal is essential for limiting future hazards, reducing impacts to the river channel, and controlling project costs.

Wood also regularly moves downstream in river channels and is broken down through abrasion and decomposition. Large floods bring an important supply of woody debris into channels that can form stable bed features (Thompson, 1995; Brooks et al., 2006) and fuel the aquatic ecosystem (Allan, 1995). Wholesale removal of large woody debris generated during a flood leaves a long-lasting negative impact. Individual pieces of wood and jams that do not divert flow into property or are not likely to clog downstream structures should be left in place to support habitat development, channel stability, and bank stability.

Habitat Maintenance

- Minimize impacts to habitat by limiting removal of sediment and woody debris.
- Retain larger cobbles and boulders in the river and standing trees in the river corridor.
- Only remove debris jams that create downstream flood risks to maintain wood load for aquatic ecosystem. Do not remove every tree.
- Reduce the need for repeat sediment and wood removal in project design.

Common Mistakes

- Removing more sediment, woody debris, and standing trees than necessary that ultimately increases flood and erosion risks.
- Digging the channel too deep (Appendix S).
- Removing the pre-flood natural sediment armor layer in the channel.
- Undermining channel banks or floodwalls by overexcavation at the edges of confined channels.
- Not removing enough sediment from the floodplain.
- Creating abrupt transitions in the profile between the project work area and adjacent reaches that initiate headcutting.
- Initiating downstream erosion on transport-dominated reaches by full removal of source sediment.
- Disposal of sediment along the edges of the channel causing the channel to be confined and cut down.

Compatibility with Emergency Temporary Repairs and Timing of Implementation

- Re-establishment of the bankfull channel and floodplain is an extension of unclogging bridges and culverts that is often performed first following large floods.

- Working in a channel that has been naturally disturbed from flooding immediately after the event will minimize the length of time required for the ecosystem to recover.
- The extent of flooding in the area and state will influence the work parameters. Use of off-road haul units may be permitted to speed work.

SITE WORK CONSTRAINTS

The primary site constraint to removing sediment after a large deposition event is finding a place to put the material. The sediment waste area must be out of the FEMA-regulated floodplain and the ANR River Corridor. No wetlands can be filled. Trucking of sediment is a large part of the project cost so the closer the waste area to the site the lower the project cost.

The Vermont ANR Natural Resources Atlas (http://anrmaps.vermont.gov/websites/anra/) can be used to perform an initial review of potential sediment waste areas prior to visiting each of the sites. Waste sites should be cleared with regulators via a site visit, phone call, or email prior to placing material. Disposal and processing of materials at waste sites can create large amounts of dust and noise and, therefore, adjacent landowners should be contacted about the proposed work, and an agreement needs to be made about allowable work hours.

Following regional floods, excavation equipment, haul units, and work crews are busy repairing widespread damages. Finding machines and work crews to move large quantities of material that fill channels and floodplains may be difficult. Phasing projects by areas based on level of threat can allow work to progress strategically when a full work crew is not available.

Weather can impact sediment and wood removal following large floods. High water complicates access to filled channels. Deposited sediment can freeze in place during winter complicating excavation.

Work in cities or villages to open up channels and floodplains where floodwalls and other infrastructure exist may be constrained by complex access, high traffic volume, the presence of abundant utilities, and reduced work hours compared to rural settings.

PRIMARY DESIGN ELEMENTS

Quantifying the Sediment Deposit

A post-flood assessment is required to determine the length of the sediment deposit and estimate the thickness of the deposit (Figure 5.7-3). Walk the channel to see the upstream and downstream limits of where post-flood material exists. Thickness can be measured by probing, observations at bridges, and comparison to pre-flood information. The lateral extents of the sediment deposition should also be measured in the field at several cross sections.

Sediment Removal Recommendations

The level of sediment removal is determined based on the risk of future damages that is commonly linked to the geomorphic stream type. More clearing is required in settings prone to excessive deposition while less clearing can take place where sediment transport is more common (Table 5.7-1 and Figure 5.7-3). In high-risk sediment deposition areas where repeat damages take place, investigate the source of the sediment and possible control alternatives. If control is not feasible, a proactive sediment removal plan may need to be developed using hydraulic modeling and pre-permitting (NOAA, 2006).

Table 5.7-1: Sediment Removal Recommendations

Stream Type	**Deposition Risk**	**Recommended Sediment Removal**	**Notes**
DEPOSITIONAL (e.g., braided, alluvial fan)	HIGH	Bankfull channel and all available floodplain	Establish as much space as possible for future flood storage. Anticipate future deposition events. Proactive sediment management plan should be created.
DEPOSITIONAL TO TRANSPORT (e.g., wandering, threshold riffle-pool)	HIGH to MODERATE	Bankfull channel, flood benches, and possibly full floodplain	Evaluate post-flood channel to see possible locations for the channel in the valley. Full removal may be required to protect critical infrastructure.
TRANSPORT (e.g., self-armored riffle-pool, plane bed, step-pool)	MODERATE to LOW	Pilot channel and low bench to initiate the natural formation of the channel and floodplain	Anticipate continued sediment transport and passive return of bankfull channel dimensions and larger floodplain. Some sediment removal may be required to protect critical infrastructure.

The proper amount of sediment removal is determined by linking damages to dominant stream processes (Appendix C), understanding the channel geomorphic stream type, and by making reach-scale post-flood observations.

Channel Design

The channel bankfull width and depth should be determined from previous geomorphic assessment of the pre-flood stable channel, assessment of a nearby reference reach, or predicted target dimensions using Vermont hydraulic geometry regression equations (HGR) (VTDEC, 2006c) (Appendix L). HGR estimates of channel dimensions tend to be low for braided and wandering channels, so field observations to verify estimates of bankfull width and depth are required on these wide channel types where sediment removal is most common.

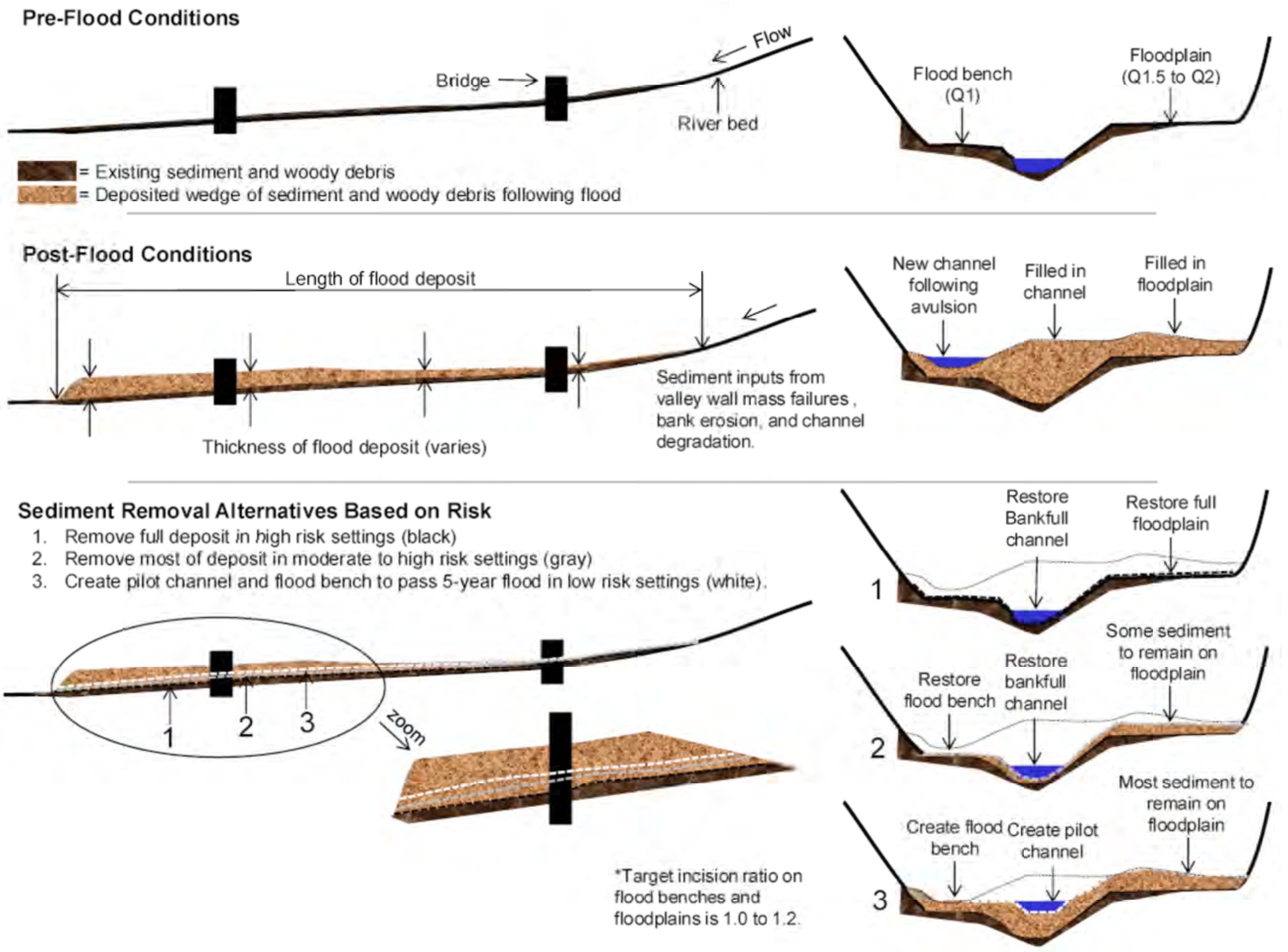


Figure 5.7-3: Sediment removal design elements.

The channel slope should establish uniform transitions into and out of the sediment removal area. If vertical faces of material are left in place upstream headcutting can occur. Sediment will typically be removed to establish a smooth transition at the upstream and downstream ends of the project that is near the average slope of the reach slope or the equilibrium slope for the size of sediment (Appendix T). Allowing the flow to passively create the profile can take place to control the project extents and cost if property will not be threatened and if clear boundary conditions such as bedrock exist in the channel to ultimately stop the erosion.

Channel pattern is typically returned to the reference type based on the valley characteristics. The target pattern is known if a geomorphic assessment has been completed. If not, refer to upstream or downstream nearby reaches to see what pattern exists. Identify if the channel is a single thread with a consistent width or multi-thread with a large and varying width. With the knowledge of the channel slope and (mean annual or bankfull) discharge it is possible to predict if a meandering single thread, braided multi-thread, or wandering channel exists (Leopold and Wolman, 1957; Church, 2002) (Appendix R). Historic channel management and floodplain filling may have altered a channel to appear single thread when the reference type is multi-thread or wandering.

Design of the stable channel dimensions and pattern of a reference single thread channel is required to form a channel following sediment removal. For a reference braided type channel, however, the design focus is on setting approximate dimensions, moving the channel away from property, and creating adequate conveyance in the combined channel and floodplain since continued sedimentation and channel movement are anticipated. The floodplain width is likely to be as wide as possible in braided channels. Rough dimensions can be set by pre-flood dimensions or by regression equations, with the understanding that bar development and a multithread channel will quickly form.

Observations of the post-flood channel and comparison to the pre-flood channel are essential for establishing a new channel alignment if at-risk property cannot be moved. Alignment is set to reduce the chances of future conflicts. The post-flood channel is typically moved back to the pre-flood location if a large sediment removal operation is taking place. When smaller amounts of material are being removed, realignment consists of moving the channel away from eroding banks and infrastructure as much as possible.

Channel realignment does not fix a channel in its place. Natural movement of the channel will take place in the future. Following sediment removal and channel realignment, braided channels will often form transverse sediment bars and begin moving laterally away from the center of the valley as sediment transport reinitiates (Figure 5.7-4). Meander bends will begin to migrate downstream, and channel dimensions will adjust with channel evolution in single-thread channels. The design must be framed in the evolutionary track of the channel (Appendix E). Wandering and threshold channels that are stable during normal flows will activate during future floods and move across the valley. Channel realignment may be done in conjunction with bank stabilization to fix the channel in place where critical infrastructure or buildings exist. This practice often creates other hazards by increasing downstream erosion potential. Moving property to higher ground out of floodplains and erosion hazard areas is the only assured way to eliminate risks.

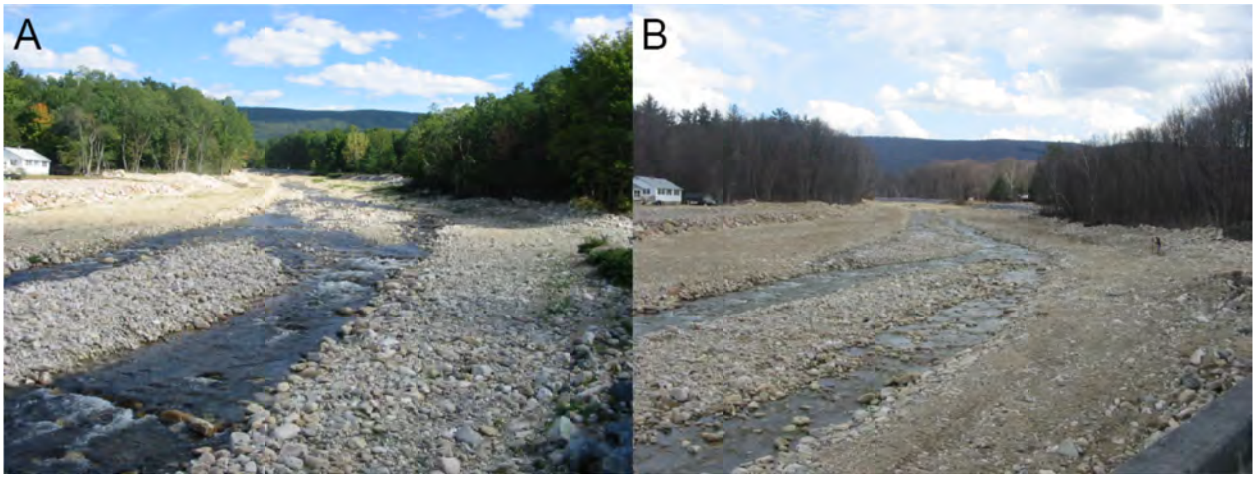


Figure 5.7-4: Transverse bar formation and adjustment following sediment removal on the Roaring Branch in Bennington, Vermont 1 year after Irene and 1.5 years after Irene. (Source: Milone & MacBroom, Inc., A – 9/20/2012: B – 2/23/2012)

Channel bed roughness must be maintained after sediment removal. Hydraulic bed features such as riffles, runs, and pools will ideally remain in the channel following removal of flood sediment that buried the original channel. Coarse material such as boulders should not be placed in rows at the toe of the riverbanks but should be allowed to remain in the channel to stabilize the bed and create hydraulic diversity as the flow moves around the protruding rocks (Figure 5.7-5). Roughness can be reintroduced during flood recovery; however, this form of enhancement can have limited utility in highly depositional areas where burial of installed elements or rapid bed change is expected.

