



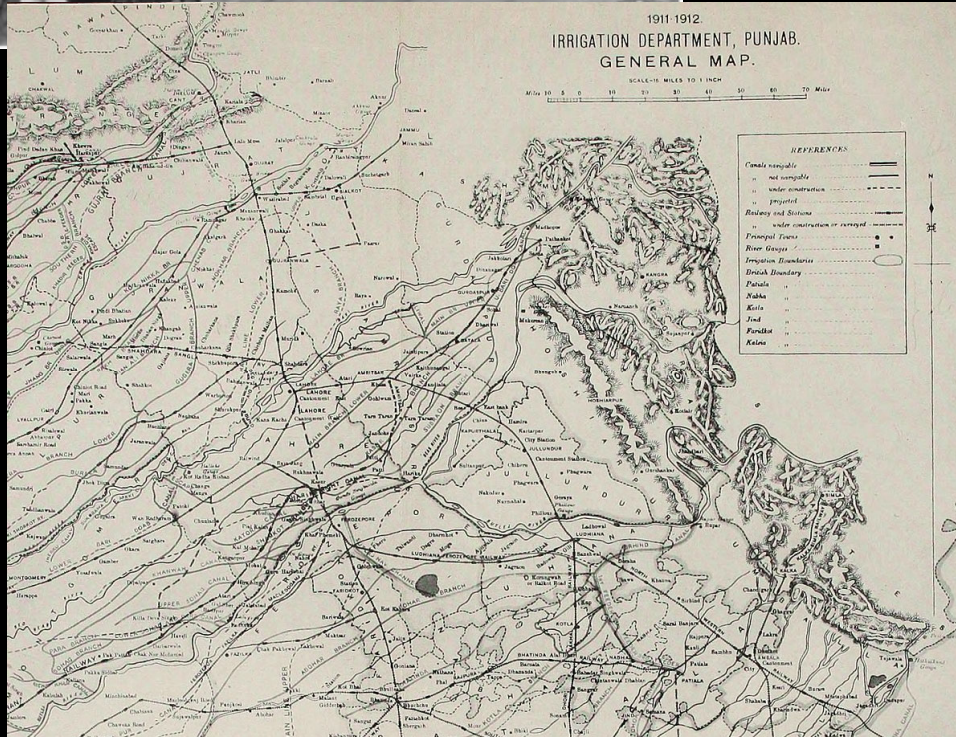
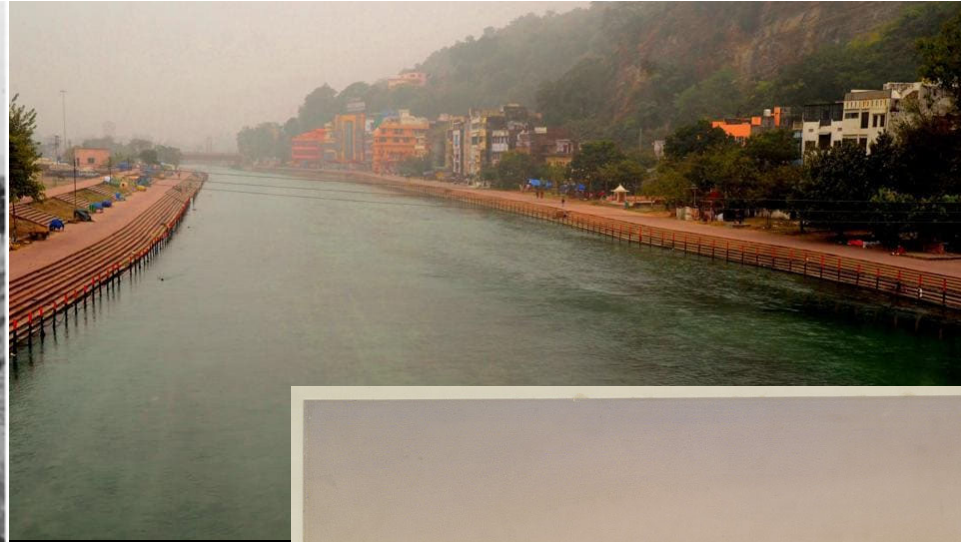
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DEPARTMENT OF WATERSHED SCIENCES

Sediment Transport & Channel Design

Peter Wilcock
1 August 2024



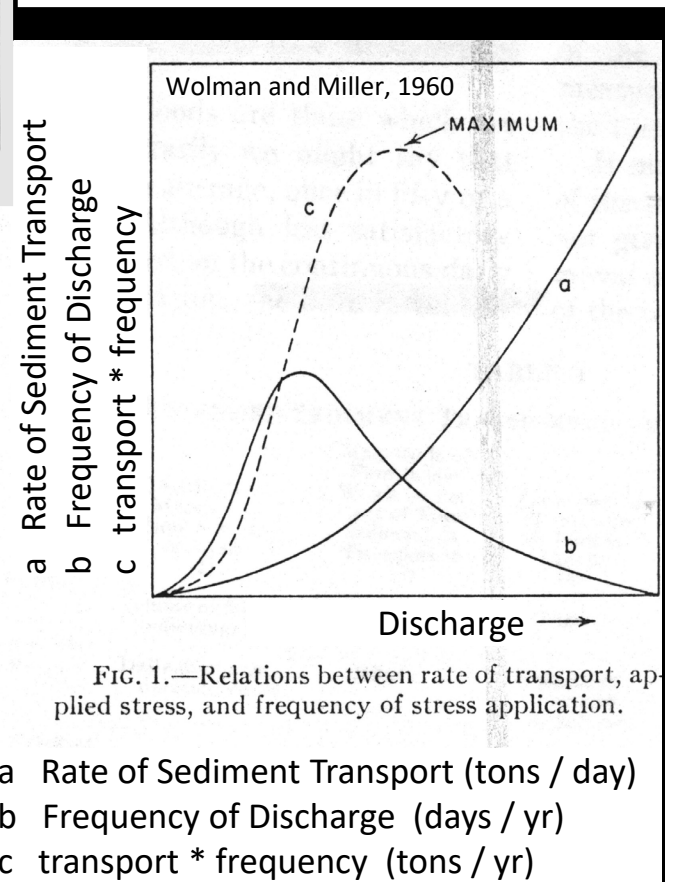
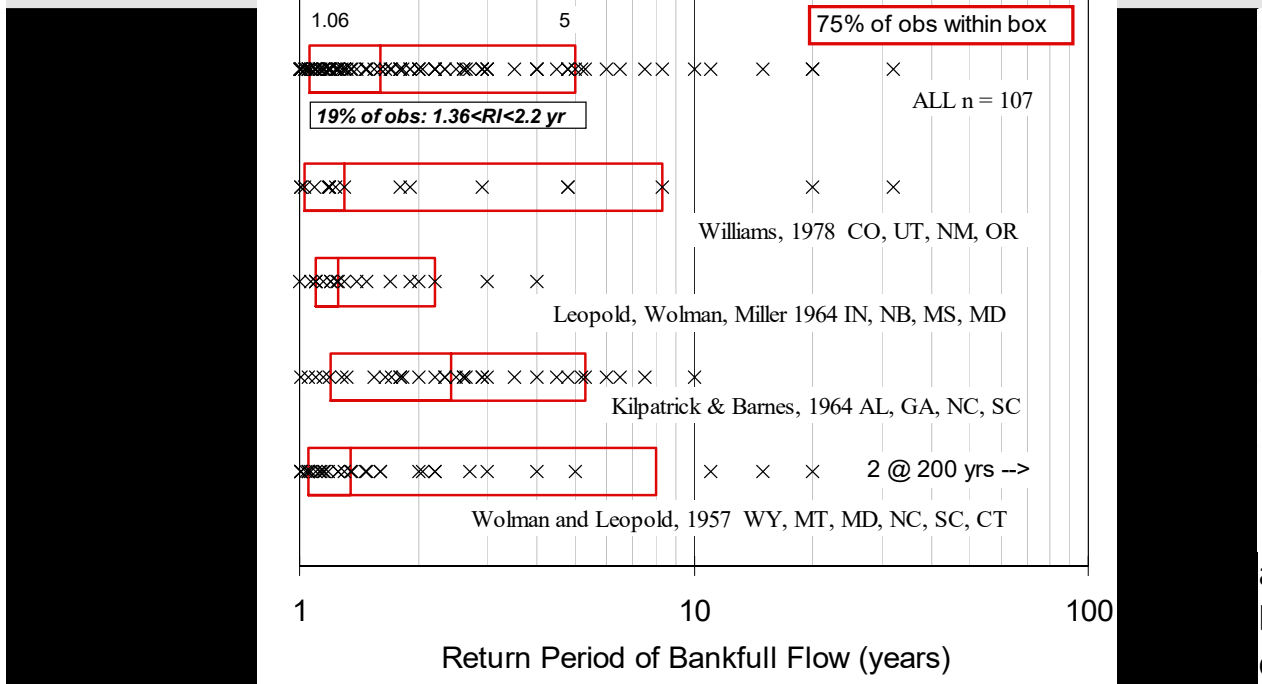
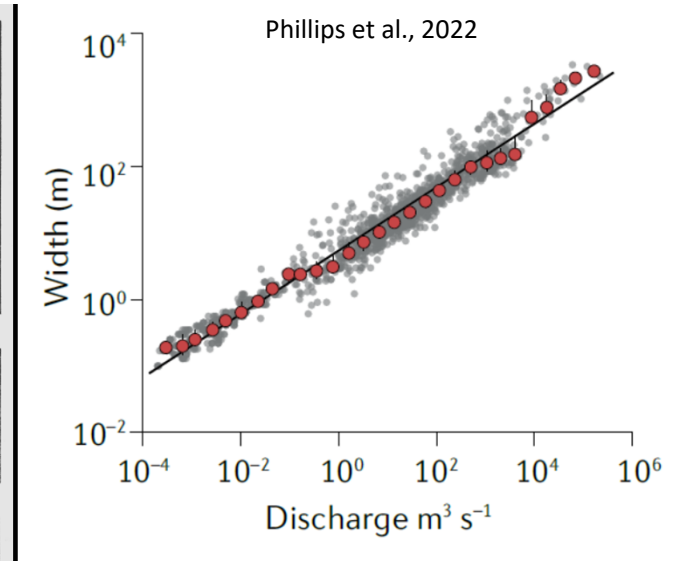
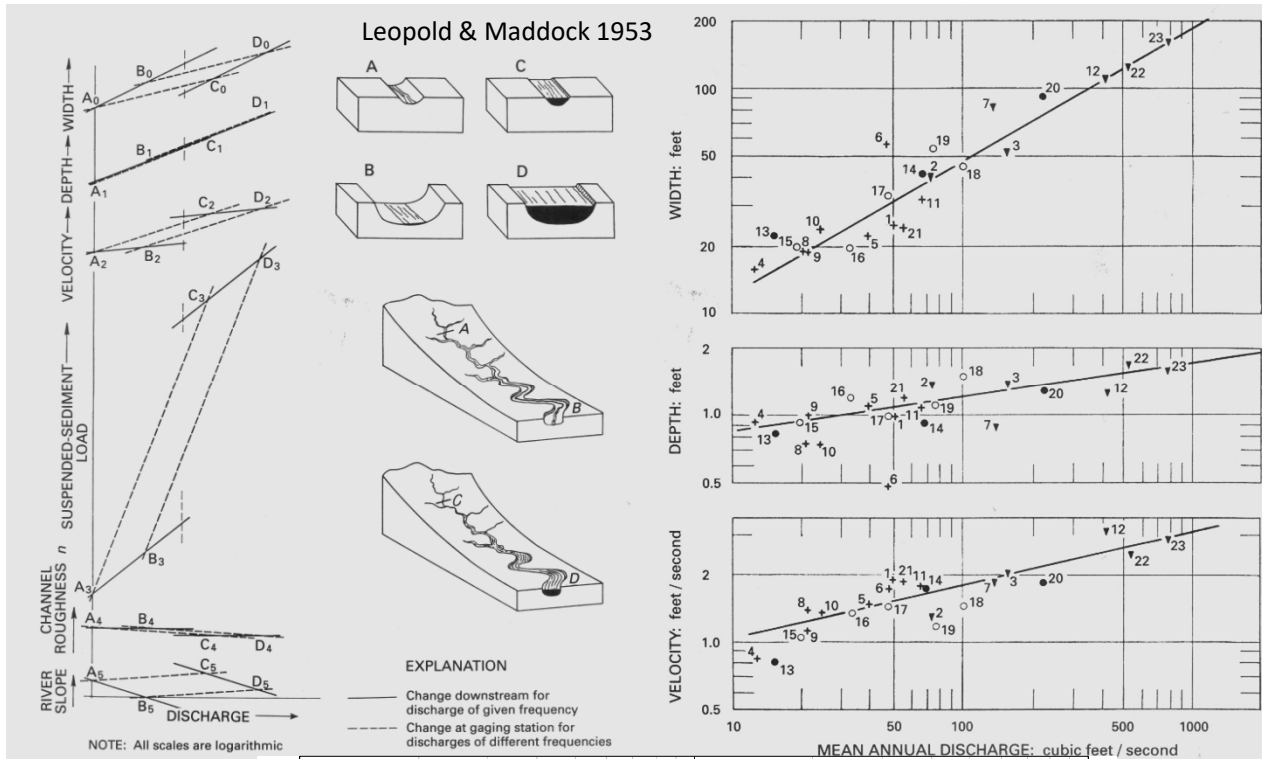


FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

a Rate of Sediment Transport (tons / day)
 b Frequency of Discharge (days / yr)
 c transport * frequency (tons / yr)

The width of channels increases consistently with the square root of discharge.

The flow that moves the most sediment, over time, tends to just fill the channel and occurs ever year or two.

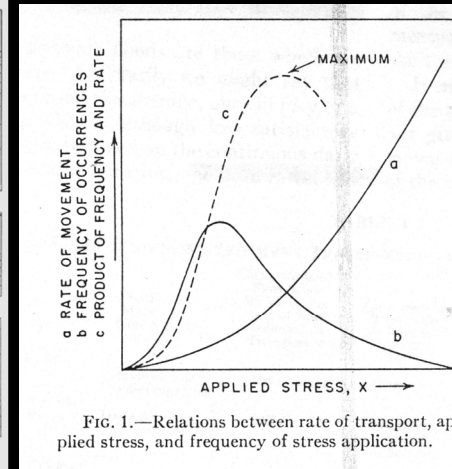
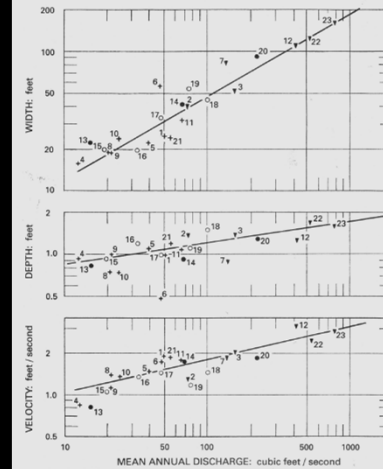
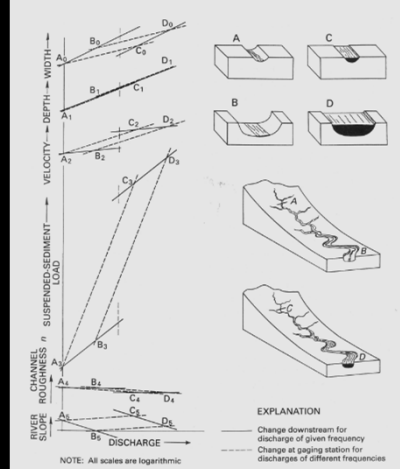


FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

The stable channel

The regime channel

The hydraulic geometry

A basis for natural channel design?

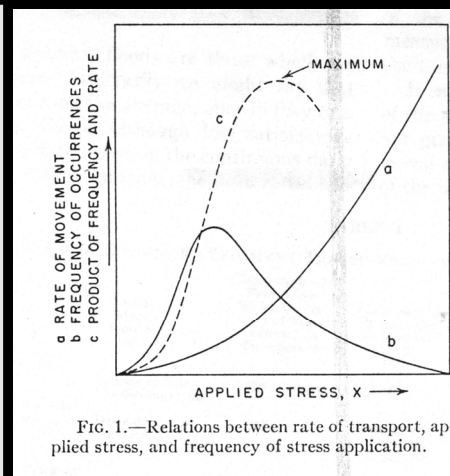
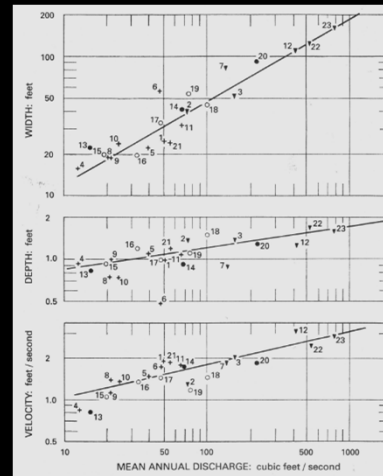
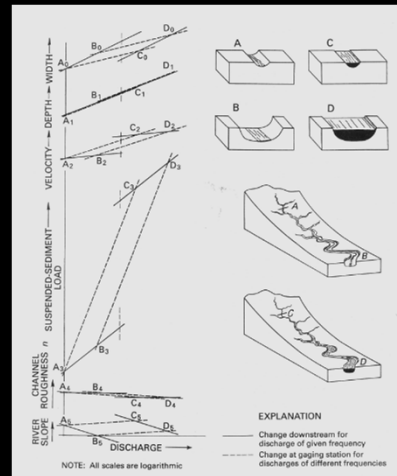


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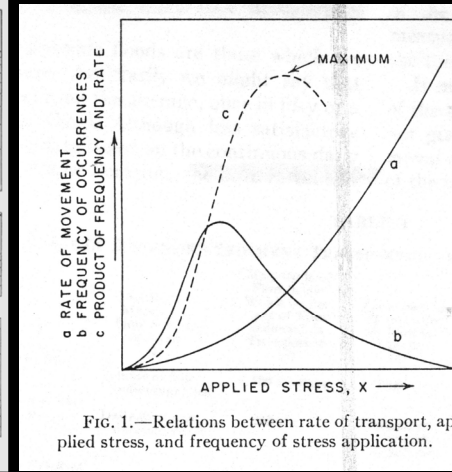
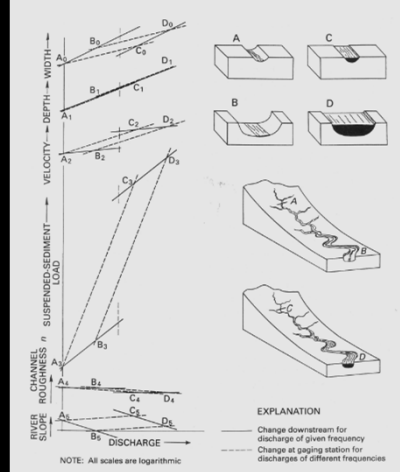


FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

At the core of these observations is a *correlation* between channel geometry, flow, and sediment supply

The correlation *requires* that the channels have *adjusted* to their water and sediment supply.

But what if channel is currently adjusting, or perpetually adjusting?

Using "the stable channel" or "the equilibrium channel" for design?

→ Streams are never in equilibrium!

Especially in Southern Ontario.

Especially those we judge to be unacceptably "out of adjustment"

→ How do we connect with specific, local, non-sediment objectives?

(if we build it like this ... good things will happen. || how do we balance?)

→ A "**rational**" approach: break problem down into its pieces:

specify drivers, quantify channel response.

→ A "**design** approach": specify objectives and design to meet them

(rather than specify design and hope that it solves the problem)

→ Connect goals to objectives to actions, through specific mechanisms

Unfortunately, for a rational design approach ...

(A) We can never forecast future conditions (e.g. water & sediment supply)
with a high degree of accuracy

(B) We will never know the exactly correct channel geometry for a river channel
(because there probably isn't one)

Can we develop a design approach that

(1) Specifies desired channel behavior

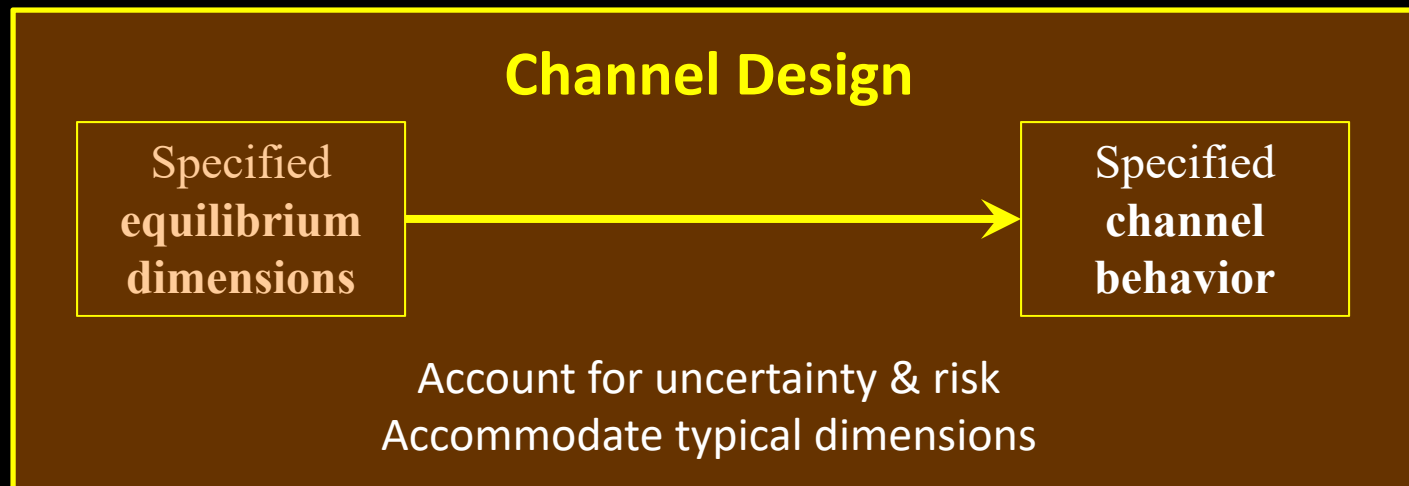
(2) Incorporates sediment transport with uncertainty

(3) Accommodates "typical" conditions

What is the supply of water and sediment?
and

What do you want to do with them?

- (1) Do you want the bed and banks to be static at a design flow?
- (2) Do you need to match transport capacity to sediment supply?
- (3) Both of the above



- (I) Mixed-size sediment transport I:
Response to fines content
- (II) Threshold Channel Design Under Uncertainty
- (III) Mixed-sized Sediment Transport II:
Size sorting and the Armoring Problem
- (IV) Alluvial Channel Design
- (V) Threshold & Alluvial Channel Design:
Together at last!
- (VI) Channel Design Strategy

(I) Mixed-sized Sediment Transport I: Response to fines content

There are many reasons why sand supply to a gravel-bed river might be increased
fire, urbanization, reservoir flushing, dam removal

What is the effect on transport rates?
Channel dynamics? Stream ecology?

Previous Experiments

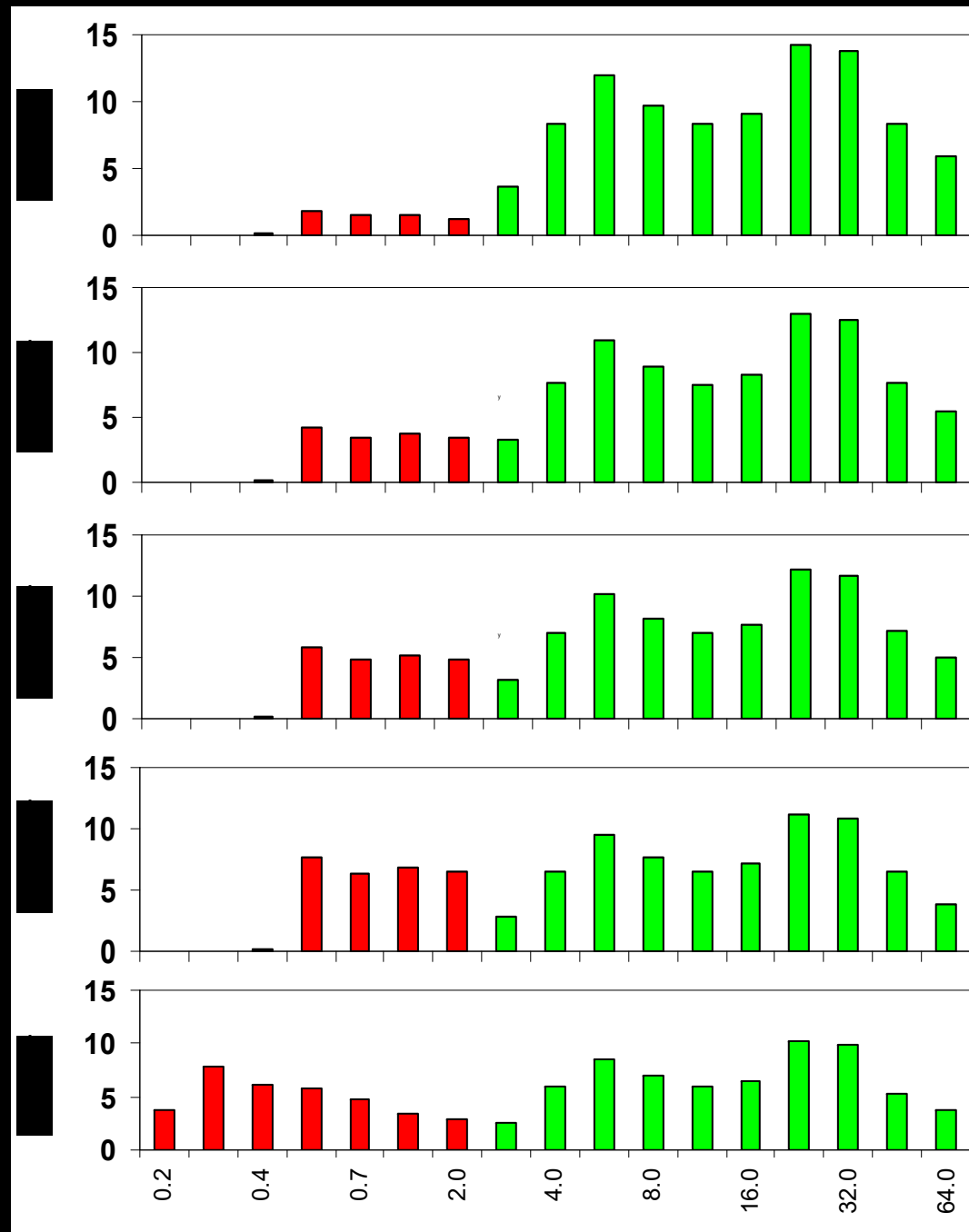
- Jackson & Beschta (1984)
- Ikeda & Iseya (1988)

→ *Adding sand increases gravel mobility*

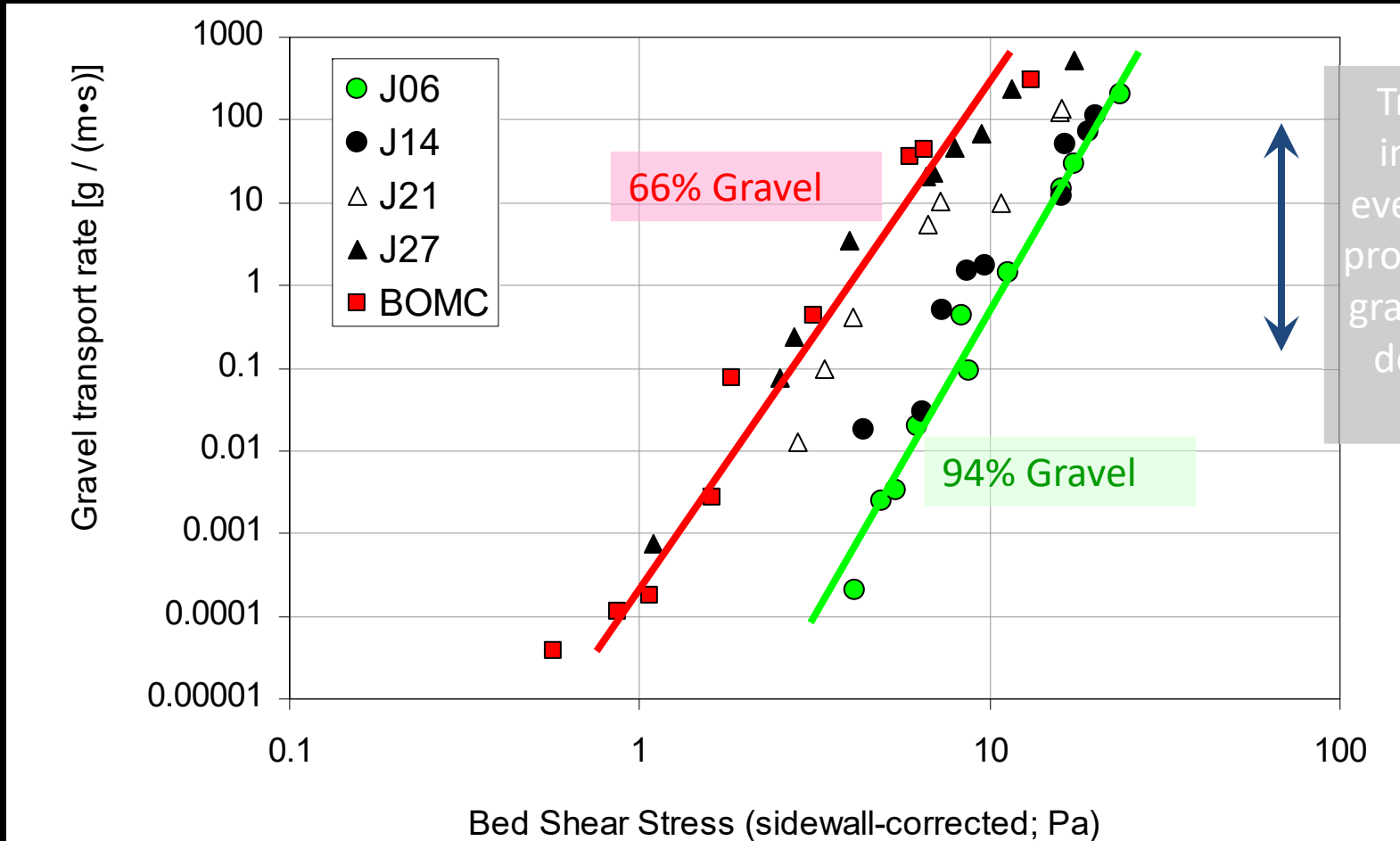


Some experimental evidence

- 5 sediments, add sand to gravel
- Sand: 0.5 – 2.0 mm
- Gravel: 2.0 – 64 mm
- Sand Content: 6, 14, 21, 27, & 34%
- 9 or 10 runs with each sediment, wide range of transport rates
- Depth & width held constant, primary variables are sand content & flow strength

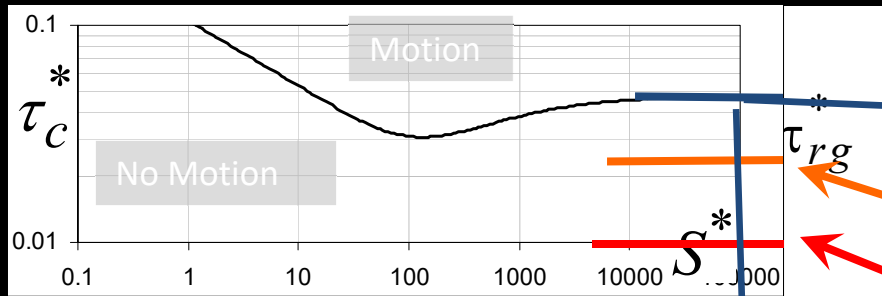


Effect of sand content on gravel transport rate



How do we capture effect of sand content on gravel transport rates?

