Milone & MacBroom

Fitzgerald Environmental Associates

Lake Champlain Basin Program

NEIWPCC
New England Interstate Water Pollution Control Commission

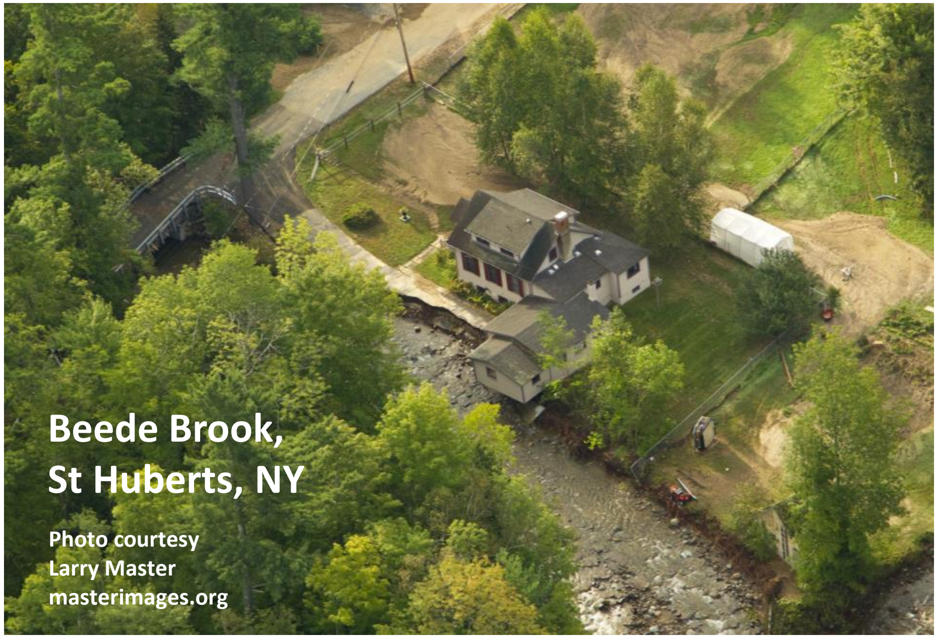
Development of Advanced Flood Recovery and River Management Training Modules

Sediment Removal, Floodplain Restoration, Channel Stabilization, and Bridge and Culvert Replacement

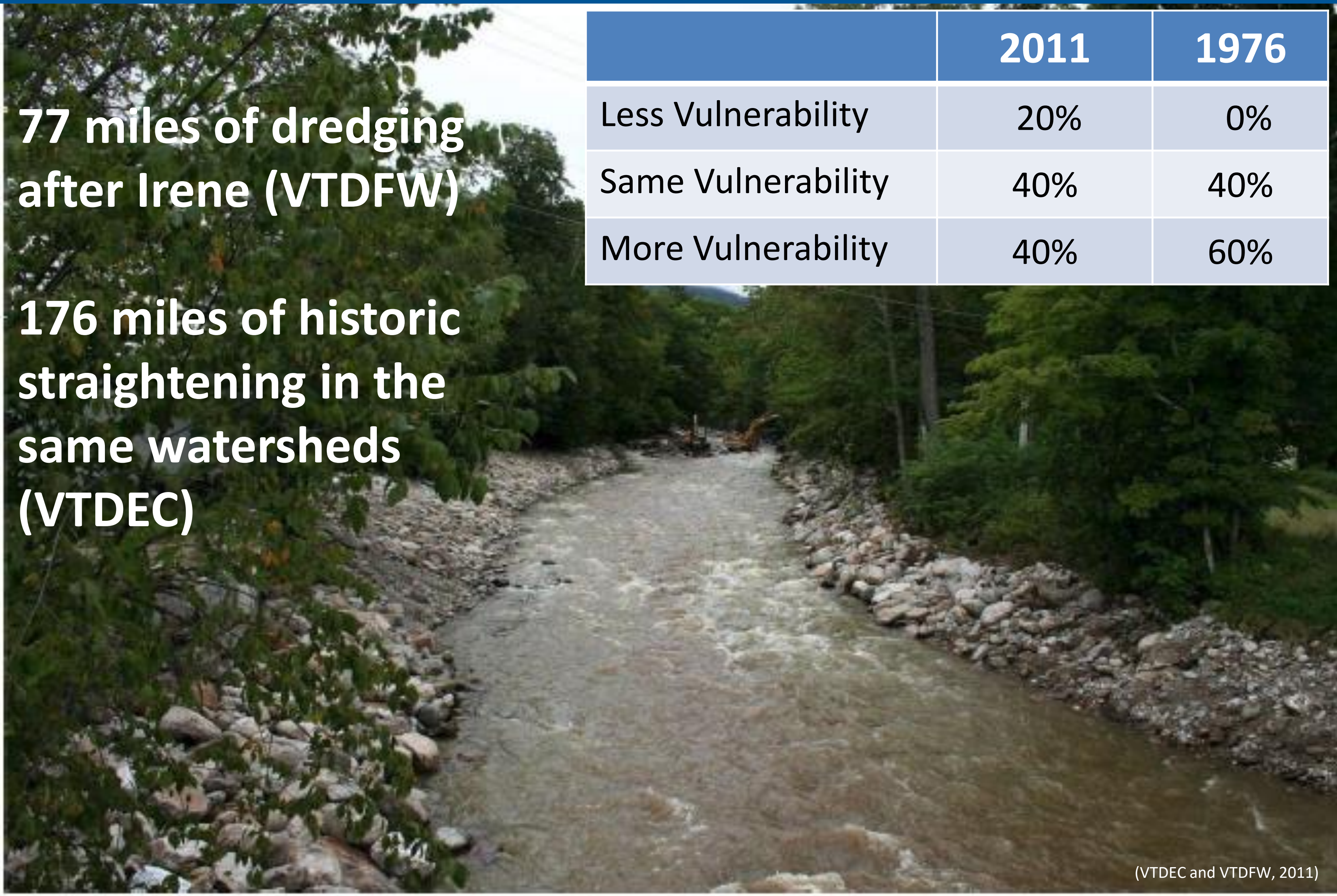
Modules Prepared By:
Roy Schiff, Jim MacBroom – Milone & MacBroom
Evan Fitzgerald – Fitzgerald Environmental

2016 Northeastern Transportation & Wildlife Conference, Lake Placid, NY

Tropical Storm Irene Flood, Aug 2011



Vermont Flood Recovery



77 miles of dredging after Irene (VTDFW)

176 miles of historic straightening in the same watersheds (VTDEC)

	2011	1976
Less Vulnerability	20%	0%
Same Vulnerability	40%	40%
More Vulnerability	40%	60%

(VTDEC and VTDFW, 2011)

Vermont Standard River Management Principles and Practices

Vermont SRMPP – Edition 1.3 (January, 2015)

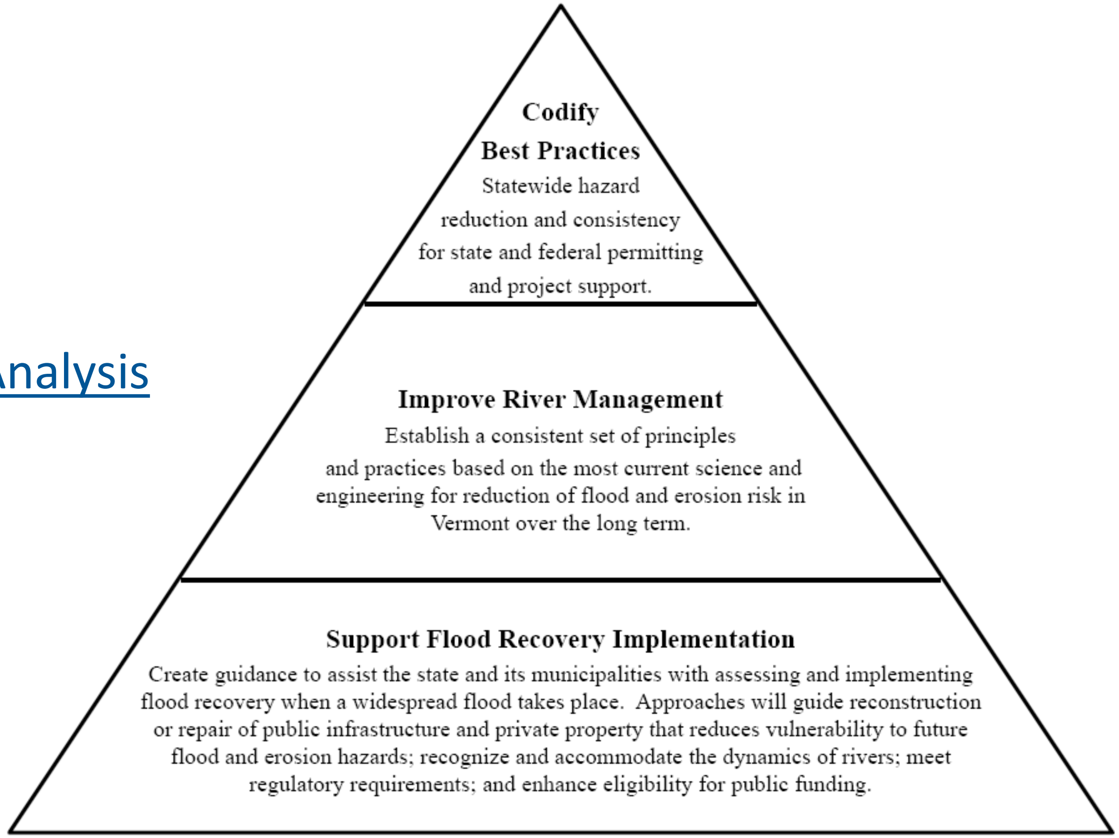
1) Guiding River and Floodplain Functions

- Dynamic Equilibrium
- Hydrology and Hydraulics
- Sediment and Debris
- Floodplain Connectivity
- Longitudinal Connectivity

2) Site Screening & Alternatives Analysis

3) Practices

- Placed Riprap Wall
- Natural Bed Stabilization
- Grade Control
- Bench and Flood Chute Restoration
- Floodplain Restoration
- Sediment/Debris Removal
- Bridge and Culvert Replacement



Schiff, R., E. Fitzgerald, J. MacBroom, M. Kline, and S. Jaquith, 2014. Vermont Standard River Management Principles and Practices (Vermont SRMPP): Guidance for Managing Vermont's Rivers Based on Channel and Floodplain Function. Prepared by Milone & MacBroom, Inc. and Fitzgerald Environmental Associates, LLC for and in collaboration with Vermont Rivers Program, Montpelier, Vermont.

River Management Training Programs in VT and NY

Vermont Rivers and Roads Training

VTANR and VTrans

Tier 1: Introduction to River Processes and Management

Tier 2: Assessing the River and Restoring Equilibrium

Tier 3: Advanced Flood Recovery Modules

New York Emergency Stream Intervention Training

NYDEC, Delaware Co SWCD, Essex Co SWCD

NETWC Conference – 8am Tuesday (9/13)

Typical Lesson Plan

MORNING

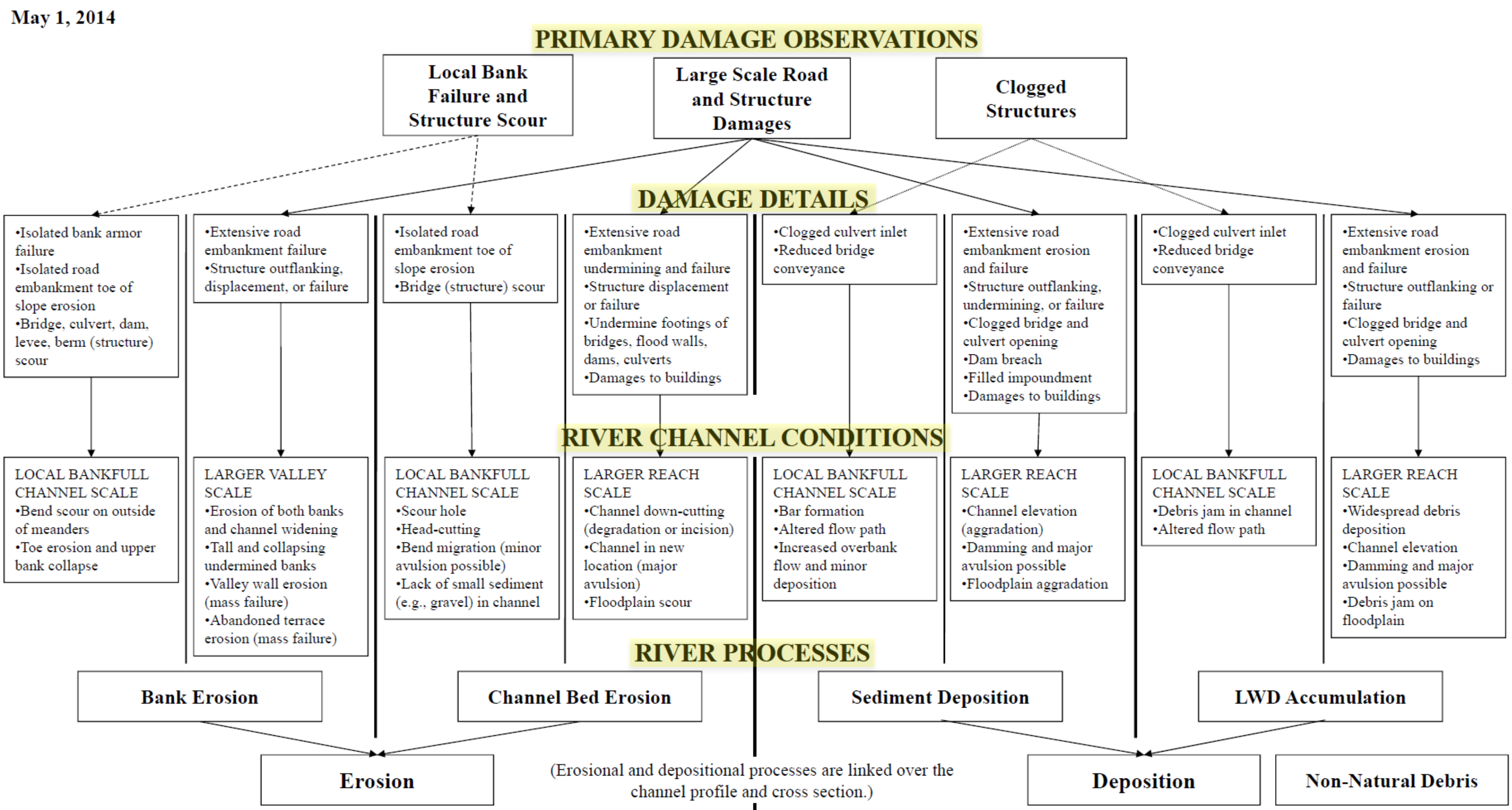
- Background and Objectives
- Problem Identification & Site Screening
- Alternatives Analysis
- Project Examples

LUNCH BREAK

AFTERNOON

- Site Assessment (field/office technical methods)
- Design Elements
- Design Exercised and Group Presentations
- Evaluations and Follow-up

