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Course Path
July 29, 2024

Monday: estimating sediment sources, sinks, rate of supply

Tuesday: channel, sediment & flow → flow model and critical discharge

Wednesday: estimating sediment transport rates: rating curves, budget, transport frequency
channel geometry and channel change

Thursday: incorporating sediment in channel assessment & design
adding geomorphic & design concepts → channel/floodplain design exercises

Friday: evaluate designs, visit field sites

RIVERS OF WATER AND SEDIMENT
AUTHOR THEIR OWN GEOMETRY AND COMPOSITION IN RESPONSE TO THE SUPPLY OF WATER AND SEDIMENT (MODERATED BY VEGETATION AND HUMANS)

We wish to understand the
CONTROLS, MECHANISMS, AND RATES OF THOSE ADJUSTMENTS
in order to Manage Streams

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(a) Rate and grain size of sediment ***supply***

Watershed history. Watershed analysis

(b) Water supply and channel properties: ***transport capacity & flow competence***

Watershed history. Watershed analysis
Discharge, channel properties → ***hydraulics*** →
sediment transport capacity & flow competence

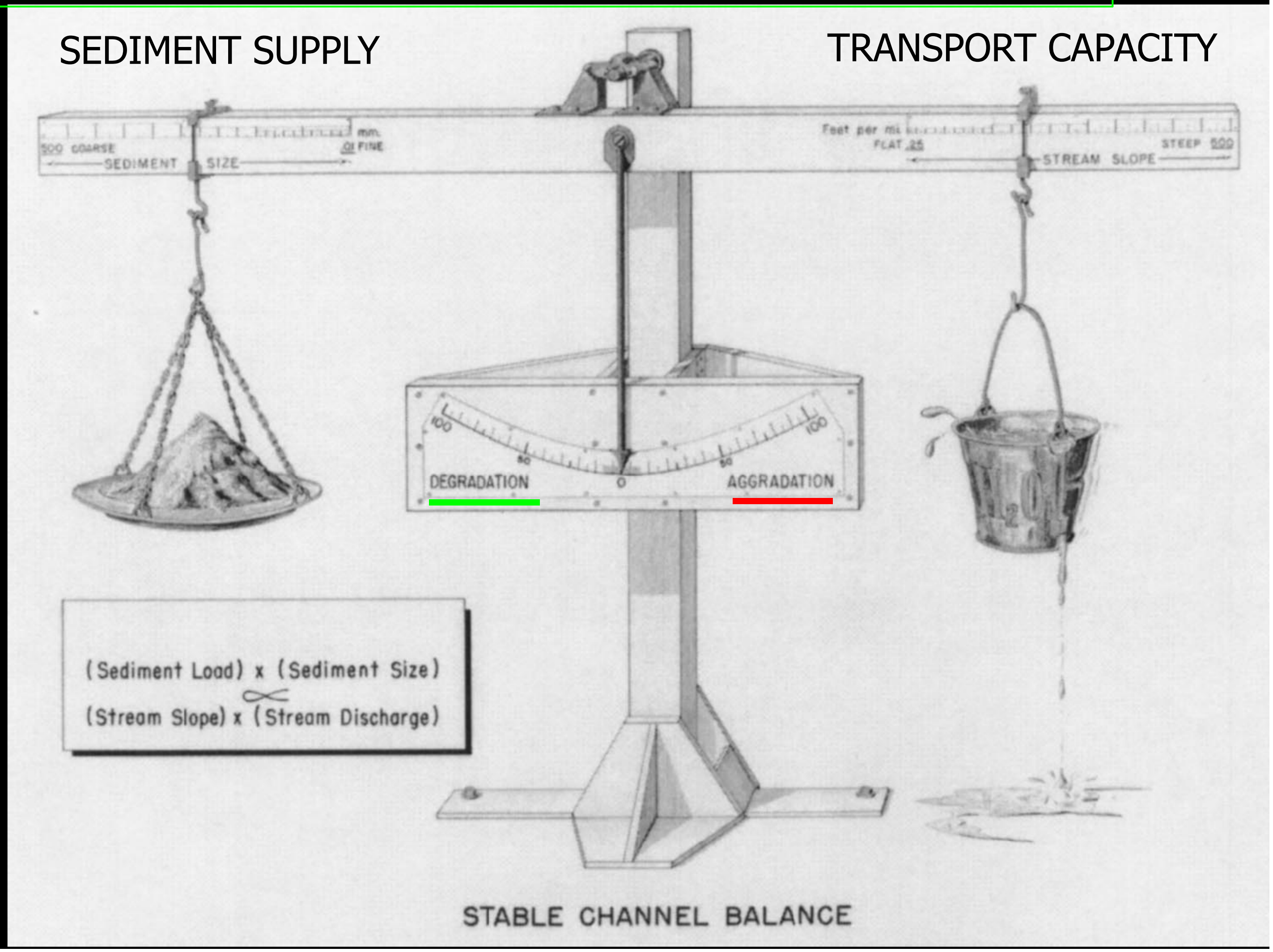
Sediment ***supply*** > transport ***capacity*** → Sediment Accumulates

Channel Response: Fans, choked channels, active channels (more varied habitat), braiding, avulsion

Sediment ***supply*** < transport ***capacity*** (I) Sediment Evacuates *or*

(II) Flow not ***competent***

Channel Response: Channels incised or armored or static (less varied habitat?)



