WRF-Hydro: System Conceptualization & Parallelization

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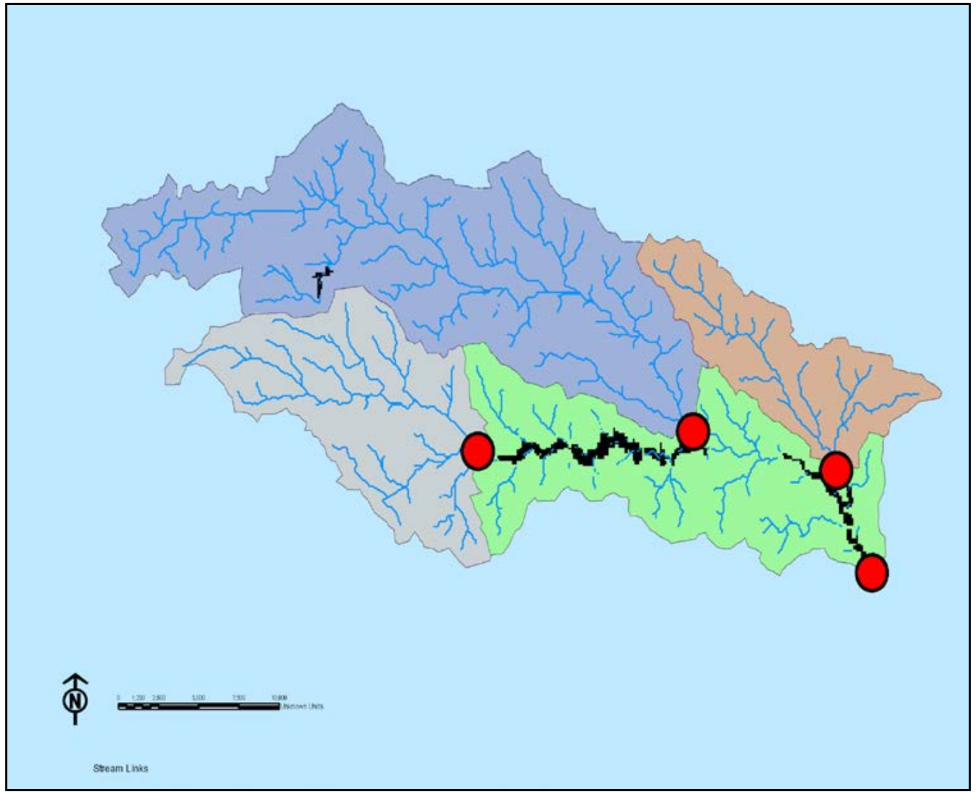
Conceptualization of Land Surface
vs.
Traditional Hydrologic Models

Description of traditional hydrological models:

- Discrete spatial elements:

  - Catchments
  - Hillslopes
  - Response Units ('X'RUs)
  - Aquifers
  - Reservoirs
  - River networks

  - Often as 'objects'



Description of traditional hydrological models:

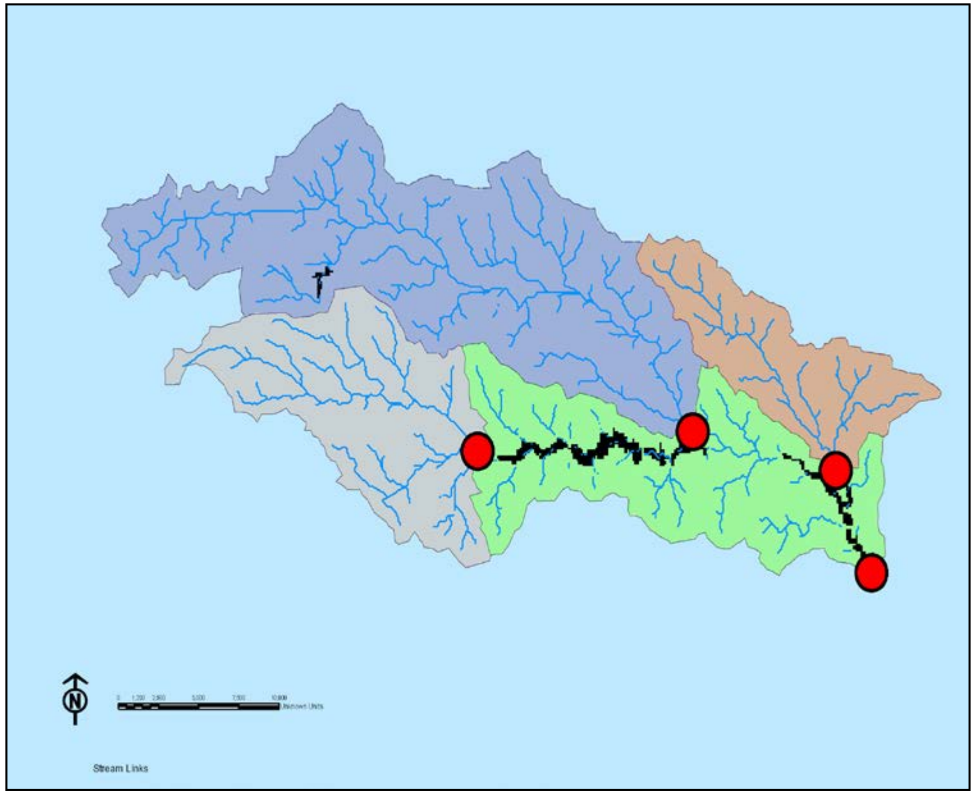
- Traditional/engineering hydrologists often viewed the world as catchments of 'black boxes':
- Rational method:

$$Q_{Peak} = CA\bar{R}$$ ca. 1851

C = coefficient/scaling parameter
A = catchment area
R = avg precip intensity

- Curve Numbers:

$$Q = \frac{(P - \lambda S_{max})}{P + (1-\lambda)S_{max}}$$

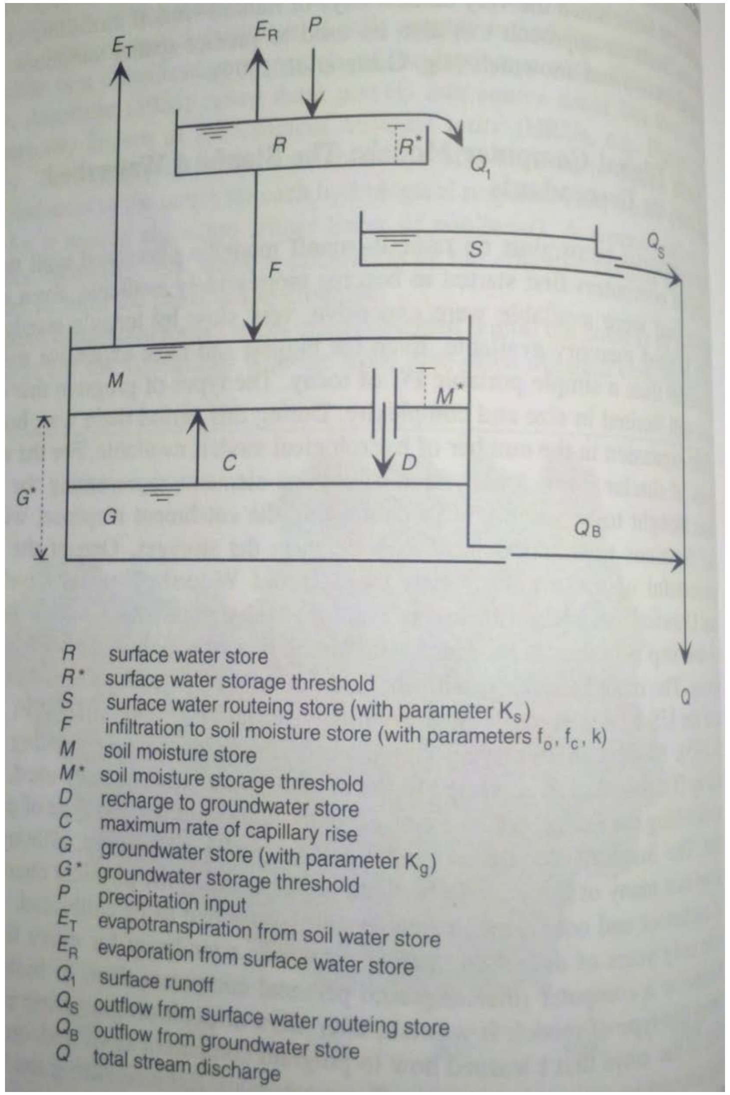


Q = total runoff volume
P = volume of precipitation
Smax = empirical maximum storage volume ~ $\left(\frac{100}{CN} - 1\right)$
CN – Curve number, empirical for land cover/land use, adjusted for antecedent moisture conditions
λ = empirical coefficient

Description of traditional hydrological models:

- Traditional/engineering hydrologists often viewed the world as catchments of ‘black boxes’:

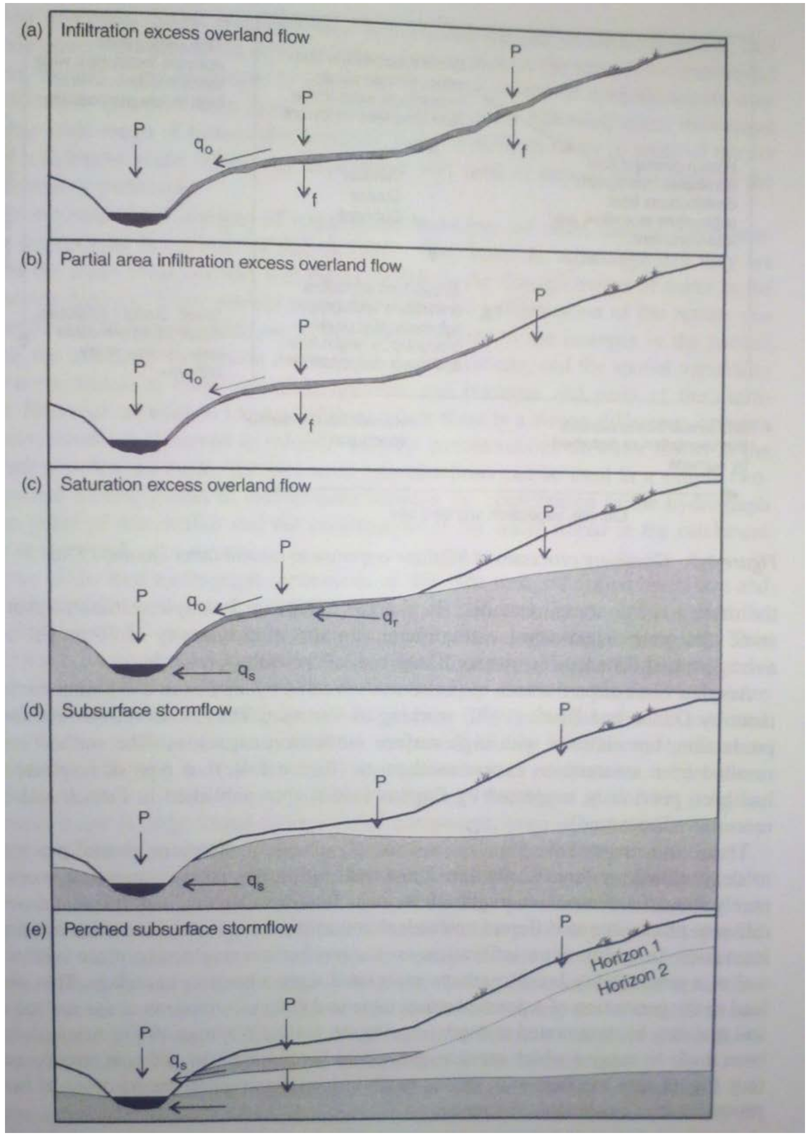
- ‘Stanford Model (soil moisture accounting):
  - Series of storages (buckets)
  - Movement between buckets
  - Discharge/ET from buckets



Beven, 2003

Description of hydrological models:

- Modern hydrologists attempt to ‘move water’ around based on spatial gradients and coupled energy and water fluxes…
  - ‘Hillslope hydrology’
  - River channel hydraulics
  - Ecosystem/atmo interactions
  - Biogeochemistry



Beven, 2003

Description of hydrological models:

- Fundamental surface flow equations expressed in terms of the St. Venant Equations:

$$-\frac{\partial A\rho g h}{\partial x} + \rho g A S_o - \tau P = \frac{\partial \rho A v}{\partial t} + \frac{\partial \rho A v^2}{\partial x}$$

along channel change in hydrostatic pressure + Loss in Potential energy + Friction loss + Local time Rate of change in momentum + Along channel Change in momentum

- Fundamental sub-surface flow equations expressed in terms of Darcy-Richard's Equations:

$$\frac{\partial \rho \theta}{\partial t} = \nabla \left[\rho K(\theta) \nabla \psi\right] + \frac{\partial \rho K(\theta)}{\partial z} - \rho E_T(x, y, z, t)$$

Time rate of Change of soil moisture

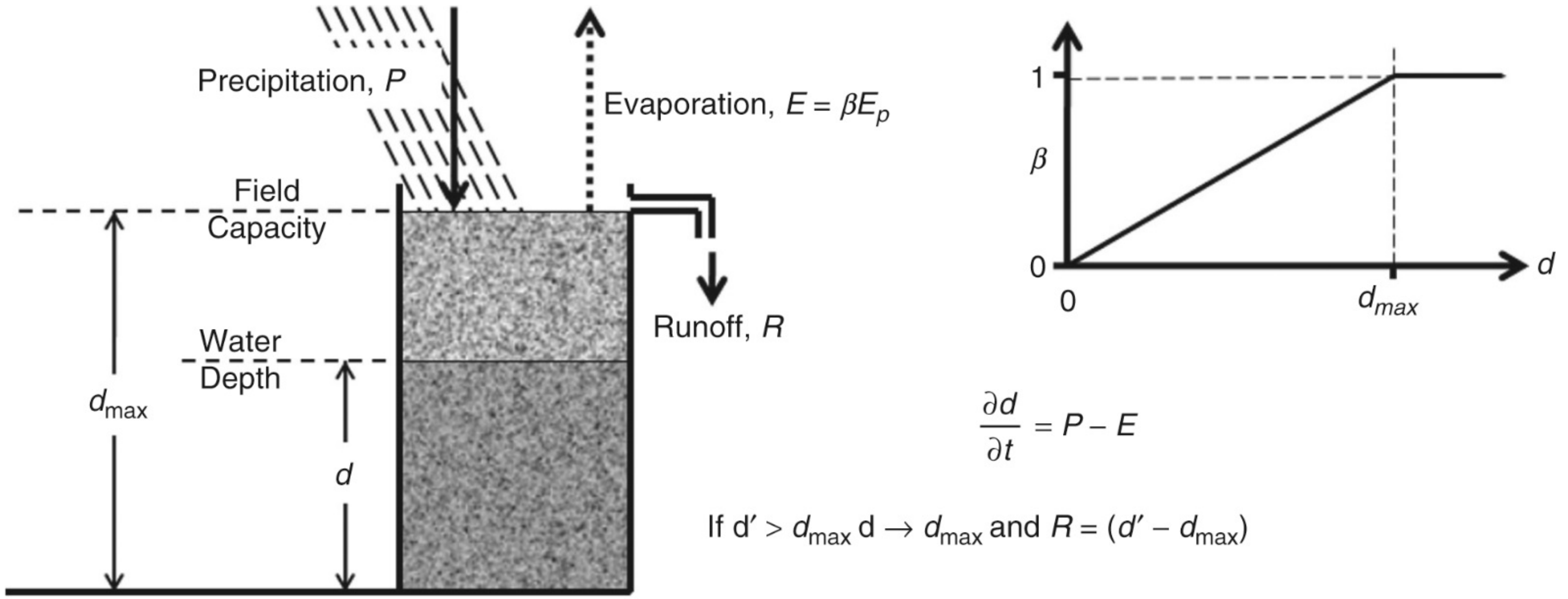
Divergence of Soil moisture expressed In terms of Darcy's law Due to soil matric poteintial

