WRF-Hydro Modeling System: Physics Components

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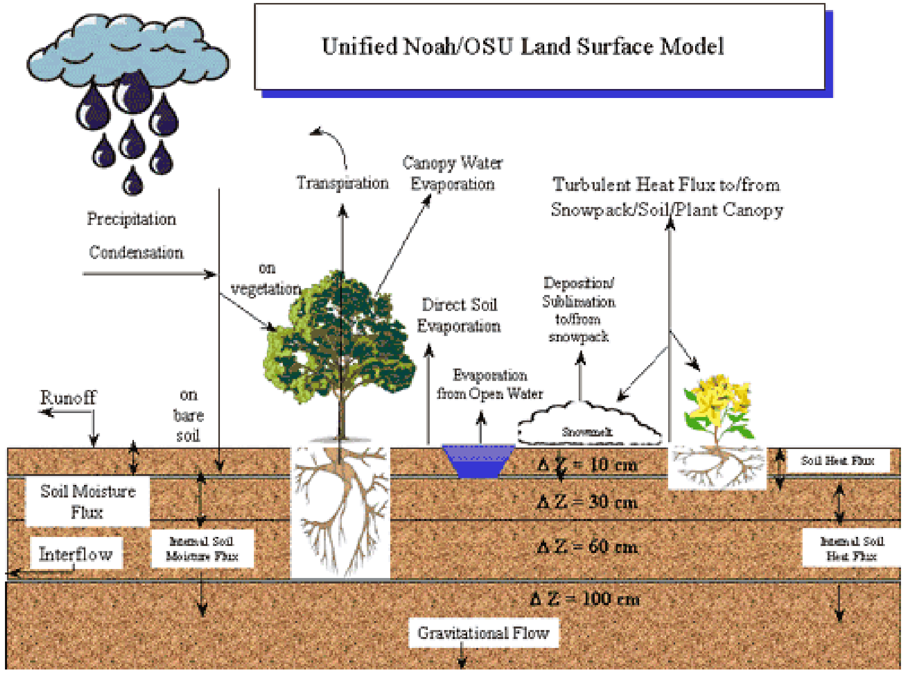
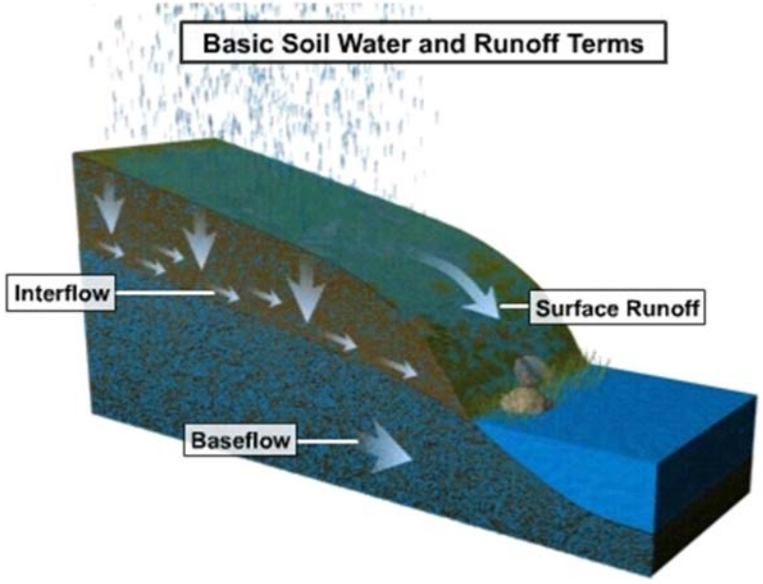
National Center for Atmospheric Research

Basic Concepts:

- Linking the column structure of land surface models with the ‘distributed’ structure of hydrological models in a flexible, HPC architecture….





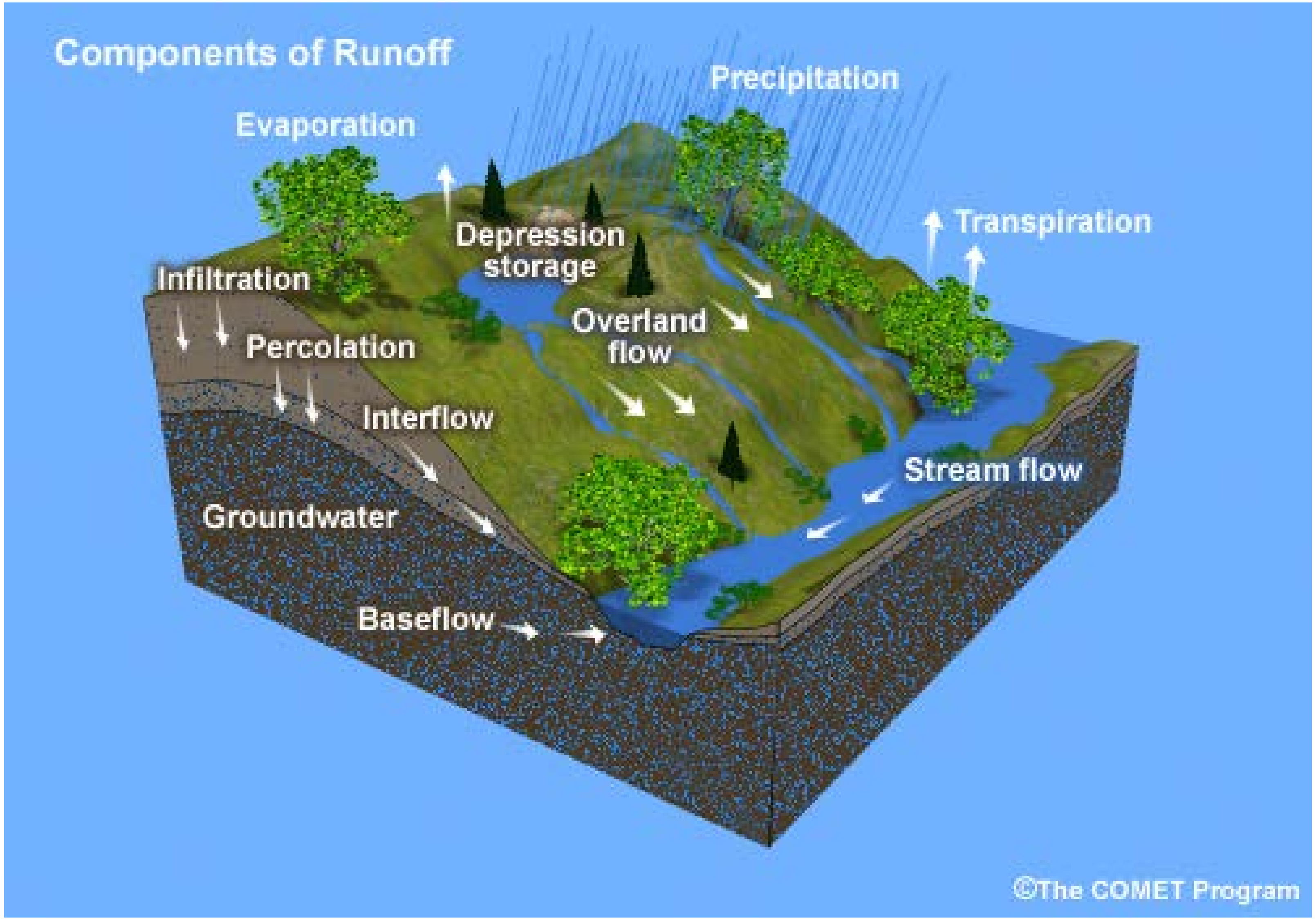
Conceptualization of WRF-Hydro

- Atmospheric coupling perspective and serving the WRF research and forecasting and CESM communities

- Oriented towards existing NCAR-supported community models, but expanding:
  - Not fully genericized coupling which has pros/cons associated…
  - Also aimed at cluster & HPC architectures

WRF-Hydro V5.0 Physics Components

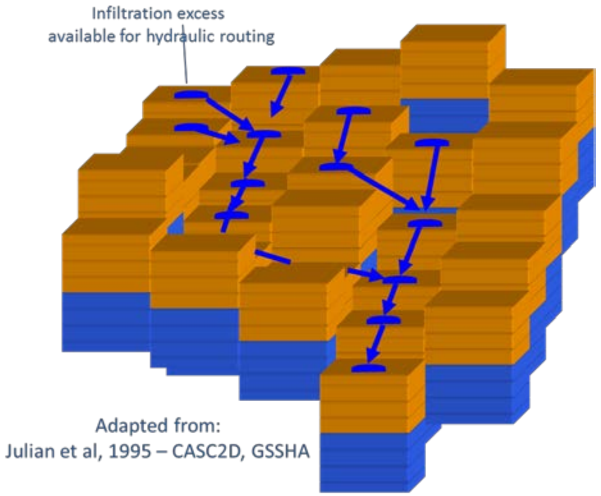
Goal…



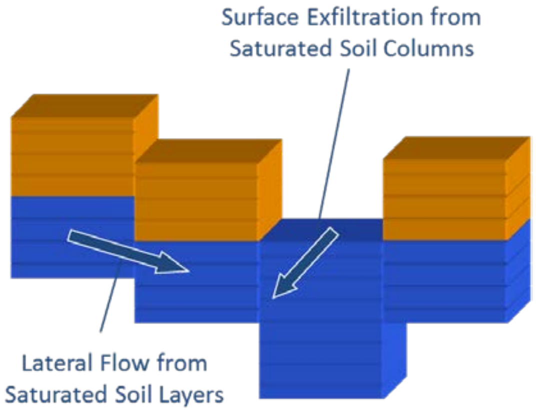
WRF-Hydro V5.0 Physics Components

Runoff and Routing Physics:

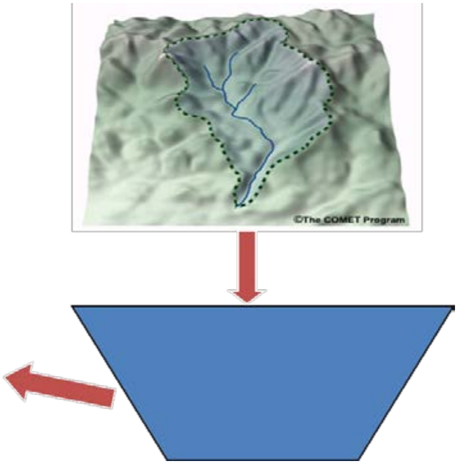
Overland Flow



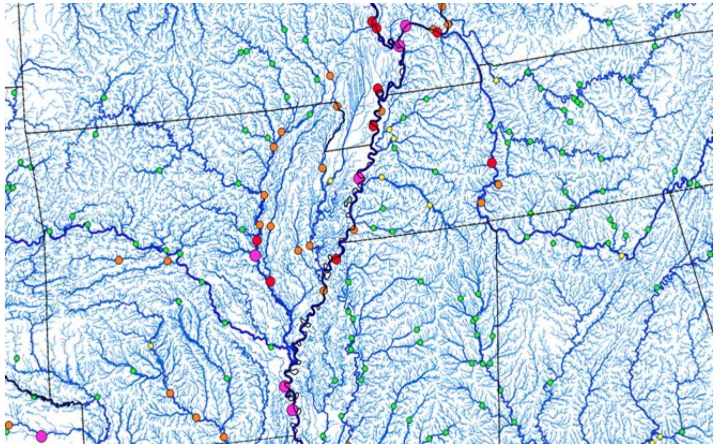
Lateral Subsurface Flow



Simplified Baseflow Parameterization

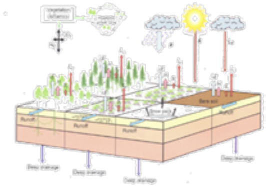
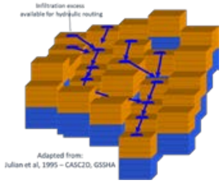
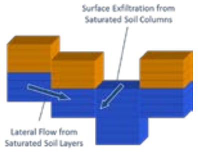
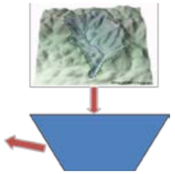
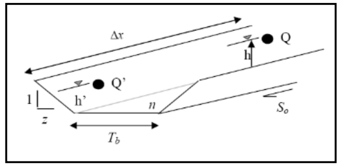
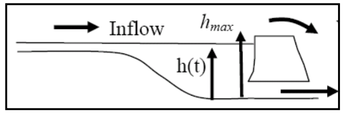


Channel Hydraulics



Simple Water Management

WRF-Hydro Physics Permutations

		WRF-Hydro Options	Current NWM Configuration
Column Land Surface Model		**<u>3 up-to-date column land models</u>:** Noah, NoahMP (w/ built-in multi-physics options), Sac-HTET	NoahMP
Overland Flow Module		**<u>3 surface routing schemes</u>:** diffusive wave, kinematic wave, direct basin aggregation	Diffusive wave
Lateral Subsurface Flow Module		**<u>2 subsurface routing scheme</u>:** Boussinesq shallow saturated flow, 2d aquifer model	Boussinesq shallow saturated flow
Conceptual Baseflow Parameterizations		**<u>2 groundwater schemes</u>:** direct aggregation storage-release: pass-through or exponential model	Exponential model
Channel Routing/ Hydraulics		**<u>5 channel flow schemes</u>:** diffusive wave, kinematic wave, RAPID, custom-network Muskingum or Muskingum-Cunge	Custom-network (NHDPlus) Muskingum-Cunge model
Lake/Reservoir Management		**<u>1 lake routing scheme</u>:** level-pool management	Level-pool management

WRF-Hydro V5.0 Physics Components

Current Land Surface Models:

– Column physics & land-atmosphere exchange

- Land surface models are used to partition incoming surface energy and water into outgoing/internal fluxes and internal storage
- Land surface models are evolving to better represent reality and to expand user bases
- Evolving land surface model structure is leading to new challenges, e.g., parameters, parameters, parameters!
- Knowledge of both model structure and parameter assumptions is essential to properly use an LSM

Noah LSM & Noah-MP

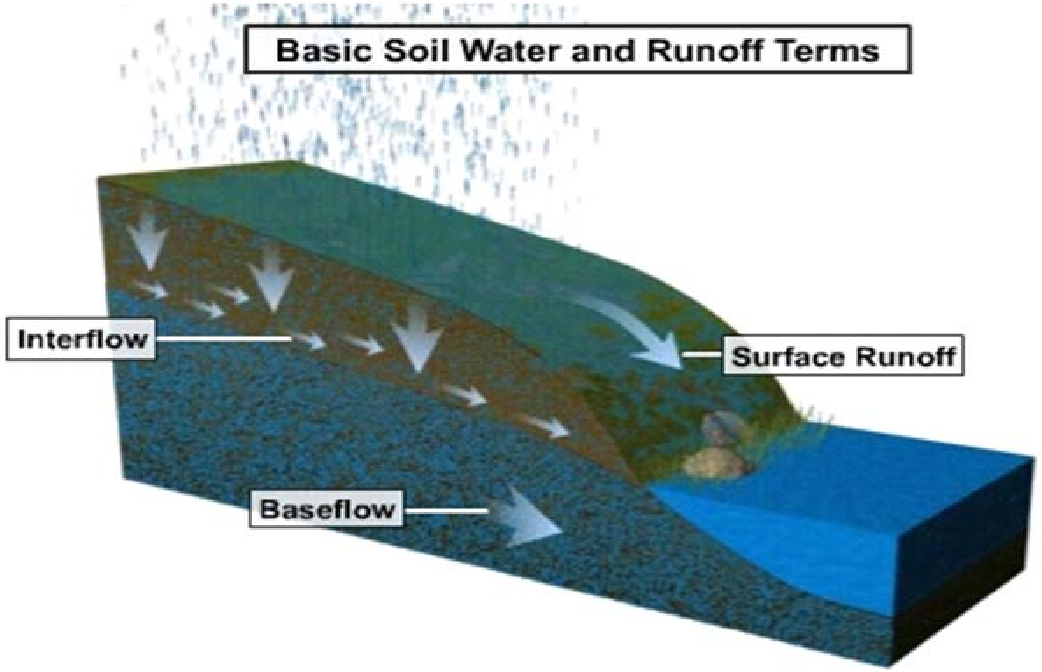
Noah-MP contains several options for land surface processes:

1. Dynamic vegetation/vegetation coverage (4 options)
2. Canopy stomatal resistance (2 options)
3. Canopy radiation geometry (3 options)
4. Soil moisture factor for stomatal resistance (3 options)
5. Runoff and groundwater (4 options)
6. Surface layer exchange coefficients (4 options)
7. Supercooled soil liquid water/ice fraction (2 options)
8. Frozen soil permeability options (2 options)
9. Snow surface albedo (2 options)
10. Rain/snow partitioning (3 options)
11. Lower soil boundary condition (2 options)
12. Snow/soil diffusion solution (2 options)

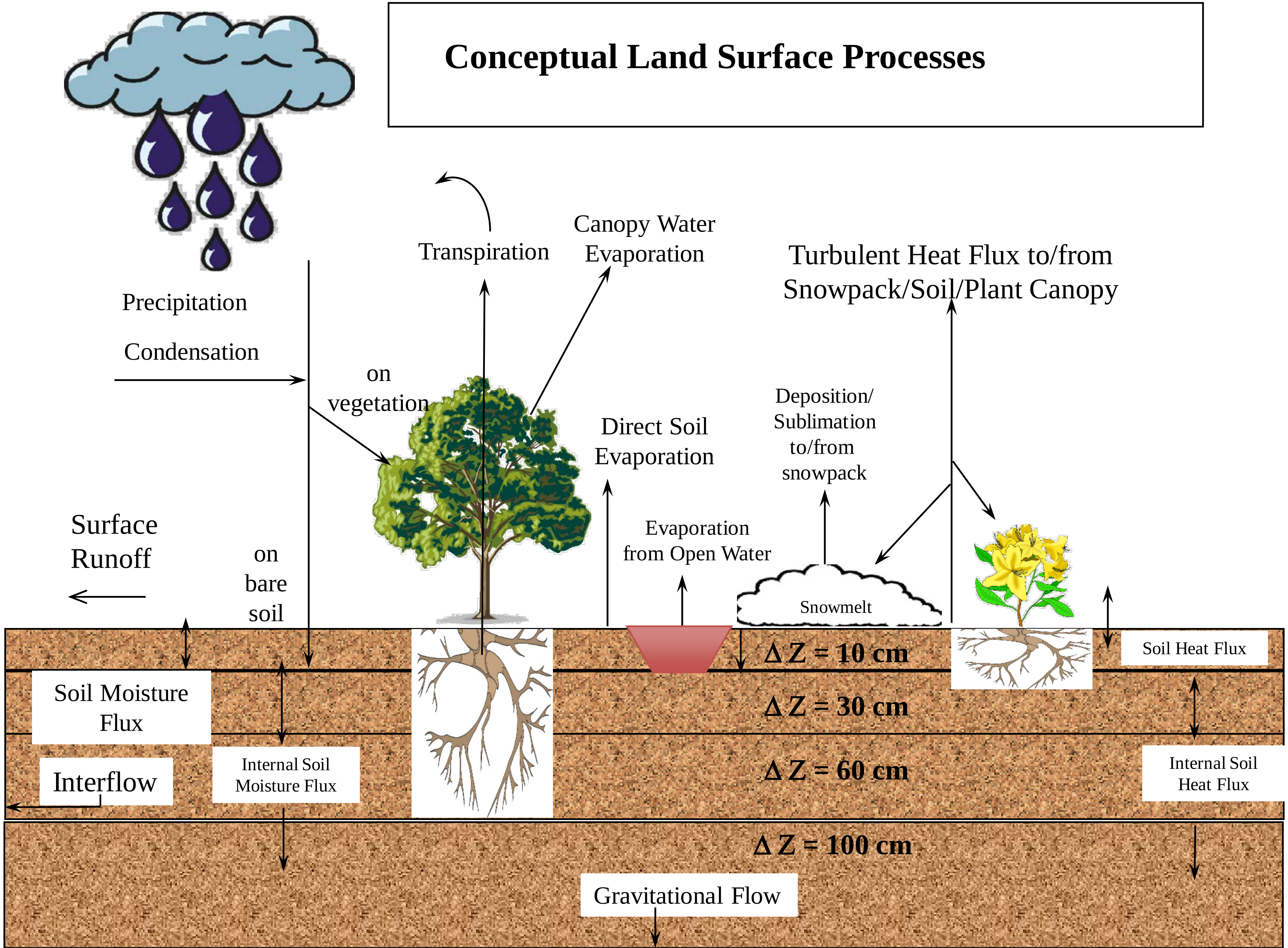
Total of ~50,000 permutations can be used as multi-physics ensemble members

Land Surface Models: One Piece of a Larger Modeling System

- Land surface models, as an upper boundary of a soil hydrology model, take:
  - Precipitation and partition into fluxes (evapotranspiration, surface/underground runoff) and storage (soil moisture and snowpack)
  - Solar and atmospheric energy and partition in fluxes (ET, sensible heat, ground/snow heat) and storage (snow/soil heat content)
- Models are generally 1D.



Conceptual Land Surface Processes



Noah-MP: A Community Land Model

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D12109, doi:10.1029/2010JD015139, 2011

The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements

Guo-Yue Niu,[1,2] Zong-Liang Yang,[1] Kenneth E. Mitchell,[3] Fei Chen,[4] Michael B. Ek,[3] Michael Barlage,[4] Anil Kumar,[5] Kevin Manning,[4] Dev Niyogi,[6] Enrique Rosero,[1,7] Mukul Tewari,[4] and Youlong Xia[3]

Received 4 October 2010; revised 3 February 2011; accepted 27 March 2011; published 24 June 2011.

The community Noah land surface model with multiparameterization options (Noah-MP): 2. Evaluation over global river basins

Zong-Liang Yang,[1] Guo-Yue Niu,[1,2] Kenneth E. Mitchell,[3] Fei Chen,[4] Michael B. Ek,[3] Michael Barlage,[4] Laurent Longuevergne,[5] Kevin Manning,[4] Dev Niyogi,[6] Mukul Tewari,[4] and Youlong Xia[3]

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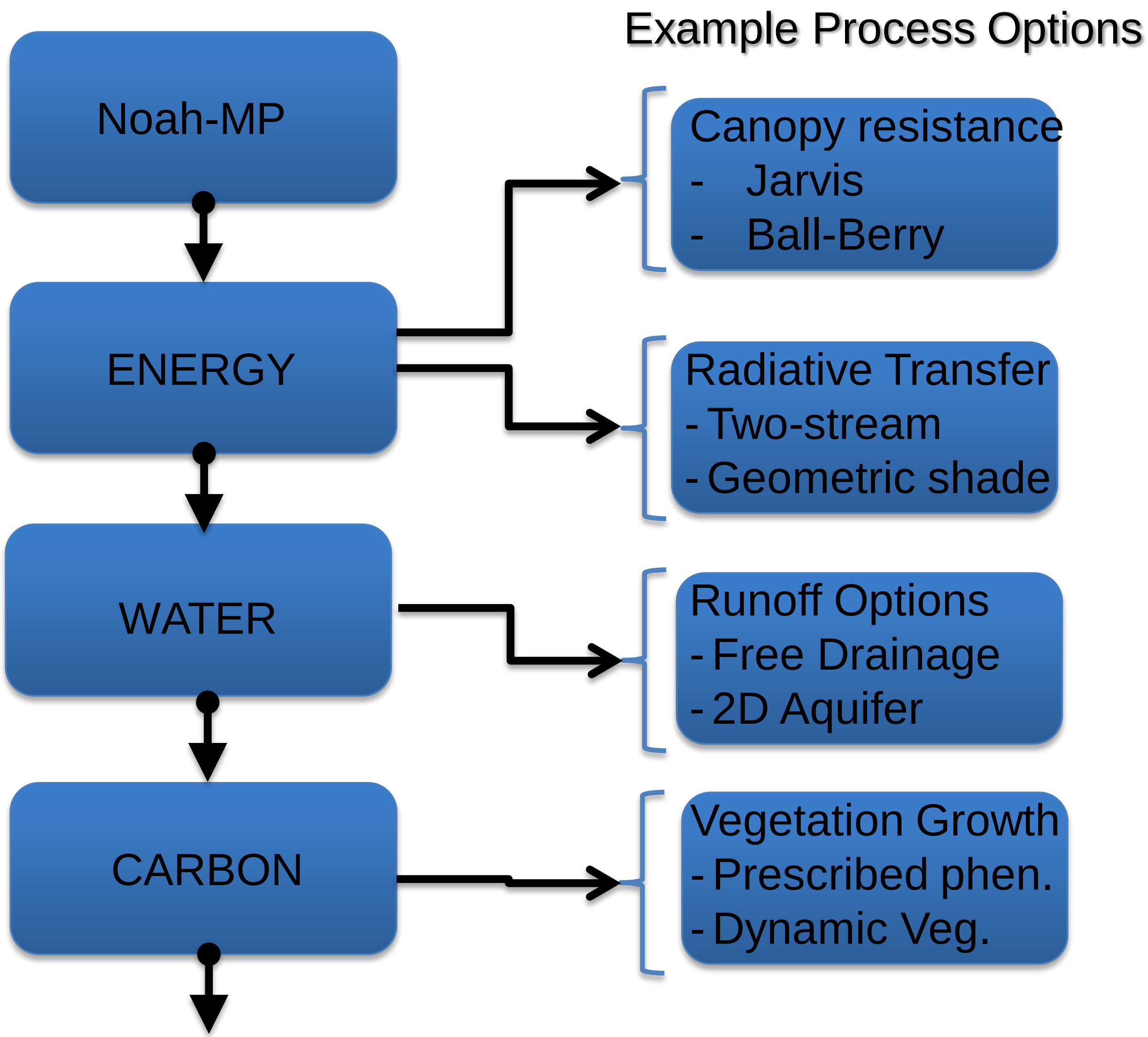
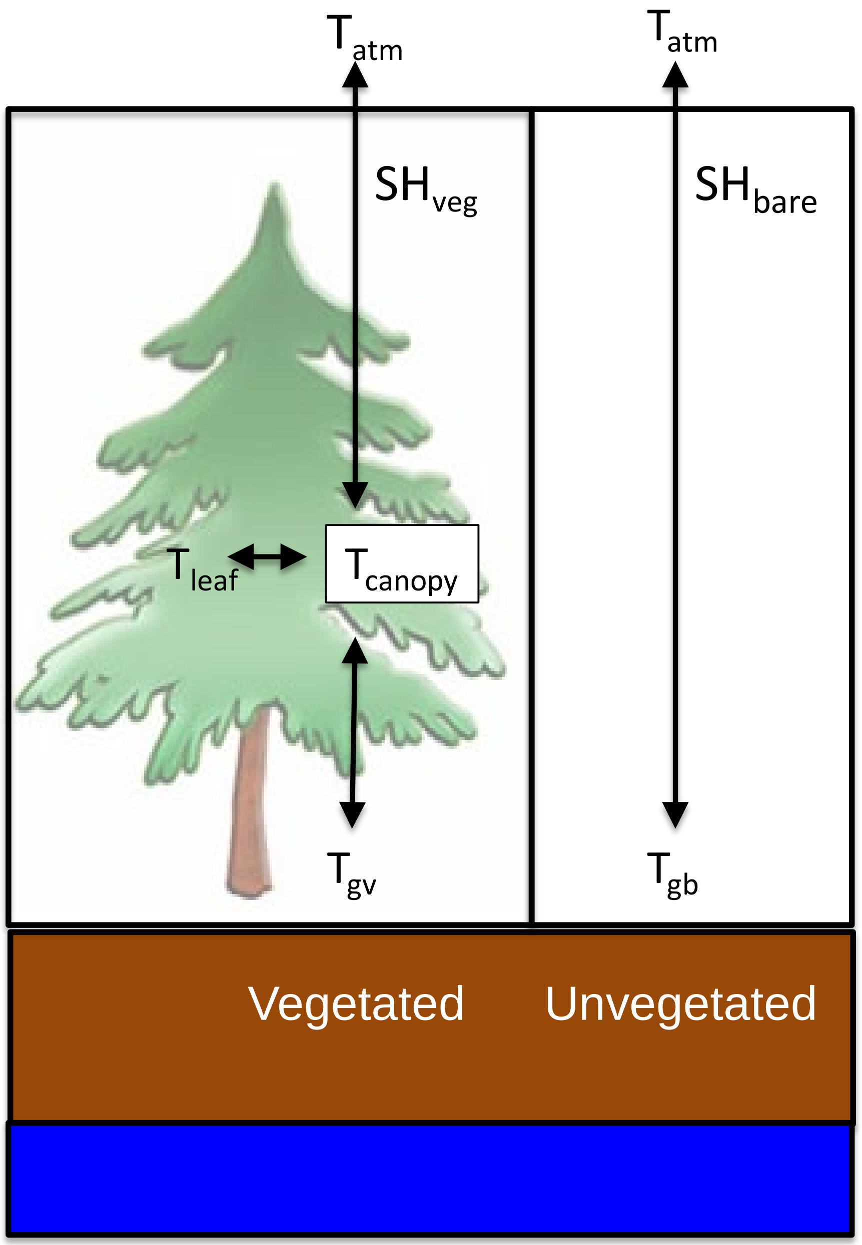
Noah-MP Calling Structure: Modularity at the Process Level



Noah-MP Physical Processes

Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
- Dynamic vegetation
- Vegetation canopy resistance
- Multi-layer snowpack
- Snowpack liquid water retention
- Simple groundwater options
- Snow albedo treatment
- New frozen soil scheme
- New snow cover



Noah-MP Surface Energy Budget

$$SW_{dn} - SW_{up} + LW_{dn} - LW_{up}\,(T_{sfc})$$
$$= SH(T_{sfc}) + LH(T_{sfc}) + G(T_{sfc})$$

SW_{dn},LW_{dn}: input shortwave and longwave radiation (external to LSM)