Lane/Borland Balance
(USBR 1955-1960)

Does the sediment balance matter in this stream?

What is the transport capacity compared to the sediment supply?

This is trying to be an ***alluvial channel***

Does the sediment balance matter in this stream?

What is the flow that is competent to move the bed material?

This was designed as ***a threshold channel***

What is the supply of water and sediment?

What is the supply of water and sediment to a stream &
what do you want to do with it?

I. What flow moves the bed material?
How often does it occur?

Flow **Com**petence

Discharge Q
Bed material D
Channel Geometry

→

Hydraulics
Incipient Motion

II. What is the sediment balance?

Transport **Cap**acity vs Sediment Supply

Discharge Q
Bed material D
Channel Geometry
Sediment Supply Q_s & D

→

Hydraulics
Transport Capacity Q_s & D

Input - Output = ***ΔStorage***

Surplus or Deficit?

Stored sediment is the real geomorphic and restoration topic!

What do you want to do with it?

There are two basic transport problems

- Flow competence

  Will a flow move the grains on the bed?

  (focus on bed material)

- **Transport Capacity**

  At what rate can the flow transport sediment?

  (focus on sediment supply)

These are different problems!!!

Define Q_c *the water discharge at which grains on the bed begin to move*

For $Q < Q_c$ … no transport, right? NO! ***consider a pipe***

For $Q \geq Q_c$ … all the sediment supply will be transported?

NO! ***consider a clogged pipe***

A couple pages of text …

Rivers are RIVERS OF WATER AND SEDIMENT.
Rivers adjust their channel to the SUPPLY OF WATER AND SEDIMENT, moderated by the influence of vegetation and humans.
Understand the nature of those adjustments – their controls, mechanisms, and rates – to manage or restore channels.

A starting point for understanding river behavior (and channel change) is the sediment balance:
we balance the ***supply*** of sediment with the river's ***capacity*** to transport that sediment.
Sediment ***supply*** includes the rate and the grain size of the supply.
Transport ***capacity*** is a function of the water supply (discharge) and the geometry, roughness, and slope of the river channel.

If sediment ***supply*** exceeds transport ***capacity***, sediment will accumulate in the channel.
How does channel geomorphology and habitat respond to sediment accumulation?

If the sediment ***supply*** is smaller than transport ***capacity***, things get complicated!
If there is plenty of moveable sediment available in the channel, excess ***capacity*** will evacuate sediment.
How does channel geomorphology and habitat respond to sediment evacuation?
If the channel is composed of coarse sediment that cannot be moved by the discharge, no sediment will be evacuated.
Yes, the supply of sediment is often finer grained than the sediment in the river bed!

History matters! In previous times, the channel might have transported a coarse supply that it is no longer able to move.
Think of such a channel as the sewer pipe between your house and the street. Hopefully it is well designed and is always able to transport the, uh, load delivered to it. It is designed such that the transport capacity exceeds the supply. And, we hope that the pipe is made of sturdy material such that the flow will not erode the pipe. The pipe is OVERcapacity with respect to the supplied load but unable to erode the pipe itself.

Processes in nature are continuous and stochastic. It is not so simple as a sewer pipe or other engineered system. When considering all the flows that your river channel might experience, your channel might be
Sometimes undercapacity with respect to the sediment load delivered by that flow and sometimes overcapacity
Undercapacity with respect to some sediment sizes supplied to it and overcapacity with respect to other (smaller) sizes
Some flows might be able to move none of the sediment in the bed, others might move some or all of the grains in the bed.

We define the ability of a flow to move the river bed material as the **flow competence**.

If a flow through a channel of given dimensions and slope and bed material, is able to move the material, it is competent.

If the flow cannot move the bed material, it is not competent.

So, consider a channel – its width, depth, bendiness, internal topography, and bed material.

If we specify a water discharge, the relations of open channel hydraulics are used to determine flow depth, flow velocity, and the flow forces acting on the bed and banks. (Tuesday)

We might calculate average values for a whole cross section or reach (this would lead to 1 1d model in which flow and transport vary only in the downstream direction)

or we might calculate velocity and forces at very small scales of space and time, throughout the channel. (this would lead to a 2d or 3d model of flow and transport)

When we have determined the forces acting on the bed and banks of the channel, we can then determine:

(i) Can the flow move the material in the bed entirely, in part, or at all (**flow competence**)?

(ii) If the flow can move the bed material, at what *rate* can the material be moved (**transport capacity**)?

Transport capacity is balanced against sediment supply:

If more is coming in than going out, some is left behind. The bed aggrades.

If more is going out than is coming in, some of the bed material is removed. The bed scours.

These two statements are always true.