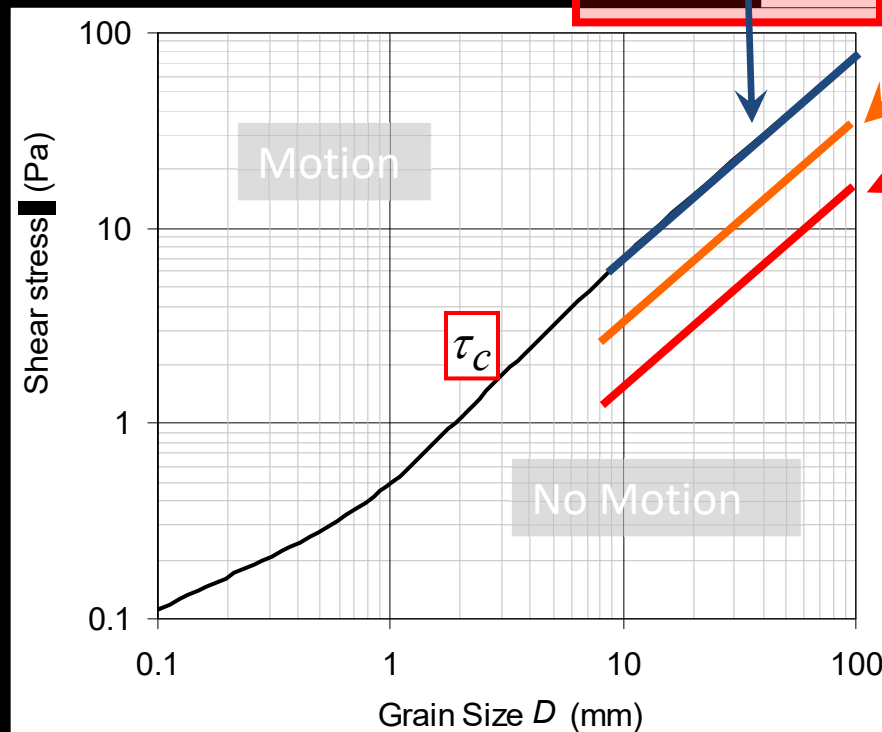
The sand effect on transport is captured by a reduced critical shear stress for incipient motion of the gravel



< 10% sand

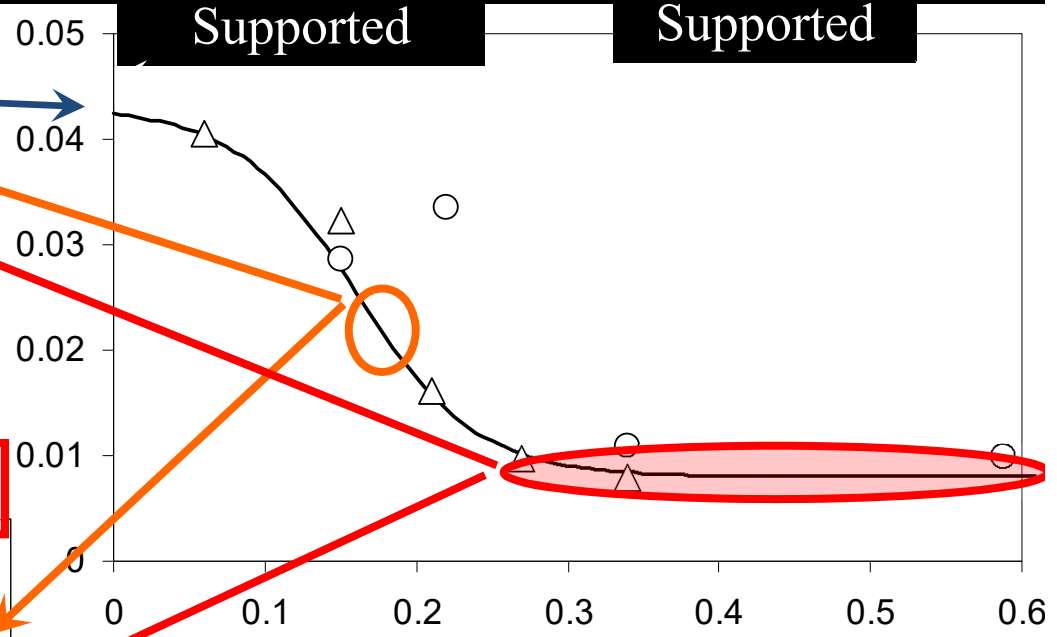
~18% sand

>34% sand



Framework Supported

Matrix Supported



$$\tau_c^* = \frac{\tau_c}{(s-1)\rho g D} \cong 0.03$$

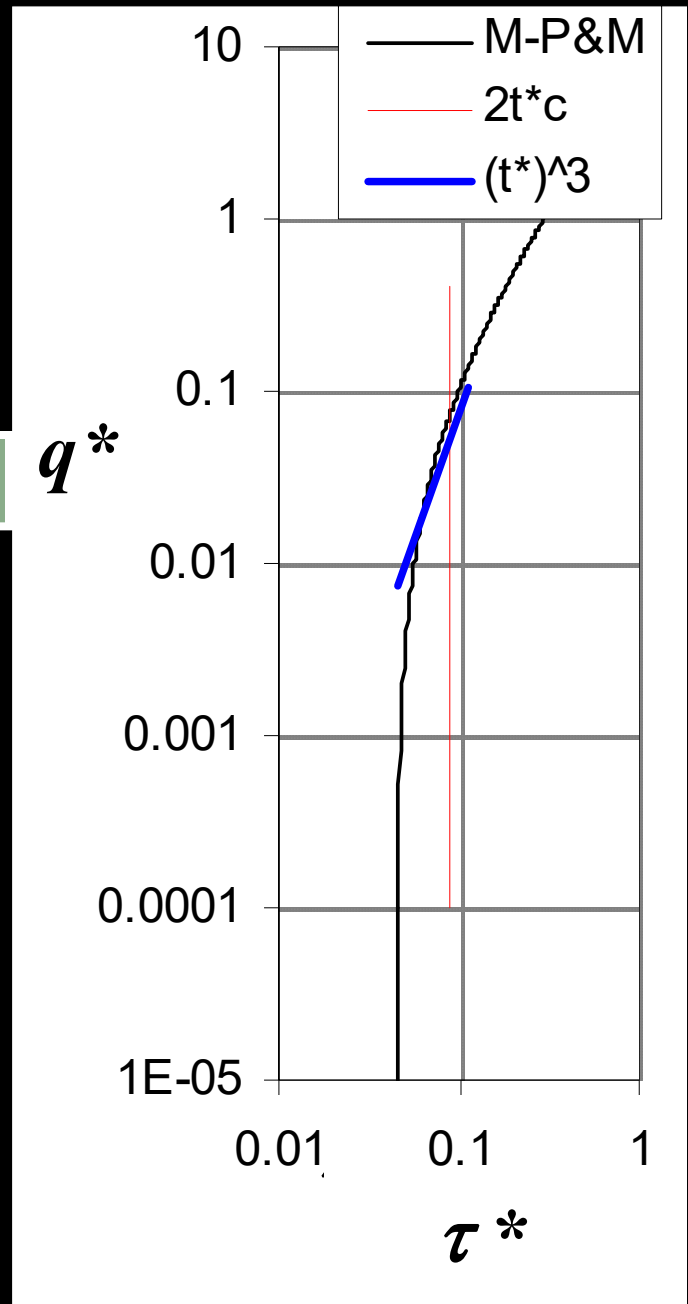
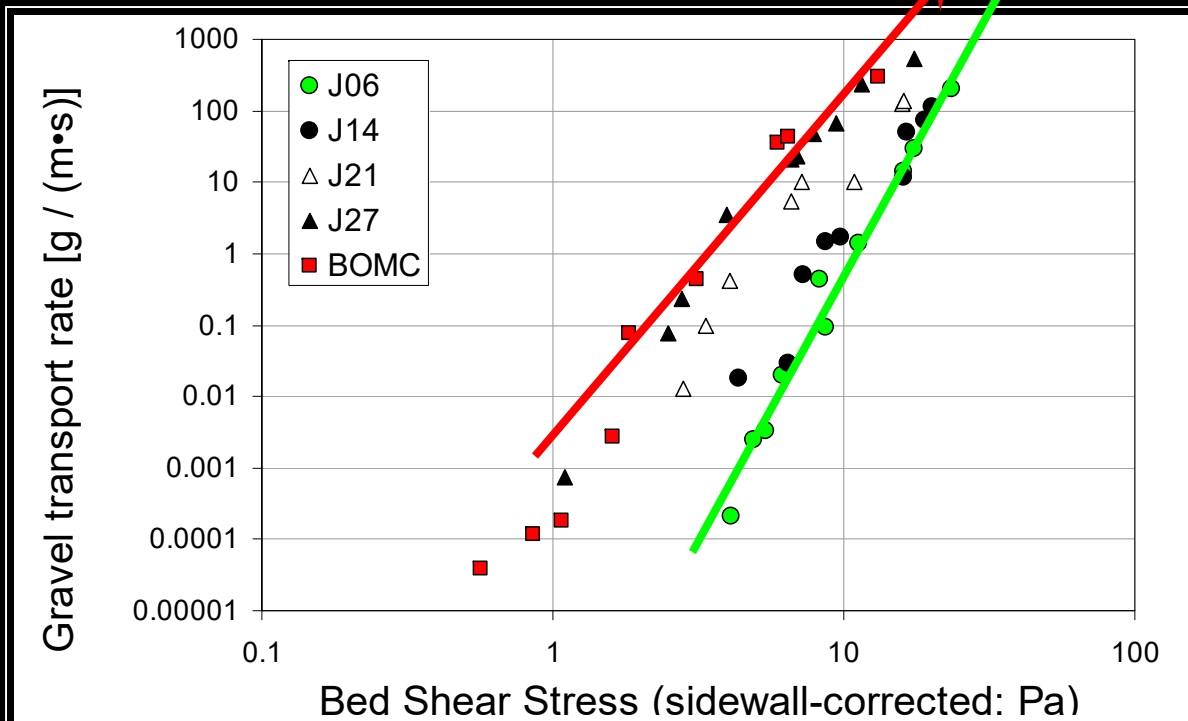
For $D > 4$ mm

quartz in water

We have captured the effect of sand on gravel transport by reducing the critical shear stress for the gravel

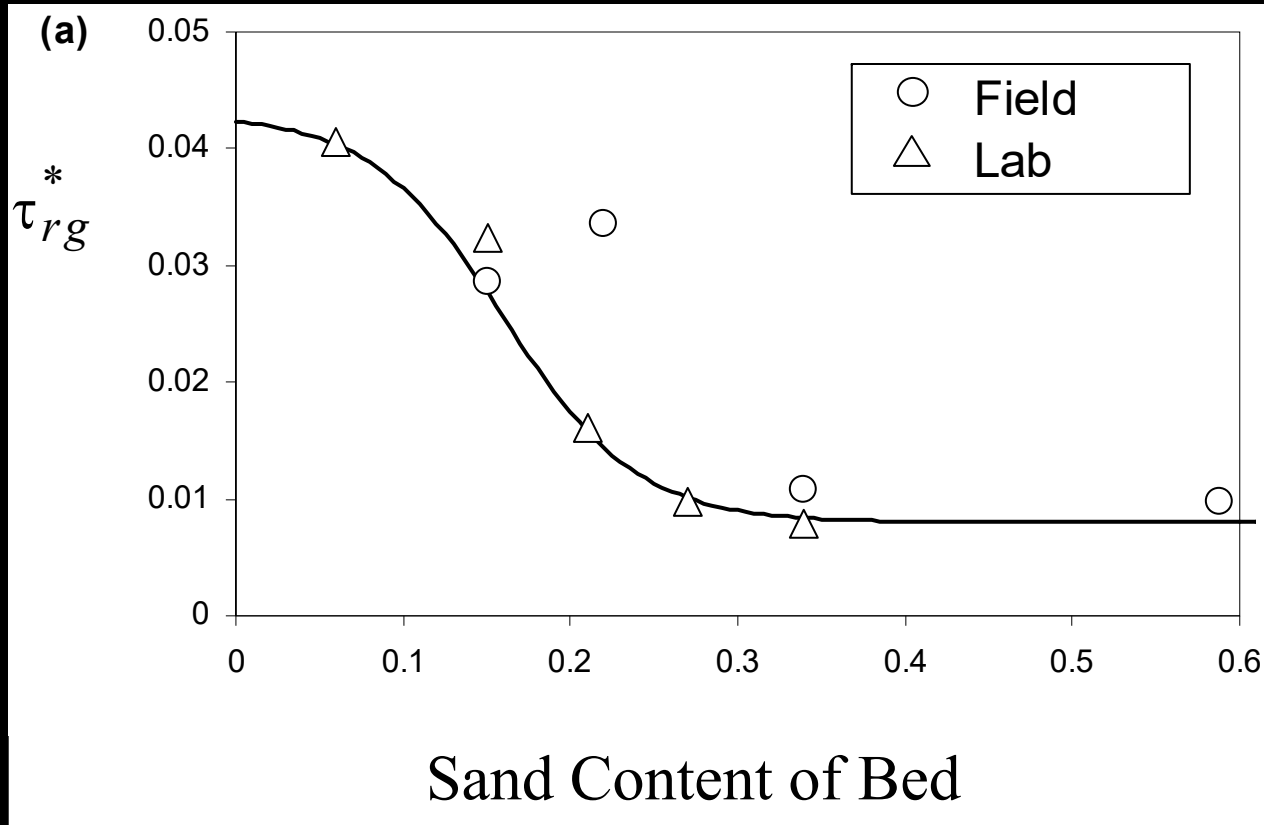
Reducing τ_c^* by a factor of four increases the transport rate by much, much more

34% sand 6% sand



← Framework Supported

Matrix Supported →



This changes our approach to predicting sediment transport rates:

A fundamental parameter depends on bed grain size

(also found in the many fraction surface-based model)

Wilcock, P.R. and Kenworthy, S.T., 2002, A two fraction model for the transport of sand/gravel mixtures, Water Resources Research, 38(10).

Wilcock, P.R., Kenworthy, S.T. and Crowe, J.C., 2001. Experimental study of the transport of mixed sand and gravel, Water Resources Research

Wilcock, P.R., 1998. Two-fraction model of initial sediment motion in gravel-bed rivers, Science 280:410-412

Pay attention to this slide

Test sand effect in a sediment feed flume

Feed gravel (2-32 mm) at same rate in each run;
Increase sand feed rate from much less to much more than gravel

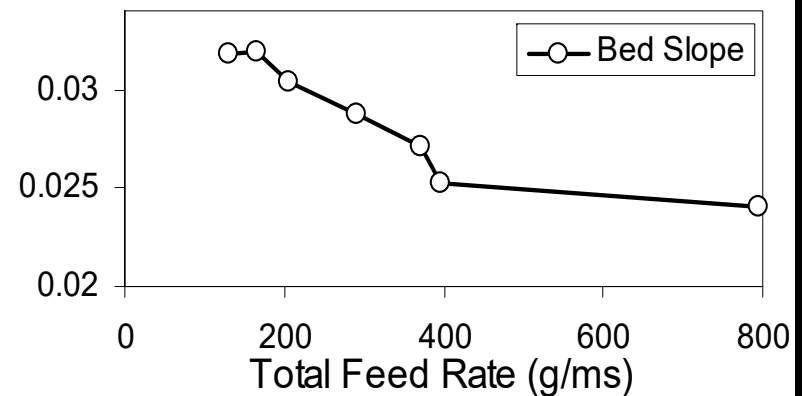
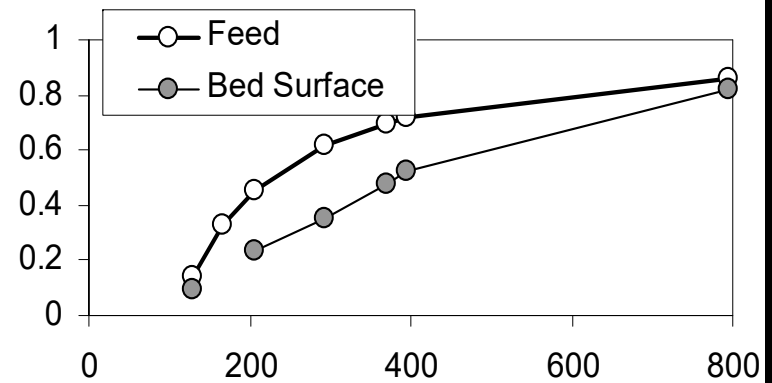
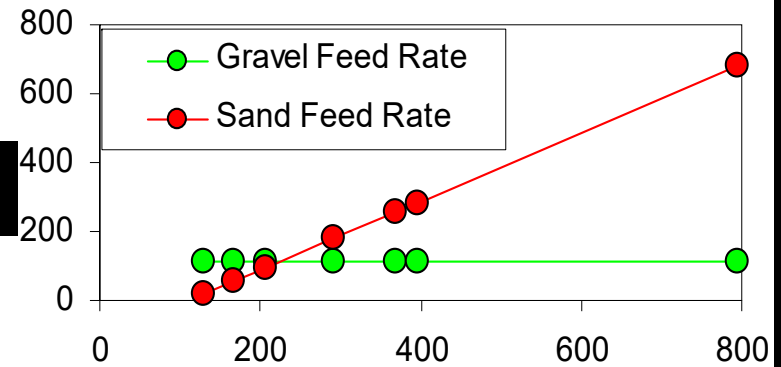
Results

As sand feed increases, bed gets sandier & slope decreases:
less stress required to carry same gravel load & increased sand load

Effect of Sand Supply on Transport Rates in a Gravel-Bed Channel

Joanna C. Curran, A.M.ASCE,¹ and Peter R. Wilcock, M.ASCE²

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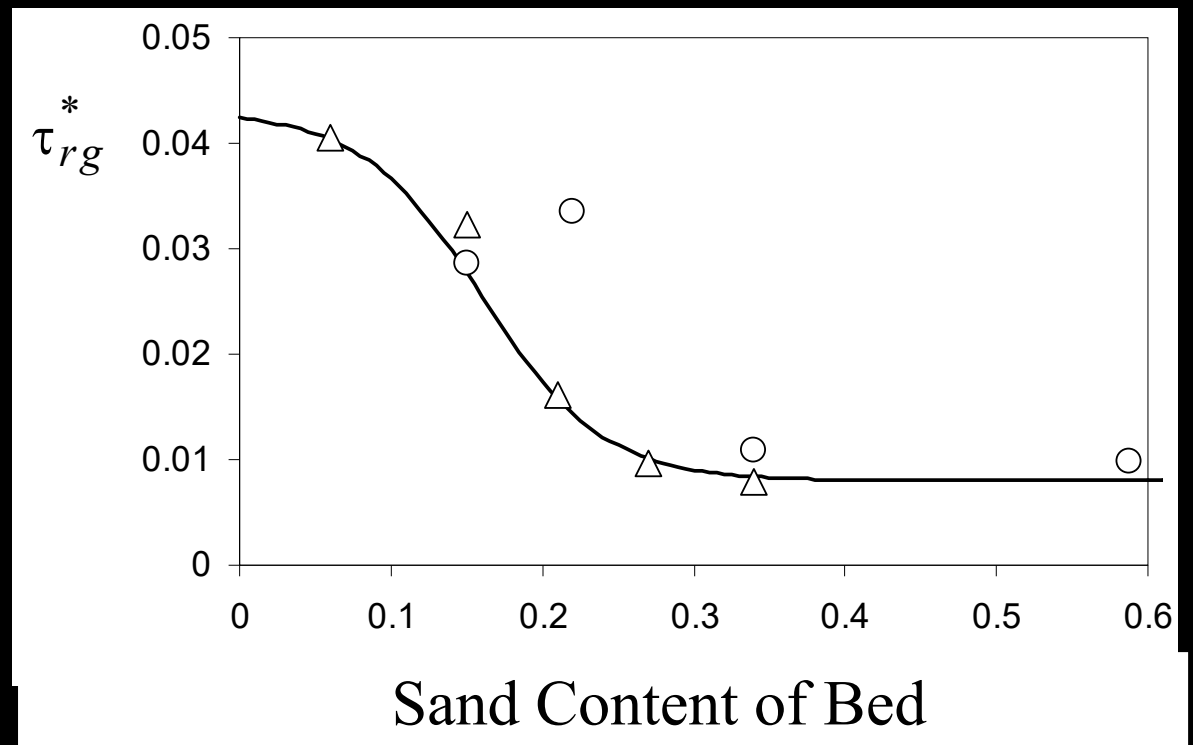


The point?

Adding sand can have a huge effect on gravel transport rates
most of this is captured in a changed critical Shields Number

There are a number of ways to increase sand supply to a gravel-bed river
fire, urbanization, reservoir flushing, dam removal

A two fraction approach captures this effect in a tractable framework



The first transport problem: incipient motion

The transport model is a defined value of critical Shields Number

For a gravel-bed river, a reasonable choice of D is the median size of the gravel portion of the bed (the framework), measured with a pebble count. For clean, loose gravel,

$$\tau_c^* = \frac{\tau_c}{(s-1)\rho g D} \cong 0.03$$

For a gravel bed that has not been entrained for some time, the grains can become weakly cemented, and they can also become arranged into subtle structures that increase their resistance to movement. This can more than double τ_c^* .



(II) Threshold Channel Design Under Uncertainty



Example problem: Threshold channel design

Given:

Valley slope = 0.007 (this is the maximum possible slope)

Bed material $D_{50} = 45 \text{ mm} = 0.148 \text{ ft}$

Bed material $D_{75} = 55 \text{ mm} = 2.17 \text{ in}$

Bed material $D_{84} = 60 \text{ mm} = 0.197 \text{ ft}$

Channel side slope = 3H:1V

Specific weight of sediment = 165 lb/ft^3

Water temperature = $68 \text{ }^\circ\text{F}$

Design discharge is 25-year storm = $400 \text{ ft}^3/\text{s}$

Problem:

Design a threshold channel to convey the design discharge.

Note: There is no unique solution with the given design constraints.

654.0808 Basic steps for
threshold channel design in
stream restoration projects

Step 1 Determine design bed-material gradation/channel boundary.

Step 2 Determine preliminary width.

Step 3 Estimate critical shear stress/velocity.

Step 4 Determine flow resistance (Manning's n).

Step 5 Calculate depth and slope.

Step 6 Determine planform.

Step 7 Assess for failure and sediment impact.

For a 'real' channel ...
we have choices to make

Design discharge

$$\tau_c^*$$

Roughness model

Drag partition?

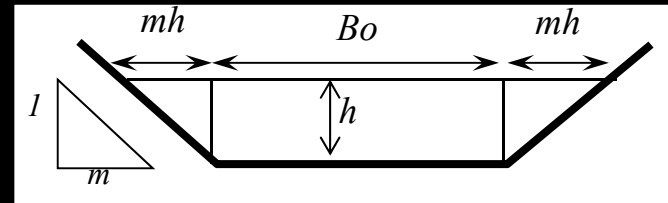
Channel Geometry

Given discharge Q , grain size D ,

critical Shields Number τ_c^* ,

Pick a roughness model & channel geometry

find slope S and depth h producing incipient motion.



Finding Normal Depth - Trapezoidal Channel

$$\text{Manning's eqn: } Q = \frac{\sqrt{S}}{n} \frac{[h(B_0 + mh)]^{5/3}}{[B_0 + 2h\sqrt{1+m^2}]^{2/3}}$$

where

$$B = B_0 + 2mh, A = B_0h + mh^2 = h(B_0 + mh), P = B_0 + 2h\sqrt{1+m^2}$$

Finding n, Q , or S is easy; to find h requires iteration

$$\text{Try Manning arranged as } h_{n+1} = \left(\frac{nQ}{\sqrt{S}} \right)^{3/5} \frac{[B_0 + 2h_n\sqrt{1+m^2}]^{2/5}}{B_0 + mh_n}$$

where n and $n+1$ subscripts indicate successive approximations

GENERAL SOLUTION STRATEGY for SLOPE and
DIMENSION for INCIPIENT MOTION in a TRAPEZOIDAL CHANNEL

Given $Q, B_0, m, \tau_c^*, D_{50}$ and D_{84} ,

find τ_c, n, R, U and S from

$$\tau_c = ((s-1)\rho g D_{50} \tau_c^*) \quad (\text{definition of } \tau_c^*)$$

Determine n (Limerinos, Lotter, or just specify it)

$$h_{l+1} = \left(\frac{n_c Q}{\sqrt{S}} \right)^{3/5} \frac{[B_0 + 2h_l\sqrt{1+m^2}]^{2/5}}{B_0 + mh_l} \quad (\text{Manning's Eqn.})$$

{Recursive calculation for depth h , showing steps l and $l+1$ }

$$R = \frac{A}{P} = \frac{h(B_0 + mh)}{B_0 + 2h\sqrt{1+m^2}} \quad (\text{definition of hydraulic radius})$$

$$U = \frac{Q}{A} \quad (\text{continuity})$$

$$S = \frac{\tau_c}{\rho gh} \quad (\text{momentum})$$

Use trapezoid with user specified bank angle and bank roughness

Roughness	Drag Partition
Limerinos (1970)	No – For wide channel with only grain roughness
Lotter (1936) Different bed and bank roughness Sum flows across panels	Yes, w/ Strickler grain roughness
$\frac{PR^{5/3}}{n_c} = \sum_i \frac{P_i R_i^{5/3}}{n_i}$	
User specified n	Yes, w/ Strickler grain roughness

Finding Normal Depth - Trapezoidal Channel

$$\text{Manning's eqn: } Q = \frac{\sqrt{S}}{n} \frac{[h(B_o + mh)]^{5/3}}{[B_o + 2h\sqrt{1+m^2}]^{2/3}}$$

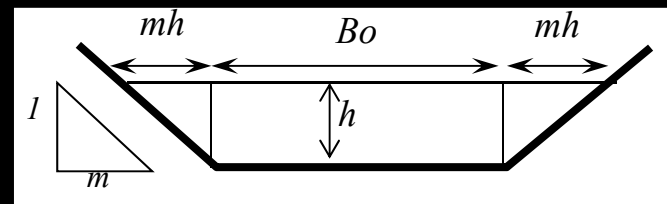
where

$$B = B_o + 2mh, A = B_o h + mh^2 = h(B_o + mh), P = B_o + 2h\sqrt{1+m^2}$$

Finding n, Q , or S is easy; to find h requires iteration

$$\text{Try Manning arranged as } h_{n+1} = \left(\frac{nQ}{\sqrt{S}} \right)^{3/5} \frac{[B_o + 2h_n\sqrt{1+m^2}]^{2/5}}{B_o + mh_n}$$

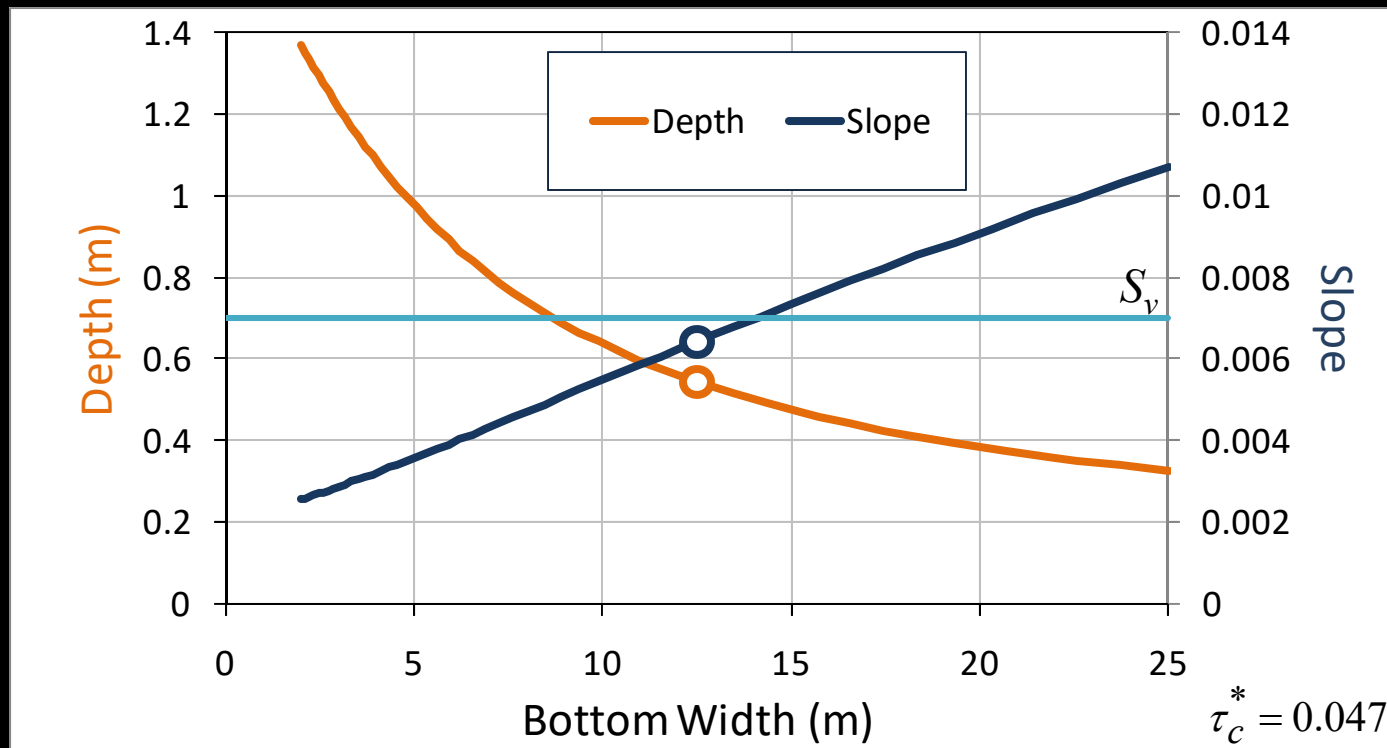
where n and $n+1$ subscripts indicate successive approximations



Given discharge Q , grain size D , Limerinos roughness & trapezoidal channel shape, find slope S producing incipient motion.

Specify $B = 12.5$ m and $\tau_c^* = 0.047$,

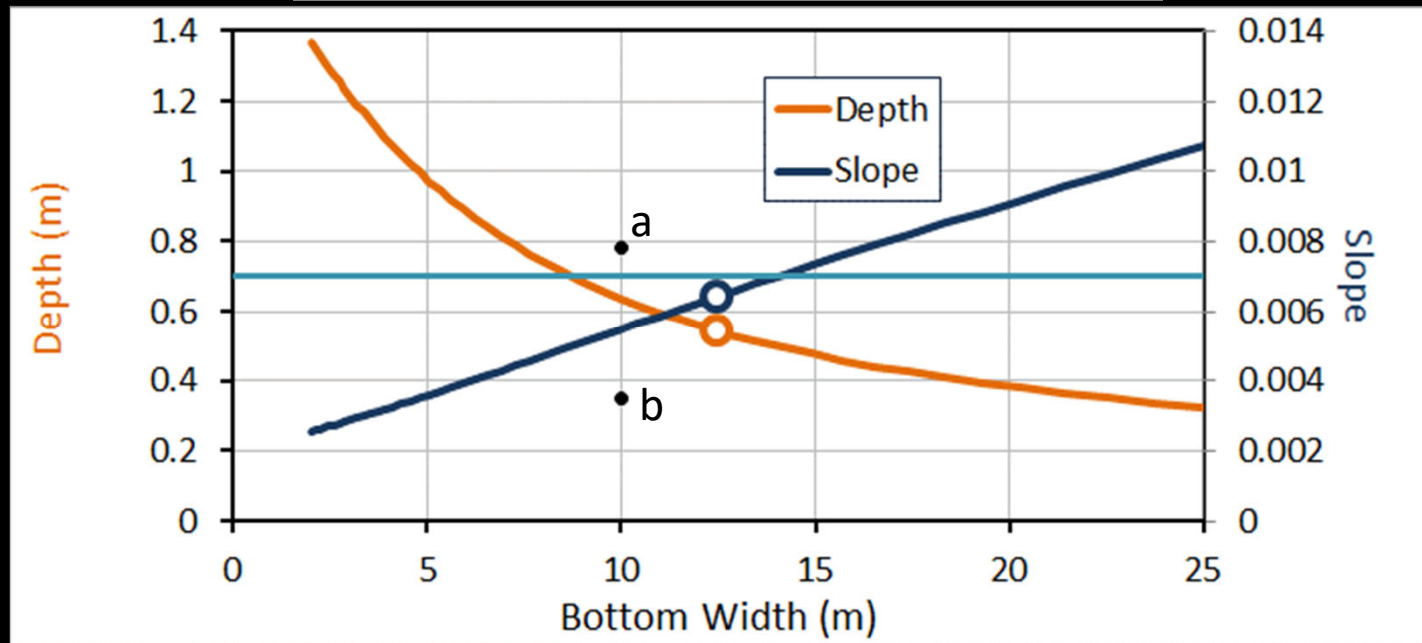
solution is $S = 0.0064$ with depth $h = 0.54$ m



Find velocity, boundary stress, depth, and slope from continuity, momentum, flow resistance, and definition of τ_c^*

Given discharge Q , grain size $D = 45$ mm,
Limerinos roughness & trapezoidal channel shape,
find slope S producing incipient motion.

