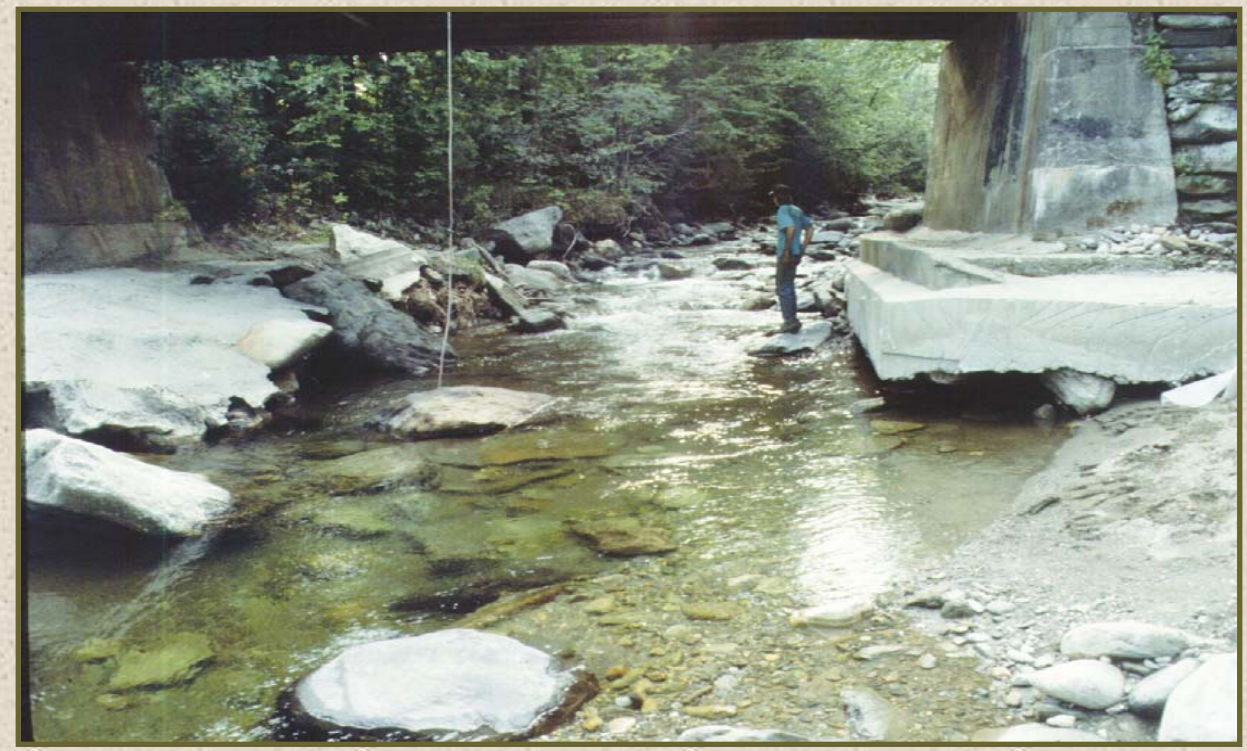
Fluvial Processes and Crossing Structures



Shayne Jaquith
River Restoration Scientist
Vermont DEC
River Management Program
(802) 241-4456
Shayne.jaquith@state.vt.us

Vermont River Management Program

- State Floodplain Management, Federal NFIP
- Stream Alterations Permitting
- Fluvial Erosion Hazard Management
- River Assessment, Restoration and Protection

70+ years of observing interactions between rivers and human investments

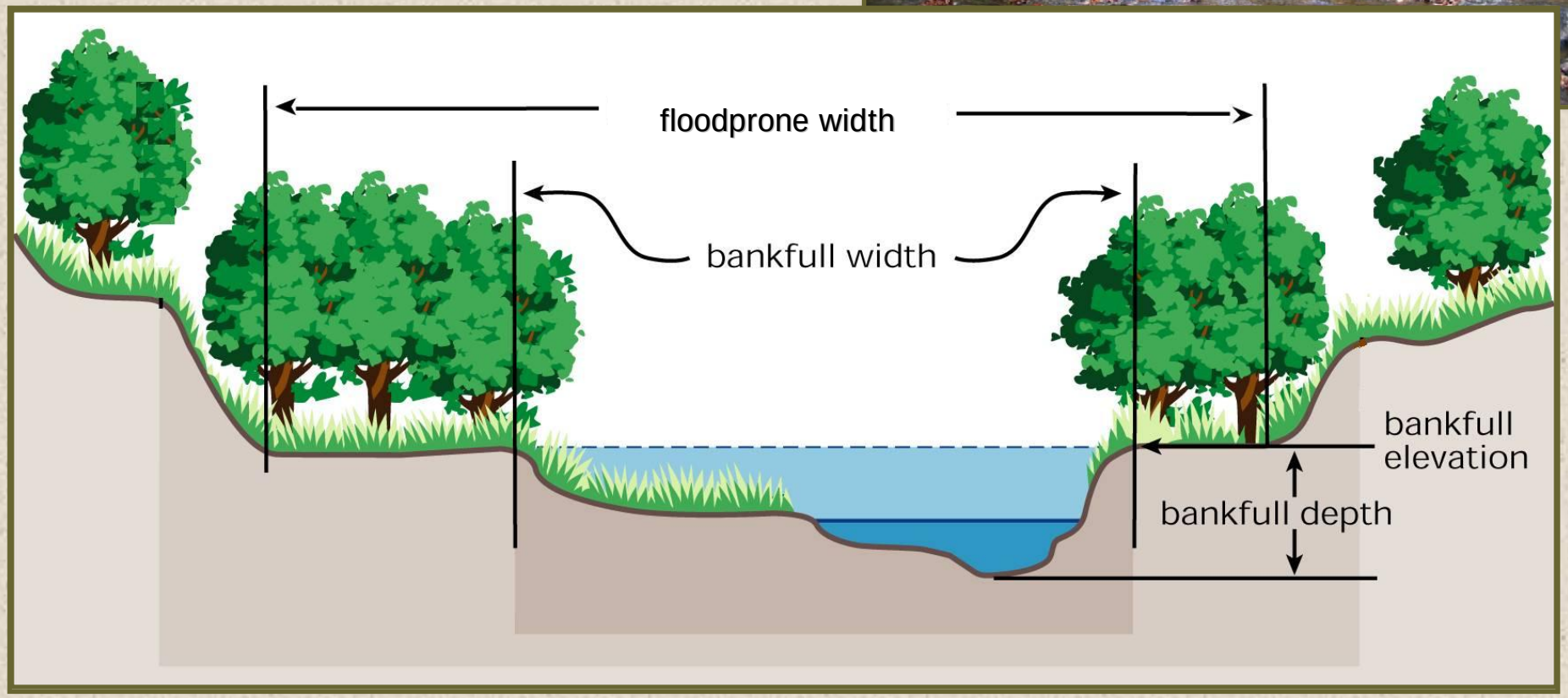
How do we understand river behavior?
Fluvial Geomorphology:
The study of landforms created by flowing water

- Fluvial Geomorphology (key concepts and principles)
  - Channel Classification/inherent sensitivity/Bedload
  - Most probable form/equilibrium/geomorphic stability
  - Channel evolution
  - Bankful, Alluvial and Threshold Channels
  - Culvert Sizing for Sediment Transport Continuity

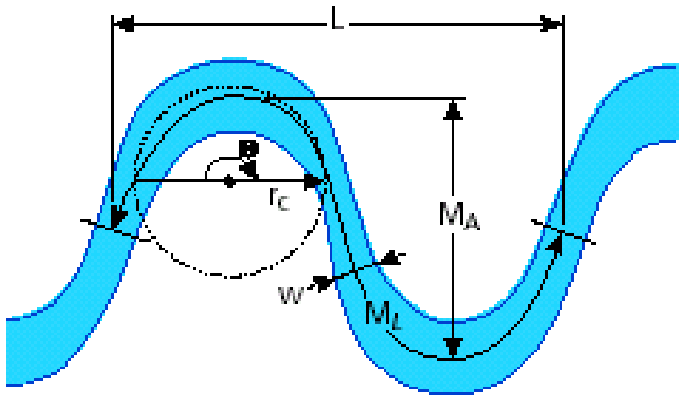
Most Probable Form

Given consistent controlling factors (sediment and hydrologic regimes boundary condition and valley slope), every river has a most probable form (reference or equilibrium condition) toward which it is constantly working (Leopold, 1994).

Most Probable Dimensions



A Most Probable Planform



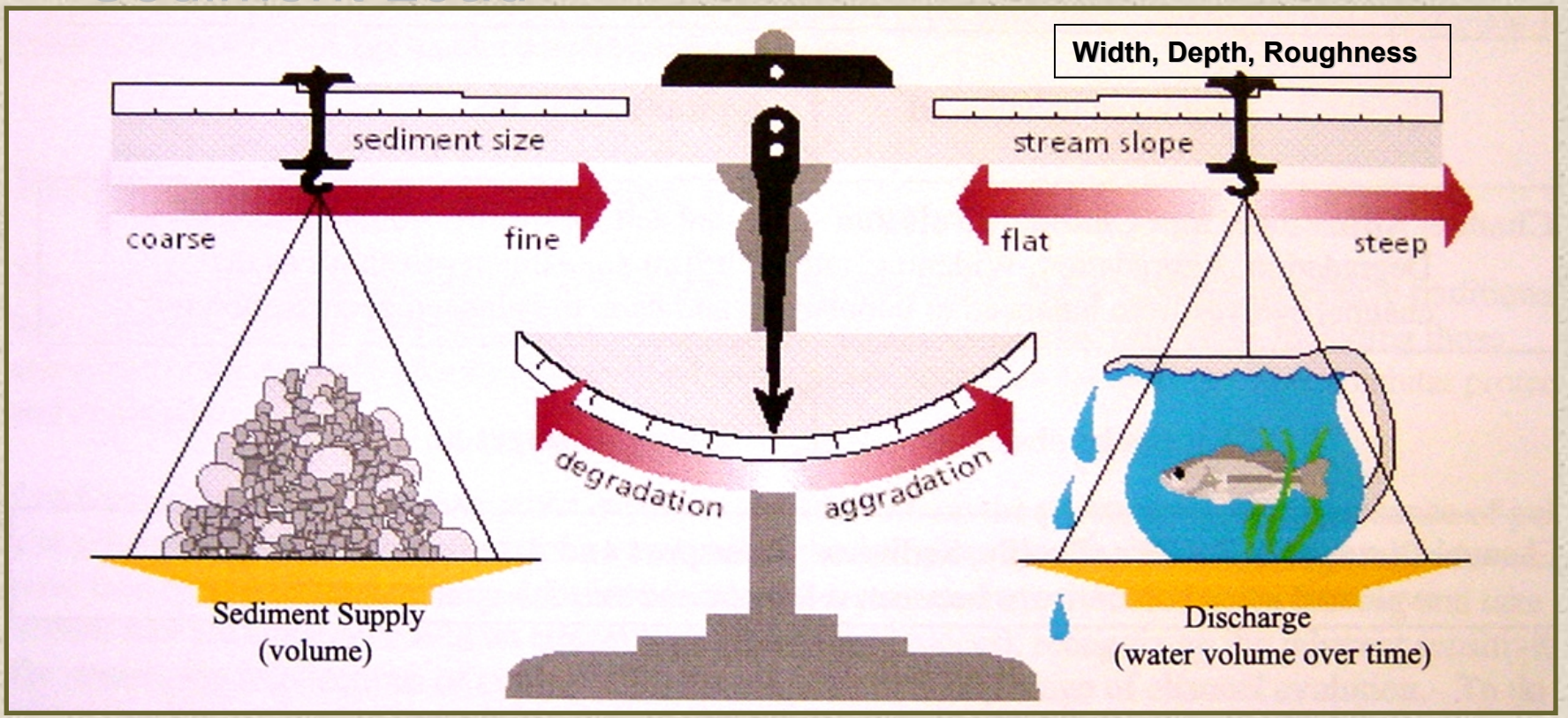
L meander wavelength
M_L meander arc length
w average width at bankfull discharge
M_A meander amplitude
r_c radius of curvature
θ arc angle

Figure 7.21: Meander geometry variables.
Adapted from Williams 1986.

Channel Equilibrium

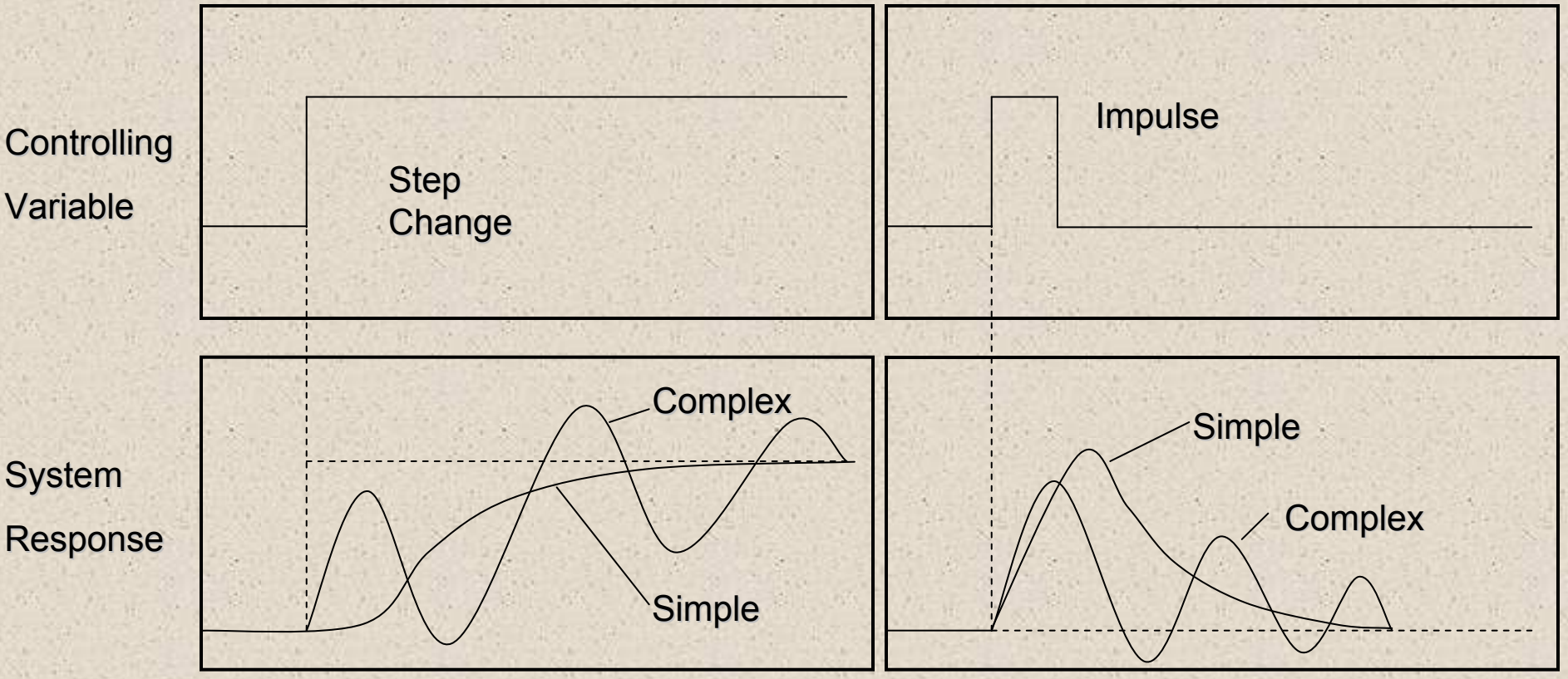
Sediment Load

Transport Capacity



Lane (1955)

The affect of changes in controlling variables



From Thorne, Hey and Newson (1997)

When a river reaches its most probable form or equilibrium condition the rate of work (erosion, deposition and migration) is minimized. The channel is geomorphically stable.