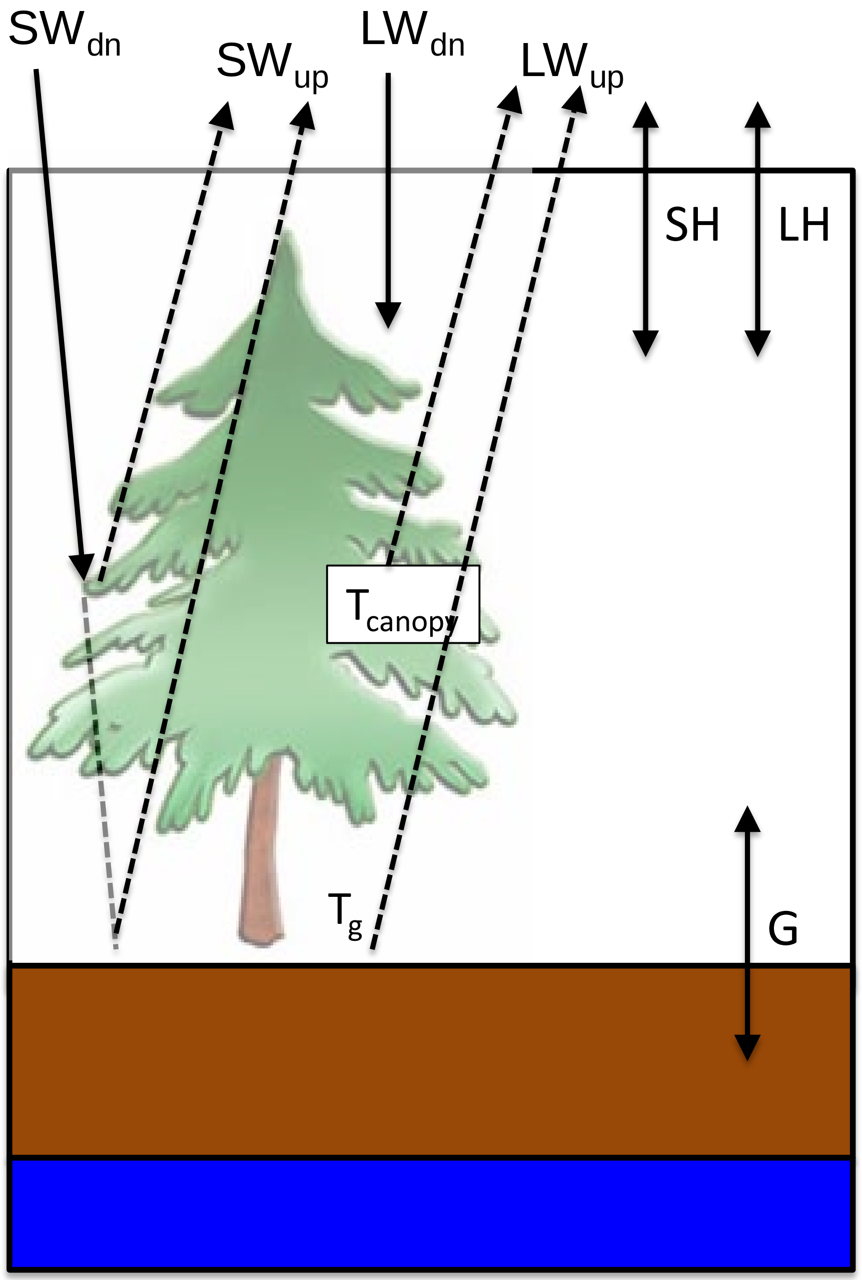
SW_{up} : reflected shortwave (albedo)

LW_{up} : upward thermal radiation

SH : sensible heat flux

LH : latent heat flux (soil/canopy evaporation, transpiration)

G : heat flux into the soil



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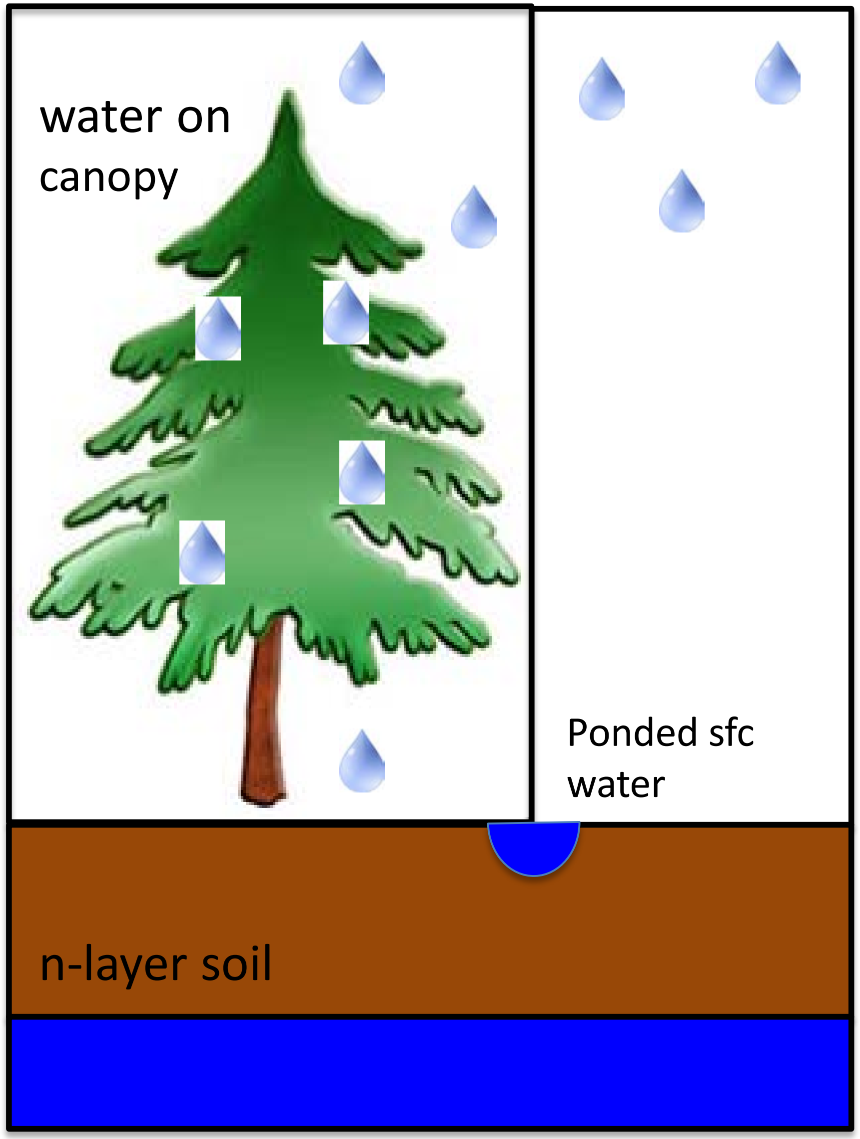

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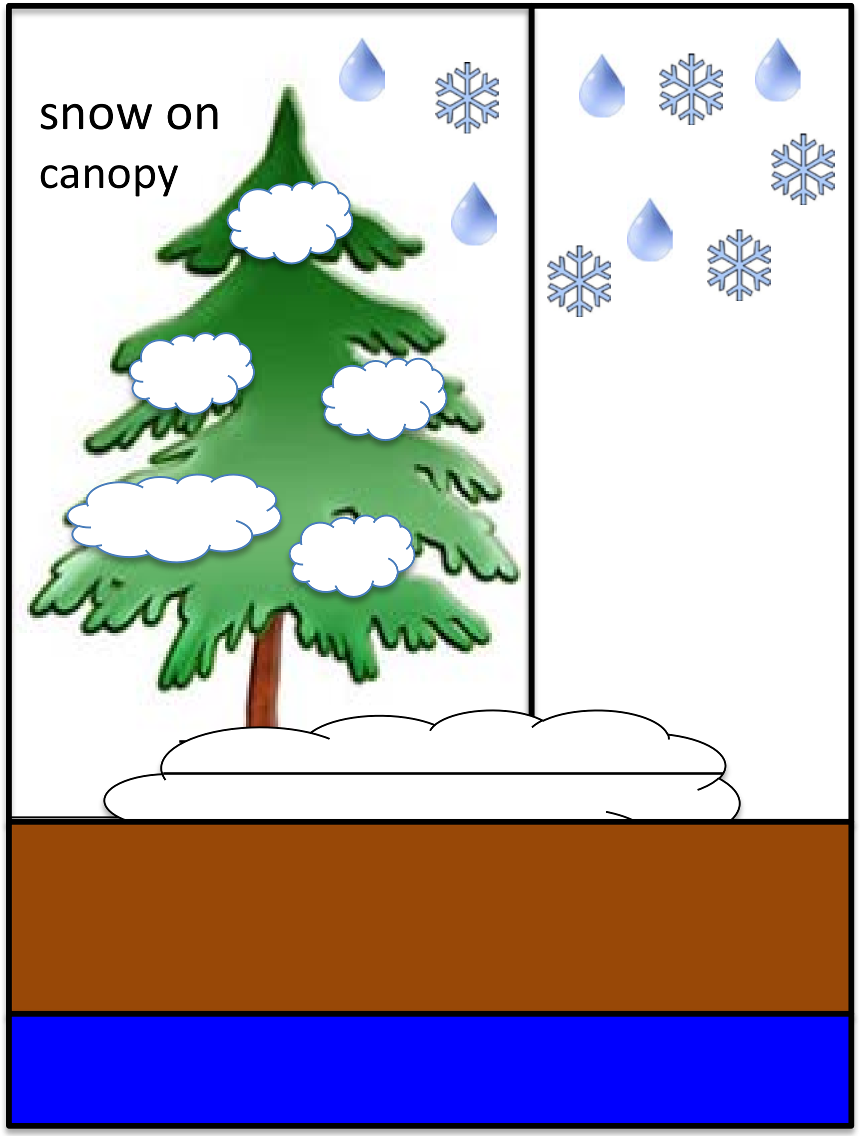


Noah-MP: Soil Water/Energy Transfer

Soil Moisture

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \theta}{\partial z} \right) + \frac{\partial K}{\partial z} + F_\theta$$

- Richards Equation for soil water movement
- D, K are functions of soil texture and soil moisture)
- F_θ represents sources (rainfall) and sinks (evaporation)

Soil/Snow Temperature

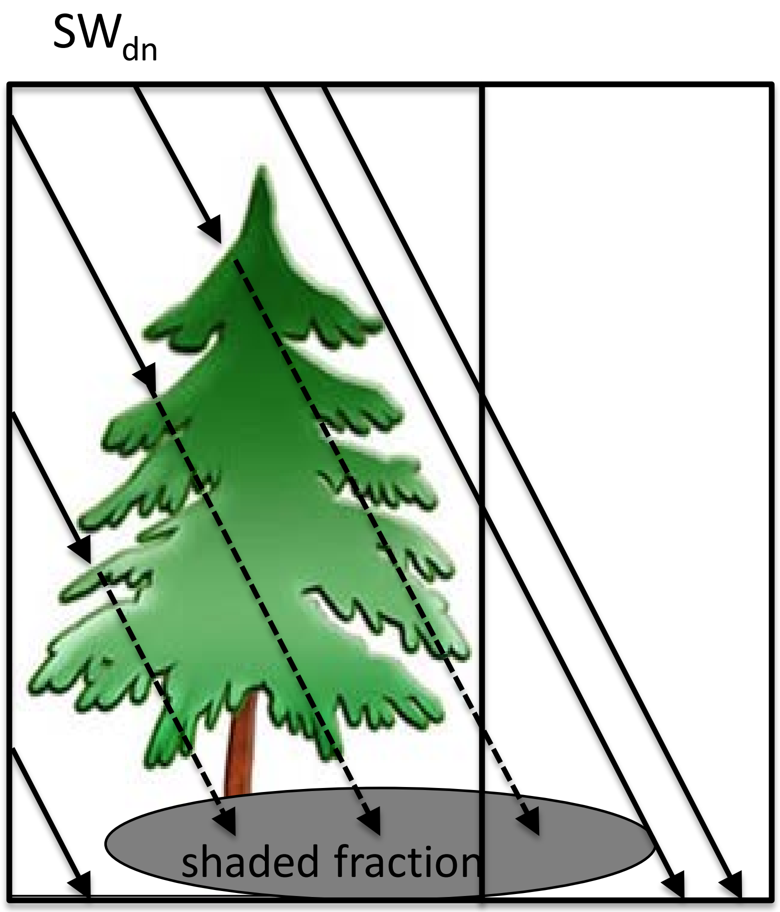
$$C(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_t(\theta) \frac{\partial T}{\partial z} \right)$$

- C, K_t are functions of soil texture and soil moisture
- Soil temperature information used to compute ground heat flux

Noah-MP: More Physics, More Parameters

Noah-MP has a separate canopy and uses a two-stream radiative transfer treatment through the canopy

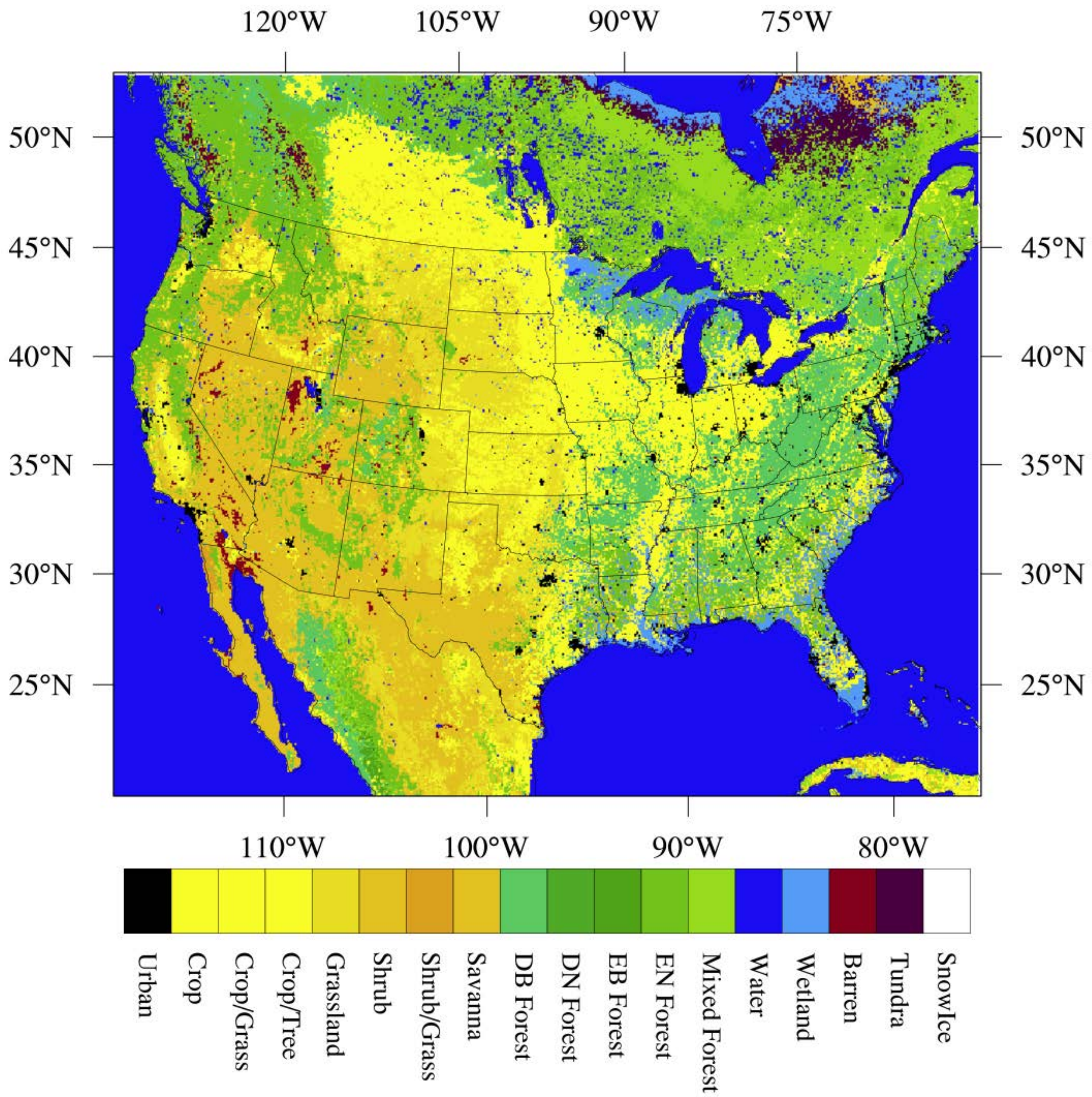
- Canopy parameters:
  - Canopy top and bottom
  - Crown radius, vertical and horizontal
  - Vegetation element density,
    i.e., trees/grass leaves per unit area
  - Leaf and stem area per unit area
  - Leaf orientation
  - Leaf reflectance and transmittance for direct/diffuse and visible/NIR radiation
- Multiple options for spatial distribution
  - Full grid coverage
  - Vegetation cover equals prescribed fractional vegetation
  - Random distribution with slant shading



Key Input into the Noah-MP LSM

- Land-cover/vegetation classification
  - Many sources, generally satellite-based and categorically broad
- Soil texture class
  - Also general with large consolidations
- Many secondary parameters that can be specified as function of the above

Datasets: NLCD Land Cover



Parameters: Land Cover

MPTABLE.TBL contains a look-up table for vegetation classes

Limitations:

