Estimating Sediment Transport

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- Incipient Motion & Sediment Transport Rates
- Uncertainty in formula calculations
- Why it’s hard to estimate transport rates
- Empirical vs formula estimates
- A calibrated method for estimating transport rates in gravel-bed rivers

The first transport problem: incipient motion

The transport model is a defined value of critical Shields Number τ_c^*

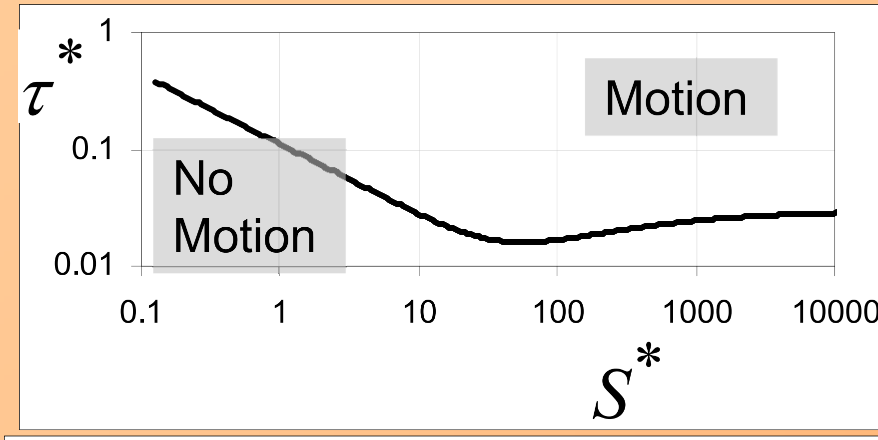
For a gravel-bed river, a reasonable choice of *D* is the median size of the gravel portion of the bed (the framework), measured with a pebble count. For clean, loose gravel,

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

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^*.

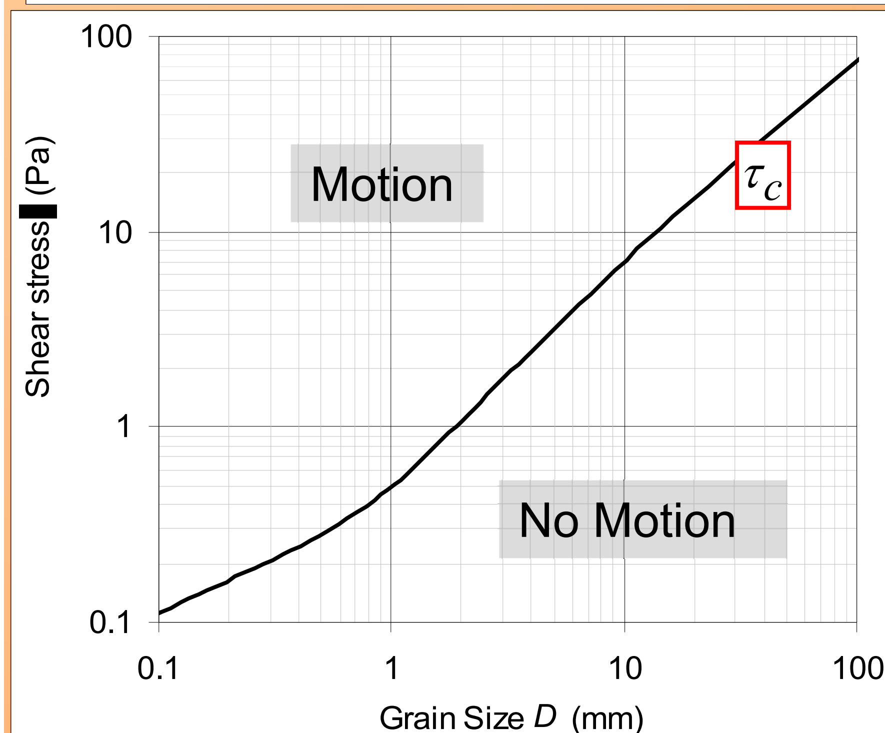
Church, Hassan, Wolcott *Water Res Res* 1998

For smaller sizes, the model is Shields Curve (at least for unisize sediment)



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

That is, grains begin a-rolling when the flow shear ***force*** is about ***three %*** of the grain weight.



Note that τ_c is directly proportion to grain size D

Why does τ_c* get relatively larger for smaller grains? ***Viscosity,*** *my friend.*

Uncertainty Exercise

For a simple, wide, prismatic channel, find Q_c directly

$$Q = BhU \quad \textit{continuity}$$

$$B = aQ^b \quad \textit{hydraulic geometry}$$

$$h = \tau / \rho g S \quad \textit{momentum}$$

$$U = \frac{\sqrt{S}}{n} h^{2/3} \quad \text{so} \quad \textit{Manning's eqn.}$$

$$Q = \left(aQ^b\right)\left(\frac{\tau}{\rho g S}\right)^{5/3} \frac{\sqrt{S}}{n} \quad \text{or}$$

$$Q = \left[\frac{a\sqrt{S}}{n}\left(\frac{\tau}{\rho g S}\right)^{5/3}\right]^{1/(1-b)}$$

$$\tau_c = \tau_c^*(s-1)\rho g D \quad \text{so}$$

$$Q_c = \left[\frac{a}{nS^{7/6}}\left(\tau_c^*(s-1)D\right)^{5/3}\right]^{1/(1-b)}$$

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

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What if you are not too sure about some of the values needed to determine Q_c?

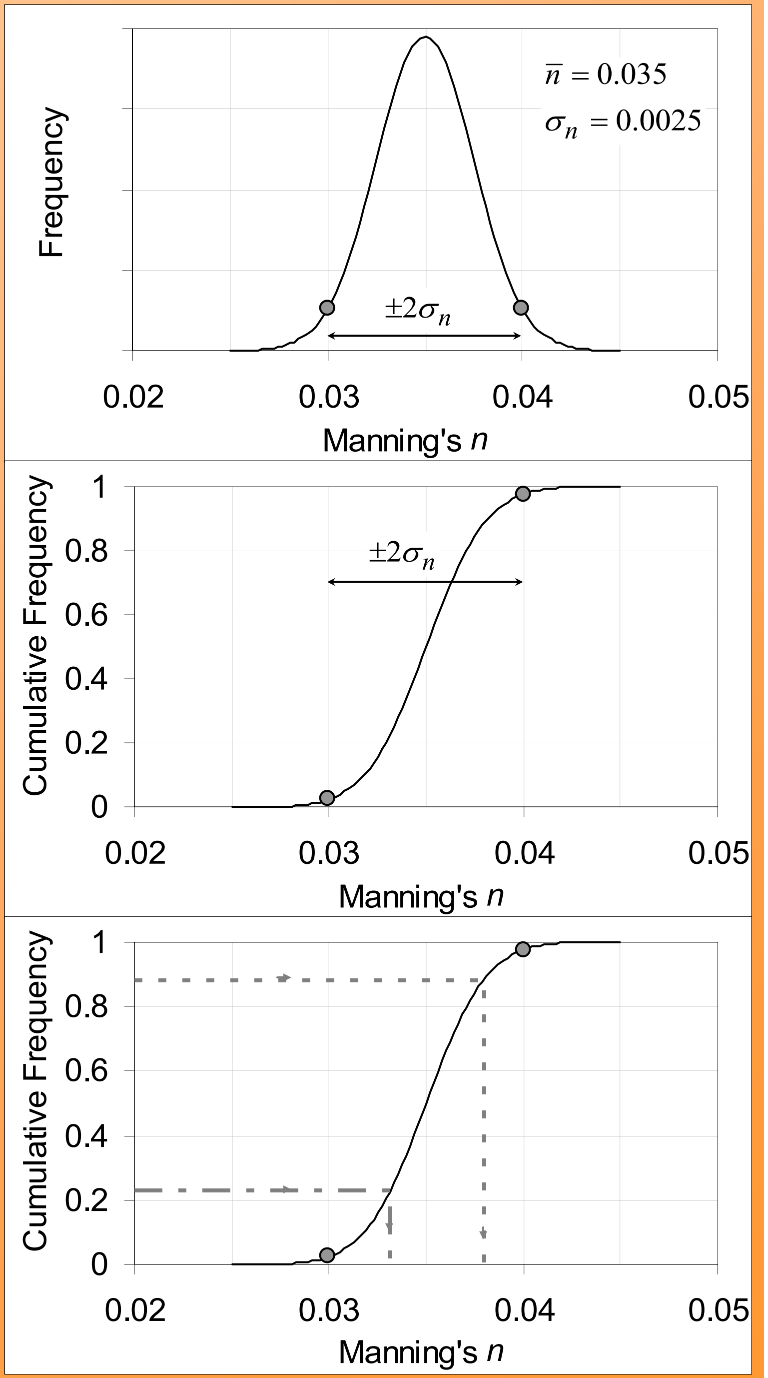
Like n, D, and τ^*_c – what do you do?

Suppose your best estimate of Manning's n is 0.035 and that you are pretty sure that the real value falls between 0.03 and 0.04.

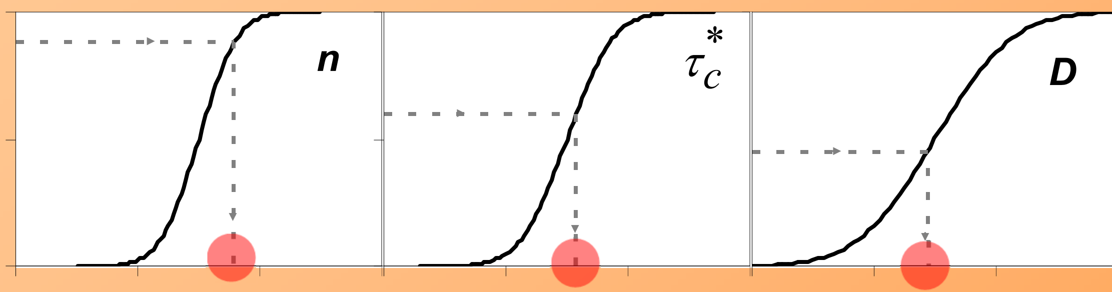
We could approximate your assessment of the value of n with a normal distribution with mean $\bar{n}$ = 0.035 & standard deviation σ_n = 0.0025.

95% of this distribution falls between 0.03 and 0.04, as can be seen in the cumulative frequency plot, so we are saying that the real value of n is 95% likely to fall between 0.03 and 0.04 and that it is more likely to be around the center of the distribution (0.035) than in the tails. We use this distribution to pick values of n in our Monte Carlo simulation.

How does that work? We use a random number generator to pick a number between 0 and 1 and then use this number to find a value of n for the cumulative frequency distribution. For example,
for 0.88, n = 0.0379
for 0.23, n = 0.0332



The Monte Carlo simulation



1. Pick values of n, τ_c^*, and D from specified frequency distributions.
2. Calculate critical discharge and transport rate.
3. Repeat 1000 times.
4. Distribution of calculated values gives estimate of the effect of input uncertainty on calculated critical discharge and transport rate.

2.

$$Q = BhU$$

$$B = aQ^b$$

$$h = \tau / \rho g S$$

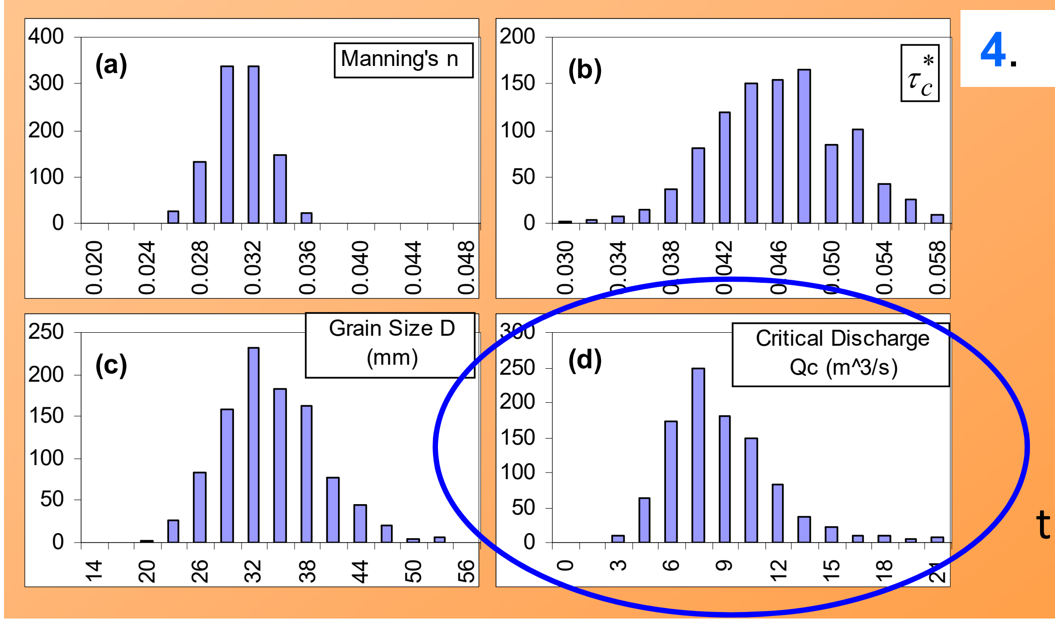
$$U = \frac{\sqrt{S}}{n} h^{2/3} \quad \text{so}$$

$$Q = \left(aQ^b\right)\left(\frac{\tau}{\rho g S}\right)^{5/3} \frac{\sqrt{S}}{n} \quad \text{or}$$

$$Q = \left[\frac{a\sqrt{S}}{n}\left(\frac{\tau}{\rho g S}\right)^{5/3}\right]^{1/1-b}$$

$$\tau_c = \tau_c^*(s-1)\rho g D \quad \text{so}$$

$$Q_c = \left[\frac{a}{nS^{7/6}}\left(\tau_c^*(s-1)D\right)^{5/3}\right]^{1/1-b}$$

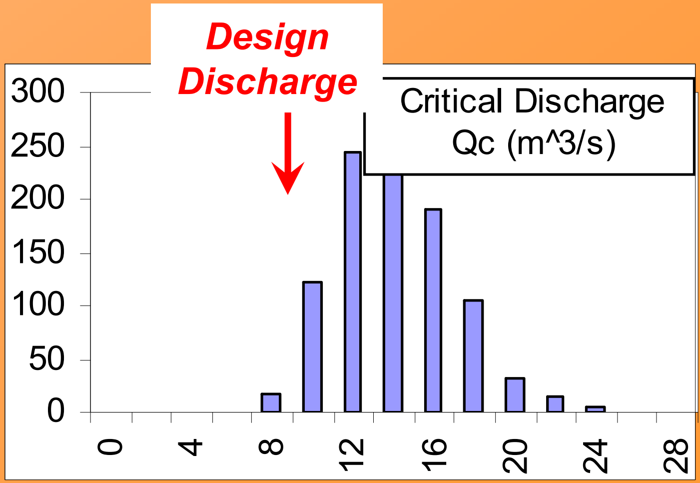


This is the (uncertain) solution to the threshold channel problem Need a better answer? ***Tracer gravels***

Application of Monte Carlo approach for assessing risk: threshold channel

Given a channel with a design discharge. The channel is intended to be static. You would like to be 90% sure that the grains in the channel bed will not move at the design discharge.

