Evolution of Disturbed Fluvial Systems: Implications for and Approaches to Stream Restoration

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Disturbed Channels







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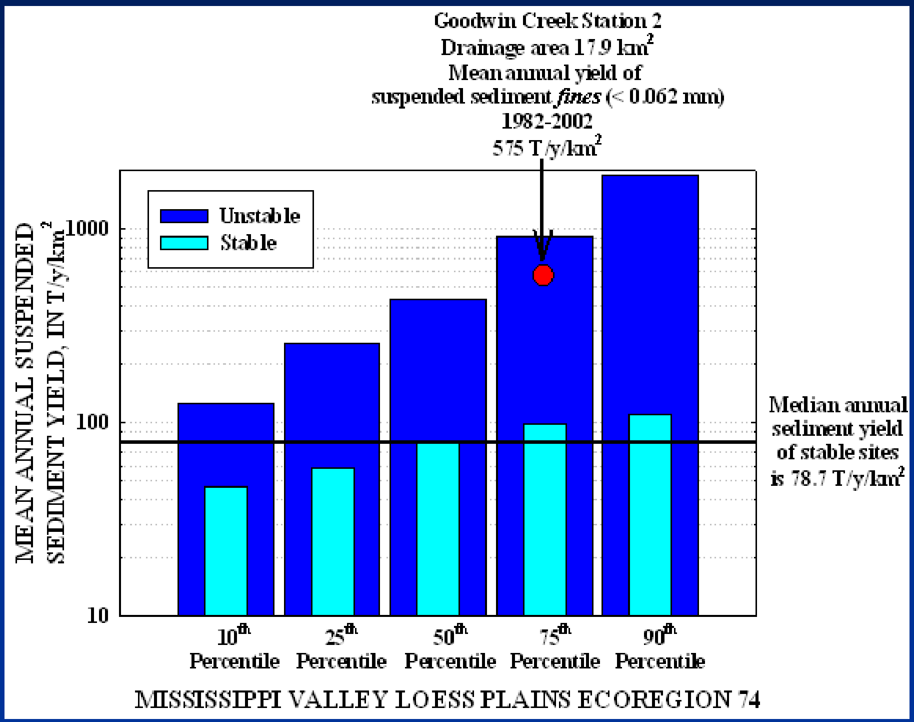
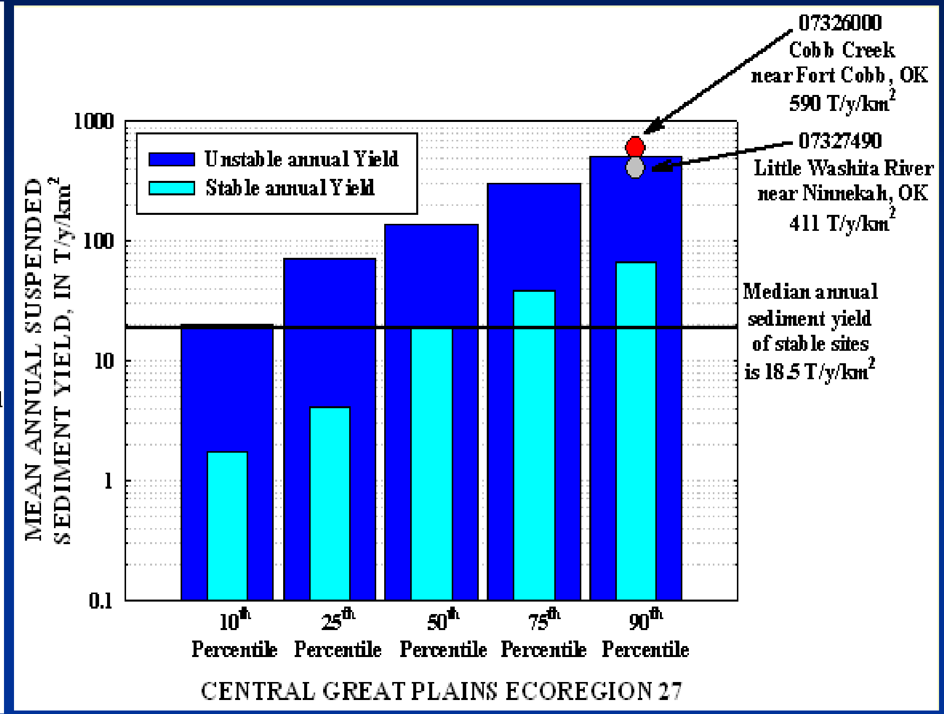
Sediment Yields from Unstable Streams

Mississippi



Oklahoma



Suspended-sediment yields from these streams are among the highest in the ecoregion (1-2 orders of magnitude greater than the median value for stable sites)

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Contributions from Streambank Erosion

Stream	Ecoregion	Dominant Bed Material	Contribution from Banks
James Creek, MS	Southeastern Plains	Sand/Clay	78%
Shades Creek, AL	Ridge and Valley	Gravel	71-82%
Goodwin Creek, MS	Mississippi Valley Loess Plains	Sand/Gravel	64%
Buffalo River, MN	Northern Glaciated Plains	Sand/Gravel	17%
Big Sioux River, SD	Northern Glaciated Plains	Sand/Gravel	22%
Upper Truckee River, CA	Sierra Nevada	Gravel	47%
Yalobusha River, MS	Southeastern Plains	Clay/Sand	90%*
Obion-Forked Deer River, TN	Mississippi Valley Loess Plains	Sand	81%*

*Represents percent contribution from channel sources

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Contributions from Streambank Erosion

Similar results are being found in Australia where it was previously reported (Brodie *et al*., 2003) that the dominant source of sediment to Moreton Bay and the Great Barrier Reef was emanating from upland and agricultural sources…

This appears not to be the case and has led to…

A two-year research project funded by the Queensland Government to develop a new integrated catchment/channel-erosion model for cost efficient sediment-load reduction to the Great Barrier Reef and Moreton Bay, Queensland, Australia

Cardno ENTRIX is partnering with the Australia Rivers Institute, Griffith University and the U.S. Army Corps of Engineers to provide state-of-the art geomorphology and numerical-modeling expertise.

Integration of HEC-RAS with our Bank-Stability and Toe-Erosion Model (BSTEM) that will be interfaced with upland models supported by the Government

Are Australian Conditions/Rivers Unique?

- World's driest continent
- Lowest and flattest continent
- Most variable flow regime

Are Australian Conditions/Rivers Unique?

1. Prolonged tectonic stability
2. Resistant bedrock in uplands limits sediment supply
3. Extensive unconfined low-gradient plains
4. No Quaternary glaciation
5. Co-evolution of rivers with riparian vegetation
6. Inter-decadal precipitation variability provides periods of establishment of vegetation
7. Dry periods allow for colonization of vegetation on bed and banks

Should We Analyze Australian Rivers Differently?

No, Gravity is A Constant!!

- The physics of erosion are the same wherever you are…no matter what hydro-physiographic province, stream type or river style you are in…channel response is a matter of *quantifying available force, and resistance of the channel boundary*
- Channel adjustment is driven by an imbalance between the driving and resisting forces
- Differences in rates and magnitudes of adjustment, sediment transport rates and ultimate channel forms are a matter of defining those forces…deterministically or empirically

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Implications for Stormwater Management

Changes in Flow Regime Affect the Stability and Sustainability of Urban Stream Systems

- Water Quantity is the key driver for determining…
- Water Quality and the need for
- Stormwater Harvesting

If discharge (Q) is increased…

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Conceptual Process-Based Framework

Streams are open systems with an ability to adjust

$$\gamma QS \propto Q_s d_{50}$$

γ = unit weight of water

Q = water discharge

S = bed or energy slope

Q_s = bed-material discharge

d_{50} = median particle size of bed material

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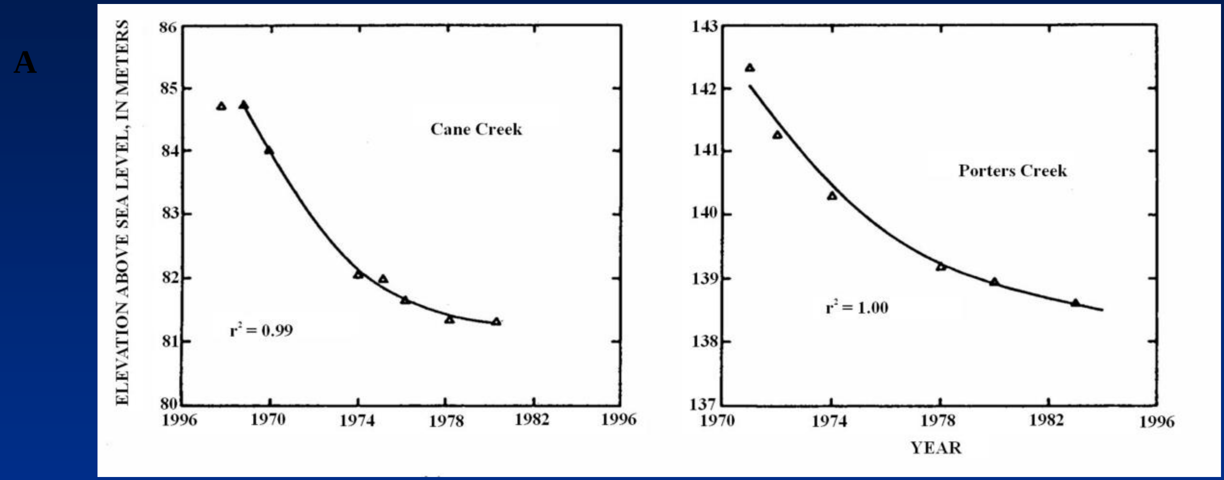
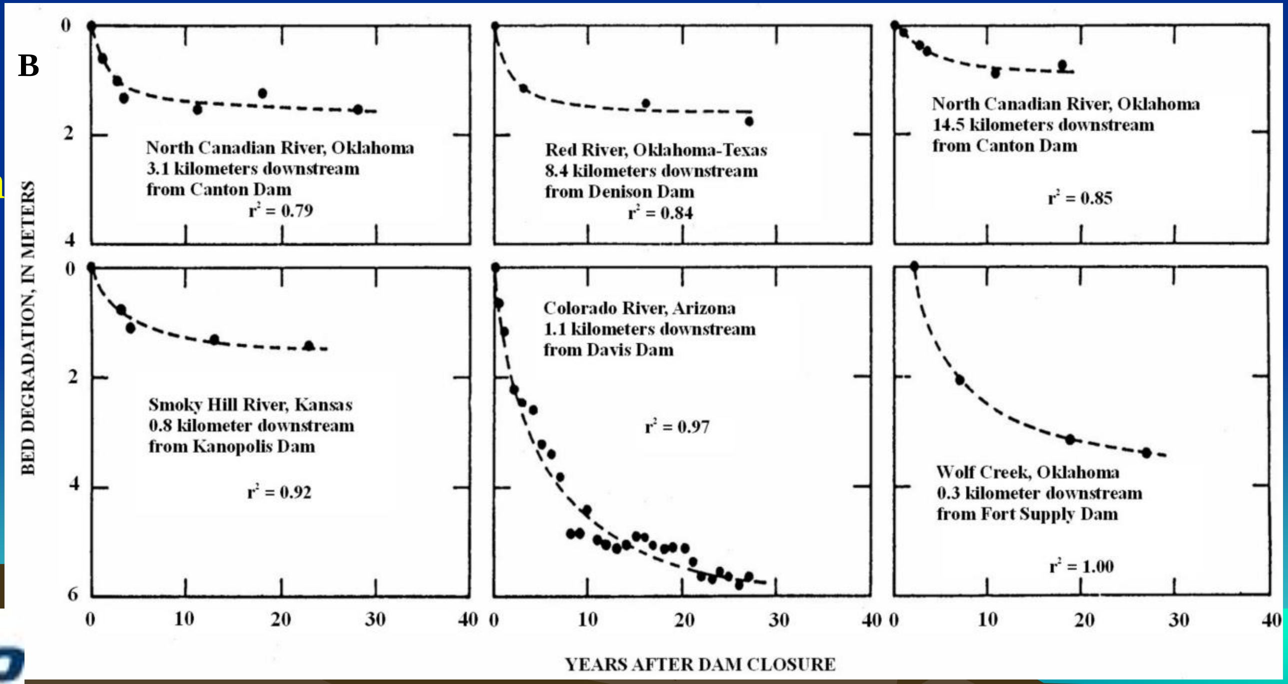
General Non-Linear Form of Incision

Following channelization



Downstream from dams



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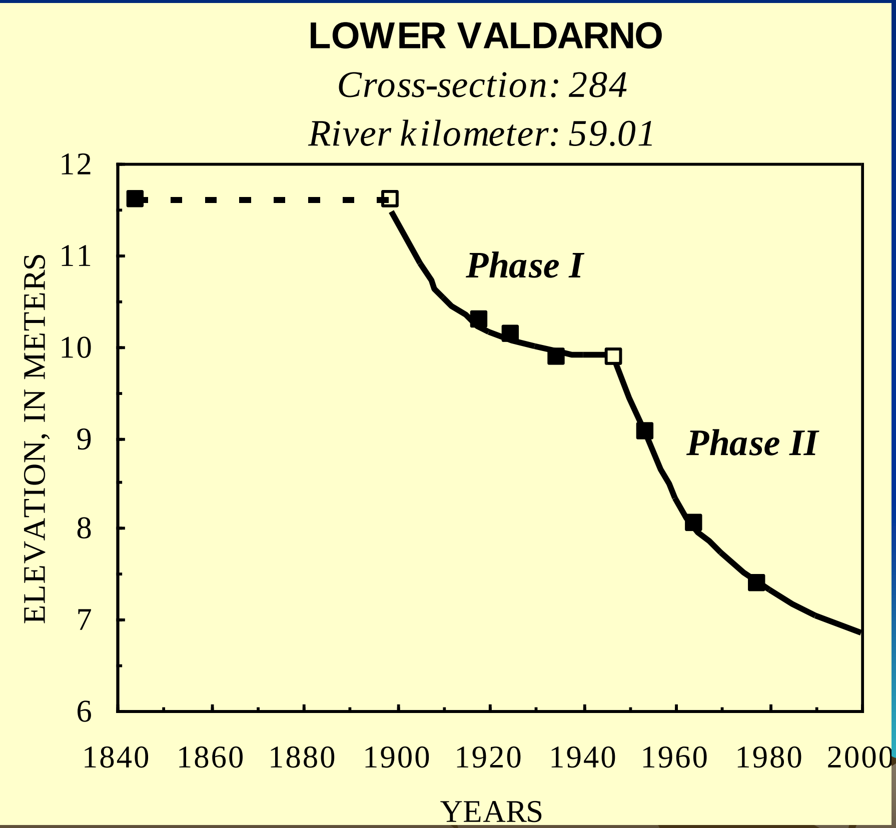
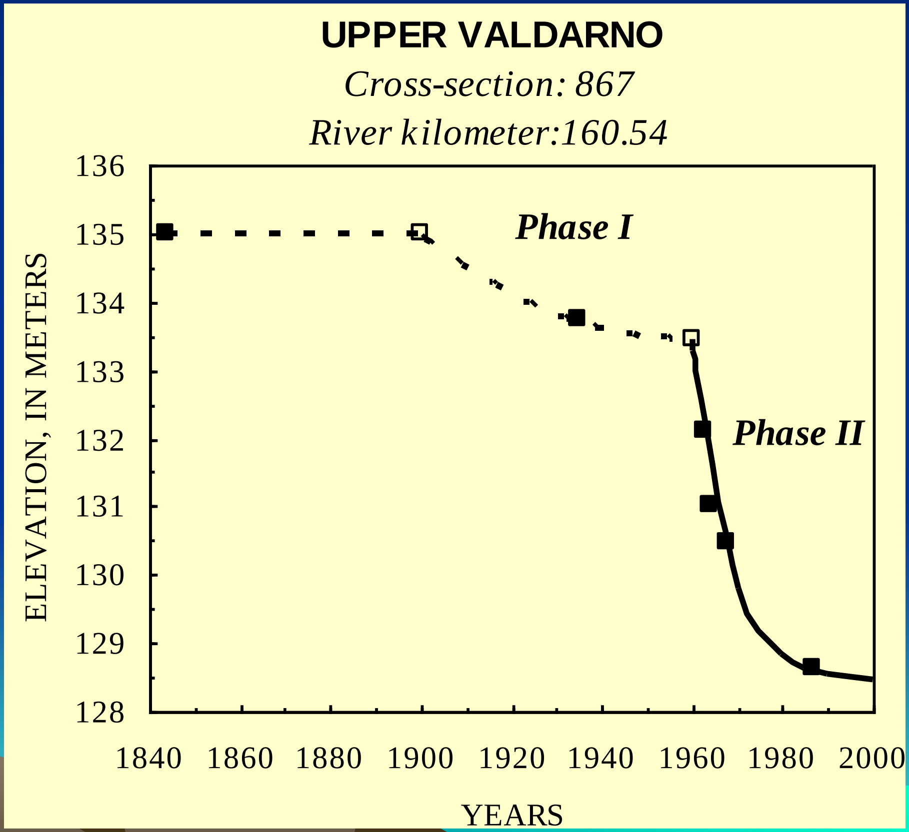
Arno River, Italy: Phases of Degradation Since 1900