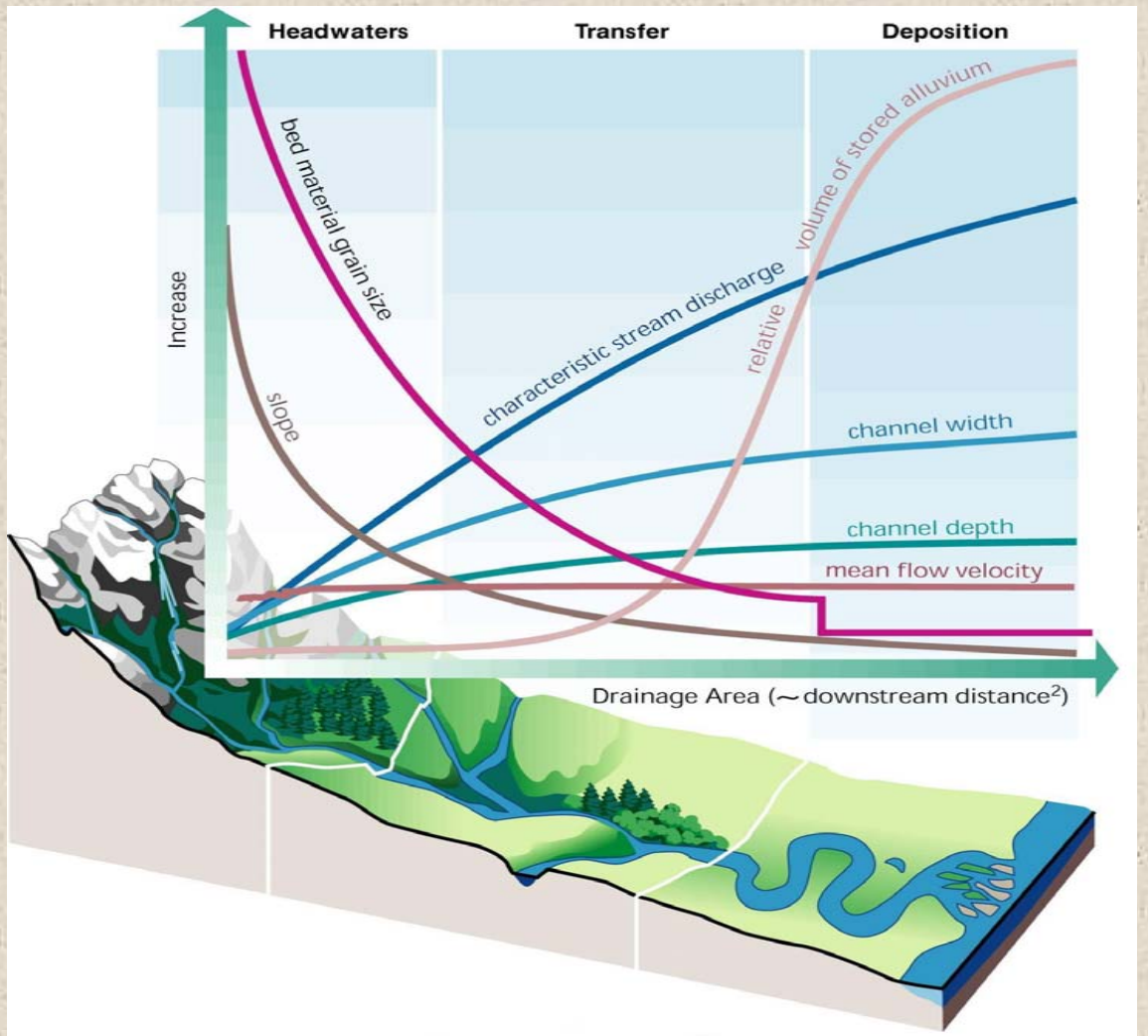
Designing structures that minimize change to the river results in a more stable built environment and increased structure longevity.

Channels are classified by how they look with the expectation that there is a correlation between appearance and behavior

<u>Relevancy to crossing structure design</u>

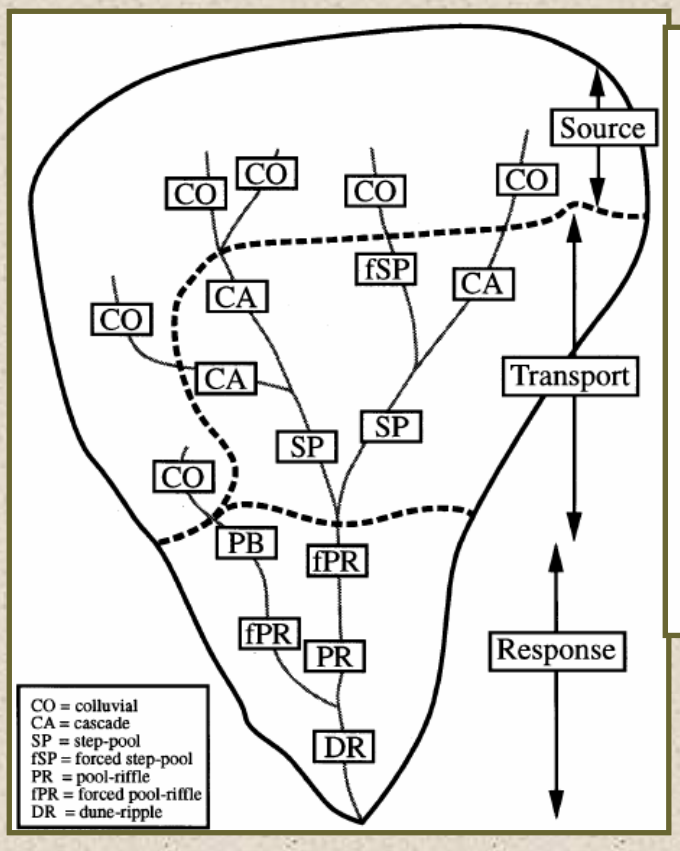
- Explain how sensitive will the channel be to a change in hydraulics and the boundary condition.
- Predict the disequilibrium channel processes.
- Describe the hydraulic geometry of the equilibrium channel.
- Describe the relation between sediment supply and transport capacity.
- Describe the important characteristics of the natural channel bed?

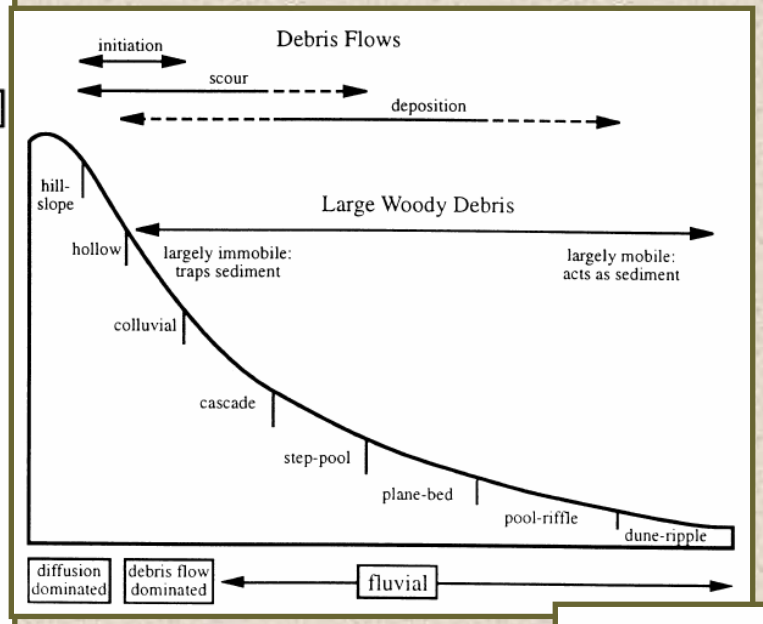
Watershed Zone Classification

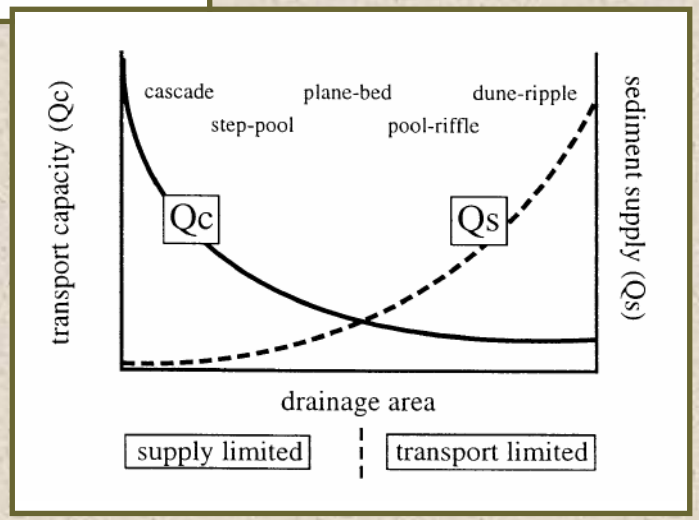


From the Stream Corridor Restoration Manual, Federal Interagency Stream Restoration Working Group, 1998.

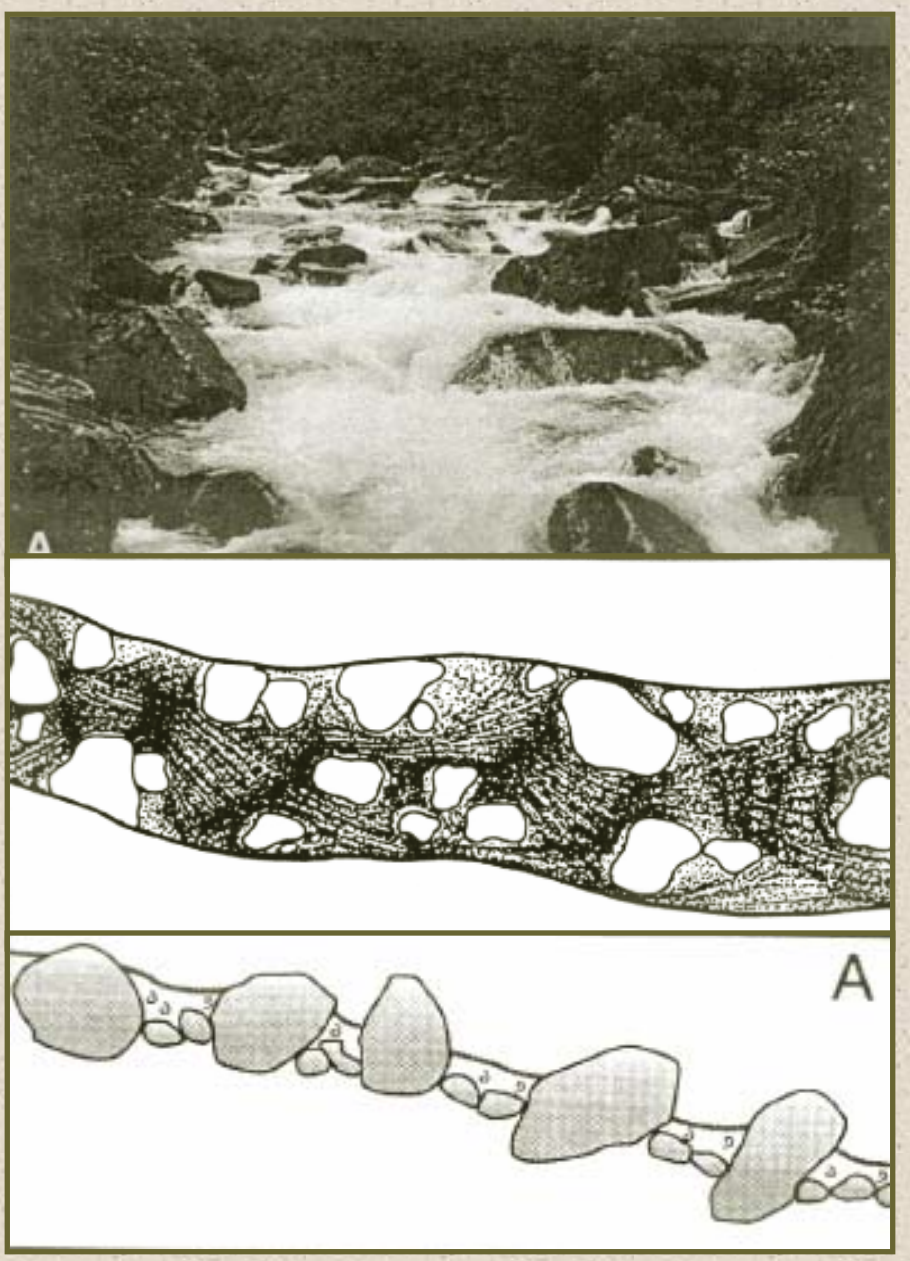
Montgomery and Buffington Stream Classification System







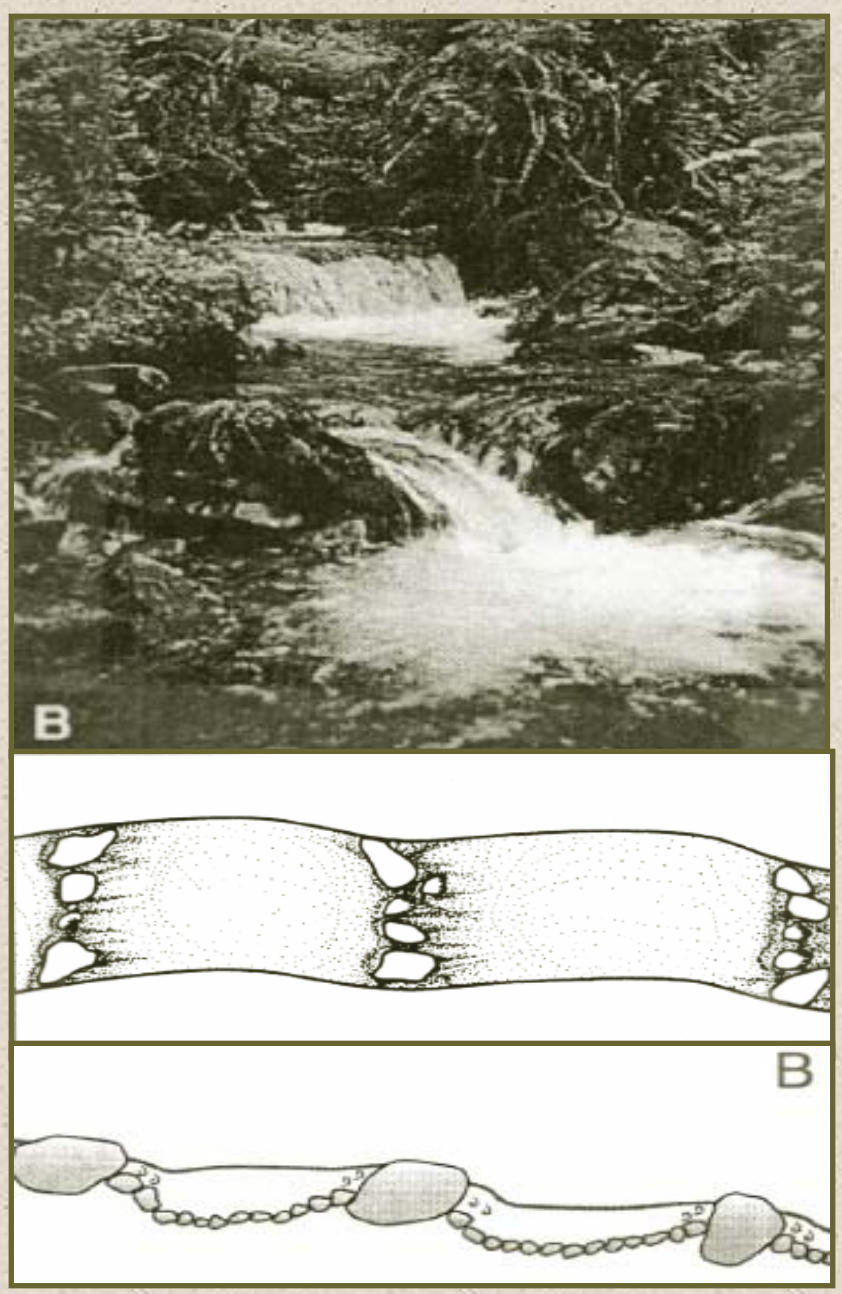
Cascade Channel



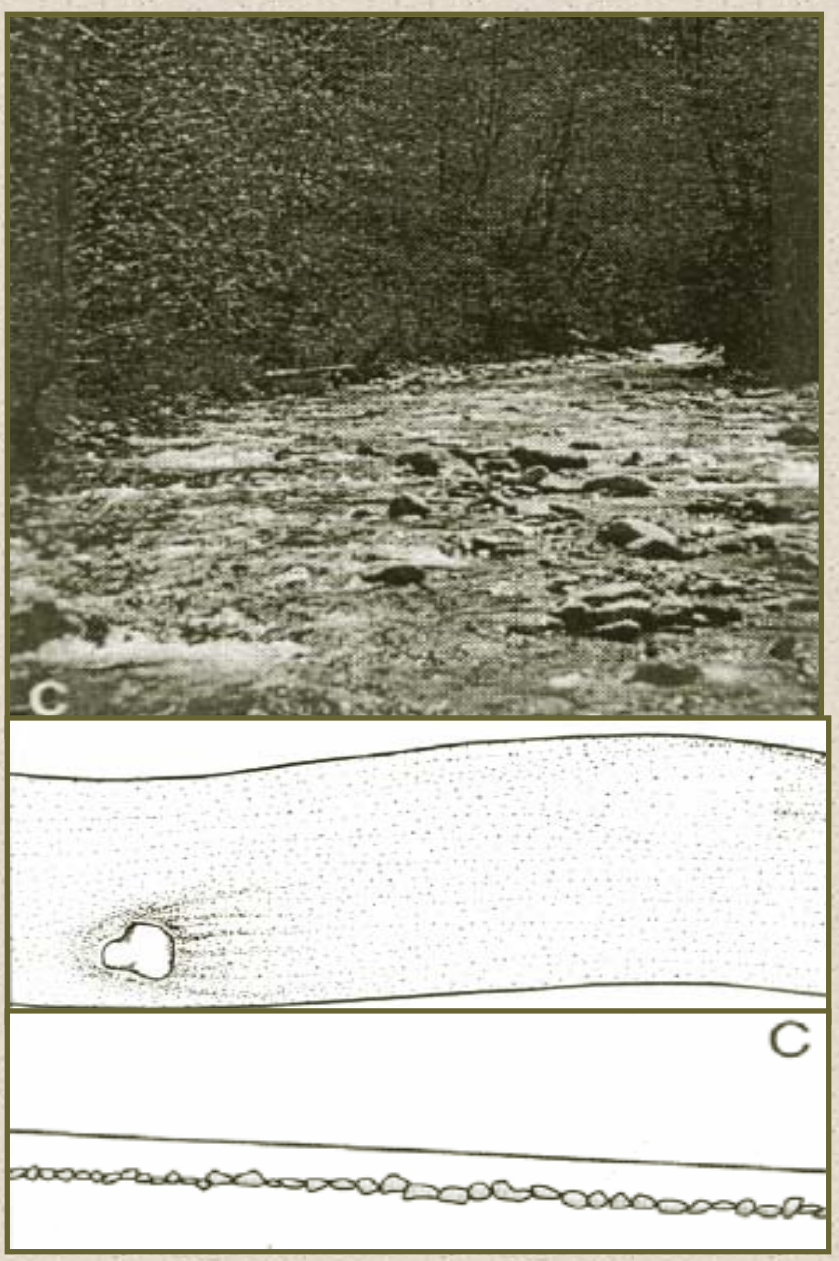
- Disorganized bed
- Continuous supercritical flow (Fr ≥ 1)
- Typically boulder bedded
- Thalweg hard to identify
- “Pool” frequency < 1 channel width
- **Transport capacity >>sediment supply**

