APPENDICES

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

(1st Edition)

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WATERSHED MANAGEMENT DIVISION

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Structural Measures and Channelization

A "channelized" river has had structural measures, such as bank armoring and berming, applied to keep it from moving. Initially rivers in Vermont were channelized into straightened forms to hasten runoff and maximize the use of valley-bottom land. Structural measures and channelization have been used for decades to protect those investments and have created the public perception that rivers should not move.

More recently, structural measures have been used to achieve environmental objectives. Streams have been armored with rock (also called rip-rap) or other revetments to try to stop erosion and reduce nutrient loading and sedimentation. Streams have even been rip-rapped to protect existing or soon-to-be planted riparian vegetation. In lieu of rip-rap, bioengineering, using a combination of live vegetation, rock and/or wood materials, is being practiced to try to stop stream bank erosion. Some river restoration projects use structural measures to mimic the forms of naturally dynamic rivers, but are then maintained as static channels. This is yet another type of channelization.

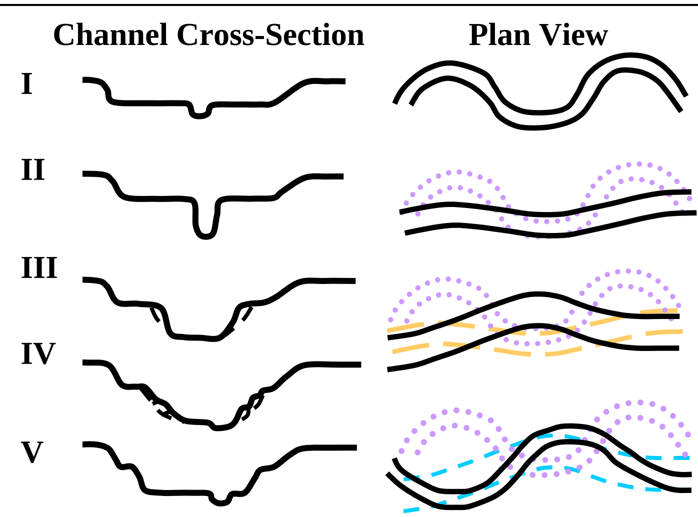
Historically, federal and state disaster relief programs provided the greatest financial support to landowners experiencing flood-related erosion. More recently, landowners needing help with controlling bank erosion have turned to other state and federal environmental programs. River channelization and structural controls are being done under the mantles of soil conservation, water quality, and habitat enhancement. People eager to stop the erosion threatening their homes or land have been the "willing landowners," ready to sign up for assistance under any environmental conservation program that will armor their stream banks.

But after a century or more of channelization with structural measures, erosion hazards have increased, aquatic and riparian habitat remain degraded, and nutrient loading from erosion is still increasing. Repeated and costly efforts to control long lengths of rivers as static channels is proof that channelization with structural measures is an unsustainable public policy. This paper will attempt to lay out an alternative program for Vermont. Some measure of structural control to protect public and private property will be necessary, but society will be better served if we start to loosen our grip on rivers.

Breaking the Cycle with Structural Measures

Government water quality programs have long emphasized the goal of reducing instream sediment loads. This may be pertinent for stream channels at or near equilibrium[1]. However, attempting to reduce instream sediment load through the control of streambank erosion during mid-stages of the channel evolution process (see diagram below), may result in short term reductions but will contribute to long term increases in sediment load.

Historically, public agencies have engaged in the practice of chasing incised streams with rip-rap only to have the entire stream network unravel during the next large flood. Relying on structural approaches, irrespective of channel evolution processes, has been counterproductive in the long term. Perhaps more importantly, this reliance has diverted limited public resources away from solving the underlying problems of land use encroachments, hydrologic and sediment regime alterations, and channel disequilibrium.



Channel evolution process showing channel down-cutting or incision in Stage II (cross-section), widening through Stages III and IV, and floodplain re-establishment in Stage V. Stages I and V represent equilibrium conditions. Plan view shows straightening and meander redevelopment that accompany cross-section changes. A flood-driven process taking place over decades.

Structural measures, and the knowledge to use them in environmentally-sound ways, will always be necessary. But there needs to be a greater understanding and agreement on the situations in which they are applied.

[1] *Fluvial Geomorphic Equilibrium*: The condition in which a persistent stream and floodplain morphology is created by the dynamic fluvial processes associated with the inputs of water, sediment, and woody debris from the watershed. The stream and floodplain morphology is derived within a consistent climate; and influenced by topographic and geologic boundary conditions. When achieved at a watershed scale, equilibrium conditions are associated with minimal erosion, watershed storage of organic material and nutrients, and aquatic and riparian habitat diversity.

For example, landowners in Vermont are permitted to armor stream banks to protect their property, but should be encouraged to forgo doing so if no substantial structures or investments are threatened, and the erosion is part of the stream's recovery from historic channelization. Stream bank revetments may warrant conservation program support when used to achieve and sustain equilibrium conditions, and when doing so, will promote the establishment of native riparian vegetation to minimize stream bank erosion over time. Otherwise, conservation programs will spend public funds trying to protect private property and improve water quality, when in the end, neither are served.

Landowners and local governments need to hear a consistent message about channelization practices from state and federal resource agencies. Cost share programs, technical guidance, and other land use incentives for local governments and private landowners that discourage river corridor encroachments will achieve the goals of the Clean Water Act faster than promoting "greener" structural measures to protect ill-conceived encroachments. Moreover, once state and federal agencies are in agreement, they will need to find the political fortitude necessary to change public programs so as **not** to intervene on every eroding stream bank, thereby allowing streams to evolve back to equilibrium conditions. Without a state-federal partnership, the traditional river management paradigm will persist; one that accommodates land use encroachments in the river corridor, a never-ending cycle of erosion hazards, and costly channel management imperatives that rely on traditional structural measures.

Encroachments on a straightened and incised channel that must now be maintained as a channelized river transferring its erosive energy and sediment load to downstream reaches.

Managing streams and watersheds toward equilibrium conditions presents a challenge far more vexing than the engineering of erosion control is capable of addressing. Geomorphic assessments to observe and explain the evolution of river channels and the failure of channelization practices to control natural processes, will be essential to increase public awareness and support.

Managing Toward Stream Equilibrium

The Vermont River Management Program (RMP) is documenting the physical condition of rivers throughout the state. The RMP is also assessing the erosion hazard, water quality, and habitat impacts associated with watershed and channel modifications. Assessment data are showing that berming, armoring, and dredging have modified the hydraulics of streams, have required ongoing maintenance, and have led to the systemic channelization of stream networks.

With a full appreciation for large scale fluvial processes and concern over the costs to society when physical river imperatives are ignored, the RMP is advocating for a change in direction. *It is the River Management Program's goal to manage toward, protect, and restore the fluvial geomorphic equilibrium conditions of Vermont rivers by resolving conflicts between human investments and river dynamics in the most economically and ecologically sustainable manner*.

The RMP seeks to minimize the need for structural measures. We are sharing the science and partnering with state and federal resource agencies to focus on the sources of sediment-related surface water impairments. These sources are the land use conversions, investments, and expectations within river corridors which result in: a) inundation and erosion conflicts with river dynamics, b) the application and maintenance of structural measures to resolve those conflicts, and c) the spiraling economic and environmental costs associated with fluvial erosion hazard mitigation.

Where feasible, the RMP promotes an avoidance strategy, one which involves the planning, designing, and protecting of river corridors to accommodate stream meander and floodplain processes, as the most economically and environmentally sustainable river management alternative.

Watershed Assessment and Project Planning

There is a great danger in project planning to weigh the effects of channel modification or "restoration" alternatives against the effect on existing conditions; particularly when existing conditions can be and so often are profoundly removed from a sustainable equilibrium condition. The landscape is littered with failed channel management projects that considered the existing condition to be static or sustainable when in fact, the existing channel dimensions, pattern, and profile were just a stage of the channel's evolution toward equilibrium.

Traditionally, project proponents have supported virtually any desired channel modification practice simply by choosing the matching management objective. For instance, projects are commonly proposed on incised channels. These channels have lost access to their floodplains and need to widen in order to form new floodplains. The project proponent sets a management objective to "reduce downstream discharges of sediment from bank erosion." The proponent often selects armoring with rip-rap as the structural measure of choice. However, bank armoring typically forces the channel to incise deeper or lead to down-cutting and incision upstream. In this scenario, it is counterproductive to armor the banks to try to prevent the erosion that is necessary for the widening process. As is so often the case, the structural controls virtually guarantee an increase in future sediment discharges and erosion hazards downstream.

Managing toward equilibrium conditions and successfully implementing projects at the local scale, will require river corridor plans that consider watershed-scale changes. Plans should explain the cumulative impacts and set priorities for treating the multiple stressors that have altered the geometry and physical characteristics of streams. The physical condition of Vermont rivers is the result of over 200 years of channel and watershed manipulation, deforestation, and floods. Nearly every contemporary management decision should be made in this context and weigh alternatives based on larger spatial and temporal considerations.

The Vermont River Management Program is promoting an analysis of <u>reference</u> fluvial processes and geomorphic condition. The RMP is examining the watershed and reach-scale stressors which explain the departure (from reference) and sensitivity of existing conditions. Mapping the departure and sensitivity of reaches in the context of vertical and lateral channel constraints throughout the stream network can explain the type and rate of channel evolution processes underway, and how adopting certain management practices can accommodate, preserve, or restore equilibrium conditions over time.

The Vermont RMP is drafting a *"River Corridor Protection and Restoration Planning Guide"* to help its partners evaluate physical stressors, channel response, and river management alternatives.

The greatest challenge is to change the public's perception that the channel widening, floodplain and meander redevelopment, and erosion that goes along with these adjustment processes are **not always bad.** Helping landowners achieve a more sustainable relationship with straightened and channelized rivers would be a cost-effective management alternative.

In conclusion, society must acknowledge that public and private investment within Vermont river corridors is the driver behind expensive structural channel controls. Over-channelizing has led to repeated structural failures, increased fluvial erosion hazards, sediment and nutrient loading, and the impairment of aquatic and riparian habitat. Consensus and support for actions that promote sustainable river corridor land use may be accelerated, when these societal costs are fully recognized.

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APPENDIX B: River Recovery & Restoration Technical Considerations

Watershed Scale Data	River Segment Scale Data	Reach Scale Issues	Construction Issues
A. Project Site Data	A. Hydrology	Watershed Context, Source Controls	Utility Check
Location Map	Watershed Size, Shape, Slope	Source, Transport, Deposition Zones	Access
Problem Statement	FEMA Data, USGS Gauge Data	Stream Power and Processes	Staging Area
Project Goal	Impervious Cover	Channel History & Evolution Stage	Construction Sequence
Property Owner	Existing & Potential Land Use	Valley Bottom , Floodplains & Terraces	Water Control
Property Permission	Flow Duration Curve	Active Channel Zone	Erosion Control
Sketch	Design Flood Frequency	Channel Pattern, Alignment & Slope	Limits of Clearing
Aerial Photo	Bankfull Discharge	Substrate Size, Type, and Bedload	Traffic Control, Detours
Topographic Map	Peak Flood Flows	Bankfull Channel Size and Shape	Disposal Areas
Flood Insurance Study	Instream Flow Needs	Total Channel Size and Shape	Regulatory Conditions
	Fish Passage Flows	Base Level, Natural Grade Controls	Seasonal Work Limitations
B. Watershed Assessment		Aggradation, Degradation, Knick points	Schedules
Subbasins	B. Geologic Data	Bank and Terrace Scarp Stability	
Land Use & History	Bedrock	Bed Features, Resistance, Roughness	Contract Documents
Climate and Vegetation	Surficial Landforms	Channel Migration and Avulsions	Title Sheet
Regional Geology & History	Soils, Hydrologic Classes	Bridges, Culverts, Levees, Dams, Scour	Legend & Notes
Stream Gauge Data	Wetlands, Recharge & Storage	Flood Hazards, Risks & Mitigation	Index Map
Rare or Endangered Species	Boring Data, Test Pits	Discharges & Diverted Flows	Existing Conditions
Water Supply Sources	Groundwater	Debris Management	Layout Plan
Wastewater Discharges	Sediment Yield	De-channelization	Grading Plan
Water Quality	Local Geology	Dam Removal or Repair	Landscaping Plan
Floodplains		Day-light Enclosed Watercourses	River Profile
	C. Geomorphic Data	Dredging, Gravel Mining Management	Cross Sections
C. River Inventory	Channel Type	Degradation, Incision Control	Standard Details
Segment and Reach Layout	Slope, Valley and Channel	Develop Meanders , Sinuosity	Special Details
Geomorphic Assessment	Channel Pattern	Deflect or Redirect Flows	Structures
Channel Confinement	Sinuosity, Valley and Channel	Demolish Levees, Setback from Channel	Specifications
Channel Evolution	Hydraulic Geometry	Floodplain Connections	
Channel Classification	Pebble Count, Sieve Test	Create/Connect Secondary Channels	**Special Issues and Concerns**
Bridges, Culverts, Dams	Cohesion, Direct Shear Tests	In-Channel Structures	No Action Option
Constraints	Critical Hydraulic Shear	Aquatic Habitat Type, Quality, Modify	Community Vision, Values
Channel Condition	Channel and Bank Stability	Fish Passage, Barrier Removal	Climate Change
Riparian Zone		Coarse Wood Material	Land Use Change
Ecological Condition	D. Hydraulics	Bank Stabilization, Biotech Treatment	Resiliency, Sustainability
Recovery/Restoration Priorities	Longitudinal Profile	Soil Contamination, Hazardous. Waste	Ecological Recovery Feasibility
	WS Elevations	Stormwater Management	Ecological Education
D. Community Data	Stage –Discharge Relations	Riparian Zones, Upland Linkages	Ecosystem Services
Political Structure	Velocity, Shear Stress, Power	Invasive Species Control	Define Acceptable Risk
Watershed Organizations	Stable Stone Size	Aesthetics, Public Access, Recreation	Do No Lasting Damage
Regulatory Procedures	Sediment Transport	Capitol Costs & Maintenance	Long-Term Monitoring
Public Comments & Contacts	Local Scour, Bridge Scour	Regulatory Conditions	Assess & Learn From Failures
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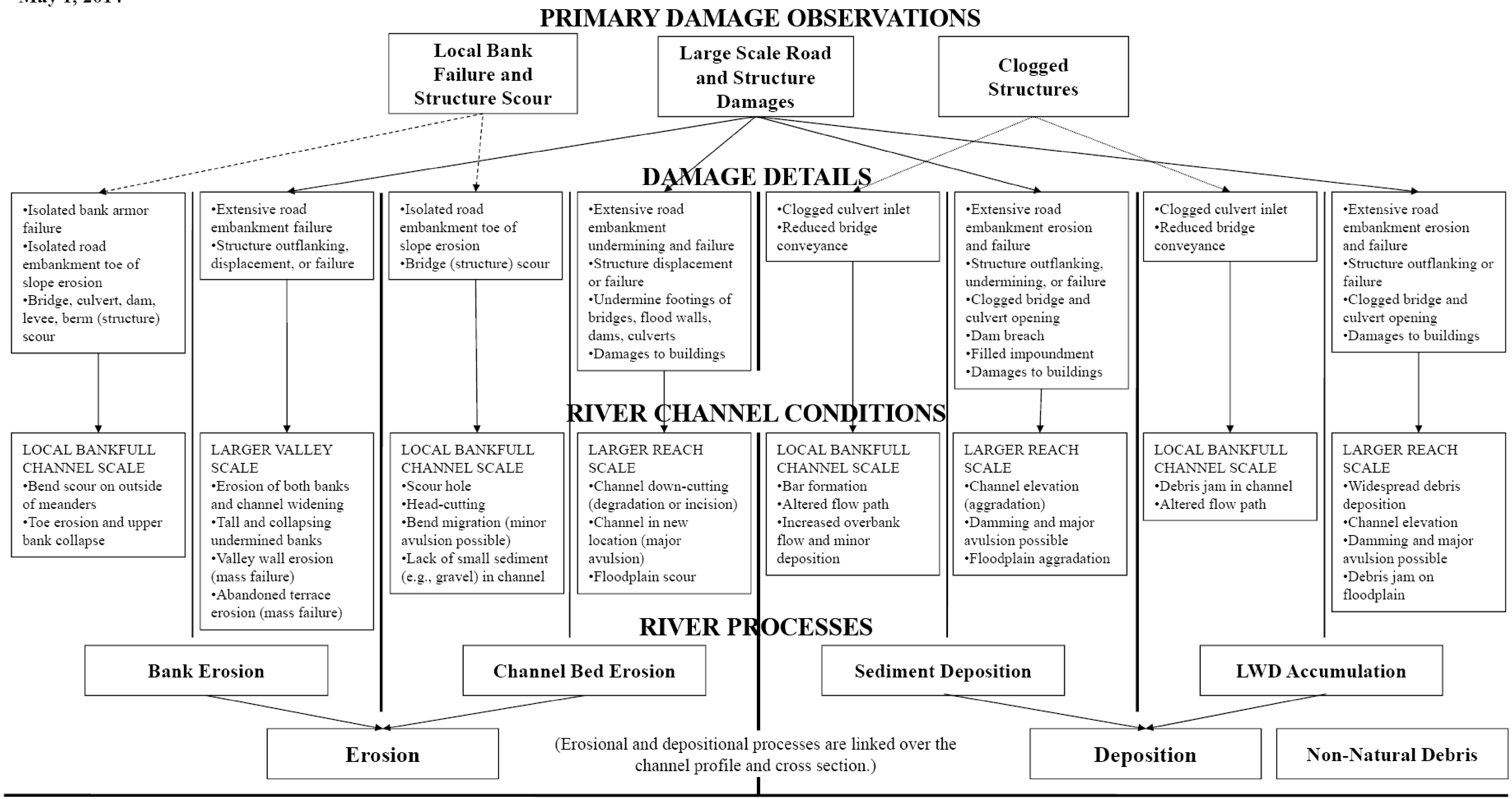
APPENDIX C: Observed Damages, River Channel Conditions, and River Processes



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

APPENDIX D: Defining River Corridors (VTDEC, 2006a) [Also see (Kline, 2010)]

Defining River Corridors

FACT SHEET ②

Vermont DEC River Management Program

Overview

A river corridor includes lands adjacent to and including the course of a river. The width of the corridor is defined by the lateral extent of the river meanders, called the **meander belt width** (Figure 1), which is governed by valley landforms, surficial geology, and the length and slope requirements of the river channel. River corridors, defined through ANR Geomorphic Assessments (2004), are intended to provide landowners, land use planners, and river managers with a meander belt width which would accommodate the meanders and slope of a balanced or equilibrium channel, which when achieved, would serve to maximize channel stability and minimize fluvial erosion hazards.