Solution: specify possible range in *n*, *D*, and τ^*_c, use Monte Carlo to determine the range of possible discharges. Adjust design until 90% of the calculated values of critical discharge are larger than the design discharge.



The second transport problem: transport rate

Most sediment transport problems are defined in terms of total sediment transport rate Q_s and water discharge Q.

A relation giving Q_s as a function of Q is a **sediment rating curve**.

$$Q_s = aQ^b \qquad (1)$$

Q_s tons per day (kg/hr, Mg/day) and Q ft^3/s, or cfs (m^3/s, or cms)

Example: with a sediment rating curve such as (1) and a record of discharge (e.g. the daily mean value of Q for 25 years), you can calculate the total sediment load (the sediment yield) by using (1) to calculate the tons of sediment transported for each day and adding up all 9131 or so values to get a total sediment yield for 25 years.

Warning:	Sediment Rating Curves can shift &
	May need a much shorter time interval

If a sediment rating curve is what we use in application, isn't there a general one available?

Will 1,000 cfs in Logan R. move the same amount of sediment as 1,000 cfs in the Columbia R.?

One thing to try: $Q_s = aQ^b \longrightarrow \frac{Q_s}{Q_{sr}} = \left(\frac{Q}{Q_r}\right)^b$

Its nice that *a* cancelled, but for this model to be general, the rate of change of *Qs* with *Q* (i.e. the exponent *b*) must be the same everywhere. But we will find that *b* varies from little more than one to more than ten!.

Basically , we are looking for a flow variable that can be accurately scaled, such that we have a general model

A flow variable that does scale well (although it not always easy to determine) is the bed shear stress τ_o. This is used in most general transport models in common use.

What might a general transport model look like? First, let's get a more formal introduction to the players. The best way to do this is with a dimensional analysis which will produce a list of dimensionless variables that represent the problem.

This helps because
* the number of dimensionless variables is (usually) 3 less than the full list of variables that we think might be important
* the dimensionless variables often have a useful physical meaning
* Any relation between the dimensionless variables should be general, if we have listed all relevant variables at the start.

Our list: $q_s = f(\tau, h, D, \rho_s, \rho, \mu, g)$

$$\frac{L^2}{T} \qquad \frac{M}{LT^2}, L, L, \frac{M}{L^3}, \frac{M}{L^3}, \frac{M}{LT}, \frac{L}{T^2}$$

Dimensional analysis gives: $q^* = f(\tau^*, S^*, s, D/h)$

$$q^* = \frac{q_s}{\sqrt{(s-1)gD^3}}, \tau^* = \frac{\tau}{(s-1)\rho g D}$$

$$S^* = \frac{\sqrt{(s-1)gD^3}}{\mu/\rho} \text{ and } s = \frac{\rho_s}{\rho}$$

If $s = const$
$D << h$
& S^* *large*

$$q^* = f(\tau^*)$$

The Shields Number

(Flow force on bed)/(bed area): τ_o

(Grain weight): $(s-1)\rho g \frac{\pi}{6} D^3$

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

Shields Number: $\frac{\text{Flow Force}}{\text{Grain weight}} = \frac{\tau_o}{(s-1)\rho g D} \equiv \tau^*$

This is THE most important variable in sediment transport

The Einstein Transport Parameter

Volumetric transport rate/width q_s

Sediment fall velocity $w \propto \sqrt{(s-1)gD}$

$$q^* \propto \frac{\text{transport rate}}{\text{fall velocity * grain size}} = \frac{q_s}{\sqrt{(s-1)gD^3}}$$

The Yalin Transport Parameter

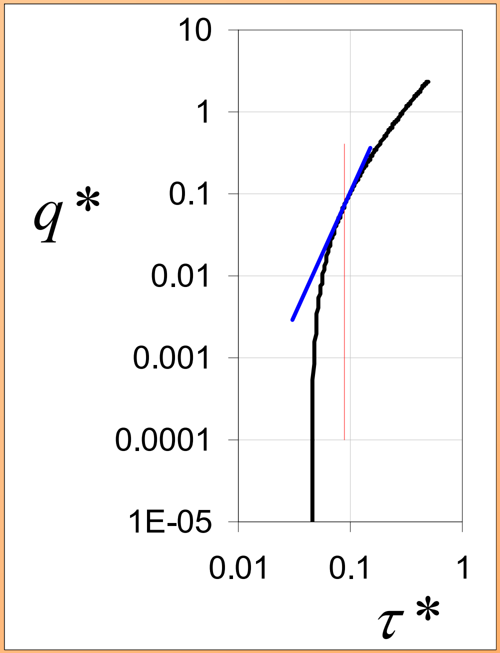
$$W^* = \frac{q^*}{(\tau^*)^{3/2}} = \frac{(s-1)gq_s}{(\tau/\rho)^{3/2}}$$

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

A typical transport model: $q^* = a(\tau^* - \tau_c^*)^b$

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

Meyer-Peter & Müller: $q^* = 8(\tau^* - \tau_c^*)^{3/2}$



$$q^* \propto \tau_*^3$$

$$\frac{q_s}{\sqrt{(s-1)gD^3}} = 8\left(\frac{\tau}{(s-1)\rho g D} - \frac{\tau_c}{(s-1)\rho g D}\right)^{3/2}$$

$$q_s = \frac{8}{(s-1)g\rho^{3/2}}(\tau - \tau_c)^{3/2}$$

$$q_s = 4(\tau - \tau_c)^{3/2}$$

for q_s in (Mg/m/day)

and τ, τ_c in (Pa)

A typical transport model: $q^* = a(\tau^* - \tau_c^*)^b$

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

Meyer-Peter & Müller: $q^* = 8(\tau^* - \tau_c^*)^{3/2}$

One more transport variable, *W**

(sorry!)

$$W^* = \frac{q^*}{(\tau^*)^{3/2}} = \frac{(s-1) g q_s}{(\tau/\rho)^{3/2}}$$

One more stress, the reference stress τ_r

Convert the M-PM formula to W* and incorporate a reference shear stress. First, we divide M-PM by $(\tau^*)^{3/2}$ to get

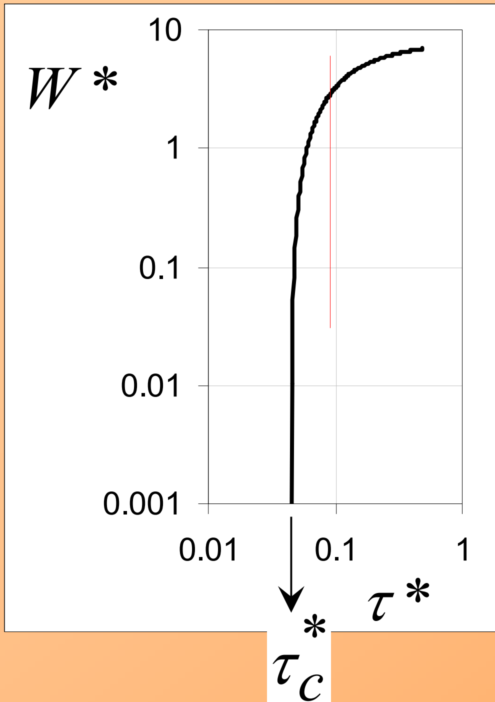
$$W^* = 8\left(1 - \frac{\tau_c^*}{\tau^*}\right)^{3/2}$$

At $\tau^* = \tau^*_r$, $W^* = W^*_r = 0.002$. Dividing by 8, raising both sides to the 2/3 power produces

$$0.004 = 1 - \frac{\tau_c^*}{\tau_r^*} \qquad \tau_c^* = 0.996\tau_r^*$$

Meyer-Peter & Müller: $W^* = 8\left(1 - 0.996\frac{\tau_r^*}{\tau^*}\right)^{3/2}$

Reference shear stress? Critical shear stress?

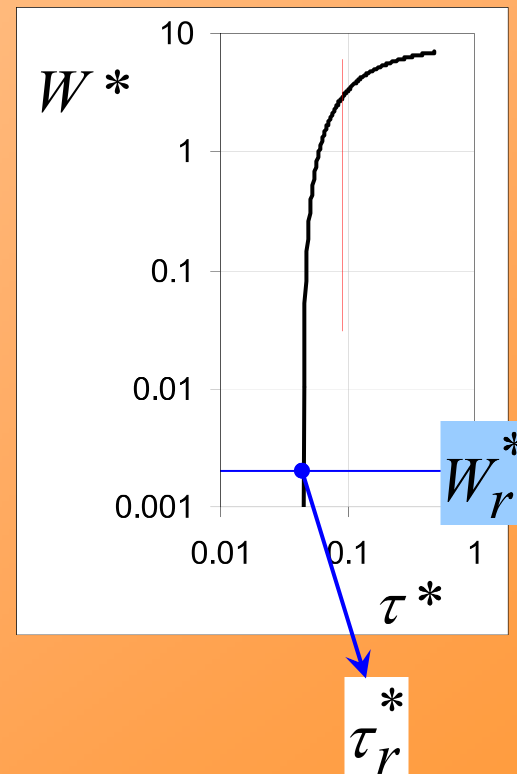


Meyer-Peter & Müller

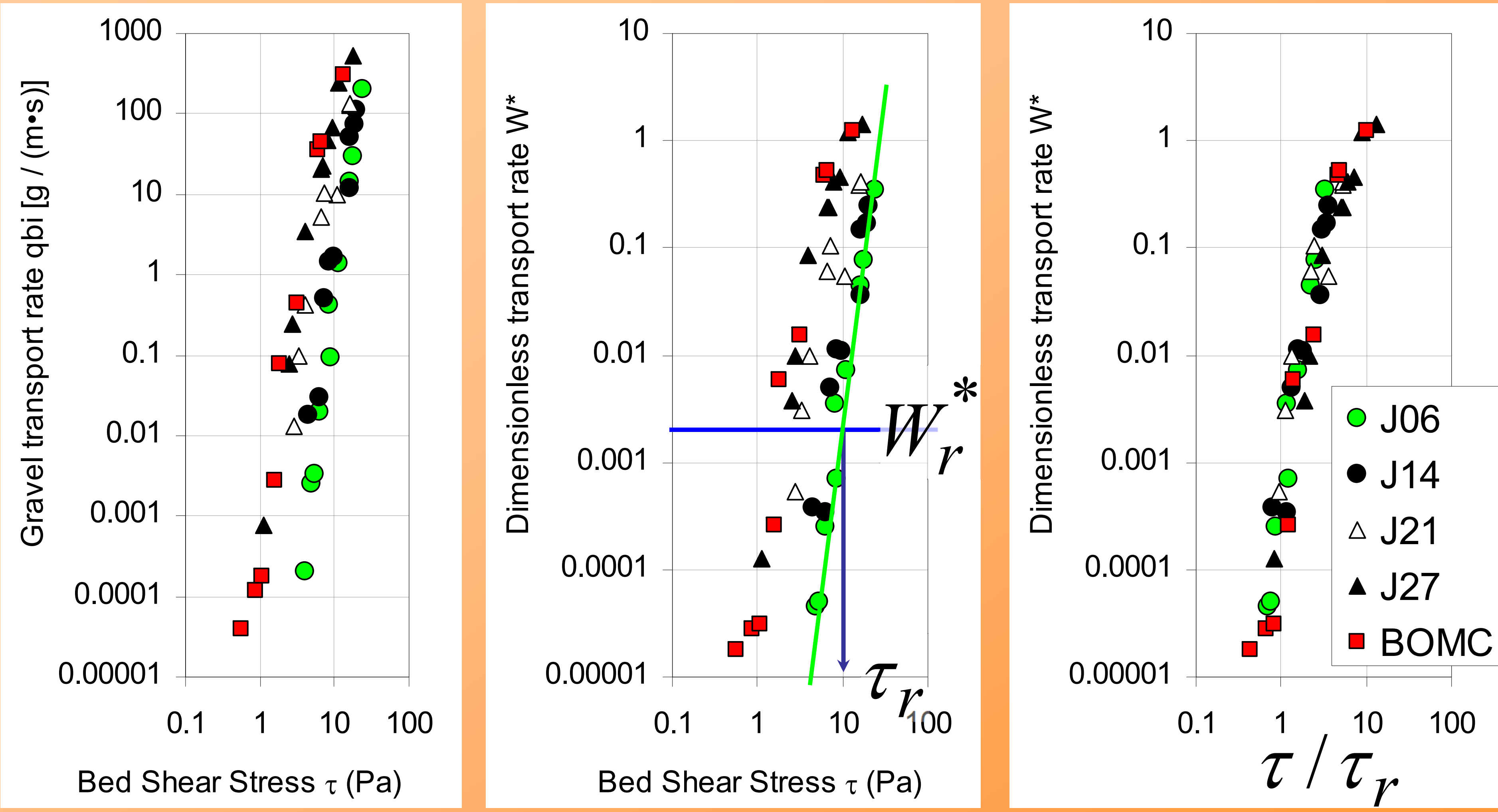
$$W^* = 8\left(1 - \frac{\tau_c^*}{\tau^*}\right)^{3/2}$$

