Sediment Transport & Bulking Factors

Goals of this Session

• Review key principals
• Review basic relationships and available tools
• Review bulking factor relationships
Purposes of Sediment Transport Analysis

• Quantify capacity of the channel to transport sediment over range of anticipated flows
• Identify aggradation/degradation tendencies
• Quantify effect of transported sediment on flow volume
**Modes of Sediment-load Transport**

**WASH LOAD**
Composition: particles finer than those found in appreciable quantities in the bed. Washload moves in suspension and is provided by available bank and watershed supply.

**BED LOAD**
Composition: particle sizes typically found in the bed that move by surface creep, sliding, saltation or rolling within the bed layer.

**SUSPENDED BED MATERIAL LOAD**
Composition: particles typically found in the bed that remain in suspension during transport.

**TOTAL SEDIMENT LOAD**

**NOTE:**
The term "suspended load" is used when referring to the sum of the "wash load" and "suspended bed material load" components. Therefore, an alternate definition of total sediment load is the sum of the suspended load and bed load.
Bed Load Processes

Direction of shear due to decrease of velocity toward bed.

Tendency of velocity to roll an exposed grain.

Diagram of saltating grains.

Suggested motion of a grain thrown up into turbulent eddies in the flow.

From: Water in Environmental Planning by Dunne and Leopold

Fig. 2.14 -- Action of water on particles near the streambed.
Suspended Load vs Bed Load

- **Particle size**
  - particle fall velocity \( (w) \)
- **Hydraulic energy**
  - shear velocity \( (u_*) \)
- **Particle motion**: \( u_*/u_*c > 1 \)
- **Suspension**: \( u_* > w \)
Data Requirements

- Hydraulic conditions
- Sediment characteristics
## Bed Material Sampling

<table>
<thead>
<tr>
<th>Maximum Particle Size</th>
<th>Minimum Weight of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
</tr>
<tr>
<td>3-inch</td>
<td>6,000</td>
</tr>
<tr>
<td>2-inch</td>
<td>4,000</td>
</tr>
<tr>
<td>1-inch</td>
<td>2,000</td>
</tr>
<tr>
<td>1/2-inch</td>
<td>1,000</td>
</tr>
<tr>
<td>&lt; No. 4 sieve</td>
<td>200</td>
</tr>
<tr>
<td>&lt; No. 10 sieve</td>
<td>100</td>
</tr>
</tbody>
</table>
Jan 2008 Sample Locations
### Bed Material Size Trends in SCAFCA Area

Upstream to downstream order by arroyo

<table>
<thead>
<tr>
<th></th>
<th>Calabacillas</th>
<th>Montoyas</th>
<th>Lomitas Negras</th>
<th>Barranca</th>
<th>Venada</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Size (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D84</td>
<td>D16</td>
<td>- D50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Particle Size (mm):**
- 100
- 10
- 1
- 0.1
- 0.01
Incipient Motion

\[ \tau_c = F^* (\gamma_s - \gamma) D_i \]

\[ F^* = \text{Shields Dimensionless Shear} \]

\[ 0.03 < F^* < 0.047 \]

Equal Mobility Concept
Bed Shear Stress

\[ \tau_0 = \gamma RS \]

\[ \tau_0 = \frac{f \rho V^2}{8} \]
Shear Partitioning

- **Grain Shear:** \( \tau' = \gamma R' S \)
  - \( R' \) from fluid mechanics using Equation B.3
- **Shear due to form resistance:** \( \tau'' = \gamma R'' S \)
- **Total Shear:** \( \tau = \gamma R S \cong \gamma (R'+R'') S \)
Armoring Potential

\[ Y_s = y_a \left( \frac{1}{P_c} - 1 \right) \]

Diagram:
- Original Steambed
- \( D_c \)
- \( Y_s \)
- \( y_3 \) = (2 to 3) \( \times \) \( D_c \)

Equations:
- \( P_c = \text{Percent Coarser} \div 100 \)
- \( y_3 = (2 \text{ to } 3) \times D_c \)
Bed Material Transport Capacity
Available Equations/Tools

• MPM-Woo
• Zeller-Fullerton
• HEC-RAS 4.0
• SAM
Diffusion Equation

General Form

\[ \varepsilon_s \frac{\partial C}{\partial y} + C(1 - C)W_s = 0 \]

@ Low Concentrations

\[ \varepsilon_s \frac{\partial C}{\partial y} + CW_s = 0 \]
Suspended Sediment Concentration Profiles