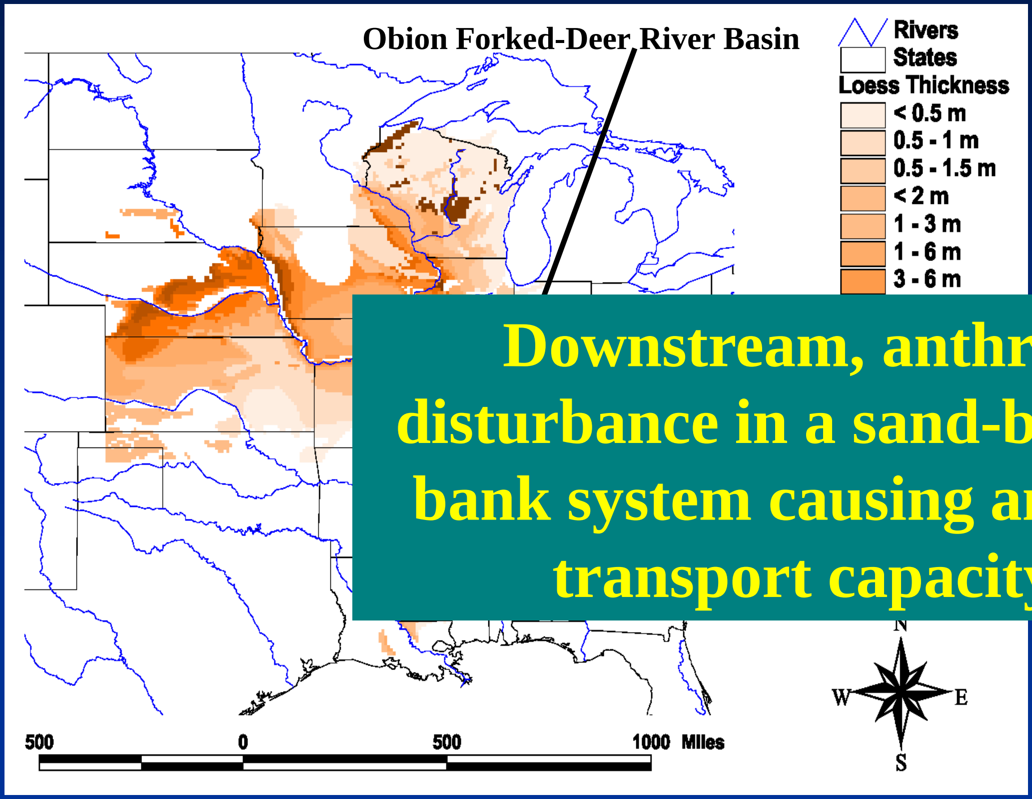
Phase I: Land use changes with a reduction in sediment supply

Phase II: Gravel mining and upstream dam construction





Case Study: Coastal-Plain System



Modified from Lutenegger (1987)

Downstream, anthropogenic disturbance in a sand-bed, cohesive-bank system causing an increase in transport capacity (γQS)

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Adjustment Processes

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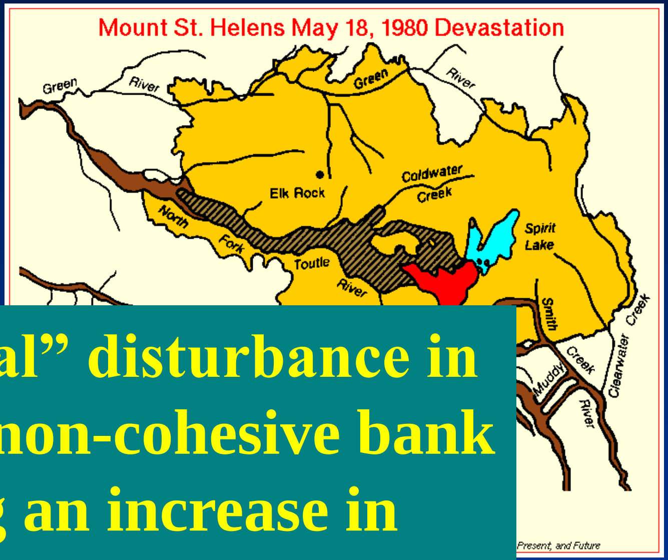
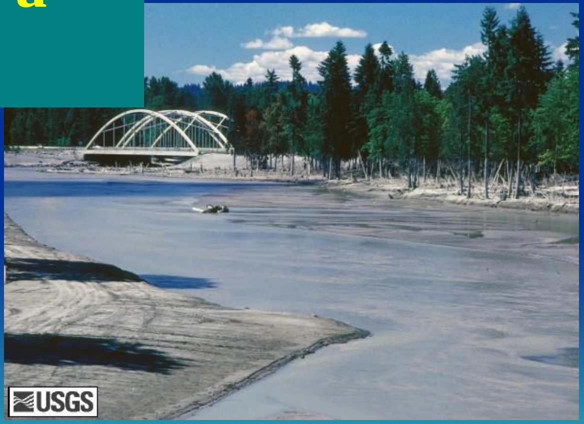
Case Study: Sub-Alpine System



Upstream "natural" disturbance in a coarse-grained, non-cohesive bank system causing an increase in transport capacity (γQS) and a decrease in resistance (d_{50})



Adjustment Processes

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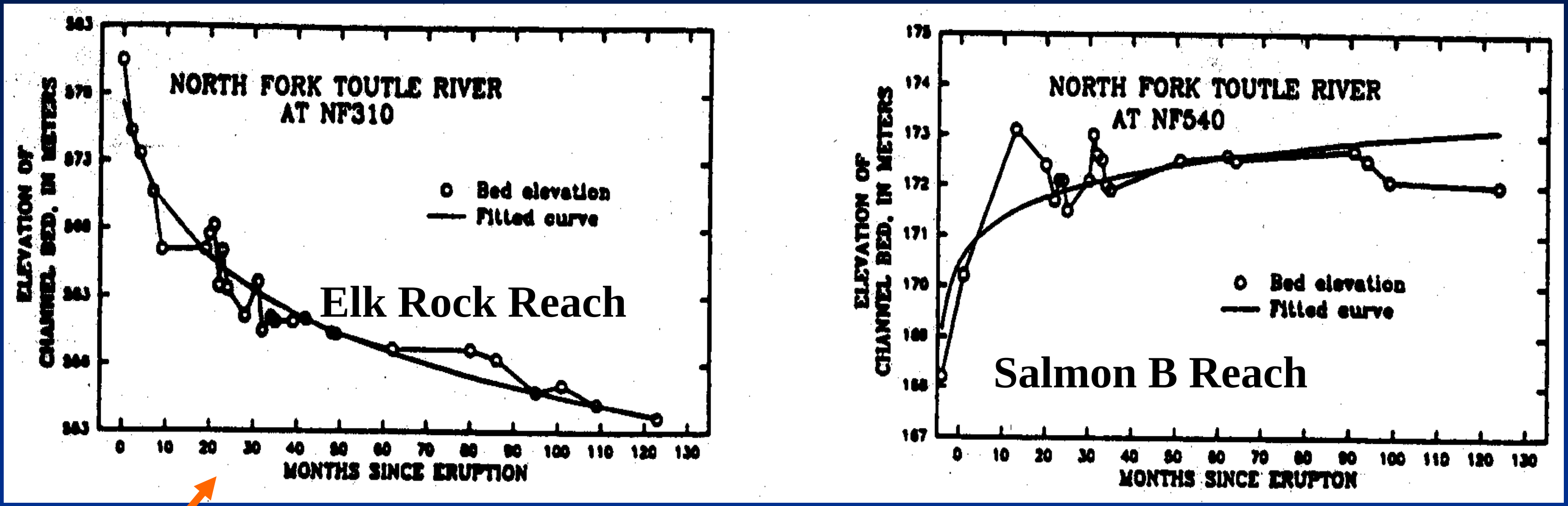
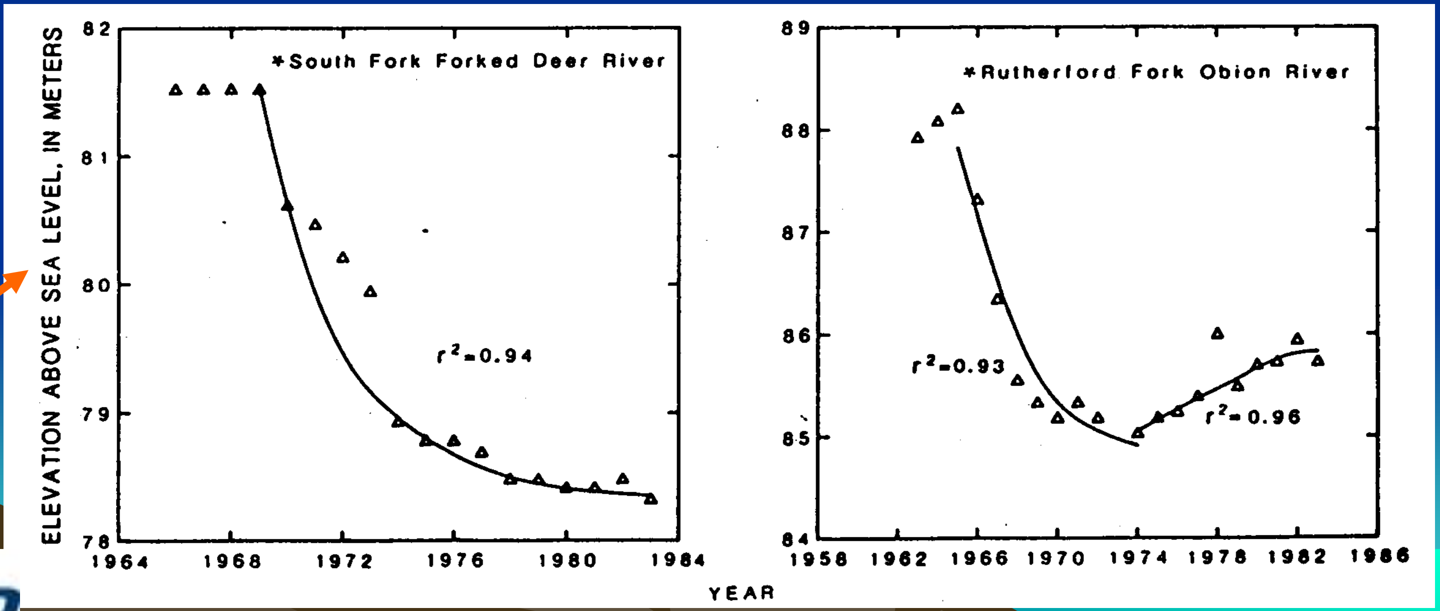
Trends of Bed-Level Change



Mt. St Helens

W. Tennessee



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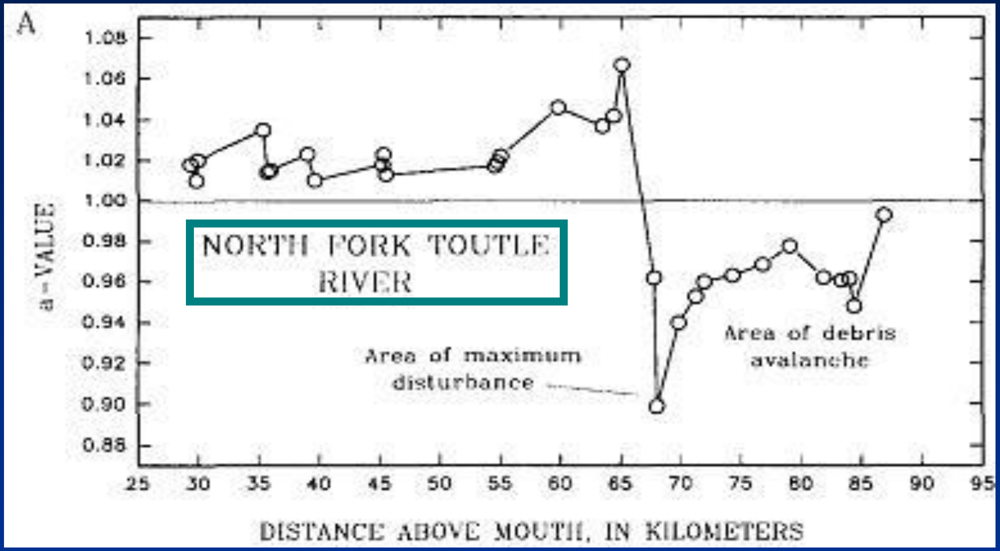
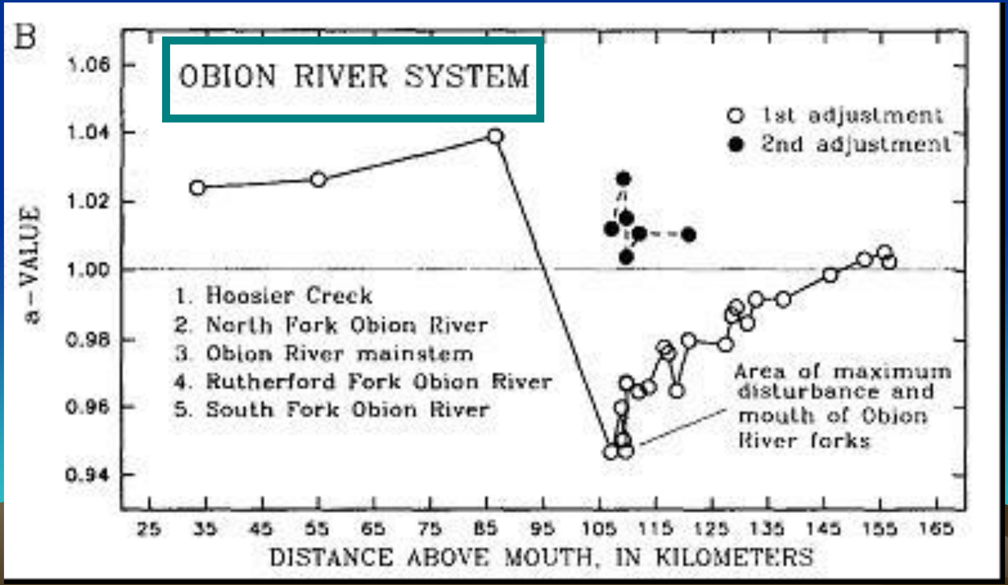
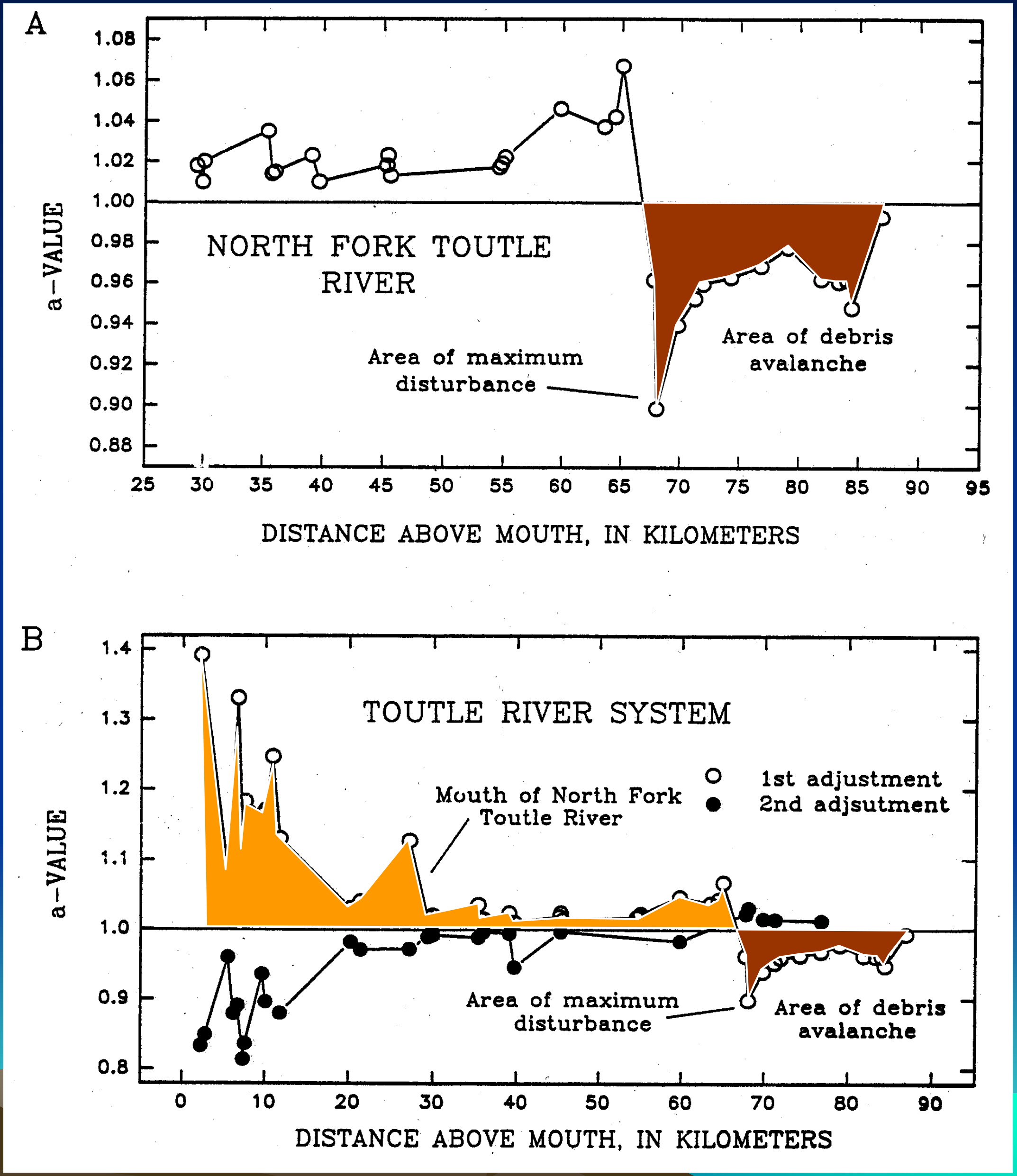
Trends of Bed-Level Change





Trends of Bed-Level Change

Coarse-grained material for aggradation derived from bank sediment.



