Development and testing of improved physically based streambank erosion and sediment routing routines in SWAT

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Outline

- Channel Erosion
- Sediment Routing
  - In SWAT2000 and SWAT2005
- Physically based approach
  - Erosion
  - Transportation
  - Deposition
- Field monitoring and model results
Channel Erosion

Channel erosion

- Can account for as much as 85% of total sediment yield of a watershed

Predicted loss in 3 km channel erosion = 1000 years of sheet and rill erosion at pre-conservation agriculture rates
Channel Erosion

Three major processes

- **Subaerial processes**
  - Climate
  - Alternate wet and dry cycles
  - Freeze/Thaw cycles
  - Cracking

- **Fluvial erosion (Hydraulic Erosion)**
  - Removal of particles by streamflow

- **Bank Failure**
  - Caused due to slope instability
Simplified Bagnold stream power equation

\[ conc_{sed,mx} = spcon \times v_{ch}^{sp_{exp}} \]

\[ sed_{deg} = (conc_{sed,mx} - conc_{sed,ch})V_{ch} K_{ch} C_{ch} \]

Channel erosion

- limited only by the stream power or transport capacity
- but not by limits on sediment supply from the actual erosion process
SWAT2000 and 2005

- No particle size distribution of eroded sediment
- No bedload

  - Hence, TSS calculated from sediment yield is often high and not directly comparable with observations
Organic nutrient load

Are we missing to quantify a significant organic nutrient load from stream bank and attributing the nutrient loads only to overland?

Cedar Creek, Texas

- 8% of orgN and
- 15% of orgP from channel erosion
- Channel erosion – 35% of total sediment yield

Hence, accurate quantification of channel erosion is very important
Complex Process: Simplify

Soil Zone
Slake Zone
Bed Load
Rock Zone
Fluvial Erosion Process

For the erosion to occur

- There should be enough shear stress exerted by the flowing water on stream bank and stream bed to dislodge the sediments
- The channel should have enough stream power to carry the eroded sediments (overland+channel)
- Deposition will occur if the sediment transport capacity is low
Wash-load particle size distribution

Sediment yield from overland (MUSLE) is partitioned using the approach used in CREAMS

\[ PSA = (SAN)(1 - CLA)^{2.4} \]

\[ PSI = 0.13SIL \]

\[ PCL = 0.20CLA \]

\[ SAG = \begin{cases} 2.0CLA & \text{for } CLA < 0.25 \\ 0.28(CL - 0.25) + 0.5 & \text{for } CLA \geq 0.25 \text{ and } CLA \leq 0.5 \\ 0.57 & \text{for } CLA > 0.5 \end{cases} \]

\[ LAG = 1.0 - PSA - PSI - PCL - SAG \]
Stream bank/bed erosion load particle distribution

Channel bank and bed D50
**Shear Stress**

- **Critical shear stress** ($\tau_c$)
  - Soil parameter that governs erosion

- Erosion based on excess shear stress:

  \[
  \xi_{\text{bank}} = k_{d,\text{bank}} \cdot (\tau_{e,\text{bank}} - \tau_{c,\text{bank}})^a \cdot 10^{-6}
  \]

  \[
  \xi_{\text{bed}} = k_{d,\text{bed}} \cdot (\tau_{e,\text{bed}} - \tau_{c,\text{bed}})^a \cdot 10^{-6}
  \]

  where $\xi$ – erosion rates of the bank and bed (m/s), $k_d$ – erodibility coefficient of bank and bed (cm$^3$/N-s) and $\tau_c$ – Critical shear stress acting on bank and bed (N/m$^2$).
Critical Shear Stress and Erodibility Coefficient

Submerged Jet Test (Hanson and Cook, 1997; Hanson and Simon, 2001)

- Erodibility calculated as a function of jet index

\[ k = 0.003e^{3.85J_i} \]

- \( J_i \) – Jet index (depth of scour hole made by the jet)

\[ \tau_c = 0.16(I_w)^{0.84} \]

- \( I_w \) – Plasticity Index
Empirical Equation for $\tau_c$

Critical Shear Estimates

**Soil Composition**

- Equation: $y = 0.1 + 0.1779x + 0.0028x^2 - 2.34E-5x^3$
- $n = 16$
- $r^2 = 0.91$
- $p < 0.001$