Add vertical flux Due to hydrostatic forces

Sink of moisture Due to ET

Land Surface Parameterizations:

- First generation: ‘Bucket’ Models



Terrestrial Hydrometeorology, First Edition. W. James Shuttleworth.

Figure 24.1 Schematic diagram of the SVATS used in early studies of the effect of land surfaces on weather and climate based on the ‘Budyko Bucket’.

Land Surface Parameterizations:

Implementation of plant/canopy resistance formulations

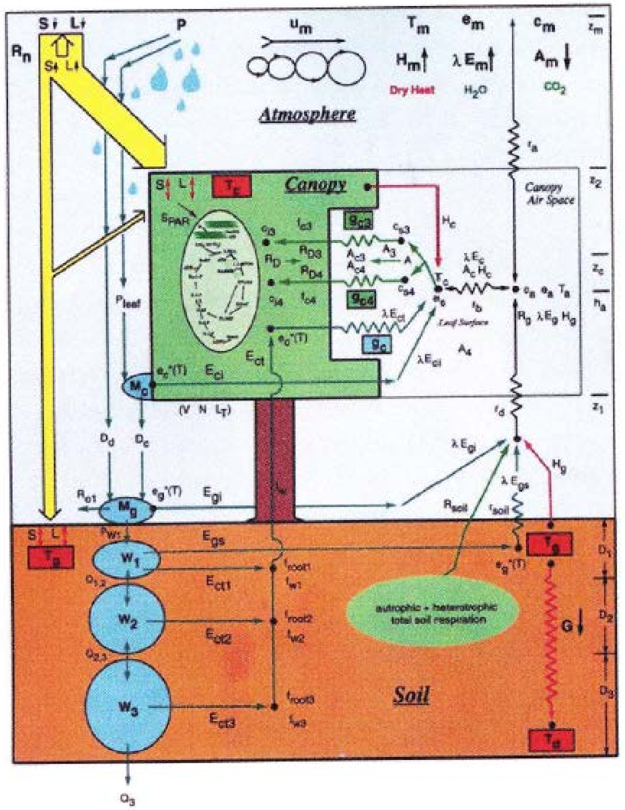


Plate 2 A schematic diagram of the physical and physiological processes represented in the second generation Simple Biosphere (SiB2) soil vegetation atmosphere transfer scheme. (From Colello *et al.*, 1998, published with permission.)

- Akin to Ohm's law for electrical circuits
- Reduces flux based on a variety of factors:
  - Plant cover fraction
  - Quality and amount of solar radiation
  - Atmospheric vapor pressure deficit
  - Leaf temperature
  - Soil moisture status

Jarvis-Stewart Model: $\frac{1}{r_s} = g_s = g_0 g_c g_R g_D g_T g_M$

Generational view of land surface models:

- 2nd Generation land models: P-M-style canopy resistance formulations

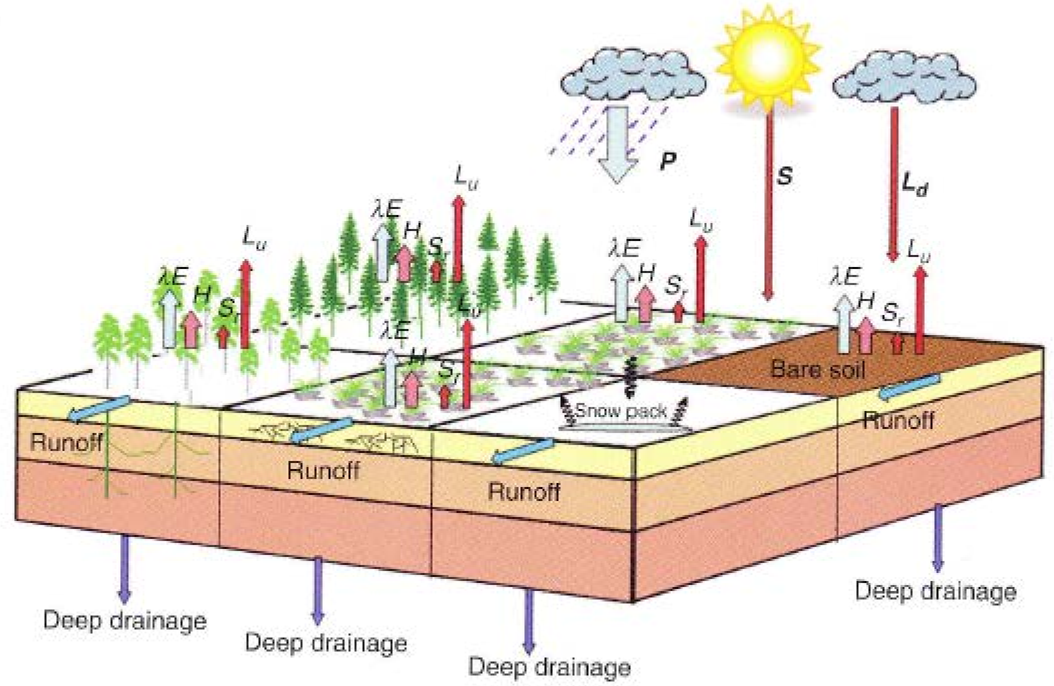


Plate 3 Schematic diagram of second generation one-dimensional SVATs in which a plot-scale micrometeorological model with an explicit vegetation canopy was applied at grid scale.

