Hydrology in the Community Land Model

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What is Hydrology?

a) the study of water
What is Hydrology?

a) the study of water

b) the science that encompasses the occurrence, distribution, movement and properties of the waters of the Earth and their relationship with the environment within each phase of the hydrologic cycle. *
The Water Cycle

Volcanic steam → Sublimation → Evapotranspiration → Evaporation → Condensation → Surface runoff → Streamflow → Infiltration

Ice and snow → Precipitation → Snowmelt runoff

Atmosphere:
- Sublimation
- Deposition
- Evaporation
- Evapotranspiration
- Condensation

Groundwater:
- Groundwater flow
- Freshwater
- Spring
- Seepage

Oceans:
- Ocean currents
- Vents

U.S. Dept. of the Interior
U.S. Geological Survey
Howard Perlman, USGS, John Evans
https://water.usgs.gov/edu/watercycle.html
What is Hydrology in CTSM?

a) the fluxes of water into and out of the land

b) the redistribution of water within the land
What is Hydrology in CTSM?

a) the fluxes of water into and out of the land

b) the redistribution of water within the land
The movement of water is inextricably linked to the flow of energy and the life cycle of vegetation.
From: Technical Description of version 5.0 of the Community Land Model (CLM)
The Water Balance

\[ P = E + R + \Delta S \]

- \( P \) = Precipitation
- \( E \) = Evapotranspiration
- \( R \) = Runoff
- \( S \) = Storage
Hydrologic models have different objectives

Flood Forecasting $\Rightarrow$ R

NWP, Climate Prediction $\Rightarrow$ E

Drought Monitoring, Groundwater $\Rightarrow$ S
Different objectives lead to different model structures

1-D $\Rightarrow$ Darcy Flow (Infiltration/Recharge)

2-D $\Rightarrow$ River Routing

3-D $\Rightarrow$ Saturated Flow (Groundwater)
CLM is tasked with simulating *all* of these phenomena...

...therefore, *trade-offs* will be made.
CLM Water Balance Operations

Precipitation
⇒ Partitioning between rain and snow, or between stratiform and convective
⇒ Canopy interception, storage, and throughfall
CLM Water Balance Operations

Evaporation
⇒ Evaporation from Soil / Canopy / Snow / Surface Water
⇒ Transpiration from vegetation
CLM Water Balance Operations

Runoff

⇒ Surface Runoff (Infiltration and/or Saturation Excess)
⇒ Subsurface Runoff (Baseflow)
⇒ River Routing
CLM Water Balance Operations

**Storage**

⇒ Soil Moisture
⇒ Groundwater and water table depth
⇒ Perched water table
⇒ Canopy water
⇒ Surface water
⇒ Snow
Canopy Hydrology

- Section 2.7.1 of the CLM Tech Note
- Interception / throughfall
- Leaf water storage and wetted fraction
- Evaporation from leaf surfaces
Ground Evaporation: 24%

Canopy Evaporation: 23%

Transpiration: 53%
Leaf Wetted Area

Throughfall

Rain

Evaporation

Drip

\[ W_{\text{max}} \]

Leaf Wetted Fraction

\[ \text{frac}_{\text{wet}} \]

\( \text{relative storage} \)
Leaf Wetted Area

Leaf Wetted Fraction vs. Relative Storage

frac_wet

0.0 0.2 0.4 0.6 0.8 1.0

0.0 0.2 0.4 0.6 0.8 1.0

relative storage
Canopy Hydrology
And
Evapotranspiration
Partitioning

Ground Evaporation:
21%

Canopy Evaporation:
18%

Transpiration:
61%
Runoff and Surface Water Processes

- Section 2.7.2 of the CLM Tech Note
- Surface runoff
- Saturated area
- Subsurface runoff
- River routing
- Surface water (wetlands)
Runoff Generation and Infiltration

- Surface Runoff
- Subsurface Runoff
- Infiltration
- Recharge
- Vegetation
- Unsaturated Zone
- Saturated Zone
- River Storage
The water table determines the fraction of the area that is saturated.

Saturated areas produce surface runoff.
Point at which water table intersects surface determines saturated fraction

- Saturated fraction = 0.36
- Saturated fraction = 0.14
Fmax variable on surface data file determines maximum saturated fraction
Dry Surface Layer (DSL)

Figure 9. Estimated thickness of the dry surface layer (DSL) during transient evaporation. The line indicates the approximate trend. Inset: Conceptual structure of near-surface transition layer used for estimating thickness of the dry surface layer (DSL) with thickness ($z$) and thermal conductivity ($\lambda$).

