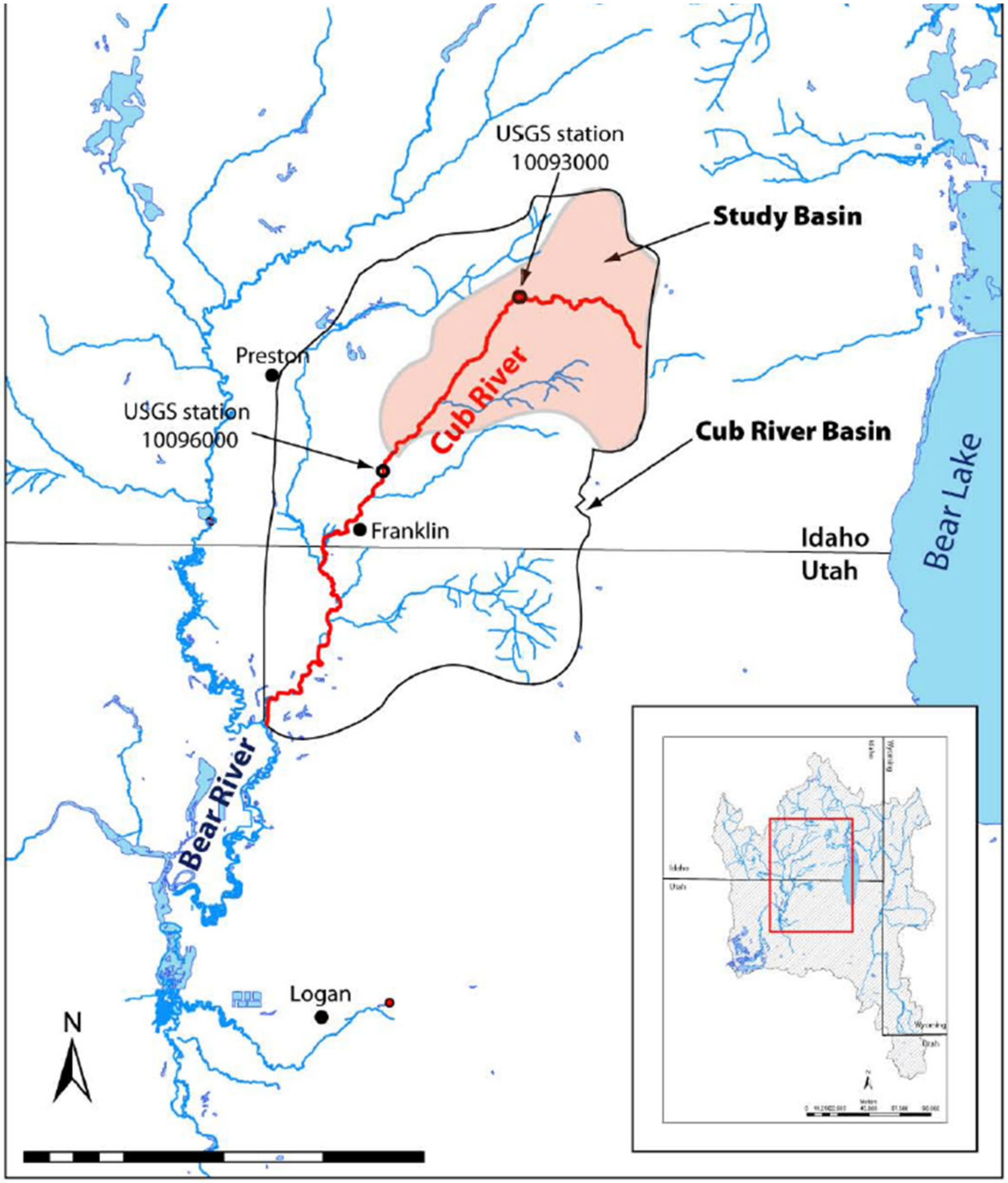
Cub River Assignment

Background information/Introduction to concepts

Christy Leonard
2 August 2023

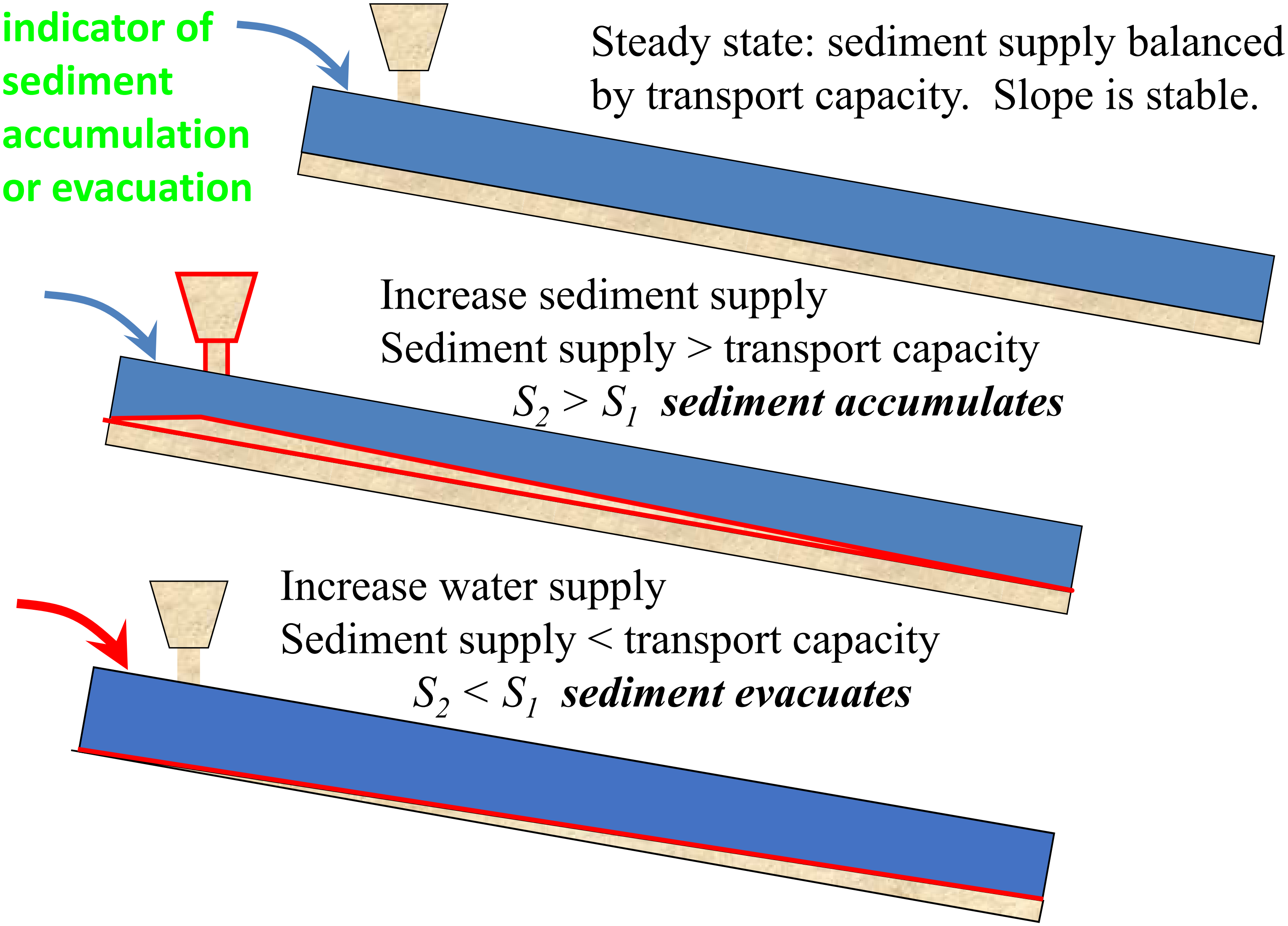


Cub River

- Like so many rivers in the western United States, this is a story of water depletion.
- Most rivers in the western United States have some surface water development for agricultural, industrial, and municipal use.
- Successful management requires an understanding of the effects of existing and potential future development on stream channels.
- If instream flow is reduced but supply remains the same, sediment may accumulate.
- If flow and supply are reduced, say by trapping of sediment behind small dams or diversion structures, sediment may accumulate, evacuate, or there may be no change in the mass balance.

Interpretation, for evaluating stream behavior

Slope is indicator of sediment accumulation or evacuation

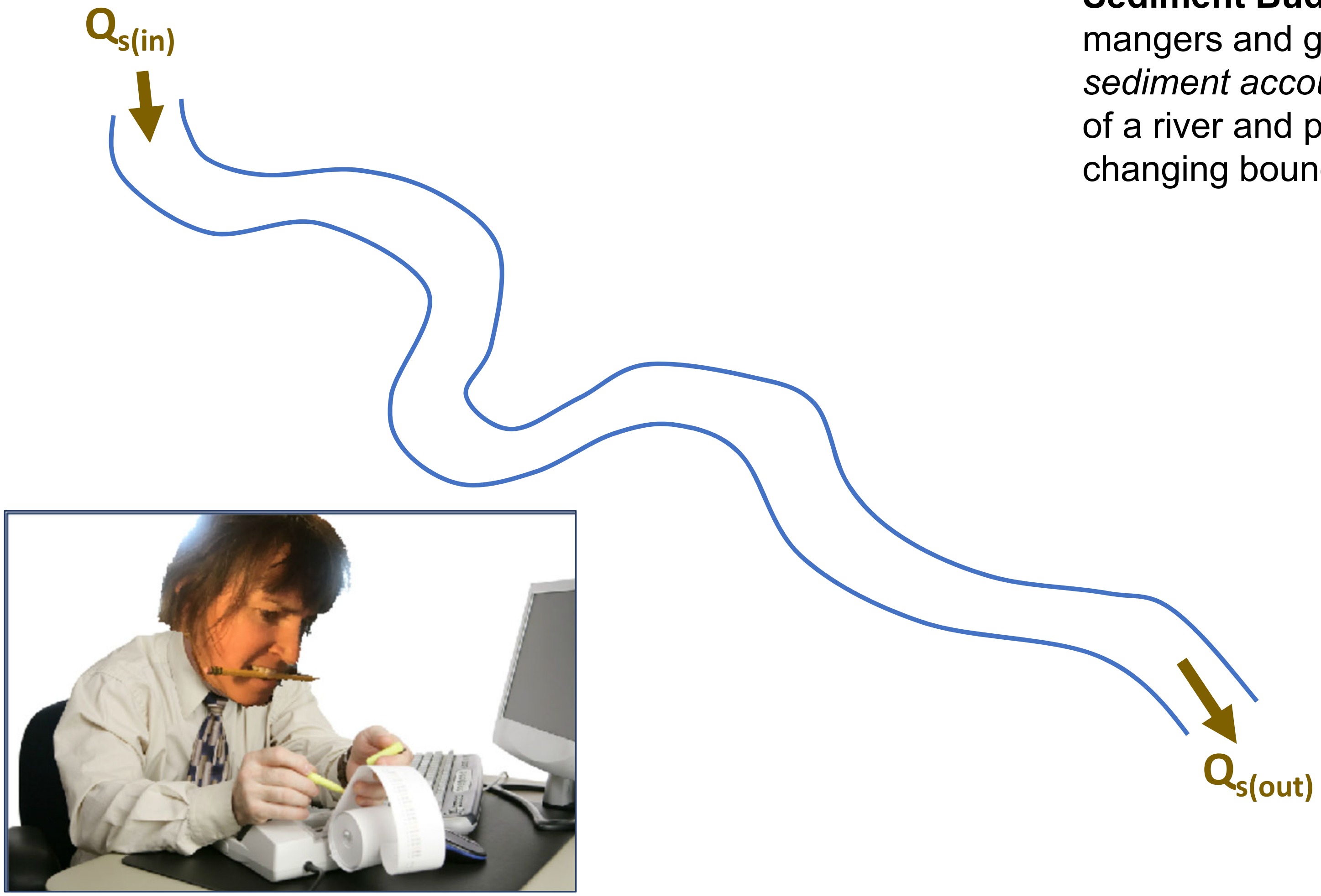


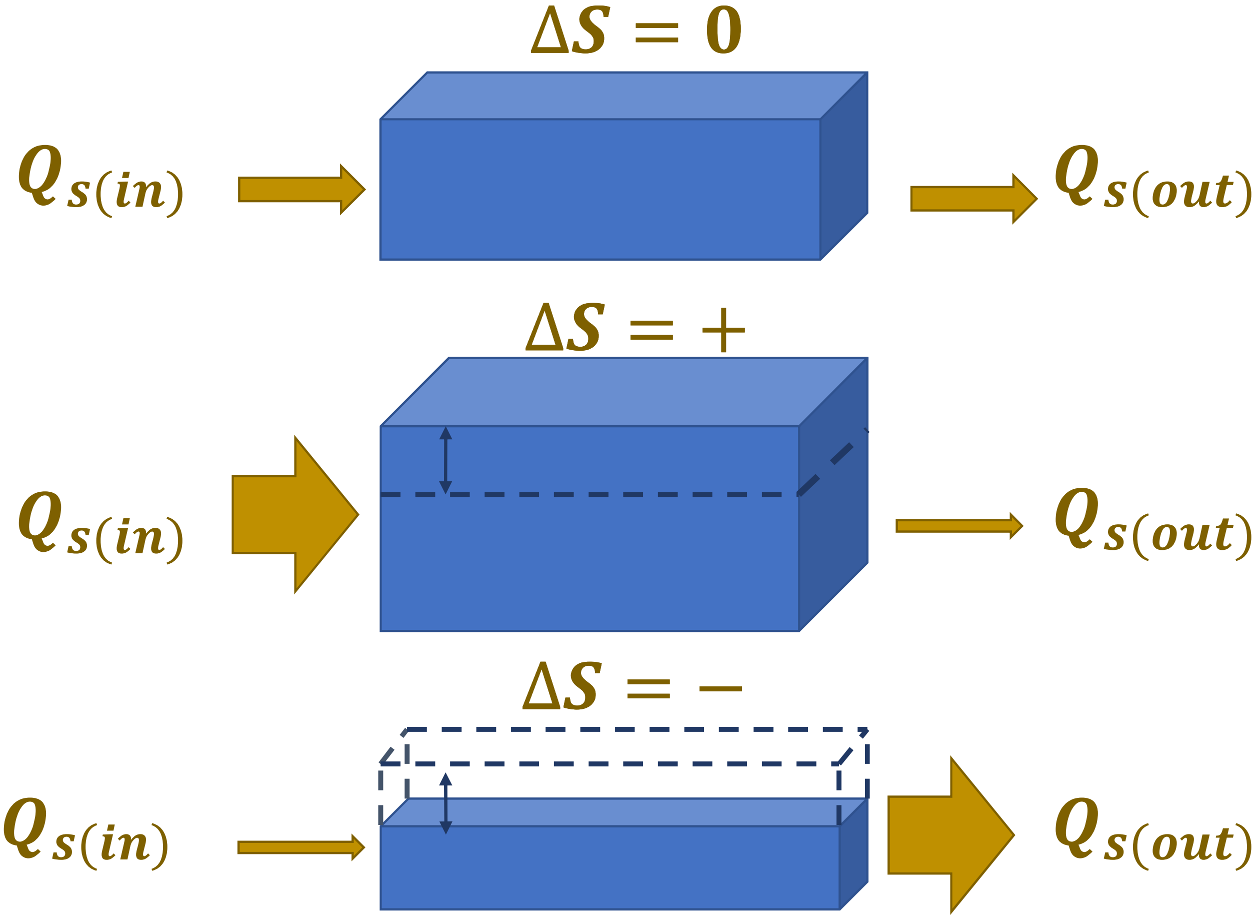
Steady state: sediment supply balanced by transport capacity. Slope is stable.