Shuttleworth, 2011

Generational view of land surface models:

- 3rd Generation land models:
  – Better soil hydrology: Richard's Eq., improved 'runoff'

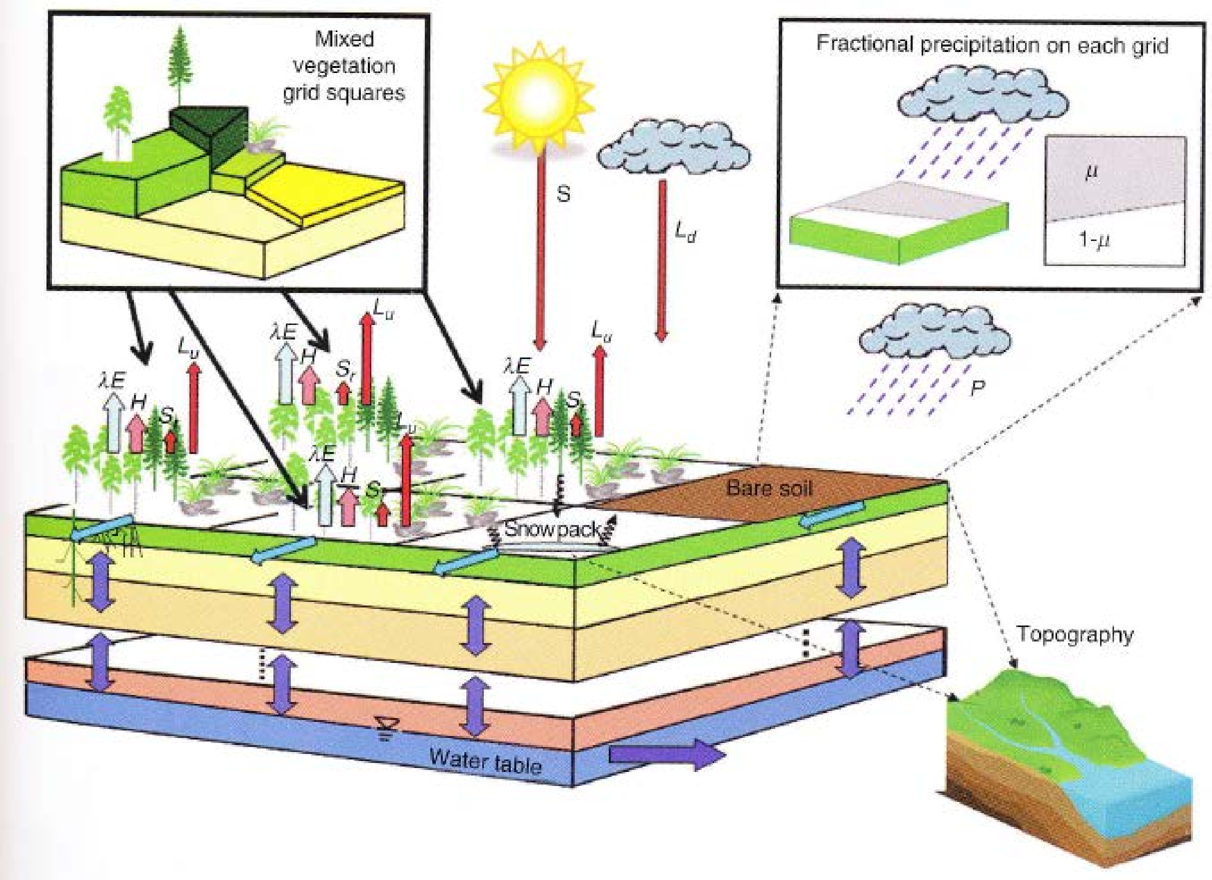


Plate 4 Schematic diagram of SVATS with improved representation of hydrologic processes.

Shuttleworth, 2011

Generational view of land surface models:

- 4th Generation land models: Photosynthesis and dynamic phenology

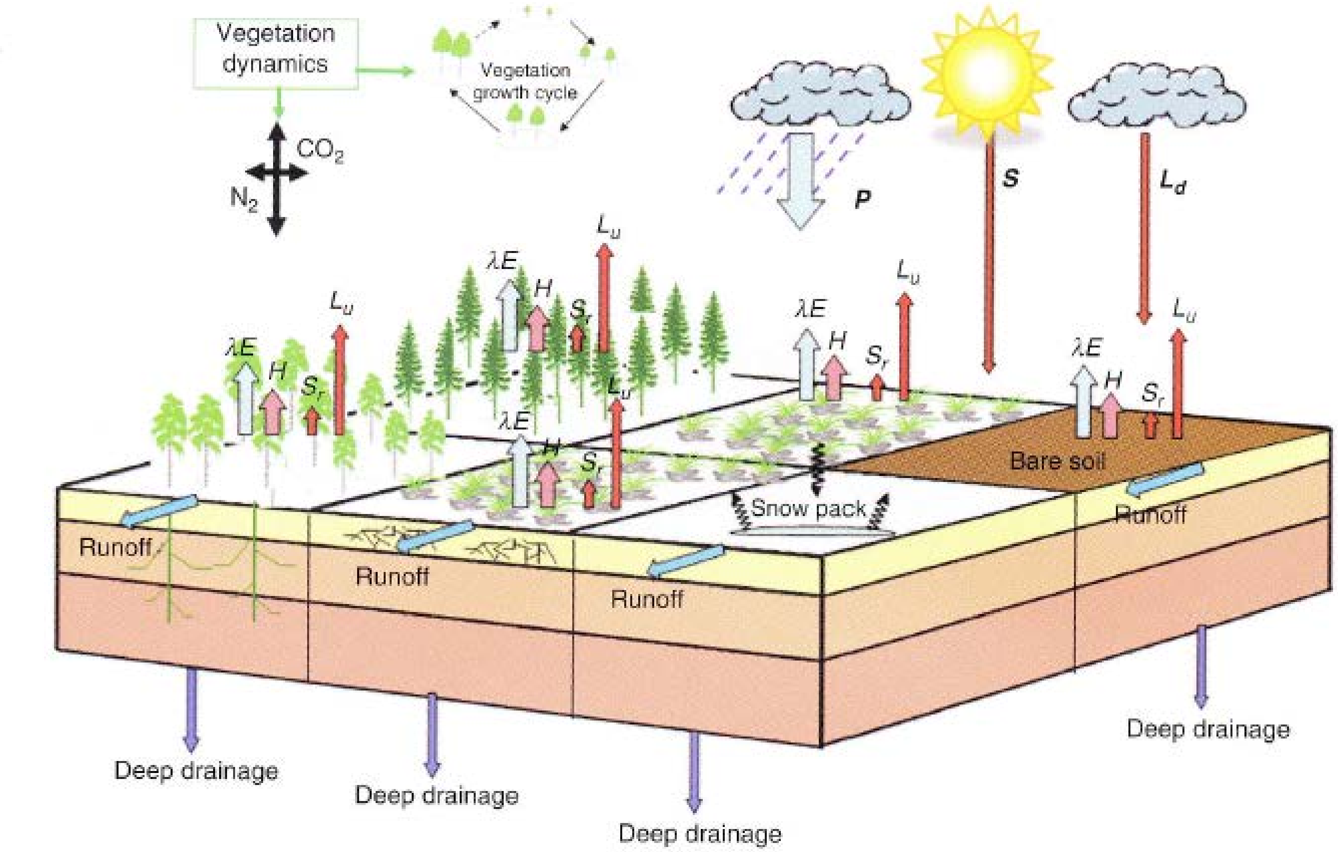


Plate 5 Schematic diagram of SVATS with improved representation of vegetation related processes, including CO_2 exchange and ecosystem evolution.

Shuttleworth, 2011

Generational view of land surface models:

- The ‘greening’ of land surface models:
  - Allowed for greater physiological control or specification of various plant resistance/conduction terms:
  - ‘Photosynthesis-based’ conductance formulation (Ball-Berry):

$$\frac{1}{r_s} = m(A_n/C_s)P_l F_e + \frac{1}{r_{s\,min}}$$

A_n – carbon assim.
C_s – CO_2 concentr.
P_l – atmosheric press.
F_e – humidity stress fact.