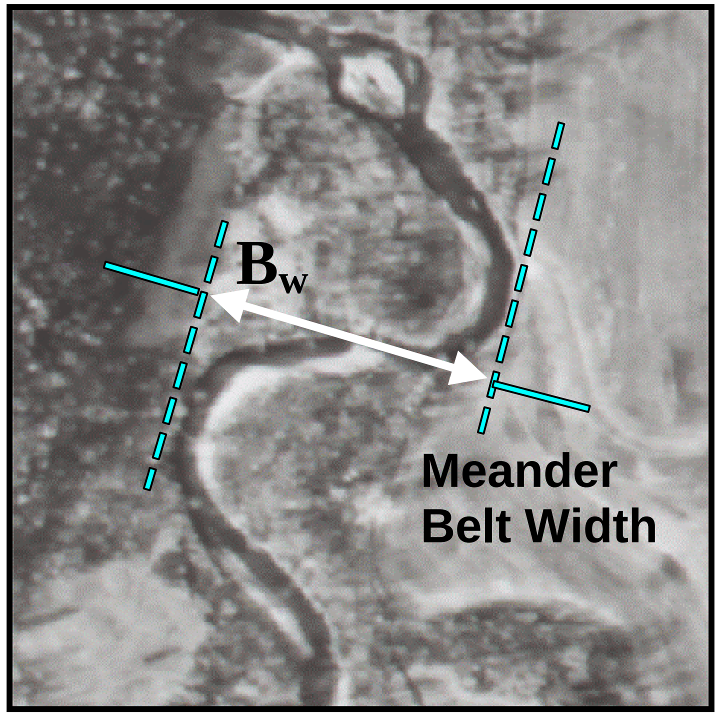


Figure 1. Meander Belt Width (**B_w**) defined by the lateral extent of meanders when the channel slope is in equilibrium with the sediment transport requirements of the river.

Managing for Meanders

Building on the "fundamental principles of river systems" and the diagrams of "floodplain access and channel evolution" laid out in River Corridor Protection and Management, Fact Sheet ①, this section will further explain the components of channel geometry and why understanding their relationship with watershed function is essential to achieving the management objective of sustainable equilibrium river channels and avoidance of fluvial erosion hazards.

Stable, equilibrium river channels erode and move in the landscape, but have the ability, over time and in an unchanging climate, to transport the flow, sediment, and debris of their watersheds in such a manner that they generally maintain their dimension (width and depth), pattern (meander length), and profile (slope) without aggrading (building up) or degrading (scouring down) (Rosgen, 1996; Leopold et. al, 1964). Stable, equilibrium rivers are considered a reasonable and sustainable management objective in consideration of the repeated and catastrophic flood damages experienced in Vermont. Many rivers are in major vertical adjustment due to human imposed changes in the condition of their bed and banks, slope and meander pattern, and/or watershed inputs (see Lane's Balance in Figure 2).

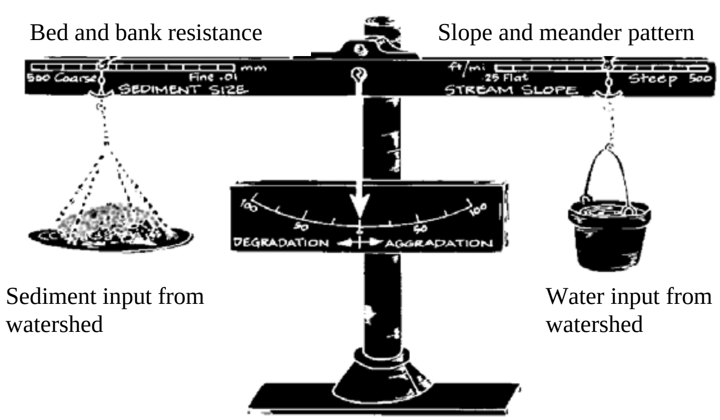


Figure 2. Stable Channel Equilibrium (Lane, 1955)

Establishing channel equilibrium as a river management objective, however, demands a recognition that the geometry of certain river channels, due to their location in the watershed, may be influenced by a net storage or net export of sediment in the reach. In such cases, the inherent vertical "instability" should be assessed and potentially managed differently than the river that is aggrading or degrading as a result of one or more human imposed changes. For instance, it may not be prudent to use the definition of stability and manage against the aggradation which occurs on an active alluvial fan, i.e. where streams transition between steep mountain and gentle valley locations. Also recognize that the potential level of achievement of this objective may frequently be tempered by the constraints of human investments on the landscape.

Protecting river corridors as defined by the meander belt width of the equilibrium channel avoids conflicts with human land uses and minimizes investments and the need to conduct expensive channel management or stabilization activities. Failure to recognize the physical imperatives of river systems and the land area that rivers **will** occupy over time will demand large, on-going private and public expenditures to maintain an unsustainable condition of dis-equilibrium which will ultimately fail.

Some Vermont rivers are presently in balance. The power produced by flood flows and channel slope (a function of meander length) is not so great as to cause significant scour (degradation) of the river bed, or so diminished as to cause a loss of sediment transport capacity and a build up of sediment (aggradation) in the channel.

In these cases, it is cost effective to simply keep investments out of the river corridor and avoid the eventual use of channel management practices, which become necessary to protect investments, but ultimately change the river's length and slope, lead to channel adjustments, and increase erosion hazards.

For many Vermont rivers and streams, a combination of watershed, floodplain, and channel modifications over the past 150 years, has led to the major vertical channel adjustments that are ongoing today. The initial stage of adjustment typically involved the bed scour and head-cutting associated with channel straightening and degradation. Steeper, straightened channels are now adjusting or "evolving" back into more gentle gradient, more sinuous channels through an aggradation process (Figure 3). The narrower belt widths observed during Stages II and III of channel evolution, which held for decades and encouraged human encroachment, have now begun to widen during recent floods as new sediments deposit and longer meanders develop putting human encroachments at risk.

The practice of dredging sediment to avoid flood hazards has typically worked until there is another flood. Berming and armoring may hold longer, but tend to cause the unbalanced condition to extend upstream and downstream. Such practices are unsustainable and will eventually unravel requiring extensive maintenance operations. A cost-effective, geomorphic approach would involve avoiding or minimizing encroachments and investments in river corridors. Corridors can be defined by applying fluvial geomorphic principles to calculate and predict the belt widths which would accommodate the meanders and slope of equilibrium river channels.

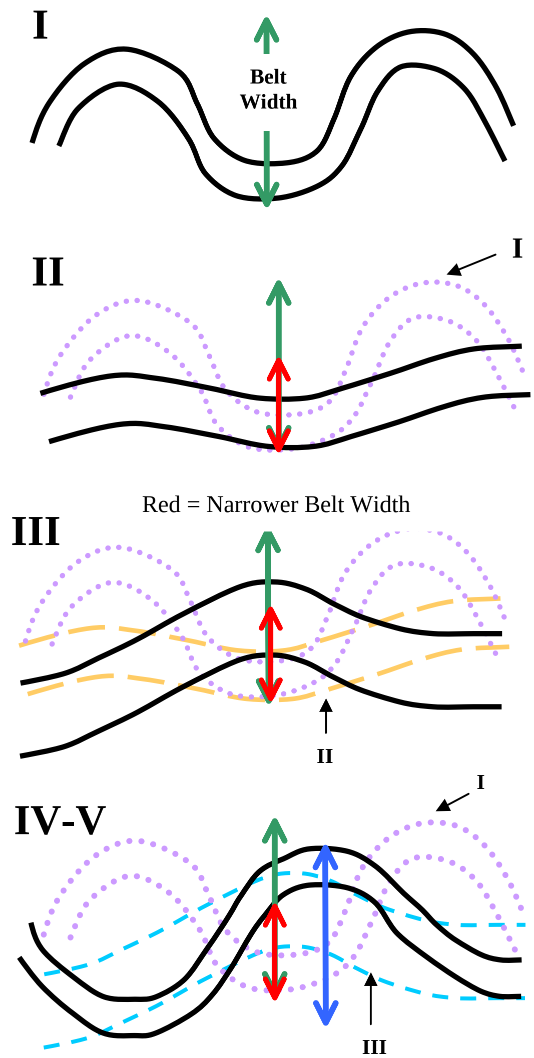


Figure 3. A planform view of the Schumm (1984) channel evolution model showing how adjustment processes lead to a narrowing and then widening of the meander **belt width** as the channel equilibrium re-establishes at a more gentle slope.

Defining the River Corridor

When rivers are in dynamic equilibrium, a sustainable meander geometry provides for the dissipation of the energy of moving water and the transportation of sediment. The fact that unconfined, single thread streams tend to follow a sinuous or meandering course is related to the vertical (up and down) oscillations of the stream bed. Flow characteristics (turbulence and secondary or lateral currents) cause the selective entrainment, transport, and deposition of bed materials which produces systematic sorting of sediment sizes between scour pools and riffle deposits. Riffles are the topographic high points in the undulating profile and pools are the intervening low points. The combination and sequence of bed features results in converging and diverging flows and leads to the development of a sinuous channel, with riffles becoming points of inflection (crossovers), where the flow switches from one side of the channel to the other (Thorne, 1997).

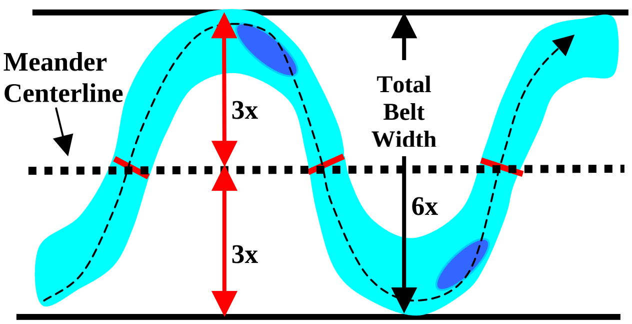


Figure 4. Idealized representation of a river corridor drawn to accommodate the meander belt width, measured out as parallel lines "3 x channel width" either side a meander centerline drawn down valley through the cross-over or inflection points of the river (dotted line).

Researchers have developed meander geometry formulas to relate channel dimensions with planform measurements. Williams (1986) using data collected from 153 alluvial rivers around the world found that the relationship between channel width and the meander belt width is expressed by the formula $B=3.7W^{1.12}$ (where B is the belt width and W is the channel width in feet for channels ranging from 5 to 13,000 ft wide). This formula results in a meander width ratio approximately equal to six (i.e., the belt width is equal to about 6 bankfull channel widths). Corridors for gentle gradient rivers and streams (slope < 2%) in narrow to broad alluvial valleys are calculated and drawn to accommodate a meander belt width that is equal to 6 times the width of the river channel.

Where rivers are assessed as being in equilibrium and the lateral extent of their meanders create a belt width that is at or near the "6 times channel width" relationship, then corridors are drawn as two roughly parallel lines, following down the valley and capturing the extent of existing meanders (Figure 4). If the river slope and sinuosity have been modified, the corridor is drawn using 3 channel widths either side of a meander centerline or 6 channel widths out from the toe of the valley if the river is presently flowing less than 3 channel widths from the toe (Figure 5)

Rarely does one find the idealized sinuosity shown in Figure 4. Rivers and streams in Vermont are usually less sinuous, many having been straightened against a valley side slope. In these cases, the river corridor (still "6 times channel width") is drawn so that the belt width extends laterally out from the valley toe (see Figure 5). These corridors are not established with the expectation that river adjustments will occur and result in a perfect sine wave pattern which conforms to the calculated belt width. Rather, they provide an area within which channel adjustments may occur, in order to re-establish an equilibrium condition, and there can be a reasonable expectation that fluvial erosion hazards will be minimized.

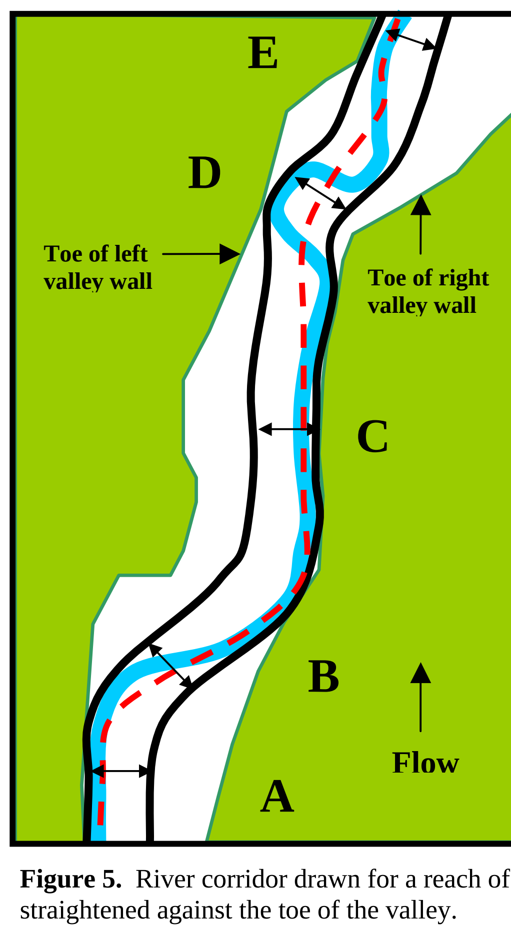


Figure 5. River corridor drawn for a reach of river straightened against the toe of the valley.

Figure 5 illustrates a river corridor, in a broad gentle gradient valley, which was drawn using a combination of river and valley features. The river starts out against the left valley wall (Segment A), flows across the valley (B), returns to the right valley wall (C), flows through a set of meanders (D), and then again along the left valley wall (E). All but Segment D represent the planform of a river reach which has been historically straightened. The meander centerline (red dashed line) travels between meander crossovers where they exist but otherwise, follows the path of the river. The river corridor is a belt width (solid black lines) equal to 6 times the channel width; 3 widths either side of the centerline in Segments B and D, and 6 widths out from the toe of the valley in Segments A, C, and E.

The River Management Program has developed GIS extension software, called the Stream Geomorphic Assessment Tool (SGAT), to automate the process of creating river corridors, once the geographical features: streams, valley walls, and meander centerlines are defined.

Adjusting Corridor Widths

Belt widths "6 times the channel width" develop on rivers which are gentle-sloped, unconstrained, and have erodible boundaries. Obviously, these conditions do not prevail in all Vermont valleys and there are both geographical and human constraints that may justify changing river corridor widths and locations, including:

- **Existing private investments and public infrastructure** for which there is a longer-term public commitment to protect (armor) against fluvial erosion hazards (e.g., town and state roadways);
- **Steeper, confined to narrow valleys with less erodible boundaries**, where corridors of "1 to 4 times channel width" are recommended based on stream type and specific valley characteristics; and
- **Extremely sensitive stream types or landslide areas** that may require corridors > 6 channel widths.

Refer to the "Technical Guidance for Determining Floodway Limits" (ANR, 2003) for more information on adjusting river corridors by stream and valley type and accommodating human developments and infrastructure.

Practical Planning and Management Tool

Defining river corridors is essential to the development and implementation of river corridor plans. Such plans should include a process for selecting and implementing river corridor management alternatives and providing a basis for corridor protection through various land use planning and incentives programs. River corridors can define flood hazard zones or overlay districts thereby supporting implementation of town pre-disaster mitigation plans, or be incorporated into the watershed (basin) plans developed by regional, state, and federal agencies. River corridors defined and "adopted" as part of a public process become a practical, science-based planning tool for directing the use of public funds to reduce fluvial erosion hazards.

River corridor plans, while setting objectives for managing toward a geomorphically-stable river and reducing fluvial erosion hazards, should also recognize that nearly all landowners have made some investment in their lands along a river. Adopting a river corridor plan would not necessarily require the removal of existing investments, but rather would work to avoid future encroachments within the meander belt width which eventually require long-term commitments to bank armoring and other channelization practices for their protection. To deal with conflict areas, for instance when the channel lengthening process threatens an existing investment either within or at the bounds of the corridor, the plan would spell out a range of alternatives and a process for resolving conflicts. At one end of the range, the plan would create the opportunity for willing landowners to be appropriately compensated for removing investments and changing land uses within the corridor. On the other end, the plan may recognize certain reaches where, for example, transportation infrastructure is located and keeping the river channelized is in the public interest.

Implementing river corridor plans will require a long-term commitment to reducing fluvial erosion hazards and restoring the natural and recreational values of rivers, while respecting traditional settlement patterns and the importance of a prosperous agriculture in Vermont. From one decade to the next, opportunities arise to work with landowners in a cooperative fashion, increasingly if not gradually giving the river more space to achieve equilibrium. Without a corridor plan, encroachments will continue, compounding the cost of flood recovery, and necessitating river management that is both economically and ecologically unsustainable.

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APPENDIX E: Channel Evolution Models and the Erosion Faces and Sediment Aggradation Common in an Adjusting River Profile

- 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)

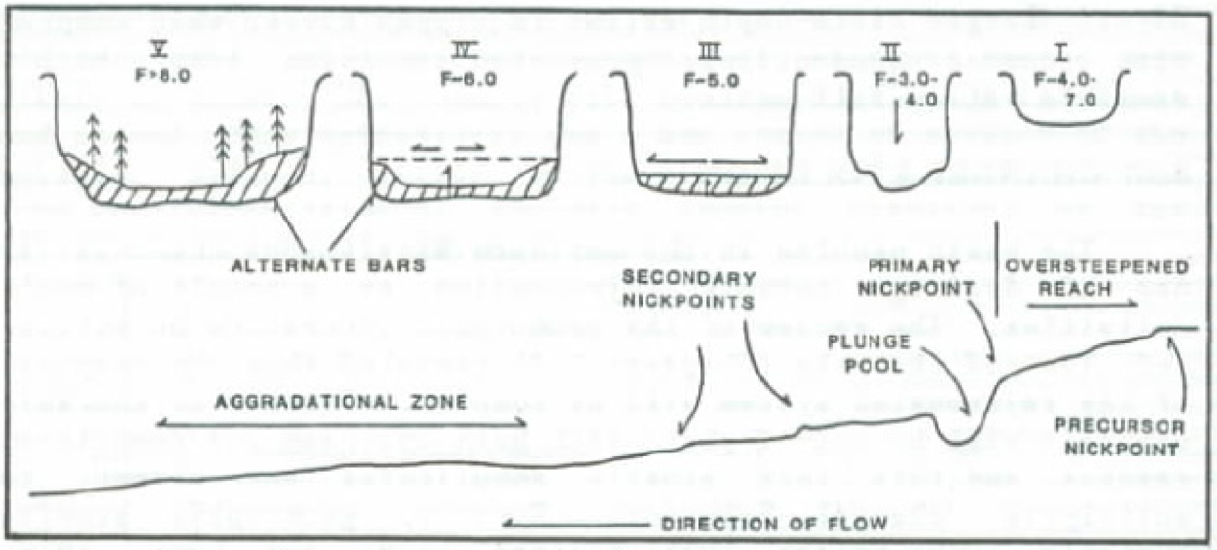


Figure 6-7. Schematic longitudinal profile of an active channel showing identifiable features. Schematic cross section profiles corresponding to reaches on the longitudinal profile show the evolution of the reaches from Type I to Type V. Typical width-depth (F) values are shown. Size of the arrows indicate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

Other useful references:

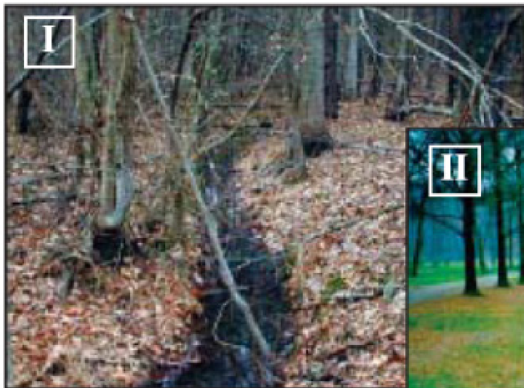
(Appendix C of VTANR, 2009) – Description of the stages and different channel evolution models. Pattern and profile diagrams for different stages of channel evolution.