***However* (!!!),** the situation is a little more complicated for real (mixed-size) sediment, particularly because the sediment supply and the bed material are often different sizes.

If the transport ***capacity*** is smaller than the sediment ***supply***, more sediment arrives than departs and the bed aggrades. Always.

If the transport ***capacity*** is larger than the sediment ***supply***, we have to consider the capacity separately for the supply and the bed.

If both supply and bed are the same size and there is plenty of sediment in the bed, then the excess capacity will recruit (erode) sediment from the bed to meet the capacity.

At the other extreme, if the flow cannot move any of the sediment in the bed (flow is not competent, as in a sewer pipe), then the excess capacity is unutilized. The flow moves the supply and there is nothing left to move. No bed scour.

There is lots of room in between these two extremes.

A few slides about sediment

Table 2-3 Sediment Grade Scale

		Size range			Approximate sieve mesh openings per inch	
Class Name	Millimeters	Φ	Microns	Inches	Tyler	U.S. standard
Very large boulders	4096 ~ 2048			160 ~ 80		
Large boulders	2048 ~ 1024			80 ~ 40		
Medium boulders	1024 ~ 512			40 ~ 20		
Small boulders	512 ~ 256	−9 ~ −8		20 ~ 10		
Large cobbles	256 ~ 128	−8 ~ −7		10 ~ 5		
Small cobbles	128 ~ 64	−7 ~ −6		5 ~ 2.5		
Very coarse gravel	64 ~ 32	−6 ~ −5		2.5 ~ 1.3		
Coarse gravel	32 ~ 16	−5 ~ −4		1.3 ~ 0.6	2 ~ 1/2	
Medium gravel	16 ~ 8	−4 ~ −3		0.6 ~ 0.3	5	5
Fine gravel	8 ~ 4	−3 ~ −2		0.3 ~ 0.16	9	10
Very fine gravel	4 ~ 2	−2 ~ −1		0.16 ~ 0.08	16	18
Very coarse sand	2.000 ~ 1.000	−1 ~ 0	2000 ~ 1000		32	35
Coarse sand	1.000 ~ 0.500	0 ~ 1	1000 ~ 500		60	60
Medium sand	0.500 ~ 0.250	1 ~ 2	500 ~ 250		115	120
Fine sand	0.250 ~ 0.125	2 ~ 3	250 ~ 125		250	230
Very fine sand	0.125 ~ 0.062	3 ~ 4	125 ~ 62			
Coarse silt	0.062 ~ 0.031	4 ~ 5	62 ~ 31			
Medium silt	0.031 ~ 0.016	5 ~ 6	31 ~ 16			
Fine silt	0.016 ~ 0.008	6 ~ 7	16 ~ 8			
Very fine silt	0.008 ~ 0.004	7 ~ 8	8 ~ 4			
Coarse clay	0.004 ~ 0.002	8 ~ 9	4 ~ 2			
Medium clay	0.002 ~ 0.001		2 ~ 1			
Fine clay	0.001 ~ 0.0005		1 ~ 0.5			
Very fine clay	0.0005 ~ 0.00024		0.5 ~ 0.24			