The natural channel bed armor layer should be preserved. Observations in areas of excessive downcutting that show a sediment profile of the riverbed following the flood or a test pit will reveal if an armor layer exists and where it is located. Work with machine operators to probe where the armor layer is and establish how to feel the layer with the excavator bucket during sediment removal. A stable post-flood channel is not achievable if the armor layer is removed.

The goal of channel design following sediment removal is to assist the return of a most-stable channel and promote that channel's existence for as long as possible. Anticipate channel adjustments following sediment removal as the dimensions, pattern, and profile adjust to the flow and sediment regime.

Figure 5.7-5: Roughened channel bed on the Middlebury River following boulder installation completed after sediment removal. (Source: Landslide Natural Resources Planning, 10/10/2013)

Floodplain Design

The design of the floodplain is equally important to the channel design, especially in areas that are prone to sediment deposition. More floodwaters and sediment are stored in the floodplain than the channel, so properly re-establishing floodplain areas is essential to reduce flood risks.

The primary design elements for the floodplain are width and elevation (see Section 5.6). Floodplain width on braided and alluvial fan channels should typically be as wide as possible until unmovable property exists (Table 5.7-1). If the full floodplain is not available for safe access by floodwater and debris, then the width should be set at the floodprone width (Appendix Q).

The target floodplain width can be on the order of hundreds to thousands of feet in depositional settings such as on braided channels and alluvial fans and should be based on a geomorphic assessment and knowledge of the pre-flood floodplain width. In the vicinity of improved property, a compromise must often be made to maintain as much floodplain width as possible to reduce future flood risks but not so wide as to create risks of inundation. Floodplain restoration, particularly in confined settings, typically includes bank stabilization at the upgradient or back edge of the floodplain to protect adjacent property.

Flood benches are small floodplain areas adjacent to the channel that carry flood flows and sediment during small floods (e.g., 1-year flood or smaller). These areas are important to re-establish following a large sediment deposition event as they can store similar amounts of water and sediment as the channel itself. In moderate- to low-risk settings where more limited sediment removal takes place to protect against the 5-year flood, flood benches rather than full floodplains still must be formed (see Section 5.5).

Properly selecting the floodplain elevation during sediment removal design is critical to reducing future flood risks. Vertical relief between the channel and floodplain surface should be set to allow floodplain inundation once every 1 to 2 years where possible. The target incision ratio (i.e., the ratio between the height of the recently abandoned floodplain and the maximum bankfull depth) is 1.0 to 1.3 for good floodplain access. Higher incision ratios mean channels and floodplains are disconnected, and downstream flood risks increase. Flood benches are typically lower and get inundated one or more times a year (Figure 5.7-6).

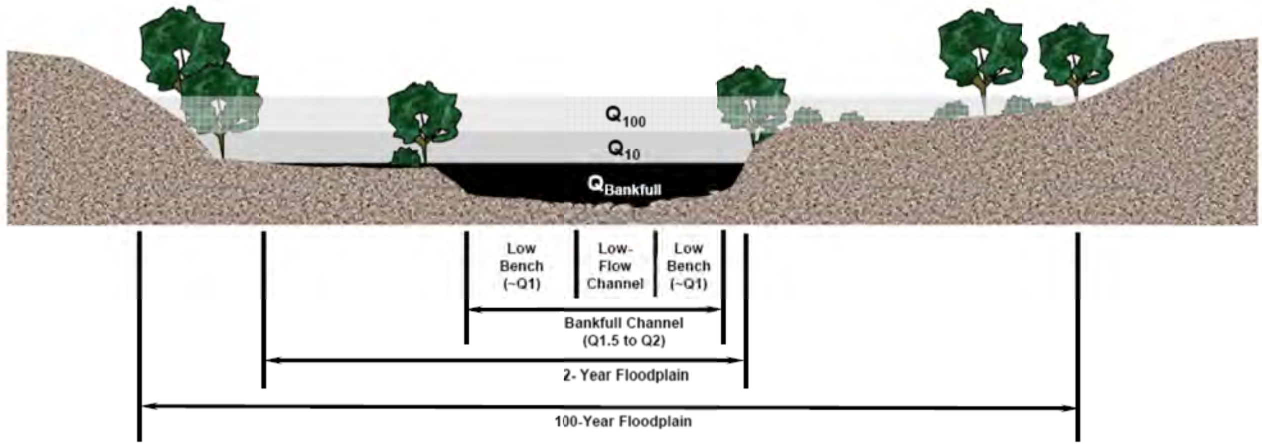


Figure 5.7-6: Schematic of low-flow channel, low benches, bankfull channel, and floodplains. (Source: Milone & MacBroom, Inc.)

A "floodplain paradox" exists in that leaving sediment on the floodplain that appears to be protecting adjacent property such as a road embankment or a house increases flood and erosion risks when the fill narrows the channel bankfull width (Figure 5.7-7). The floodplain fill confines flows increasing velocity that leads to more erosion and channel downcutting. If the floodplain were lower, it would inundate more frequently, so flows would spread out, velocity would be lower, and erosion potential would be lower. A compromise is often required when selecting the floodplain elevation next to property to achieve a desired reduction in inundation frequency while not encouraging the river to erode and move toward the property. Bank armoring (see Section 5.2) can be used immediately next to the property in conjunction with floodplain re-establishment to maximize risk reduction.

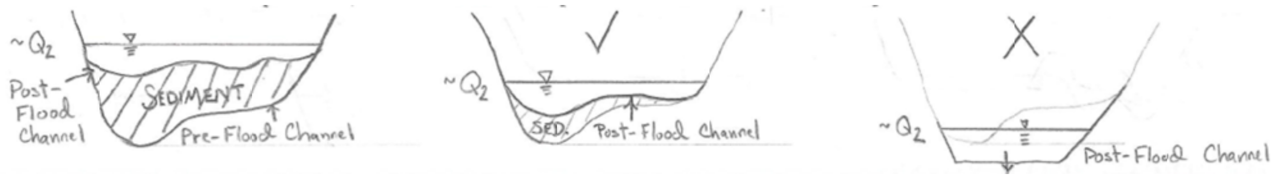


Figure 5.7-7: Schematic of a "floodplain paradox" where a wider channel and floodplain reduce risks (√), and a narrower setting under the false pretense of protecting adjacent property actually increases risks (X). (Source: Milone & MacBroom, Inc.)

Where increased floodplain access is acceptable, sediment deposition from a large flood should be left in the channel to reduce incision. Sometimes the material can be left in place as it lies while other times some minor reshaping needs to take place to realign the flow path away from banks or property. Sediment reshaping in the channel is less expensive than sediment removal and creates less channel impacts. Leaving sediment in place to reverse the trend of widespread channel incision and reconnecting floodplains reduces erosion hazards that are widespread in Vermont (Kline and Cahoon, 2010).

Crossing Structures

Removal of sediment and woody debris often begins at clogged bridges and culverts following large floods. Material should be removed throughout the entire structure and in the adjacent bankfull channel entering and leaving the structure. The cover over the footings should be reviewed at structures to identify if the structure remains stable following the flood. Conditions can vary at a single structure. For example, sediment deposition can take place on one side of a channel under a bridge while scour occurs on the other side of the channel.

Sediment removal typically must extend beyond the clogged structures to reduce flood risks. Sediment removal at structures is usually designed in conjunction with channel and floodplain sediment removal. Partial sediment removal around structures following a large deposition event can actually lead to increased chances of avulsion and future flood damages (Kline, 2012b) (Appendix U). When removing sediment and woody debris from bridges and culverts, an acceptable profile needs to be established that will not lead to headcutting or risk of avulsion. Uniform and gradual slope transitions in and out of the structure should be established.

Replacement of undersized structures that block sediment and debris should be considered to reduce the risks during future floods.

Woody Debris Removal

Woody debris accumulations should be assessed to see if they pose high, moderate, or low risk during future floods (Homer et al., 2004). Do not remove all of the woody debris from post-flood channels as some debris does not pose a risk during future floods (Table 5.7-2). If the transport potential of debris is small, the material will remain in place over time and can have a positive effect on habitat and stability with relatively low risk to downstream infrastructure. If large debris is highly mobile, it can lead to high risks downstream. Cut large debris into small pieces so it may pass downstream structures and remain in the ecosystem if possible.

Large jams that could lead to avulsion, bank erosion, or clogging of downstream structures due to sudden release should be removed. Large trees should be stockpiled for future habitat restoration work if storage space is available. When large quantities of removed woody debris are generated during a flood (e.g., > 100 trees), chippers are often used to process the material on site.

Table 5.7-2: Woody Debris Removal Recommendations (Adapted from Homer et al., 2004)

Risk Level	Risk Description	Recommendation
HIGH	Channel-spanning debris jams with altered flow path and high risk of avulsion. Remobilization of large amount of debris and downstream structure clogging likely. Structure completely or mostly clogged.	Remove debris jam.
HIGH TO MODERATE	Large mid-channel or bank accumulations of woody debris. Flow path may be altered, but risk of avulsion is low. Remobilization of large amount of debris and downstream structure clogging likely. Structure partially clogged.	Remove debris jam.
MODERATE	Large mid-channel or bank accumulations of woody debris. Flow path may be altered, but risk of avulsion is low. Remobilization of large amount of debris not likely.	Leave debris in place.
LOW	Bank accumulations of woody debris or individual embedded pieces of wood in channel. Flow path may be altered, but risk of avulsion is low. Remobilization of debris not likely.	Leave debris in place.

Standing and rooted trees in the river corridor should not be removed following a flood. A common misperception exists that these could be hazardous during the next flood after seeing a large input of woody debris during a flood. The standing trees reduce bank erosion and typically decrease flood risks by slowing flow velocity and reducing erosion. Standing trees also catch sediment and debris and hold it on the floodplain instead of allowing all material to deposit in the channel.

Rootwads and tangles of large trees remaining on the banks should not be excavated. Cut trees 6 to 10 feet above the base of the trunks to remove only the upper sections of the trees. The remaining roots will hold the bank together. Minimize the use of large machinery in the channel and the number of access points to control impacts.

Sediment Removal Volume

Once channel and floodplain dimensions have been established, calculate the volume of sediment that is occupying the proposed removal areas in the channel and floodplain. Survey is ideal for designing and quantifying the project yet, in large floods, mobilizing a survey crew into a damage area may be complicated or impossible due to work constraints. Approximate methods with a laser range finder or a level and rod are acceptable to initially quantify work.

Estimating deposition depths based on prior knowledge of the site can be performed. Measuring the distance between the bottom of bridge beams to the surface of sediment and comparison to pre-flood conditions or design plans is helpful to ballpark the amount of deposition in large areas. Digging test pits with an excavator may be necessary to view the sediment profile and locate the natural armor layer to determine removal depths. Care should be taken when estimating sediment removal volumes as this will indicate the amount of space needed for wasting material, the amount of trucking needed to move the sediment, and ultimately the cost of the project. For larger projects, survey should be performed when possible to refine the initial design and quantities as recovery work progresses.

COSTS

The ballpark cost of sediment excavation is $10 per cubic yard for large quantities of material (e.g., >5,000 cubic yards). The price typically ranges from $6.50 to $14.80 per cubic yard based on past flood recovery experience in the state and from average work rates along the state highway system (VTrans, 2009). Hauling is an additional cost that can range from $75 to $150 per hour of truck time.

Thorough documentation is required when seeking reimbursement from funding agencies. Information and applications should be filed prior to construction in nonemergency scenarios. After-the-fact submissions must take place in emergency situations.

- GPS the perimeter of the deposition to get footprint, widths, and length
- Note channel versus floodplain deposits.
- Establish several sediment depth estimates across the deposition field to be able to create sediment deposit cross sections. For larger floods, this is often done at each bridge at the project site.
- Identify the level of risk for future flood and erosion events to establish the desired level of clearing.
- Quantify the amount of sediment to be removed from the channel and floodplain.
- Count large woody debris jams and individual trees in the channel, on the banks, and in the floodplain.
- Determine the risk level for each woody debris jam and individual trees.
- Quantify the amount of wood to be removed from the channel and floodplain.
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or during emergency work.
    - FEMA
    - NRCS
    - USACE
    - VTANR
    - VTrans
    - Municipality

- Document how the project meets applicable State Performance Standards and permit requirements.

PERMITTING

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
    - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
    - Identify reporting category
    - Contact Vermont Field Office
- Vermont Stream Alteration Permit
    - Meet Performance Standards as identified above
    - Identify reporting category
    - Contact river management engineer
- Local Zoning Permit
    - Contact Town Administrator for reporting needs

CONSTRUCTION

Constructability

Gravel dredging and woody debris removal are practices that have historically been performed without proper design or consideration of resultant flood and erosion risks for centuries. There is a high degree of experience with removal of sediment and woody debris, but the methods identified here will be new to most people involved with the assessment, design, construction, permitting, and funding of this work. If enough machinery is available to complete the job based on the size of the deposition event and nearby waste sites exist, removal of sediment and woody debris can take place efficiently. A detailed plan review during a pre-construction meeting and frequent construction oversight at the beginning of the project are essential for proper implementation.

Since most of the removal of sediment and woody debris takes place in the channel and floodplain, road closures are only needed if deposits spilled onto roadway, or large embankment failures took place adjacent to the deposition field. Some traffic control may be required where dump truck or haul units enter and leave the site while travelling to waste disposal areas.

Temporary Construction Controls

Project demarcation fencing is needed in any location that the public could come in contact with the channel or floodplains, staging locations, stockpiles, or waste disposal areas. Silt fencing is required around most stockpile areas in the floodplain to control the movement of fine sediment during construction. Refer to the VTrans Construction Specifications (VTrans, 2011) for guidelines on locating and identifying staging and stockpiling areas.

During removal of sediment and woody debris, water control is often not needed as the channel has slid to the edge of the corridor away from the majority of the deposits. The channel will often end up next to the banks or in a new location in an incised narrow channel following a large flood. Work can progress to remove sediment and woody debris away from the channel without water control. Once the channel and floodplain are re-established working upstream, the water can be transferred from the post-flood channel.