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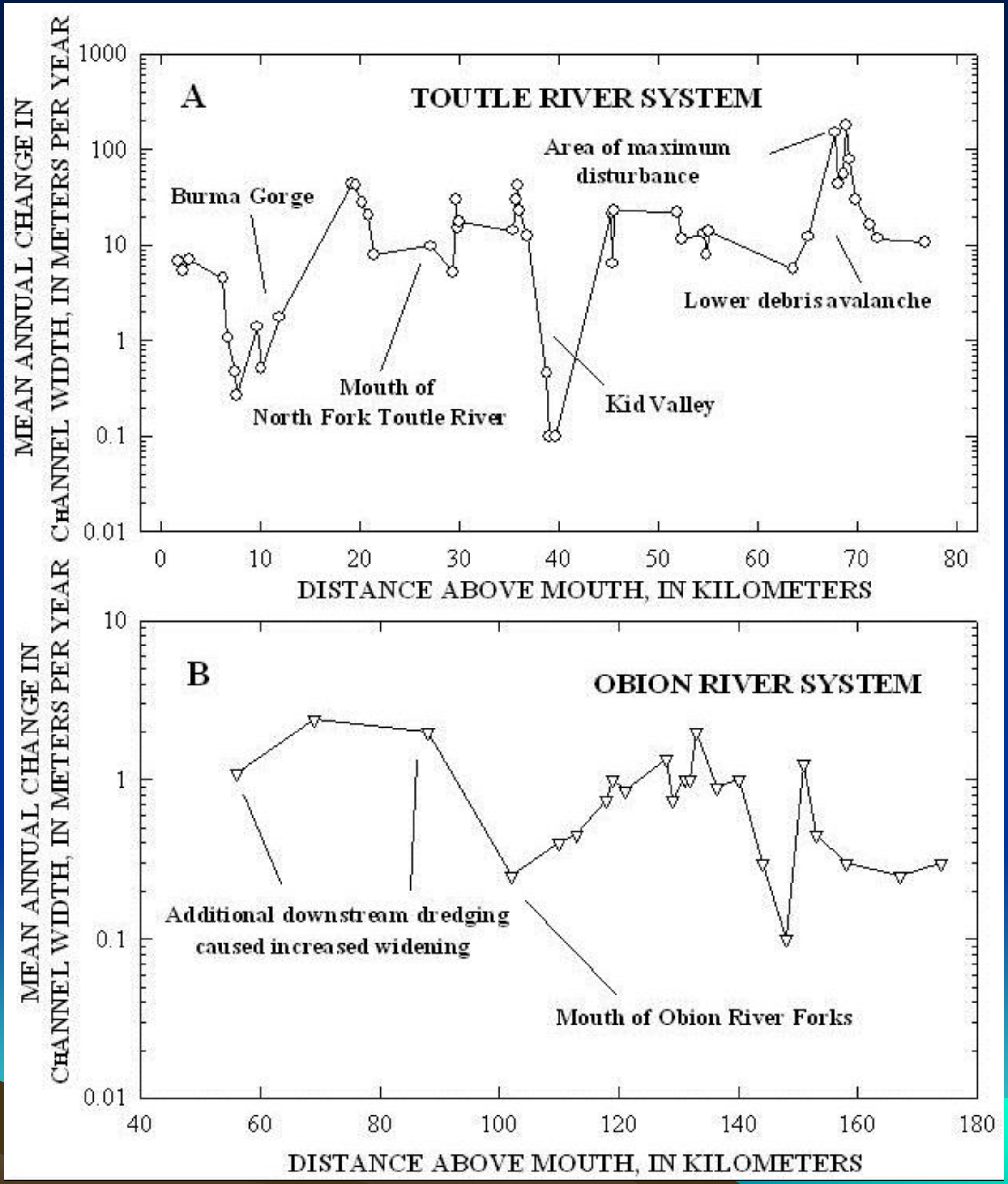
Widening

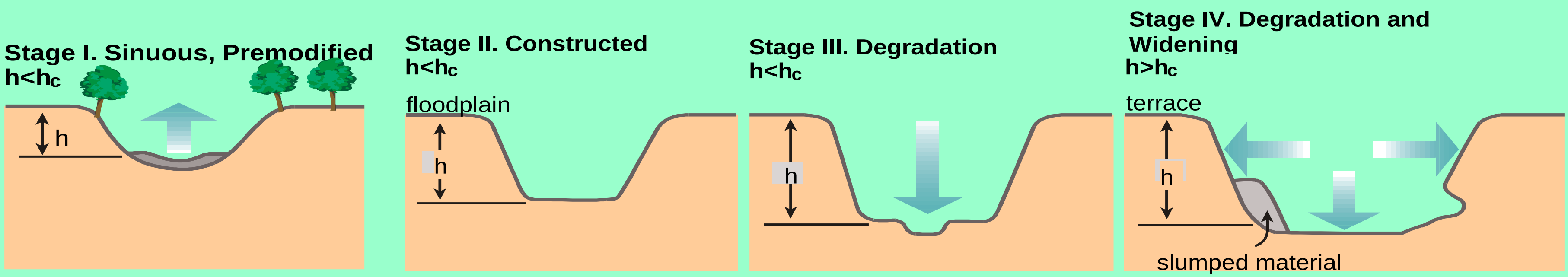
Incision creates the conditions for bank instability and widening by creating higher, steeper banks

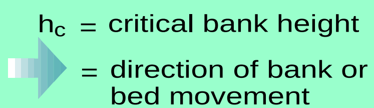
But why are they so different ?

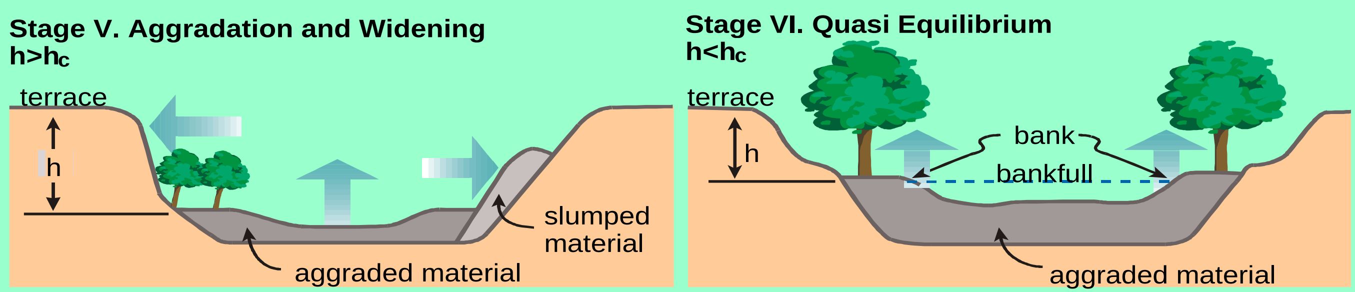
Resistance

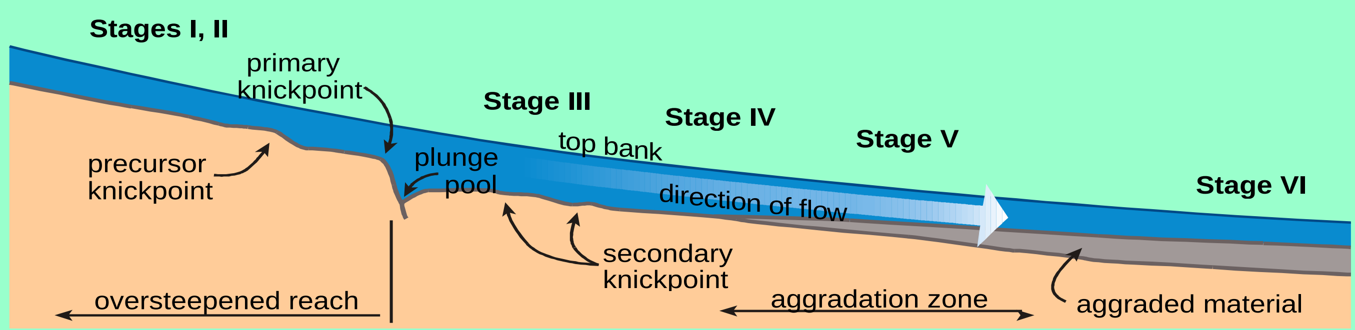


Stages of Channel Evolution (an empirical model)









“References”

- Stage I
- Stage VI

Not for engineering design or quantifying channel response

Boundary Resistance and Channel Response

- General trends of channel response to disturbance (channelization , reduction of sediment supply, increased discharge) provide only a semi-quantitative view of how different disturbances can cause similar responses.

- Similar channels may respond differently as a function of the relative and absolute resistance of the boundary (bed and banks) to hydraulic AND geotechnical forces

- Alluvial-channel response has been defined by many with non-linear decay functions that become asymptotic and reach minimum variance with time.

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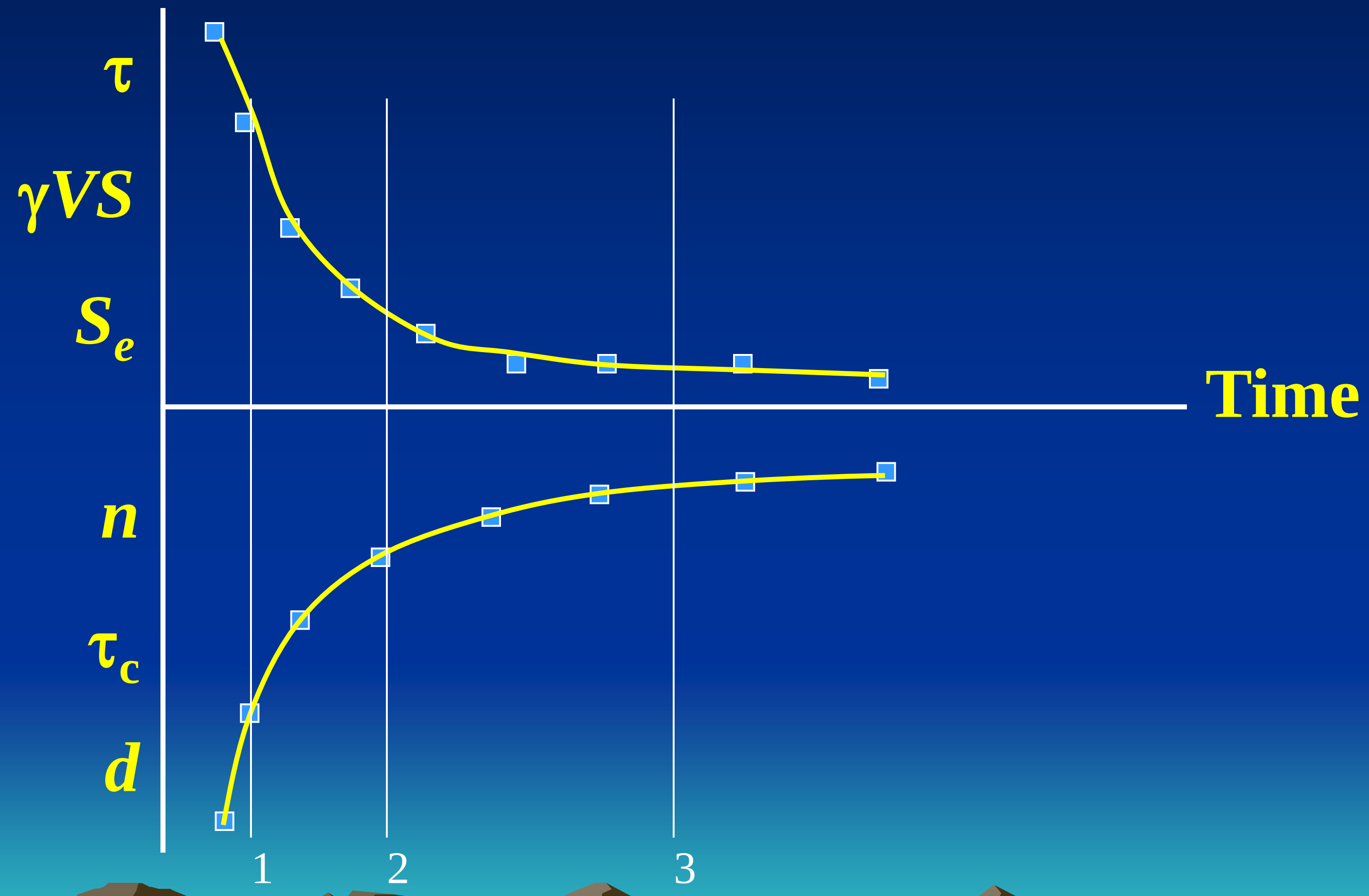
Idealized Adjustment Trends

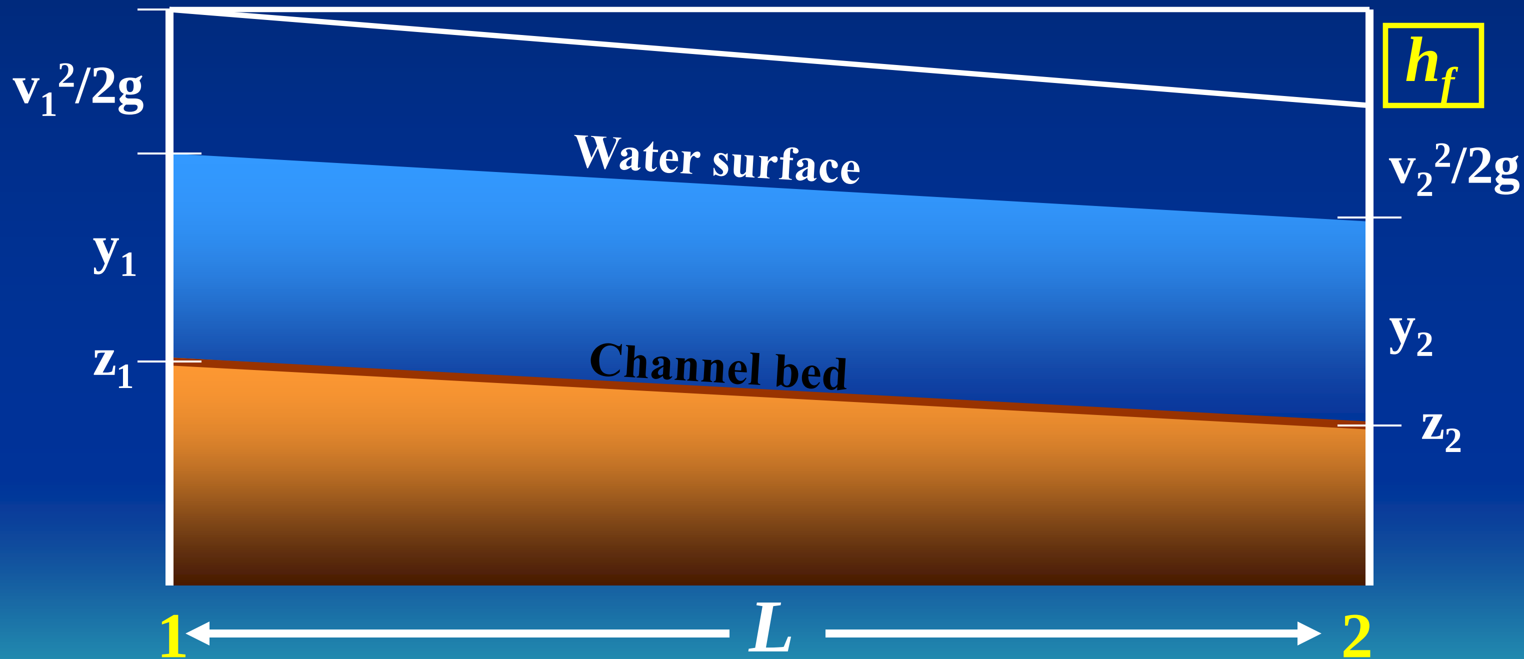
For a given discharge (*Q*)



Flow Energy and Energy Dissipation

$$E = z + y + v^2/2g$$

$$h_f = (z_1 + y_1 + v_1^2/2g) - (z_2 + y_2 + v_2^2/2g)$$



Energy slope: $S_e = h_f / L$

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Processes That Effect Components of Total Mechanical Energy (*E*)

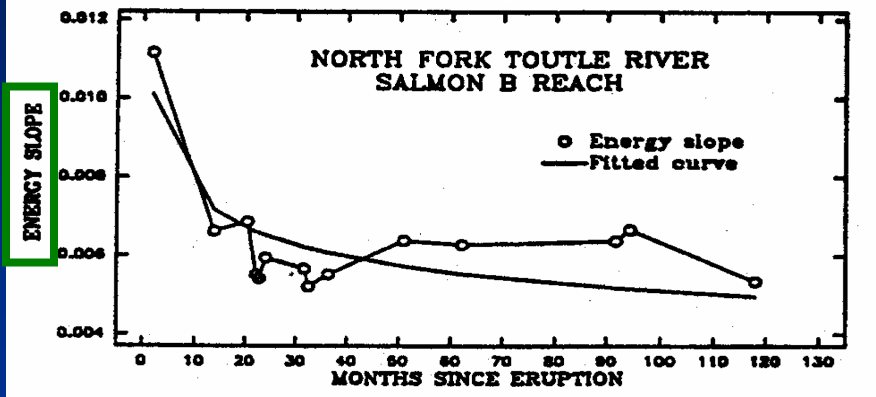
For each parameter comprising ***E***, what processes would result in a reduction in those values?