GRAVEL

PEA

SAND

MUD

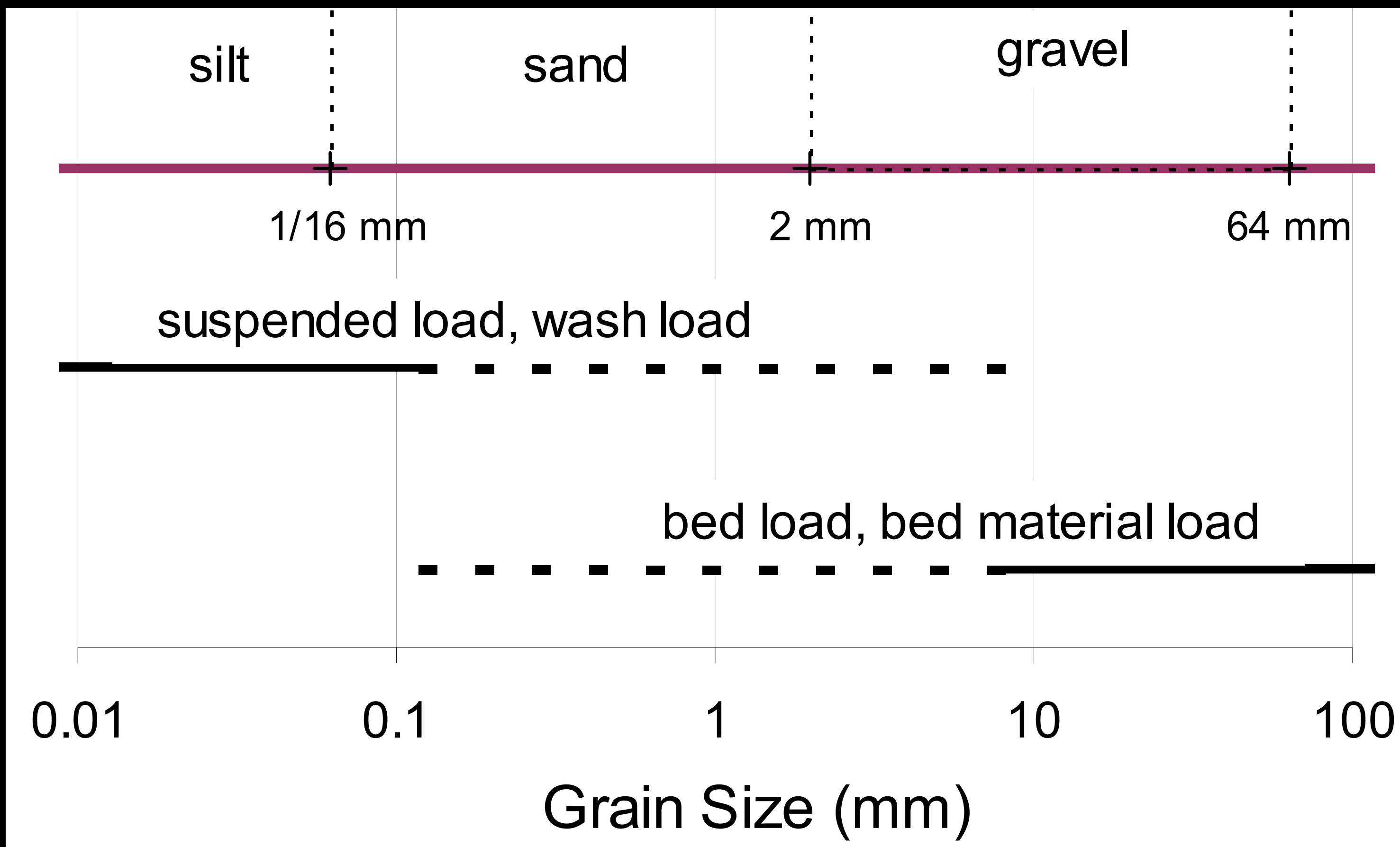
$$D\,(\mathrm{mm}) = 2^{-\phi} = 2^{\psi}$$

We can classify transport by

Mechanism — bedload vs suspended load, or

Source — bed-material load vs. wash load

The boundary between each subcategory is diffuse



We can classify transport by ***mechanism*** or ***source***

Size Fraction	Mechanism	Source	Notes
Washload clay, silt, fine sand, **more?**	Suspended load	?? uplands, banks, backwaters, …	Washload: (a) Transport not 'predictable' (b) too little in bed to affect transport of other fractions
Bed Material – **Fine** med-crs sand, *pea gravel*	bed load or suspended load	Bed matrix: interstices, stripes dunes, subsurface	grain path in near-bed region dominated by larger grains; hard to sample & model
Bed Material – **Coarse** med-crs gravel, cobble	bed load	Bed framework	displacements generally rare and hard to capture
Bed Material – **Huge** boulder	immobile at typical high flows	Bed surface	Requires decision regarding grains to exclude from the transportable population

Background: Calculus, differential eq., elementary mechanics, fluid mechanics, numerical methods

Open Channel Hydraulics

Henderson, F., 1966. Open channel Flow, Macmillan.

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Sedimentation

Wilcock, P; Pitlick, J; Cui, Y. 2009. Sediment Transport Primer: Estimating Bed-Material Transport in Gravel-bed Rivers. RMRS-GTR-226. USDA Forest Service, http://www.stream.fs.fed.us

Garcia, M. (ed.) 2008. Sedimentation Engineering: Theory, Measurement, Modeling, and Practice, ASC Manual 110

Hydrology, Geomorphology, Ecology

Dingman, L., Physical Hydrology, Culinary and Hospitality Industry Publications Services?

Freeze, A. and Cherry, J., 1979, Groundwater, Prentice Hall

Knighton, D., 1998. *Fluvial Forms and Processes*. Arnold

Kondolf, G.M. and H. Piegay (eds.), 2003. *Tools in Fluvial Geomorphology*. John Wiley.

Allan, J.D., 1995. *Stream Ecology: structure and function of running waters*. Chapman Hall.

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Naiman, R.J., H. Decamps, M.E. McClain, 2005. *Riparia: Ecology, conservation, and management of streamside communities*. Elsevier Academic Press, 430 p.

Restoration Design & Practice

Copeland, R., D.N. McComas, C.R. Thorne, P.J. Soar, M.M. Jonas, J.B. Fripp, 2001. Hydraulic Design of Stream Restoration Projects, ERDC/CHL TR-01-28. ERDC/CHL TR-01-28

Shields, F D, R R Copeland, P C Klingeman, M W Doyle, and A Simon; 2003 (August); Design for Stream Restoration, Journal of Hydraulic Engineering; 129, 8: 575-584

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes and Practices. Springfield, Va: National Technical Information Service. http://www.nrcs.usda.gov/technical/stream_restoration/newgra.html.