Problem Identification Review

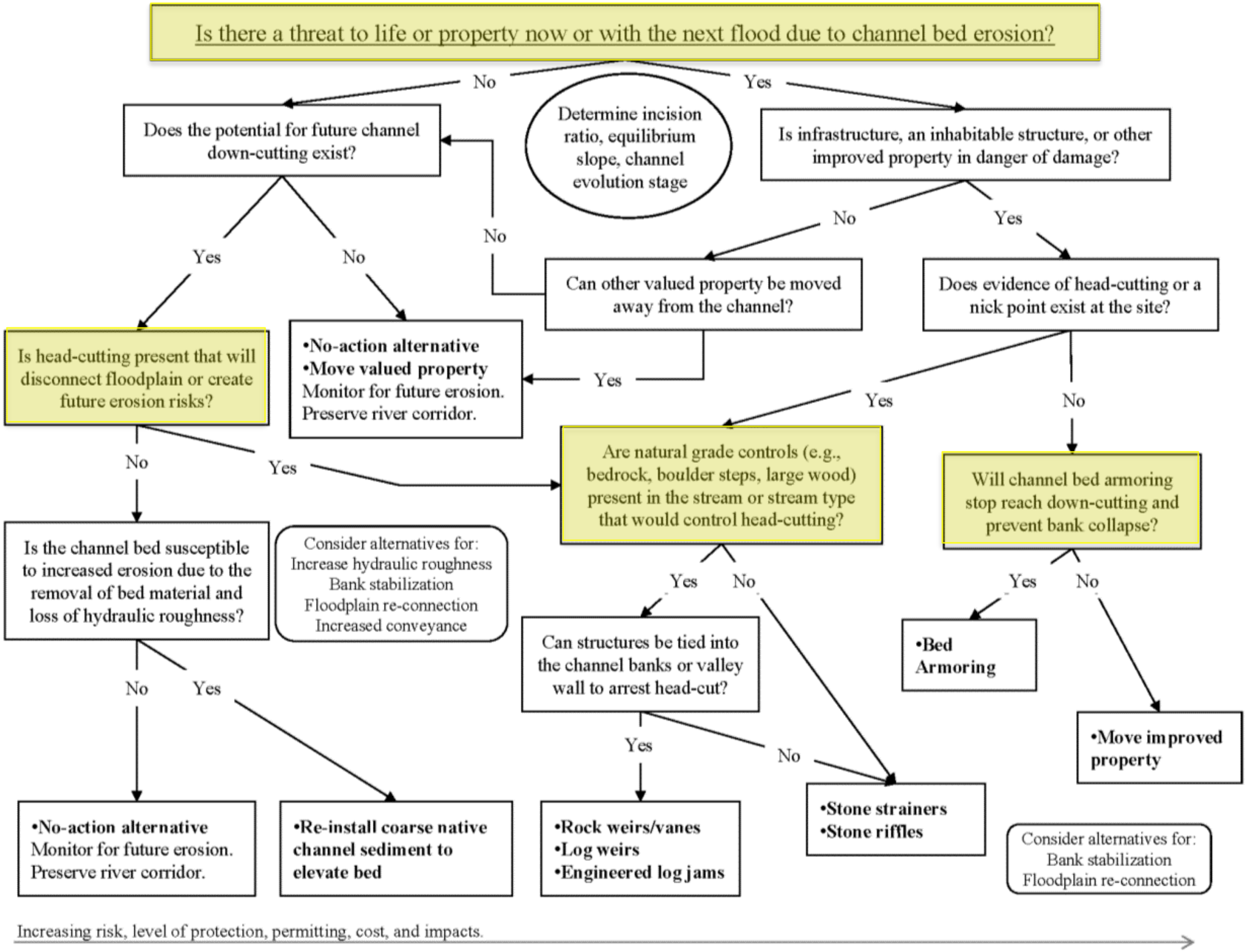


APPLICABLE GUIDING DESIGN PRINCIPLES BASED ON DAMAGES (1 = MOST IMPORTANT)

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

(Schiff et al., 2014)

Bed Erosion Alternatives Analysis Review



Alternatives Analysis

(Schiff et al., 2014)

Grade Control Project Examples: Weirs

Great Brook, Plainfield, VT (R. Schiff, 2010)

Great Brook, Plainfield, VT (R. Schiff, 2010)

Gulf Brook, Keene, NY (E. Fitzgerald, 2015)

Broad Street Hollow (J. MacBroom, 2013)

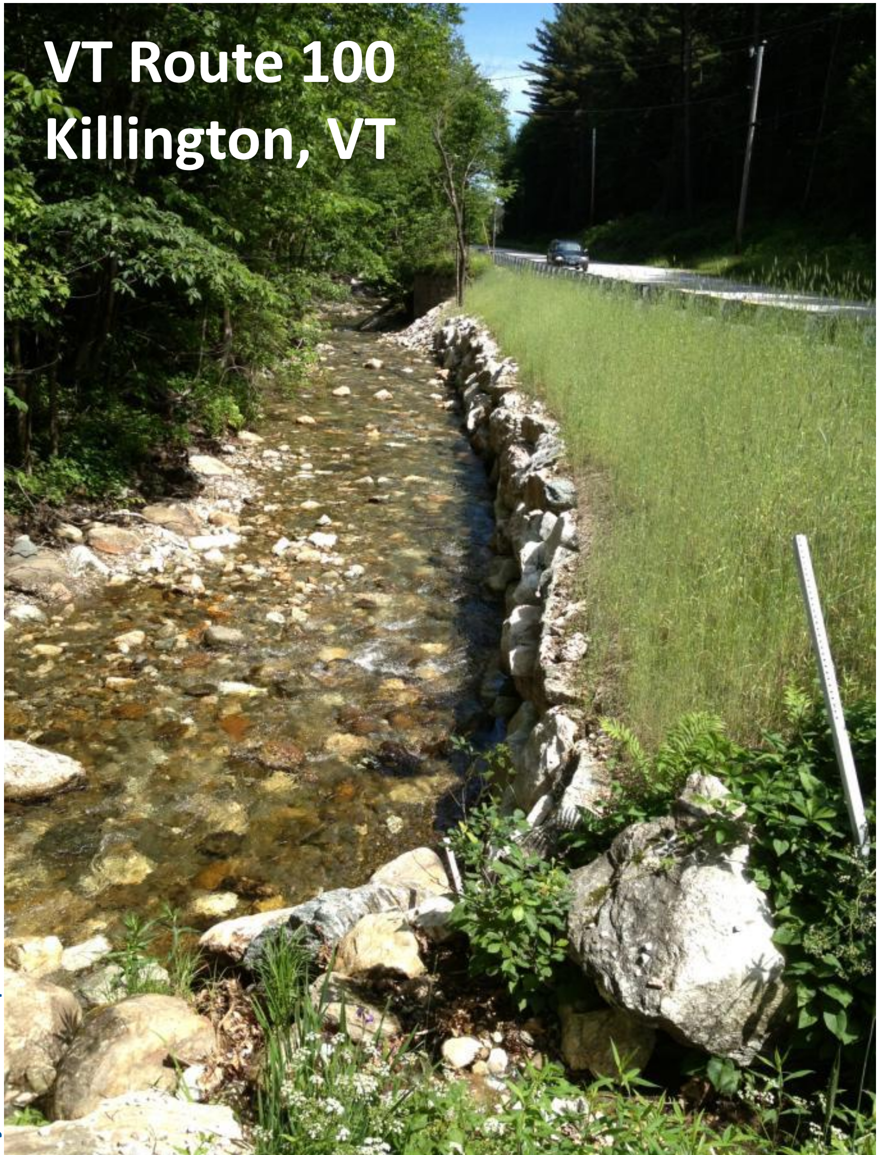
Grade Control Project Examples: Vanes, Riffles, Strainers

Broad Street Hollow (J. MacBroom,2015)

Plymco Dam Channel Restoration (J. MacBroom,2015)

Boquet River , Willsboro, NY (E. Fitzgerald, 2015)

Bank Stabilization Project Examples: Placed riprap wall



(E. Fitzgerald, 2013)

VT Route 155, Mt. Holly, VT

Bank Stabilization Project Examples: Bioengineering and ELJs

Bioengineering

Plymco Dam Channel Restoration (J. MacBroom, 2015)

Clair Road (J. MacBroom, 2014)

Boquet River , Willsboro, NY (E. Fitzgerald, 2015)

Assessment and Design Overview

Independent Variables (Assessment)

- Physical Site Constraints
- Existing Floodplain Dimensions
- Confinement
- Floodplain Connectivity
  - Entrenchment
  - Incision
- Channel Evolution
- Flow
- Stream Power ($\Omega=\gamma QS$)
- Sediment and Large Wood

Increasing complexity and variables that may drop out of basic assessment during quick emergency repairs.

Dependent Variables (Design)

- Channel Profile and Dimensions
- Channel Bed Forms
- Channel Pattern and Dynamics
- Floodplain Width and Elevation
- Stabilization Measures
- Excavation or Fill Volume

Approximate Channel Sizing – NY HGR

[DA, drainage area in square miles; R^2, coefficient of determination]

Hydrologic region	Number of cross sections surveyed	Regression equation	Standard error of estimate (percent)	R^2
1 and 2	55	$21.5\ DA^{0.362}$	28	0.89
3	40	$24.0\ DA^{0.292}$	23	.85
4	21	$17.1\ DA^{0.460}$	26	.87
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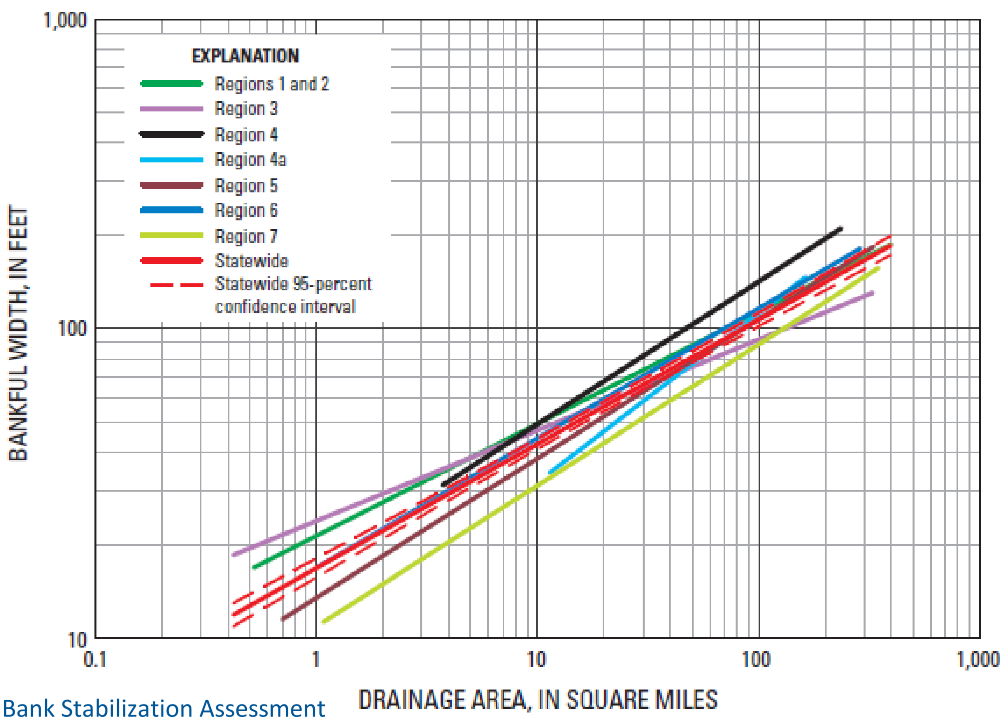
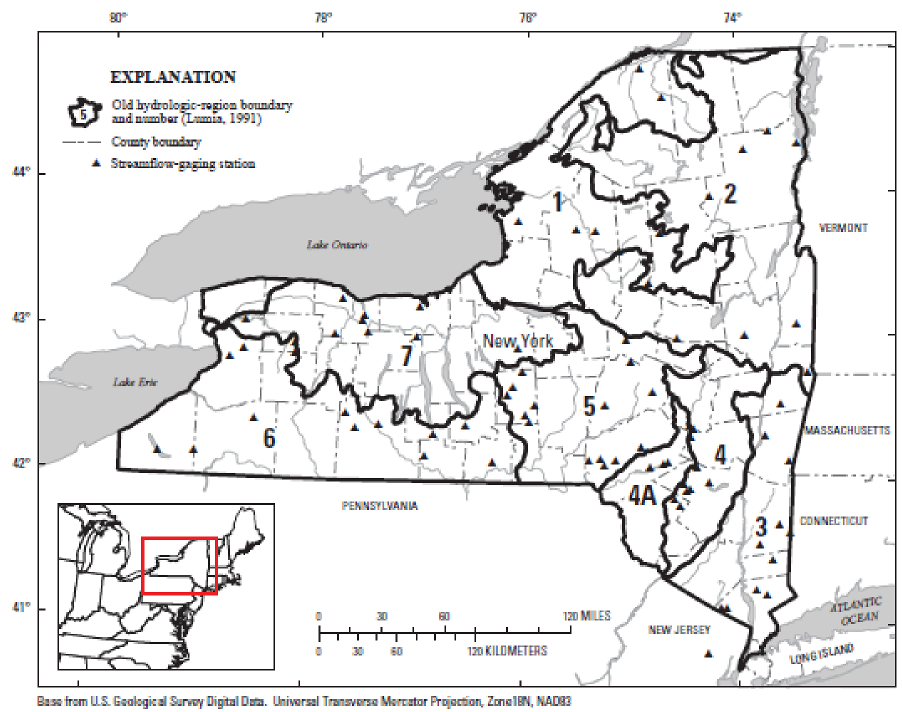
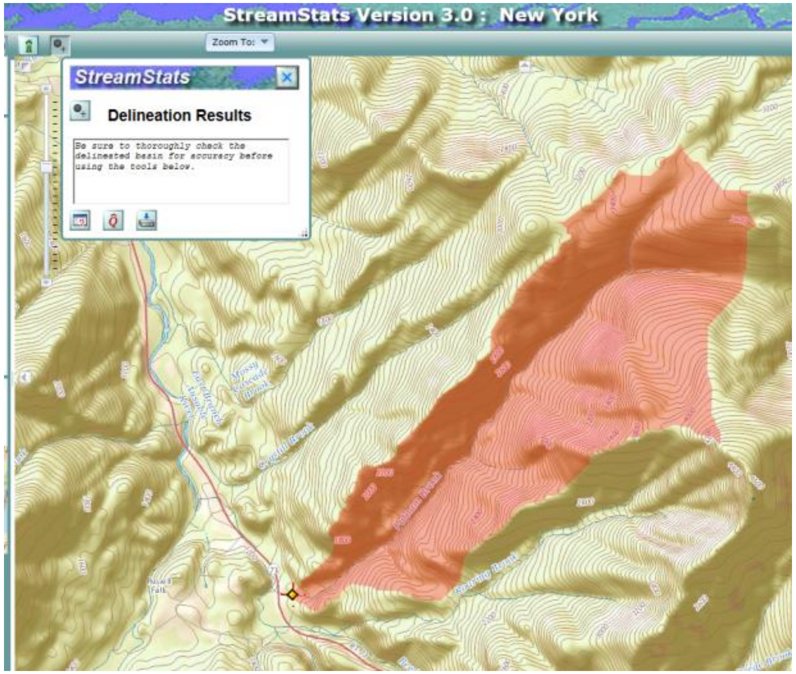
5	73	$13.5\ DA^{0.449}$	27	.92
6	50	$16.9\ DA^{0.419}$	36	.79
7	33	$10.8\ DA^{0.458}$	30	.89
Statewide	281	$16.9\ DA^{0.401}$	32	.84

