Future Directions: Subgrid Hydrology in CLM

Justin Perket[1,2], Martyn Clark[1], Dave Lawrence[1], Ying Fan Reinfelder[2], Sean Swenson[1]

[1] NCAR [2] RUTGERS

Photo Credit: NSIDC, A. Racoviteanu

CUAHSI-NCAR collaboration

- CUAHSI (Consortium of Universities for the Advancement of Hydrologic Science, Inc.)

CUAHSI
UNIVERSITIES ALLIED FOR WATER RESEARCH

- CUAHSI / NCAR initiative to improve representation of hydrologic processes in ESMs
    - Hillslope hydrology
    - Plant hydrodynamics

Water Resources Research

REVIEW ARTICLE
10.1002/2015WR017096

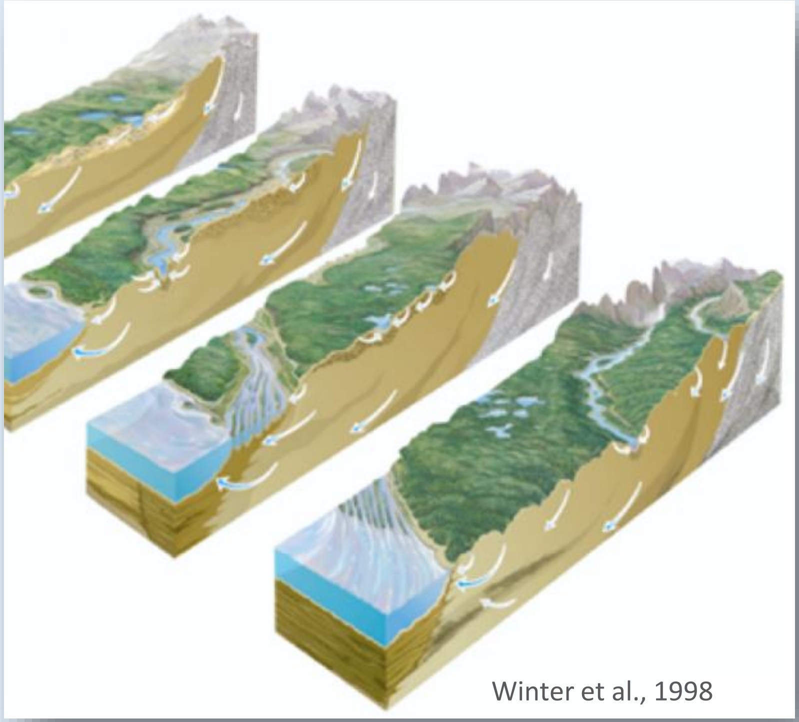
Special Section:
The 50th Anniversary of Water Resources Research

Improving the representation of hydrologic processes in Earth System Models

Martyn P. Clark[1], Ying Fan[2], David M. Lawrence[1], Jennifer C. Adam[3], Diogo Bolster[4], David J. Gochis[1], Richard P. Hooper[5], Mukesh Kumar[6], L. Ruby Leung[7], D. Scott Mackay[8], Reed M. Maxwell[9], Chaopeng Shen[10], Sean C. Swenson[1], and Xubin Zeng[11]

Open Hydroclimatology Questions

- How can we improve climate predictions by advancing representation of the terrestrial water cycle?

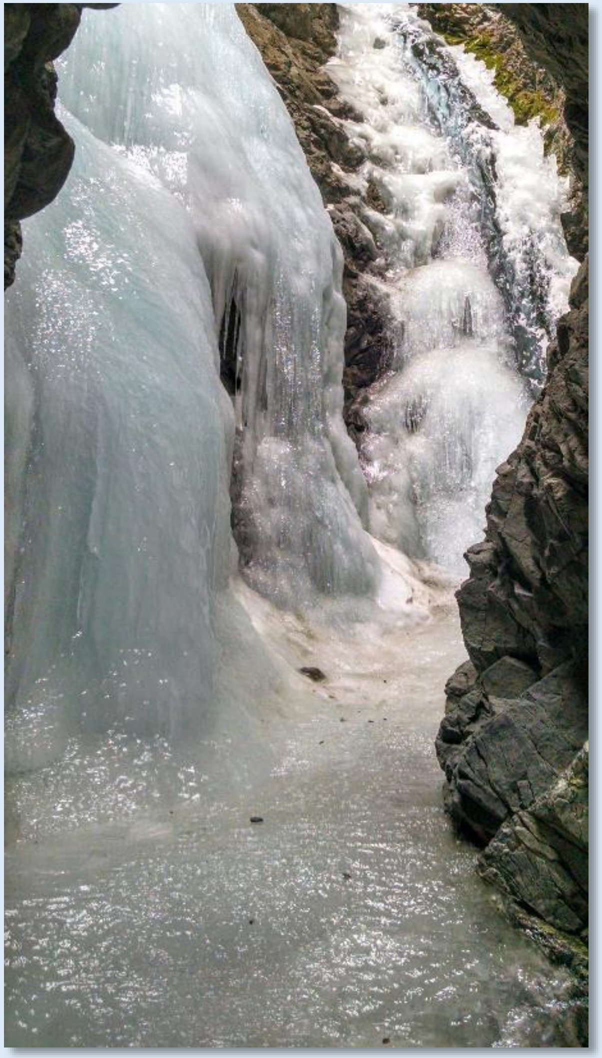


Open Hydroclimatology Questions

- How can we improve climate predictions by advancing representation of the terrestrial water cycle?
- How does the hydrologic influence of land-atmosphere fluxes affect climate?

Open Hydroclimatology Questions

- How will natural and anthropogenic forcings affect:
  - Stores (e.g., canopy, snowpack, soil moisture, groundwater, rivers, lakes)?
  - Fluxes (e.g., evaporation, transpiration, snowmelt, infiltration, runoff, subsurface lateral flow, river discharge)?

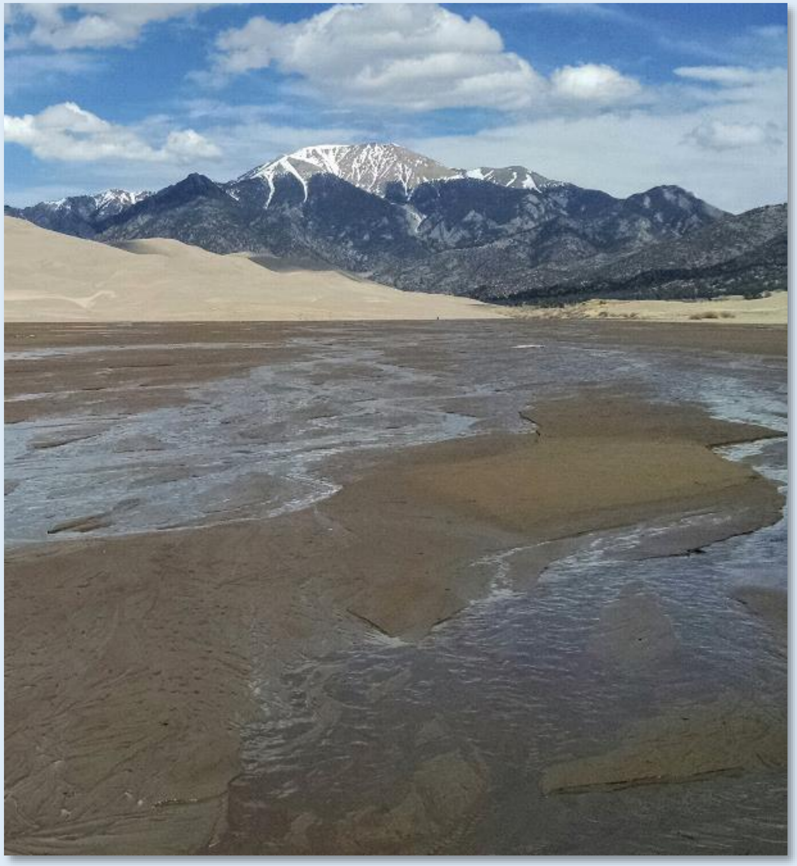


Open Hydroclimatology Questions

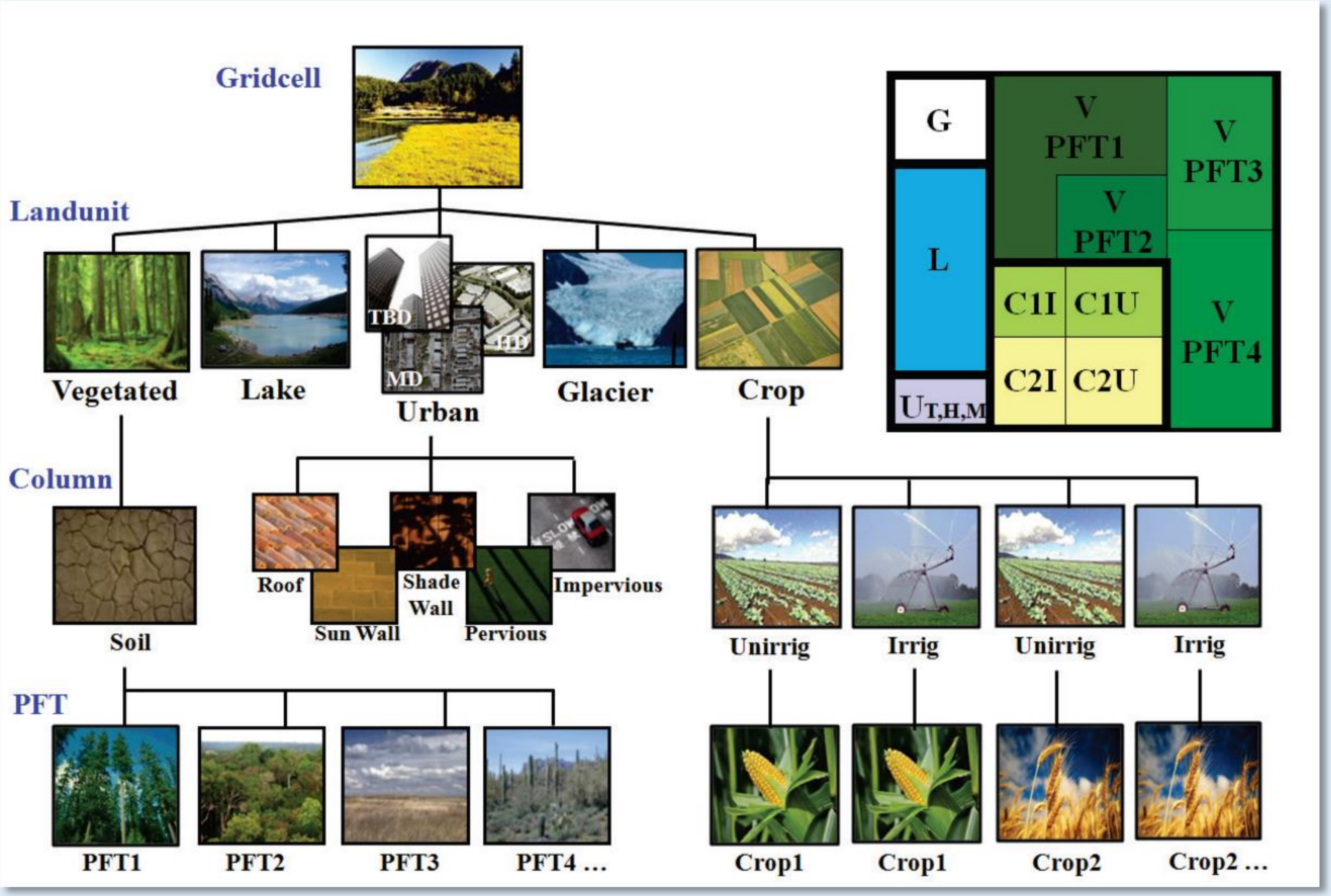
- How can climate influence freshwater availability? Vegetation stress?

