Development Efforts in Soil Hydrology and Instream Water Quality

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https://engineering.purdue.edu/ecohydrology
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• Support from Kiel University for data collection
• Model developments are required to:
  – *improve confidence in the model*
  – *provide representative predictions*

• Potential for improving various landscape and channel processes
Objectives

To improve two key processes in SWAT model:

1) Soil water hydrology
   - Climate
   - Hydrology
   - Soil Moisture
   - Nutrients
   - Plants

   Critical linking process in water quality predictions, but dynamics have limited representation

2) Instream water quality

   Need to refine water quality algorithms in SWAT (Migliaccio et al., 2006; Gassman et al., 2007)
1. Soil Water Hydrology
Soil Water Modeling Approaches

1) Bucket Approach
- Threshold function
- Simple, efficient
- Ignores some conditions
- Ex: WEPP, SWAT

2) Richard’s Equation
- Physically based
- Numerical solutions
- Captures all conditions
- Ex: HYDRUS, MIKE-SHE
Modified Soil Hydrology Approach

Darcy’s Law

\[ q = \frac{Q}{A} = K(h) \times \frac{dh}{dl} \rightarrow \text{Assume constant downward flow} \rightarrow q \approx K(\theta) \]

Hydraulic Conductivity

\[ K(\theta) = f(\theta)^b \rightarrow \text{Parameterize} \]

Key = Equations based on Relative Saturation

- **Campbell 1974 (CA)**
  \[ K(\theta) = K_{sat} (\theta/\theta_{sat})^{3+2b} \]

- **van Genuchten 1980 (VG)**
  \[ K(\theta) = K_{sat}(\theta/\theta_{sat})^{1/2}\{1-[(\theta/\theta_{sat})^{1/m}]^{m}\}^2 \]

**Compare to default**
- Uncalibrated
- 8 years (‘07-14)
Experimental Watersheds

Sensor Depths
CCW: 5, 20, 40, 60 cm
LRW: 5, 20, 30 cm

Cedar Creek Watershed
Little River Watershed
New approaches tend to retain more water in soil
More retention of soil water decreases subsurface transport of nutrients

**CCW**

![Bar chart showing average annual output at watershed outlet for DEF, CA, and VG, with categories Flow (cms), TotN (kg/ha), TotP (kg/ha), and Sed (t/ha).]
More retention of soil water decreases subsurface transport of nutrients

<table>
<thead>
<tr>
<th></th>
<th>DEF</th>
<th>CA</th>
<th>VG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (cms)</td>
<td>5.5</td>
<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>TotN (kg/ha)</td>
<td>9.0</td>
<td>7.5</td>
<td>8.0</td>
</tr>
<tr>
<td>TotP (kg/ha)</td>
<td>3.0</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Sed (t/ha)</td>
<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**LRW**

Average Annual Output at Watershed Outlet
Summary & Future Efforts

**Model Development**
- New soil water equations implemented

**Key Findings**
- More water retention with new approaches, potentially less flushing
- Water balance reflects relative rate of vertical conductivity
- Changes in water quality dependent upon subsurface soil transport

**Next Steps**
- Test with calibrated models
- More detailed analyses of results across layers
2. In-stream water quality
In-stream water quality modeling

- Water quality models are crucial for predicting water quality status in streams
  - QUAL2E/K, WASP (reach models)
  - SWAT, HSPF (watershed models)
  - OTIS (solute transport model)

**In-stream processes**

- NO$_3$, NO$_2^-$, NH$_3$, OrgN, OrgP, DissP, Algae

- Advection
- Dispersion
- Transformations/reactions
- Transient Storage exchange

Existing Models

Transient storage (O’Connor et al., 2010)
Why do we need another model?

How existing models behave?

- **OTIS**
  - Processes: Advection, Dispersion, **Transient Storage**
  - Sub-daily scale
  - One value of decay rate

- **QUAL2E/K**
  - Processes: Advection, Dispersion, **Reactions**
  - Sub-daily scale
  - Steady state analysis

- **SWAT**
  - Processes: Reactions
  - Daily scale

**New Model**: Advection, Dispersion, Reactions, Transient storage, Sub-daily scale
Model Development

Advection-dispersion-reaction model was developed based on finite difference approach using knowledge from existing water quality models

\[
\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - U \frac{\partial c}{\partial x} - kC \text{(sources/sinks)} + \alpha (C_s - C)
\]

Dispersion | Advection | Transformations | Transient storage exchange

Replaced with QUAL2E reactions

\[
\frac{\partial C_s}{\partial t} = -\alpha \frac{A}{A_s} (C_s - C)
\]

Breakthrough curve is fitted to calibrate the transient storage parameters

- A (cross-sectional area, m²)
- \(A_s\) (transient storage area, m²)
- D (dispersion coefficient, m²/s)
- \(\alpha\) (storage exchange coefficient, s⁻¹)
Tracer tests were conducted in two separate stream reaches in Germany

- 30L salt solution mix (Chloride + Phosphate) injected instantaneously at an upstream location
- Downstream, conductivity was monitored and grab samples were taken to analyze nutrient concentrations over time

<table>
<thead>
<tr>
<th>Location</th>
<th>Discharge (L/s)</th>
<th>Reach length (m)</th>
<th>Amount of NaCl (g)</th>
<th>Amount of KH₂PO₄ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soltfeld</td>
<td>124</td>
<td>120</td>
<td>8000</td>
<td>250</td>
</tr>
<tr>
<td>Freienwill</td>
<td>306</td>
<td>135</td>
<td>8000</td>
<td>250</td>
</tr>
</tbody>
</table>
Modelled breakthrough curves

Fitted transient storage parameters with NaCl curve

Tested phosphate curve with fitted parameters

Freienwill
Summary & Future Efforts

**Recent model development**
Regression models were developed to estimate storage parameters from other easily available stream parameters (avoids extensive reach-specific calibration)

**Key Takeaways**

- *Reasonable simulation of conservative and reactive solutes*

- Inclusion of reactions, transient storage, finite difference approach and sub-daily scale simulation gives the model *better confidence compared to the existing models*

- Model *will be validated with other test data* showing significant N and P uptake

- The developed model along with regression estimates of storage parameters *will be coupled with SWAT* to improve nutrient predictions at sub-daily scale
Global Water Security

for

Agriculture and Natural Resources

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