Increase sediment supply
Sediment supply > transport capacity
$S_2 > S_1$ ***sediment accumulates***

Increase water supply
Sediment supply < transport capacity
$S_2 < S_1$ ***sediment evacuates***

Sediment Budget: Tool used by river mangers and geomorphologists (*i.e., sediment accountants*) to assess the state of a river and predict channel response to changing boundary conditions.





$\Delta S = 0$

$Q_{s(in)}$ $Q_{s(out)}$

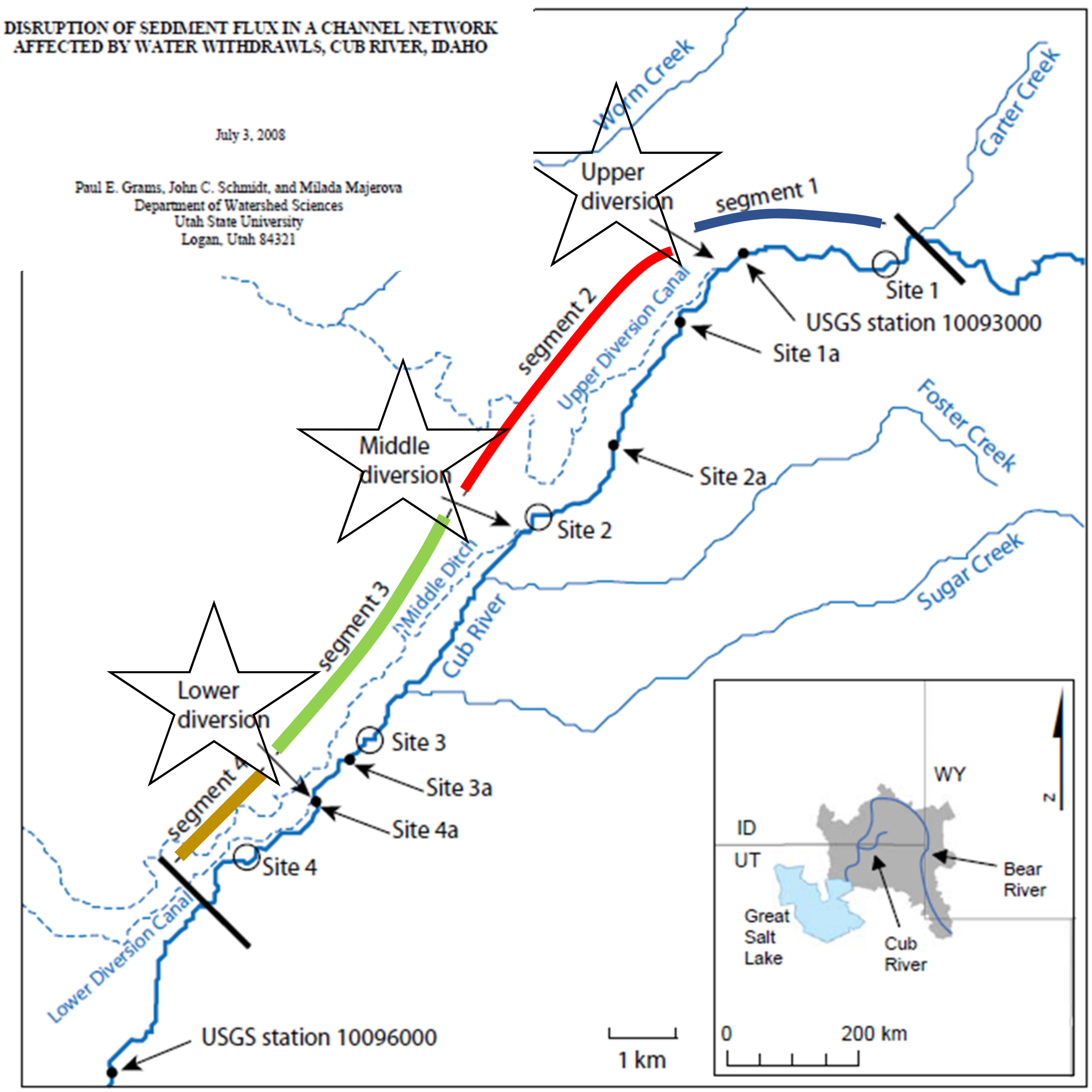
$\Delta S = +$

$Q_{s(in)}$ $Q_{s(out)}$

$\Delta S = -$

$Q_{s(in)}$ $Q_{s(out)}$

Note: $\Delta S = \textit{Net Change in Storage}$

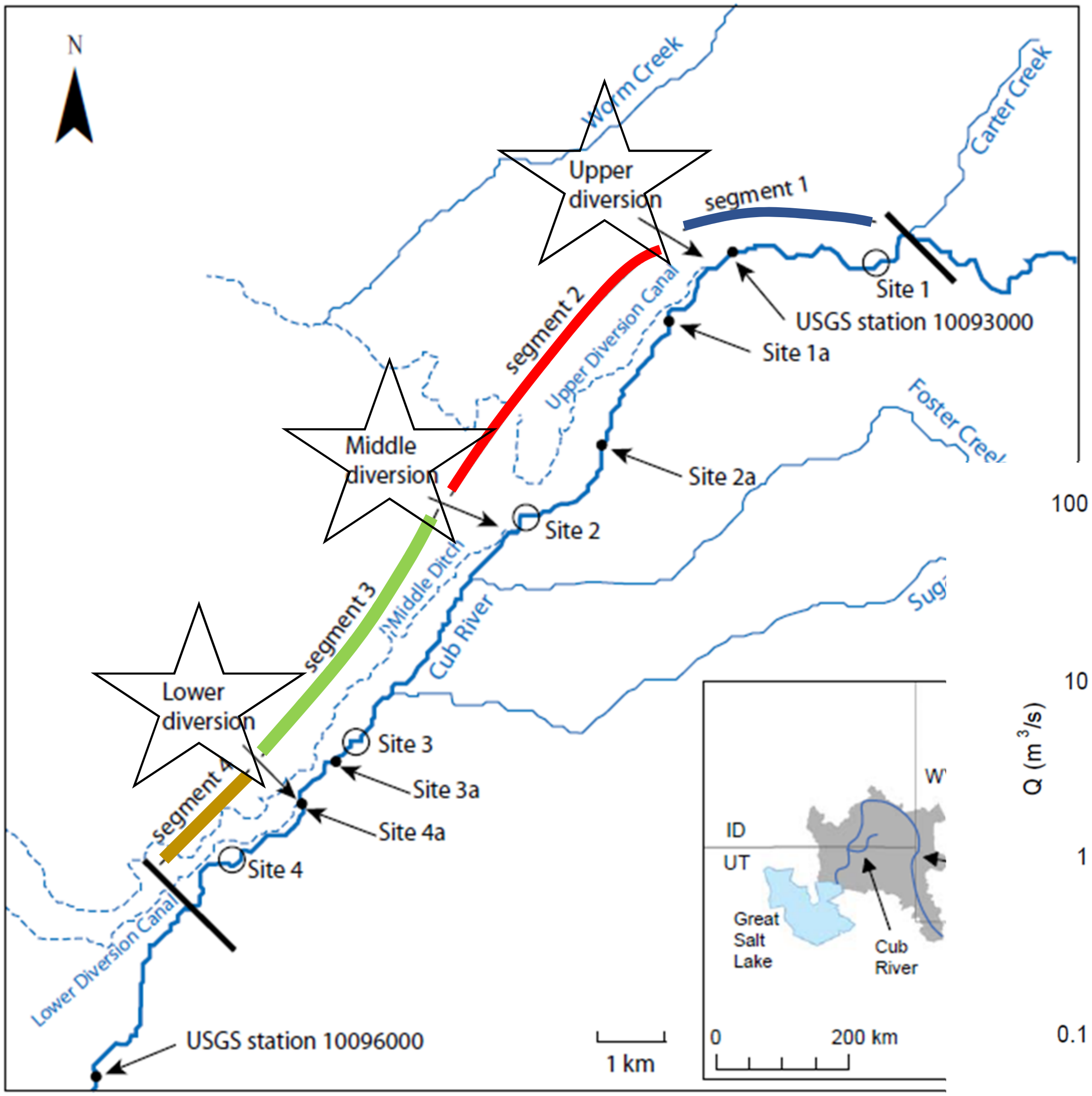


DISRUPTION OF SEDIMENT FLUX IN A CHANNEL NETWORK
AFFECTED BY WATER WITHDRAWLS, CUB RIVER, IDAHO

July 3, 2008

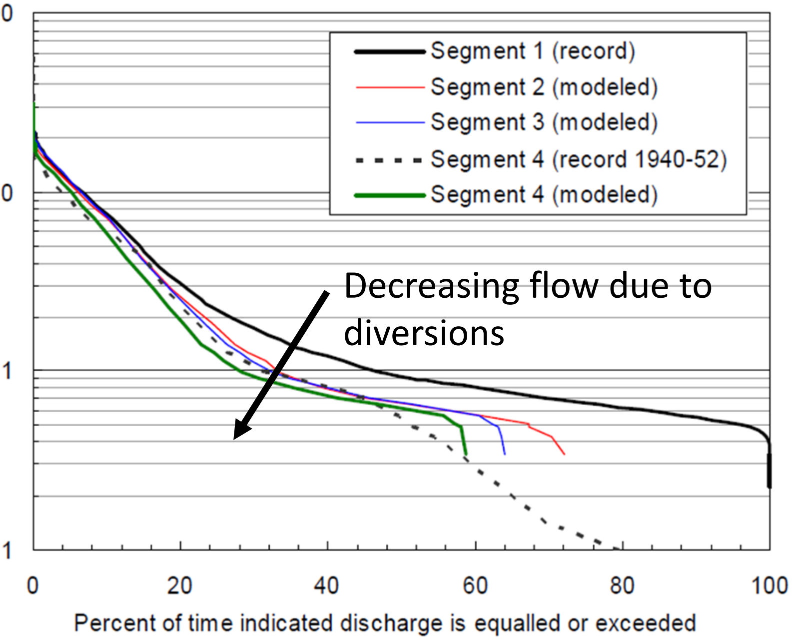
Paul E. Grams, John C. Schmidt, and Milada Majerova
Department of Watershed Sciences
Utah State University
Logan, Utah 84321

- Stream flow diverted at three points.
  - Upper diversion is trans-basin and completely removes water from the basin.
  - Middle and lower diversion are only operated during the irrigation season (May through mid-October).
  - Diversion have been diverting water since early 1880s.
- Segment 1 – confluence of Carter Creek to Upper Diversion
- Segment 2 – Upper to Middle diversions
- Segment 3 – Middle to Lower diversions
- Segment 4 – 1.8 km downstream of Lower diversion.
- Sampling sites established in each segment in a reach with mobile bed material and a wide (~18 m) shallow channel with minimal cross-section variation in bed elevation.