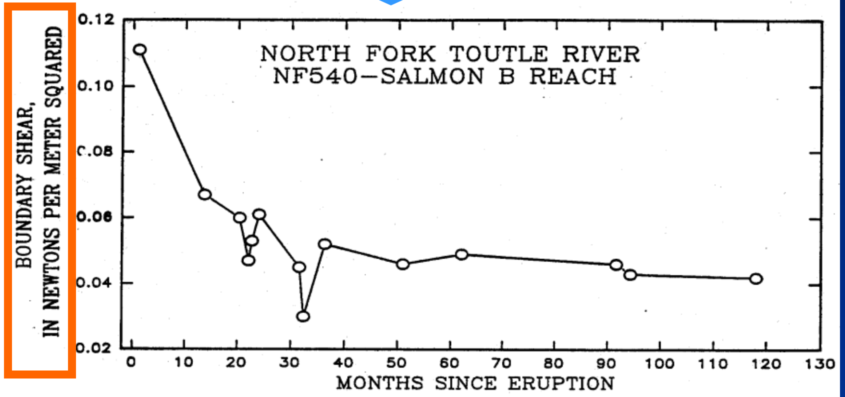
- ***z*:** **degradation**
- ***y*:** **widening, aggradation**
- **$v^2/2g$:** **widening, increase in relative roughness, growth of vegetation, aggradation,**

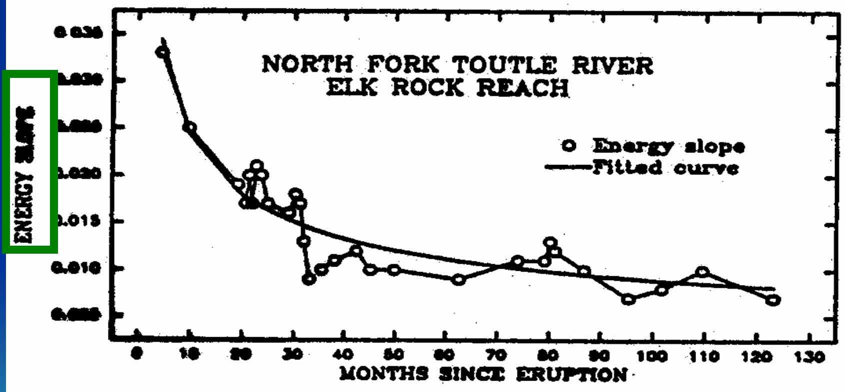
Thus, different and often opposite processes can have the same result

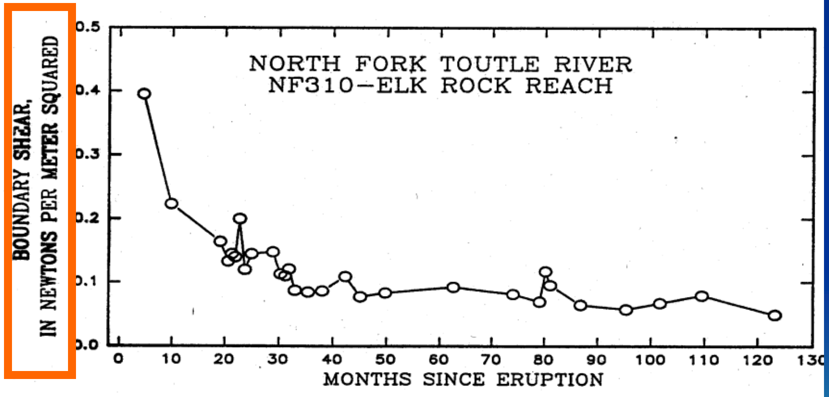
Adjustment by Different Processes

Aggradation and widening









Degradation and widening

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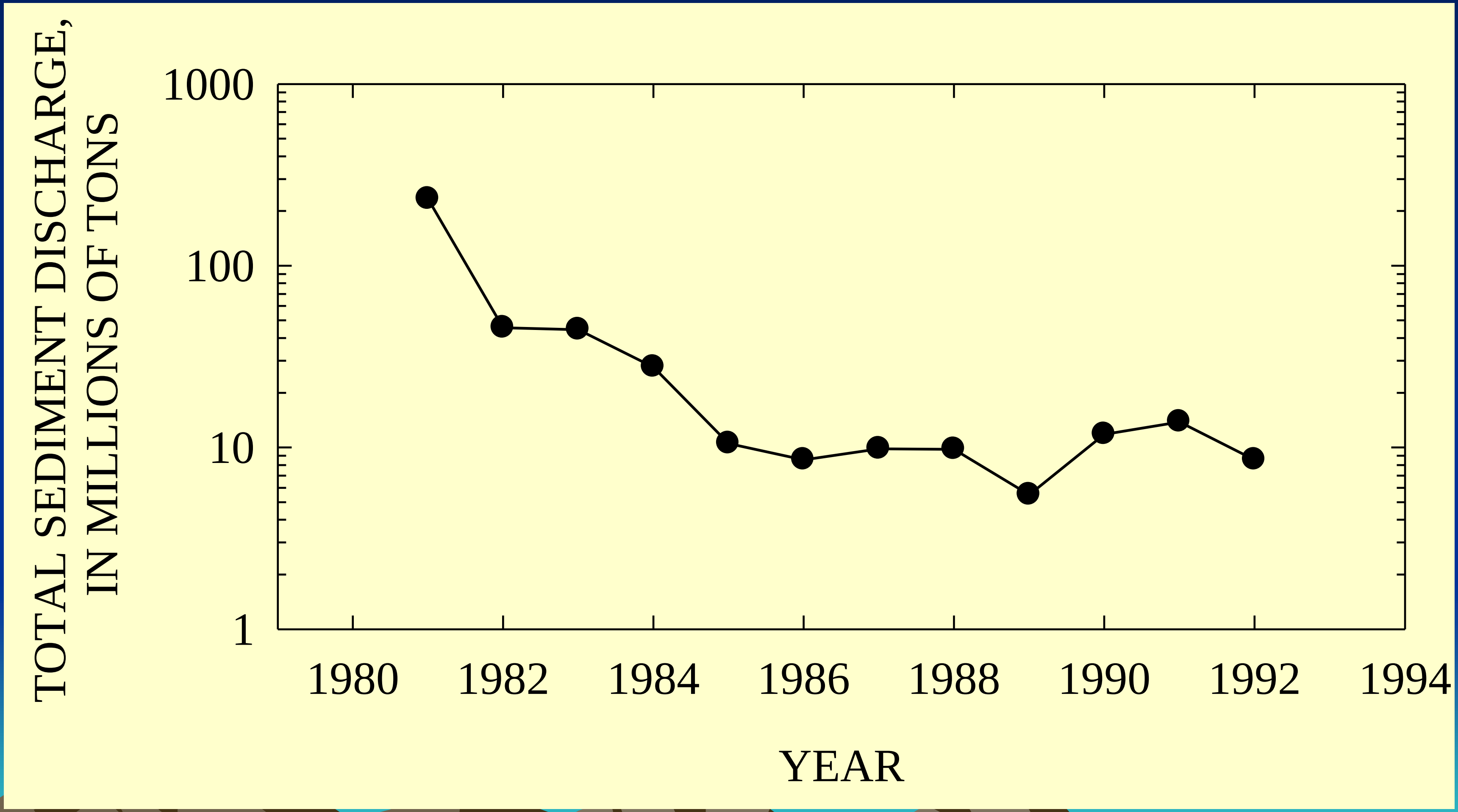
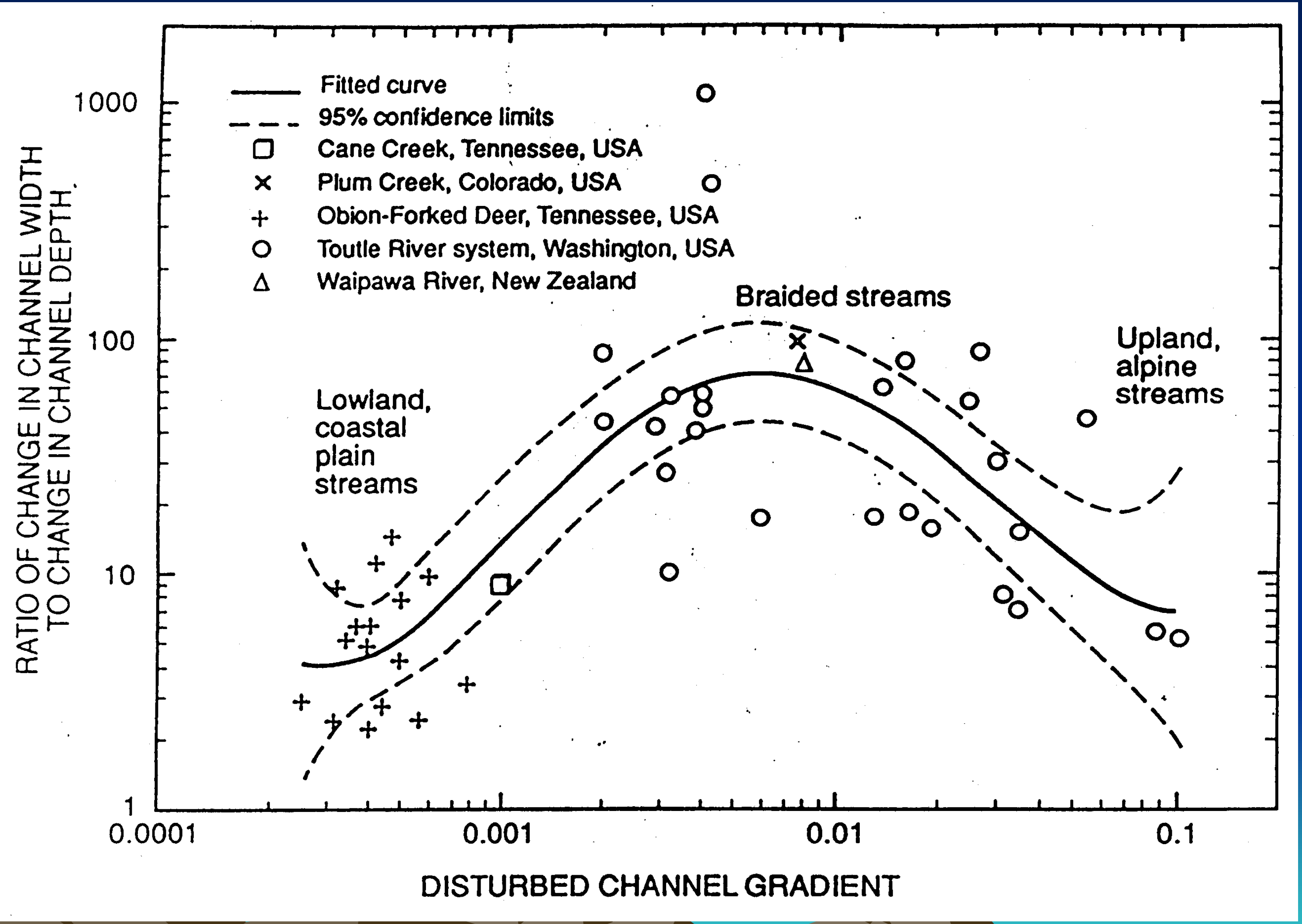
Results of Energy Minimization

(Sediment Discharge: Mount St Helens)



These Changes Occur at Different Rates and Magnitudes



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Effect of Bank Materials on Adjustment and Ultimate Stable Forms

- Assume that $\gamma QS \; \alpha \; Q_s d_{50}$ is balanced
- How does a channel respond if disturbed?
- Will the channel incise?
- Will the channel fill?
- Will the channel widen?
- Will the channel narrow?
- Will it equilibrate to the same geometry?

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Provides Only Limited Insight

$$\gamma QS \ \alpha \ Q_s d_{50}$$

γ = unit weight of water

Q = water discharge

S = bed or energy slope

Q_s = bed-material discharge

d_{50}= median particle size of bed material

Where will erosion occur?

How will channel form change?

Simulated using a numerical model of bed deformation and channel widening (Darby, 1994; Darby *et al*., 1996)

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Disturbing a Sand-Bed Channel

- Assume that $\gamma QS \propto Q_s d_{50}$ becomes un-balanced
- $Q_s d_{50} = 0.5 * \text{capacity}$

- Slope = 0.005
- Initial width/depth ratio = 13.5

Bank material	Bed d_{50} (mm)	Bank cohesion (kPa)	Friction angle (°)	Sand content (%)
Sand	1.0	4.0	32.5	100
Silt	1.0	7.5	32.5	20
Clay	1.0	40.0	32.5	10

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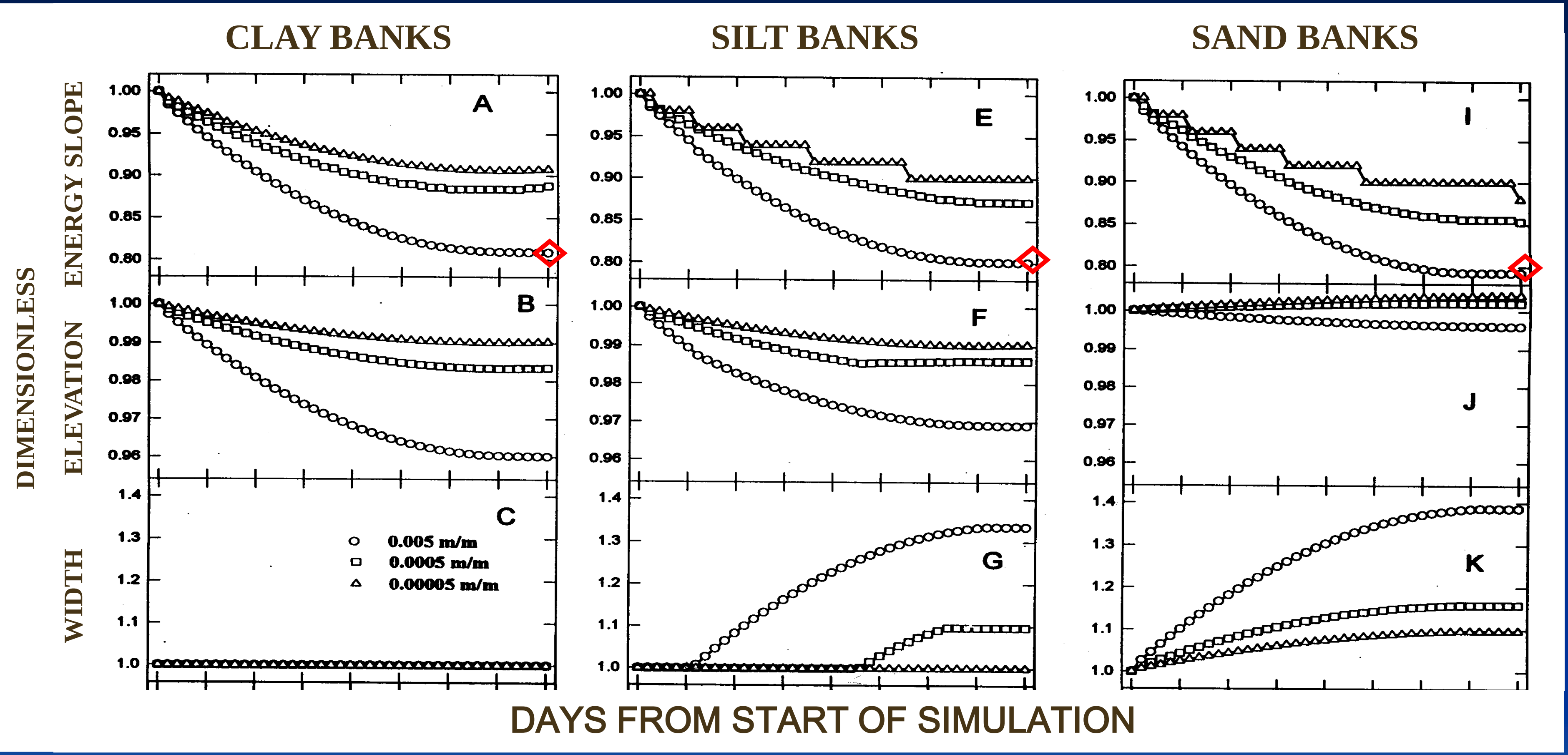
Adjustment for Different Boundary Materials



- ▲ 0.00005 @ 0.90
- ■ 0.0005 @ 0.87
- ● 0.005 @ 0.80

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Adjustments for Different Boundary Materials

Clay-bank channel				
Gradient	0.005 m/m	0.001 m/m[a]	0.0005 m/m	0.00005 m/m
Degradation	3.51	2.60	1.25	0.73
Widening	0	0	0	0
W_o/D_o	13.5	13.5	13.5	13.5
W_f/D_f	5.62	6.68	9.02	10.5
τ_o	103	20.5	10.3	1.03
τ_f	98.7	18.9	9.47	0.96
Silt-bank channel				
Degradation	2.74	1.83	1.09	0.73
Widening	11.3	7.17	3.27	0
W_o/D_o	13.5	13.5	13.5	13.5
W_f/D_f	8.62	9.31	10.5[b]	10.5
τ_o	103	20.5	10.3	1.03
τ_f	69.3	14.1	8.44	0.95
Sand-bank channel				
Degradation	0.35	0.28	-0.15[c]	-0.29[c]
Widening	13.1	7.81	5.36	3.27
W_o/D_o	13.5	13.5	13.5	13.5
W_f/D_f	16.4	15.0	16.6	16.8
τ_o	103	20.5	10.3	1.03
τ_f	64.8	13.0	7.85	0.83

Response to similar disturbance: Sediment supply = 0.5 * capacity

From Simon and Darby (1997)

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How Do We Apply this in Restoration?

