Channel Stabilization

Development of Advanced Flood Recovery and River Management Training Modules

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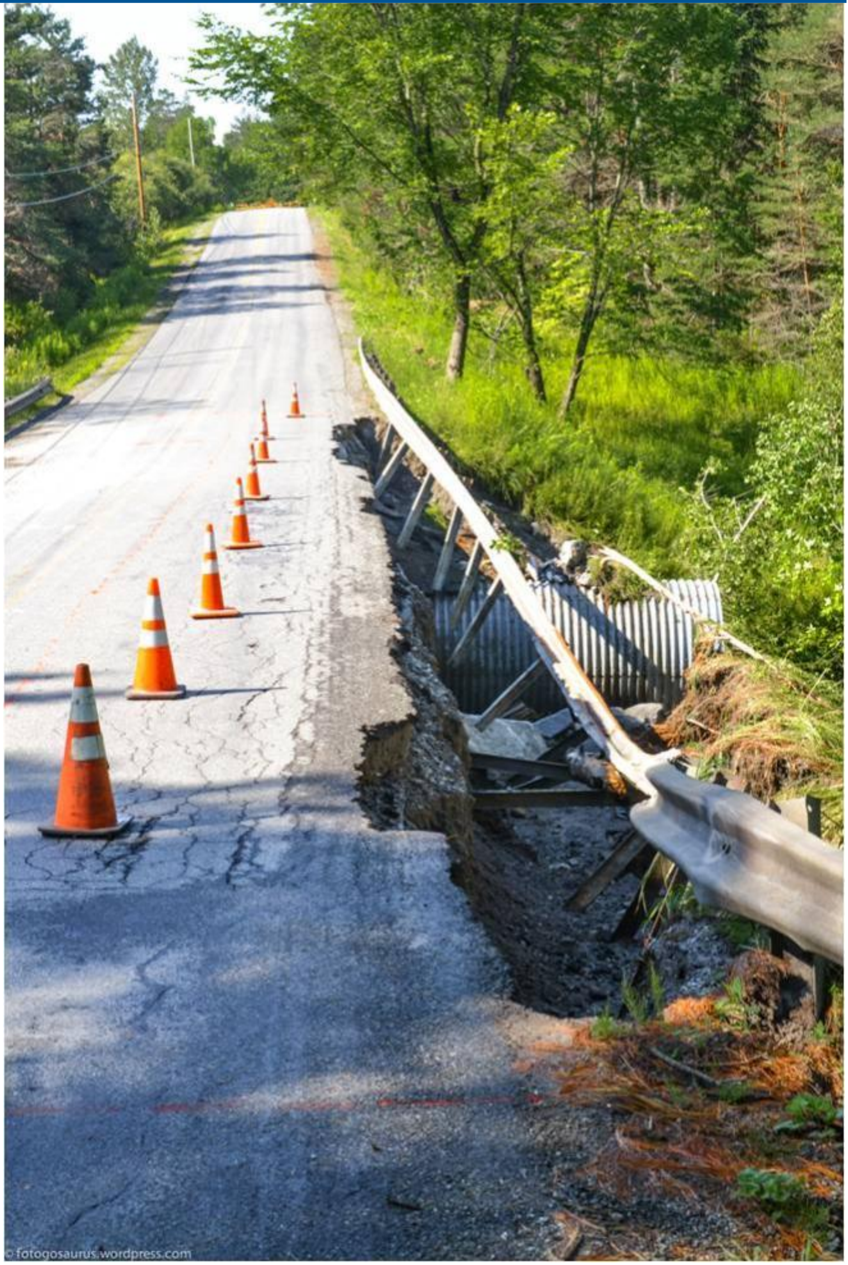
Developed September 2016

Lesson Plan / Table of Contents

Large-Scale Damages

Local Damages

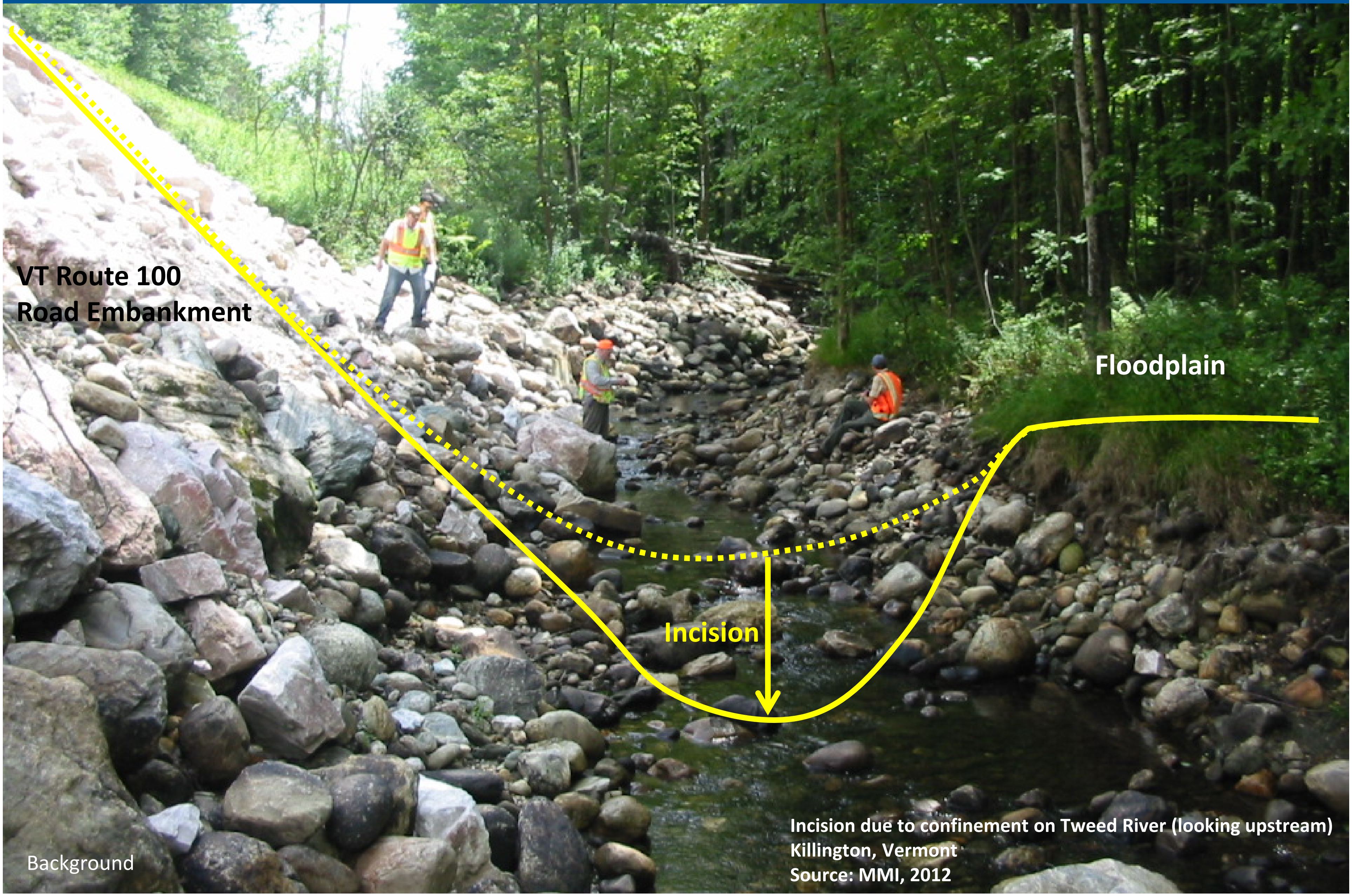
Great Brook
Creamery Street in Plainfield, VT
5/27/2011
Photo taken by G. Springston



Great Brook
Brook Road in Plainfield, VT
7/20/2015
Photo taken by B. Towbin

Background

Local Damages



Incision due to confinement on Tweed River (looking upstream)
Killington, Vermont
Source: MMI, 2012

Bed Stabilization Objectives

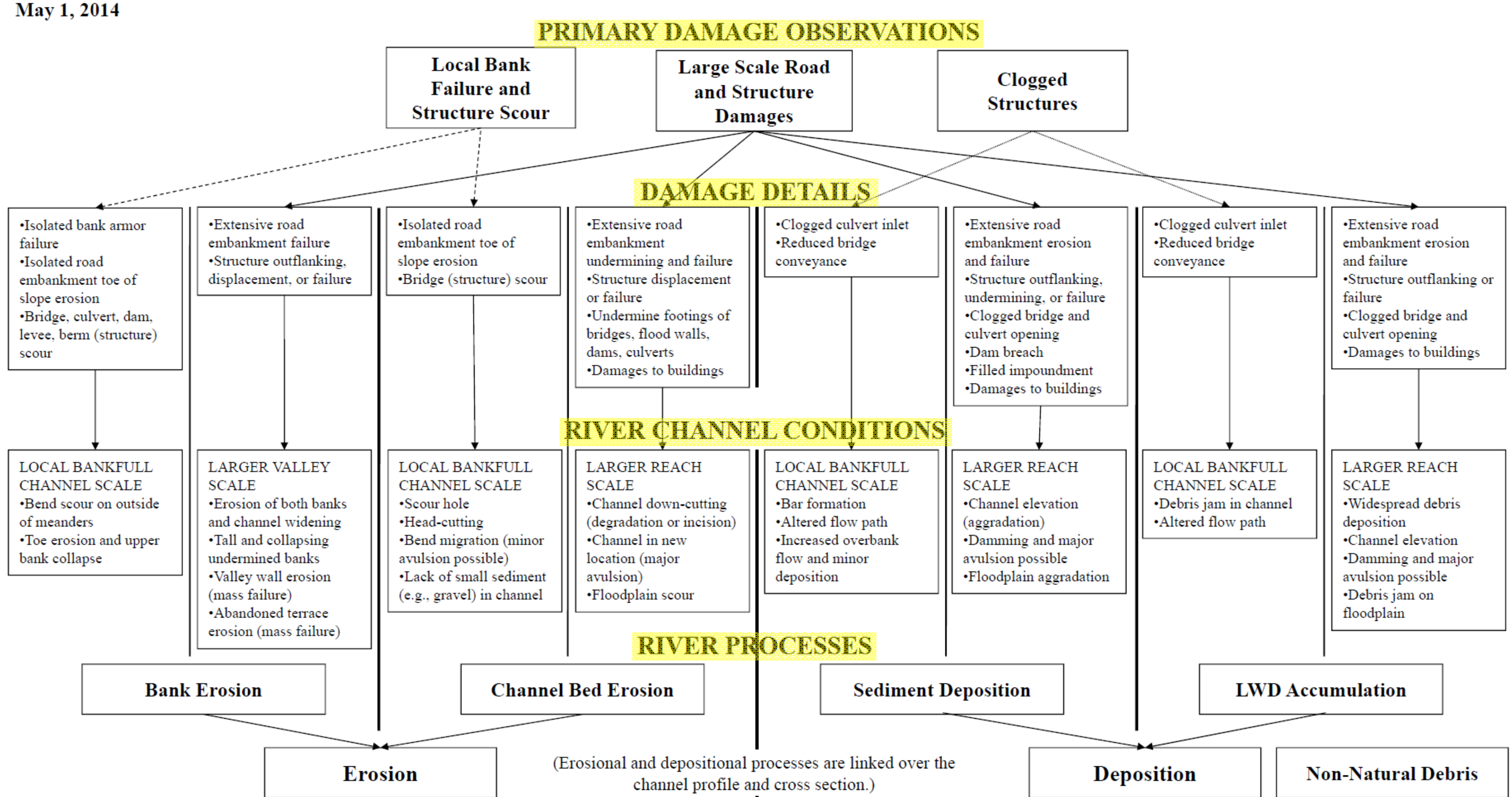
1. Maintain or re-establish vertical stability over the reach to prevent unnatural raising or lowering of channel bed.
2. Re-connect as much floodplain as possible given site constraints.
3. Maintain or improve instream habitat.
4. Protect water quality.

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.

Problem Identification Review

May 1, 2014



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

Background

(Schiff et al., 2014)

Alternatives Analysis Objectives

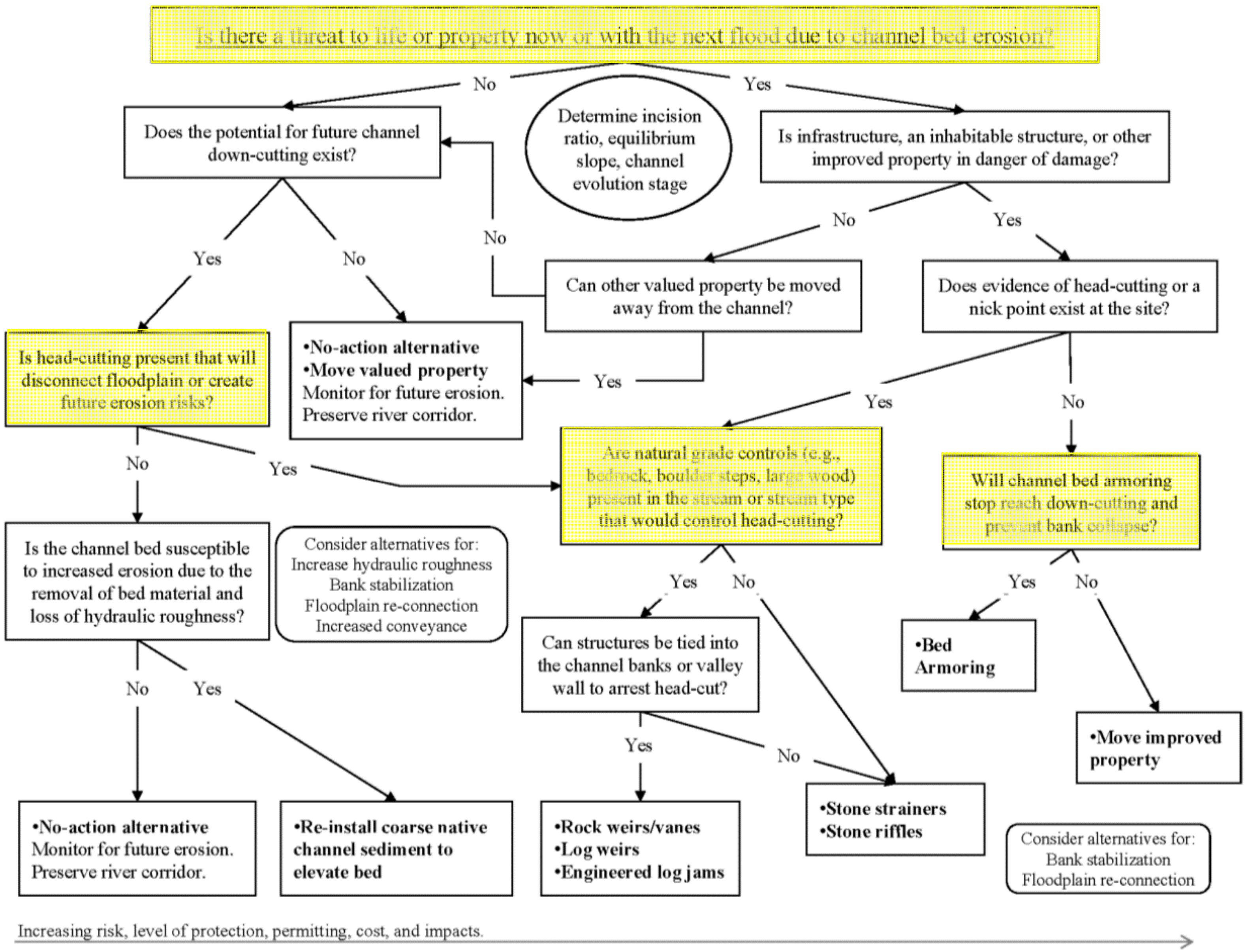
GENERAL

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

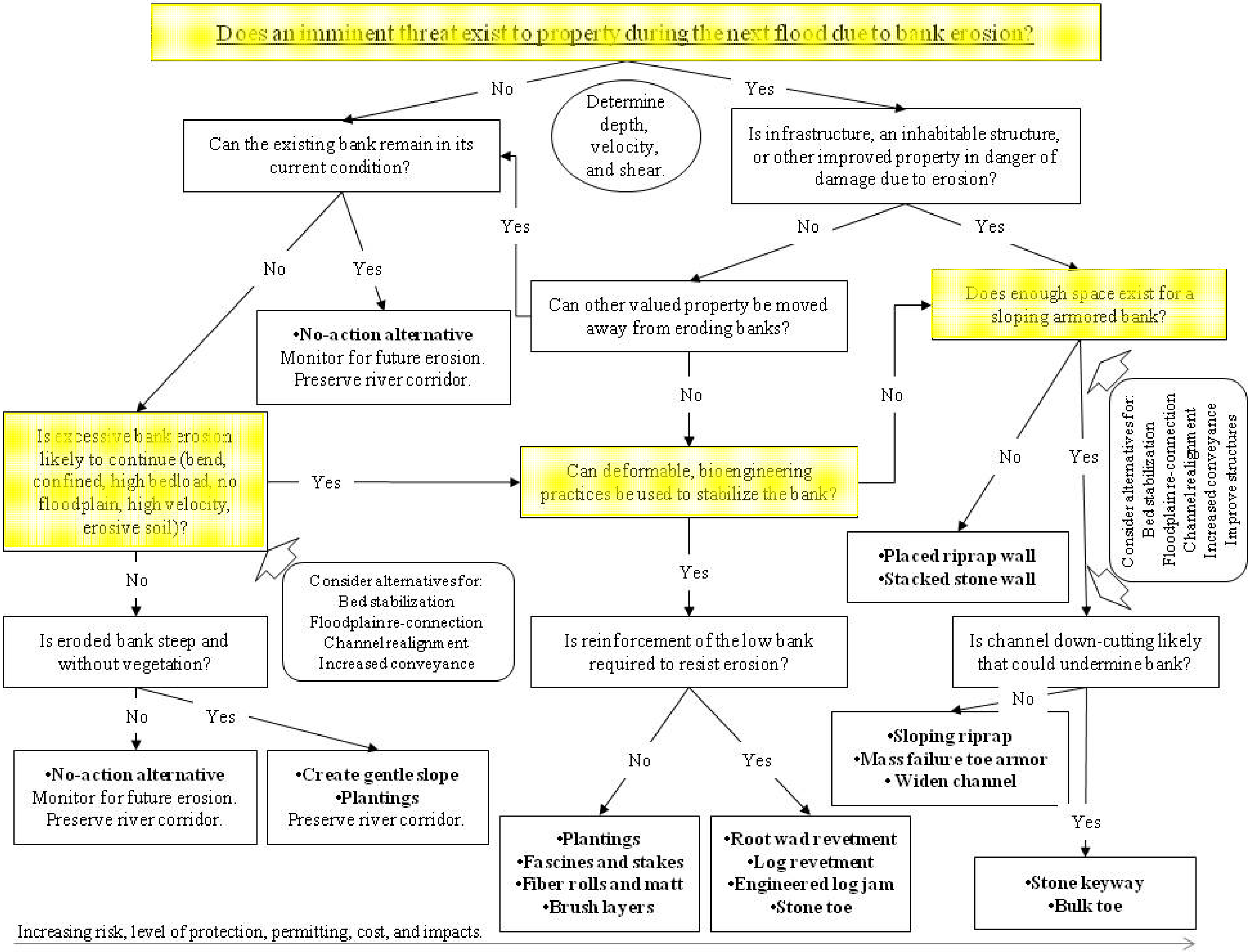
A. Maintain or re-establish vertical channel stability and floodplain connectivity (bed).
B. Reduce encroachments and provide resistance for the design flood to protect improved property (banks).
C. Maximize the use of vegetation (banks).

Bed Erosion Alternatives Analysis Review



(Schiff et al., 2014)

Bank Erosion Alternatives Analysis Review



(Schiff et al., 2014)

Alternatives Analysis Review Questions

1. *Is relocating valued property following flood damages a possible alternative?*

2. *How does the severity of channel adjustment influence the selection of stabilization alternatives?*

3. *How are changes in watershed hydrology influencing channel stability and subsequent design process?*

Grade Control Project Examples: Reinstallation of native bed material

South Branch Tweed River, VT Route 100 (E. Fitzgerald, 2012)

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)

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, YEAR?)

Grade Control Project Examples: 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 Project Examples: Bed Armor

Projects Examples

Bank Stabilization Project Examples: Sloping Riprap

(E. Fitzgerald, 2013)

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)

Bank Stabilization Project Examples: Bioengineering and ELJs

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

Lake Champlain, Alburgh, VT (E. Fitzgerald, 2014)

Bioengineering: Terracing and Branch Layering

Grade Control Module

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

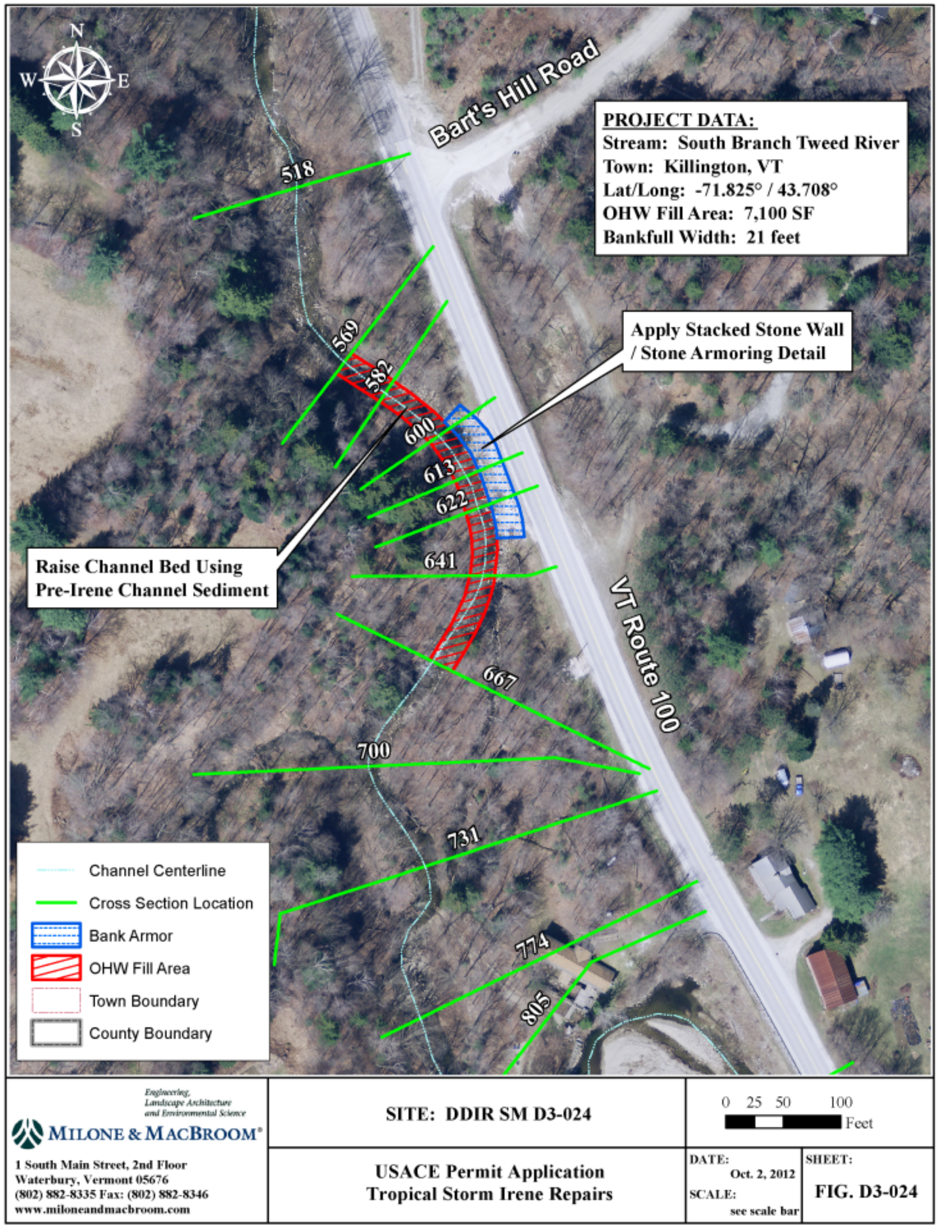
(Design)

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

Bed Stabilization Design Objectives

1. Maintain or re-establish vertical stability over the reach to prevent unnatural raising or lowering of channel bed.
2. Re-connect as much floodplain as possible given site constraints
3. Maintain or improve instream habitat.
4. Protect water quality.