  - Plant physiology-based ‘carbon-assimilation’ capacity (Farquhar)

Shuttleworth, 2011

Generational view of land surface models:

- 5th Generation land models: Sub-grid variability, distributed hydrology, data assimilation

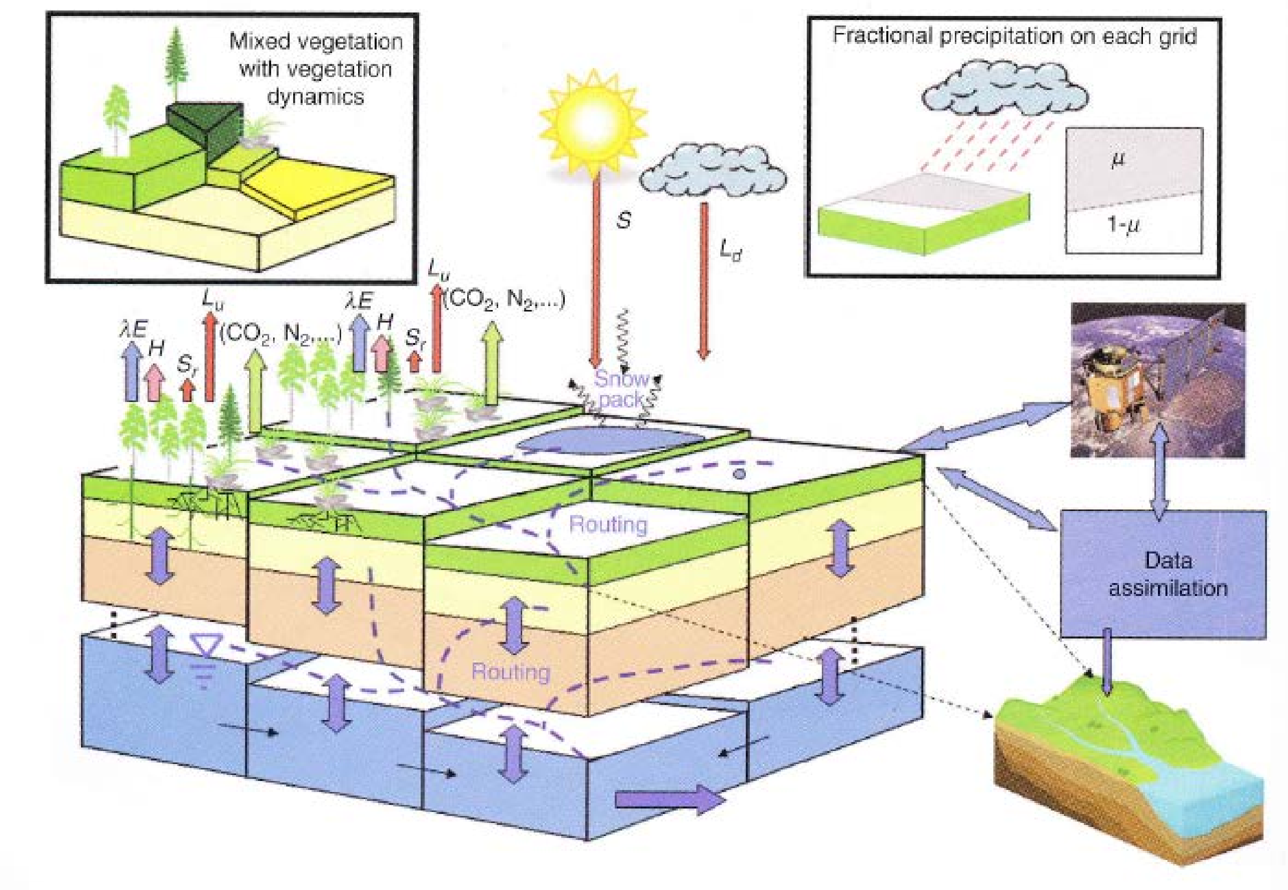
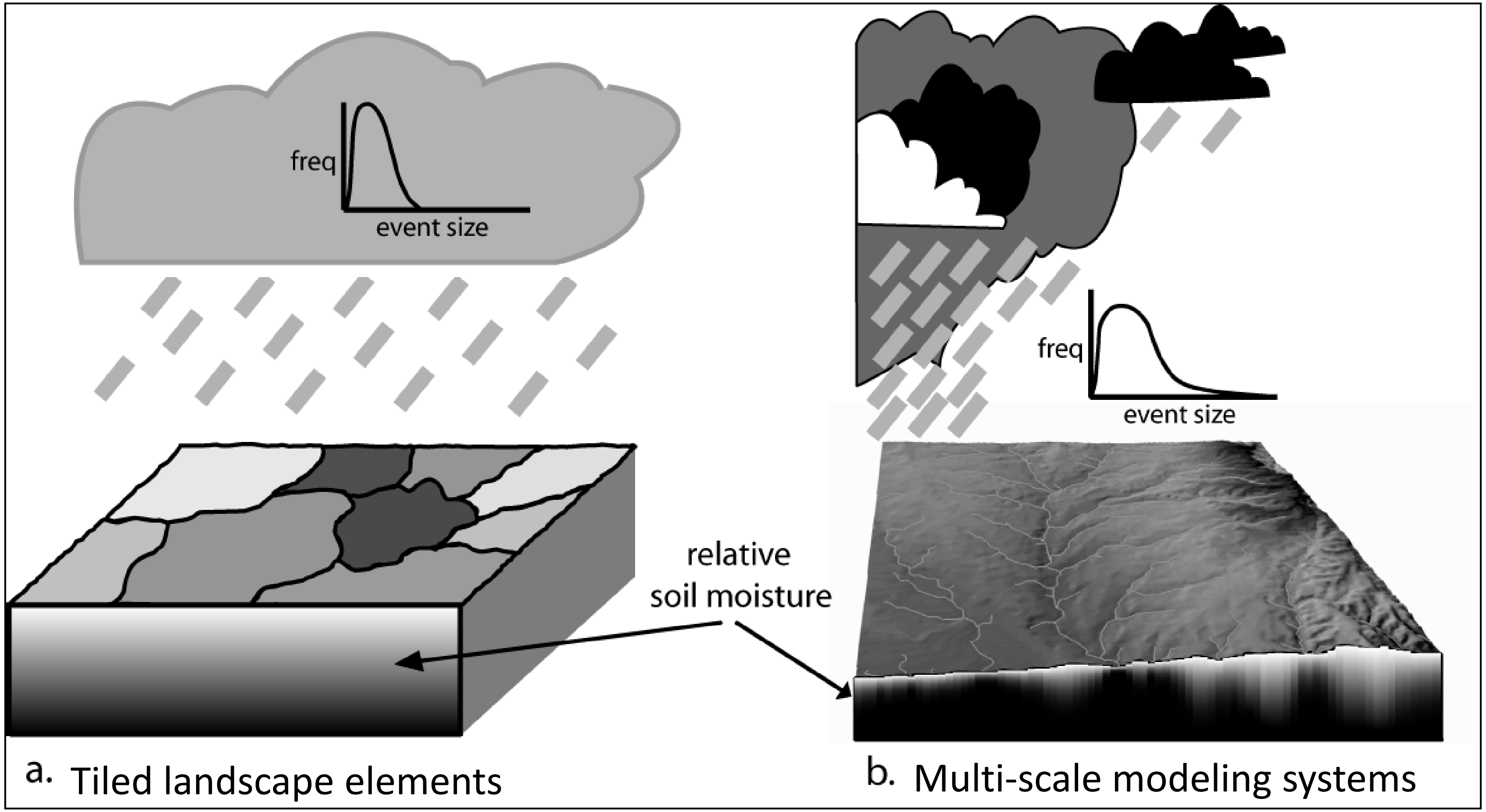


Plate 6 Schematic diagram of potential future developments in SVATS.