or

$$W^* = 8\left(1 - \frac{.996\tau_r^*}{\tau^*}\right)^{3/2}$$



How the reference shear stress gets used



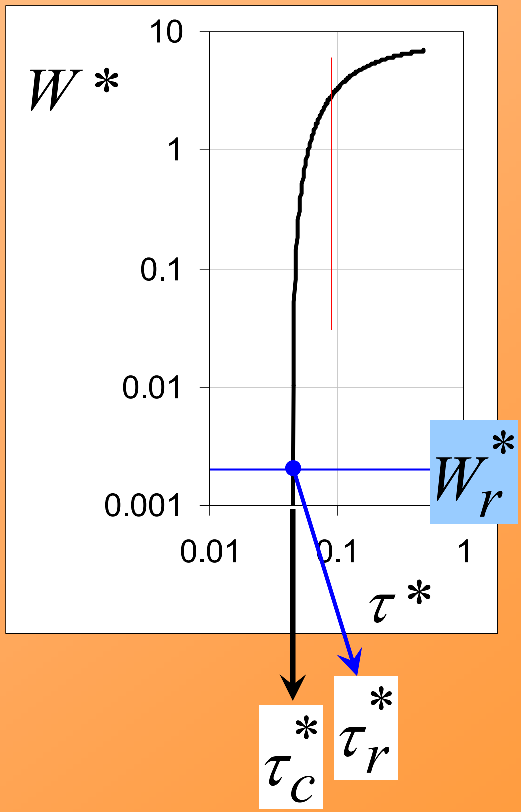
The Difference Between τ_c and τ_r

τ_c : boundary between motion & no motion. Definable exactly for an individual grain; definable statistically for a river bed

Hard to measure, tracer grains are your best shot

τ_r : the stress associated with a small, agreed-upon transport rate ($W^* = 0.002$) provides a threshold for transport estimate

Easy to determine from transport observations; new efforts using tracer grains

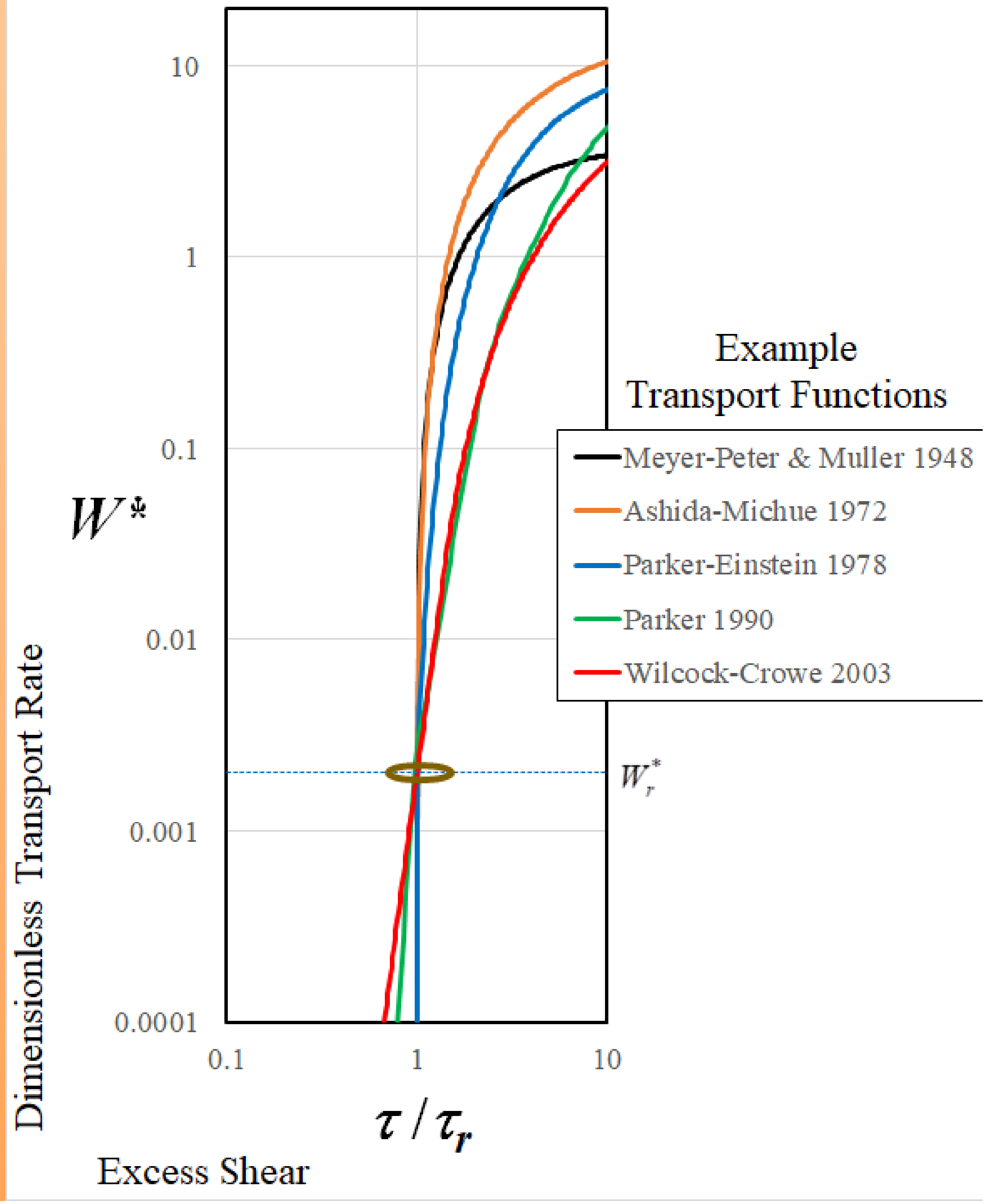


tracers (painted rocks, magnetic rocks, radio rocks, rock scum) answer the ***competence*** question “did the grain move at all?” (place tracers, return after flow, measure # moved, repeat for range of flows, develop relation between %entrained, grain size, and flow)

Need large numbers of grains for reliable sample

Need to place “naturally”

It's a unit process model



It’s a unit process model

At unit scale, all internal adjustments and interactions, producing sorting, bedforms, armoring, anything, will be similar and produce the same transport rate at the same

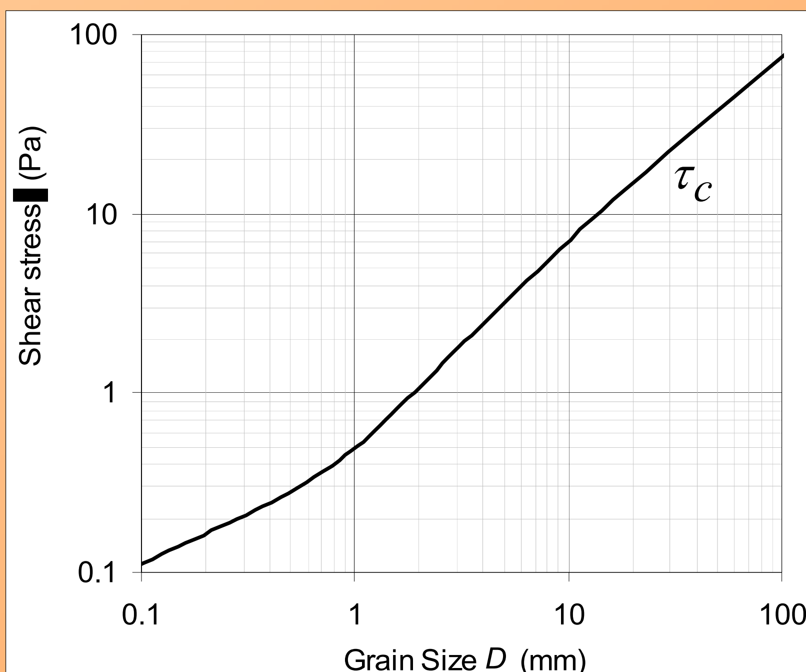
Did I mention that there is no grain size is most transport formulas?

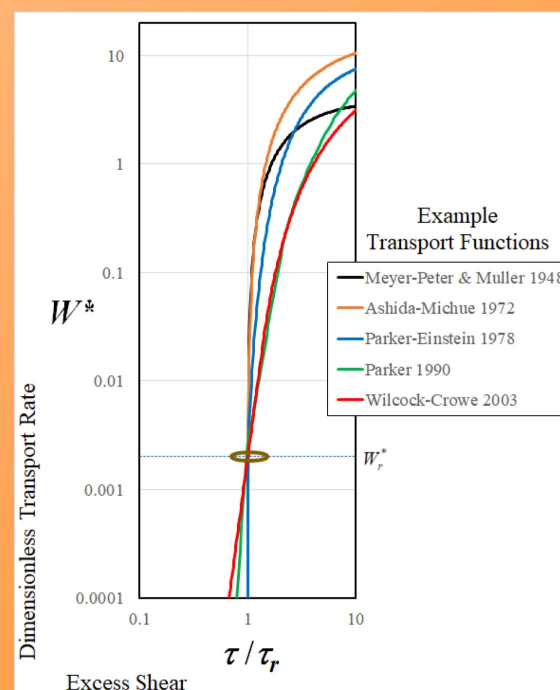
The big challenge: finding the correct critical or reference stress.

$$q^* = 8\left(\tau^* - \tau_c^*\right)^{3/2}$$

$$\frac{q_s}{\sqrt{(s-1)gD^3}} = 8\left(\frac{\tau}{(s-1)\rho g D} - \frac{\tau_c}{(s-1)\rho g D}\right)^{3/2}$$

$$q_s = \frac{8}{(s-1)g\rho^{3/2}}(\tau - \tau_c)^{3/2}$$





Garcia, Vanoni Bed Load Transport Relations

SEDIMENT TRANSPORTATION MECHANICS

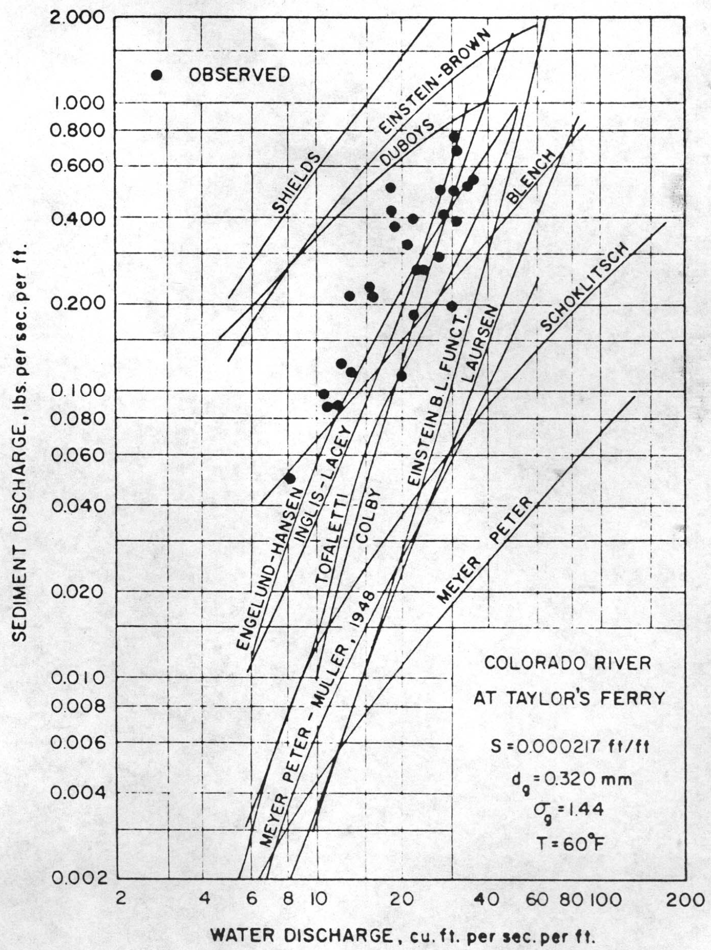


FIG. 2.113.—Sediment Discharge as Function of Water Discharge for Colorado River at Taylor's Ferry Obtained from Observations and Calculations by Several Formulas