**Rouse (1937):**

\[
\frac{C}{C_a} = \left[ \frac{d-y}{y} \left( \frac{a}{d-a} \right) \right]^z
\]

\[
z = \frac{W_s}{\beta ku^*}
\]
Suspended Sediment Concentration Profiles from (Woo, 1983)
Application of Woo (1983) Solution

• Bed load from Meyer-Peter, Muller
• Fall velocity modified by Maude and Whitmore (1958):
  \[ W_p = \omega_p (1 - C)^\alpha \]
• Viscosity modified by O’Brien and Julien (1988):
  \[ \mu = \alpha e^{\beta C_v} \]
Application of Woo (1983) Solution

- Power-law velocity profile
- Reference concentration at bed layer from Karim and Kennedy (1983):

\[ \tau_{bl} = D_{50} \frac{u^*}{u^*_c} \]

- Limitations in computation procedure:
  - Reference concentration < 650,000 ppm
  - Total concentration < 510,000 - 65,000D_{50}
The MPM-Woo Equation

\[ Q_s = a V^b D^c (1 - C_f) d \]
### The MPM-Woo Equation

**Range of Applicability**

<table>
<thead>
<tr>
<th>Unit Discharge (cms/m)</th>
<th>Velocity (m/s)</th>
<th>Depth (m)</th>
<th>Gradient</th>
<th>Fine Sediment Concentration (ppm)</th>
<th>D$_{50}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.6</td>
<td>0.1</td>
<td>0.005</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>7.4</td>
<td>6.3</td>
<td>2.2</td>
<td>0.04</td>
<td>60,000</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Effect of $C_f$**

![Graph showing the effect of $C_f$ on $(1-C_f)d$](MEI)

D$_{50}$(mm) values for different $C_f$ values:
- **0.2**
- **0.3**
- **1.0**
- **1.5**
- **4.0**
Validation Data

Yellow Canyon (Site 15)

Coal Mine Wash
Validation Data

Yellow Canyon (Site 15)

Coal Mine Wash

Water Discharge (CMS)

Range of Measured Data

Estimated Transport Rate

Bed Material Discharge (Metric Tons/Day)
Sediment Bulking

- Mudflow (2)
- Mudflow (1)
- Mud Flood (3)
- Mud Flood (2)
- Mud Flood (1)
- Water flood

Typical conditions in SSCAFCA Arroyos

Graph showing bulking factor vs. concentration for various flood types (by weight and by volume).
Bulking Factors

\[ B_f = \frac{Q + Q_{total}}{Q} = 1 - \frac{1}{C_s / 10^6} \left( S_g - \left( \frac{C_s}{10^6} \right) (S_g - 1) \right) \]

where
- \( B_f \) = bulking factor
- \( Q \) = clear-water discharge
- \( Q_{total} \) = total sediment load (i.e., combination of bed material and wash load)
- \( C_s \) = total sediment concentration by weight
- \( S_g \) = specific gravity of the sediment
### Recommended Bulking Factors for Q_{100}

<table>
<thead>
<tr>
<th>Median (D50) Bed Material Size (mm)</th>
<th>Bulking Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.00</td>
</tr>
<tr>
<td>0.15</td>
<td>1.05</td>
</tr>
<tr>
<td>0.20</td>
<td>1.10</td>
</tr>
<tr>
<td>0.25</td>
<td>1.15</td>
</tr>
</tbody>
</table>

**Dominant Discharge (Q_d):**
- 50 cfs
- 100 cfs
- 250 cfs
- 500 cfs
- 1000 cfs

**Upper size-limit of applicability**

**Median (D50) Bed Material Size (mm) vs. Bulking Factor**

Diagram showing the relationship between median bed material size and bulking factor for different discharge rates (50, 100, 250, 500, and 1000 cfs). The diagram highlights the upper size-limit of applicability for each discharge rate.
### Table 3.5: Estimated Sediment Bulking Factors for Other Events