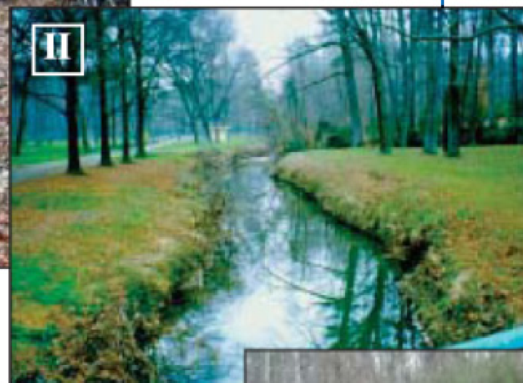
(FISRWG, 1998) – Diagram of stages of channel evolution.

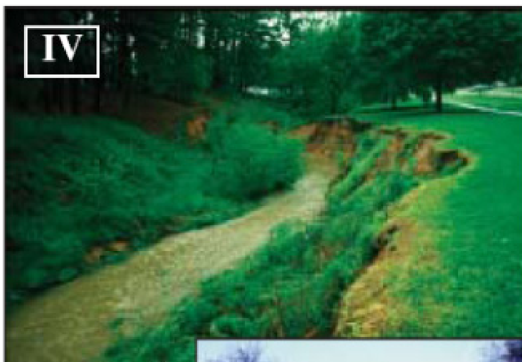
(Simon, 1989) – Diagram of stages of channel evolution.

Photograph examples of the stages of channel evolution (Doll et al., 2003)

Six evolutionary stages of channel evolution







Description of the processes and form of the stages of channel evolution (Doll et al., 2003). Note the last column on the right with "geobotanical" observation guidance for identifying the stage of evolution.

Class		Dominant Process		Characteristic Forms	Geobotanical Evidence
No.	Name	Fluvial	Hillslope		
I	Premodified	Sediment transport—mild aggradation; basal erosion on outside bends; deposition on inside bends		Stable, alternate channel bars; convex top-bank shape; flow line high relative to top bank; channel straight or meandering	Vegetated banks to flow line
II	Constructed (Channelized)			Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank	Removal of vegetation
III	Degradation	Degradation; basal erosion on banks	Pop-out failures	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank	Riparian vegetation high relative to flow line and may lean toward channel
IV	Threshold (Degradation and Widening)	Degradation; basal erosion on banks	Slab, rotational and pop-out failures	Large scallops and bank retreat; vertical face and upper-bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank	Riparian vegetation high relative to flow line and may lean toward channel
V	Aggradation and Widening	Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks	Slab, rotational and pop-out failures; low-angle slides of previously failed material	Large scallops and bank retreat; vertical face, upper bank and slough line; flattening of bank angles; flow line low relative to top bank; development of new floodplain	Tilted and fallen riparian vegetation; re-establishing vegetation on slough line; deposition of material above root collars of slough-line vegetation
VI	Restabilization (Quasi-equilibrium)	Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition on floodplain and bank surfaces	Low-angle slides; some pop-out failures near flow line	Stable, alternate channel bars; convex-short vertical face on top bank; flattening of bank angles; development of new floodplain; flow line high relative to top bank	Re-establishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough-line and upper-bank vegetation; some vegetation establishing on bars

Table 3.2. Channel-evolution model description
Simon, 1989, 24, and FISRWG, 1998, 7-36
(photographic examples of each of the six evolutionary stages are provided in Figure 3.7)

APPENDIX F: Permissible Shear and Velocity (Fischenich, 2001)

Table 2. Permissible Shear and Velocity for Selected Lining Materials[1]

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

[1] Ranges of values generally reflect multiple sources of data or different testing conditions.

A. Chang, H.H. (1988).
B. Florineth. (1982)
C. Gerstgraser, C. (1998).
D. Goff, K. (1999).
E. Gray, D.H., and Sotir, R.B. (1996).
F. Julien, P.Y. (1995).
G. Kouwen, N.; Li, R. M.; and Simons, D.B., (1980).
H. Norman, J. N. (1975).
I. Schiechtl, H. M. and R. Stern. (1996).
J. Schoklitsch, A. (1937).
K. Sprague, C.J. (1999).
L. Temple, D.M. (1980).
M. TXDOT (1999)
N. Data from Author (2001)
O. USACE (1997).

APPENDIX G: Draft Large Riprap Specifications (Prepared by Chris Bump of VTrans in 2012)

Item 900.608 CY Stone Fill Type VI

Type VI. The longest dimension of the stone shall be at least 72 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 24 inches. The least dimension of the stone shall be greater than 33 percent of the longest dimension. Stone for stone fill shall be approved, hard, blasted, angular rock other than serpentine rock containing the fibrous variety chrysotile (asbestos).

Item 900.608 CY Stone Fill Type VII

Type VIII. The longest dimension of the stone shall be at least 96 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 24 inches. The least dimension of the stone shall be greater than 33 percent of the longest dimension. Stone for stone fill shall be approved, hard, blasted, angular rock other than serpentine rock containing the fibrous variety chrysotile (asbestos).

Item 900.608 CY Stone Fill Type X

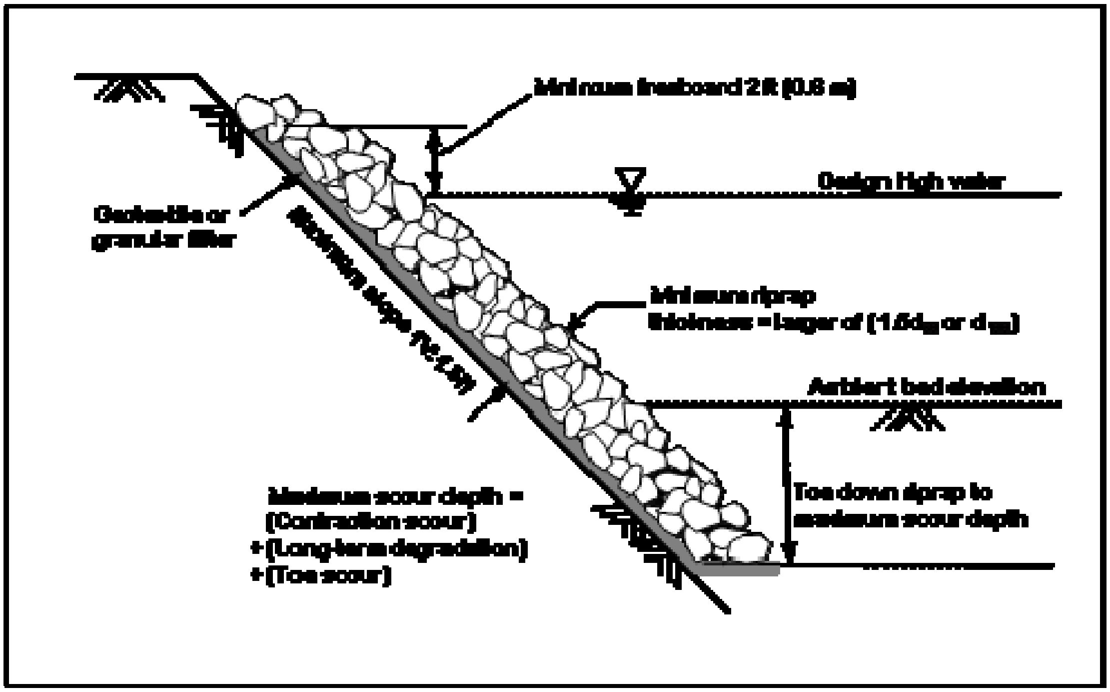
Type X. The longest dimension of the stone shall be at least 120 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 24 inches. The least dimension of the stone shall be greater than 33 percent of the longest dimension. Stone for stone fill shall be approved, hard, blasted, angular rock other than serpentine rock containing the fibrous variety chrysotile (asbestos).

APPENDIX H: Sample Standard Riprap Notes (Prepared by Matt Murawski of Dubois & King, Inc. for VTrans in 2012)

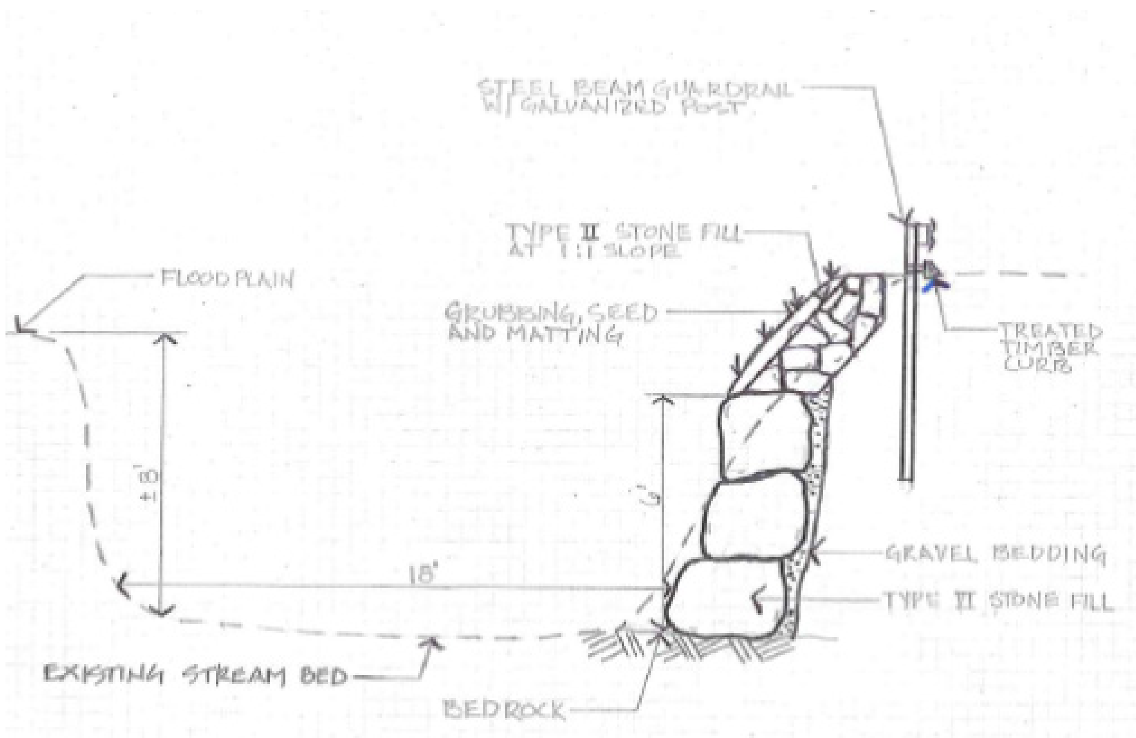
Suggested Standard Riprap Notes:

1. To the extent practical, excavation and placement of riprap must be done outside of flowing water to minimize the discharge of sediment-laden water. The contractor is responsible for diverting, pumping, bypass piping, or otherwise controlling water to meet this requirement. Contractor must submit control of water plan to the engineer approval prior to construction.
2. Riprap must be placed in a manner that will not separate small and large stones. Placement by dump truck or dozer will not be allowed. Regular mixing of the riprap stockpile during installation may be necessary to prevent separation of small and large stones.
3. The contractor is responsible for installing the riprap as a well-compacted mass, with stones interlocked with each other and with no large voids to reduce the potential for uplift and movement and to prevent grubbing material from washing into the stone.
4. To achieve a well-compacted mass, contractor may be required to follow the initial placement of riprap with additional passes of smaller material. Selective hand placement of stone followed by compaction may also be required.
5. Relatively large boulders shall be used at the toe of the riprap slope below normal low water level with no chinking stone on the front face so that gaps remain between stone to provide for improved aquatic habitat.
6. Granular borrow for rock riprap bedding shall be 9-inch minus, and be uniformly graded from course to fine. This material shall consist of crushed quarried rock (or approved equivalent) and shall be reasonably free from silt, loam, clay or organic matter. It shall be obtained from approved sources and acceptable to the engineer.
7. The contractor must provide the engineer an opportunity to inspect, with 48-hour prior notice, an in-place riprap test section. The test section must be between 10 and 20 feet long and be installed to the thickness and elevations indicated in the construction documents. Installation of additional riprap is not to continue until the engineer has completed or waived this inspection.
8. Contractor shall place a 6” (minimum) layer of grubbing material over the top of the finished riprap slope down to normal low water elevation. Grubbing material shall be worked in to the riprap mass, and into any small remaining surface voids and crevasses. On-site excavated grubbing material may be used if, in the opinion of the engineer, an adequate percentage of fines and organics are present in the material to support a grass cover.
9. Grubbing material shall be seeded with a standard conservation mix and protected with biodegradable erosion matting / loose mulch.

APPENDIX I: Granular Bedding Detail

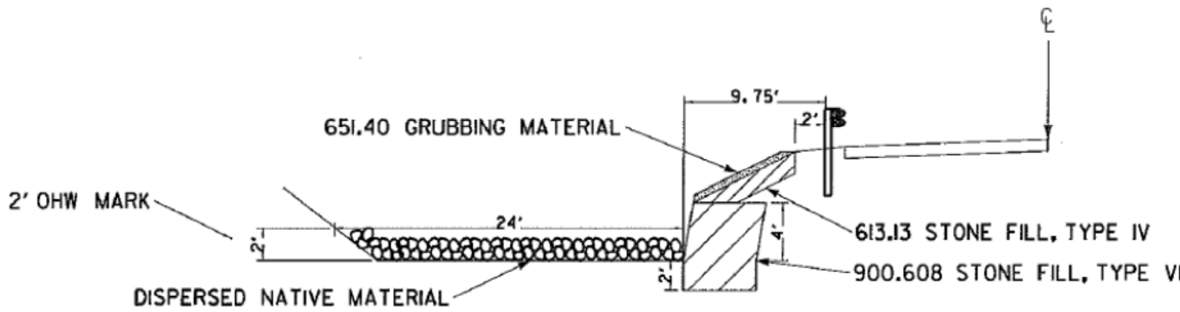


Riprap slope showing granular filter placement (Lagasse et al., 2009)

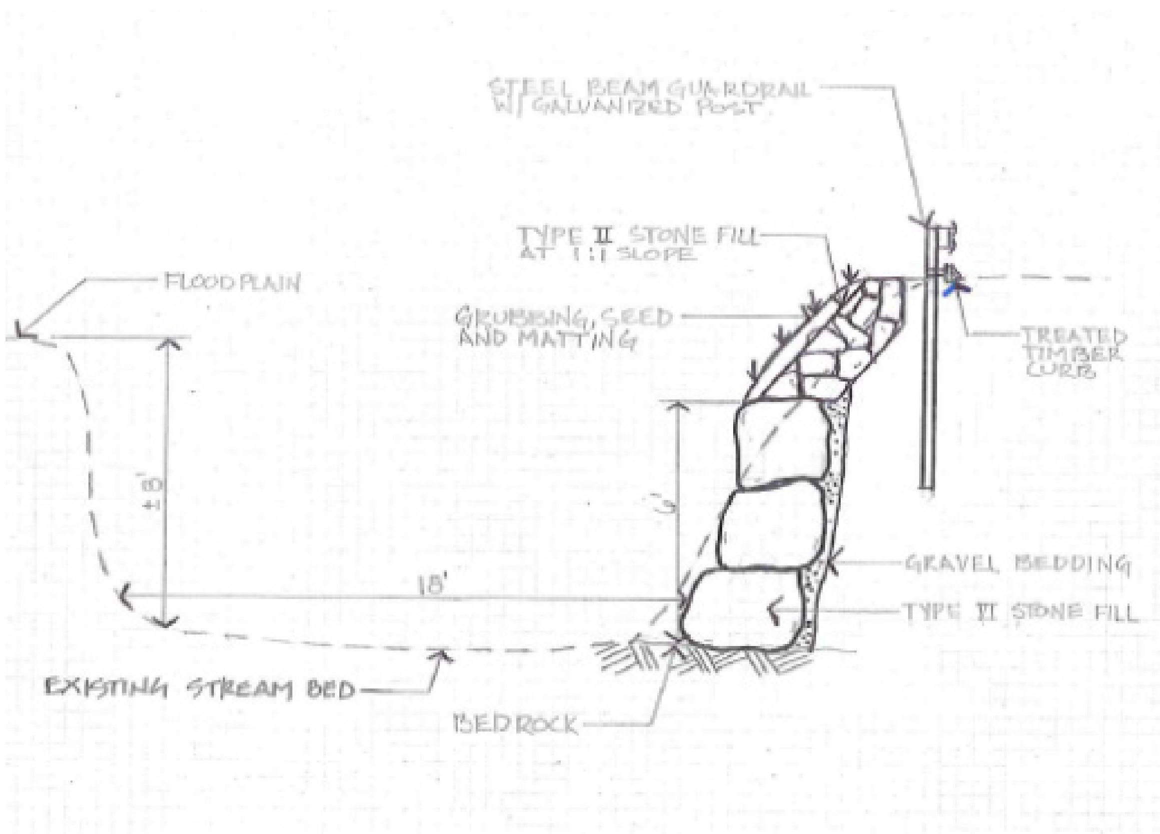


Detail showing gravel bedding behind placed riprap wall (Prepared by Chris May, VTrans, 2011)