- *Empirical:* regime equations; not cause and effect; time independent

  Morphology related to discharge (hydraulic geometry) etc.

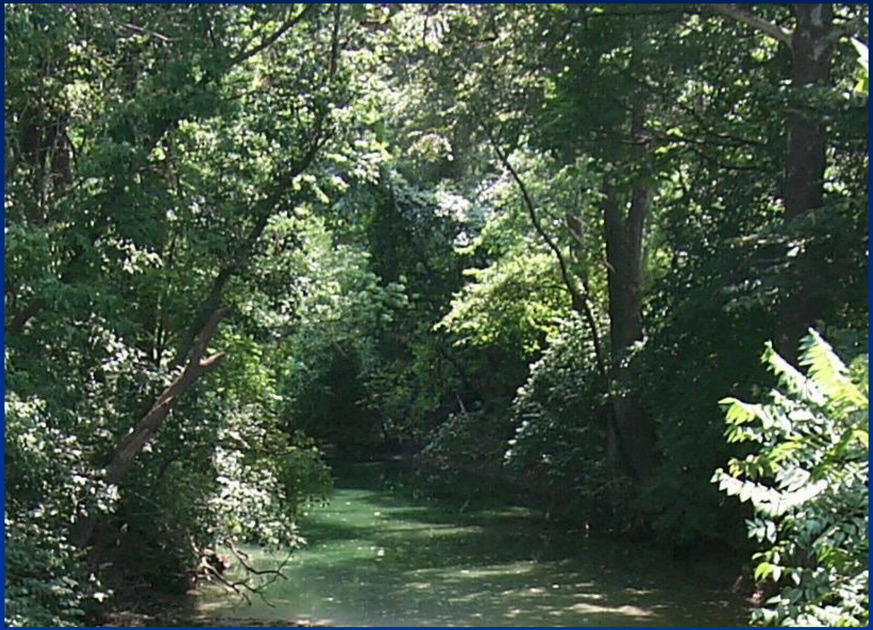
It's a big toolbox! Use what is appropriate for the scale and objective of the project. Approaches are NOT mutually exclusive!

  Quantifies driving forces and resistance of boundary sediments to the appropriate processes and functionally linked to upland delivery of flow and sediment.

Dynamic System?

Unstable reach

"Reference reach"



Unstable reach is 100 m from "reference reach"

Is a reference reach approach viable here?

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A Tiered Approach

- **Reconnaisance Level:**

  1. **Use form to define dominant processes and relative stability. Determine if the instability is localized or systemwide (scope) from rapid geomorphic assessments (RGAs), gauging station records, air photos. Identify the *problem* not just the *symptom*.**

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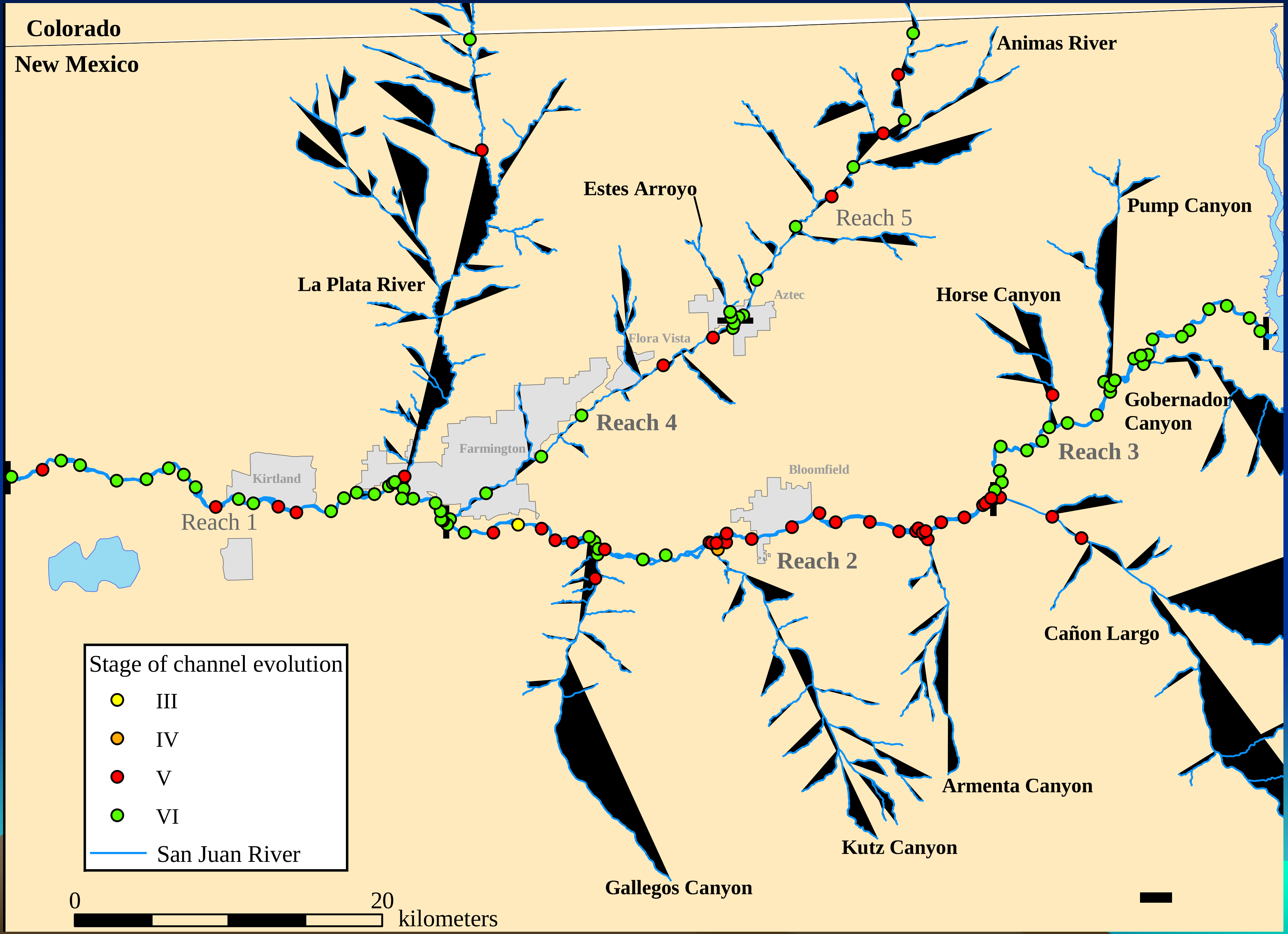
Example: Stage of Channel Evolution



A Tiered Approach

If the problem is localized (*ie.* Bridge constriction; local structure; livestock impacts; deflected flow) the practitioner has more options, including a "reference-reach" approach.

But you can just as easily use a deterministic approach that is based on implicitly analyzing the specific processes (*ie. bed and/or bank instability*).

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A Tiered Approach

However, If the problem is systemwide instability, or in an urban setting, the practitioner had better obtain a complete quantitative understanding of hydrology, magnitudes and trends of adjustment processes, as well as the absolute and relative resistance of the boundary materials to erosion by hydraulic and geotechnical forces.

If this is the case, then the practitioner needs to rely on validated numerical models, populated with field data to predict response and stable geometries.

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A Tiered Approach

- **Analytic Level: Static and Dynamic Numerical Modeling**

1. Collect data to define the variables that control processes (force and resistance)

2. Use the best available numerical models for prediction

We cannot ignore the watershed and its delivery of energy and materials to the channel system. In fact, changes to the watershed may be the cause (problem) of the channel instability. ***An upland model that provides flow and sediment loadings as lateral inputs can be coupled with a deterministic channel-process model (that also handles mass failures***). This way changes at the watershed level can be incorporated into potential channel effects

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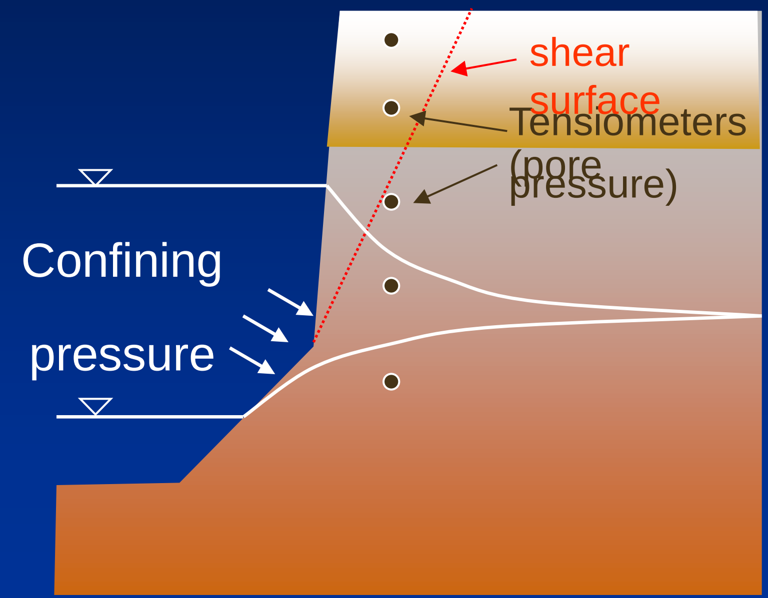
Channel-Modeling Capabilities

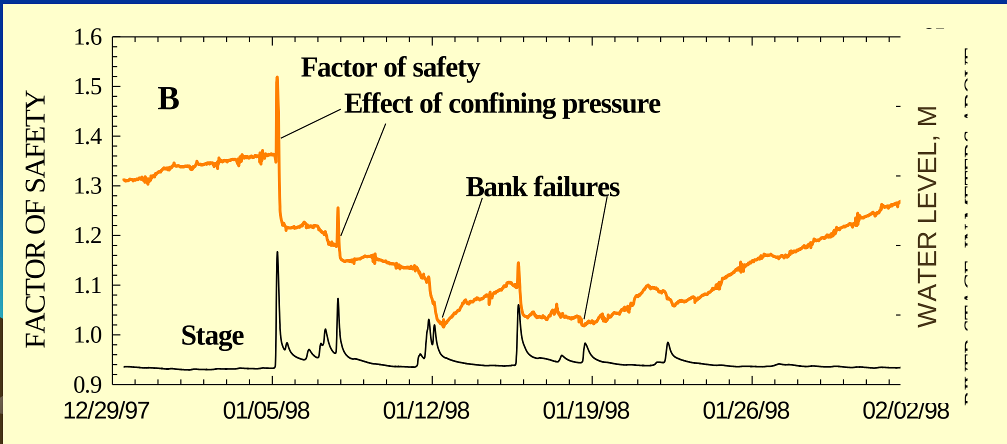
Process	BSTEM	HEC-RAS	SRH-2D	HEC+ BSTEM	SRH-2D+BSTEM
Shear in meanders	🗐		🗐		🗐
Bank-toe erosion	🗐			🗐	🗐
Mass-failures	🗐			🗐	🗐
Bed erosion		🗐	🗐	🗐	🗐
Sediment transport		🗐	🗐	🗐	🗐
Vegetation effects	🗐			🗐	🗐
‘Hard’ engineering	🗐	🗐	🗐	🗐	🗐
Channel evolution				🗐	🗐
Rapid Assessments	🗐				

For Bank Erosion:

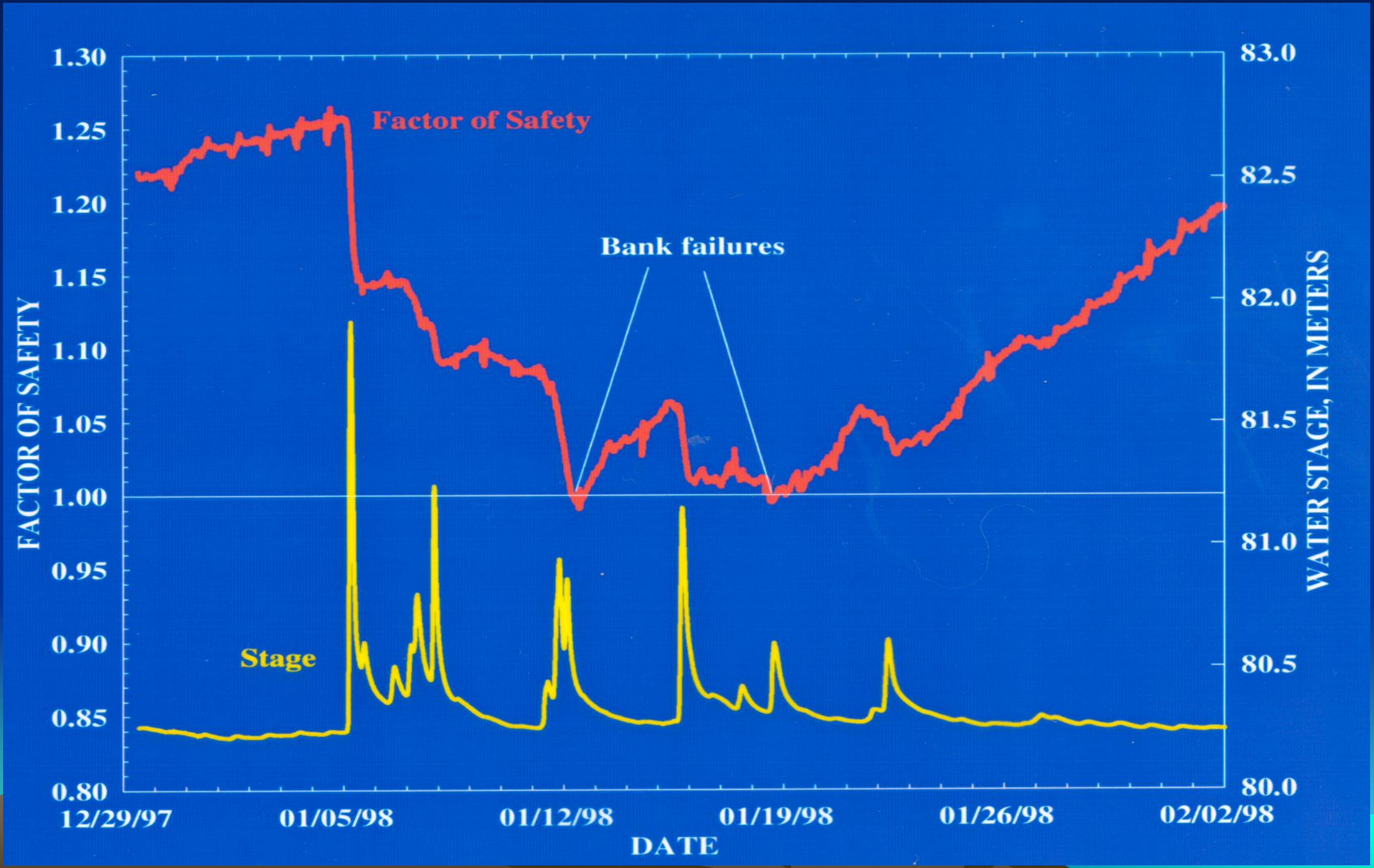
Bank-Stability Model Version 5.4

- 2-D wedge- and cantilever-failures
- Tension cracks
- Search routine for failures
- Hydraulic toe erosion
- Increased shear in meanders
- Accounts for grain roughness
- Complex bank geometries
- Positive and negative pore-water pressures
- Confining pressure from flow
- Layers of different strength
- Vegetation effects: RipRoot
- Inputs: g_s, *c*', f', f^b, *h*, u_w, *k*, t_c