Motivation

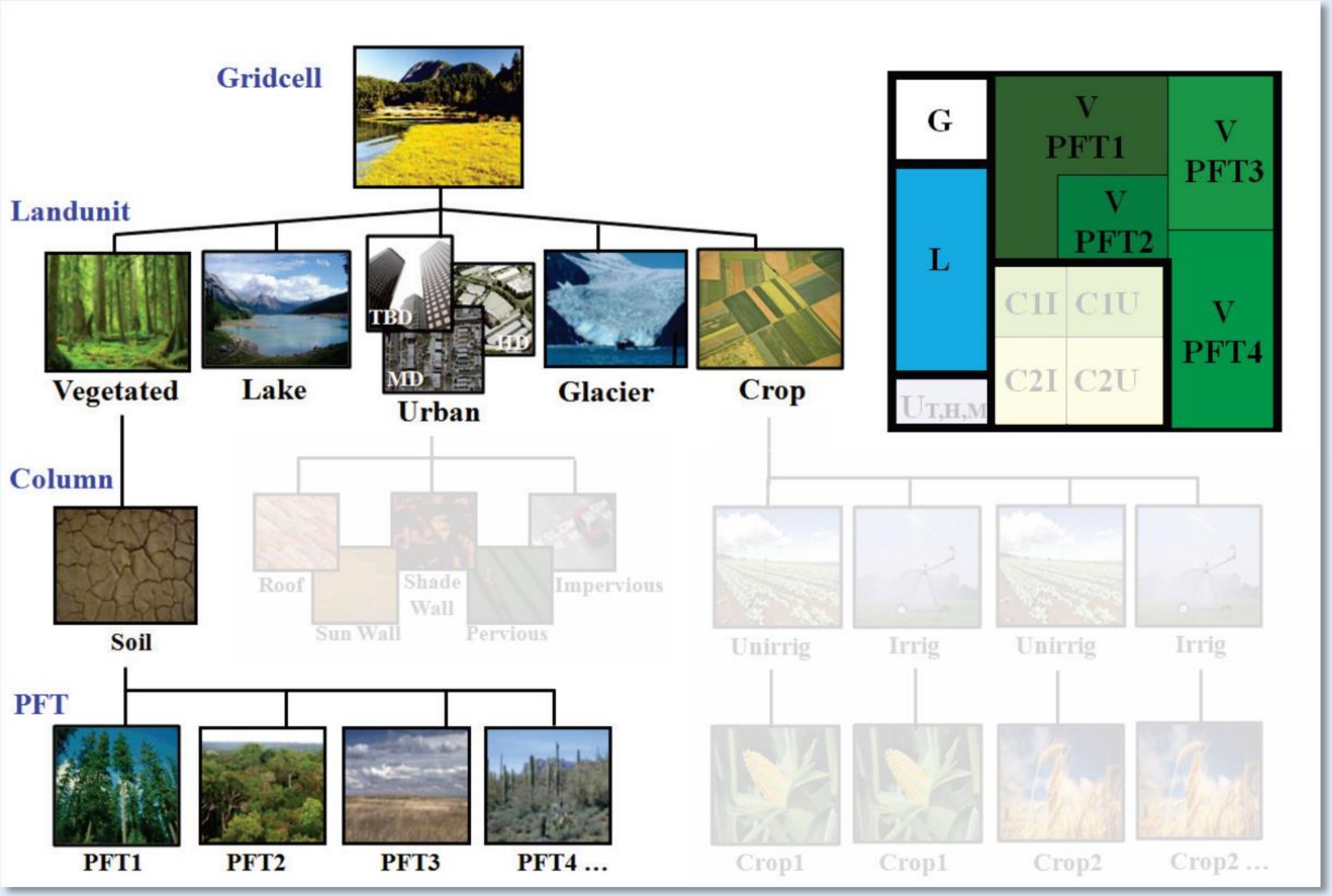
- Need efficient representation of hillslope hydrology dynamics (with subgrid variability) for global water cycle interactions with climate
- Lateral subsurface flow critical to represent terrestrial water connectivity, but missing from most earth system models



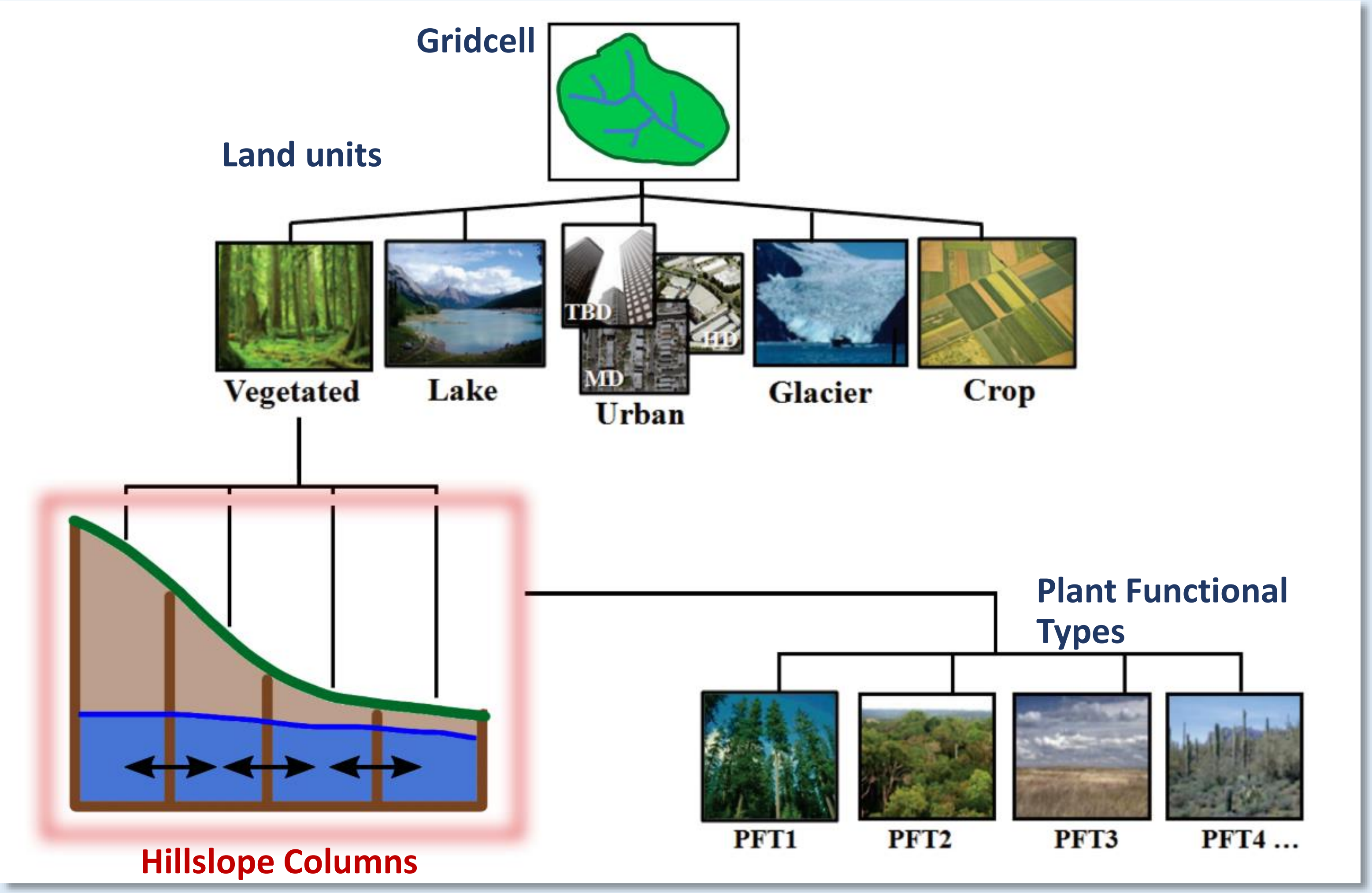
CLM 5.0 Subgrid Hierarchy



CLM 5.0 Subgrid Hierarchy



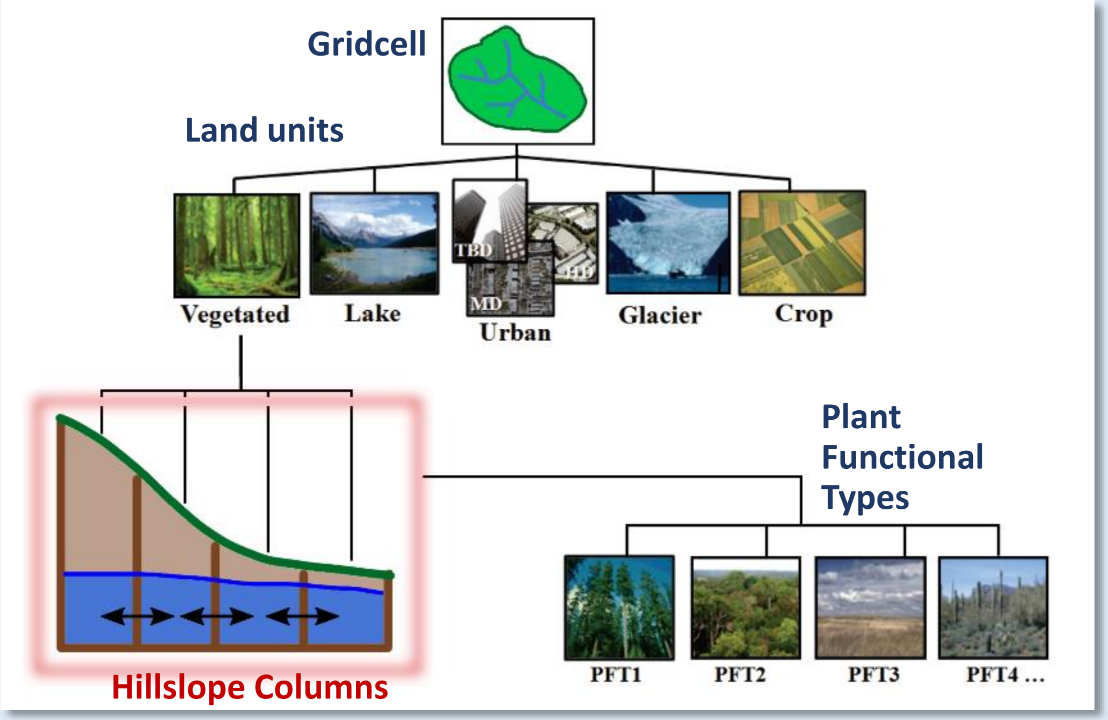
CLM Subgrid Hierarchy with Hillslope Representation