APPENDIX J: Riprap Planting Options

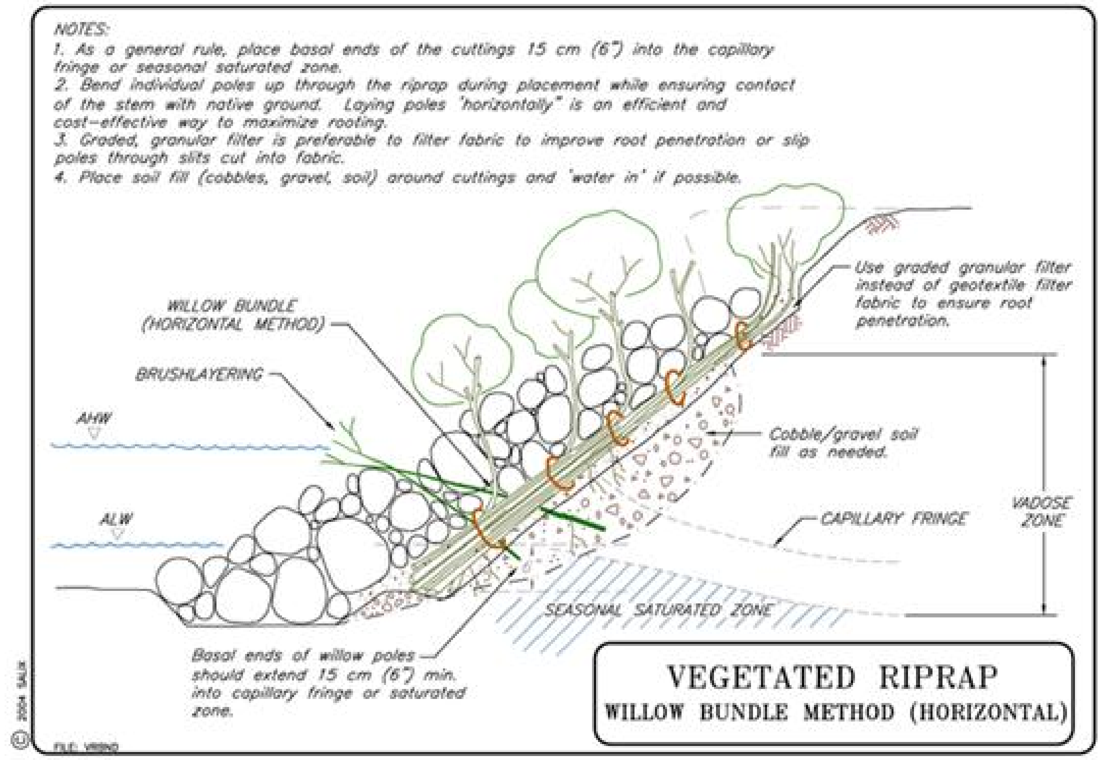


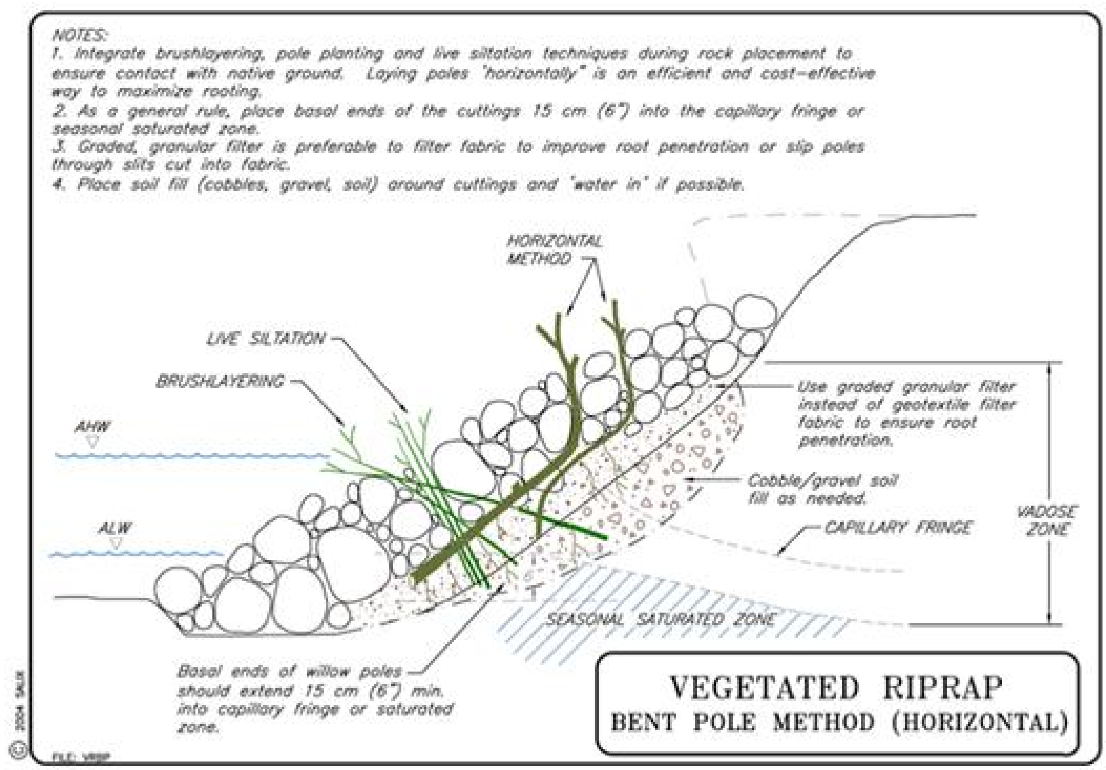
Detail showing placement of grubbing material and seeding over stone fill mid to upper bank
(Prepared by Todd Eaton, VTrans, 2012)

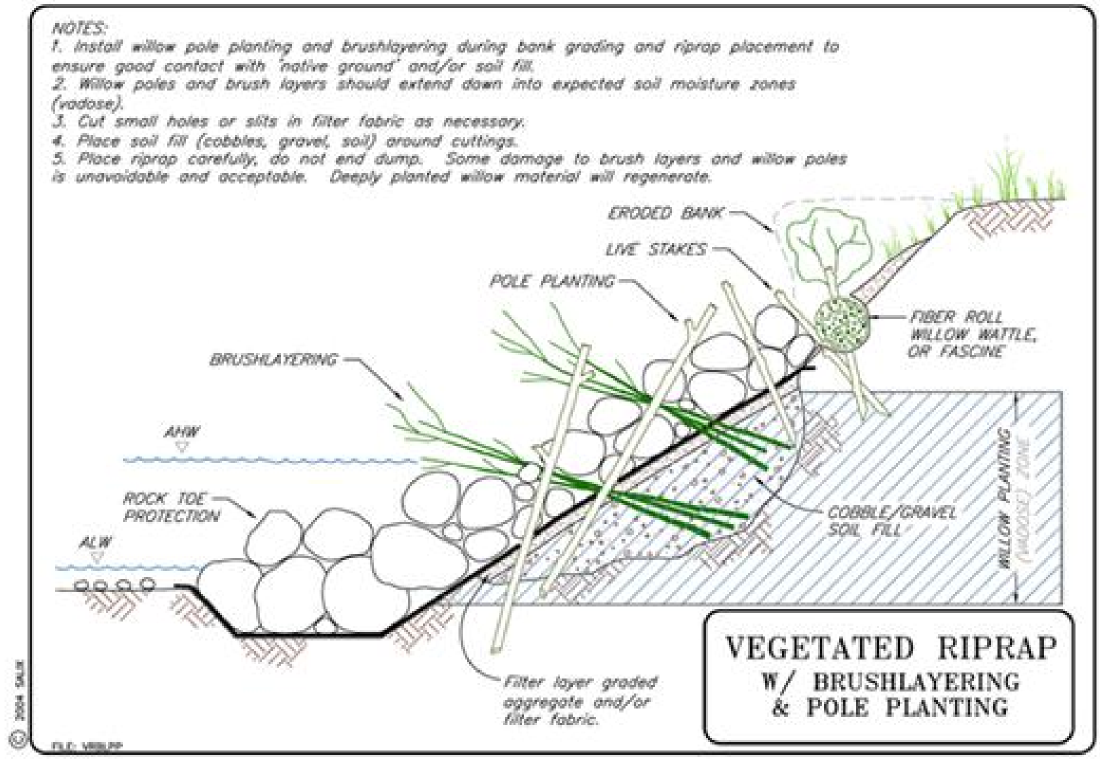


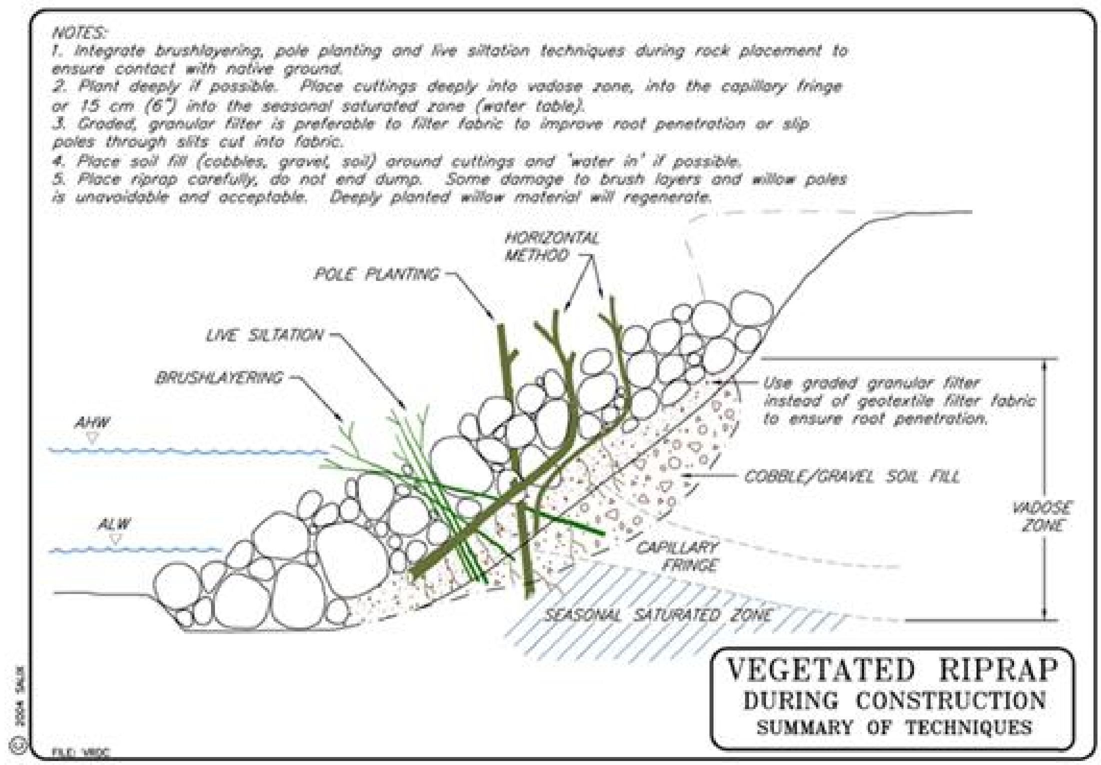
Detail showing placement of grubbing material and seeding over stone fill mid to upper bank
(Prepared by Chris May, VTrans, 2011)

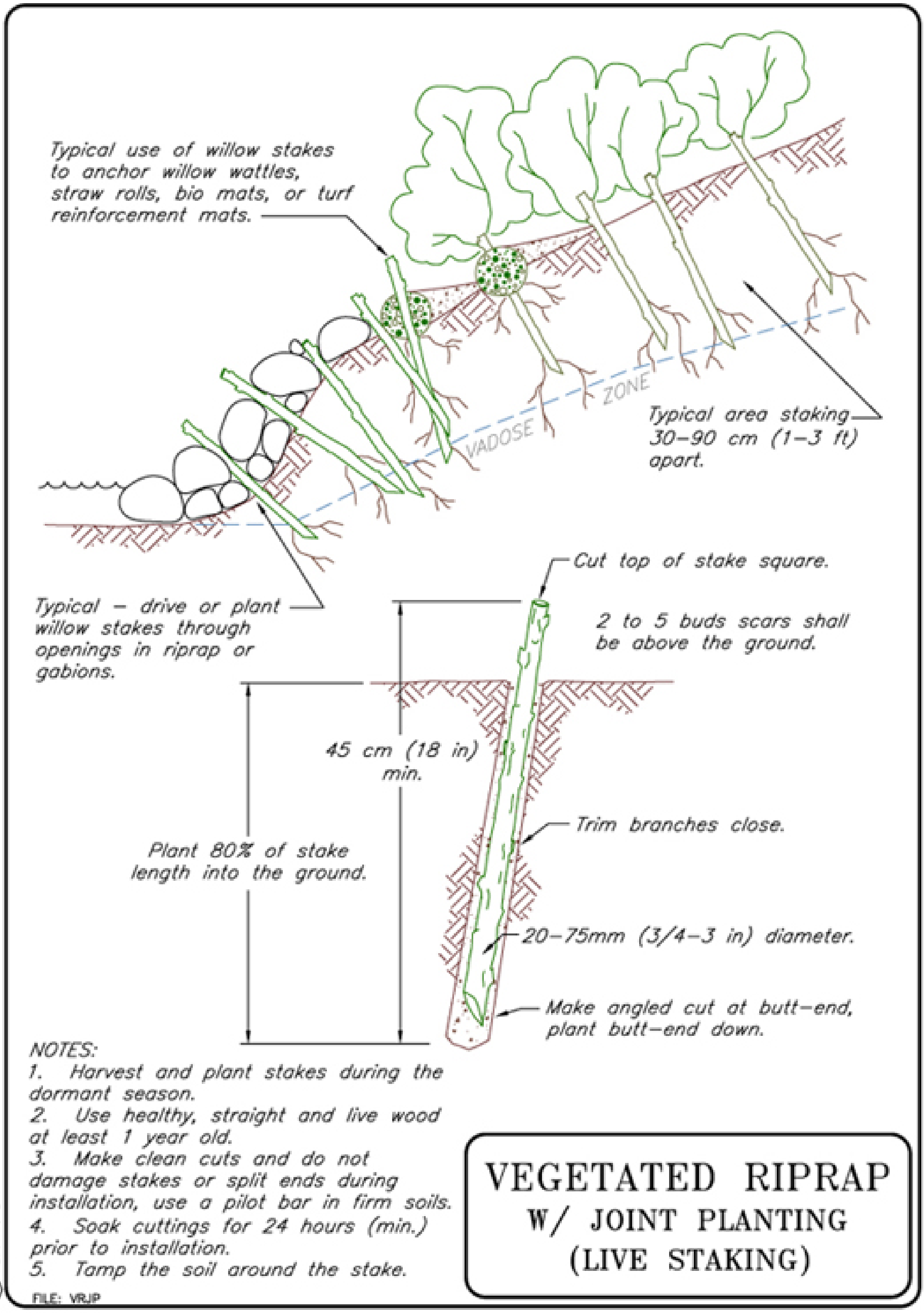
Details for Plantings to Accompany Riprap (McCullah and Gray, 2005)






NOTES:
1. Install willow pole planting and brushlayering during bank grading and riprap placement to ensure good contact with 'native ground' and/or soil fill.
2. Willow poles and brush layers should extend down into expected soil moisture zones (vadose).
3. Cut small holes or slits in filter fabric as necessary.
4. Place soil fill (cobbles, gravel, soil) around cuttings.
5. Place riprap carefully, do not end dump. Some damage to brush layers and willow poles is unavoidable and acceptable. Deeply planted willow material will regenerate.
ERODED BANK
LIVE STAKES
POLE PLANTING
FIBER ROLL WILLOW WATTLE, OR FASCINE
BRUSHLAYERING
AHW
ROCK TOE PROTECTION
ALW
COBBLE/GRAVEL SOIL FILL
WILLOW PLANTING (VADOSE) ZONE
Filter layer graded aggregate and/or filter fabric.
VEGETATED RIPRAP
W/ BRUSHLAYERING & POLE PLANTING
© 2004 SALIX
FILE: VRBLPP


NOTES:
1. Integrate brushlayering, pole planting and live siltation techniques during rock placement to ensure contact with native ground.
2. Plant deeply if possible. Place cuttings deeply into vadose zone, into the capillary fringe or 15 cm (6") into the seasonal saturated zone (water table).
3. Graded, granular filter is preferable to filter fabric to improve root penetration or slip poles through slits cut into fabric.
4. Place soil fill (cobbles, gravel, soil) around cuttings and 'water in' if possible.
5. Place riprap carefully, do not end dump. Some damage to brush layers and willow poles is unavoidable and acceptable. Deeply planted willow material will regenerate.
HORIZONTAL METHOD
POLE PLANTING
LIVE SILTATION
BRUSHLAYERING
AHW
ALW
Use graded granular filter instead of geotextile filter fabric to ensure root penetration.
COBBLE/GRAVEL SOIL FILL
VADOSE ZONE
CAPILLARY FRINGE
SEASONAL SATURATED ZONE
VEGETATED RIPRAP
DURING CONSTRUCTION
SUMMARY OF TECHNIQUES
© 2004 SALIX
FILE: VRDC



Typical use of willow stakes to anchor willow wattles, straw rolls, bio mats, or turf reinforcement mats.
VADOSE ZONE
Typical area staking 30–90 cm (1–3 ft) apart.
Typical – drive or plant willow stakes through openings in riprap or gabions.
Cut top of stake square.
2 to 5 buds scars shall be above the ground.
45 cm (18 in) min.
Plant 80% of stake length into the ground.
Trim branches close.
20–75mm (3/4–3 in) diameter.
Make angled cut at butt-end, plant butt-end down.
NOTES:
1. Harvest and plant stakes during the dormant season.
2. Use healthy, straight and live wood at least 1 year old.
3. Make clean cuts and do not damage stakes or split ends during installation, use a pilot bar in firm soils.
4. Soak cuttings for 24 hours (min.) prior to installation.
5. Tamp the soil around the stake.
VEGETATED RIPRAP
W/ JOINT PLANTING
(LIVE STAKING)
© 2004 SALIX
FILE: VRJP

APPENDIX K: Ordinary High Water Mark Identification (USACE, 2005)

REGULATORY GUIDANCE LETTER

US Army Corps of Engineers®

No. 05-05 **Date: 7 December 2005**

SUBJECT: Ordinary High Water Mark Identification

1. **Purpose and Applicability**

a. **Purpose.** To provide guidance for identifying the ordinary high water mark.

b. **Applicability.** This applies to jurisdictional determinations for non-tidal waters under Section 404 of the Clean Water Act and under Sections 9 and 10 of the Rivers and Harbors Act of 1899.

2. **General Considerations**

a. **Regulation and Policy.** Pursuant to regulations and inter-agency agreement,[1] the U.S. Army Corps of Engineers (Corps) determines, on a case-by case basis, the extent of geographic jurisdiction for the purpose of administering its regulatory program. For purposes of Section 404 of the Clean Water Act (CWA), the lateral limits of jurisdiction over non-tidal water bodies extend to the ordinary high water mark (OHWM), in the absence of adjacent wetlands. When adjacent wetlands are present, CWA jurisdiction extends beyond the OHWM to the limits of the adjacent wetlands. For purposes of Sections 9 and 10 of the Rivers and Harbors Act of 1899, the lateral extent of Federal jurisdiction, which is limited to the traditional navigable waters of the United States, extends to the OHWM, whether or not adjacent wetlands extend landward of the OHWM.

Corps regulations define the term "ordinary high water mark" for purposes of the CWA lateral jurisdiction at 33 CFR 328.3(e), which states:

> "The term *ordinary high water mark* means that line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas."

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1. Memorandum of Agreement between the Department of the Army and Environmental Protection Agency Concerning the Determination of the Geographical Jurisdiction of the Section 404 Program and the Application of the Exemptions under Section 404(f) of the Clean Water Act, January 19, 1989

This definition is virtually identical to the definition of the term “ordinary high water mark” found at 33 CFR Section 329.11(a)(1), describing the lateral extent of Federal jurisdiction over non-tidal traditional navigable waters of the United States subject to Sections 9 and 10 of the Rivers and Harbors Act of 1899 (RHA). When the definition from 33 CFR Section 329.11(a)(1) was reproduced at 33 CFR 328.3(e), the semi-colons of the former definition were mistakenly changed to commas in the latter definition. Consequently, the definition of “ordinary high water mark” in Part 328 is not as clear in meaning as is the definition of the same term in Part 329, even though the two definitions were to serve the same basic purpose (i.e., establishing the lateral extent of jurisdiction, in the absence of adjacent wetlands).[2]

Both definitions of the term “ordinary high water mark” begin by discussing physical characteristics that indicate the location of the OHWM on the shore of a water body. Furthermore, both OHWM definitions conclude with the statement the OHWM can be determined using “other appropriate means that consider the characteristics of the surrounding areas”.[3] Prior to this Regulatory Guidance Letter (RGL), neither the Corps nor the U.S. Environmental Protection Agency has issued any additional clarifying national guidance for use by Corps regulatory program staff in identifying the location of the OHWM for the CWA on a case-by-case basis.[4]

b. **Practice.** In making OHWM determinations, Corps districts generally rely on physical evidence to ascertain the lateral limits of jurisdiction, to whatever extent physical evidence can be found and such evidence is deemed reasonably reliable. Physical indicators include the features listed in the definitions at 33 CFR Sections 328.3(e) and 329.11(a)(1) and other appropriate means that consider the characteristics of the surrounding areas. In addition, districts use other methods for estimating the line on the shore established by the fluctuations of water, including, but not limited to, lake and stream gage data, flood predictions, historic records of water flow, and statistical evidence. To the maximum extent practicable, districts generally use more than one physical indicator or other means for determining the OHWM.

3. **Guidance.**

a. In determining the location of the OHWM for non-tidal water bodies under the CWA or the RHA, districts should give priority to evaluating the physical characteristics of the area that are determined to be reliable indicators of the OHWM. Physical evidence to be evaluated includes those items listed in the definitions at 33 CFR Sections 328.3(e) and 329.11(a)(1). Because many types of water bodies occur with varying conditions, including topography, channel morphology and flow dynamics, districts may consider other physical characteristics indicative of the OHWM.