If water control is needed, temporary berms made of pushed up deposited material are often used to guide water out of the work areas. Machine crossings can be made with built-up sediment. Culverts can be used to create dry crossings to reduce downstream turbidity.

Large gravel and cobble deposits are very permeable and, thus, subsurface flow will be taking place during sediment removal. Abrupt changes in subsurface flow levels have been observed following large floods and sediment removal. Test pits may be dug to observe groundwater levels in several spots around the work area and if any water diversion is needed.

Silt fence is used around the construction site to control sediment and erosion at stockpiles and waste areas. Applying silt fencing at large sediment removal projects has proven to be of limited use and infeasible given the length of the project and proximity to the channel. A series of check dams and sediment trap pools is often used during sediment and debris removal to capture fine sediment and control downstream turbidity. Several check dams and pools can be placed downstream of the work area. The pools should be periodically cleaned out as work takes place.

Access

Access to remove sediment and woody debris from channels and floodplains is typically made from state or municipal roads. Ownership of proposed access locations must be verified by reviewing roadway right-of-way mapping and local parcel mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access must take place across private land, agreements with the landowners are common. Access agreements typically include discussions or notes about returning the land to the original condition following the project. Planting of the upper bank with perennials, shrubs, and trees may be requested to naturalize the site following the construction work.

For larger projects or those likely requiring frequent future maintenance, easements can be drafted to allow periodic access for specified work such as flood damage repair or sediment management.

CONCEPTUAL DESIGN PLANS/DETAILS

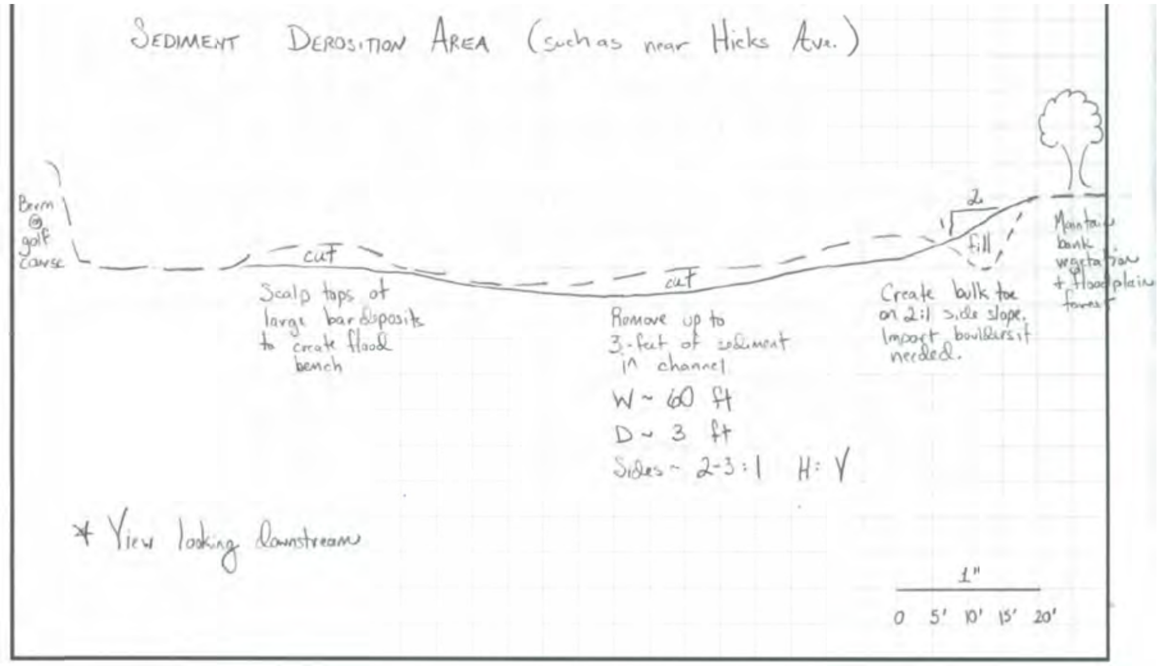


Figure 5.7-8: Sediment removal sketch plan showing initial cut and fill areas following large flood. (Source: Milone & MacBroom, Inc.)

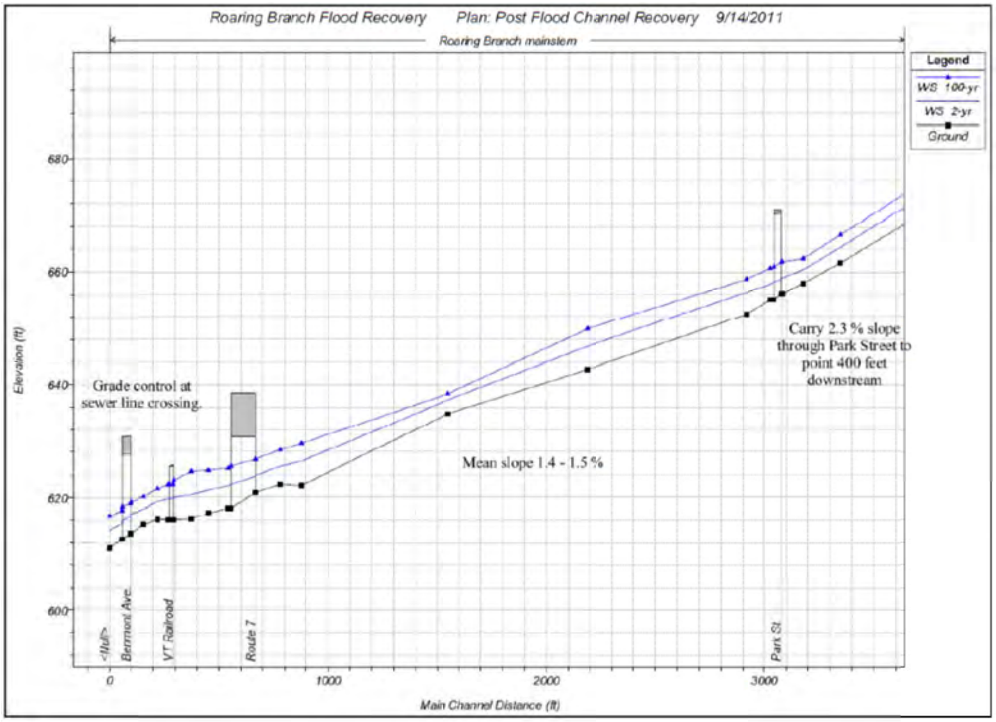


Figure 5.7-9: Hydraulic model profile showing proposed channel slope for sediment removal following large flood. (Source: Milone & MacBroom, Inc.)

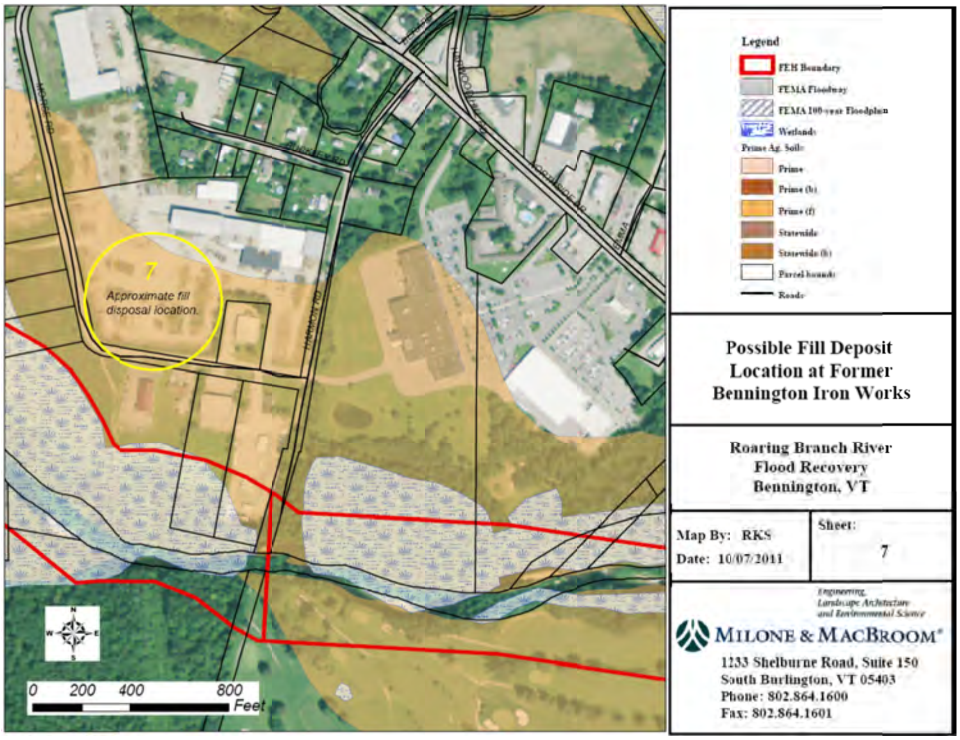


Figure 5.7-10: Sediment disposal area review map. (Source: Milone & MacBroom, Inc.)

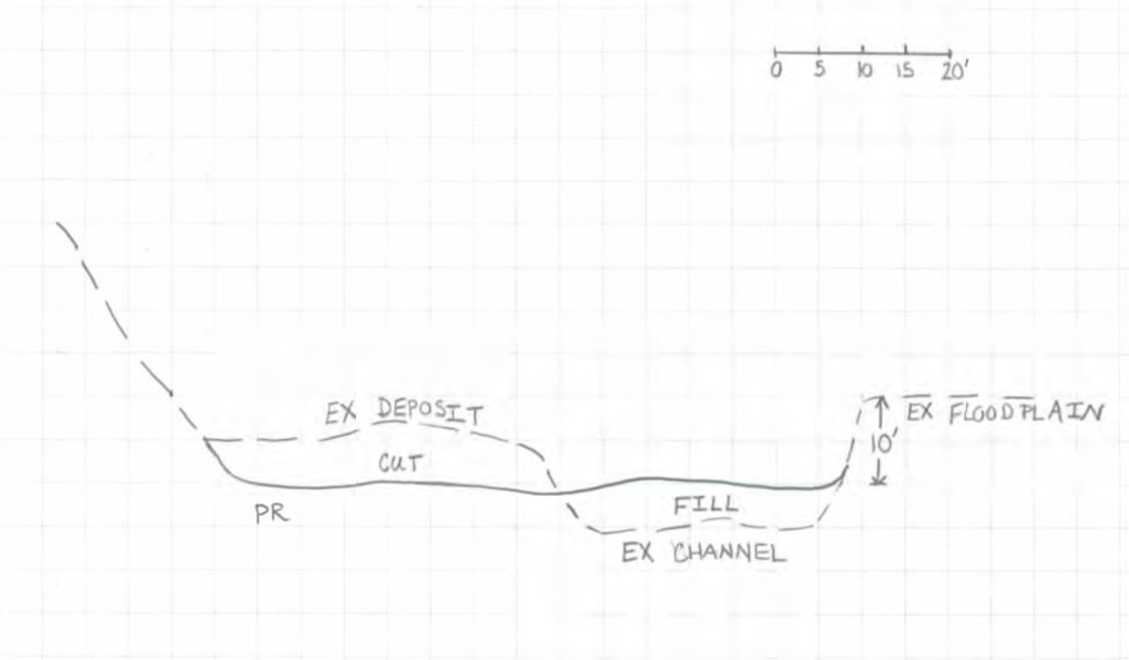


Figure 5.7-11: Sediment reshaping sketch plan to lower large bars, fill deep scour areas, and retain sediment in channel to improve floodplain connection. (Source: Milone & MacBroom, Inc.)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- To Dig or Not to Dig (Appendix S)
- Rationale for Flood Debris Clearing in the Mountainous Rivers of Vermont (Kline, 2012b) (U)
- Linking damages to dominant stream processes (C)
- Vermont hydraulic geometry regression equations (HGR) (VTDEC, 2006c) (L)
- Equilibrium slope for the size of sediment (T)
- Meandering, braided, or wandering channel pattern (R)
- Channel evolution model (E)
- Floodprone width (Q)

POSSIBLE COMPANION PRACTICES

- Placed riprap wall or traditional bank armor at back edge of floodplain (Section 5.2)
- Grade control (Section 5.4)
- Floodplain restoration (Section 5.6)
- Increase channel roughness. Reinstall boulders from bank.

5.8 BRIDGE AND CULVERT REPLACEMENT

DESCRIPTION

Bridge and Culvert Replacement

Assessment

- Channel bankfull dimensions
- Channel type and stability
- Channel evolution
- Channel profile
- Floodplain setting
- Sediment and debris load estimate
- Hydraulics
- Aquatic organism passage

Design

- Structure width and height
- Embeddedness
- Channel bed composition
- Structure length and slope
- Access and right-of-way

The hydraulic sizing of bridges and culverts is well established (e.g., FHWA, 1985; VTrans, 2014), yet current design guidelines (e.g., UNH, 2009; MassDOT, 2010) are now turning to geomorphic principles to both naturalize stream crossings and make them less prone to flood damages. Structures commonly fail due to geomorphic incompatibility such as stream instability (FHWA, 2012b) and clogging with sediment and debris (Furniss et al., 1998).

The primary principle behind the geomorphic-engineering design approach is to optimize structure size and shape so that the river channel form and processes can play out in a more natural way. Structures that are sized at the bankfull channel width or larger are:

- Able to convey more water, sediment, debris, and ice;
- Less prone to clogging;
- Less prone to bridge scour;
- More compatible with a stable channel; and
- Able to pass fish and wildlife.

The risk reduction and environmental benefits of geomorphic design for crossing structures has led to the establishment of new bridge and culvert design guidelines and Performance Standards in many states such as Vermont (2014).

The practice described here builds on the existing knowledge of hydraulic design for bridges and culverts and merges these approaches with geomorphic design principles that guide river management activities.

(Also referred to as bridge or culvert design, crossing design, structure sizing, stream simulation)

APPLICATION

Proper Use

Structures are fixed constrictions in channels that are prone to flood and erosion damages. A history of structure damages during floods has shown that many crossing structures need to be larger than the sizes determined strictly from hydraulic design approaches to reduce risks of failure.