Shuttleworth, 2011

Modern integrated land surface models:

- Linking multi-scale process models in a consistent Earth System Modeling framework



Land surface parameterizations:

Table 24.1 Requirements in a Soil-Vegetation-Atmosphere Transfer (SVAT) scheme: (A) Basic variables that must be calculated at each model time step by a SVAT if it is used in a meteorological model; (B) Additional required calculations to allow representation of the hydrological impacts of climate; (C) Additional required calculations to allow representation of changes in CO_2 (and perhaps other trace gases) in the atmosphere.

A. Basic requirements in meteorological models

1. *Momentum absorbed from the atmosphere by the land surface* – requires the effective area-average aerodynamic roughness length.
2. *Proportion of incoming solar radiation captured by the land surface* – requires the effective area-average, wavelength average solar reflection coefficient or albedo.
3. *Outgoing longwave radiation* (calculated from area-average land surface temperature) – *requires the effective area-average, wavelength average emissivity of the land surface.*
4. *Effective area-average surface temperature* of the soil-vegetation-atmosphere interface - required to calculate longwave emission and perhaps energy storage terms.
5. *Area-average fraction of surface energy leaving as latent heat (with the remainder leaving as sensible heat)* - to calculate this other variables such as soil moisture and/or measures of vegetation status are often required, these either being prescribed or calculated as state variables in the model.
6. *Area-average of energy entering or leaving storage* in the soil-vegetation-atmosphere interface (required to calculate the instantaneous energy balance).

B. Required in hydro-meteorological models to better estimate area-average latent heat and to describe the hydrological impacts of weather and climate

7. *Area-average partitioning of surface water* into evapotranspiration, soil moisture, surface runoff, interflow, and baseflow.

C. Required in meteorological models to describe indirect effect of land surfaces on climate through their contribution to changes in atmospheric composition

8. Area-average exchange of carbon dioxide (and possibly other trace gases).

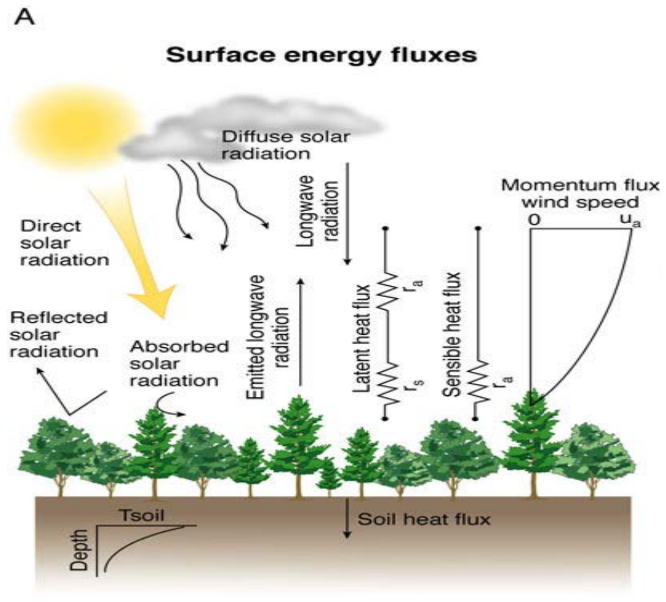
Shuttleworth, 2011

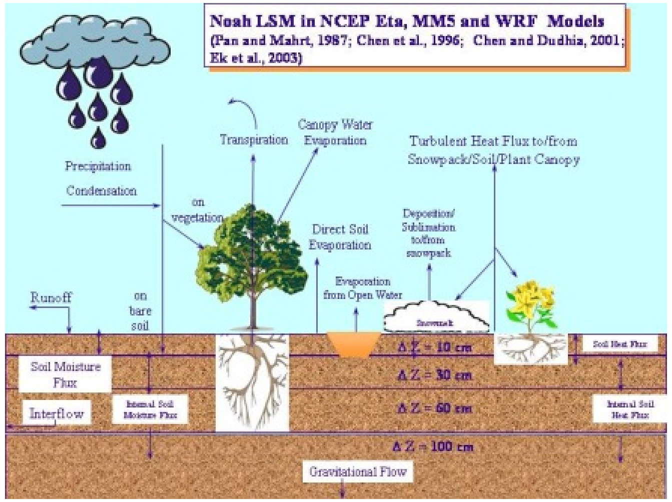
Community land surface models:

1. Community Land Model (CLM-deprecated):
    a) Designed for climate/Earth system modeling
    b) Emphasizes biogeochemical (C/N) and ecosystem complexity
    c) Coupled to CCSM and regional climate models where ***timescale of terrestrial dynamics is relevant for climate behavior***

2. Community 'Noah' and 'NoahMP' land surface model:
    a) Designed for use in numerical weather prediction
    b) Relatively simple, robust and efficient, emphasizing computational efficiency for operational forecasting
    c) Coupled to NCEP NAM, GFS and NCAR WRF

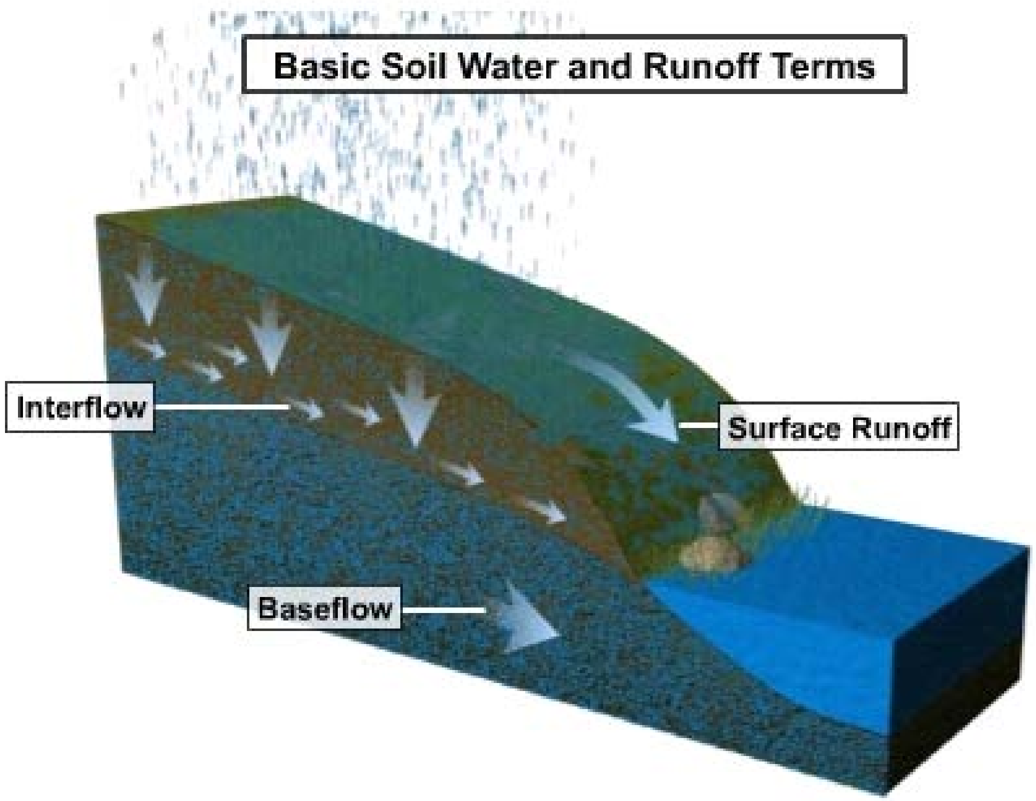
3. Both models have an open and mature working group structure comprised of scientists from many disciplines (though clearly biased towards atmospheric sciences)