Step-Pool Channel

- Sediment organized into channel-spanning steps
- Flow alternates between supercritical and subcritical flow
- Typically gravel to boulder bedded
- Pools 1-4 channel widths apart
- Gravel in pool is annually mobile; steps mobile during multi-decade flows
- **Transport capacity > sediment supply**



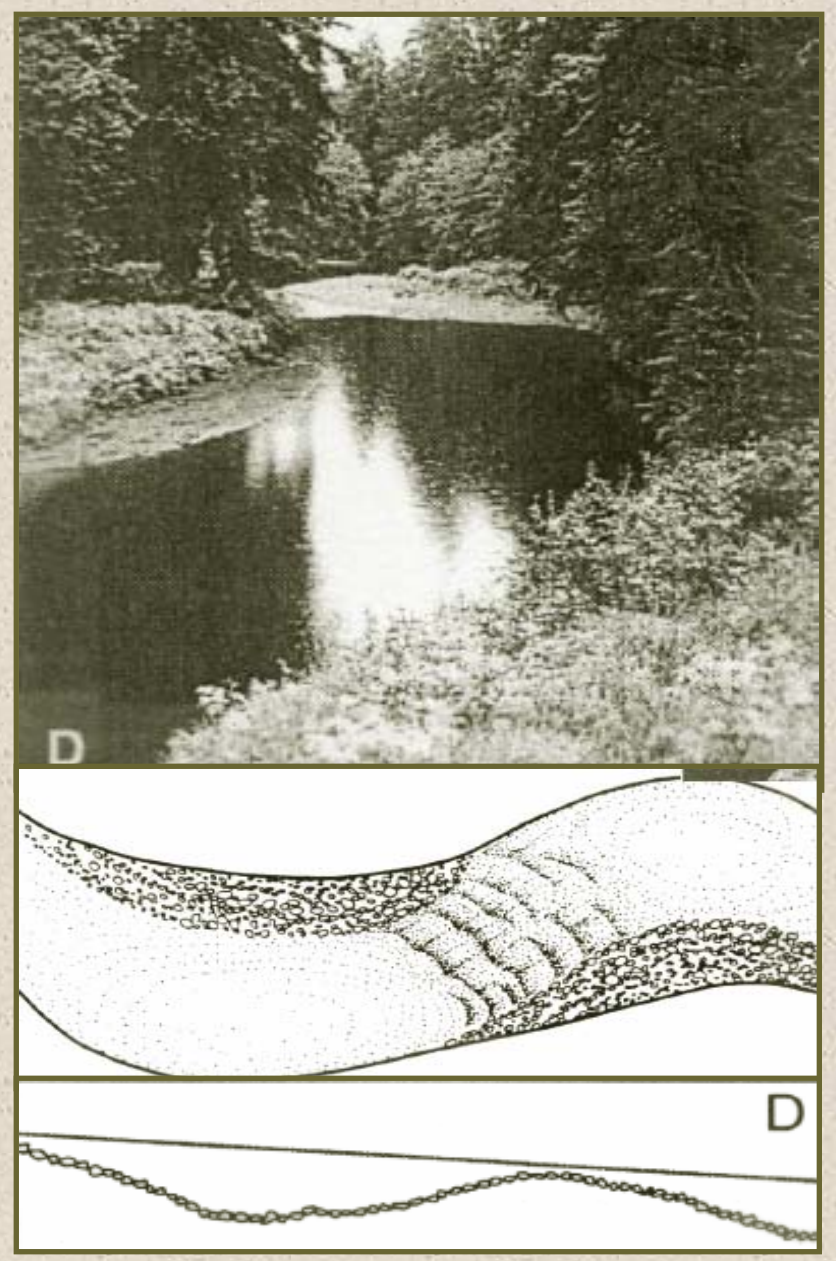
Plan Bed Channel



- Flume-like
- No organization to bed, but not chaotic
- Relatively uniform grain size, typically cobble and gravel
- Pools are infrequent, around isolated boulders or logs
- **Transport capacity ≈ sediment supply**
- Grain size can adjust to accommodate changing sediment supply

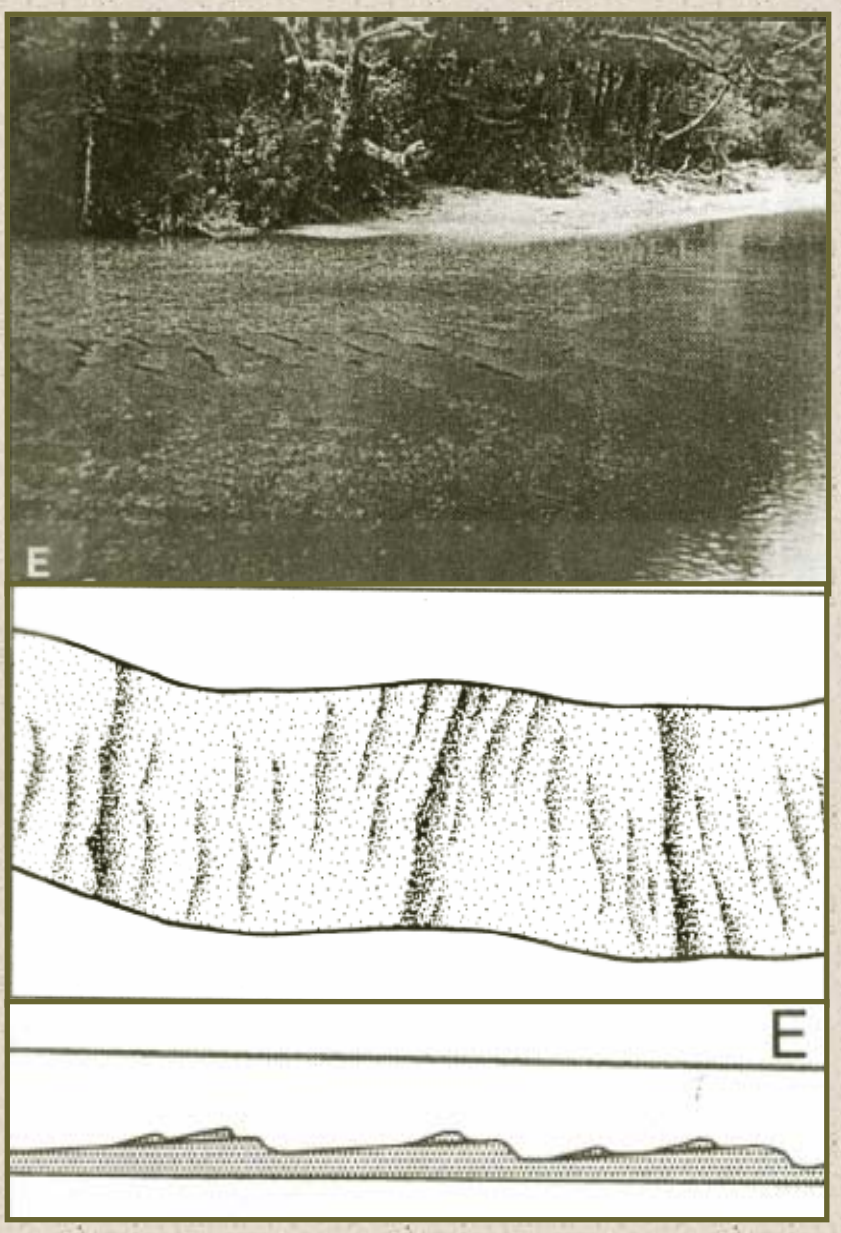
Riffle Pool Channel

- The “classic” fluvial channel
- Alternate bars, meander bends, floodplains
- Gravel bedded
- Pools typically 5-7 channel widths apart
- **Transport capacity << sediment supply**

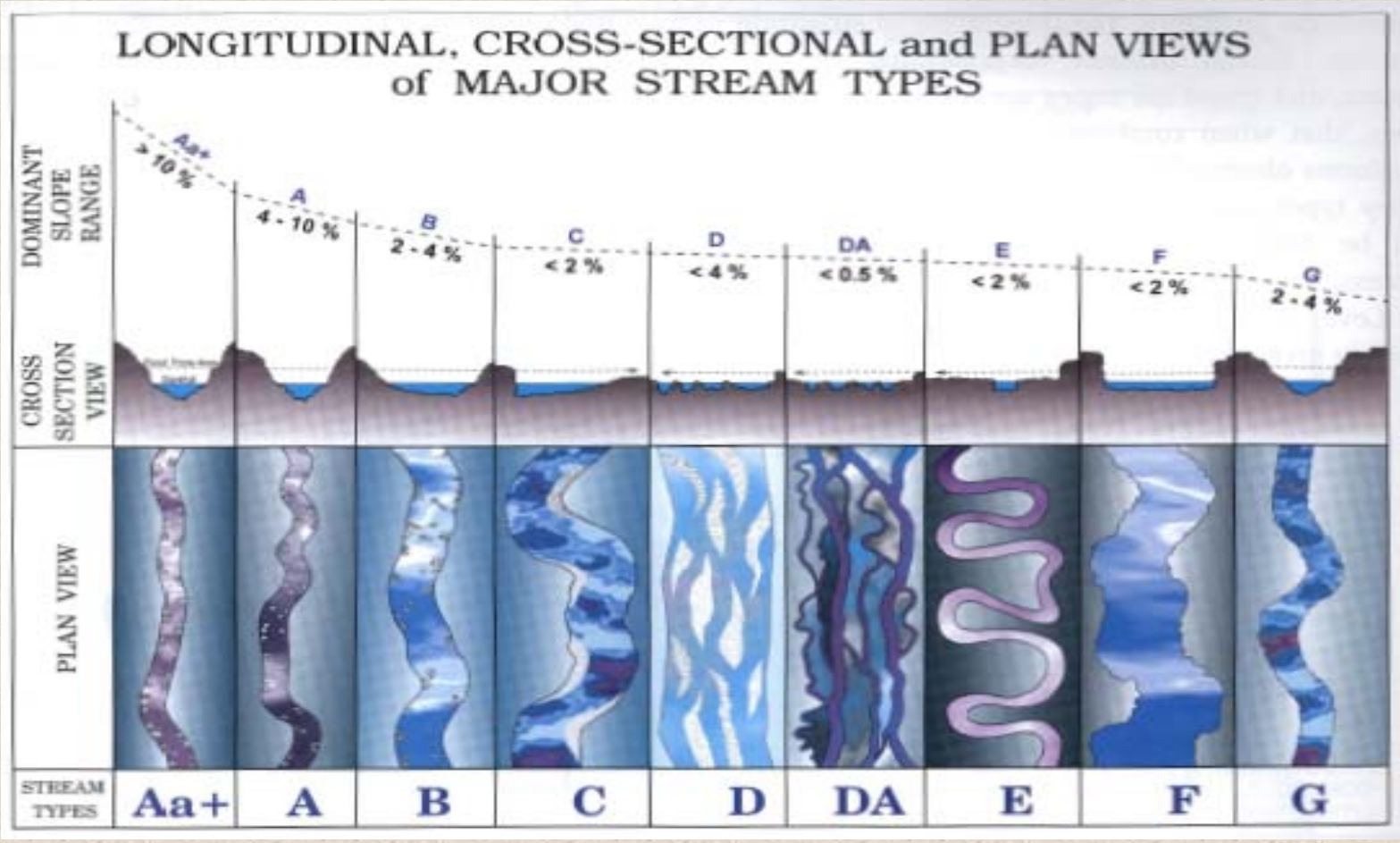


Ripple Dune Channel

- Multiple-scale bedforms
- Sediment mobile at low flows
- Typically sand bedded
- Pools occur where forced by channel pattern
- **Transport capacity << sediment supply**



Structure Location, Consider Valley Setting, Stream and Valley Morphology and Inherent Stability



Rosgen (1996)

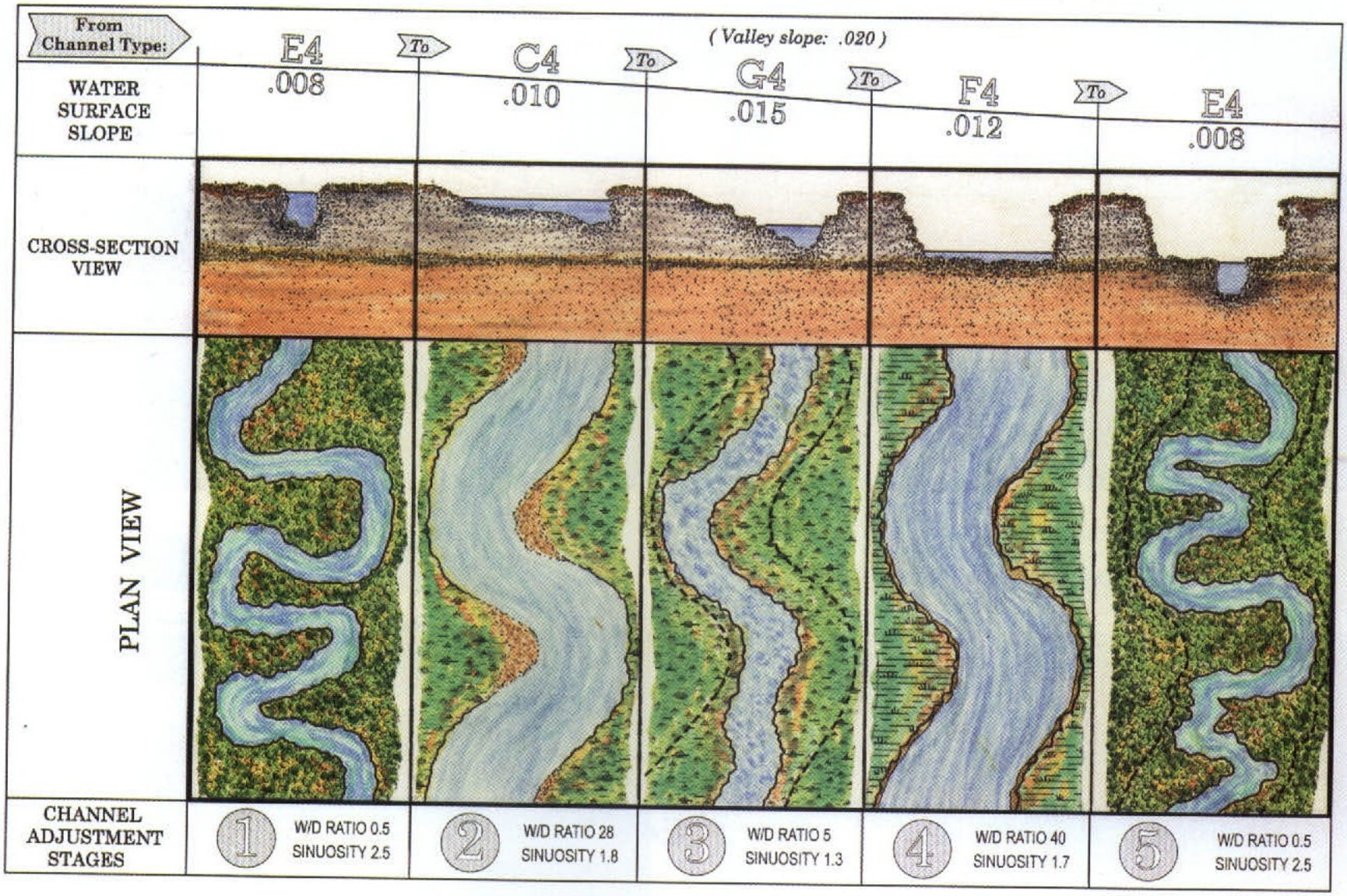
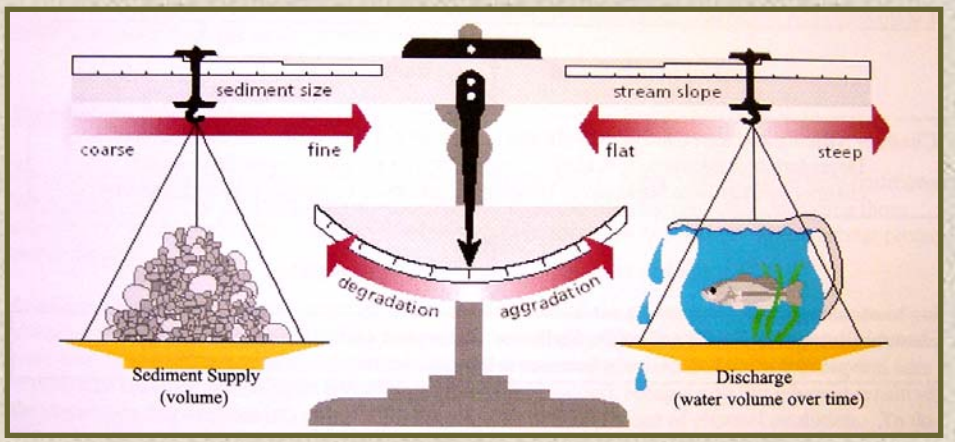