**Vegetation**

<table>
<thead>
<tr>
<th>Type / Density</th>
<th>$\tau_c$ Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>1</td>
</tr>
<tr>
<td>Ivy / Sparse</td>
<td>1.5</td>
</tr>
<tr>
<td>Ivy / Dense</td>
<td>2.5</td>
</tr>
<tr>
<td>Privet / Sparse</td>
<td>5.4</td>
</tr>
<tr>
<td>Privet / Dense</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Range mostly between: 0 and 100 N/m$^2$
But could go as High as 400 N/m$^2$

Julian and Torres, 2001

data from Dunn (1959)  
derived from Huang and Nanson (1998)
Shear Stress

Effective shear stress based on channel hydraulics: (Eaton and Millar, 2004)

\[ \frac{\tau_{e,\text{bank}}}{\gamma \cdot \text{depth} \cdot \text{slp}_{\text{ch}}} = \frac{SF_{\text{bank}}}{100} \left( \frac{(W + P_{\text{bed}}) \cdot \sin \theta}{4 \cdot \text{depth}} \right) \]

\[ \frac{\tau_{e,\text{bed}}}{\gamma_{w} \cdot \text{depth} \cdot \text{slp}_{\text{ch}}} = \left( 1 - \frac{SF_{\text{bank}}}{100} \right) \left( \frac{W}{2 \cdot P_{\text{bed}}} + 0.5 \right) \]

\[ \log SF_{\text{bank}} = -1.4026 \cdot \log \left( \frac{P_{\text{bed}}}{P_{\text{bank}}} + 1.5 \right) + 2.247 \]
Empirical Equation for $K_d$

**Erodibility Coefficient, $K_d$:** (Temple and Hanson, 1994; Zhu et al. 2006)

$$K_d = 0.0034 \cdot \exp \left( \frac{0.0176}{M_e} \right)$$

$$M_e = \frac{\left( (s-1) \cdot 9.8 \cdot D_{50} \right)^{0.5}}{(s-1)^3 \cdot C}$$

$$C = 4.14 \cdot (Clay\%)^{-0.91}$$

Where $s$ is relative density of sediment

Range mostly between 0 and 0.01 cm$^3$/N-s but could go as high as 3.75 cm$^3$/N-s for highly erodible material
Stream Power/Transport Capacity

Four new transport equations

- Simplified Bagnold Equation
  - Silt type bed material
  \[ \text{conc}_{sed, mx} = spcon \times v_{ch}^{sp_{exp}} \]

- Kodatzie model
  - Silt to gravel size bed materials

- Molinas and Wu model
  - Large sand bed rivers

- Yangs sand and gravel model
  - Sand and gravel bed material
Kodatie Model

Kodatie (2000)

\[
\text{conc}_{sed, ch, mx} = \left( \frac{a \cdot v_{ch}^b \cdot y^c \cdot S^d}{Q_{in}} \right) \cdot \left( \frac{W + W_{btm}}{2} \right)
\]

a, b, c and d coefficients depend on \(D_{50}\)

**Table 7.2-2. Regression coefficients for Kodatie equation**

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt-bed rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>((D_{50}) * ≤ 0.05 mm)</td>
<td>281.4</td>
<td>2.622</td>
<td>0.182</td>
<td>0</td>
</tr>
<tr>
<td>Very fine to fine-bed river</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.05 mm &lt; (D_{50}) ≤ 0.25 mm)</td>
<td>2,829.6</td>
<td>3.646</td>
<td>0.406</td>
<td>0.412</td>
</tr>
<tr>
<td>Medium to very coarse sand-bed rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.25 mm &lt; (D_{50}) ≤ 2 mm)</td>
<td>2,123.4</td>
<td>3.300</td>
<td>0.468</td>
<td>0.613</td>
</tr>
<tr>
<td>Gravel-bed rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>((D_{50}) &gt; 2mm)</td>
<td>431,884.8</td>
<td>1.000</td>
<td>1.000</td>
<td>2.000</td>
</tr>
</tbody>
</table>

\*\(D_{50}\) – median bank/bed-sediment size
Molinas and Wu Model

\( \text{Molinas and Wu (2001):} \)

\[
C_w = \frac{1430 \cdot (0.86 + \sqrt{\psi}) \cdot \psi^{1.5}}{0.016 + \psi} \cdot 10^{-6}
\]

\[
\psi = \frac{v_{ch}^3}{(S_g - 1) \cdot g \cdot \text{depth} \cdot \omega_{50} \cdot \left[ \log_{10} \left( \frac{\text{depth}}{D_{50}} \right) \right]^2}
\]

\[
\omega_{50} = \frac{411 \cdot D_{50}^2}{3600}
\]

\[
\text{conc}_{sed, ch. mx} = \frac{C_w}{C_w + (1 - C_w) \cdot S_g} \cdot S_g
\]
**Yangs Sand and Gravel Model**