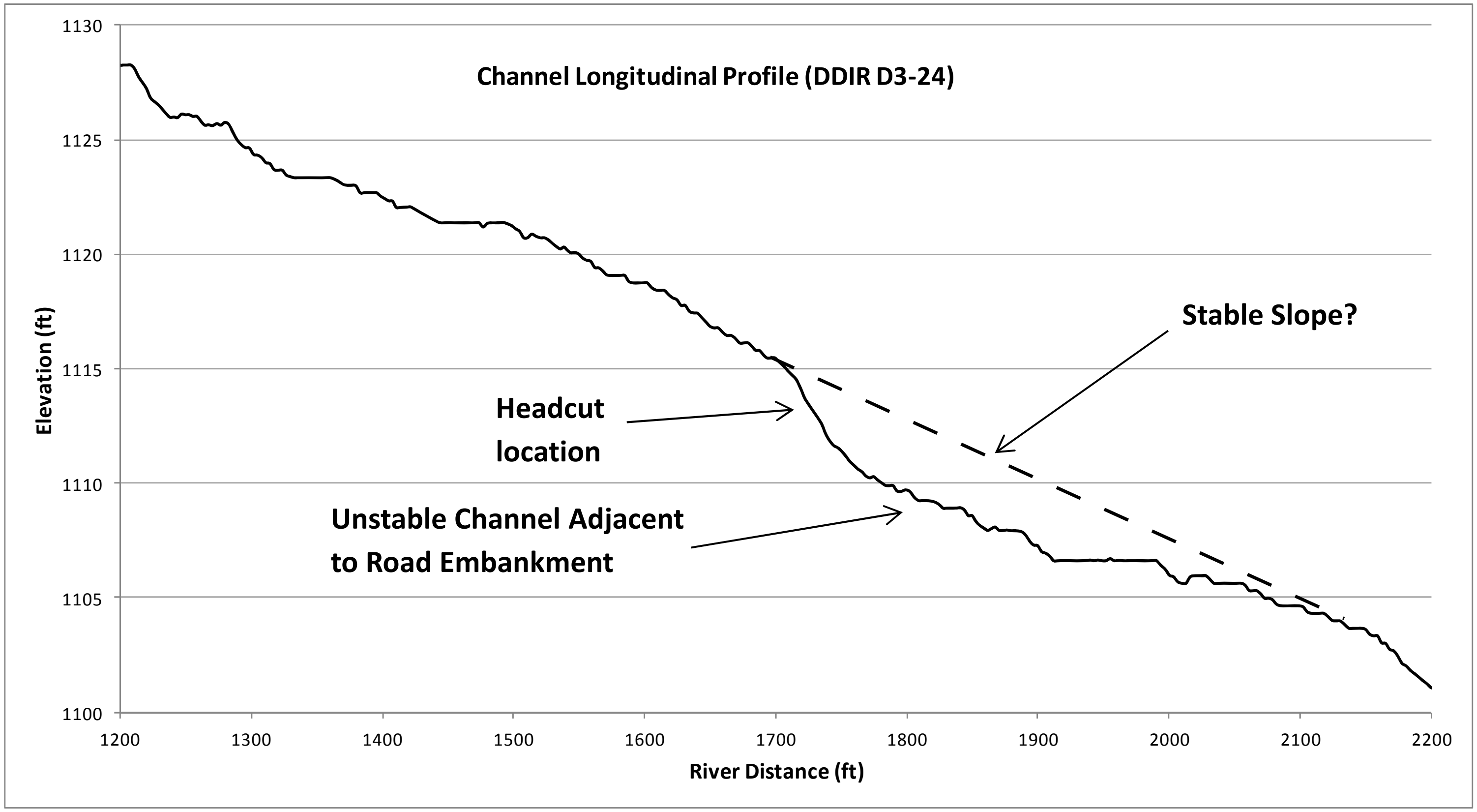
Grade Control Assessment: Identify Project Limits



- Walk river reach upstream and downstream of site
- Note extents of instability and completed flood repairs
- Identify changes in bankfull width, bed profile and form, sediment gradation, and dredged materials along the banks or floodplain

(MMI, 2012)

Grade Control Assessment: Stable Channel Dimensions and Slope



(FEA & MMI, 2012)

Reach Slope Data:

- Field survey measurements, roadway survey
- LiDAR digital elevation models (DEM)
- Past geomorphic assessment data; Statewide DEMs

Channel Slope

What is reach slope as determined from field survey and Manning's equation?

What is valley slope as determined from survey and mapping?

Compare reach and valley slope to calculated equilibrium slopes below.

Shield's resistance to motion

γ*R*S*304 = 5*d50 (=τ)

γ = 62.4 lb/ft^3 specific weight

d50 = _______mm median particle size

R~d = _______ft hydraulic radius~depth

S= _______ft/ft slope

Solve for Slope (ft/ft)

(Sediment stability in uniform soils)

(Shields, 1936; BOR, 1987)

USACOE - Lacey graph

S=[0.00021*d50*Wbf/Qbf]$^{0.75}$

d50= _______mm median particle size

wbf= _______ft bankfull width

Qbf= _______cfs bankfull flow

Solve for Slope ft/ft)

(Regime equation)

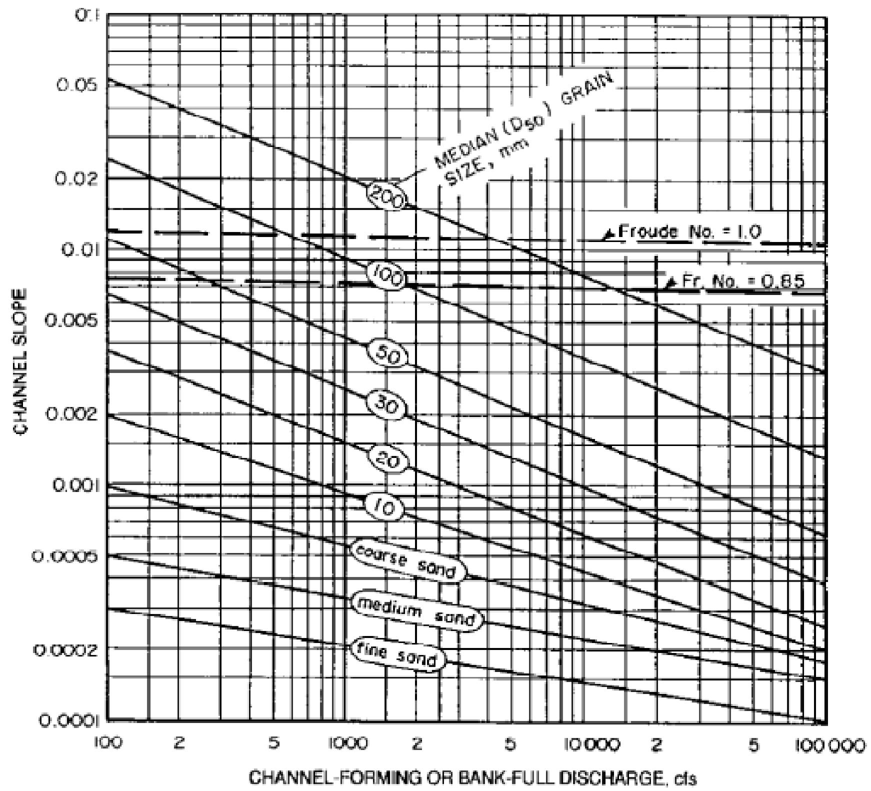
(USACE, 1994)

Channel Slope – Regime

USACE Stable Channel Design Charts (USACE, 1994)

d50 = ______mm median particle size
Qbf= ______cfs bankfull flow

Identify slope (%), bankfull width (ft), bankfull depth (ft)



NOTE: FOR LIMITATIONS SEE PARAGRAPH 5.5. CURVES ARE BASICALLY FOR SINGLE CHANNELS WITH FULLY ALLUVIAL BED BUT LOW BED SEDIMENT TRANSPORT. SLOPES MAY BE MUCH HIGHER WITH HIGH SEDIMENT TRANSPORT, ESPECIALLY WITH SAND BEDS.

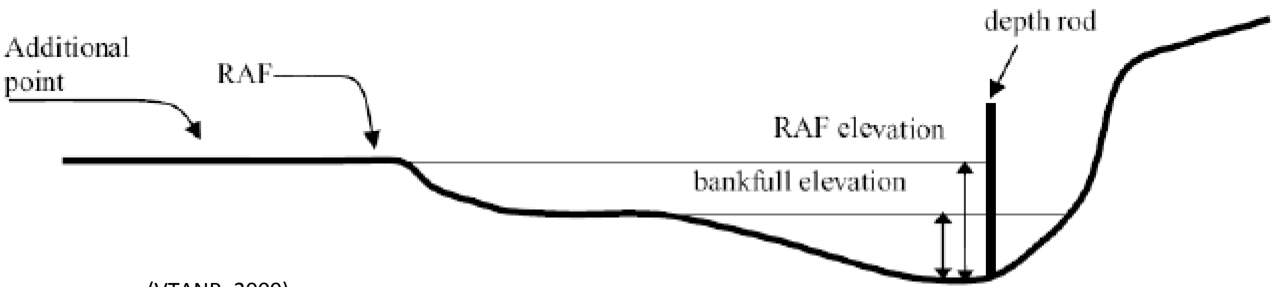
(USACE, 1994)

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

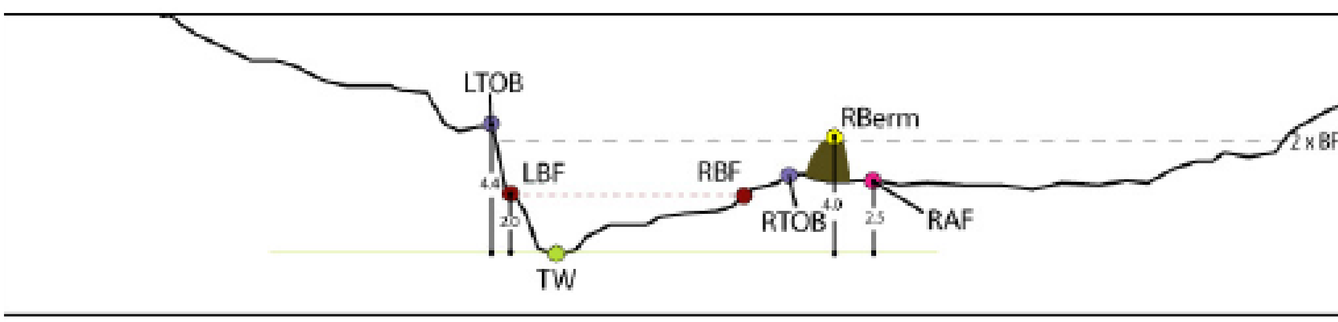
(Adapted from Montgomery and Buffington, 1993; Rosgen, 1994)

Incision Ratio



(VTANR, 2009)

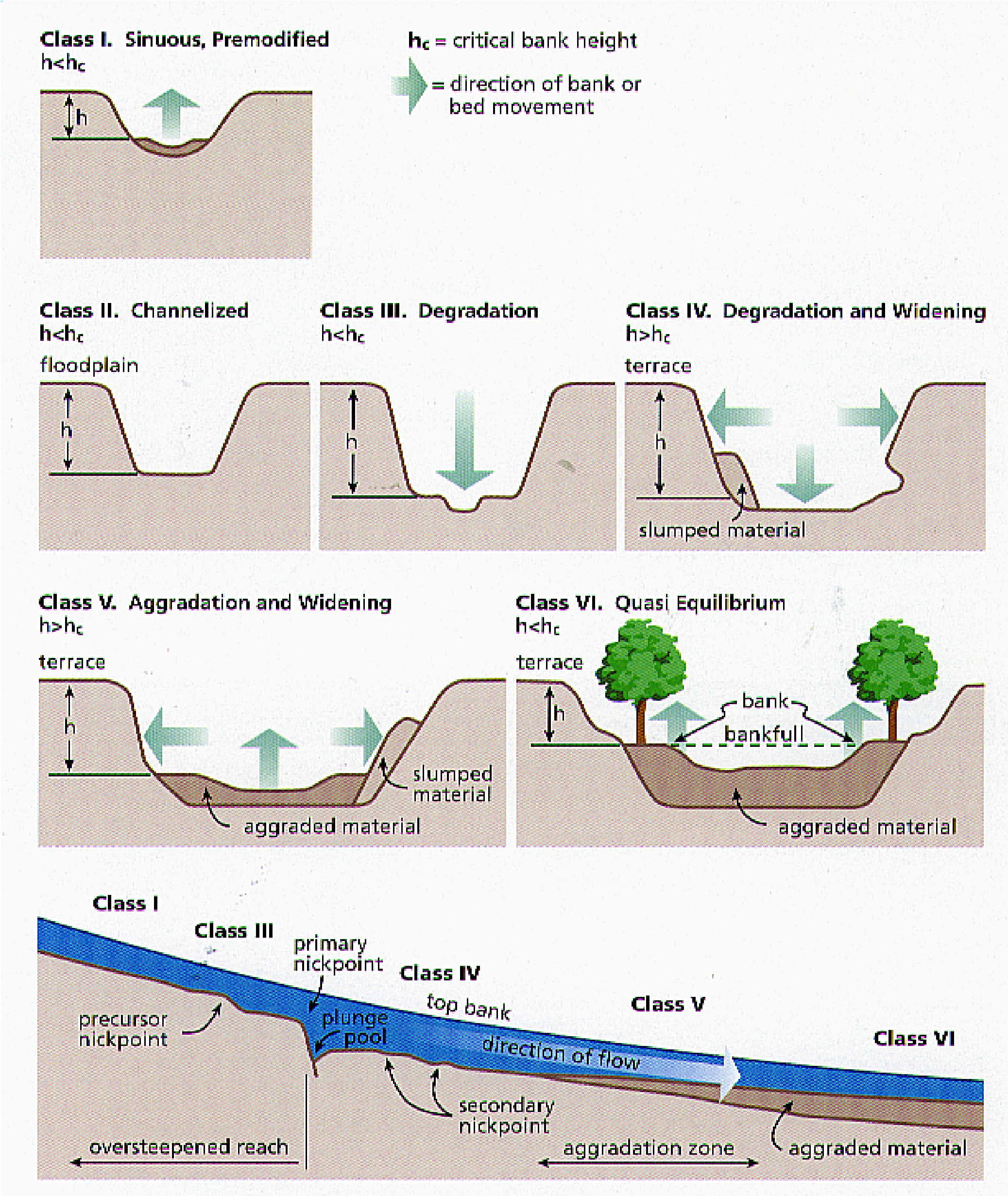
$$IR = \frac{\text{floodplain height}}{\text{bankfull height}}$$



IR_{HEF}	IR_{RAF}
$\frac{RBermH}{BFH} = \frac{4}{2}$	$\frac{RAFH}{BFH} = \frac{2.5}{2}$
2	1.25

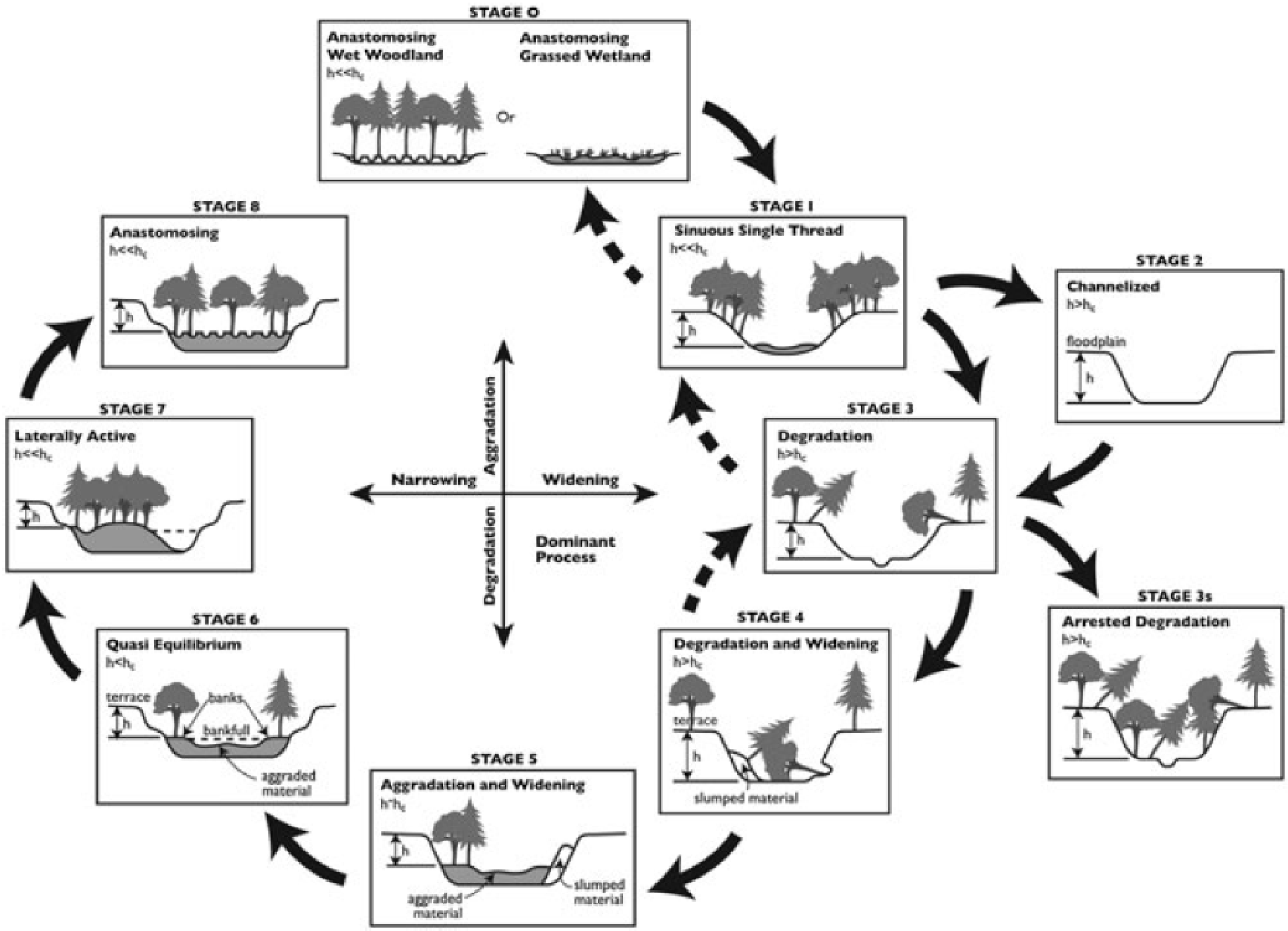
(VTANR, 2009)

Identify the Likely Channel Evolution



(Simon 1989; FISRWG, 1998)

Channel Evolution Model



(Cluer and Thorne, 2013)

Head-cut Initiation

- Look for erosion faces (i.e., nickpoints) and aggradation areas in post-flood assessment.
- Is the project area upstream or downstream of a primary nickpoint?
- Are precursor nickpoints evident on an over steepened reach?
- Is the channel in stages I or V indicating likely stability, or is the channel in stages II, III, or IV indicating likely down-cutting and widening?

(Schumm et al., 1984)

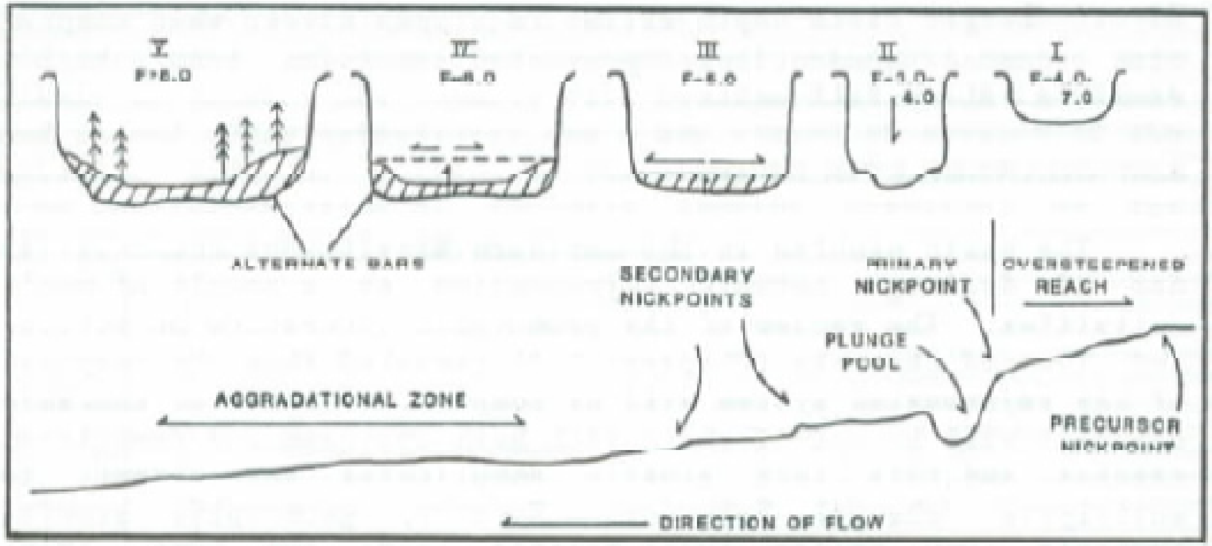
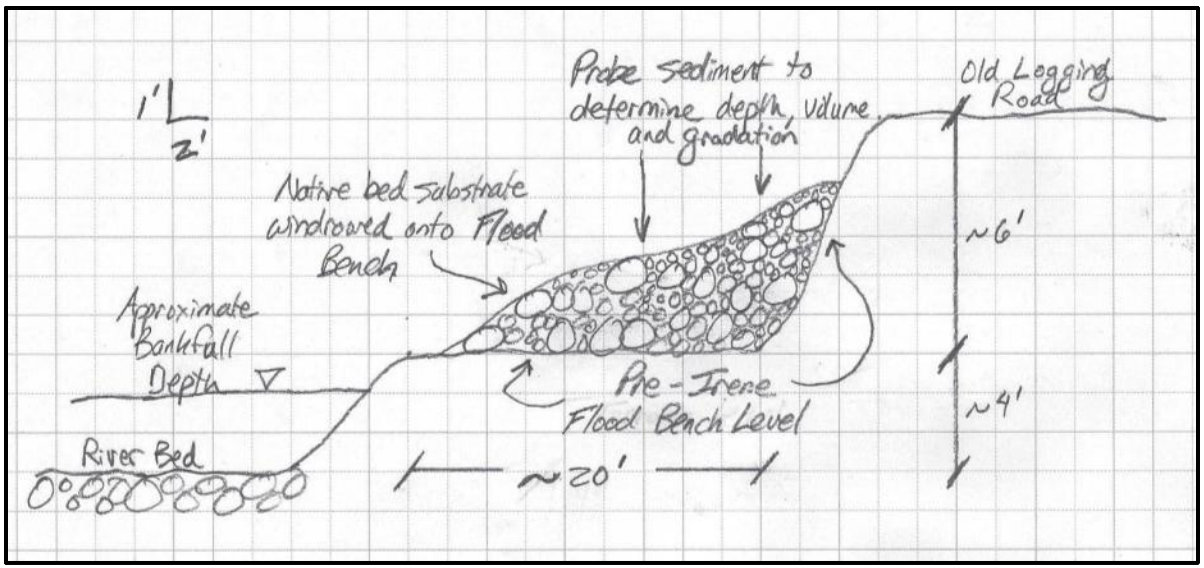


Figure 6-7. Schematic longitudinal profile of an active channel showing identifiable features. Schematic cross section profiles corresponding to reaches on the longitudinal profile show the evolution of the reaches from Type I to Type V. Typical width-depth (F) values are shown. Size of the arrows indicate the relative importance and direction of the dominant processes, degration, aggradation and lateral bank erosion.