Meeting the General Stream Alteration (General Permit or GP) Requirements

Proposed structures must meet the equilibrium and connectivity standards and require written approval from the Secretary of the Vermont Agency of Natural Resources for authorization under the Vermont Stream Alteration General Permit. For consideration under the General Permit (VTANR, 2014), new and replacement crossings are presumed to meet the Equilibrium and Connectivity Performance Standards of the Stream Alteration Rules (§27-402) (2013) when meeting the following design requirements:

- **Vermont Stream Alteration General Permit (GP) Design Requirements**
  - **$W_{structure} = 1.0 \times W_{bankfull\ channel}$**
  - **$H_{opening} = 4 \times D_{bankfull\ channel}$**
  - **$D_{embed} = 30\%\ H_{opening}$ or D_{84} for boulder bed, whichever is larger**
  - **Match channel profile and create uniform longitudinal transitions at inlet and outlet.**
  - **Structure shall not obstruct aquatic organism passage.**
- Evaluate structure for clear flow hydraulics and perform checks for material deposition/clogging and scour.
  - Where physical constraints preclude achievement of the 4.0X opening height standard and any potential increase in flooding hazard associated with a reduced opening height will be offset by other factors such as a lower roadway fill height, the minimum opening height shall be $\geq$ 3.0X the mean bankfull channel depth, as approved by the Secretary of VTANR, and as specified in the most current version of the VTrans Hydraulics Manual (VTrans, 2014).
  - Where more capacity is needed based on flow, material deposition, or scour, structure width shall be 1.2 x bankfull width or larger (e.g., floodprone width).
  - Where channel gradient is 0.5% or less or the structure is under outlet control, depth of embeddedness may be reduced, as approved by the Secretary of VTANR.
- Retain sediment throughout structure and maintain natural sediment transport.
- Avoid backwatering at inlet and naturalize the movement of large woody debris and ice.
- Design Q and $Hw/H_{opening}$ from state hydraulic standards (VTrans, 2014).
- Match channel hydraulic conditions for design flood, fish passage, and low flows.
- Align structure parallel to flow in channel.
- Maximize fish and wildlife passage.

Bankfull channel width and depth are measured from suitable reference cross sections and checked using the Vermont hydraulic geometry regression equations:
$W=13.1(DA)^{0.44}$ and
$D=0.96(DA)^{0.30}$ (see Appendix L).

Other instream practices may be required in conjunction with the crossing to establish vertical stability and ensure compliance with the Equilibrium and Connectivity Performance Standards.

Meeting the Individual Stream Alteration (Individual Permit or IP) Requirements

Proposed structures must meet the Equilibrium and Connectivity Performance Standards of the Stream Alteration Rules (§27-402) (2013) to receive an Individual Stream Alteration Permit from the Secretary of the Vermont Agency of Natural Resources. In certain stream settings, structures may be engineered to meet the Performance Standards and yet not exactly match one or more of the design requirements as outlined in the General Permit.

To meet the Performance Standards a stream crossing cannot result in hydraulic conditions that cause or perpetuate the unnatural aggrading (raising) or degrading (lowering) of the channel bed at the reach scale; create significant stream bed or stream bank disconnections at the local scale that increase damage related to erosion or deposition in the stream; or create a barrier to the movement of aquatic life.

In replacing certain structures located in narrow settings on altered, but vertically stable (i.e., “modified”) stream reaches that are confined by public infrastructure and habitable structures, it may not possible to meet the GP design requirements without removing buildings, roads, or utilities and placing significant fill in the floodway. In these settings, the Performance Standards shall be met using the design requirements in this Standard Practice (Stream Alteration Rules §27-601 (f)) (2013). Replacement bridges or culverts on human-constrained, vertically stable reaches, as identified by the River Management Engineer using the Vermont Stream Geomorphic Assessment Protocols (VTANR, 2009), are designed to have a width and height as large as possible with dimensions at or greater than those of the pre-existing structure. Other instream practices may be required in conjunction with the replacement crossing to safeguard vertical stability. Elements of the geomorphic – engineering structure sizing method (see Figure 5.8-2) are performed as part of a permit application to ensure compliance with the Equilibrium and Connectivity Performance Standards.

Limitations

- Geomorphic design principles often lead to using larger culverts that cost more than the smaller culverts that have traditionally been installed.
- Sites where smaller culverts such as corrugated metal pipes have been used may need replacement with a different structure type such as a reinforced concrete box culvert or a multi-plate pipe-arch culvert to allow installation of a larger structure to pass sediment and debris. The road profile may need to be elevated in some locations.
- Larger culverts may require geotechnical or structural design for proper implementation.
- Construction of larger culverts requires more sediment, erosion, and water control to limit environmental impacts than installation of smaller culverts.

Geomorphic Context

The geomorphic compatibility of a structure is how well a crossing structure matches the form and process of a channel. The more a structure matches the channel type (i.e., the sediment regime) the lower the risk of failure due to flood and erosion. Good compatibility also leads to better passage of aquatic organisms since the hydraulic characteristics of a geomorphically compatible structure and the channel are similar. Geomorphic compatibility screening is performed in Vermont (Schiff et al., 2008) based on the following variables:

- Percent bankfull width (structure width/bankfull width x 100);
- Sediment and debris continuity: upstream deposits and downstream scour;
- Structure slope versus channel slope, and break in valley slope;
- Approach angle; and
- Bank armoring and erosion upstream and downstream.

Crossing structures should be sized at or larger than the bankfull channel dimensions to allow conveyance of water, sediment, debris, and ice to pass through the structure while maintaining natural hydraulics (i.e., depth and velocity). Narrow structures are prone to flood and erosion damages since they tend to backwater flows, clog with materials, and increase exit velocities. Wide-spanning culverts and open-bottom structures allow a slight buffer against lateral and vertical stream adjustments, specifically on high-gradient channels (Bates et al., 2003). Wider structures are less prone to nonuniform flow paths that lead to ponding, racking of wood, and structure clogging (Furniss et al., 1998). Large structures also create hydraulic conditions that are more likely to accommodate aquatic and terrestrial organism passage (e.g., fish, salamanders, eels, turtles, mink, etc.).

Structures must be designed with an understanding of the geomorphic channel type in order to achieve geomorphic compatibility. Structures on high-power erosive settings in mid-order channels where incision is likely (i.e., riffle-pool or plane bed) will differ from those on low-power depositional settings where channel migration and possible avulsion will take place (i.e., braided). Review the geomorphic stream type, expected width, and possible changes in width such as when threshold channels or wandering channels move from single thread to multi-thread during flood.

The channel type and valley setting can be used to estimate or model the sediment regime at the crossing site. Aggradation is common at bridges and culverts that cause backwatering and increase the risk of damages (Johnson and Brown, 2000; Johnson et al., 2001). Structures in channels with large amounts of cobble and boulder bedload are prone to clogging and reduced conveyance. If a structure is prone to clogging, design should evaluate the structure's flood capacity in a partially clogged condition (e.g., 25% to 50% blocked) in addition to clear flow.

Sedimentation is the primary cause of structure failure. Sedimentation can lead to structure clogging and outflanking. If a large deposit of sediment takes place at a structure inlet, a channel avulsion can occur that can wash away the roadway embankment. Sediment accumulation also leads to scour around the structure inlet due to a skewed angle of the approach flow. Scour can also take place at the structure outlet due to flow dropping off of the accumulated sediment. Assess the channel stability in the project reach (VTANR, 2009) and at the crossing structure (Johnson et al., 1999). Scour analysis (FHWA, 2012a) and countermeasures (Lagasse et al., 2009) are commonly needed at bridges and may be needed at larger culverts in high-risk settings.

The potential input of large woody debris during a flood needs to be evaluated along the channel reach and watershed to know if the structure is prone to clogging with debris. In northern climates, ice can also clog structures. If past flood damages have occurred due to clogging or are suspected due to a high possible woody debris load during a flood, the bridge or culvert should be designed to fill to 80% of the opening height (i.e., $Hw/D \leq 0.8$) during clear flow to allow vertical space in the structure to pass sediment, woody debris, and ice. Post-flood evaluations of failed structures indicate that structures that were filled or overtopped during a flood were typically damaged due to debris accumulation and clogging (Furniss et al., 1998) (Figure 5.8-1).

Proper structure design must consider the floodplain setting. Does the channel have broad floodplains or narrow benches? The floodplain width and frequency of inundation are important to fine tune the structure width to achieve an acceptable level of flow constriction during floods.

Habitat Maintenance

- Improve aquatic organism passage
- Potential to improve wildlife passage
- Naturalize sediment transport to allow downstream bed features to establish
- Stabilize channel bed and habitat features
- Provide for overbank flows near culvert for development of riparian habitat

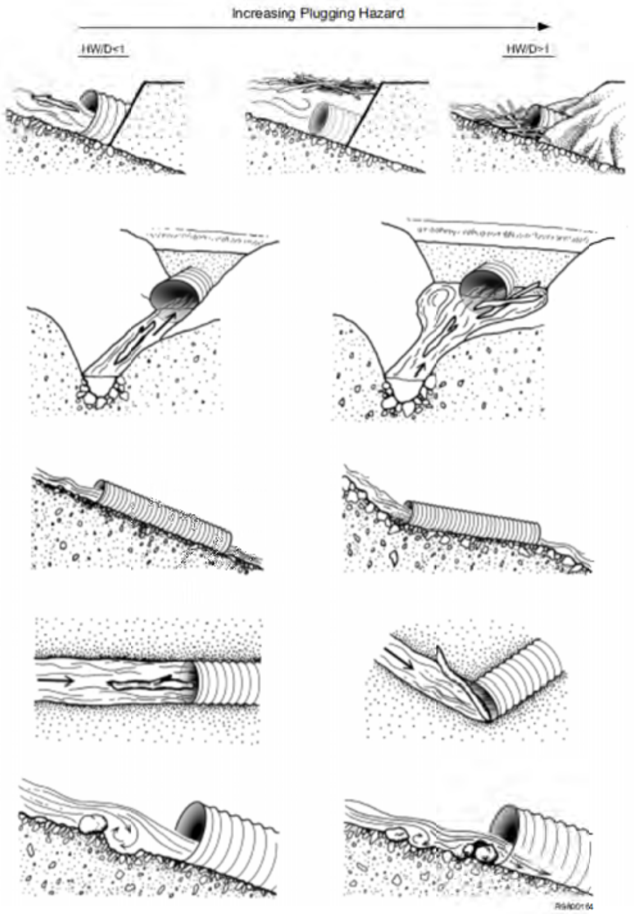


Figure 5.8-1: Schematic of increased plugging hazard for culverts when floodwaters fill over the top of the structure. (Source: Furniss et al., 1998)

Common Mistakes

- Replacing damaged structures with smaller temporary or same-sized permanent structures that do not reduce flood and erosion risks
- Evaluation of proposed culverts only using clear flow (i.e., without consideration of sediment and debris transport)
- Not prescribing both a mobile bed and immobile bed inside a proposed structure
- Allowing for Hw/D > 1 for culverts on channels with high sediment and debris loads that leads to structure clogging during floods
- Only evaluating a single design flow
- Minimizing near-term cost by selecting an undersized structure that often leads to channel impacts and having to replace the structure following flood damages
- Not explicitly verifying aquatic organism passage criteria of outlet drop, depth, and velocity for local species

Compatibility with Emergency Temporary Repairs and Timing of Implementation

- The design of culverts that are sized for proper hydraulic conveyance, geomorphic compatibility, and aquatic organism passage takes time that is not typically available in emergency recovery settings following structure failure. For this reason, smaller culverts, temporary bridges, or fords may be commonly installed to reopen roads, and the permanent repairs follow outside of the flood recovery setting.
- If an assessment and design has been prepared for structures prone to flood and erosion damages pre-emergency, the time to properly repair the structure will be shorter following flood damages.

SITE WORK CONSTRAINTS

If larger structures are being installed, land ownership needs to be confirmed beyond the existing structure. Right-of-way mapping and parcel boundaries need to be reviewed. Deed research may be needed to confirm landowners. An agreement will be needed with landowners for installation of a structure on their property along with a permanent maintenance easement.

The nonemergency work window in river channels is typically July to October. Structure installation should be performed during low flow. A water control plan will be needed along with a sediment and erosion control plan to reduce impacts during construction.

If a larger structure is going to be installed with a taller opening, the road profile may need to be elevated. This will require design of a portion of the roadway approaches next to the structure.

Utilities are often located under bridges or buried over culverts that must be addressed during design. Contact Dig Safe and then review the locations of the utilities with the project team and landowners. A plan to move or eliminate redundant utilities will be needed to construct the project.

PRIMARY GEOMORPHIC DESIGN ELEMENTS

The geomorphic design elements of width, height, embeddedness, channel bed material, length, and structure slope are presented here. This information must be paired with hydraulic and structural design elements such as the inlet/outlet treatments, headwalls, footings, and scour countermeasures that are covered in other documents. A method has been developed to iteratively size a geomorphically compatible structure that meets hydraulic design principles (Figure 5.8-2). Information on the watershed, channel, and roadway is needed to support the analysis (Figure 5.8-3).

