Some General Sediment Concepts
July 30, 2018

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
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
   
   Hydraulics
   Incipient Motion

II. What is the sediment balance?
   
   **Transport Capacity** vs Sediment Supply
   
   Discharge $Q$
   Sediment Supply $Q_s$ & $D$
   Bed material $D$
   Channel Geometry
   
   Hydraulics
   Transport Capacity $Q_s$ & $D$

   $Input - Output = \Delta Storage$

   Surplus or Deficit?
   
   **Stored sediment** is the real geomorphic and restoration topic!
Lane/Borland Balance (USBR 1955-1960)

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

*Wash load is not just for mud!*
## Competence v. Capacity

<table>
<thead>
<tr>
<th>Flow Competence</th>
<th>Transport Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can a flow entrain the grains on the bed?</td>
<td>At what rate can a flow transport sediment?</td>
</tr>
<tr>
<td>Applied to the channel <strong>bed</strong></td>
<td>Compare to sediment <strong>supply</strong></td>
</tr>
<tr>
<td><em>Leads to a threshold channel</em></td>
<td><em>Leads to a mobile channel</em></td>
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</table>
Example channel problems – **competence or capacity?**

( ) Channel design: will a channel be able to transport the imposed sediment load with the available flow without substantial aggradation and degradation?

( ) Channel design: will the bed and banks of a canal remain intact at a design flow? What is the chance that the channel will need ‘repair’ in the next 10 yrs? 25 yrs?

( ) How much sediment do we need to add to restore streams below dams?

( ) How much flow is needed to mobilize >90% of the sediment on the bed surface, in order to flush fines from the subsurface?

( ) Can we mine sediment from the stream w/o causing downstream problems?

( ) Will the frequency of bed disturbance change with alterations to the flood regime? (changes in climate, land use, reservoir operation, fire)

( ) How will a channel respond to changes in water and sediment supply? How far downstream will changes occur? How long will it take? Can it be reversed or managed? (changes in climate, land use, or reservoir operation, fire, tributary floods)
Sediment Transport in Channel Design

- **Objective**
  - Sediment & nutrients
  - Property & infrastructure
  - Biological recovery
  - Aesthetic
  - Penance

- **What needs fixing?**
- Nothing
- Stormwater control
- Introduced species
- Channel change

- **Disturbance Internal or external?**
- Internal
- External
- Fence out the cows!
- Remove the concrete!
- Template approach can work

- **Small**
- Large

- **Channel Design**
  - Sediment supply large or small?

- **Estimate flood frequency**
- Design threshold channel
- Estimate sediment supply & flow duration
- Design alluvial channel