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2. CWA jurisdiction extends laterally landward of the OHWM to include all adjacent wetlands wherever such adjacent wetlands are present. This guidance addresses situations where no such adjacent wetlands exist.

3. Changes in the limits of waters of the U.S. are addressed in 33 CFR 328.5.

4 . On 3 June 1983 the Corps of Engineers’ Chief Counsel distributed legal guidance to all Corps district and division counsel offices regarding certain legal questions relating to the geographic jurisdiction of Section 10 of the Rivers and Harbors Act of 1899, including questions relating to the OHWM.

b. The following physical characteristics should be considered when making an OHWM determination, to the extent that they can be identified and are deemed reasonably reliable:

Natural line impressed on the bank	Sediment sorting
Shelving	Leaf litter disturbed or washed away
Changes in the character of soil	Scour
Destruction of terrestrial vegetation	Deposition
Presence of litter and debris	Multiple observed flow events
Wracking	Bed and banks
Vegetation matted down, bent, or absent	Water staining
	Change in plant community

This list of OHWM characteristics is not exhaustive. Physical characteristics that correspond to the line on the shore established by the fluctuations of water may vary depending on the type of water body and conditions of the area. There are no "required" physical characteristics that must be present to make an OHWM determination. However, if physical evidence alone will be used for the determination, districts should generally try to identify two or more characteristics, unless there is particularly strong evidence of one.

c. Where the physical characteristics are inconclusive, misleading, unreliable, or otherwise not evident, districts may determine the OHWM by using other appropriate means that consider the characteristics of the surrounding areas, provided those other means are reliable.[5] Such other reliable methods that may be indicative of the OHWM include, but are not limited to, lake and stream gage data, elevation data, spillway height, flood predictions, historic records of water flow, and statistical evidence.

d. When making OHWM determinations, districts should be careful to look at characteristics associated with ordinary high water events, which occur on a regular or frequent basis. Evidence resulting from extraordinary events, including major flooding and storm surges, is not indicative of the OHWM. For instance, a litter or wrack line resulting from a 200-year flood event would in most cases not be considered evidence of an OHWM.

e. Districts will document in writing the physical characteristics used to establish the OHWM for CWA and/or RHA jurisdiction. If physical characteristics are inconclusive, misleading, unreliable, or not evident, the Districts' written documentation will include information about the physical characteristics (or lack thereof) and other appropriate means that consider the characteristics of the surrounding areas, which it used to determine the OHWM.

f. To complete an approved jurisdictional determination, districts will have complete and accurate documentation that substantiates the Corps decision. At a minimum, decisions will be documented using the standardized jurisdictional determination information sheet established by

5. In some cases, the physical characteristics may be misleading and would not be reliable for determining the OHWM. For example, water levels or flows may be manipulated by human intervention for power generation or water supply. For such cases, districts should consider using other appropriate means to determine the OHWM.

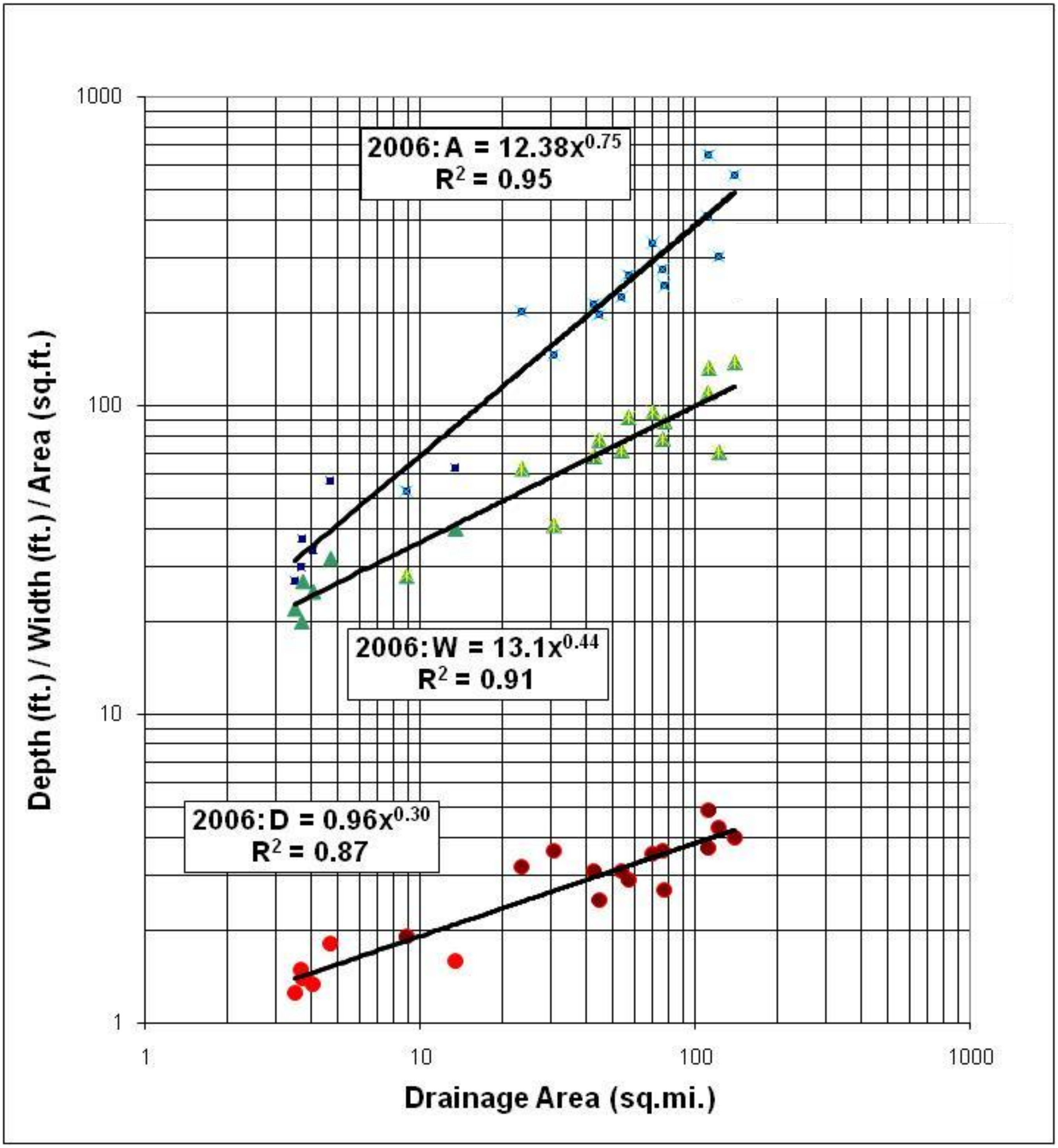
Headquarters and provided to the districts on August 13, 2004 (or as further amended by Headquarters). Documentation will allow for a reasonably accurate replication of the determination at a future date. In this regard, documentation will normally include information such as data sheets, site visit memoranda, maps, sketches, and, in some cases, surveys and photographs documenting the OHWM.

4. **Duration.** This guidance remains in effect unless revised or rescinded.

DON T. RILEY
Major General, US Army
Director of Civil Works

APPENDIX L: Vermont Hydraulic Geometry Regression Equations (VTDEC, 2006b)

2006 Vermont Hydraulic Geometry Curves



Regression equations for cross-sectional area (A) and bankfull channel width (W) and depth (D) against drainage area (x). To access the full report on the development of the 2006 VT HGC, go to: http://www.vtwaterquality.org/rivers/docs/rv_hydraulicgeocurves.pdf

APPENDIX M: Draft Streambed Fill Specifications (Prepared by Patrick Ross and Barry Cahoon of VTANR in 2014)

Streambed Stone Fill Design Guidance

Type	**Velocity Range (fps)***	**Embeddedness (in)**
E1	$V \leq 9$	18
E2	$9 < V \leq 11$	24
E3	$11 < V \leq 13$	36
E4	$13 < V \leq 15$	48

*Maximum velocity should be based on a minimum 50-year design flow rate and calculated at the structure outlet.

Item xxx.xxx CY Streambed Stone Fill Specification

Type E1. The longest dimension of the stone shall be at least 18 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 12 inches, and at least 25 percent of the particles shall have a maximum dimension of 2 inches and be well graded material.

Type E2. The longest dimension of the stone shall be at least 24 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 18 inches, and at least 25 percent of the particles shall have a maximum dimension of 2 inches and be well graded material.

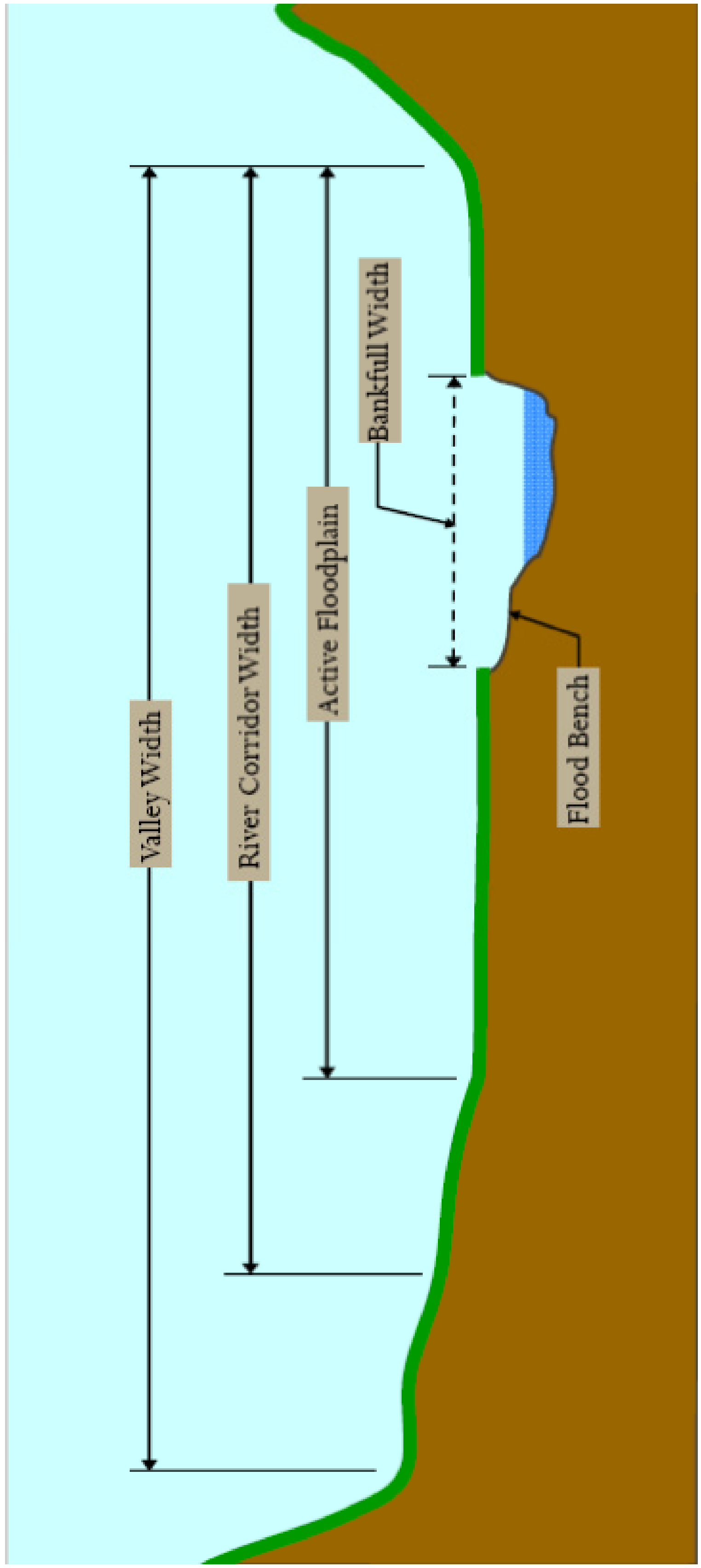
Type E3. The longest dimension of the stone shall be at least 36 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 24 inches, and at least 25 percent of the particles shall have a maximum dimension of 2 inches and be well graded material.

Type E4. The longest dimension of the stone shall be at least 48 inches, and at least 50 percent of the volume of the stone in place shall have a least dimension of 36 inches, and at least 25 percent of the particles shall have a maximum dimension of 2 inches and be well graded material.

Notes

- The streambed stone fill shall be hard, blasted, angular rock other than serpentine rock containing the fibrous variety chrysotile (asbestos). Similar sized river sediment is an acceptable alternative as is a mixture of angular material and river sediment.
- Stone placed inside of a closed structure shall be placed such that the structure is not damaged.
- Care shall be taken to limit segregation of the materials.
- Add sand borrow item as needed to seal the bed and prevent subsurface flow.
- There shall be no subsurface flow upon final inspection.

APPENDIX N: Schematic Showing River Corridor in Relation to the Valley, Floodplain, Bankfull Channel, and Flood Bench


Valley Width
River Corridor Width
Active Floodplain
Bankfull Width
Flood Bench

APPENDIX O: Incision Ratio Based on the Recently Abandoned Floodplain and the Human-Elevated Floodplain (VTANR, 2009)

2.5 RECENTLY ABANDONED FLOODPLAIN (RAF)

Background

The height of the recently (approximately past 200 years) abandoned floodplain, relative to the elevation of the bankfull maximum depth, is an important parameter to measure on streams that have eroded downward but may still have access to this floodplain during larger flood events. When looking for an RAF, key in on floodplain features that the stream had access to within the past 200 years, but due to an incision process the stream has lost access to the feature at the bankfull flow. The stream may still have access to the features at higher flows.

If you have a berm adjacent to the stream you will NOT use the berm height as the RAF elevation. Use the elevation of the floodplain on the other side of the berm. The berm height is captured under Step 1.3.

The RAF height is divided by bankfull maximum depth to determine the incision ratio (IR_{RAF}) for the channel (Step 2.8). The recently abandoned floodplain may be one of the nearby terraces identified and recorded as part of the cross-section measurements (Step 2.3 side box and Figure 2.3). In some cases where the stream has not incised there will not be an abandoned floodplain and the bankfull elevation and the current floodplain elevation will be the same. Be sure to record the current bankfull elevation if the river has access to a floodplain at bankfull flows. In the case of no RAF the incision ratio should be 1.

Evaluation

Stretch a tape taut and level across the channel from the top of the lowest of the two banks to a measuring rod positioned at the bankfull maximum depth, or thalweg (Figure 2.4). Record the height of the recently abandoned floodplain to the nearest tenth of a foot, which is the distance between the measuring tape and the streambed at the thalweg. Record at least one point out beyond the top of bank point to help with determining if the feature continues at the same elevation for some distance or changes slope within a give distance.

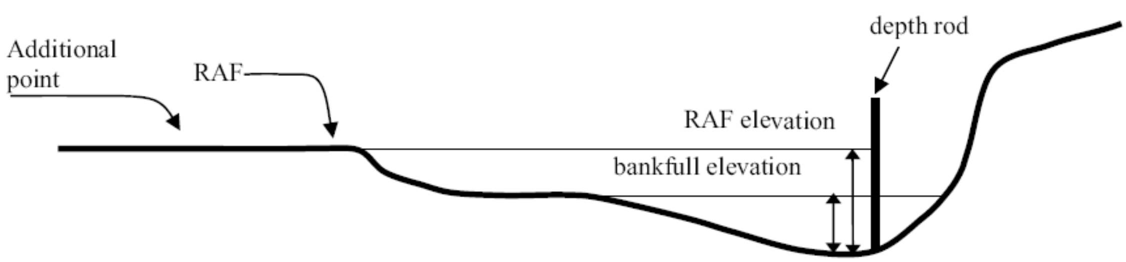


Figure 2.4 Measuring Recently Abandoned Floodplain (RAF)

If the bankfull maximum depth is identical to the height of the RAF then the same number will be recorded for both parameters on the Field Notes form. The height to the adjacent RAF may be greater than the bankfull maximum depth in situations where bed degradation has occurred and what was once an active floodplain during bankfull flows has been abandoned. You are trying to key in on recently abandoned features (that flooded on an annual basis). One way to do this is to only consider terrace **features that are no more than 3 bankfull widths** and typically less than one bankfull width from the left or right bankfull pins. You also what to avoid terraces that were active flood plains before historic times. Do not measure to high abandoned terraces that are more than 3 times the bankfull maximum depth.

Human Elevated Floodplain (IR_{HEF}) Vs. Abandoned Floodplain (IR_{RAF})

When fill or encroachments such as railroads, roads, berms, levees, and improved paths cause **the incision of the reach to be increased** there is a need to look at the incision ratio caused by the encroachment (IR_{HEF}) for the RGA; as compared to the incision ratio calculated with the floodplain in front of/behind the encroachment (IR_{RAF}).

Human elevated incision ratios should be calculated for <u>all</u> encroachments (berms, roads, railroads, and improved paths) where the encroachment is not considered to be the new valley wall and is blocking access to the floodplain or recently abandoned floodplain (RAF).

Take a moment to look at the encroachment situations below.

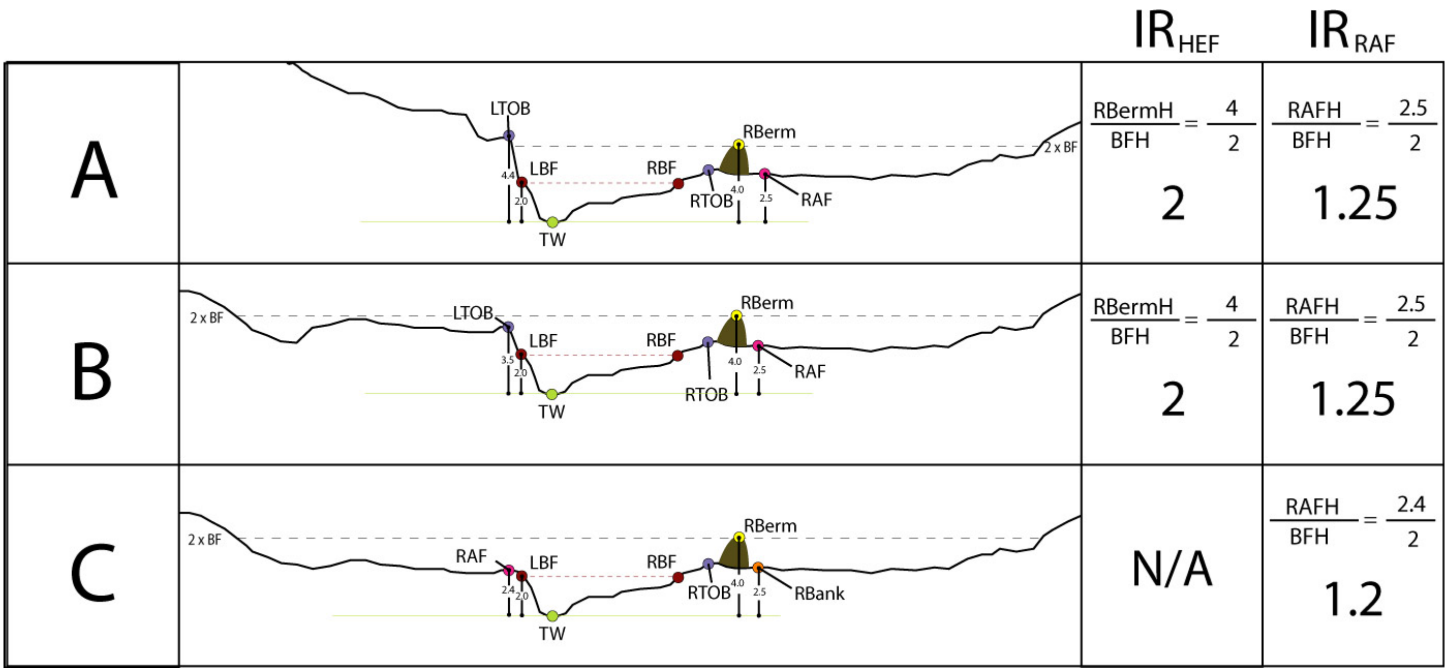


Figure caption: Three different cross section scenarios for a berm within the corridor. Labels are provided for the Left top of bank (LTOB), Left bankfull (LBF), Thalweg (TW), Right bank full (RBF), Right top of bank (RTOB), Right berm (RBerm), and the Right Bank (RBank). The solid green line represents the thalweg height. The red dashed line is equal to bankfull and the gray dashed line is equal to two times bankfull. Numbers represent heights (H) above the thalweg for each of the points.