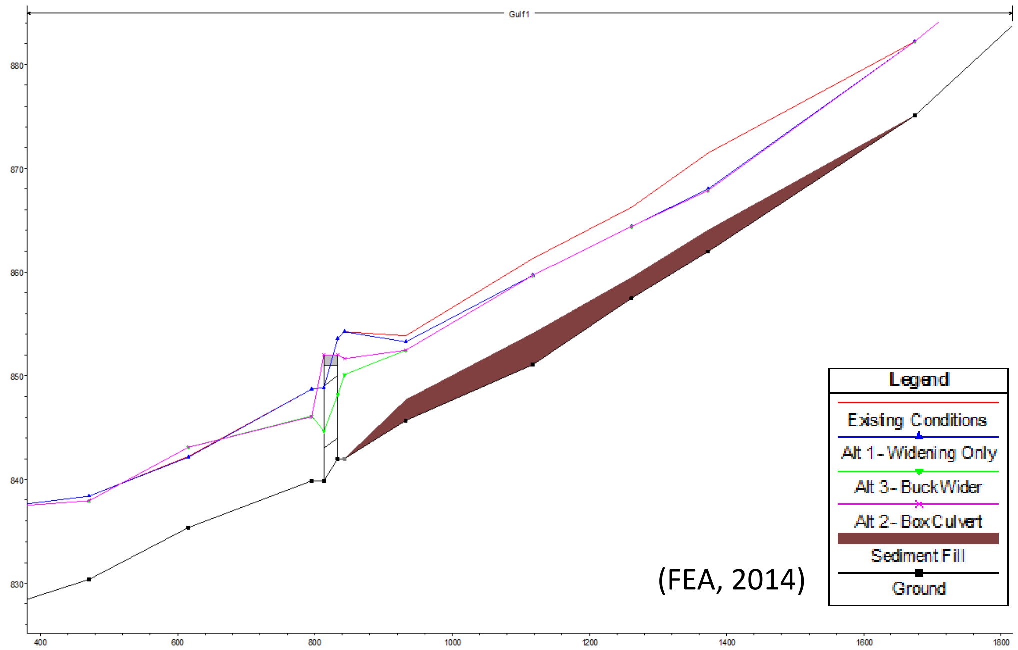
(Mulvihill et al., 2009)





Grade Control Design: Hydrology & Hydraulics





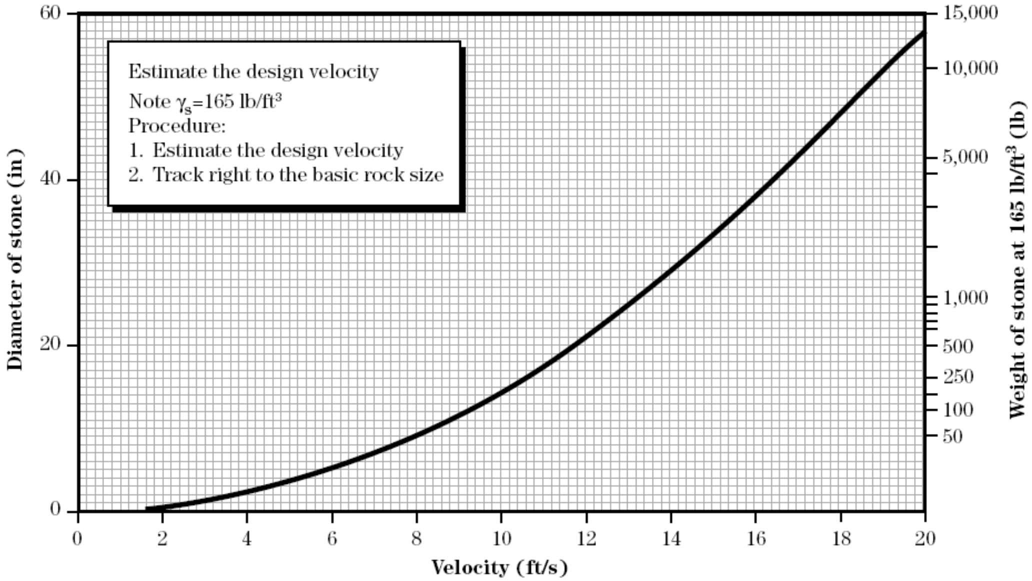
(FEA, 2014)

- Pace of repair work will determine whether an assessment of hydrology and hydraulics is necessary or feasible.
- Models are useful for stone sizing and to confirm that raising the channel bed will not increase flood risks to adjacent property.
- Hydrology from regression equations (Olson, 2002; Lumia et al., 2007) and StreamStats
- Simple uniform flow calculation (i.e., Manning's equation)
- Hydraulic model (HEC-RAS; USACE, 2010) to analyze flood depth, velocity, etc.

Grade Control Design: Rock Sizing & Type

VTrans Standard Rock Sizing (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

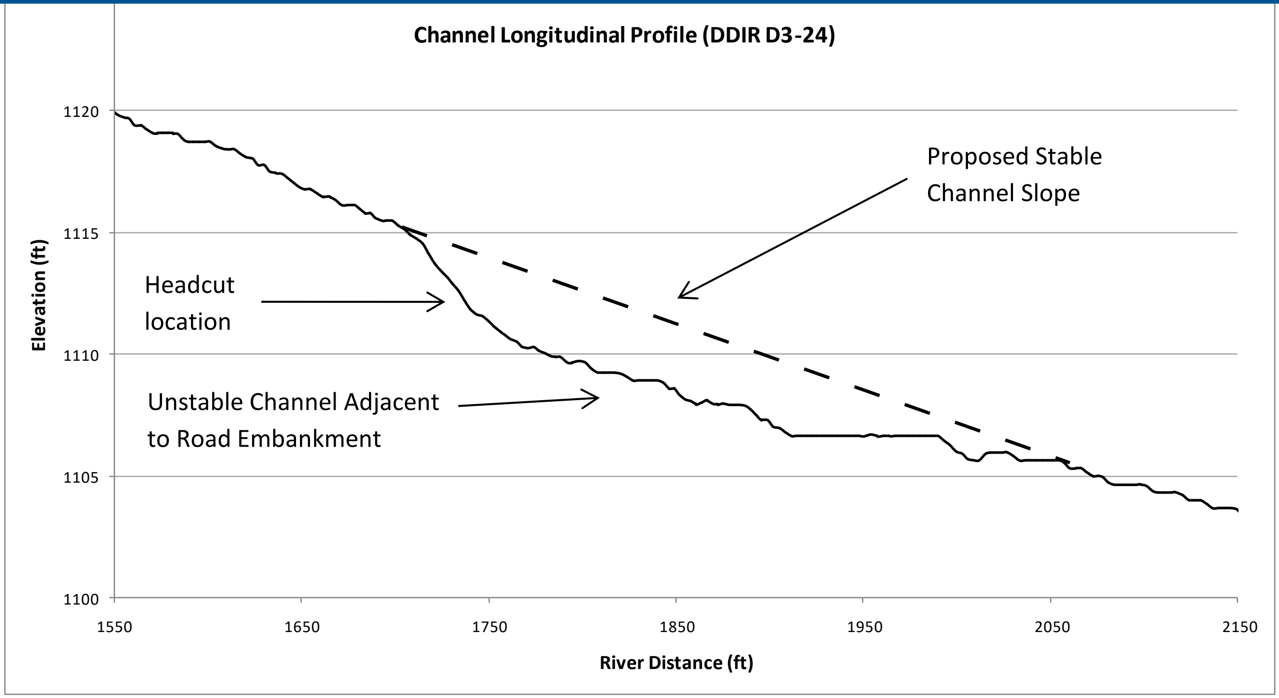


Rock sizing based on the Isbash curve. (Source: Isbash, 1963; NRCS, 2007)

Design Elements

- Grade control structures must resist erosion due to the design flood flow velocity and resultant shear stress
- Diameter larger than the 84th percentile particle size (D84) in the channel
- Natural river rock is preferred over angular rock for stone riffles and strainers to naturalize in-stream habitat.
- Angular rock is typically used for weirs to lock the rocks together and properly secure the structure in the bed and banks.