From Channel Type:
(Valley slope: .020)
E4
.008
To
C4
.010
To
G4
.015
To
F4
.012
To
E4
.008
WATER SURFACE SLOPE
CROSS-SECTION VIEW
PLAN VIEW
CHANNEL ADJUSTMENT STAGES
1
W/D RATIO 0.5
SINUOSITY 2.5
2
W/D RATIO 28
SINUOSITY 1.8
3
W/D RATIO 5
SINUOSITY 1.3
4
W/D RATIO 40
SINUOSITY 1.7
5
W/D RATIO 0.5
SINUOSITY 2.5

FIGURE 6-8e. Example of a E5 streamtype evolved from a G5-F5-C5 type conversion.

FIGURE 6-8f. Example of G5 stream type 150 feet downstream of (6-8e) due to culvert crossing. An important comparison of adjustment, reverting back to a G5 from an E5 streamtype.

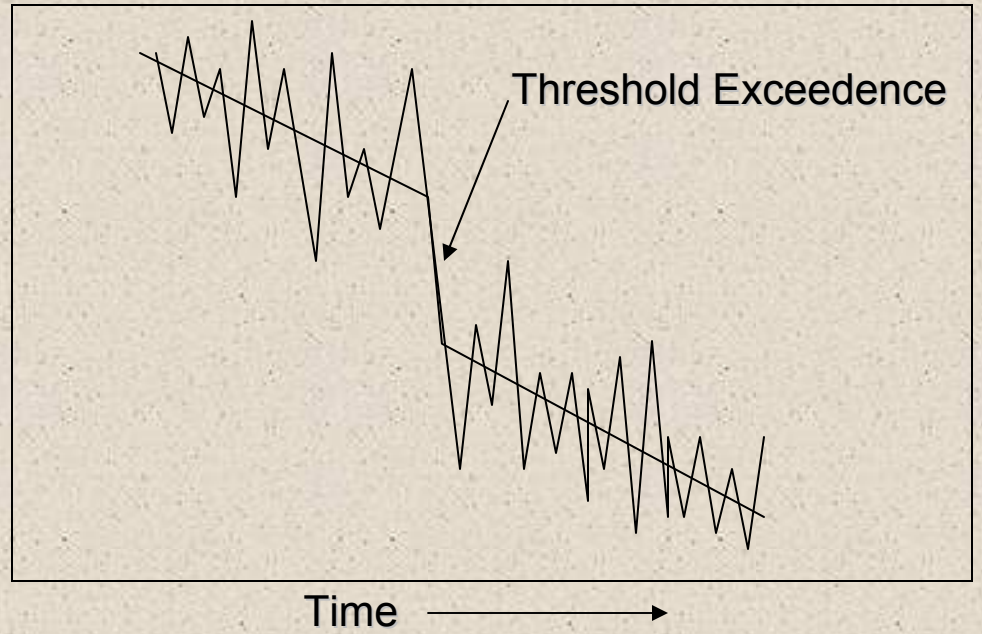
Channel Evolution

The sequence of adjustments processes that a channel goes through when changes to controlling factors exceed a “geomorphic threshold”.

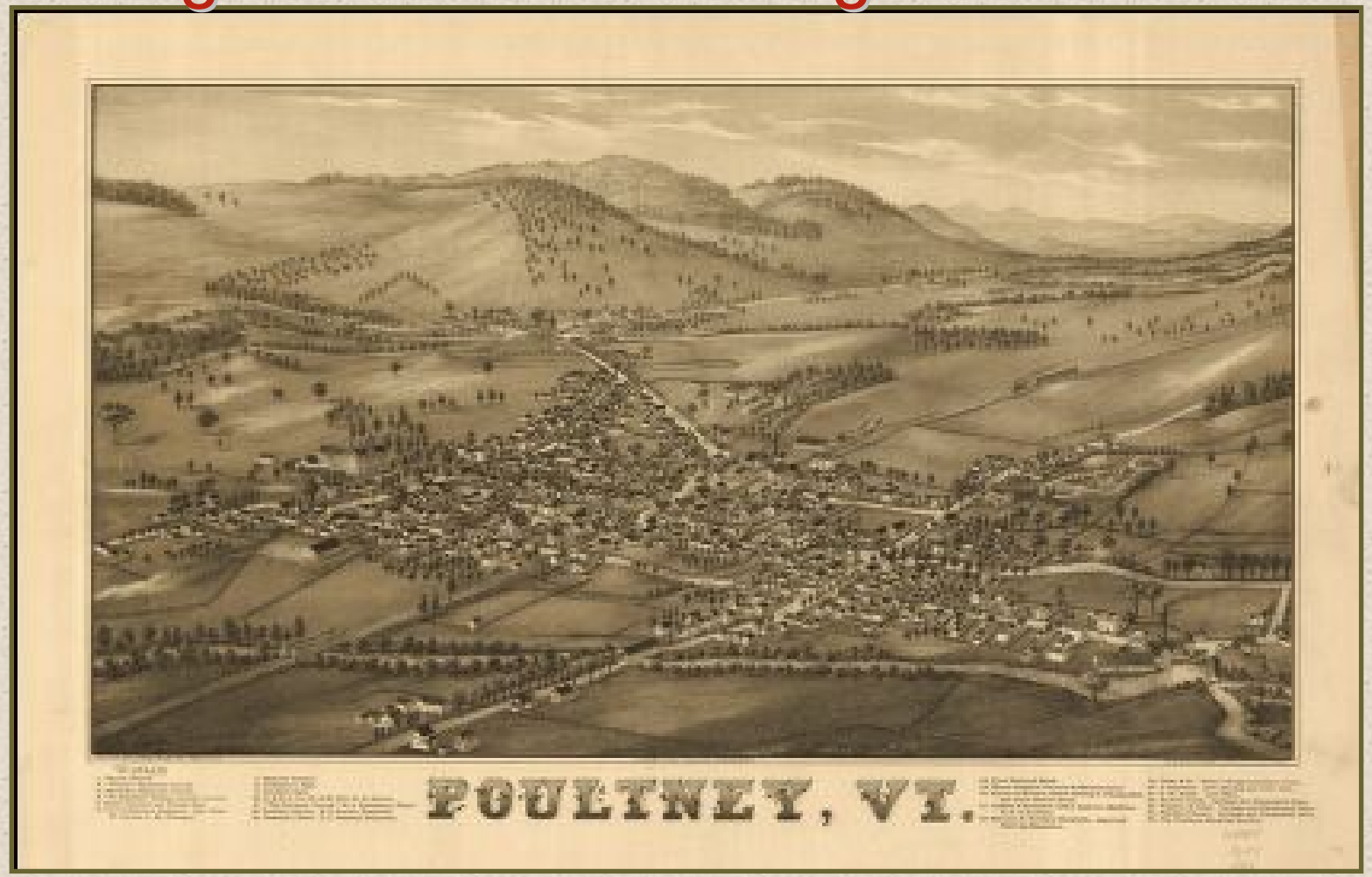


Controlling Factors

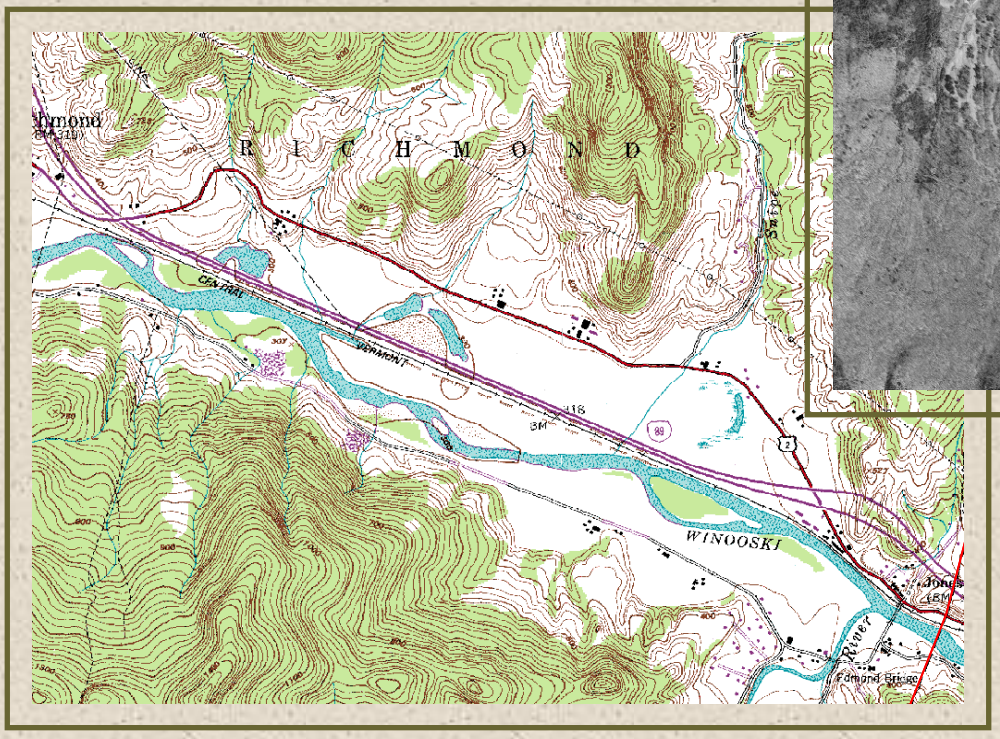
- Flow regime
- Sediment regime
- Slope
- Cross section
- Boundary condition
- Channel Roughness



Throughout Vermont changes in land cover and land use have resulted in changing hydrologic and sediment regimes



Channel **slope and dimension** have been significantly altered to accommodate transportation infrastructure agriculture and other land uses.



Post flood recovery works have altered channel dimension and boundary condition.

Timescale of Geomorphic Response (relaxation period)

Micro-scale changes (bedforms): 1-10 yrs.

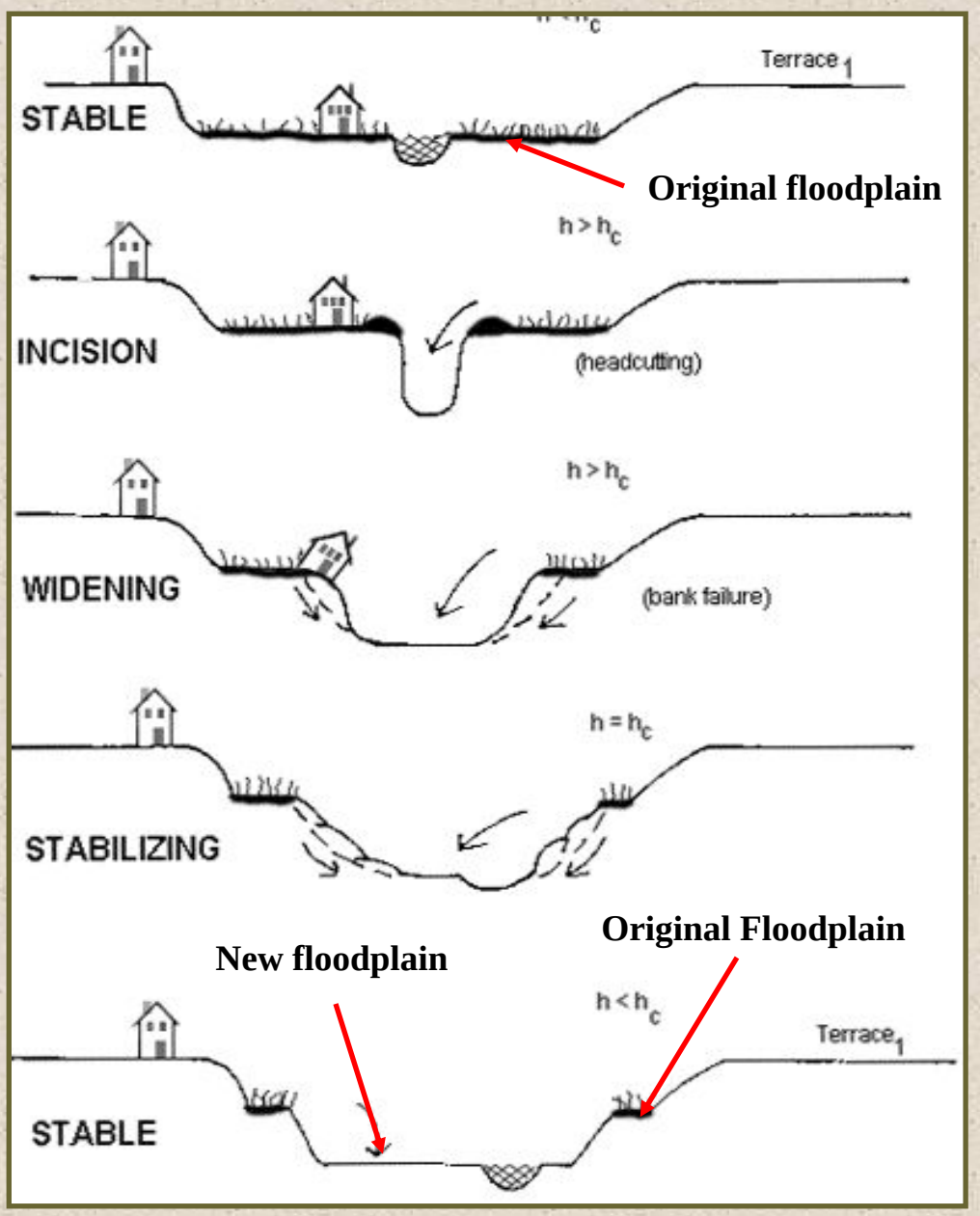
Meso-scale changes (cross section dimensions) 10-100 yrs.

Macro-scale changes (meander geometry and floodplain) 100+ yrs.