A. There is no access to the flood plain; due to a natural feature on left side and a berm on the right side. The height of the berm would be used to calculate the incision ratio to be used in the RGA. Human caused incision ratio is calculated using the height of the berm (as measured from the thalweg of the channel) divided by the max depth. The human elevated incision ratio (IR_{HEF}) is 2.0. To determine what the incision ratio would be if the berm were removed; use the "recently abandoned floodplain" (RAF), to calculate the incision ratio. A berm removal project would make the incision ratio equal to 1.25. This incision ratio would be used in project planning.

B. There is access to an abandoned flood plain on the left side of the river, but a more recently abandoned and more accessible feature exists behind the berm on the right side. In this case the height of the berm would be used to calculating the incision ratio (IR_{HEF}) and the IR_{HEF} would be used in the RGA. In this scenario, the human elevated incision ratio is 2.0 and is calculated using the height of the berm (as measured from the thalweg of the channel) divided by the max depth. To determine what the incision ratio would be if the berm were removed; use the “recently abandoned floodplain” (RAF), to calculate the incision ratio (IR_{RAF}). A berm removal project would make the incision ratio equal to 1.25.

C. There is access to the floodplain on the left side of the river opposite the berm. In this case, the top of the berm is not considered the “recently abandoned flooplain” (RAF). The human caused incision ratio (IR_{HEF}) does not need to be calculated for use in the RGA, as there is flood access to a feature on the left side that is at or slightly lower than the abandoned floodplain or terrace on the back side of the berm. The (IR_{RAF}) incision ratio would be used in the RGA, and is calculated using the RAF on the left (as measured from the thalweg of the channel) divided by the max depth for an incision ratio of 1.2. If the berm was removed incision would not change, but the river would have access to flood access to the terrace on both sides.

APPENDIX P: Stream Power of Floodplains and Channels (Nanson and Croke, 1992)

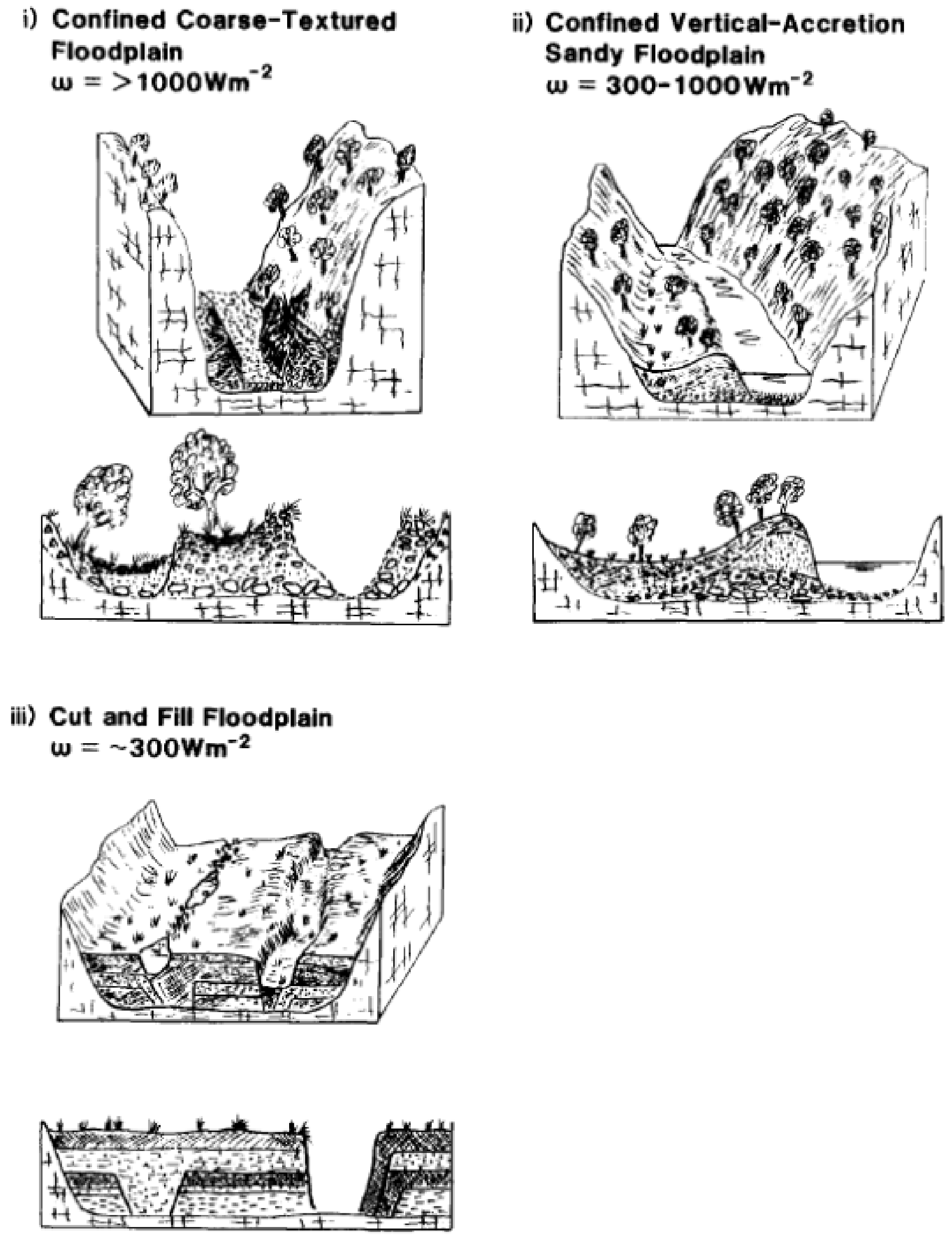


Fig. 1. High energy non-cohesive floodplains. (i) Confined coarse-textured floodplain (after Stewart and Lamarche, 1967 and Baker, 1977). (ii) Confined vertical-accretion sandy floodplain (after Nanson, 1986). (iii) Cut and fill floodplain (after Prosser, 1988).

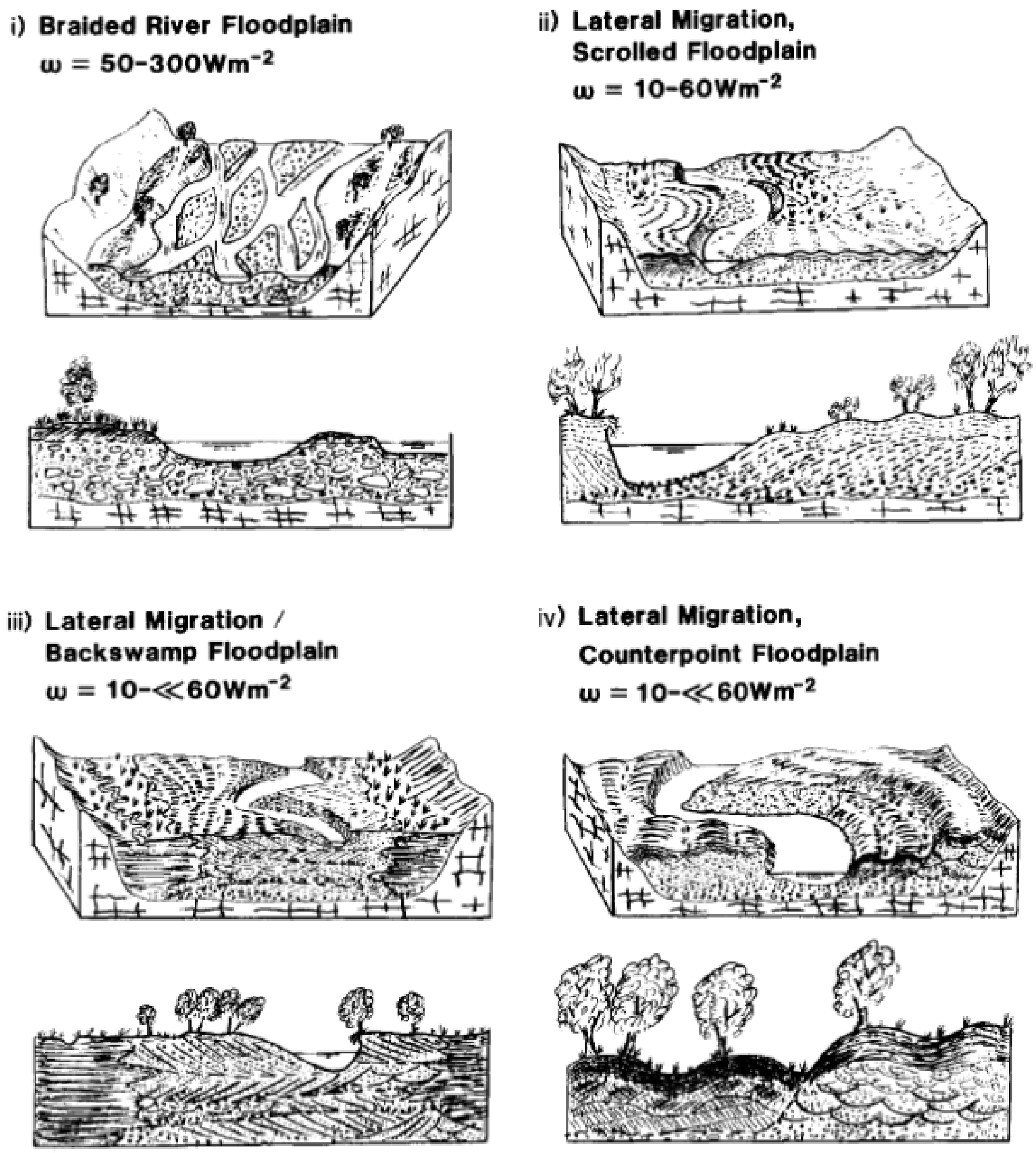


Fig. 2. Medium-energy, non-cohesive floodplains. (i) Braided river floodplain showing gravel bars and fine overbank deposition on the floodplain. (ii) Lateral-migration scrolled floodplain (after Nanson, 1980). (iii) Lateral-migration/ backswamp floodplain (after Blake and Ollier, 1971 and Kesel et al. 1974). Lateral migration results in a central deposit of laterally accreted alluvium flanked by organic and fine-grained clastic overbank accretion. (iv) Lateral-migration counterpoint floodplain (after Nanson and Page, 1983). The counterpoint floodplain is forming against the concave bank of the nearest bend at a slightly lower elevation with its surface deposits finer grained and higher in organics than those on the rest of the floodplain. Flow is towards the observer.

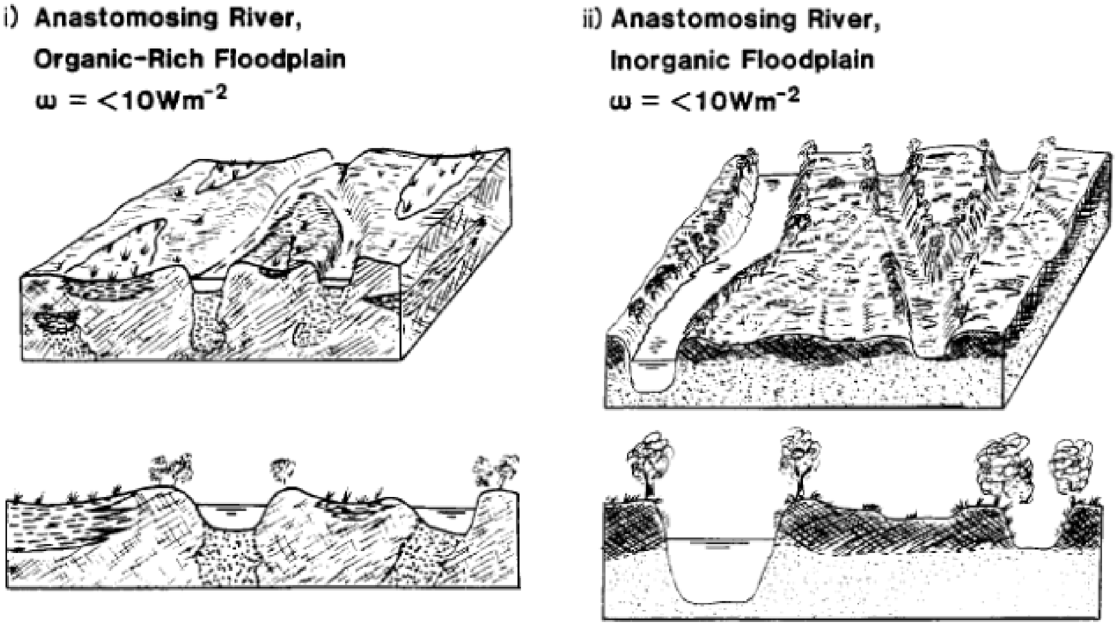


Fig. 3. Low-energy, cohesive floodplains. (i) Anastomosing river, organic-rich floodplains (after Smith and Smith, 1980). Vertical accretion is laying down overbank muds and lacustrine deposits around near-vertical stringers of sand or gravel beneath each channel. Swamps and lakes can result in widespread paludization. (ii) Anastomosing river, inorganic floodplains (after Nanson et al., 1986, 1988 and Rust and Nanson, 1986). To the right of the diagram, anastomosing channels are incised into cohesive floodplain mud with coexistent shallow braid-channels over the floodplain surface. To the left of the diagram, a waterhole has scoured beneath the mud into a sand sheet deposited during an earlier flow regime (Nanson et al., 1988).

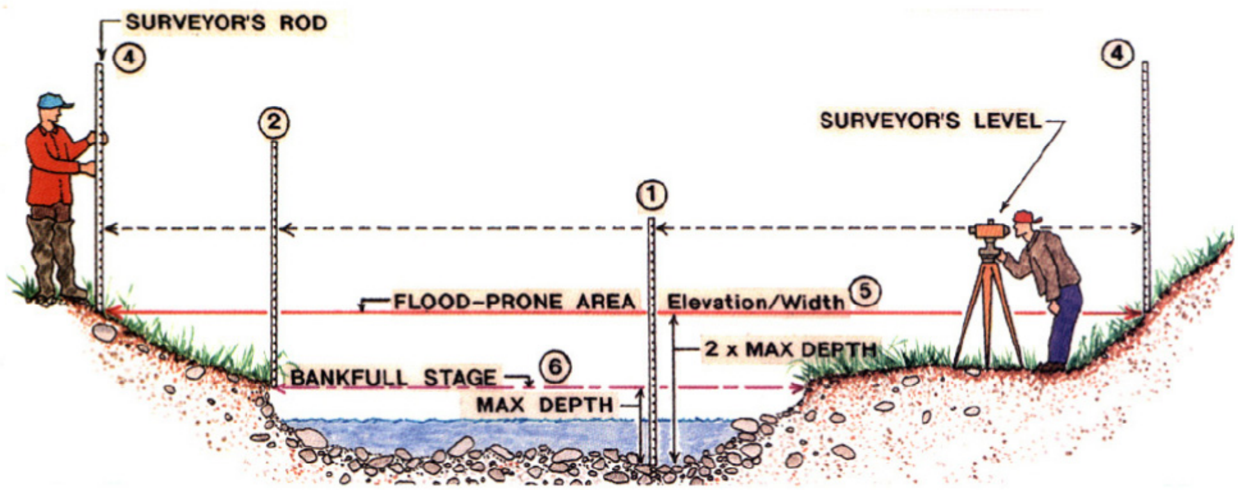
APPENDIX Q: Diagram of Floodprone Width (Rosgen and Silvey, 1996)

STEPS: 1. Obtain a ROD READING for an Elevation at the "MAX DEPTH" Location.

2. Obtain a ROD READING for an Elevation at the "BANKFULL STAGE" Location.

3. Subtract the "Step 2" reading from the "Step 1" reading to obtain a "MAX DEPTH" value; then multiply the Max. Depth Value times 2 for the "2x MAX. DEPTH" Value.

4. Subtract the "2x Max. Depth" value from the "Step 1 Rod Reading" for the FLOOD-PRONE AREA Location Rod Reading. Move the rod upslope, online with the cross-section, until a Rod Reading for the Flood-Prone Area Location is obtained.



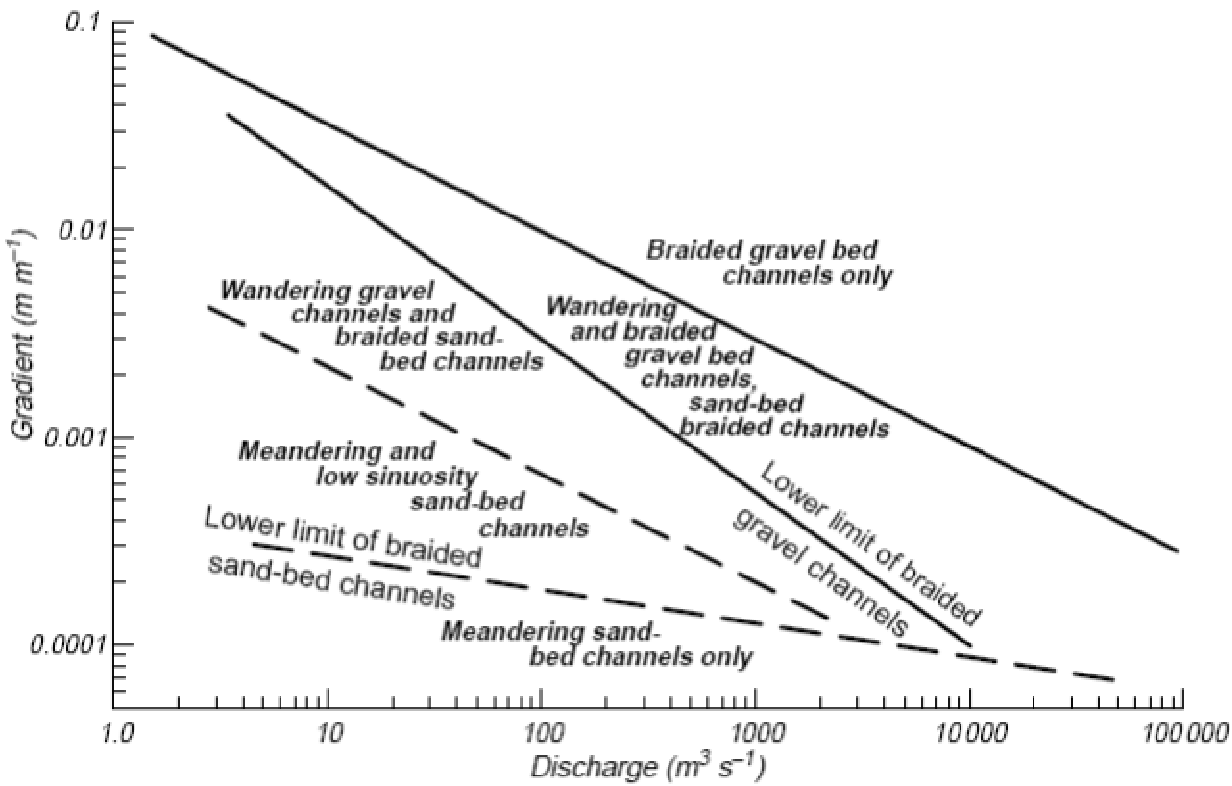
5. Mark the Flood-Prone Area locations on each bank. Measure the DISTANCE between the two "FPA" locations.