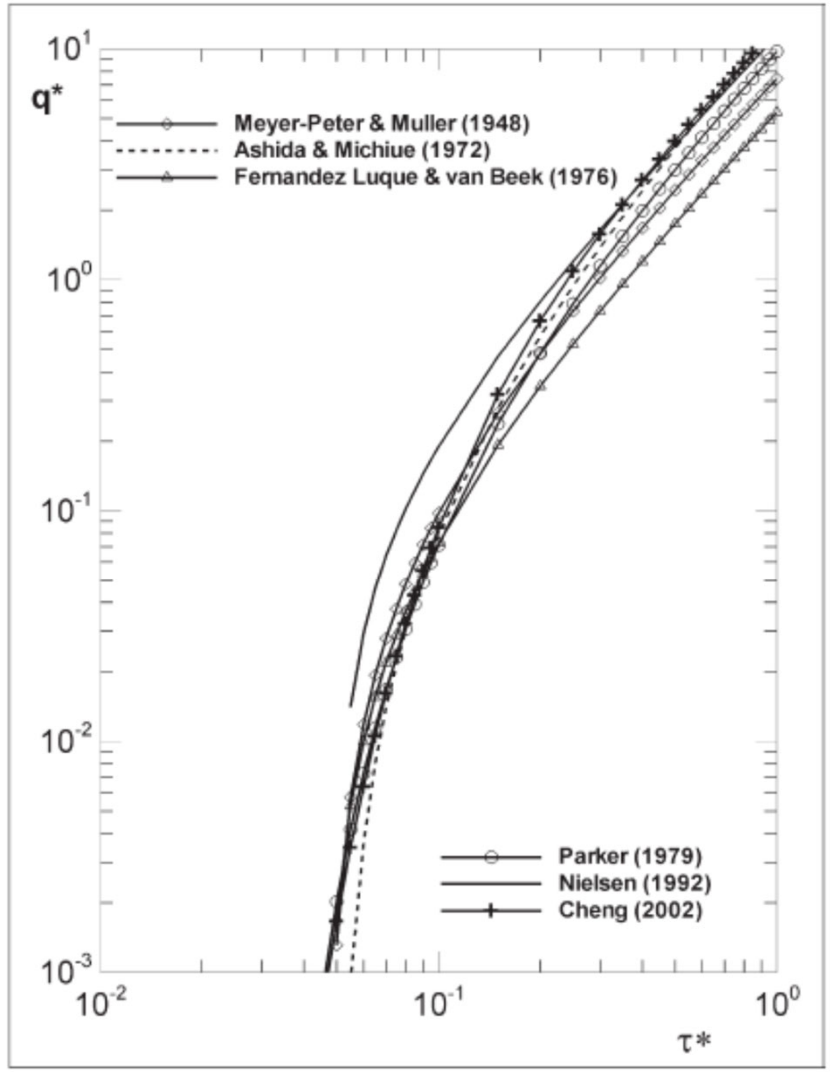
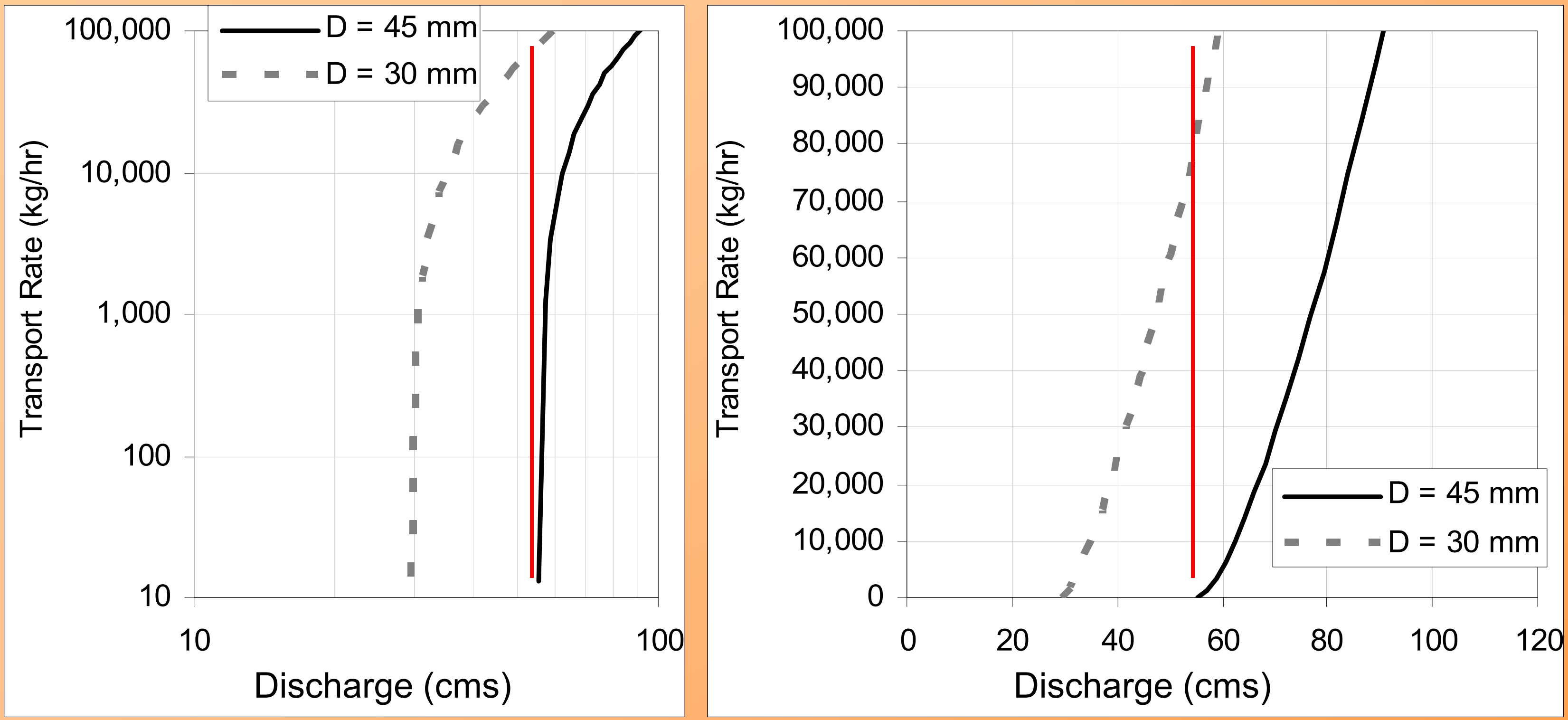


Fig. 2-33. Plot of several bed load functions found in the literature.

Sediment Transport ***Why its hard to estimate 0***



Example calculation using Meyer-Peter and Muller for a channel with slope S =0.002, roughness n= 0.025, and width b = 15m. The solid curve uses τ_c^* = 0.045 and D = 45 mm. The dashed curve uses τ_c^* = 0.045 and D = 30 mm.

Note that at discharge Q = 55 cms, one curve indicates zero transport and the other a transport rate of 80,000 kg/hr.

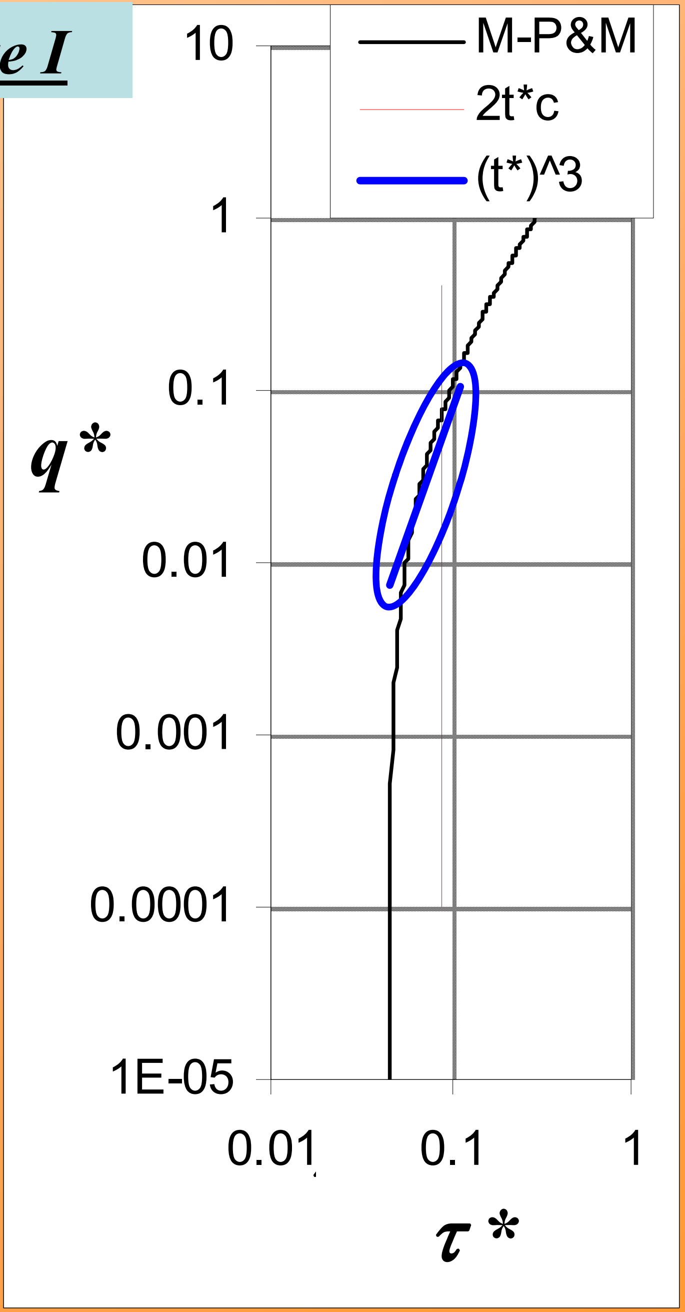
Sediment Transport ***Why its hard to estimate I***

Transport rate is a ***steep, nonlinear*** function of bed shear stress

Small error in τ can produce big error in q_s

Three things make it difficult to accurately estimate τ:

1. Accelerations in ***unsteady, nonuniform*** (i.e. real) flow
2. Only a portion of the total τ acts to transport sediment
3. τ varies locally. Because transport is a nonlinear *fn* of τ, estimates based on total τ will be in error



St. Venant Equation

$$\tau_0 = \rho g R\left(S - \frac{\partial h}{\partial x} - \frac{U}{g}\frac{\partial U}{\partial x} - \frac{1}{g}\frac{\partial U}{\partial t} \right)$$

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$$\tau_0 = \rho g R\left(S - \frac{\partial h}{\partial x} - \frac{U}{g}\frac{\partial U}{\partial x} \right)$$

$$\tau_0 = \rho g R S_f$$

NOTE:

Backwater programs compute S_f

The Drag Partition

So far, the stress we are talking about is the total stress τ_0, or force per area, that the flow exerts on the boundary of the channel.

Three things make it difficult to accurately estimate τ:

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2. Only a portion of the total τ acts to transport sediment
3. τ varies locally. Because transport is a nonlinear *fn* of τ, estimates based on total τ will be in error

But only a portion of the total τ_0 acts on the sediment grains to produce transport. To estimate transport rates, we need to *partition* τ_0 into the part that acts only on the sediment grains. We call this the skin friction, or grain stress τ'.

There is no direct way to do this. We will develop an approximate method, using Manning's equation.