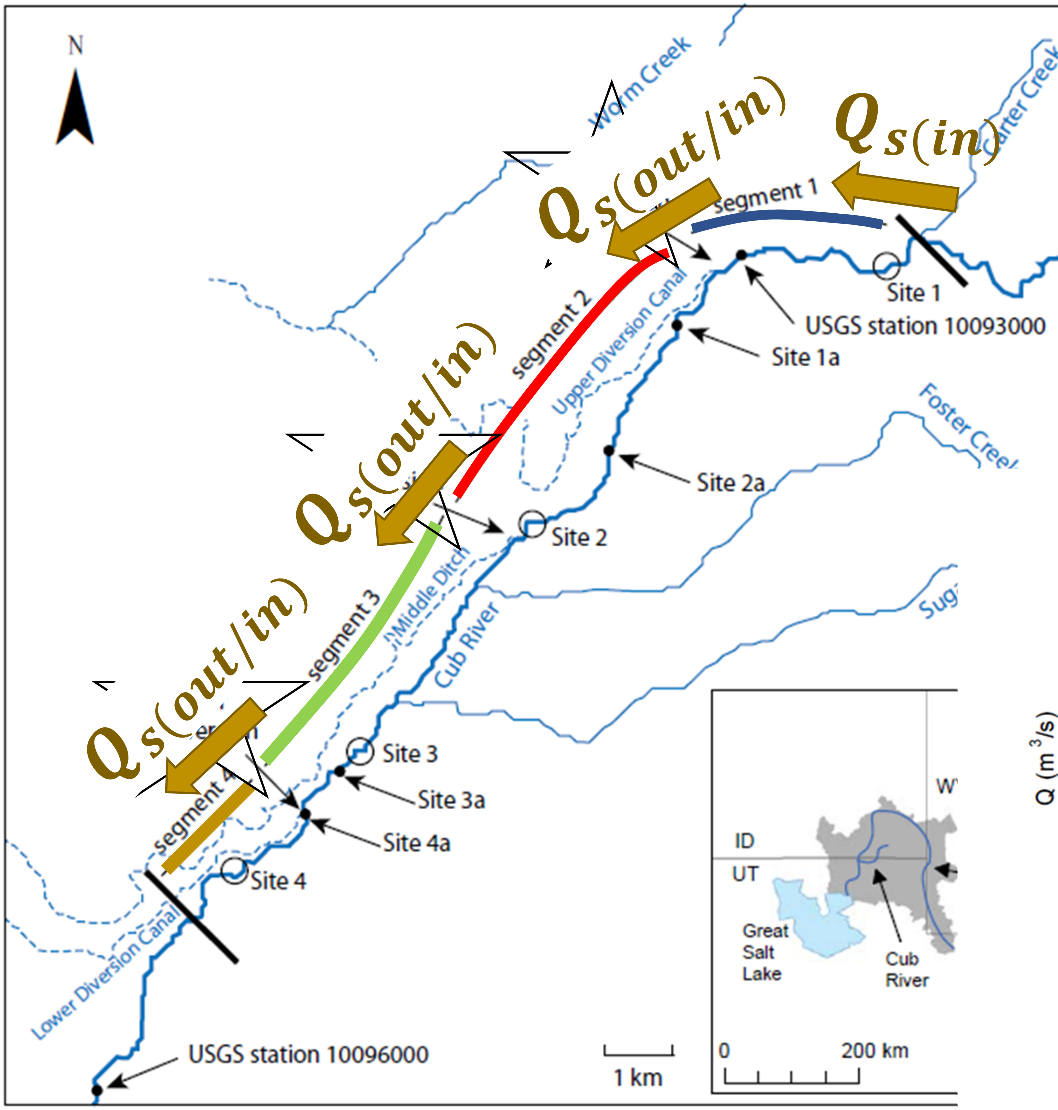


- Discharge estimated for each segment.
- Discharge at site 1 based on USGS gage.
- Discharge in segments 2, 3, and 4 based on regional relations between drainage area and discharge and diversion records.
- Flow exceedance curves shown below.

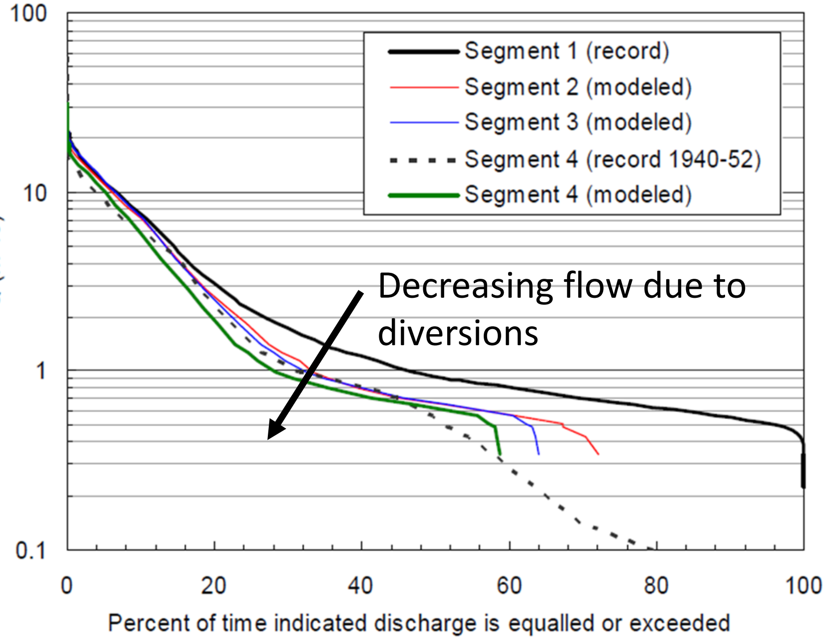
How does the sediment budget change downstream due to dewatering?



Decreasing flow due to diversions



- How does the sediment budget change downstream due to dewatering?
  - We know the amount of sediment entering and leaving different segments.
  - We must know transport rates in each segment.
  - How do you think the sediment budget may differ in these segments?



How do we estimate transport?

- Calibrated estimates of transport rates by fitting a transport equation to transport measurements.
- Benefits of this approach:
    - Tells you the grain sizes of what is moving, which may be much finer than what is on the bed.
    - Provides the drag partition by giving you the grain stress at the discharge when the reference transport rate occurs (W^*_r).

We will implement this approach at site 1. Let's take a look at field data collected at this site.

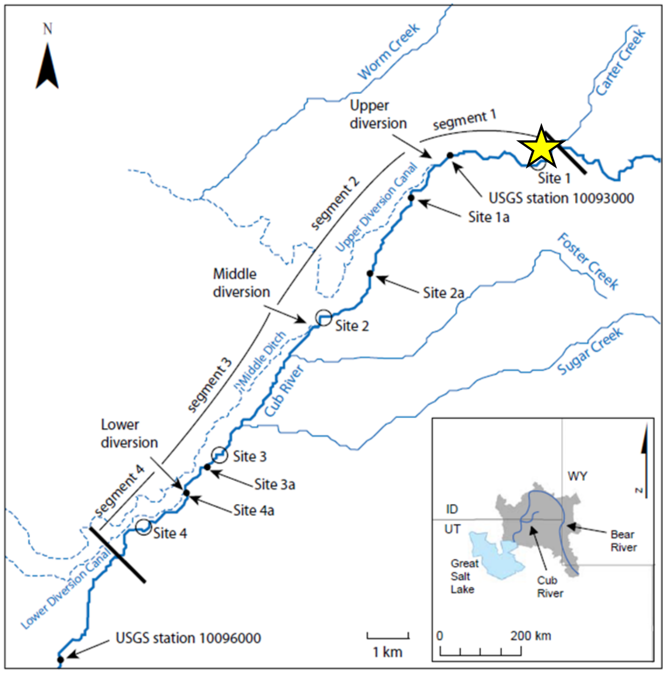
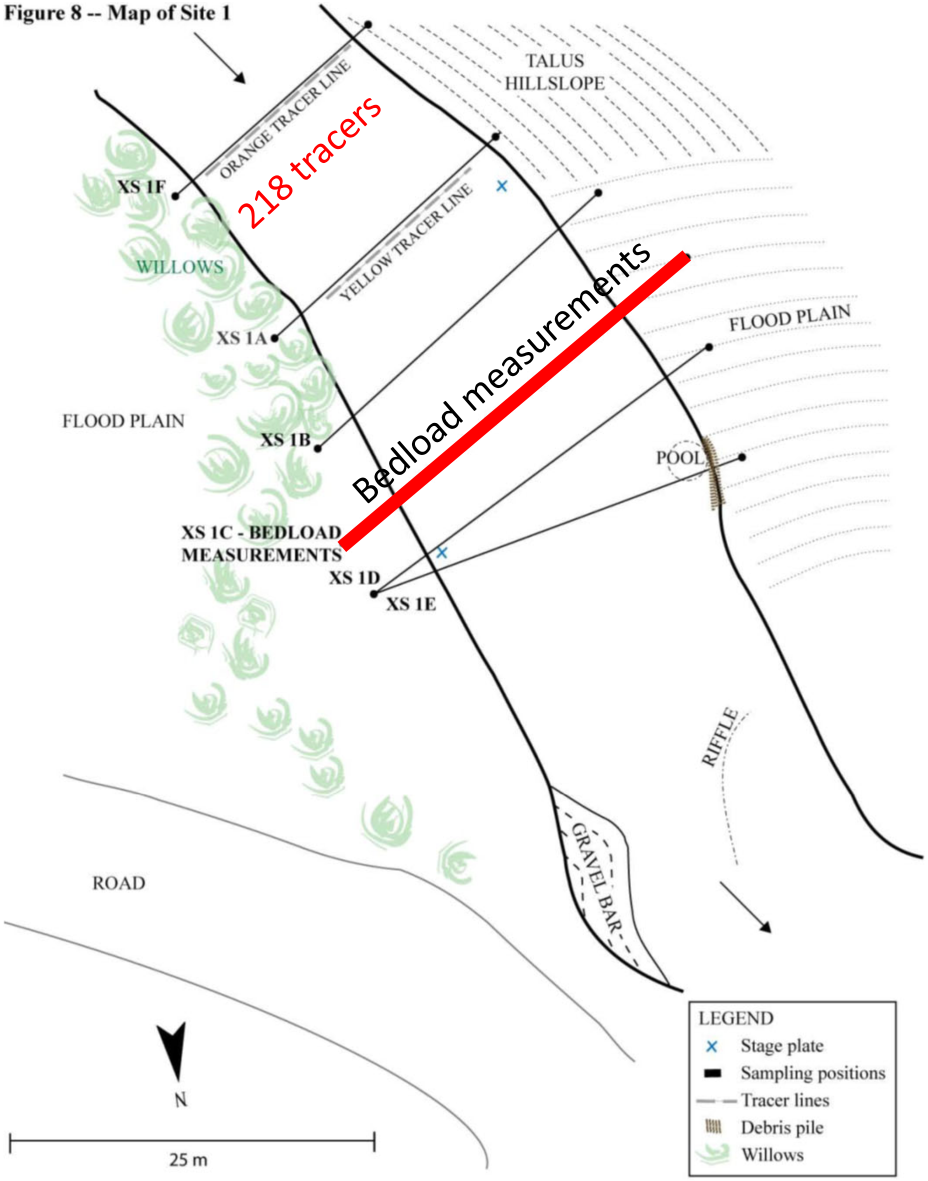
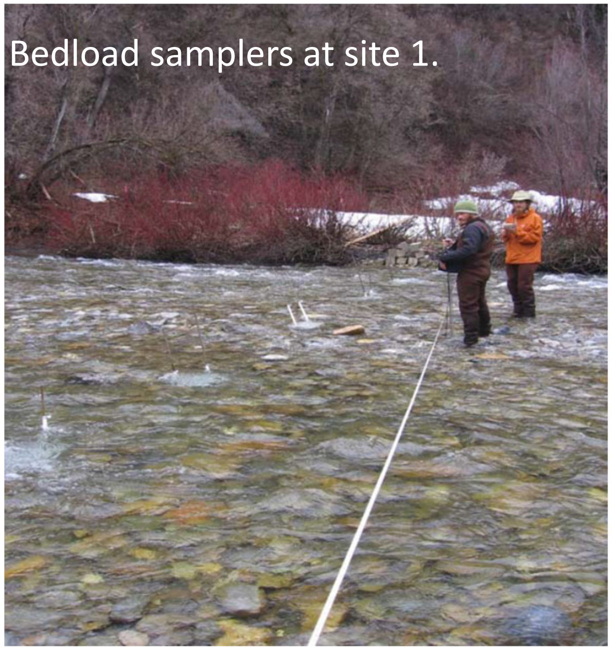


