SEDIMENT TRANSPORT RATES DURING UNSTEADY FLOW EVENTS

Joanna Crowe Curran, Ph.D. and Kevin A. Waters, Ph.D.
Goals

• Quantify impact of repeated unsteady flows on sediment yield, transport rate, and bed structure

• Connect unsteady flow induced hysteresis with sediment yield, transport rates, and bed structure

• Adjust sediment transport models for hysteresis during unsteady flows

Channel bed adjusts under steady, low flow

Sediment transport alters bed surface

Unsteady, flood flow occurs

Hysteresis affects sediment transport
Unsteady Flow Experiments

Developed from the NRCS curvilinear dimensionless unit hydrograph

Hydrograph work and unsteadiness both varied over an order of magnitude

30% gravel / 70% sand
D₅₀ = 0.55 mm

70% sand/ 30% silt
D₅₀ = 0.27 mm
Sediment transport hysteresis

Sand / Gravel (7)
- Clockwise
- Figure 8
- Counter-Clockwise
- None

Sand / Silt (12)
- Clockwise
- Figure 8
- Counter-Clockwise
- Single-value + Loop
Sand/Gravel Bed Structure

**Low flow hydrographs**
- Surface sand content decreased by 14%
- No bedforms

**High flow hydrographs**
- Surface sand content increased by 18%
- Limited bedforms
Sand/Silt Bed Structure

Surface sand and bedform steepness increased with successive hydrographs

Low flow hydrographs
• Ripples formed

High flow hydrographs
• Ripples and patches developed
Hysteresis and Sediment Yield

Combine flow data with channel width and $D_{50}$ to estimate sediment yield

$$Y_s^* = 22762 \left[ \frac{h_p (h_p - h_o) U_{*o} U}{D_{50} t_d g h_o^3 B} \right]^{1.072}$$
Hysteresis and Sediment Transport Rate

1. Using estimates of bed slope and depth during the flow, separate data from rising and falling limbs of the hydrograph
2. Calculate \( \tau \)
3. With grain size, convert to \( \tau^* \)
4. Use in Parker-Einstein equation with \( W^* = 0.002 \) to find \( \tau^*_r \)
5. With \( \tau^*, \tau^*_r, \) velocity, depth, and bed slope, calculate \( q_s \)
Connect Bed Structure with Transport

\[ \tau^*_rs \]

Sand/Gravel

Sand/Silt

White boxes: rising limb only
Grey boxes: falling limb only
Diamonds: total hydrograph

Clockwise

Counter-Clockwise

Clockwise

Counter-Clockwise
Transport Equations: Sand/Silt Sediment

<table>
<thead>
<tr>
<th>Equation</th>
<th>0.5 ≤ DR ≤ 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ackers-White (1973)</td>
<td>33%</td>
</tr>
<tr>
<td>Einstein and Brown (1950)</td>
<td>19%</td>
</tr>
<tr>
<td>Engelund and Hansen (1967)</td>
<td>39%</td>
</tr>
<tr>
<td>Laursen (1958)</td>
<td>49%</td>
</tr>
<tr>
<td>Van Rijn (1984)</td>
<td>42%</td>
</tr>
<tr>
<td>Yang (1973)</td>
<td>58%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equation</th>
<th>0.5 ≤ DR ≤ 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method Calculating Rising and Falling Limbs Separately</td>
<td>68%</td>
</tr>
</tbody>
</table>

Equation 0.5 \(\equiv DR \equiv 2.0\)

Ackers-White (1973) - 33%

Einstein and Brown (1950) - 19%

Engelund and Hansen (1967) - 39%

Laursen (1958) - 49%

Van Rijn (1984) - 42%

Yang (1973) - 58%

New method with RL and FL separated - 68%

Greater under-prediction at low flows

Measures vs Predicted q_s (g/m/s)

- Yang, 1973
- New method with RL and FL separated
Transport Equations: Sand/Gravel Sediment

<table>
<thead>
<tr>
<th>Equation</th>
<th>0.5 ≤ DR ≤ 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einstein and Brown (1950)</td>
<td>22%</td>
</tr>
<tr>
<td>Ackers-White (1973)</td>
<td>33%</td>
</tr>
<tr>
<td>Yang (1973, 1984)</td>
<td>33%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equation</th>
<th>0.5 ≤ DR ≤ 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method Calculating Rising and Falling Limbs Separately</td>
<td>68%</td>
</tr>
</tbody>
</table>

1.08 kg/m/s . . . On a river 5 m wide (16.4 ft) over 15 minutes of full sediment mobility, this is 4890 kg / 10,780 pounds / 5.4 tons
Impact of Unsteady Flows

Unsteady flow alters the bed surface structure

- Bedforms develop and sediment yield increases
- Surface fines or coarsens
- Structure develops over successive hydrographs

Accounting for hysteresis improves sediment yield and transport rate predictions, especially at low flows

- Transport rates vary with hydrograph limb creating hysteresis

Reference shear stresses adjust with changes in bed surface and slope
What is ‘good enough’ in sediment transport?

Only need an estimate of the amount of sediment that will be / has been moved during a storm?
– Use storm variables (depth, velocity, duration), channel width, and bed $D_{50}$ to predict yield for the event

Have a sand bed and ok with half transport estimates between 0.5-2 times actual and not concerned with low flow rates? Have a gravel and sand bed and ok with 1/3 between 0.5-2 times actual?
– Use the standard sediment transport equations

Is there sensitive habitat or infrastructure and a need to evaluate bed structure response to a storm? Want to do better?
– Spend the time to calculate transport rates over hydrograph rising and falling limb separately
  ~70% within 0.5-2 times actual
  not consistently overpredicting gravel/sand transport
Questions

jcurran@nhcweb.com
kevin.waters@email.virginia.edu

Watch for the paper:

Road surface