Solve the Manning eqn for the boundary stress:

$$U = \frac{\sqrt{S} R^{2/3}}{n}$$

$$(\rho g)^{2/3} S^{1/6} nU = (\rho g R S)^{2/3}$$

$$\rho g S^{1/4} (nU)^{3/2} = \tau_0$$

Estimate the part of the roughness due to the bed grains:

$$n_D = 0.013 D^{1/6} \longrightarrow \rho g (0.013)^{3/2} (SD)^{1/4} U^{3/2} = \tau'$$

Manning-Strickler Roughness
for D in mm

Combine $\frac{U}{u_*} \cong 8.1 \left(\frac{R}{k_s} \right)^{1/6}$

and $u_* = \sqrt{gRS}$

to get $n_D = \frac{k_s^{1/6}}{8.1\sqrt{g}}$

$$\tau' = 17 (SD_{65})^{1/4} U^{3/2}$$

where we use $D = 2D_{65}$

$\rho = 1000 \text{ kg/m}^3$ & $g = 9.81 \text{ m/s}^2$

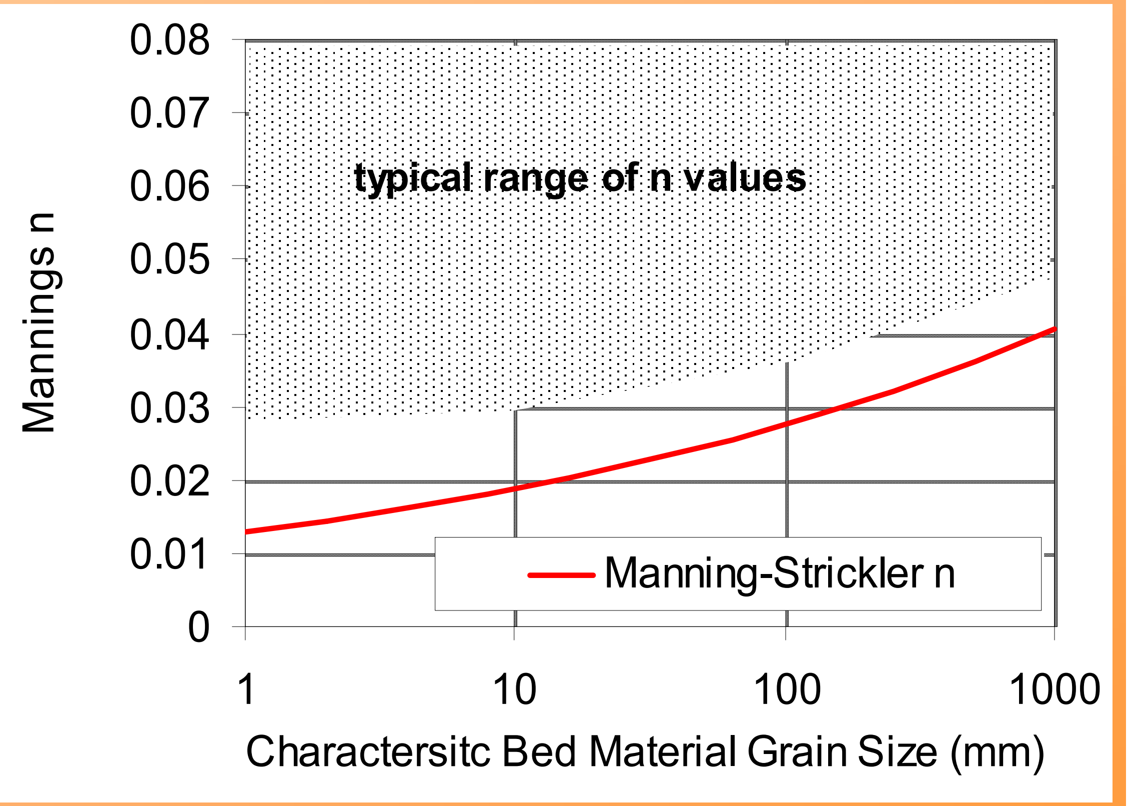
Using both the grain roughness and total roughness, we have an estimate of the portion of the total stess acting on the grains – *the grain stress.*

$$\tau_o = \rho g S^{1/4} (nU)^{3/2}$$

$$\tau' = \rho g S^{1/4} (n_D U)^{3/2}$$

$$\frac{\tau'}{\tau_o} = \left(\frac{n_D}{n}\right)^{3/2}$$

$$\tau' = \left(\frac{n_D}{n}\right)^{3/2} \tau_o$$



Basically the same drag partition suggested by Meyer-Peter & Muller in the '40s. Using Manning's *n* incorporates general experience, supports application in HEC-RAS

Three things make it difficult to accurately estimate τ:

1. Accelerations in ***unsteady, nonuniform*** (i.e. real) flow

2. **Only a portion of the total τ acts to transport sediment**

3. τ varies locally. Because transport is a nonlinear *fn* of τ, estimates based on total τ will be in error

The power of an average does not equal the average of a power!

$$q_s = 78.7(\tau - \tau_c)^{3/2}$$

for q_s in (tons/day)

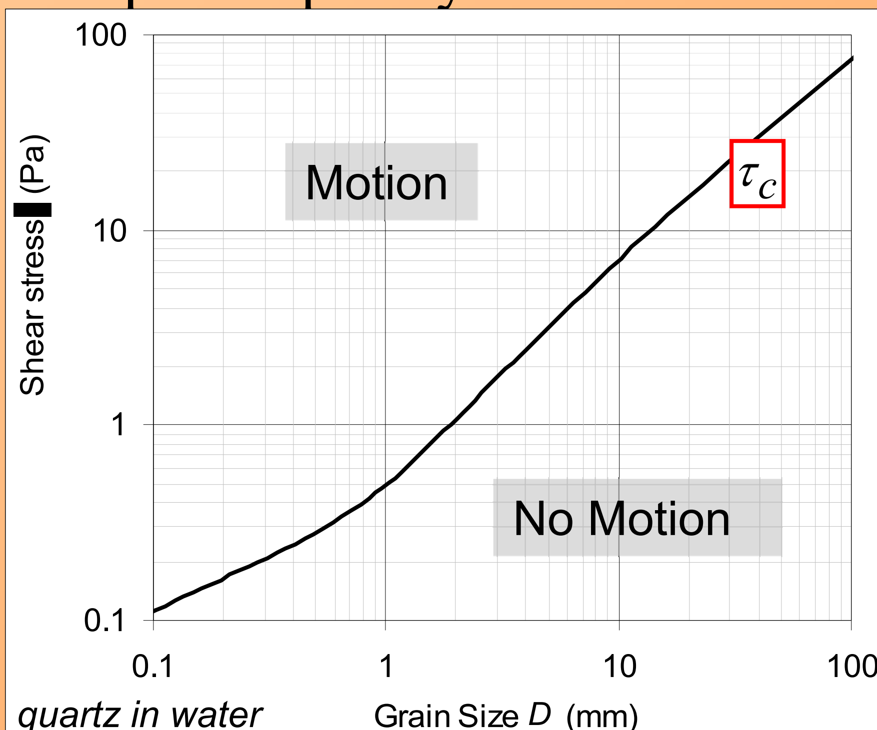
and τ, τ_c in (Pa)

Sediment Transport ***Why its hard to estimate II***

What is *D* for a reach?

What if *D* is not even in the reach?

Critical shear stress depends linearly on grain size, but the grain size of the transport is poorly known!



Transport rate is a steep, nonlinear function of bed shear stress

Small error in τ_c can produce big error in q_s

Estimating Sediment Transport: Why its hard

- Sediment transport is a local process: between individual grains and the near-bed flow they encounter
- The transport process is highly nonlinear: a very steep function with a threshold between motion and no motion
- Real streams have considerable variability in topography, flow, and bed composition
- The local flow acting on grains is hard to estimate
- The distribution of bed grain sizes is hard to determine
- You never know either local flow or local bed composition in detail, so you have to estimate
- Errors in estimated transport rates are typically very large (often well in excess of an order of magnitude!)
- Next, we examine an approach to provide reliable transport estimates, of greater accuracy, with acceptable effort

Estimating Bed-Material Transport in Gravel-Bed Rivers

Dealing with Grain Size

- Bed/Suspended Load vs Wash/Bed Material Load
- How many sizes?

Dealing with Grain Size

Fraction	Mode	Source	Notes
Washload clay, silt, *fine sand*	suspension	?? uplands, banks, backwaters, …	true 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 suspension	interstices, stripes and 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	Requires decision regarding grains to exclude from the transportable population

We focus on fine and coarse bed material

What about more fractions?

Many-fraction models available: including ones based on the grain size of the bed surface, which allow for the prediction of transient conditions.

These models are fragile – output is sensitive to the quality of the input.

To simulate transport at a particular location, at a particular time,
need large amounts of detailed bed and flow data

Use these models to ask more general questions:
e.g. change in bed composition & transport with
a change in flow releases from dams or
a change in sediment supply from dam removal

We will apply such a model later …

Estimating Sediment Transport: Three overarching constraints bound the problem

- Large spatial & temporal ***variability***

Need BIG samples

- ***Strongly nonlinear*** processes

bed-material transport is a local affair

Modeling with spatial/temporal averages produces error

- ***Sparse information*** available relative to that needed to model transport

Modeling with high spatial/temporal resolution requires vast amounts of data

- Generally, we need a ***robust*** approach

1. Estimating Transport: Formulas

- Threshold channels, Incipient motion: What is Q_c?
- Mobile-bed channels, Transport rate: What is Q_s?

We have trouble estimating τ_c, as well as hydraulic parameters

Calculating cumulative sediment transport in a simple, prismatic channel, over a hydrograph

Major uncertainty in *n*, *D*, and τ^*_c – what are the consequences?

Replace τ in Meyer-Peter & Muller:

$$Q_s = 8B_o\left(\frac{2650}{1000}\right)(3600)\sqrt{(s-1)gD^3}\left(\left(\frac{nQ^{1-b}}{a}\right)^{3/5}\frac{S^{0.7}}{(s-1)D}-\tau_c^*\right)^{3/2}$$

$$h = \frac{Q}{BU}$$

$$B = aQ^b$$

$$U = \frac{\sqrt{S}}{n}h^{2/3}$$

$$h = \frac{nQ}{\left(aQ^b\right)\sqrt{S}h^{2/3}}$$

$$h = \left(\frac{nQ^{1-b}}{a\sqrt{S}}\right)^{3/5}$$

Replace h in

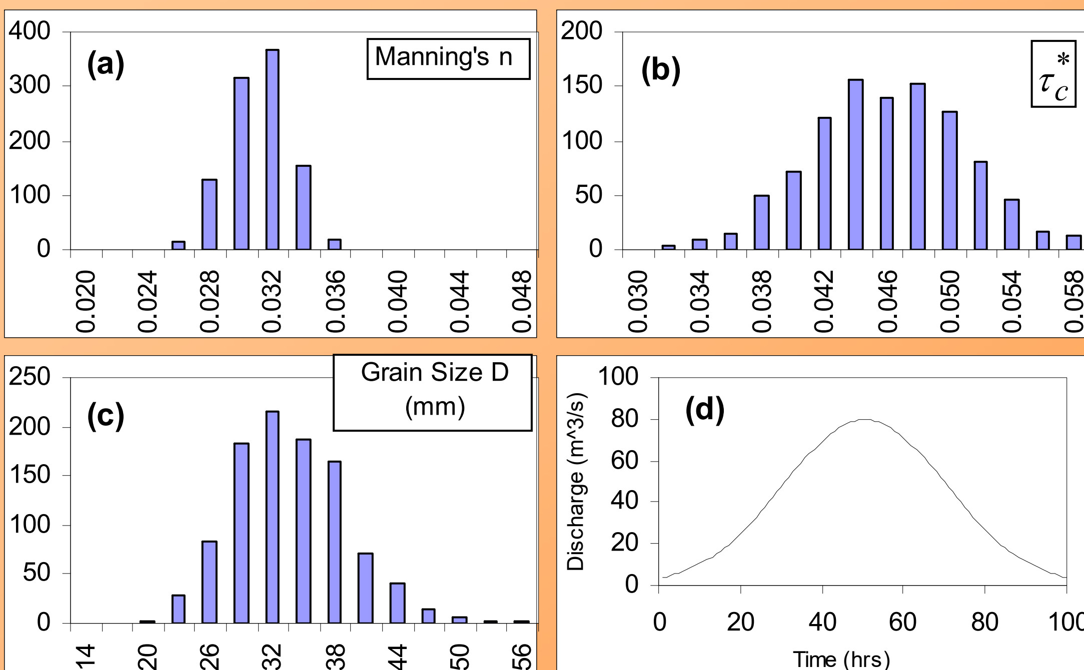
$$\tau = \rho g h S$$

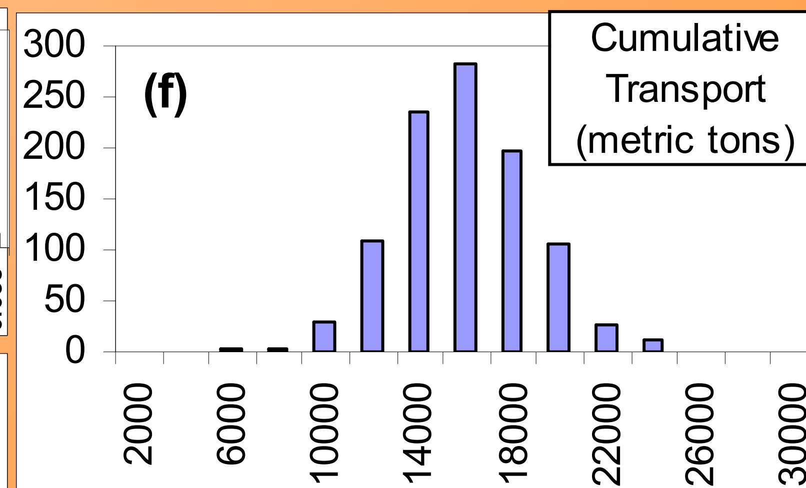
$$\tau = \rho g\left(\frac{nQ^{1-b}}{a}\right)S^{0.7}$$

Monte Carlo Simulation of ΣQs calculation, using 1000 trials

LEGEND

Specify	Mean	St. Deviation	pdf
Manning's n	0.03	0.002	normal
τ*c	0.045	0.0050	normal
Grain size ψ	5	0.25	normal
D (mm)	32		lognormal
			95% Pred.
Calculate	Mean	St. Deviation	Interval
Cumulative transport (tons)	14,997	2,806	5,509





Useful for evaluating uncertainty in sediment balance between sections

"MonteCarloTransport.xls"

- If a good transport estimate is required: field observations are needed (no different than Manning’s eqn.)
- Trying different equations to evaluate uncertainty by using different transport formulas misses the point: the main source of uncertainty is in the input!