Figure 8 -- Map of Site 1

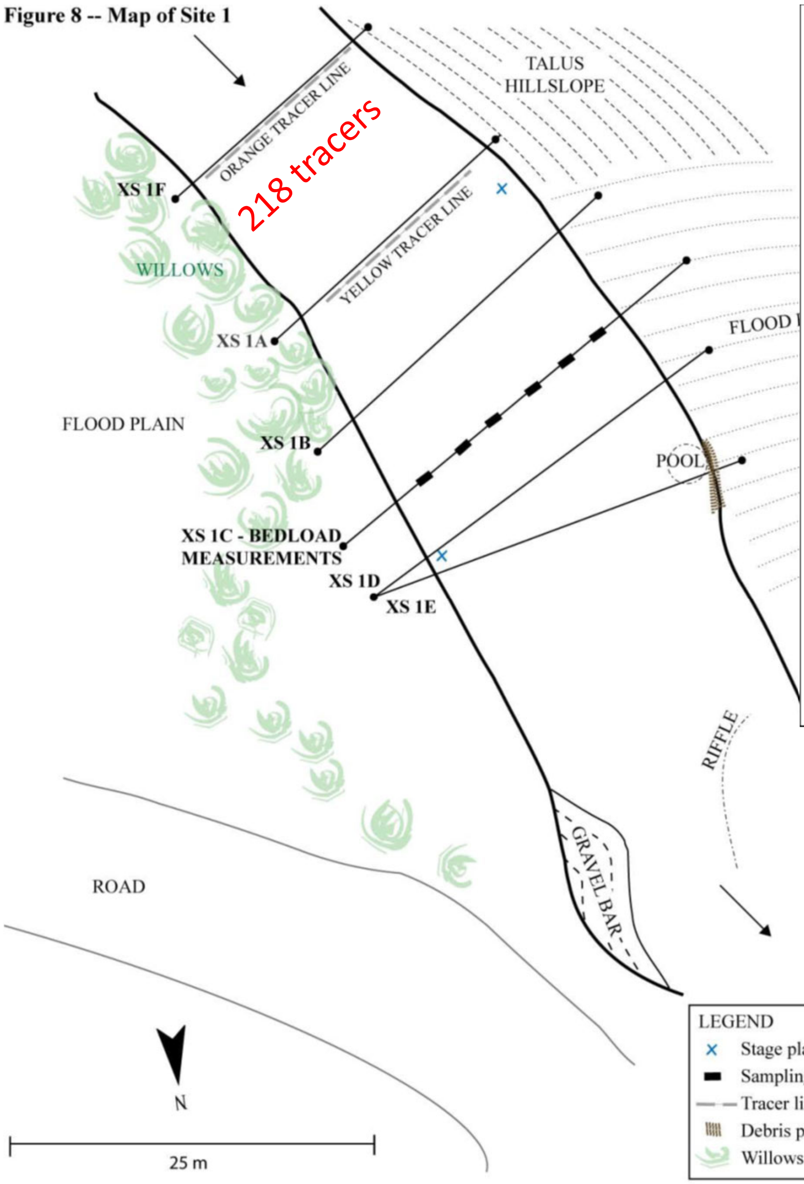


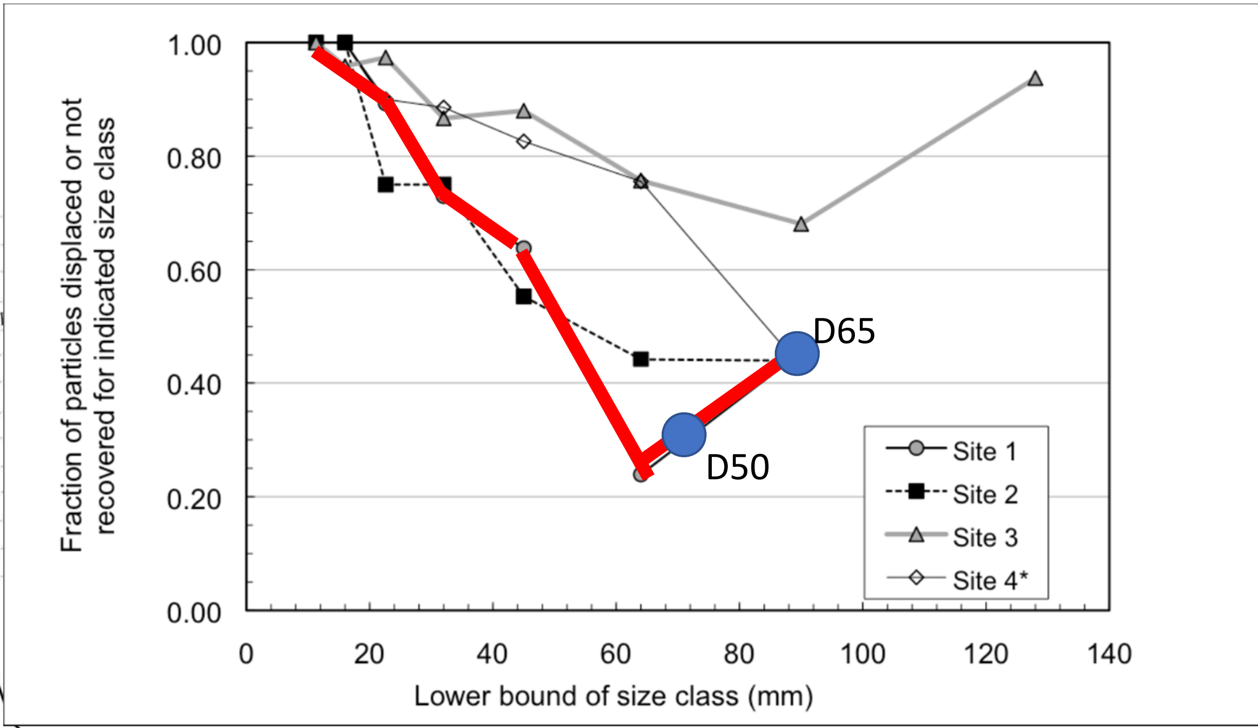
Looking upstream at site 1. Site 1 has a pool-riffle morphology.



Bedload samplers at site 1.

Figure 8 -- Map of Site 1





- During 2007, 100% of particles 16 mm or finer were mobilized, with mobilization decreasing to 40% for 90 mm particles.
- Peak flow in 2007 was 13 cms (459 cfs) which has a recurrence of slightly less than 1.5 years.

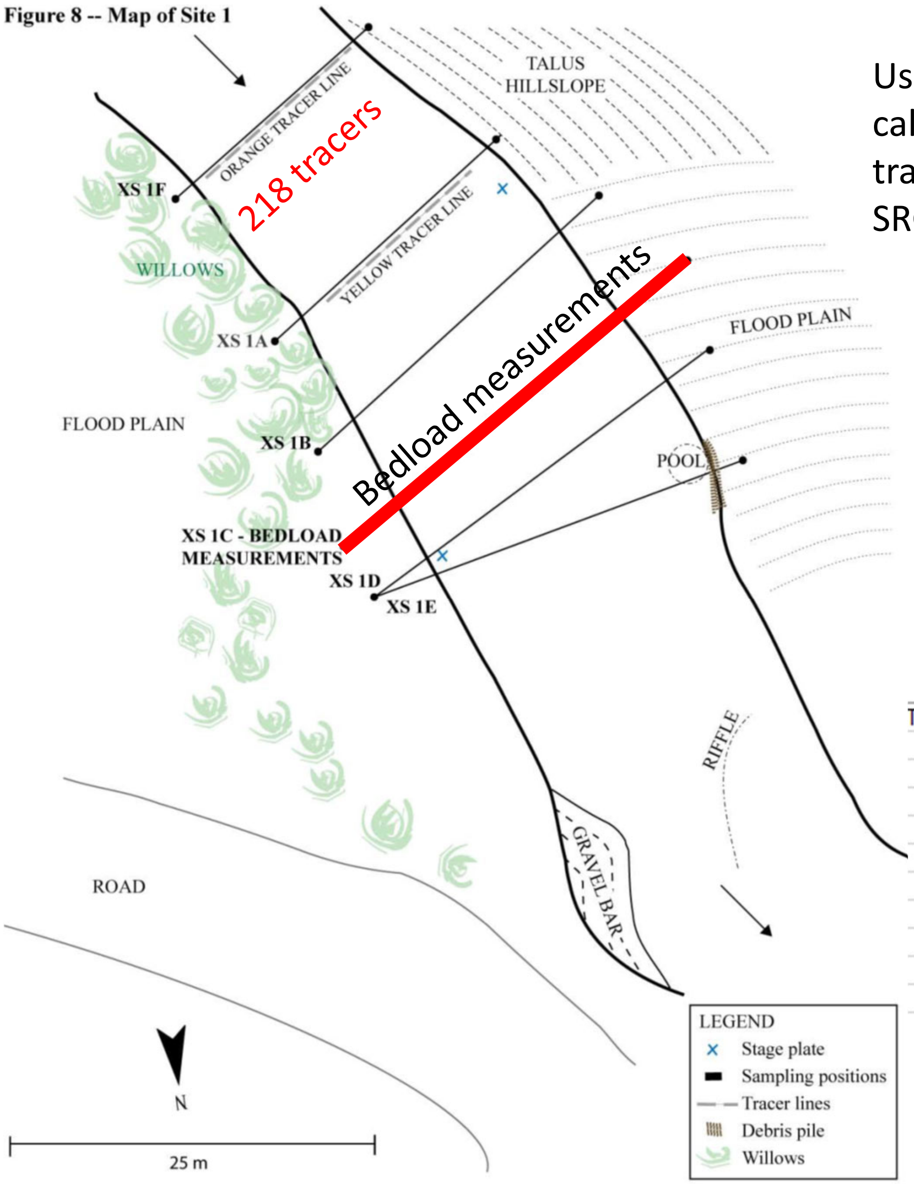
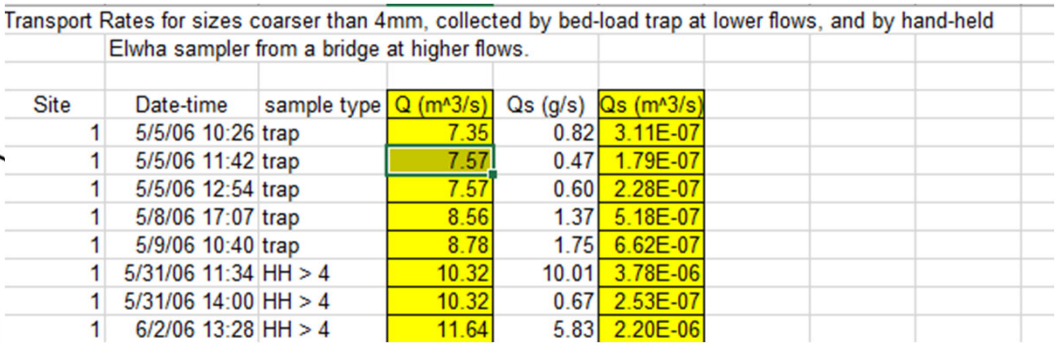


Figure 8 -- Map of Site 1

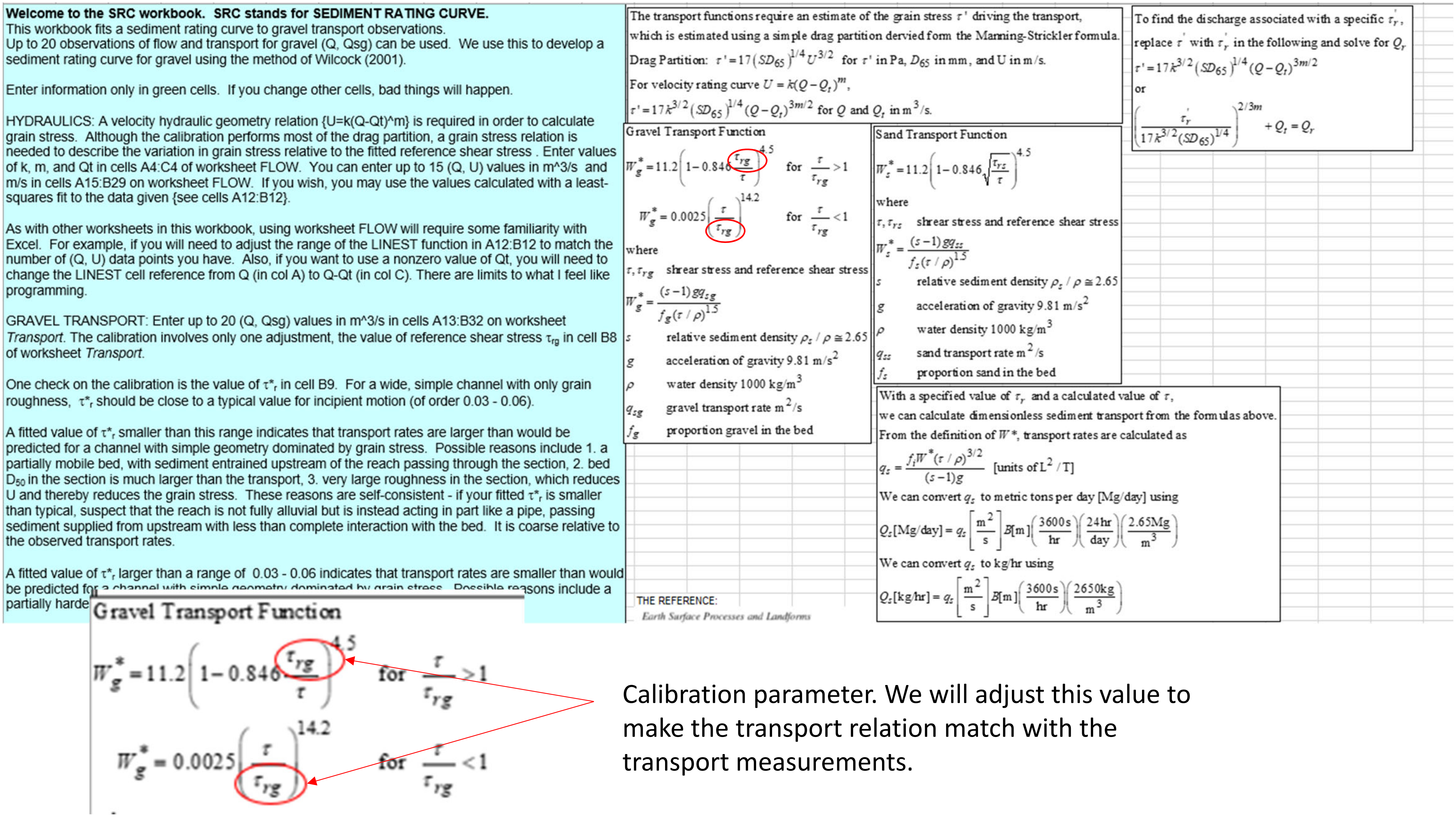
Using this data, let's calibrate the sediment transport function. SRC2023.xlsx


Bedload samplers at site 1.


Transport Rates for sizes coarser than 4mm, collected by bed-load trap at lower flows, and by hand-held Elwha sampler from a bridge at higher flows.

Site	Date-time	sample type	Q (m^3/s)	Qs (g/s)	Qs (m^3/s)
1	5/5/06 10:26	trap	7.35	0.82	3.11E-07
1	5/5/06 11:42	trap	7.57	0.47	1.79E-07
1	5/5/06 12:54	trap	7.57	0.60	2.28E-07
1	5/8/06 17:07	trap	8.56	1.37	5.18E-07
1	5/9/06 10:40	trap	8.78	1.75	6.62E-07
1	5/31/06 11:34	HH > 4	10.32	10.01	3.78E-06
1	5/31/06 14:00	HH > 4	10.32	0.67	2.53E-07
1	6/2/06 13:28	HH > 4	11.64	5.83	2.20E-06

CubR_Input_2023.xlsx



Welcome to the SRC workbook. SRC stands for SEDIMENT RATING CURVE.
This workbook fits a sediment rating curve to gravel transport observations.
Up to 20 observations of flow and transport for gravel (Q, Qsg) can be used. We use this to develop a sediment rating curve for gravel using the method of Wilcock (2001).

Enter information only in green cells. If you change other cells, bad things will happen.

HYDRAULICS: A velocity hydraulic geometry relation {U=k(Q-Qt)^m} is required in order to calculate grain stress. Although the calibration performs most of the drag partition, a grain stress relation is needed to describe the variation in grain stress relative to the fitted reference shear stress . Enter values of k, m, and Qt in cells A4:C4 of worksheet FLOW. You can enter up to 15 (Q, U) values in m^3/s and m/s in cells A15:B29 on worksheet FLOW. If you wish, you may use the values calculated with a least-squares fit to the data given {see cells A12:B12}.