Specify $B = 12.5$ m and $\tau_c^* = 0.047$,
solution is $S = 0.0064$ with depth $h = 0.54$ m



a: $D = 64$ mm

b: $D = 32$ mm (or $\tau_c^* = 0.3$)

Strategy

What is probability of failure? What probability are you willing to accept?

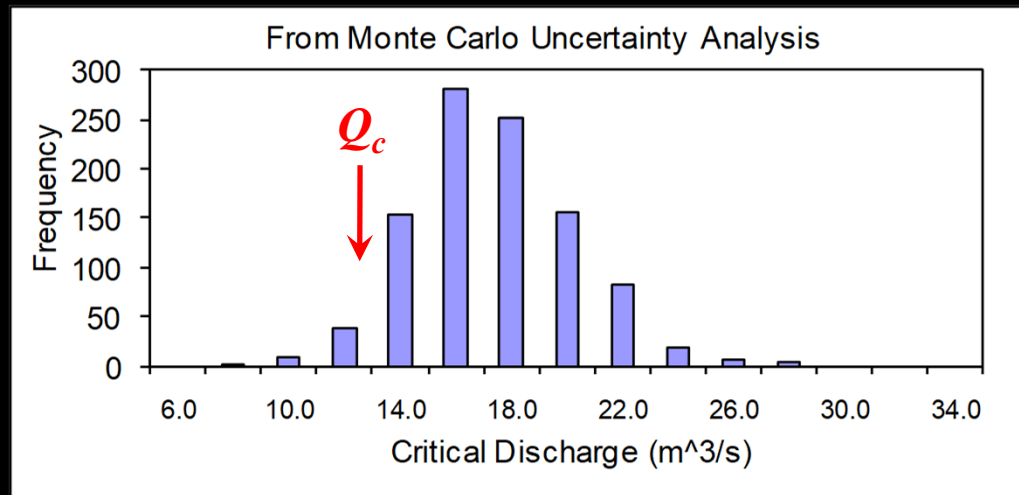
$$P(\text{failure}) = P(Q_D)P(Q_D > Q_c)$$

Choose width, slope combination to match acceptable risk.

For example, for a 25yr Q_D and a channel design with 10% failure probability,

$$P(\text{failure}) = P(Q_D)P(Q_D > Q_c) = (0.04)(0.1) = 0.004$$

giving a 0.4% chance of failure in any year.



(III) Mixed-sized Sediment Transport II: Size sorting and the Armoring Problem

1. Stream-bed armoring *surface composition & the problem of predicting transport rates*

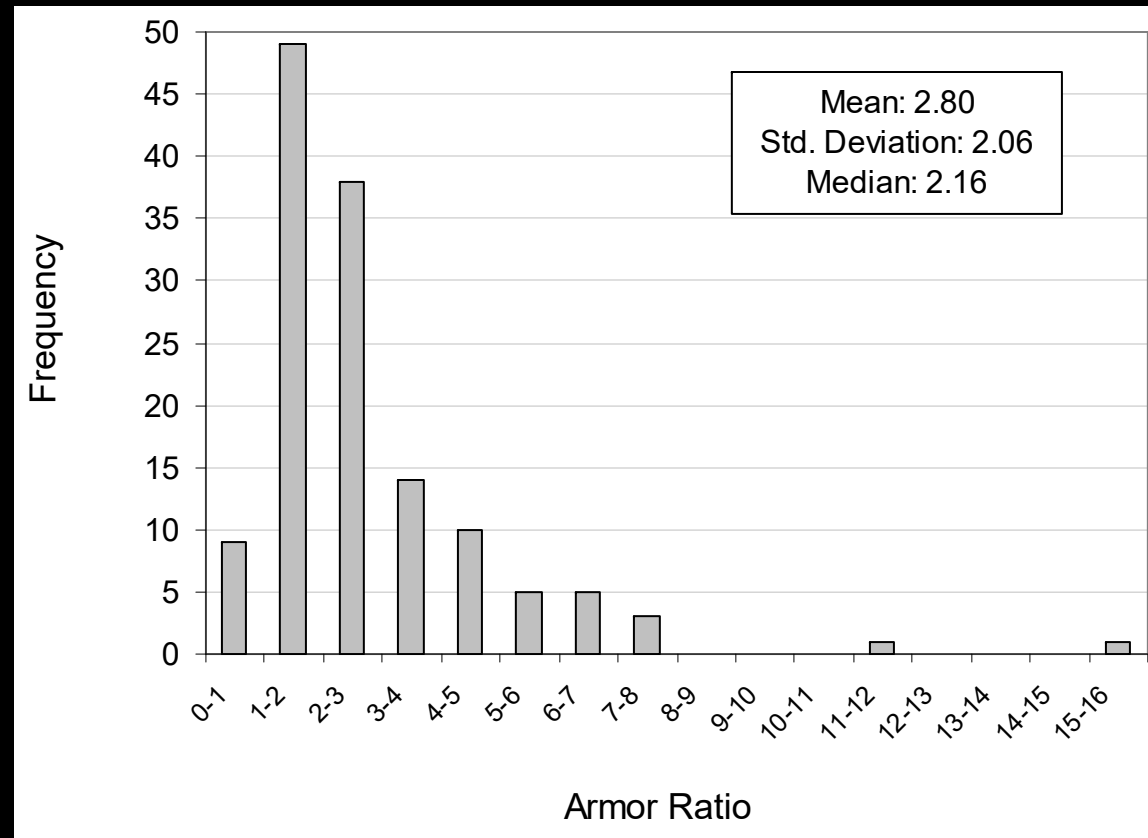


Streambed Armoring

Stream-bed armoring is pervasive in gravel-bed streams

Armor Ratio =

$$\frac{D50(\text{surface})}{D50(\text{subsurface})}$$



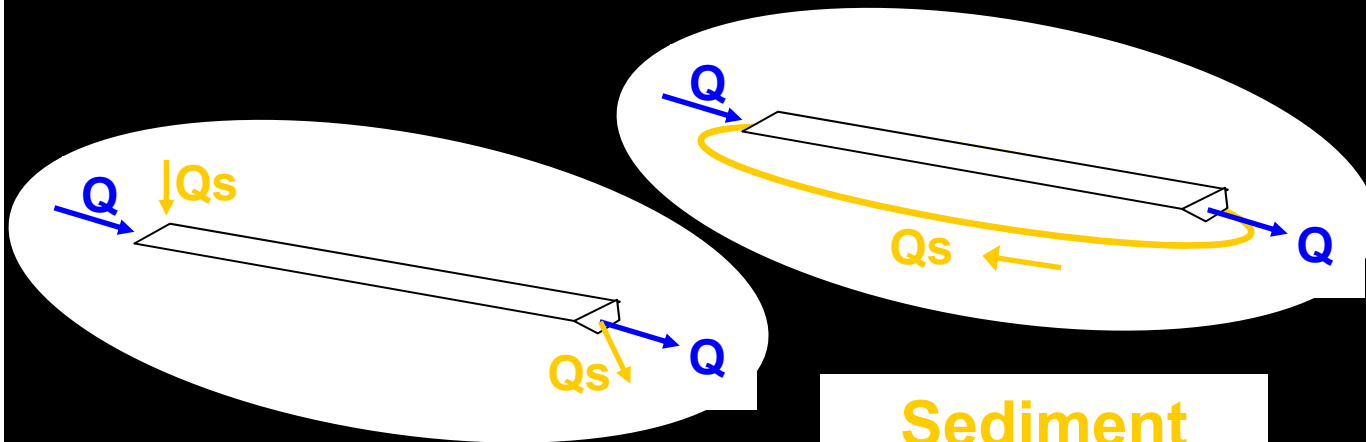
Bed surface composition determines:

- grains available for transport
- hydraulic roughness
- bed permeability
- living conditions for bugs & fish

The armor problem

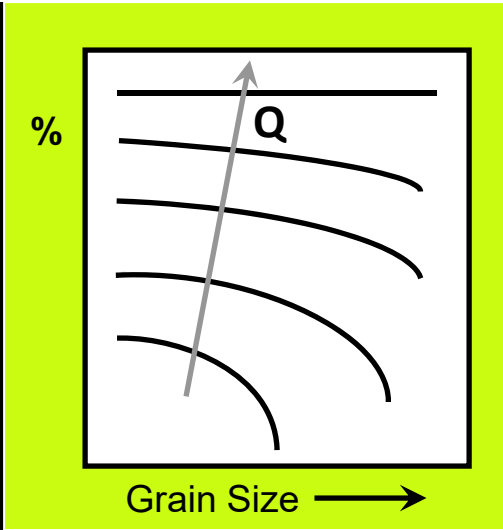
- We can measure the bed surface size at low flow, but not at flows moving sediment
- We don't know what the bed surface looks like at the flows that create it
- ***Does the armor layer stay or go during floods?***

Flume studies do not resolve the issue

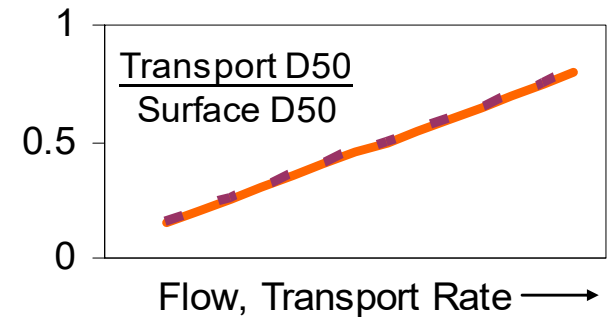
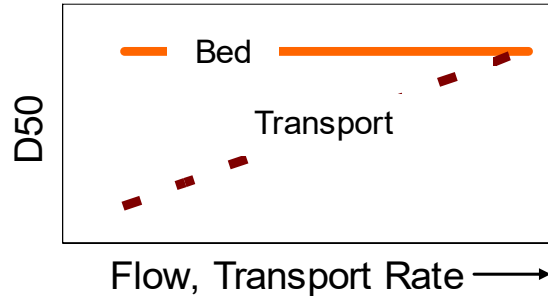
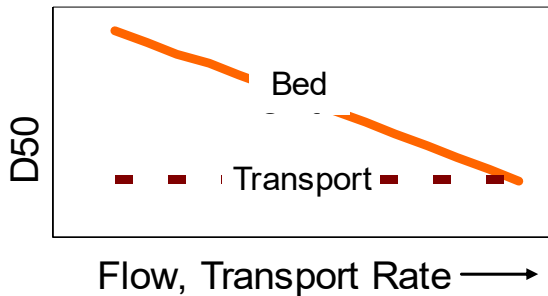


Sediment Feed

Sediment Recirculation



Both Cases



Mobility – driven armoring

Zero divergence Kinematic sorting

To address the armor problem, we first tackle the transport problem

- Transport rates depend on transport of grains available for transport on bed surface
- But nearly all transport data provide composition of the bed *subsurface, not surface!*
- This means that the resulting transport models must somehow implicitly account for surface sorting (armoring)

Transport Modeling Basics - 1

Given fully rough flow with boundary stress τ , sediment of mean size D_m , with individual fractions of size D_i and proportion f_i . Transport rate q_{bi} depends on

$$q_{bi} = fn(f_i, D_i, D_m, \tau, \text{sed})$$

where sed = other sediment properties. We search a transport model of form

$$\frac{q_{bi}}{f_i} = fn_1(\tau, \tau_{ri})$$

$$\tau_{ri} = fn_2(D_m, D_i / D_m, \text{sed})$$

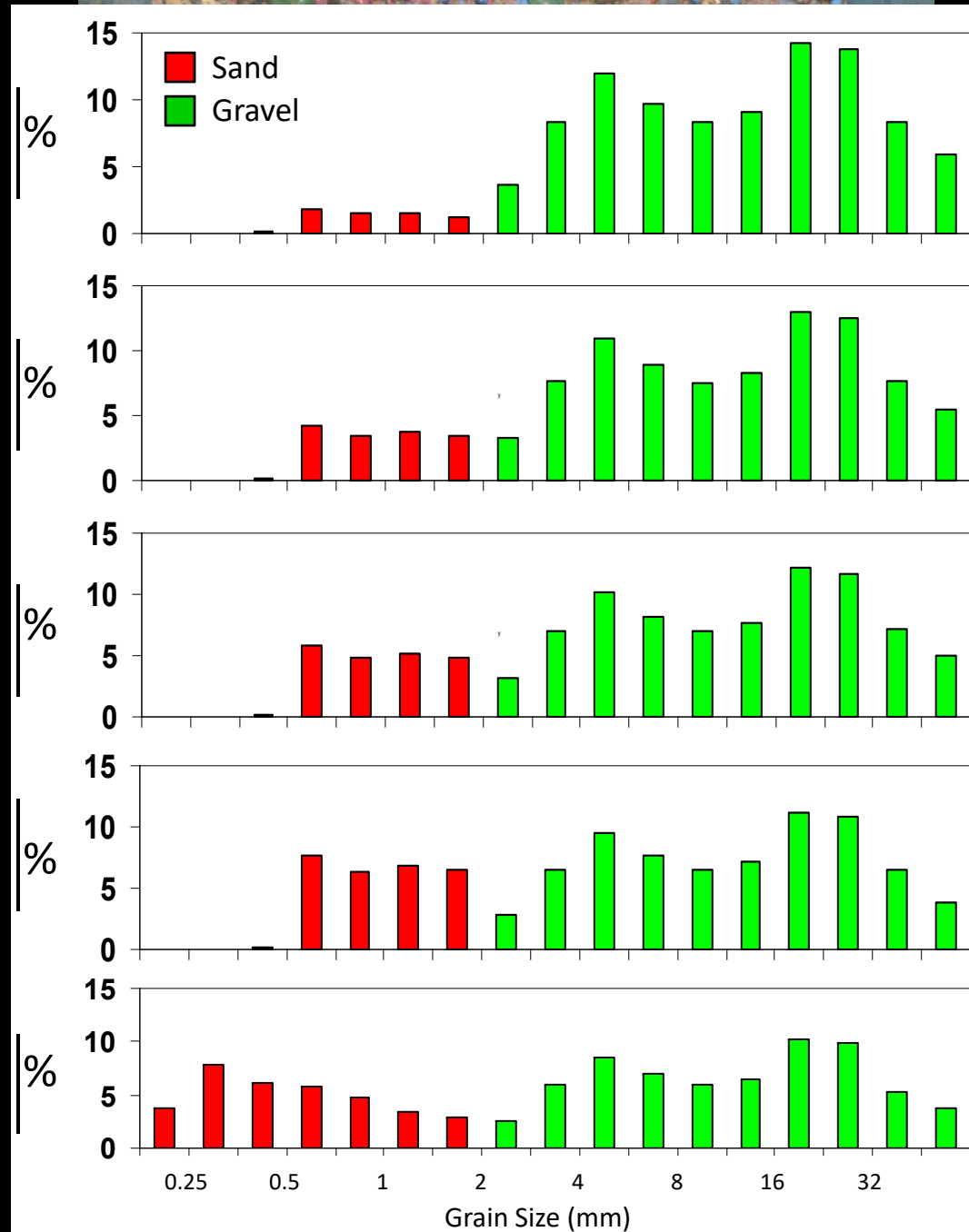
where τ_{ri} is a reference value of τ near the onset of sediment motion

But, what size distribution should we use for f_i ?

ans: surface

There were essentially no surface-based transport observations, so we made some

- 5 sediments, add sand to gravel
- Sand: 0.5 – 2.0 mm
- Gravel: 2.0 – 64 mm
- Sand Content: 6, 14, 21, 27, & 34%
- 9 or 10 runs with each sediment, wide range of transport rates
- Depth & width held constant, primary variables are sand content & flow strength



Transport Modeling Basics - 2

To develop a general transport model, we nondimensionalize

$$\frac{q_{bi}}{F_i} = fn_1(\tau, \tau_{ri})$$

in the form of a similarity collapse

$$W_i^* = fn_3\left(\frac{\tau}{\tau_{ri}}\right)$$

where

$$W_i^* = \frac{(s-1)gq_{bi}}{F_i(\tau/\rho)^{3/2}}$$

F_i surface proportion;

g gravity;

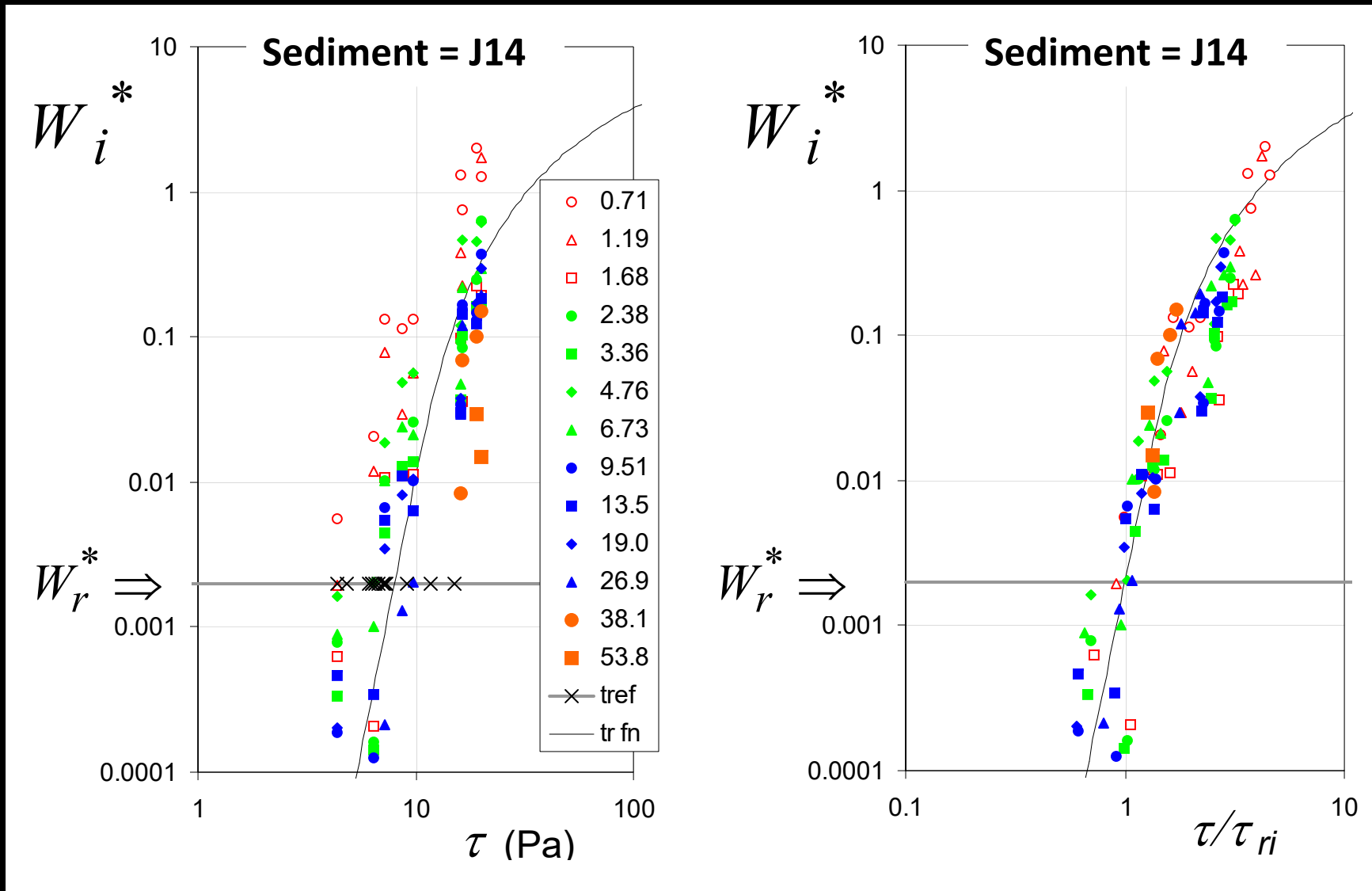
ρ water density;

s sed spec. gr.

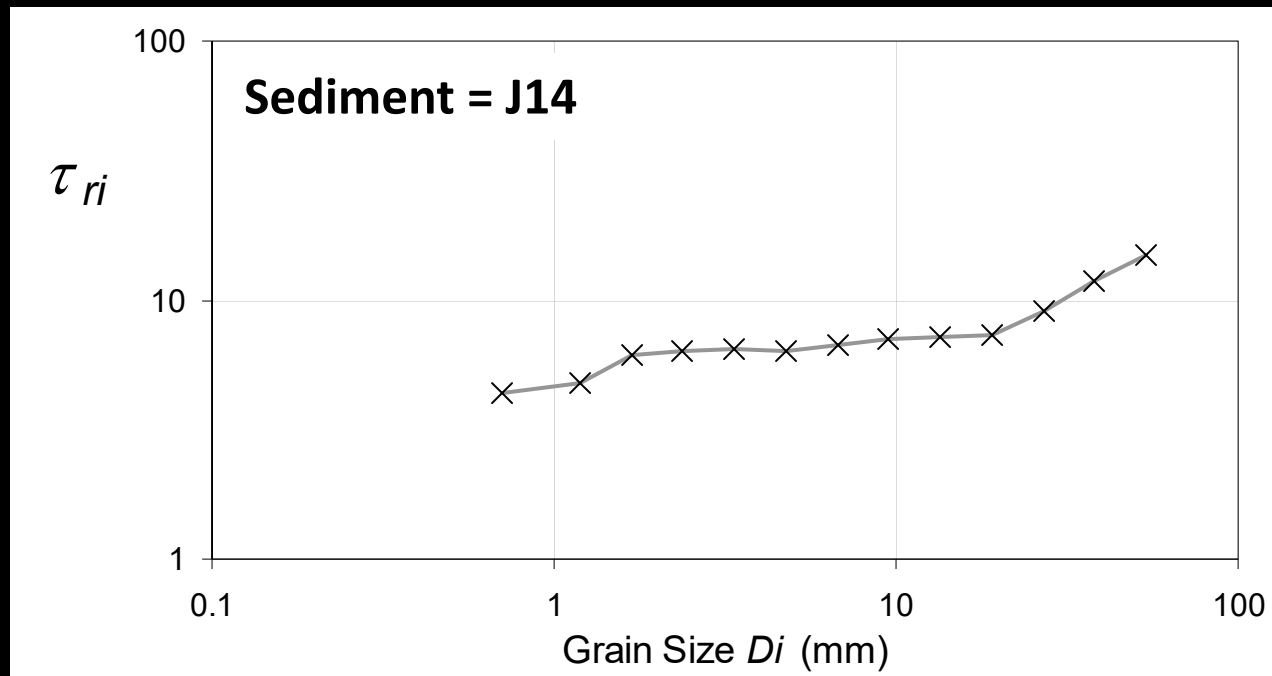
The Point:

The transport function does not contain grain size!

Building a surface-based transport model



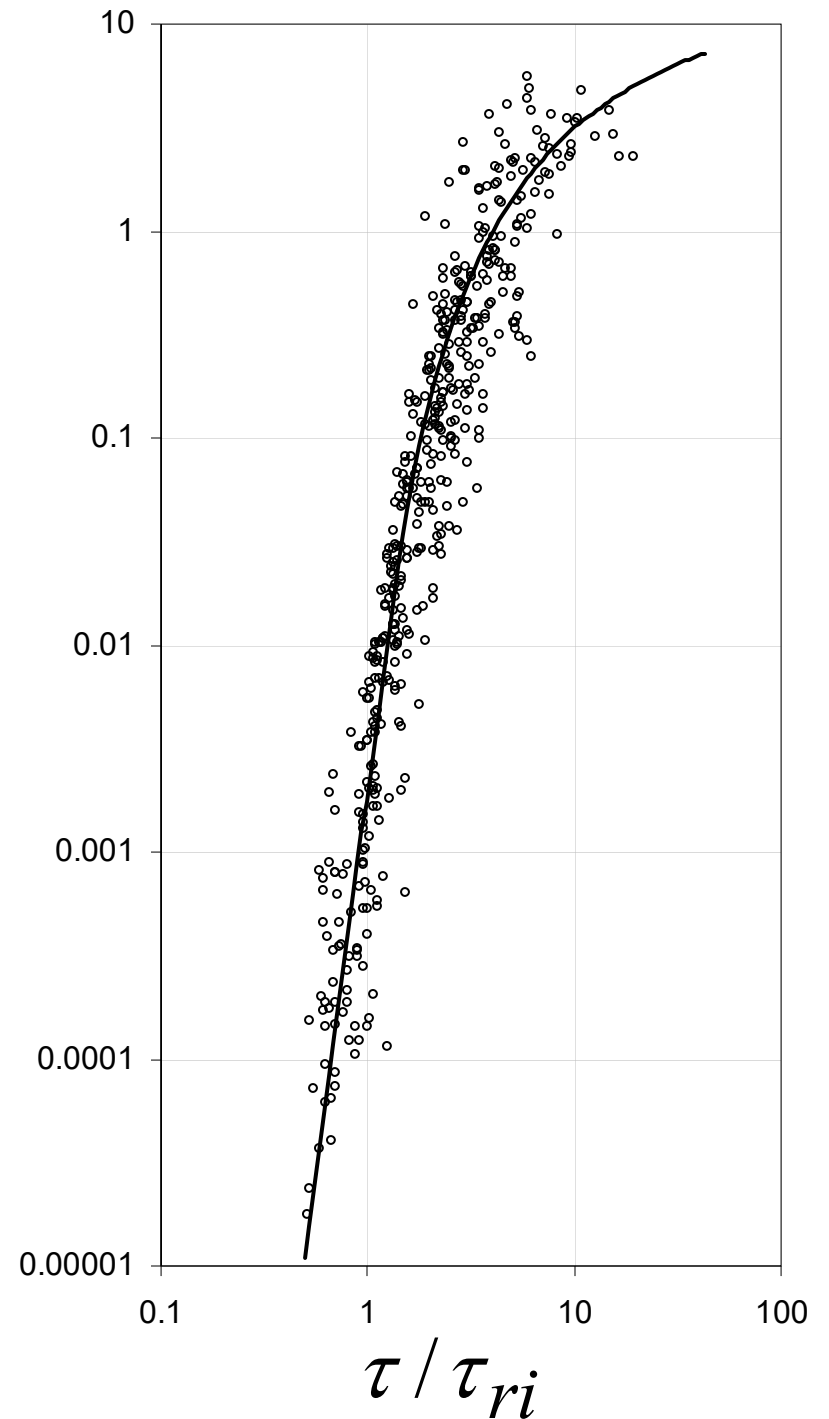
It remains to explain $\tau_{ri} \dots$



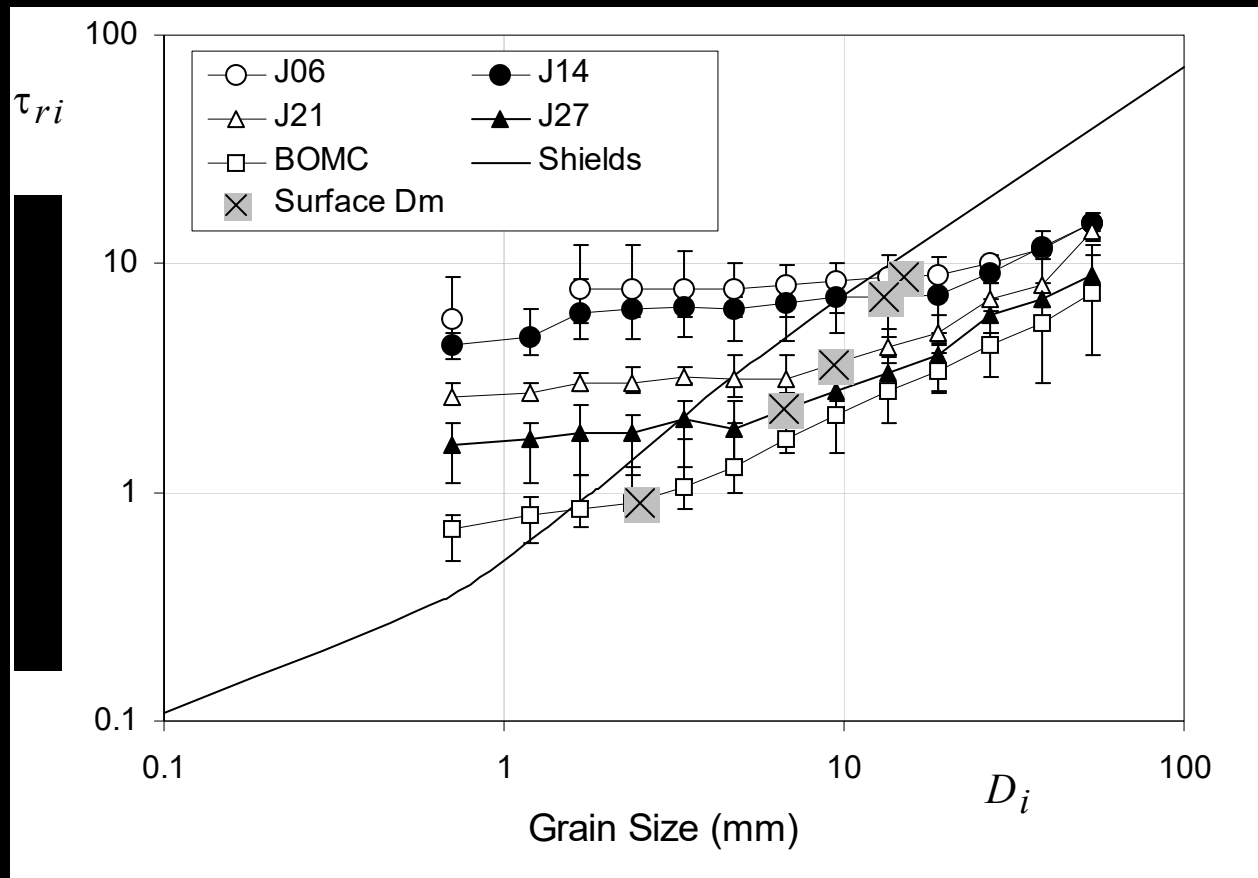
Surface-Based Transport Model

All sizes,
All runs,
All sediments

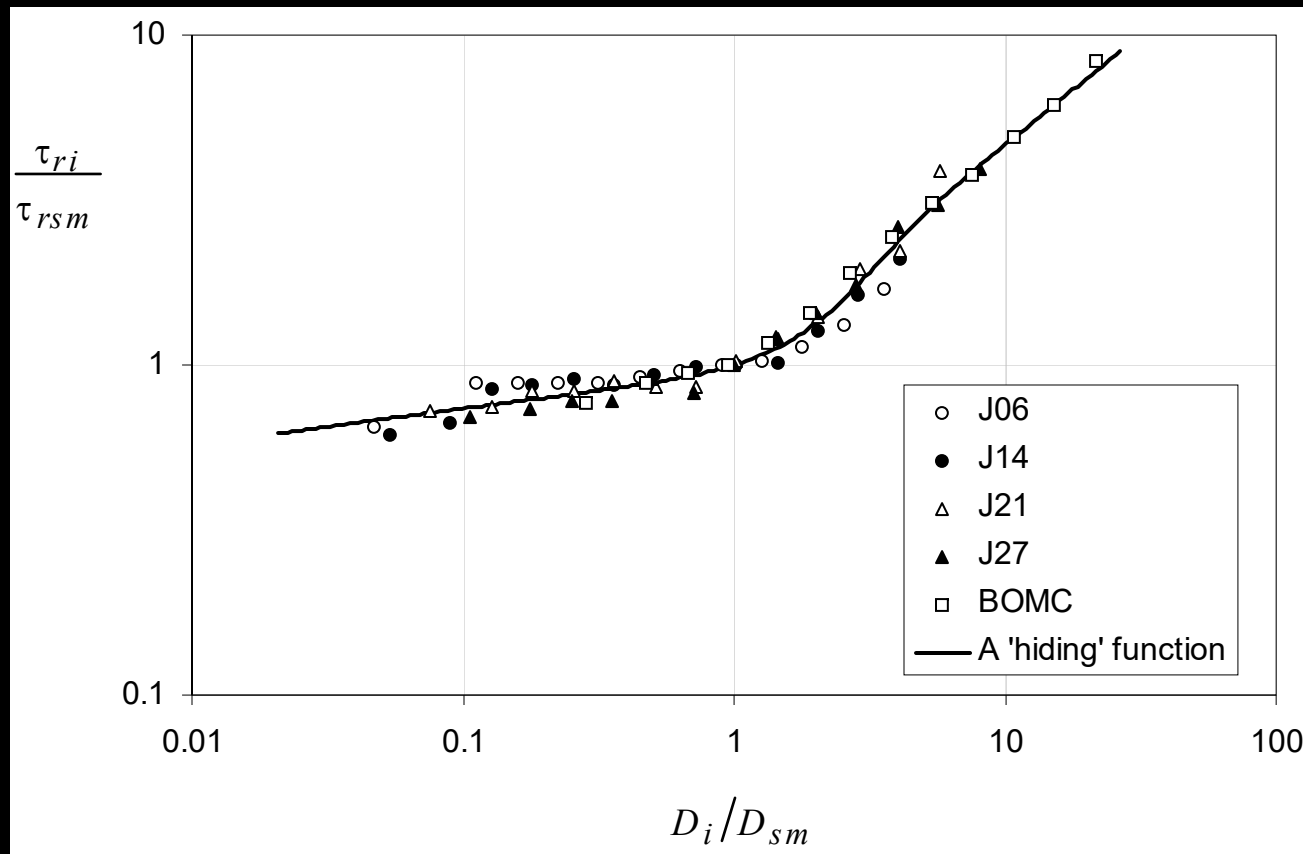
W_i^*



Values of τ_{ri} for all sizes and all sediments



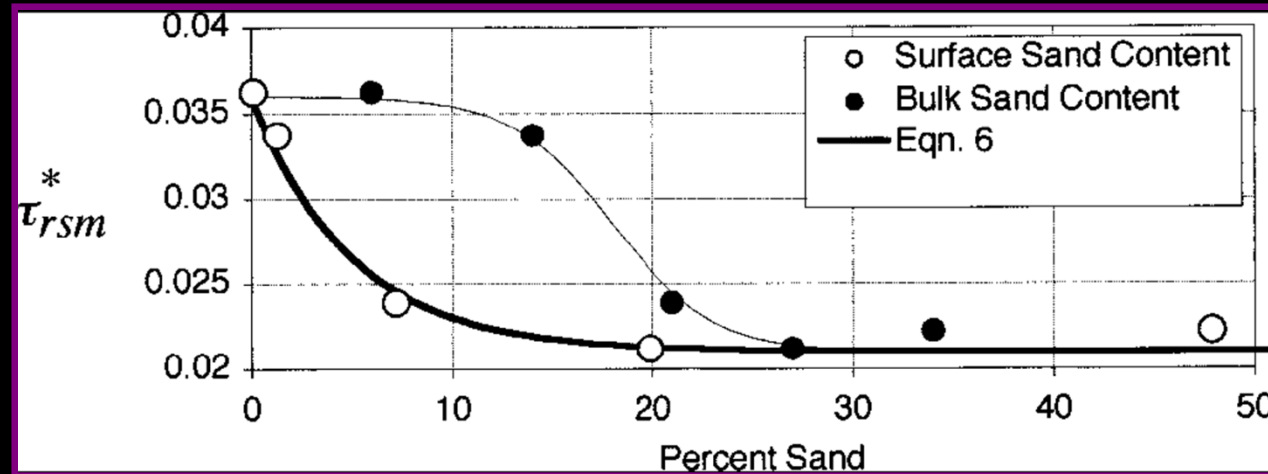
Values of τ_{ri} collapse nicely when divided by values at the mean size D_{sm}