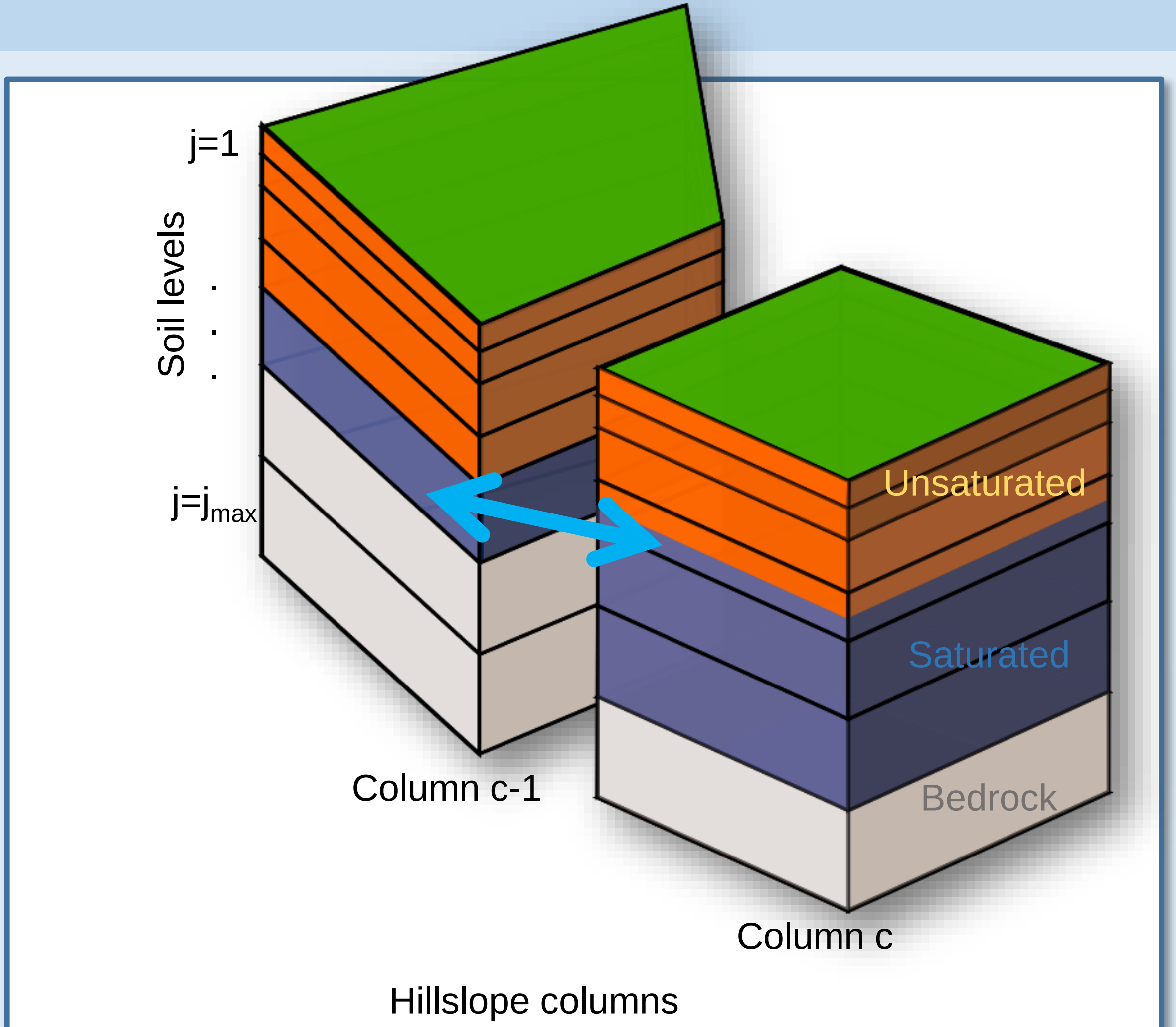
Implemented Intra-Gridcell Hillslope Representation

- Gridcell level assumes role of drainage basin
- Few representative hillslopes per basin (if not singular)
- Lateral connections between neighboring columns in hillslope

CLM Hierarchy with Hillslope Representation

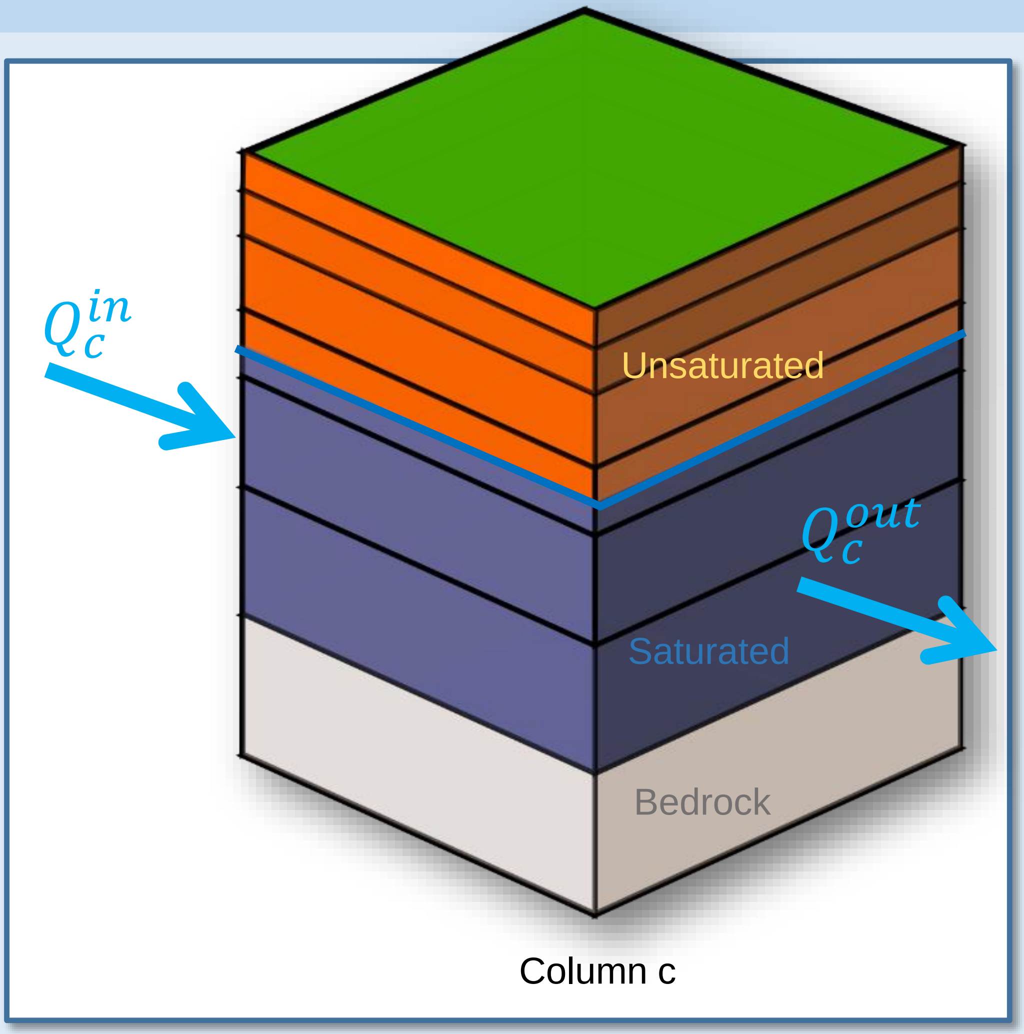


Implemented Hillslope Lateral Flow



- Columns have distinct:
  - Elevations
  - Slopes
  - Surface areas
  - Bedrock depths
- Lateral saturated flow between columns based on:
  - Topographic height
  - Water table slope

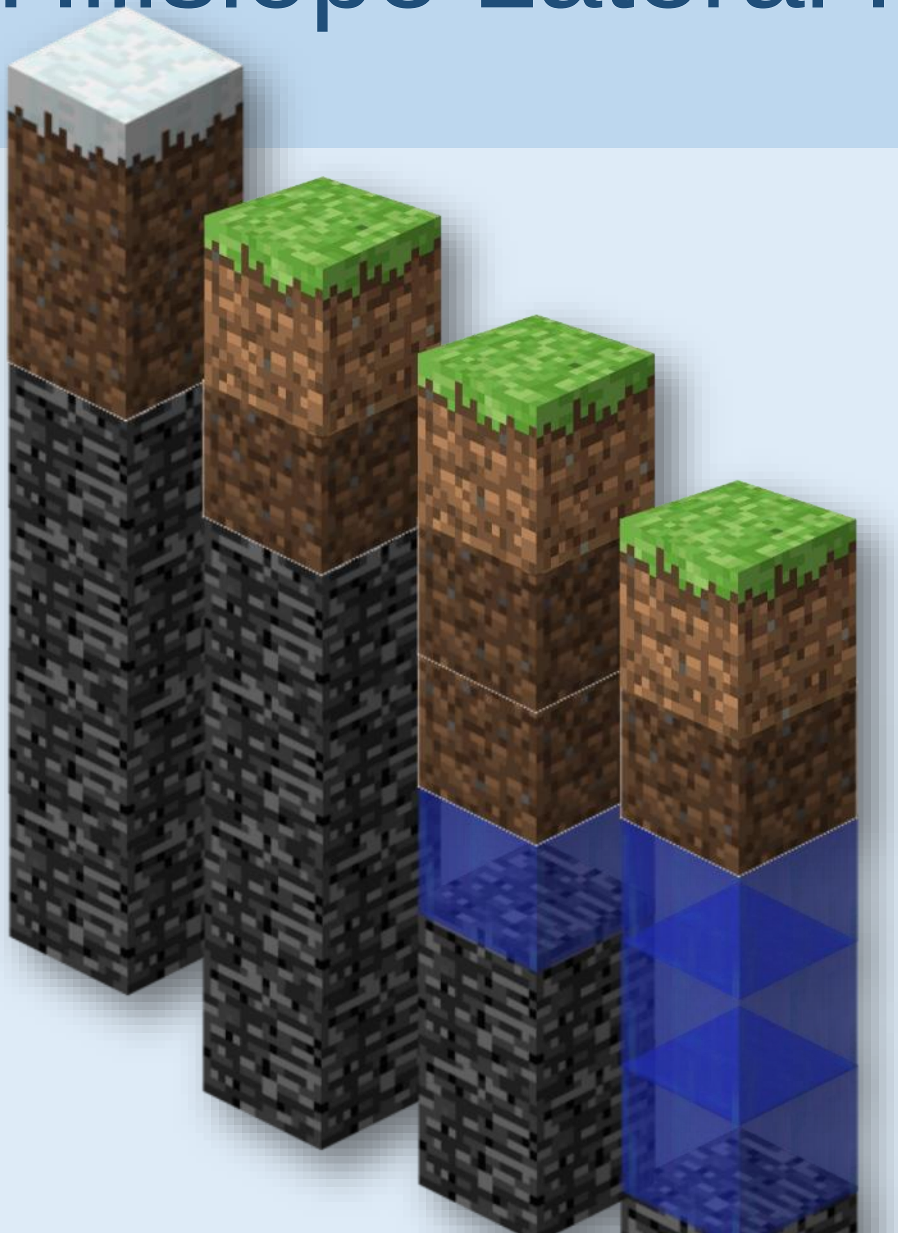
Implemented Hillslope Lateral Flow



- $Q_c^{out} = \frac{-K_0 * D_{soil} * \tan(\text{slope})}{n}\left(1 - \frac{D_{table}}{D_{soil}}\right)^n$
- Checks to prevent soil moisture < specific yield in any layer
- Withdraws from deeper layers if needed
- Q_c^{in} adds to water table layer
- $Q_c^{net} = Q_c^{out} - \underbrace{\frac{Area_{(c-1)}}{Area_c} Q_{c-1}^{out}}_{Q_c^{in}}$