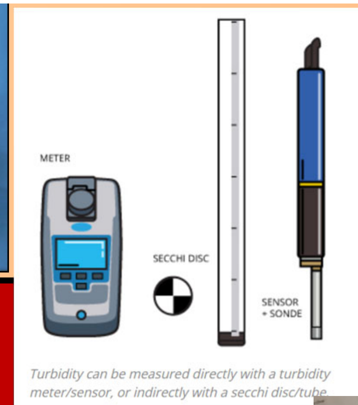
2. Estimating Transport: Sampling

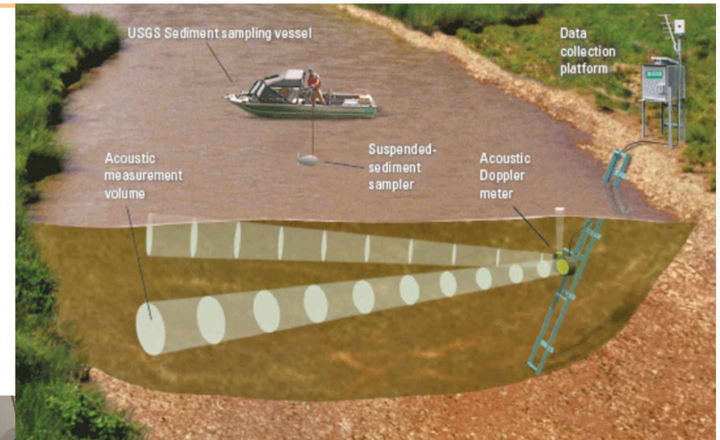
Option 1: trap all the transport in a weir, slot, or pool

Option 2: point samples: portable or pit/net-frame samplers installed on the bed.

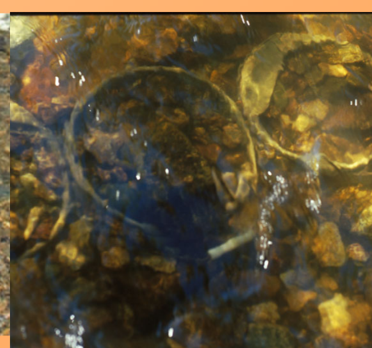
Option 1 is best, but generally not practical

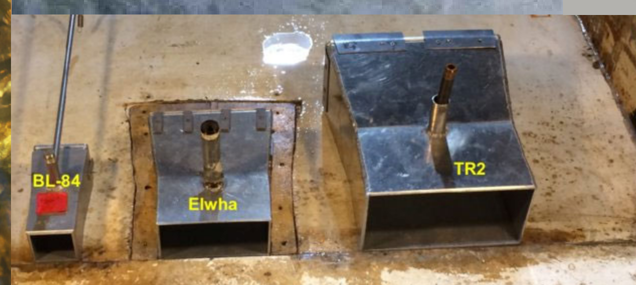
Option 2 is ≈ practical, but involves larger error, some risk, some luck, and lots of effort



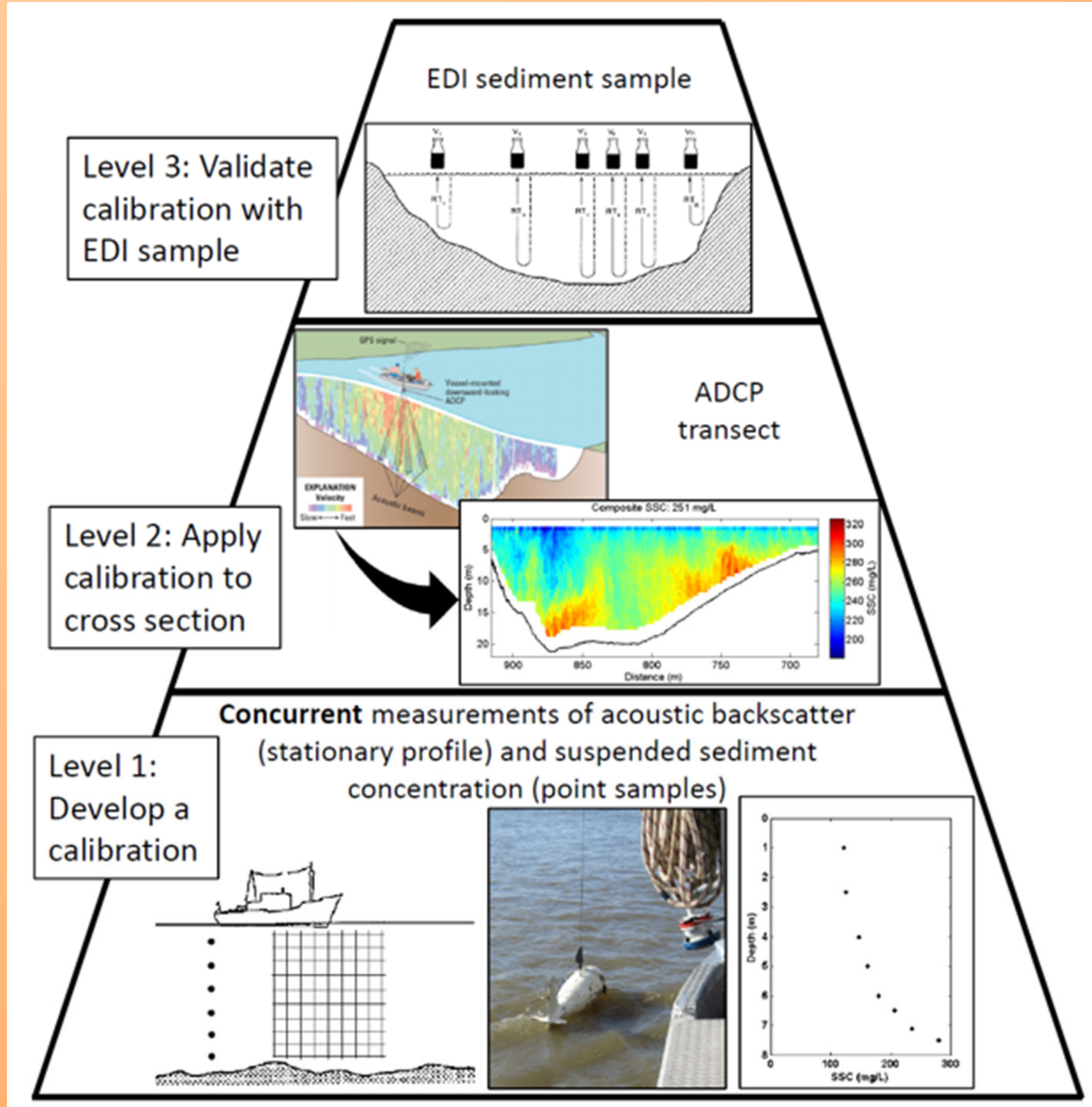


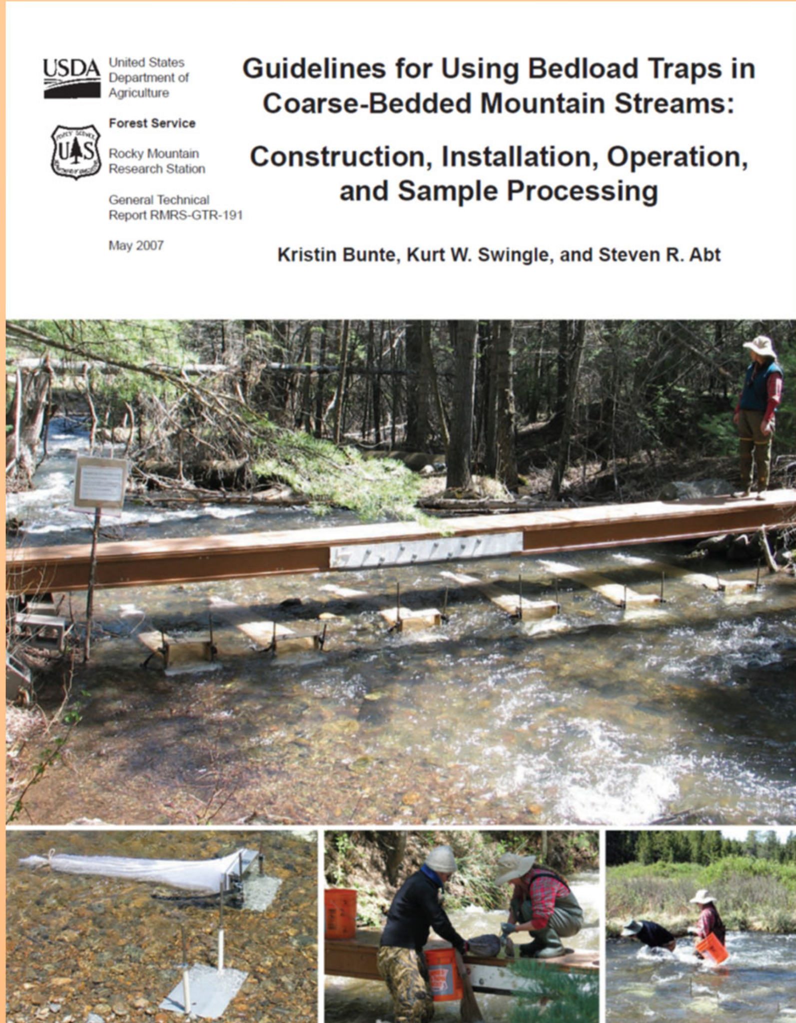
Fraction	Physical Sampler	Surrogate Sampler
Wash load	Suspended sed samplers	Sound & light
Fine Bed Material	Handheld base or suction?	
Coarse Bed Material	Net, pit traps, ponds, *ad hoc*	Acoustic





Geay, T., Zanker, S., Misset, C., & Recking, A. (2020). Passive acoustic measurement of bedload transport: Toward a global calibration curve?. Journal of Geophysical Research: Earth Surface, 125, e2019JF005242. https:// doi.org/10.1029/2019JF005242


EDI sediment sample
Level 3: Validate calibration with EDI sample
ADCP transect
Level 2: Apply calibration to cross section
Composite SSC: 251 mg/L
Depth (m)
Distance (m)
SSC (mg/L)
Concurrent measurements of acoustic backscatter (stationary profile) and suspended sediment concentration (point samples)
Level 1: Develop a calibration
SSC (mg/L)
Depth (m)



USDA United States Department of Agriculture

Forest Service

Rocky Mountain Research Station

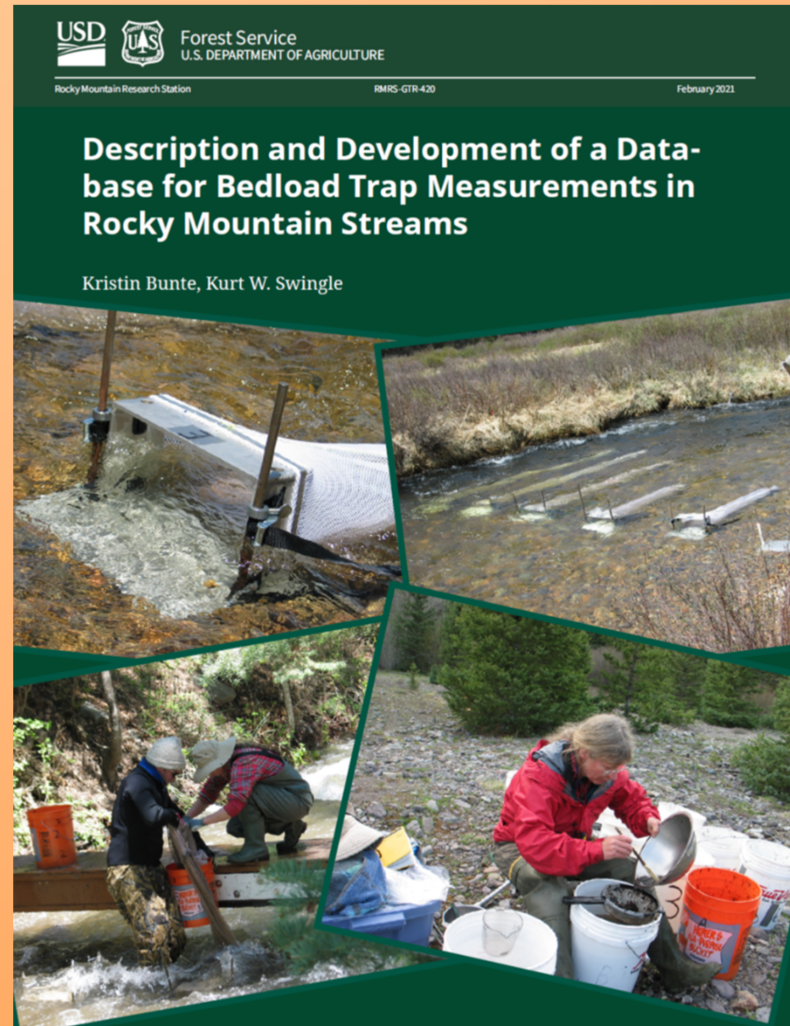
General Technical Report RMRS-GTR-191

May 2007

Guidelines for Using Bedload Traps in Coarse-Bedded Mountain Streams:

Construction, Installation, Operation, and Sample Processing

Kristin Bunte, Kurt W. Swingle, and Steven R. Abt



USDA Forest Service U.S. DEPARTMENT OF AGRICULTURE

Rocky Mountain Research Station RMRS-GTR-420 February 2021

Description and Development of a Data-base for Bedload Trap Measurements in Rocky Mountain Streams