Grade Control Design Example



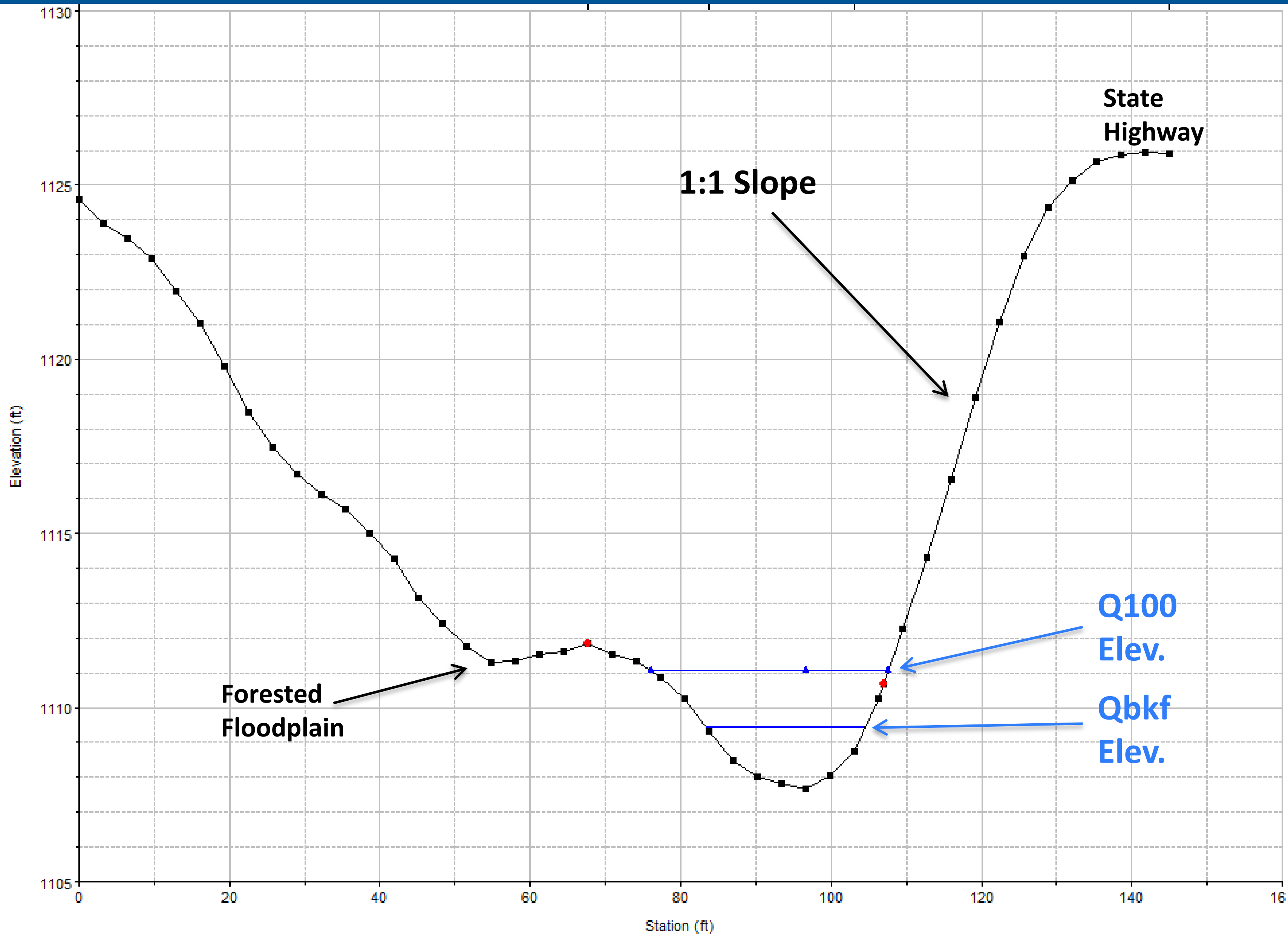
VT Route 100
Killington, VT

South Branch
Tweed River

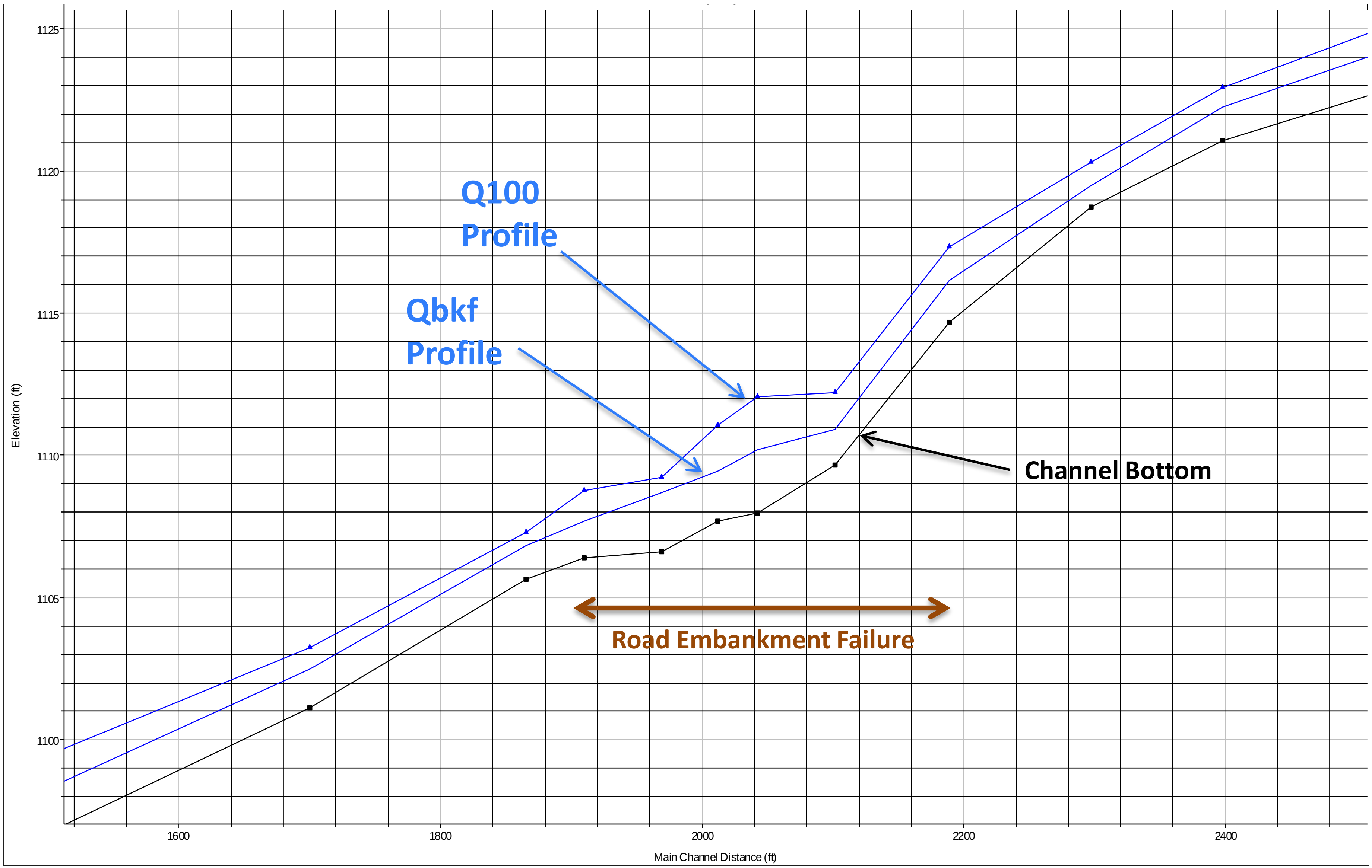
Headcut upstream of embankment

Unstable channel and embankment

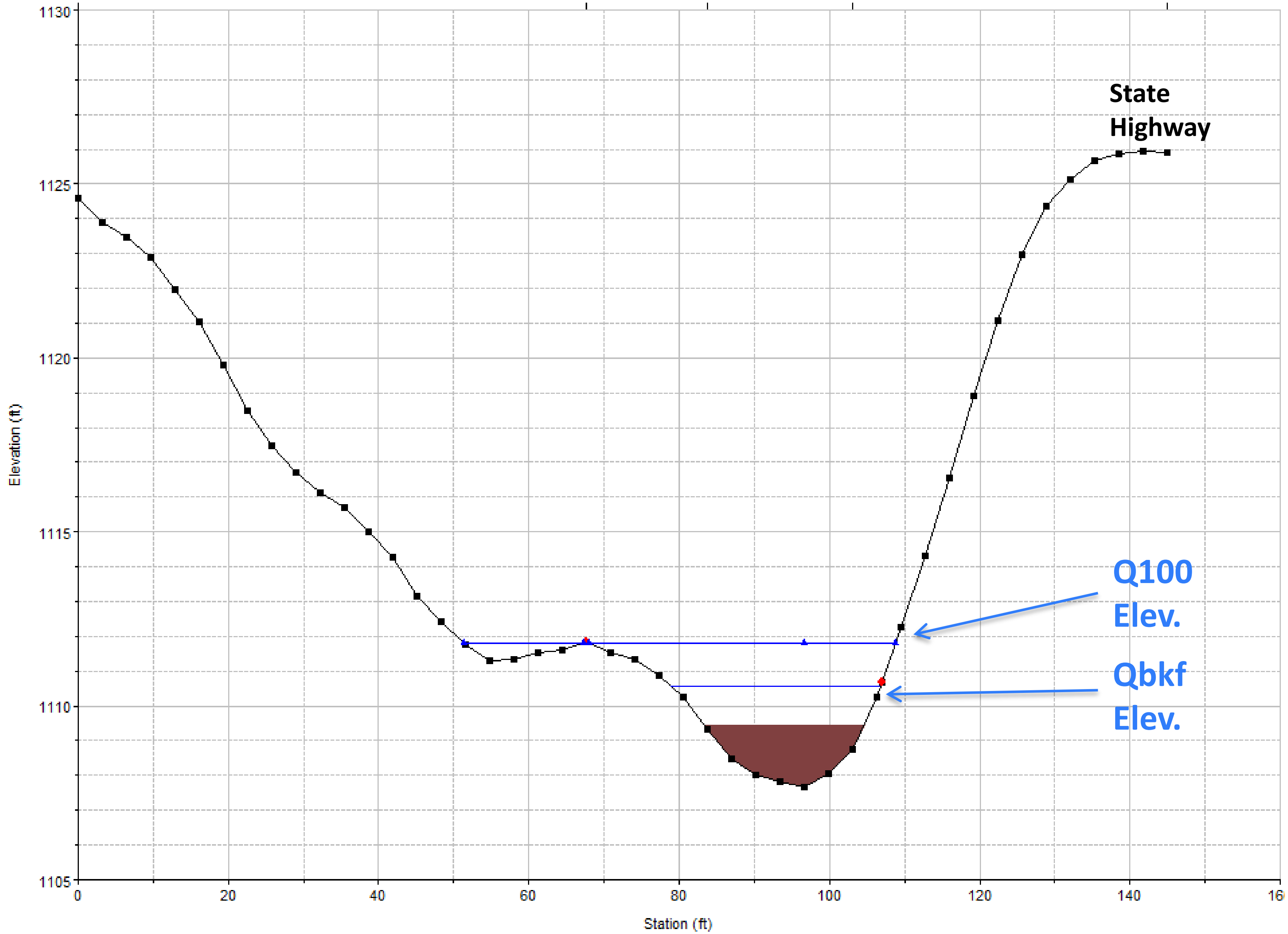
Grade Control Design Example



Grade Control Design Example



Grade Control Design Example



Grade Control Project Example: Bed Armor

(R. Schiff & E. Fitzgerald, 2012-13)

Successful Bed Armor Project Post-Irene

South Branch of the Tweed River, VT Route 100, Killington

Grade Control Project Examples: Bed Armor

(Fitzgerald Environmental, 2015)

Projects Examples

Problematic Irene Bed Armor Projects:

Whetstone Brook, VT Route 9, Marlboro, VT
Dover Brook, VT Route 100, Wardsboro, VT

Grade Control Design: Bed Armor Performance Standards

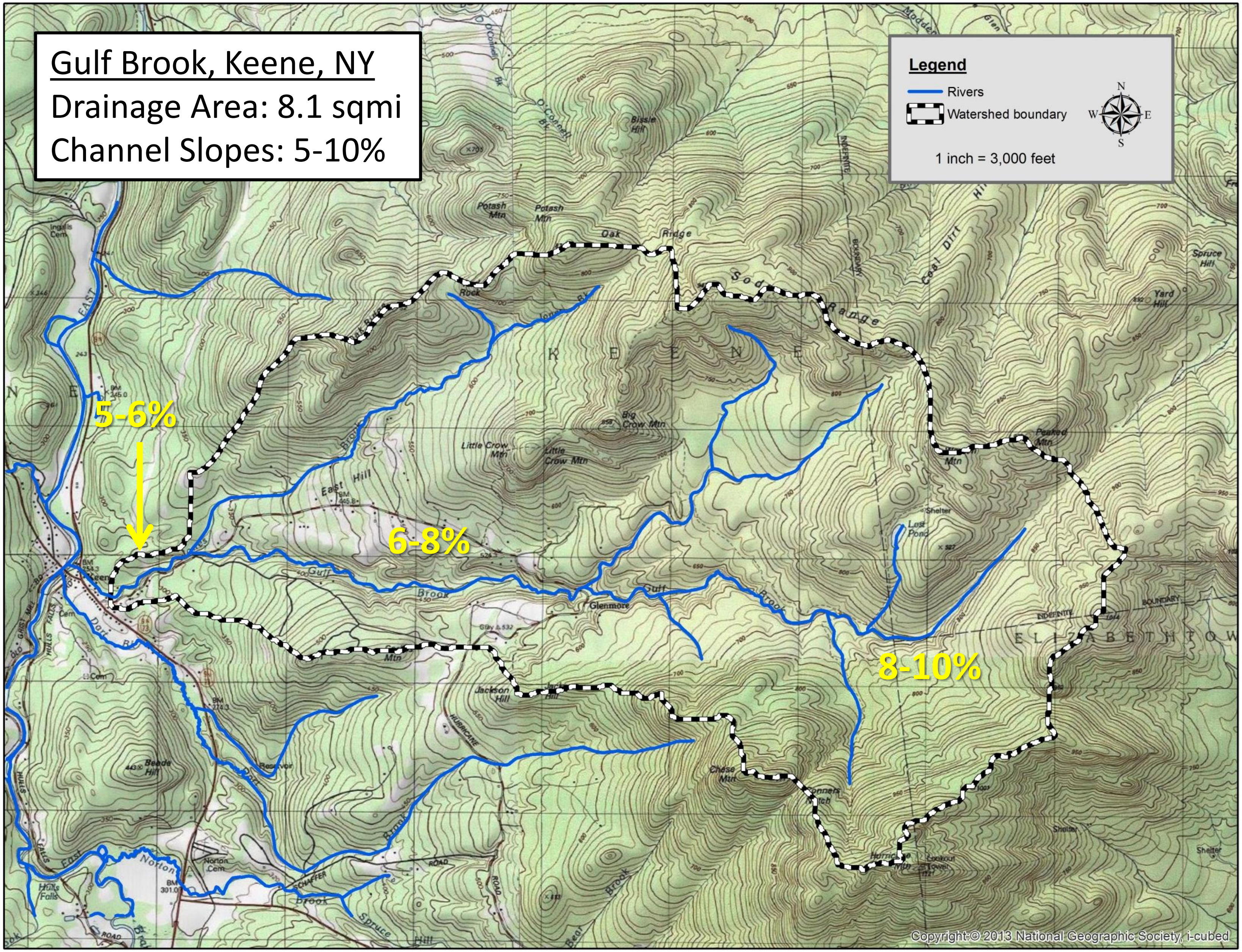
(MMI, 2014)

(Fitzgerald Environmental, 2015)

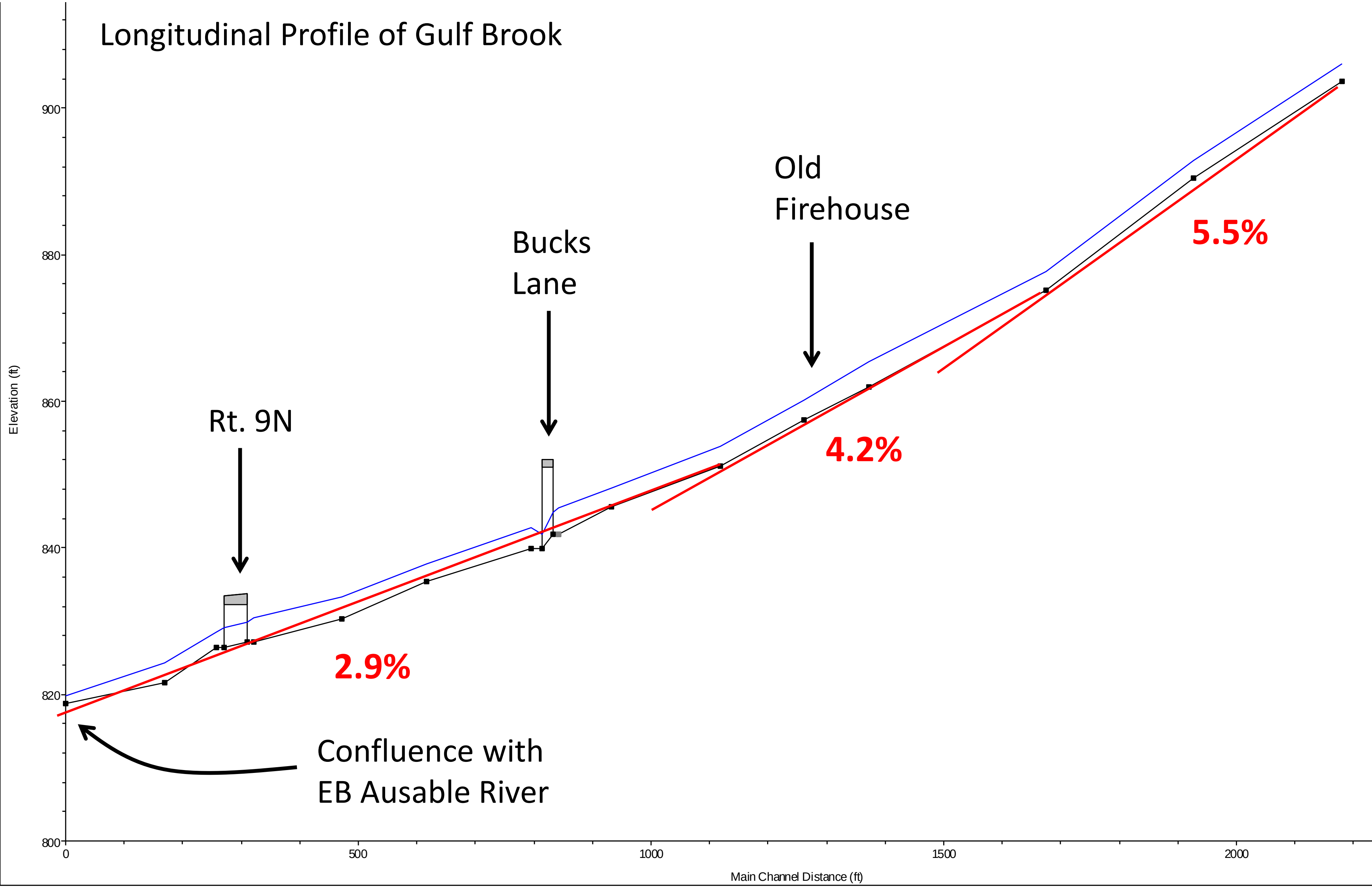
Vermont Standard River Management Principals and Practices

- Halt channel downcutting.
- Halt horizontal channel migration threatening infrastructure and unmovable habitable buildings. (Avoid horizontal channel migration along opposite bank of threatened infrastructure.)
- Provide aquatic organism passage and continuous surface flow.
- Create final channel dimensions and cross sections similar to adjacent channel