Implemented Hillslope Lateral Flow

- Now the vegetated land unit kinda looks like…

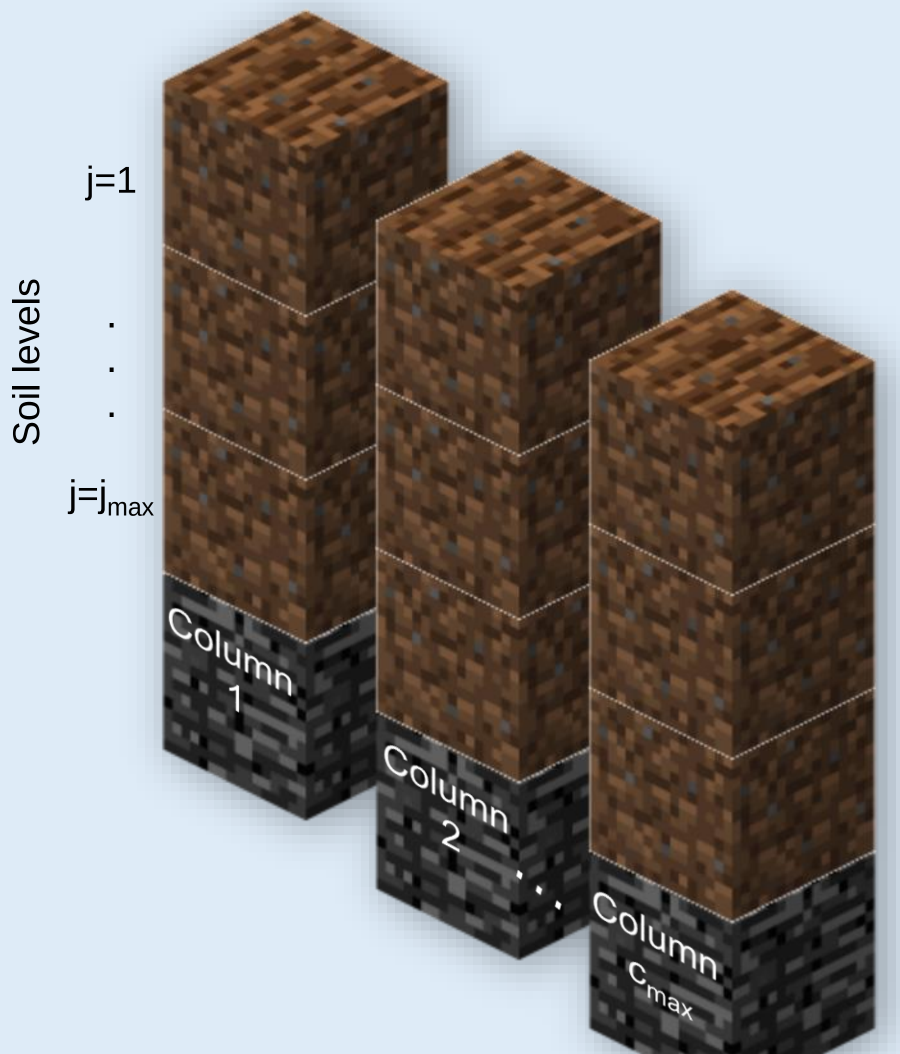


Synthetic Test Cases

- Constant slope with 700 hour constant rain

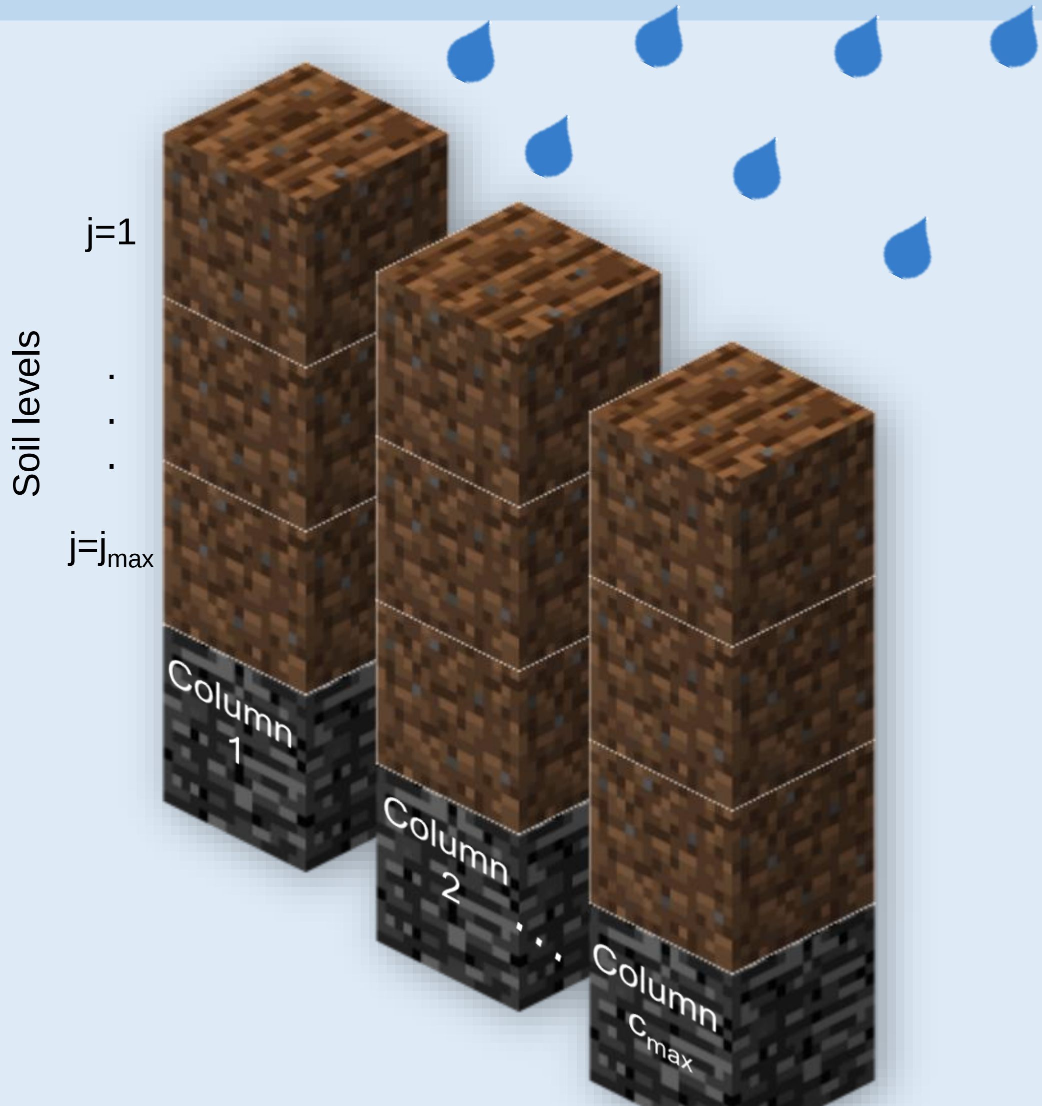
- Saturated flow downhill (kinematic wave)

- Compared to simple analytical & numerical solutions

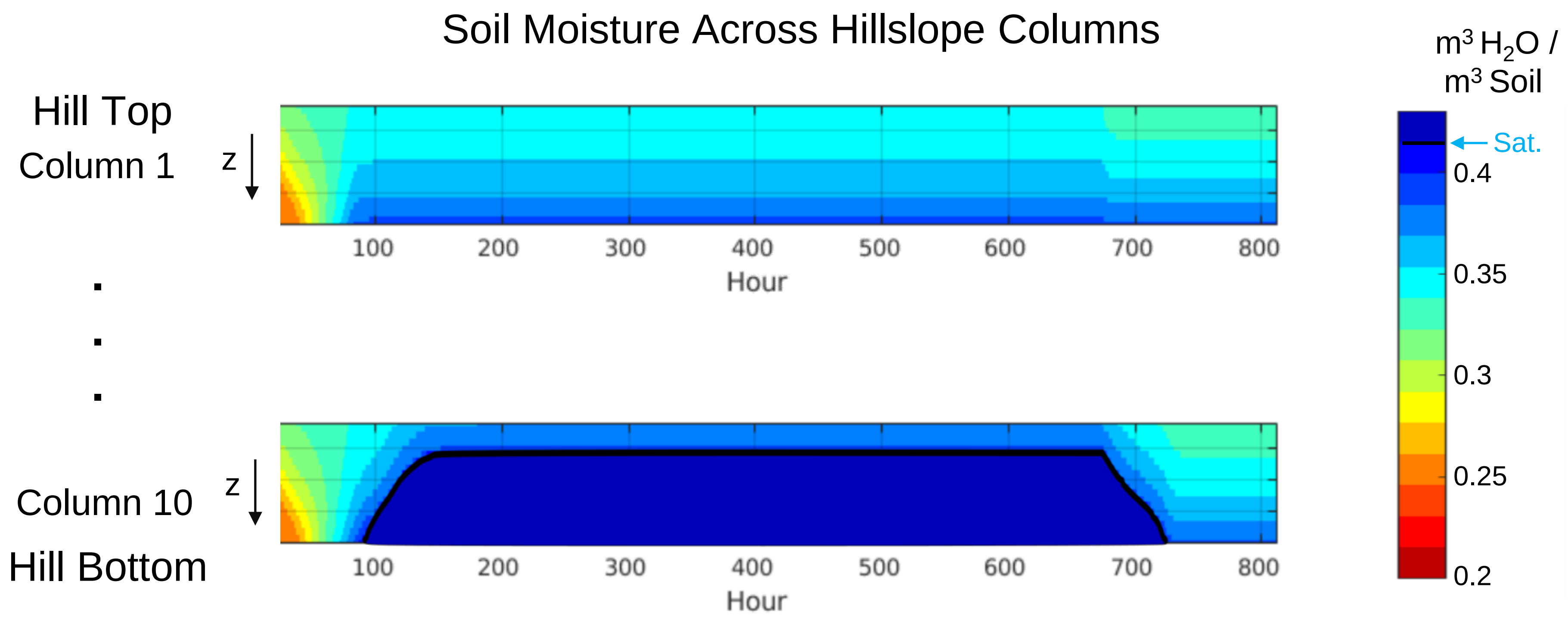


Synthetic Test Cases

- Constant slope with 700 hour constant rain
- Saturated flow downhill (kinematic wave)
- Compared to simple analytical & numerical solutions