As with other worksheets in this workbook, using worksheet FLOW will require some familiarity with Excel. For example, if you will need to adjust the range of the LINEST function in A12:B12 to match the number of (Q, U) data points you have. Also, if you want to use a nonzero value of Qt, you will need to change the LINEST cell reference from Q (in col A) to Q-Qt (in col C). There are limits to what I feel like programming.

GRAVEL TRANSPORT: Enter up to 20 (Q, Qsg) values in m^3/s in cells A13:B32 on worksheet *Transport*. The calibration involves only one adjustment, the value of reference shear stress τ_{rg} in cell B8 of worksheet *Transport*.

One check on the calibration is the value of τ^*_r in cell B9. For a wide, simple channel with only grain roughness, τ^*_r should be close to a typical value for incipient motion (of order 0.03 - 0.06).

A fitted value of τ^*_r smaller than this range indicates that transport rates are larger than would be predicted for a channel with simple geometry dominated by grain stress. Possible reasons include 1. a partially mobile bed, with sediment entrained upstream of the reach passing through the section, 2. bed D_{50} in the section is much larger than the transport, 3. very large roughness in the section, which reduces U and thereby reduces the grain stress. These reasons are self-consistent - if your fitted τ^*_r is smaller than typical, suspect that the reach is not fully alluvial but is instead acting in part like a pipe, passing sediment supplied from upstream with less than complete interaction with the bed. It is coarse relative to the observed transport rates.

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or

$$\left(\frac{\tau_r'}{17k^{3/2}(SD_{65})^{1/4}}\right)^{2/3m} + Q_t = Q_r$$

Gravel Transport Function

$$W_g^* = 11.2\left(1 - 0.846\frac{\tau_{rg}}{\tau}\right)^{4.5} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} > 1$$

$$W_g^* = 0.0025\left(\frac{\tau}{\tau_{rg}}\right)^{14.2} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} < 1$$

where

τ, τ_{rg} shrear stress and reference shear stress

$W_g^* = \dfrac{(s-1)gq_{sg}}{f_g(\tau/\rho)^{1.5}}$

s relative sediment density $\rho_s/\rho \cong 2.65$

g acceleration of gravity 9.81 m/s^2

ρ water density 1000 kg/m^3

q_{sg} gravel transport rate m^2/s

f_g proportion gravel in the bed

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$$q_s = \frac{f_i W^*(\tau/\rho)^{3/2}}{(s-1)g} \quad \text{[units of } L^2/T]$$

We can convert q_s to metric tons per day [Mg/day] using

$$Q_s[\text{Mg/day}] = q_s\left[\frac{m^2}{s}\right]B[m]\left(\frac{3600\,s}{hr}\right)\left(\frac{24\,hr}{day}\right)\left(\frac{2.65\,Mg}{m^3}\right)$$

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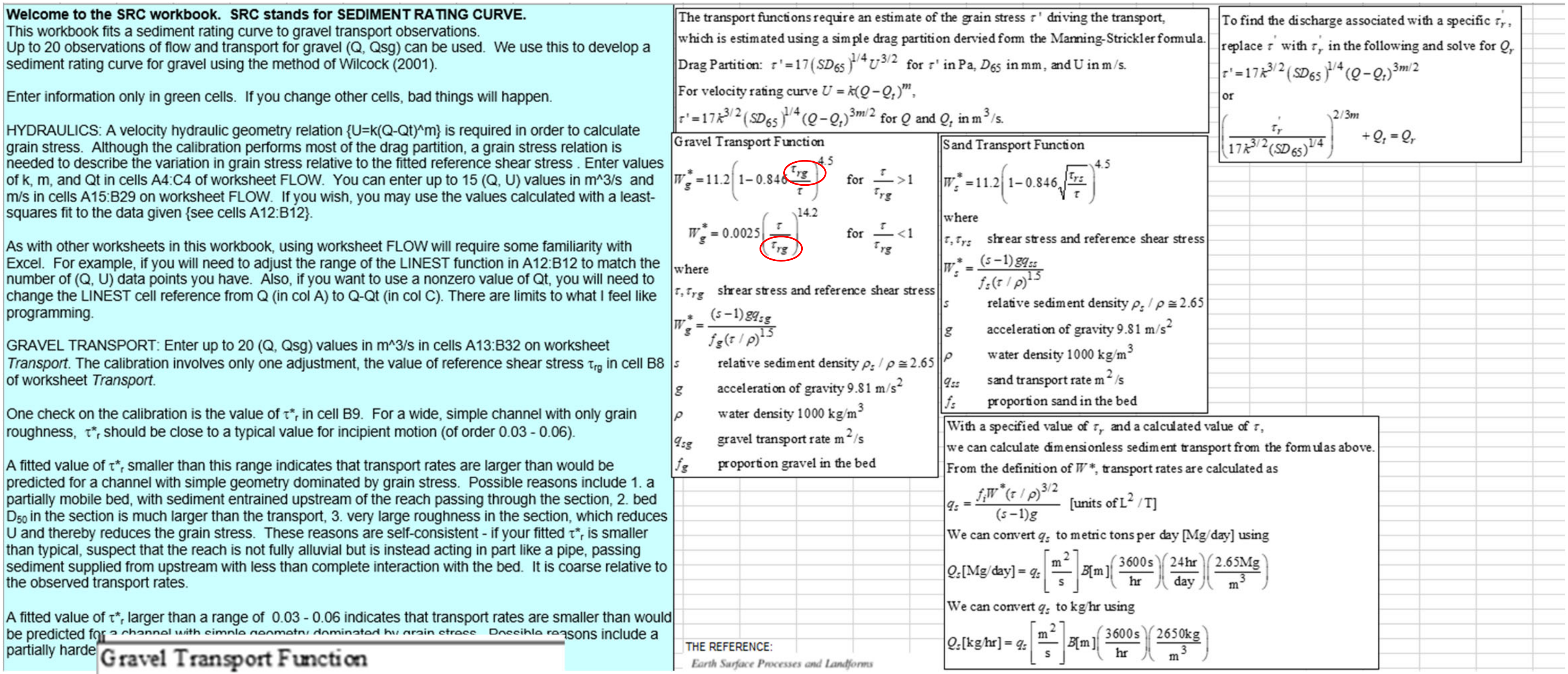
Calibration parameter. We will adjust this value to make the transport relation match with the transport measurements.



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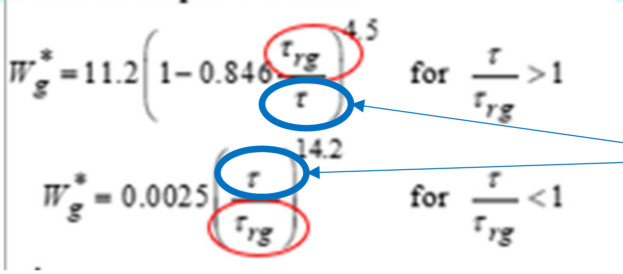

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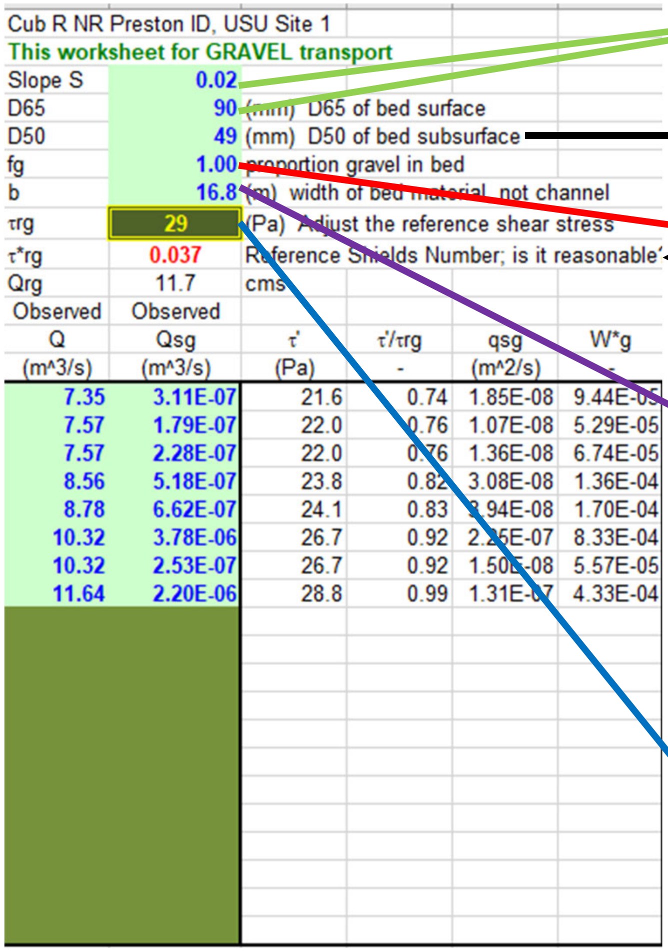
Need the velocity hydraulic geometry relation to estimate the drag partition at different flows in order to predict the grain shear stress.

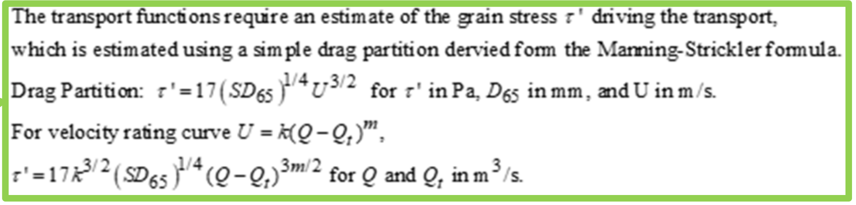
Let’s check this out in the spreadsheet.



Cub R NR Preston ID, USU Site 1					
This worksheet for GRAVEL transport					
Slope S	**0.02**				
D65	**90**	(mm) D65 of bed surface			
D50	**49**	(mm) D50 of bed subsurface			
fg	**1.00**	proportion gravel in bed			
b	**16.8**	(m) width of bed material, not channel			
τrg	**29**	(Pa) Adjust the reference shear stress			
τ*rg	**0.037**	Reference Shields Number; is it reasonable?			
Qrg	11.7	cms			
Observed	Observed				
Q (m^3/s)	Qsg (m^3/s)	τ' (Pa)	τ'/τrg -	qsg (m^2/s)	W*g -
7.35	**3.11E-07**	21.6	0.74	1.85E-08	9.44E-05
7.57	**1.79E-07**	22.0	0.76	1.07E-08	5.29E-05
7.57	**2.28E-07**	22.0	0.76	1.36E-08	6.74E-05
8.56	**5.18E-07**	23.8	0.82	3.08E-08	1.36E-04
8.78	**6.62E-07**	24.1	0.83	3.94E-08	1.70E-04
10.32	**3.78E-06**	26.7	0.92	2.25E-07	8.33E-04
10.32	**2.53E-07**	26.7	0.92	1.50E-08	5.57E-05
11.64	**2.20E-06**	28.8	0.99	1.31E-07	4.33E-04

Gut check!

Predict grain shear stress



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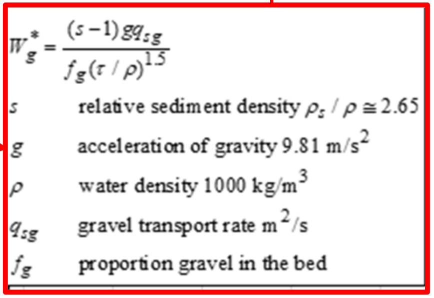
Convert dimensionless transport rate to unit transport rate.



$$W_g^* = \frac{(s-1)gq_{sg}}{f_g(\tau/\rho)^{1.5}}$$

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g	acceleration of gravity 9.81 m/s^2
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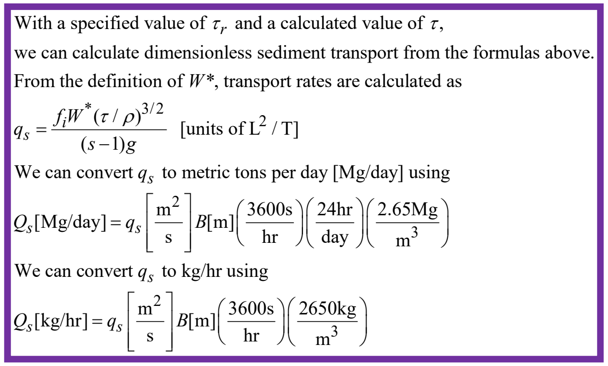
q_{sg}	gravel transport rate m^2/s
f_g	proportion gravel in the bed

Convert unit transport rate to total transport



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From the definition of W^*, transport rates are calculated as

$$q_s = \frac{f_i W^*(\tau/\rho)^{3/2}}{(s-1)g} \quad \text{[units of L}^2\text{/T]}$$

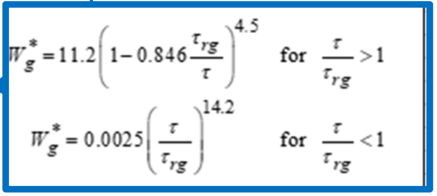
We can convert q_s to metric tons per day [Mg/day] using

$$Q_s[\text{Mg/day}] = q_s\left[\frac{\text{m}^2}{\text{s}}\right]B[\text{m}]\left(\frac{3600\text{s}}{\text{hr}}\right)\left(\frac{24\text{hr}}{\text{day}}\right)\left(\frac{2.65\text{Mg}}{\text{m}^3}\right)$$

We can convert q_s to kg/hr using

$$Q_s[\text{kg/hr}] = q_s\left[\frac{\text{m}^2}{\text{s}}\right]B[\text{m}]\left(\frac{3600\text{s}}{\text{hr}}\right)\left(\frac{2650\text{kg}}{\text{m}^3}\right)$$