Rivers today are likely still adjusting to changes going back to the 1800's deforestation

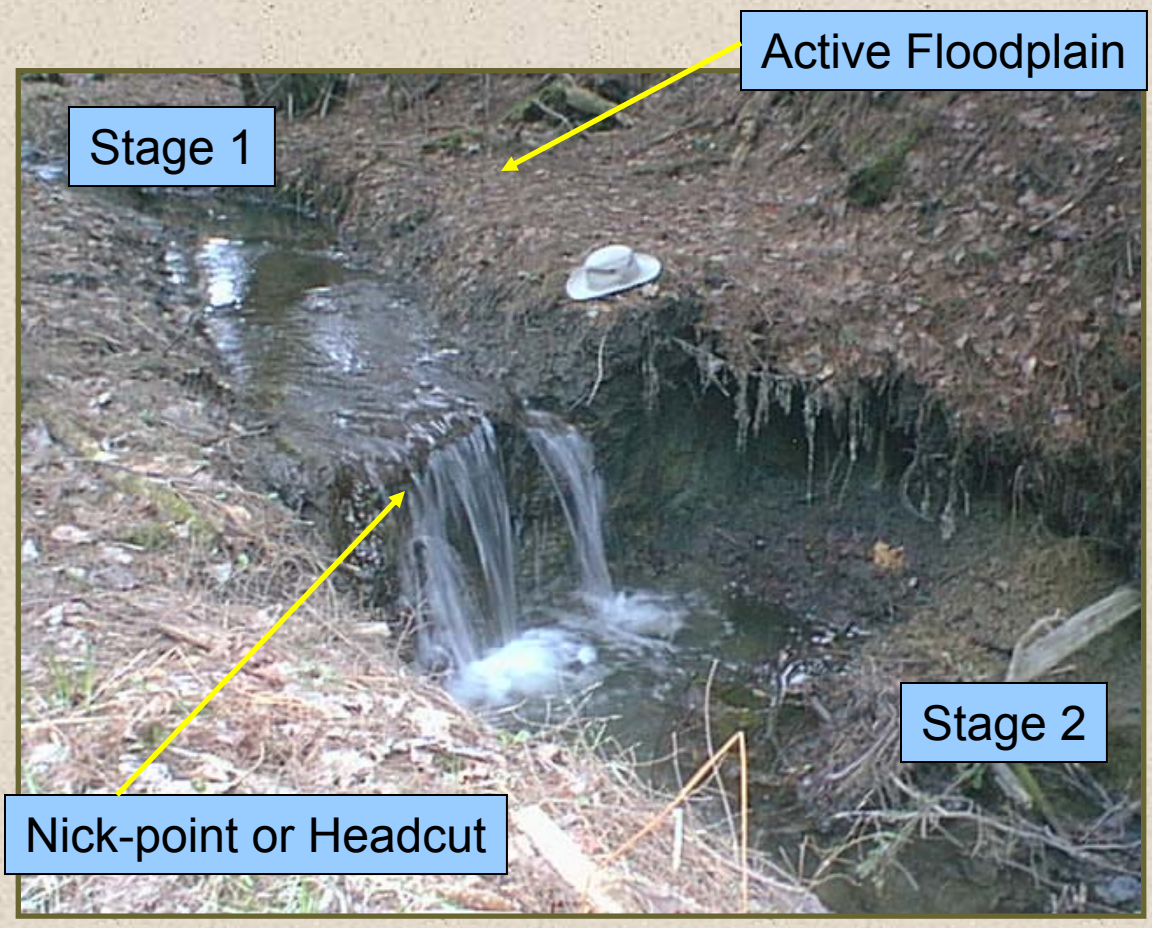
Channel Evolution

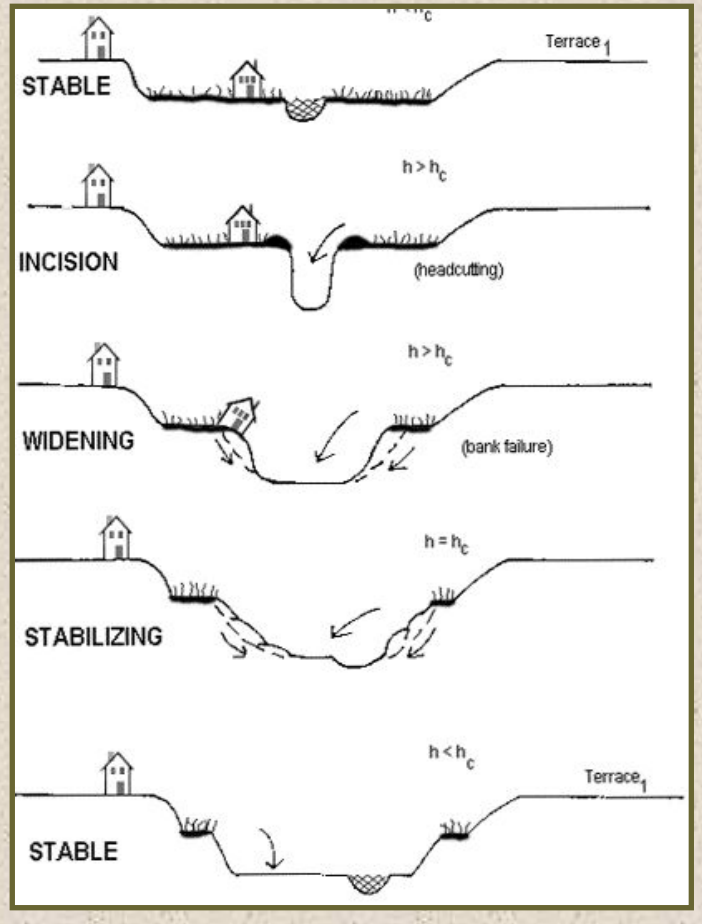
When destabilized a river will begin working back toward the equilibrium condition through a fairly predictable channel evolution process.