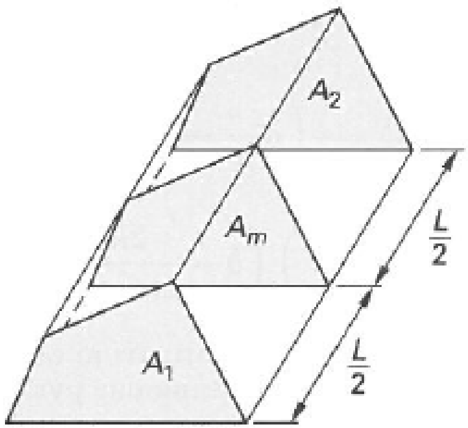
Natural Bed Stabilization: Quantify Available Sediment Volume & Gradation

- Probe coarse sediments on channel margins, berms, and floodplains
- Estimate sediment gradation
- Test pit or exploratory trench may be necessary
- Use end-area method to estimate volume of deposit



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

Volume Estimation

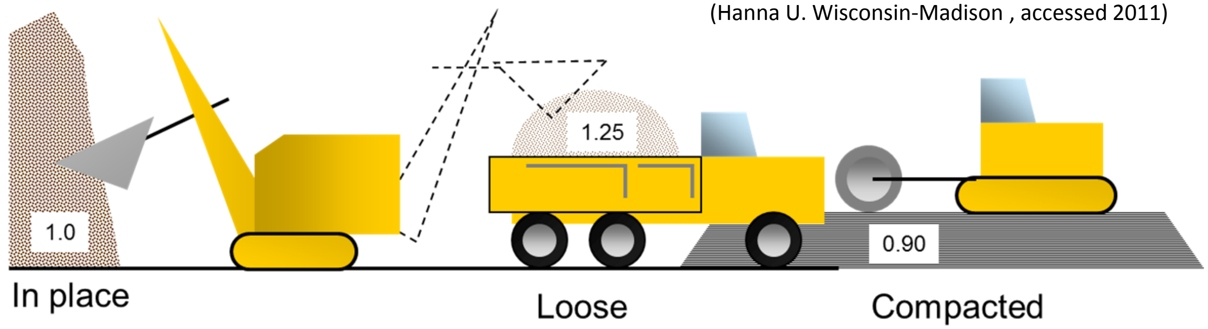


$$V = \frac{L(A_1 + A_2)}{2}$$

(Lindeburg, 2003)

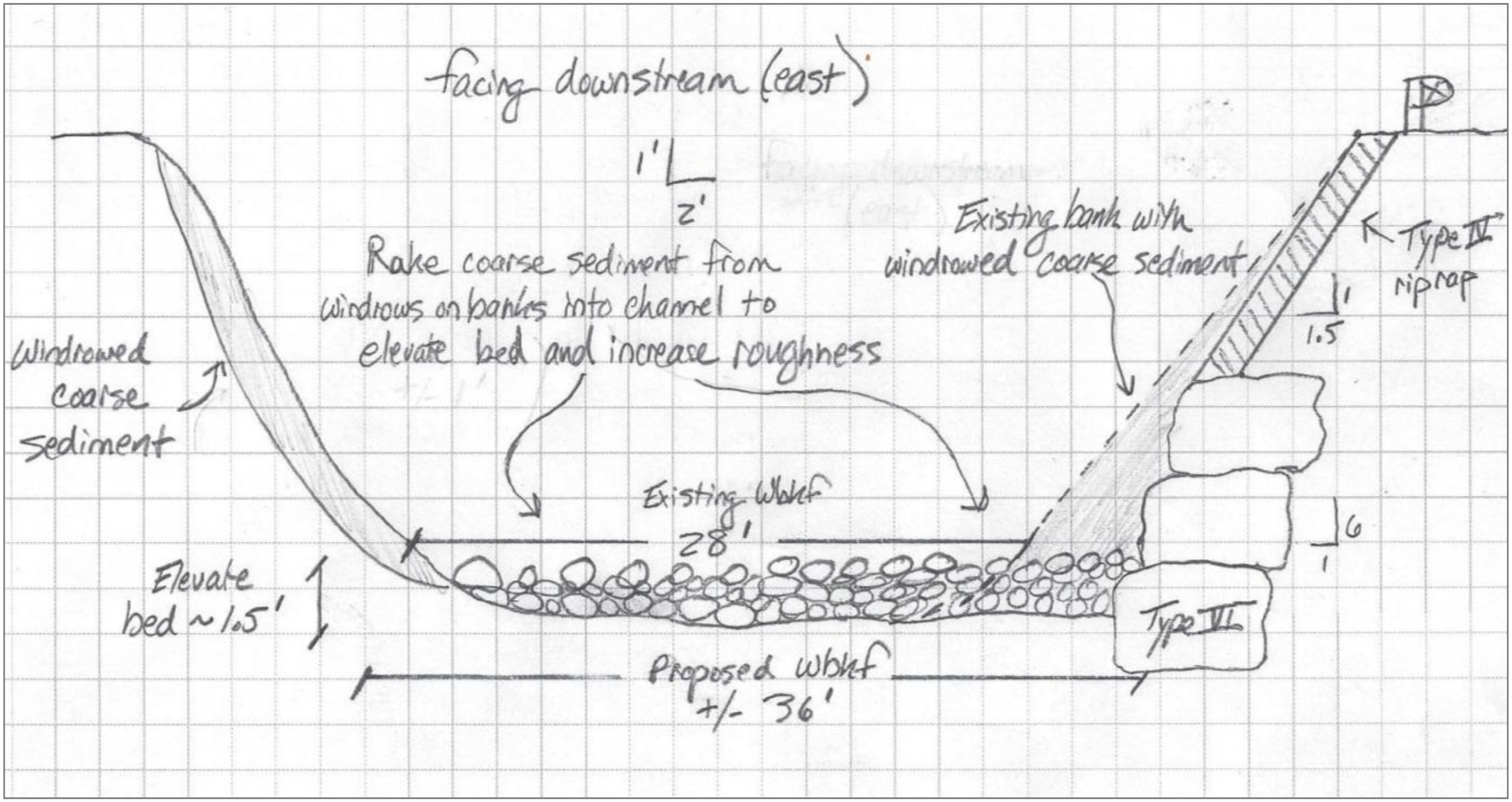
1.0 CUBIC YARD IN NATURAL CONDITION (IN-PLACE YARD) = 1.25 CUBIC YARD AFTER DIGGING (LOOSE YARDS) = 0.90 CUBIC YARD AFTER COMPACTED (COMPACTED YARDS)

(Hanna U. Wisconsin-Madison , accessed 2011)



Soil Type	Initial Soil Condition	Bank	Convrted to: Loose	Compacted
Clay	Bank	100	127	0.90
	Loose	0.79	100	0.71
	Compacted	111	141	100
Common earth	Bank	100	125	0.90
	Loose	0.80	100	0.72
	Compacted	111	139	100
Rock (blasted)	Bank	100	150	130
	Loose	0.67	100	0.87
	Compacted	0.77	115	100
Sand	Bank	100	112	0.95
	Loose	0.89	100	0.85
	Compacted	105	118	100

Natural Bed Stabilization: Channel Fill Recommendations



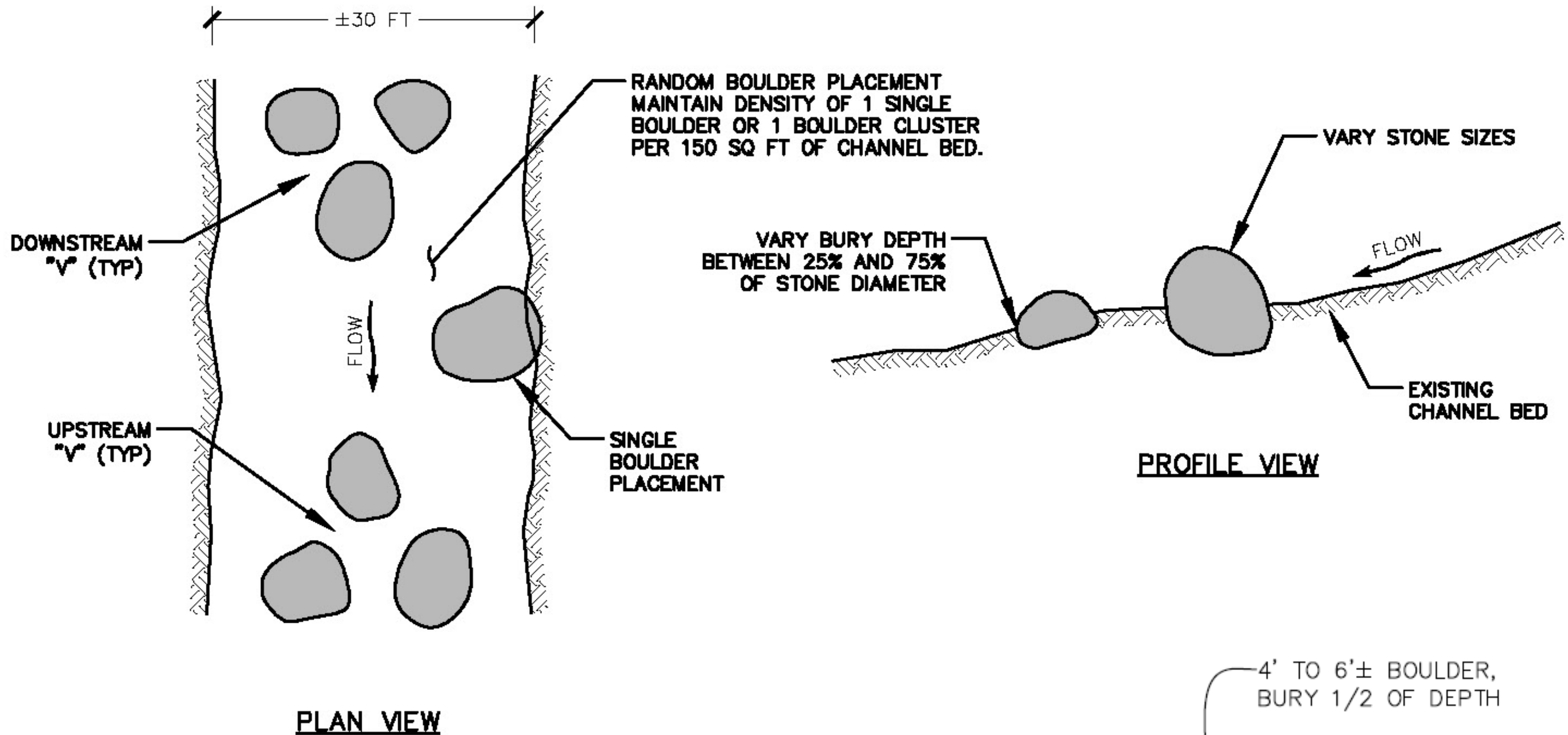
Design plans to elevate and roughen channel bed using native coarse sediment along channel banks in Bridgewater, VT. (FEA & MMI, 2012)

Natural Bed Stabilization: Channel Fill Recommendations

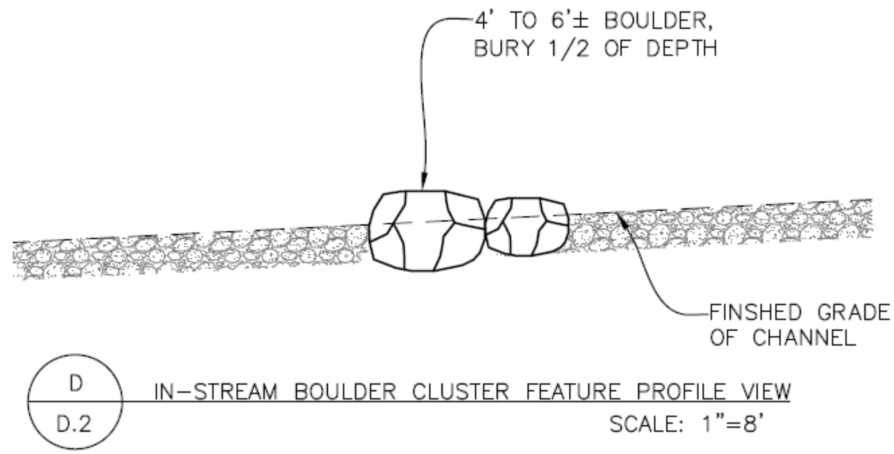
- Maximize the bankfull channel width and floodprone width where possible
- Compare the existing and proposed channel incision ratios
- Consider adjacent property and infrastructure to ensure no increase in risk due to fill.
- Carefully excavate deposits over floodplains and benches while leaving a veneer 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. Boulders should be large enough to remain in place during moderate floods (e.g., 10-year flood).

Neshobe River, VT Route 73 (E. Fitzgerald, 2012)

Natural Bed Stabilization: Channel Roughening

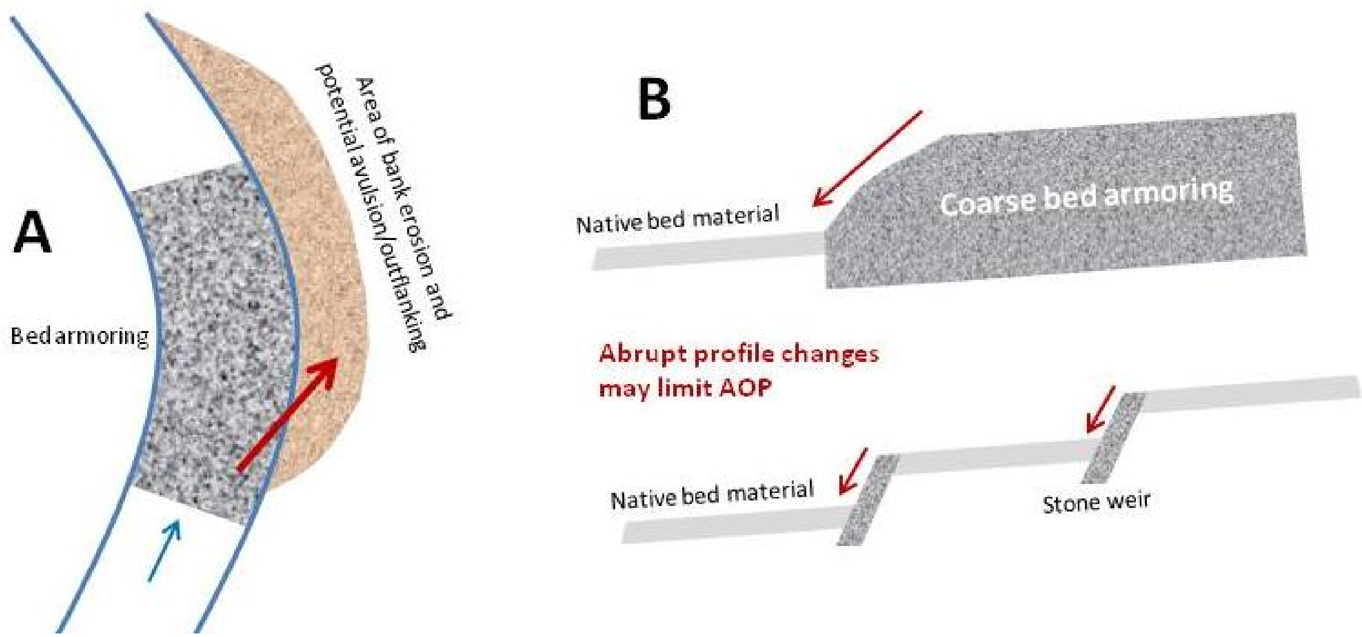


Top: Design plans to install boulders and improve aquatic habitat on Great Brook in Plainfield, Vermont. (MMI, 2010)



Boulder Cluster Design on Gulf Brook in Keene, NY (ESPC and Fitzgerald Environmental, 2014)

Grade Control Design: Bed and Bank Transitions



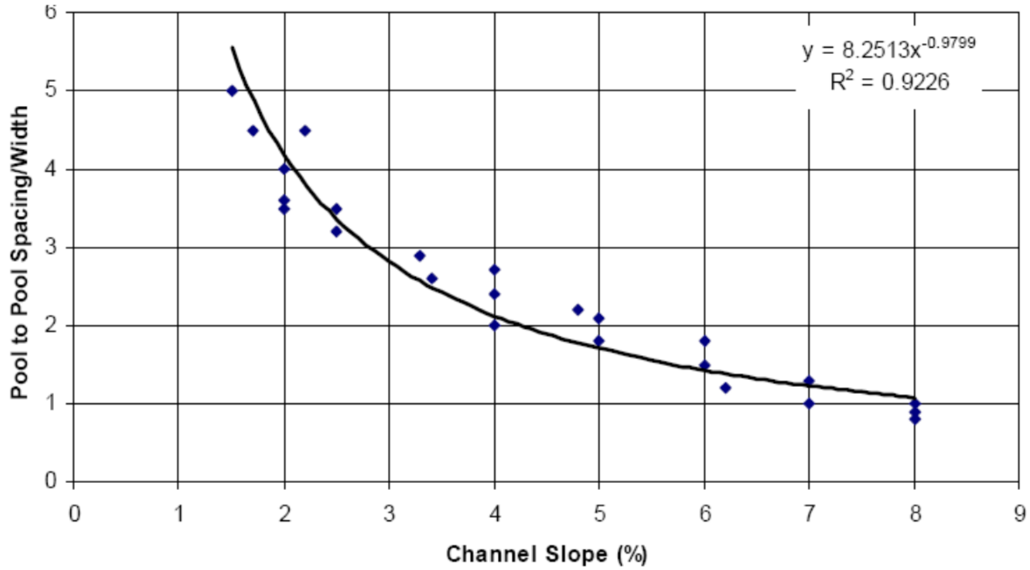
(Schiff et al., 2014)

Design Elements:

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

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

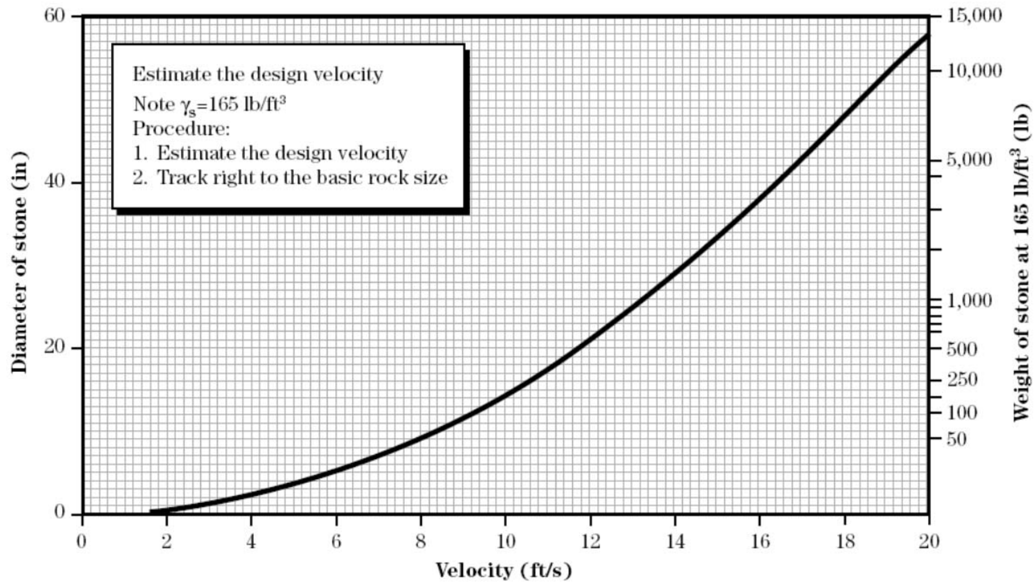
Profile:

- 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

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: Rock Sizing & Type

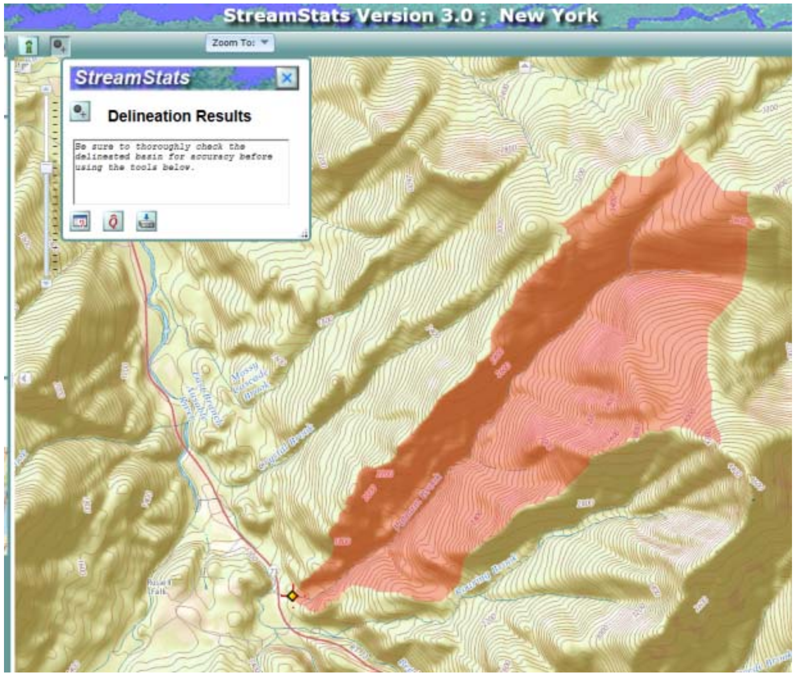
Table TS14C–3 Summary of techniques

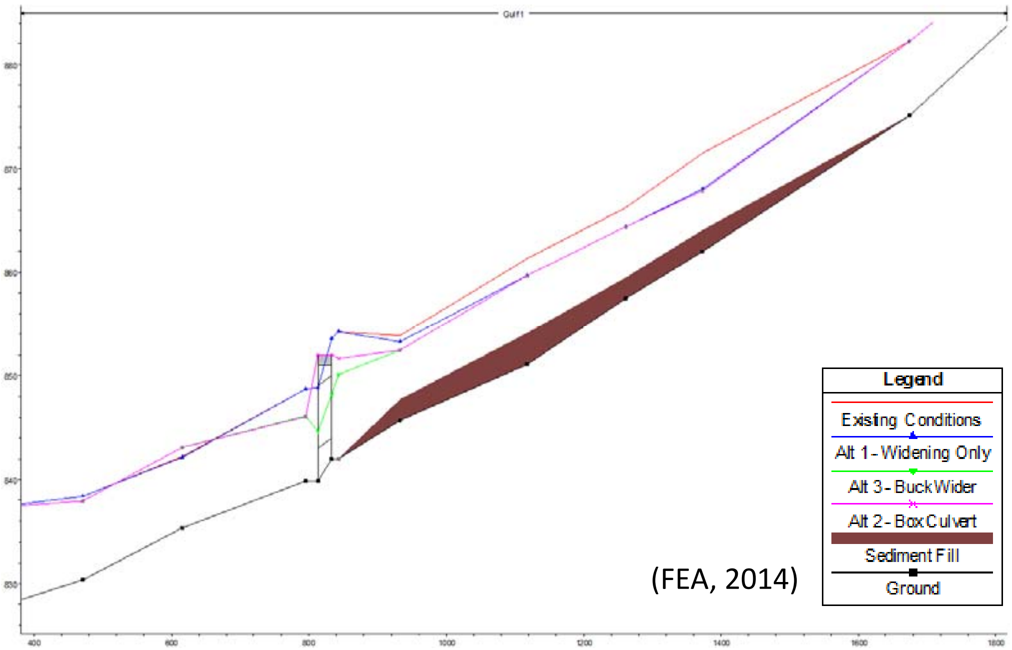
Technique	High or low energy	Slopes	Typical application(s)
Isbash	Both	Not specified	Rock revetment, stilling basins, river closures
108 Report	Both	<10%	Quick assessments for stable stone requirements
Maynord	Low	<2%	Rock revetment, bank protection, stone toe
Abt and Johnson	High	2% to 20%	Overtopping, grade protection
ARS – rock chute	High	2% to 40%	Overtopping, rock chutes, grade protection
USBR	High	Not specified	Riprap below a stilling basin
USGS Blodgett	Both	Not specified	Riprap stability
USACE Steep Slope Riprap	High	2% to 20%	Rock chutes, grade protection
USACE Habitat Boulder	High	Not specified	Instream boulders for habitat enhancement
CALTRANS RSP	Low	<2%	Rock revetment, bank protection, stone toe
Lane's (FWS)	Low	<2%	Stone bank protection, stream barbs with adjustments

(210–VI–NEH, August 2007) TS14C–11

NRCS, 2007. Technical Supplement 14c, Stone Sizing Criteria in Part 654 of the National Engineering Handbook. 210–VI–NEH, August 2007. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/?cid=stelprdb1044707. Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, DC.