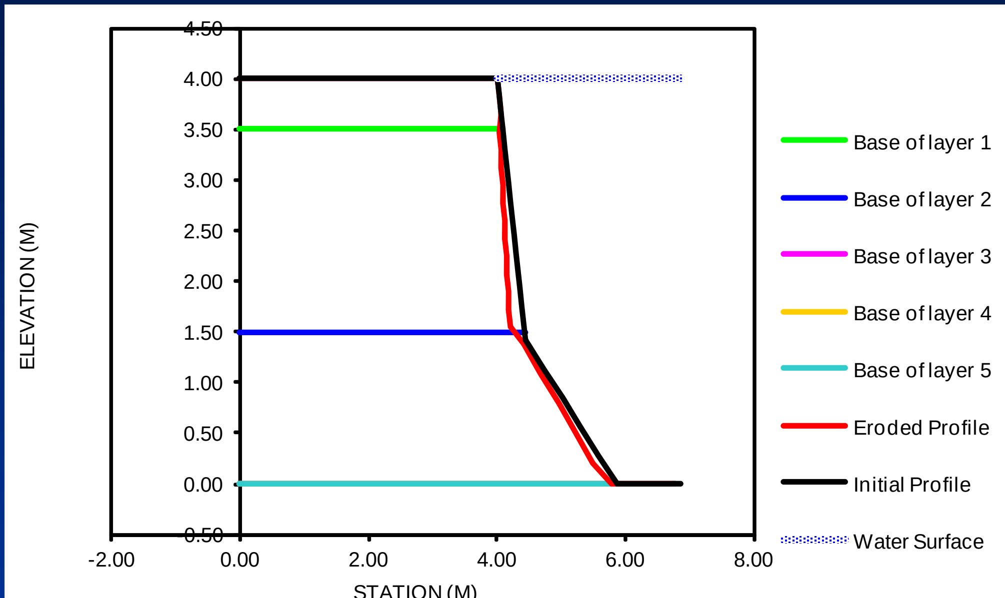




Thresholds in Bank Stability: Effects of Stage and Pore-Water Pressure



Example Output

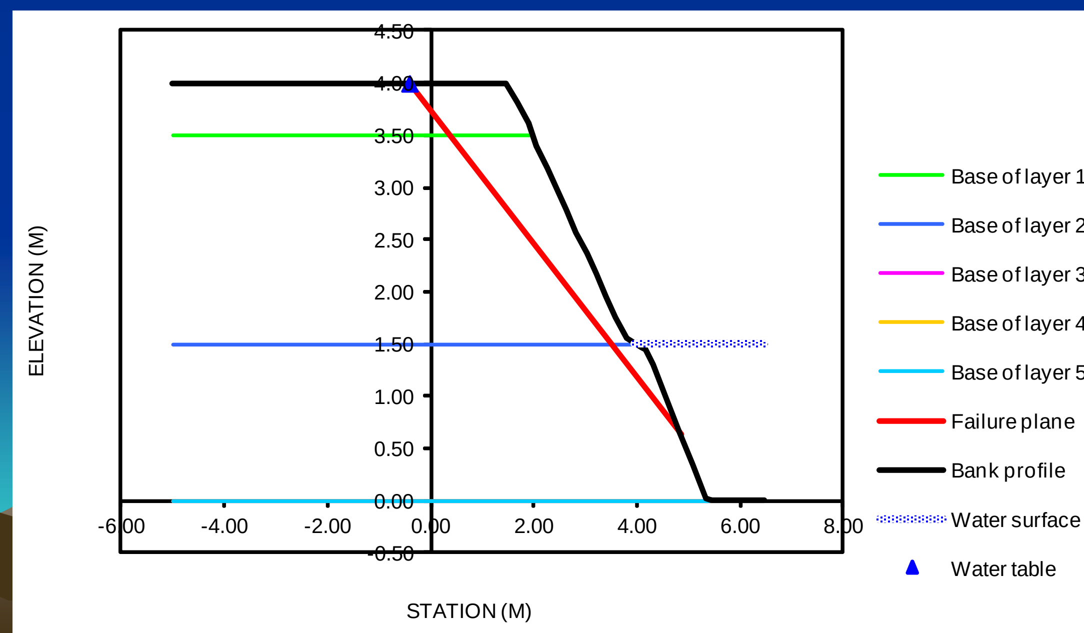


Toe Erosion: 1st event

Average applied boundary shear stress	84.190	Pa
Maximum Lateral Retreat	22.547	cm
Eroded Area - Bank	0.291	m^2
Eroded Area - Bank Toe	0.164	m^2
Eroded Area - Bed	0.000	m^2
Eroded Area - Total	0.455	m^2

Mass Failure: 1st event

Failure width	1.90	m
Failure volume	3	m^3
Sediment loading	5771	kg



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Differentiate Between Hydraulic and Geotechnical *Processes*

- Hydraulic protection reduces the available boundary hydraulic shear stress, and increases the shear resistance to particle detachment

Hydraulic Protection

- Geotechnical protection increases soil shear strength and decreases driving forces

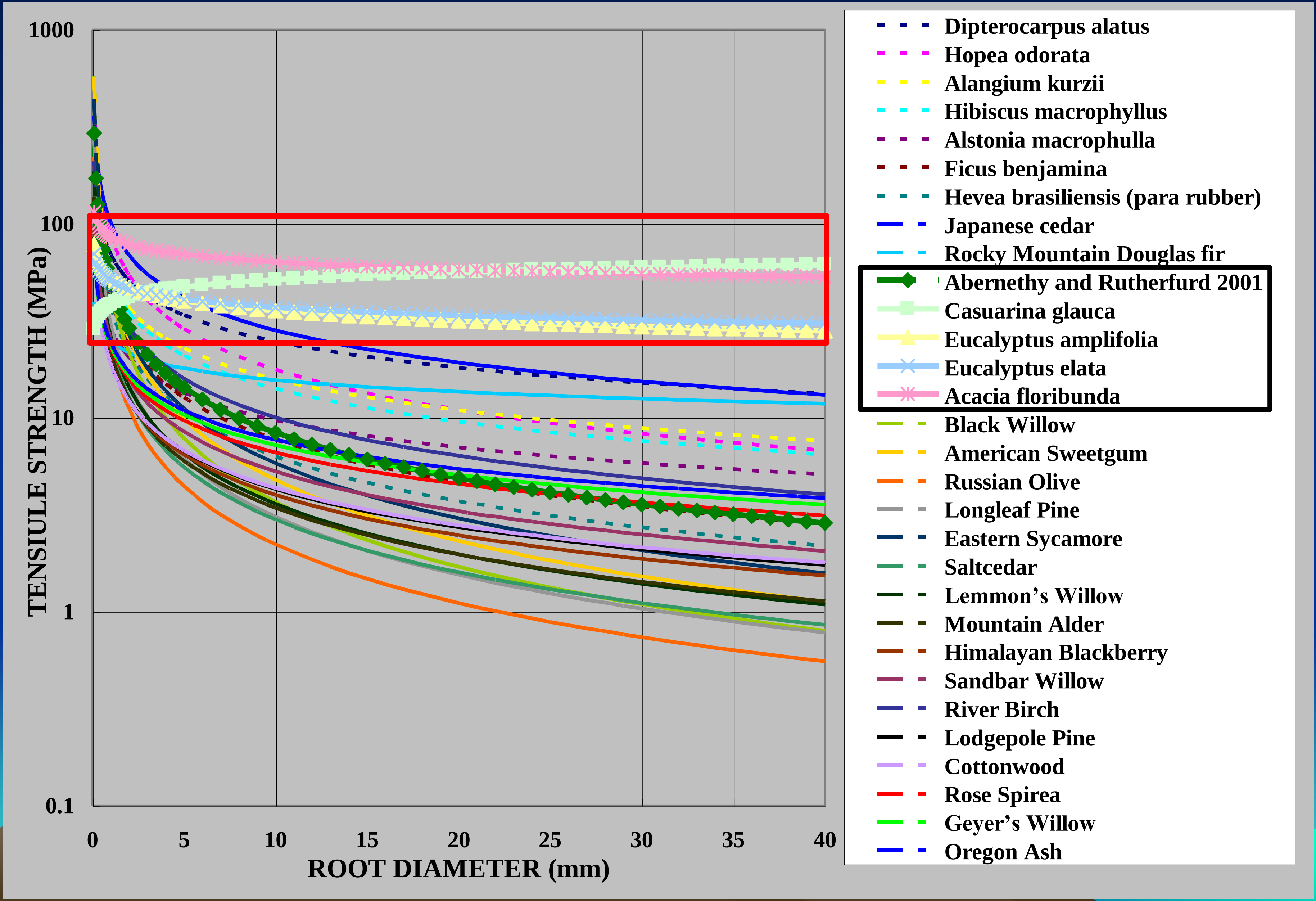
Geotechnical Protection

Vegetation as a River Engineer

- Above and below-ground biomass
- Process Domains
- "Engineers" in channel adjustment

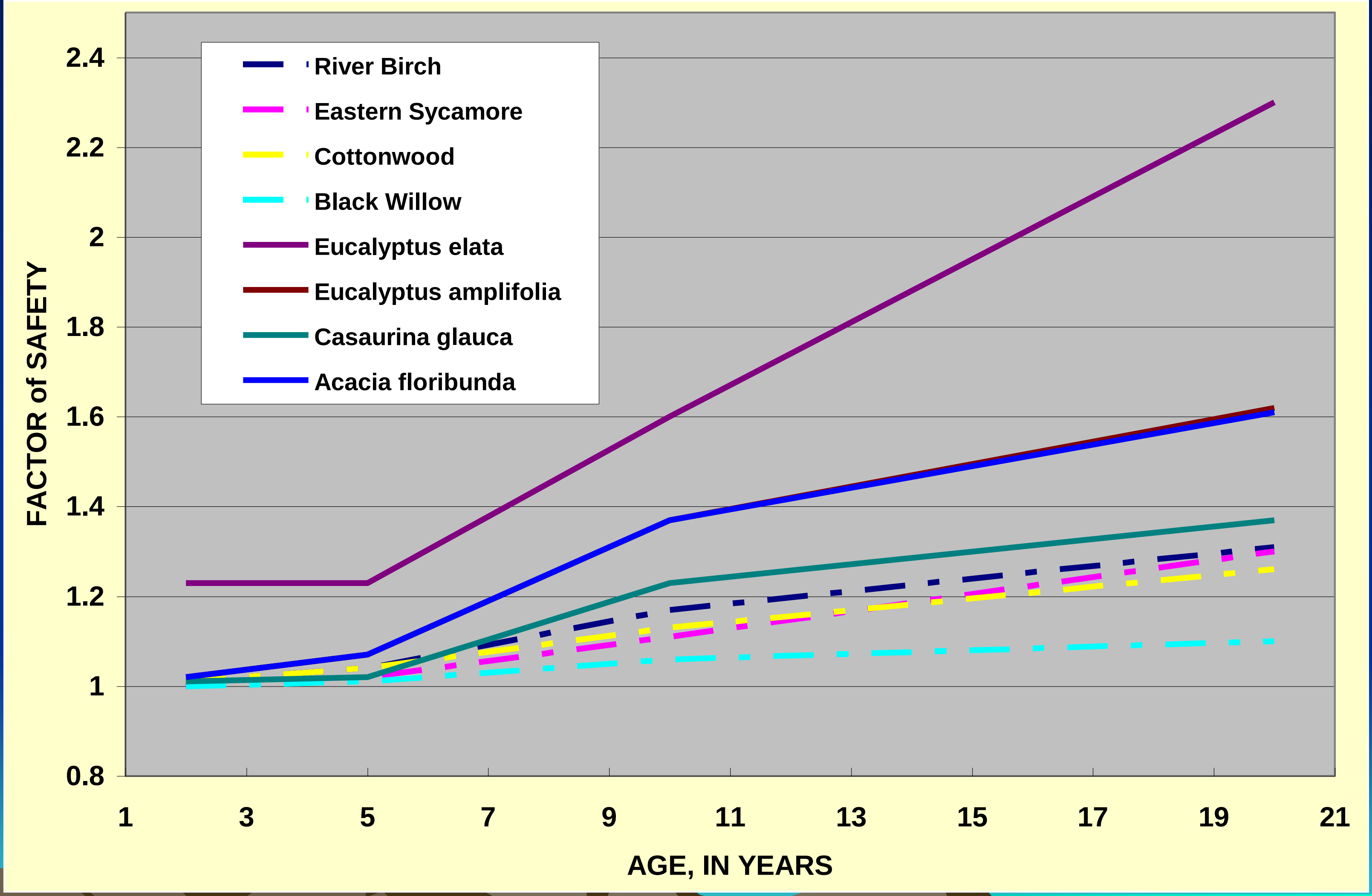
Process Domain	Geotechnical	Hydrologic	Hydraulic
Above Ground	Surcharge	Interception Evapo-transpiration	Roughness Applied shear stress
Below Ground	Root reinforcement	Infiltration Matric suction	Critical shear stress

Accounting for Root Reinforcement



Root Reinforcement and Factor of Safety

North American vs. Australian Species



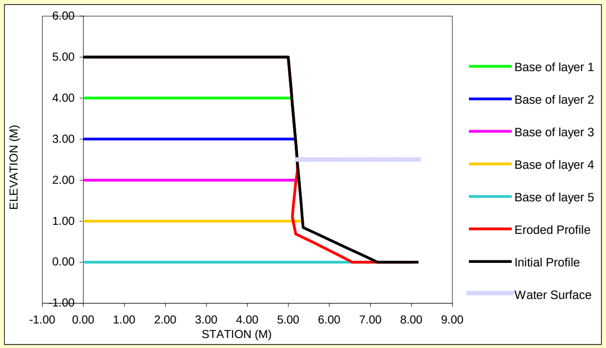
4 m-high silt bank

Example: The Role of Toe Protection

Toe Model Output

Verify the bank material and bank and bank-toe protection information entered in the "Bank Material" and "Bank Vegetation and Protection" worksheets. Once you are satisfied that you have completed all necessary inputs, hit the "Run Toe-Erosion Model" button (Center Right of this page).

	Bank Material				Bank Toe Material	
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5		
Moderate cohesive	Moderate cohesive	Moderate cohesive	Moderate cohesive	Moderate cohesive	Moderate cohesive	**Material**
5.00	5.00	5.00	5.00	5.00	5.00	**Critical shear stress (Pa)**
0.045	0.045	0.045	0.045	0.045	0.045	**Erodibility Coefficient (cm^3/Ns)**



Run Toe-Erosion Model

Account for:

Stream Curvature ☐

Effective stress acting on each grain ☐

Average applied boundary shear stress	51.060	Pa
Maximum Lateral Retreat	24.966	cm
Eroded Area - Bank	0.232	m^2
Eroded Area - Bank Toe	0.423	m^2
Eroded Area - Bed	0.000	m^2
Eroded Area - Total	0.655	m^2

Export New (Eroded) Profile into Model

Slope = 0.0035 m/m

Depth = 2.5 m

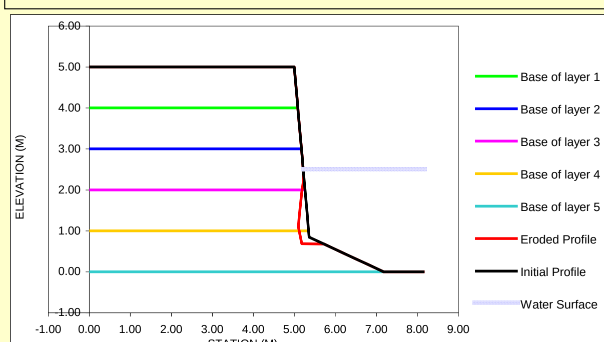
Toe material: silt

Eroded: 0.66 m^2

Toe Model Output

Verify the bank material and bank and bank-toe protection information entered in the "Bank Material" and "Bank Vegetation and Protection" worksheets. Once you are satisfied that you have completed all necessary inputs, hit the "Run Toe-Erosion Model" button (Center Right of this page).