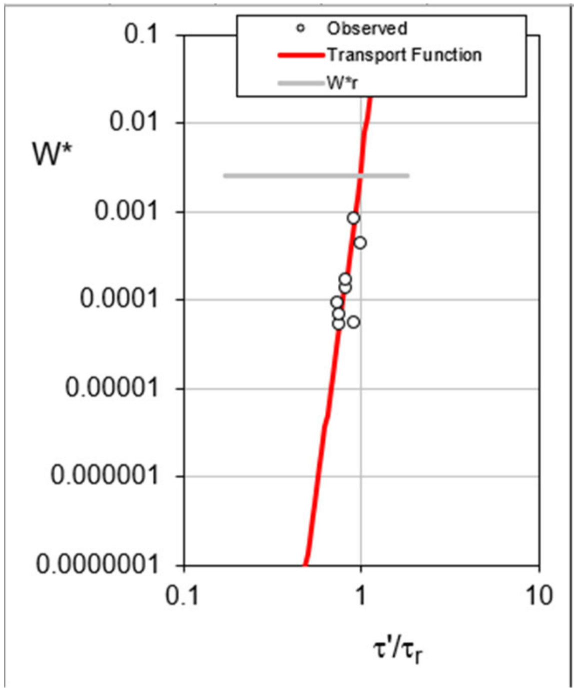
Calculate dimensionless transport rate



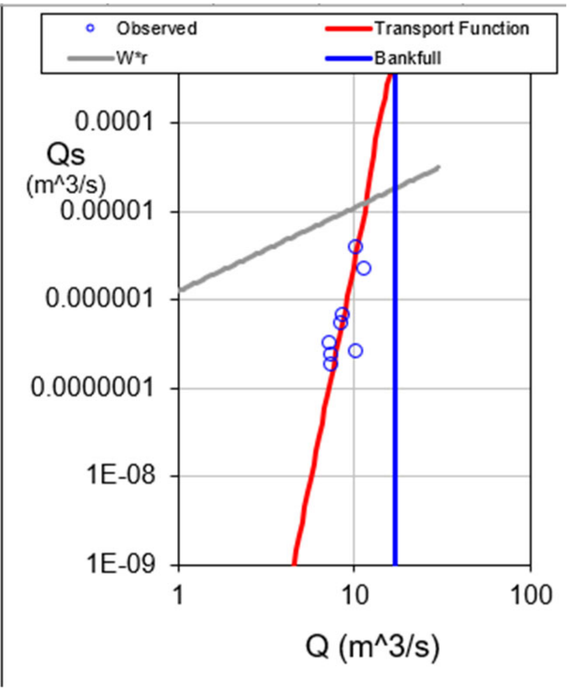
$$W_g^* = 11.2\left(1 - 0.846\frac{\tau_{rg}}{\tau}\right)^{4.5} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} > 1$$

$$W_g^* = 0.0025\left(\frac{\tau}{\tau_{rg}}\right)^{14.2} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} < 1$$

Nondimensional



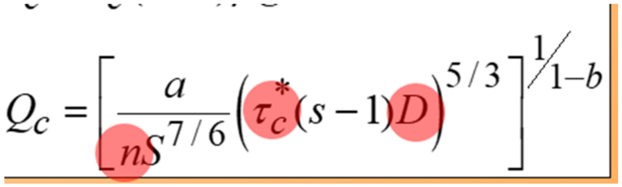
Dimensional



- Flow scaled by reference shear stress.
- Observed transport moves when τr changes.
- Transport relation stays constant.
- Why?

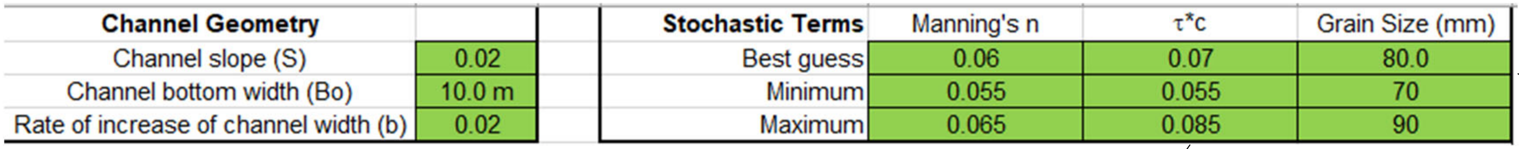
- Transport relation moves when τr changes.
- Transport measurements stay constant.
- Why?

OK, now that we have calibrated our transport function, let’s estimate the discharge when transport begins.



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

Here’s what we need….

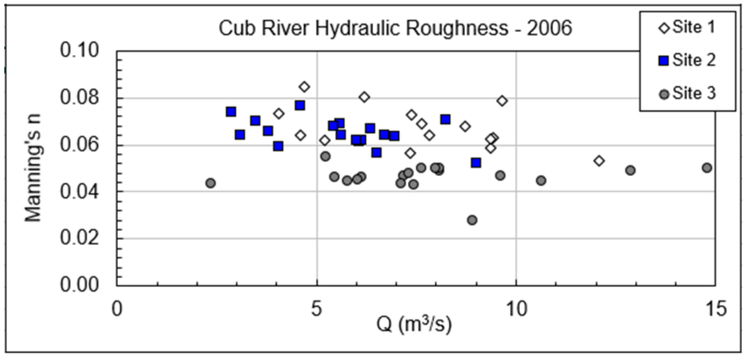


Channel Geometry	
Channel slope (S)	0.02
Channel bottom width (Bo)	10.0 m
Rate of increase of channel width (b)	0.02

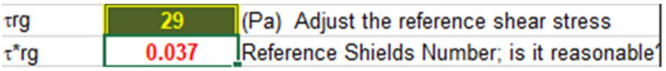
Stochastic Terms	Manning's n	τ*c	Grain Size (mm)
Best guess	0.06	0.07	80.0
Minimum	0.055	0.055	70
Maximum	0.065	0.085	90

What grain size should we use? How accurate are the grain size measurements?

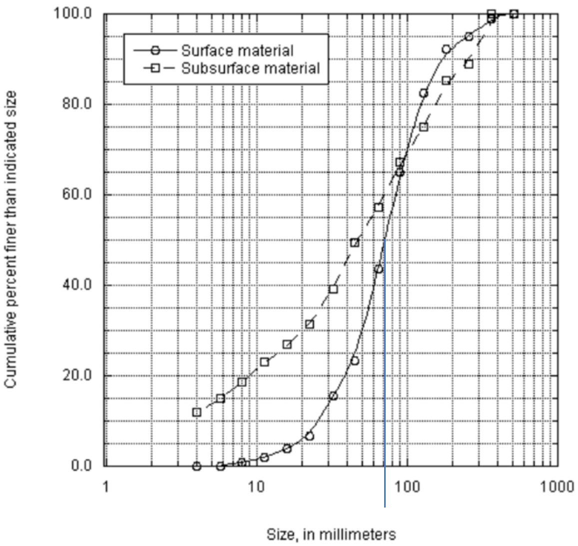
What should this be? Roughness changes with discharge.



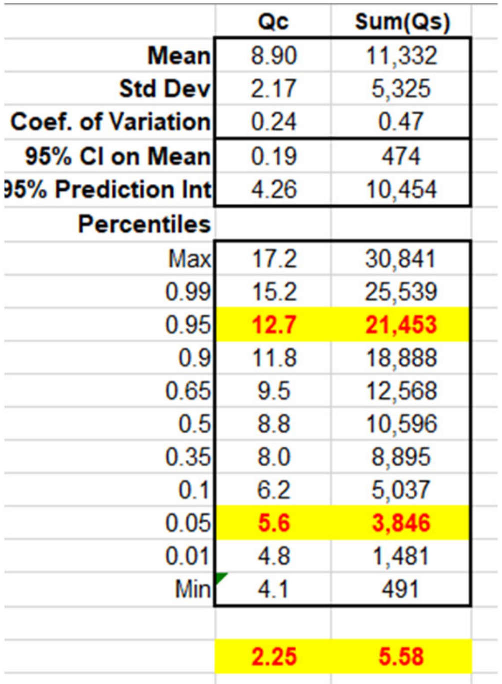
What critical shields number should we use?



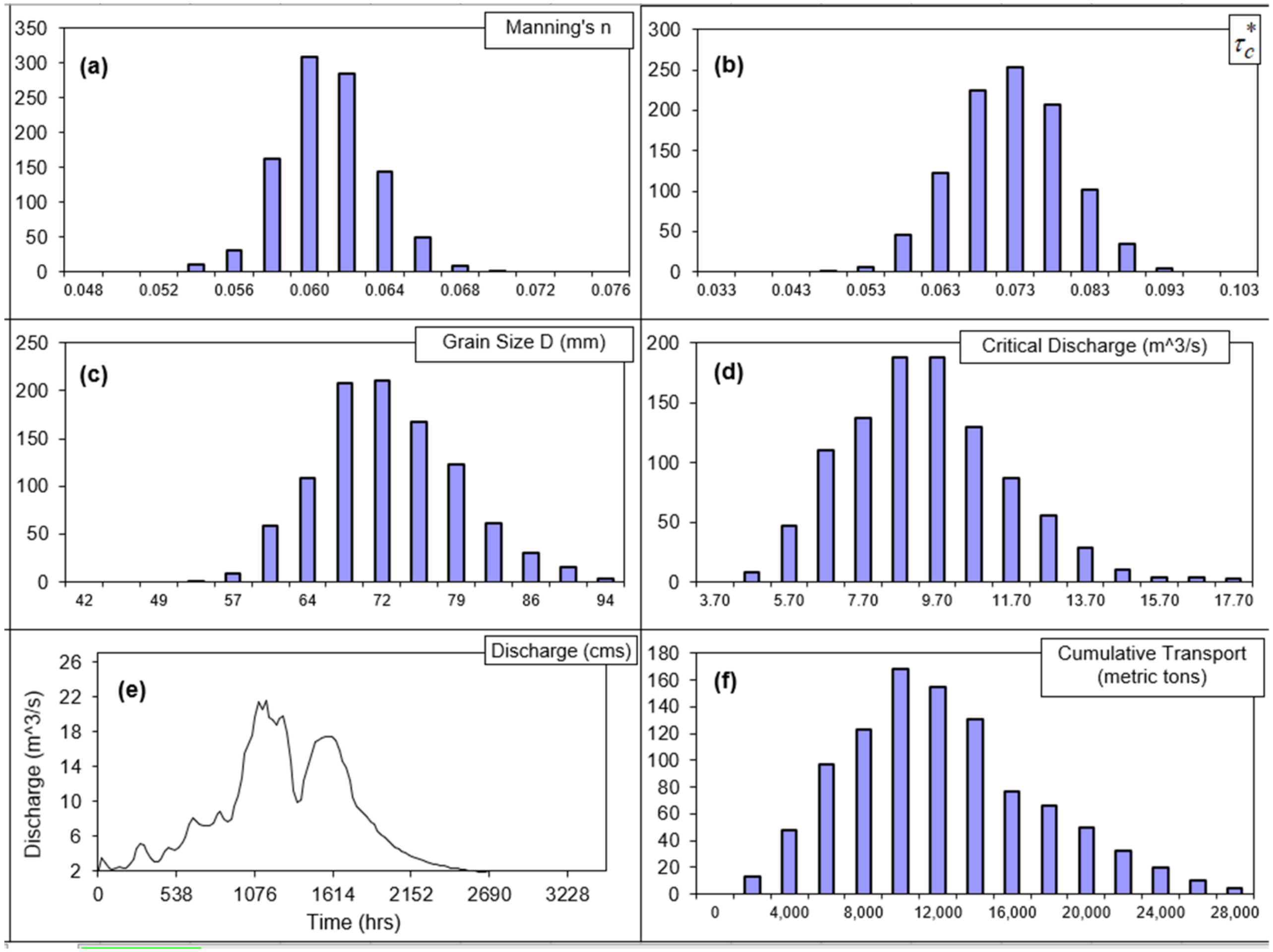
τrg	29	(Pa) Adjust the reference shear stress
τ*rg	0.037	Reference Shields Number; is it reasonable?



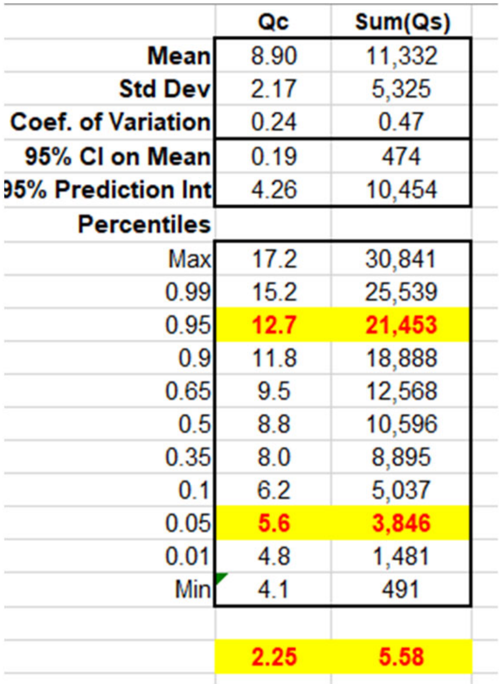
Lots of uncertainty…let’s take that into account.



	Qc	Sum(Qs)
Mean	8.90	11,332
Std Dev	2.17	5,325
Coef. of Variation	0.24	0.47
95% CI on Mean	0.19	474
95% Prediction Int	4.26	10,454
Percentiles		
Max	17.2	30,841
0.99	15.2	25,539
0.95	**12.7**	**21,453**
0.9	11.8	18,888
0.65	9.5	12,568
0.5	8.8	10,596
0.35	8.0	8,895
0.1	6.2	5,037
0.05	**5.6**	**3,846**
0.01	4.8	1,481
Min	4.1	491
	2.25	**5.58**



How does this compare to what was measured?