Channel Stabilization Design Example



Channel Stabilization Design Example



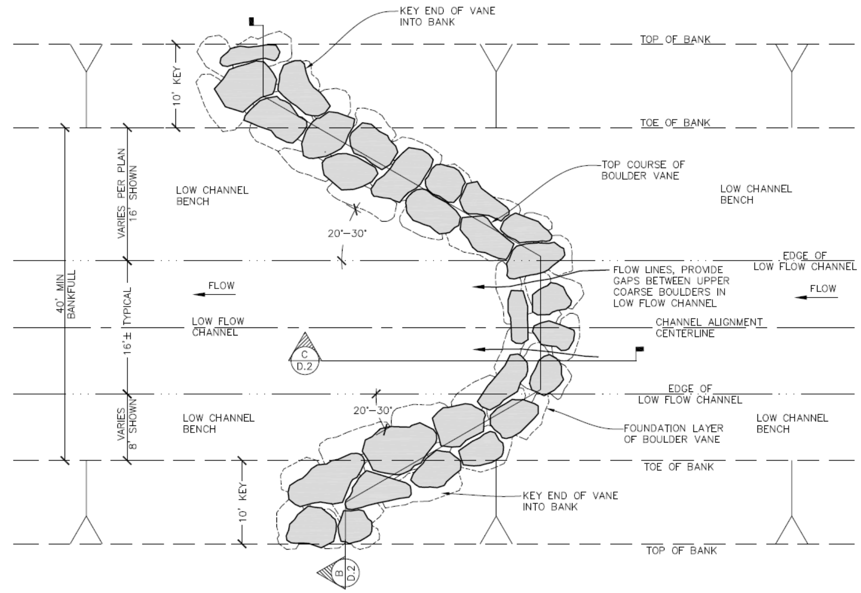
Channel Stabilization Design Example

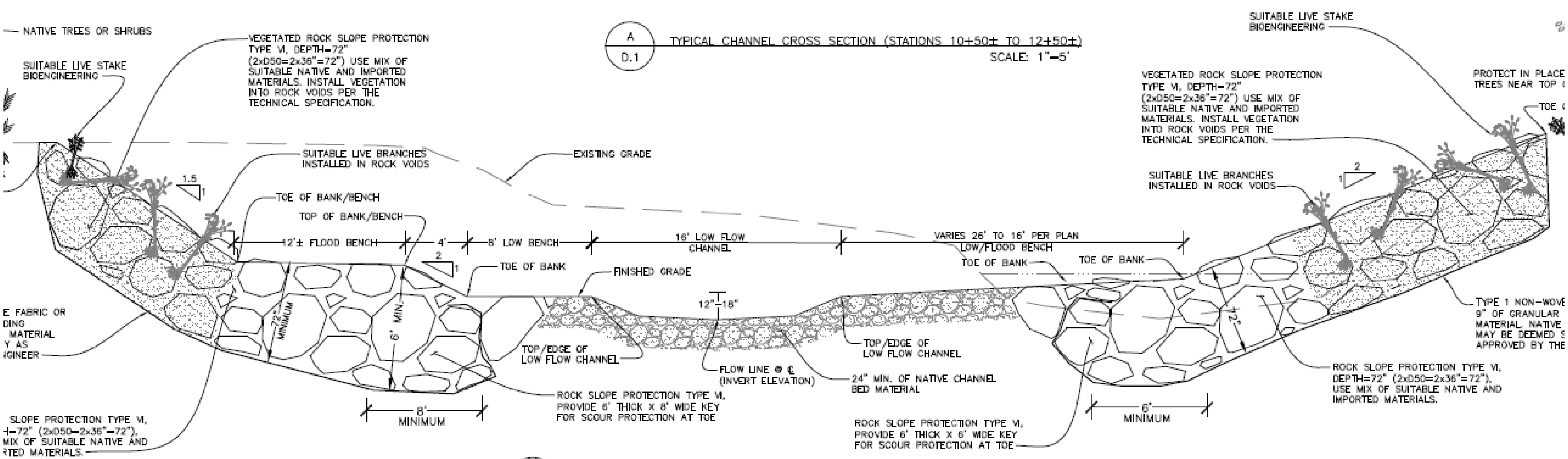
Channel Stabilization Design Example

1 day after flood

2 days after flood

Channel Stabilization Design Example





Questions?

www.lcbp.org

Lake Champlain Basin Program

NEIWPCC

New England Interstate Water Pollution Control Commission

Extra Slides

Alternatives Analysis Objectives

GENERAL

1. No action is preferred. Should we be doing this?
2. Protect life, infrastructure, and unmovable property as needed.
3. Evaluate site constraints.
4. Enable natural recovery.
5. Use natural materials first.

CHANNEL STABILIZATION

A. Maintain or re-establish vertical channel stability and floodplain connectivity (bed).
B. Reduce encroachments and provide resistance for the design flood to protect improved property (banks).
C. Maximize the use of vegetation (banks).

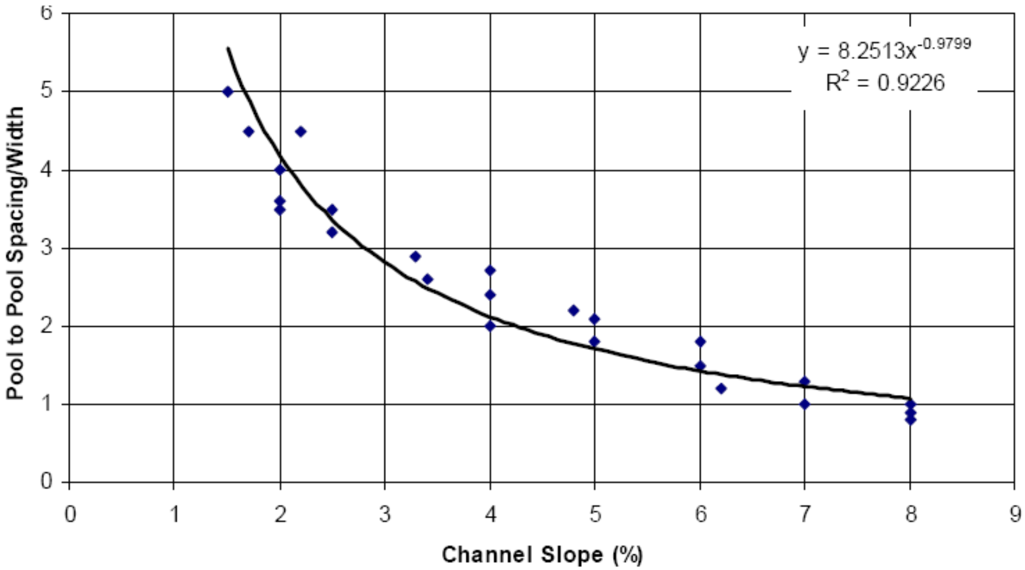
Channel Slope / Bedforms – Empirical

- 0.0 – 0.5 % Mild slope, sandy bed, low velocity
- O.2 – 2.0 % Pool riffle profile, sand and gravel
- 1.0 – 3.0 % Plain bed, gravel and cobbles
- 3.0 – 10.0 % Step pools, gravel, cobbles, logs
- 5.0 – 30.0 % Cascades, falls, cobbles, boulders

(Adapted from Montgomery and Buffington, 1993; Rosgen, 1994)

Grade Control Design: Weir and Riffle Spacing & Dimensions

Great Brook, Plainfield, VT (R. Schiff, 2010)



Ratio of pool spacing to bankfull width as a function of channel slope. (Rosgen, 2001)

Design Elements

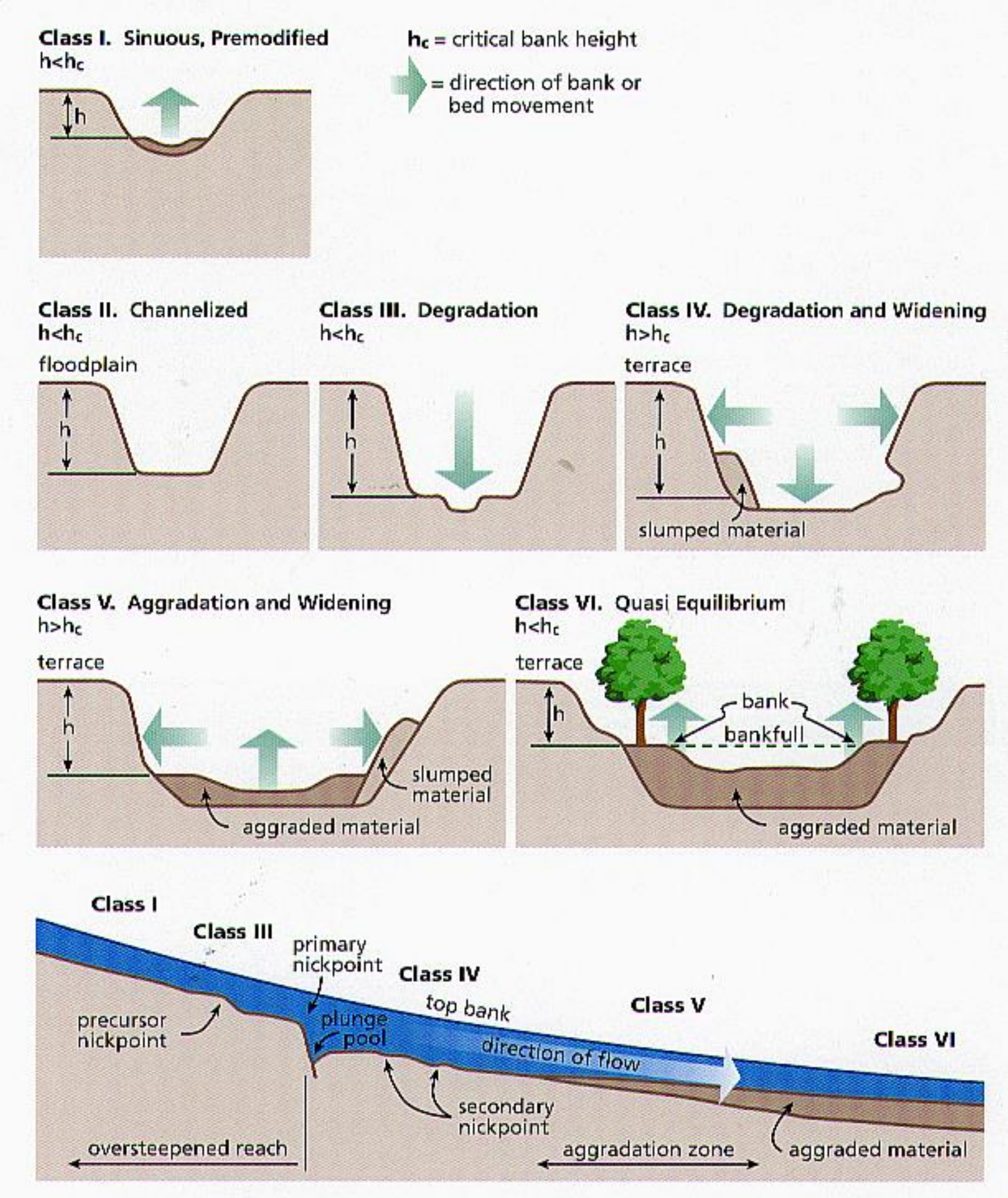
Cross Section:

- 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
- Create uniform transitions between bed and grade control structure

Identify the Likely Channel Evolution



(Simon 1989; FISRWG, 1998)

Grade Control Design: Bed Armor Performance Standards

(MMI, 2014)

(Fitzgerald Environmental, 2015)

Vermont Standard River Management Principals and Practices

- Halt channel downcutting.
- Halt horizontal channel migration threatening infrastructure and unmovable habitable buildings. (Avoid horizontal channel migration along opposite bank of threatened infrastructure.)
- Provide aquatic organism passage and continuous surface flow.
- Create final channel dimensions and cross sections similar to adjacent channel

Summary – Grade Control Design

Assessment

- Longitudinal profile
- Geomorphic stream type
- Bankfull width and depth
- Profile bed forms
- Equilibrium sediment slope
- Incision ratio
- Channel evolution

Design

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

Grade Control 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.
- 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.

Grade Control Design 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.

Grade Control Design Review Questions

1. *How does the degree of channel incision and risk to adjacent property dictate the selection of grade control treatment?*

2. *What are ways a grade control structure could fail (i.e., destabilize)?*

Grade Control: Common Mistakes

- Not considering stream velocity and 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.
- 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., head cuts) in future floods
- Uneven dispersal of native sediments along channel cross-sectional area

(Schiff et al., 2014)

Grade Control: Permitting Requirements

- U.S. Army Corps of Engineers (CWA Section 404 and 401)
  - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
  - Identify reporting category
  - Contact Field Office
- Vermont Stream Alteration Permit
  - Meet Performance Standards as identified above
  - Identify reporting category
  - Contact river management engineer
- New York Article 15 Protection of Waters Permit
  - Emergency Authorization for quick review in emergency
  - General Permit for Disaster Recovery for longer timeframes
- Local Permits
  - FEMA National Flood Insurance Program criteria
  - Wetlands (NY) (State for Vermont)
  - Contact Town Administrator for reporting needs

Grade Control: Construction

Constructability

Construction oversight is needed to ensure:

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

Temporary Construction Controls

- Complete work during low flow periods to limit downstream sedimentation and allow for proper visibility to successfully complete the work
- Plan dewatering and work to isolate impacts from channel.
- Install silt fencing as needed to control runoff when ground not flat.
- Use series of sediment filter berms to create sediment trap pools and limit sedimentation of downstream areas.
- The pools should be periodically cleaned out as work takes place.
- If water control is needed, temporary berms made of pushed up deposited material are often used to guide water out of the work areas.

Bank Stabilization Module

Bank Stabilization Objectives

1. Establish local lateral stability to protect improved property by providing adequate resistance to bank erosion for the design flood.
2. Reduce encroachments into the bankfull channel.
3. Maintain or improve instream habitat.
4. Protect water quality.

Bank Stabilization Assessment: Erosion Severity & Dimensions

Mass Wasting – Valley Erosion

Bank Erosion in Alluvium

(FEA, 2012-15)

Bank Stabilization Assessment: Adjacent Land Use/Property

(FEA, 2012-15)

Bank Stabilization Assessment: Risk of Continued Erosion & Damages

(FEA, 2011-13)

Bankfull Channel and Floodplain Dimensions

1. Past field observations of many similar channels (*empirical approach such as HGR and regime*).
2. Historic observations / prior knowledge before sediment deposition event such as survey or geomorphic assessment (aerial photos).
3. Current field measurements in undisturbed reference reach (*analog approach*).
4. Field observations of remnants of impacted channel.
5. Estimation methods such as uniform flow or sediment transport analysis (*analytical approach*).