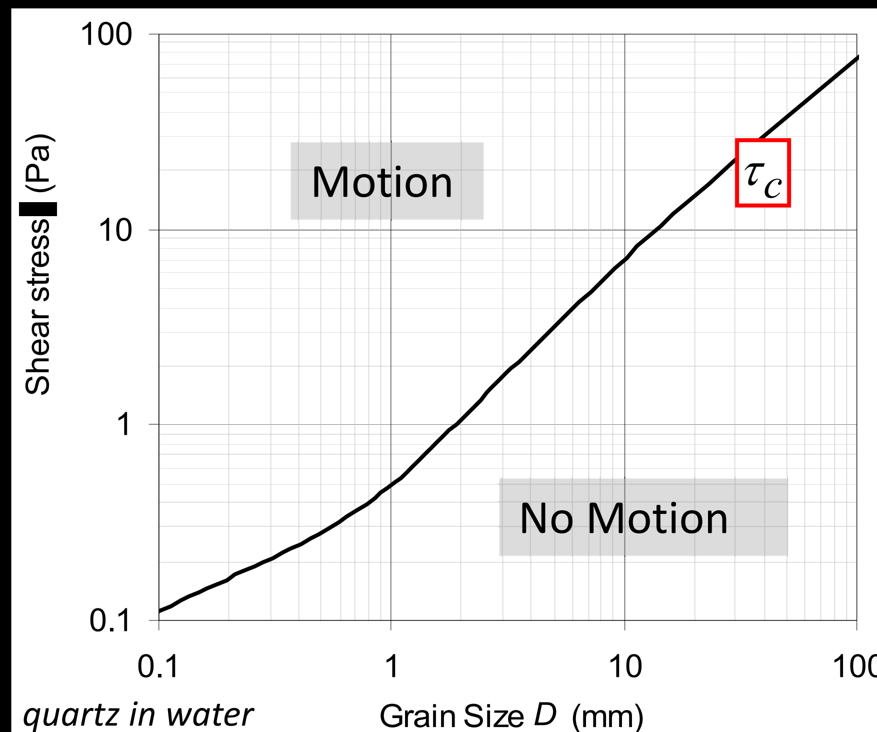
NRCS, 2007. Stream Restoration Design, Part 654 National Engineering Handbook download: http://policy.nrcs.usda.gov/index.aspx, request CD: http://landcare.nrcs.usda.gov/

A few slides about sediment transport & incipient grain motion

When does transport begin?

What is the critical shear stress τ_c at incipient grain motion?

Shields Curve: gives critical shear stress as a function of grain size



What drives grain motion?

(Flow force on bed)/(bed area): τ_o

The Shields Number

(Grain weight): $(\rho_s - \rho) g \frac{\pi}{6} D^3$

Number of grains/area $\propto 1/D^2$

Shields Number: $$\frac{\text{Flow Force}}{\text{Grain weight}} = \frac{\tau_o}{(\rho_s - \rho) g D} \equiv \tau^*$$

This is THE most important variable in sediment transport

D grain size; g acceleration of gravity; ρ, ρ_s water, sediment density; $s = \rho_s / \rho$

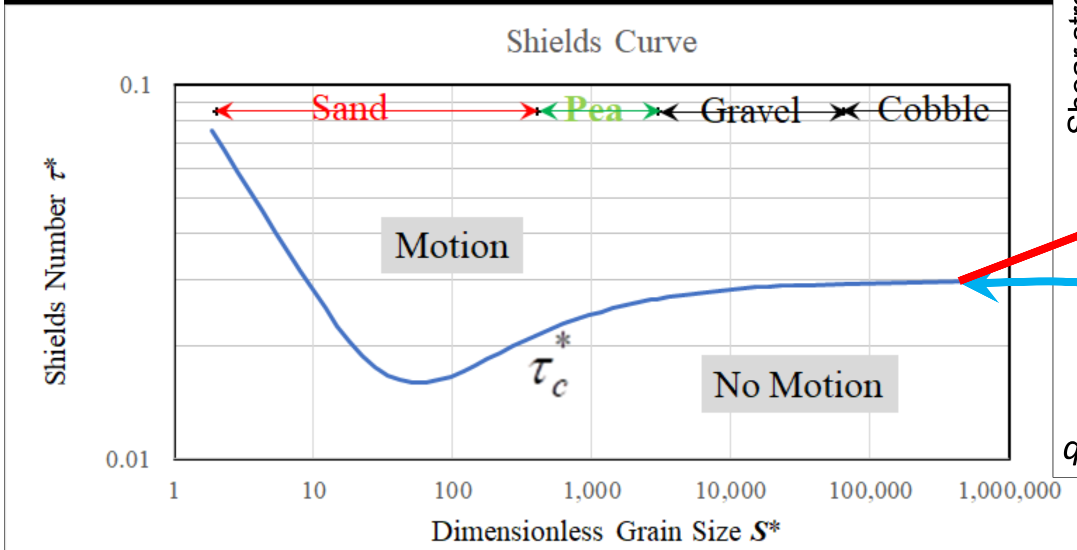
Quite generally, to estimate sediment transport, we face a