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: Bed Armor Performance Standards

(MMI, 2014)

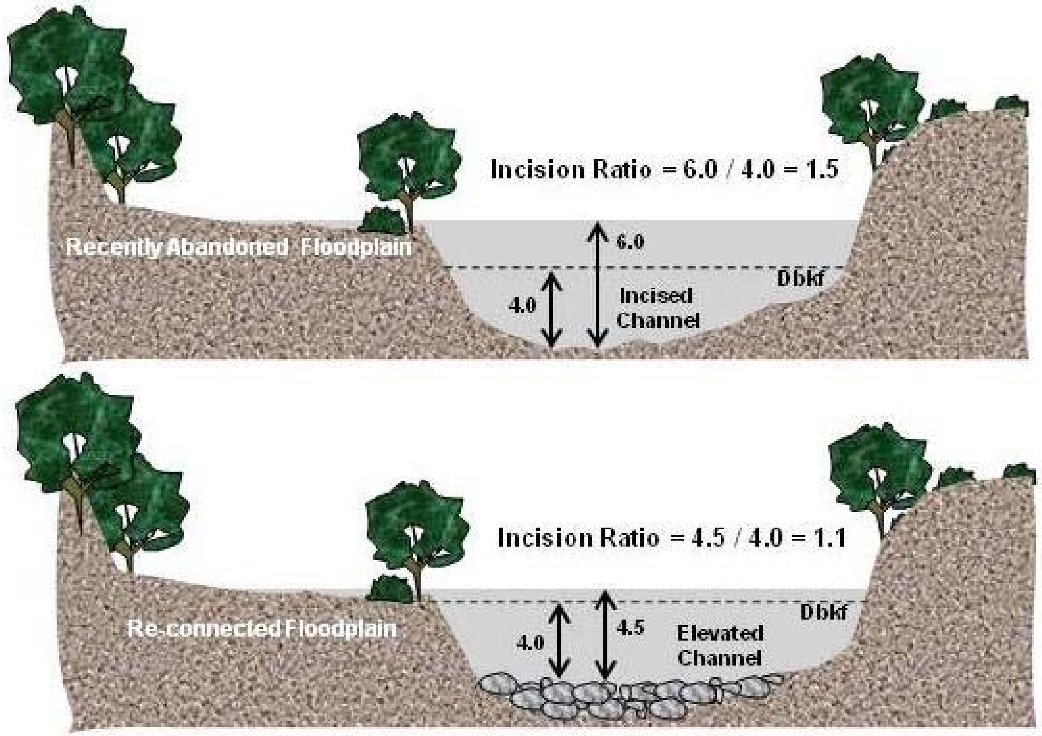
(Fitzgerald Environmental, 2015)

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

Grade Control Design: Bed Armoring Example

South Branch Tweed River (R. Schiff & E. Fitzgerald ,2012-13)



Schematic of increased floodplain access and subsequent increase in cross-sectional flow area resulting from an elevated channel bed achieved through bed armoring. Channel incision is reduced by decreasing the ratio between overbank flow depth and bankfull depth (Dbkf).

(Milone & MacBroom, Inc. and Fitzgerald Environmental, 2013)

Summary – Grade Control Design

<u>Assessment</u>

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

<u>Design</u>

- 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
  - New York State Environmental Quality Review (SEQR) for larger projects
- Adirondack Park Agency
  - Bank stabilization projects jurisdictional if area exceeds 100 square feet
  - In-stream rock/log vanes are not jurisdictional
- 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

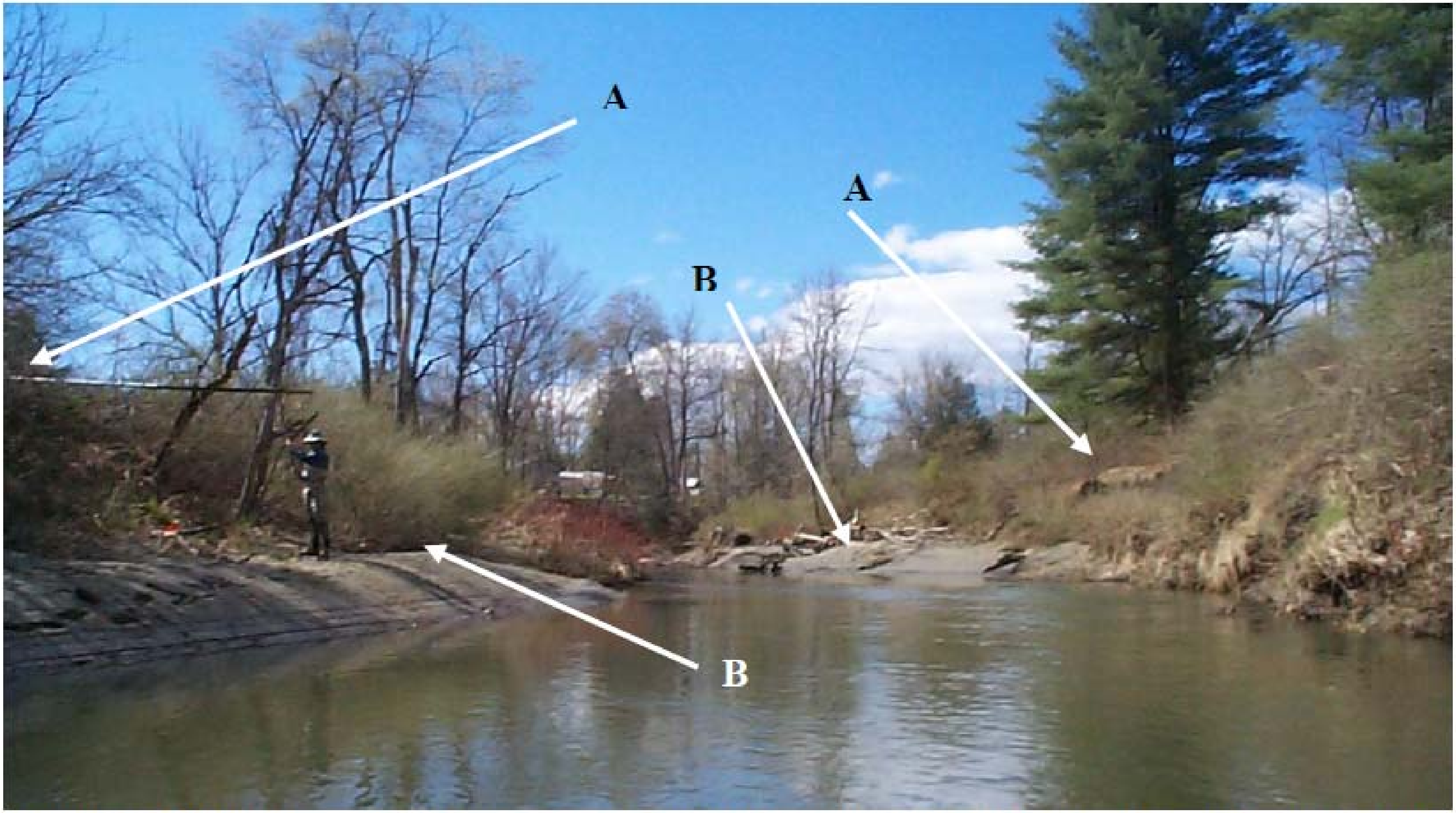


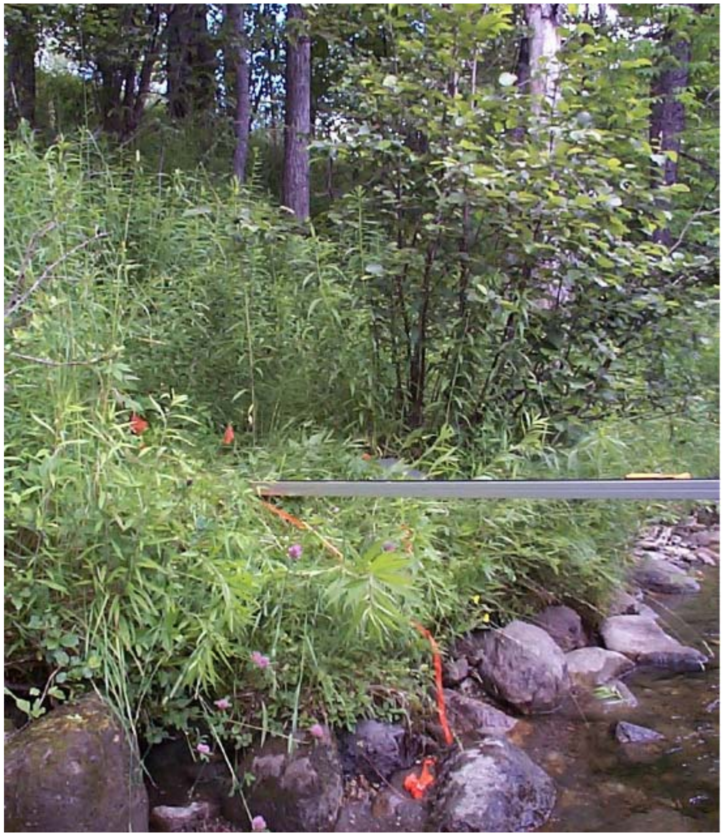
Figure 1 Embryonic active floodplain developing in incised channel. Stage IV of channel evolution.

a. Abandoned floodplain

b. Active floodplain indicating bankfull stage

(VTANR, 2009)

Bankfull Indicators

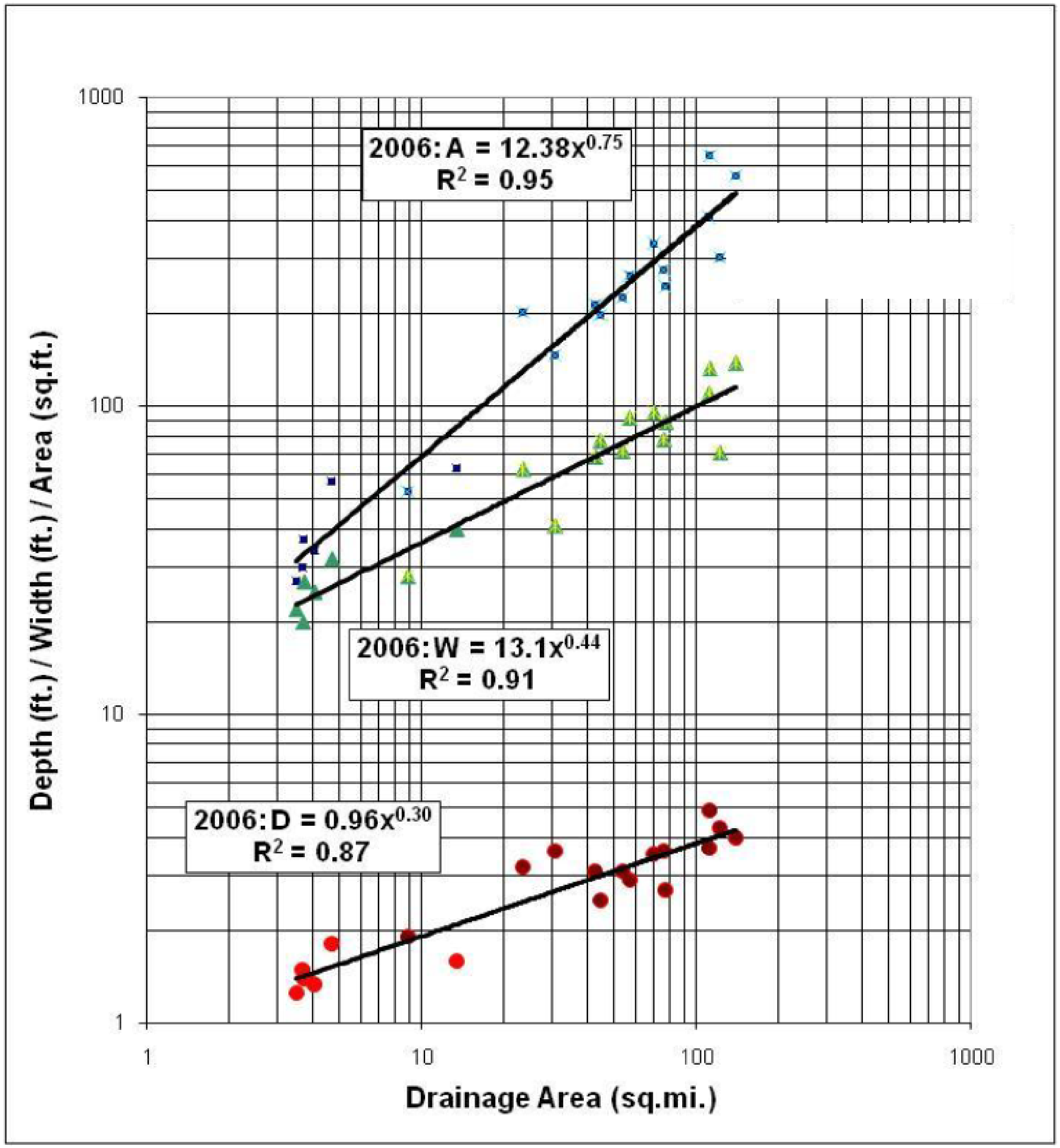


(VTANR, 2009)

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 – VT HGR



(VTANR, 2006)

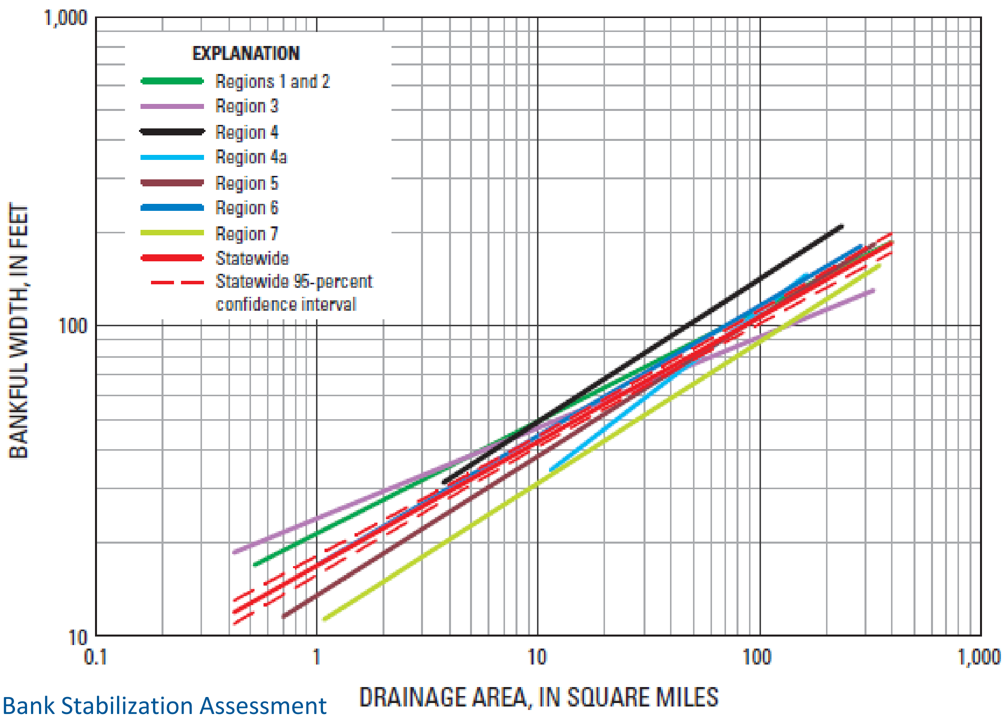
Bank Stabilization Assessment

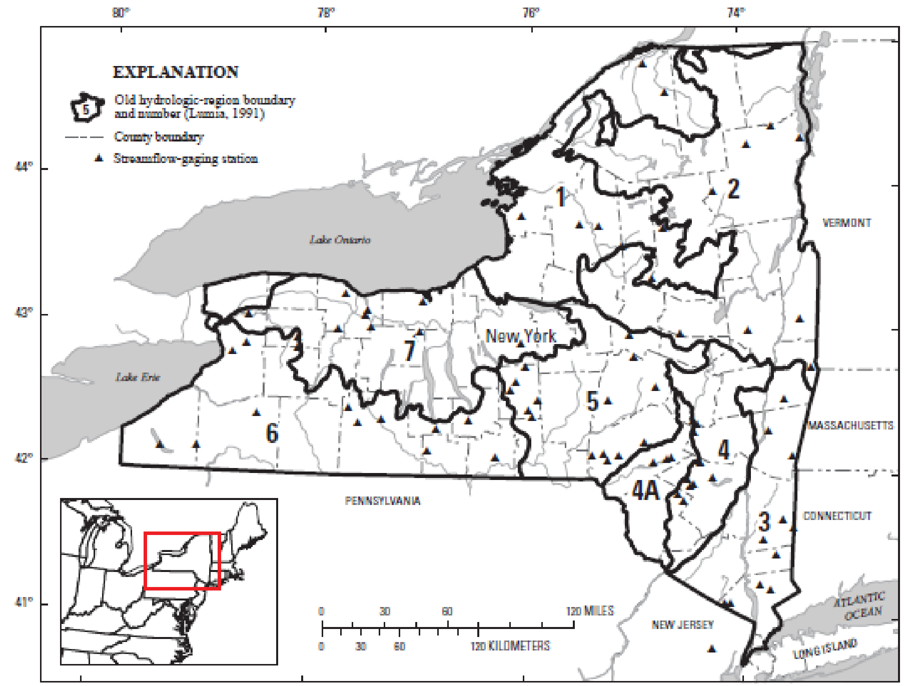
Approximate Channel Sizing – NY HGR

[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
4a	9	$9.1\ DA^{0.545}$	10	.98
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

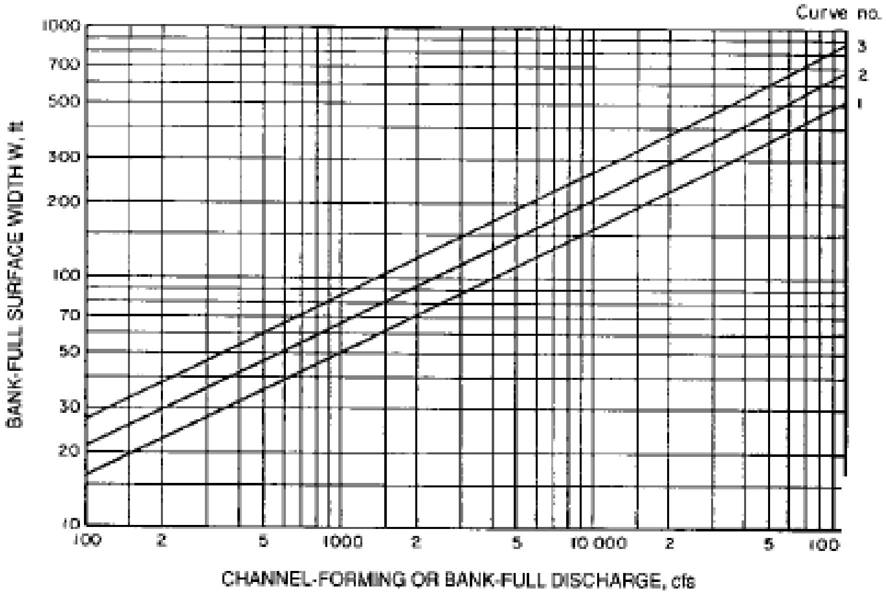
(Mulvihill et al., 2009)





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

Approximate Channel Sizing – Regime

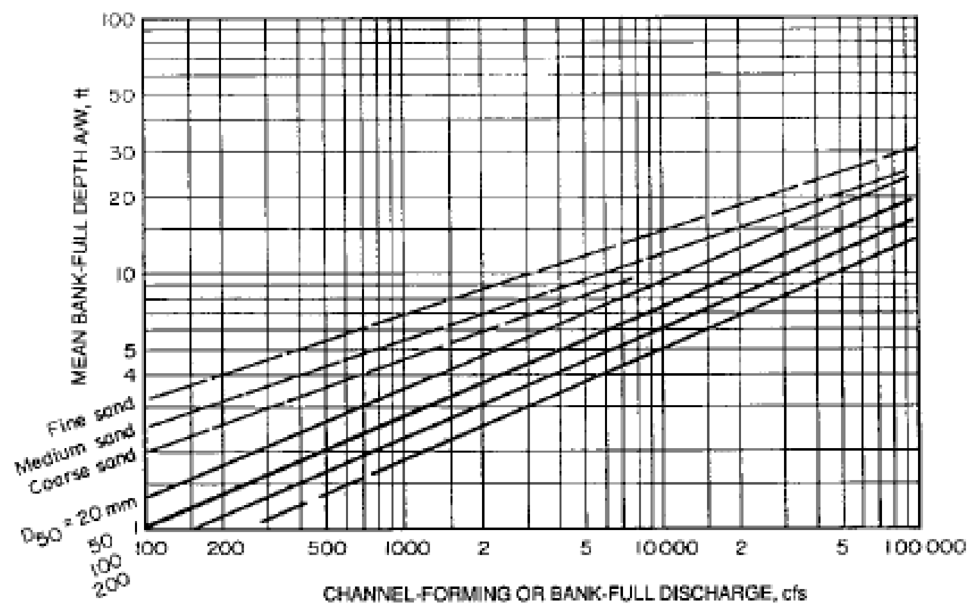


TENTATIVE GUIDANCE: CURVE 1: STIFF COHESIVE OR VERY COARSE GRANULAR BANKS
CURVE 2: AVERAGE COHESIVE OR COARSE GRANULAR BANKS.
CURVE 3: SANDY ALLUVIAL BANKS.

SEE PARAGRAPH 5-5 FOR LIMITATIONS.

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

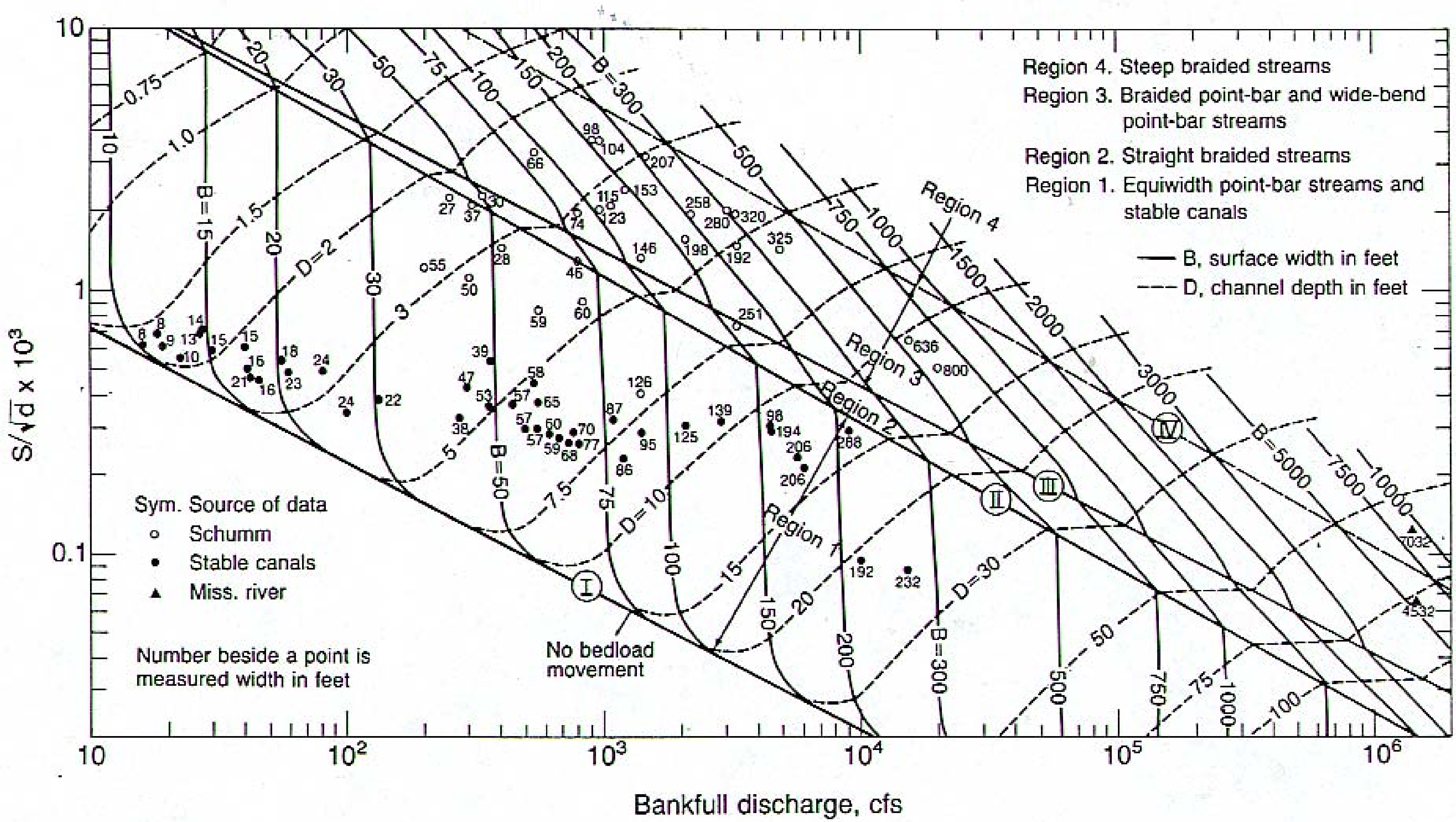
(USACE, 1994)



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).