All pixels with the same vegetation have the same parameters

Modifying parameters affects all vegetation of the same type

```
!-----------------------------------------------------------------------------------------------------------------
!          1      2      3      4      5      6      7      8      9      10     11     12     13     14     15     16     17
!-----------------------------------------------------------------------------------------------------------------
CH2OP =   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,   0.1,
DLEAF =  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0.04,  0
Z0MVT =  1.00,  0.15,  0.15,  0.15,  0.14,  0.50,  0.12,  0.06,  0.09,  0.50,  0.80,  0.85,  1.10,  1.09,  0.80,  0.00,  0.12,  0
HVT   =  15.0,  2.00,  2.00,  2.00,  1.50,  8.00,  1.00,  1.10,  1.10,  10.0,  16.0,  18.0,  20.0,  20.0,  16.0,  0.00,  0.50,  1
HVB   =  1.00,  0.10,  0.10,  0.10,  0.10,  0.15,  0.05,  0.10,  0.10,  0.10,  11.5,  7.00,  8.00,  8.50,  10.0,  0.00,  0.05,  0
DEN   =  0.01,  25.0,  25.0,  25.0,  25.0,  25.0,  100.,  10.0,  10.0,  0.02,  0.10,  0.28,  0.02,  0.28,  0.10,  0.01,  10.0,  0
RC    =  1.00,  0.08,  0.08,  0.08,  0.08,  0.08,  0.03,  0.12,  0.12,  3.00,  1.40,  1.20,  3.60,  1.20,  1.40,  0.01,  0.10,  1
MFSNO =  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2.50,  2

! Row 1:  Vis
! Row 2:  Near IR
RHOL_VIS=0.00,  0.11,  0.11,  0.11,  0.11,  0.11,  0.11,  0.07,  0.10,  0.10,  0.10,  0.07,  0.10,  0.07,  0.10,  0.00,  0.11,  0
RHOL_NIR=0.00,  0.58,  0.58,  0.58,  0.58,  0.58,  0.58,  0.35,  0.45,  0.45,  0.45,  0.35,  0.45,  0.35,  0.45,  0.00,  0.58,  0

! Row 1:  Vis
! Row 2:  Near IR
RHOS_VIS=0.00,  0.36,  0.36,  0.36,  0.36,  0.36,  0.36,  0.16,  0.16,  0.16,  0.16,  0.16,  0.16,  0.16,  0.16,  0.00,  0.36,  0
RHOS_NIR=0.00,  0.58,  0.58,  0.58,  0.58,  0.58,  0.58,  0.39,  0.39,  0.39,  0.39,  0.39,  0.39,  0.39,  0.39,  0.00,  0.58,  0

! Row 1:  Vis
! Row 2:  Near IR
TAUL_VIS=0.00,  0.07,  0.07,  0.07,  0.07,  0.07,  0.07,  0.05,  0.05,  0.05,  0.05,  0.05,  0.05,  0.05,  0.05,  0.00,  0.07,  0
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! Row 1:  Vis
! Row 2:  Near IR
TAUS_VIS=0.00, 0.220, 0.220, 0.220, 0.220, 0.220, 0.220, 0.001, 0.001, 0.001, 0.001, 0.001, 0.001, 0.001, 0.001, 0.000, 0.220, 0.
TAUS_NIR=0.00, 0.380, 0.380, 0.380, 0.380, 0.380, 0.380, 0.001, 0.001, 0.001, 0.001, 0.001, 0.001, 0.001, 0.001, 0.000, 0.380, 0.

XL     = 0.000, -0.30, -0.30, -0.30, -0.30, -0.30, -0.30, 0.010, 0.250, 0.010, 0.250, 0.010, 0.010, 0.010, 0.250, 0.000, -0.30, 0.
! CWPVT =   3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,    3.0,
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KC25  =  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  30.0,  3
AKC   =   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,   2.1,
KO25  =  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3.E4,  3
AKO   =   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,   1.2,
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DILEFW=  0.00,  0.20,  0.20,  0.20,  0.20,  0.20,  0.10,  0.20,  0.20,  0.50,  0.20,  0.20,  4.00,  0.20,  0.20,  0.00,  0.20,  0
RMF25 =  0.00,  1.00,  1.40,  1.45,  1.45,  1.45,  1.80,  0.26,  0.26,  0.80,  3.00,  4.00,  0.65,  3.00,  3.00,  0.00,  3.20,  3