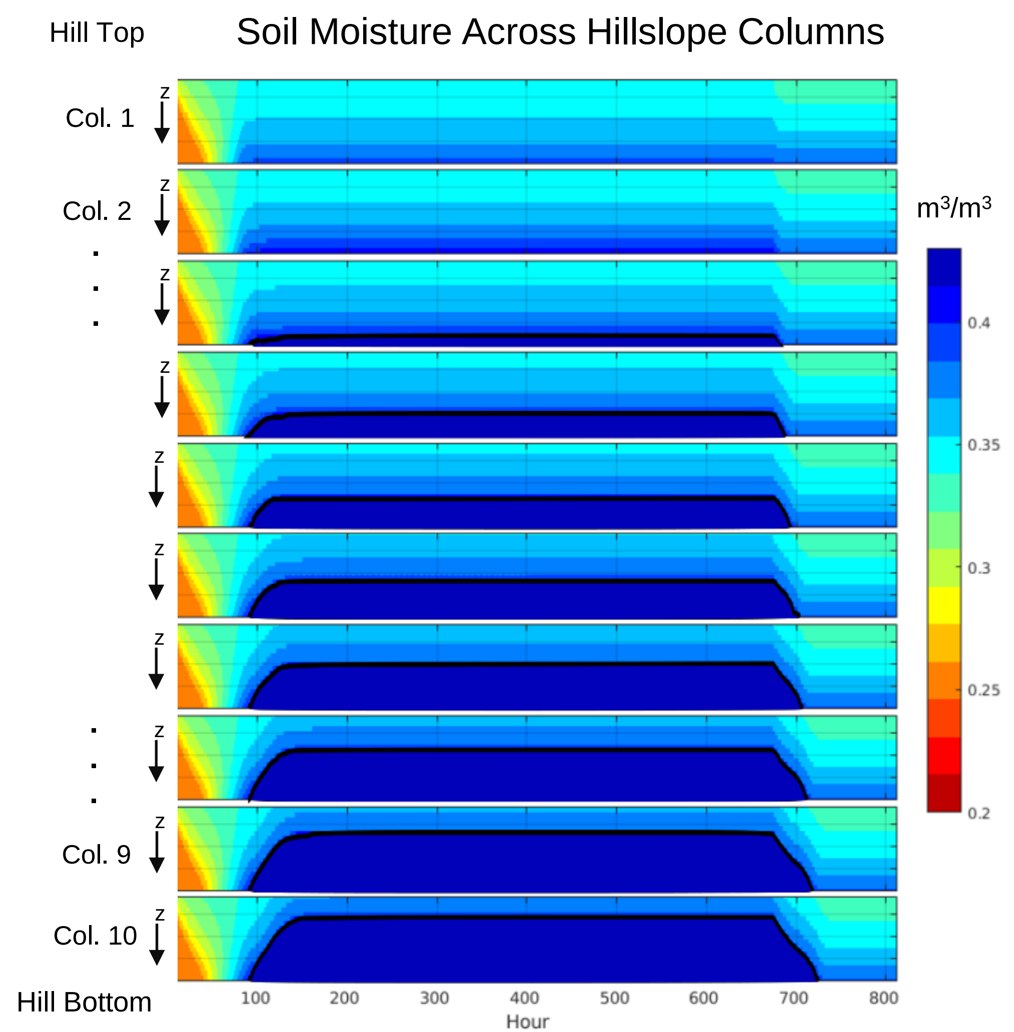


Synthetic Test Cases



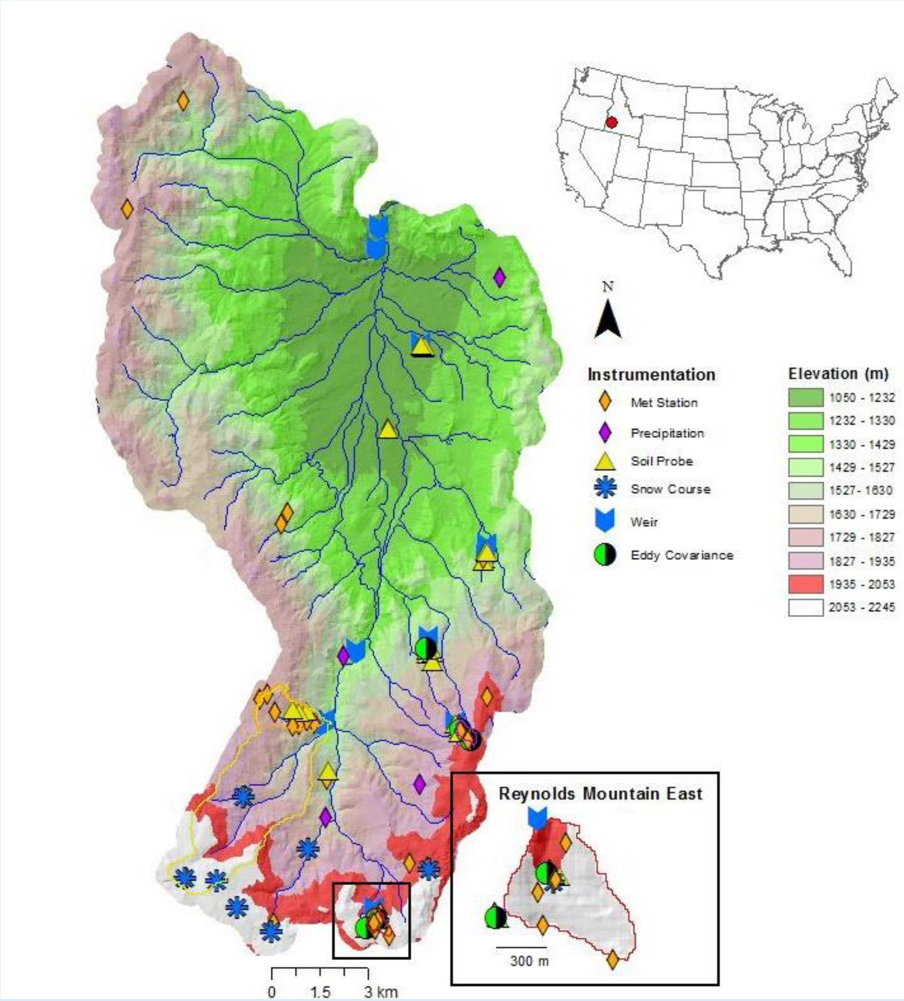
Synthetic Test Cases

- Constant slope w/ 700 hour constant rain
- Increased water storage, higher water table going downhill
- Compares well with analytical solutions for matching hillslope geometry and soil properties



Reynolds Creek Watershed

- Compared Single Point CLM w/ site forcing to Critical Zone Observatory measurements

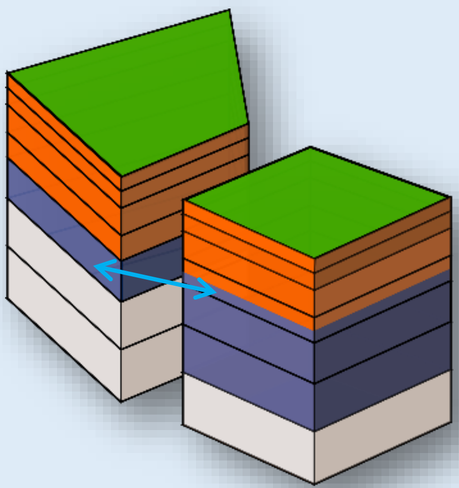


criticalzone.org/reynolds/

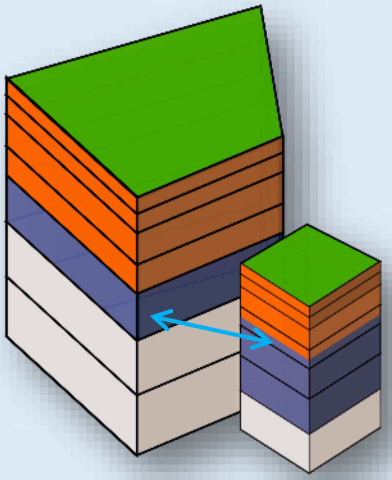
Topographic Sensitivity

- Control:
  - 1m soil depth
  - 10% slope
- 2 columns: upland & lowland
- Trial Series 1: converging basin

		Column	
Trial #	Parameter Varied	Upslope	Downslope
1a	Area (relative to 1st col.)	1	1/2
1b	Area (relative to 1st col.)	1	1/4
1c	Area (relative to 1st col.)	1	1/8