Deol et al.  
WRR, 2012

Vapor Diffusion

Liquid Diffusion

Vapor Diffusion < Liquid Diffusion
Soil Evaporative Resistance

Surface Soil Moisture vs Soil Resistance

Section 2.5.2 of CLM Tech Note
Little infiltration – precipitation rapidly returned to atmosphere

Larger infiltration events during winter – evaporation peaks during summer
Soil Moisture Redistribution

- Section 2.7.3 of the CLM Tech Note
- Moisture form of Richards equation with adaptive sub-stepping
- Water moves due to gravity and gradients in soil matric potential
Soil model

Treats processes such as:

- Soil moisture redistribution
  - Infiltration
  - Darcy flow
  - Recharge

- Soil moisture phase change
- Soil temperature redistribution

Default structure has 20 layers of variable thickness, spanning about 8 meters depth
  - Thermal calculations use additional deep layers
a) Soil moisture (% saturation)

b) Soil temperature (°C)

Stippling indicates frozen soil
Percent sand

Percent clay
Soil Hydraulic Properties

Soil Matric Potential

Soil Hydraulic Conductivity
Adaptive time stepping method for soil water distribution

Variable time step length depending on solution error

Eliminates numerical instabilities in Richards equation solution
Groundwater and Water Table Dynamics

- bulk aquifer layer
- bedrock (zero vertical flux) lower boundary
- subsurface discharge depends on water table depth
Soil Depth

- deep soil / variable soil depth
- high vertical resolution soil
Overall Depth to Bedrock (~1 km resolution)

- 0 - 2 meters
- 2 - 10 meters
- 10 - 20 meters
- 20 - 30 meters
- 30 + meters

Slide courtesy M. Brunke, U. Arizona
River model

- Routes runoff to the oceans

- Flow directions are obtained from an input dataset

- Calculates water volume and discharge
Hillslope routing accounts for event dynamics and impacts of overland flow on soil erosion, nutrient loading, etc.

Sub-network routing: scale adaptive across different resolutions to reduce scale dependence

Main channel routing: explicit estimation of in-stream status (velocity, water depth, etc).

(Li et al., JHM, 2013)
Model Validation Tools

Ideally, should be:

• Global
• Directly comparable to modeled process/state/flux
• Same spatial / temporal scale
• High accuracy
• Long record

In reality, no datasets meeting these criteria exist...
Soil Moisture Networks

Top panel: CLM soil moisture
Bottom: Observed soil moisture
River Discharge

Ob at Salehard

Yenisey at Igarka

Lena at Kusur

Mekong at Pakse

Ganga at Farakka

Mississippi at Vicksburg
Gridded Model-Data Synthesis Products

Examples: FLUXNET-MTE, FLUXCOM

Top panel: FLUXNET-MTE
Bottom: CLM
FLUXNET-MTE

Columbia River Basin
Evapotranspiration

Red: FLUXNET-MTE
Blue/Green: CLM

Evapotranspiration

Columbia
GRACE Total Water Storage

Top panel: GRACE
Bottom: CLM
GRACE Total Water Storage

Columbia River Basin
Total Water Storage

Red: GRACE
Blue/Green: CLM
CLM Application Example: Anthropogenic Groundwater Withdrawal

Human-induced groundwater changes can be estimated by removing the CLM estimate of TWS from the GRACE estimate of TWS:

- **GRACE TWS**
- **CLM TWS**
- **Groundwater**
Example I
Effects of Parameter Change

60W / 5S
Hydrologically Relevant Surface Data
Hydrologically Relevant Surface Data
lon:300.0/lat:-5.2

**Precipitation**

![Precipitation Graph](image)

**Runoff**

![Runoff Graph](image)

**Evapotranspiration**

![Evapotranspiration Graph](image)
lon:300.0/lat:-5.2

Runoff

Saturation

Water Table
Example: Effects of Modifying the Water Table

\[ \Delta ZWT = Q_{\text{drainage}} - Q_{\text{recharge}} \]

\[ Q_{\text{drainage}} = A \exp(-f z) \]

\[ Q_{\text{surface}} = F \exp(-g z) P_{\text{throughfall}} \]
Example II
Model Structural Change

NE Australia
GRACE Water Storage Comparison

NE_Australia

![Graph showing total water storage over time with two lines representing GRACE and CLM4.5 models.](image-url)

Map of Australia highlighting a region of interest.
GRACE Water Storage Comparison

- Total Water Storage
- Groundwater Storage
- Soil Water Storage
Spatially Variable Soil Depth
GRACE Water Storage Comparison

Graphs showing water storage trends over time in NE Australia, comparing GRACE and CLM4.5 models. The graphs include data for Total Water Storage, Groundwater, Soil Moisture, and Total Water Storage (TWS).
Current and Future Challenges

• Subgrid heterogeneity and covariance of vegetation, soil moisture, surface water and snow
• Within-canopy turbulent fluxes
• Human management and withdrawals
• Groundwater dynamics
• Dynamic lakes
• Hydrological response to land cover change
Questions?