Relative size effect weaker for larger sizes
(absolute size effect makes τ_{ri} increase with D_i)

It remains to explain $\tau_{rm} \dots$

Sand Interaction Function



The sand interaction function completes the surface-based transport model

Surface-based Transport Model for Mixed-Size Sediment

Peter R. Wilcock, M.ASCE,¹ and Joanna C. Crowe²

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Surface-based transport model can be used in both forward & inverse forms

- **Forward:** predict transport rate & grain size as function of τ and bed surface grain size
- **Inverse:** predict τ and bed surface grain size as function of transport rate & grain size

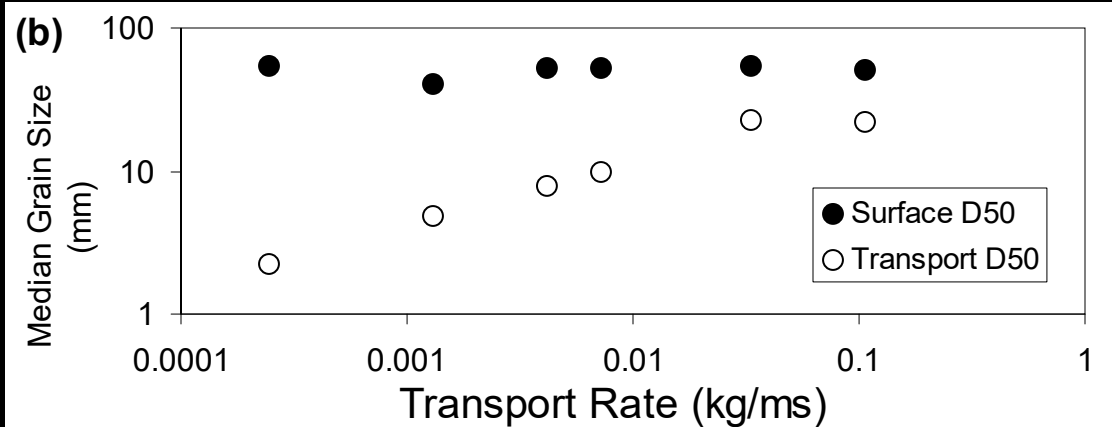
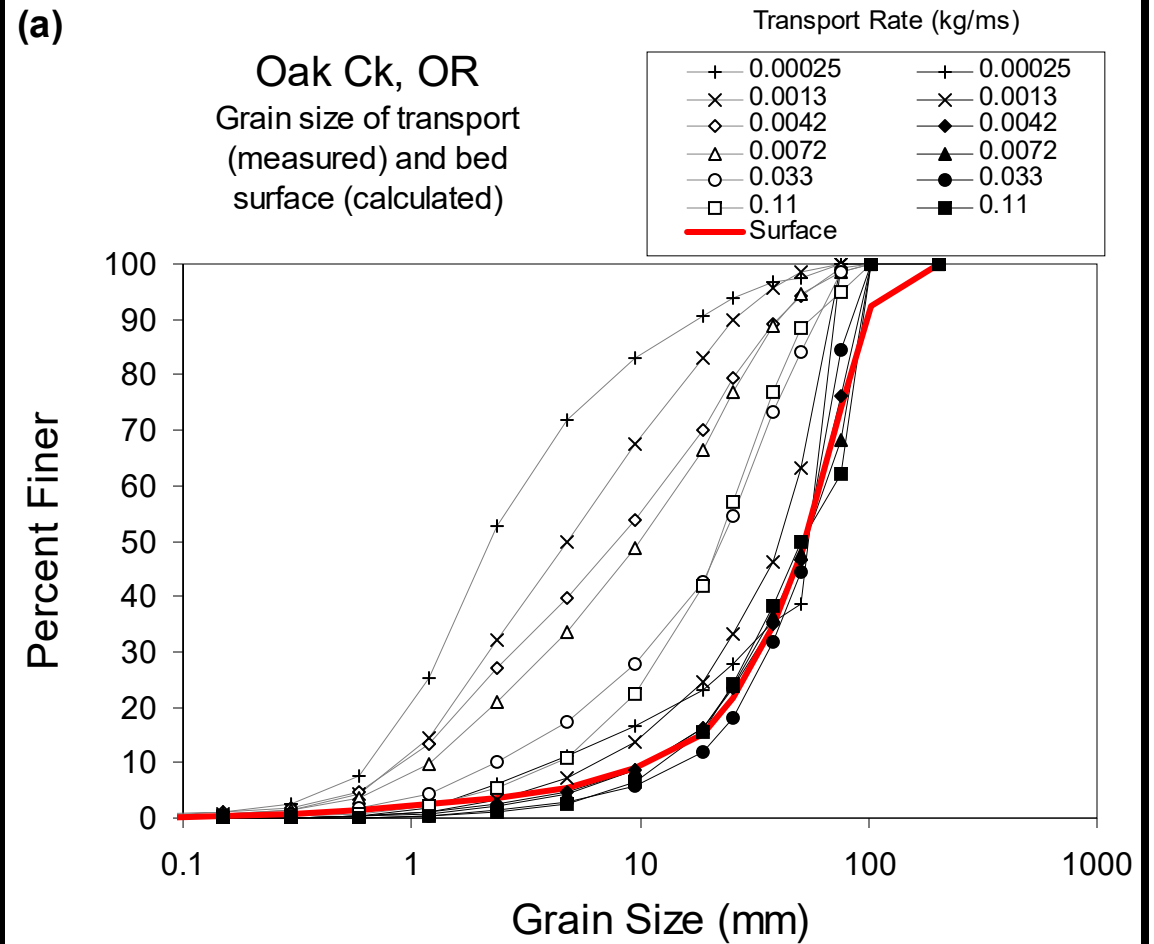
Don't try this with a subsurface –based model!

The **inverse** model provides a useful tool for considering **armor persistence** – because we do have good transport data from the field

To the field! →

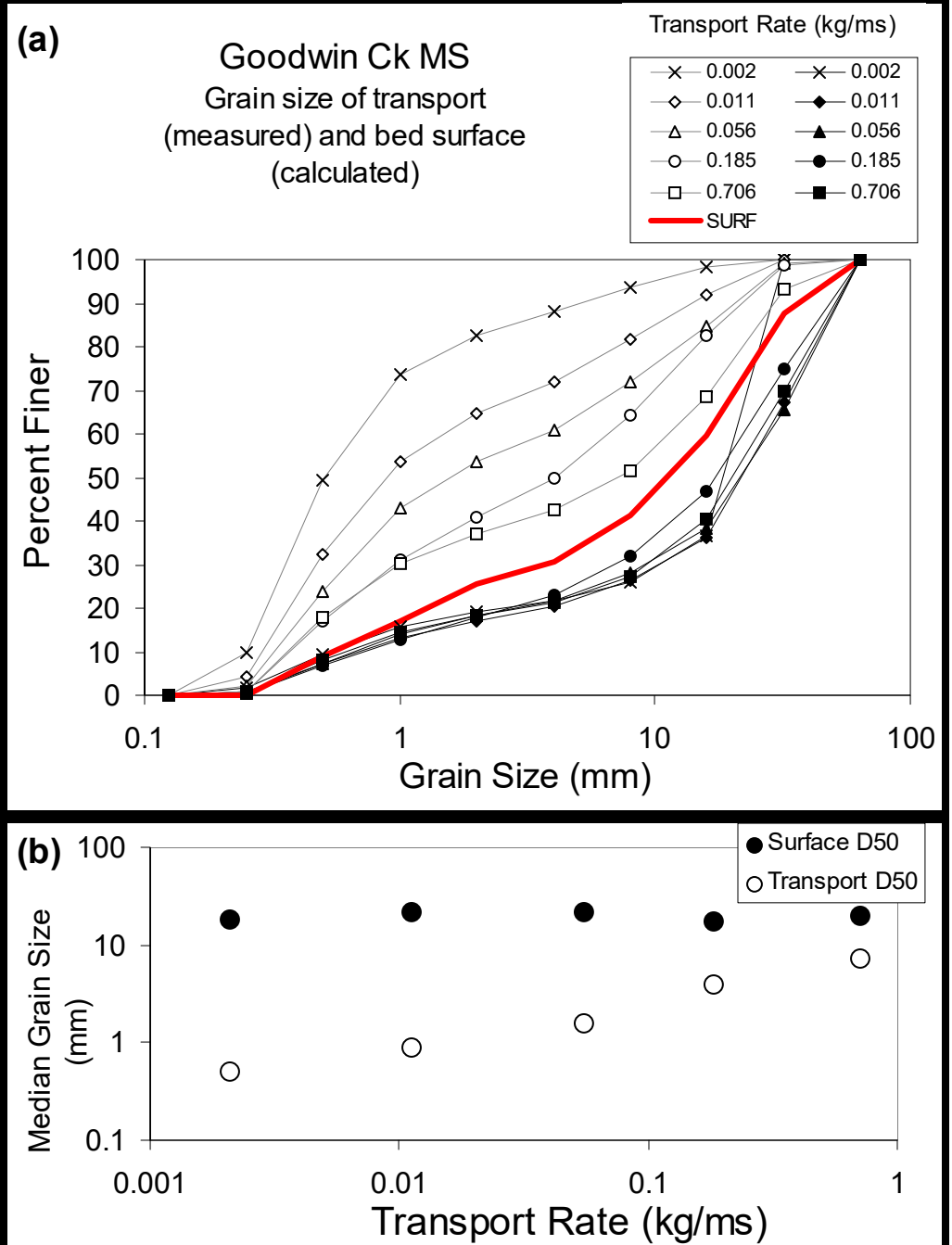
Transport grain size increases with flow!

iSBTM not only predicts a persistent armor layer, it also predicts the surface grain size observed in the field!



Again,
transport grain
size increases
with flow!

Again, iSBTM
predicts a persistent
armor layer. This
time it overpredicts
the surface grain size
observed in the field!
Reason: *dunes*!



At “reach” and “storm” scales of space and time

- Armor layer grain size appears to be persistent – a real advantage for predicting roughness & transport during floods: a low flow measurement of bed composition may suffice (unless dunes develop)



Increasing transport grain size balances change in grain mobility to produce a constant bed surface

A SBTM needed to model transients



(IV) Alluvial Channel Design

Connecting sediment supply to the design problem

- 1. Reconnaissance phase:** What is the trajectory of the stream? How has it responded to changes in water and sediment supply over the years? *{Henderson relation \rightarrow mixed-size sed}*
- 2. Develop flood series, specify flood frequency $\rightarrow Q_{bf}$.**
{Select Q_{bf} for flood frequency specified to maintain riparian ecosystem & prevent vegetation encroachment}
- 3. Estimate sediment supply**
- 4. Planning phase:** What slope S is needed to carry the sediment supply with the available flow?
{How does S vary with Q_s and width b ?}
- 5. Develop flow duration curve**
- 6. Design phase:** Evaluate trial designs. Will the sediment supply be routed through the reach over the flow duration curve?
{Build 1-d hydraulic model for trial design. Calculate cumulative transport over flow duration curve at each section; evaluate sediment continuity.}

A mixed-size transport model can be used in both forward & inverse forms

- **Forward:** Given τ and bed surface grain size \rightarrow predict transport rate & grain size
- **Inverse:** Given transport rate & grain size \rightarrow predict τ and bed surface grain size

Forward: predict transport rate & grain size
as a function of τ and bed surface grain size

Hydraulic Model

$$q, U, h, S \Rightarrow \tau$$

Transport Model

$$\tau, \text{bed grain size} \Rightarrow q_b, \text{transport grain size}$$

Inverse: predict τ and bed surface grain size
as function of transport rate & grain size

Hydraulic Model

$$U, h, S \Leftarrow q, \tau$$

Transport Model

$$\tau, \text{bed grain size} \Leftarrow q_b, \text{transport grain size}$$

We can use an inverse transport model to forecast, or design, a steady state channel that will transport a specified sediment supply rate *and* grain size with the available flow (!)

Presenting

iSURF

1. State Diagram I –

transport v. discharge, lines of constant slope

2. State Diagram II –

transport v. slope, lines of constant discharge

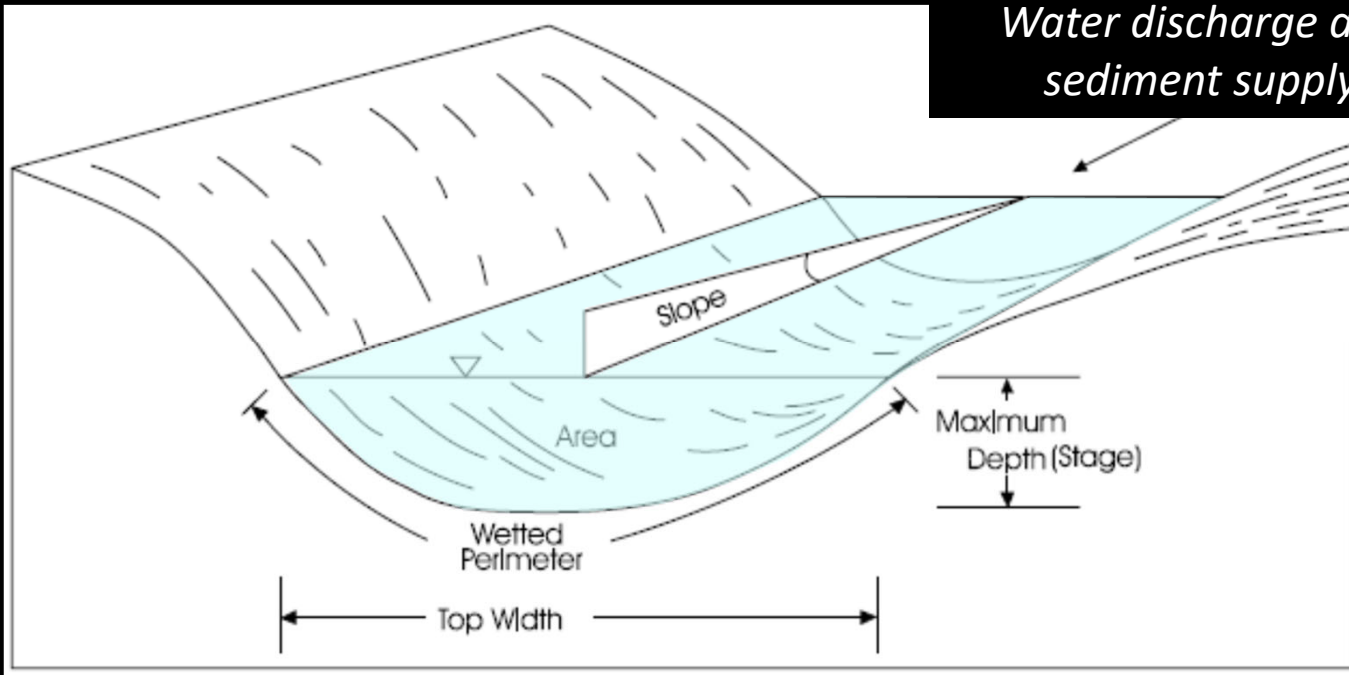
3. Channel Stability Diagram

- **Inverse Model:** predict τ and bed surface grain size as $\text{fn}(\text{transport rate \& grain size})$
- Specify discharge and basic channel geometry and solve for slope (*& depth*)

How big the channel?

Given

Water discharge and
sediment supply



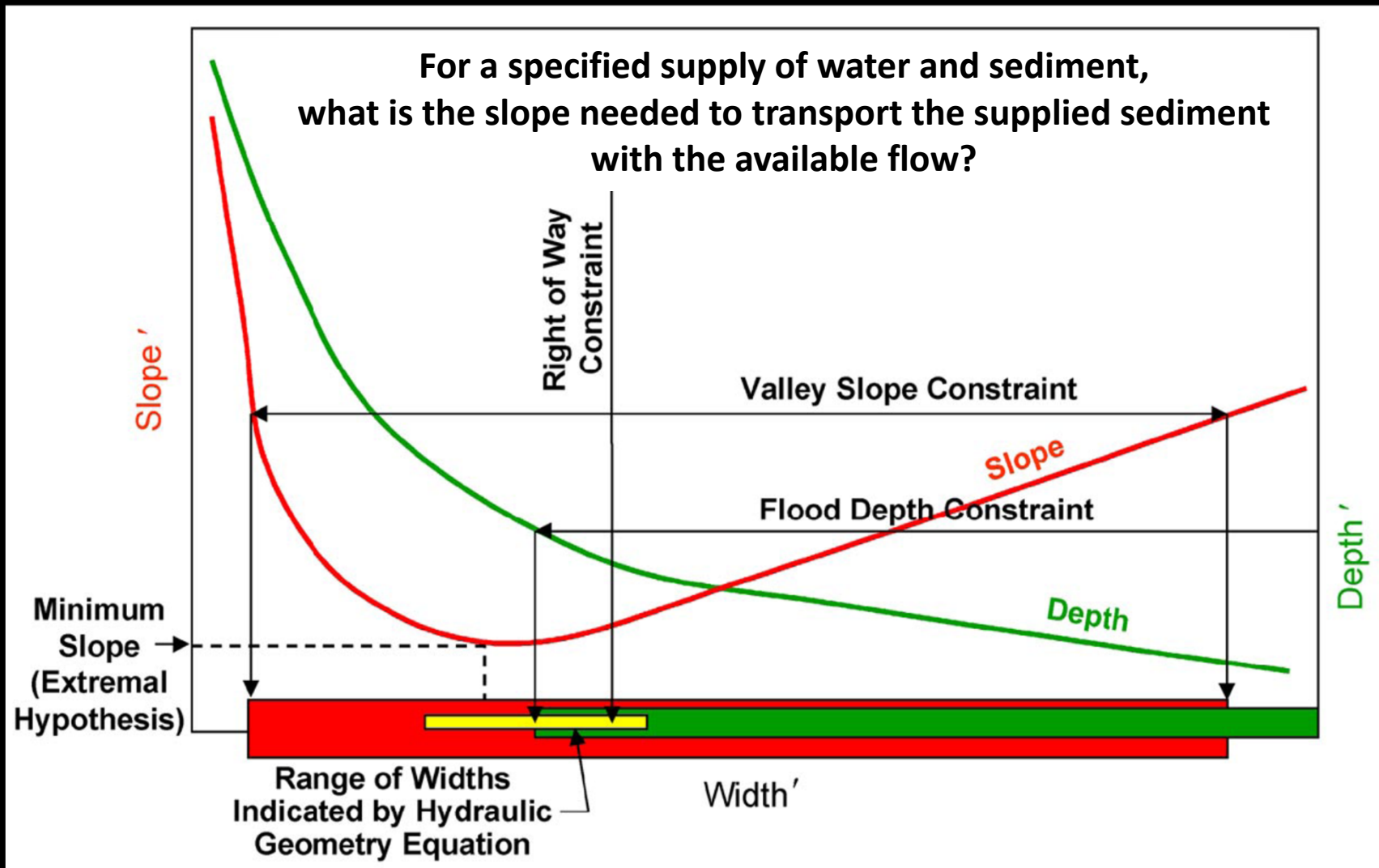
Find

channel
slope, depth & width
(& velocity & shear)

*We have enough general relations to solve for
all but one of these unknown variables*

If we specify channel width, we can solve for the rest of the variables

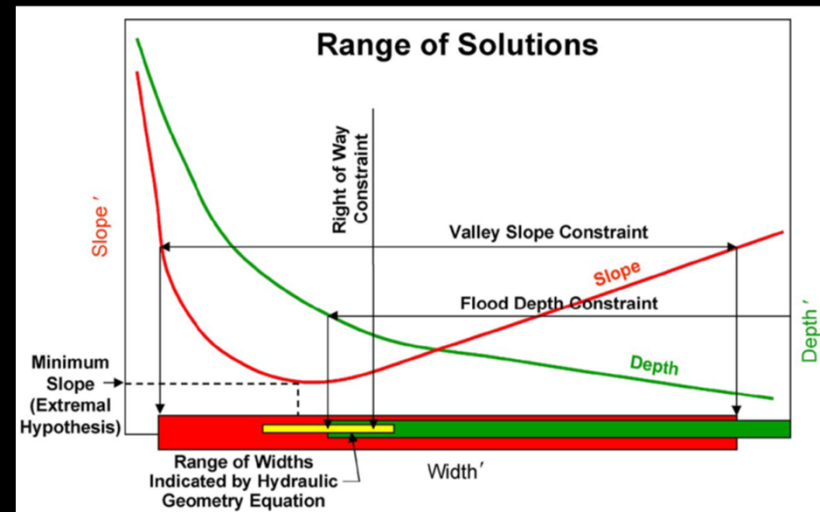
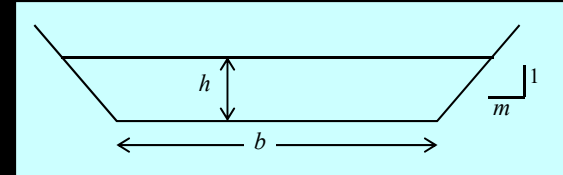
What slope is needed to transport the supplied sediment with the available water?



Hydraulic Design of Stream Restoration Projects September 2001
RR Copeland, DN McComas, CR Thorne, PJ Soar, MM Jonas, JB Fripp

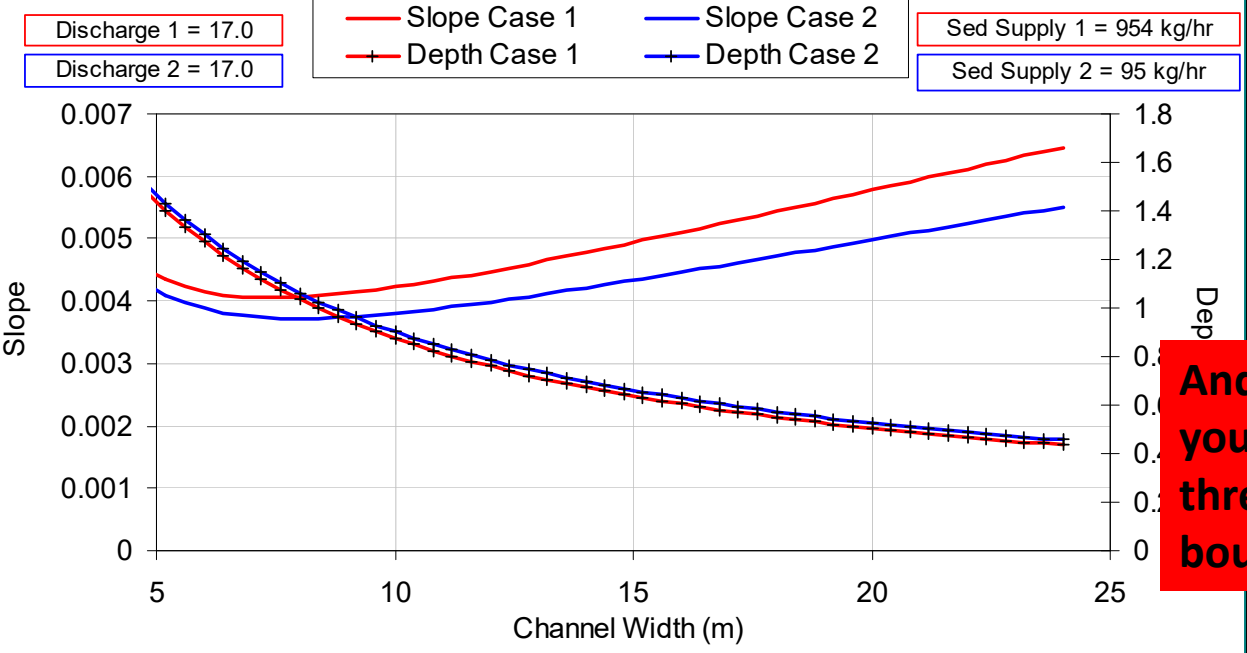
iSURF Channel Stability Diagram

what slope is needed to transport a specified sediment supply of specified size distribution with a specified discharge?

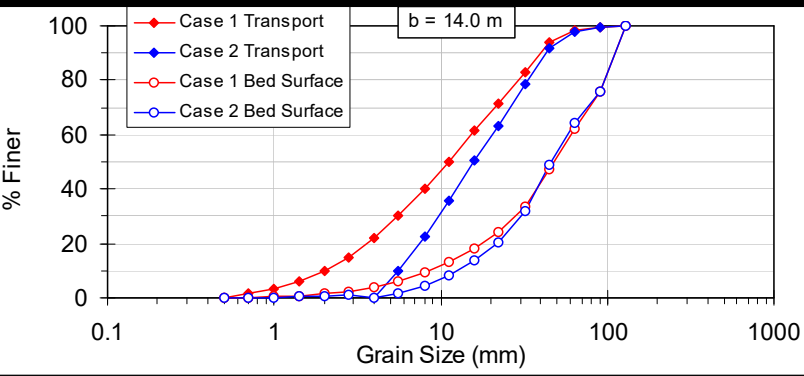


Find velocity, boundary stress, depth, slope, and bed surface grain size from continuity, momentum, flow resistance, and the Wilcock-Crowe Surface-Based Mixed-Size Sediment Transport Model

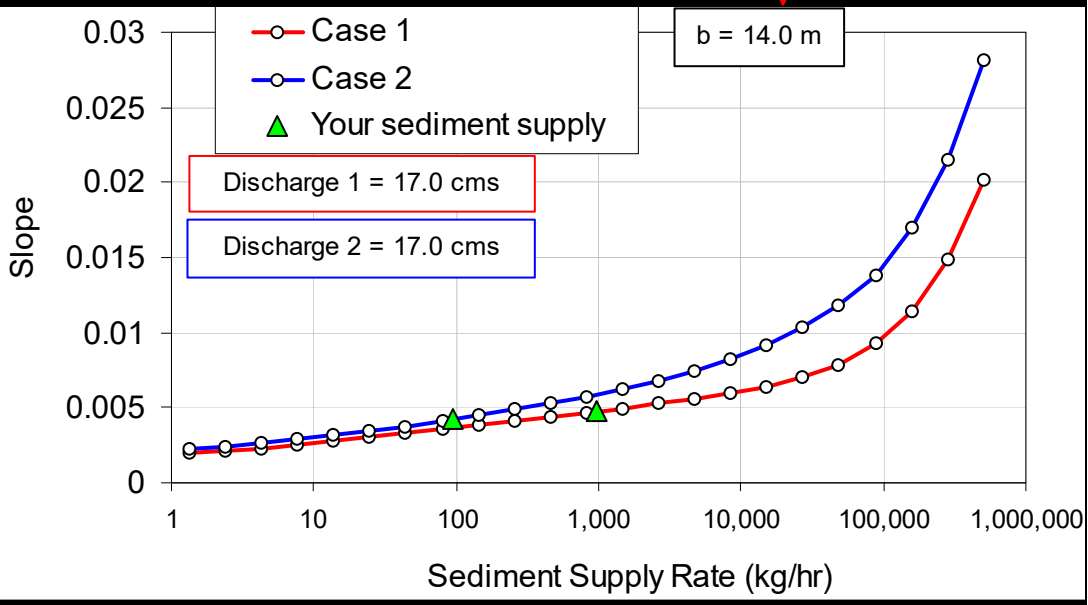
Channel Stability Diagram



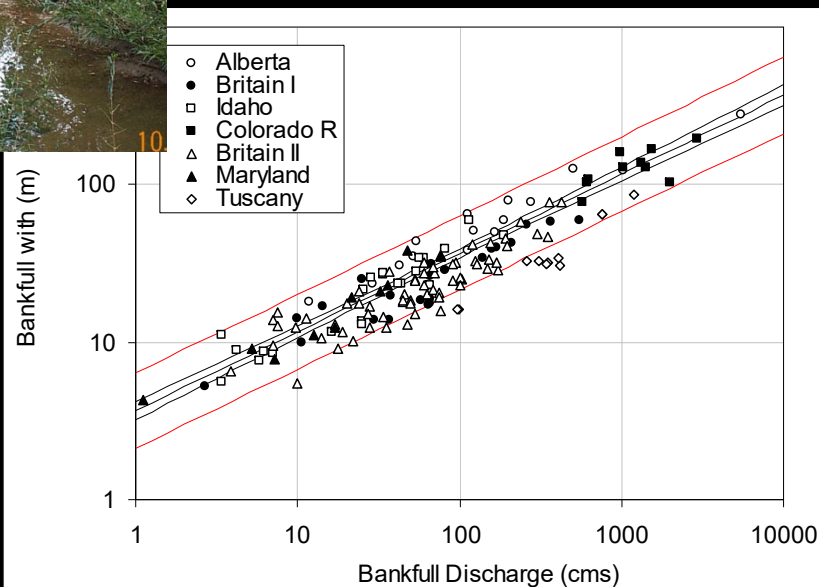
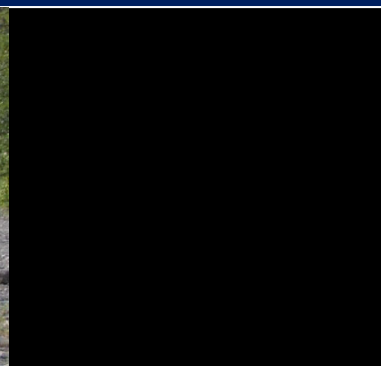
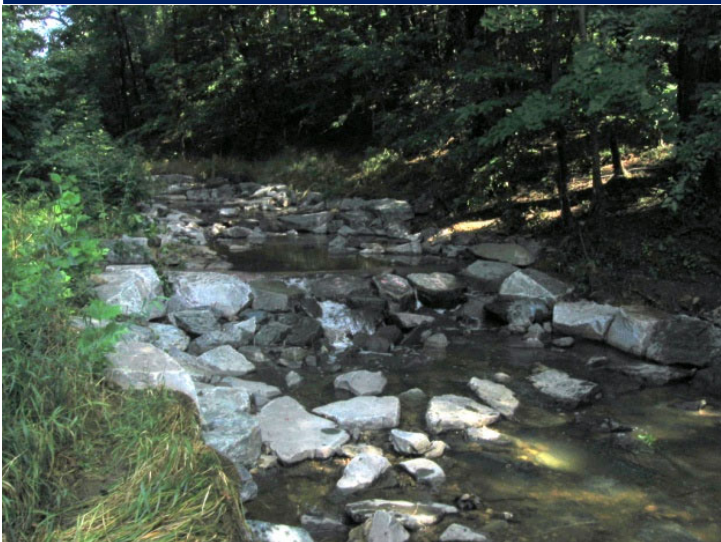
And get a measure of where you are relative to the threshold/alluvial channel boundary !