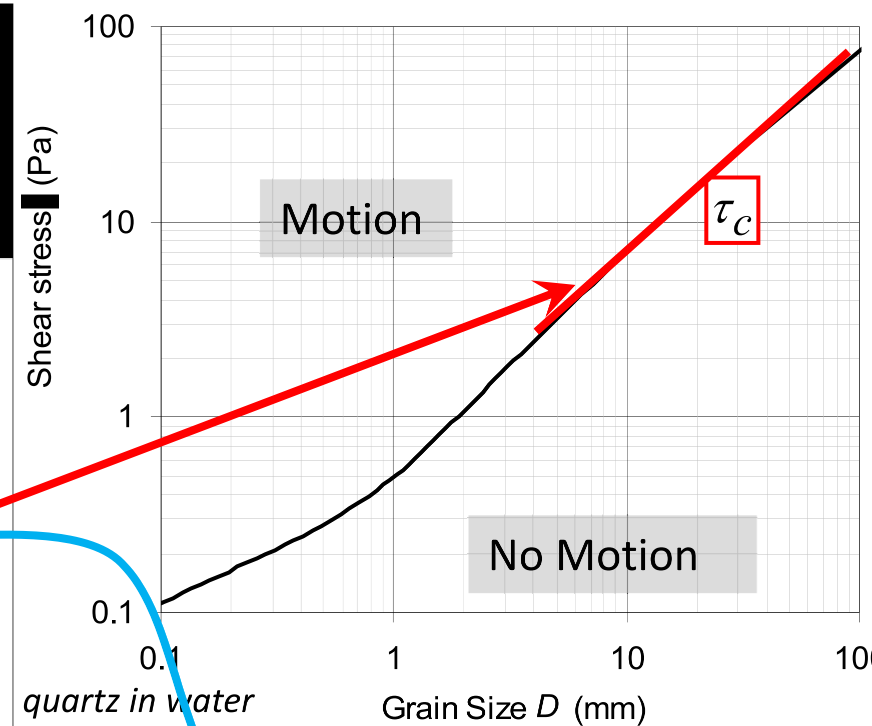
(i) ***sediment problem*** – specifying the model and parameter values to estimate incipient motion and transport rate as a function of boundary stress τ

(ii) ***hydraulics problem*** – estimating boundary stress τ in terms of channel geometry, bed roughness, and flow

When does transport begin?

Shields Curve: relates critical Shields Number τ_c^* and Dimensionless Grain Size S^*





$$\tau^* = \frac{\tau_o}{(\rho_s - \rho) g D}$$

$$S^* = \frac{D^{3/2}}{\nu}\sqrt{(s-1)g}$$

For $D > 4$ mm

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

$$\tau_c = 0.5 D$$

For τ_c in Pa & D in mm

D grain size; ρ, ρ_s water, sediment density;

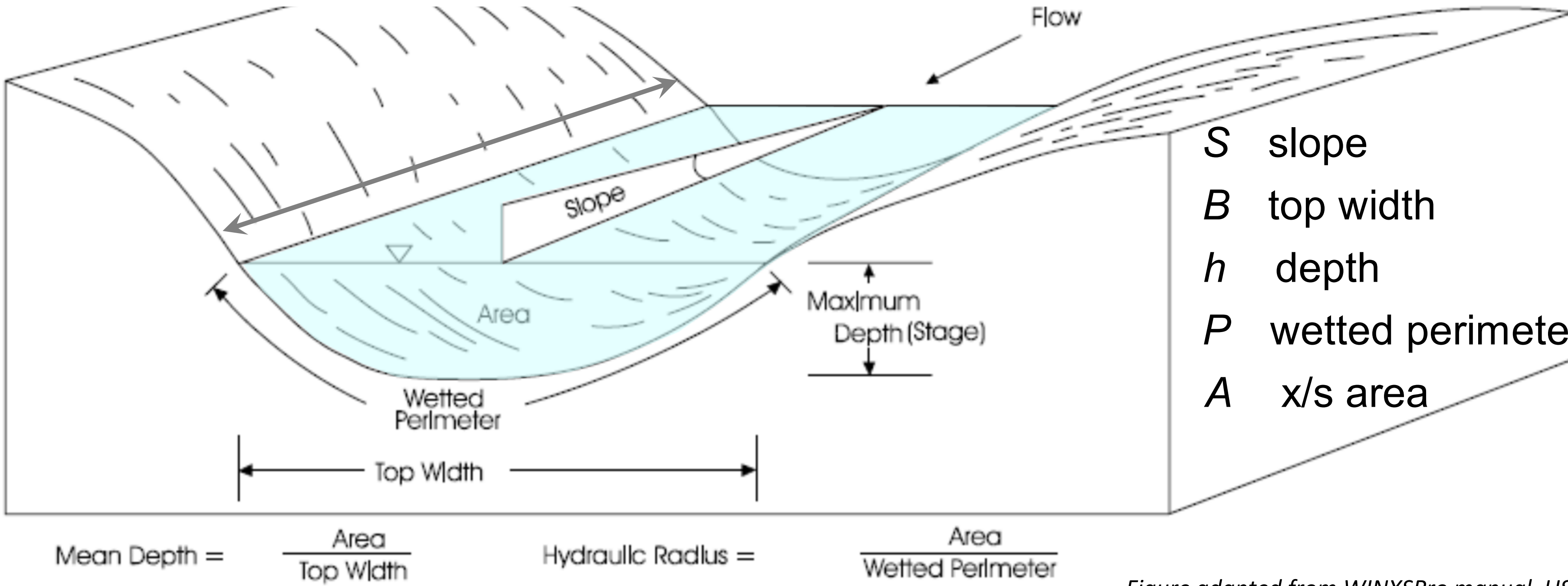
g acceleration of gravity;