Bankfull Indicators / Incised Channel

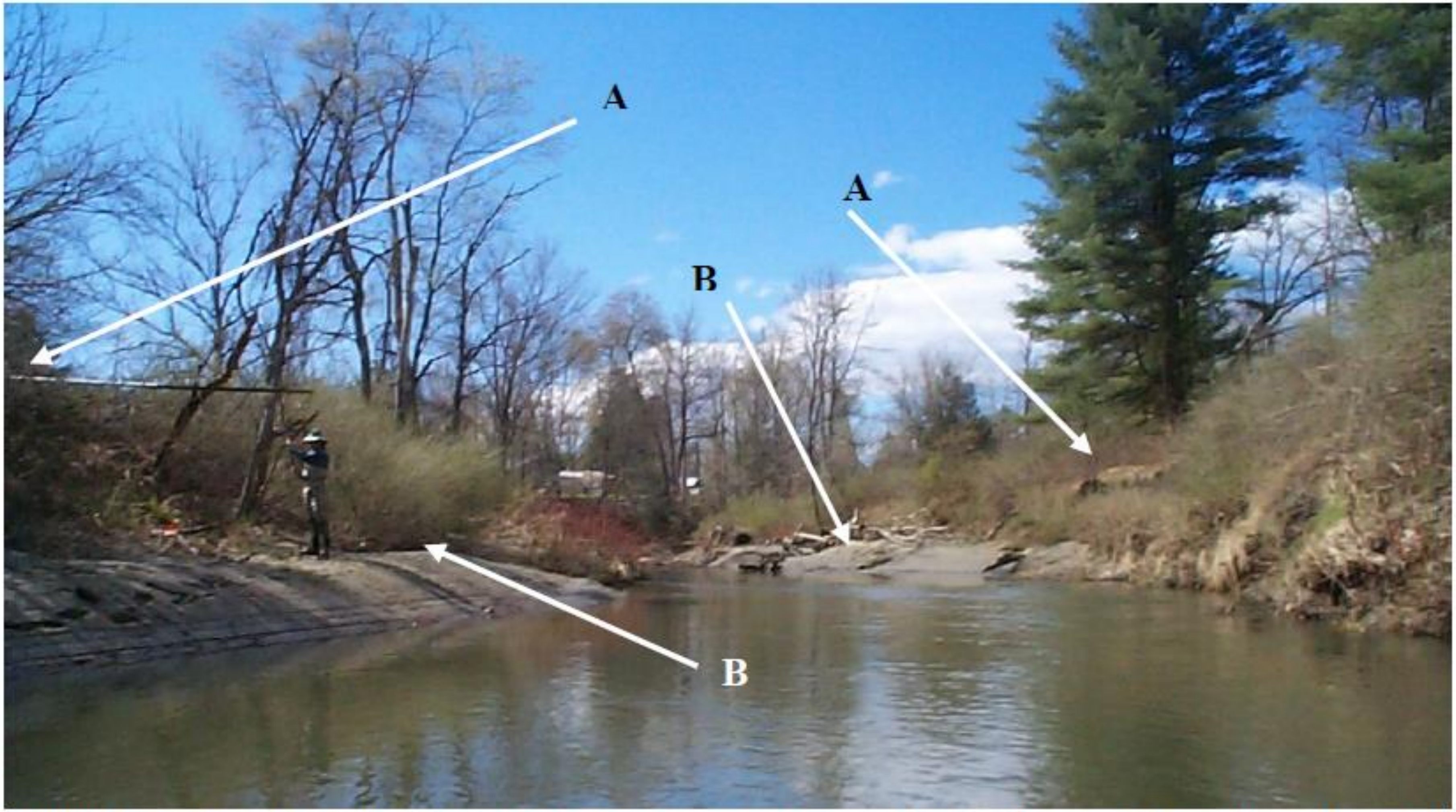
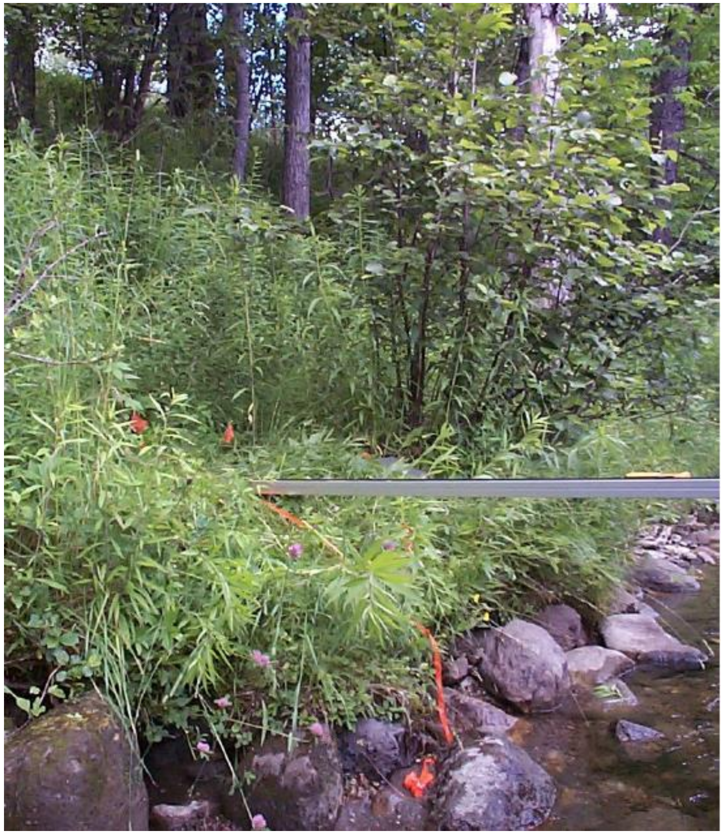


Figure 1 Embryonic active floodplain developing in incised channel. Stage IV of channel evolution.

a. Abandoned floodplain
b. Active floodplain indicating bankfull stage

(VTANR, 2009)

Bankfull Indicators



(VTANR, 2009)

Scour line	Change in particle size distribution
Depositional bench (active channel)	Staining of rocks
Inflection point	Upper limits of sand-sized particles
Lower limits in perennial vegetation	Top of point bars
Valley flat	Middle bench for braided rivers
Exposed root hairs below an intact soil layer	Break in slope of banks (floodplain break)
Active floodplain	Undercuts

(USACE, 2012)

Approximate Channel Sizing – NY HGR

[DA, drainage area in square miles; R^2, coefficient of determination]

Hydrologic region	Number of cross sections surveyed	Regression equation	Standard error of estimate (percent)	R^2
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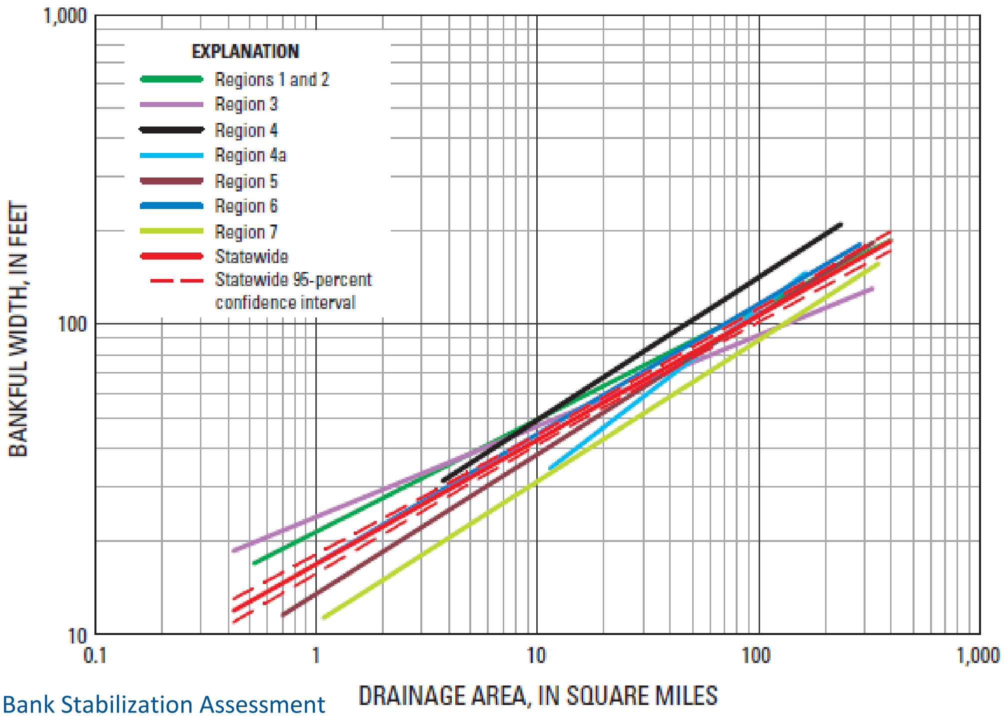
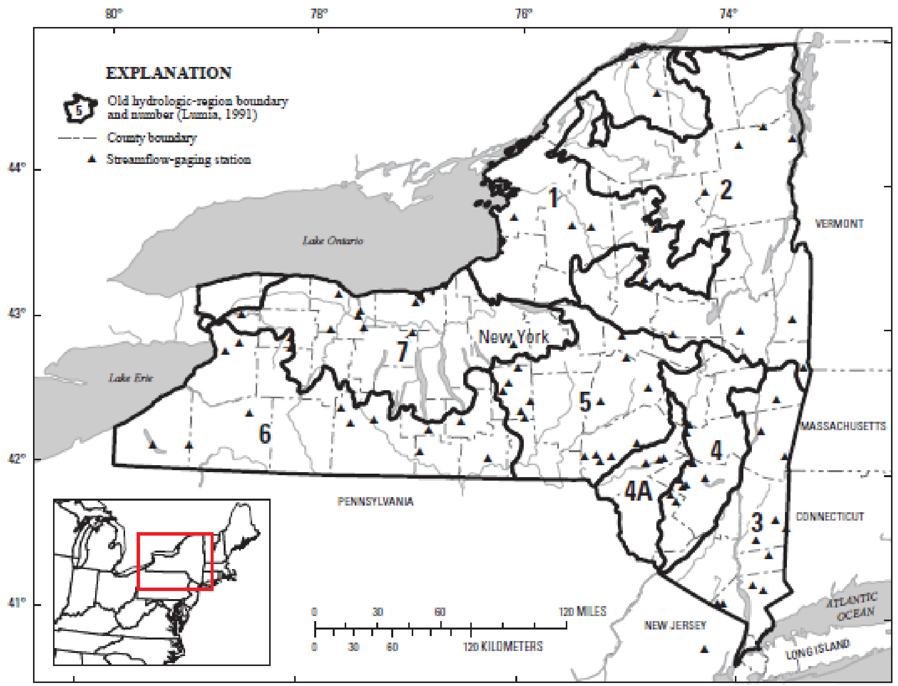
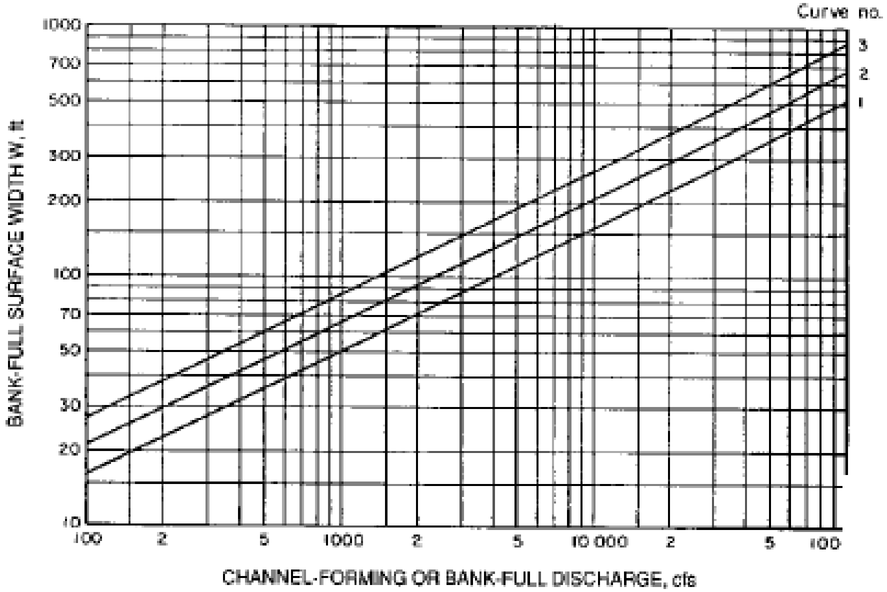
(Mulvihill et al., 2009)





Base from U.S. Geological Survey Digital Data. Universal Transverse Mercator Projection, Zone18N, NAD83

Approximate Channel Sizing – Regime

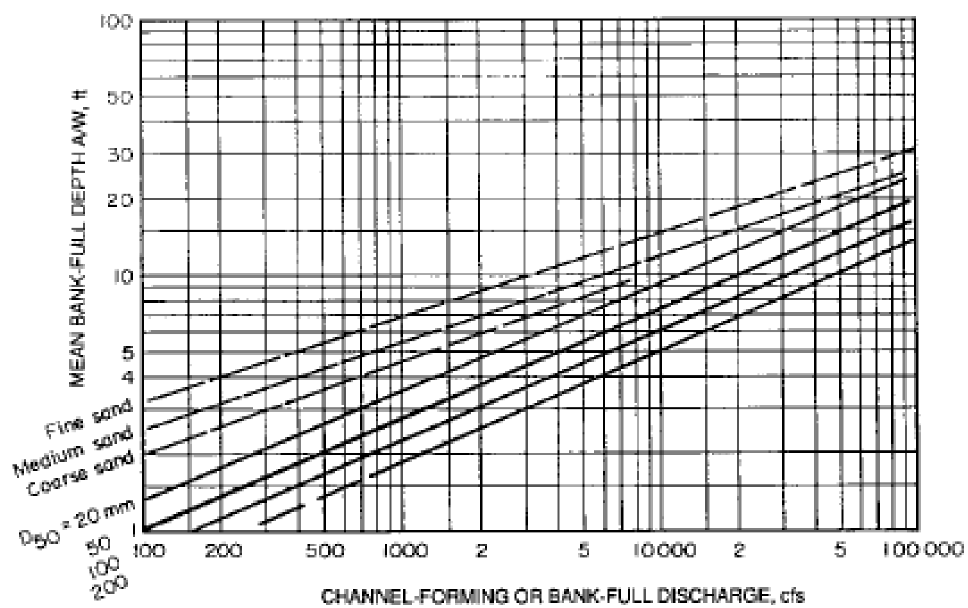


TENTATIVE GUIDANCE: CURVE 1: STIFF COHESIVE OR VERY COARSE GRANULAR BANKS
CURVE 2: AVERAGE COHESIVE OR COARSE GRANULAR BANKS.
CURVE 3: SANDY ALLUVIAL BANKS.

SEE PARAGRAPH 5-5 FOR LIMITATIONS.

FORMULA: $W = C Q^{0.5}$ WITH $C = 1.6, 2.1, 2.7$

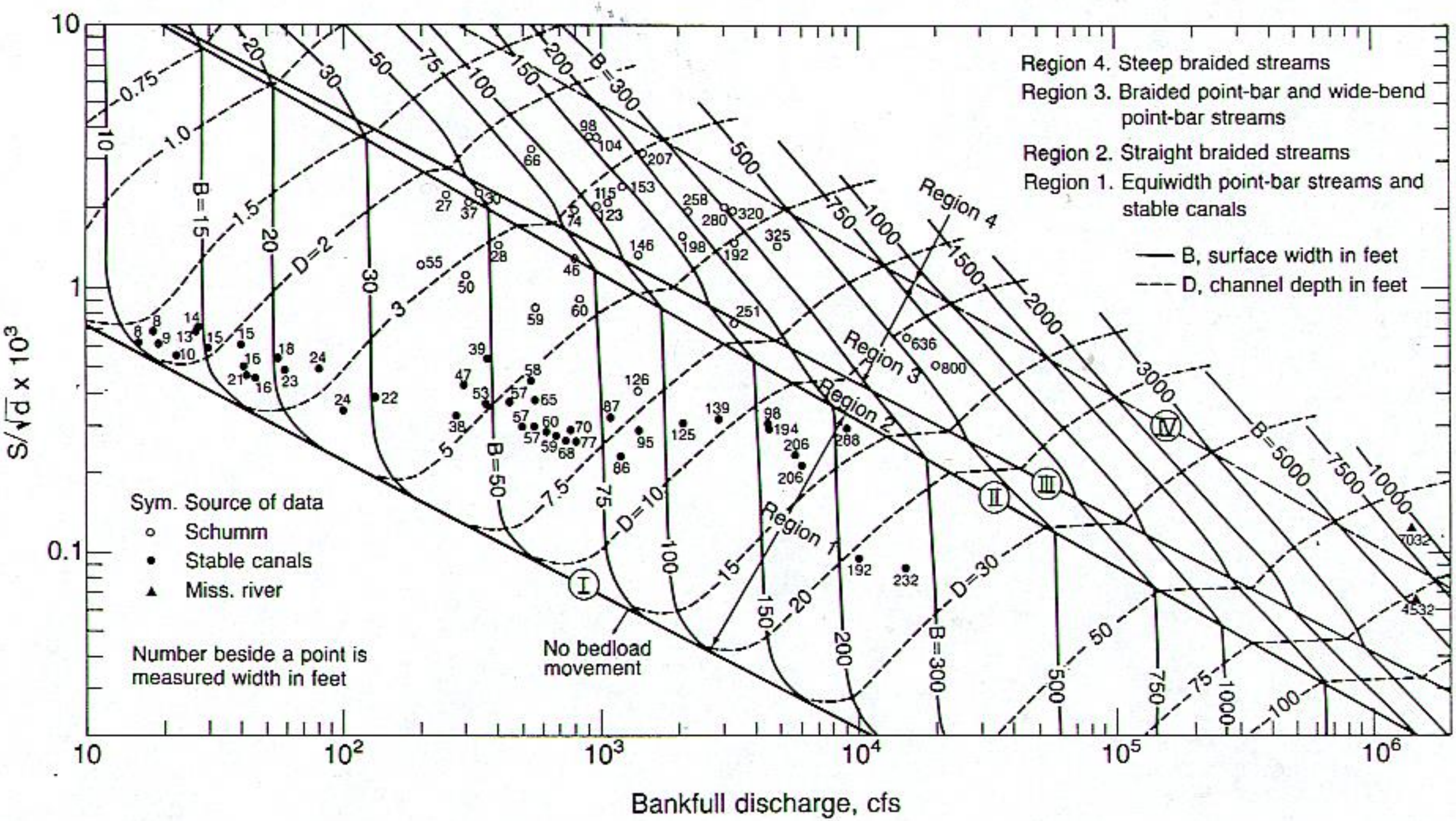
(USACE, 1994)



NOTE: FOR VERY APPROXIMATE GUIDANCE ONLY; DEPTHS SHOULD BE CHECKED BY UNIFORM-FLOW CALCULATION USING SELECTED WIDTH AND SLOPE (FIGURES 5-4 AND 5-5) AND ESTIMATED ROUGHNESS (SEE PARAGRAPH 4-7E).