As a bonus, you find out how armored the bed becomes !



Sometimes, sediment supply does not matter



So, what is a SMALL sediment supply rate?

That sounds dangerously like a real question, so first, lets deal with real sediments, which contain a mixture of sizes

But for mixed-size sediment, there are complications ...

- Grain size of bed \neq grain size of transport
- Bed is sorted spatially and vertically
- Transport is a function of the changing population of grains on the bed surface

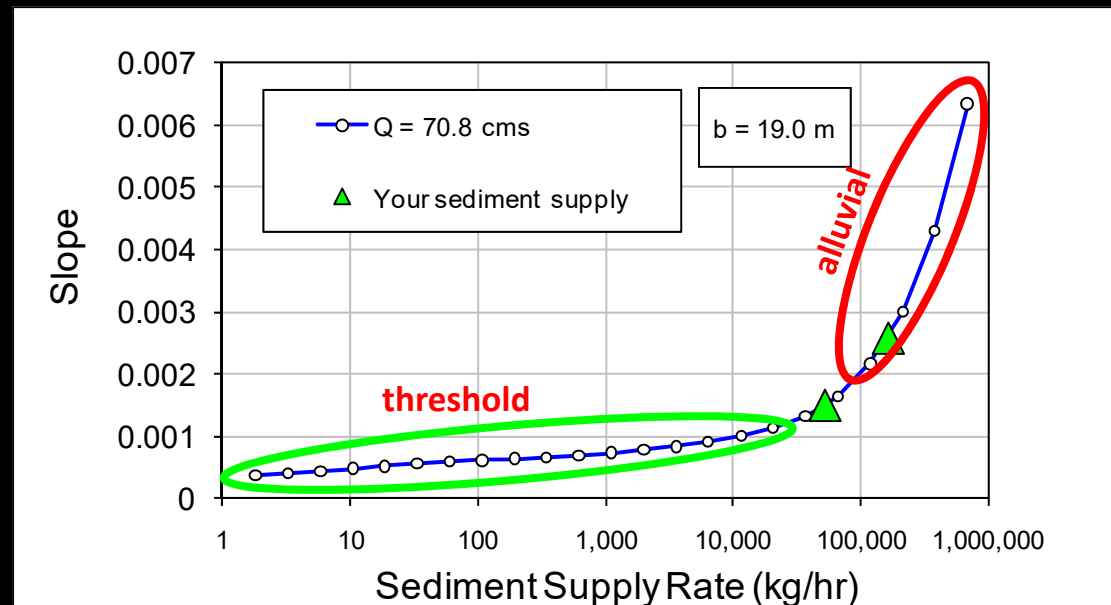


Is an accurate sediment supply estimate needed?

If your sediment supply is safely below the boundary between “low” slope and “high” slope, channel slope is relatively insensitive to sediment supply – you are less likely to accumulate sediment given an error in estimating sediment supply

Threshold Design Approach

Just make the channel strong enough to stand up to high flows



Design steps incorporating sediment supply

1. **Reconnaissance phase:** What is the trajectory of the stream? How has it responded to changes in water and sediment supply over the years?

iSURF State Diagrams

$$\frac{S_2}{S_1} = \sqrt{\frac{q_{b2}}{q_{b1}}} \left(\frac{D_2}{D_1} \right)^{3/4} \left(\frac{q_1}{q_2} \right)$$

2. **Develop flood series, specify flood frequency → Design Q.**

{Select Q_{bf} for flood frequency specified to maintain riparian ecosystem & prevent vegetation encroachment}

3. **Estimate sediment supply**

4. **Planning phase:** What slope S will transport the sediment supply with the available Q_{bf} ? Calculate (b, S) combination { S and valley slope determine sinuosity}

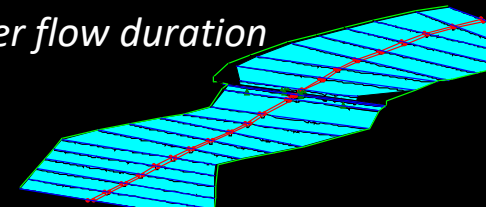
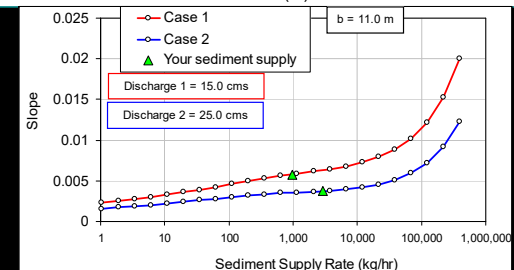
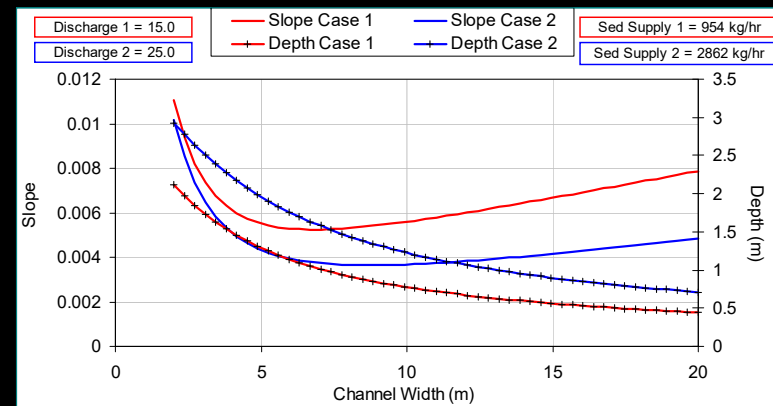
Check if alluvial v. threshold channel

5. **Develop flow duration curve**

6. **Design phase:** Evaluate trial designs. Will the sediment supply be routed through the reach over the flow duration curve?

{Build 1-d hydraulic model for trial design. Calculate cumulative transport over flow duration curve at each section; evaluate sediment continuity.}

7. Bottlenecks or blowouts? Adjust for sediment continuity



Alluvial Channel Design Example

Example 2: Stable channel analytical method

Given: Dimensions of the upstream natural channel reach are:

Base width = 22 ft (6.7 m)

Side slopes

Left bank = 2.2H:1V

Right bank = 1.1H:1V

Side slope roughness coefficient = 0.07

Channel slope = 0.0025

Bed material — sandy gravel

$D_{84} = 22 \text{ mm}$ $D_{50} = 3.7 \text{ mm}$

$D_{16} = 0.43 \text{ mm}$

Design discharge = 2,500 ft³/s (70.8 m³/s)

Design values for the bypass channel:

Side slopes = 3H:1V

Side slope roughness coefficient = 0.045

Valley slope = 0.0020 (maximum design slope)

Objective: Determine stable channel dimensions for a diversion channel. Upstream natural stream is coming out of a hillside watershed.

1. Supply reach

Estimate sediment transport rate

2. Design reach

Given discharge and sediment supply rate and grain size, calculate slope needed to transport supplied sediment at a specified channel width

1. Find stress in upstream "supply" channel

NEH-654 Chapter 9 Example 2, p. 39

Given geometry of a trapezoid channel w/ specified bed material and side roughness, find boundary and grain stresses

Q	70.79	cms
S	0.0025	
D50	3.7	mm
D84	22	mm
m	1.6	
nD	0.022	
ns	0.07	

Enter information only in green cells!!
No cutting and pasting!
No inserting or deleting rows!

Given: Dimensions of the upstream natural channel reach are:

Base width = 22 ft

Side slopes

Left bank = 2.2H:1V

Right bank = 1.1H:1V

Side slope roughness coefficient = 0.07

Channel slope = 0.0025

Bed material — sandy gravel

$D_{84} = 22 \text{ mm}$ $D_{50} = 3.7 \text{ mm}$

$D_{16} = 0.43 \text{ mm}$

Channel-forming discharge = 2,500 ft³/s

B_o m	nc composite n	h m	B m	A m ²	R m	U m/s	τ_o Pa	τ' Pa	$u^{*'}m/s$
6.71	0.0369	2.97	16.2	34.0	1.90	2.08	46.6	21.1	0.145
B_o ft	nc	h ft	B ft	A ft ²	R ft	U ft/s	total boundary stress	Grain stress	Grain stress as a shear velocity
22.0	0.0369	9.74	53.2	366.3	6.23	6.83			

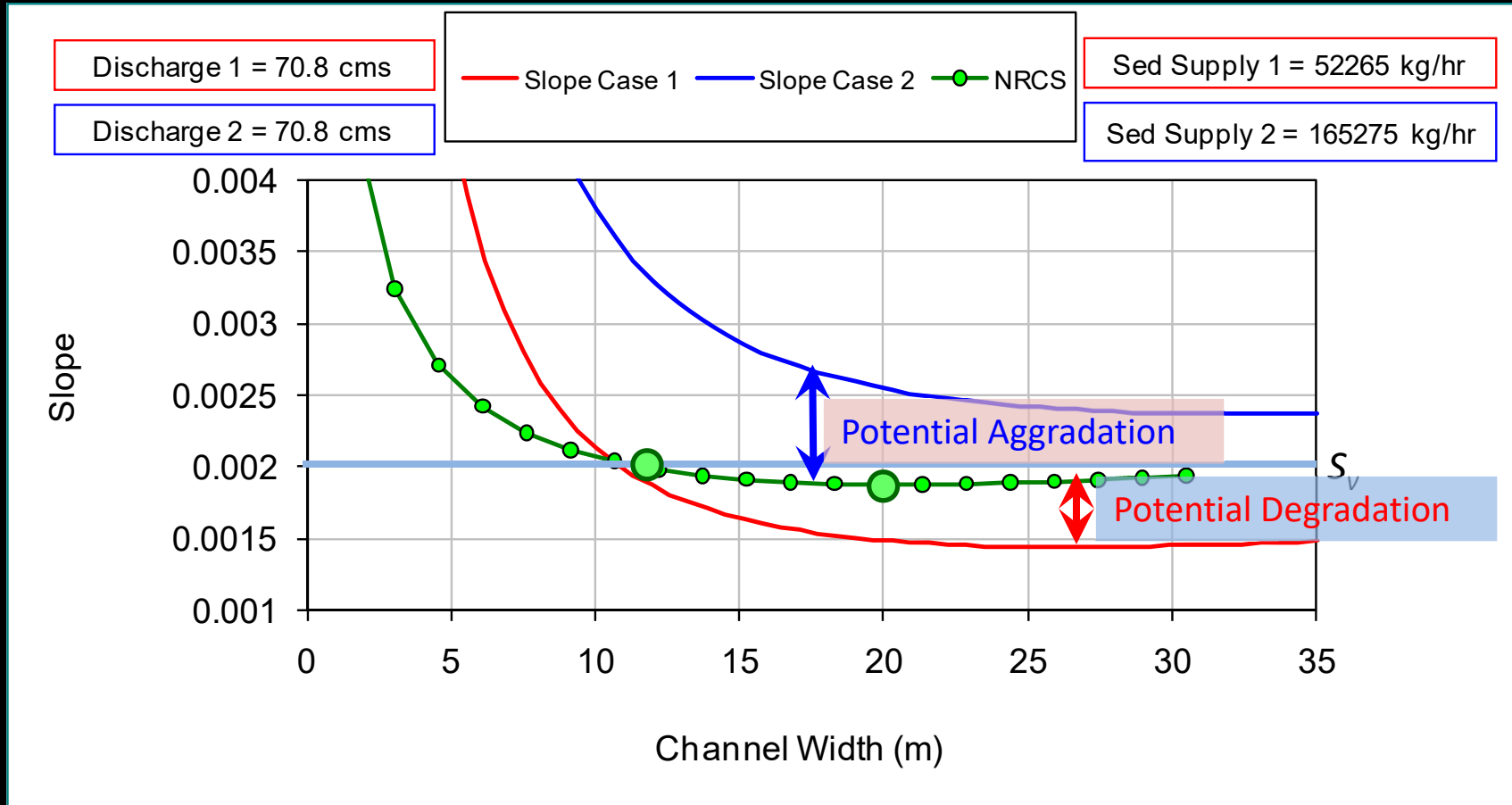
2. Find transport rate in upstream “supply” channel

SBTM - calculate transport rate and transport grain size from specified shear velocity and bed surface grain size			
RULES, CONVENTIONS, AND UNITS			
1. Cells for input data are highlighted in GREEN, cells for output data are ORANGE			
2. Grain-diameters must be in millimeters (mm)			
3. Cumulative percentiles, not fractions, are used			
4. Cumulative grain-size distribution percentiles must span from 0 to 100 %			
5. Shear velocity must be in meters-per-second (m/s)			
6. The 0 and 100 % must be EXACTLY 0 and 100			
INSTRUCTIONS			
1. In table below, enter grain size and cumulative % in order of decreasing grain size			
2. Enter your bed shear velocity			
3. Check input for errors, press Enter , and then click once on the Run SBTM button			
Parameter	Value	Description	Units
u*	1.45E-01	Bed shear velocity	m/s
qT	8.17E-04	Total transport rate	m ² /s
D (mm)	Surface CDF GSD (% Finer)	Transport CDF GSD (% Finer)	
64.00	100.00	100.00	
32.00	93.00	98.86	
16.00	77.00	93.03	
8.00	65.00	84.94	
4.00	53.00	72.39	
2.00	45.00	62.51	
1.00	35.00	49.35	
0.50	20.00	28.82	
0.25	10.00	14.65	
0.13	0.00	0.00	

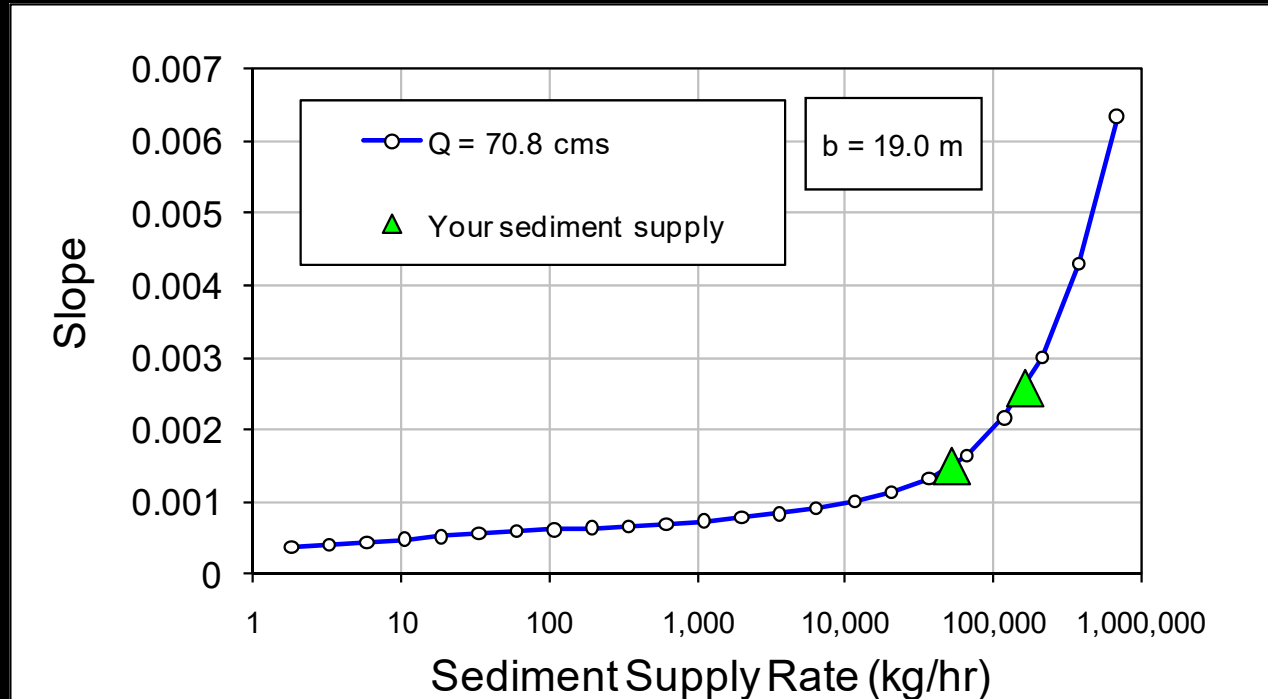
3. Enter transport rate and grain size from upstream “supply” channel as input to the channel stability code

Parameter	Value	Description	Units
Q_1	70.8	Case 1 water discharge	m ³ /s
Q_{T1}	0.005478475	Case 1 sediment supply rate	m ³ /s
Q_2	70.8	Case 2 water discharge	m ³ /s
Q_{T2}	0.01095695	Case 2 sediment supply rate	m ³ /s
b_{min}	3.00	Minimum bottom width	m
b_{max}	35.00	Maximum bottom width	m
D (mm)	Case 1 Transport Grain Size (% Finer)	Case 2 Transport Grain Size (% Finer)	
64.00	100.00	100.00	
32.00	98.86	98.86	
16.00	93.03	93.03	
8.00	84.94	84.94	
4.00	72.39	72.39	
2.00	62.51	62.51	
1.00	49.35	49.35	
0.50	28.82	28.82	
0.25	14.65	14.65	
0.13	0.00	0.00	

iSURF (Wilcock&Crowe) solution including case with 3x sediment supply



For this design problem, slope is very sensitive to sediment supply rate (because it is large)



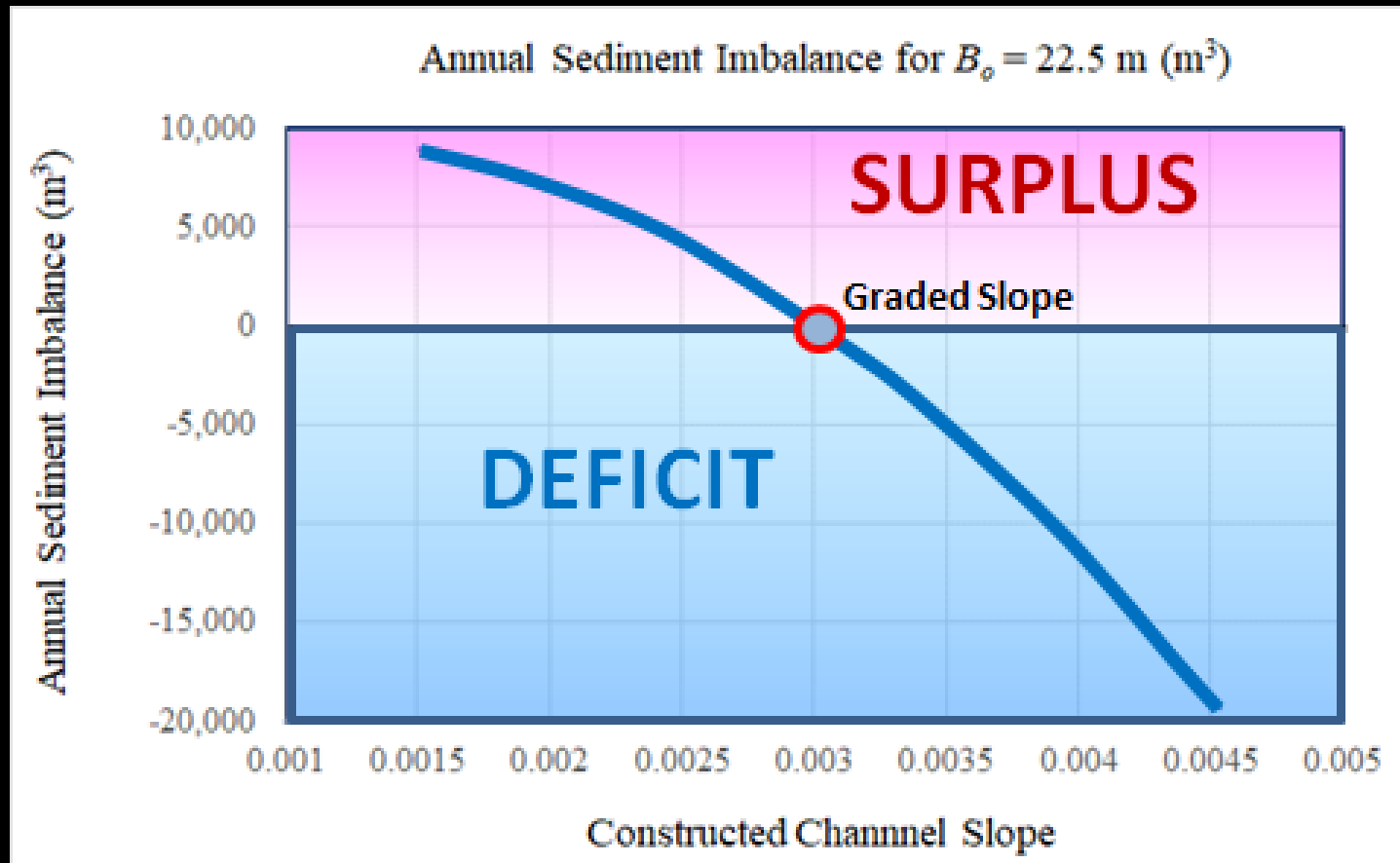
iSURF design module provides this plot of slope vs. sediment supply rate

What happens if we build the channel at a slope other than the graded slope?

$S = 0.003$ for a bottom width $B_o = 22.5$ m

We will either accumulate sediment (slope too small) or evacuate sediment (slope too large).

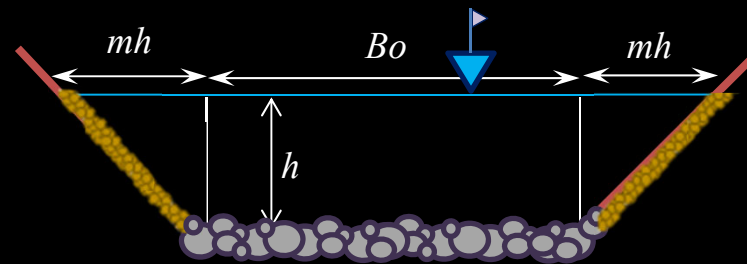
How much? Also a measure of consequences of uncertainty.



(V) Threshold & Alluvial Channel:
Together at last!

A simple view of channel behavior options

Consider a channel,
with bed and bank materials & dimensions,
Specify **water discharge**, **sediment supply**



1. Threshold channel

at what slope does
bed material move?

2. Mobile channel

at what slope does capacity
to transport sediment
match supply of sediment?

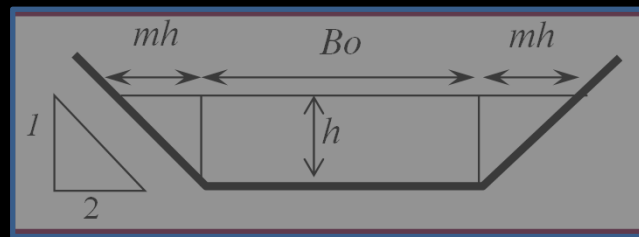
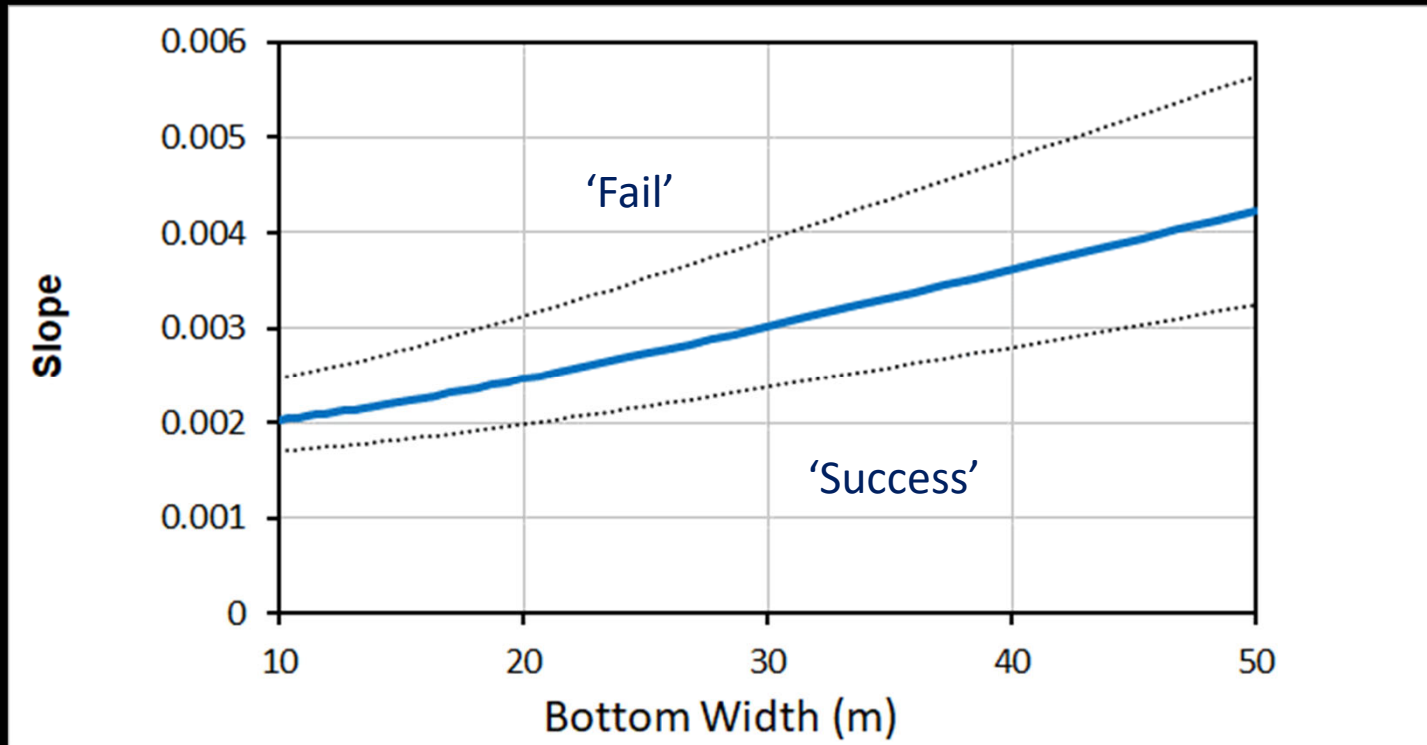
$Q = 100 \text{ m}^3/\text{s}$
 $D_{50} = 64 \text{ mm}$
 $D_{84} = 128 \text{ mm} \pm 10\%$
 $n = 0.04 \pm 10\%$
 $\tau_c^* = 0.03 \pm 10\%$

Supply v. Capacity

Competence

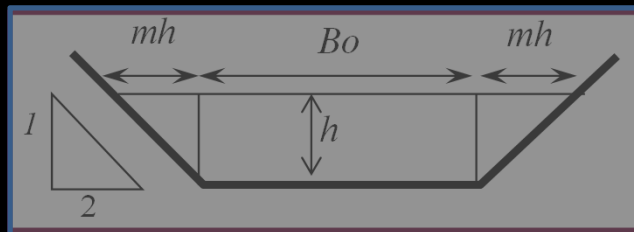
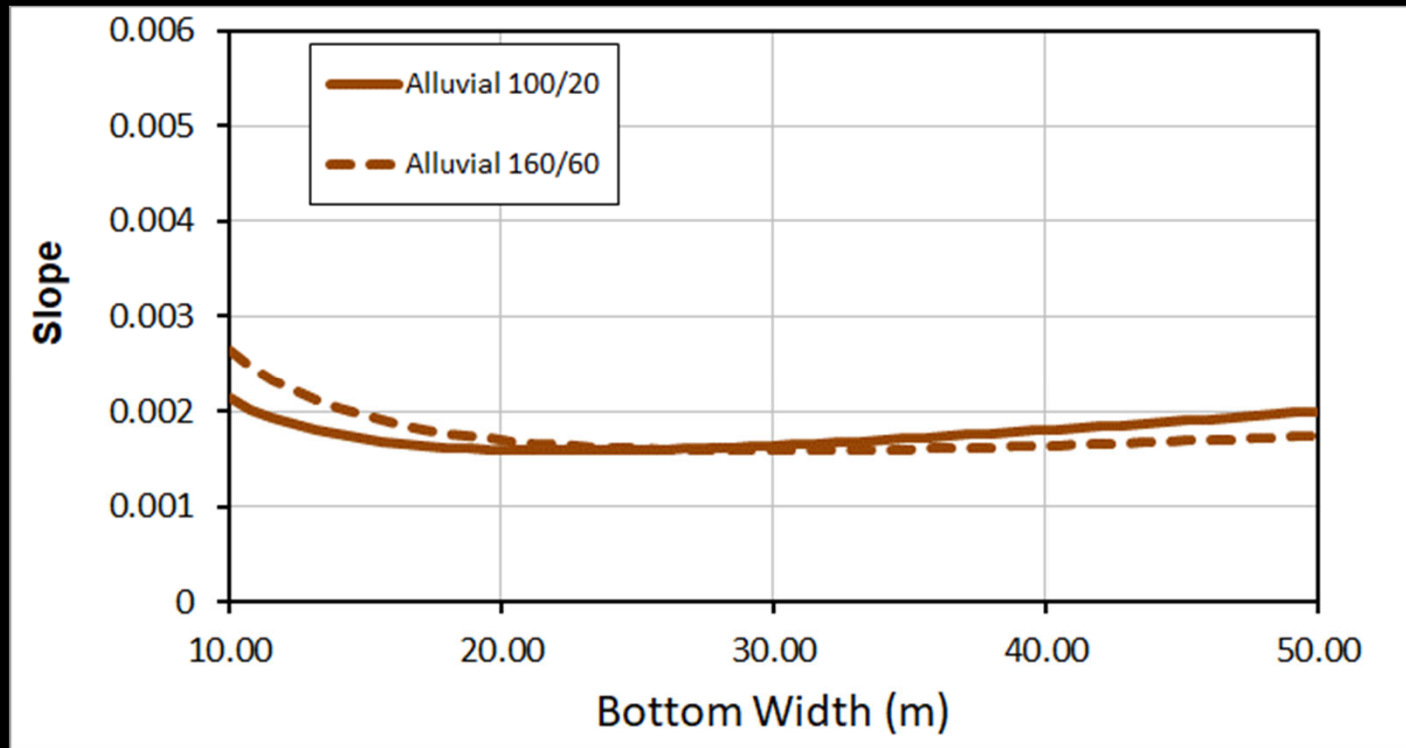
$Q = 100 \text{ m}^3/\text{s} \quad \{160 \text{ m}^3/\text{s}\}$
 $Q_s = 20 \text{ t/hr} \quad \{60 \text{ t/hr}\}$
Supply $D_{50} = 13 \text{ mm} (0.5 \text{ mm} - 128 \text{ mm})$