6. Determine the DISTANCE between the two BANKFULL Stage locations.

7. Divide the "FPA" WIDTH by the "BANKFULL" WIDTH to calculate the ENTRENCHMENT RATIO.

APPENDIX R: Predicting Channel Pattern (Meandering, Braided, or Wandering)

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



- Measure channel slope and bankfull flow in English units and use plot by (Leopold and Wolman, 1957).

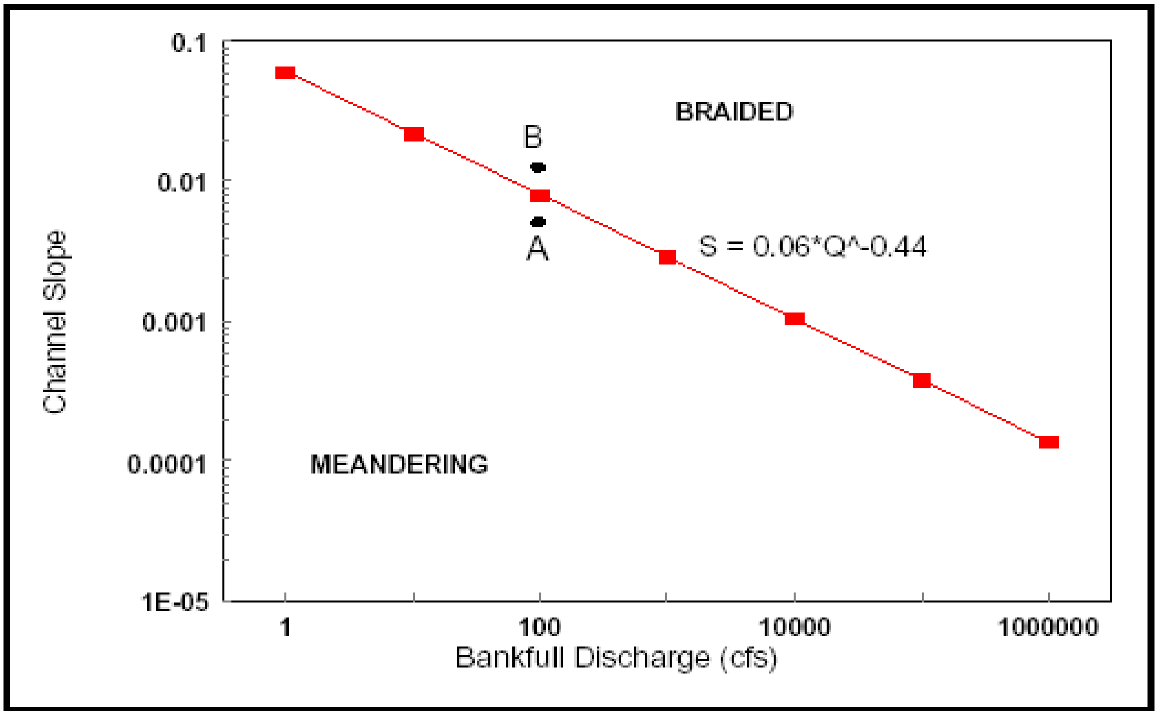
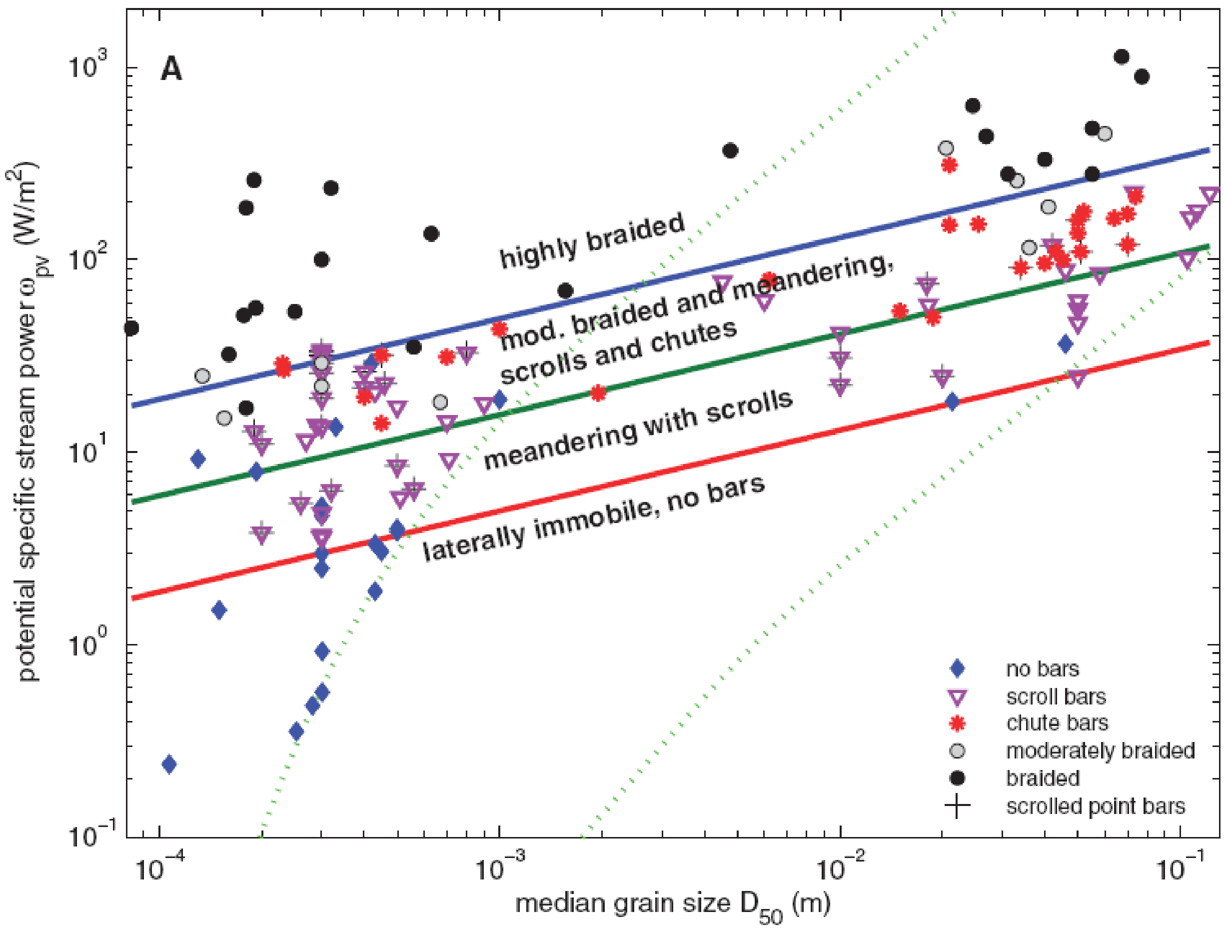


Figure 3.11 Leopold and Wolman's (1957) Relationship Between Channel Patterns, Channel Gradient, and Bankfull Discharge

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



APPENDIX S: To Dig or Not to Dig: Vermont's Rivers Following Irene (Schiff et al., 2011)

To Dig or Not to Dig: Vermont's Rivers Following Irene

Roy Schiff, Ph.D., P.E., Water Resource Engineer and Scientist, Milone & MacBroom, Inc.
Julie Moore, P.E., Senior Engineer, Stone Environmental, Inc.
Elise Annes, Vice President for Community Relations, Vermont Land Trust

As the immediate crisis of the flood following Tropical Storm Irene lessens, growing public debate about gravel mining our State's rivers has emerged. Many in the most impacted communities suggest that gravel mining and armoring our rivers is necessary to ensure stability and safety, and believe it is the lack of gravel mining over the past decade that has led to the destruction during this flood. Meanwhile, there are those that strongly caution against the removal of sediment from the rivers. These individuals and groups refer to current river science that shows that removal of sediment from rivers usually leads to a more unstable river and destroys aquatic habitat. What is the best way forward?

We all cherish Vermont's rivers and rely on the infrastructure in the state, and thus we all have a stake in evaluating how best to recover and plan for the future. A balanced and deliberate approach is now needed to move Vermont's flood recovery forward. To achieve a pre-flood level of safety in developed areas, the removal of an appropriate amount of sediment to protect permanent infrastructure will be a necessary response in some locations. At the same time, the goal of recovery should not be the wholesale removal of gravel and trees from rivers. Many rivers should remain untouched allowing the channel to naturally redistribute sediment, form habitat, and take its course where infrastructure is not at risk. Although the urge to act immediately can be powerful and with good intent, the decisions about where and how to manage our rivers must be considered carefully following a large and damaging flood.

The rivers of Vermont have been forever changed by Irene. We need to take a path toward recovery that involves the State, Towns, and public, and that considers a broad range of science-based, prioritized alternatives. We must first pause to evaluate where our villages, schools, businesses, homes, roads, and bridges are located now and where they should be in the future, so that the communities of Vermont will remain sustainable in the long-run.

Irene has confirmed that giving a river space to meander in floodplains, wherever possible, is the easiest and most cost-effective way to reduce flooding and erosion hazards. Floodplains must continue to be preserved across Vermont to provide rivers ample space to move, store water, and store sediment during floods.

We can all agree that it is humbling to see areas in the state where flooding was most destructive. As crisis moves towards long-term recovery, the path forward will be much more complicated than the question to dig or not to dig. Here are some guidelines to help the process moving forward:

Flood Recovery Guidelines

Strategize Flood Recovery – Consider the needs of both the built and the natural environment in evaluating a range of alternatives for both the short and long term, including: public safety, infrastructure protection, floodplain agriculture, water quality, aquatic habitat, cost-effectiveness, and longevity. Seek a preferred alternative that will benefit multiple objectives, aiding both the river and people.

Floodplain Protection – Where space allows, move away from rivers to reduce risks of future flood and erosion damage and protect aquatic habitat. Seek financial incentives through River Corridor Easements from the Vermont Rivers Program, Vermont River Conservancy, Vermont Land Trust, and others that support risk reduction by limiting new permanent infrastructure in floodplains.

Community Planning – Recognize that flowing water does not respect political boundaries, and therefore it is essential to have discussions that involve both individual towns and all those within a watershed about a range of alternatives for long-term flood recovery and avoidance. Consider past and future flooding and how best to reduce risks from inundation, channel movement, sediment deposition, and woody debris. Think about watershed neighbors and how to minimize downstream risks.

Stay Committed – Whether actively engaged in the ongoing recovery or working to prevent future damage, successfully reducing flood and erosion hazards and protecting Vermont's river corridors is a challenging and long-term process. This task is an essential part of our future if we are to create safer communities amongst healthier rivers in a mountainous state with many Village Centers located in floodplains.

Common Flood Recovery Myths

1. *You can dig yourself out of a flood.*

   Rivers move water, sediment, and woody debris. The shape of a natural river channel reflects a balance between the flow of water and the amount of sediment and woody debris that the stream carries. The wider and deeper a channel is, the slower the water moves, making it more likely that excessively large sediment bars will form in the future. As water gets pushed around growing sediment bars, gravel extraction often has the unintended consequence of increasing the likelihood of channel movement and therefore increasing the risk of flooding.

   In channels in a narrow valley, digging deeper usually leads to more down-cutting and collapse of the banks increasing the risks to nearby infrastructure.

2. *No removal of sediment from river channels should occur after large floods.*

In mountainous areas, there are many locations where flood and erosion risks are high due to the presence of areas that are prone to large amounts of sediment deposition. For example, alluvial fans are the flat areas located at the base of the mountains that are prone to sediment deposition during small to large floods. These areas are often characterized by naturally unstable stream channels flowing over loose sediment. Towns were historically set up in these areas because of the availability of water power. Early settlers were, however, more mobile than our current towns with fixed infrastructure. In these areas, some sediment removal is likely needed following flooding to protect this permanent infrastructure.

For example, the Town of Bennington is located on an alluvial fan. It is estimated that 3,500 dump truck loads of sediment (500,000 cubic yards) was deposited over a few miles of the Roaring Branch of the Walloomsac River in Bennington as a result of Irene. The cobbles and boulders eroded from the upstream mountains filled bridge openings, formed 10-foot tall bars in the channel, and caused the river channel to move side to side destroying homes, garages, part of a levee, and bridges. Sediment removal and bank armoring to protect existing homes and roads in these most vulnerable areas is required to return a pre-flood acceptable level of safety.

3. *It is possible to ensure against future flood damage by straightening and armoring stream channels.*

There is no way of completely avoiding future flood damages beyond moving all permanent infrastructure out of river corridors and above historic and predicted flood levels. Armoring banks and straightening channels provide short-term fixes that will be effective until the next large flood. In addition, these approaches often have the unintended consequence of increasing downstream flooding and erosion risks during moderate flood events.

4. *Cutting trees down in the floodplain will prevent debris jams during the next flood.*

Large numbers of trees were carried down river channels during the Irene flood clogging bridges and culverts, depositing on islands, and making local flooding worse in some areas. However, post-flood surveys indicate that wide forested floodplains stayed intact and the trees captured and retained flood debris. Tree loss was most abundant along narrow buffers and thin stands in floodplains. Wider forested buffers provide more space to slow water and store sediment and other wood.

Trees play vital roles in river ecosystems and are a natural component of all rivers in New England. Design and planning is needed to consider the expected load of trees that will be coming down the river channels during future floods.

5. *Irene was the 100-year flood so we will never see another flood like this during our lifetime.*

Recent data from assessments, design projects, and studies are all showing that Vermont is seeing larger and more frequent flooding. Several counties had disaster declarations for severe flooding in both May and August this year alone. It seems likely that we will experience more floods in the future.

The gauge data indicate that flooding from Irene ranged from a 25-year to 500-year flood, with many gauges landing near the 100-year event. Several gauges experienced the highest flood since they were installed (post 1927 flood). Over the past several years more large storms have taken place than the gauge statistics suggest should be happening.

The intensity of the rain event in the mountains and the resulting torrent of water, sediment, and woody debris seem to have led to higher flood stages than the predicted 100-year level. Localized blockages of sediment and debris likely increased local flood stages beyond what stream gauges predict.

6. *It is ok to fill in widened channels and floodplains.*

Many channels expanded two to ten times the pre-flood width, effectively forming floodplains during the flood. It is tempting to fill in some or all of these areas to reclaim land. However, the post-flood river channel has shown the space it needs to convey the water, sediment, and debris during a large flood. This same area will likely be active river area during the next large flood. Filling should be as limited as possible to minimize future flood and erosion risks.

7. *All of the aquatic life is dead after such a large flood so it does not matter what we do to our rivers now.*

Fish and insects that live in streams have amazing survival instincts given how dynamic their home is. When floods or droughts take place fish find safe areas to hide behind rocks, under logs, along the channel edges, or in small tributaries. Insects burrow into the streambed and hide from the turbulent flow. Although mortality does happen during stressful times such as floods or droughts, these disturbances are actually an essential part of the aquatic ecosystem. Floods regenerate the bed by moving large amounts of sediment, clean the channel of waste and decayed material, and create new habitat features.

8. *The rapid replacement of failed culverts and bridges with structures of the same size is suitable.*

Countless culverts and bridges failed during tropical storm Irene due to high flows, plugging with sediment and trees, and water flowing around the structure. Many of the failed structures were designed using best practices at the time of installation; unfortunately traditional design methods were based on a flow rate without consideration of channel characteristics, sediment load and woody debris. We now know that the ideal structure imitates natural channel conditions and is invisible to the stream. At a minimum the structure should span the full channel width, and consider the sediment load and woody debris that may be washing through the structure during flooding. Paying once for a larger structure that fits the stream channel is more economical than replacing smaller structures that repeatedly fail.

9. All sediment should be scraped off of floodplains.

River flooding into flat floodplains on valley bottoms is responsible for the historic formation of the fertile fields of many of Vermont's most productive farms. The size and quality of newly deposited river sediment can widely vary. Whenever possible, deposited sediment should be left on fallow land or incorporated into active fields to grow food, build soil, and protect water quality by limiting soil and nutrient export to Lake Champlain or the other receiving waters of the state. Selective removal of the coarser or contaminated parts of the deposited sediment could be performed while leaving the finer clean sediment often associated with nutrients on the fields for the next growing season.

10. FEMA or the State will pay for flood damages.

The unfortunate reality is that federal and state funding is not adequate to cover all of the damages. It is likely that many towns and people are going to shoulder some of the financial burden of Irene for a long time. This harsh reality makes it more critical to engage in planning to minimize vulnerability to future flooding. Planning, proactive flood protection, and risk avoidance are more cost-effective than crisis response.

11. Proper river management is new to Vermont and we must look elsewhere for answers.

Vermont responds to flood disasters every year. The Vermont Rivers Program, scientific community, watershed groups, and conservation districts have helped establish and successfully implement current river science, channel management, and floodplain protection approaches. The methods used in Vermont today that have developed from this experience in reducing flood and erosions risks, improving water quality, and protecting aquatic habitat are being explored and implemented throughout the United States.