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VCMX25=  0.00,  80.0,  80.0,  80.0,  60.0,  70.0,  40.0,  40.0,  40.0,  40.0,  60.0,  60.0,  60.0,  50.0,  55.0,  0.00,  50.0,  5
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BP    = 1.E15,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3,  2.E3, 1.E15,  2.E3,  2
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QE25  =    0.,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.06,  0.00,  0.06,  0
RMS25 =  0.00,  0.10,  0.10,  0.10,  0.10,  0.10,  0.10,  0.10,  0.10,  0.32,  0.10,  0.64,  0.30,  0.90,  0.80,  0.00,  0.10,  0
RMR25 =  0.00,  0.00,  0.00,  0.00,  0.00,  0.00,  1.20,  0.00,  0.00,  0.01,  0.01,  0.05,  0.05,  0.36,  0.03,  0.00,  0.00,  0
ARM   =   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,   2.0,
FOLNMX=  0.00,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,   1.5,  0.00,   1.5,
WDPOOL=  0.00,  0.00,  0.00,  0.00,  0.00,  0.00,  0.00,  1.00,  1.00,  1.00,  1.00,  1.00,  1.00,  1.00,  1.00,  0.00,  0.00,  1
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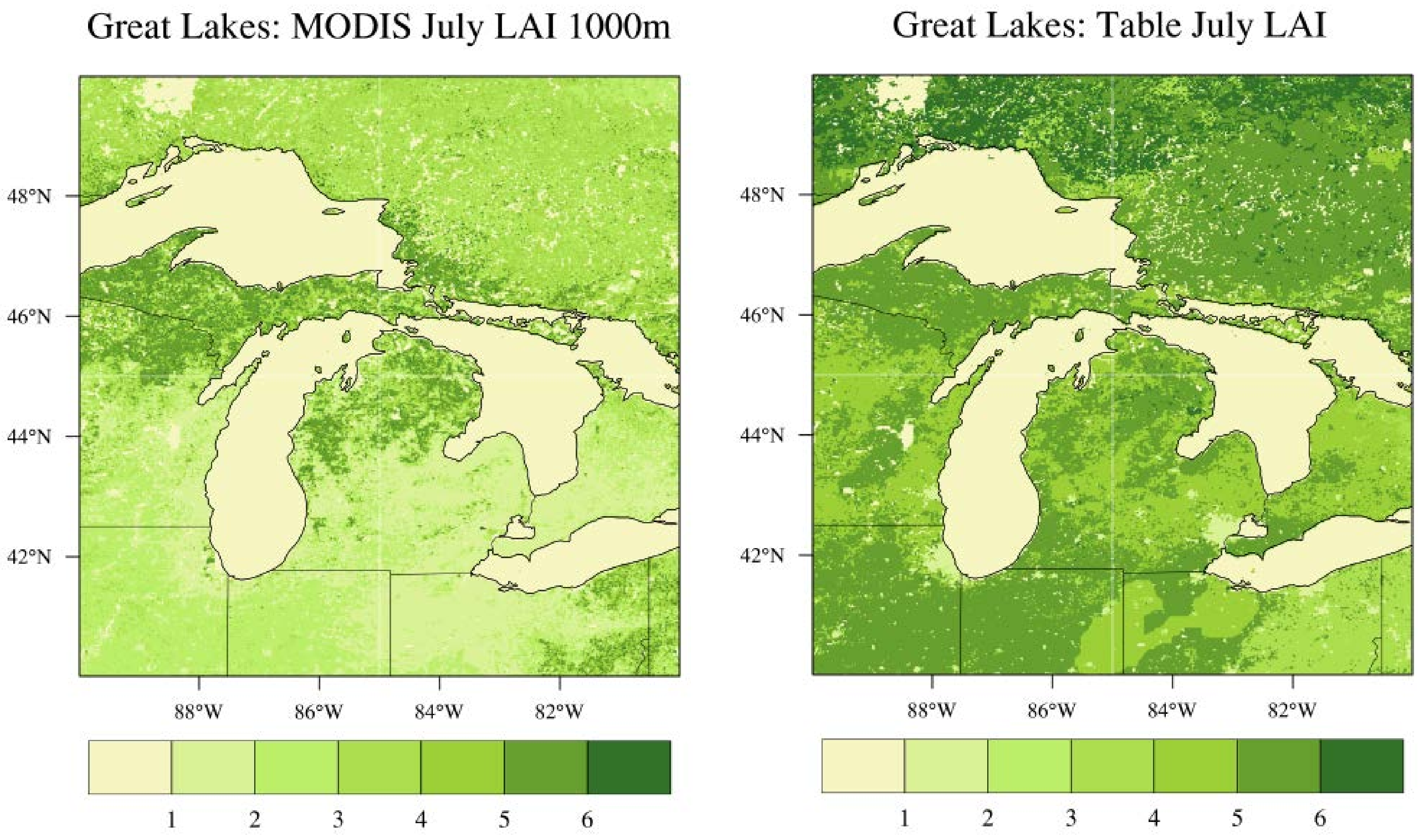
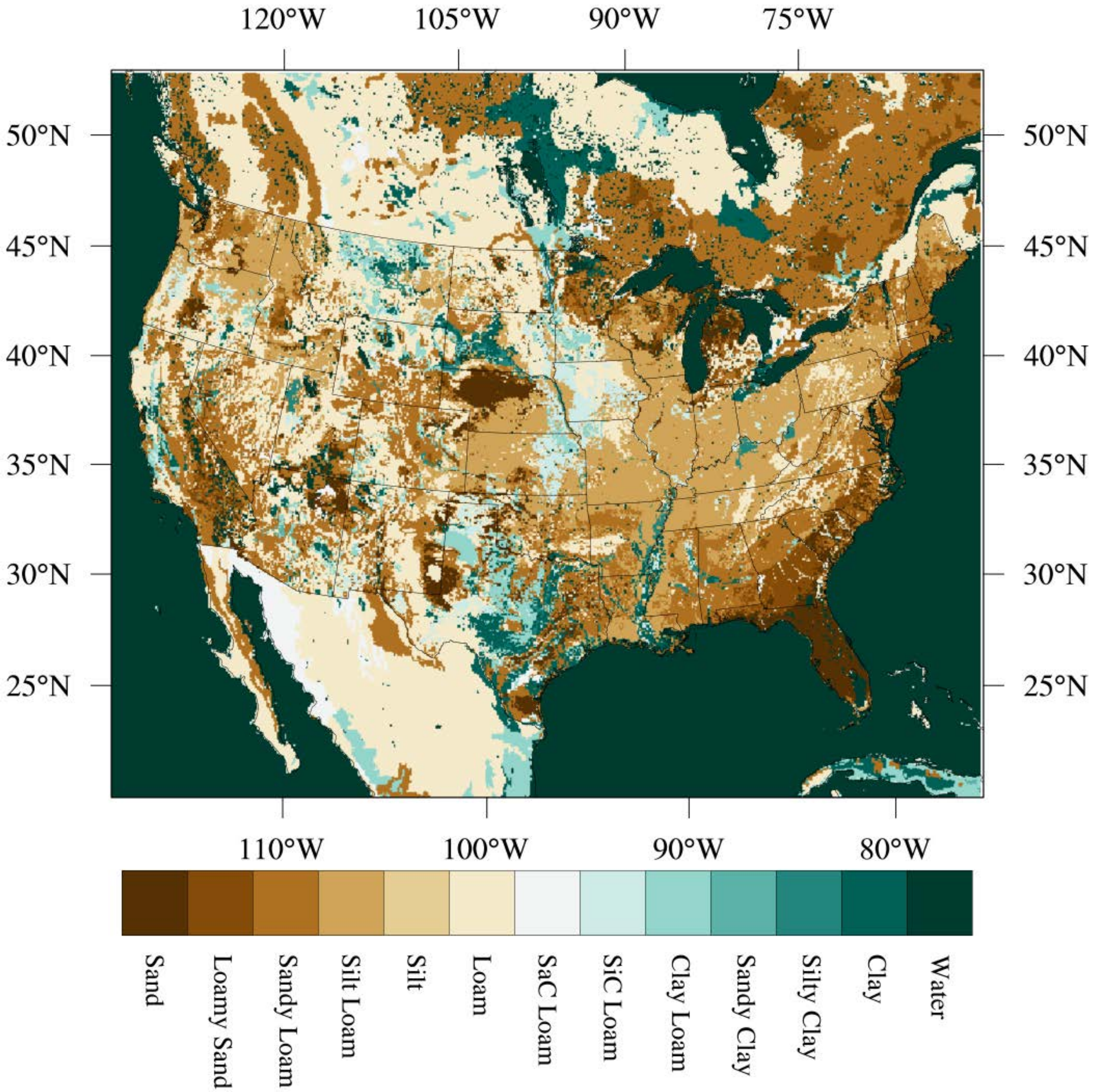
MODIS 1km Leaf Area Index Climatology

- Vegetation varying in time and space
- Comparison of MODIS LAI to default table-based LAI



Datasets: Soil Texture



Parameters: Soil Texture

Soil Parameters
STAS

19,1	'BB	DRYSMC	F11	MAXSMC	REFSMC	SATPSI	SATDK	SATDW	WLTSMC	QTZ	'
1,	2.79,	0.010,	-0.472,	0.339,	0.236,	0.069,	4.66E-5,	0.608E-6,	0.010,	0.92,	'SAND'
2,	4.26,	0.028,	-1.044,	0.421,	0.383,	0.036,	1.41E-5,	0.514E-5,	0.028,	0.82,	'LOAMY SAND'
3,	4.74,	0.047,	-0.569,	0.434,	0.383,	0.141,	5.23E-6,	0.805E-5,	0.047,	0.60,	'SANDY LOAM'
4,	5.33,	0.084,	0.162,	0.476,	0.360,	0.759,	2.81E-6,	0.239E-4,	0.084,	0.25,	'SILT LOAM'
5,	5.33,	0.084,	0.162,	0.476,	0.383,	0.759,	2.81E-6,	0.239E-4,	0.084,	0.10,	'SILT'
6,	5.25,	0.066,	-0.327,	0.439,	0.329,	0.355,	3.38E-6,	0.143E-4,	0.066,	0.40,	'LOAM'
7,	6.77,	0.067,	-1.491,	0.404,	0.314,	0.135,	4.45E-6,	0.990E-5,	0.067,	0.60,	'SANDY CLAY LOAM'
8,	8.72,	0.120,	-1.118,	0.464,	0.387,	0.617,	2.03E-6,	0.237E-4,	0.120,	0.10,	'SILTY CLAY LOAM'
9,	8.17,	0.103,	-1.297,	0.465,	0.382,	0.263,	2.45E-6,	0.113E-4,	0.103,	0.35,	'CLAY LOAM'
10,	10.73,	0.100,	-3.209,	0.406,	0.338,	0.098,	7.22E-6,	0.187E-4,	0.100,	0.52,	'SANDY CLAY'
11,	10.39,	0.126,	-1.916,	0.468,	0.404,	0.324,	1.34E-6,	0.964E-5,	0.126,	0.10,	'SILTY CLAY'
12,	11.55,	0.138,	-2.138,	0.468,	0.412,	0.468,	9.74E-7,	0.112E-4,	0.138,	0.25,	'CLAY'
13,	5.25,	0.066,	-0.327,	0.439,	0.329,	0.355,	3.38E-6,	0.143E-4,	0.066,	0.05,	'ORGANIC MATERIAL'
14,	0.0,	0.0,	0.0,	1.0,	0.0,	0.0,	0.0,	0.0,	0.0,	0.60,	'WATER'

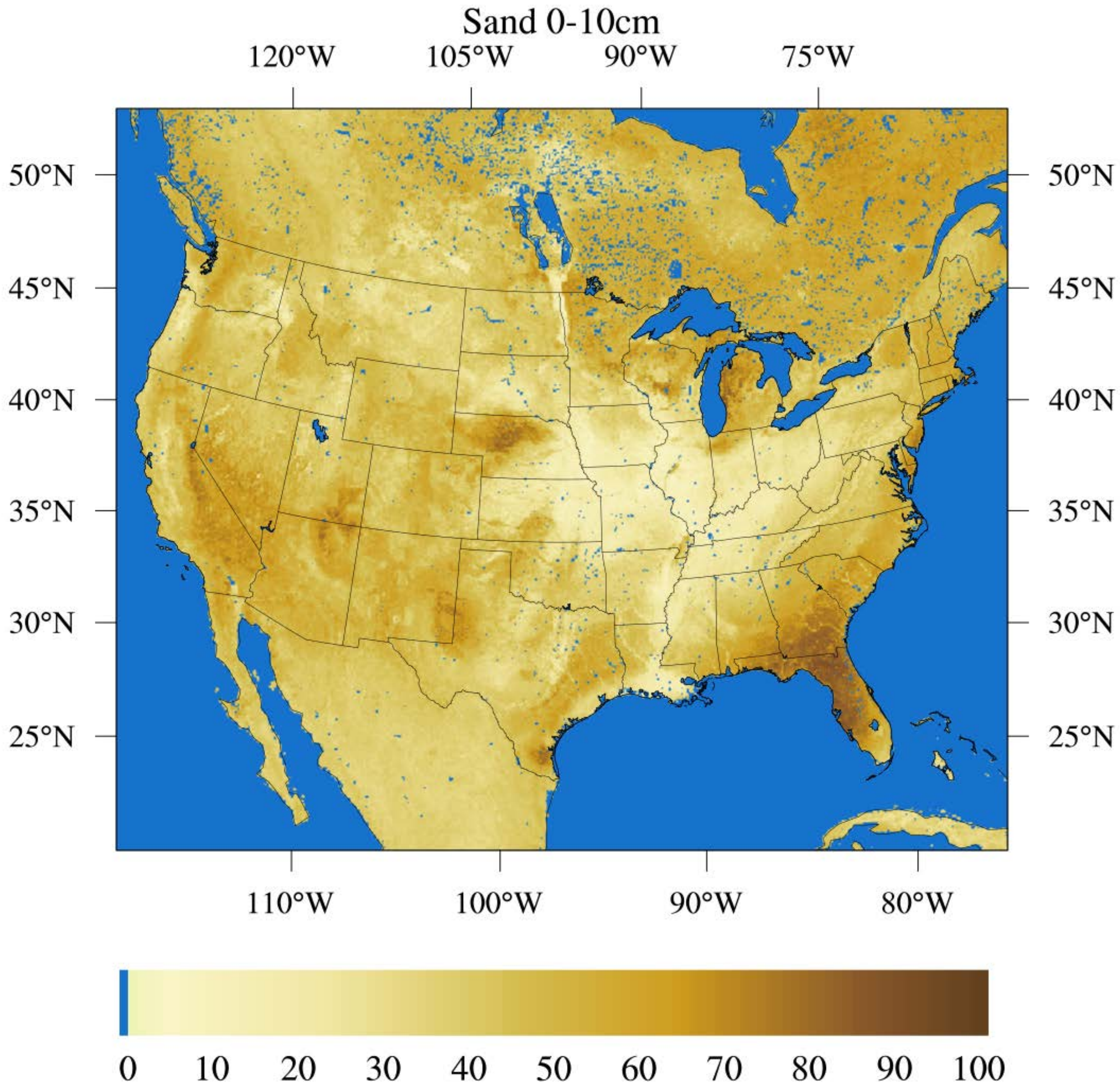
SOILPARM.TBL contains a look-up table for soil texture classes

Limitations:

All pixels with the same soil type have the same parameters

Modifying parameters affects all soil of the same type

Datasets: Soil Composition



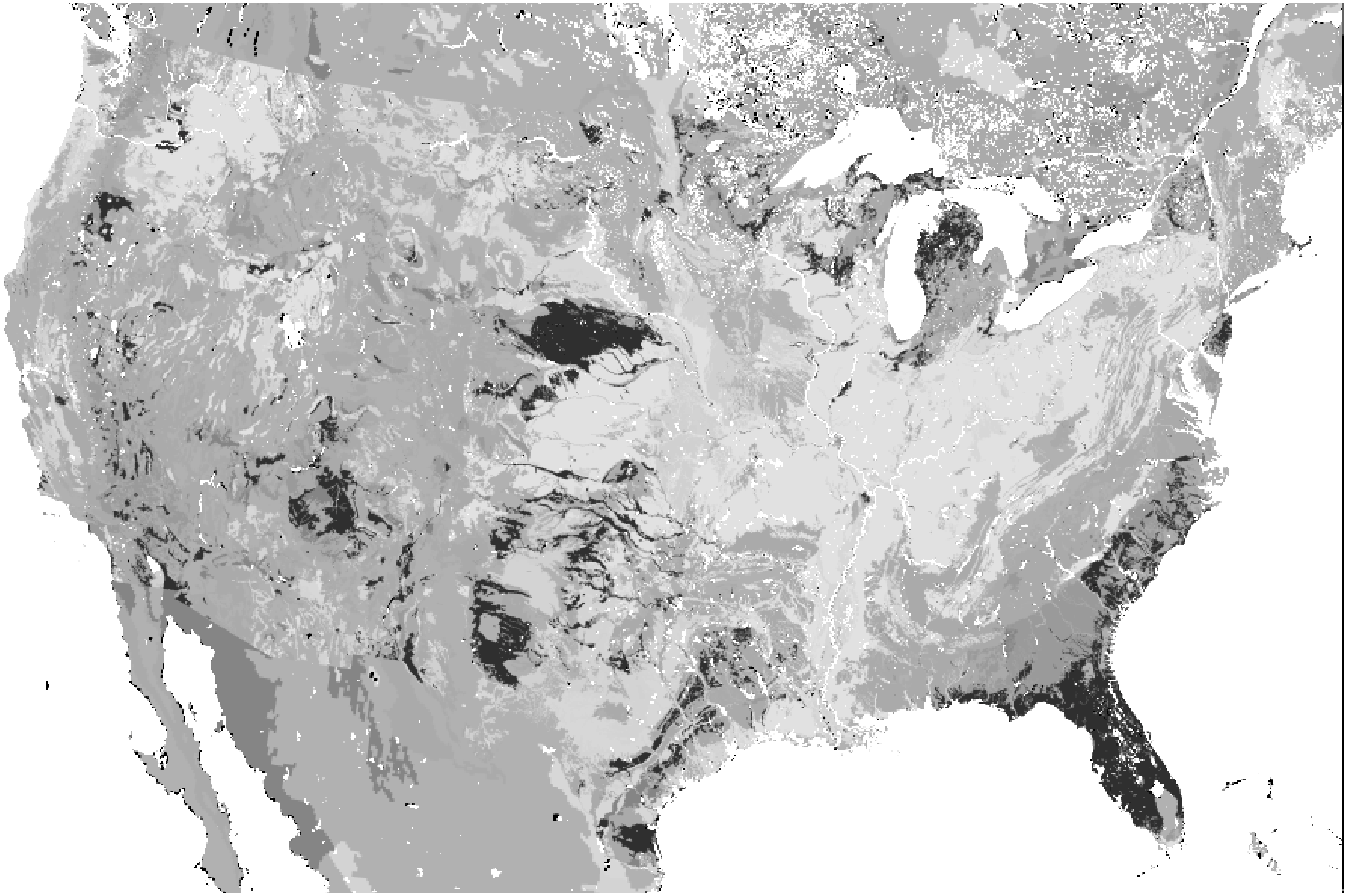
Parameters: Customization

Some capabilities exist within Noah-MP to read spatially-dependent soil and vegetation properties

Allows users who have local information to access it in the model

Soil properties: b, dksat, dwsat, psisat, smcdry, smcmax, smcref, smcwlt, slope, refdk, refkdt, rsurfexp, quartz

Vegetation properties: cwpvt, hvt, mp, vcmx25, mfsno