Failure in a threshold channel = grain entrainment



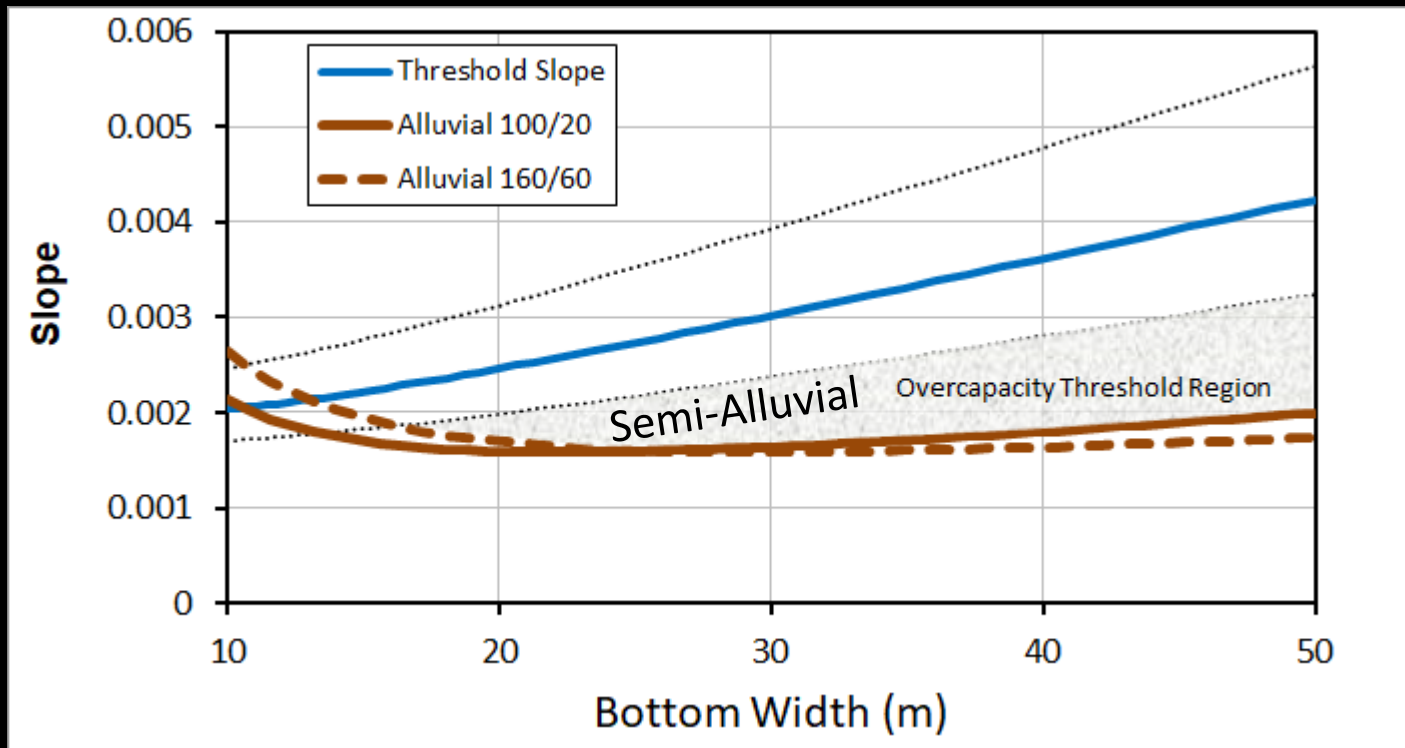
$Q = 100 \text{ m}^3/\text{s}$
 $D_{50} = 64 \text{ mm}$
 $D_{84} = 128 \text{ mm} \pm 10\%$
 $n = 0.04 \pm 10\%$
 $\tau_c^* = 0.03 \pm 10\%$

Mobile channel design = match transport capacity to sediment supply



$Q = 100 \text{ m}^3/\text{s}$ { $160 \text{ m}^3/\text{s}$ }
 $Q_s = 20 \text{ t/hr}$ { 60 t/hr }
 Supply $D_{50} = 13 \text{ mm}$ (0.5 mm - 128 mm)

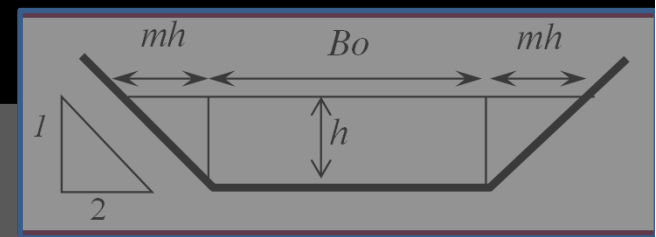
Over-capacity Threshold: combine threshold and alluvial



$Q = 100 \text{ m}^3/\text{s}$
 $D_{50} = 64 \text{ mm}$
 $D_{84} = 128 \text{ mm} \pm 10\%$
 $n = 0.04 \pm 10\%$
 $\tau_c^* = 0.03 \pm 10\%$

Supply v. Capacity

Competence



$Q = 100 \text{ m}^3/\text{s} \quad \{160 \text{ m}^3/\text{s}\}$
 $Q_s = 20 \text{ t/hr} \quad \{60 \text{ t/hr}\}$
 Supply $D_{50} = 13 \text{ mm} (0.5 \text{ mm} - 128 \text{ mm})$

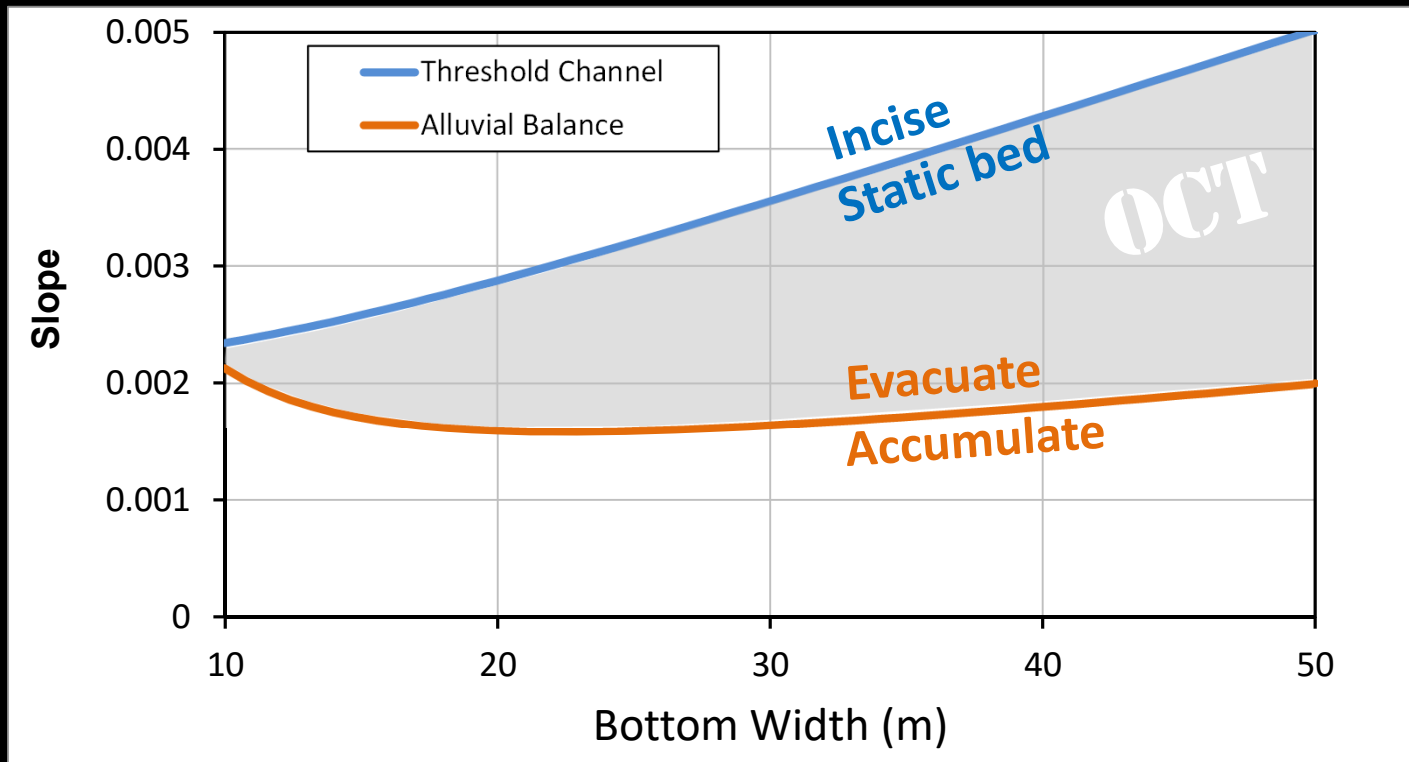
Bottom Line:

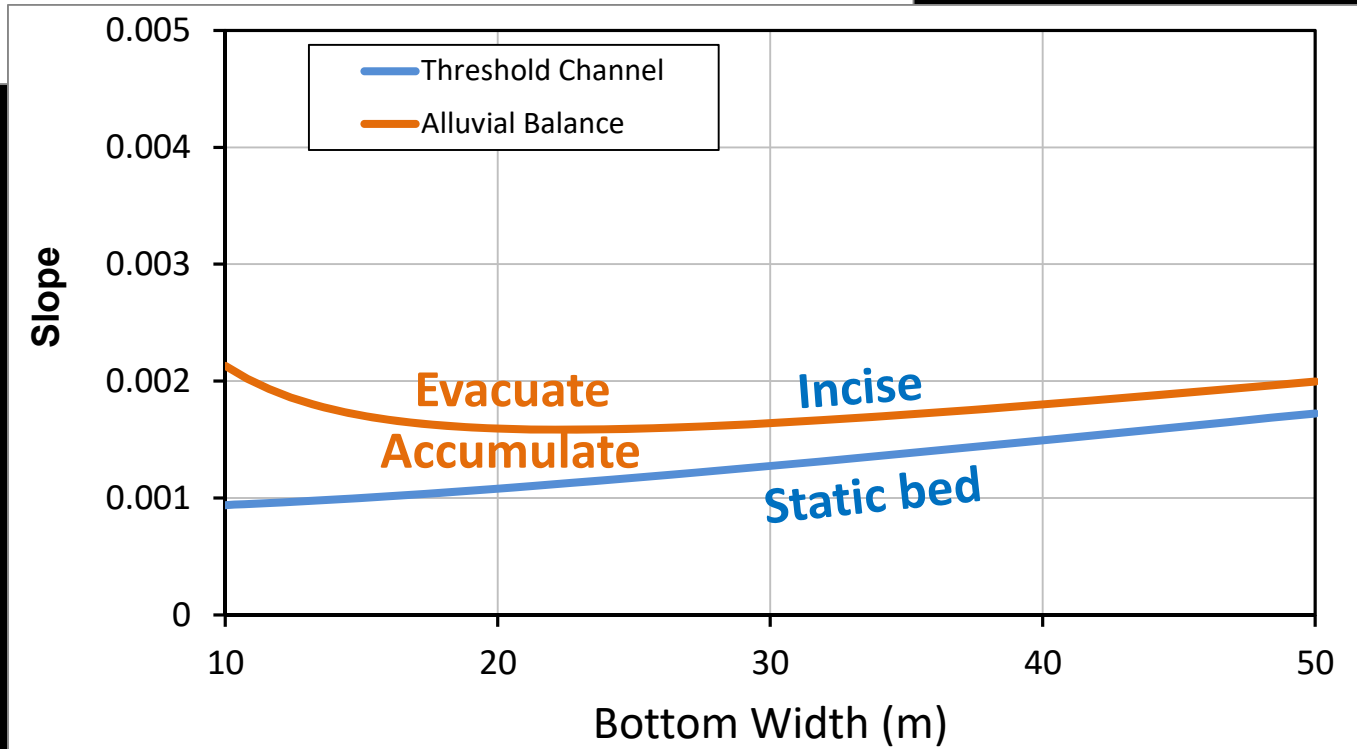
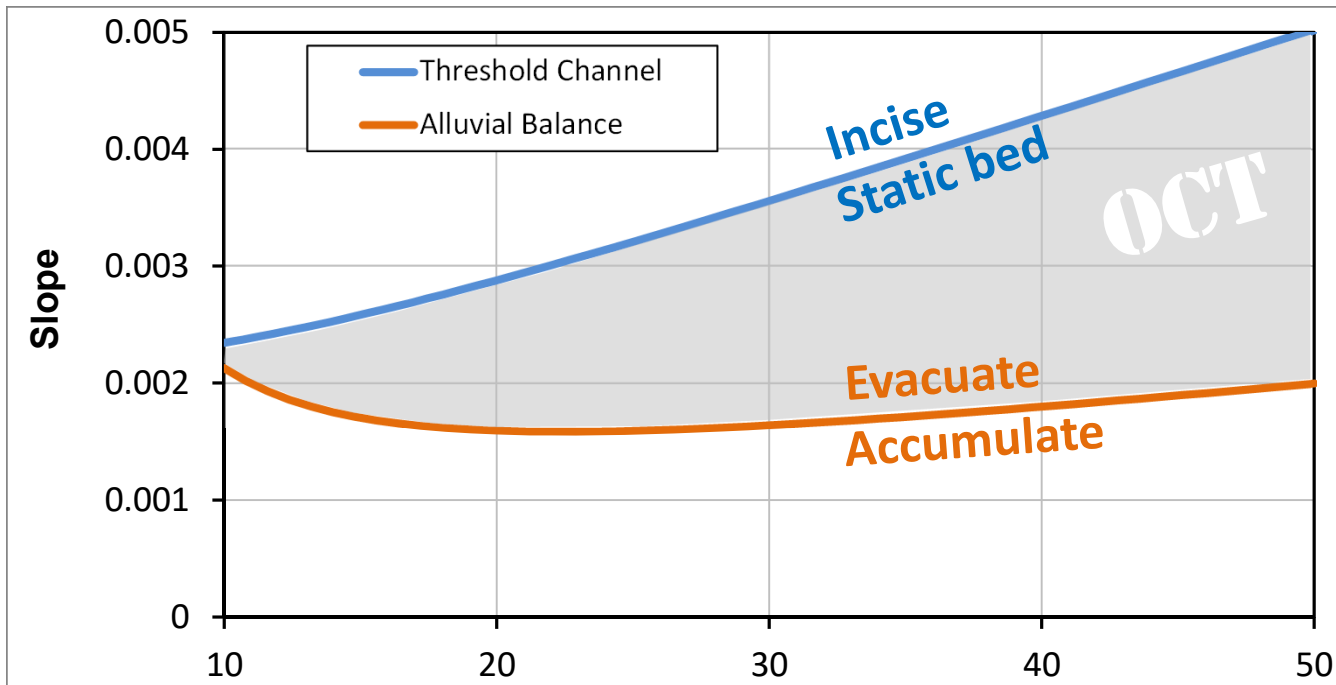
specify a width, a channel and its bed material, and a water & sediment supply

Critical Shields Number gives threshold channel slope

Transport Model gives alluvial channel slope

Range of widths gives indication of adjustments with respect to bed material transport



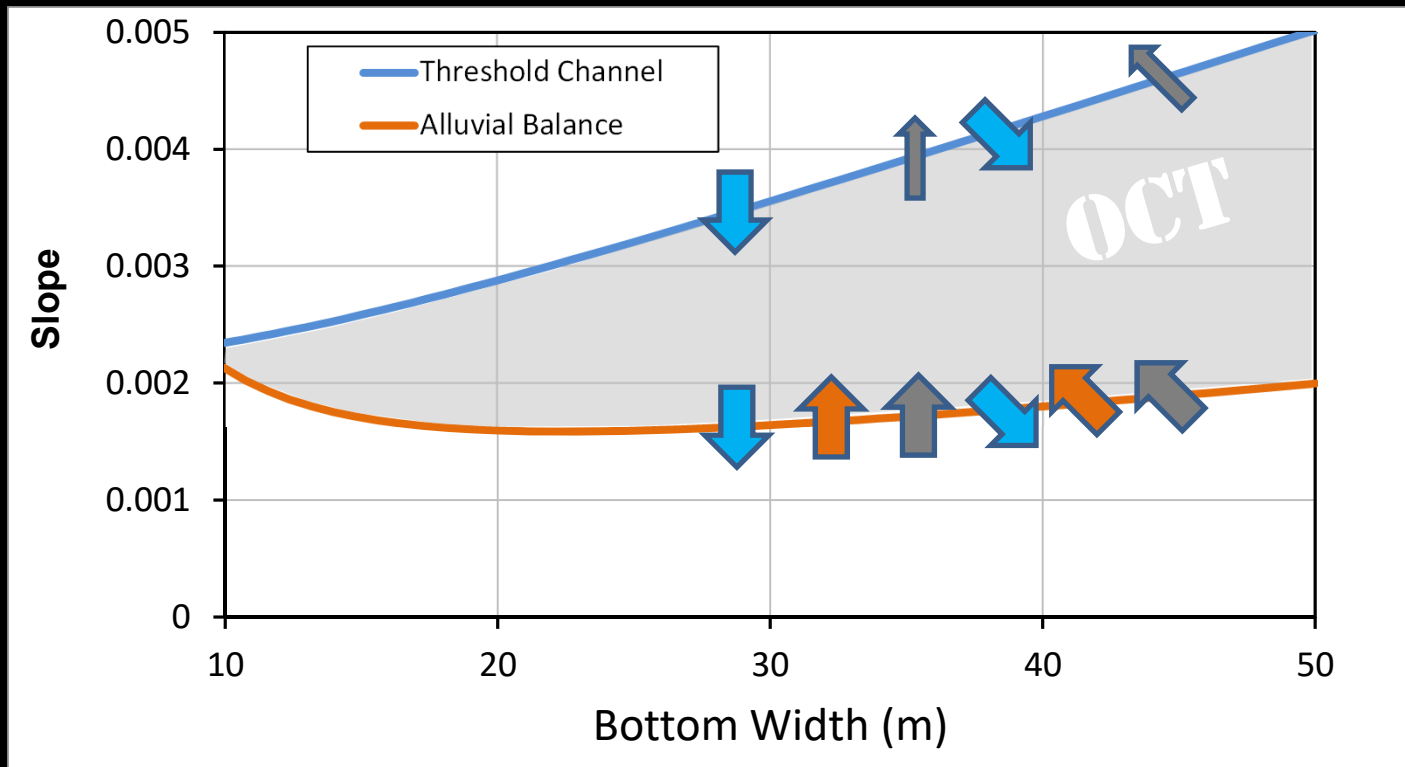


But the watershed, and the water and sediment supply may also be changing aka 'moving the goalposts'

Discharge

Rate of Sediment Supply

Grain Size of Sediment Supply

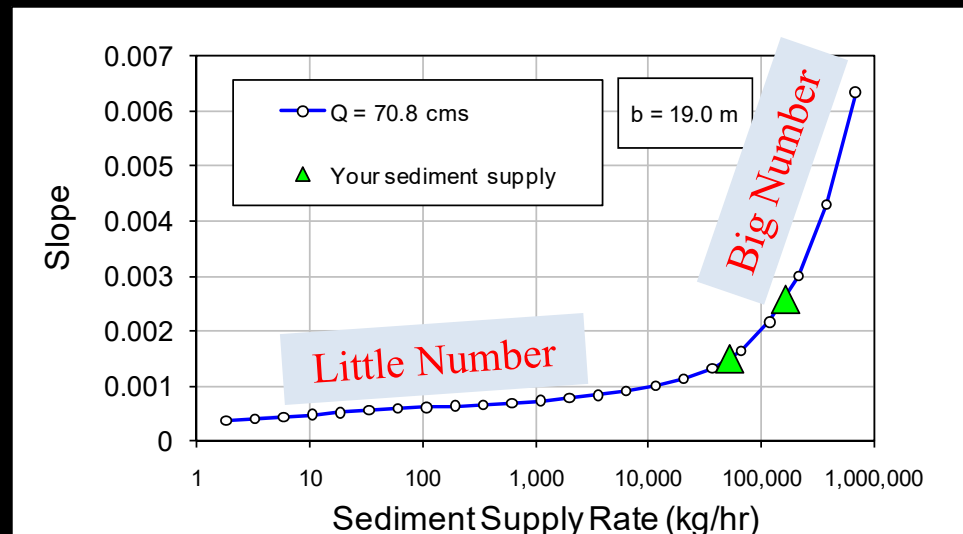


Arrows indicate response to an INCREASE in each driving variable

(VI) Channel Design Strategy

Strategy

- (i) Determine if the sediment supply is a big number or a little number
 - (a) if big, invest in more accurate estimate of sediment supply
be prepared for a dynamic channel
reserve riparian corridor and let the stream go
or plan to trap and remove sediment
 - (b) if little, design a threshold channel
- (ii) Estimate uncertainty and account for the consequences
esp. potential for aggradation, degradation



OR, Make your channel
 (i) steep enough: transport capacity
 exceeds supply *and*
 (ii) strong enough: bed material immobile

... an overcapacity threshold channel

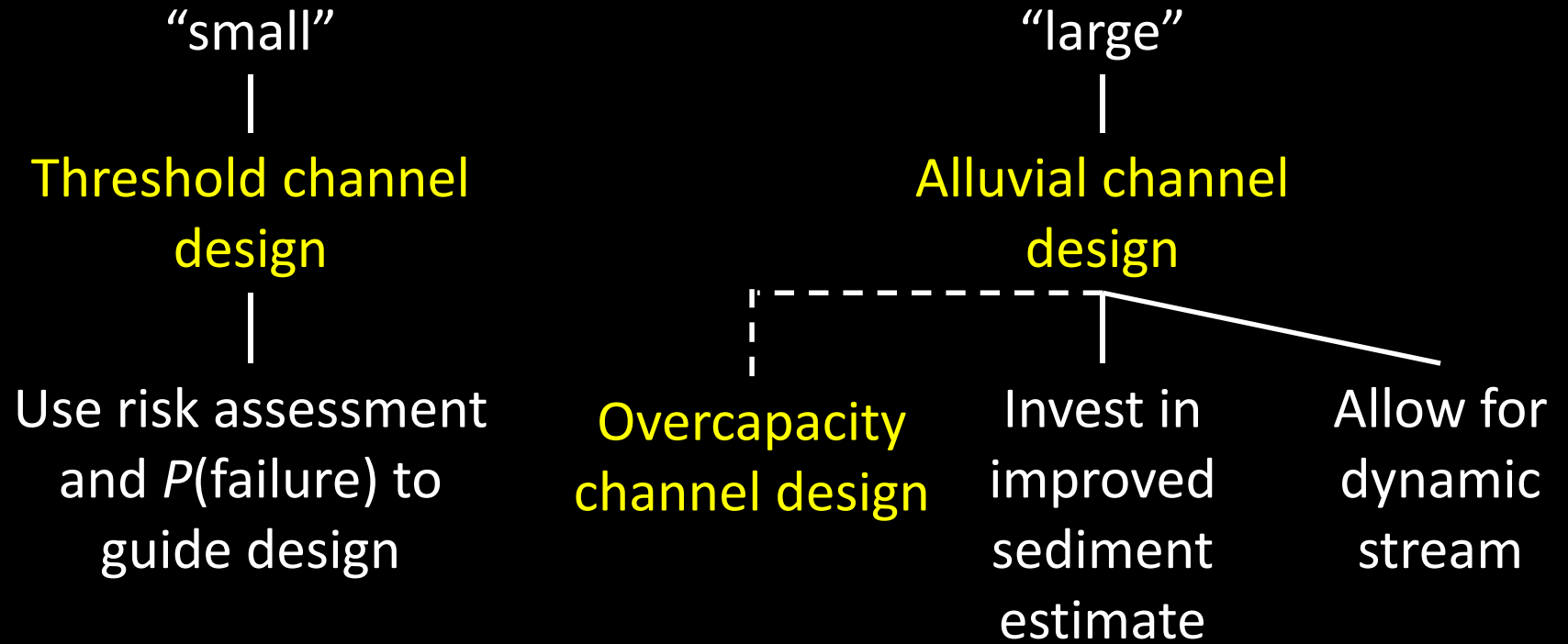


Design Basis:	Flow Competence	Competence & Capacity	Transport Capacity
Channel Type	Threshold Channel	Overcapacity Threshold	Alluvial Channel
Topography & Bed Material	Static	Static	Dynamic

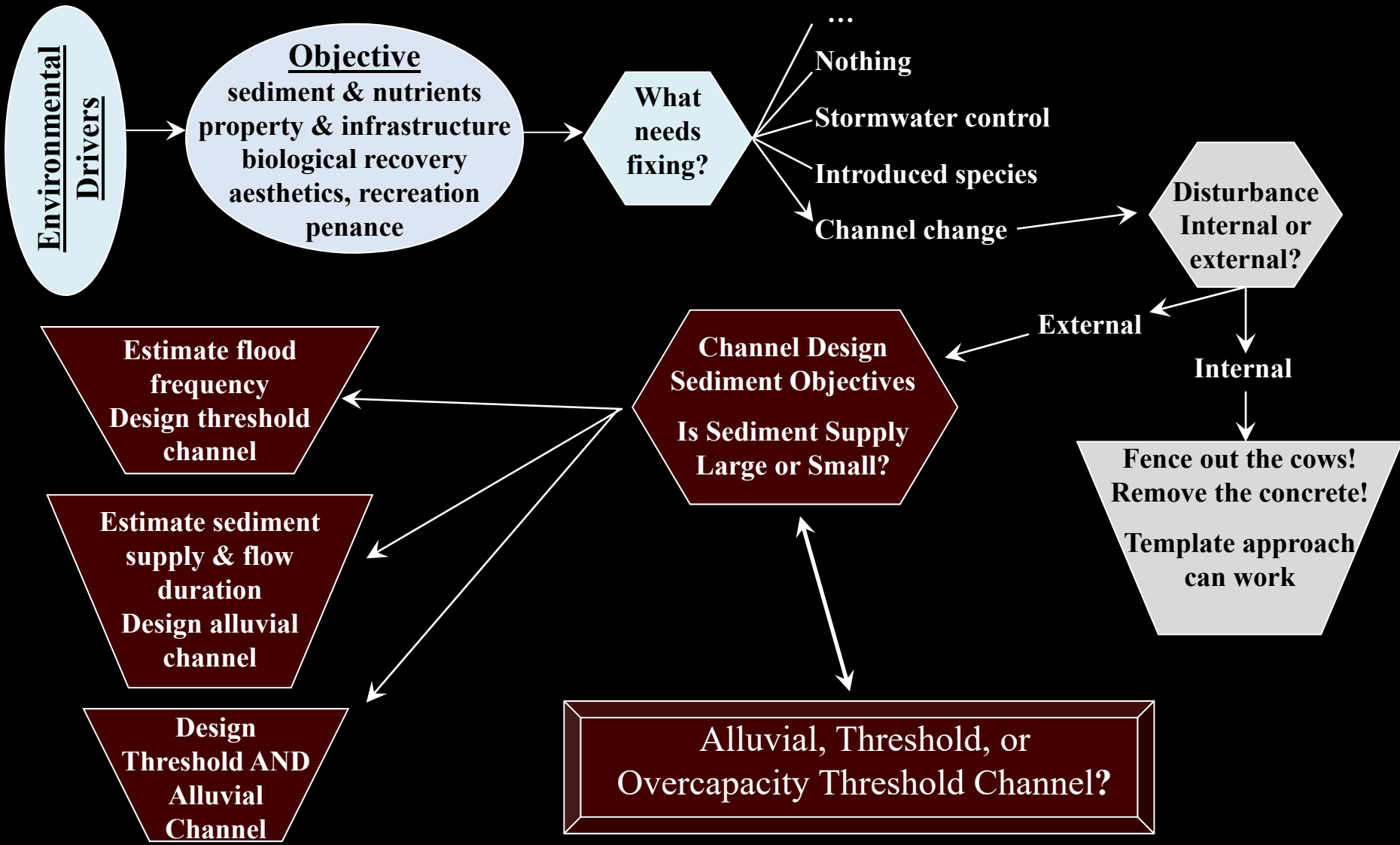


Pipe-like channels: an increasingly common & safe design option,
 may provide acceptable aesthetics.
 Does not provide anything like native structure & function