ν water viscosity

How do we get this boundary shear τ_o?

Normal flow
no accelerations, so $\Sigma F = 0$

τ_o balances the downslope component of the weight of the water



S slope
B top width
h depth
P wetted perimeter
A x/s area

Figure adapted from WINXSPro manual, USFS

Volume of water: AL
Weight of water: ρgAL
Downslope component of weight of water: $\rho gALS$

Boundary stress: τ_o
(stresss is force/area)
Boundary force: $\tau_o PL$

$$\tau_o PL = \rho gALS$$
$$\tau_o = \rho gRS$$
$$\tau_o \simeq \rho ghS$$
in a wide channel

τ_o is the boundary shear stress - the flow force per unit area - it drives the sediment transport

The 'depth-slope' product
$\tau_o = hS$ (h in cm, S in %, τ_o in Pa)

As discharge Q increases, up goes the depth.

Bed shear $\tau_o \simeq \rho g h S$ incrases also.

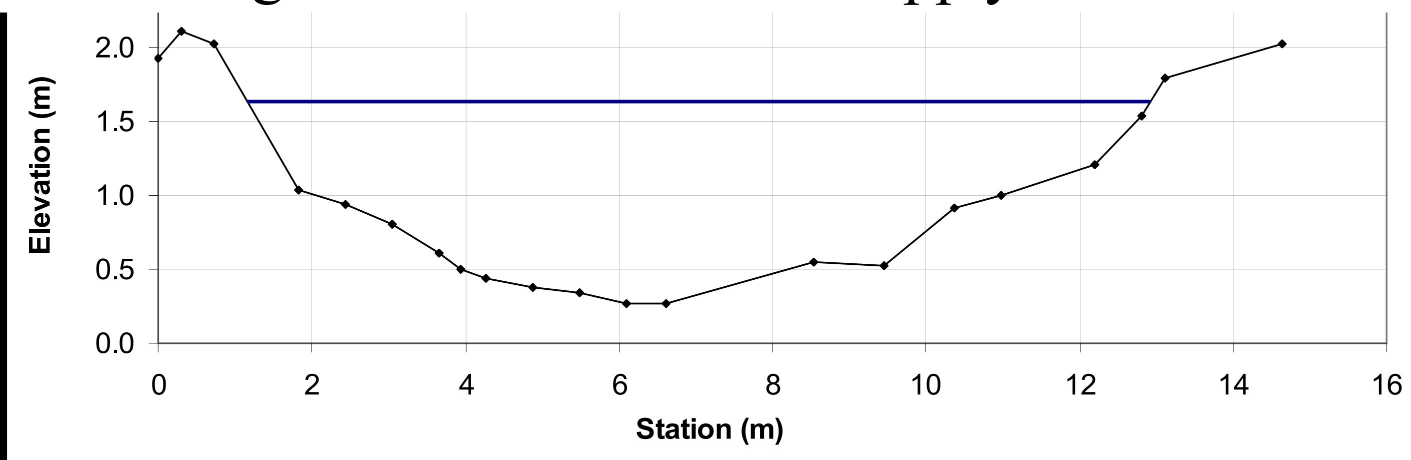
Will sediment move? Is $\tau_o > \tau_c$?

Incipient motion - critical discharge - flow competence

How fast will sediment move? *By how much* does τ_o exceed τ_c?

The transport rate is transport capacity -

match against rate of sediment supply



We have to calculate the flow – solve the flow problem – to find τ_o as a function of water discharge, channel geometry, and roughness. Sediment properties – and a transport model – gives us τ_c, the stress that initiates motion.

Competence *v.* Capacity

Flow Competence

Can a flow entrain the grains on the bed?

Applied to the channel ***bed***

Leads to a threshold channel

Transport Capacity

At what rate can a flow transport sediment?

Compare to sediment ***supply***

Leads to a mobile channel

Incipient Motion

does a grain move?

Does τ_o exceed τ_c ?

Tranpsort model:

Specified τ_c^*

Transport Rate

How fast do grains move?

By how much does τ_o exceed τ_c ?

$$\text{Transport rate} = f(\tau_o - \tau_c)$$

Big Deal: does τ_c refer to the BED or the SUPPLY ???