APPENDIX T: Equilibrium Slope Based on Sediment Size

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

$\tau = \gamma*R*S*304 = 5*d50$

γ =	62.4	lb/ft^3	specific weight
d50 =	______	mm	median particle size
R~d =	______	ft	hydraulic radius~depth
τ =	______	lb/ft^2	shear stress

Solve for Slope (%)

USACOE - Lacey graph

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

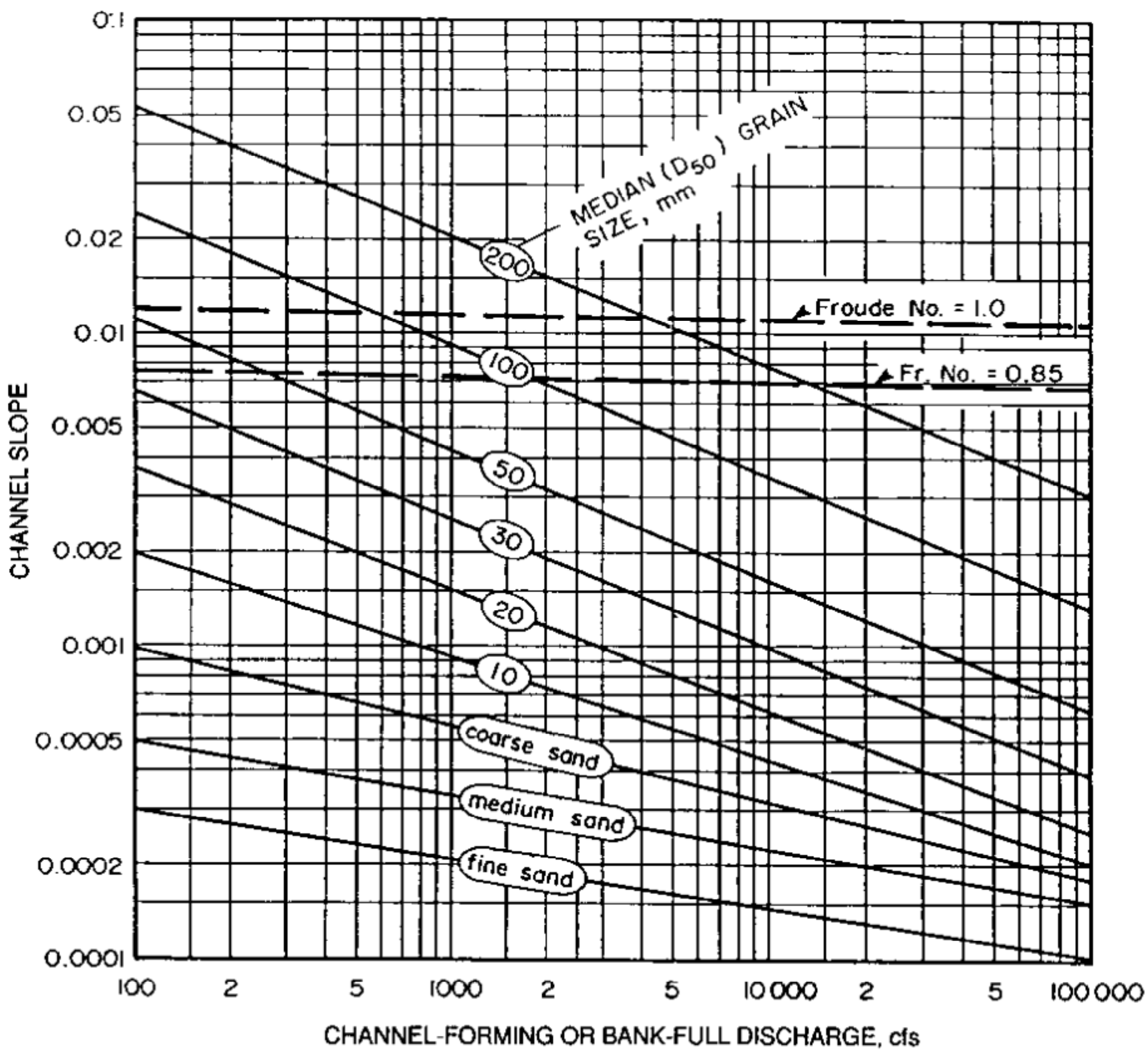
d50=	______	mm	median particle size
wbf=	______	ft	bankfull width
Qbf=	______	cfs	bankfull flow

Solve for Slope (%)

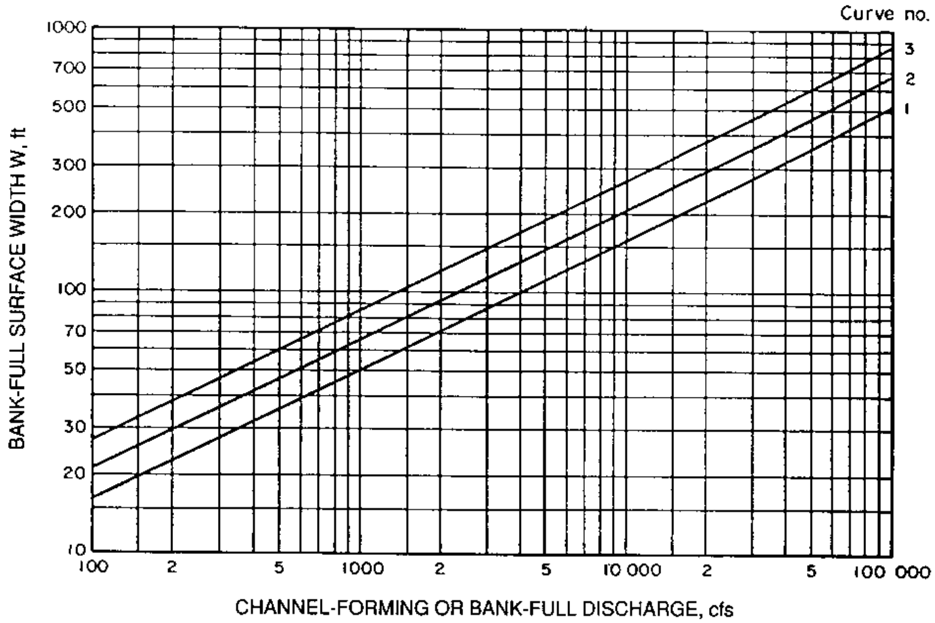
USACE Stable Channel Design Charts (USACE, 1994)

d50 = ______mm median particle size
Qbf= ______cfs bankfull flow

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



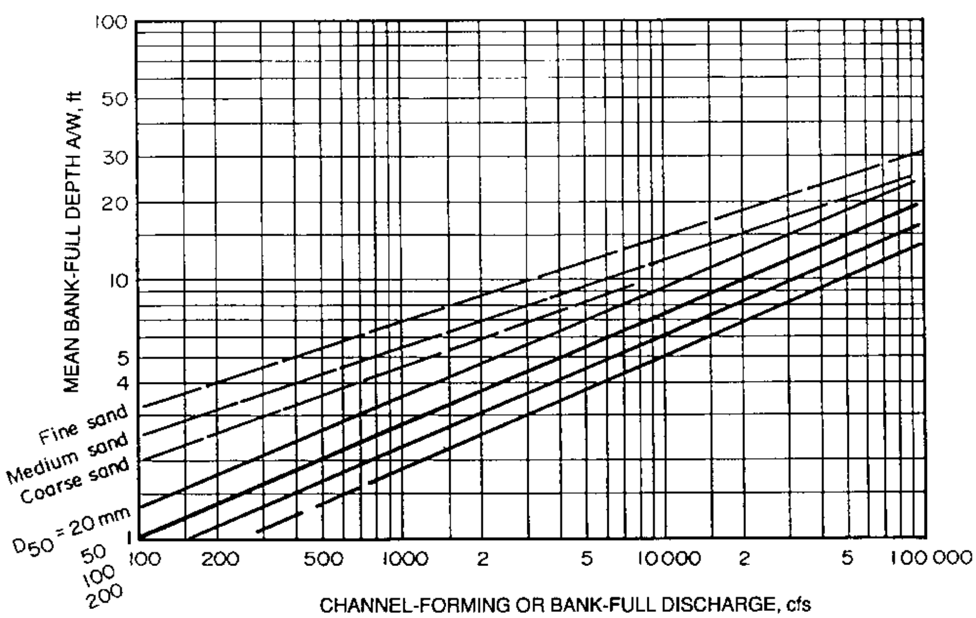
NOTE: FOR LIMITATIONS SEE PARAGRAPH 5.5. CURVES ARE BASICALLY FOR SINGLE CHANNELS WITH FULLY ALLUVIAL BED BUT LOW BED SEDIMENT TRANSPORT. SLOPES MAY BE MUCH HIGHER WITH HIGH SEDIMENT TRANSPORT, ESPECIALLY WITH SAND BEDS.



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 $C = 1.6, 2.1, 2.7$



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.

APPENDIX U: Rationale for Flood Debris Clearing in the Mountainous Rivers of Vermont (Kline, 2012)

Rationale for flood debris clearing in the mountainous rivers of Vermont

Mike Kline, Vermont Rivers Program Manager

Many Vermont villages and associated public infrastructure are situated on and around streams where they flow out of mountainous valleys into wider river valleys. When streams under flood conditions go through such abrupt changes in gradient, stream power drops, and the large volume of sediment and debris being tumbled downstream begins to deposit within the channel. In larger events the debris from landslides and streambed erosion upstream may fill in long lengths of stream channel downstream.

Braided channels form rapidly when massive amounts of sediment and debris begin to deposit on channel and valley bottoms, sending flood flows into adjacent areas of the floodplain (referred to as river avulsions). The flowages of a braided channel are not slow and spread thin as would be typical on floodplains, but rather are concentrated flows with significant depth, slope and velocity. Head cuts form (backwards or upstream-directed stream bed erosion) where the braided flows reenter the original channel, often eroding and forming entirely new river channels. In these debris deposition zones, the potential for meander cut-offs and river avulsions will threaten miles of valley bottom infrastructure during a flood, and during subsequent floods where channel blockages have not been cleared.

Bennington, VT is an example of a community built on a debris deposition zone (called an alluvial fan, in this case). During Tropical Storm Irene a large amount of woody debris and an estimated 550,000 cubic yards of sediment were deposited over 3.5 miles of the Roaring Branch in a heavily developed and densely populated section of Bennington between the Route 9 Bridge and Harmon Road. Woody debris and between 3 and 8 feet of sediment filled the channel and bridge openings. Sediment deposition filled the channel and elevated flood waters to the top of the USACE flood control levee designed for a 120-year flood.

If the Town had taken no action to clear sediment and debris from the Roaring Branch after Irene, and flood flows from Tropical Storm Lee (10 days after Irene) or another flood were to enter the valley, the river would have avulsed over the levees and berms, inundating and eroding lands and structures far removed from where the river originally left the channel. The Roaring Branch, filled as it was after Irene, represented an imminent threat to most of the public property in the town, including schools and other public building and miles of public roads and bridges. Given the history of Roaring Branch debris flowage during floods, a full avulsion of the river in Bennington would be catastrophic.

If the Town of Bennington had acted to clear only that sediment debris in the channel immediately adjacent to bridges or other infrastructure (within 200 ft./yds.), due to limitations in the FEMA Public Assistance Program, the full risks and imminent threats, described above for the do-nothing alternative, would have persisted. If channel clearing had been limited to the near vicinity of the 5 bridges within the village area, then miles of the Roaring Branch would have remained filled with large sediments and woody debris. A 5 yr flood (with a 20% chance of occurring in any given year), would bring even more sediment and debris into the valley, and the Roaring Branch would have avulsed destroying hundreds of structures, many miles of road, bridges, and utility infrastructure.

From experience, the Town acted in the public interest to address the imminent threats facing the community. Woody debris was removed and disposed of, and sediment excavation was performed to remove 278,480 cubic yards of material, or 50 % of the total sediment deposition, to reduce flood risks due to loss of channel conveyance capacity and address the imminent threats to life and property. The Roaring Branch debris removal was closely coordinated with the Vermont Agency of Natural Resources. The project was authorized under the Vermont Stream Alteration Permit and the U.S. Army Corps of Engineers Vermont General Permit.

Bennington worked with fluvial geomorphologists and state river engineers to clear a channel and floodplain cross-section in a manner necessary, and in combination with bank stabilization, to address imminent threats posed by not only by the flows of a 5 year storm but the sediment/debris load of the river under such flood conditions. After repeated failures and damages when post-flood river work involved only the trenching of a channel through the deepening debris, HEC-RAS river modeling was used to show the need to bench the channel with a floodplain area to reduce velocities, bank erosion, sediment loading, and bridge backwater conditions. Without floodplain benching and allowance for future flood debris storage, the imminent threats posed by the Roaring Branch flooding river avulsions would have remained.

Typical post-flood sediment dam and debris jam on the Roaring Branch.

While this example focusses on the work performed in Bennington, the sediment and debris deposition and channel blockages cleared by other Vermont communities after Irene was also important in addressing imminent threats to public infrastructure and property. Deposition zones, where emergency measures are required after a disaster, vary in size in direct relationship with the watershed size, upstream debris sources, and the decreases in channel slope and depth. If major parts of these zones are not clear after the disaster the channel will braid or avulse. If there are public structures or infrastructure down-valley they will remain threatened.

Figure 1. Longitudinal profiles showing persistence of imminent threat when debris clearance is limited.

Time series showing river passing through 2 bridges - from a steep, narrow valley to a low gradient, wide valley

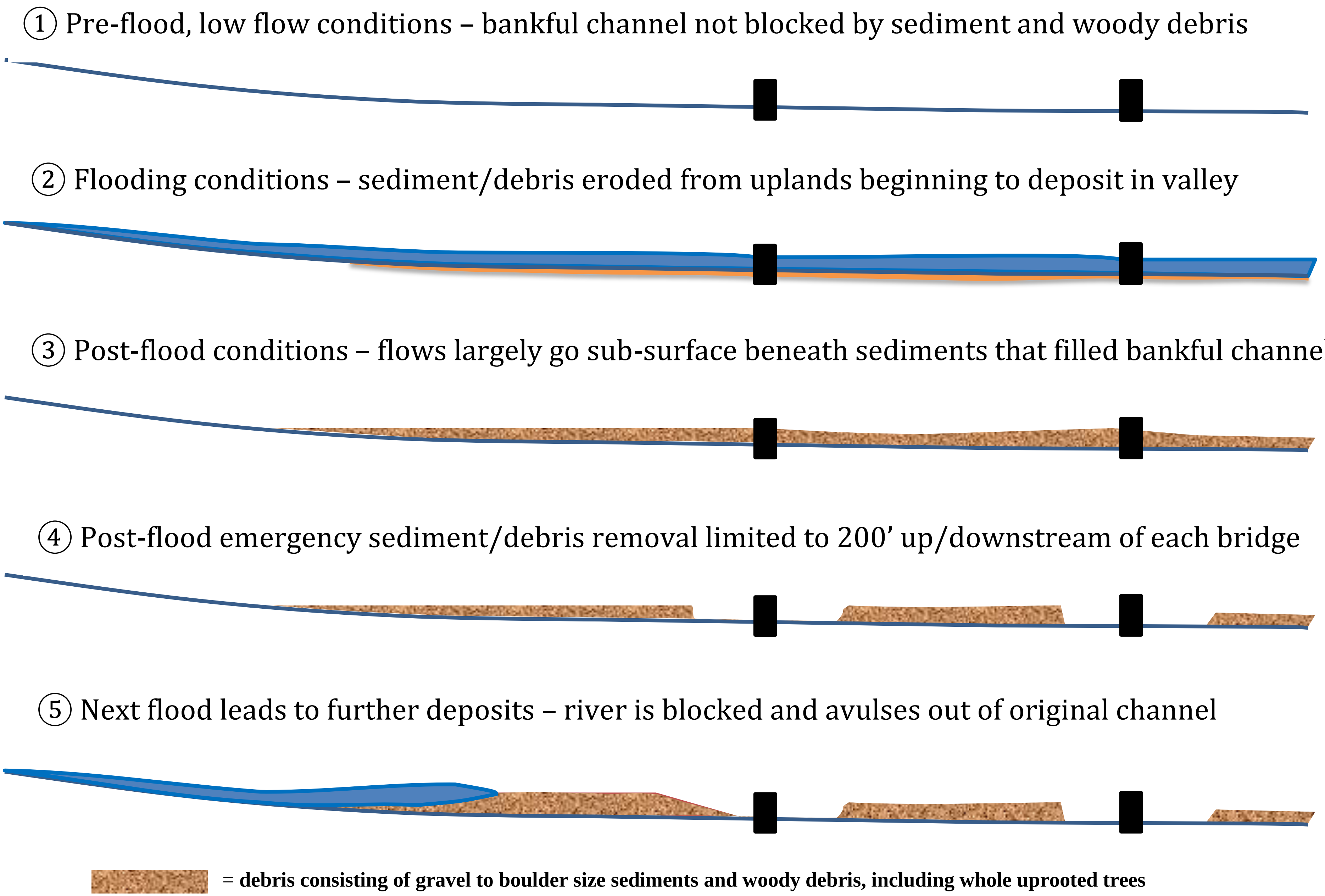
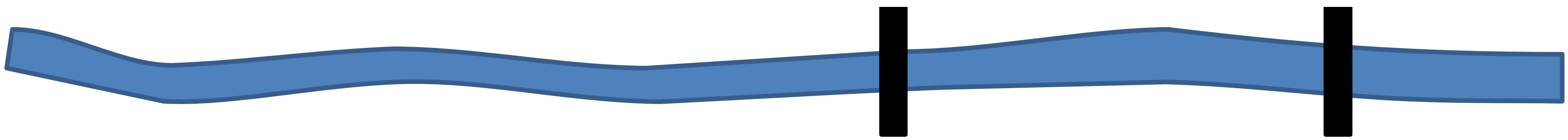


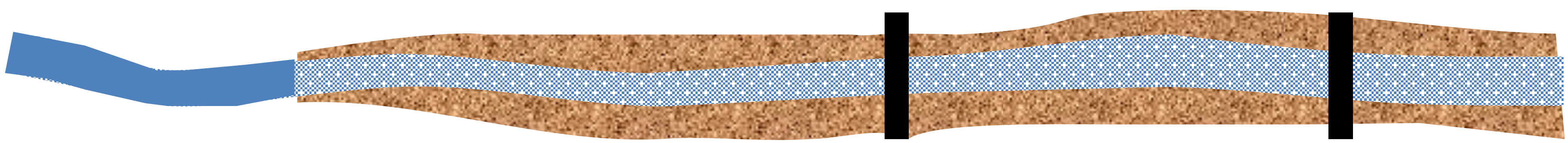
Figure 2. Planform views showing persistence of imminent threat when debris clearance is limited.

Planform depictions of the river at points 1, 3, and 5 in the time series shown in Figure 1.

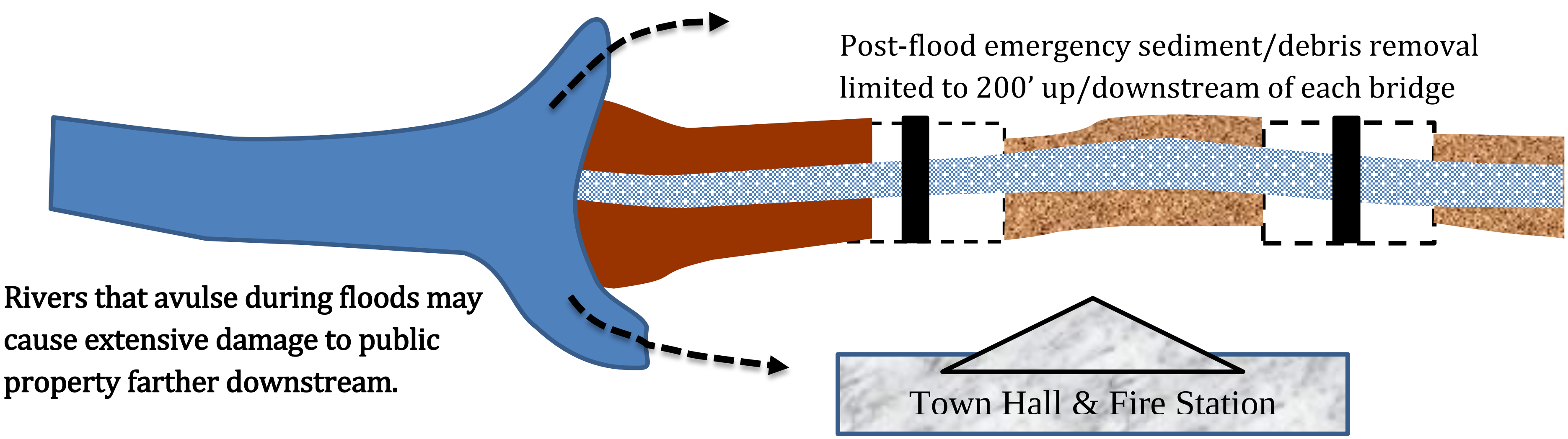
① Pre-flood, low flow conditions – bankful channel not blocked by sediment and woody debris



③ Post-flood conditions – flows largely go sub-surface beneath sediments that filled bankful channel



⑤ Next flood leads to further deposits – river is blocked and avulses out if original channel



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