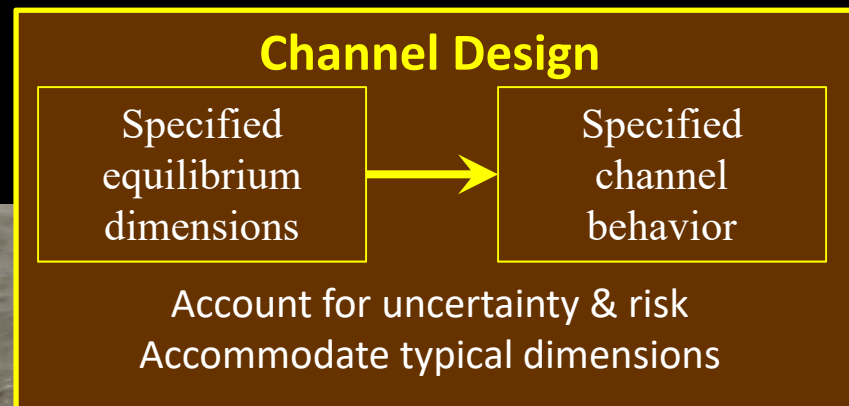
Assess magnitude of sediment supply



Sediment Transport in Channel Design



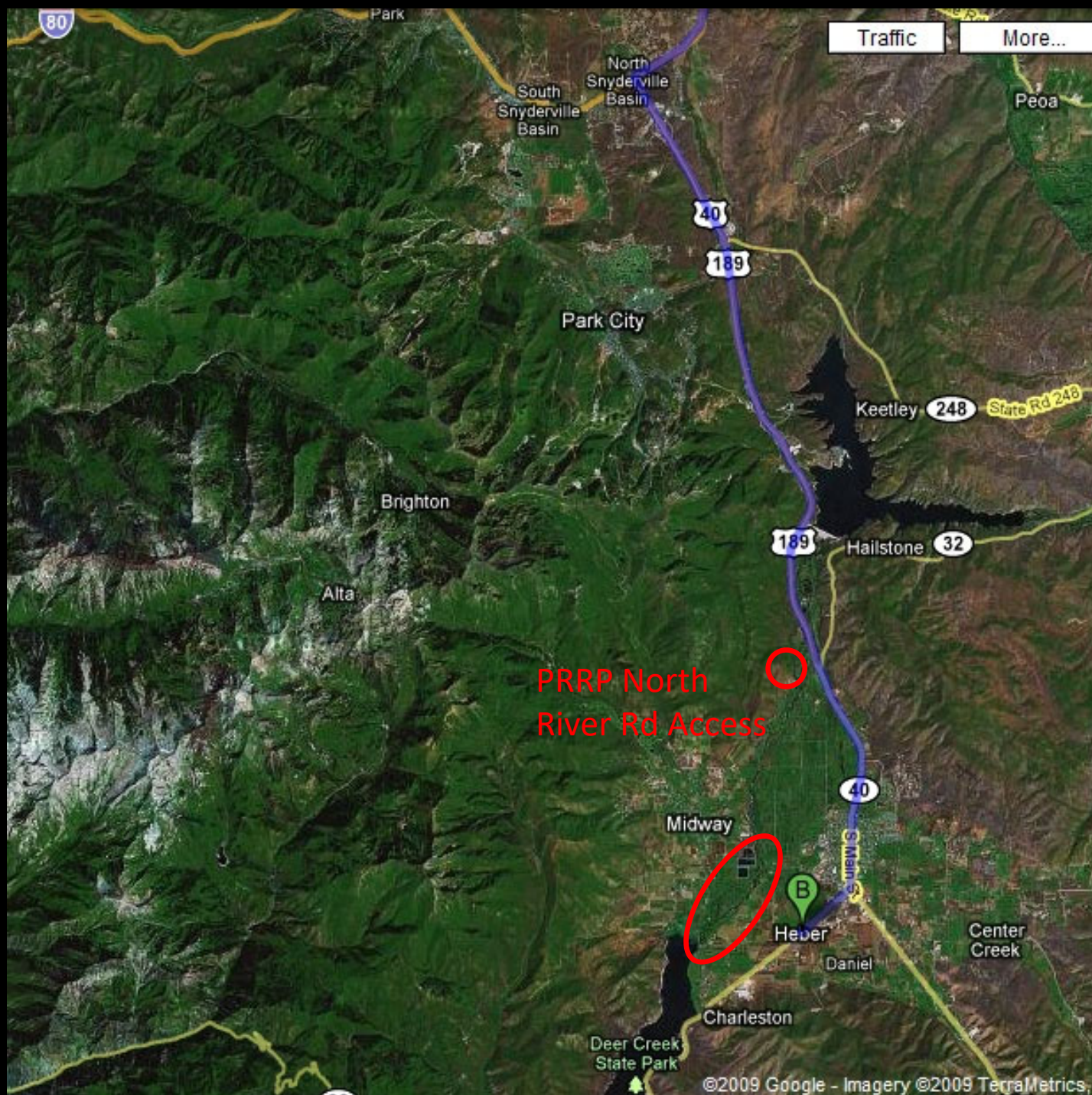
We can go beyond equilibrium channel design by
Specifying **desired channel behavior** and
incorporating sediment transport with **uncertainty**,
Which allows calculation of risk of undesirable behavior
while accommodating “typical” channel dimensions

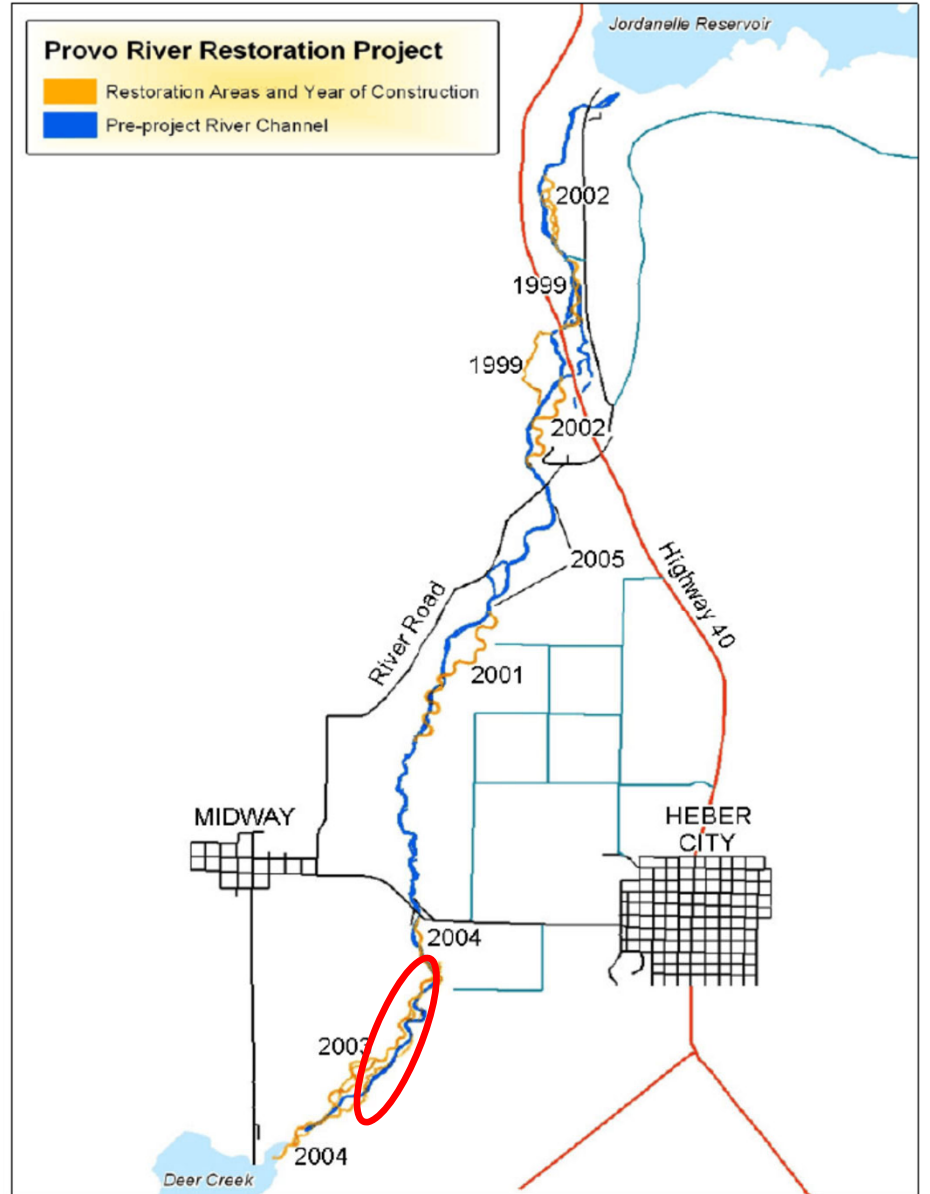
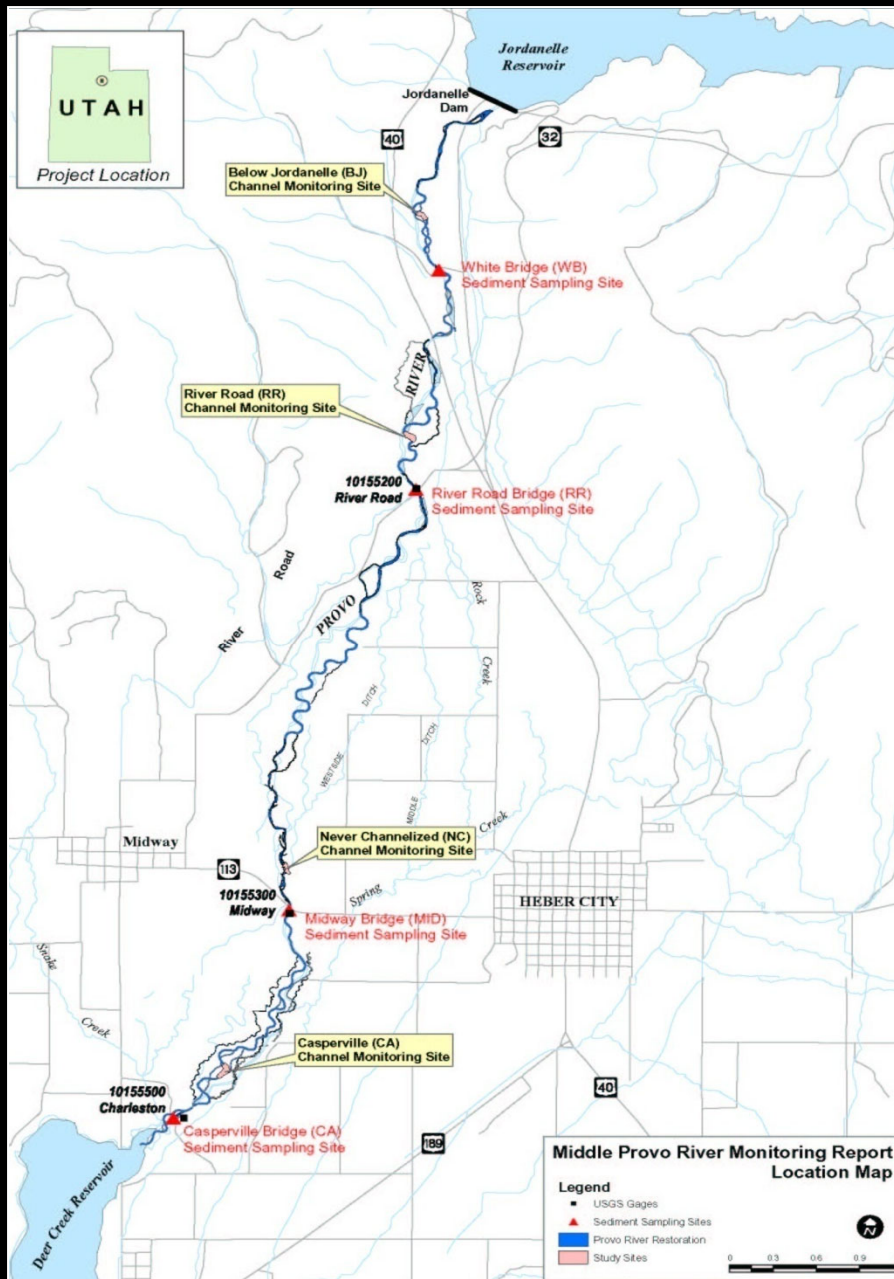


iSURF does Middle Provo

P

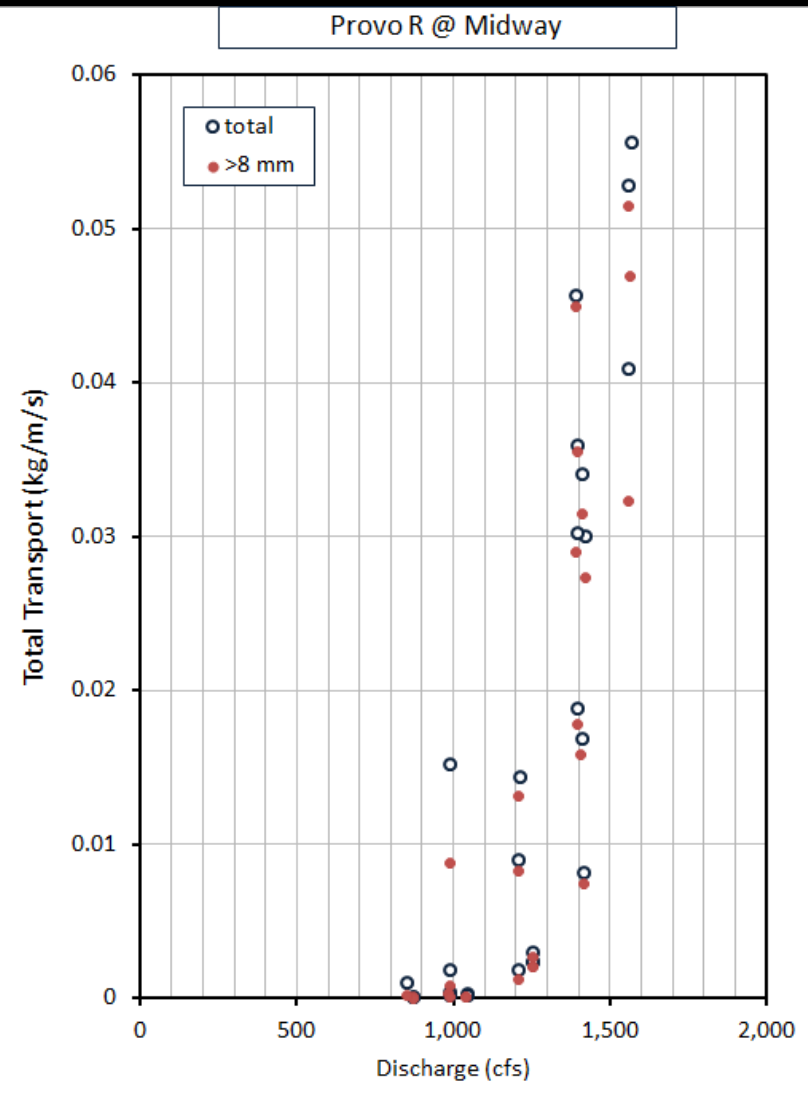
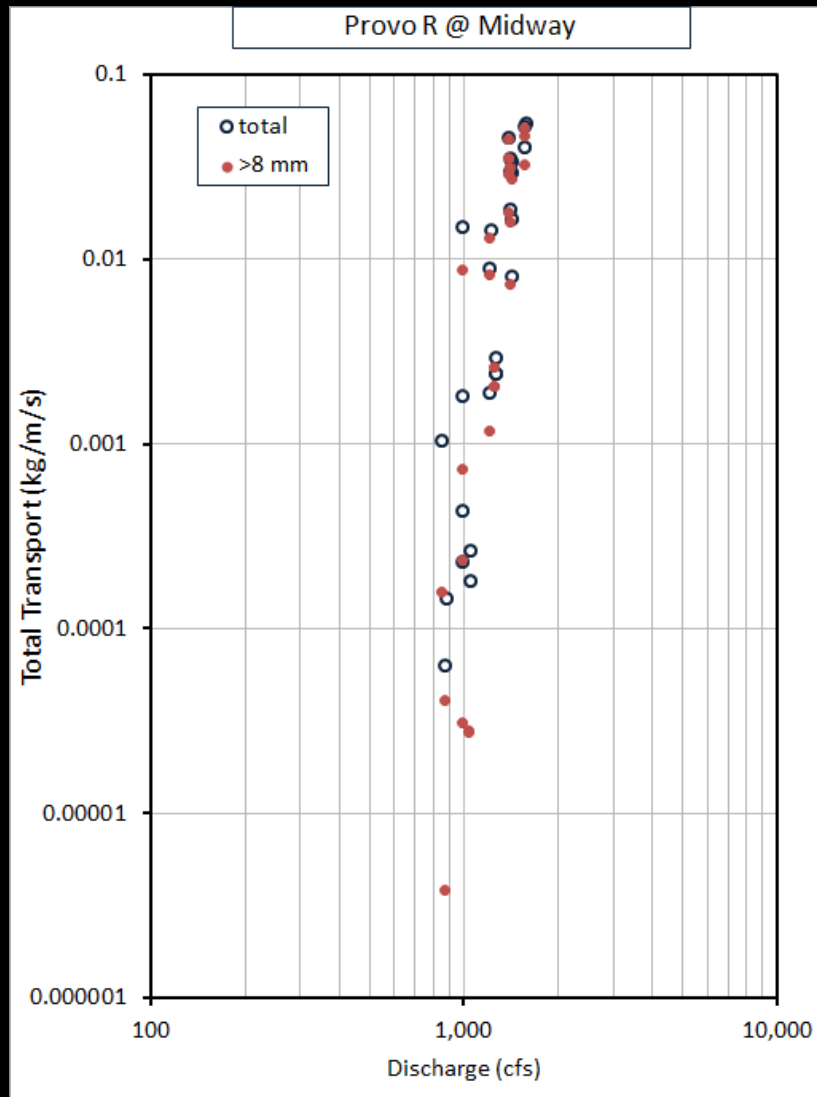


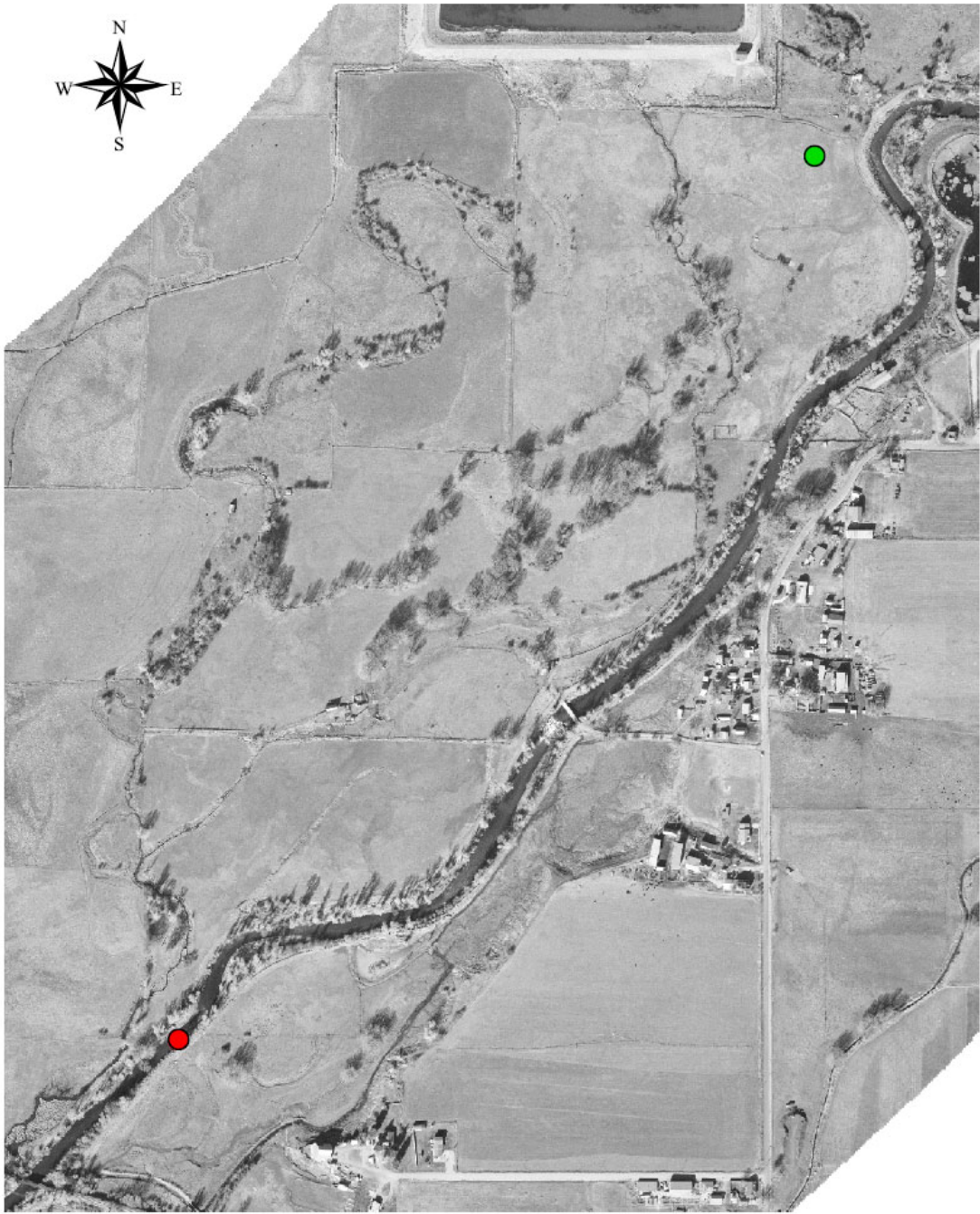




MAP 1.2. MAP OF THE PROVO RIVER RESTORATION PROJECT.

Midway Transport Observations by Erwin et al.





400 0 400 800 Feet

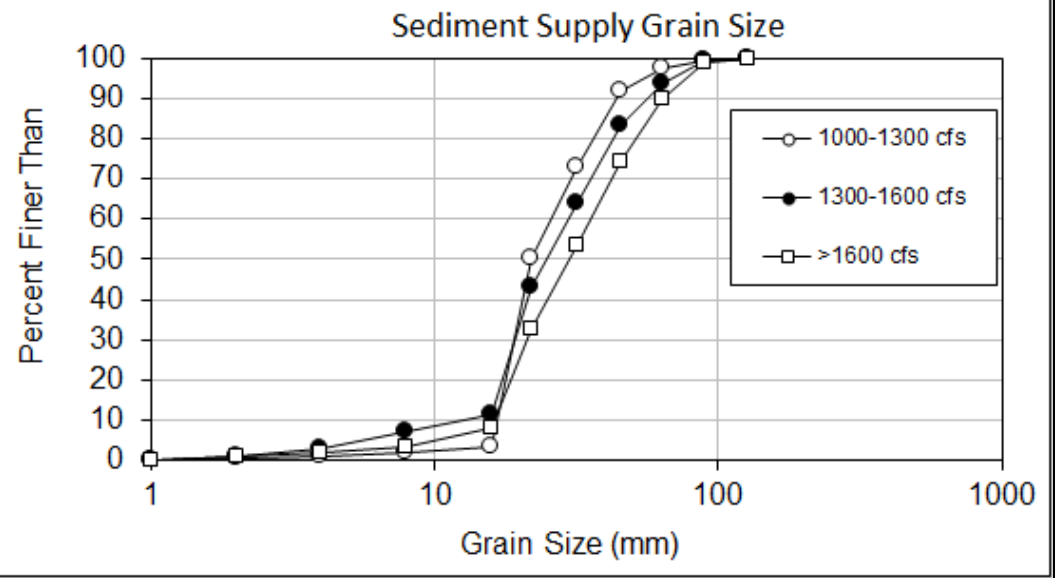


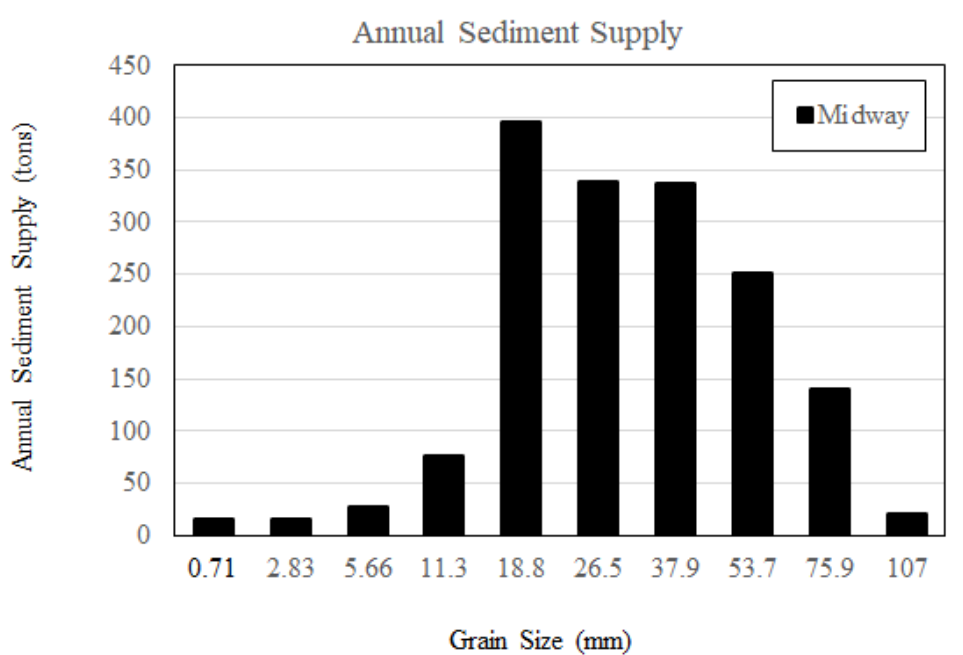
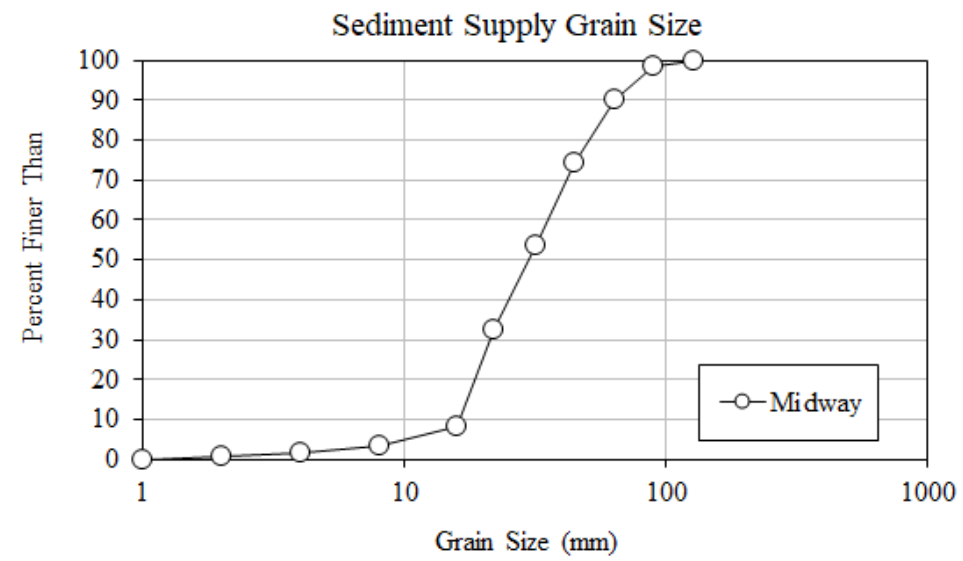
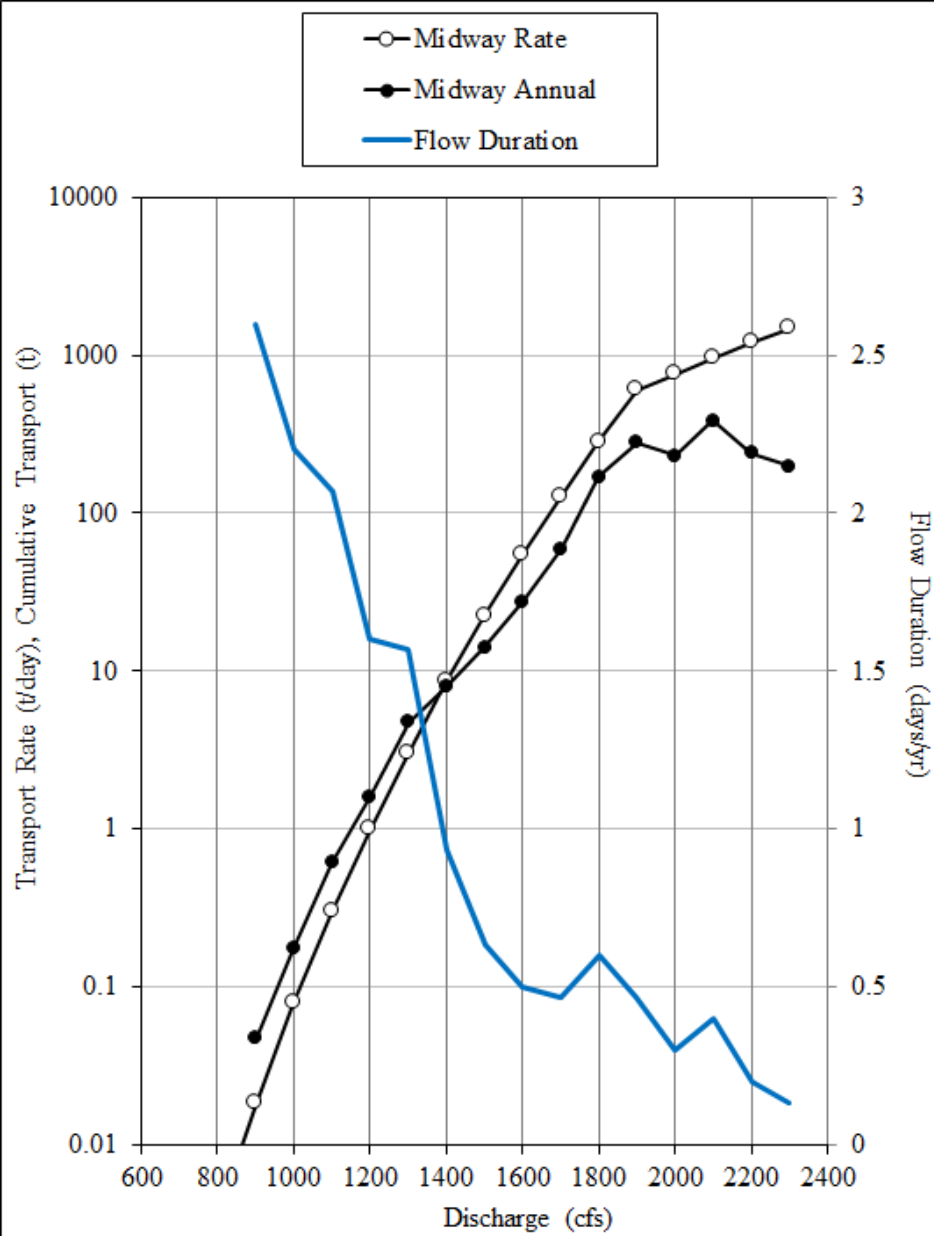
These are transport observations from the Midway sampling site located just upstream from the design reach

Valley Slope 0.0068 (design reach)

Design Q cfs	Design Qs t/d	Design Q m ³ /s	Design Qs m ³ /s	kg/hr
800	0.001	22.7	2.18E-09	0.0
900	0.003	25.5	1.21E-08	0.1
1000	0.014	28.3	5.59E-08	0.5
1100	0.056	31.1	2.24E-07	2
1200	0.200	34.0	7.94E-07	8
1300	0.64	36.8	2.54E-06	24
1400	1.88	39.6	7.48E-06	71
1500	5.1	42.5	2.04E-05	195
1600	13.1	45.3	5.22E-05	498
1700	32	48.1	1.26E-04	1,203
1800	73	51.0	2.90E-04	2,764
1900	160	53.8	6.36E-04	6,071
2000	338	56.6	1.34E-03	12,805
2100	688	59.5	2.73E-03	26,044
2200	1353	62.3	5.37E-03	51,248
2300	2583	65.1	1.03E-02	97,853

Grain Size (mm)	% finer than 1000-1300 cfs	% finer than 1300-1600 cfs	% finer than >1600 cfs
128	100	100	100
90	99.5	99.1	98.7
64	97.6	93.9	90.0
45	92.0	83.3	74.3
32	73.1	64.1	53.5
22	50.4	43.0	32.6
16	3.3	11.5	8.2
8	2.1	7.3	3.5
4	1.1	3.1	1.8
2	0.6	1.3	0.9
1	0.0	0.0	0.0





iSURF Channel Stability Diagram for 1200 cfs and 1800 cfs flows

CHANNEL STABILITY DIAGRAM FOR GRAVEL-BED RIVERS - INPUT WORKSHEET

RULES, CONVENTIONS, AND UNITS

1. Cells for input data are highlighted in GREEN
2. Grain-diameters must be in millimeters (mm)
3. Cumulative percentiles, not fractions, are used
4. Cumulative grain-size distribution percentiles must span from 0 to 100 %
5. The 0 and 100 % must be EXACTLY 0 and 100

INSTRUCTIONS

1. In first table below, enter water discharge and sediment supply rate in units of m^3/s and the minimum and maximum channel widths to be evaluated
2. In second table below, enter grain size and cumulative % in order of decreasing grain size
3. In cells to right, enter side slope angle z and side slope roughness ns
4. Check input for errors and then click once on the **Run STAB** button
5. Results appear on Worksheet "STAB OUTPUT"

For the input entered below, here are max and min values of water discharge per unit width

Maximum q	Minimum q	
4.25 m^2/s	0.68 m^2/s	Case 1
6.38 m^2/s	1.02 m^2/s	Case 2

For the input entered below, here are max and min values of sediment transport rate per unit width