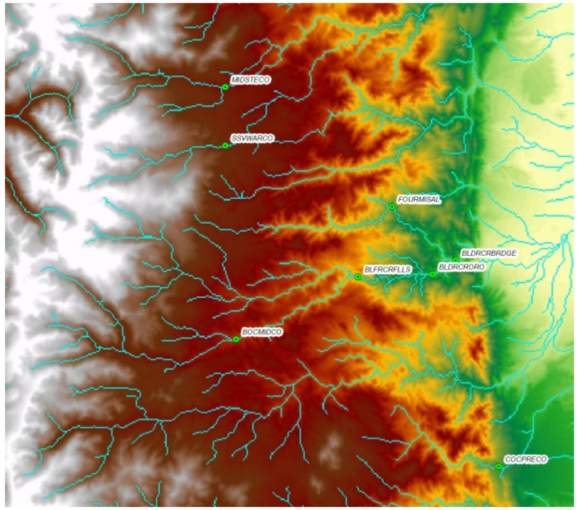


Example of 2D porosity field in NWM

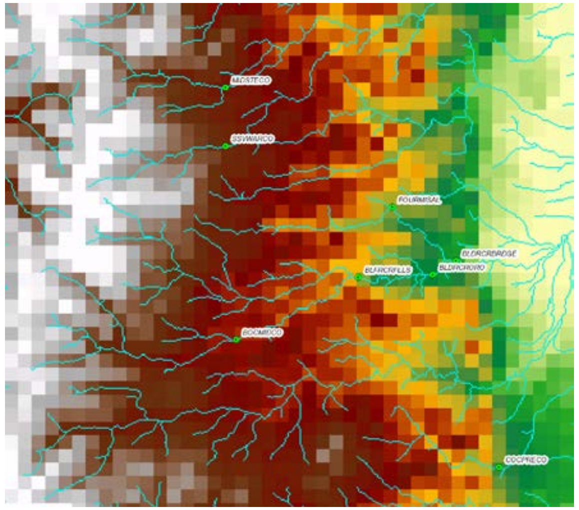
WRF-Hydro V5.0 Physics Components

- Multi-scale aggregation/disaggregation:

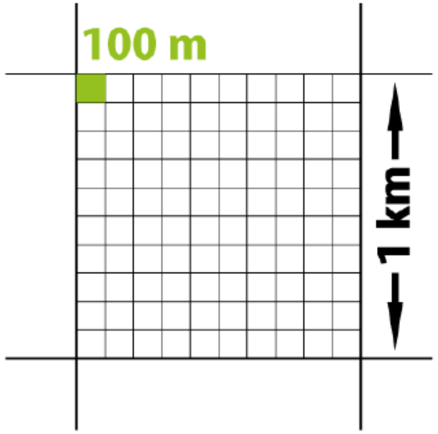
100m Terrain

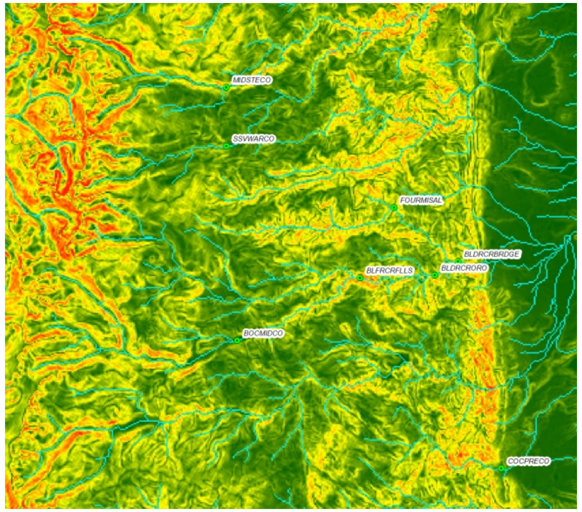


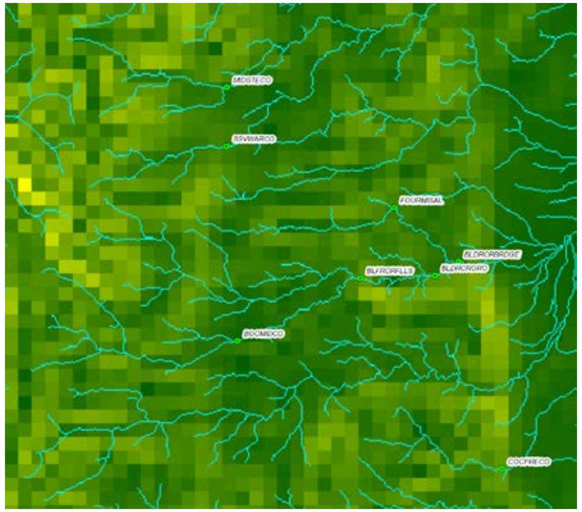
1 km Terrain



Current ‘Regridding’

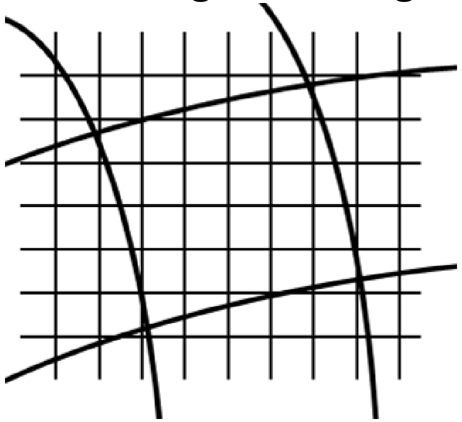






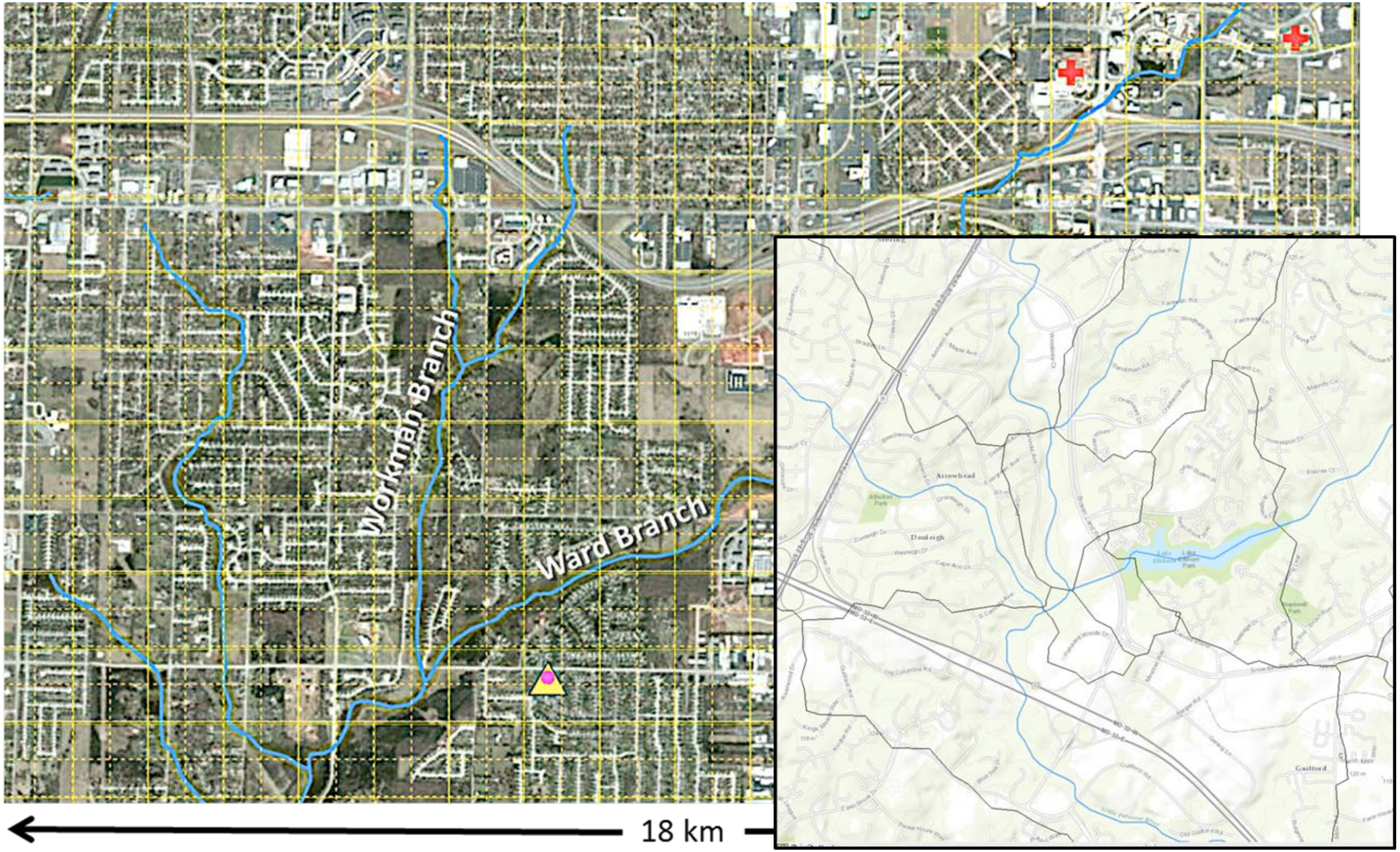
Terrain slope (0-45 deg)

Implementing ESMF Regridders



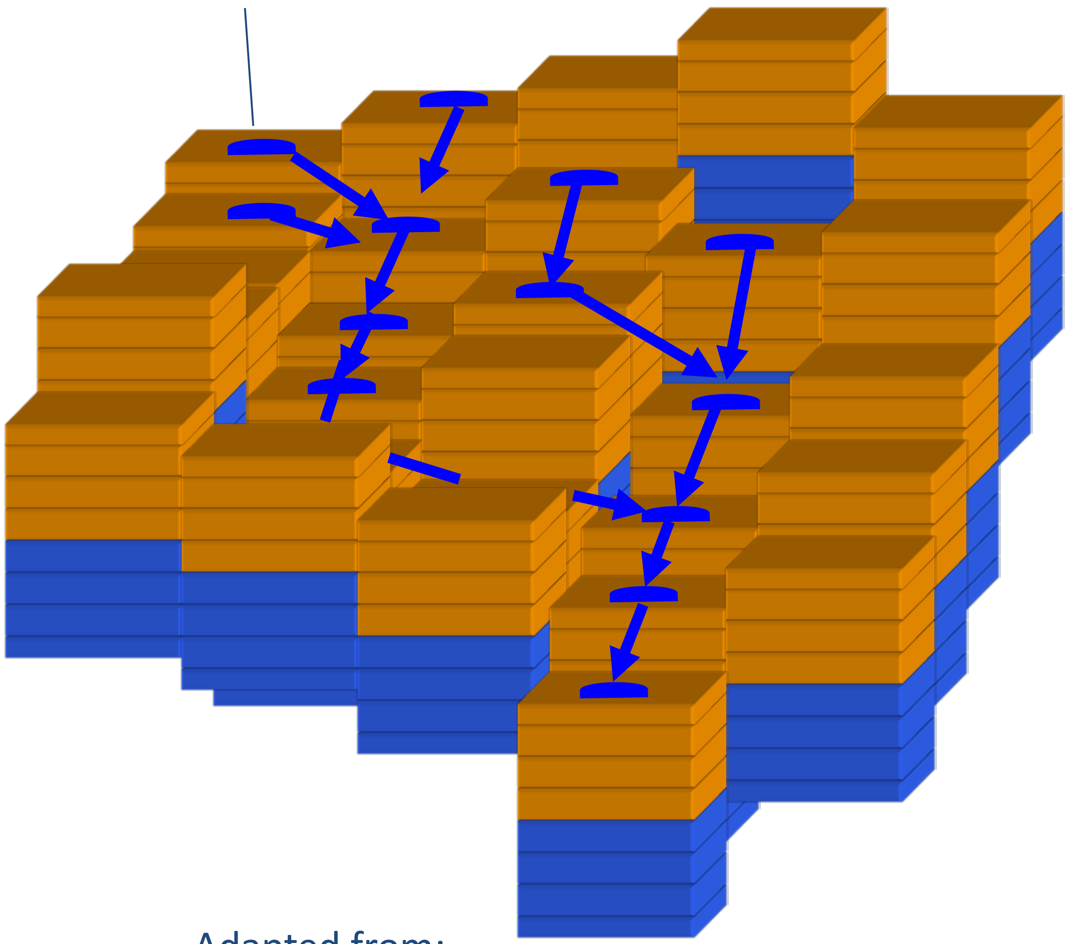
WRF-Hydro V5.0 Physics Components

- Multi-scale aggregation/disaggregation:



Terrain Routing

Surface Routing



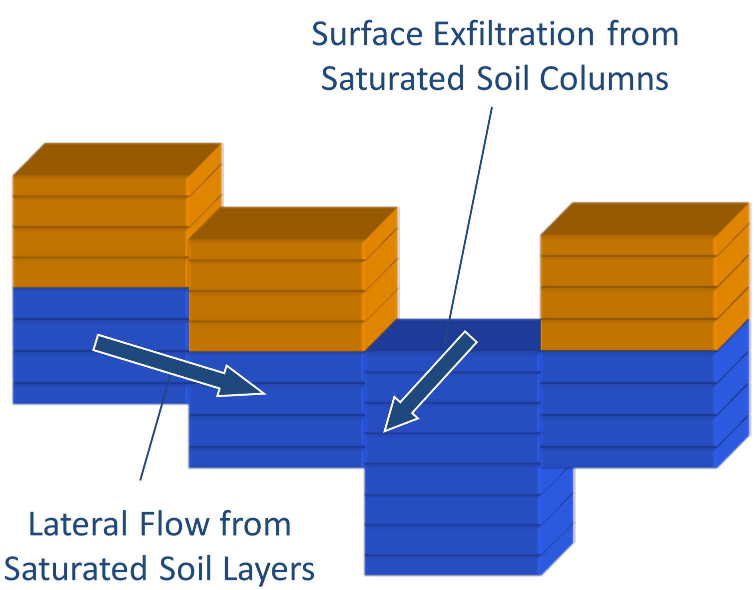
Adapted from:
Julian et al, 1995 – CASC2D, GSSHA

- Pixel-to-pixel routing
  - Steepest descent or 2d
  - Diffusive wave/backwater permitting
  - Explicit solution
- Ponded water (surface head) is fully-interactive with land model
- Sub-grid variability of ponded water on routing grid is preserved between land model calls

Surface Routing: Key Settings and Parameters

Parameter/Setting	Description	Scale/File	Estimate
Runtime Settings			
OVRTSWCRT	Overland routing physics switch (on/off)	hydro.namelist	Landscape/event, compute resources (computationally intensive)
DTRT_TER	Overland routing timestep	hydro.namelist	Based on grid size, landscape/event
Parameters			
TOPOGRAPHY	Land surface elevation; routing based on elevation+head gradient	Routing grid (Fulldom)	Various sources
OV_ROUGH2D	Overland roughness (Manning’s n for land)	LSM grid (hydro2dtbl)	Estimated based on land cover type
OVROUGHRTFAC	Multiplier on overland roughness	Routing grid (Fulldom)	Calibrated
RETDEPRTFAC	Multiplier on maximum retention depth on surface before overland flow processes are initiated	Routing grid (Fulldom)	Calibrated (internally scaled based on topographic slope)

Subsurface Routing in v5



Adapted from:
Wigmosta et. al, 1994

- Quasi steady-state, Boussinesq saturated flow model
- Exfiltration from fully-saturated soil columns
- Anisotropy in vertical and horizontal Ksat
- No ‘perched’ flow
- Soil depth is uniform

- **Critical initialization value: water table depth**

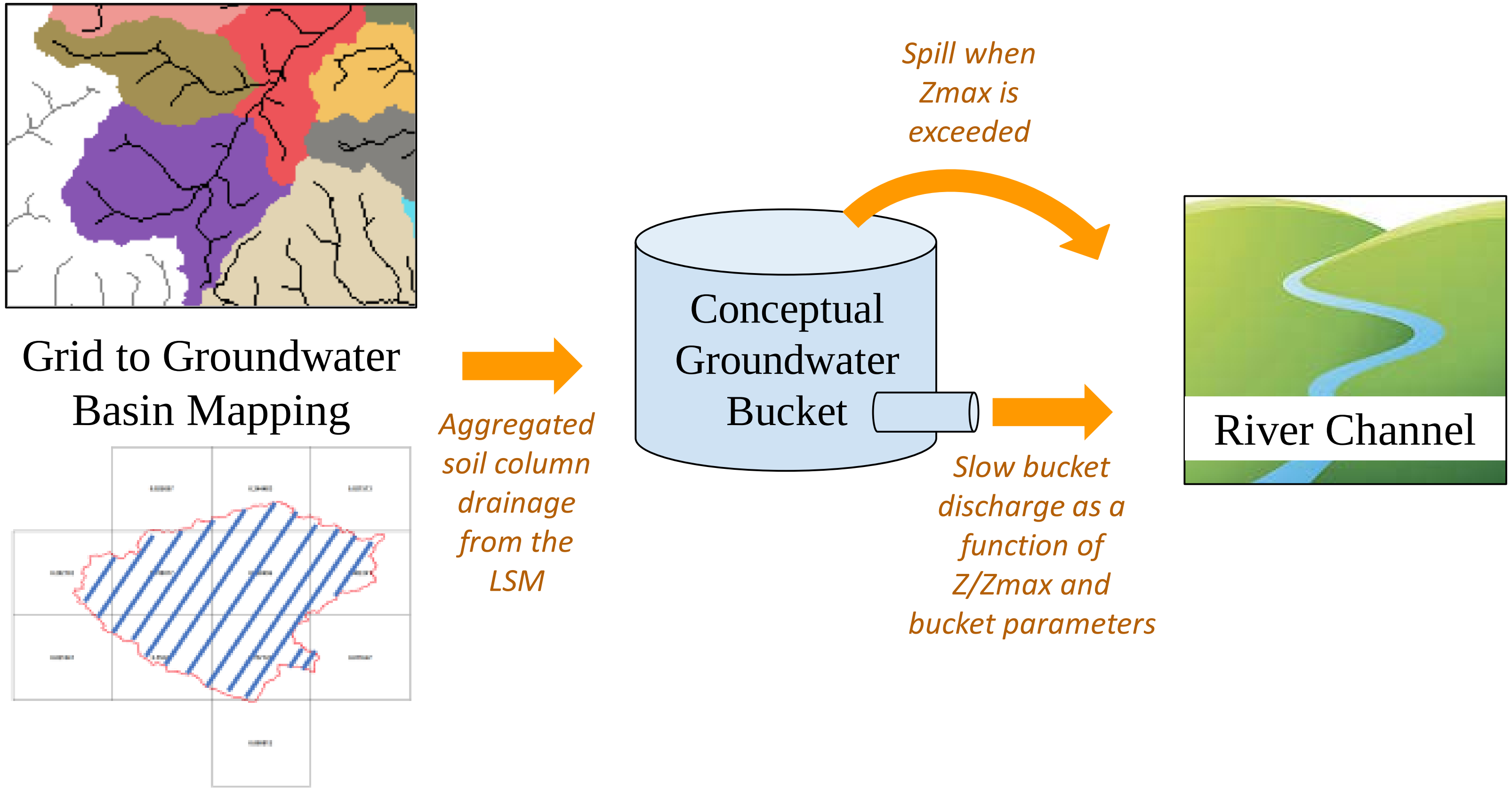
Subsurface Routing: Key Settings and Parameters

Parameter/Setting	Description	Scale/File	Estimate
Runtime Settings			
SUBRTSWCRT	Subsurface routing physics switch (on/off)	hydro.namelist	Landscape/event
NOAH_TIMESTEP	LSM timestep	namelist.hrldas	Landscape/event
Parameters			
TOPOGRAPHY	Land surface elevation; routing based on elevation+head gradient	Routing grid (Fulldom)	Various sources
LKSAT	Lateral saturated hydraulic conductivity	LSM grid (hydro2dtbl)	Estimated based on soil texture class
LKSATFAC	Multiplier on lateral conductivity	Routing grid (Fulldom)	Calibrated
SMCMAX1	Soil porosity	LSM grid (hydro2dtbl)	Estimated based on soil texture class; calibrated
SMCREF1	Soil field capacity	LSM grid (hydro2dtbl)	Estimated based on soil texture class; calibrated

Runoff and Routing Physics: Deep Groundwater

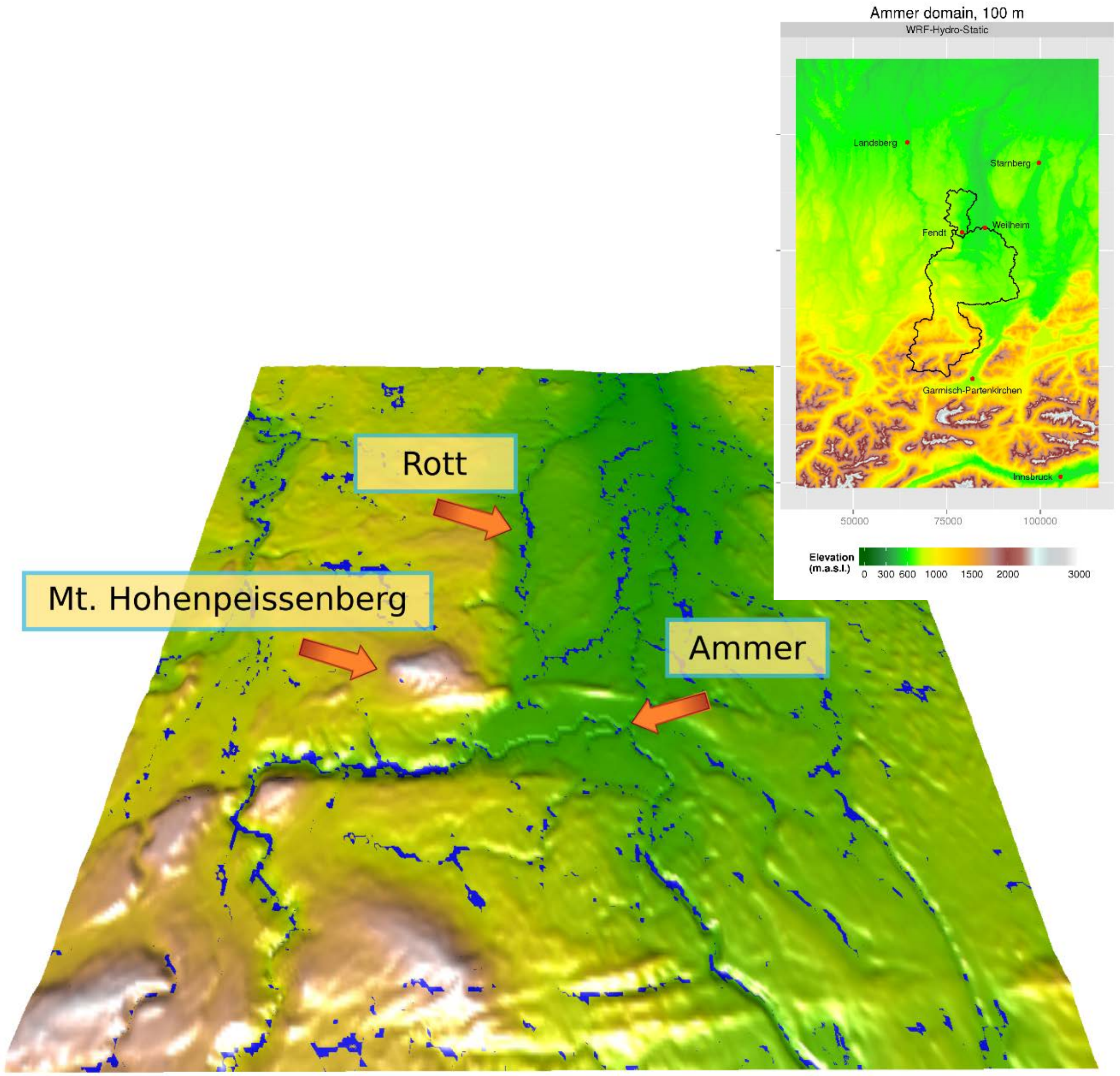
Conceptual groundwater baseflow “bucket” model:

- Simple pass-through or 2-parameter exponential model
- Bucket discharge gets distributed to channel network



Subsurface Routing in v5