	Bank Material				Bank Toe Material	
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5		
Moderate cohesive	Moderate cohesive	Moderate cohesive	Moderate cohesive	Moderate cohesive	Rip Rap (D50 0.256 m)	**Material**
5.00	5.00	5.00	5.00	5.00	204.00	**Critical shear stress (Pa)**
0.045	0.045	0.045	0.045	0.045	0.007	**Erodibility Coefficient (cm^3/Ns)**



Run Toe-Erosion Model

Account for:

Stream Curvature ☐

Effective stress acting on each grain ☐

Average applied boundary shear stress	51.060	Pa
Maximum Lateral Retreat	24.159	cm
Eroded Area - Bank	0.232	m^2
Eroded Area - Bank Toe	0.044	m^2
Eroded Area - Bed	0.000	m^2
Eroded Area - Total	0.276	m^2

Export New (Eroded) Profile into Model

Slope = 0.0035 m/m

Depth = 2.5 m

Toe material: rip rap

Eroded: 0.28 m^2

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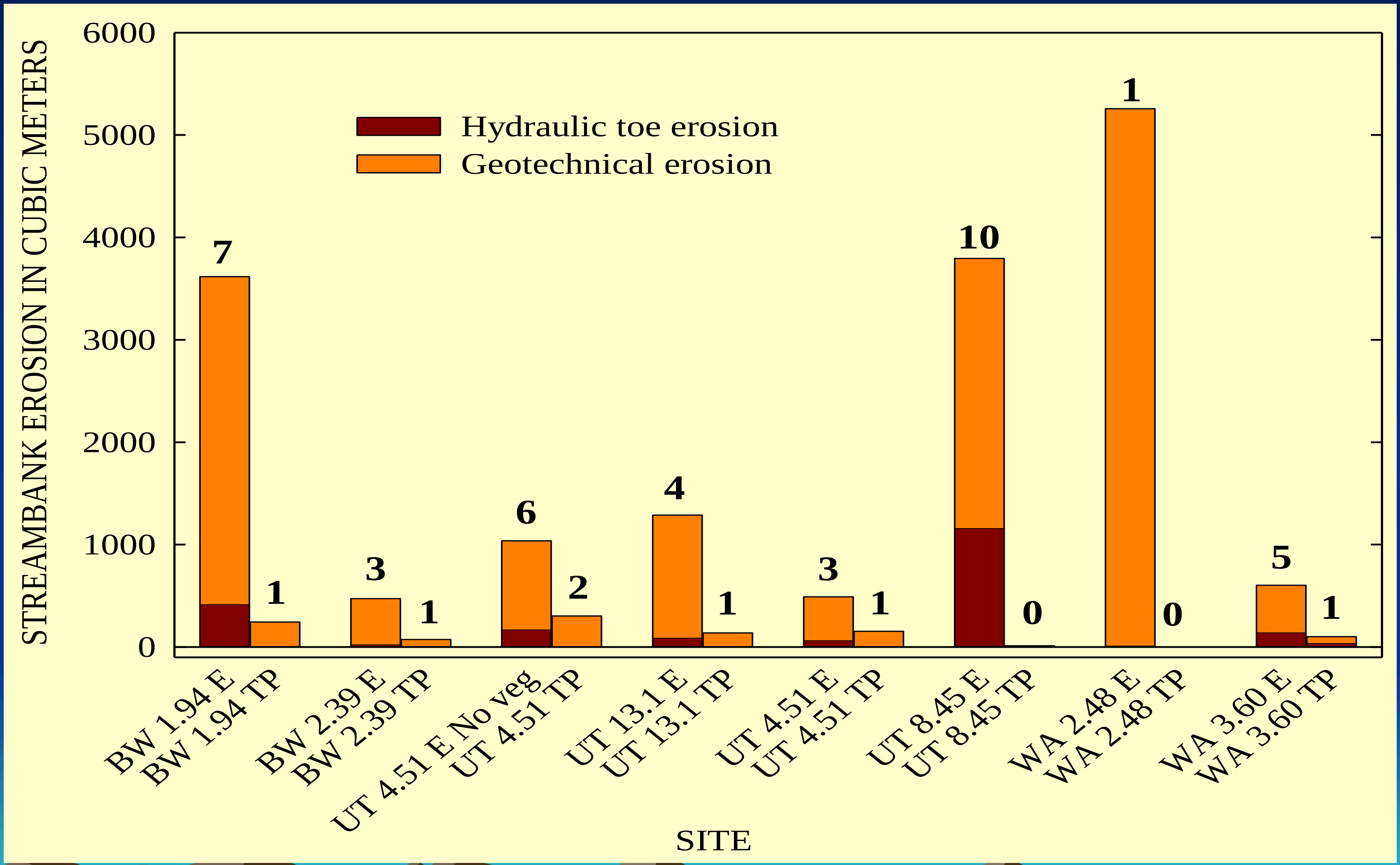
Example: Effects of Bank-Toe Protection



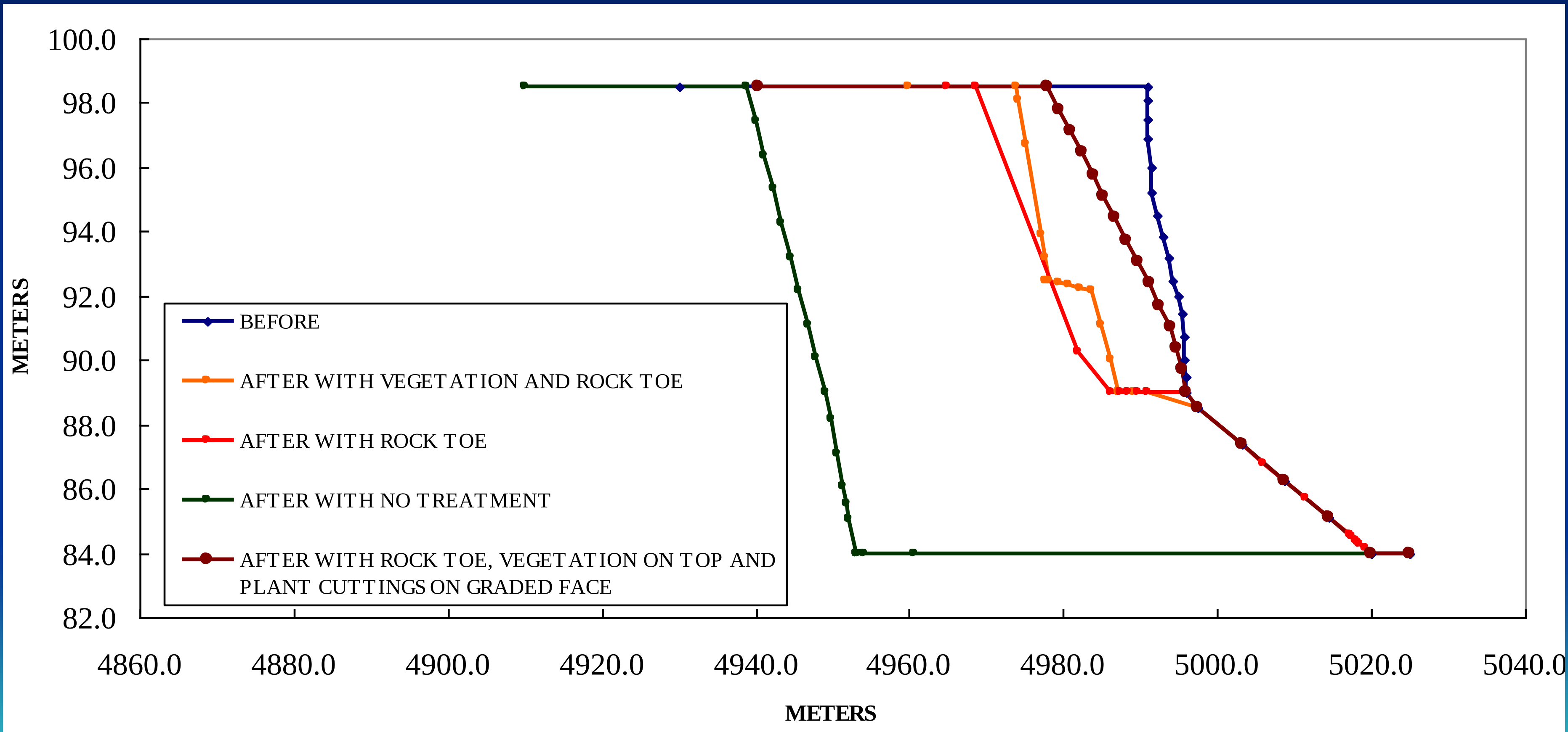
Average load reduction: 87%

Application: Test Mitigation Strategies to Reduce Bank Retreat

1. Model existing bank conditions during the 90th percentile flow year.

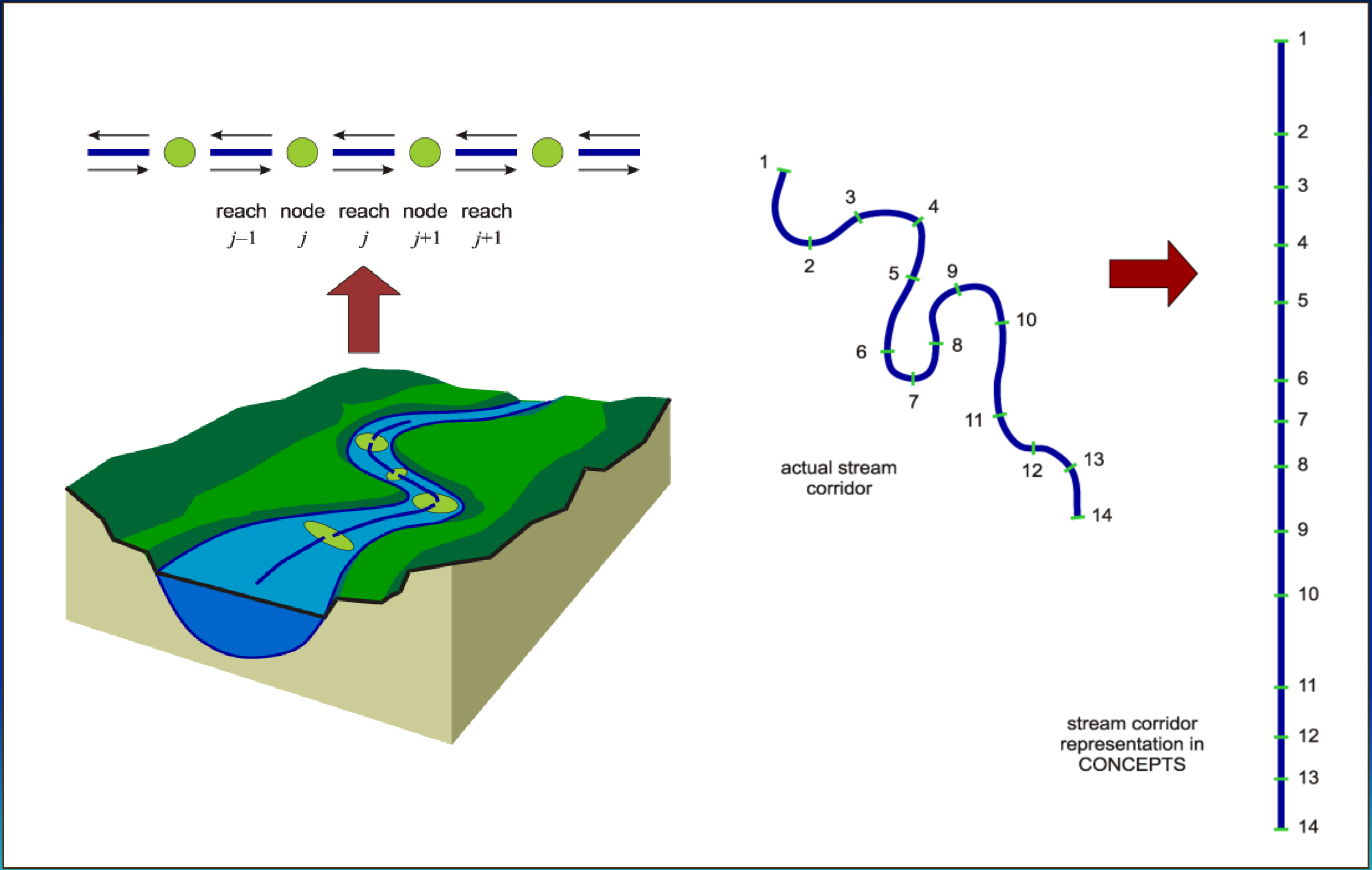
2. Model various mitigation strategies during the 90th percentile flow year

Summary of Modeled Mitigation Results…



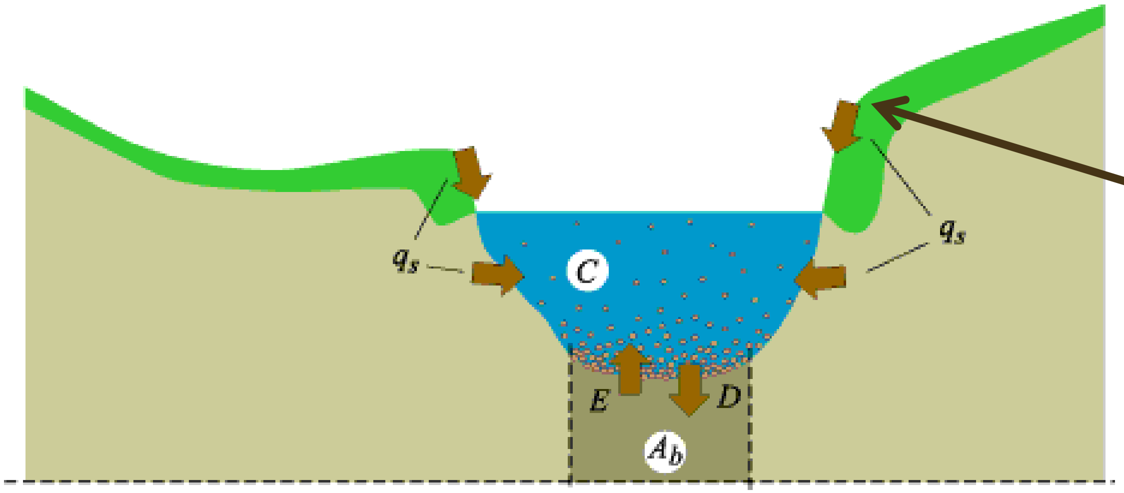
Integration With Channel Model

Integration with Channel Model



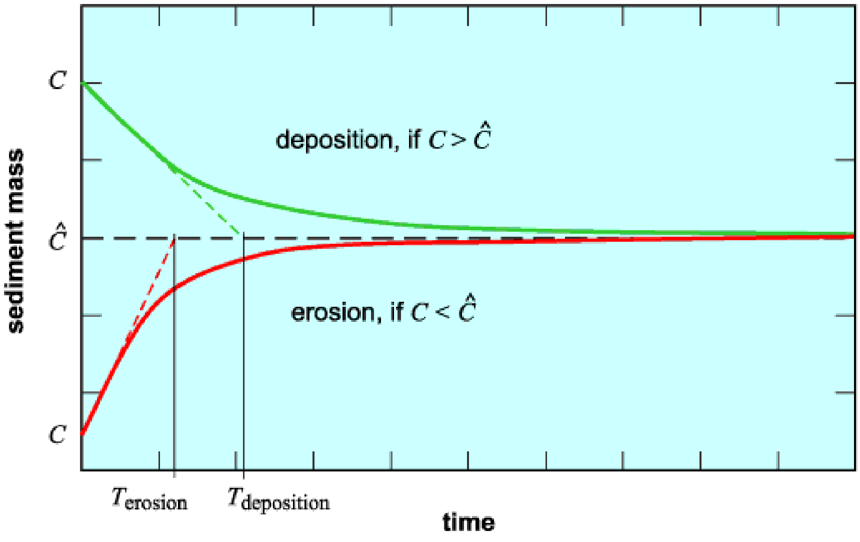
Discretize river corridor

Sediment Sources and Fate



Sediment can come from the ***surrounding area (upland model)***, banks, bed or upstream

