Representative Hillslopes in the Community Terrestrial Systems Model

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Soil Moisture Heterogeneity

Observed vegetation patterns imply variations in soil moisture.
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
Evolution of Process Representation in Land Models

Focus on land-atmosphere energy fluxes

Mechanistic modeling of land processes

Properties define processes (focus on short-term fluxes)

Land as a lower boundary to the atmosphere

Limited representation of land processes & feedbacks

Processes define properties (feedbacks and interactions across time scales)

Land as an integral component of the Earth System

Simulate the dynamics of change (e.g., dynamic vegetation)

The Evolution of Land Modeling

- Surface Energy Fluxes
  - Plant Canopies
  - Stomatal Resistance
  - Soil Moisture

- Heterogeneity
- Dynamic Vegetation
- Lakes, Rivers, Wetlands
- Groundwater
- Urban
- Nutrients
- Crops, Irrigation
- Lateral Flow

Timeline:
- 70's
- 80's
- 90's
- 00's
- 10's

R. Fisher
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**

**REVIEW ARTICLE**

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

Special Section: The 50th Anniversary of Water Resources Research

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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
Conceptual Hillslopes

Serial subsurface flow inputs to riparian zone

Independent (parallel) subsurface flow inputs to riparian zone
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.

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

1. Analytical Landform Equations

Unfortunately, integrable expressions are limited and often lead to unrealistic flowpaths.

Fig. 5. Three-dimensional view of the nine different hillslopes used in this study. The numbers in the figure refer to Table 1.

Troch et al., 2002, Analytical solutions to a hillslope-storage kinematic wave equation for subsurface flow, AWR.

Fig. 6. Plan view of drainage divides (solid lines) and contour lines (dashed lines) of nine hillslopes. The upslope divide of each hillslope is at x = 0.
Characterizing Hillslopes

2. DEM Analysis

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

Fig. 4. Kui River catchment and the Stanley and Bumbrae sub-basins in Australia. SMART delineates (a) first order sub-basins (b) hillslopes and (c) landforms of the catchment. Soil moisture probes in (c) are used for model comparison.

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.

This work is ongoing at this time...

Hoori Ajami (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
Topographic Properties

- Gridcell Mean Slope
- Lowland Elevation
- Upland Elevation
Impact of Subsurface Lateral Flow

Saturated Thickness greater in Lowland column relative to Upland column

Convergence leads to shallower water tables in transitional regions
Impact of Subsurface Lateral Flow

In water limited regions, higher latent heat fluxes are then possible.
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

310/−20 (point)

Col 2

Col 3

Col 1

To Stream
Test Case: Reynolds Mountain East Catchment
NSF Critical Zone Observatory

Fig. 1. Location map of Reynolds Mountain East Catchment.

Spatially Varying Snowpack

Figure 3. $\overline{S_b}$ calculated from the DEM for the resultant mean wintertime wind direction of 230°. Decreasing the $\overline{S_b}$ threshold for determining drift zones from 7° to 5° resulted in a 46% increase in delineated drift cells.

Figure 4. Snow accumulation and wind factors calculated for 230° winds with no snow on the ground. Accumulation and wind factors were derived for all possible wind directions with observations interpolated over the appropriate image.

Model Configuration

- One hillslope, four columns
- Three upland columns are connected in parallel to one lowland column
- All columns forced with identical meteorological data
- Snowfall is transferred from a 'wind-scoured' column to a 'wind-drifted' column
- Vegetation distribution approximates observed distribution
- Soil thicknesses are ~1 m
- Kinematic wave lateral flow approximation
Snowpack & Streamflow Comparison
Latent Heat Flux Comparison
Soil Moisture

Snowpack determines spring soil moisture inputs. Compared to upland column, lowland column has longer wet period due to lateral flow inputs.
Impact of Subsurface Lateral Flow

Without lateral flow (bottom), spring wet period is shorter; in some years no outflow occurs. Lateral flow extends spring wet period (top).

Increased soil moisture delays late summer dry down (red) relative to uncoupled simulation (green).
Evapotranspiration

Black line = Obs

With Lateral Flow

Without Lateral Flow
Summary

• Realistically configured model validated at Reynolds Mountain East

  • 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