Schumm Channel Evolution Model

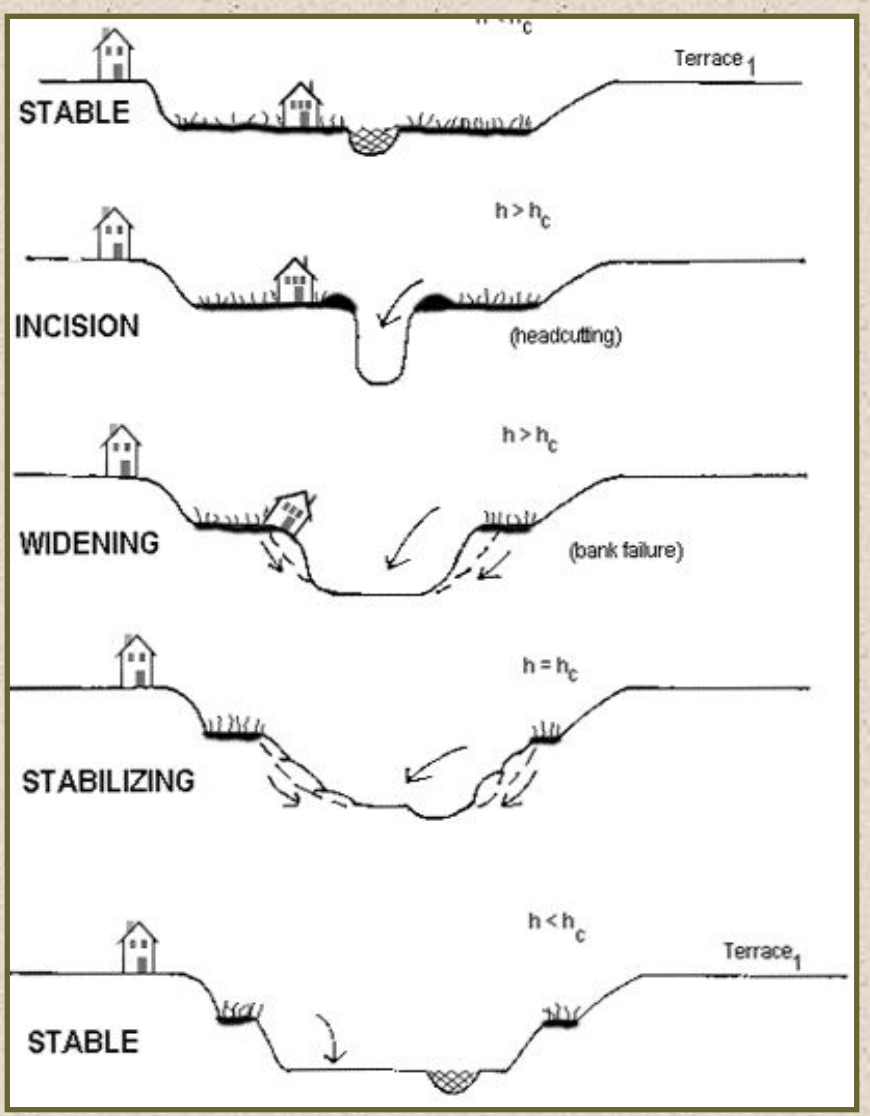
Stages 1 and 2: Equilibrium to Incision



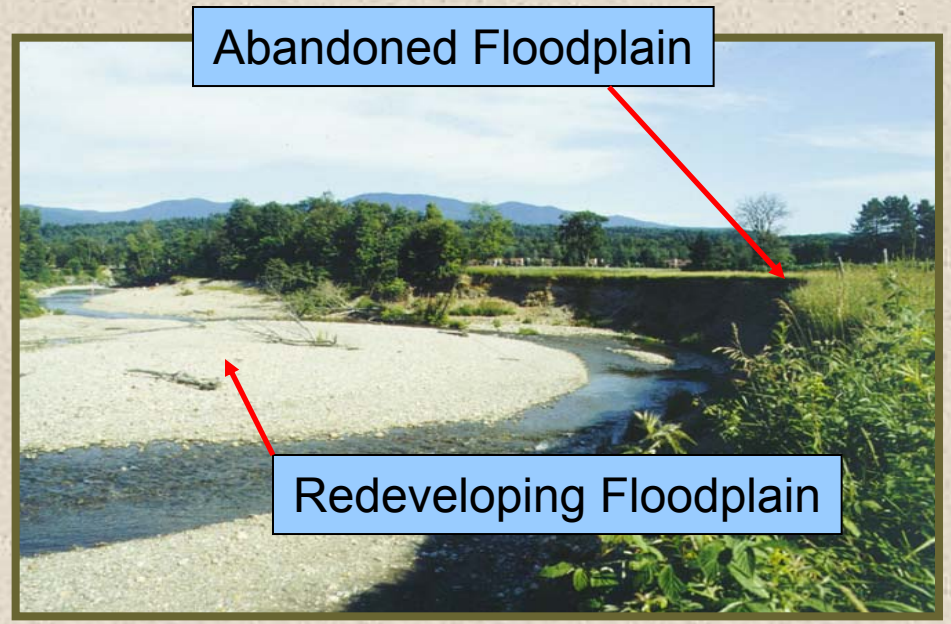


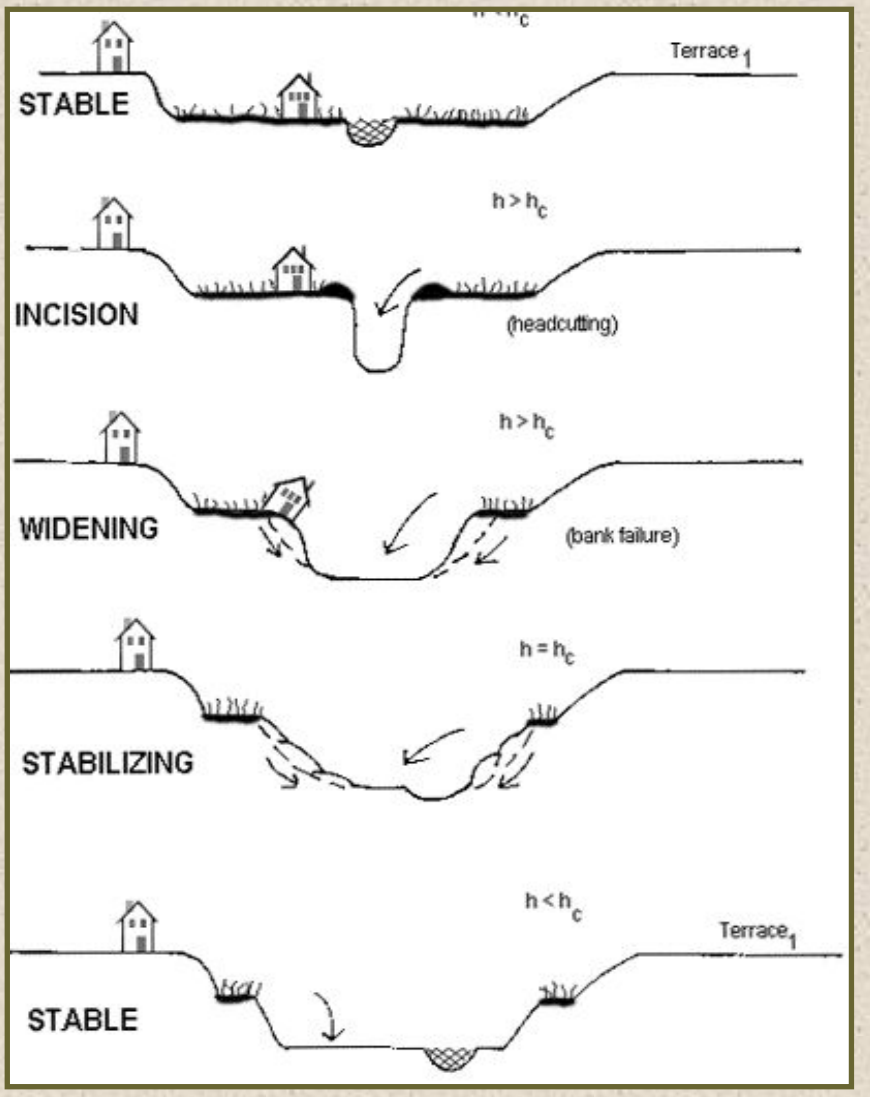
Stage 3: Widening

Abandoned Floodplain



Stage 4: Continued widening and floodplain development

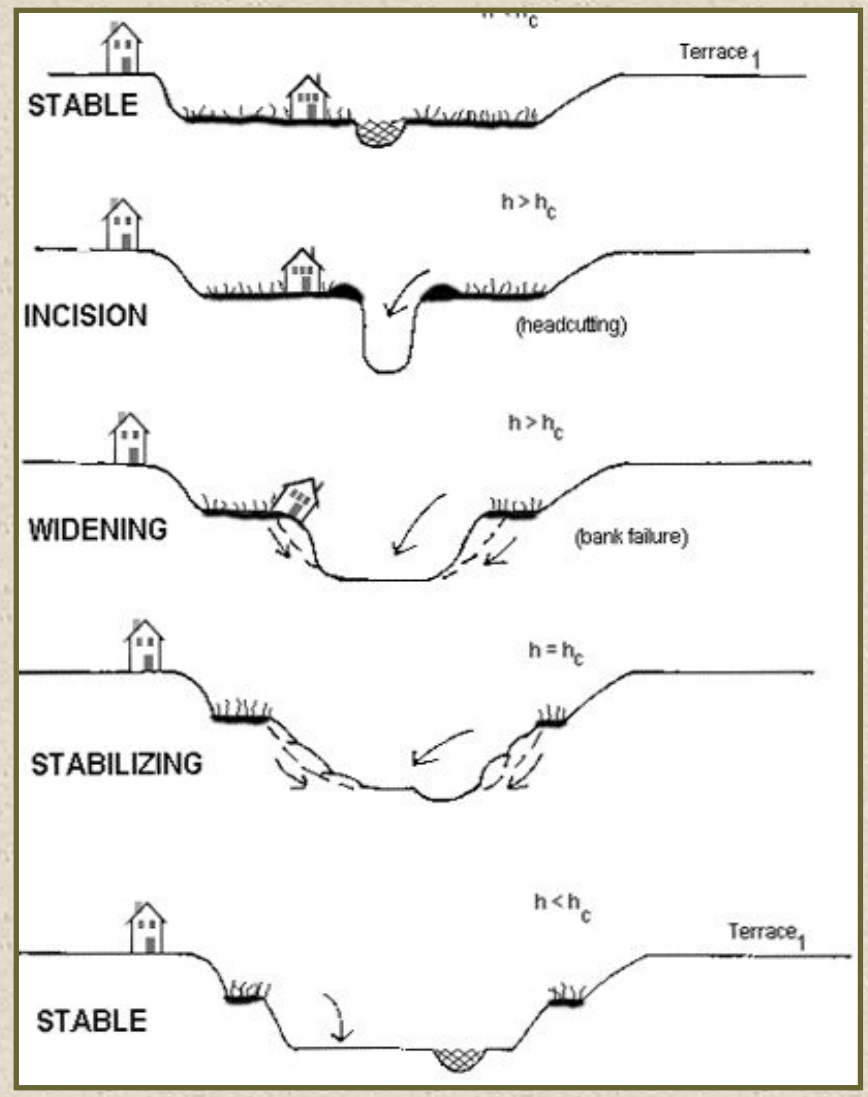




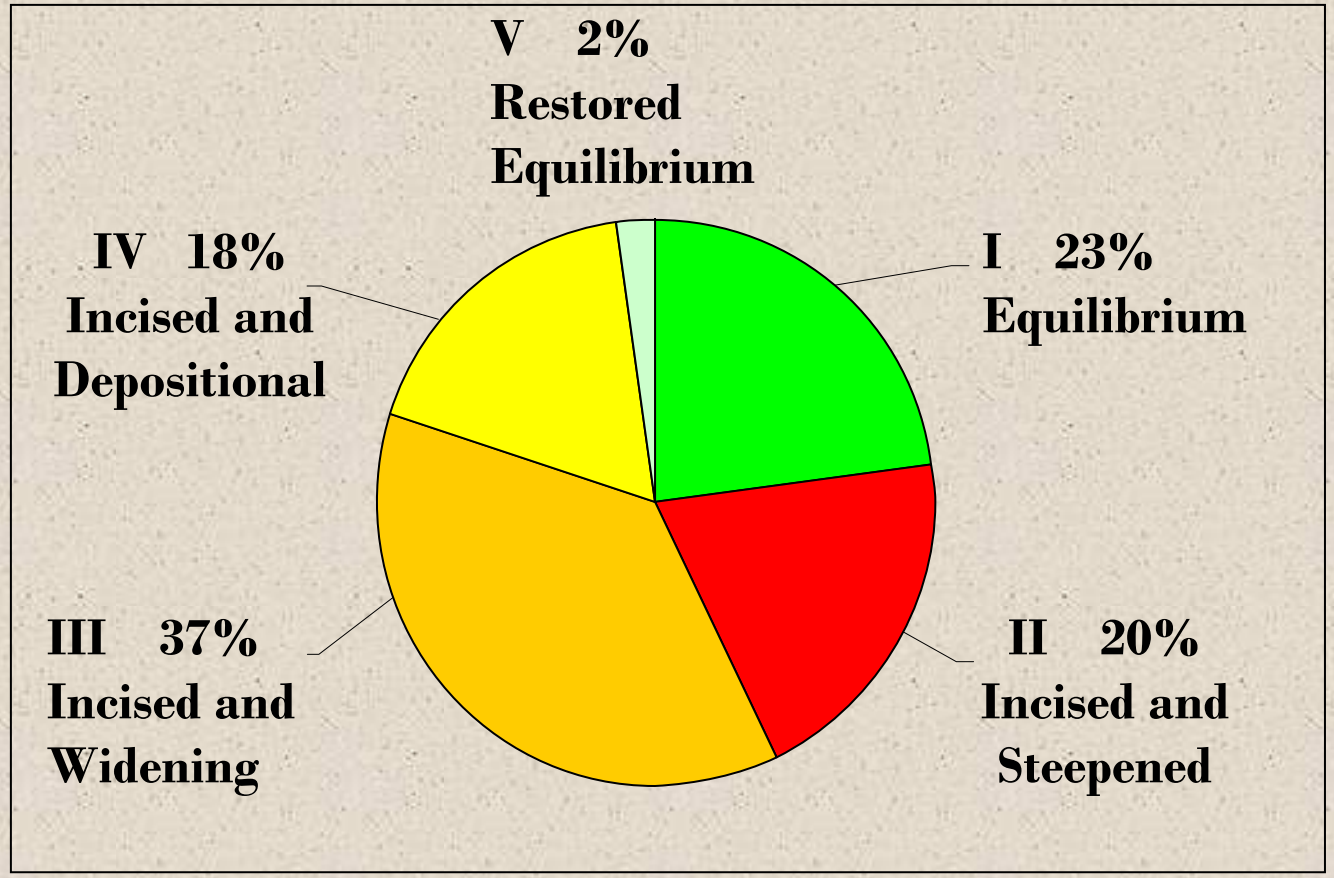
Stage 5: Return to Equilibrium

Abandoned Floodplain

Redeveloped Floodplain



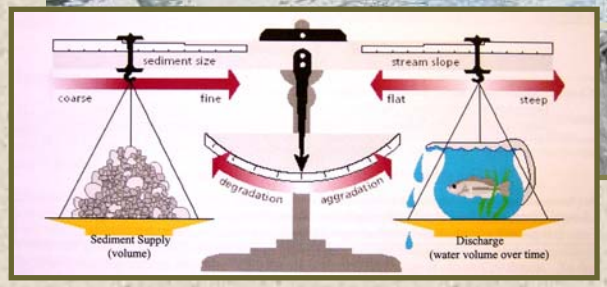
Approx. 900 Miles Assessed



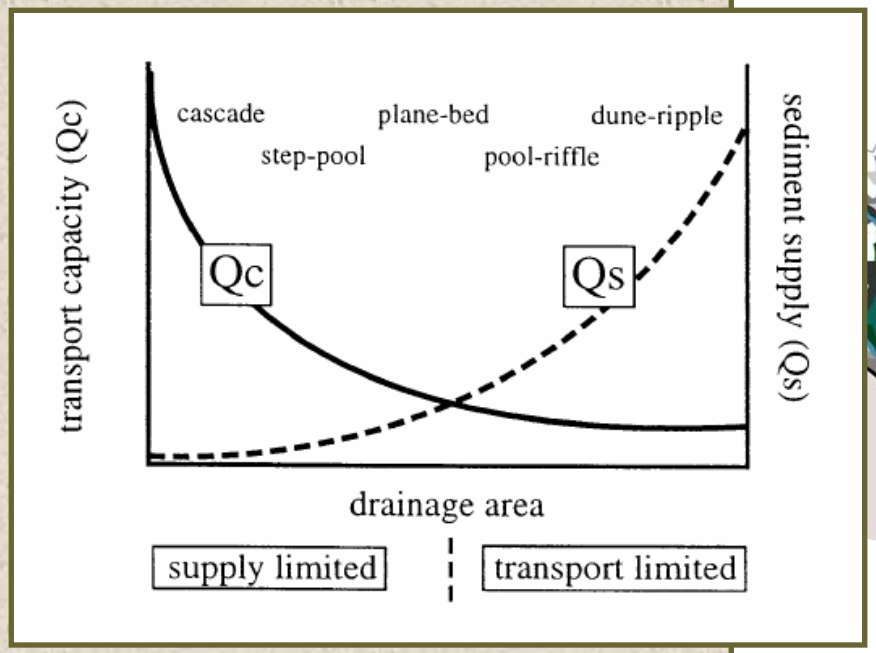
Considering River Processes in Structure Design

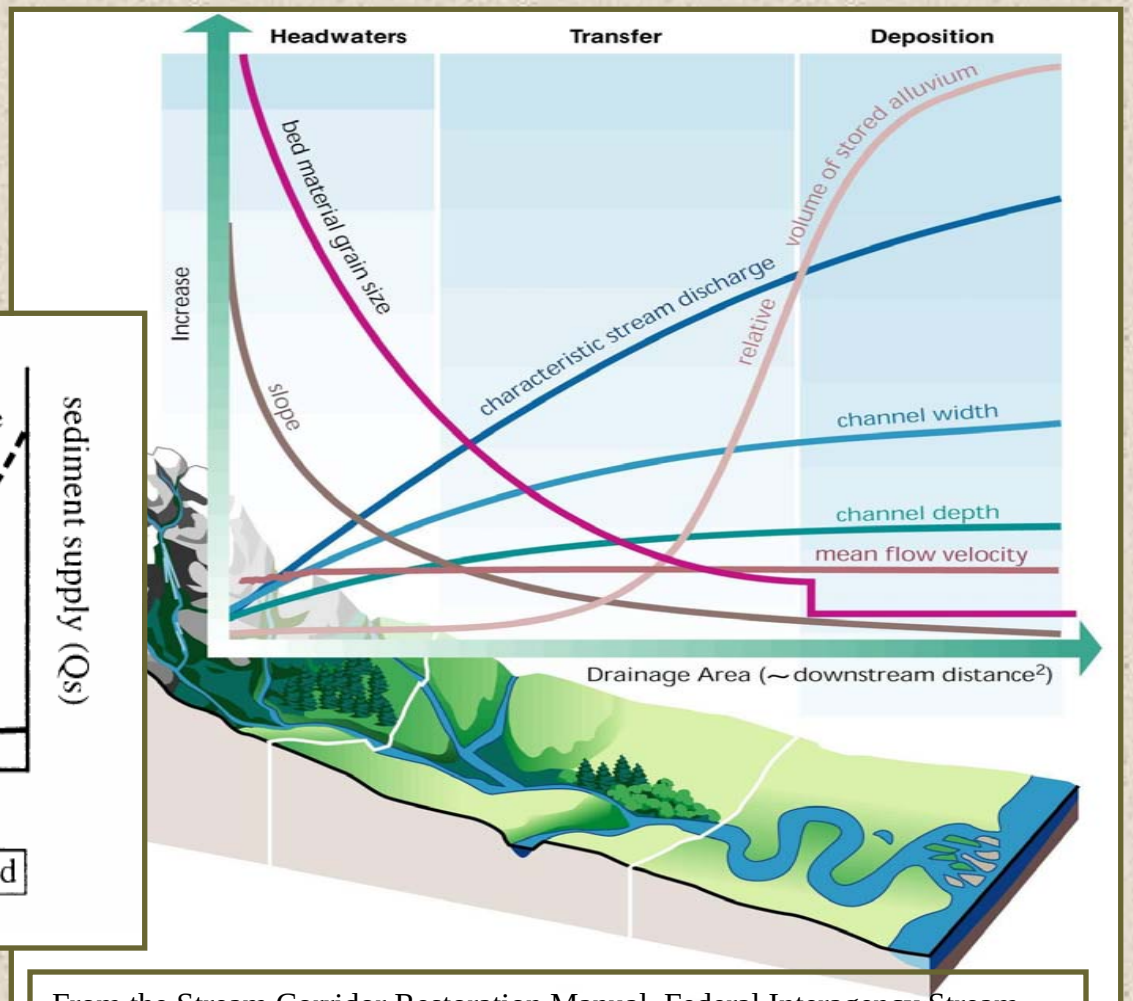
- Selecting Most Stable Location
  - Sensitivity
  - Alluvial Fans
  - Channel Evolution
- Sizing
  - Bankfull Channel Width
  - Sensitivity (sediment supply:transport capacity)

The most common problem created by crossing structures is a sudden decrease in sediment transport capacity.



Structure Location, Consider Valley Setting, Stream and Valley Morphology and Inherent Stability



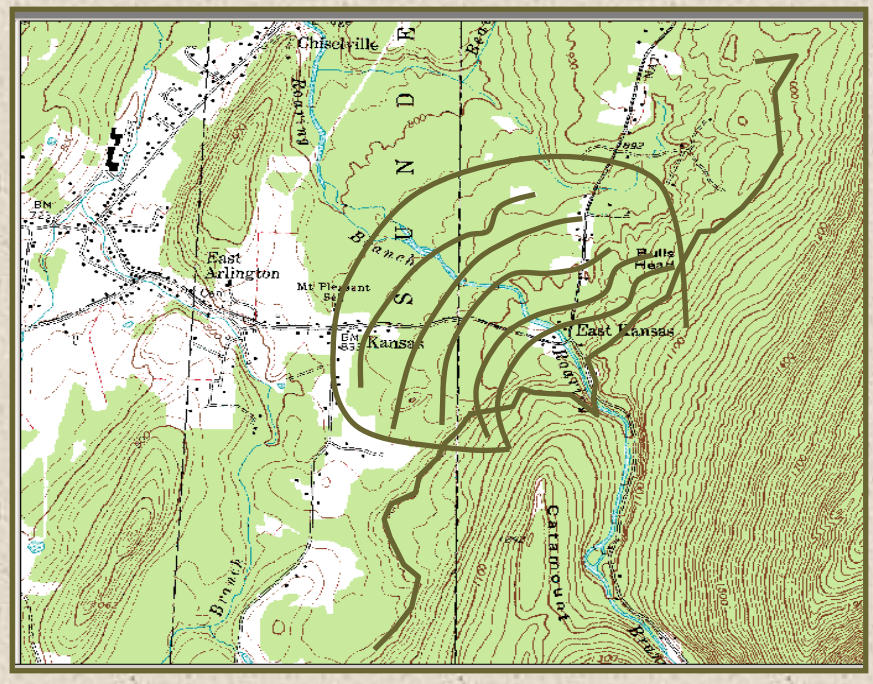


From the Stream Corridor Restoration Manual, Federal Interagency Stream Restoration Working Group, 1998.

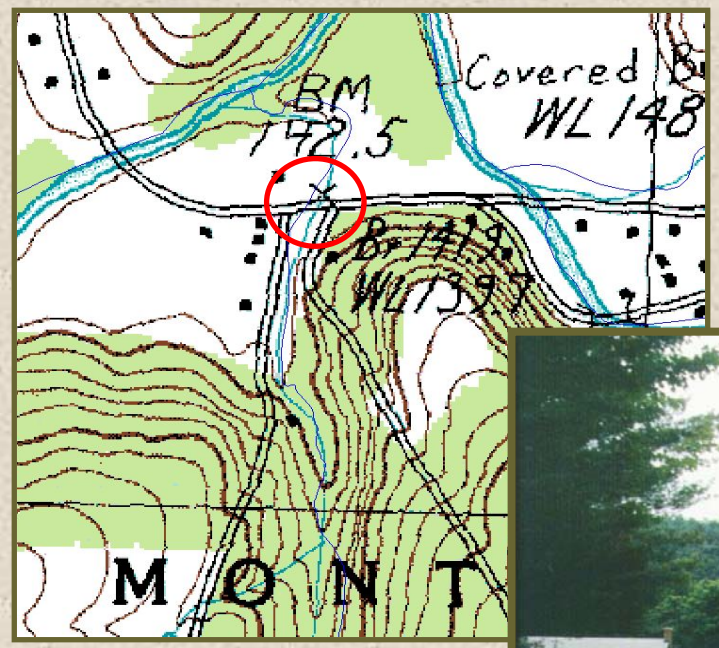
Alluvial Fans

- Sediment naturally deposits at locations of significant decrease in valley slope.
- These highly depositional zones may form “alluvial fans”.

Figure 1.1 A small alluvial fan deposited from a steep tributary due to a change in slope.



Fans aren’t good crossing structure locations



Structures placed at the toe of the valley wall often require repetitive maintenance.

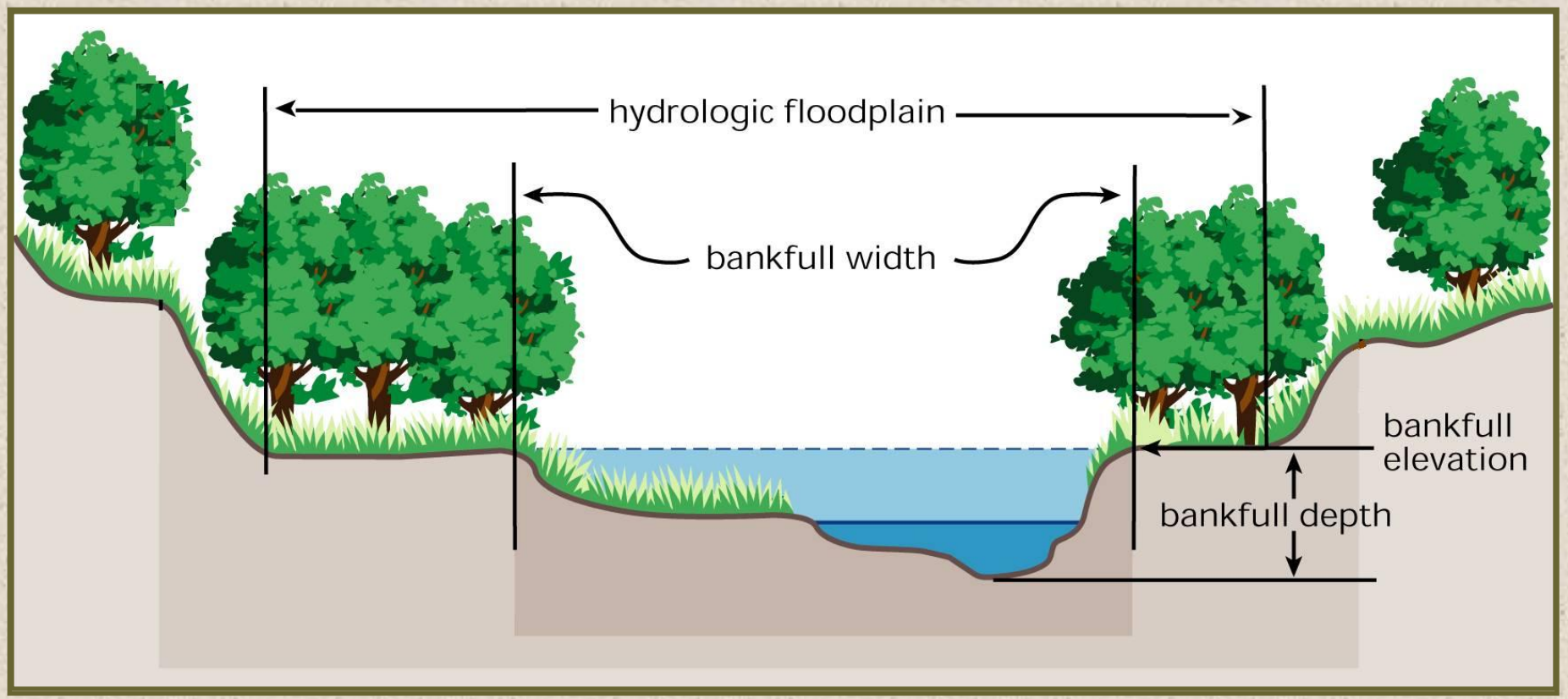
Through headcutting and transport of sediment waves the affects of channel evolution travel up and downstream

Sizing the Structure to Maintain Sediment Transport Continuity

- Start by Maintaining hydraulic characteristics of the channel by sizing to the bankfull width.
- Adjust size according to stream sensitivity or the relation between sediment load and transport capacity.