Sand equation: \((D_{50} \text{ less than } 2\text{mm})\):

\[
\log C_w = 5.435 - 0.286 \log \left( \frac{\omega_{50} D_{50}}{v} \right) - 0.457 \log \left( \frac{V^*}{\omega_{50}} \right) \\
+ \left( 1.799 - 0.409 \log \left( \frac{\omega_{50} D_{50}}{v} \right) - 0.314 \log \left( \frac{V^*}{\omega_{50}} \right) \right) \log \left( \frac{V_{ch} S}{\omega_{50}} - \frac{V_{cr} S}{\omega_{50}} \right)
\]

Gravel equation: \((D_{50} \text{ between } 2\text{mm and } 10\text{mm})\):

\[
\log C_w = 6.681 - 0.633 \log \left( \frac{\omega_{50} D_{50}}{v} \right) - 4.816 \log \left( \frac{V^*}{\omega_{50}} \right) \\
+ \left( 2.784 - 0.305 \log \left( \frac{\omega_{50} D_{50}}{v} \right) - 0.282 \log \left( \frac{V^*}{\omega_{50}} \right) \right) \log \left( \frac{V_{ch} S}{\omega_{50}} - \frac{V_{cr} S}{\omega_{50}} \right)
\]
Selecting the appropriate model

<table>
<thead>
<tr>
<th>Model</th>
<th>Gravel</th>
<th>Sand</th>
<th>Very Fine sand and silt</th>
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</thead>
<tbody>
<tr>
<td>Bagnold</td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>Kodatie</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Molinas and Wu</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Yangs</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Deposition

If the sediment concentration in the channel is more than the transport capacity then deposition occurs:

Einstein equation (1965):

\[ Dep_{frac} = \left(1 - \frac{1}{e^x}\right) \]

\[ x = \frac{1.055 \cdot L_{ch} \cdot \omega_{50}}{v_{ch} \cdot depth} \]

\[ \omega_{50} = \frac{411 \cdot D_{50}^2}{3600} \]

Flood plain deposition

If the streamflow goes overbank
Excess transport capacity

\[ \text{SedEx} = V_{ch} \cdot (\text{conc}_{sed, ch. mx} - \text{conc}_{sed, ch. i}) \]

- Excess sediment beyond transport capacity is also deposited.
- But the channel is eroded only based on excess shear stress and not the available transport capacity.
  - Bank scour always occurs when excess shear stress is available.
  - Bed scour occurs only after all the deposited bed materials are scoured.
Study Area

Kings Creek Watershed
Figure 8. Photograph of the upper and lower bank erosion pin locations shown in yellow, spaced 1 m apart after Zaines et al. 2005.
Field Data Collection

- Stage height
- Erosion rate (mm/event)
- Channel dimension
- Particle size distribution
- Submerged jet test
  - Erodibility
- Period: 2007
Width

\[ y = 1.8091x^{0.3549} \]
\[ R^2 = 0.5384 \]

Depth

\[ y = 1.0622x^{0.2763} \]
\[ R^2 = 0.6326 \]
Flow Calibration (1971-1987)
$R^2$: 0.67
$NSE$: 0.65
$RMSE$: 13.61 m³/s
Pred. Mean: 4.78 m³/s
Obs. Mean: 4.50 m³/s
Flow Validation (2007)
Model Inputs

- Default model
  - spcon, spexp, CH_cov, CH_Erod

- Physically based models
  - D50 – Median particle size of bank and bed material
  - Cover factor of bank and bed
  - Critical shear stress of bank and bed
    - If not given, calculated based on SC% and cover
  - Erodibility coefficient of bank and bed
    - If not given, calculated based on SC%
  - Bulk density of bank and bed
    - If not given, calculated based on SC%
  - Particle size distribution of bank and bed material
    - Assumed based on the D50 size
Model Output

- File name: output.sed
- Default
  - Total sediment
  - Bed erosion, deposition, TSS
- Physically based models
  - Total sediment
    - Sand, silt, clay, SAGG, LAGG, gravel
  - Bank erosion
  - Bed erosion
  - Channel deposition / Flood plain deposition
    - Total remaining in deposits at the end of the time step
  - TSS
    - Only based on silt and clay particles
Conclusion

- Already most of the code is available in the present release
- Few changes are being made to represent the mass balance in a better way
- Detailed calibration and validation study is underway to evaluate the new routines

New Components
- Active channel eroding length based on channel sinuosity
- Effect of alternate wetting and drying on erodibility
Thank You