When excess sediment is entrained, the surplus settles out



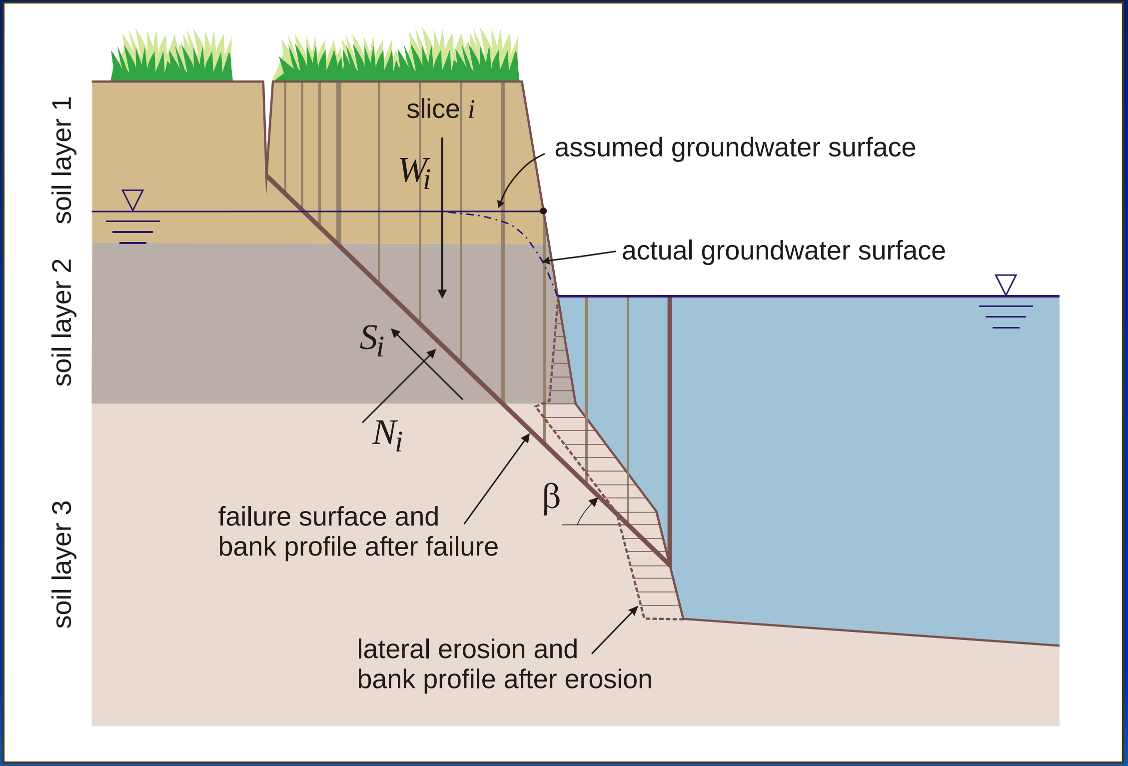
Streambank-Erosion Modeling

- Combination of hydraulic erosion and mass failure
- Hydraulic erosion of cohesive soils is expressed by an ***excess shear stress relation***

$$E = K(\tau - \tau_c)$$

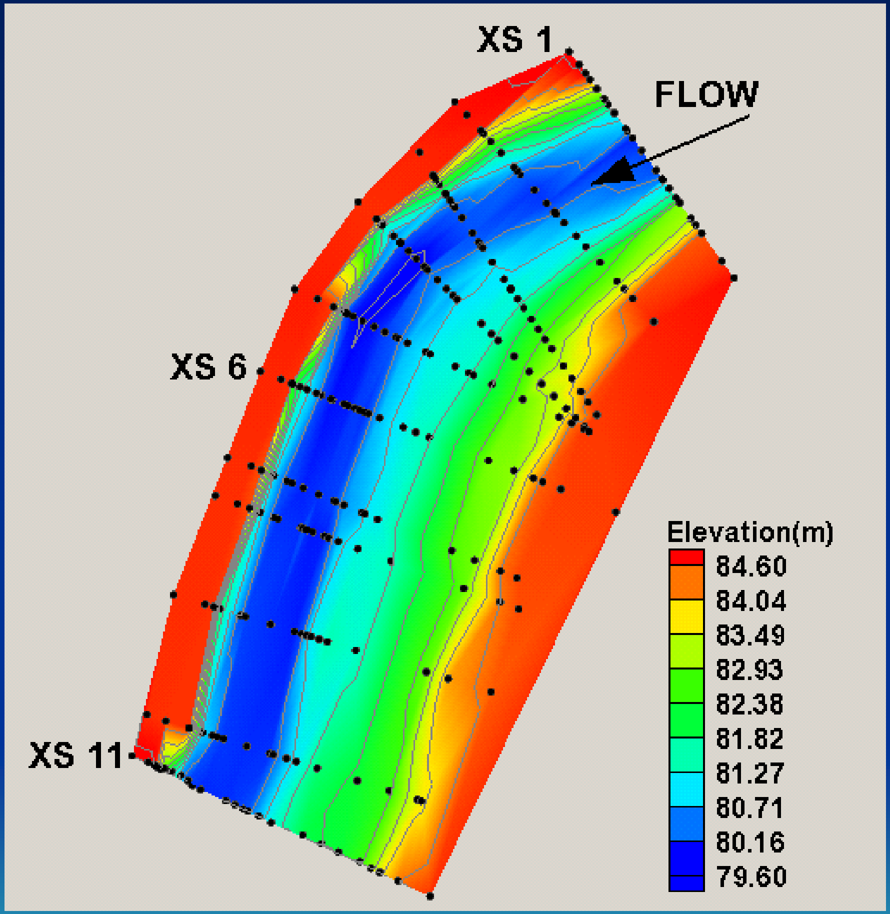
- Bank stability is expressed by a Factor of Safety

$$FOS = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

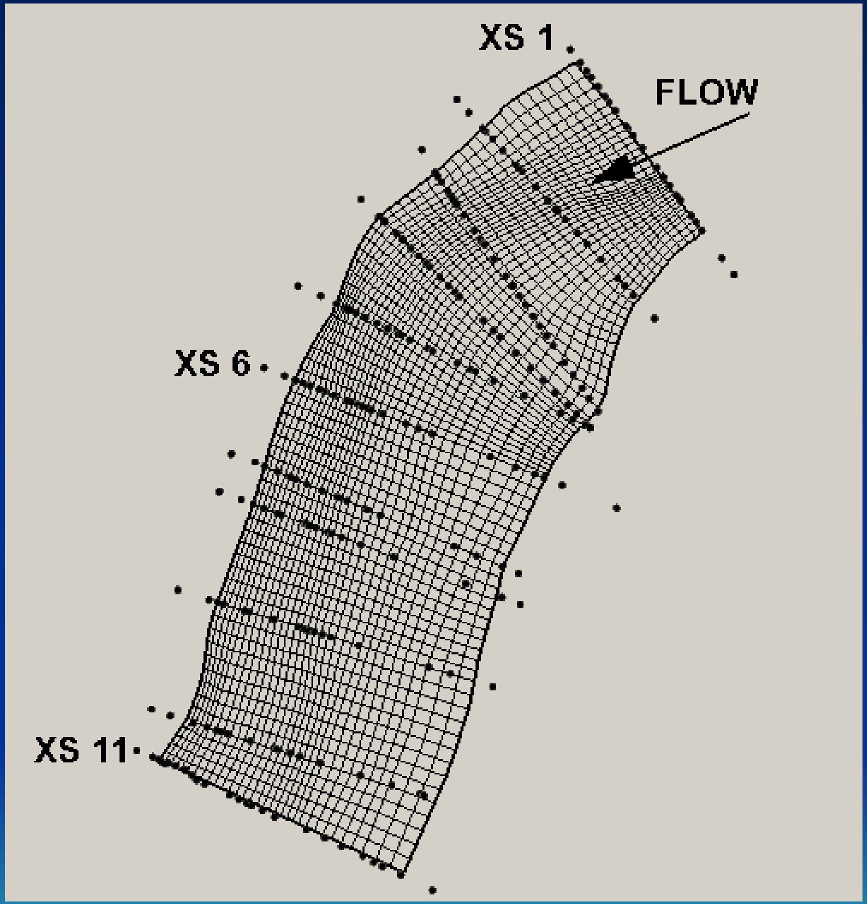


Integration with SRH-2D

Develop Moveable Mesh

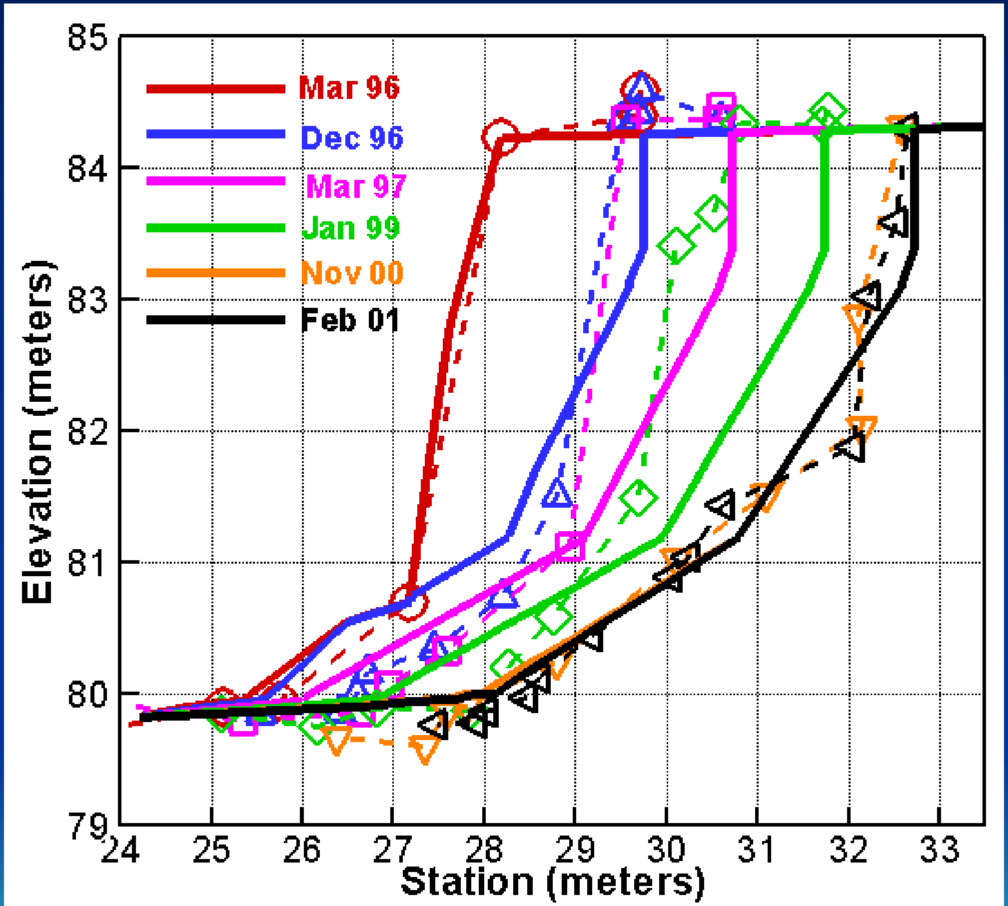


(a) Topography

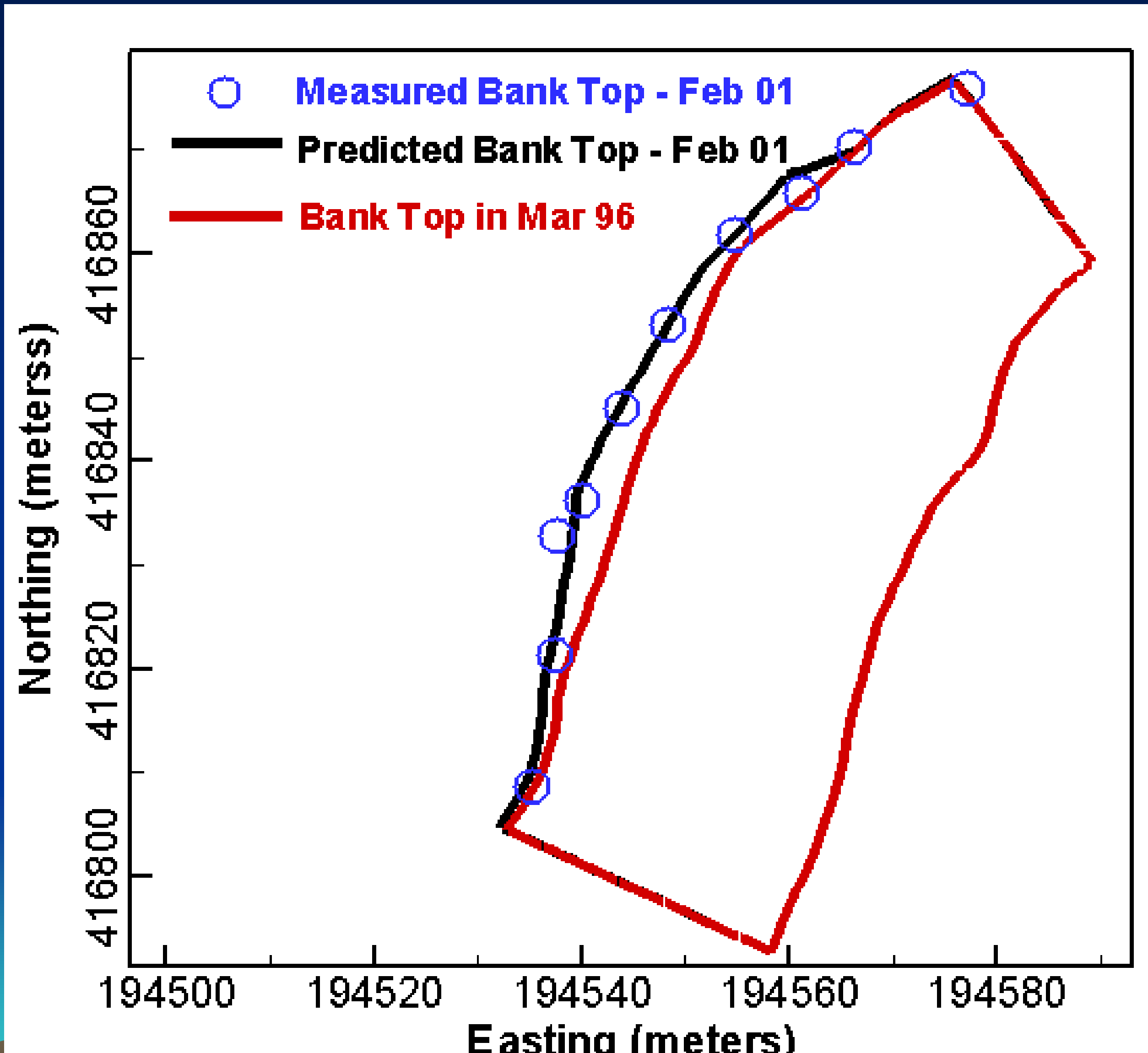


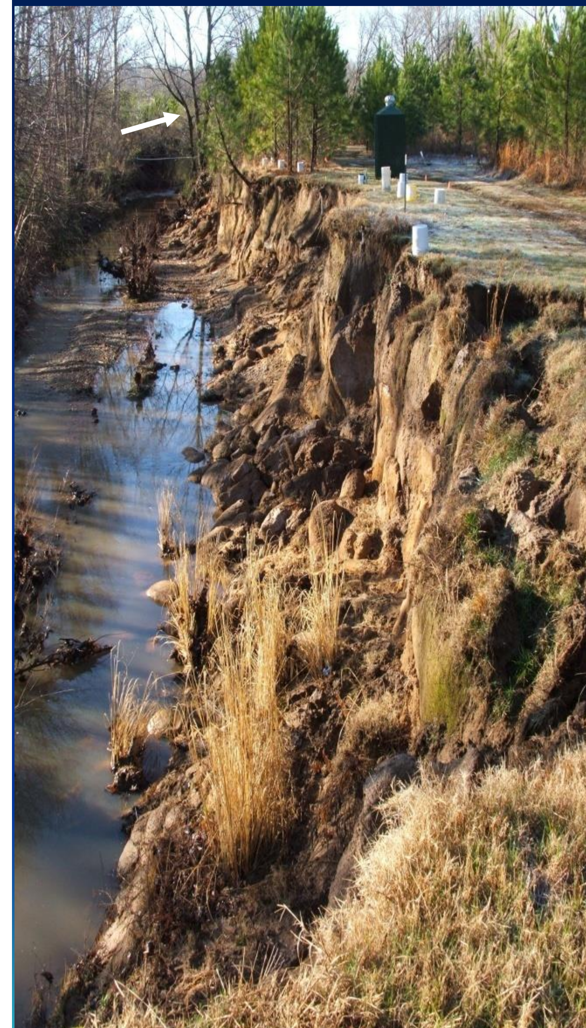
(b) Mesh for SRH-2D

Temporal Changes



Validation of Results





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Summary and Conclusions

- Gravity and the physics of erosion and sediment transport are a constant, allowing us to quantify force and resistance mechanisms.
- Whether disturbances are “natural” or anthropogenic, occur at slow rates over long periods of time or are catastrophic and instantaneous, adjustment occurs because of an imbalance between driving and resisting forces.
- Resistance of the boundary to hydraulic and geotechnical forces provide partial control of the type of adjustment processes and stable channel morphologies.
- Thus, restoration approaches and designs in unstable systems MUST explicitly account for adjustment processes that vary over time and space.

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Summary and Conclusions, cont'd

- It's a big tool box. A given tool may not be appropriate for all projects

- Consider scale!! Is it a reach problem or a system-wide problem?

- Determine the appropriate tool(s) based on the scale and cause of the instability (If it's a system-wide problem, a reference-reach approach is not appropriate because conditions are changing over time and space).

- Collect the data and perform analyses required to analyze the problem not just the symptom.

- Integration of bank stability, flow and sediment routing and upland models is the solution for catchment evaluations of sediment sources, magnitudes and delivery to receiving waters.

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