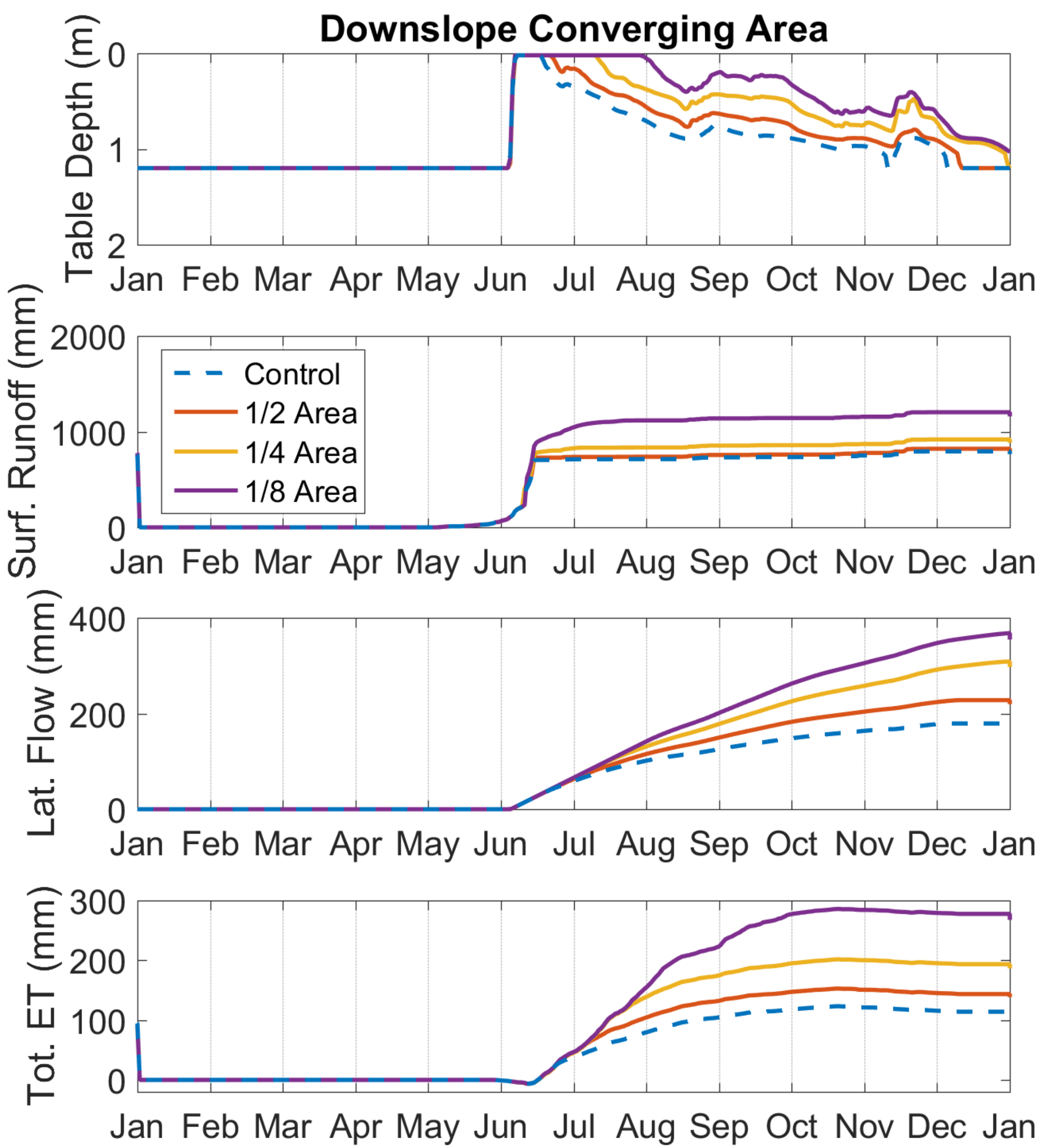
Control



Shrinking Downslope Area

Parameter Variation:
Converging Area

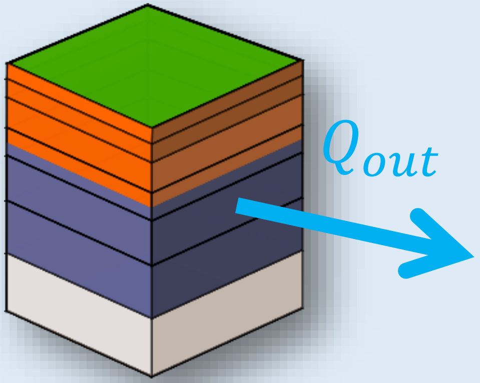
- Representative Year 2004, cumulative fluxes
- Control:
  - 1m soil depth
  - 10 % slope
- Converge to 1/2th, 1/4th, 1/8th area



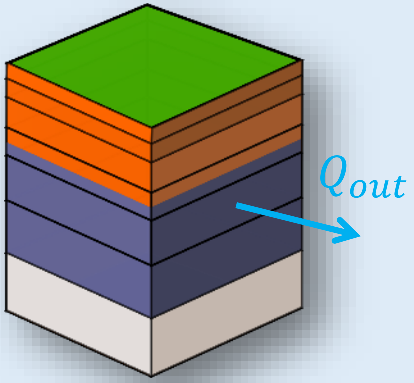
Topographic Sensitivity

- Control:
  - 1m soil depth
  - 10 % slope
- 2 columns: upland & lowland
- Trial Series 2: Slowing slope downhill

		Column	
Trial #	Parameter Varied	Upslope	Downslope
1a	Area (relative to 1st col.)	1	1/2
1b	Area (relative to 1st col.)	1	1/4
1c	Area (relative to 1st col.)	1	1/8
2a	Baseflow strength	1	0.5
2b	Baseflow strength	1	0.25
2c	Baseflow strength	1	0.125
2d	Baseflow strength	1	0.01



Control

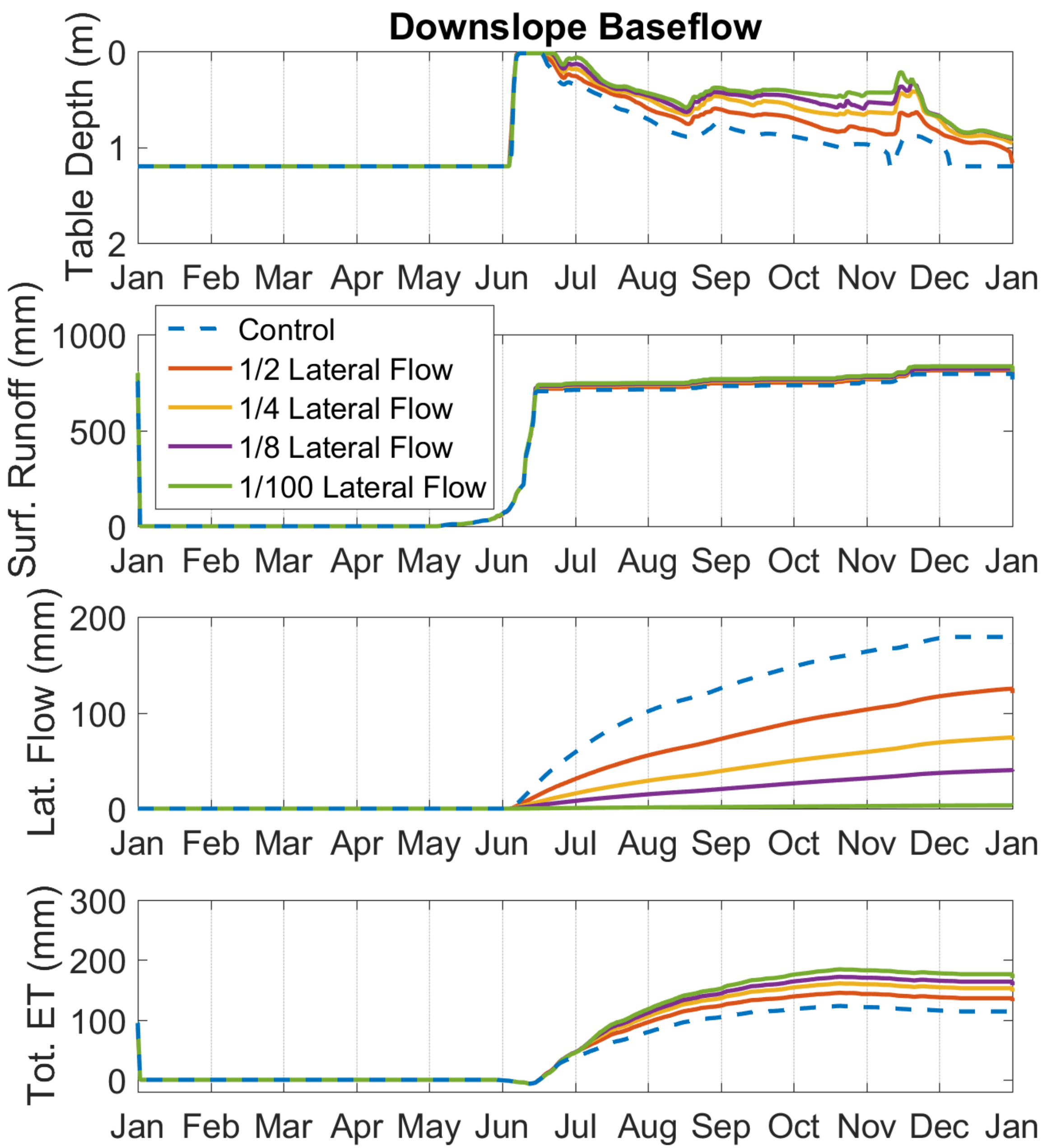


Smaller Downslope Lateral Flow

Parameter Variation:

Subsurface Flow / Slope

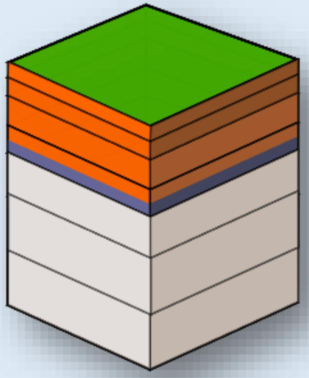
- Representative Year 2004, cumulative fluxes
- Control:
  - 1m soil depth
  - 10 % slope
- 1/2, 1/4, 1/8, 1/100 lateral flow

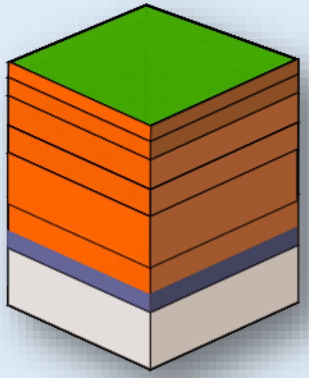


Topographic Sensitivity

- Control:
  - 1m soil depth
  - 10 % slope
- Trial Series 3: deepening soil downhill

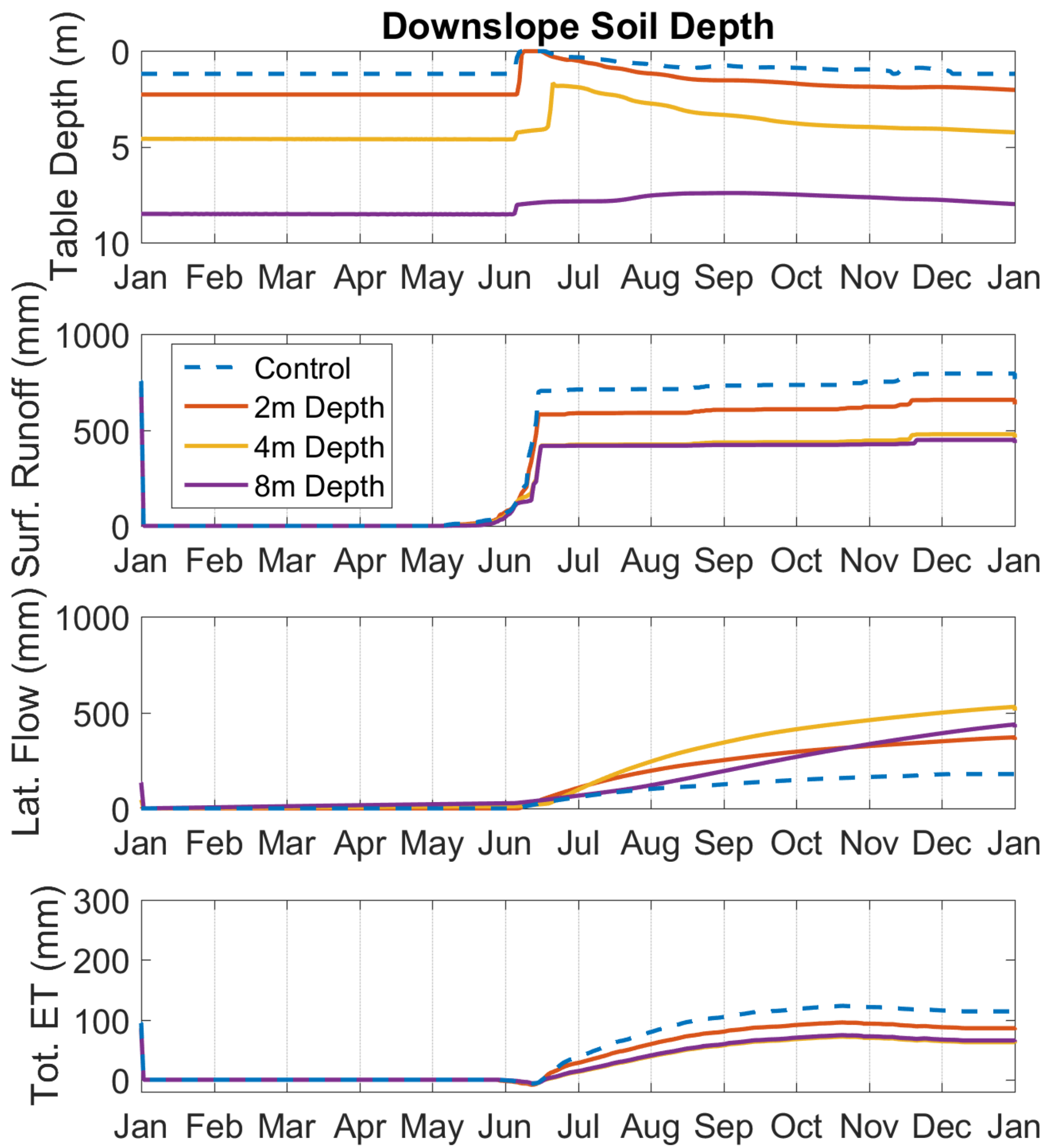
		Column	
Trial #	Parameter Varied	Upslope	Downslope
1a	Area (relative to 1st col.)	1	1/2
1b	Area (relative to 1st col.)	1	1/4
1c	Area (relative to 1st col.)	1	1/8
2a	Baseflow strength	1	0.5
2b	Baseflow strength	1	0.25
2c	Baseflow strength	1	0.125
2d	Baseflow strength	1	0.01
3a	Soil Depth (m)	1	2
3b	Soil Depth (m)	1	4
3c	Soil Depth (m)	1	8