Maximum q_s	Minimum q_s	
0.00 $kg/m/s$	0.00 $kg/m/s$	Case 1
0.48 $kg/m/s$	0.08 $kg/m/s$	Case 2

this cell intentionally left blank

Reset

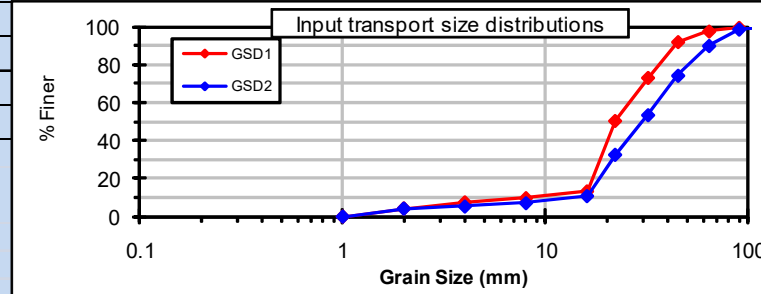
Reset: inserts some harmless data and cleans up output cells

Run STAB

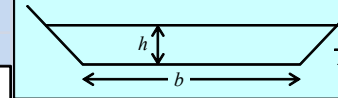
Parameter	Value	Description	Units
Q_1	34	Case 1 water discharge	m^3/s
Q_{T1}	0.00000397	Case 1 sediment supply rate	m^3/s
Q_2	51	Case 2 water discharge	m^3/s
Q_{T2}	0.00145	Case 2 sediment supply rate	m^3/s
b_{min}	8.00	Minimum bottom width	m
b_{max}	50.00	Maximum bottom width	m

Parameter	Value	Description	Units
z	1	side slope z:1 H:V	0
ns	0.08	side slope roughness	#&%@\$

D (mm)	Case 1 Transport Grain Size (% Finer)	Case 2 Transport Grain Size (% Finer)
128.00	100.00	100.00
90.00	99.50	98.70
64.00	97.60	90.00
45.00	92.00	74.30
32.00	73.10	53.50
22.00	50.40	32.60
16.00	13.30	10.80
8.00	9.70	7.10
4.00	7.50	5.30
2.00	4.30	4.20
1.00	0.00	0.00

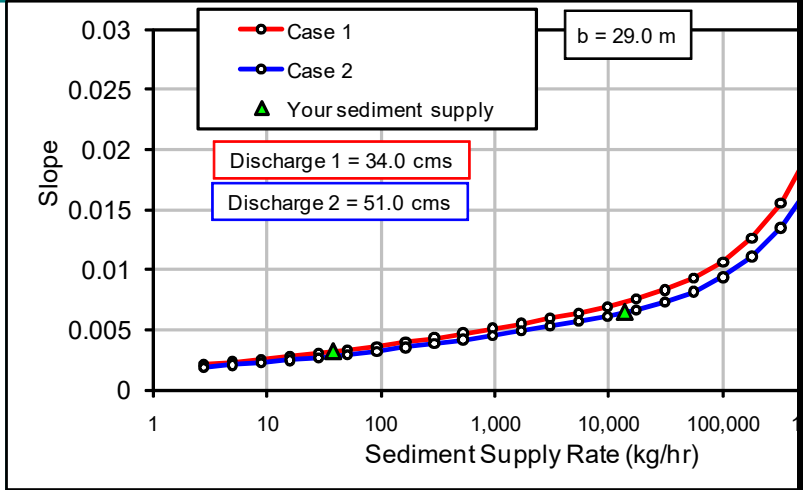
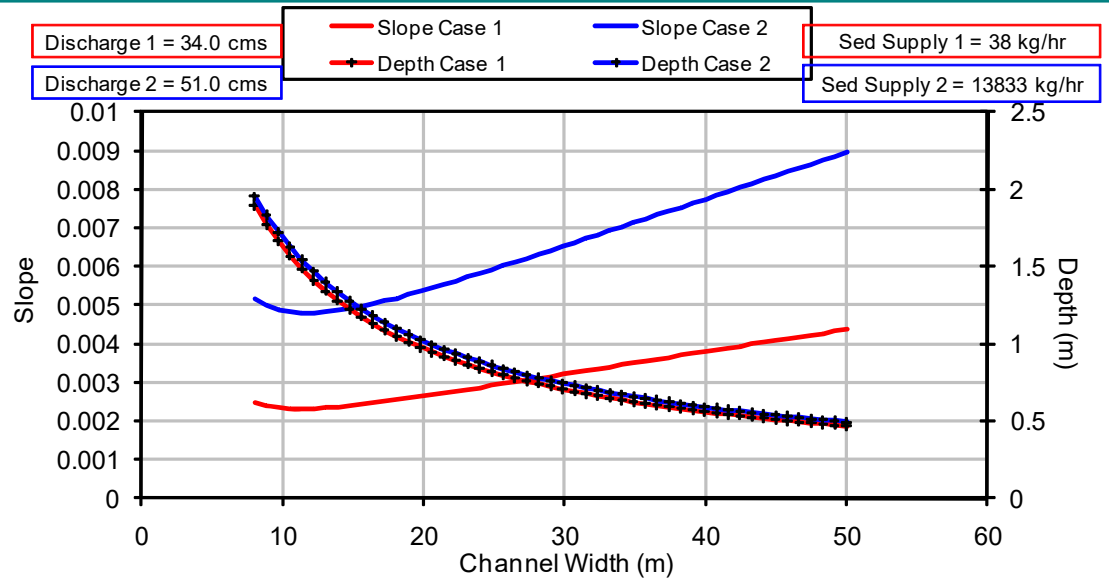


Statistic	FIRST Transport GSD	SECOND Transport GSD	Units
D_{min}	1.00	1.00	mm
D_{max}	128.00	128.00	mm
D_{50}	21.92	30.05	mm
D_g	20.52	26.85	mm
σ_g	1.18	1.24	ϕ/ψ -units
F_s	4.30	4.20	%

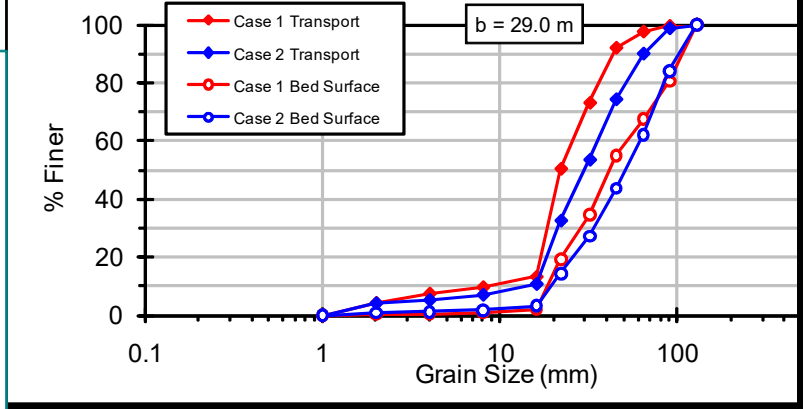
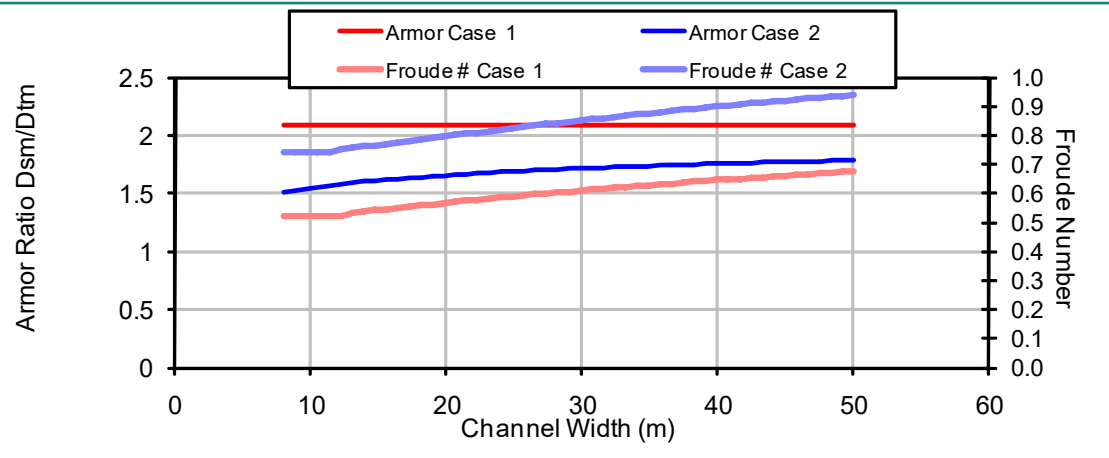


iSURF Channel Stability Diagram for 1200 cfs and 1800 cfs flows

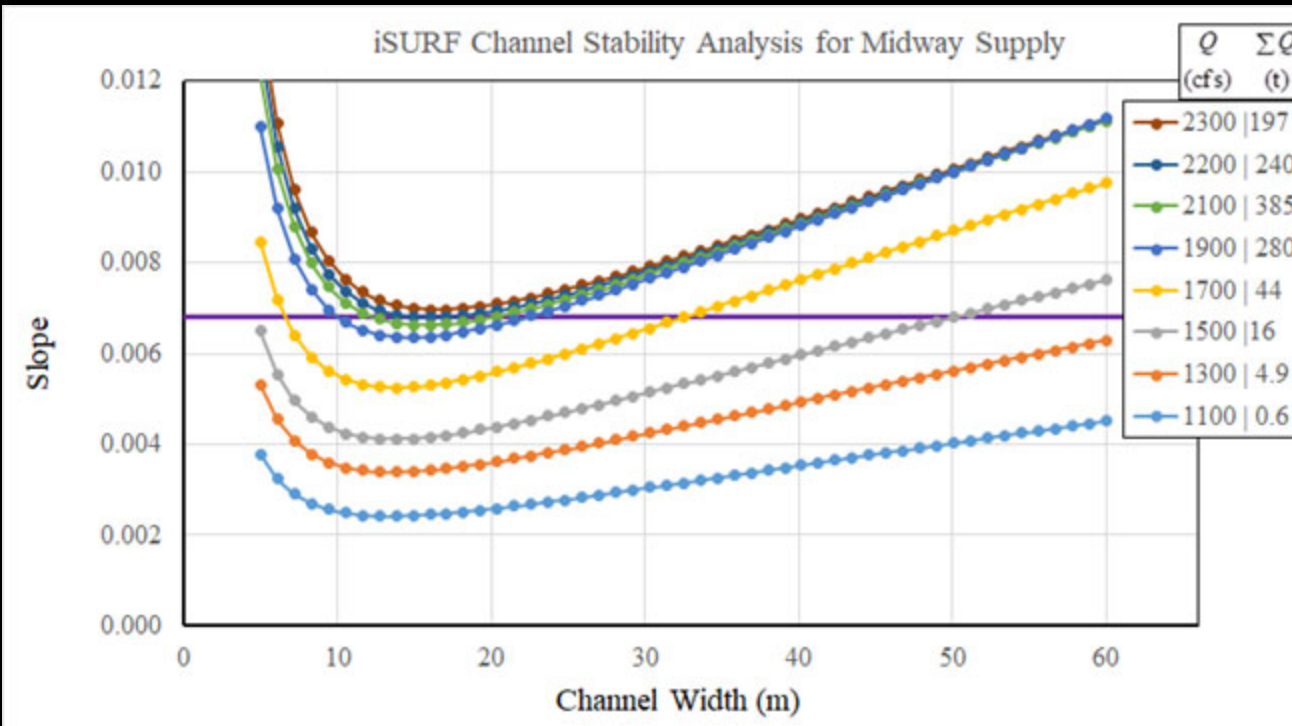
z 1 side slope z:1 H:V ns 0.08 side slope



At b=29.0m U=1.6m/s qt=0.000kg/m/s
 At b=29.0m U=2.3m/s qt=0.133kg/m/s



We have run iSURF-STAB for a range of different discharges and their associated sediment supply.



Fraction of sediment delivered by flows greater than

1800 cfs	0.93
1900 cfs	0.82
2000 cfs	0.65
2100 cfs	0.51
2200 cfs	0.27
2300 cfs	0.12

(VI) Overtime
Threshold & Alluvial Channel Design
from the guys who invented it

Some useful readings

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

**Part 654 Stream Restoration Design
National Engineering Handbook**

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Chapter 7

**Basic Principles of Channel
Design**

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Chapter 8

Threshold Channel Design

Chapter 9

Alluvial Channel Design

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

Part 654 Stream Restoration Design National Engineering Handbook

Chapter 7

Basic Principles of Channel Design

654.0701 Overview of channel design

A stable channel is often defined as a channel where the planform, cross section, and longitudinal profile are sustainable over time. While channel migration may not always be acceptable due to project or site constraints, it is important to note that a natural channel can migrate and still be considered stable, in that its overall shape and cross-sectional area do not change appreciably. Design methodologies and approaches may be used to estimate the conditions that may result in such movements. Design features are also often employed to reduce the frequency and magnitude of these changes.

Another common goal for a channel restoration design is that long-term aggradation and/or degradation should be small enough to allow for economical channel maintenance. Ideally, a channel should be self-sustaining and not require any maintenance. Many design methodologies can be used to design a channel which is in balance with the incoming sediment load. However, it is also important for the designer to recognize that manmade, as well as natural channels may aggrade or degrade over time or in response to specific storm events. Sediment impact assessments can be used to quantify what storm events may result in a sediment disequilibrium and to quantify the expected aggradation, so that appropriate maintenance can be budgeted. Design features can also be employed to counteract a tendency for bed degradation.

Table 7-1 Characteristics of threshold and alluvial channels

	Threshold channel	Alluvial channel
Channel boundary	Immobile at design discharge	Mobile
Bed-material sediment inflow	Usually small or negligible	Significant
Dependent variables	Width Depth Slope Roughness, if there is a choice of boundary materials	Width Depth Slope Planform Bank roughness Roughness due to obstructions or structures
Independent variables	Design discharge Channel roughness	Design hydrograph Channel-forming discharge Bed-material sediment inflow Bed material Streambank characteristics
Design equations	Energy Momentum Resistance	Energy Momentum Resistance Sediment transport Geomorphic relationship
Design goal with respect to channel stability	Pass the design discharge below the top of bank without mobilizing the boundary	Pass the incoming sediment load without significant aggradation or degradation or planform change

Table 7-2 Hydraulic design philosophies

	Threshold channels	Alluvial channels
Design discharges	Maximum design discharge	Channel-forming discharge Flow-duration curve and/or long-term hydrograph
Design criteria	Critical velocity/shear stress	Continuity of sediment
Dependent variables	Width, depth, and slope (roughness if there is a choice of boundary material)	Width, depth, slope, planform, bank roughness, and roughness due to obstructions or structures
Design equations	Energy, momentum, and hydraulic resistance	Energy, momentum, hydraulic resistance, sediment transport, and geomorphic relationship

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

Part 654 Stream Restoration Design National Engineering Handbook

Chapter 8

Threshold Channel Design

Table 8-1 General guidance for selecting the most appropriate channel design technique

Technique	Significant sediment load and movable channel boundaries	Boundary material smaller than sand size	Boundary material larger than sand size	Boundary material does not act as discrete particles	No baseflow in channel. Climate can support permanent vegetation
Allowable velocity		X			
Allowable shear stress			X		
Tractive power				X	
Grass lined/tractive stress					X
Alluvial channel design techniques	X				

Table 8-3 Maximum permissible canal velocities

Original material excavated for canals	Mean velocity, for straight canals of small slope, after aging with flow depths less than 3 ft (0.9 m)					
	Clear water, no detritus		Water transporting colloidal silts		Water transporting noncolloidal silts, sands, gravels, or rock fragments	
	ft/s	m/s	ft/s	m/s	ft/s	m/s
Fine sand (noncolloidal)	1.5	0.46	2.5	0.76	1.5	0.46
Sandy loam (noncolloidal)	1.75	0.53	2.5	0.76	2.0	0.61
Silt loam (noncolloidal)	2.0	0.61	3.0	0.91	2.0	0.61
Alluvial silt (noncolloidal)	2.0	0.61	3.5	1.07	2.0	0.61
Ordinary firm loam	2.5	0.76	3.5	1.07	2.25	0.69
Volcanic ash	2.5	0.76	3.5	1.07	2.0	0.61
Stiff clay (very colloidal)	3.75	1.14	5.0	1.52	3.0	0.91
Alluvial silt (colloidal)	3.75	1.14	5.0	1.52	3.0	0.91
Shales and hardpans	6.0	1.83	6.0	1.83	5.0	1.52
Fine gravel	2.5	0.76	5.0	1.52	3.75	1.14
Graded, loam to cobbles (when noncolloidal)	3.75	1.14	5.0	1.52	5.0	1.52
Graded silt to cobbles (when colloidal)	4.0	1.22	5.5	1.68		
Coarse gravel (noncolloidal)	4.0	1.22	6.0	1.83		
Cobbles and shingles	5.0	1.52	5.5	1.68		

Table 8-2 Suggested minimum radius of curvature in stable soils without bank protection

Type of ditch	Slope	Minimum radius of curvature		Approximate of curve (degrees)
		(ft)	(m)	
Small ditches with maximum top width 15 ft (4.6 m)	<0.00057	300	90	19
	0.00057 to 0.00114	400	120	14
Medium-sized ditches with top width 15 to 35 ft (4.6-10.7 m)	<0.00057	500	150	11
	0.00057 to 0.00114	600	180	10
Large ditches with top width >35 ft (10.7 m)	<0.00057	600	180	10
	0.00057 to 0.00114	800	240	7

654.0803 Allowable velocity method

Increased Bank Velocity in Bends

$$\frac{V_{ss}}{V_{avg}} = 1.74 - 0.52 \log \left(\frac{R}{W} \right)$$

V_{ss} : depth-averaged velocity at 20% slope length from toe

V_{avg} : X/S average velocity

R : bend hydraulic radius

W : channel top width

Figure 8-3 Allowable velocity-depth grain chart

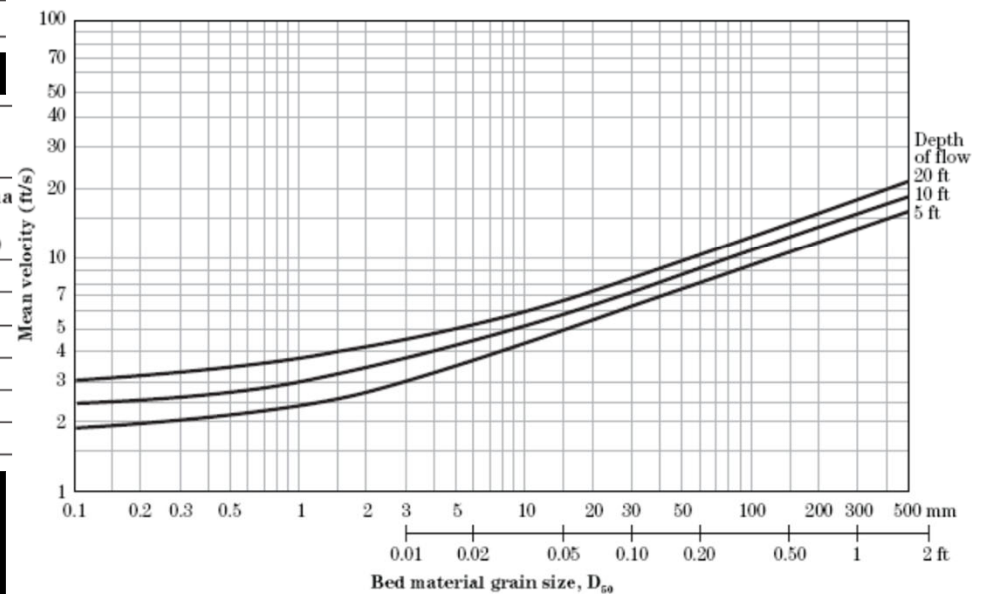


Figure 8-5 Applied maximum shear stress, τ_b , on bed of straight trapezoidal channels relative to an infinitely wide channel, τ_∞

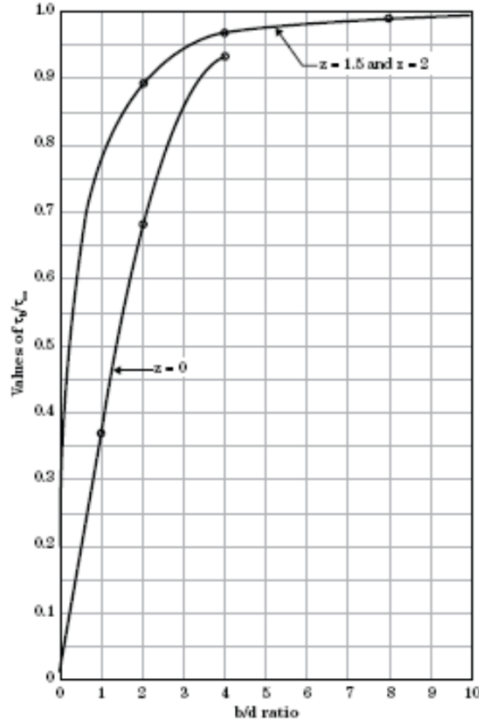
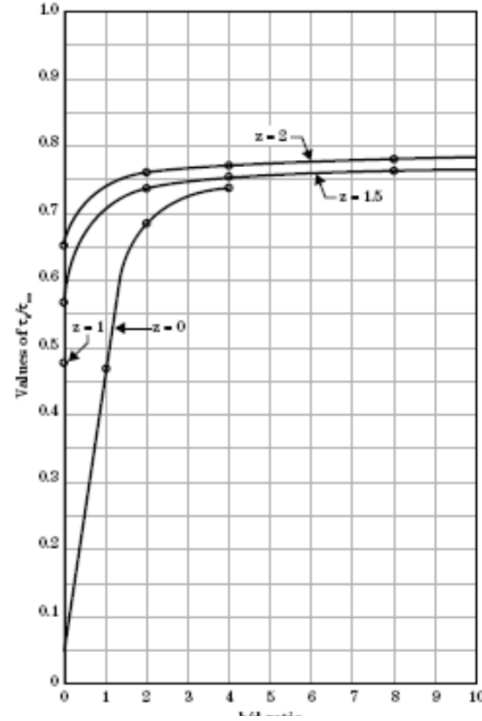


Figure 8-6 Applied maximum shear stress, τ_s , on sides of trapezoidal channels relative to an infinitely wide channel, τ_∞



Note:
 b = bottom width
 d = depth
 z = side slope, zH:1V
 τ_∞ = shear stress on a straight, infinitely wide channel
 τ_b = applied shear stress on a channel bed
 τ_s = applied shear stress on the side of a channel

654.0804 Allowable shear stress approach

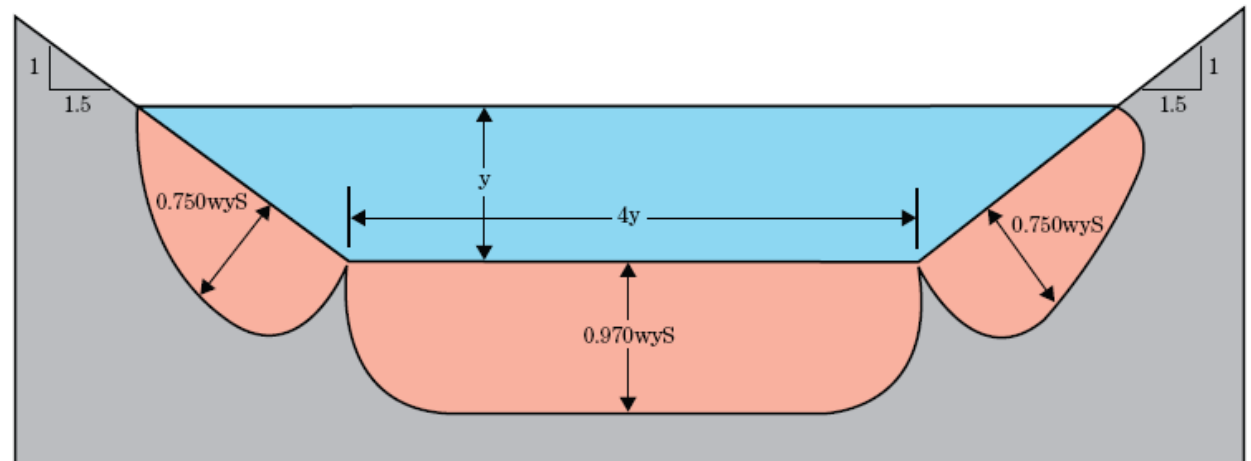
1. Calculate total stress
 (use RAS if flow non-uniform)
2. Calculate grain stress τ' using

$$\tau' = \left(\frac{n_D}{n} \right)^{3/2} \tau_0 \quad \text{and} \quad n_D = 0.013D^{1/6}$$

for D in mm

3. Choose critical Shields Number
4. Compare τ' and τ_c

Figure 8-7 Lateral distribution of shear stress in a trapezoidal channel



w=specific weight of water, y=depth, and S=slope

654.0808 Basic steps for
threshold channel design in
stream restoration projects

Step 1 Determine design bed-material gradation/channel boundary.

Step 2 Determine preliminary width.

Step 3 Estimate critical shear stress/velocity.

Step 4 Determine flow resistance (Manning's n).

Step 5 Calculate depth and slope.

Step 6 Determine planform.

Step 7 Assess for failure and sediment impact.

Example problem: Threshold channel design

Given:

Valley slope = 0.007 (this is the maximum possible slope)

Bed material $D_{50} = 45 \text{ mm} = 0.148 \text{ ft}$

Bed material $D_{75} = 55 \text{ mm} = 2.17 \text{ in}$

Bed material $D_{84} = 60 \text{ mm} = 0.197 \text{ ft}$

Channel side slope = 3H:1V

Specific weight of sediment = 165 lb/ft^3

Water temperature = $68 \text{ }^\circ\text{F}$

Design discharge is 25-year storm = $400 \text{ ft}^3/\text{s}$

Problem:

Design a threshold channel to convey the design discharge.

Note: There is no unique solution with the given design constraints.

Step 1 Estimate channel width using hydraulic geometry equation (fig. 9–9, NEH654.09):

$$W = 2.03Q^{0.5}$$

$$W = 2.03(400)^{0.5}$$

$$W = 41 \text{ ft}$$

Note from figure 9–9 in NEH654.09 that widths between 22 and 74 feet are within the 90 percent single response confidence bands. If there are width constraints on the project design they may be applied here. If there are minimum depth requirements, a narrower width may be necessary. It should also be noted that the figure refers to measurements of top width. However, the difference between the top and bottom width is within the error bounds. This example will proceed with the mean width of 41 feet.

Figure 9–8 Downstream width hydraulic geometry for North American gravel-bed rivers, $W = 3.68Q_b^{0.5}$ and U.K. gravel-bed rivers, $W = 2.99Q_b^{0.5}$

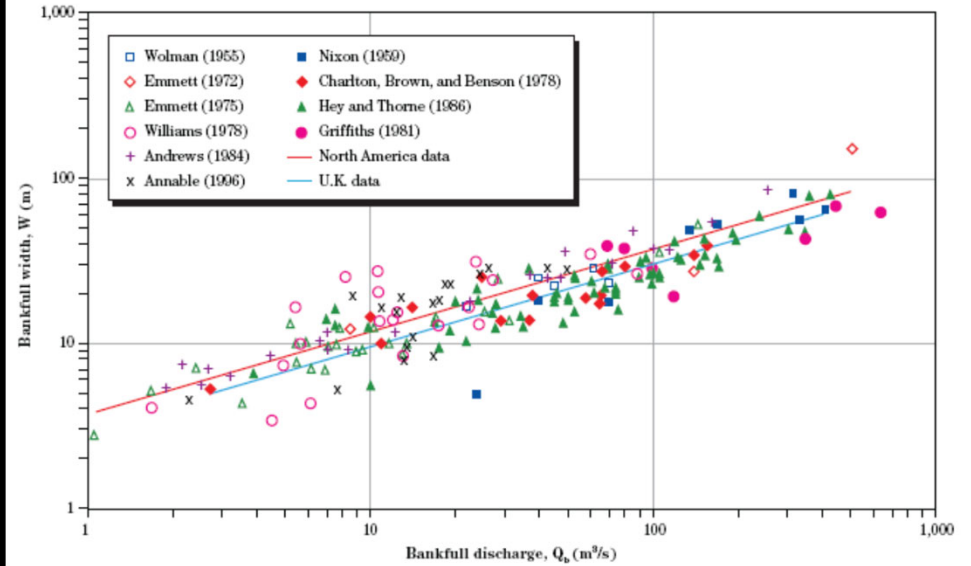


Figure 9–9 Downstream width hydraulic geometry for North American gravel-bed rivers, $W = aQ_b^{0.5}$ with confidence bands. Based on 94 sites in North America. SI units – m and m³/s (English units ft and ft³/s)

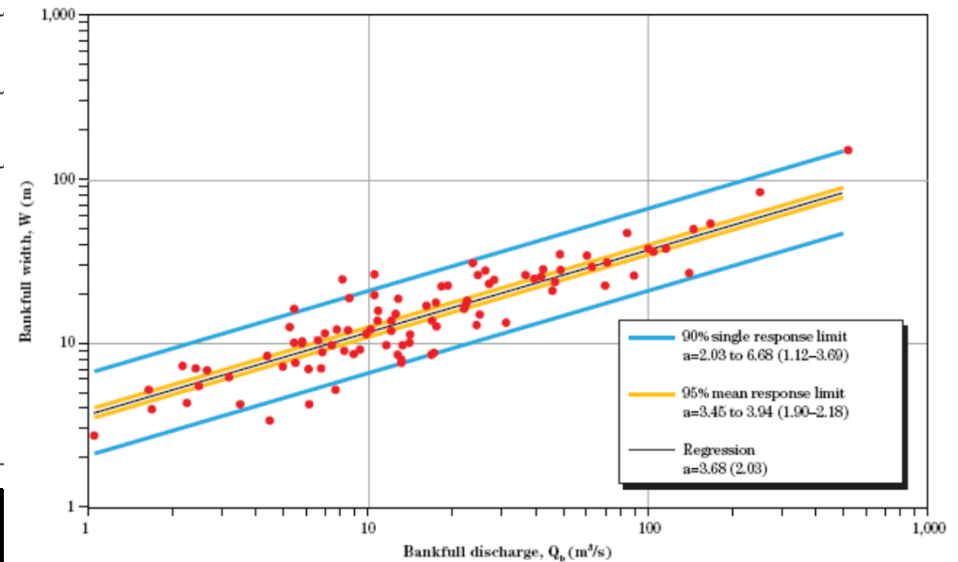


Table 9–9 Hydraulic geometry width predictors for gravel-bed rivers

Data source	Sample size	$W = aQ^b$			
		a	90% single response limit for a	95% mean response limit for a	b
All North American gravel-bed rivers	94	3.68 (2.03)	2.03–6.68 (1.12–3.69)	3.45–3.94 (1.90–2.18)	0.5
All U.K. gravel-bed rivers	86	2.99 (1.65)	1.86–4.79 (1.02–2.64)	2.83–3.16 (1.56–1.74)	0.5
<5% tree or shrub cover, or grass-lined banks (U.K. rivers)	36	3.70 (2.04)	2.64–5.20 (1.46–2.87)	3.49–3.92 (1.93–2.16)	0.5
≥5% tree or shrub cover (UK rivers)	43	2.46 (1.36)	1.87–3.24 (1.03–1.79)	2.36–2.57 (1.30–1.42)	0.5

Example 2: Stable channel analytical method

Given: Dimensions of the upstream natural channel reach are:

Base width = 22 ft (6.7 m)

Side slopes

Left bank = 2.2H:1V

Right bank = 1.1H:1V

Side slope roughness coefficient = 0.07

Channel slope = 0.0025

Bed material — sandy gravel

$D_{84} = 22 \text{ mm}$ $D_{50} = 3.7 \text{ mm}$

$D_{16} = 0.43 \text{ mm}$

Design discharge = 2,500 ft³/s (70.8 m³/s)

Design values for the bypass channel:

Side slopes = 3H:1V

Side slope roughness coefficient = 0.045

Valley slope = 0.0020 (maximum design slope)

Objective: Determine stable channel dimensions for a diversion channel. Upstream natural stream is coming out of a hillside watershed.

1. Supply reach

Estimate sediment transport rate

2. Design reach

Given discharge and sediment supply rate and grain size, calculate slope needed to transport supplied sediment at a specified channel width

NRCS (Brownlie, SAM) solution