‘Moving Water Around’: scale and process issues

- Terrain features affecting moisture availability (scales ~1km)
  - Routing processes: the redistribution of terrestrial water across sloping terrain
    - Overland lateral flow (dominates in semi-arid climates)
    - Subsurface lateral flow (dominates in moist/temperate climates)
    - Shallow subsurface waters (in topographically convergent zones)
  - Channel processes
  - Built environment/infrastructure
  - Water management
  - Other land surface controls:
    - Terrain-controlled variations on insolation (slope-aspect-shading)
    - Soil-bedrock interactions



Courtesy the COMET Program

Model Parallelization

Data Grids:

- Three Data Grids

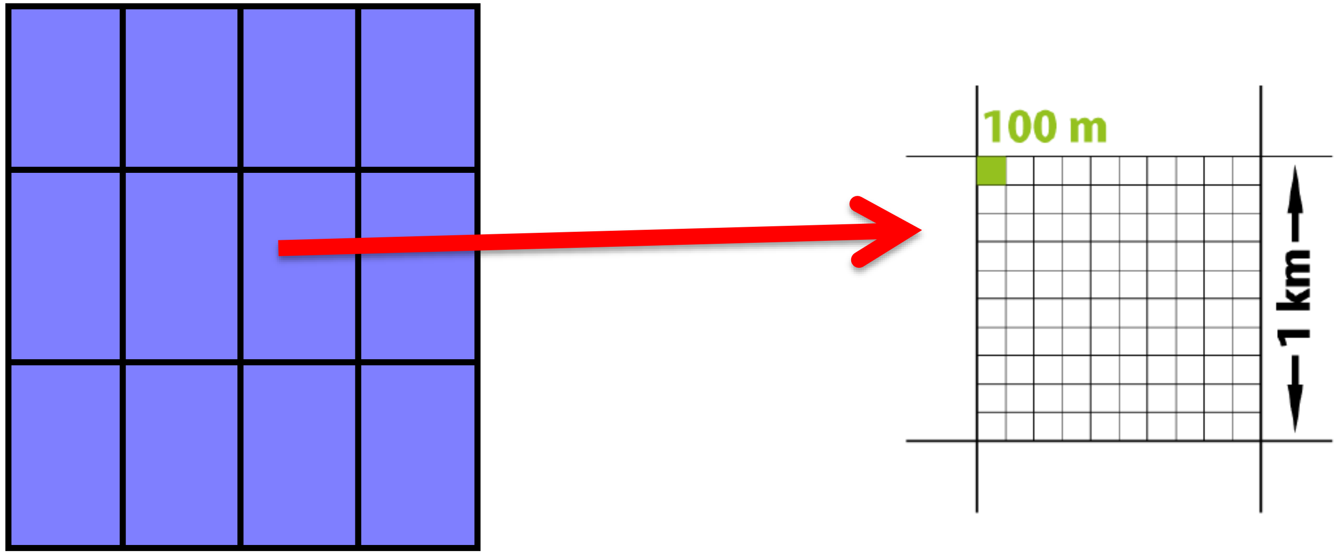
  Land Grids: (ix,jx), (ix,jx, n_soil_layer)

  Land Routing: (ixrt,jxrt), (ixrt,jxrt,n_soil_layer)

  Channel Routing: (n_nodes), (n_lakes)

- Parallel Scheme
  - Two dimensional domain decomposition
  - Distributed system only

WRF-Hydro Multi-Grids Domain Decomposition:

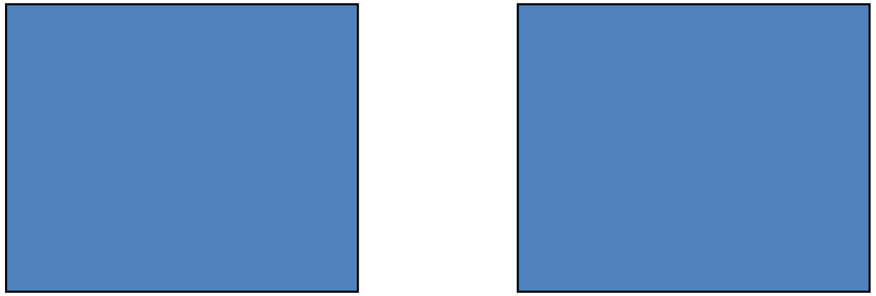


Land grid

Land routing grid cell: regridding

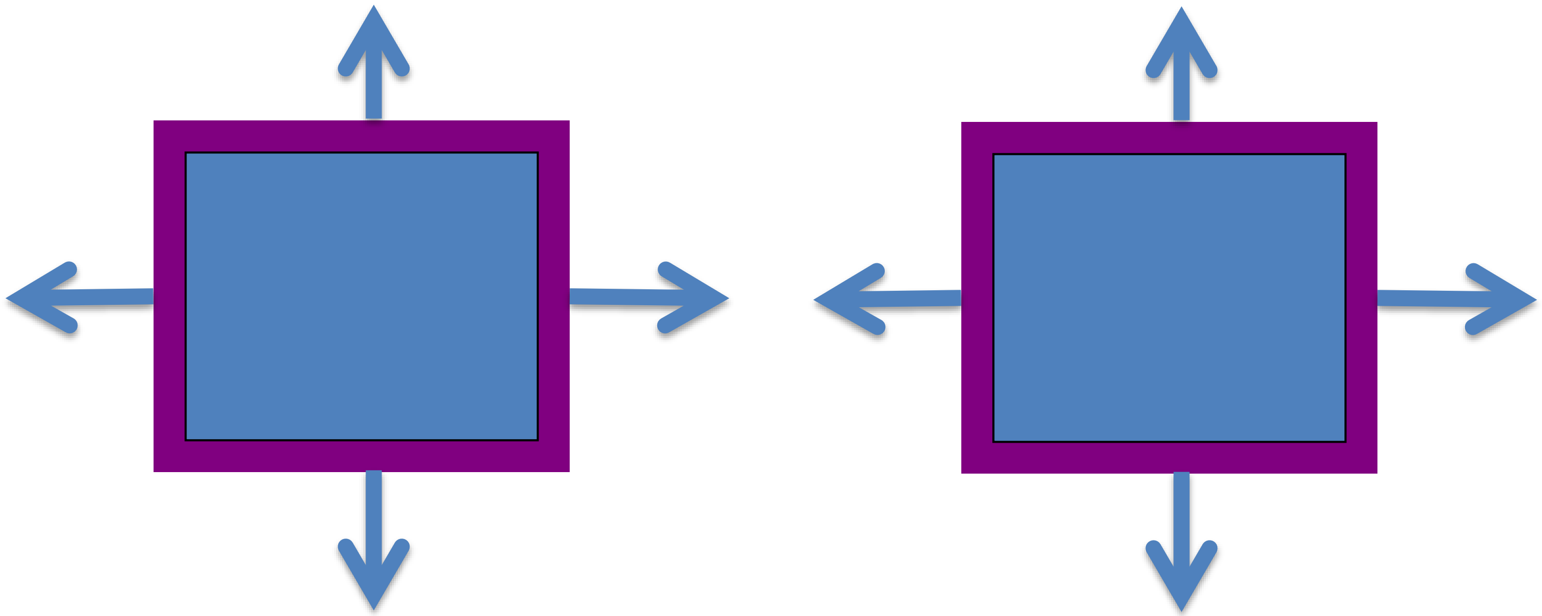
One CPU: Land grid, land routing grid cell, and channel routing nodes.