Control


Deeper Downslope Soil

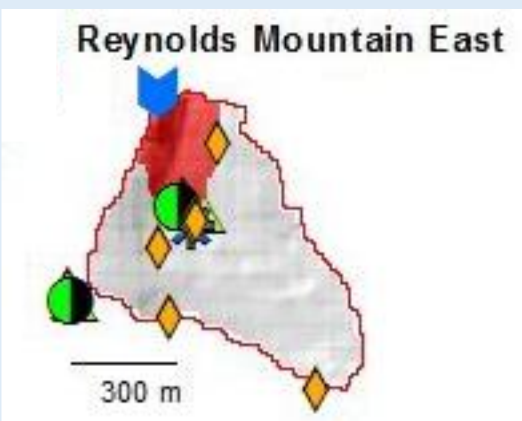
Parameter Variation:
Soil Depth

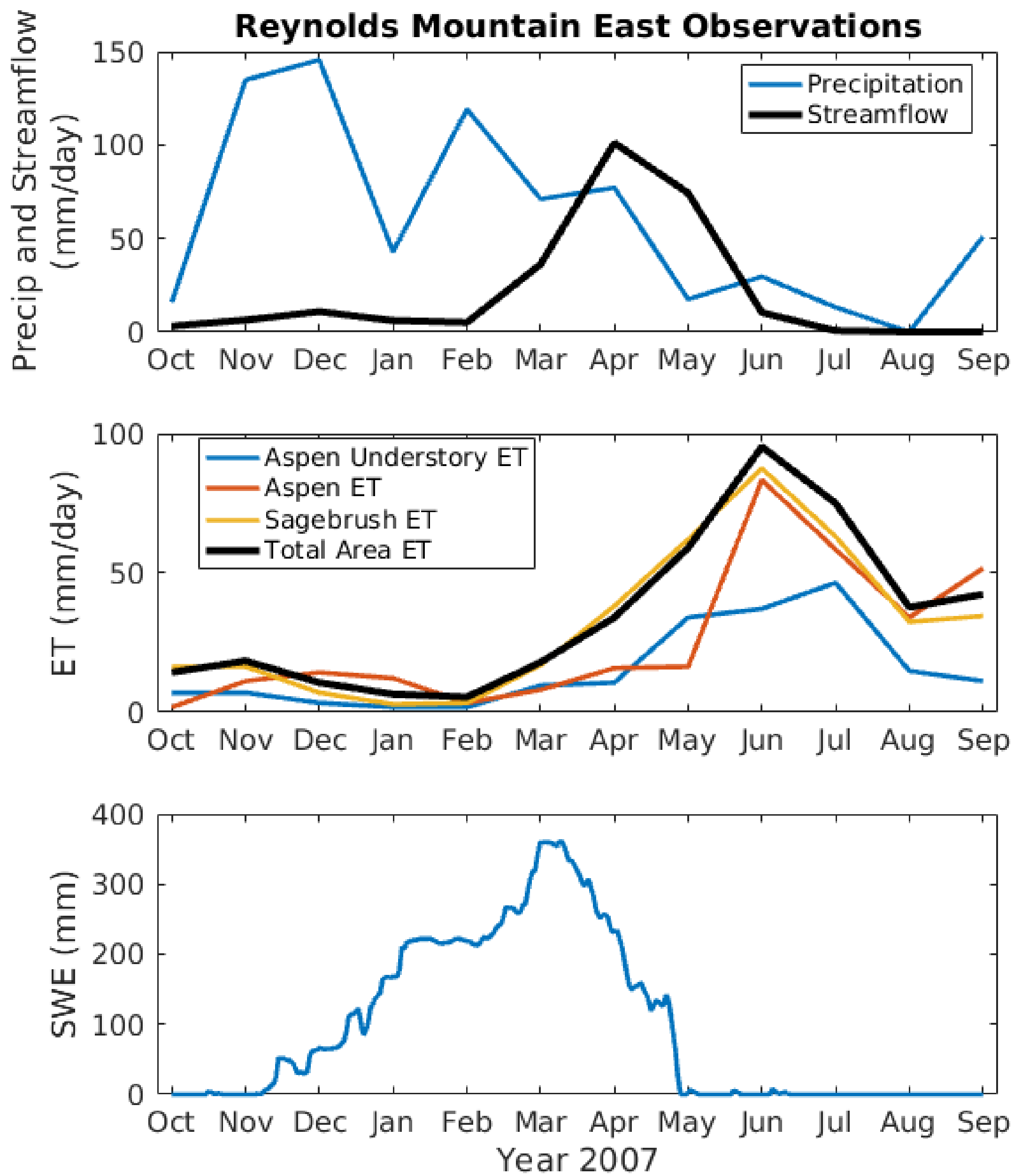
- Representative Year 2004, cumulative fluxes
- Control:
  - 1m soil depth
  - 10 % slope
- Depth to bedrock: 2m, 4m, 8m



Reynolds Creek Mountain East

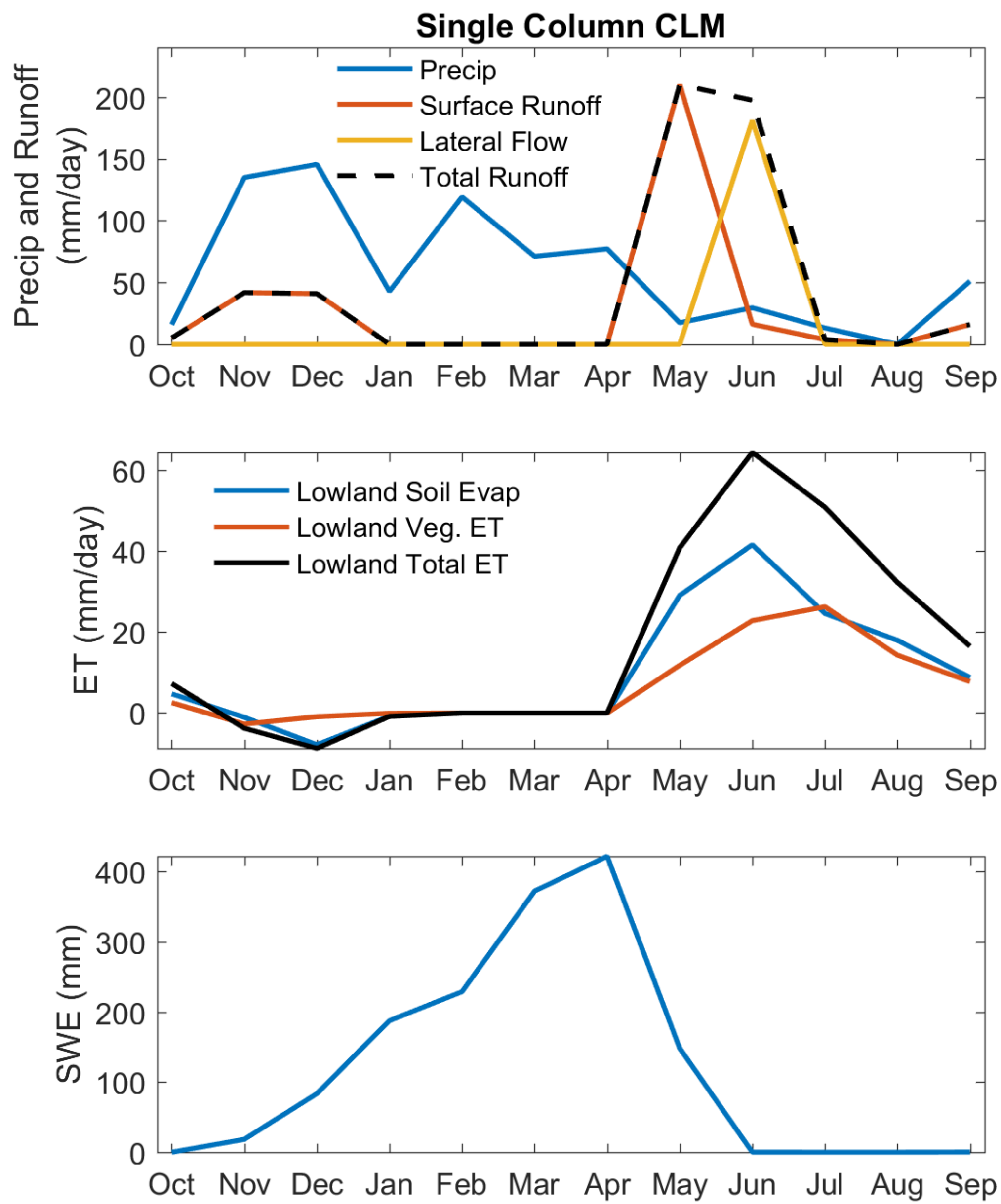
- Eddy flux towers, streamflow and SWE observations