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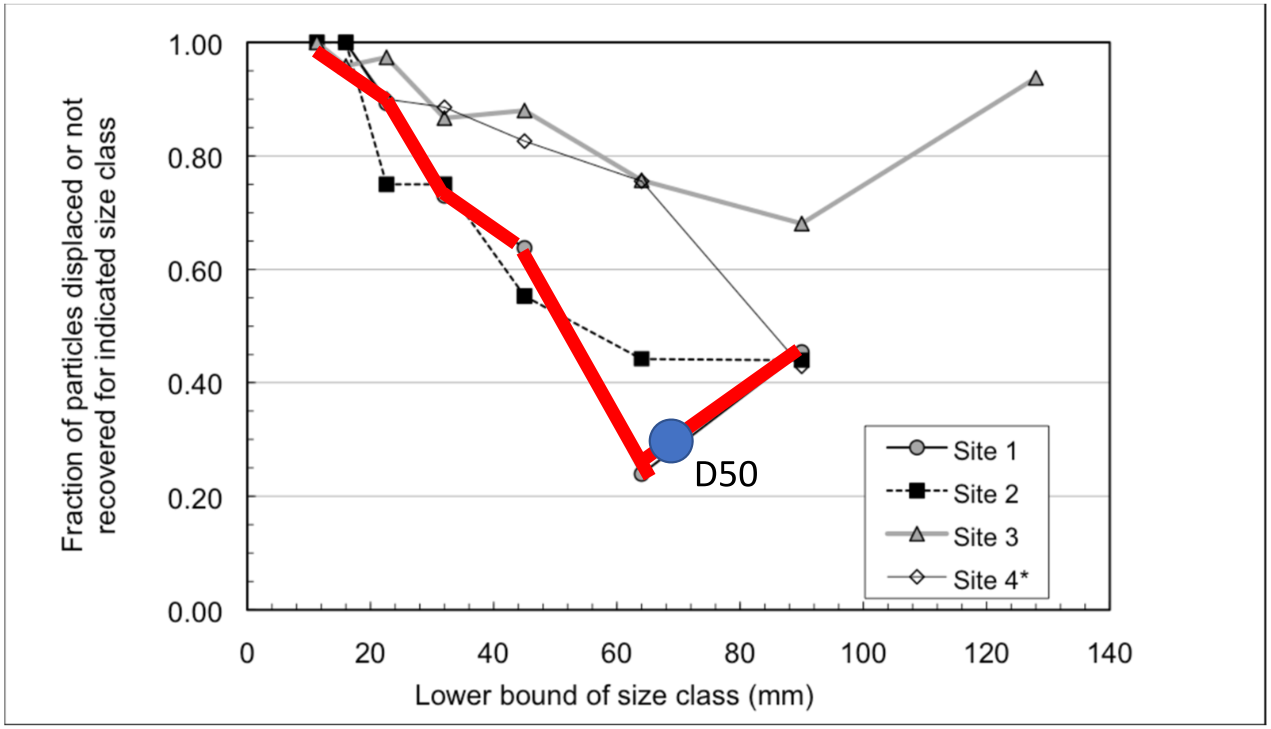
Min	4.1	491
	2.25	**5.58**

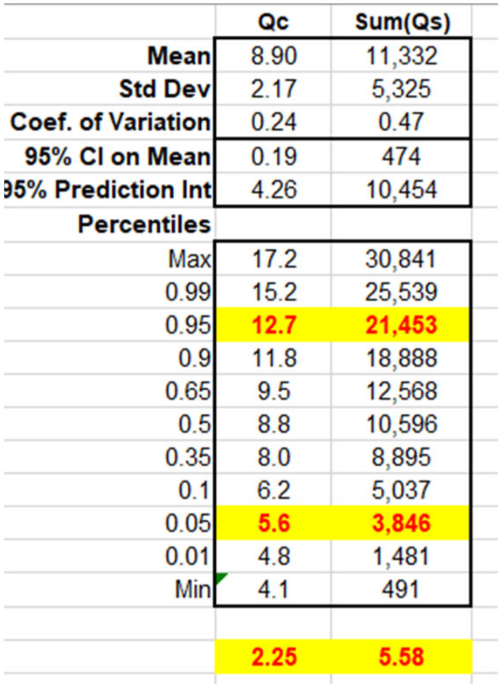
448 cfs

198 cfs



- During 2007, 100% of particles 16 mm or finer were mobilized, with mobilization decreasing to 40% for 90 mm particles.
- Peak flow in 2007 was 13 cms (459 cfs) which has a recurrence of slightly less than 1.5 years.

Lots of uncertainty…Does it matter?



	Qc	Sum(Qs)
Mean	8.90	11,332
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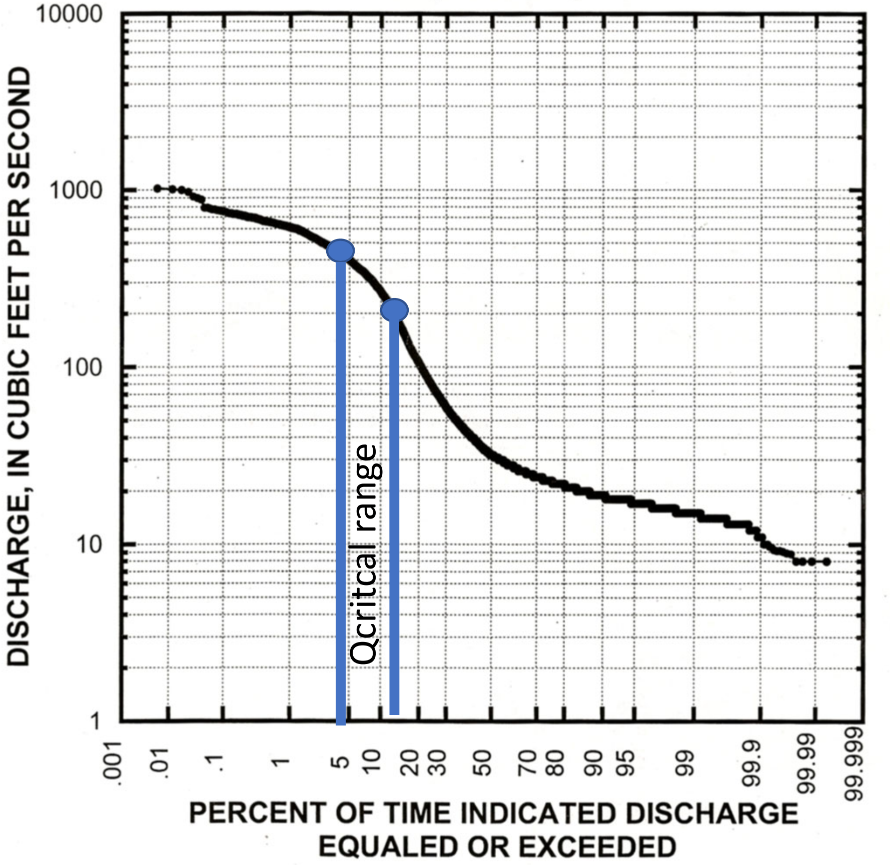
Min	4.1	491
	2.25	**5.58**

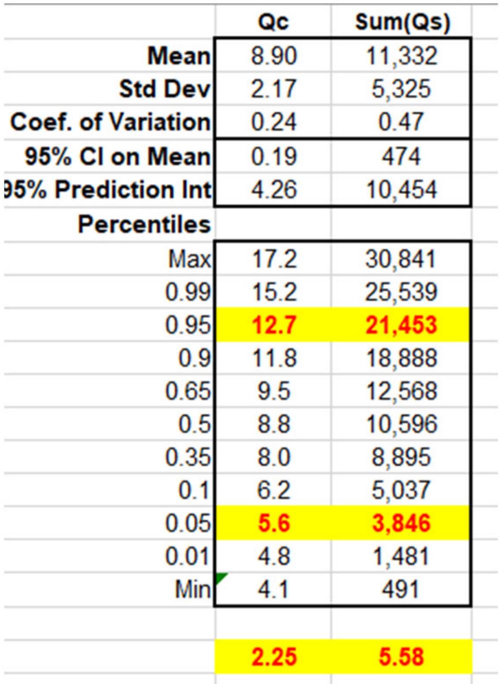
448 cfs

198 cfs

Figure 6. -- Flow Duration Curve for Period of Record, Cub River near Preston, gage 10093000 (1940-2008)



Lots of uncertainty…Does it matter?



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0.05	**5.6**	**3,846**
0.01	4.8	1,481
Min	4.1	491
	2.25	**5.58**

448 cfs

198 cfs

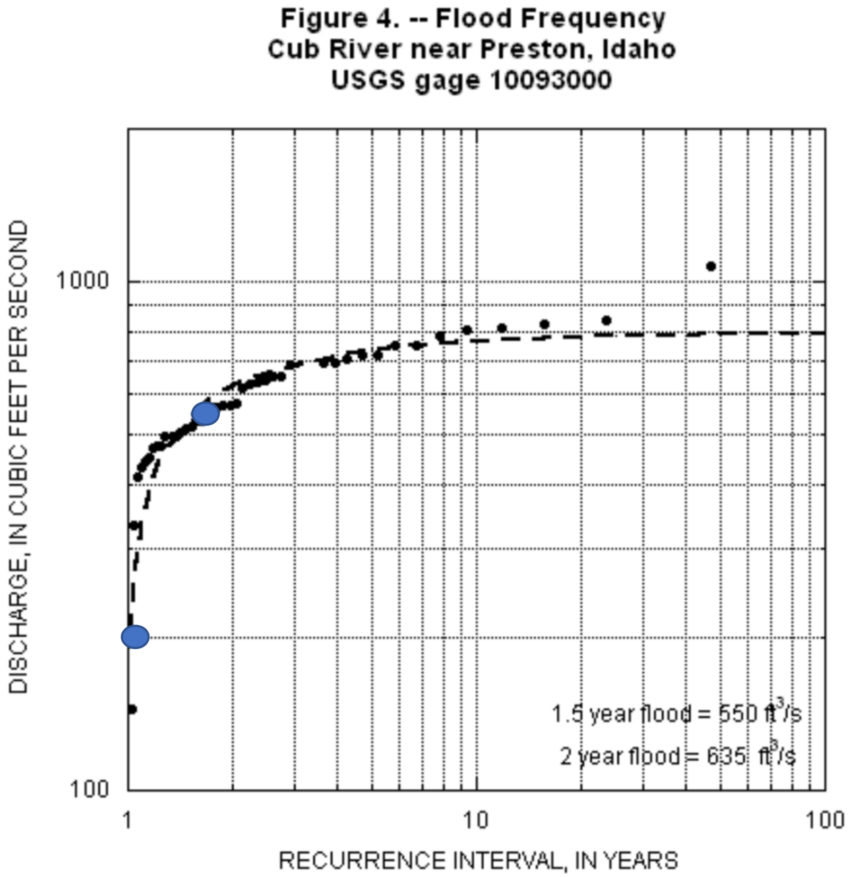


Figure 4. -- Flood Frequency
Cub River near Preston, Idaho
USGS gage 10093000

What about that effective Q everyone loves to talk about?

Effective Discharge? The flow that moves the most sediment over time.

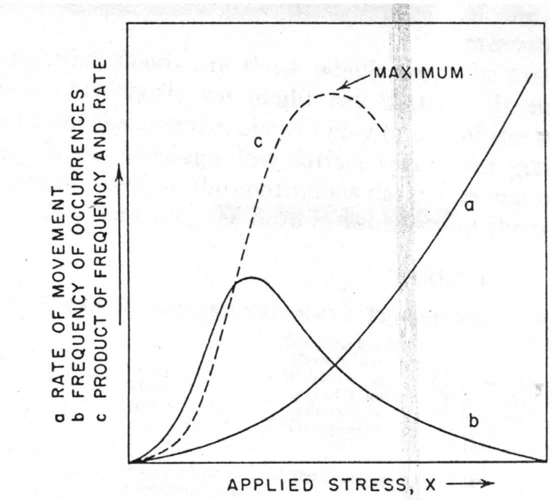


FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

Wolman & Miller (1960)

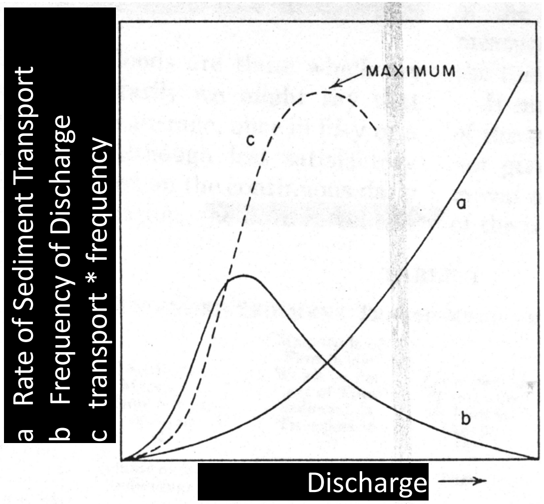


FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

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

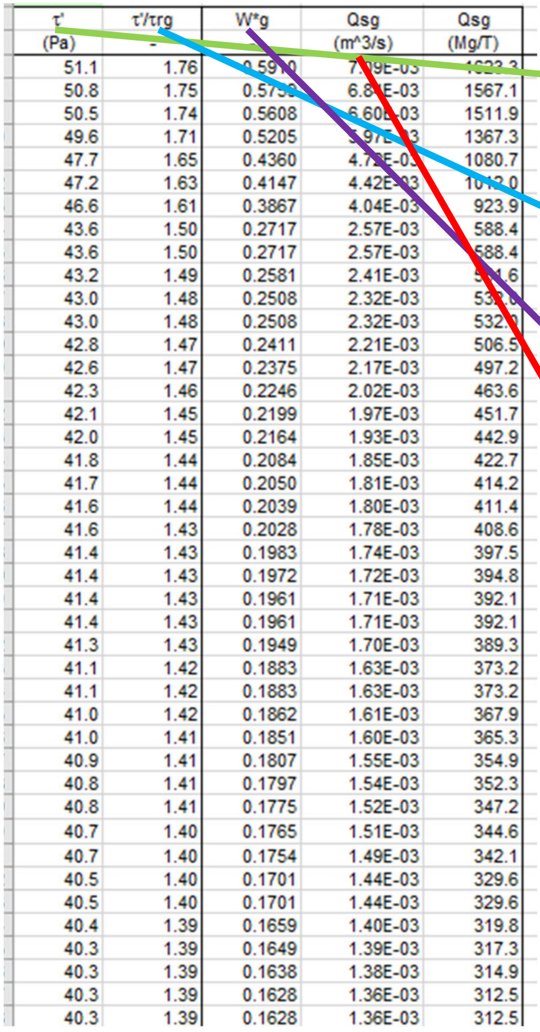
Curve c tells you how much sediment is moved by each flow. The area under the curve tells you how much sediment is moved each year.