<table>
<thead>
<tr>
<th>Recurrence Interval (yrs)</th>
<th>Dominant Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;50&lt;/sub&gt; (mm) = 0.5 mm</strong></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
</tr>
<tr>
<td>5</td>
<td>1.02</td>
</tr>
<tr>
<td>10</td>
<td>1.03</td>
</tr>
<tr>
<td>25</td>
<td>1.05</td>
</tr>
<tr>
<td>50</td>
<td>1.07</td>
</tr>
<tr>
<td>100</td>
<td>1.08</td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;50&lt;/sub&gt; (mm) = 1.0 mm</strong></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
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<tr>
<td>5</td>
<td>1.01</td>
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<tr>
<td>10</td>
<td>1.01</td>
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<tr>
<td>25</td>
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<tr>
<td>50</td>
<td>1.02</td>
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<tr>
<td>100</td>
<td>1.03</td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;50&lt;/sub&gt; (mm) = 1.5 mm</strong></td>
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<tr>
<td>2</td>
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<tr>
<td>50</td>
<td>1.01</td>
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<tr>
<td>100</td>
<td>1.02</td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;50&lt;/sub&gt; (mm) = 2.0 mm</strong></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
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<tr>
<td>5</td>
<td>1.01</td>
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<tr>
<td>10</td>
<td>1.01</td>
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<tr>
<td>25</td>
<td>1.01</td>
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<tr>
<td>50</td>
<td>1.01</td>
</tr>
<tr>
<td>100</td>
<td>1.01</td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;50&lt;/sub&gt; (mm) = 3.0 mm</strong></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
</tr>
<tr>
<td>5</td>
<td>1.01</td>
</tr>
<tr>
<td>10</td>
<td>1.01</td>
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<td>25</td>
<td>1.01</td>
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<tr>
<td>50</td>
<td>1.01</td>
</tr>
<tr>
<td>100</td>
<td>1.01</td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;50&lt;/sub&gt; (mm) = 4.0 mm</strong></td>
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<tr>
<td>2</td>
<td>1.01</td>
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<td>10</td>
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<td>25</td>
<td>1.01</td>
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<tr>
<td>50</td>
<td>1.01</td>
</tr>
<tr>
<td>100</td>
<td>1.01</td>
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</tbody>
</table>
Sediment Transport Workshop
The watershed upstream of the location analyzed in the previous problems has the following characteristics:

- Drainage area = 370 acres
- Watershed soil type: 52% Rock outcrop, Orthids Complex (ROF) 48% Tesajo-Millett (Te)
- Percent impervious (roads, roofs, etc.) = 9.5%
- Average overland slope = 25%
- Average slope length = 100 feet
- Rangeland, grass-like plants, 10% ground cover, no canopy
- 100-year storm runoff volume = 40.2 ac-ft
Fine Sediment Yield
Example Problem #1

1. Compute fine sediment yield from the watershed using MUSLE:

\[ Y_S = C \times 95 \left( V_w \times Q_p \right)^{0.56} \times K \times LS \times C \times P \]

where C is a calibration factor (for the SSCAFCA jurisdictional area, use 3.0, unless data are available indicating a more appropriate value).
Fine Sediment Yield
Example Problem #1

Estimate K from Table A.2.1 (see also SCS, 1992):
for Te use 0.1 - very gravelly, sandy loam and loamy sand
for ROF use 0.0 (Rock outcrop 40%, Orthids 30%)
Compute weighted K:

\[
K' = \left( \frac{A_{ROF} K_{ROF} + A_{T\theta} K_{T\theta}}{A_{total}} \right) = \frac{0.52(0) + 0.48(0.1)}{1.0} = 0.048
\]

Estimate C value from Table A.2.2:

\[C = 0.32\]

P = 1.0 (no terracing)

Estimate LS using Equation A.3:
Fine Sediment Yield
Example Problem #1

\[ \text{LS} = \left( \frac{\lambda}{72.6} \right)^n \left( 0.065 + 0.0454S + 0.0065S^2 \right) \]

\[ = \left( \frac{100}{72.6} \right)^{0.5} \left[ 0.065 + 0.0454(9.45) + 0.0065(9.45)^2 \right] \]

\[ = 2150 \text{ tons fine sediment} \]

This result assumes 100% of the watershed is pervious. Adjust for given percent impervious:

\[ Ys' = (1 - \% \text{ impervious}) \ Ys = (1 - 0.095) \ (2150) = 1946 \text{ tons} \]
2. Compute average fine sediment concentration from watershed for the 100-year storm:

\[ C_f \ (ppm) = 10^6 \ \frac{W_s}{W_w + W_s} \]

\[ = 10^6 \ \frac{1946 \ (2000)}{[(40.5 \times 43560 \times 62.4) + (1946 \times 2000)]} \]

\[ = 34,147 \ ppm - w \]
Compute the bed material transport capacity, total sediment load and bulking factors for the peak of the 100-year storm, for the arroyo in the previous problems.