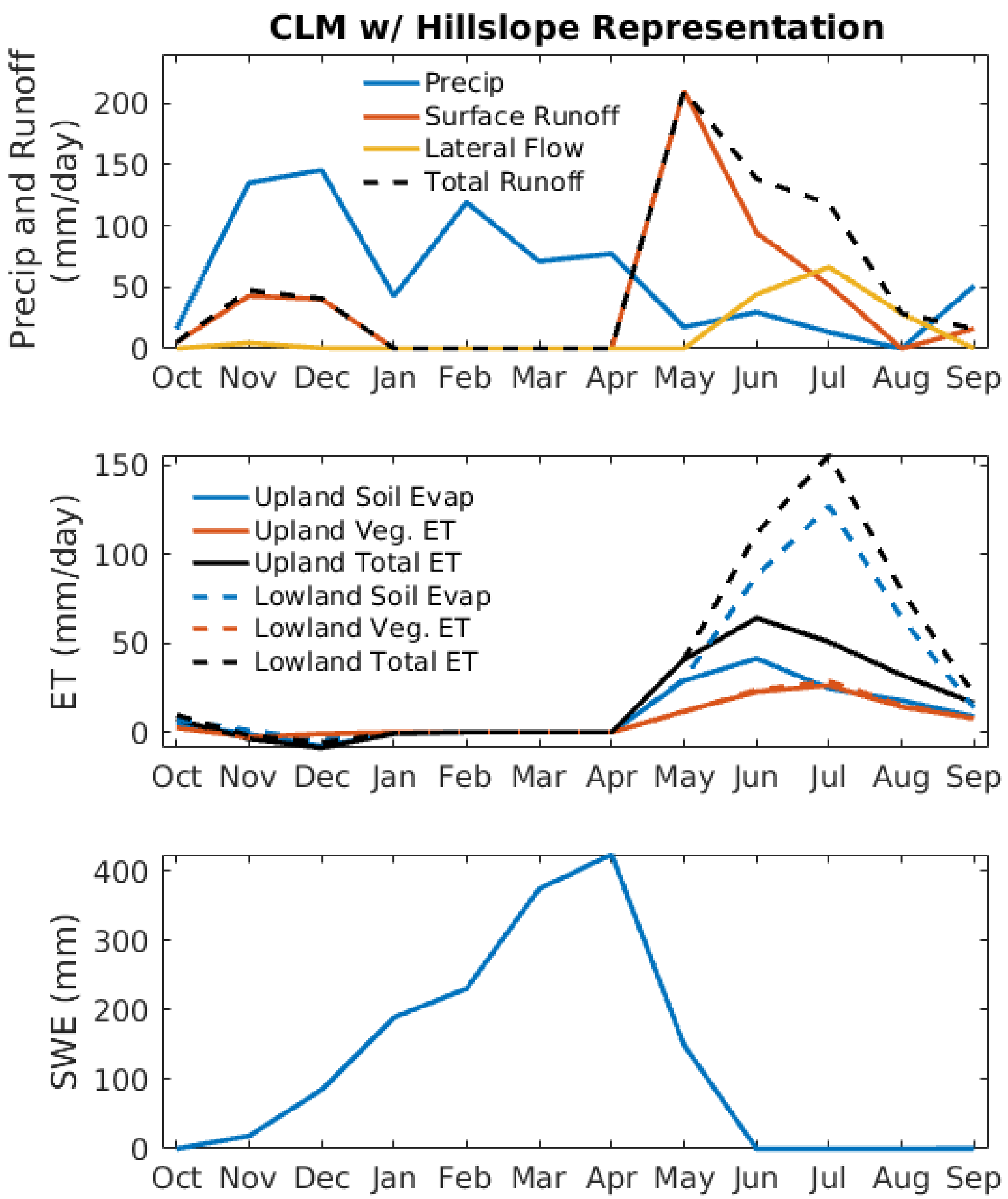
Reynolds Creek Mountain East

- Single Column CLM gives low lowland evapotranspiration compared to obs.

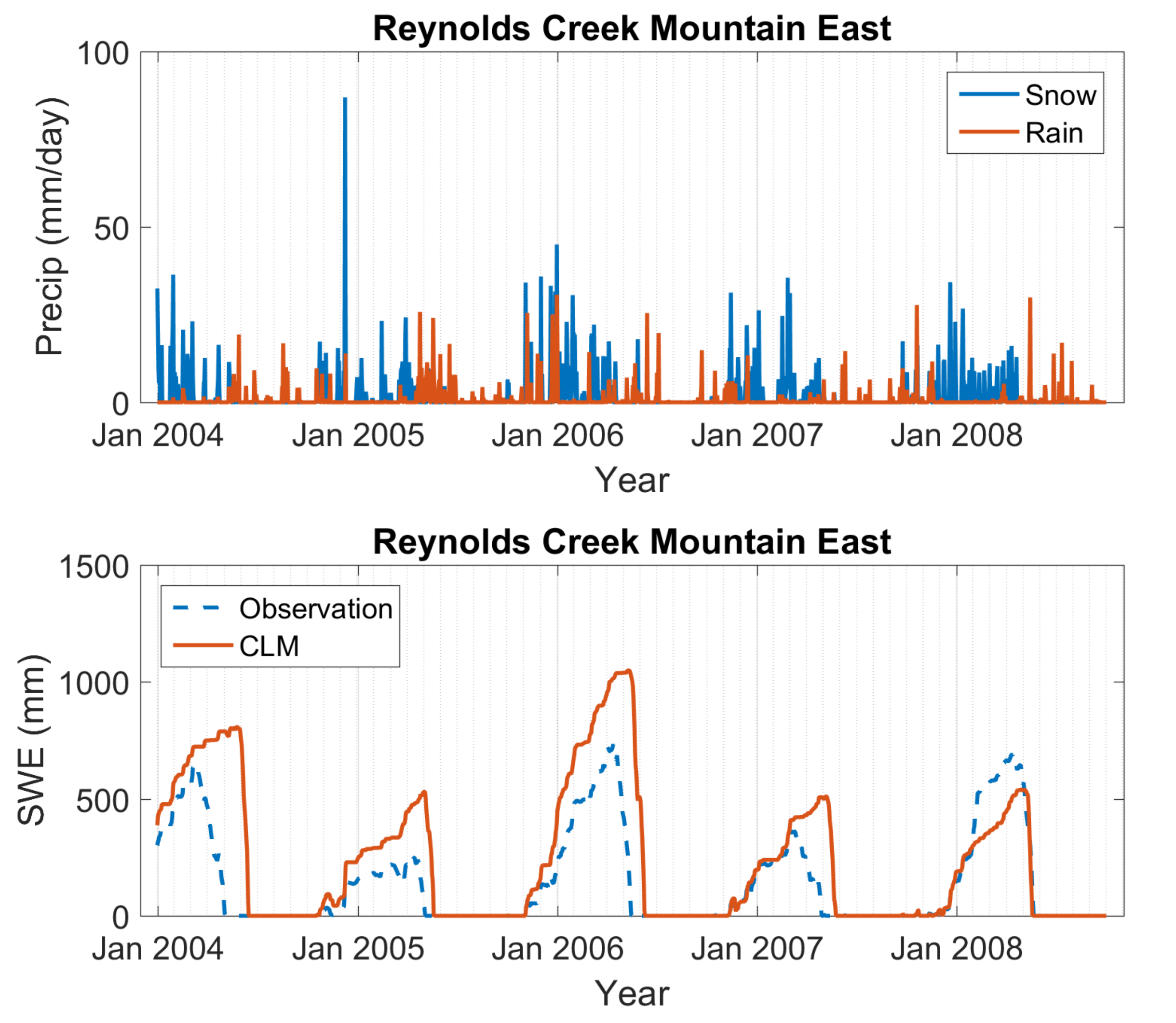


Reynolds Creek Mountain East

- CLM w/ multi-column hillslope increases ET



Reynolds Creek Mountain East

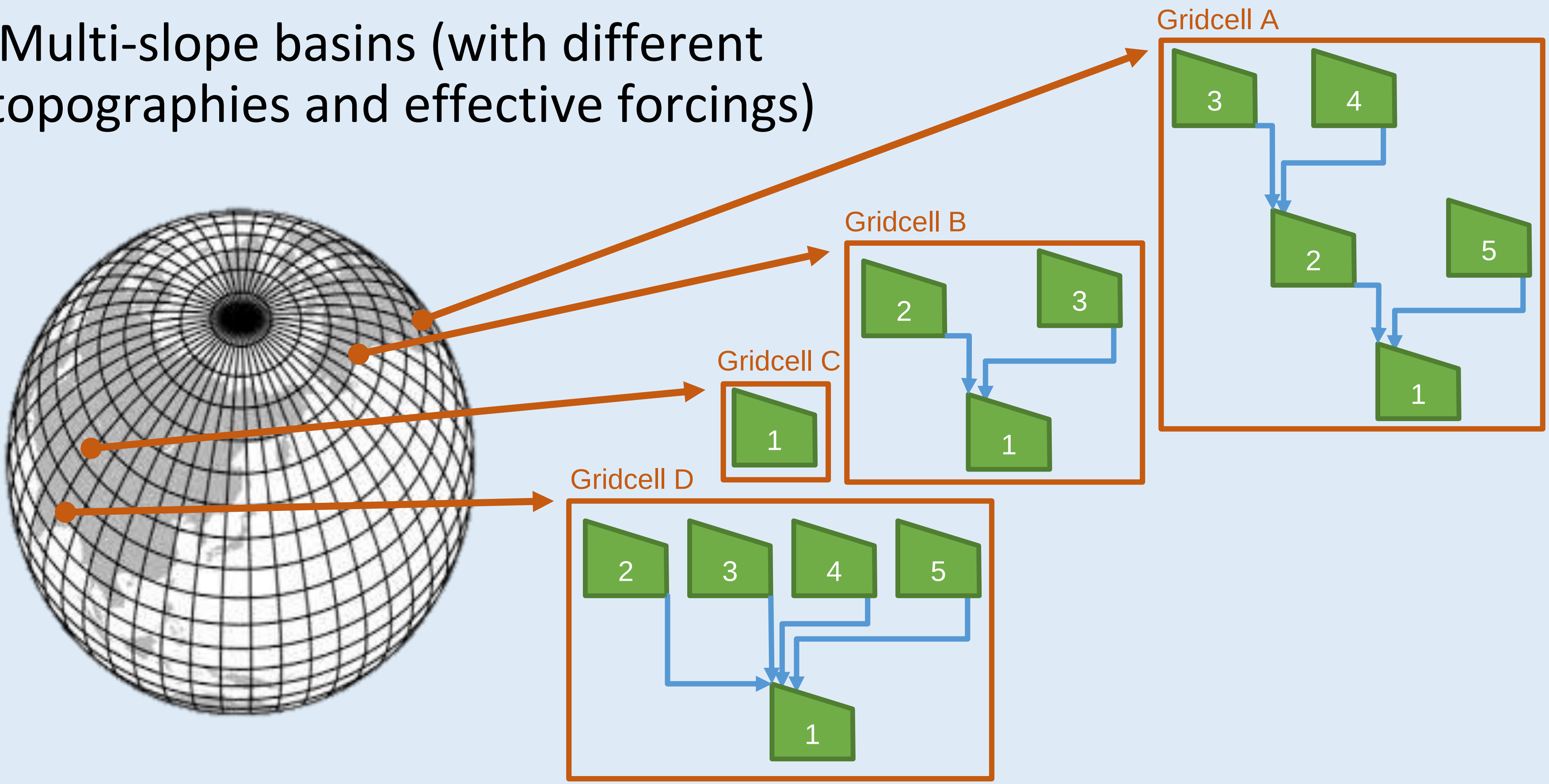


Next Steps

- Columns having unique vegetation

Next Steps

- Columns having unique vegetation
- Multi-slope basins (with different topographies and effective forcings)



Next Steps

- Columns having unique vegetation
- Multi-slope basins (with different topographies and effective forcings)
- Global simulations with Digital Elevation Model-derived datasets