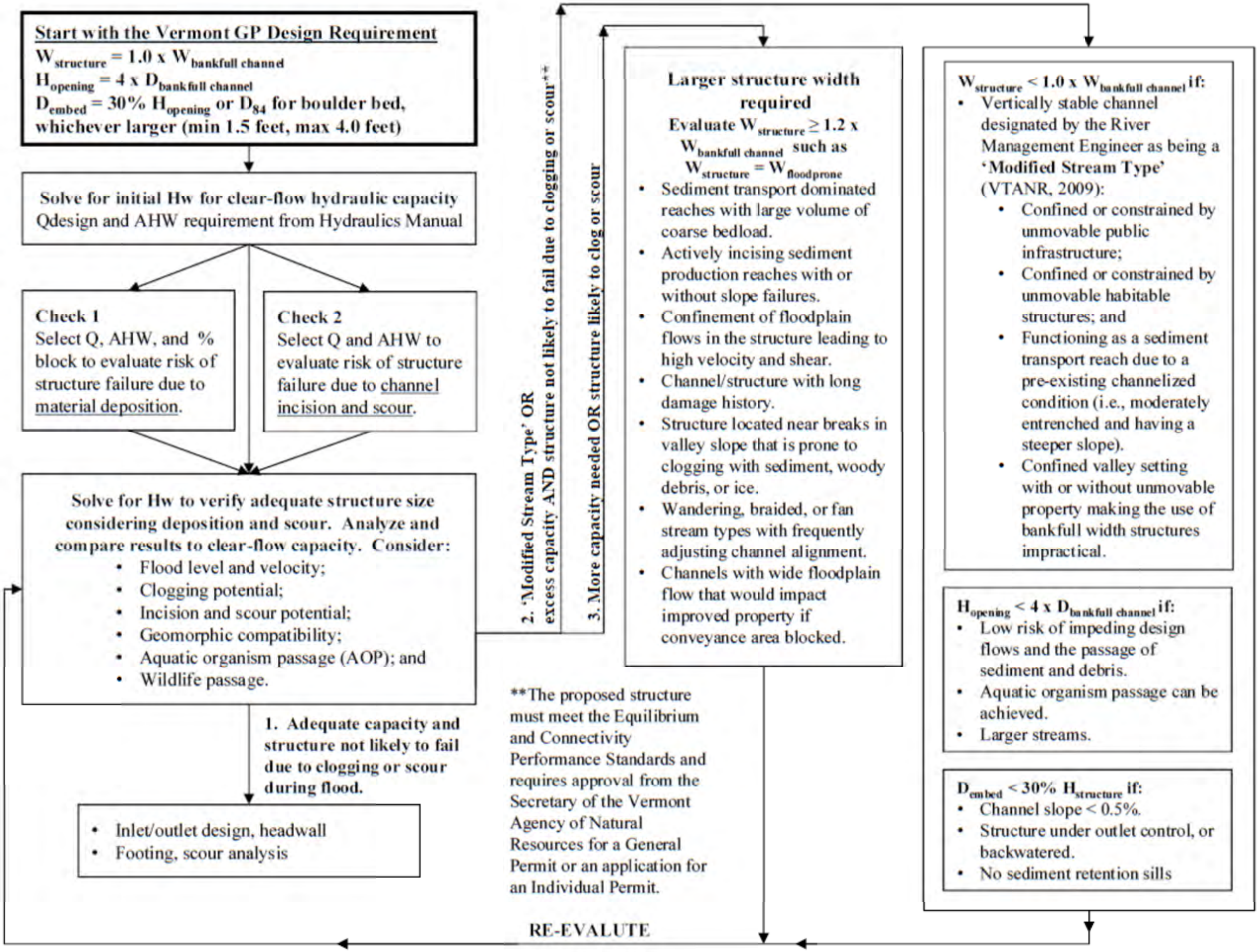
Width

To gain authorization under the Vermont General Permit, the design requirement for structure opening width (i.e., the width of a culvert or length or span of a bridge) is at least 1.0 times (1X) the width of the bankfull channel. The bankfull width can be determined by measurements at the project site outside the direct hydraulic influence of the road embankment, measurements at a nearby reference site without floodplain encroachments, or estimation from regional hydraulic geometry regression equations (Appendix L). Ideally a combination of measurements and calculations is used to determine the channel bankfull width to size a structure.

At sites with a "Modified Stream Type" (defined as an altered, vertically stable stream reach, confined by public infrastructure and habitable structures) or where excess capacity exists and structure failure is not likely, a smaller structure width may be possible with approval from the Secretary of the Vermont Agency of Natural Resources of an application under the General Permit or an application for an Individual Permit. A hydraulic analysis will be needed to show that the proposed structure meets the equilibrium and connectivity standards as described in the Vermont Stream Alteration Rules. Hydraulic modeling or calculations should evaluate flood levels, velocity, likely change in erosion and deposition, geomorphic compatibility, aquatic organism passage, and wildlife passage.

Larger structure widths are needed in high-risk settings where repeat flood damages have occurred, the valley setting leads to high stream power, the size and volume of bedload lead to a high potential for structure clogging, a large woody debris load leads to a high potential for clogging, or the channel is unstable. A structure that spans the floodprone width (Appendix Q) may be necessary to reduce flood and erosion risks. Consideration of sediment transport and debris loading is recommended for high-risk sites to properly select the structure width.

The bankfull channel width is measured in the field over the reach that contains the proposed crossing. An initial estimation of the bankfull channel width can be taken from the Vermont hydraulic geometry regression equations (Appendix L).



Start with the Vermont GP Design Requirement

$W_{structure} = 1.0 \times W_{bankfull\ channel}$

$H_{opening} = 4 \times D_{bankfull\ channel}$

$D_{embed} = 30\%\ H_{opening}$ or D_{84} for boulder bed, whichever larger (min 1.5 feet, max 4.0 feet)

Solve for initial Hw for clear-flow hydraulic capacity Qdesign and AHW requirement from Hydraulics Manual

Check 1
Select Q, AHW, and % block to evaluate risk of structure failure due to material deposition.

Check 2
Select Q and AHW to evaluate risk of structure failure due to channel incision and scour.

Solve for Hw to verify adequate structure size considering deposition and scour. Analyze and compare results to clear-flow capacity. Consider:

- Flood level and velocity;
- Clogging potential;
- Incision and scour potential;
- Geomorphic compatibility;
- Aquatic organism passage (AOP); and
- Wildlife passage.

1. Adequate capacity and structure not likely to fail due to clogging or scour during flood.

- Inlet/outlet design, headwall
- Footing, scour analysis

2. 'Modified Stream Type' OR excess capacity AND structure not likely to fail due to clogging or scour**

3. More capacity needed OR structure likely to clog or scour

Larger structure width required
Evaluate $W_{structure} \geq 1.2 \times W_{bankfull\ channel}$ such as $W_{structure} = W_{floodprone}$

- Sediment transport dominated reaches with large volume of coarse bedload.
- Actively incising sediment production reaches with or without slope failures.
- Confinement of floodplain flows in the structure leading to high velocity and shear.
- Channel/structure with long damage history.
- Structure located near breaks in valley slope that is prone to clogging with sediment, woody debris, or ice.
- Wandering, braided, or fan stream types with frequently adjusting channel alignment.
- Channels with wide floodplain flow that would impact improved property if conveyance area blocked.

$W_{structure} < 1.0 \times W_{bankfull\ channel}$ if:

- Vertically stable channel designated by the River Management Engineer as being a **'Modified Stream Type'** (VTANR, 2009):
  - Confined or constrained by unmovable public infrastructure;
  - Confined or constrained by unmovable habitable structures; and
  - Functioning as a sediment transport reach due to a pre-existing channelized condition (i.e., moderately entrenched and having a steeper slope).
  - Confined valley setting with or without unmovable property making the use of bankfull width structures impractical.

$H_{opening} < 4 \times D_{bankfull\ channel}$ if:

- Low risk of impeding design flows and the passage of sediment and debris.
- Aquatic organism passage can be achieved.
- Larger streams.

$D_{embed} < 30\%\ H_{structure}$ if:

- Channel slope < 0.5%.
- Structure under outlet control, or backwatered.
- No sediment retention sills

**The proposed structure must meet the Equilibrium and Connectivity Performance Standards and requires approval from the Secretary of the Vermont Agency of Natural Resources for a General Permit or an application for an Individual Permit.

RE-EVALUTE

Figure 5.8-2: Geomorphic – engineering structure sizing method.

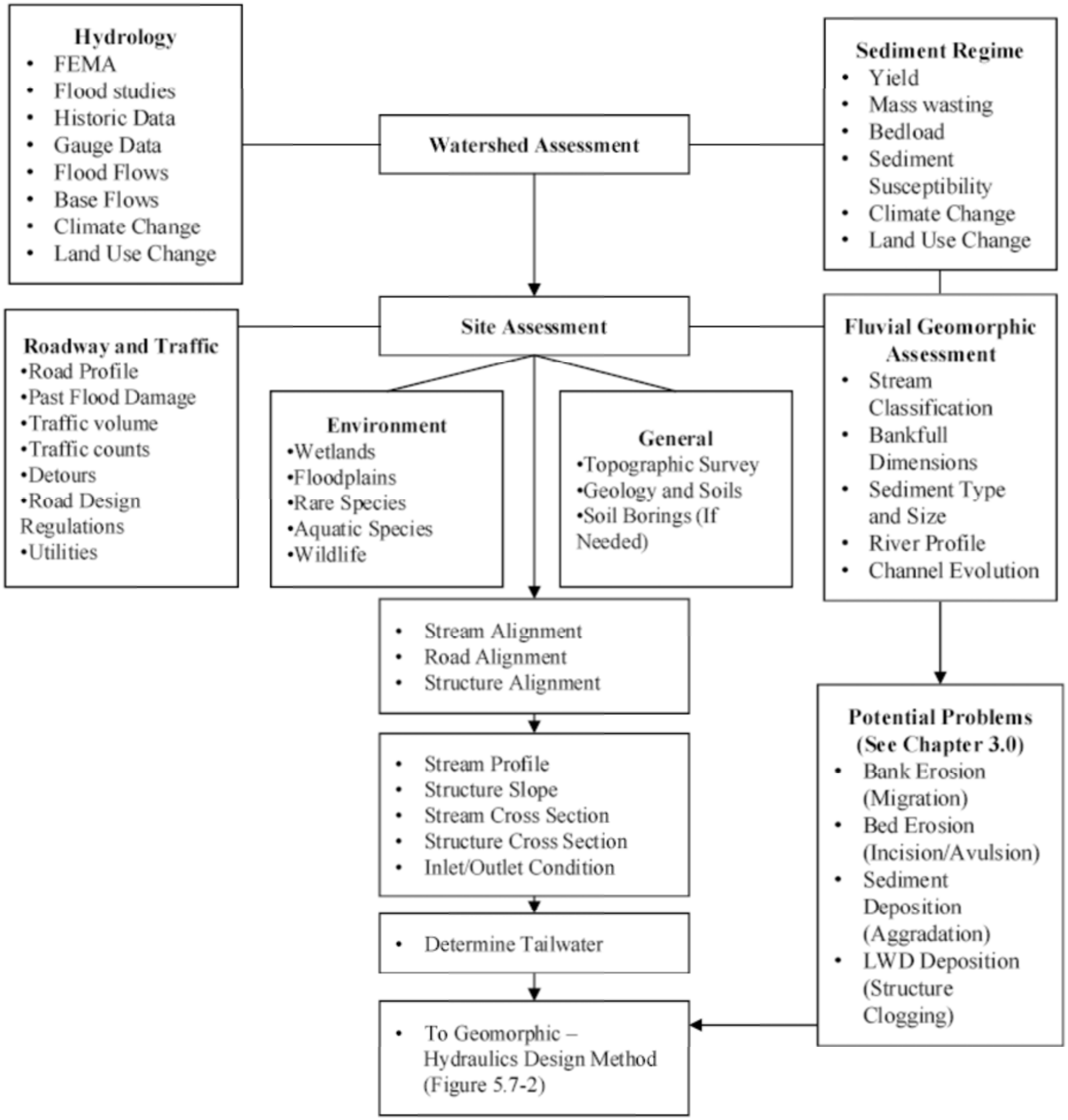


Figure 5.8-3: Watershed, channel, and roadway information used in structure design.

Opening Height

The Vermont GP Design Requirement for structure opening height is 4 times (4X) the depth of the bankfull channel. At crossing sites over a "Modified Stream Type" or structures with excess clear flow capacity that are not likely to fail due to clogging and scour, a smaller structure opening height such as 3.0 times the channel bankfull depth may be allowed under the Vermont Stream Alteration GP with approval of the Secretary of the Agency of Natural Resources or an application for an Individual Permit. In either case, a hydraulic analysis will be required to confirm that the structure still meets the Equilibrium and Connectivity Performance Standards.

Embeddedness

The Vermont GP Design Requirement for embeddedness for closed-bottom structures is 30% the height of the structure opening. Where the immobile bed sediments (> D84) are boulders (diameter of the median axis is larger than 10 inches), the minimum structure embeddedness is 30% the height of the structure or one times (1X) the D84, whichever is greater. The minimum allowable structure embeddedness is 1.5 feet; the maximum required structure embeddedness is 4 feet.

Where the channel gradient is 0.5% or less or the structure is under outlet control, the depth of embeddedness may be reduced since the likelihood of retaining bed sediment in the structure is high. A lower embeddedness may be allowed under the Vermont Stream Alteration GP with approval of the Secretary of the Agency of Natural Resources or an application for an Individual Permit if an analysis is performed that shows the Equilibrium and Connectivity Performance Standards are achieved.

Channel Bed Composition

Natural river sediment should exist throughout the crossing structure to allow for sediment transport, migration of bed features, and aquatic organism passage. The composition of the bed should match the channel as closely as possible. When constructing a new bed under a bridge or inside of a culvert, the minimum requirement is to specify the dominant mobile and immobile particle sizes, as well as chinking material to fill the voids in the immobile bed (Appendix M). D84 is a common immobile bed specification that only may move during extreme floods. The size of the dominant particle in the natural armor layer in the channel is another option for the immobile particle size in the structure. More conservative immobile bed design using larger boulders is common in high-power and confined settings where a modified stream type may exist since flood velocities and shear stress are likely to be higher than in the channel.

Hydraulic analysis and an understanding of the upstream sediment source are typically required to properly size both the immobile and mobile bed material. A mobile particle size may be the dominant bed or bar particle upstream of the culvert outside the direct hydraulic influence of the crossing. The hydraulic analysis should calculate the flood velocity and shear stress for clear flow and for a reduced opening size if sediment and debris clogging is likely. Sediment sizing may need to vary across a structure from side-to-side with different hydraulics. For example, if the structure is located on a channel bend and flow is concentrated and moving faster on the side of the structure nearest to the outside of the bend then larger sediment will need to be installed in this location.

A full bed design under the stream simulation approach typically includes designing the full gradation of particles, including fines, and the appearance of the post-construction bed (Bates and Kirn, 2009). A proper channel bed composition in the structure is essential for maintaining structure stability and aquatic organism passage over the long term.

Structure Slope

The structure slope should match the slope of the channel. For closed-bottom structures, the proposed channel bottom through the structure must be properly located relative to the channel profile that is a function of embedment and structure size.

Where structures are located at a break in channel slope, the slope of the structure should be lower than the upstream reach and higher than the downstream reach to create a uniform longitudinal profile. Create uniform and gradual channel-structure slope transitions at the inlet and outlet. For large slope transitions, downstream grade control may be needed to accomplish a uniform profile. Locate natural grade controls upstream and downstream of the structure to understand where the future bed may be changing and where it is naturally fixed. Estimate the vertical adjustment range of the channel bed between existing grade controls (Bates and Kirn, 2009). Anticipate future changes to the channel profile with a new structure in place that will likely reinitiate sediment transport.

Plan for anticipated channel downcutting and lateral channel movement due to channel evolution (Appendix E). If the channel is in evolution stages II and III, downcutting is likely.