- 2d groundwater model
- Coupled to bottom of LSM soil column through Darcy-flux parameterization
- Independent hydraulic characteristics vs. soil column
- Full coupling to gridded channel model through assumed channel depth and channel head
- Detailed representation of wetlands



Surface ponded water from coupled groundwater in WRF-Hydro
B. Fersch, KIT, Germany

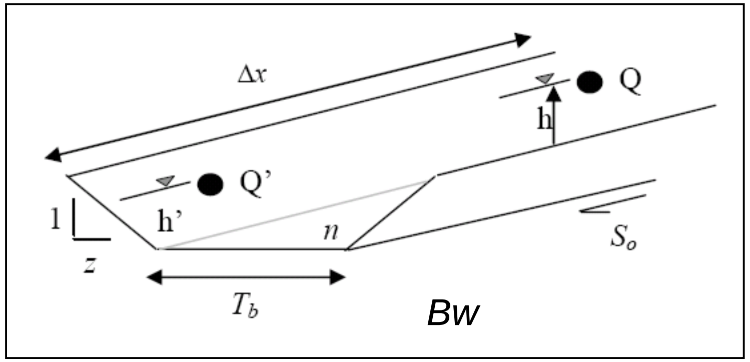
Deep Groundwater: Key Settings and Parameters

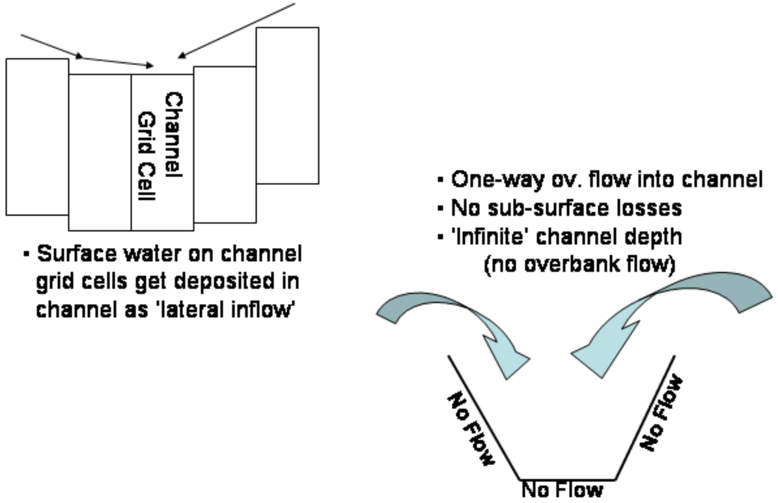
Parameter/Setting	Description	Scale/File	Estimate
Runtime Settings			
GWBASESWCRT	Baseflow bucket model switch (pass-through, exp, off)	hydro.namelist	Landscape/event
NOAH_TIMESTEP	LSM timestep	namelist.hrldas	Landscape/event
Parameters			
GWBASINS/spatialweights	Groundwater "basins"	LSM (GWBASINS) or routing grid (spatialweights)	Landscape
slope	"Openness" of bottom soil column boundary	LSM grid (soil_properties)	Calibrated
Coeff	Coefficient in exponential bucket equation	Bucket objects (GWBUCKPARM)	Calibrated
Expon	Exponent in exponential bucket equation	Bucket objects (GWBUCKPARM)	Estimated based on soil texture class; calibrated
Zmax	Maximum bucket depth	Bucket objects (GWBUCKPARM)	Estimated based on soil texture class; calibrated

Channel Routing

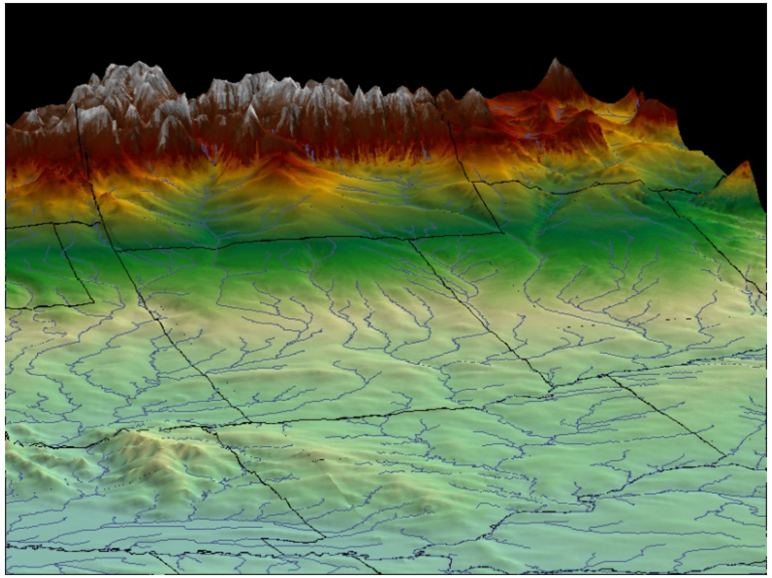
WRF-Hydro V5.0 Physics Components

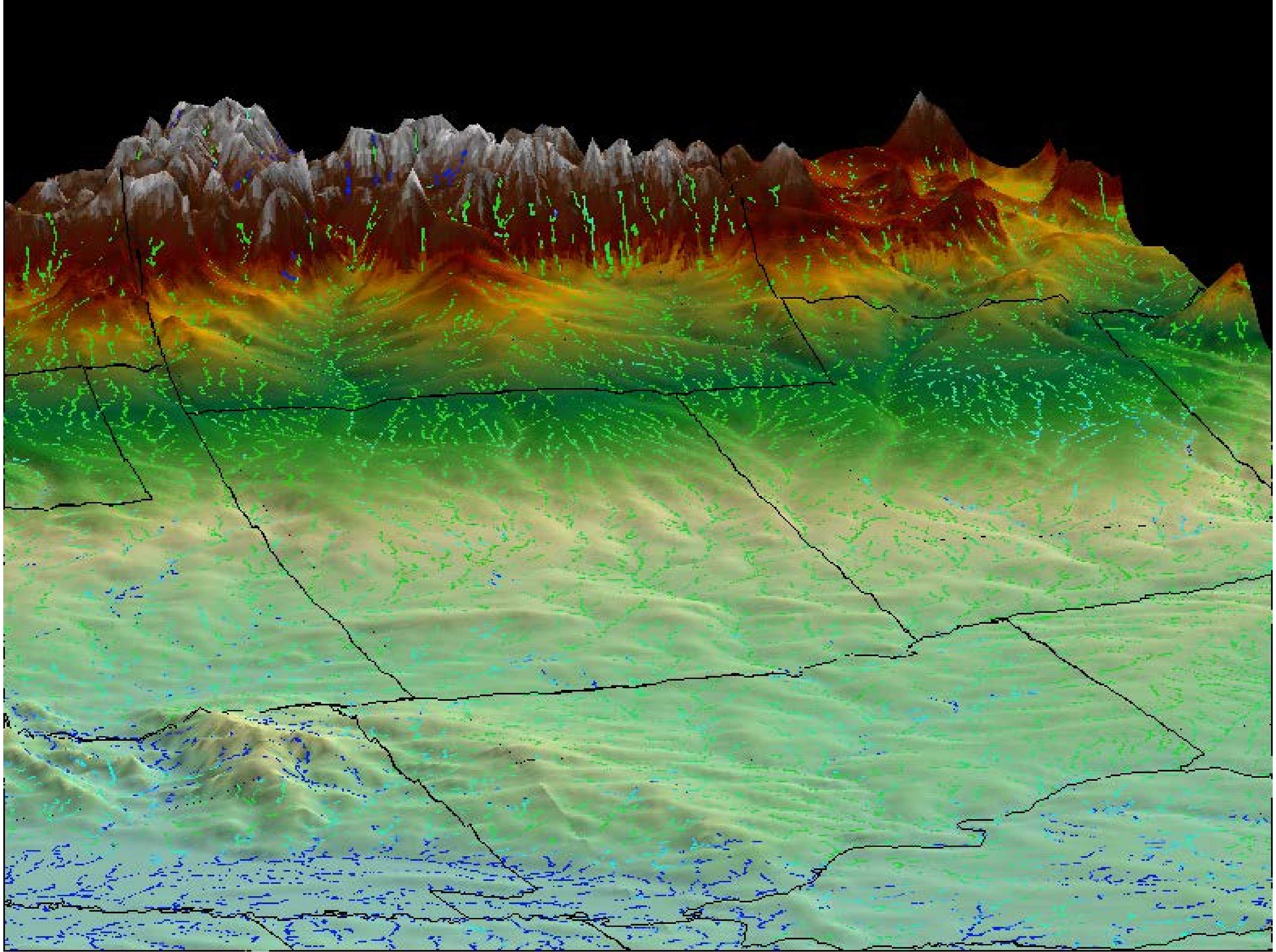
Channel routing: Gridded vs. Reach-based



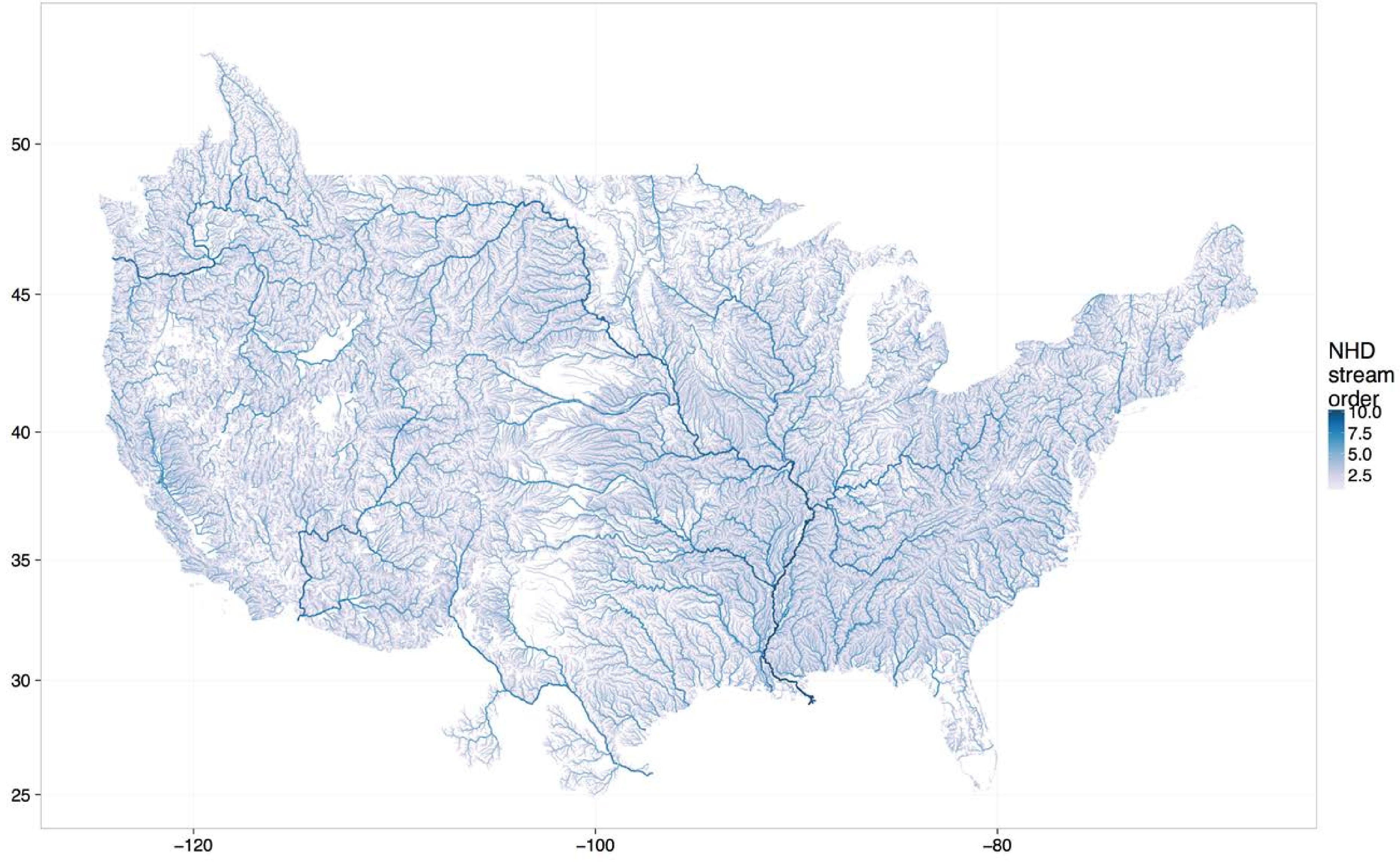


- Solution Methods:
  - Gridded: 1-d diffusive wave: fully-unsteady, explicit, finite-difference
  - Reach: Muskingum, Muskingum-Cunge *(much faster)*
- Parameters:
  - A priori function of Strahler order
  - Trapezoidal channel (bottom width, side slope)





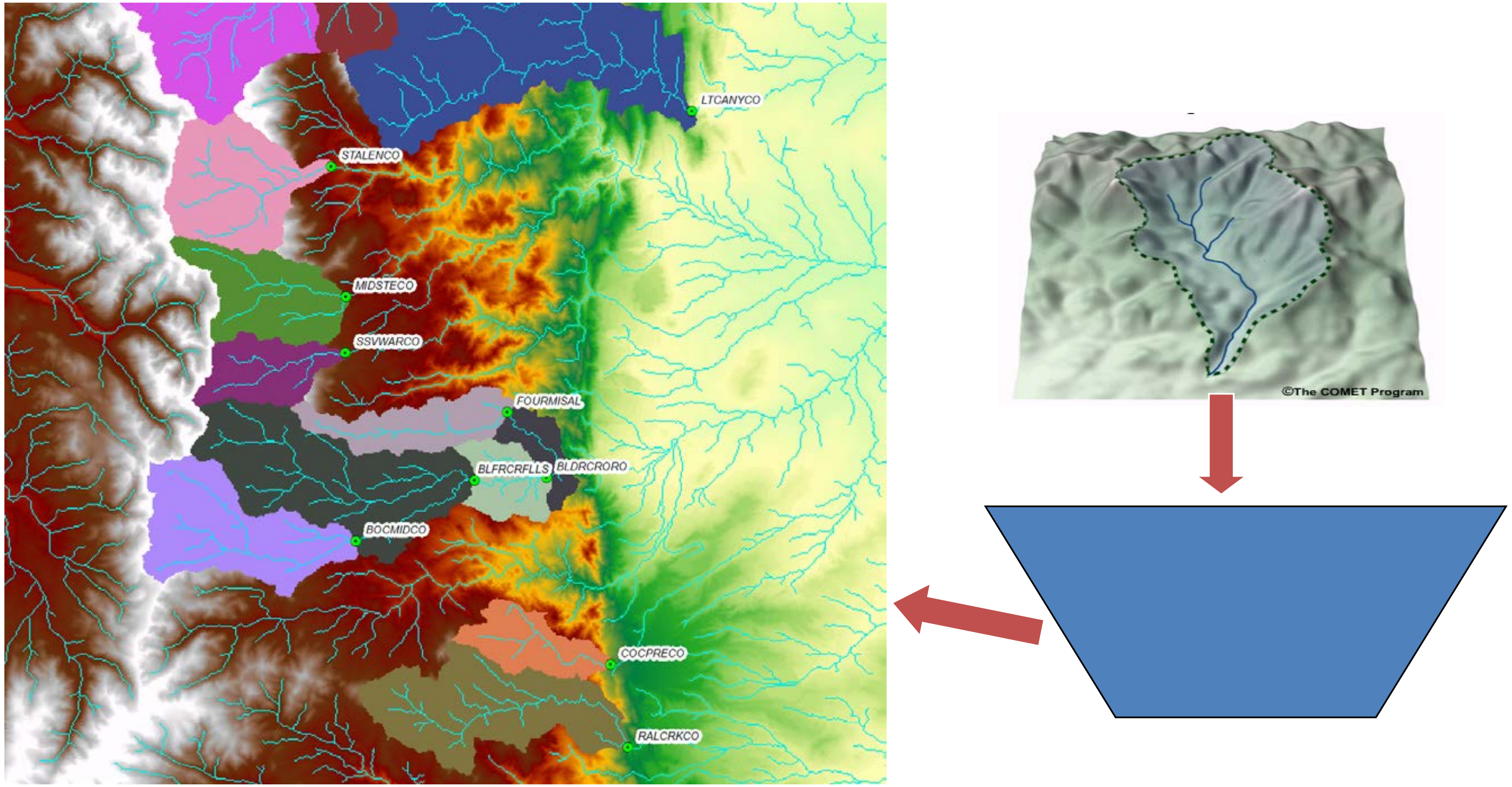
NHDPlus Reach Channel Network



WRF-Hydro V5.0 Physics Components

Optional conceptual ‘Bucket’ models:

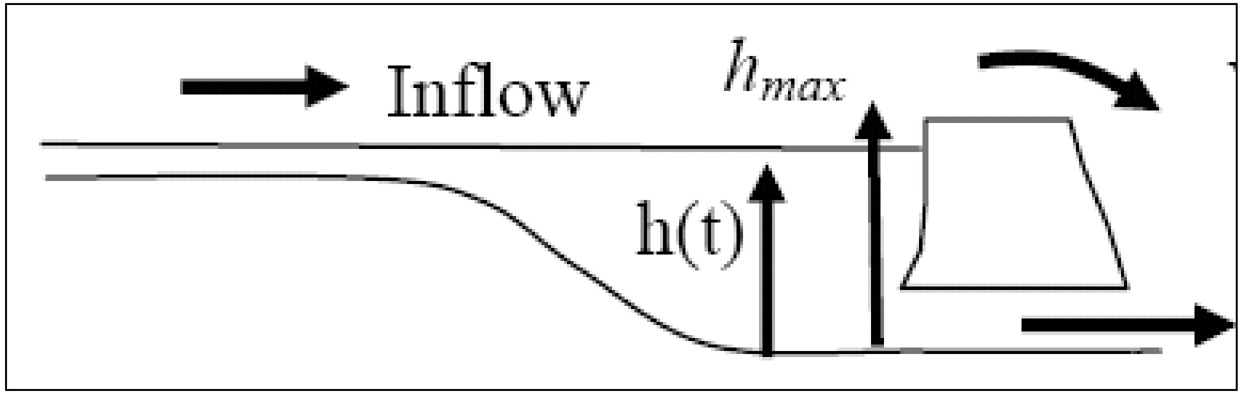
- Used for continuous (vs. event) prediction
- Simple pass-through or 2-parameter exponential model
- Bucket discharge gets distributed to channel network



WRF-Hydro V5.0 Physics Components

Optional lake/reservoir model:

- Level-pool routing (i.e. no lagging of wave or gradient in pool elevation)
- Inflows via channel and overland flow
- Discharge via orifice and spillway to channel network
- Parameters: lake and orifice elevations, max. pool elevation, spillway and orifice characteristics; specified via parameter table
- Active management can be added via an operations table
- Presently no seepage or evaporative loss functions



Gridded or Diffusive Wave Routing

- Explicit, 1-D, variable time-stepping
- Diffusive wave in the model: simplified version of Continuity and Momentum St. Venant equations.

$$\frac{\partial V}{\partial t} + \underbrace{V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f)}_{} = 0 \quad \Rightarrow \quad Q = -\mathrm{SIGN}\left(\frac{\partial Z}{\partial x}\right)K\sqrt{\left|\frac{\partial Z}{\partial x}\right|}$$

Diffusive wave: includes pressure in addition to friction and gravity forces

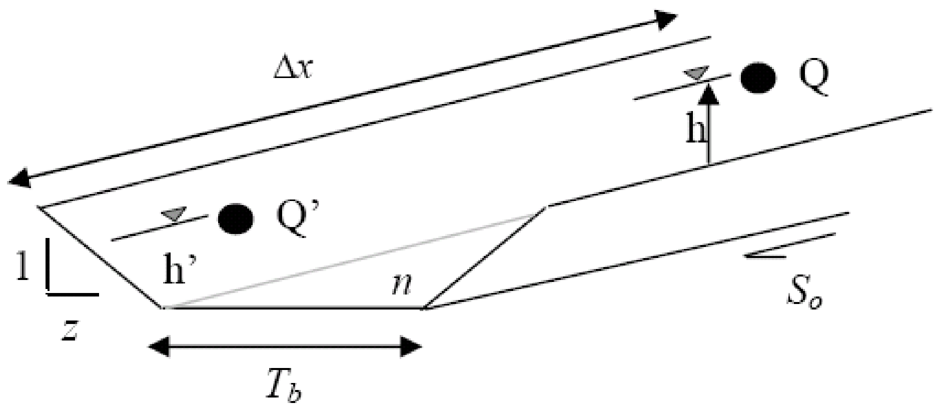
where K is conveyance and *Z* is the water surface elevation. The SIGN function is 1 for $\partial Z/\partial x > 0$ and -1 for $\partial Z/\partial x < 0$

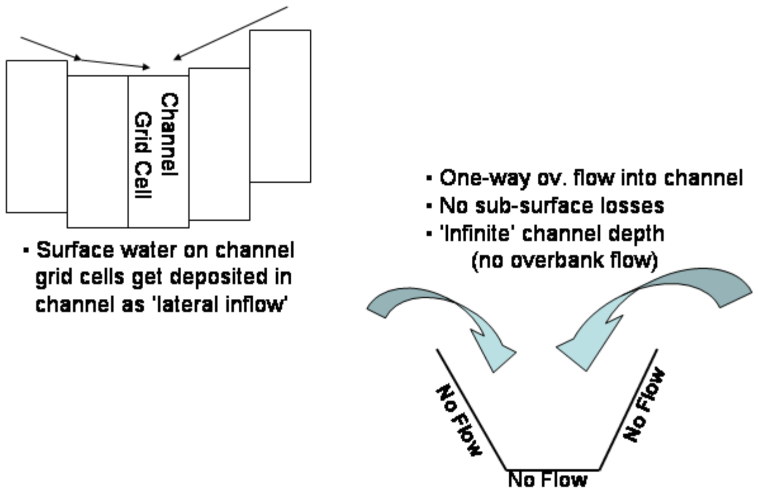