1. Compute bed material transport capacity at $Q_{100} = 1,045$ cfs using Equation C.3.

From Figure C.2:
- $a' = 1.5 \times 10^{-6}$
- $b = 5.8$
- $c = -0.7$
- $d = -1.9$

From hydraulics example problem:
- $V_{100} = 13.4$ fps
- $y_{100} = 2.0$ feet
- $W = 39$ feet

Assume constant fine sediment yield throughout the storm:
- $C_f = 34,147$ ppm-w
Bed Material and Total Sediment Load: Example Problem #1

Apply Equation C.3:

\[ q_s = a' V^b y^c (1 - \frac{C_f}{10^6})^d \]

\[ = 1.5 \times 10^{-6} (13.4)^{5.8} (2.0)^{-0.7} \left( 1 - \frac{34,147}{10^6} \right)^{-1.9} = 3.40 \text{ cfs/ft} \]

\[ Q_s = q_s W \]

\[ = (3.40)(39) = 132.6 \text{ cfs} \]
2. Compute the bed material concentration.

From Equation C.5:

\[ C_s = \frac{2.65 \times 10^6 Q_s}{(Q + 2.65 Q_s)} \]

\[ = \frac{2.65 \times 10^6 (132.6)}{1045 + 2.65(132.6)} \]

\[ 251,642 \text{ ppm} - w \]
Bed Material and Total Sediment Load: Example Problem #3

3. Compute the total sediment load. \( (Q_f) \):

Compute the wash load discharge

\[
Q_f = \left( \frac{Q}{2.65} \right) \left( \frac{C_f}{10^6 - C_f} \right)
\]

(rearranging C.7)

\[
= \left( \frac{1045}{2.65} \right) \left( \frac{34,147}{10^6 - 34,147} \right) = 13.9 \text{ cfs}
\]

\[
Q_{sTotal} = Q_s + Q_f
\]

\[
= 132.6 + 13.9 = 146.5 \text{ cfs}
\]
4. Compute the total sediment concentration, bulking factor, and bulked peak discharge.

\[ C_{S_{Total}} = \frac{2.65 \times 10^6 \ Q_{S_{Total}}}{(Q + 2.65 \ Q_{S_{Total}})} \]

\[ = \frac{2.65 \times 10^6 \ (146.5)}{1045 + 2.65 \ (146.5)} \]

\[ = 270,875 \ ppm \ ~ w \]
Bed Material and Total Sediment Load: Example Problem #4

\[ BF = \frac{1}{1 - \frac{C_{s, Total} / 10^6}{2.65 - \left(\frac{C_{s, Total} / 10^6}{10^6}\right)(S - 1)}} \]

\[ = \frac{1}{1 - \frac{270,875 / 10^6}{2.65 - \frac{270,875}{10^6}(2.65 - 1)}} = 1.14 \]

\[ Q_{P, bulked} = BF \cdot Q_P \]
Annual Sediment Yield

The following total sediment yield results were obtained by integrating the bed-material transport capacity and adding the fine sediment for each storm.

<table>
<thead>
<tr>
<th>Return Period (years)</th>
<th>Water Yield (ac-ft)</th>
<th>Total Sediment Yield (tons)</th>
<th>Unit Sediment Yield (tons/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>40.2</td>
<td>6,142</td>
<td>16.6</td>
</tr>
<tr>
<td>50</td>
<td>33.8</td>
<td>4,863</td>
<td>13.1</td>
</tr>
<tr>
<td>25</td>
<td>27.5</td>
<td>3,774</td>
<td>10.2</td>
</tr>
<tr>
<td>10</td>
<td>19.4</td>
<td>2,413</td>
<td>6.5</td>
</tr>
<tr>
<td>5</td>
<td>13.7</td>
<td>1,559</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>7.1</td>
<td>668</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Compute the mean annual water and sediment yields.
Annual Sediment Yield
Example Problem

From Equation 3.26:

\[ Y_{x \text{ Annual}} = 0.015 Y_{x \text{100}} + 0.015 Y_{x \text{50}} + 0.04 Y_{x \text{25}} + 0.08 Y_{x \text{10}} + 0.20 Y_{x \text{5}} + 0.40 Y_{x \text{2}} \]

where \( x \) = Either the total sediment or water yield.

(1) Water yield:

\[ Y_{w a} = 0.015 (40.2) + 0.015 (33.8) + 0.04 (27.5) + 0.08 (19.4) + 0.2 (13.7) + 0.4 (7.1) \]

\[ = 9.34 \text{ ac – ft} \]

Sediment yield:

\[ Y_{s a} = 0.015 (6142) + 0.015 (4863) + 0.04 (3774) + 0.08 (2413) + 0.2 (1559) + 0.4 (668) \]

\[ = 1088 \text{ tons} \]
Annual Sediment Yield
Example Problem

Unit sediment yield:

\[ Y_{sa} = \frac{1088}{370} = 2.94 \text{ tons/acre} \]

\[ = 2.94/3.4^* = 0.86 \text{ ac - ft/mi}^2 \]

(*assuming bulked unit weight of 100 pcf, see Constants and Conversions)