Sediment Retention Sills

Embedding a structure so it naturally retains sediment based on proper placement in the channel profile is preferred over sediment retention sills, yet sometimes sills are needed as insurance to retain sediment in the structure during flood. Sills are commonly used in culverts located in steep mountain channels that have high flood velocity. Hydraulic and sediment transport analyses are recommended to confirm the need for sills.

Sill height should be 1 foot for steeper grades (>2%) and 0.5 feet for flatter grades (0.5% to 2%). Sills are not needed on channels with slopes less than 0.5% or for culverts under permanent outlet control. Flat sills should be used, and a minimum sediment cover over the sills should be 1 foot. The recommended thickness of a sill is 6 inches.

Structure Length

The structure should be parallel to the channel flow direction that sets the structure length. Sometimes the structure is turned toward perpendicular to the road embankment to minimize the length. This alignment could create a strong skew that could interfere with flood hydraulics and debris transport.

Scour Protection

Open-bottom culverts and bridges enable channel bed continuity and aquatic organism passage, but require scour analysis (FHWA, 2012a) and possibly protection for the footings and abutments (Lagasse et al., 2009). Two-thirds of all bridge failures are due to scour. Structural scour countermeasures include deep spread footings, piles, and riprap.

Guard Rails

Wherever possible, roadways over hydraulic structures should have open traffic safety barriers along the edges of the road to allow more conveyance of floodwaters, debris, and ice during roadway overtopping. Tubular rail and wire cable systems tend to pass flow and material. In regular floodprone crossing areas, planned gated road closures can be designed to allow the passage of flood and debris flows.

Secondary Structures on Broad Floodplains

Roadways on broad floodplains and those that cross multiple channels may necessitate secondary bridges or culverts to convey wide flood flows and limit lateral flows along road embankments.

COSTS

The cost to replace a bridge or culvert can vary widely depending on the structure size, site setting, ease of access for construction, and water control requirement. Recent geomorphically compatible culvert projects on moderate-sized streams (4th order) had total project costs that included design, permitting, bid assistance, and construction of $250,000 to $500,000. Structure width was set at 1.25 the channel bankfull width and ranged from 20 to 35 feet. A smaller culvert with width of 13 feet had a total project cost of $170,000.

Access to materials, familiarity with structure work in rivers, and current workload lead to a range of construction costs. In a recent project for installation of two 18-foot-wide culverts that are geomorphically compatible with the channel and allowed for aquatic organism passage, the construction cost ranged from $170,000 to $500,000. The engineer's opinion of probable construction cost was $235,000.

The Vermont GP Performance Standards that call for properly sized culverts to reduce future flood risks should facilitate future funding efforts for structure replacement. Thorough documentation of the design basis will increase the chances of receiving funding to implement the project. Information and applications should be filed prior to construction in nonemergency situations. After-the-fact submissions may be required in emergency situations if an enlarged structure has been designed before the occurrence of a flood and then is installed during flood recovery to repair an essential roadway.

- GPS the structure location.
- Compare the size of the damaged and proposed structures, with specific reference to the GP Performance Standards.

- Describe the new structure relative to improvements in geomorphic compatibility and the reduction of flood and erosion risks.
- Hold and document conversations with all potential funders and regulatory agencies prior to the start of work if possible, or as emergency work progresses.
    - FEMA
    - NRCS
    - USACE
    - VTANR
    - VTrans
    - Municipality
- Document how the project meets applicable State Performance Standards and permit requirements.

PERMITTING

- U.S. Army Corps of Engineers Vermont Programmatic General Permit
    - Quantify length, area, and volume of existing and proposed fill below ordinary high water (OHW)
    - Note geomorphic compatibility and aquatic organism passage relative to permit requirements
    - Identify reporting category
    - Contact Vermont Field Office
- Vermont Stream Alteration Permit
    - Meet GP Performance Standards as identified above
    - Identify reporting category
    - Contact River Management Engineer
- Local Zoning Permit
    - Contact Town Administrator for reporting needs
    - Local National Flood Insurance Program (NFIP) floodplain development jurisdiction

CONSTRUCTION

Constructability

A lot of experience exists in bridge and culvert replacements. The constructability challenges come with installation of structures that are larger than previously existed. Digging deeper in the channel to embed large culverts or widening out an existing crossing location may take longer to construct and cost more to build than smaller structures.

Temporary Construction Controls

Project demarcation fencing is needed in any location that the public could come in contact with at the project site, staging locations, stockpiles, or waste disposal areas. Refer to the VTrans Construction Specifications (VTrans, 2011) for guidelines on locating and identifying staging and stockpiling areas.

A sediment and erosion control plan is needed for larger structure replacements. For simple projects with low risk, the Vermont Low Risk Site Handbook For Erosion Prevention and Sediment Control (VTDEC, 2006b) can be used.

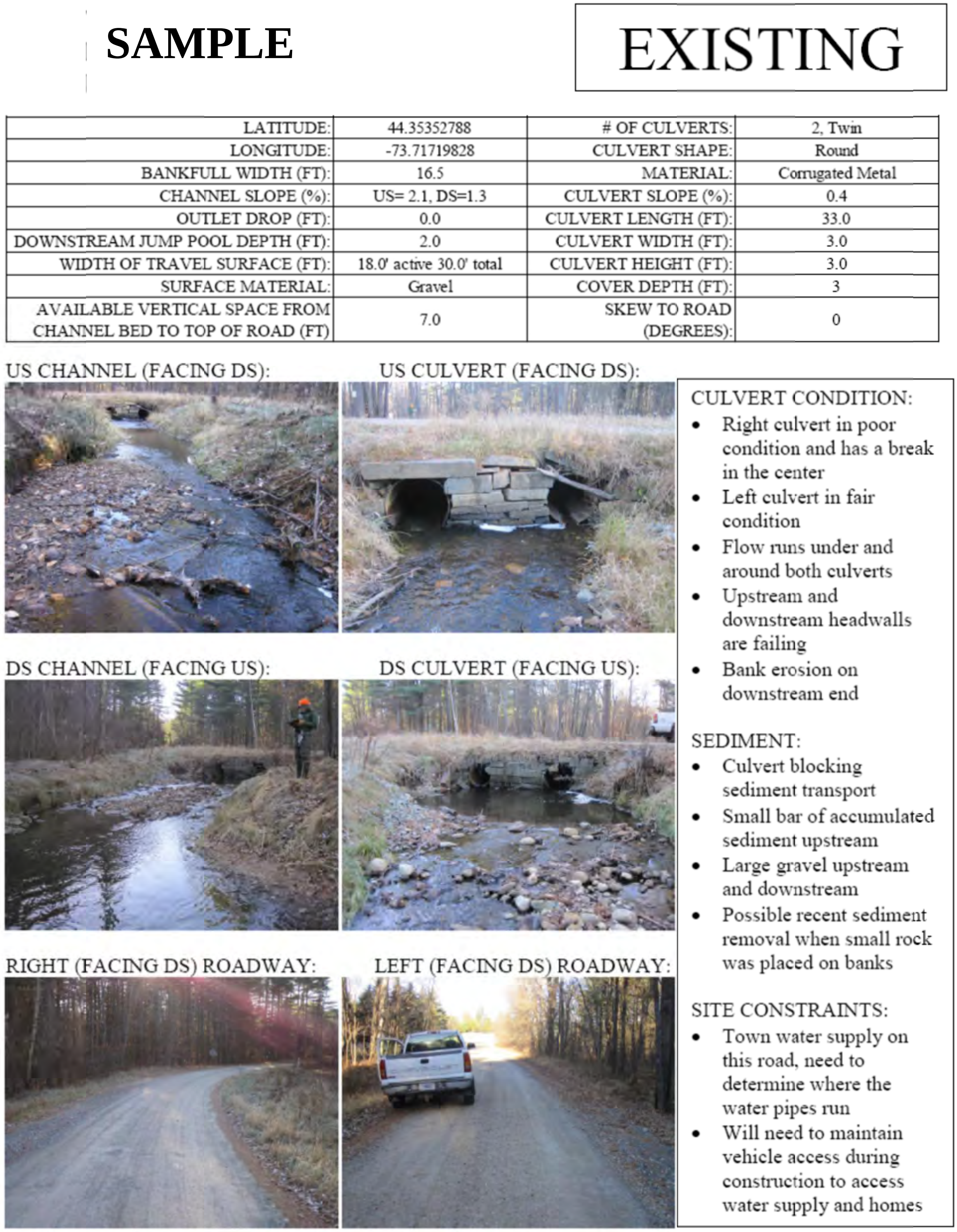
Staging and stockpile areas that can contain sediment, soil, the old structure, the new structure that is getting assembled, and construction materials need temporary controls. Surround these areas with silt fence and locate them out of the floodplain if possible.

Water control is common during structure installation. Pushing coarse river sediment to guide flow to a side of the channel may be adequate to create a suitable work area and protect water quality. A coffer dam made of sandbags, concrete bock, or sheeting may be used to control water. For projects where work must take place in the dry, pumping flow around the work site into a dewatering basin on the floodplain is used. All construction activities should occur during low flows.

Access

Access to structures is typically made from state highways or municipal roads. Sometimes a portion of an access may cross private property. Ownership of the proposed access locations must be verified by conversations with landowners or by reviewing local parcel mapping and roadway right-of-way mapping. In some cases where ownership is not clear, past right-of-way mapping and deed research may be needed to confirm where access is possible.

If access is proposed across private land, agreements with the landowners are common. Agreements for access to structures will typically include maintenance easements.



SAMPLE

EXISTING

LATITUDE:	44.35352788	# OF CULVERTS:	2, Twin
LONGITUDE:	-73.71719828	CULVERT SHAPE:	Round
BANKFULL WIDTH (FT):	16.5	MATERIAL:	Corrugated Metal
CHANNEL SLOPE (%):	US= 2.1, DS=1.3	CULVERT SLOPE (%):	0.4
OUTLET DROP (FT):	0.0	CULVERT LENGTH (FT):	33.0
DOWNSTREAM JUMP POOL DEPTH (FT):	2.0	CULVERT WIDTH (FT):	3.0
WIDTH OF TRAVEL SURFACE (FT):	18.0' active 30.0' total	CULVERT HEIGHT (FT):	3.0
SURFACE MATERIAL:	Gravel	COVER DEPTH (FT):	3
AVAILABLE VERTICAL SPACE FROM CHANNEL BED TO TOP OF ROAD (FT)	7.0	SKEW TO ROAD (DEGREES):	0

US CHANNEL (FACING DS):

US CULVERT (FACING DS):

DS CHANNEL (FACING US):

DS CULVERT (FACING US):

RIGHT (FACING DS) ROADWAY:

LEFT (FACING DS) ROADWAY:

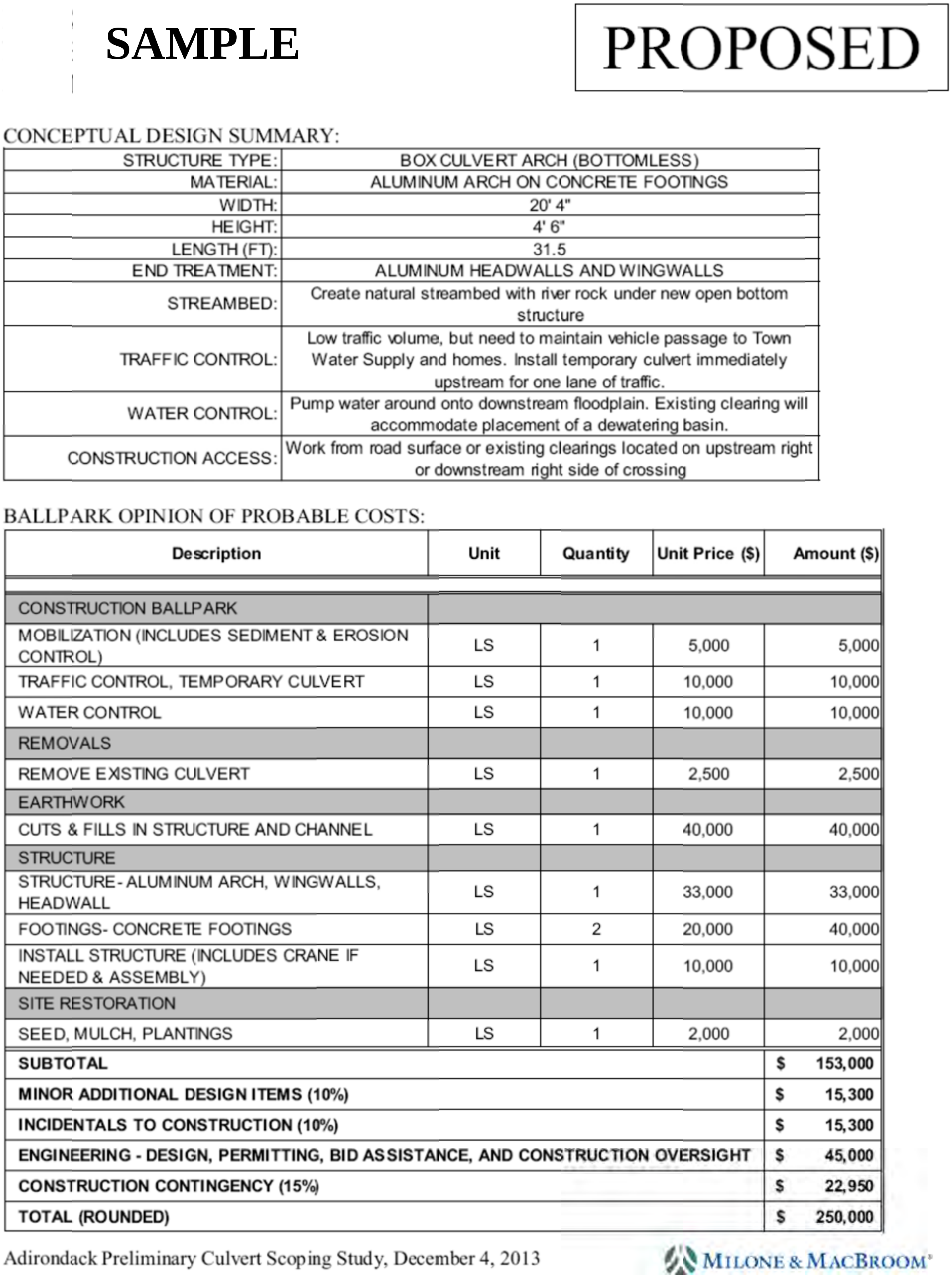
CULVERT CONDITION:
- Right culvert in poor condition and has a break in the center
- Left culvert in fair condition
- Flow runs under and around both culverts
- Upstream and downstream headwalls are failing
- Bank erosion on downstream end

SEDIMENT:
- Culvert blocking sediment transport
- Small bar of accumulated sediment upstream
- Large gravel upstream and downstream
- Possible recent sediment removal when small rock was placed on banks

SITE CONSTRAINTS:
- Town water supply on this road, need to determine where the water pipes run
- Will need to maintain vehicle access during construction to access water supply and homes

Figure 5.8-4a: Culvert scoping study (existing conditions).