Distributed memory communications land grid:



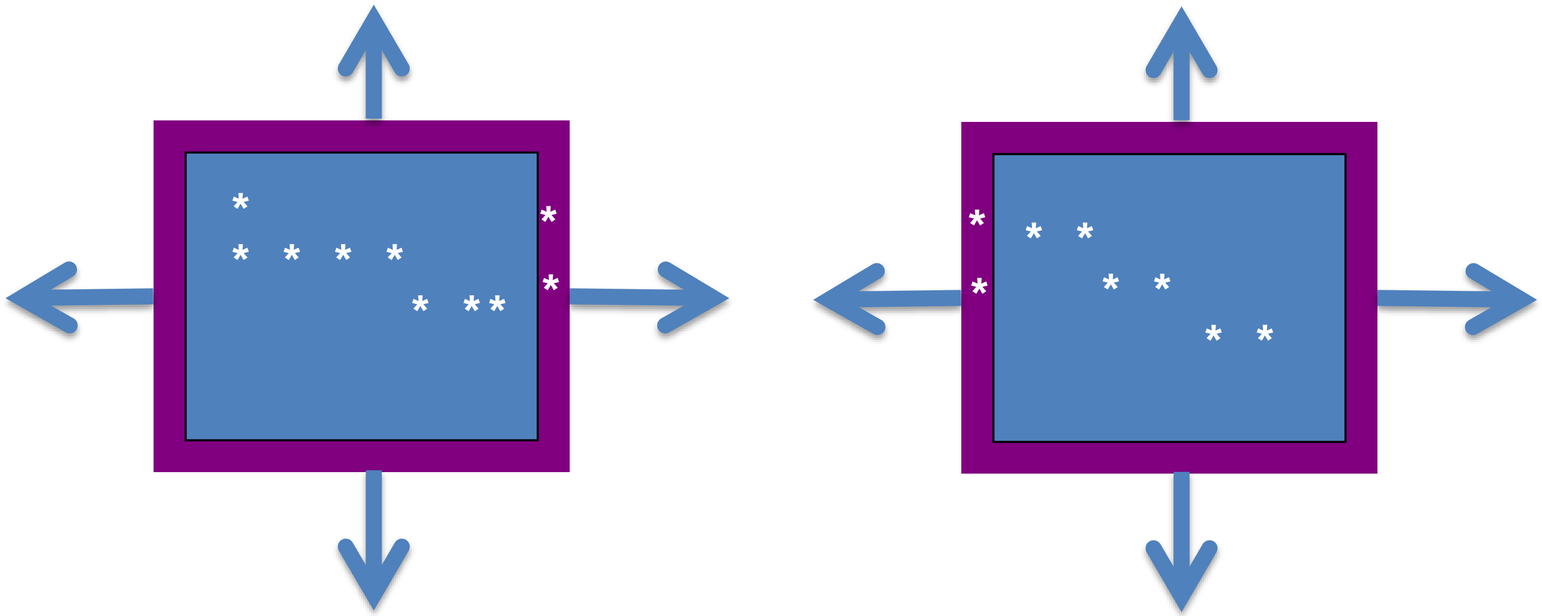
Stand alone columns require no memory communication between neighbor processors

Distributed memory communications land routing grid:



Lateral routing DOES require memory communication between neighbor processors

Distributed memory communications channel routing:

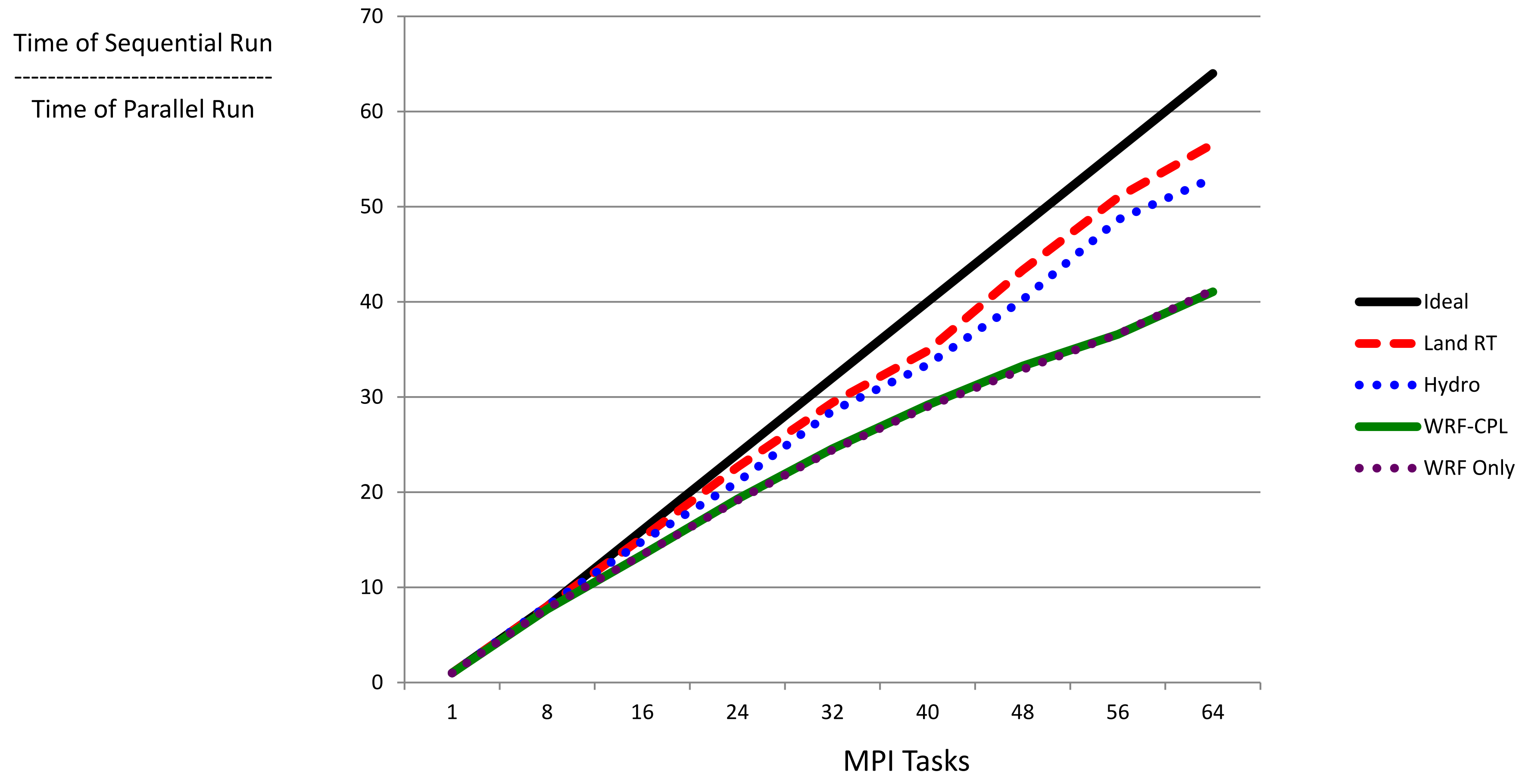


Lateral channel routing DOES require memory communication between neighbor processors, although the arrays are reduced to the sparse matrix of the channel elements

WRF-Hydro Coupling:

- Coupled with WRF
- ‘Un-coupled’ with HRLDAS (1-d Noah land model driver, Noah-MP)
- Coupled with LIS
- Coupled with CLM under CESM coupler (working on recent release of CLM in WRF)

WRF-Hydro performance speed up:



WRF-Hydro: http://www.ral.ucar.edu/projects/wrf_hydro/