Bankfull Width

- The stream channel that is bounded by the active floodplain. It is maintained by the dominant discharge.



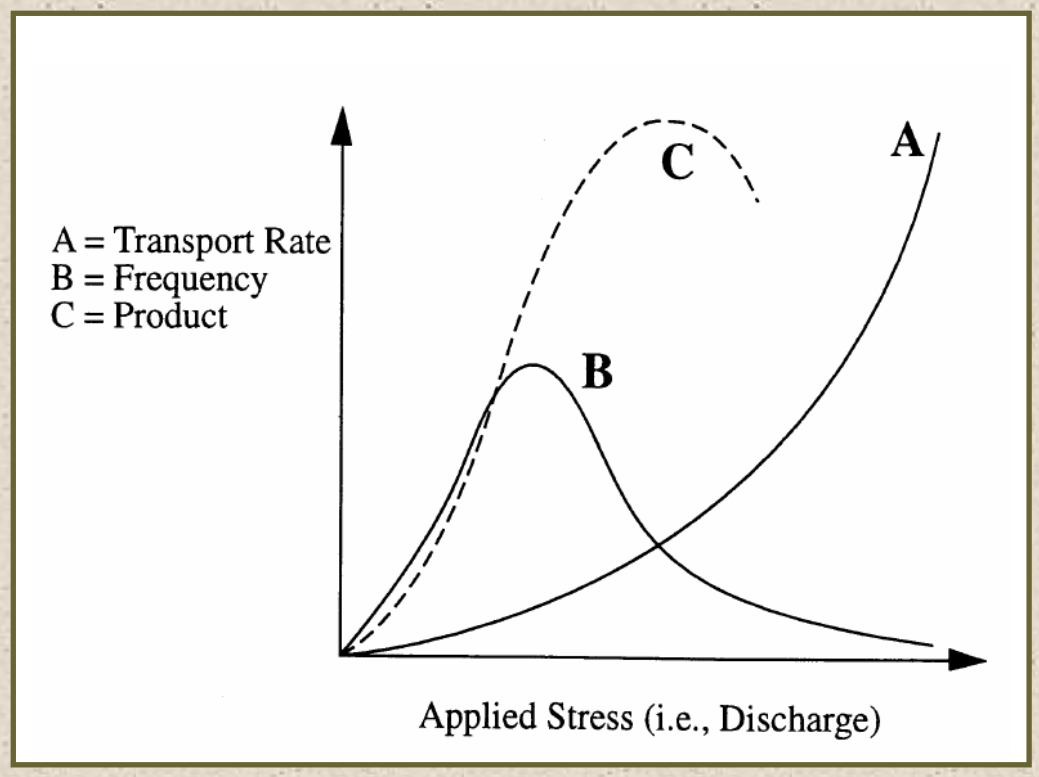
Bankfull or Dominant Discharge

- The discharge that has the right combination of frequency and magnitude to transport the greatest volume of sediment over time.
- It is the flow that maintains the channel.
- In humid environments such as Vermont's it has been shown to have a recurrence interval of 1.5 – 2 yrs.

Sizing the Structure to Maintain Sediment Transport Continuity Design for the Bankfull Flow A.K.A. Dominant or Effective Discharge

The discharge that is large enough yet occurs frequently enough to move the most sediment over time.

Recurrence Interval = 1.5 yrs
Exceedence Probability = 66%



Threshold Channel Concept

Streams where the boundary materials are remnants of processes no longer active in the stream system may be threshold streams. Streams formed by post-glacial hydrology or running through colluvial deposits.

Threshold shear is just equaled at the maximum sustained discharge of record.

At flows < Qm.s. the channel boundary is immobile.

At flows > Qm.s. the channel perimeter mobilizes and the channel enlarges until the boundary shear is reduced to the threshold value.

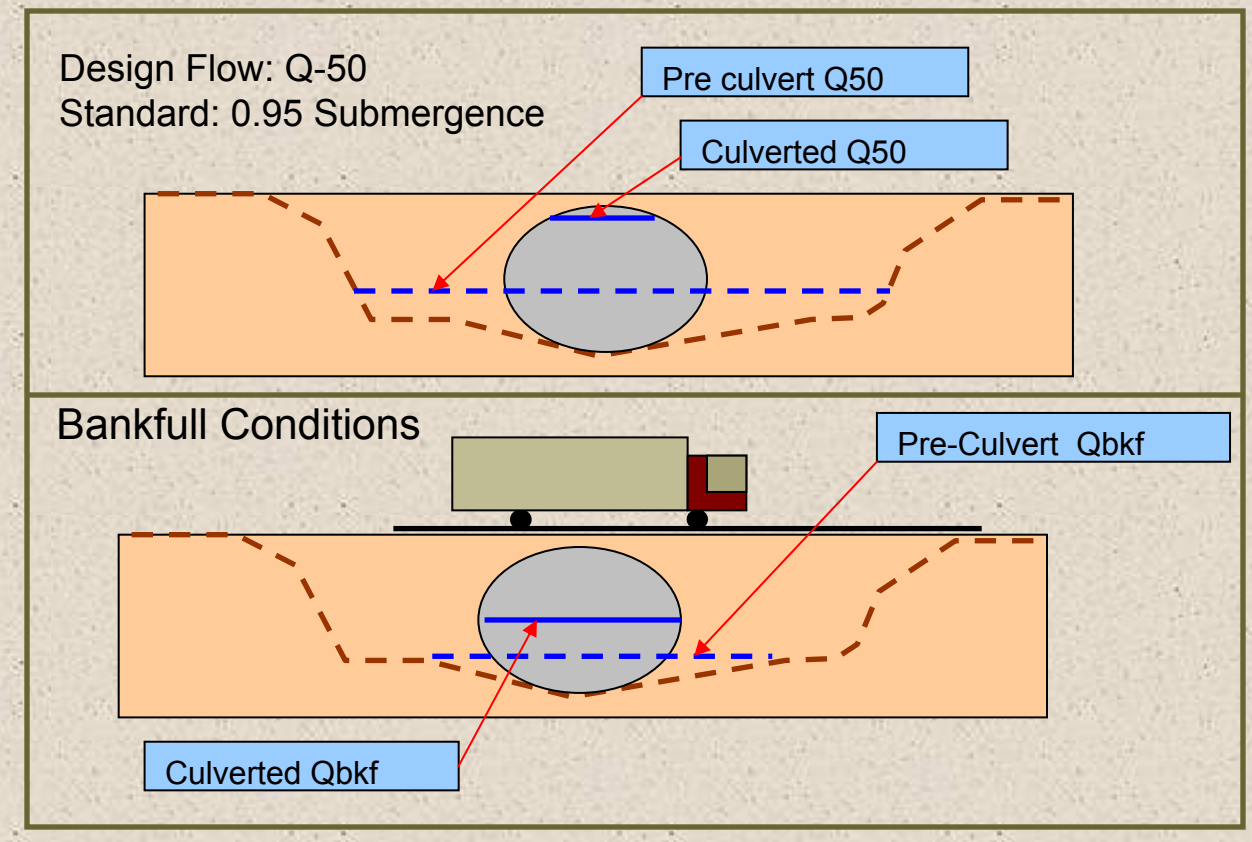
An implicit assumption is that supply of coarse material to channel is negligible. Otherwise, the channel would aggrade at flows less than Qm.s. and would not necessarily degrade at flows > threshold.

What about using hydraulic criteria?

Vermont Hydraulic Criteria:

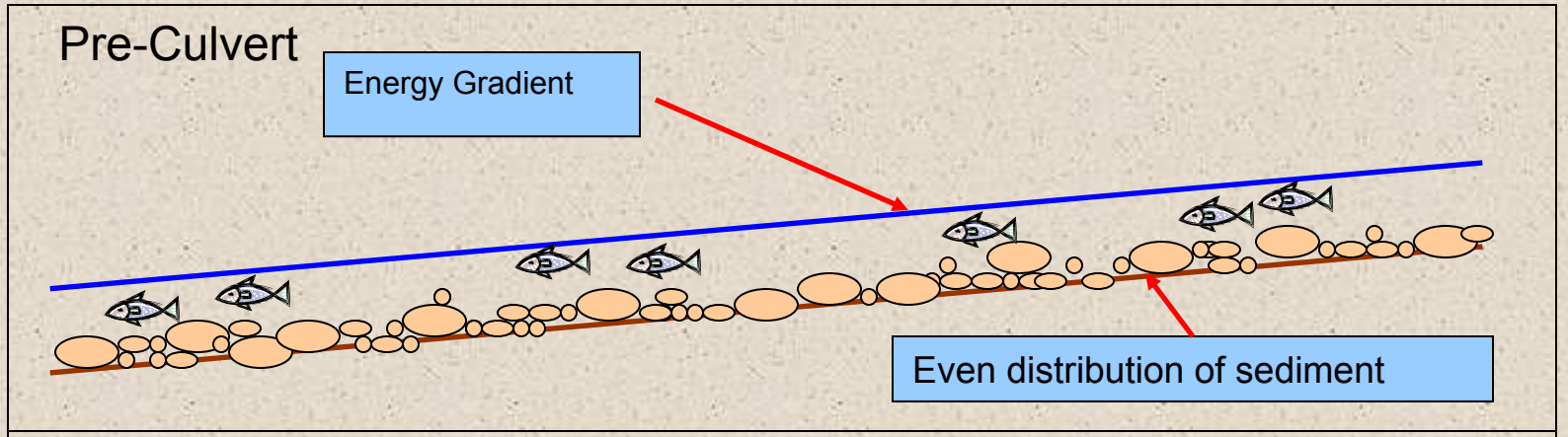
- Interstate highways: Q100
- State highways: Q50
- Town Roads: Q25
- 95% Max Submergence

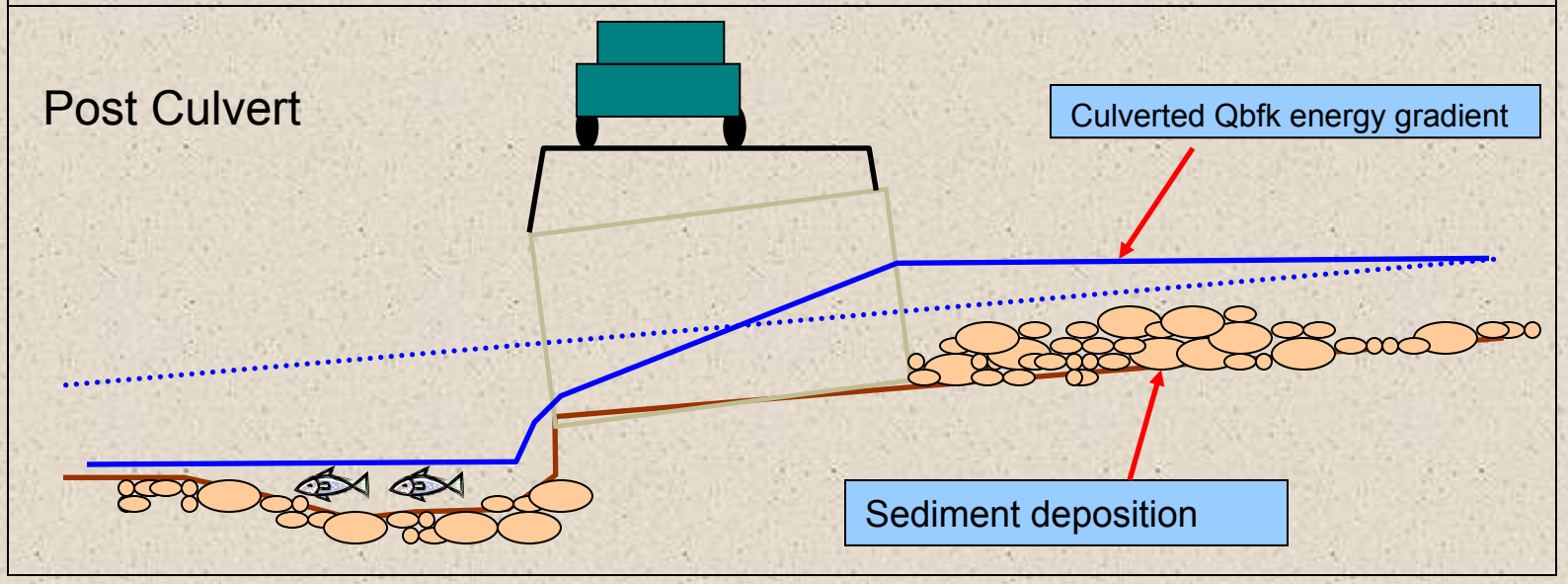
Hydraulic or flow criterion based design (i.e., pass design flow with max. specified submergence) results in decreased flow width and increased flow depth. Even at flows as low as Q2



The flattened water surface upstream of the culvert results in sediment deposition.

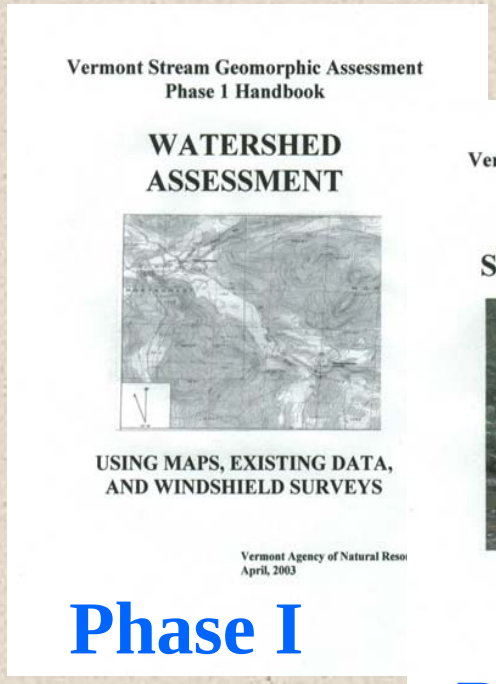
The elevated water surface in the structure results in increased velocities and scour at the culvert outlet which can create a barrier to fish movement.



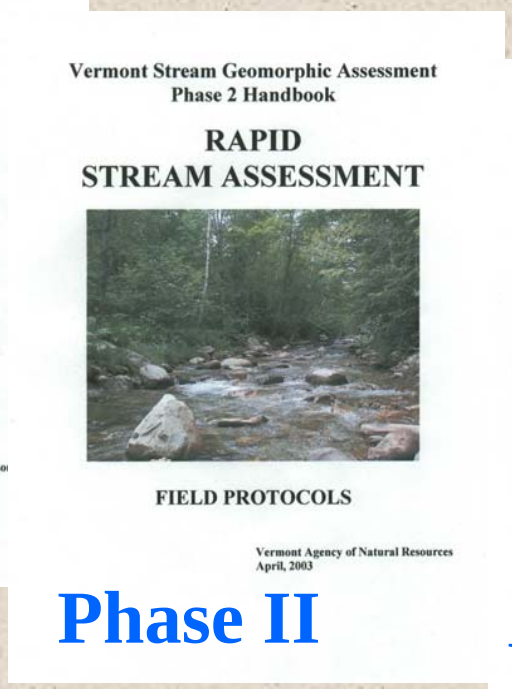


A reduced water surface (energy gradient) upstream of structure usually means an increased slope through the structure

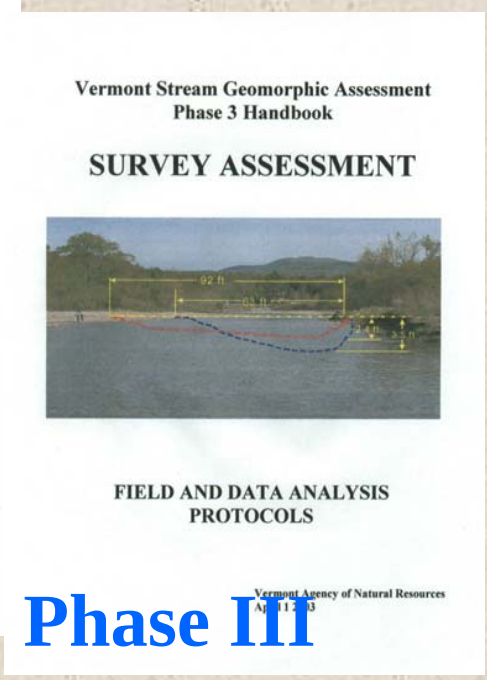
Geomorphic Assessment to Understand Stream Type, Sensitivity and Ongoing Adjustments



Remote Sensing



Qualitative & Rapid Field Assessment



Quantitative Field Surveys

Obtaining the data

Stream Geomorphic Assessment

home | projects | datasets | staff | log out

SGA Home
Instructions
Protocol

home

Stream Geomorphic Assessment Data Management System

Welcome

Welcome to the Vermont Stream Geomorphic Assessment data management system (DMS)! This site was developed to allow for efficient data entry and retrieval of Vermont Stream Geomorphic data. We hope you find it a useful tool and we welcome your feedback.