Spatial variability: implications for ***sampling*** and ***modeling***

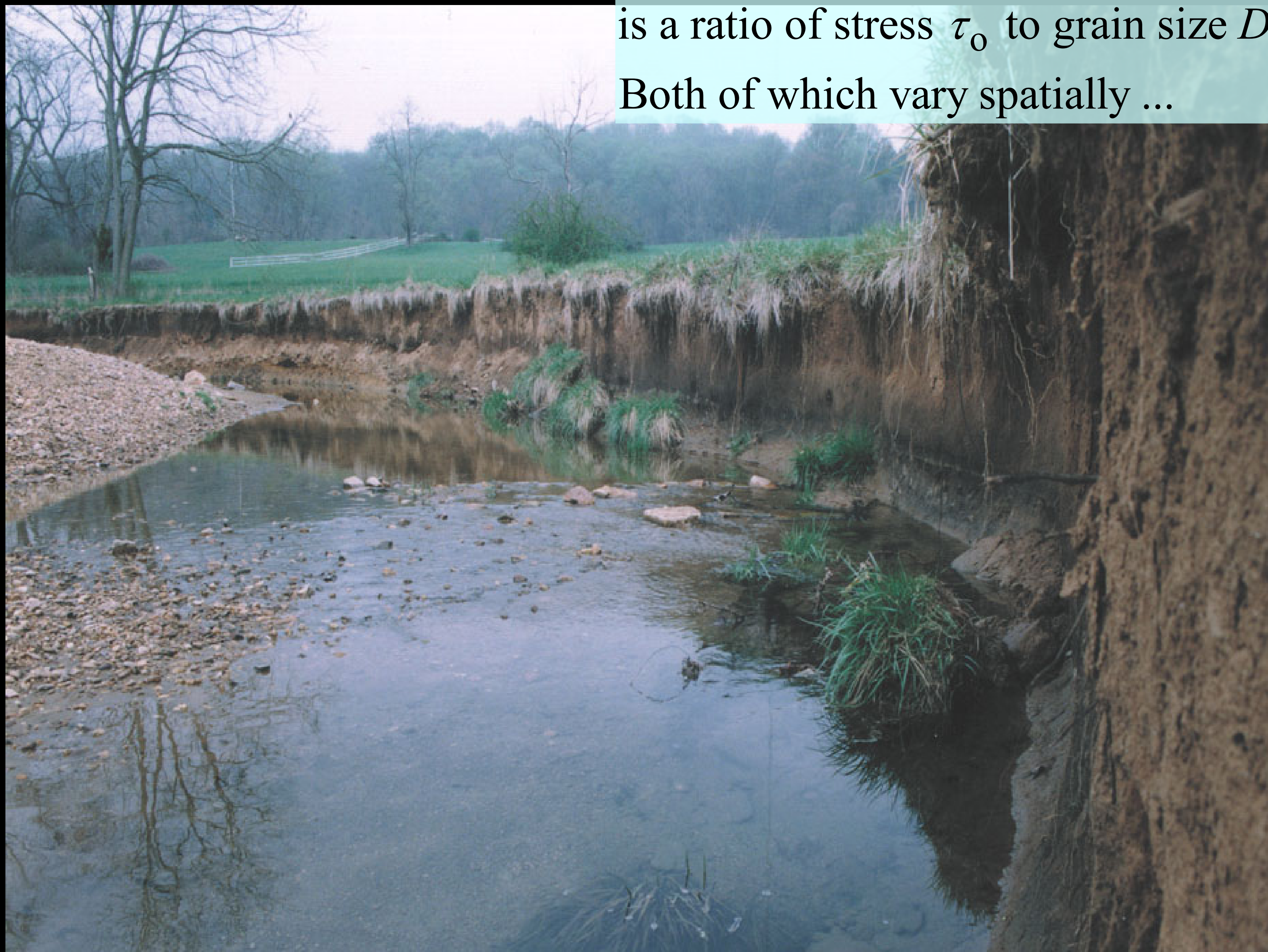
Entrainment and transport are ***local*** and ***nonlinear*** processes

In a quasi linear system

The Shields Number $\tau^* = \dfrac{\tau_o}{(s-1)\rho g D}$

is a ratio of stress τ_{o} to grain size D

Both of which vary spatially ...



Some topics to ponder

in the field today, at each channel reach.

$$\tau_c \cong 0.5D$$

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)gD} \cong 0.03$$

$$\tau_o = \rho g R S$$

$$\tau_o \simeq \rho g h S$$

in a wide channel

Think Shields Number.

What is **critical stress of grains** in the reach?

Use median size D_{50} of the gravel bed material

and $\tau_c = 0.5\ D_{50}$ (D_{50} in mm)

What is the approximate shear stress from flow at different flow depths?

Use $\tau_o = hS$ (h in cm, S in %)

$$\tau_c \simeq 0.5 D_{50}$$

$$\tau_o \simeq hS$$

$$h_c \sim \frac{0.5D}{S}$$

D_{50} [mm], h [cm], S [%]

What depth of flow is needed to move the bed material?

What discharge produces this flow depth?

What is grain size of the sediment **supply** compared to the bed?