Kristin Bunte, Kurt W. Swingle

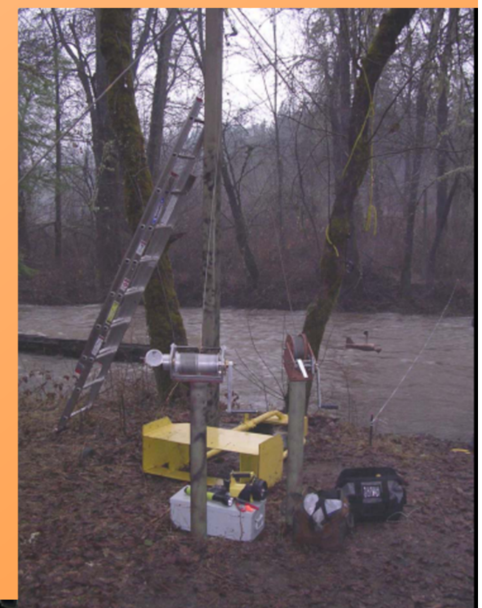

pipe hydrophone

Big River Sampling 1991


Big River Sampling 2008

Big River Sampling 2007

GMA
GRAHAM MATTHEWS & ASSOCIATES
Hydrology • Geomorphology • Stream Restoration
P.O. Box 1516 Weaverville, CA 96093-1516
(530) 623-5327 ph (530) 623-5328 fax



Cross Sectional Distribution
Three Consecutive Measurements at each Station

Total Daily Sediment Transport Collected

Really Big River Sampling 2007

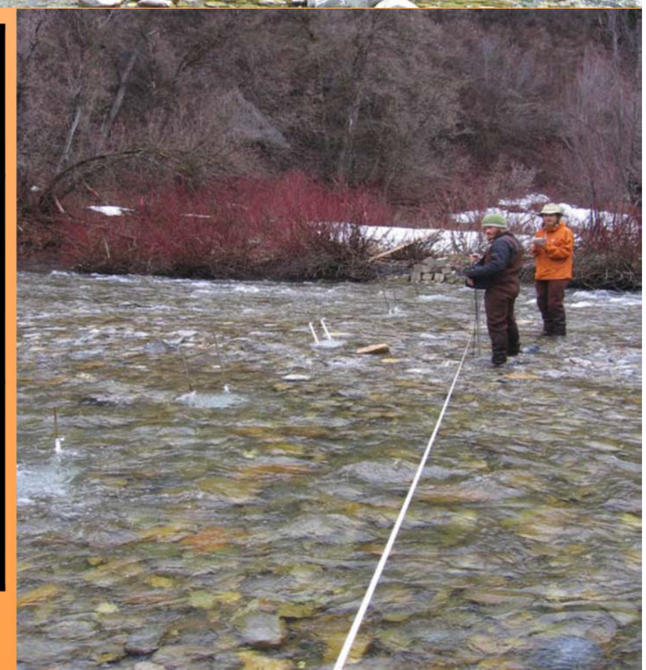
Sampling I

Bed-load transport field is highly variable in space & time

→ Need LARGE samples!

Define ***Sampling Intensity*** for17 m stream

Total Intensity	[17 m] X [3600s] = **23,400** m•s	
Hand-held ***Sampling Intensity***	[13 * 0.076m] X [120s] = **119** m•s	**(0.2%)**
Pit/Trap ***Sampling Intensity***	[6 X 0.3m] X [3600s] = **6,584** m•s	**(11%)**



So, pit or net-frame traps look pretty good …

Pit samplers fill up
at high transport rates

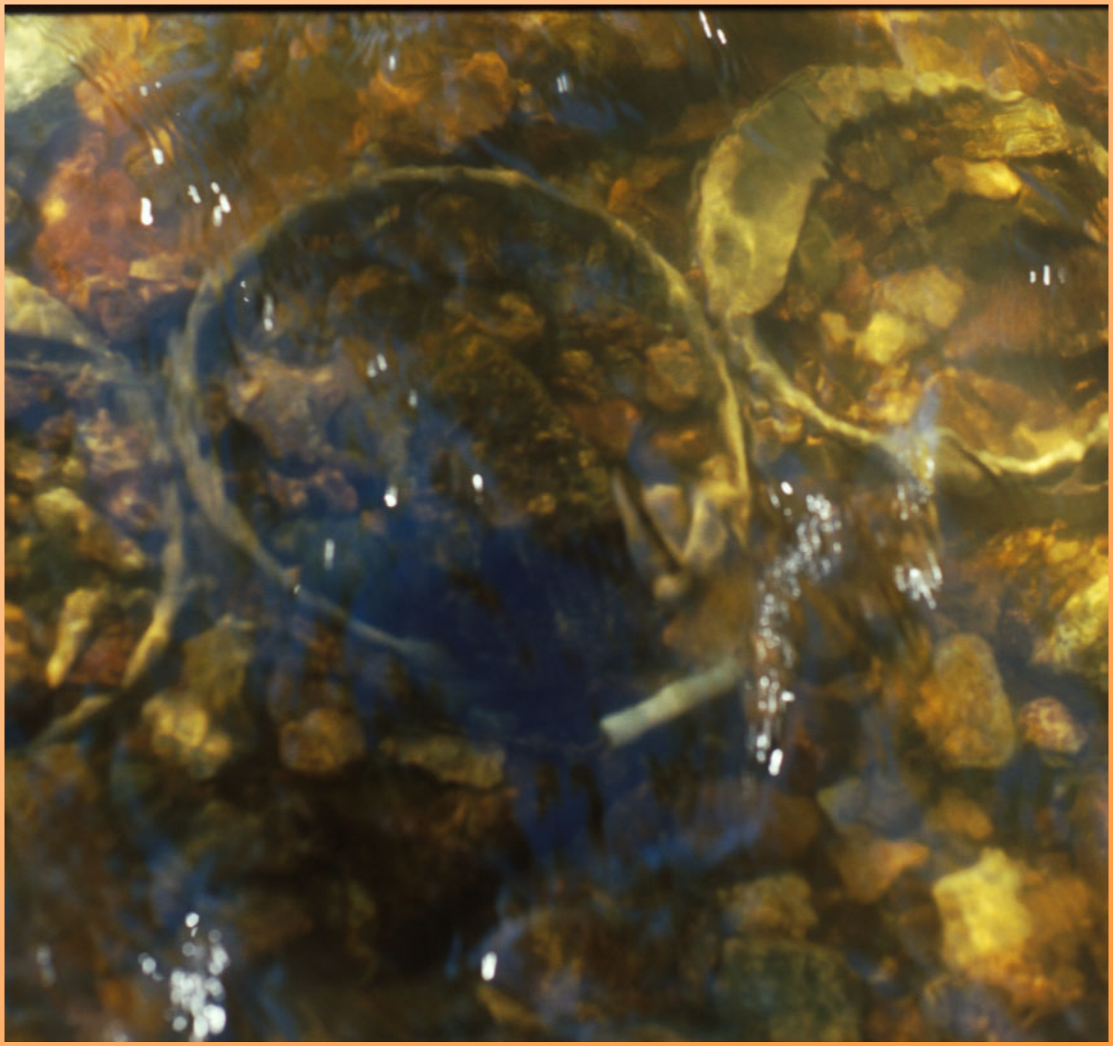


Photo J Pizzuto, U Delaware, home of big samples

So do net-frame samplers

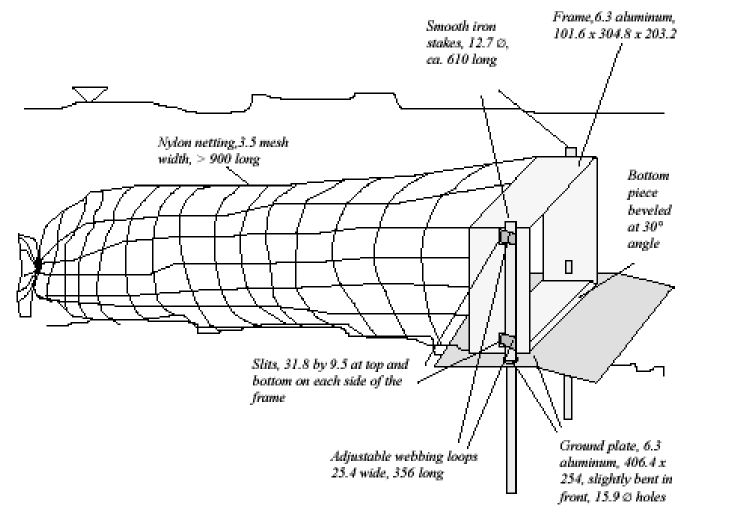


Fig. 1: Schematic diagram of a bedload trap. All measurements in mm (from Bunte 1998).

3. Estimating Sediment Transport

•Direct sampling

+ gives a direct relation between Q and Qs
- requires a big effort
- cannot predict future conditions
- error: is it random or systematic?
- <u>Handheld samplers</u>: Scooping, perching, limited grain size & TINY SAMPLES
- <u>Pit/Net-frame samples</u>: better sampling, only at low rates

•Formula predictions

+ can predict future changes
- highly inaccurate
  - flow hard to scale
  - boundary conditions poorly known

The alternative? Join forces.

Need for both accuracy and efficiency indicate that the future is a combination of **simple robust models** and **efficient measurement**.

A first cut, using today's technology

- If pit/trap samplers can collect good samples of small transport rates, why not use these to calibrate a model of coarse bed-material transport
- **GOOD** samples! (long duration, spatially extensive)
- Two sizes: sand and gravel
- Combine in robust framework that is insensitive to major sources of error

Transport Formula (Gravel)

$$W_i^* = \begin{cases} 11.2\left(1-0.846\dfrac{\tau_r}{\tau}\right)^{4.5} & \tau > \tau_r \\ 0.0025\left(\dfrac{\tau}{\tau_r}\right)^{14.2} & \tau < \tau_r \end{cases}$$

Calibrate τ_r

Dimensionless transport rate

$$W^* = \frac{q^*}{\tau_*^{3/2}} = \frac{(s-1)gq_b}{(\tau/\rho)^{3/2}}$$

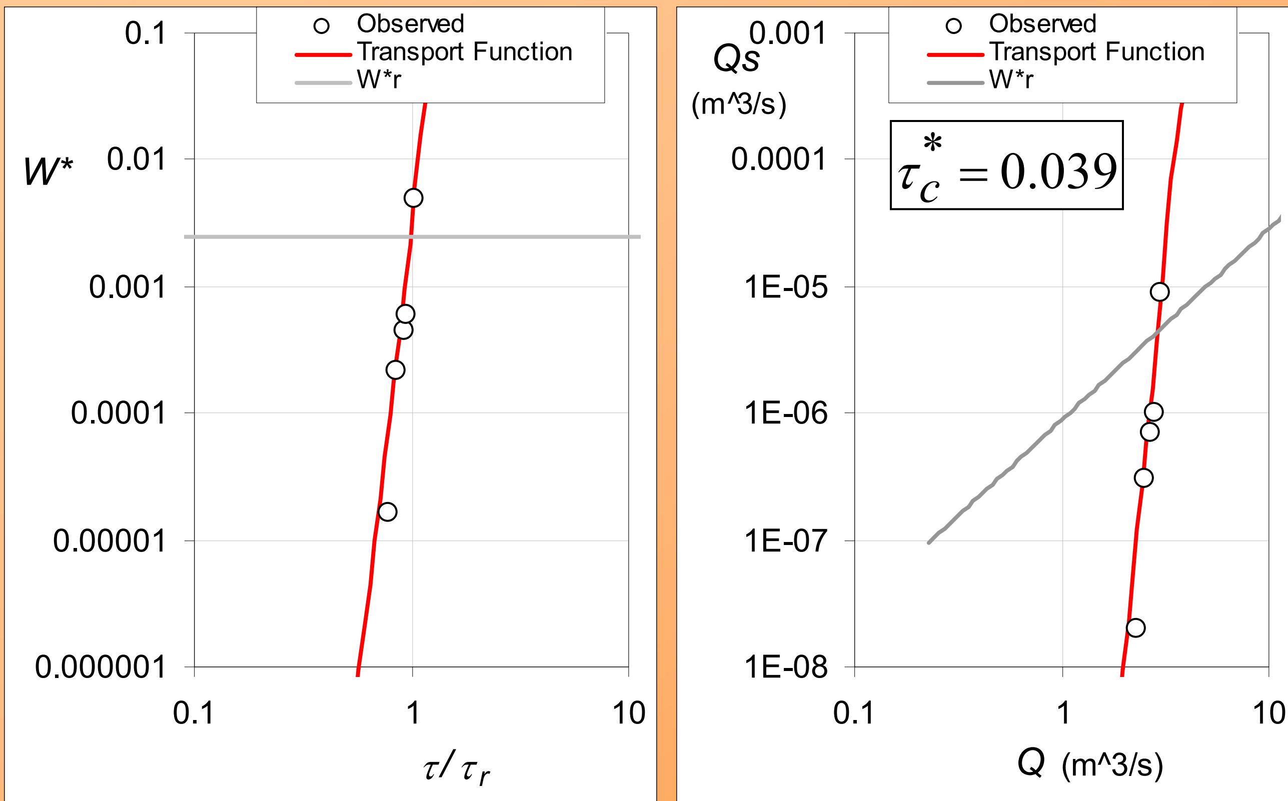
Choice of formula does not make that much difference!