Please read the DMS instructions prior to entering any data. Data must be entered in the order described in the instructions. Any deviation from the process could result in errors. To ensure the accuracy of the data entered into the state geomorphic database, there are several QA checks built into the DMS.

- Stream Geomorphic Assessment Database
  http://www.anr.state.vt.us/dec/waterq/rivers.htm

Changes to the Database Management System

Note: This log shows that have been made to the DMS to add new features or to correct errors.

Date	Component	Topic	
01/05/2007	All	Bug report feature on the home page	View
12/19/2006	Structures	Bridge and Culvert (Structure) report availability.	View
11/13/2006	Phase 2	Interacive Quality Assurance Checking Feature	View

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Vermont Department of Environmental Conservation

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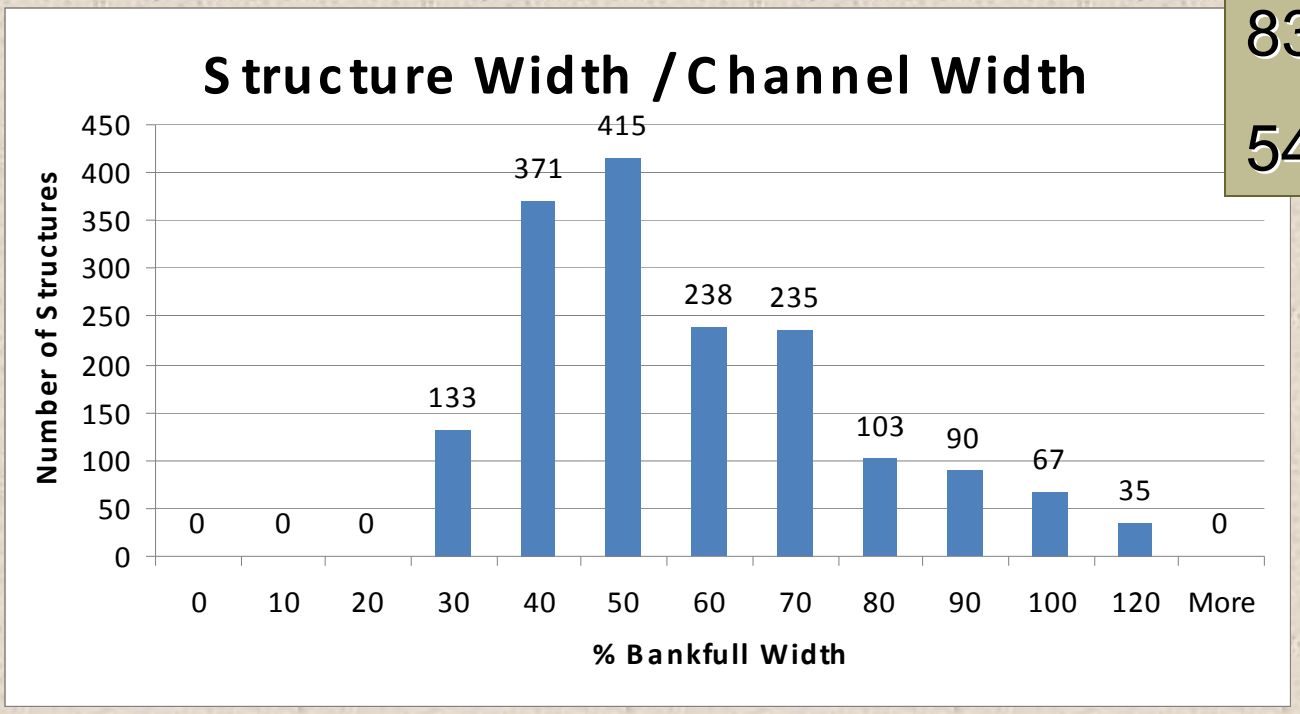
VERMONT.gov

Shayne Jaquith
River Restoration Scientist
Vermont DEC
River Management Program
(802) 241-4456
Shayne.jaquith@state.vt.us

Scoring Categories

Category Name	GC Screen Score	Threshold Conditions	Description of geomorphic compatibility between structure and channel
Fully compatible	20<GC≤25	n/a	Structure fully compatible with natural channel form and process. There is a low risk of failure. No replacement anticipated over the lifetime of the structure. A similar structure is recommended when replacement is needed.
Mostly compatible	15<GC≤20	n/a	Structure mostly compatible with current channel form and process. There is a low risk of failure. No replacement anticipated over the lifetime of the structure. Minor design adjustments recommended when replacement is needed to make fully compatible.
Partially compatible	10<GC≤15	n/a	Structure compatible with either current form or process, but not both. Compatibility likely short term. There is a moderate risk of structure failure and replacement may be needed. Re-design suggested to improve geomorphic compatibility.
Mostly incompatible	5<GC≤10	% Bankfull Width + Approach Angle scores ≤ 2	Structure mostly incompatible with current form and process, with a moderate to high risk of structure failure. Re-design and replacement planning should be initiated to improve geomorphic compatibility.
Fully incompatible	0≤GC≤5	% Bankfull Width + Approach Angle scores ≤ 2 **AND** Sediment Continuity + Erosion and Armoring scores ≤ 2	Structure fully incompatible with channel and high risk of failure. Re-design and replacement should be performed as soon as possible to improve geomorphic compatibility.



1687 Structures

83% < 70% BF

54% < 50% BF

White River Results					
# of Structures	5	93	165	145	26
	Fully Compatible	Mostly Compatible	Partially Compatible	Mostly Incompatible	Fully Incompatible
% of Structures	1%	21%	38%	33%	6%

Ottauquechee Results					
# of Structures	0	36	69	78	17
	Fully Compatible	Mostly Compatible	Partially Compatible	Mostly Incompatible	Fully Incompatible
% of Structures	0%	18%	35%	39%	9%

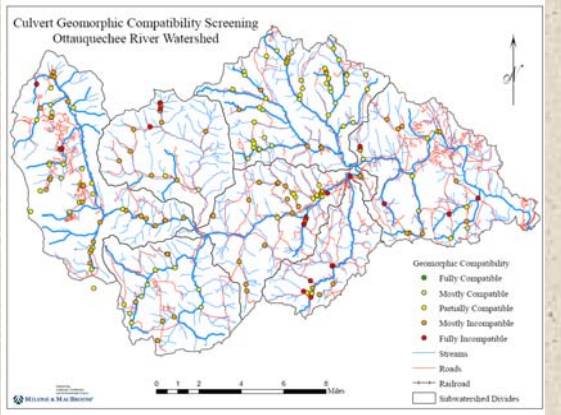
ACOE General Permit Effective Dec. 5, 2007

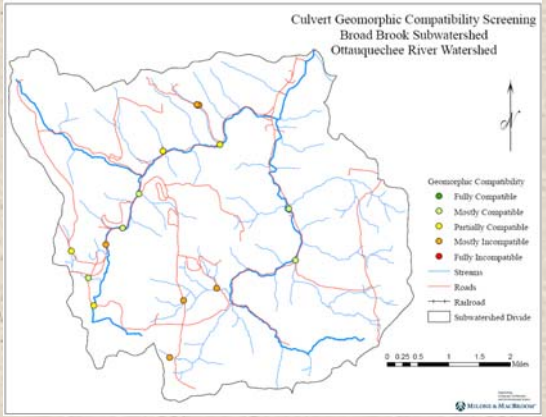
- **21. Waterway/Wetland Work and Crossings**
- (a) All temporary and permanent crossings of waterbodies shall be suitably culverted, bridged, or otherwise designed to withstand and to prevent the restriction of high flows, to maintain existing low flows, and to not obstruct the movement of aquatic life indigenous to the waterbody beyond the actual duration of construction.
- (b) No activity may substantially disrupt the necessary life-cycle movements of those species of aquatic life indigenous to the waterbody,
- (c) To meet the objective of aquatic organism passage in (a) and (b) above, all temporary and permanent crossings of rivers, streams, brooks, etc. (hereon referred to as “streams”) shall meet the following performance standards in order to qualify for Category 1 (refer to Additional References on Page 18): VT GP 13 December 2007
- i. maintain a streambed composition
- ii. Maintain velocities, turbulence and depths within the structure similar to those found in adjacent stream reaches across a range of desired flows.
- (e) Applicants proposing new crossings, or maintenance or replacement of serviceable crossings should refer to the Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont when the State finalizes these guidelines. Refer to Additional References on Page 18.

Crossing Structures Will Change the Form of the River

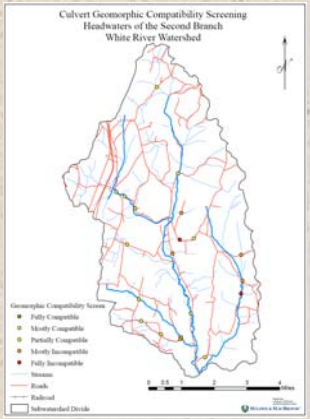
Regulatory Jurisdiction

- Any crossing on stream draining 10sq. mi. or more requires a stream alterations permit.
- Crossings on streams draining between 1 and 10 sq. mi. require the completion of a crossing application
- Contact regional Stream Alterations Engineer. http://www.anr.state.vt.us/dec/waterq/rivers.htm or **241-3770 for SAE's contact info.**

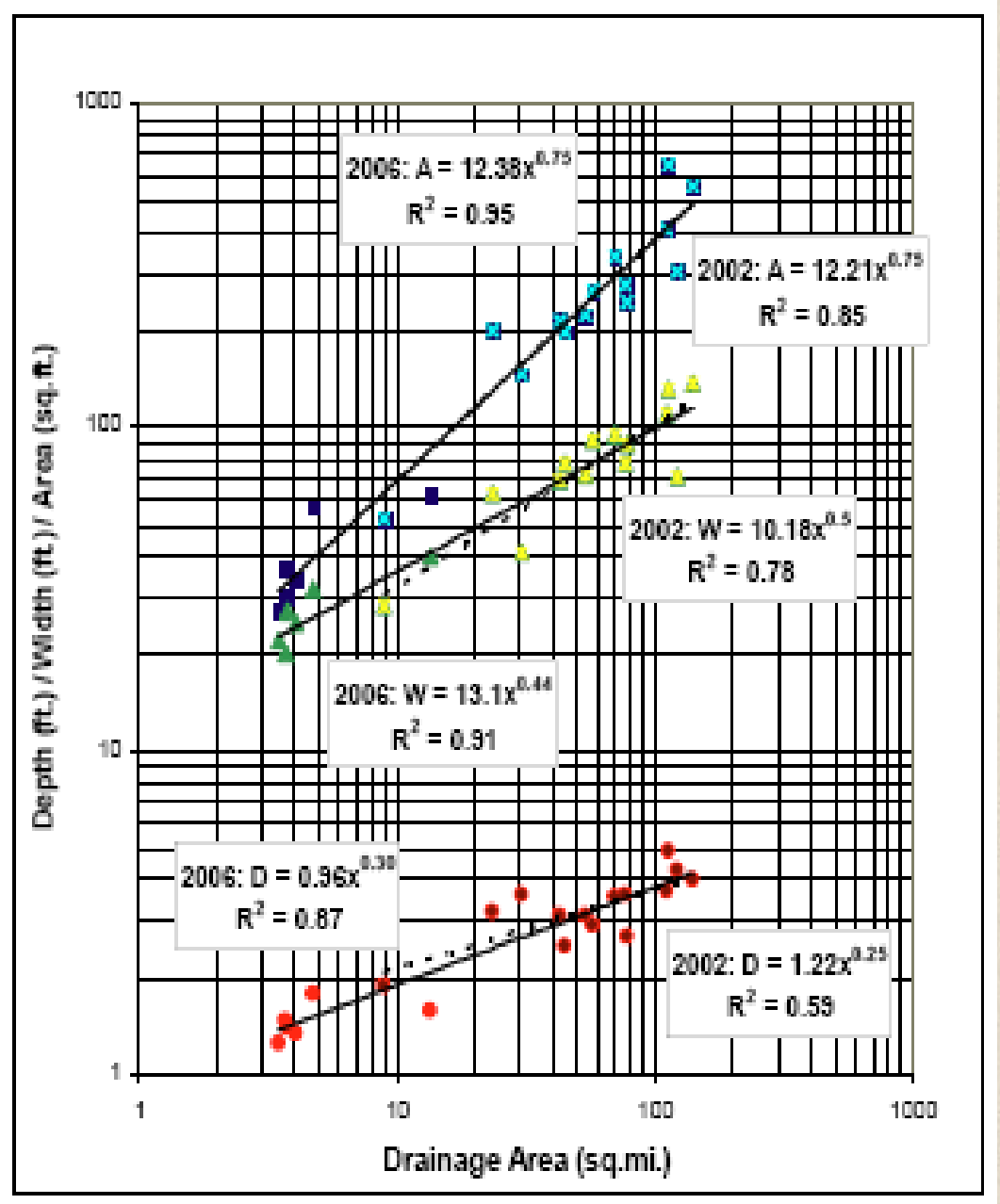

Culvert Geomorphic Compatibility Screening
Ottauquechee River Watershed
Geomorphic Compatibility
Fully Compatible
Mostly Compatible
Partially Compatible
Mostly Incompatible
Fully Incompatible
Streams
Roads
Railroad
Subwatershed Divides
0 1 2 4 6 8
Miles


Culvert Geomorphic Compatibility Screening
Broad Brook Subwatershed
Ottauquechee River Watershed
Geomorphic Compatibility
Fully Compatible
Mostly Compatible
Partially Compatible
Mostly Incompatible
Fully Incompatible
Streams
Roads
Railroad
Subwatershed Divide
0 0.25 0.5 1 1.5 2
Miles

Culvert Geomorphic Compatibility Screening
White River Watershed
Geomorphic Compatibility Screen
Fully Compatible
Mostly Compatible
Partially Compatible
Mostly Incompatible
Fully Incompatible
Streams
Roads
Railroad
Subwatershed Divides
0 1.5 3 6 9 12
Miles


Culvert Geomorphic Compatibility Screening
Headwaters of the Second Branch
White River Watershed
Geomorphic Compatibility Screen
Fully Compatible
Mostly Compatible
Partially Compatible
Mostly Incompatible
Fully Incompatible
Streams
Roads
Railroad
Subwatershed Divide
0 0.5 1 2 3 4
Miles

Vermont 2006 Regional Hydraulic Geometry Curves



http://www.anr.state.vt.us/dec/waterq/rivers.htm

Variable Scoring

Score	% Bankfull Width	Sediment Continuity	Slope	Approach Angle	Erosion and Armoring
5	$W_{st/bkf} \geq 120$	No upstream deposition or downstream bed scour	Structure slope equal to channel slope, and no break in valley slope	Naturally straight	No erosion **or** armoring
4	$100 \leq W_{st/bkf} < 120$	**Either** upstream deposition **or** downstream bed scour, **without** upstream deposits taller than 0.5 bankfull height **or** high downstream banks	n/a	n/a	No erosion **and** intact armoring, **or** low upstream **or** downstream erosion **without** armoring
3	$75 \leq W_{st/bkf} < 100$	**Either** upstream deposition **or** downstream bed scour, **with** either upstream deposits taller than 0.5 bankfull height **or** high downstream banks	Structure slope equal channel slope, with local break in valley slope	Mild bend	Low upstream **or** downstream erosion **with** armoring
2	$50 \leq W_{st/bkf} < 75$	**Both** upstream deposition **and** downstream bed scour, **without** upstream deposits taller than 0.5 bankfull height **or** high downstream banks	Structure slope higher or lower than channel slope, and no break in valley slope	Channelized straight	Low upstream **and** downstream erosion
1	$30 \leq W_{st/bkf} < 50$	**Both** upstream deposition **and** downstream bed scour, **with** upstream deposits taller than 0.5 bankfull height **or** high downstream banks	n/a	n/a	Severe upstream **or** downstream erosion
0	$W_{st/bkf} < 30$	**Both** upstream deposition **and** downstream bed scour, **with** upstream deposits taller than 0.5 bankfull height **and** high downstream banks	Structure slope higher or lower than channel slope, with local break in valley slope	Sharp bend	Severe upstream **and** downstream erosion, **or** failing armoring upstream **or** downstream