SAMPLE



PROPOSED

CONCEPTUAL DESIGN SUMMARY:

STRUCTURE TYPE:	BOX CULVERT ARCH (BOTTOMLESS)
MATERIAL:	ALUMINUM ARCH ON CONCRETE FOOTINGS
WIDTH:	20' 4"
HEIGHT:	4' 6"
LENGTH (FT):	31.5
END TREATMENT:	ALUMINUM HEADWALLS AND WINGWALLS
STREAMBED:	Create natural streambed with river rock under new open bottom structure
TRAFFIC CONTROL:	Low traffic volume, but need to maintain vehicle passage to Town Water Supply and homes. Install temporary culvert immediately upstream for one lane of traffic.
WATER CONTROL:	Pump water around onto downstream floodplain. Existing clearing will accommodate placement of a dewatering basin.
CONSTRUCTION ACCESS:	Work from road surface or existing clearings located on upstream right or downstream right side of crossing

BALLPARK OPINION OF PROBABLE COSTS:

Description	Unit	Quantity	Unit Price ($)	Amount ($)
CONSTRUCTION BALLPARK				
MOBILIZATION (INCLUDES SEDIMENT & EROSION CONTROL)	LS	1	5,000	5,000
TRAFFIC CONTROL, TEMPORARY CULVERT	LS	1	10,000	10,000
WATER CONTROL	LS	1	10,000	10,000
REMOVALS				
REMOVE EXISTING CULVERT	LS	1	2,500	2,500
EARTHWORK				
CUTS & FILLS IN STRUCTURE AND CHANNEL	LS	1	40,000	40,000
STRUCTURE				
STRUCTURE - ALUMINUM ARCH, WINGWALLS, HEADWALL	LS	1	33,000	33,000
FOOTINGS- CONCRETE FOOTINGS	LS	2	20,000	40,000
INSTALL STRUCTURE (INCLUDES CRANE IF NEEDED & ASSEMBLY)	LS	1	10,000	10,000
SITE RESTORATION				
SEED, MULCH, PLANTINGS	LS	1	2,000	2,000
SUBTOTAL				**$ 153,000**
MINOR ADDITIONAL DESIGN ITEMS (10%)				**$ 15,300**
INCIDENTALS TO CONSTRUCTION (10%)				**$ 15,300**
ENGINEERING - DESIGN, PERMITTING, BID ASSISTANCE, AND CONSTRUCTION OVERSIGHT				**$ 45,000**
CONSTRUCTION CONTINGENCY (15%)				**$ 22,950**
TOTAL (ROUNDED)				**$ 250,000**

Adirondack Preliminary Culvert Scoping Study, December 4, 2013

MILONE & MACBROOM®

Figure 5.8-4b: Culvert scoping study (proposed conditions and cost opinion.)

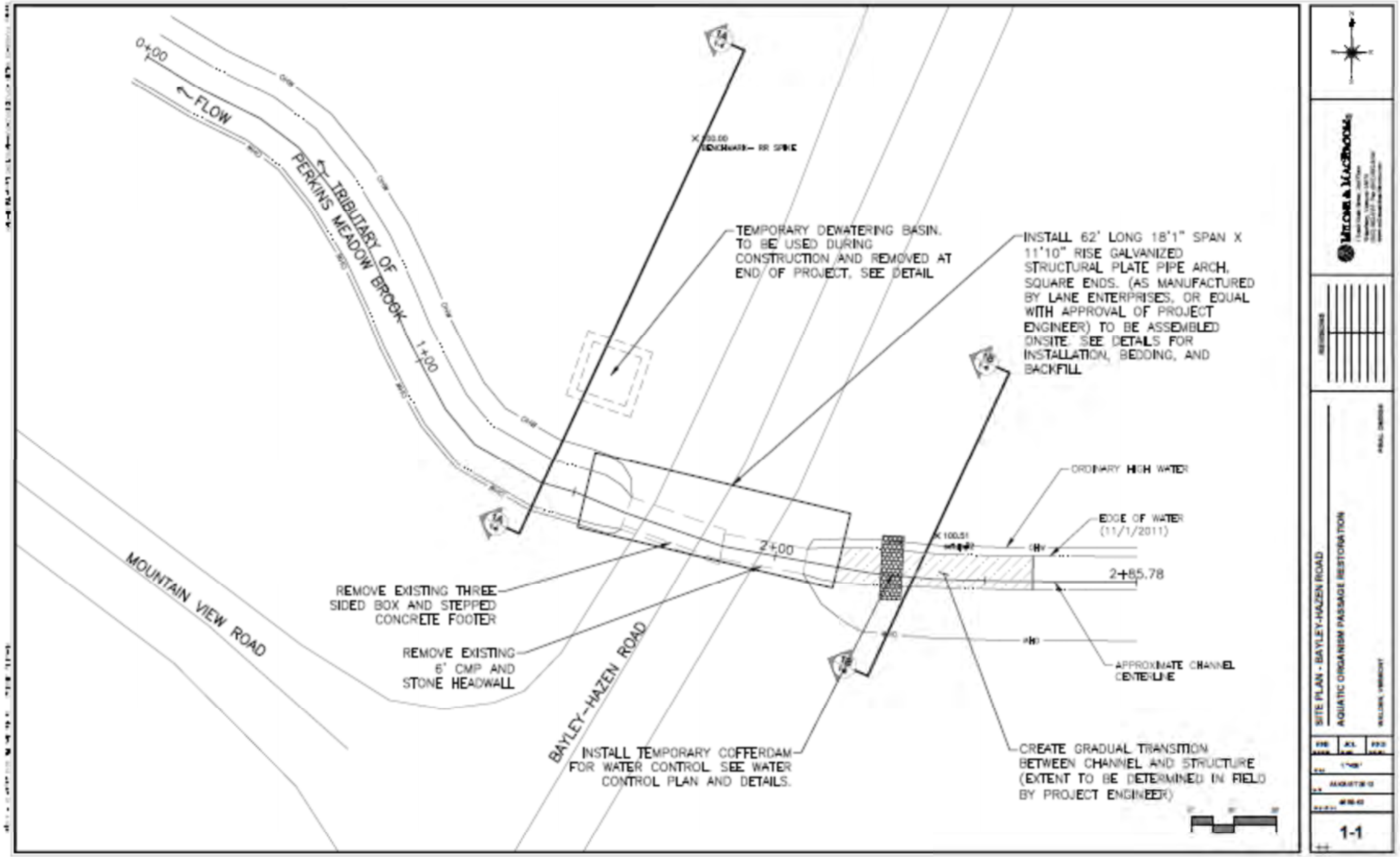


Figure 5.8-5: Proposed culvert replacement layout and specification to improve geomorphic compatibility and aquatic organism passage. (Source: Milone & MacBroom, Inc., 2013)

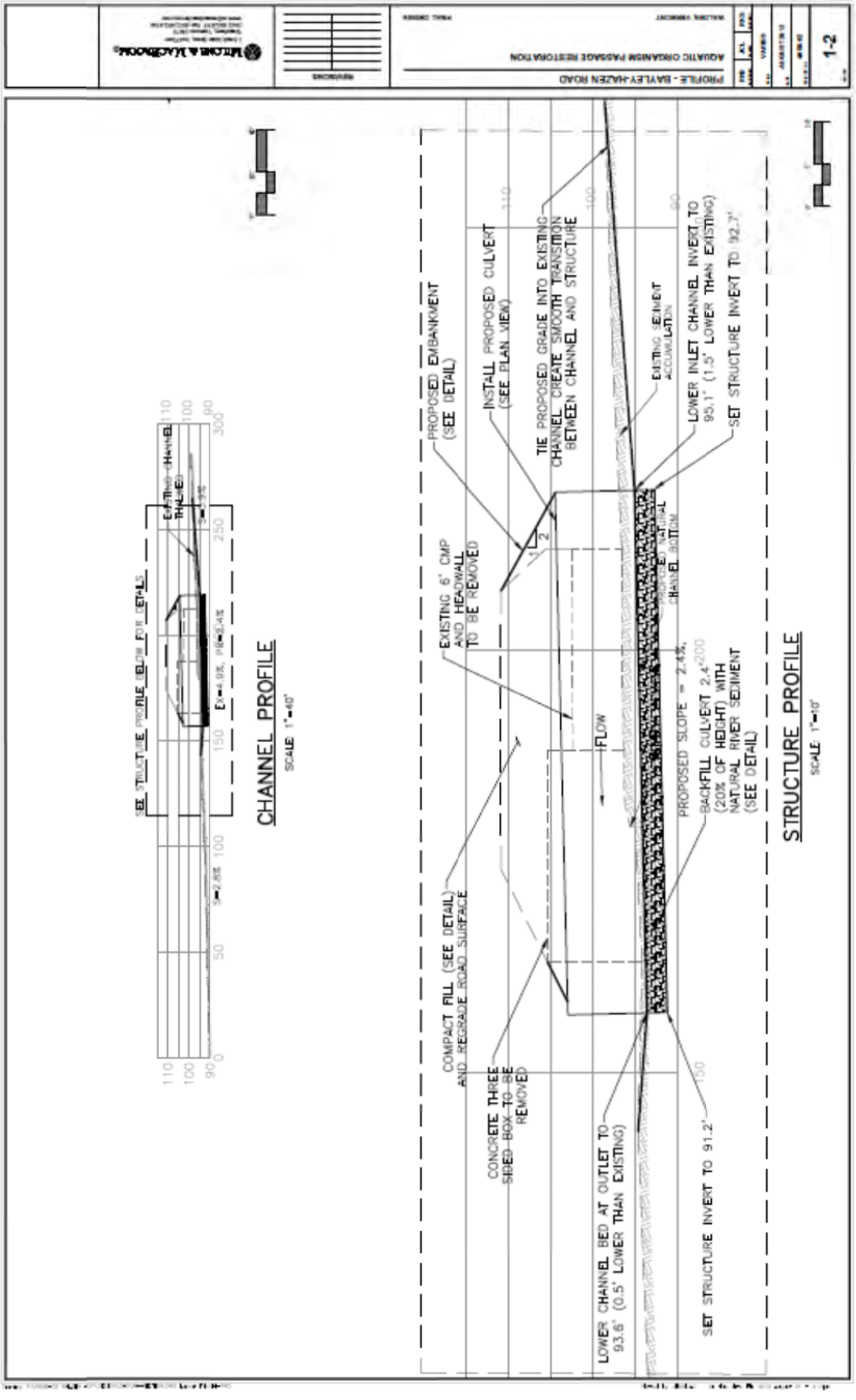


Figure 5.8-6: Channel and culvert profile. (Source: Milone & MacBroom, Inc., 2013)