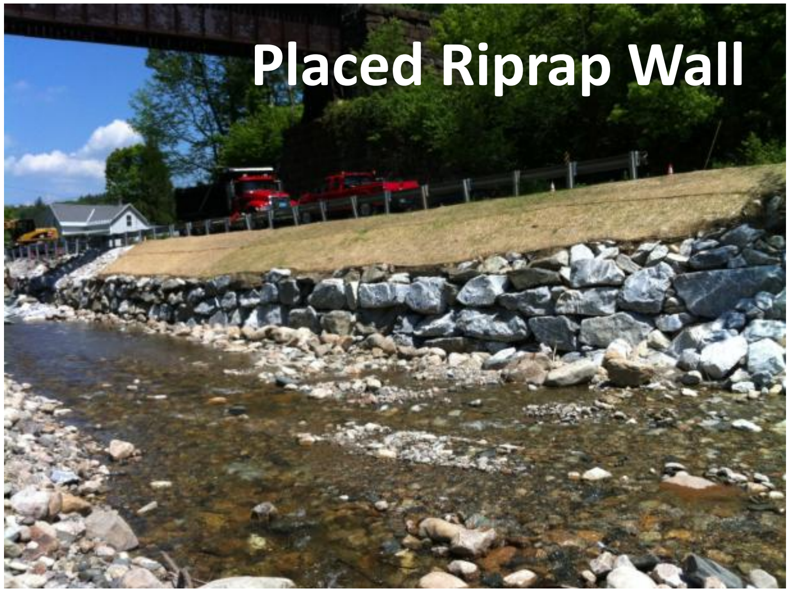
APPLIES BASICALLY TO CHANNELS WITH LOW BED SEDIMENT TRANSPORT.

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

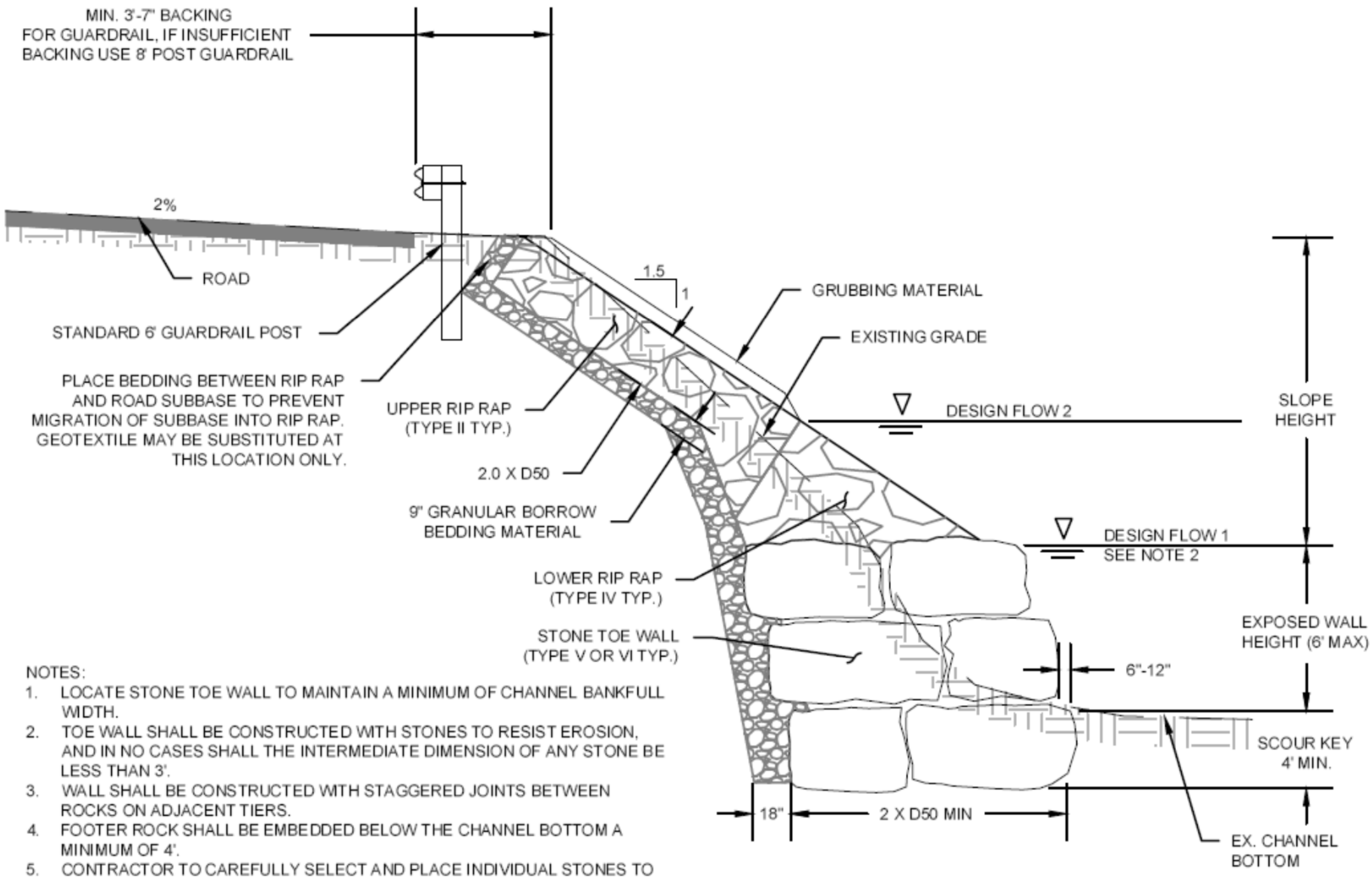
- Increase roughness
- Push thalweg away from bank
- Enhance habitat
- Hydraulic modeling needed
- Force-balance analysis
- Piles, wood species, etc

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



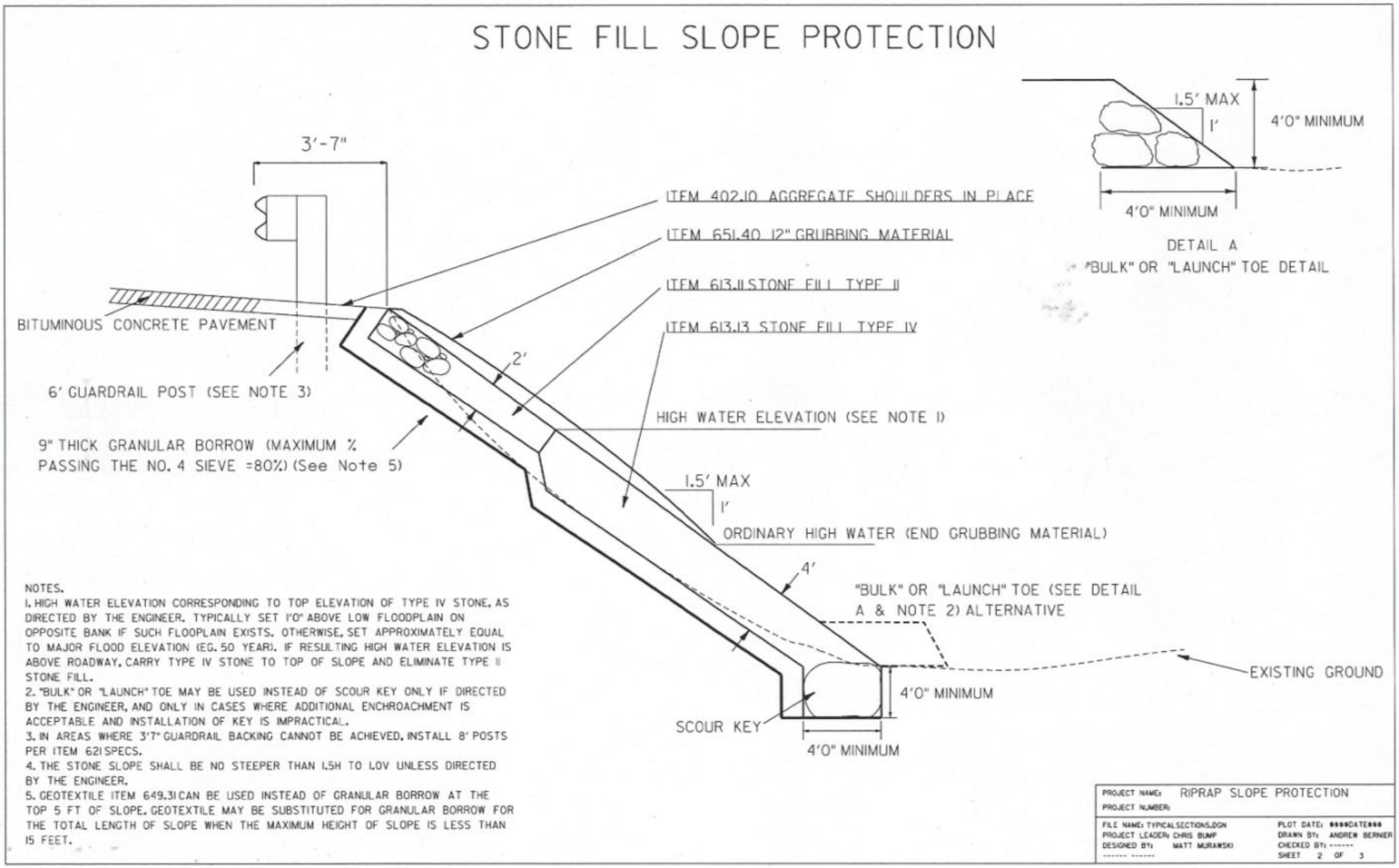
NOTES:
1. LOCATE STONE TOE WALL TO MAINTAIN A MINIMUM OF CHANNEL BANKFULL WIDTH.
2. TOE WALL SHALL BE CONSTRUCTED WITH STONES TO RESIST EROSION, AND IN NO CASES SHALL THE INTERMEDIATE DIMENSION OF ANY STONE BE LESS THAN 3'.
3. WALL SHALL BE CONSTRUCTED WITH STAGGERED JOINTS BETWEEN ROCKS ON ADJACENT 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.

TYPICAL PLACED RIP RAP WALL SECTION

SCALE: 1' = 5'

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

Bank Stabilization Design: Riprap Slope



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

Placed Riprap Wall Design

Placed Riprap Wall Design: Rock Type and Sizing

Rock Type

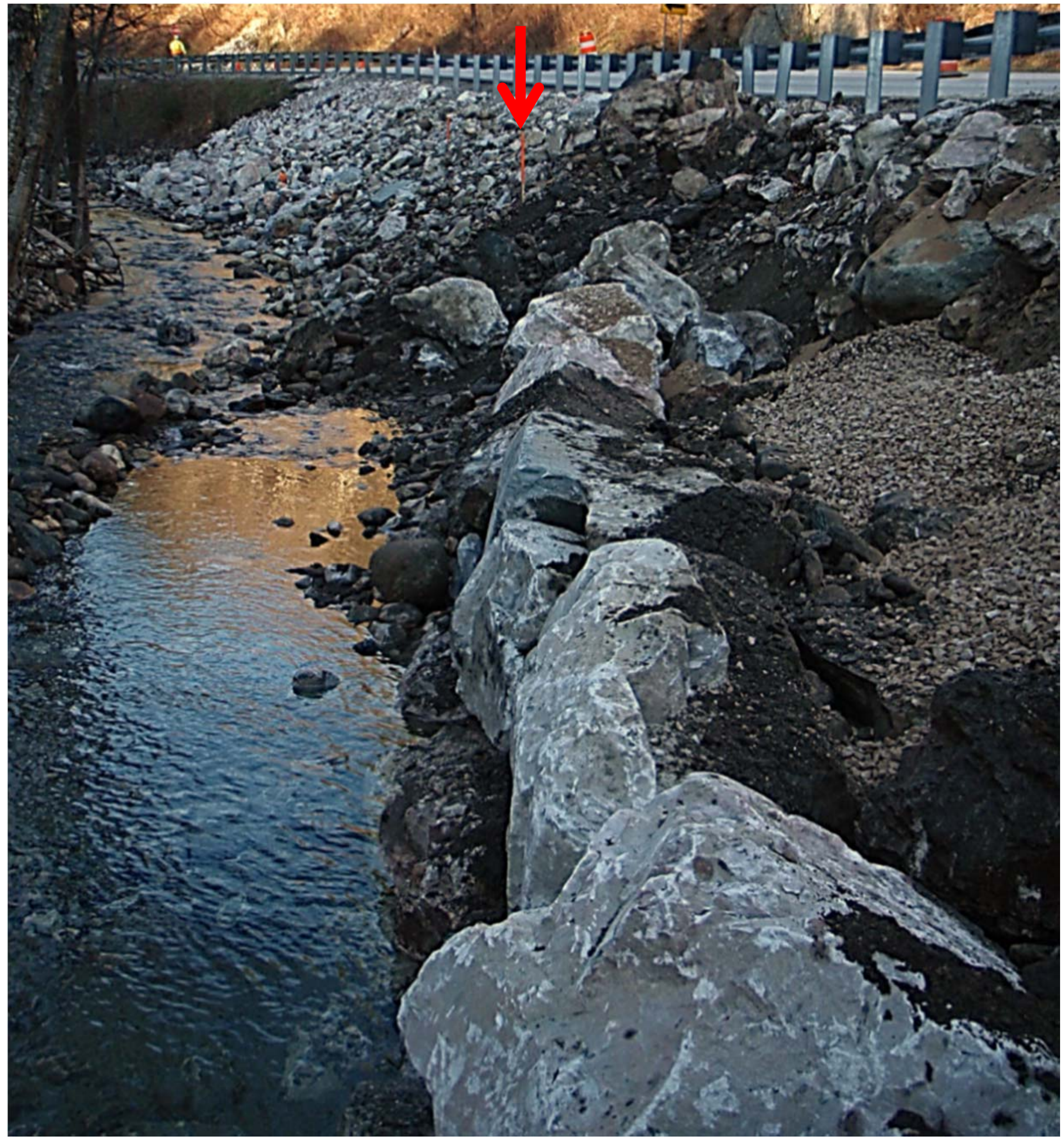
- Large (3-6 ft diameter), blocky rock for stacking
- Special sourcing and selection at quarry
- Maintain voids at bottom of wall at water interface for fish refuge during high flows

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

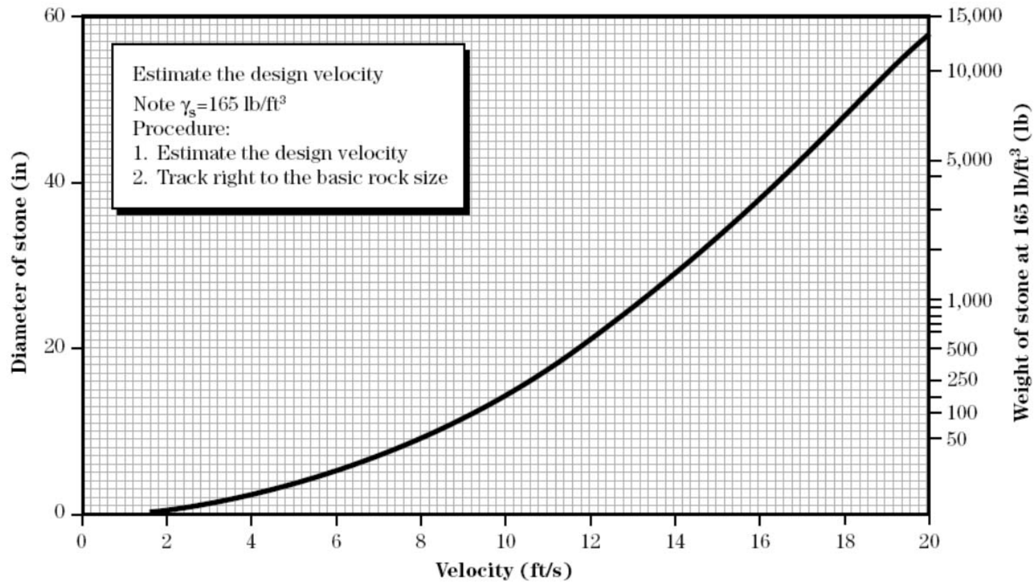
(E. Fitzgerald, 2013)

Placed Riprap Wall Design: Height and Slope

Placed Riprap Wall Design: Rock Type and Sizing

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

- Bank armor must resist erosion due to the design flood flow velocity and resultant shear stress
- Consider channel planform for rock sizing – moderate to severe bends may have increased velocity and scour potential
- Rock size transitions should be linked to the bankfull channel and floodplain elevations – rock size can typically be decreased above the floodplain stage

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 $\gamma_s = 165.36$ 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:

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

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 Below Channel Bottom (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

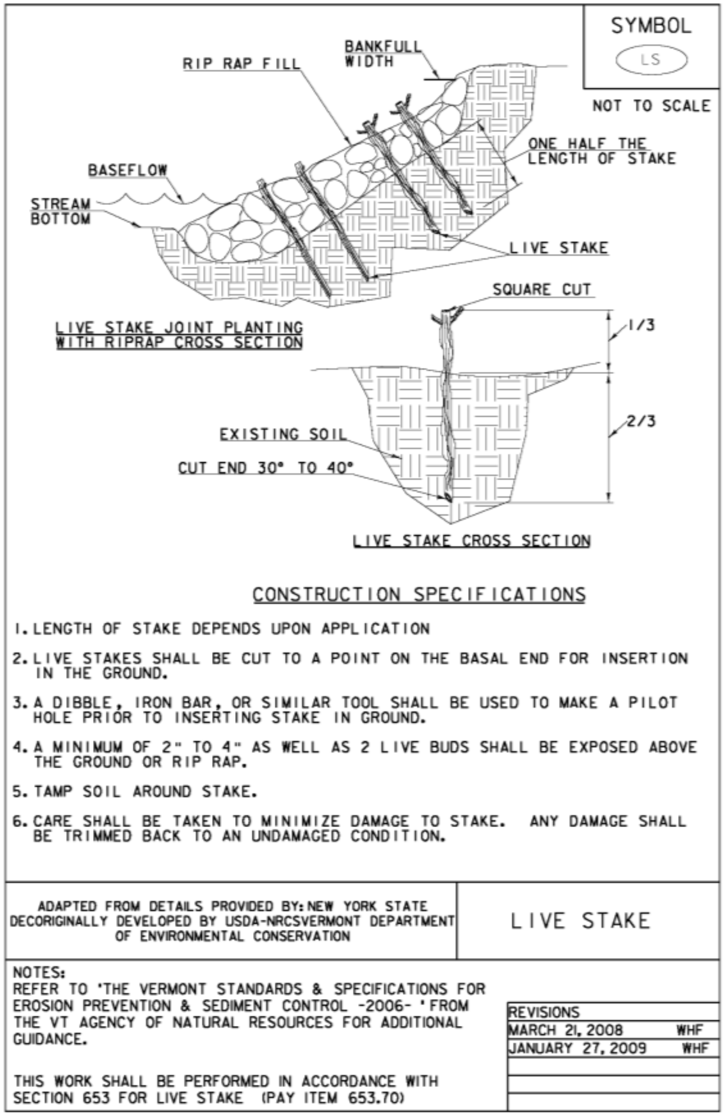
(E. Fitzgerald, 2013)

Placed Riprap Wall Design: Revegetation

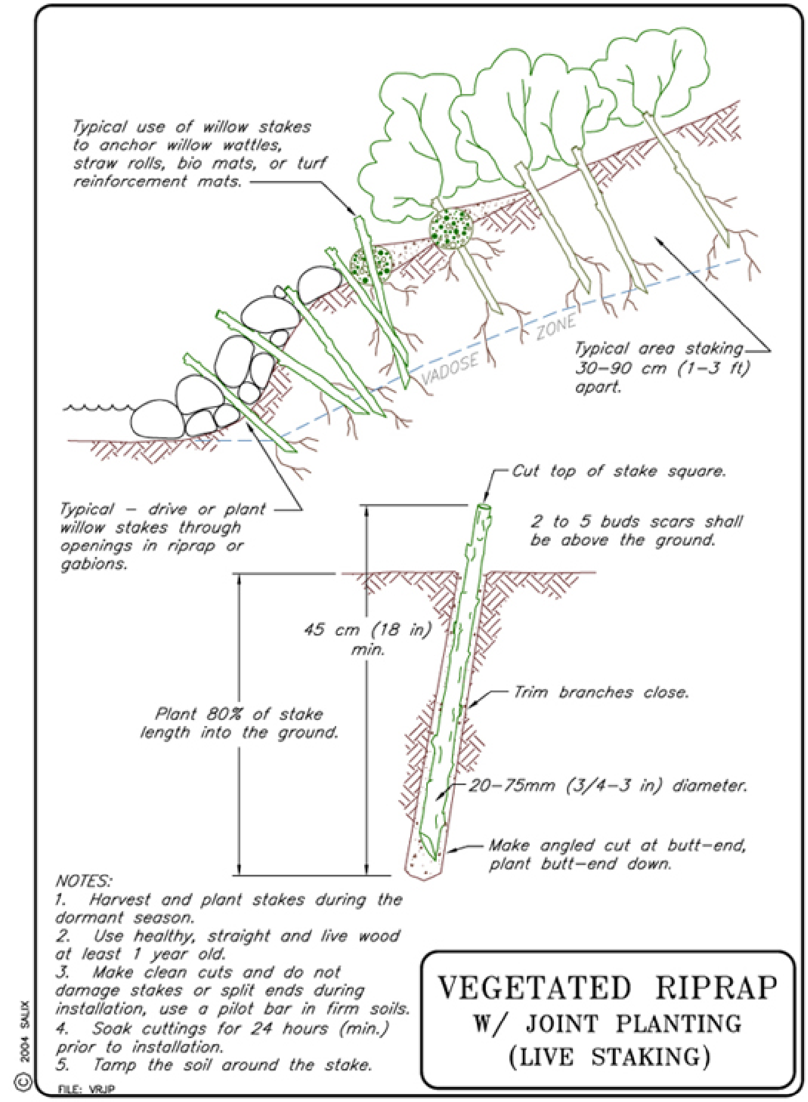
Post-Irene Repairs – Placed Riprap Wall with Vegetated Slope
South Branch of the Tweed River, VT Route 100, Killington

(E. Fitzgerald, 2013)

Placed Riprap Wall Design: Revegetation



(VTrans EPSC Specifications, 2009)



(McCullah and Gray, 2005)

Summary – Placed Riprap Wall Design

<u>Assessment</u>

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

<u>Design</u>

- 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 a placed riprap wall preferred over sloping riprap? Vice versa?*

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
  - New York State Environmental Quality Review (SEQR) for larger projects
- Adirondack Park Agency
  - Bank stabilization projects jurisdictional if area exceeds 100 square feet
  - In-stream rock/log vanes are not jurisdictional
- 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

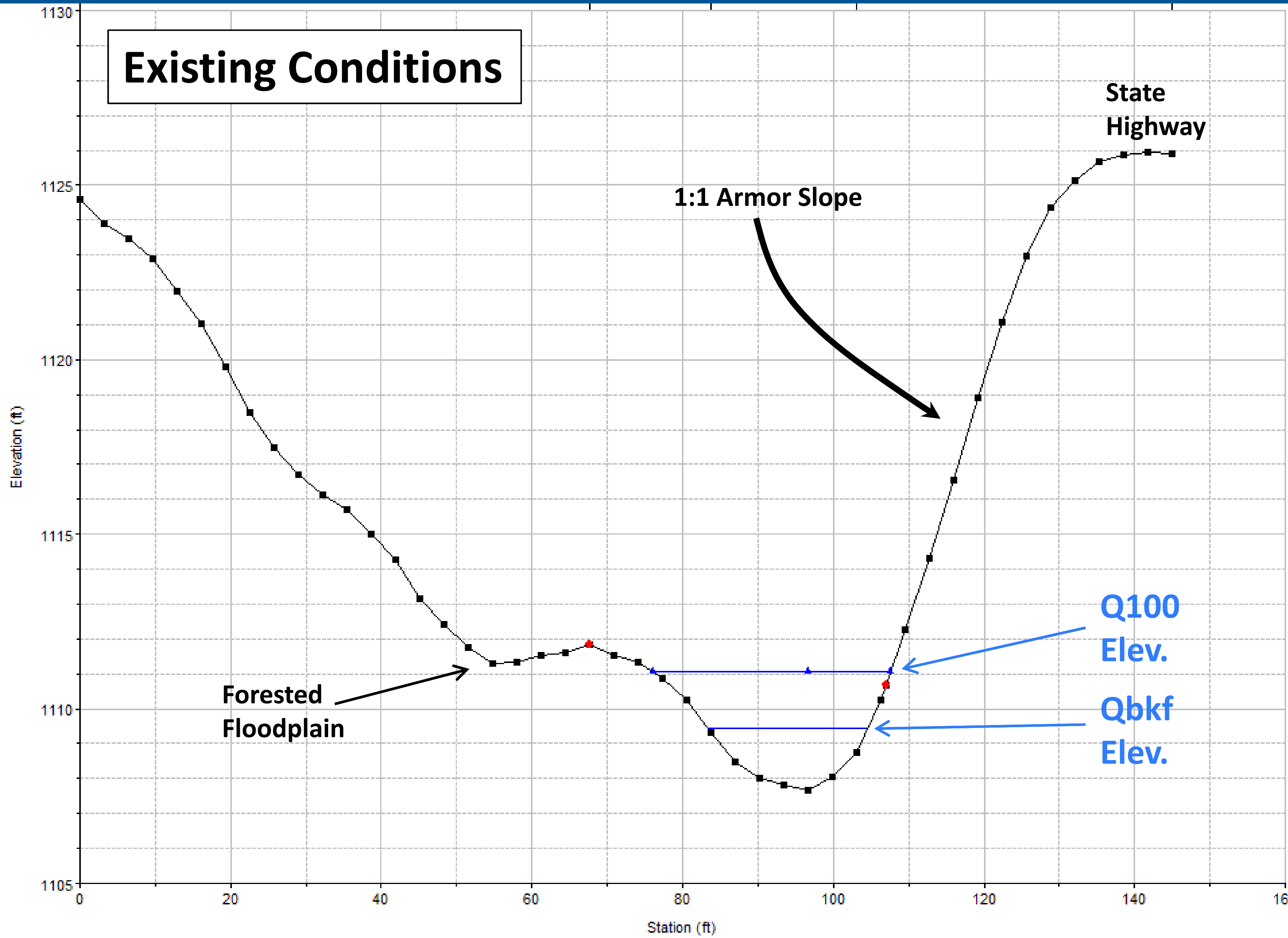
- Complete work during low flow periods to limit downstream sedimentation and allow for proper visibility to successfully complete the work.
- Temporary berm made of pushed up deposited material are often used to guide water out of the work areas and provide a work platform to keep machinery out of main 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.