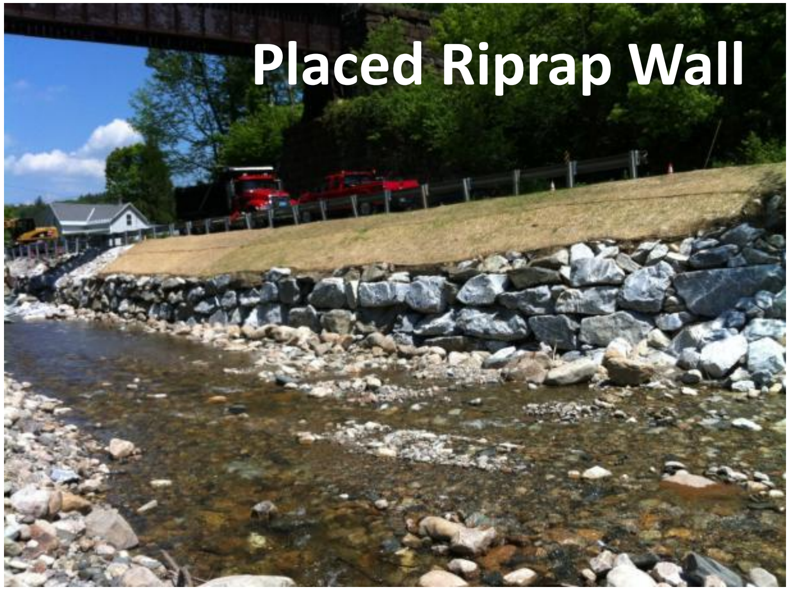
APPLIES BASICALLY TO CHANNELS WITH LOW BED SEDIMENT TRANSPORT.

Approximate Channel Sizing – Analytical



(Chang, 1986)

Bank Stabilization Design: Common Practices



(E. Fitzgerald, 2012-2015)

Related Practices: Bioengineering

Bioengineering Purpose and Design

- Increase roughness
- Enhance riparian habitat
- Low slope/power settings
- Hydraulic modeling needed to check velocity
- Soils and geotechnical concerns
- Fabrics, wood species, etc

Bioengineering

Plymco Dam Channel Restoration (J. MacBroom, 2015)

Crosby Brook, Brattleboro, VT (E. Fitzgerald, 2010)

Related Practices: ELJs

ELJ Purpose and Design

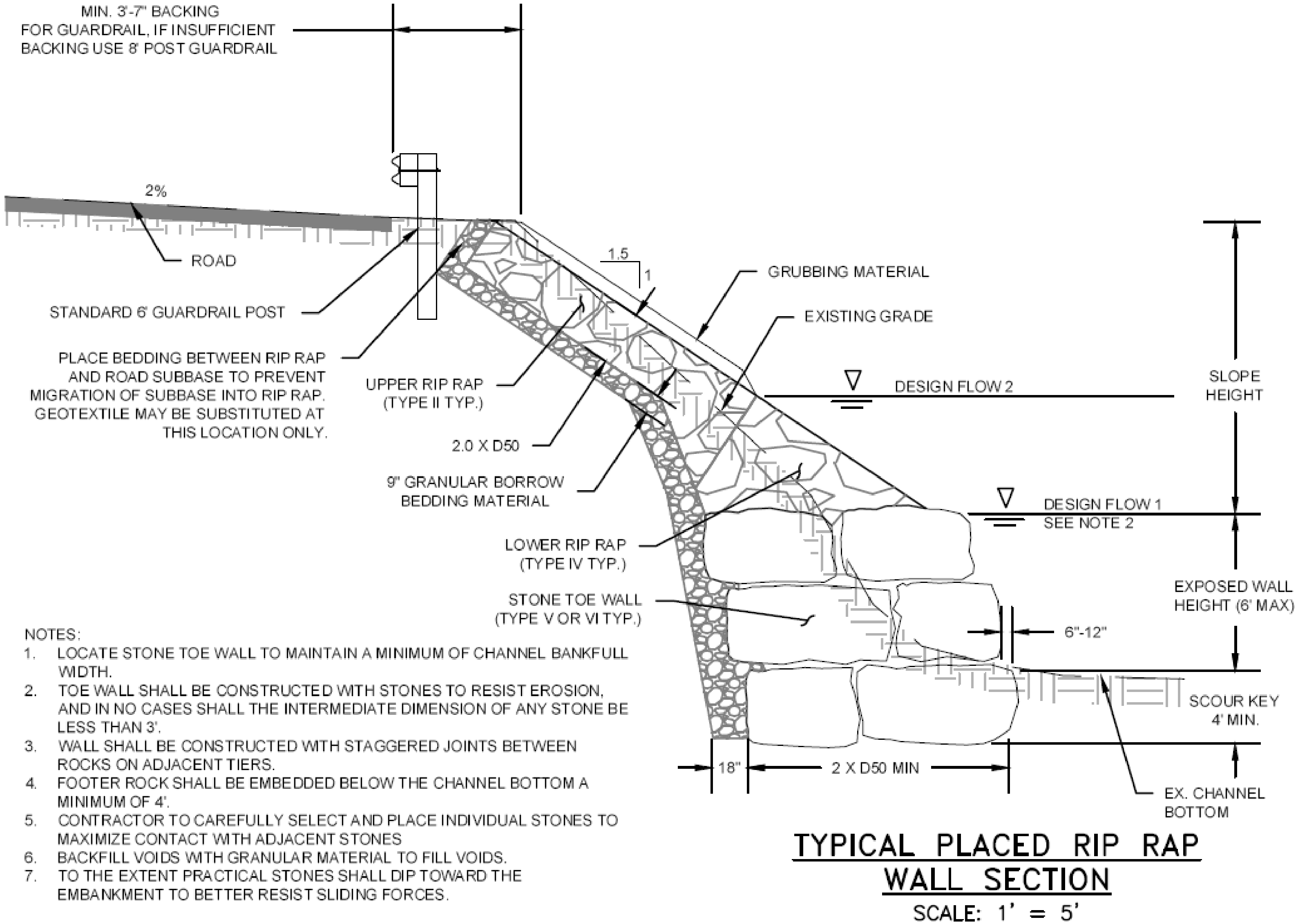
- Increase roughness
- Push thalweg away from bank
- Enhance habitat
- Hydraulic modeling needed
- Force-balance analysis
- Piles, wood species, etc

Boquet River , Willsboro, NY (E. Fitzgerald, 2015)

Boundary Category	Boundary Type	Permissible Shear Stress (lb/sq ft)	Permissible Velocity (ft/sec)	Citation(s)
Soils	Fine colloidal sand	0.02 - 0.03	1.5	A
	Sandy loam (noncolloidal)	0.03 - 0.04	1.75	A
	Alluvial silt (noncolloidal)	0.045 - 0.05	2	A
	Silty loam (noncolloidal)	0.045 - 0.05	1.75 – 2.25	A
	Firm loam	0.075	2.5	A
	Fine gravels	0.075	2.5	A
	Stiff clay	0.26	3 – 4.5	A, F
	Alluvial silt (colloidal)	0.26	3.75	A
	Graded loam to cobbles	0.38	3.75	A
	Graded silts to cobbles	0.43	4	A
	Shales and hardpan	0.67	6	A
Gravel/Cobble	1-in.	0.33	2.5 – 5	A
	2-in.	0.67	3 – 6	A
	6-in.	2.0	4 – 7.5	A
	12-in.	4.0	5.5 – 12	A
Vegetation	Class A turf	3.7	6 – 8	E, N
	Class B turf	2.1	4 - 7	E, N
	Class C turf	1.0	3.5	E, N
	Long native grasses	1.2 – 1.7	4 – 6	G, H, L, N
	Short native and bunch grass	0.7 - 0.95	3 – 4	G, H, L, N
	Reed plantings	0.1-0.6	N/A	E, N
	Hardwood tree plantings	0.41-2.5	N/A	E, N
Temporary Degradable RECPs	Jute net	0.45	1 – 2.5	E, H, M
	Straw with net	1.5 – 1.65	1 – 3	E, H, M
	Coconut fiber with net	2.25	3 – 4	E, M
	Fiberglass roving	2.00	2.5 – 7	E, H, M
Non-Degradable RECPs	Unvegetated	3.00	5 – 7	E, G, M
	Partially established	4.0-6.0	7.5 – 15	E, G, M
	Fully vegetated	8.00	8 – 21	F, L, M
Riprap	6 – in. d_{50}	2.5	5 – 10	H
	9 – in. d_{50}	3.8	7 – 11	H
	12 – in. d_{50}	5.1	10 – 13	H
	18 – in. d_{50}	7.6	12 – 16	H
	24 – in. d_{50}	10.1	14 – 18	E
Soil Bioengineering	Wattles	0.2 – 1.0	3	C, I, J, N
	Reed fascine	0.6-1.25	5	E
	Coir roll	3 - 5	8	E, M, N
	Vegetated coir mat	4 - 8	9.5	E, M, N
	Live brush mattress (initial)	0.4 – 4.1	4	B, E, I
	Live brush mattress (grown)	3.90-8.2	12	B, C, E, I, N
	Brush layering (initial/grown)	0.4 – 6.25	12	E, I, N
	Live fascine	1.25-3.10	6 – 8	C, E, I, J
	Live willow stakes	2.10-3.10	3 – 10	E, N, O
Hard Surfacing	Gabions	10	14 – 19	D
	Concrete	12.5	>18	H

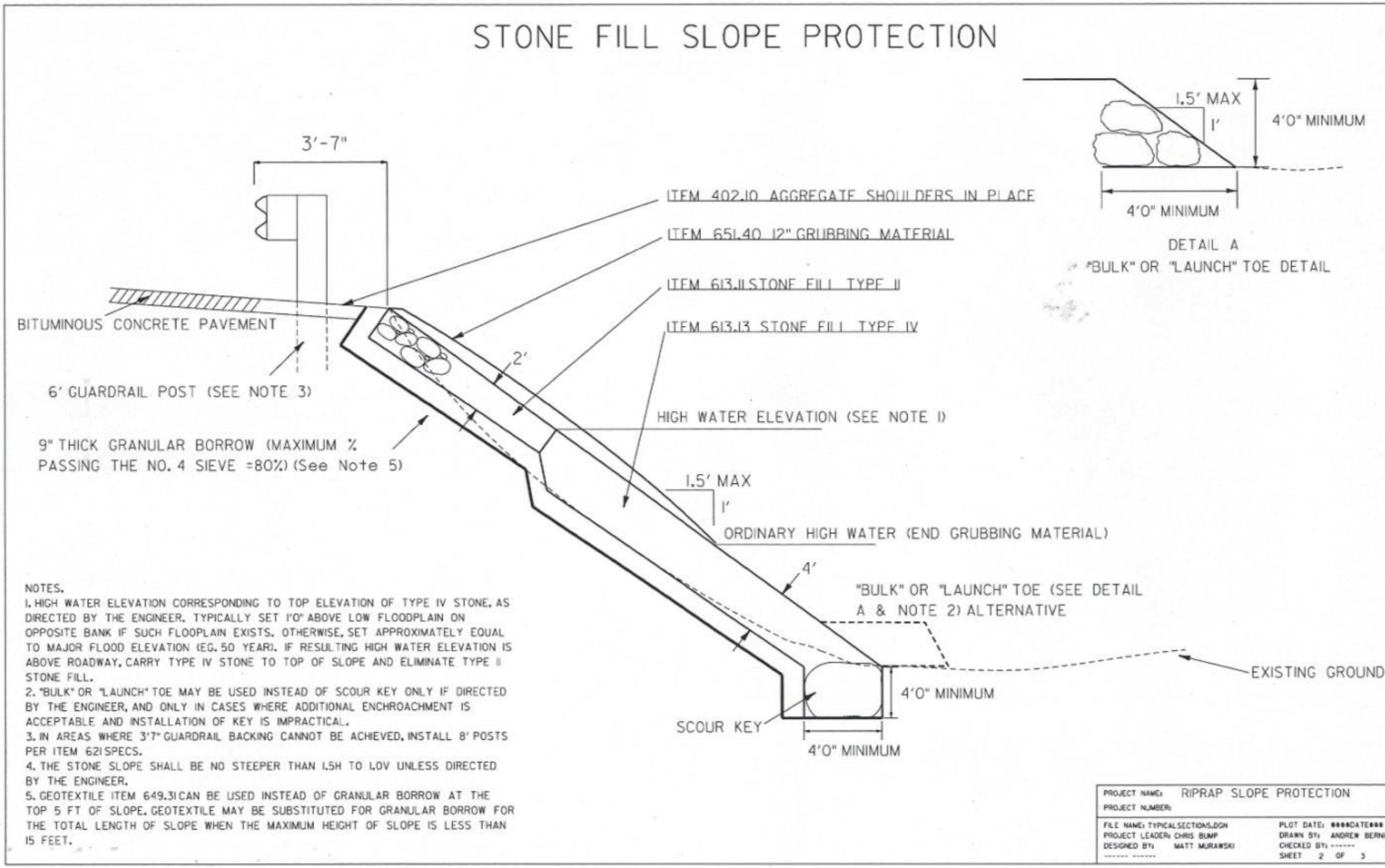
(Fischenich, 2001)

Bank Stabilization Design: Placed Riprap Wall



(Dubois & King and Milone & MacBroom, Inc., 2014)

Bank Stabilization Design: Riprap Slope



(VTrans, Dubois & King, Milone & MacBroom, Inc., 2013)

Placed Riprap Wall Design: Rock Type and Sizing

Rock Type

- Large (3-6 ft diameter), blocky rock for stacking
- Special sourcing and selection at quarry

VT Route 155 repairs, Mt. Holly, VT (E. Fitzgerald, 2013)

Placed Riprap Wall Design: Wall Location & Alignment

Design Elements

- 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.

