Some General Sediment Concepts
July 29, 2019

Monday: estimating sediment sources, sinks, transport rates
Tuesday: channel, sediment & flow → RAS model and critical discharge
Wednesday: estimating sediment transport rates: rating curves, budget, transport frequency
Thursday: incorporating sediment in channel assessment & design
   add geomorphic & design concepts → channel/floodplain design exercise
Friday: present & evaluate designs, visit field site
Sediment transport application to urban streams
application to non-urban streams
Monitoring and modeling sediment transport
Sediment Transport in stable channel design
When and how to apply sediment transport analysis
I have lots of RAS - how do I bring in sediment?
How to deal with ST uncertainty in assessment & design
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 Competence**

- Discharge $Q$
- Bed material $D$
- Channel Geometry

II. What is the sediment balance?  
**Transport Capacity** vs Sediment Supply

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

$Input - Output = \Delta\text{Storage}$

Surplus or Deficit?  
*Stored sediment* is the real geomorphic and restoration topic!
Design a stream channel that is in equilibrium with the present regime of water and sediment supply.
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*
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
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 toll booth
<table>
<thead>
<tr>
<th>Competence v. Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow Competence</strong></td>
</tr>
<tr>
<td>Can a flow entrain the grains on the bed?</td>
</tr>
<tr>
<td>Applied to the channel <em>bed</em></td>
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<td><em>Leads to a threshold channel</em></td>
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<td><strong>Transport Capacity</strong></td>
</tr>
<tr>
<td>At what rate can a flow transport sediment?</td>
</tr>
<tr>
<td>Compare to sediment <em>supply</em></td>
</tr>
<tr>
<td><em>Leads to a mobile channel</em></td>
</tr>
</tbody>
</table>
Sediment Transport in Channel Design

Objective
sediment & nutrients
property & infrastructure
biological recovery
aesthetic
penance

What needs fixing?

Disturbance
Internal or external?

Stormwater control
Introduced species
Channel change

Environmental Drivers

Estimate flood frequency
Design threshold channel

Channel Design
Sediment supply large or small?

Small
External
Internal

Fence out the cows!
Remove the concrete!
Template approach can work

Estimate sediment supply & flow duration
Design alluvial channel

Alluvial Channel? Threshold Channel? Both!
A few slides about sediment
Table 2-3  Sediment Grade Scale

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

\[ D \text{ (mm)} = 2^{-\phi} = 2^\psi \]
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*

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>Mechanism</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
</table>
| **Washload** clay, silt, *fine sand* | 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

Sedimentation

Hydrology, Geomorphology, Ecology
Dingman, L., Physical Hydrology, Culinary and Hospitality Industry Publications Services?
Freeze, A. and Cherry, J., 1979, Groundwater, Prentice Hall

Restoration Design & Practice
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
A few slides about sediment transport & incipient grain motion
What drives grain motion?

Flow force on bed)/(bed area): $\tau_o$

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

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

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

This is THE most important variable in sediment transport

$D$ grain size; $g$ acceleration of gravity; $\rho$, $\rho_s$ 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 $\tau$

(ii) hydraulics problem – estimating boundary stress $\tau$ in terms of channel geometry, bed roughness, and flow
**When does transport begin?**

How do we find the critical stress \( \tau_c \) at incipient grain motion?

Shields Curve: relates critical Shields Number and Dimensionless viscosity \( S^* \)

\[
\tau^* = \frac{\tau_o}{(\rho_s - \rho)gD}
\]

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

For \( D > 4 \text{ mm} \)

\[
\tau_c = \frac{\tau_c}{(\rho_s - \rho)gD} \approx 0.03
\]

\( \tau_c = 0.5D \)

For \( \tau_c \) in Pa & \( D \) in mm

\( D \) grain size; \( \rho, \rho_s \) water, sediment density;

\( g \) acceleration of gravity;

\( \nu \) water viscosity
How do we get this boundary shear $\tau_0$?

$\tau_0$ balances the downslope component of the weight of the water.

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

$\tau_0$ is the boundary shear stress - the flow force per unit area - it drives the sediment transport.

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

**Boundary stress:** $\tau_0$
(stress is force/area)

**Boundary force:** $\tau_0PL$

The 'depth-slope' product
$\tau_0 = hS$  
($h$ in cm, $S$ in %, $\tau_0$ in Pa)

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

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**Figure adapted from WINXSPro manual, USFS**
As discharge $Q$ increases, up goes the depth. Bed shear $\tau_o = \rho ghS$ increases also.

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

Incipient motion - critical discharge - flow competence
How fast will sediment move? By how much does $\tau_o$ exceed $\tau_c$?

The transport rate is transport capacity - match against rate of sediment supply

We have to calculate the flow – solve the flow problem – to find $\tau_o$ as a function of water discharge, channel geometry, and roughness. Sediment properties – and a transport model – gives us $\tau_c$, 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 $\tau_o$ exceed $\tau_c$?
Transport model:
Specified $\tau^*_c$

### Transport Rate
How fast do grains move?
By how much does $\tau_o$ exceed $\tau_c$?
Transport rate $= f(\tau_o - \tau_c)$

Big Deal: does $\tau_c$ refer to the BED or the SUPPLY???
The Shields Number $\tau^* = \frac{\tau_o}{(s-1)\rho g D}$ is a ratio of stress $\tau_o$ to grain size $D$. Both of which vary spatially ...
Some questions to ponder
in the field today, at each channel reach.

Think Shields Number.
What is critical stress of grains in the reach?
Use median size $D_{50}$ of the gravel bed material
and $\tau_c = 0.5 \times D_{50}$ ($D_{50}$ in mm)

What is the approximate shear stress from flow
at different flow depths?
Use $\tau_o = hS$ ($h$ in cm, $S$ in %)

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?

\[ \tau_c = \frac{\tau_c}{(\rho_s - \rho)gD} \approx 0.03 \]
\[ \tau_c = 0.5D \]
\[ \tau_o = \rho gRS \]
\[ \tau_o \approx \rho ghS \]
in a wide channel