Grade Control Design Exercise

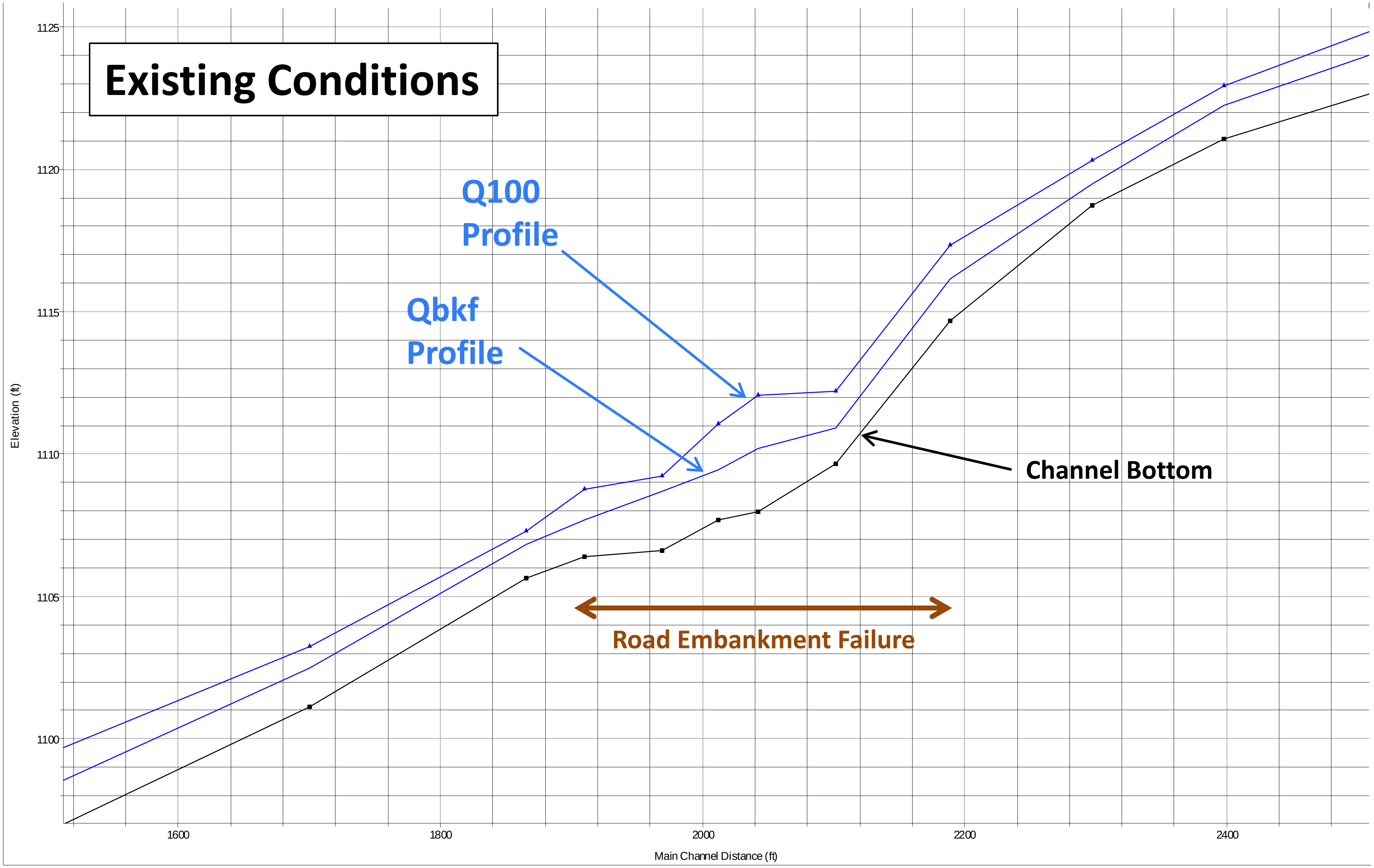
- *1% annual exceedance probability flood leads to severe localized channel bed erosion and failure of an adjacent road embankment for 300 linear feet.*
- *The embankment slope was repaired during emergency recovery with a steep riprap slope 1V:1H. The rock size is adequate but the top and toe of slope cannot be moved, and the toe of slope remains vulnerable to erosion due to channel downcutting.*
- *See channel and flood profiles and section on following pages.*
- *There is a forested floodplain across the river from the road embankment.*
- *Drainage area = 4.5 square miles; Channel Slope = 2.3%*
- *Cobble bed with median bed sediment size (D_{50}) = 80 millimeters*
- *Bankfull discharge = 200 cubic feet per second (average velocity = 6 fps)*
- *100-year flood discharge = 830 cubic feet per second (average velocity = 9 fps)*
- *Reach incision ratio = 1.3; Site incision ratio = 2.0*

1. *Predict the reference bankfull channel dimensions (feet): VTHGR (Trial 1); Regime (Trial 2); and Chang (Trial 3).*
2. *Evaluate the departure of existing channel dimensions from reference dimensions.*
3. *Evaluate changes in channel dimensions required to reduce erosion vulnerability.*
4. *Select an appropriate bed stabilization practice to restore reference channel dimensions and reduce threat of erosion along embankment toe.*
5. *Summarize your vision of the proposed grade control design.*

Grade Control Design Exercise



Grade Control Design Exercise



Grade Control Design Solution

Fitzgerald Environmental Associates, LLC
18 Severance Green, Suite 203
Colchester, VT 05446
Telephone: 802.876.7778
www.fitzgeraldenvironmental.com

Job: Grade Control Design Example

Sheet No. ______ of ______

Date: 1/13/16 Drawn by: EPF

Vertical Scale: ______ Horizontal Scale: ______

Solution:

① Channel Dimensions

Trial 1: VTHGR $W = 25'$, $D_m = 1.5'$ $A = 38 ft^2$

Trial 2: Use Curve 2 w/ $C = 2.1$

$$W = C\sqrt{Q} = 2.1\sqrt{200} = 29.7'$$
$$D = 1.5'$$

Trial 3: Chang $S/\sqrt{d} = \frac{0.023}{\sqrt{80}} \times 1000 = 2.6$

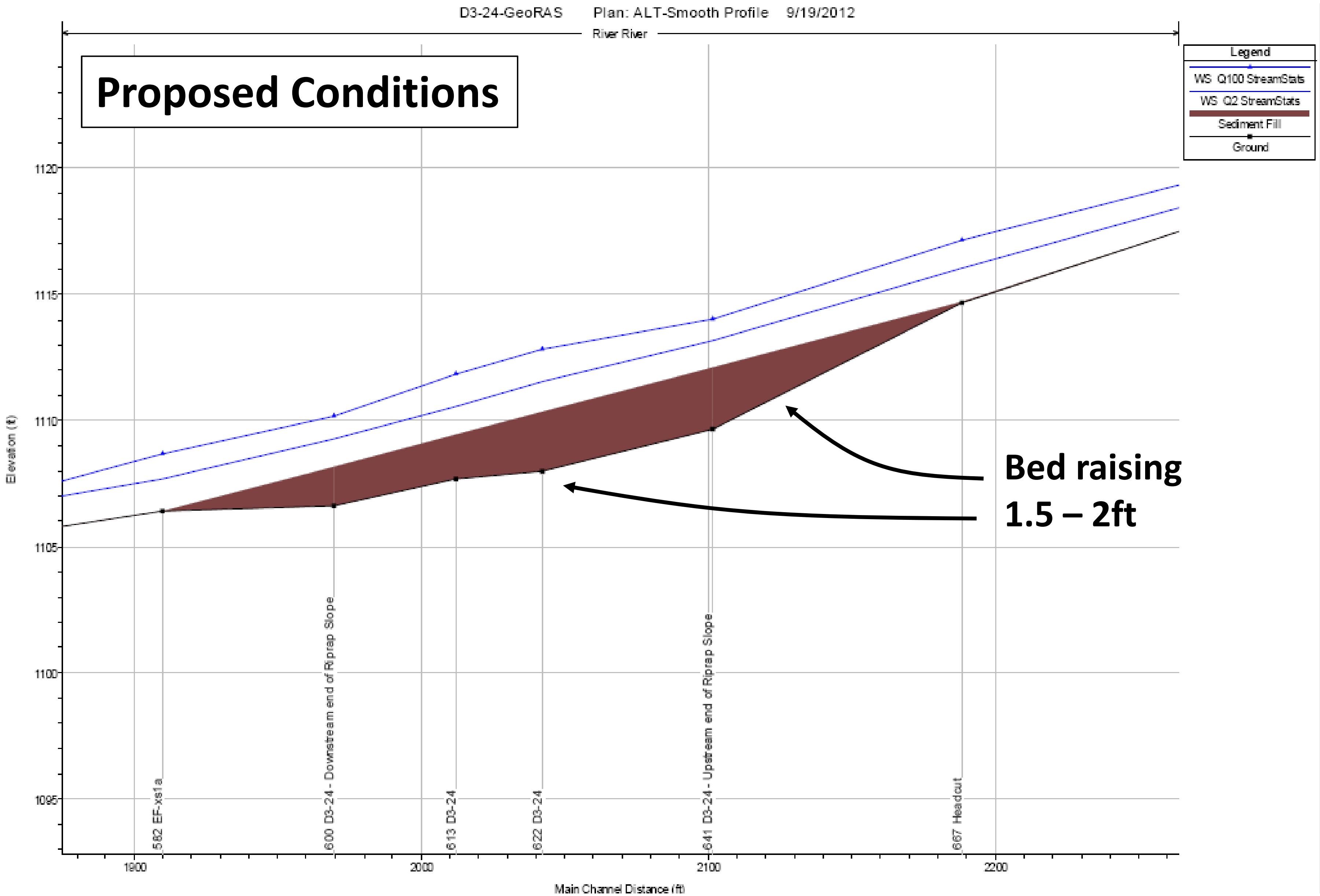
$$W = 35' \quad D = 2'$$

Design: $W = 30'$, $D = 1.5' - 2.0'$

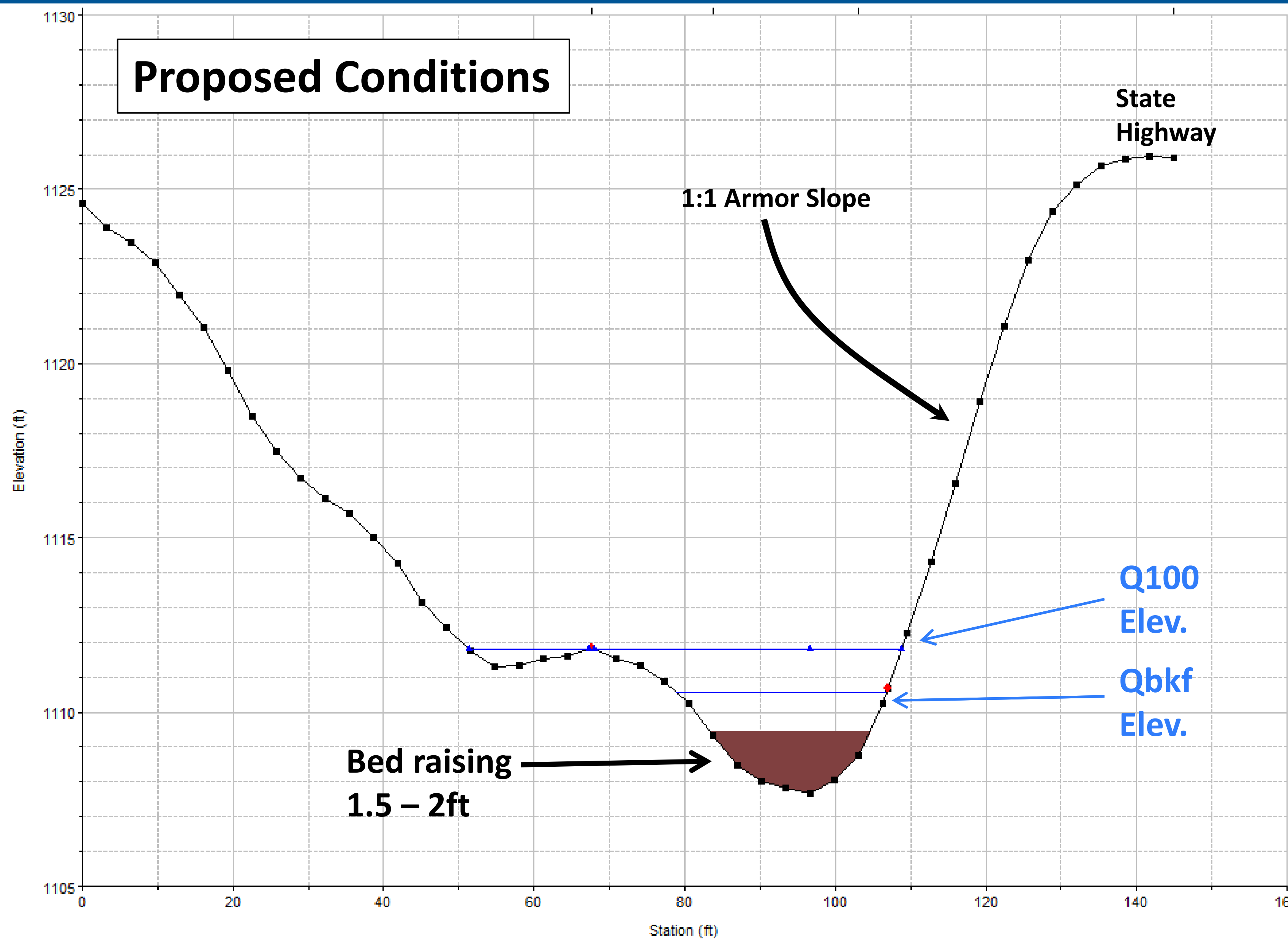
② Current width $= 20'$ $(-10')$
depth $= 1.5'$ $(0$ to $-0.5')$

Incision ration $= 2.0$, bed needs to be raised $1.5 - 2.0'$

Grade Control Design Solution



Grade Control Design Solution

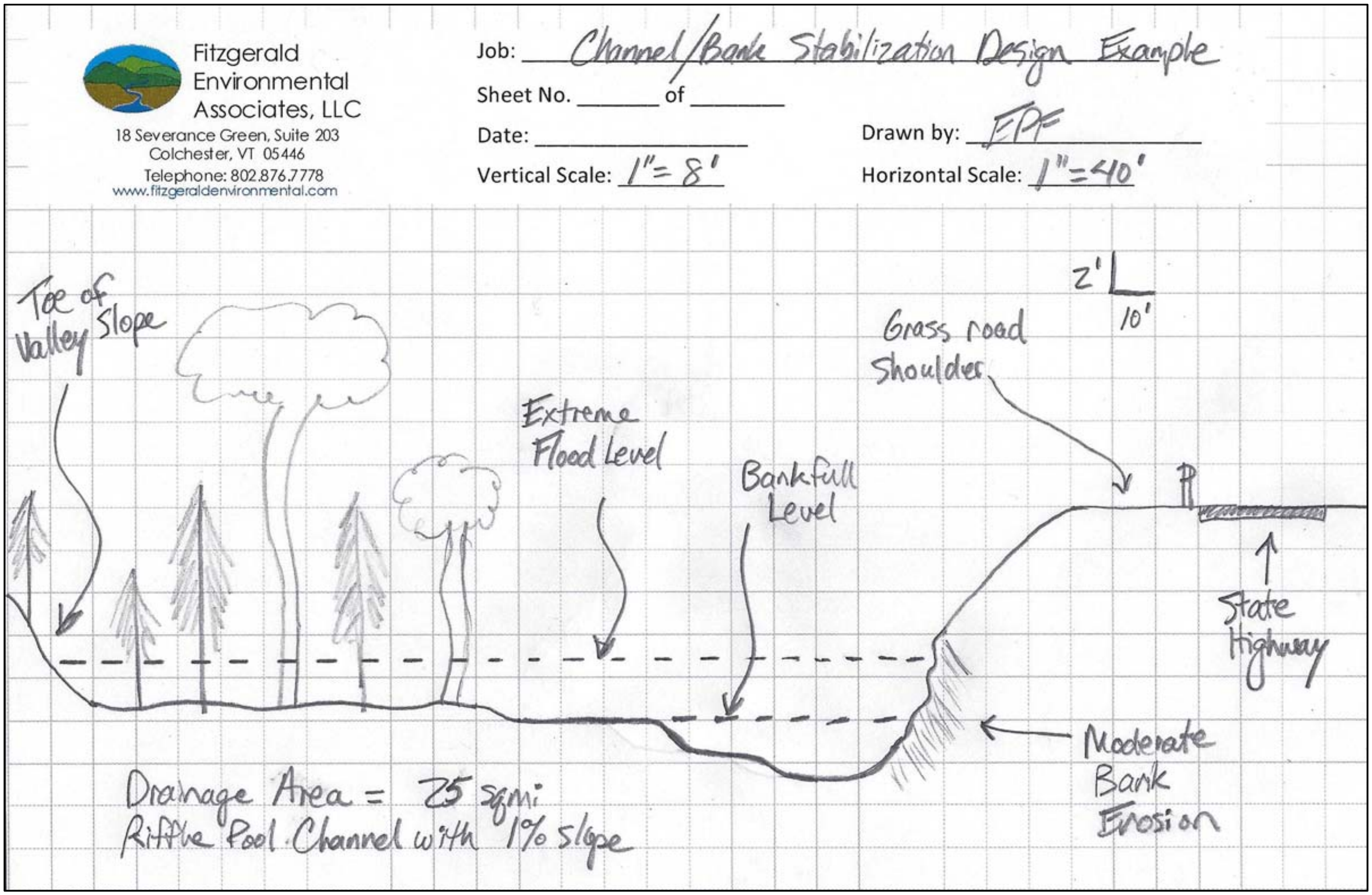


Bank Stabilization Design Exercise

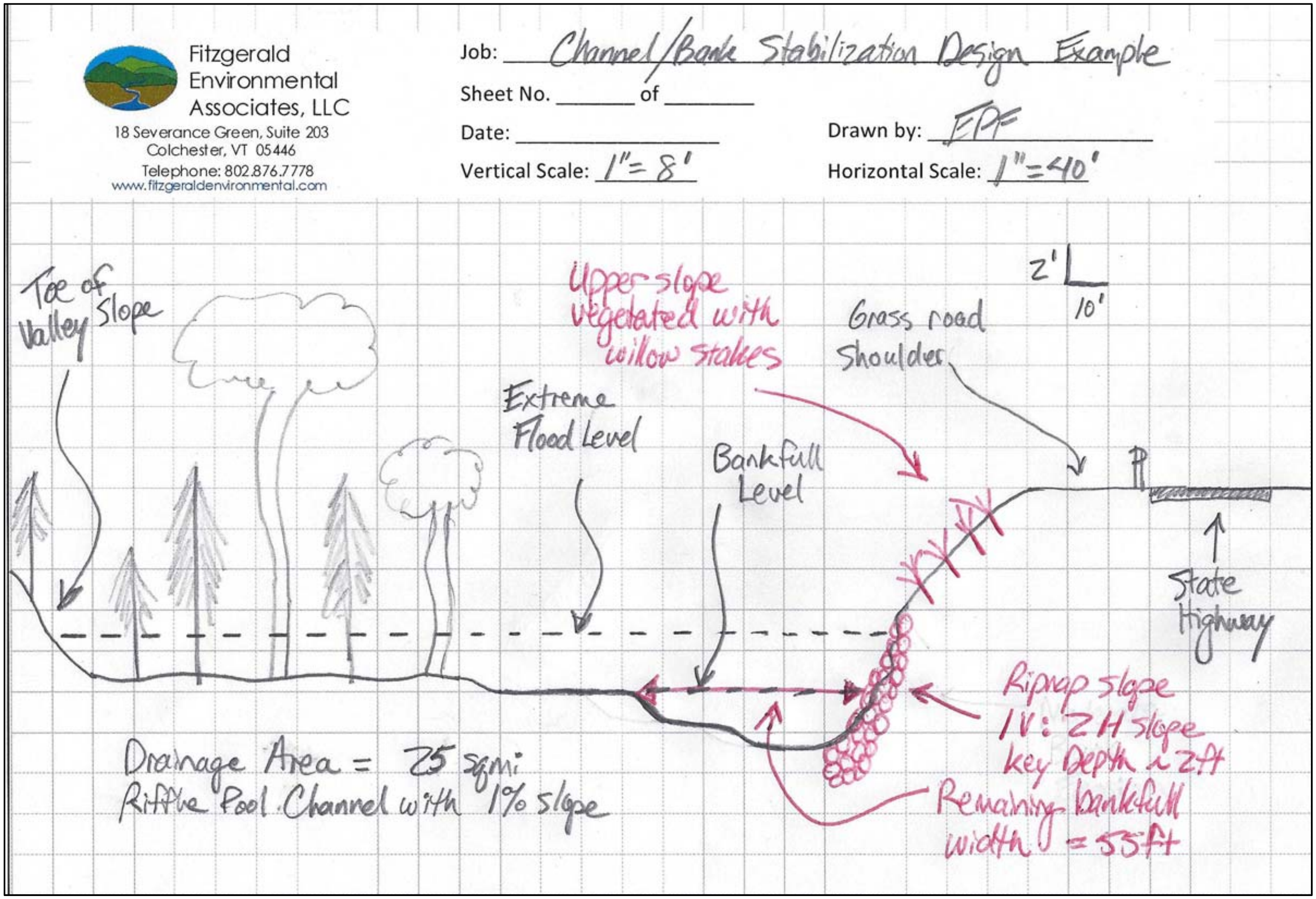
- *1% annual exceedance probability flood leads to moderate localized bend erosion within 60 feet of a state highway.*
- *The river planform includes a moderate bend upstream of the erosion.*
- *Adjacent land use includes a state highway on one side and a forested floodplain on the opposite side.*
- *Drainage area = 25 square miles*
- *Riffle-pool channel with 1% slope*
- *Bankfull discharge = 1,000 cubic feet per second (average velocity = 7 fps)*
- *100-year flood discharge = 3,000 cubic feet per second (average velocity = 10 fps)*
- *Reach incision ratio = 1.2*