Does the ***maximum*** of the curve tell us something specific about channel geometry?

Hypothesis:

> *Alluvial channels adjust their morphology to move the most sediment (over time) at the bankfull stage, which has a return period between 1-2 years*

Make these calculations for each day in the hydrograph



τ' (Pa)	τ'/τrg -	W*g -	Qsg (m^3/s)	Qsg (Mg/T)
51.1	1.76	0.5910	7.09E-03	1623.3
50.8	1.75	0.5759	6.84E-03	1567.1
50.5	1.74	0.5608	6.60E-03	1511.9
49.6	1.71	0.5205	5.97E-03	1367.3
47.7	1.65	0.4360	4.72E-03	1080.7
47.2	1.63	0.4147	4.42E-03	1012.0
46.6	1.61	0.3867	4.04E-03	923.9
43.6	1.50	0.2717	2.57E-03	588.4
43.6	1.50	0.2717	2.57E-03	588.4
43.2	1.49	0.2581	2.41E-03	551.6
43.0	1.48	0.2508	2.32E-03	532.0
43.0	1.48	0.2508	2.32E-03	532.0
42.8	1.47	0.2411	2.21E-03	506.5
42.6	1.47	0.2375	2.17E-03	497.2
42.3	1.46	0.2246	2.02E-03	463.6
42.1	1.45	0.2199	1.97E-03	451.7
42.0	1.45	0.2164	1.93E-03	442.9
41.8	1.44	0.2084	1.85E-03	422.7
41.7	1.44	0.2050	1.81E-03	414.2
41.6	1.44	0.2039	1.80E-03	411.4
41.6	1.43	0.2028	1.78E-03	408.6
41.4	1.43	0.1983	1.74E-03	397.5
41.4	1.43	0.1972	1.72E-03	394.8
41.4	1.43	0.1961	1.71E-03	392.1
41.4	1.43	0.1961	1.71E-03	392.1
41.3	1.43	0.1949	1.70E-03	389.3
41.1	1.42	0.1883	1.63E-03	373.2
41.1	1.42	0.1883	1.63E-03	373.2
41.0	1.42	0.1862	1.61E-03	367.9
41.0	1.41	0.1851	1.60E-03	365.3
40.9	1.41	0.1807	1.55E-03	354.9
40.8	1.41	0.1797	1.54E-03	352.3
40.8	1.41	0.1775	1.52E-03	347.2
40.7	1.40	0.1765	1.51E-03	344.6
40.7	1.40	0.1754	1.49E-03	342.1
40.5	1.40	0.1701	1.44E-03	329.6
40.5	1.40	0.1701	1.44E-03	329.6
40.4	1.39	0.1659	1.40E-03	319.8
40.3	1.39	0.1649	1.39E-03	317.3
40.3	1.39	0.1638	1.38E-03	314.9
40.3	1.39	0.1628	1.36E-03	312.5
40.3	1.39	0.1628	1.36E-03	312.5

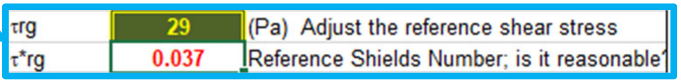
Predict grain shear stress

The transport functions require an estimate of the grain stress τ' driving the transport, which is estimated using a simple drag partition dervied form the Manning-Strickler formula.

Drag Partition: $\tau' = 17\left(SD_{65}\right)^{1/4} U^{3/2}$ for τ' in Pa, D_{65} in mm, and U in m/s.

For velocity rating curve $U = k(Q - Q_t)^m$,

$\tau' = 17k^{3/2}\left(SD_{65}\right)^{1/4}(Q - Q_t)^{3m/2}$ for Q and Q_t in m^3/s.



τrg	29	(Pa) Adjust the reference shear stress
τ*rg	0.037	Reference Shields Number; is it reasonable?

Calculate dimensionless transport rate

$$W_g^* = 11.2\left(1 - 0.846\frac{\tau_{rg}}{\tau}\right)^{4.5} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} > 1$$

$$W_g^* = 0.0025\left(\frac{\tau}{\tau_{rg}}\right)^{14.2} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} < 1$$

Calculate dimensionless transport rate

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$$W_g^* = 0.0025\left(\frac{\tau}{\tau_{rg}}\right)^{14.2} \quad \text{for} \quad \frac{\tau}{\tau_{rg}} < 1$$

Convert unit transport rate to total transport

With a specified value of τ_r and a calculated value of τ, we can calculate dimensionless sediment transport from the formulas above. From the definition of W^*, transport rates are calculated as

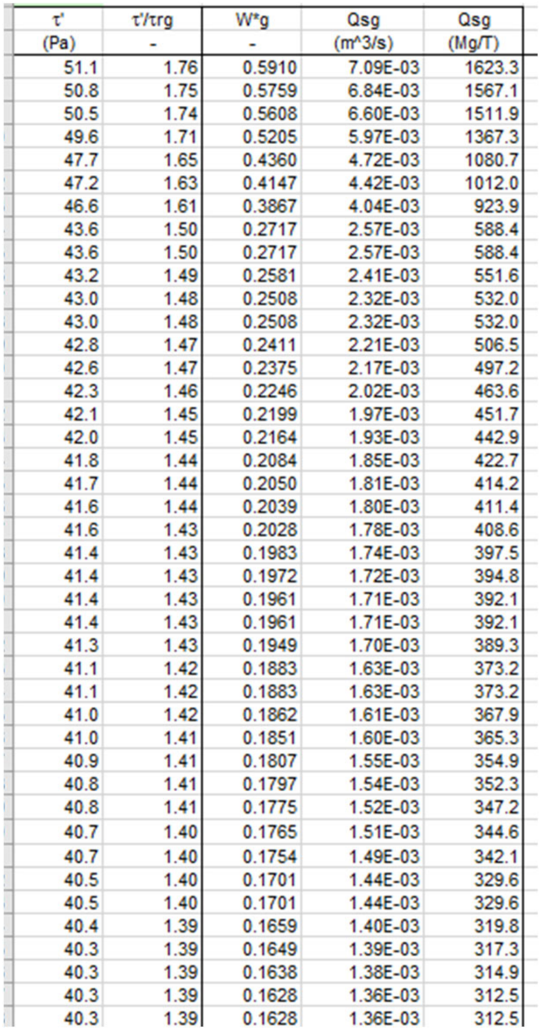
$$q_s = \frac{f_i W^* (\tau / \rho)^{3/2}}{(s-1)g} \quad [\text{units of L}^2/\text{T}]$$

We can convert q_s to metric tons per day [Mg/day] using

$$Q_s[\text{Mg/day}] = q_s\left[\frac{\text{m}^2}{\text{s}}\right] B[\text{m}]\left(\frac{3600\text{s}}{\text{hr}}\right)\left(\frac{24\text{hr}}{\text{day}}\right)\left(\frac{2.65\text{Mg}}{\text{m}^3}\right)$$

We can convert q_s to kg/hr using

$$Q_s[\text{kg/hr}] = q_s\left[\frac{\text{m}^2}{\text{s}}\right] B[\text{m}]\left(\frac{3600\text{s}}{\text{hr}}\right)\left(\frac{2650\text{kg}}{\text{m}^3}\right)$$



τ' (Pa)	τ'/τrg -	W*g -	Qsg (m^3/s)	Qsg (Mg/T)
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50.5	1.74	0.5608	6.60E-03	1511.9
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47.7	1.65	0.4360	4.72E-03	1080.7
47.2	1.63	0.4147	4.42E-03	1012.0
46.6	1.61	0.3867	4.04E-03	923.9
43.6	1.50	0.2717	2.57E-03	588.4
43.6	1.50	0.2717	2.57E-03	588.4
43.2	1.49	0.2581	2.41E-03	551.6
43.0	1.48	0.2508	2.32E-03	532.0
43.0	1.48	0.2508	2.32E-03	532.0
42.8	1.47	0.2411	2.21E-03	506.5
42.6	1.47	0.2375	2.17E-03	497.2
42.3	1.46	0.2246	2.02E-03	463.6
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42.0	1.45	0.2164	1.93E-03	442.9
41.8	1.44	0.2084	1.85E-03	422.7
41.7	1.44	0.2050	1.81E-03	414.2
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41.4	1.43	0.1972	1.72E-03	394.8
41.4	1.43	0.1961	1.71E-03	392.1
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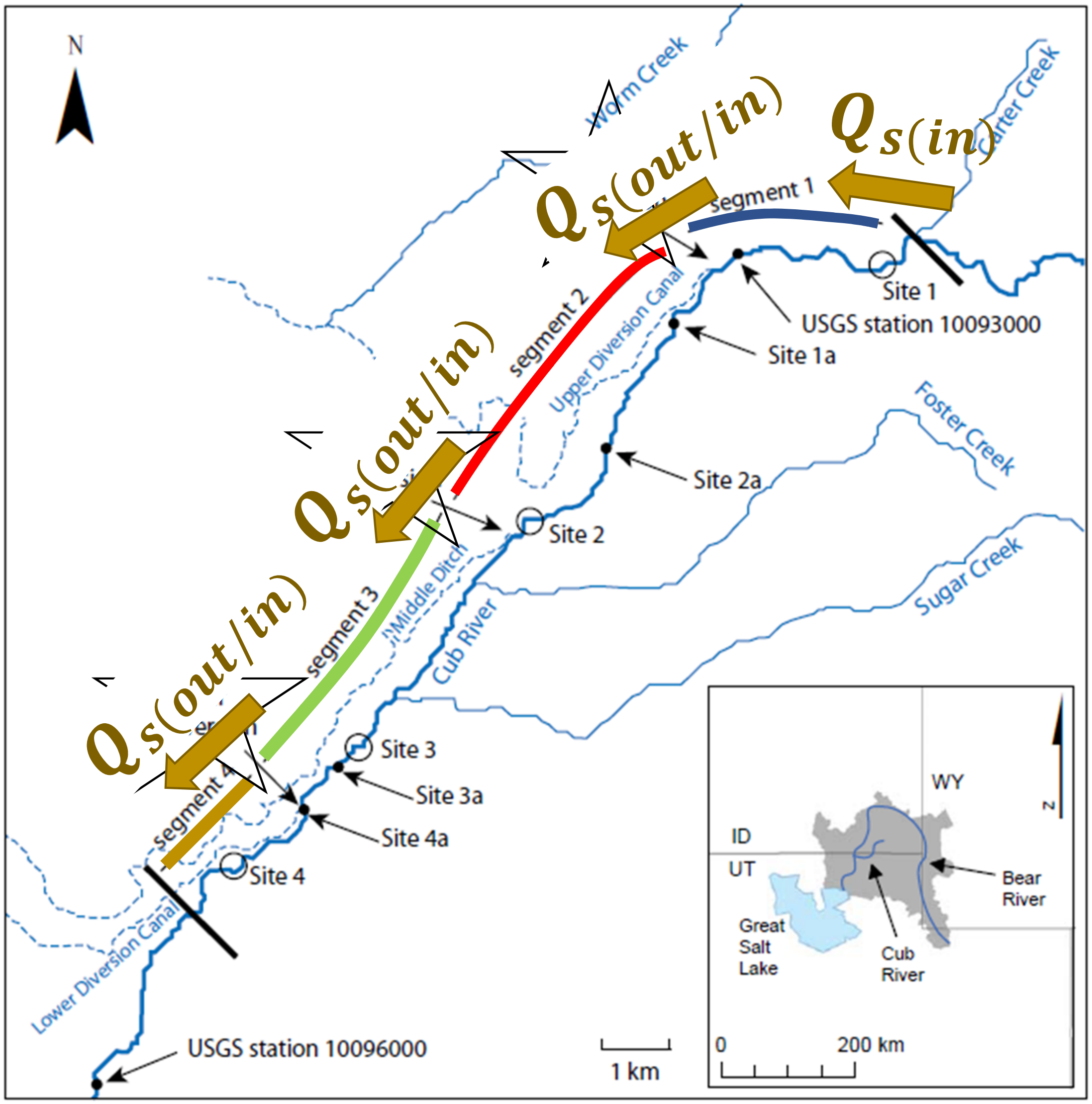
41.3	1.43	0.1949	1.70E-03	389.3
41.1	1.42	0.1883	1.63E-03	373.2
41.1	1.42	0.1883	1.63E-03	373.2
41.0	1.42	0.1862	1.61E-03	367.9
41.0	1.41	0.1851	1.60E-03	365.3
40.9	1.41	0.1807	1.55E-03	354.9
40.8	1.41	0.1797	1.54E-03	352.3
40.8	1.41	0.1775	1.52E-03	347.2
40.7	1.40	0.1765	1.51E-03	344.6
40.7	1.40	0.1754	1.49E-03	342.1
40.5	1.40	0.1701	1.44E-03	329.6
40.5	1.40	0.1701	1.44E-03	329.6
40.4	1.39	0.1659	1.40E-03	319.8
40.3	1.39	0.1649	1.39E-03	317.3
40.3	1.39	0.1638	1.38E-03	314.9
40.3	1.39	0.1628	1.36E-03	312.5
40.3	1.39	0.1628	1.36E-03	312.5

Bin these values and calculate the total transport over each bin.

What bin size should we use?
Does the bin size matter?
When might Qeffective be more or less sensitive to bin size?

Let’s find out!



OK, so we have…

1. Calibrated a transport relation at site 1.
2. Estimated when the bed is mobilized at site 1.
3. Predicted the effective discharge at site 1.

But, site 1 is upstream from all the diversions. So, what can we do with this data to figure out the sediment budget downstream?

- Use the calibrated transport equation to predict transport rates in different segments. Why would transport rates change downstream?
- How does the sediment mass balance change going downstream?
- How does the frequency of bed mobility change going downstream?
- How might the channel might respond in the future to current (or new) diversions?

Consider these questions as you work through this exercise.