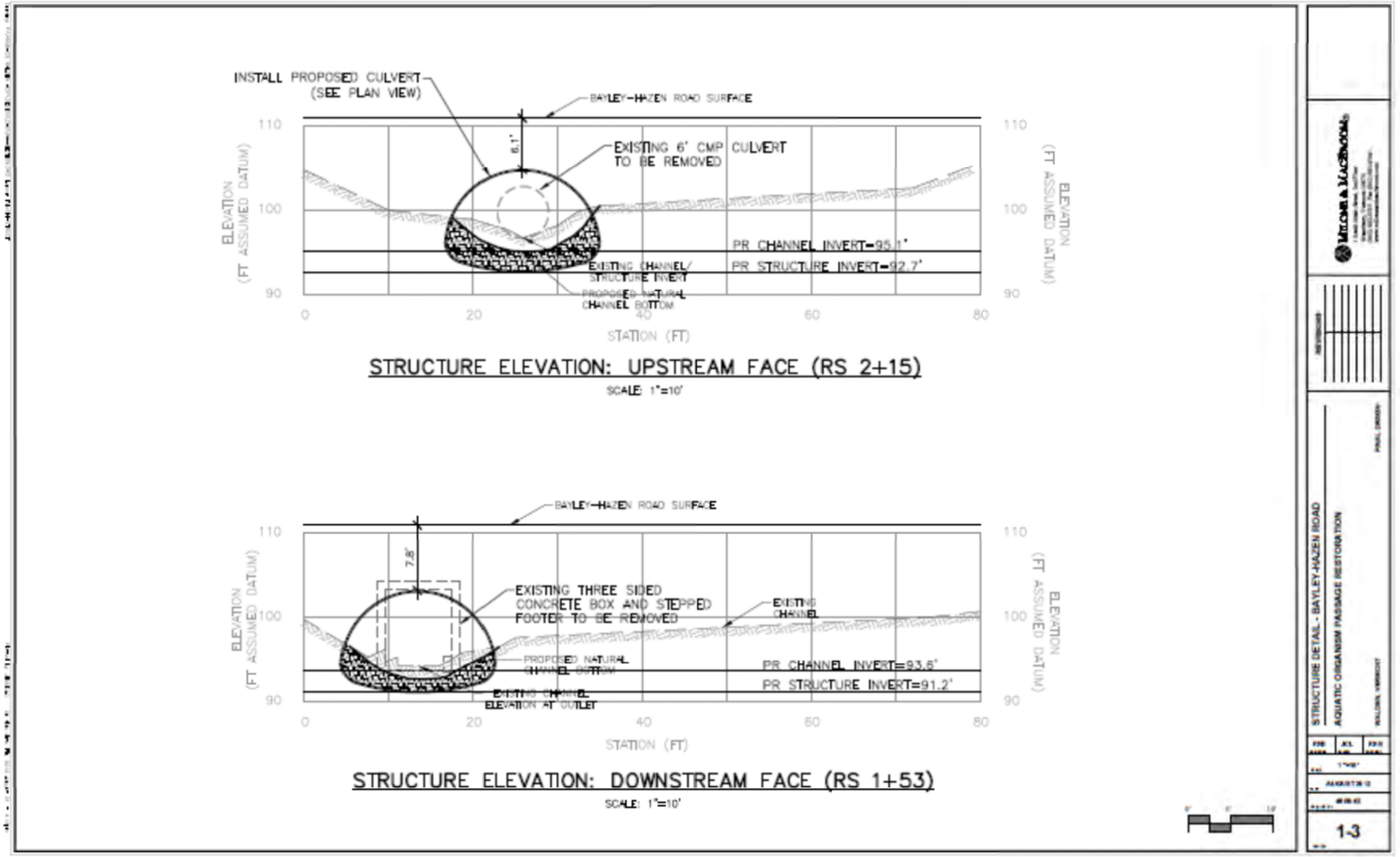
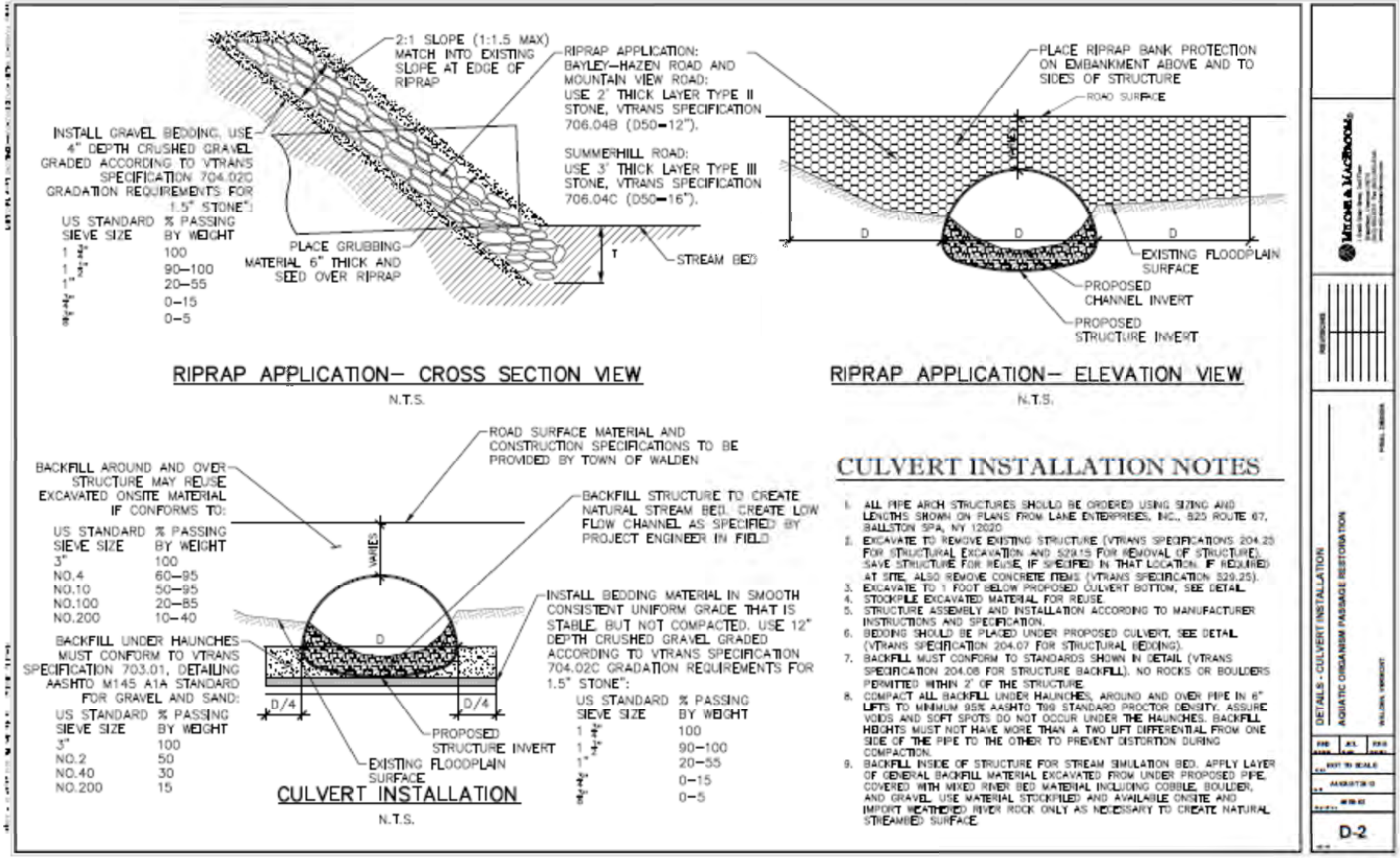


Figure 5.8-7: Culvert cross section. (Source: Milone & MacBroom, Inc., 2013)



INSTALL GRAVEL BEDDING, USE 4" DEPTH CRUSHED GRAVEL GRADED ACCORDING TO VTRANS SPECIFICATION 704.02C GRADATION REQUIREMENTS FOR 1.5" STONE":

US STANDARD SIEVE SIZE	% PASSING BY WEIGHT
1 3/4"	100
1 1/2"	90–100
1"	20–55
3/4"	0–15
3/8"	0–5

PLACE GRUBBING MATERIAL 6" THICK AND SEED OVER RIPRAP

RIPRAP APPLICATION:
BAYLEY–HAZEN ROAD AND MOUNTAIN VIEW ROAD:
USE 2' THICK LAYER TYPE II STONE, VTRANS SPECIFICATION 706.04B (D50=12").

SUMMERHILL ROAD:
USE 3' THICK LAYER TYPE III STONE, VTRANS SPECIFICATION 706.04C (D50=16").

BACKFILL AROUND AND OVER STRUCTURE MAY REUSE EXCAVATED ONSITE MATERIAL IF CONFORMS TO:

US STANDARD SIEVE SIZE	% PASSING BY WEIGHT
3"	100
NO.4	60–95
NO.10	50–95
NO.100	20–85
NO.200	10–40

BACKFILL UNDER HAUNCHES MUST CONFORM TO VTRANS SPECIFICATION 703.01, DETAILING AASHTO M145 A1A STANDARD FOR GRAVEL AND SAND:

US STANDARD SIEVE SIZE	% PASSING BY WEIGHT
3"	100
NO.2	50
NO.40	30
NO.200	15

ROAD SURFACE MATERIAL AND CONSTRUCTION SPECIFICATIONS TO BE PROVIDED BY TOWN OF WALDEN

BACKFILL STRUCTURE TO CREATE NATURAL STREAM BED. CREATE LOW FLOW CHANNEL AS SPECIFIED BY PROJECT ENGINEER IN FIELD

INSTALL BEDDING MATERIAL IN SMOOTH CONSISTENT UNIFORM GRADE THAT IS STABLE, BUT NOT COMPACTED. USE 12" DEPTH CRUSHED GRAVEL GRADED ACCORDING TO VTRANS SPECIFICATION 704.02C GRADATION REQUIREMENTS FOR 1.5" STONE":

US STANDARD SIEVE SIZE	% PASSING BY WEIGHT
1 3/4"	100
1 1/2"	90–100
1"	20–55
3/4"	0–15
3/8"	0–5

CULVERT INSTALLATION NOTES

1. ALL PIPE ARCH STRUCTURES SHOULD BE ORDERED USING SIZING AND LENGTHS SHOWN ON PLANS FROM LANE ENTERPRISES, INC., 825 ROUTE 67, BALLSTON SPA, NY 12020
2. EXCAVATE TO REMOVE EXISTING STRUCTURE (VTRANS SPECIFICATIONS 204.25 FOR STRUCTURAL EXCAVATION AND 529.15 FOR REMOVAL OF STRUCTURE). SAVE STRUCTURE FOR REUSE, IF SPECIFIED IN THAT LOCATION. IF REQUIRED AT SITE, ALSO REMOVE CONCRETE ITEMS (VTRANS SPECIFICATION 529.25).
3. EXCAVATE TO 1 FOOT BELOW PROPOSED CULVERT BOTTOM, SEE DETAIL.
4. STOCKPILE EXCAVATED MATERIAL FOR REUSE.
5. STRUCTURE ASSEMBLY AND INSTALLATION ACCORDING TO MANUFACTURER INSTRUCTIONS AND SPECIFICATION.
6. BEDDING SHOULD BE PLACED UNDER PROPOSED CULVERT, SEE DETAIL (VTRANS SPECIFICATION 204.07 FOR STRUCTURAL BEDDING).
7. BACKFILL MUST CONFORM TO STANDARDS SHOWN IN DETAIL (VTRANS SPECIFICATION 204.08 FOR STRUCTURE BACKFILL). NO ROCKS OR BOULDERS PERMITTED WITHIN 2' OF THE STRUCTURE.
8. COMPACT ALL BACKFILL UNDER HAUNCHES, AROUND AND OVER PIPE IN 6" LIFTS TO MINIMUM 95% AASHTO T99 STANDARD PROCTOR DENSITY. ASSURE VOIDS AND SOFT SPOTS DO NOT OCCUR UNDER THE HAUNCHES. BACKFILL HEIGHTS MUST NOT HAVE MORE THAN A TWO LIFT DIFFERENTIAL FROM ONE SIDE OF THE PIPE TO THE OTHER TO PREVENT DISTORTION DURING COMPACTION.
9. BACKFILL INSIDE OF STRUCTURE FOR STREAM SIMULATION BED. APPLY LAYER OF GENERAL BACKFILL MATERIAL EXCAVATED FROM UNDER PROPOSED PIPE, COVERED WITH MIXED RIVER BED MATERIAL INCLUDING COBBLE, BOULDER, AND GRAVEL. USE MATERIAL STOCKPILED AND AVAILABLE ONSITE AND IMPORT WEATHERED RIVER ROCK ONLY AS NECESSARY TO CREATE NATURAL STREAMBED SURFACE.

Figure 5.8-8: Culvert installation. (Source: Milone & MacBroom, Inc., 2013)

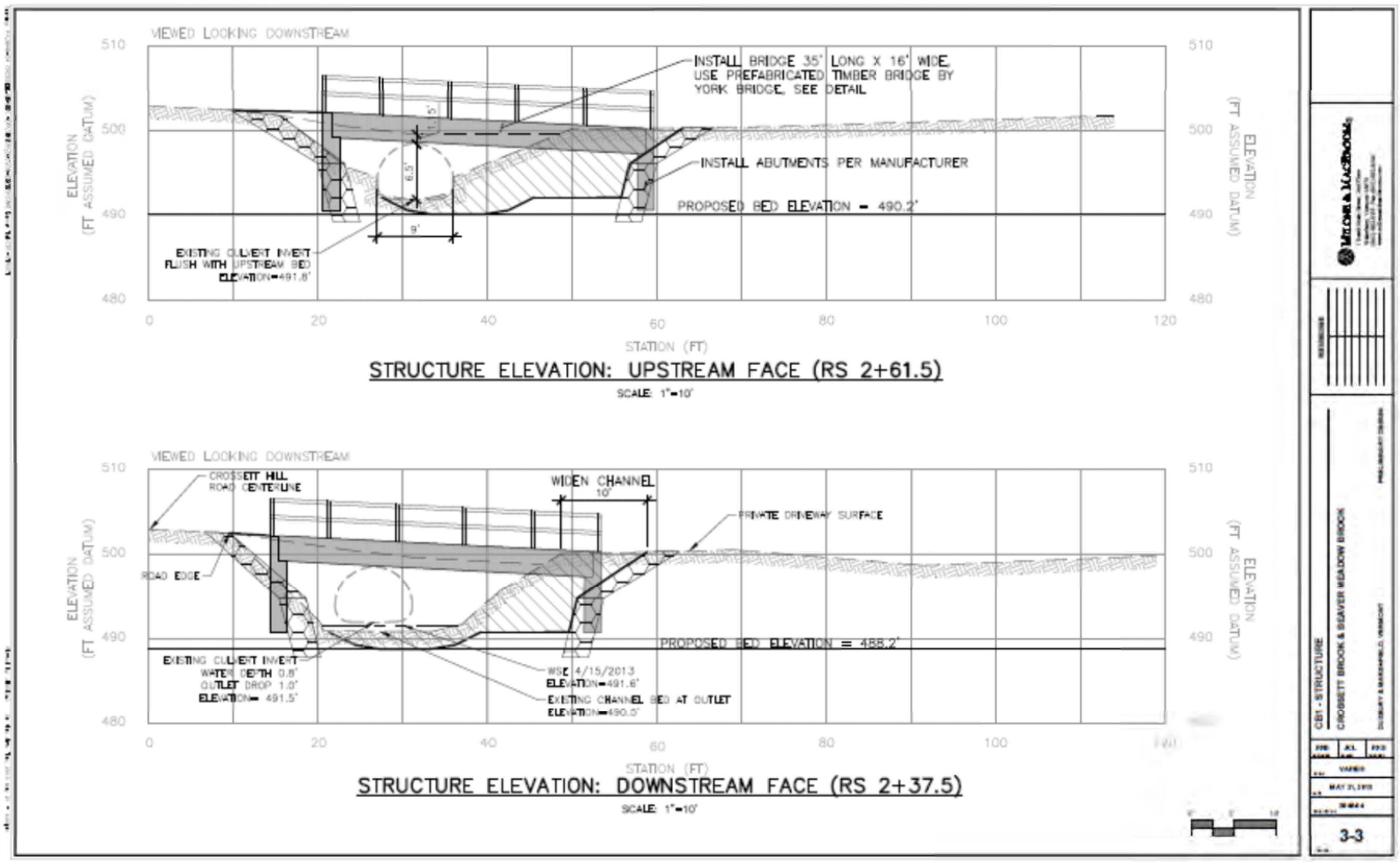


Figure 5.8-9: Driveway bridge design to improve geomorphic compatibility and aquatic organism passage. (Source: Milone & MacBroom, Inc., 2013)

SUMMARY OF SUPPORTING DESIGN INFORMATION IN APPENDICES

- Vermont HGR (VTANR, 2009) (L)
- Channel evolution model (E)

POSSIBLE COMPANION PRACTICES

- Placed riprap wall or traditional bank armor at road embankment (Section 5.2)
- Vertical bed stabilization (Sections 5.3 and 5.4)
- Flood bench restoration (Section 5.5)
- Floodplain restoration (Section 5.6)
- Sediment and woody debris removal (Section 5.7)

6.0 SUPPORTING INFORMATION/APPENDICES (TIER 4) (UNDER SEPARATE COVER)

- *What information do I need to help with assessment and design?*
- *What technical references should I refer to for help with assessment and design?*

6.1 Description

The appendices that accompany this document are found under separate cover. The appendices contain essential supporting information for the alternatives analysis and design.

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