1. *Predict the reference bankfull channel dimensions (feet) using the Vermont Hydraulic Geometry Regressions, and compare with existing conditions on the plot.*
2. *Evaluate channel setting and floodplain connectivity (i.e., incision and entrenchment ratios) to determine level of site risk.*
3. *Select appropriate bank stabilization practice(s) to maintain the reference bankfull width and ensure bank stability.*
4. *If rock stabilization is needed, select the appropriate stone sizing, keyway depth, and transitions for slope treatments to resist the predicted velocities for design storms.*
5. *Summarize your vision of the proposed bank treatment.*

Bank Stabilization Design Exercise



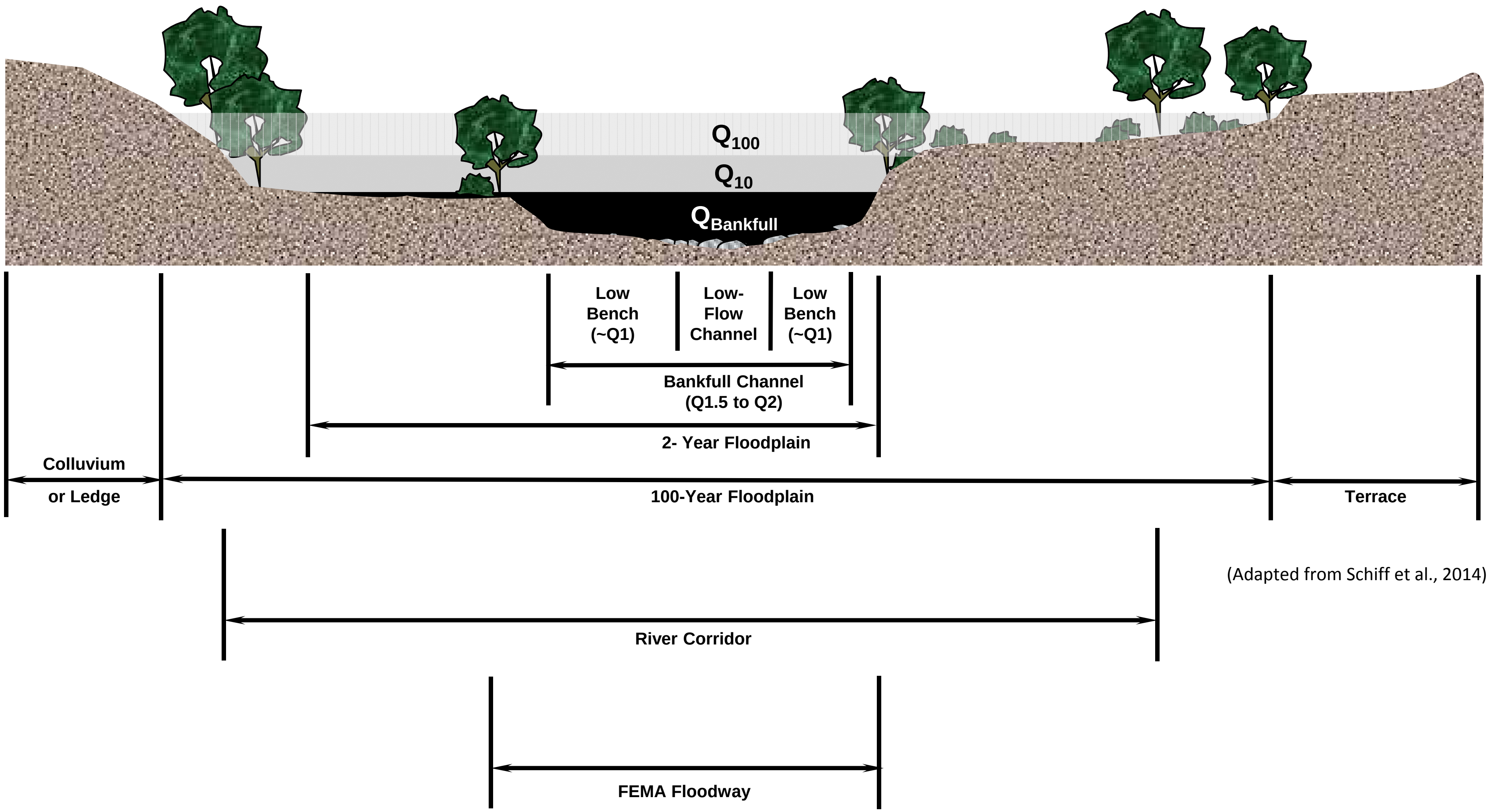
Bank Stabilization Design Solution



EXTRA SLIDES

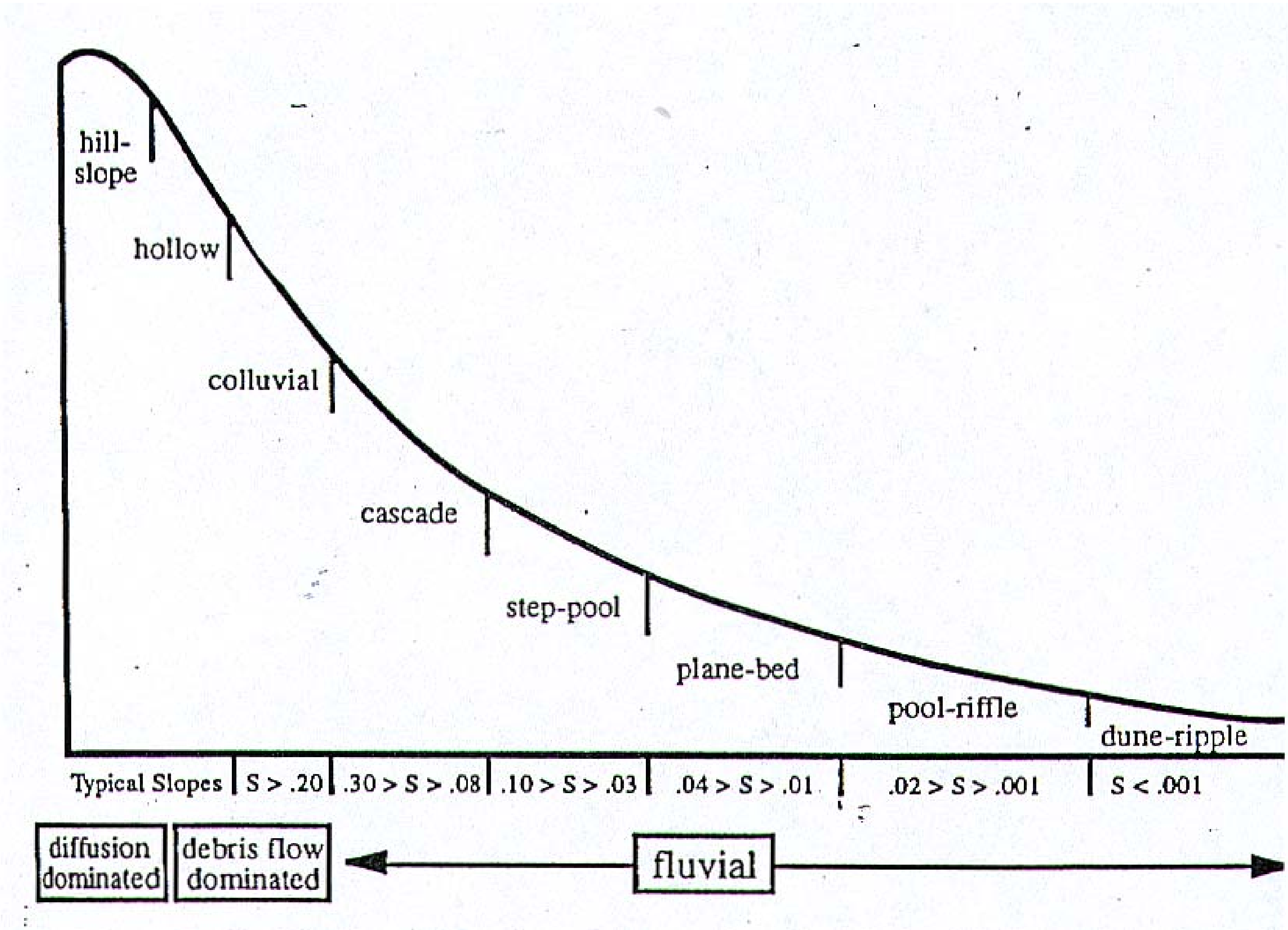
Basic Geomorphic Assessment

Compound Channel/Floodplain Cross Section



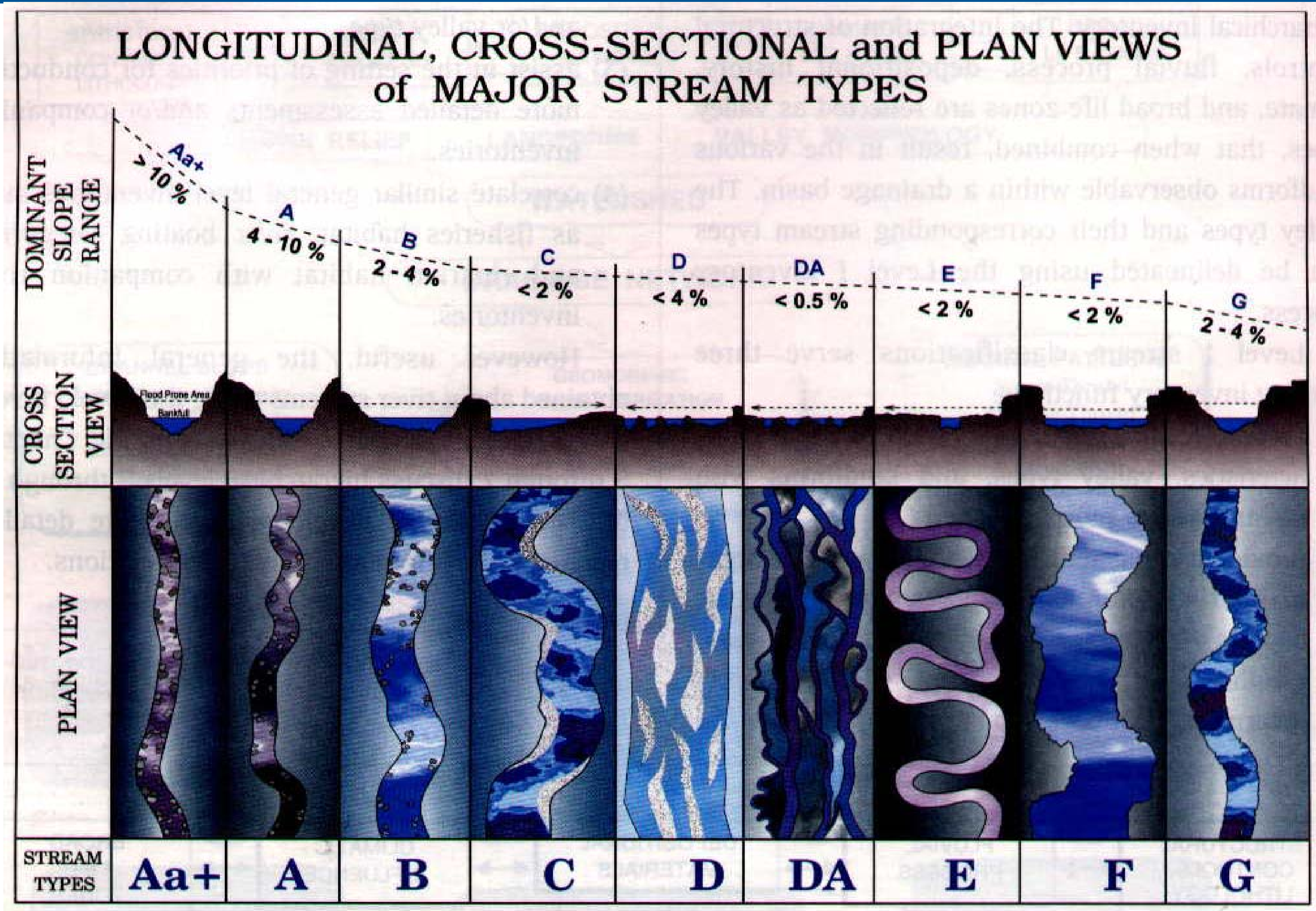
(Adapted from Schiff et al., 2014)

Geomorphic Channel Type



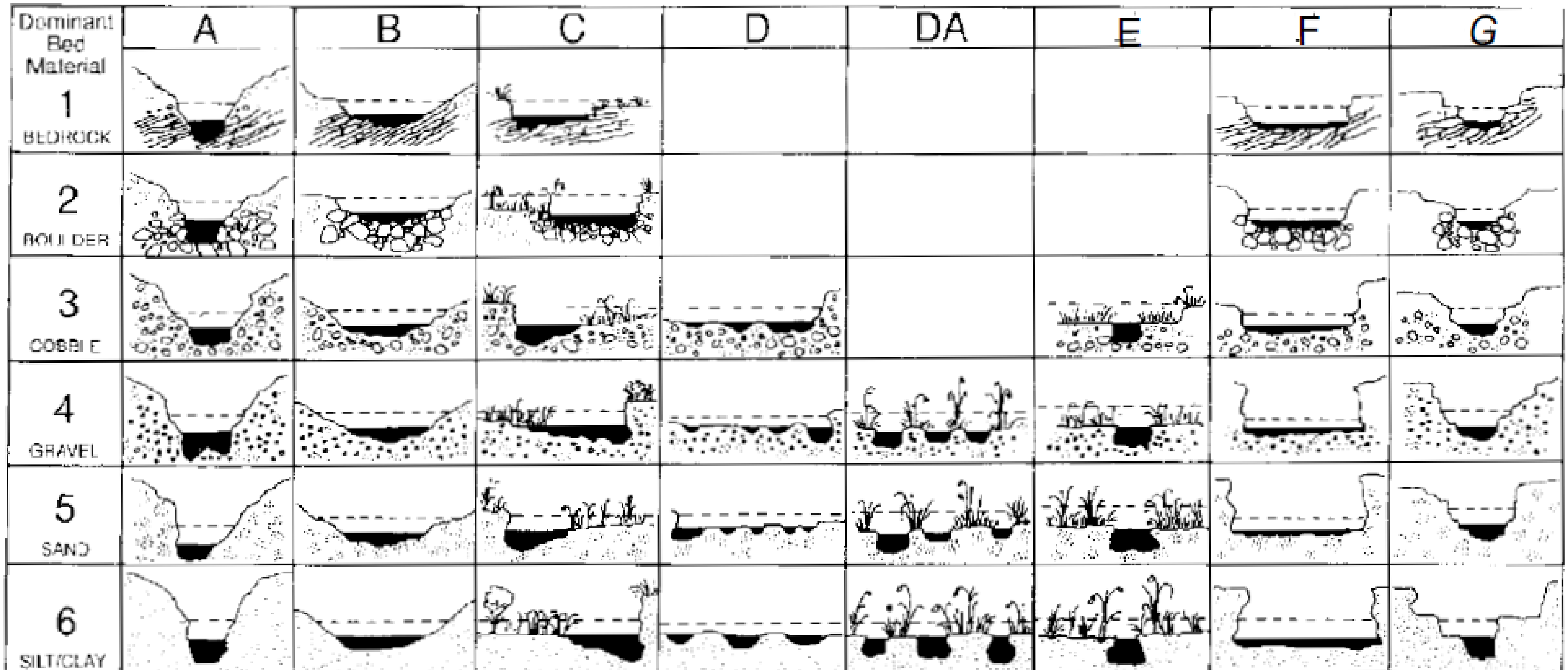
(Montgomery and Buffington, 1993)

Geomorphic Channel Type



(Rosgen, 1994)

Geomorphic Channel Type

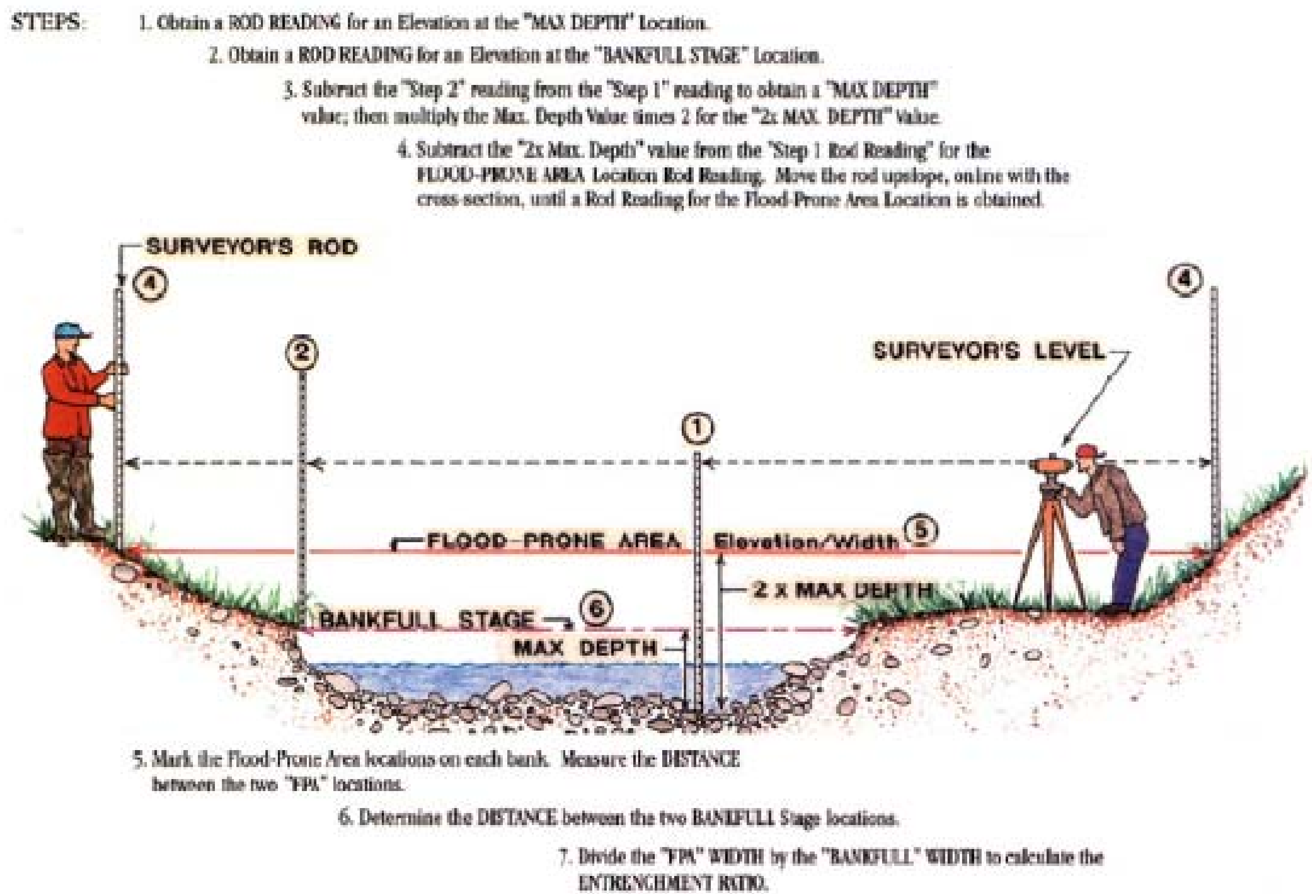


	A	B	C	D	DA	E	F	G
ENTRH.	<1.4	1.4-2.2	>2.2	N/A	>2.2	>2.2	<1.4	<1.4
SIN.	<1.2	>1.2	>1.4	<1.1	1.1-1.6	>1.5	>1.4	>1.2
W/D	<12	>12	>12	>40	<40	<12	<12	<12
SLOPE	.04-.099	.02-.039	<.02	<.04	<.005	<.02	<.02	.02-.039

Figure 3. Cross-section view of stream types (adapted from Rosgen 1994). Original drawings by Lee Silvey. Courtesy of Catena Verlag.

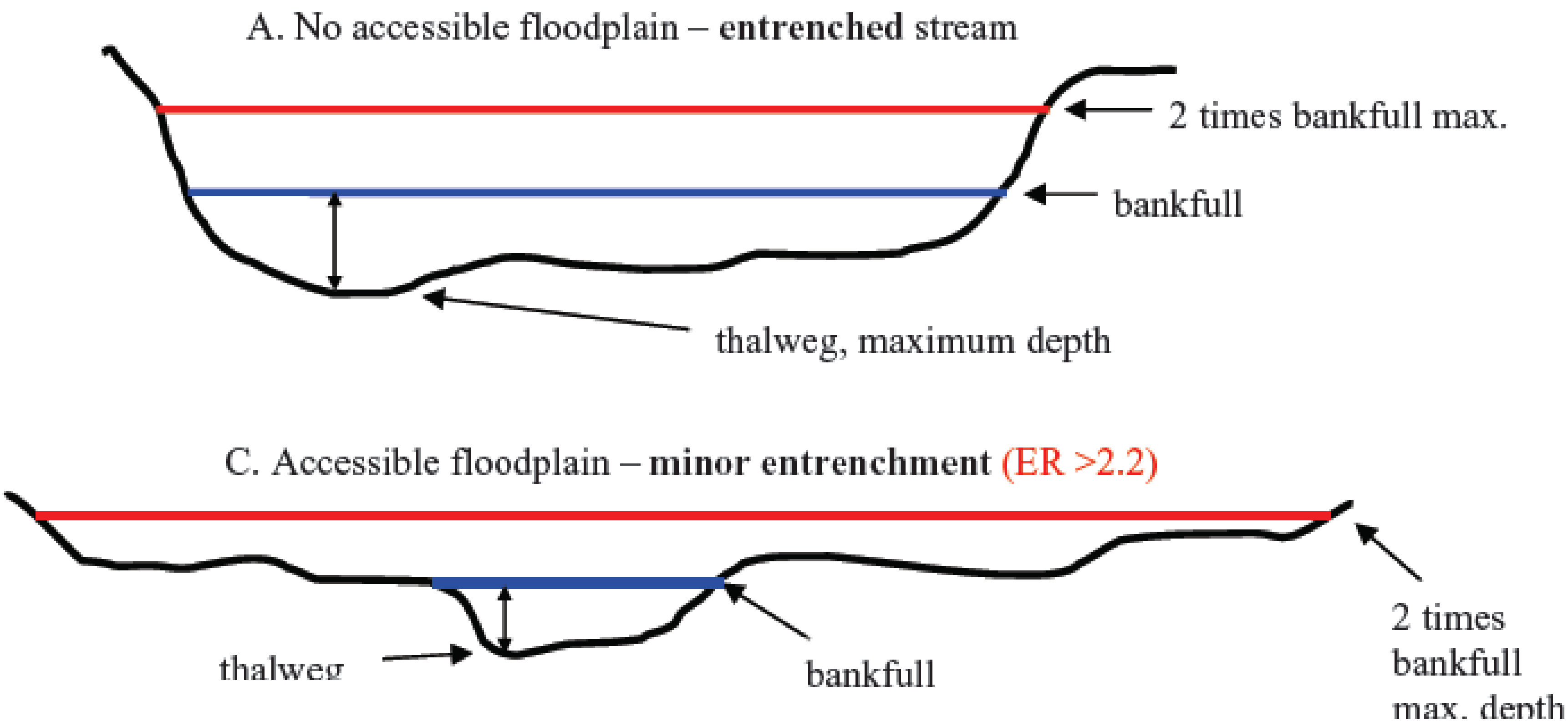
(Harrelson et al., 1994)

