Representative Hillslopes in the Community Terrestrial Systems Model

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CUAHSI / NCAR Collaboration

- **CUAHSI** (Consortium of Universities for the Advancement of Hydrologic Science, Inc.) supports and enables community activities to advance hydrologic science

- **NCAR** (National Center for Atmospheric Research) supports and enables community activities to advance atmospheric and related sciences

- CUAHSI / NSF initiative to improve the representation of hydrologic processes in ESMs
  - Accelerate implementation of state-of-the-art hydrologic understanding into large-scale land models
  - Emphasis on model evaluation / benchmarking utilizing catchment-scale observations
  - Initial focus on implementation of hillslope hydrology into CLM

![Water Resources Research](https://example.com/water-resources-research.png)

**Improving the representation of hydrologic processes in Earth System Models**

*Special Section: The 50th Anniversary of Water Resources Research*
Soil Moisture Heterogeneity

Observed vegetation patterns imply variations in soil moisture
CLM Treatment of Soil Moisture Heterogeneity

TOPMODEL based expression used to parameterize saturated fraction based on column water table depth.

Saturated fraction only affects runoff; other processes experience a single soil moisture profile.

Point at which water table intersects surface determines saturated fraction.

Saturated fraction = 0.36

Saturated fraction = 0.14
Representing Spatial Heterogeneity
Representative Hillslopes
Spatial Covariation
Conceptual Hillslopes

Serial subsurface flow inputs to riparian zone

Independent (parallel) subsurface flow inputs to riparian zone
CLM Subgrid Tiling Structure

Standard Configuration:
PFT/Patches share a single column and compete for water
Multicolumn Configuration
(1 pft per col):
PFT/Patches occupy individual columns
Hillslope Multicolumn Configuration:
Individual columns interact via lateral flow
## Hillslope Connectivity

### Hillslope Multi-Column Configurations

<table>
<thead>
<tr>
<th>Single Column</th>
<th>Serial Connectivity</th>
<th>Parallel Connectivity</th>
<th>Combined Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Subsurface Flow</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>To Stream</td>
<td>To Stream</td>
<td>To Stream</td>
<td>To Stream</td>
</tr>
</tbody>
</table>
Characterizing Hillslopes
1. Analytical Landform Equations

Basic hillslope forms, e.g. convergent, uniform, and divergent, can be expressed with parametric equations.

Key features include: elevation, slope, width, and area as functions of distance from base of hillslope.

*Fan and Bras, 1998, Analytical solutions to hillslope subsurface storm flow and saturation overland flow, WRR.*

**Figure 2.** Schematic illustration of the three characteristic hillslope types.
Characterizing Hillslopes

2. DEM Analysis

Geospatial analysis of DEMs can be used to directly extract geomorphological information and generate representative hillslopes.

Ajami et al., 2016, Development of a computationally efficient semi-distributed hydrologic modeling application for soil moisture, lateral flow and runoff simulation, EMS.
Characterizing Hillslopes

2. DEM Analysis

Statistical analysis provides information on distributions of hillslope characteristics within a region.

Hoori Ajami (personal communication), 2018.
Characterizing Hillslopes

3. HAND Analysis

Height Above Sea Level

Height Above Nearest Drainage

Nobre et al., J. Hydrology, 2011.
Characterizing Hillslopes

3. HAND Analysis

Number of columns per hillslope

Hillslope geomorphology

Aaron Potkay (personal communication), 2018.
Simple Global Test Case

- One hillslope, three columns
- Two upland columns are connected in parallel to one lowland column
- Identical column width and area, spatially varying elevation and slope derived from global topographic dataset
- Atmospheric forcing from global reanalysis-based dataset
- Spatially varying vegetation and soil properties
Impact of Subsurface Lateral Flow

Saturated Thickness greater in Lowland column relative to Upland column

Convergence leads to shallower water tables in transitional regions
Gridcell Average ET

Difference in ET: Lateral Flow minus No Lateral Flow
Moisture Convergence

Lowland column (bottom) has higher saturation level than upland columns (top).
Soil Thickness Variations
High Resolution Test

Ion: 272.0 / lat: 38.0 (Illinois)

Saturation

Ion: 272.0 / lat: 38.0 / time: day 93
Summary

- CTSM-Hillslope model infrastructure in place
- Covariation of landscape quantities important
- Global simulation shows interaction of hydrology with climate
- “Hillslope Hydrology” model will be available via Github with upcoming versions of CTSM
Applications

- Soil moisture heterogeneity impacts on:
  - prognostic vegetation and ecosystem cycling
  - permafrost distribution
  - boundary layer formation

- Saturation heterogeneity impacts on:
  - soil carbon decomposition
  - methane production and oxidation
  - runoff production
Research Opportunities

• Terrain analysis
• Catchment decomposition
• Radiation partitioning due to varying slope and aspect
• Downscaling of meteorological forcing
• Sensitivity analyses
• Parameterization formulation
Open Question

Does vegetation in CLM respond to soil moisture realistically?