(E. Fitzgerald, 2013)

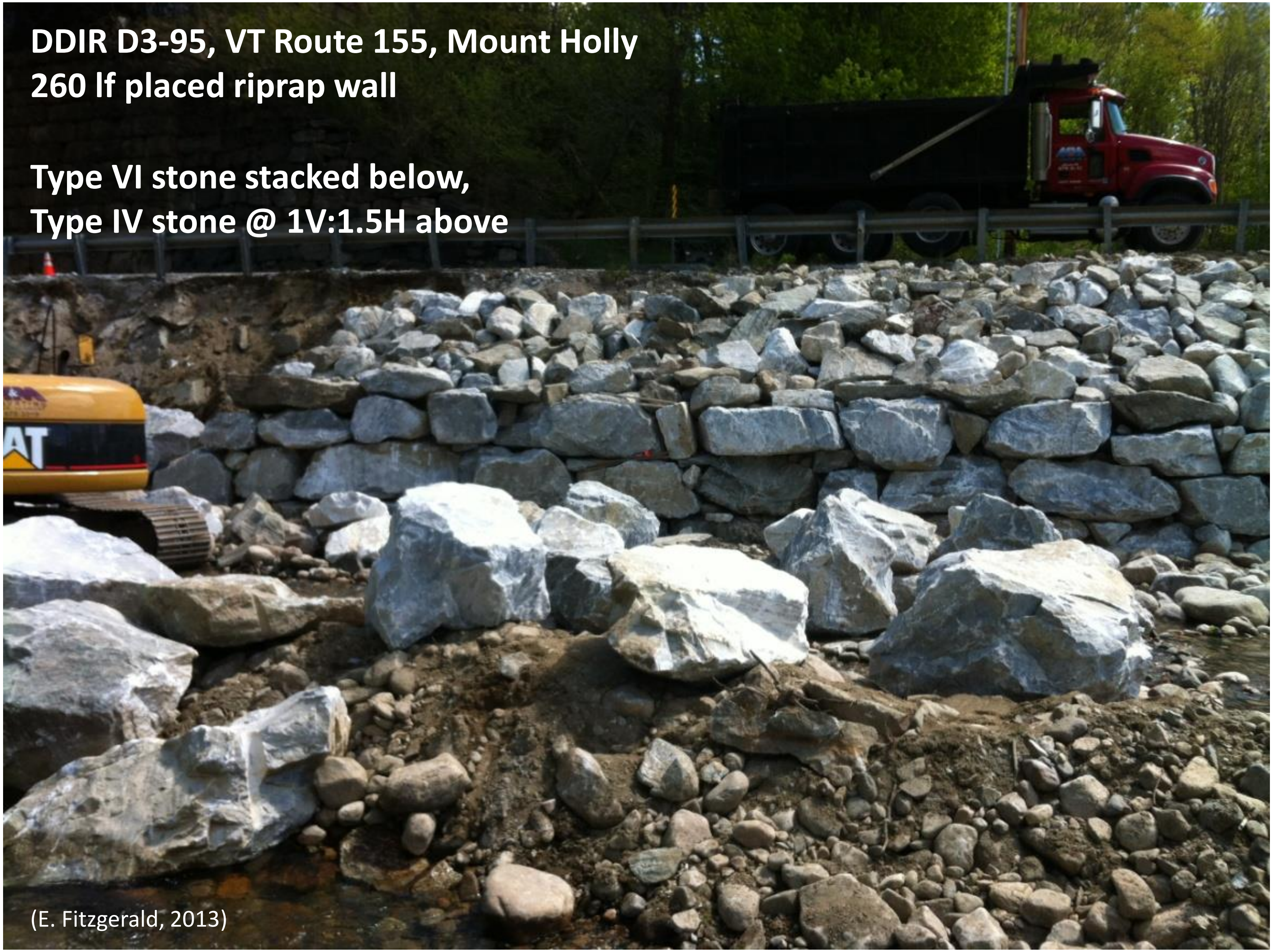
Placed Riprap Wall Design: Height and Slope

Design Elements

- Set wall height based on 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
- Maximum wall slope 6V:1H; gentle batter of 6V:2H is more common
- The target slope of the sloping riprap above the wall is 2H:1V, with a maximum of 1.5H:1V

(E. Fitzgerald, 2013)

Placed Riprap Wall Design: Height and Slope



Placed Riprap Wall Design: Rock Type and Sizing

Example problem: Steep slope

Problem: For the following flow conditions, determine the required rock size for a rock chute.

G_s = 2.65 or γ_s=165.36 lb/ft^3
Width = 40 ft
n = 0.045
Slope = 0.06 ft/ft
Depth = 3.5 ft

Solution: Solve relevant hydraulic parameters

Vel = 16.7 ft/s
Q = 2,340 ft^3/s
Y_{crit} = 4.7 ft

The riprap size determined from several methods is:

Isbash	D_{50}	= 1.6 ft
Maynord	D_{30}	= 1.6 ft, D_{50} = 1.9 ft
Lane's (FWS)	D_{75}	= 3.7 ft, D_{50} = 3.2 ft
Abt and Johnson	D_{50}	= 1.3 ft
ARS rock chute	D_{50}	= 1.1 ft

USACE steep slope riprap design

This high-energy technique is outlined in standard USACE guidance as provided in EM 1110–2–1601. It is designed for use on slopes from 2 to 20 percent.

However, the side slopes should be 1V:2.5H or flatter. A typical application would be a rock-lined chute. The formula is:

$$D_{30} = \frac{1.95 S^{0.555} (Cq)^{\frac{2}{3}}}{g^{\frac{1}{3}}} \qquad \text{(eq. TS14C–12)}$$

where:

D_{30} = stone size; m percent finer by weight
S = channel slope
q = unit discharge (q = Q/b, where b = bottom width of chute and Q is total flow)
C = flow concentration factor (usually 1.25, but can be higher if the approach is skewed)
g = gravitational constant

This equation is applicable to thickness = 1.5 D_{100}, angular rock, unit weight of 167 pounds per cubic foot, D_{85}/D_{15} from 1.7 to 2.7, slopes from 2 to 20 percent, and uniform flow on a downslope with no tailwater. This equation typically predicts conservative sizes.

Placed Riprap Wall Design: Bedding

Design Elements

- Granular bedding (Appendix I of SRMPP) is recommended behind the placed riprap wall and riprap slope to prevent fine material from piping through the crevices in the large rock.
- 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.

Deerfield River, VT Route 9 Wilmington, VT (R. Schiff, 2012)

Placed Riprap Wall Design: Bedding

Placed Riprap Wall Design: Keyway Thickness & Depth

(E. Fitzgerald, 2013)

Keyway Depths Based on Channel Incision and Evolution (Schiff et al., 2014)

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

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

Placed Riprap Wall Design: Keyway Thickness & Depth

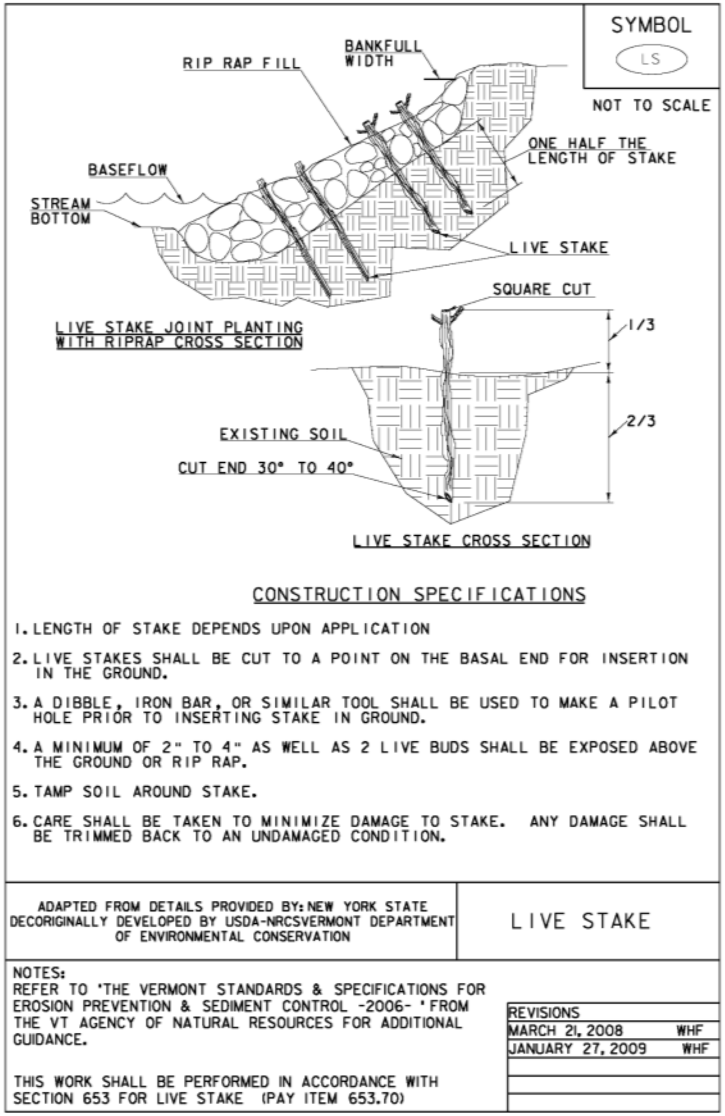
(E. Fitzgerald, 2013)

Placed Riprap Wall Design: Revegetation

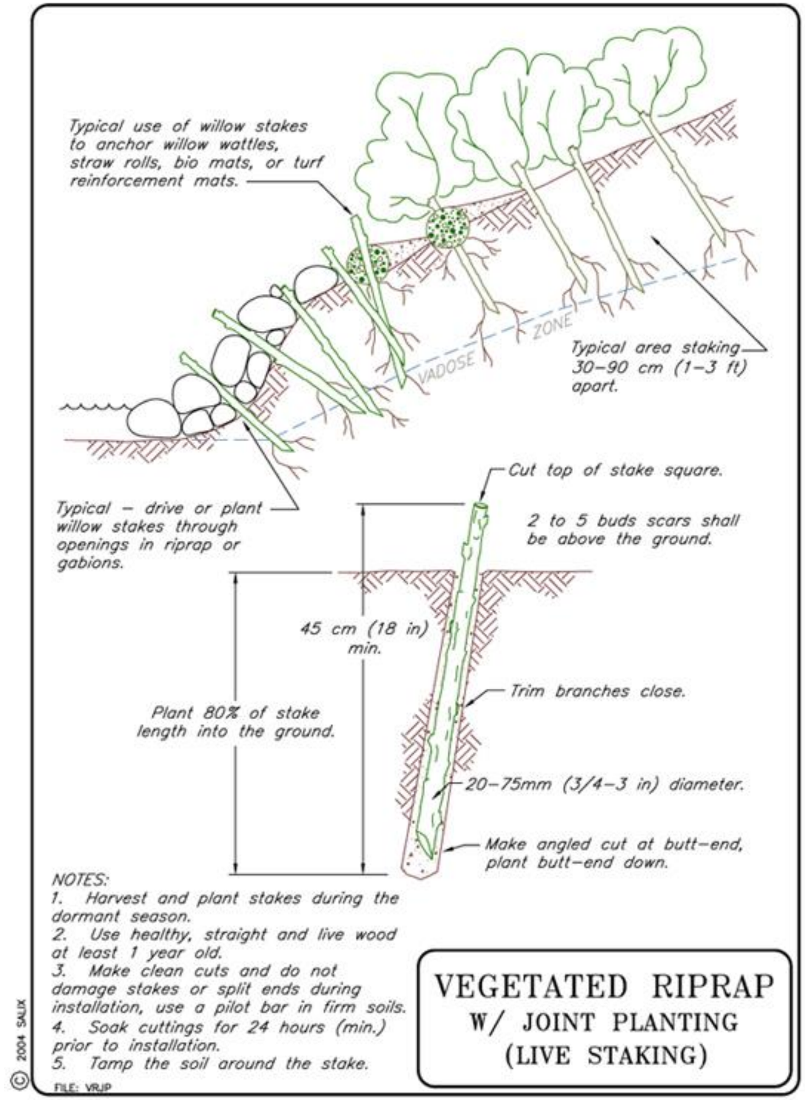
Post-Irene Repairs – Placed Riprap Wall with Vegetated Slope
South Branch of the Tweed River, VT Route 100, Killington

(E. Fitzgerald, 2013)

Placed Riprap Wall Design: Revegetation



(VTrans EPSC Specifications, 2009)



(McCullah and Gray, 2005)

Summary – Placed Riprap Wall Design

Assessment

- Location, length, width, and height of bank erosion
- Bankfull channel dimensions
- 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

Placed Riprap Wall Design Design <u>Objectives</u>

- 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.

Placed Riprap Wall Design 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.

Placed Riprap Wall Design Review Questions

1. *How does the degree of channel encroachment and risk to adjacent property dictate the selection of bank stabilization treatment?*

2. *Where is sloping riprap preferred over a placed riprap wall?*

Placed Riprap Wall: 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.

(Schiff et al., 2014)

Placed Riprap Wall: Permitting Requirements

- U.S. Army Corps of Engineers (CWA Section 404 and 401)
  - Quantify length, area, and volume of disturbance below ordinary high water (OHW)
  - Identify reporting category
  - Contact Field Office
- Vermont Stream Alteration Permit
  - Meet Performance Standards as identified above
  - Identify reporting category
  - Contact river management engineer
- New York Article 15 Protection of Waters Permit
  - Emergency Authorization for quick review in emergency
  - General Permit for Disaster Recovery for longer timeframes
- Local Permits
  - FEMA National Flood Insurance Program criteria
  - Wetlands (NY) (State for Vermont)
  - Contact Town Administrator for reporting needs

Placed Riprap Wall: Construction

Constructability

- Application has become much more common since TS Irene in 2011
- Need large machinery and good supply of large rock
- Closure of single lane often required
- Taller road embankments may require removal and replacement of travel lane to establish a work platform to reach channel bottom for keyway, etc.

Temporary Construction Controls

- Complete work during low flow periods to limit downstream sedimentation and allow for proper visibility to successfully complete the work.
- Temporary berm made of pushed up deposited material are often used to guide water out of the work areas and provide a work platform to keep machinery out of main channel bed.
- Use series of sediment filter berms to create sediment trap pools and limit sedimentation of downstream areas.
- The pools should be periodically cleaned out as work takes place.
- Install silt fencing as needed to control runoff when ground not flat and soils or grubbings are stockpiled.