Floodprone Width



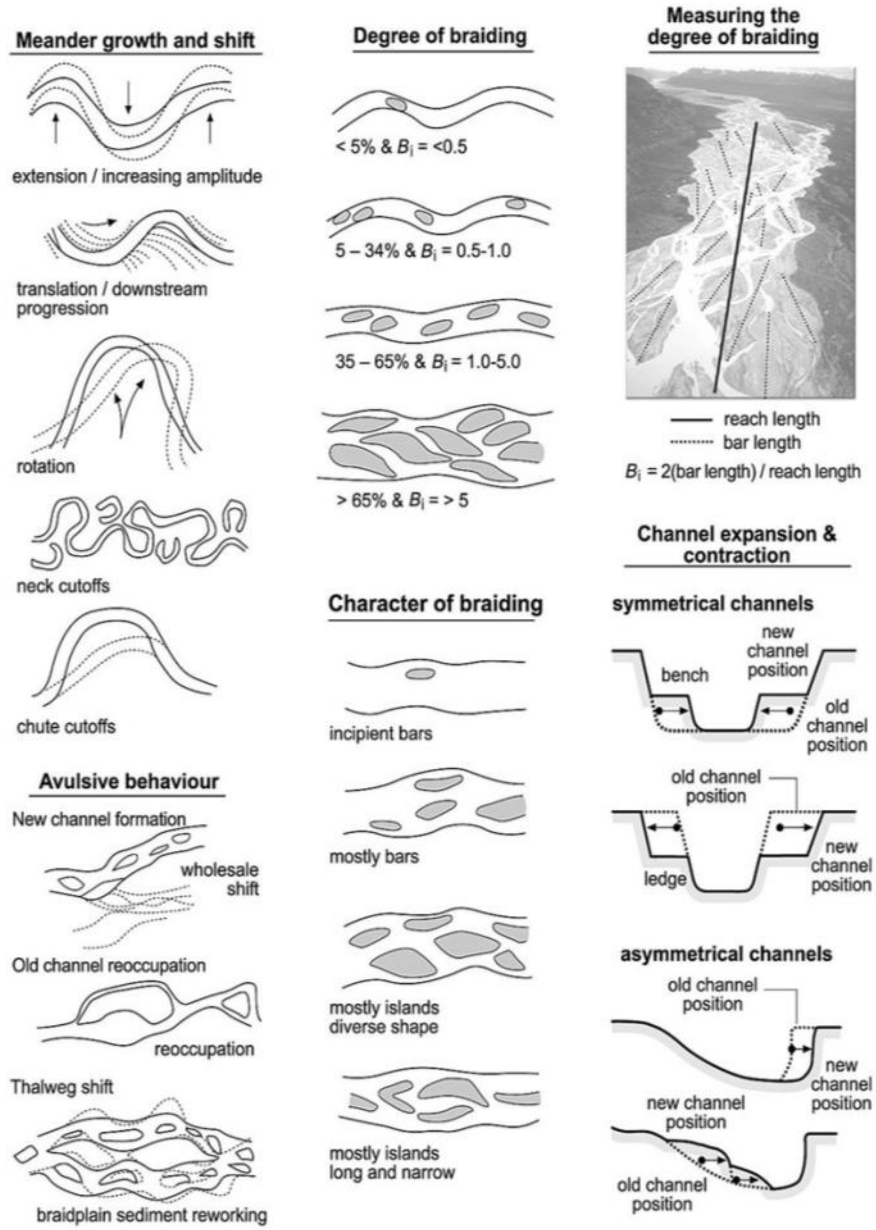
(Rosgen, 1996)

Entrenchment Ratio



(VTANR, 2009)

Channel Dynamics



(Brierley and Fryirs, 2005)

Channel Context

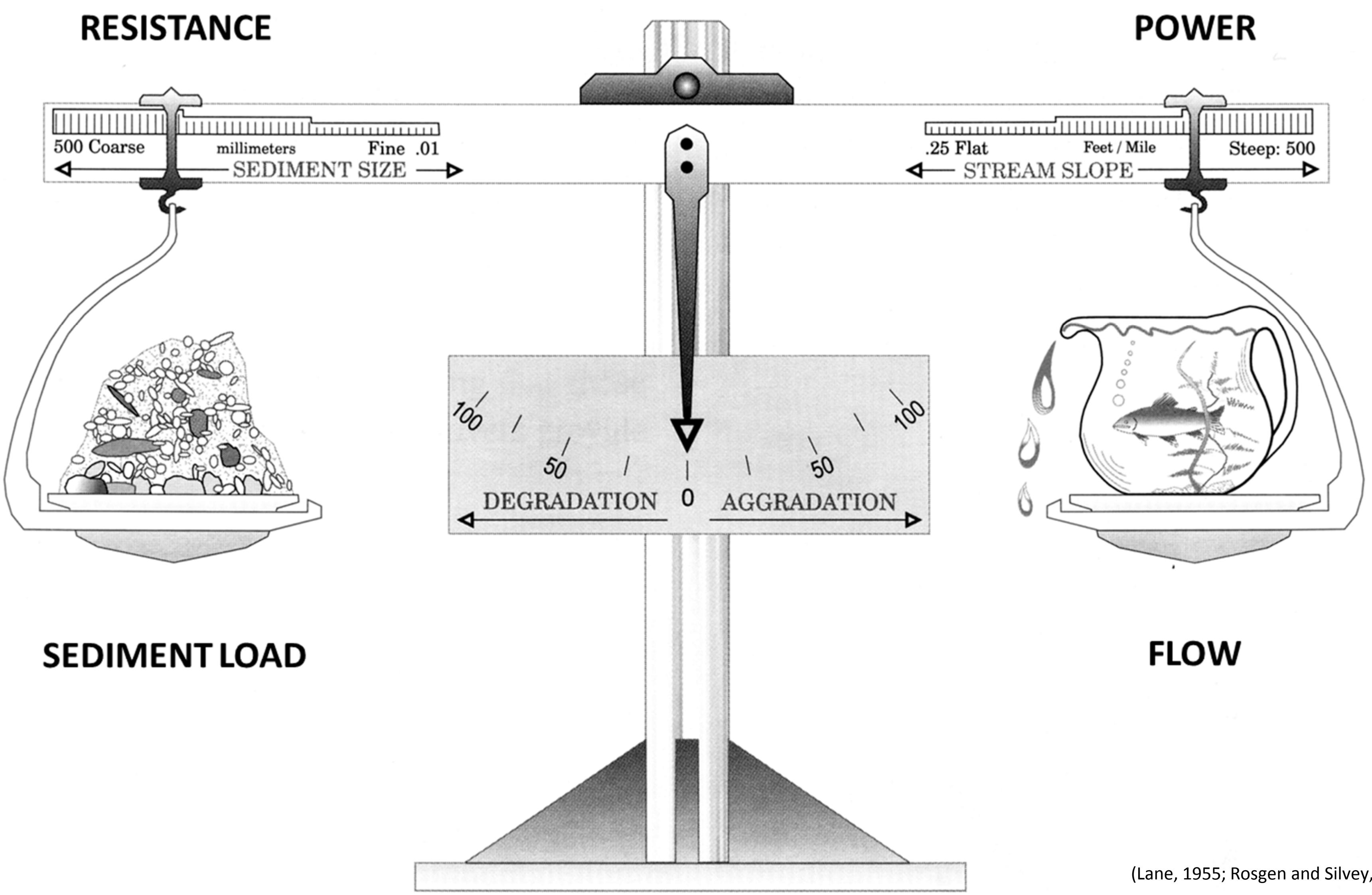
Independent Variables

- Flow
- Valley Slope
- Stream Power ($\Omega = \gamma QS$)
- Sediment Size and Load
- Bed and Bank Material
- Confinement

Dependent Variables

- Channel Dimensions
- Channel Slope
- Channel Pattern
- Bed Forms
- Side Slope
- Velocity
- Floodplain Features

Sediment Processes

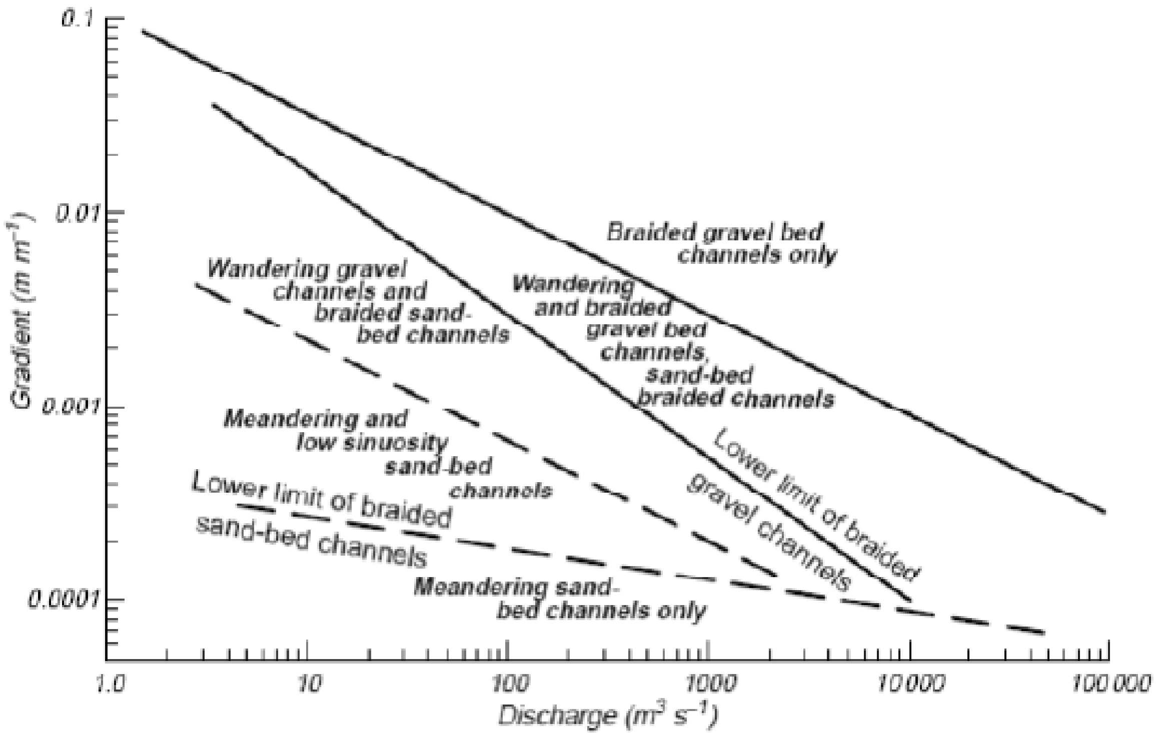


(Lane, 1955; Rosgen and Silvey, 1996)

(Sediment LOAD) x (Sediment SIZE) $\propto$ (Stream SLOPE) x (Stream DISCHARGE)

Understanding the Channel Pattern

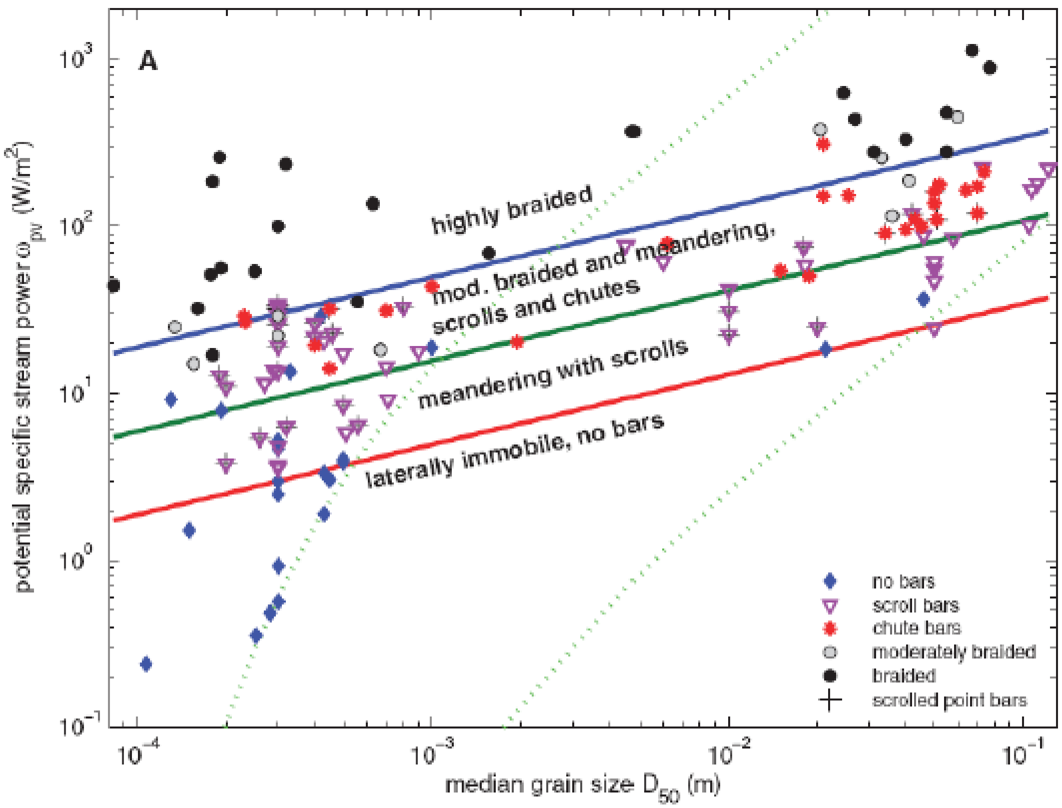
- Measure channel slope and bankfull (or mean annual) flow in metric units and use plot by (Church, 2002).



(Church, 2002)

Understanding the Channel Pattern

- Calculate D50 and specific stream power and use plot by (Kleinhans and van den Berg, 2011).

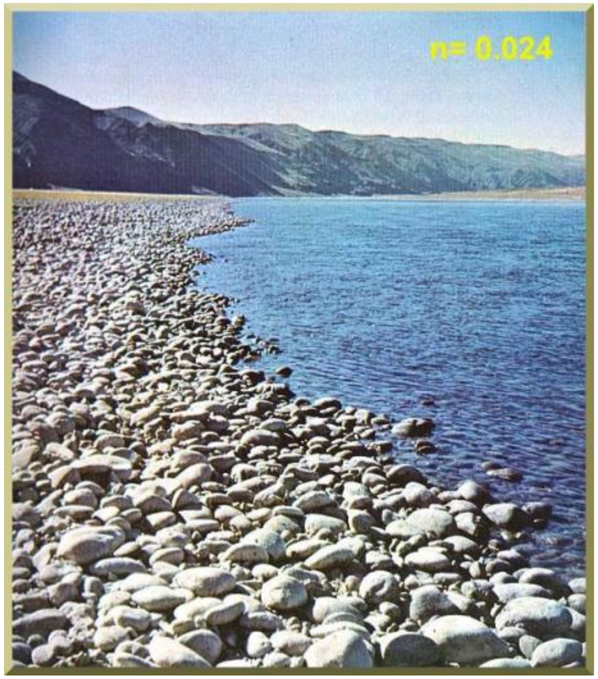


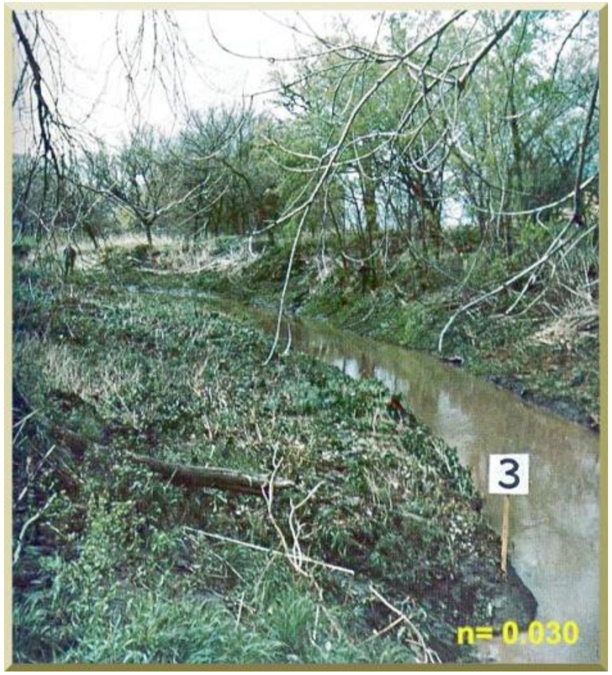
(Kleinhans and van den Berg, 2011)

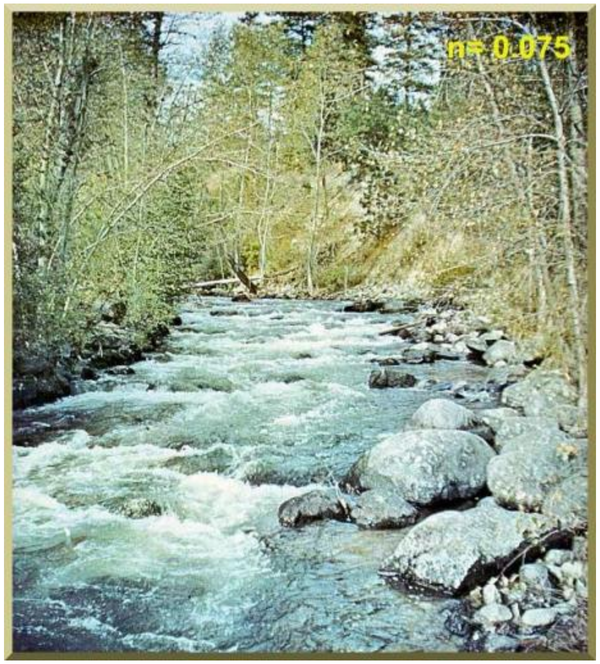
EXTRA SLIDES

Channel roughness Slides

Channel Roughness

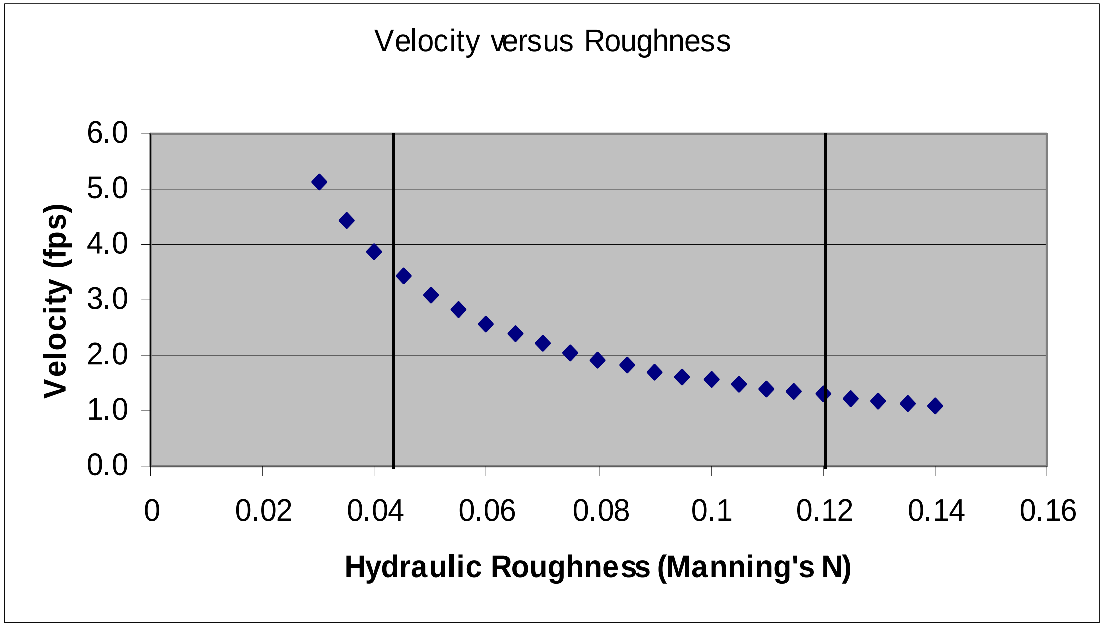






(Arcement and Schneider, 2006)

Channel Roughness



Area = 20 square feet
Slope = 1%

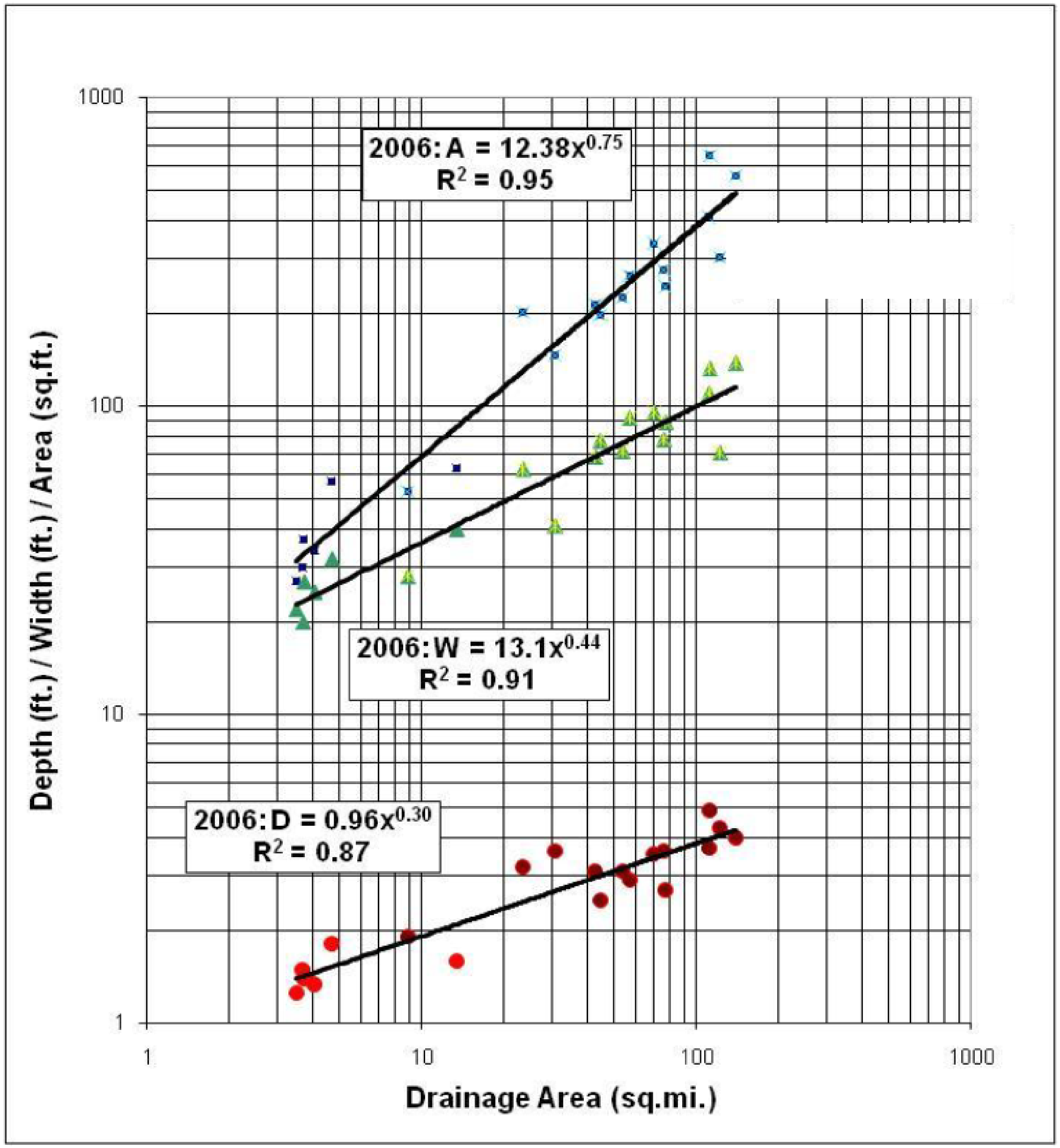
Small vegetated channel
Young growth and stubble perennials
N=0.04

Small vegetated channel
Tall, dense perennials
N=0.12

MANNING'S EQUATION

$$V = \frac{1.486}{N} R^{2/3} S^{1/2}$$

Approximate Channel Sizing – VT HGR



(VTANR, 2006)

Approximate Channel Sizing – HGR

Rough Channel Dimensions for the Roaring Branch
Bennington, VT
9/5/2011

Drainage Area (Square Miles)	Bankfull Width (feet)	Bankfull Depth (feet)	Cross Section Area (squre feet)	Location
2	18	1	21	
4	24	1	35	
5	27	2	41	
10	36	2	70	
15	43	2	94	
20	49	2	117	
25	54	3	138	
30	59	3	159	
35	63	3	178	
40	66	3	197	Bennington/Woodford
45	70	3	215	
50	73	3	233	
55	76	3	250	
60	79	3	267	
190	132	5	634	
195	133	5	646	
200	135	5	658	
Source: VTDEC, 2006	$W=13.1*DA^{0.44}$	$D=0.96*DA^{0.30}$	$A=12.38*DA^{0.75}$	

(MMI, 2011)