Formula provides the trend,but the samples provide the accuracy

Transport formula based on shear stress τ, so we need a drag partition relation to get grain stress from discharge. We return to our Manning-Strickler formula:

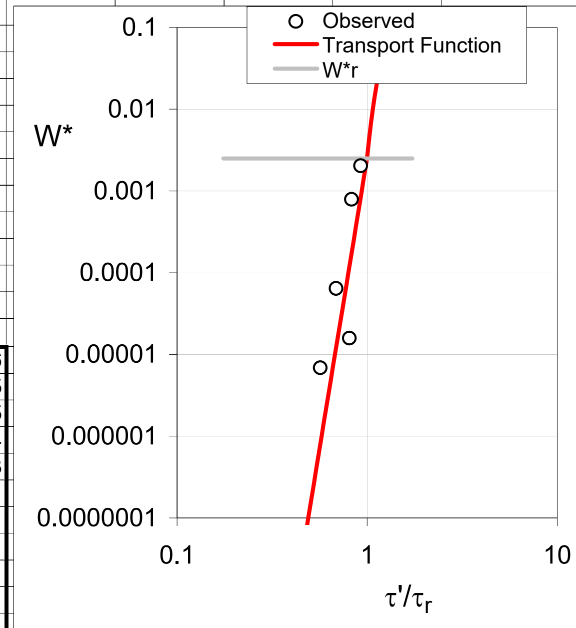
$$\tau = 17(SD_{65})^{1/4}U^{3/2}$$

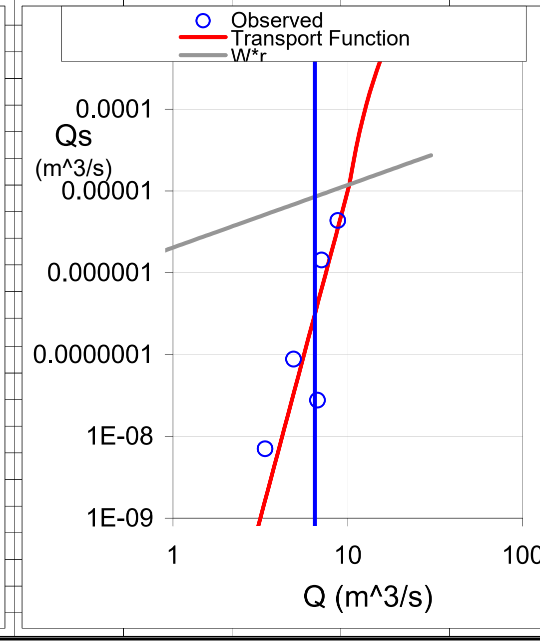
- For Cub River:
- Slope S = 0.02
- D_{65} = 90 mm
- Mean velocity $U = 0.46\, Q^{0.42}$


Observed
Transport Function
W*r
W*
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.1
1
10
τ/ τr
Observed
Transport Function
W*r
Qs
(m^3/s)
0.001
0.0001
1E-05
1E-06
1E-07
1E-08
0.1
1
10
Q (m^3/s)
$\tau_c^* = 0.039$

SRC.xls

	A	B	C	D	E	F
1	Lonely R. NR Whirlpool					
2	This worksheet for GRAVEL transport					
3	Slope S	0.015				
4	D65	90	(mm) D65 of bed surface			
5	D50	42	(mm) D50 of bed subsurface			
6	fg	0.50	proportion fravel in bed			
7	b	15.0	(m) width of bed material, not channel			
8	τrg	30	(Pa) Adjust the reference shear stress			
9	τ*rg	0.044	Reference Shields Number; is it reasonable?			
10	Qrg	10.2	cms			
11	Observed	Observed				
12	Q	Qsg	τ'	τ'/τrg	qsg	W*g
13	(m^3/s)	(m^3/s)	(Pa)	-	(m^2/s)	-
14	3.37	7.07E-09	17.0	0.57	4.71E-10	6.87E-06
15	4.90	8.80E-08	20.6	0.69	5.87E-09	6.42E-05
16	6.71	2.76E-08	24.2	0.81	1.84E-09	1.59E-05
17	7.08	1.43E-06	24.9	0.83	9.57E-08	7.90E-04
18	8.78	4.35E-06	27.7	0.92	2.90E-07	2.03E-03
19						
20						
21						
22						
23						
24						





Lonely R. NR Whirlpool

Enter parameters of velocity rating curve here

k = 0.63 m = 0.34 Qc = 0.00

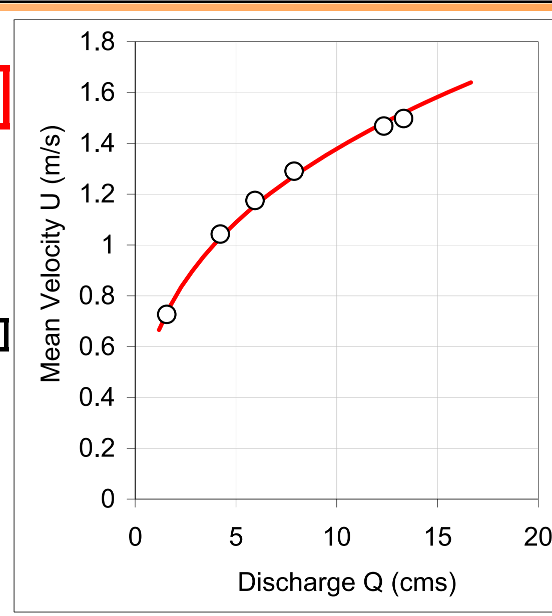
$$U = k(Q - Q_t)^m$$

The cells below contain values of k and m fitted to the (Q, U) values for specified Qc

k = 0.63 m = 0.34

0.3382 -0.1983 LINEST results

Q (m^3/s)	U (m/s)	Q-Qt (m^3/s)
1.568	0.73	1.568
4.225	1.04	4.225
5.946	1.17	5.946
7.891	1.29	7.891
12.340	1.47	12.340
13.326	1.50	13.326
		0.000
		0.000



Transport samples provide accuracy by

(1) Establishing grain size D of the transport &

(2) Scaling the flow

Calculate grain stress: $\tau = 17\left(SD_{65}\right)^{0.25} U^{1.5}$

for two different flows & take the ratio: $\dfrac{\tau_1}{\tau_2} = \left(\dfrac{U_1}{U_2}\right)^{1.5}$

Suppose $U = aQ^b$

then $\dfrac{\tau_1}{\tau_2} = \left(\dfrac{Q_1}{Q_2}\right)^{1.5b}$

$$\frac{\tau}{\tau_r} = \left(\frac{Q}{Q_r}\right)^{1.5b}$$

If you calibrate, the transport formula is needed only to give the change in transport with the change in discharge.

Most of the transport occurs at high flows & you base your estimate on samples at low flow?

Wilcock, P, 2001. Toward a practical method for estimating sediment transport rates in gravel-bed rivers, *Earth Surface Processes & Landforms* 26, 1395-1408.

Estimating bed-material transport in gravel-bed rivers

- **Conceptual basis**
  - fine and coarse bed material
  - (supply of one affects the transport of the other)
- **Sampling**
  - standard needed for minimum sample size
  - fine bed material – Helley-Smith or ?
  - coarse bed material – pit or net frame samplers
  - big rivers – ???
- **Modeling**
  - 2-fraction model captures essential interaction between fine & coarse
    & facilitates integral measure of reach grain size
  - But it can't do everything (armoring; change in sand or gravel size)
- **Future**
  - combine simple, robust models with efficient monitoring
  - can be done now in wadeable streams, although effort is non-trivial

SRC & BAGS

Software and accompanying manual to support estimates of bed-material transport rates in gravel-bed rivers. Stream Systems Technology Center, (the "Stream Team"), US Forest Service

BAGS (Yantao Cui, Stillwater Science): supports variety of transport formulas, allows variety of input, includes calibrated approach

User's Manual by John Pitlick

Primer by Peter Wilcock

USDA

United States Department of Agriculture

Forest Service

Rocky Mountain Research Station

General Technical Report

RMRS-GTR-226

May 2009

Sediment Transport Primer
Estimating Bed-Material Transport in Gravel-bed Rivers

Peter Wilcock, John Pitlick, Yantao Cui

USDA United States Department of Agriculture

Forest Service

Rocky Mountain Research Station

General Technical Report

RMRS-GTR-226

May 2009

Wilcock, Peter; Pitlick, John; Cui, Yantao. 2009. **Sediment transport primer: estimating bed-material transport in gravel-bed rivers.** Gen. Tech. Rep. RMRS-GTR-226. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 78 p.

Abstract

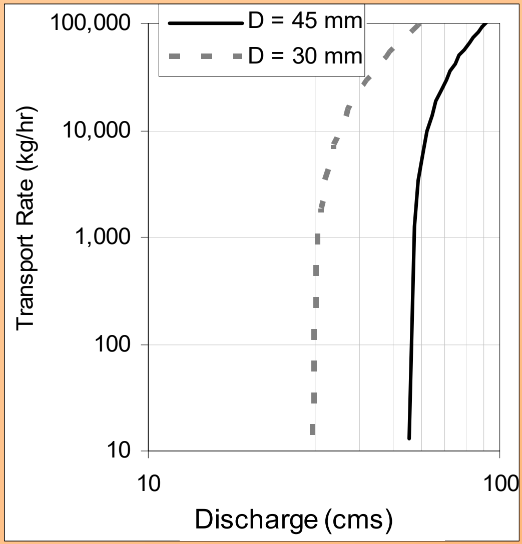
This primer accompanies the release of BAGS, software developed to calculate sediment transport rate in gravel-bed rivers. BAGS and other programs facilitate calculation and can reduce some errors, but cannot ensure that calculations are accurate or relevant. This primer was written to help the software user define relevant and tractable problems, select appropriate input, and interpret and apply the results in a useful and reliable fashion. It presents general concepts, develops the fundamentals of transport modeling, and examines sources of error. It introduces the data needed and evaluates different options based on the available data. Advanced expertise is not required.

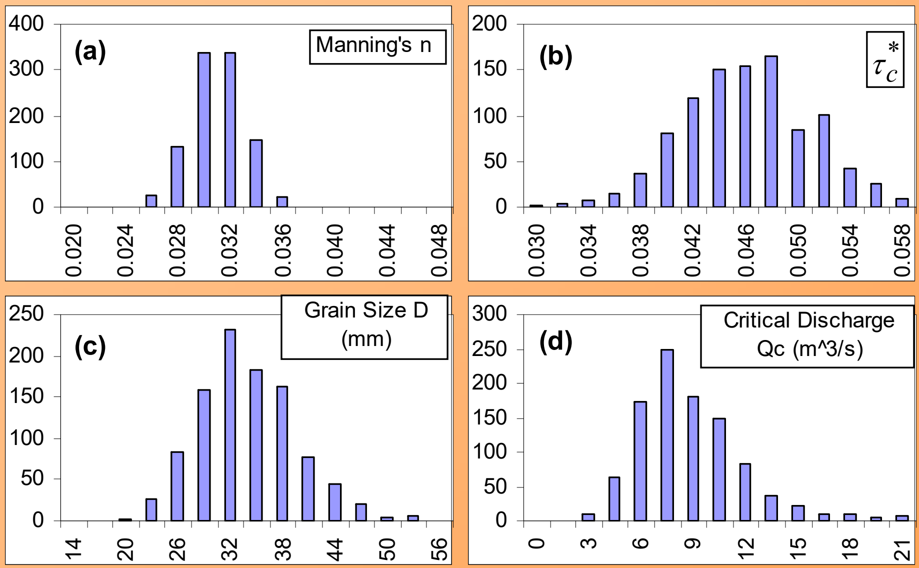
Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **26**, 1395–1408 (2001)
DOI: 10.1002/esp.301

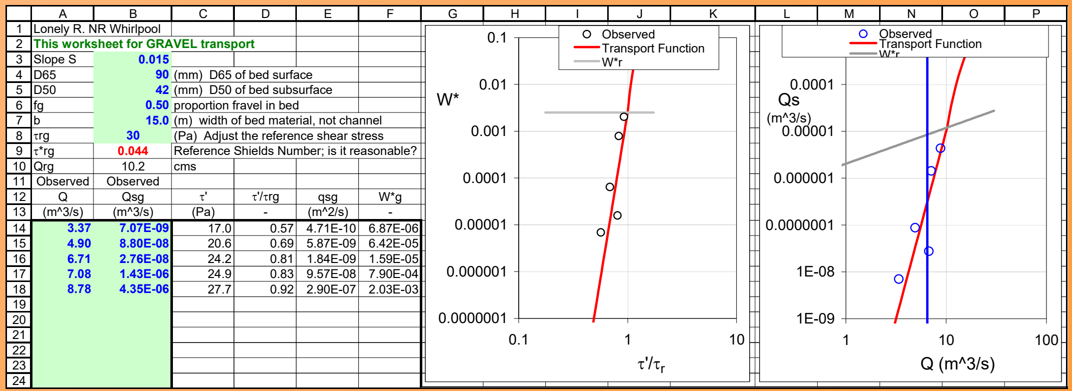
TOWARD A PRACTICAL METHOD FOR ESTIMATING SEDIMENT-TRANSPORT RATES IN GRAVEL-BED RIVERS

PETER R. WILCOCK*
Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD 21218, USA

Your assignment – calculate transport for Cub R







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18	8.78	4.35E-06	27.7	0.92	2.90E-07	2.03E-03
19						
20						
21						
22						
23						
24						

Apply calculated sediment transport rates to estimates of annual load and effective discharge