- **Alluvial Channel?**
- Threshold Channel?
- Other ???
A few slides about sediment
<table>
<thead>
<tr>
<th>Class Name</th>
<th>Size range</th>
<th>Size range</th>
<th>Approximate sieve mesh openings per inch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millimeters</td>
<td>Microns</td>
<td>Inches</td>
</tr>
<tr>
<td>Very large boulders</td>
<td>4096 ~ 2048</td>
<td></td>
<td>160 ~ 80</td>
</tr>
<tr>
<td>Large boulders</td>
<td>2048 ~ 1024</td>
<td></td>
<td>80 ~ 40</td>
</tr>
<tr>
<td>Medium boulders</td>
<td>1024 ~ 512</td>
<td></td>
<td>40 ~ 20</td>
</tr>
<tr>
<td>Small boulders</td>
<td>512 ~ 256</td>
<td>−9 ~ −8</td>
<td>20 ~ 10</td>
</tr>
<tr>
<td>Large cobbles</td>
<td>256 ~ 128</td>
<td>−8 ~ −7</td>
<td>10 ~ 5</td>
</tr>
<tr>
<td>Small cobbles</td>
<td>128 ~ 64</td>
<td>−7 ~ −6</td>
<td>5 ~ 2.5</td>
</tr>
<tr>
<td>Very coarse gravel</td>
<td>64 ~ 32</td>
<td>−6 ~ −5</td>
<td>2.5 ~ 1.3</td>
</tr>
<tr>
<td>Coarse gravel</td>
<td>32 ~ 16</td>
<td>−5 ~ −4</td>
<td>1.3 ~ 0.6</td>
</tr>
<tr>
<td>Medium gravel</td>
<td>16 ~ 8</td>
<td>−4 ~ −3</td>
<td>0.6 ~ 0.3</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>8 ~ 4</td>
<td>−3 ~ −2</td>
<td>0.3 ~ 0.16</td>
</tr>
<tr>
<td>Very fine gravel</td>
<td>4 ~ 2</td>
<td>−2 ~ −1</td>
<td>0.16 ~ 0.08</td>
</tr>
<tr>
<td>Very coarse sand</td>
<td>2000 ~ 1.000</td>
<td>−1 ~ 0</td>
<td>2000 ~ 1000</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>1000 ~ 0.500</td>
<td>0 ~ 1</td>
<td>1000 ~ 500</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.500 ~ 0.250</td>
<td>1 ~ 2</td>
<td>500 ~ 250</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.250 ~ 0.125</td>
<td>2 ~ 3</td>
<td>250 ~ 125</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.125 ~ 0.062</td>
<td>3 ~ 4</td>
<td>125 ~ 62</td>
</tr>
<tr>
<td>Coarse silt</td>
<td>0.062 ~ 0.031</td>
<td>4 ~ 5</td>
<td>62 ~ 31</td>
</tr>
<tr>
<td>Medium silt</td>
<td>0.031 ~ 0.016</td>
<td>5 ~ 6</td>
<td>31 ~ 16</td>
</tr>
<tr>
<td>Fine silt</td>
<td>0.016 ~ 0.008</td>
<td>6 ~ 7</td>
<td>16 ~ 8</td>
</tr>
<tr>
<td>Very fine silt</td>
<td>0.008 ~ 0.004</td>
<td>7 ~ 8</td>
<td>8 ~ 4</td>
</tr>
<tr>
<td>Coarse clay</td>
<td>0.004 ~ 0.002</td>
<td>8 ~ 9</td>
<td>4 ~ 2</td>
</tr>
<tr>
<td>Medium clay</td>
<td>0.002 ~ 0.001</td>
<td>2 ~ 1</td>
<td></td>
</tr>
<tr>
<td>Fine clay</td>
<td>0.001 ~ 0.0005</td>
<td>1 ~ 0.5</td>
<td></td>
</tr>
<tr>
<td>Very fine clay</td>
<td>0.0005 ~ 0.00024</td>
<td>0.5 ~ 0.24</td>
<td></td>
</tr>
</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>
<tbody>
<tr>
<td>Washload</td>
<td>Suspended load</td>
<td>?? uplands, banks, backwaters, …</td>
<td>Washload: (a) Transport not ‘predictable’ (b) too little in bed to affect transport of other fractions</td>
</tr>
<tr>
<td>clay, silt, <em>fine sand</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed Material – Fine</td>
<td>bed load or suspended load</td>
<td>Bed matrix: interstices, stripes dunes, subsurface</td>
<td>grain path in near-bed region dominated by larger grains; hard to sample &amp; model</td>
</tr>
<tr>
<td>bed load or suspended load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>med-crs sand, <em>pea gravel</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed Material – Coarse</td>
<td>bed load</td>
<td>Bed framework</td>
<td>displacements generally rare and hard to capture</td>
</tr>
<tr>
<td>bed load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>med-crs gravel, cobble</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed Material – Huge</td>
<td>immobile at typical high flows</td>
<td>Bed surface</td>
<td>Requires decision regarding grains to exclude from the transportable population</td>
</tr>
<tr>
<td>boulder</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We can classify transport by *mechanism* or *source*.
**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): \( \tau_0 \)  

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

Number of grains/area \( \propto \frac{1}{D^2} \)

Shields Number: \( \frac{\text{Flow Force}}{\text{Grain weight}} = \frac{\tau_0}{(s - 1) \rho g D} \equiv \tau^* \)

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 $S^*$

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

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

$D$ grain size; $\rho, \rho_s$ water, sediment density;
$g$ acceleration of gravity;
$\nu$ water viscosity

For $D > 4$ 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
How do we get this boundary shear $\tau_0$?

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

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

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

Boundary stress: $\tau_0$
(stresss is force/area)
Boundary force: $\tau_0PL$

$\tau_0PL = \rho gALS$
$\tau_0 = \rho gRS$
$\tau_0 = \rho ghS$

The ‘depth-slope’ product
As discharge $Q$ increases, up goes the depth. Bed shear $\tau_o \approx \rho ghS$ increases also.

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

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

Transport problem - determines transport rate

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 vs. 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** ???
Spatial variability: implications for **sampling** and **modeling**

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

In a quasi linear system

\[
\frac{\tau_s}{\tau_0} = \frac{(s-1)\rho g D}{\tau_0}
\]

The Shields Number, \( \tau_s \), is a ratio of stress \( \tau_0 \) 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 \( \tau_c = 0.5 \ D_{50} \)  \((D_{50} \text{ in mm})\)

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

Use \( \tau_o = hS \)  \((h \text{ in cm}, S \text{ in } \%))\)

What kind of flows might move the bed material?

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