- A numeric solution per channel grid pixel is obtained by discretizing the continuity eqn.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \quad \Rightarrow \quad A^{n+1} - A^n = \frac{\Delta t}{\Delta x}\left(Q^n_{i+\frac{1}{2}} - Q^n_{i-\frac{1}{2}}\right) + \Delta t q^n_{lat}$$

Channel Routing Methods

- Set in hydro.namelist with the channel_option = 1, 2 or 3
- Channel_option 1 or 2 is “reach-based” or “vector” routing
- Channel_option = 3 is “gridded” or 1d diffusive wave





Muskingum Routing

- Storage routing method based on the continuity equation where,

$I - O = \frac{dS}{dt}$, I = inflow, O is outflow, S is storage and t is time

- General Muskingum equation: $S = K[xI + (1 - x)O]$

where K is a storage constant (also referred to as lag, travel time, etc.) and X is a weighting factor expressing relative importance of I & O to S.

- Simplified, implemented per reach in the channel network:

$$O_2 = c_0 I_2 + c_1 I_1 + c_2 O_1$$

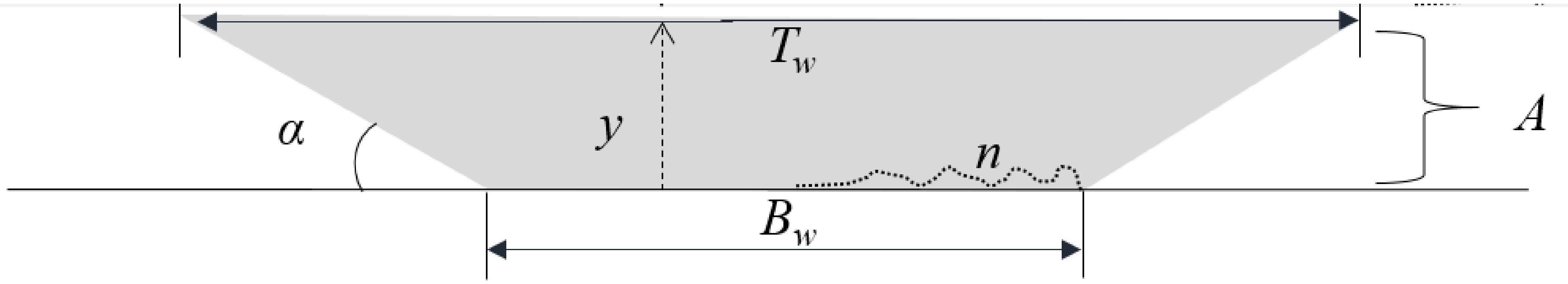
where c_o, c_1 and c_2 are functions of K, X and t, whose sum is 1.

Muskingum – Cunge Routing

- Similar to Muskingum, but with hydraulically derived parameters, *K*, the "storage constant" and *X*, "weighting factor"
- $K = \frac{\Delta x}{c}$, where Δx = reach length and c is the celerity (wave speed)
- $X = \frac{1}{2}\left(1 - \frac{Q}{BcS_0\Delta x}\right)$, where B = bottom width, S_0 is the slope
- NWM channel routing uses this option for CONUS.
- Benefits: faster computation and stable; Cons – flat, long reaches may not be appropriate.

Channel Parameters

- For gridded, channel_option = 3, we use the CHANPARM.TBL file to specify bottom width (Bw), side slope (z), roughness (n), HLINK.
- For reach-based, channel_option = 1 or 2, the Routelink.nc file specifies the parameters for every reach.
- Defaults for both: order based parameters.



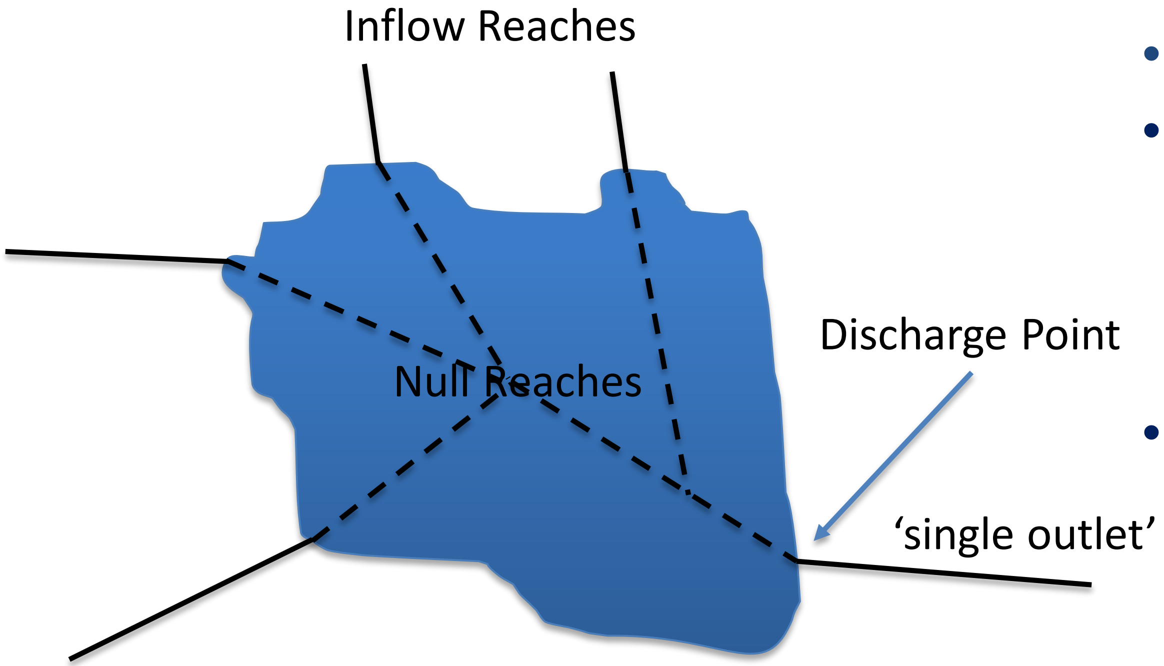
Channel Routing: Key Settings & Parameters

Parameter/Setting	Description	Scale/File	Estimate
Runtime Settings			
CHANRTSWCRT	Channel switch (on or off)	hydro.namelist	Landscape/event
channel_option	Routing method (Muskingum, Musk-Cunge, diffusive wave)	hydro.namelist	Landscape/event, compute resources (can be computationally intensive)
DTRT_CH	Channel routing timestep	hydro.namelist	Based on channel reach or grid size, landscape/event
Parameters			
CHANNELGRID	Channel/land mapping	Routing grid (Fulldom)	Landscape
BtmWidth, ChSlp	Channel geometry: bottom width and side slope	Reach (Route_Link) or CHANPARM lookup table	Linear model based on stream order or statistically derived
n	Channel roughness (Manning's n)	Reach (Route_Link) or lookup table	Linear model based on stream order
So	Longitudinal downstream channel slope (reach only)	Reach (Route_Link)	Calculated from topography
MusK, MusX	Muskingum routing parameters (reach only)	Reach (Route_Link)	Estimated based on channel properties

Lakes & Reservoirs

WRF-Hydro V5.0 Physics Components : Lake/Reservoir Represenation

- Defined in GIS Pre-processing, integrated with channel hydrograph
- Specified spillway characteristics (length, height)



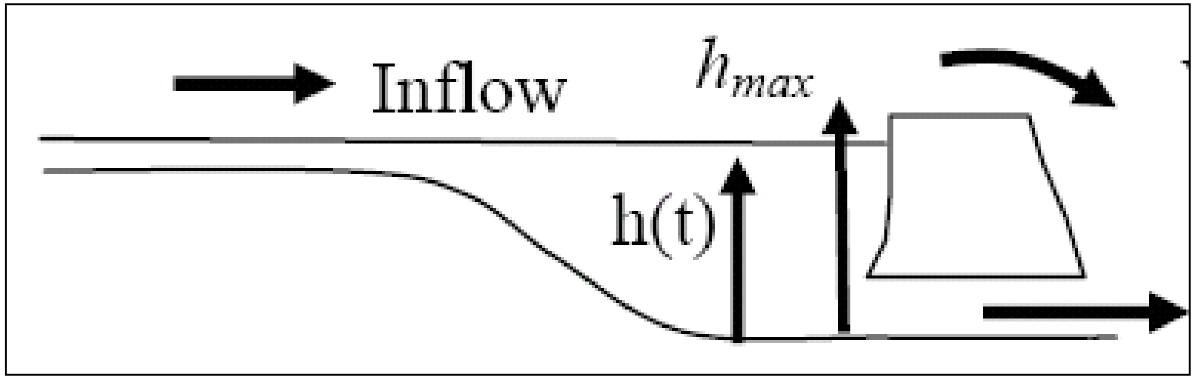
- Level Pool Scheme:
- 3 'passive' discharge mechanisms:
  - Orifice flow
  - Spillway flow
  - Direct Pass-through
- Development:
  - Basic thermodynamics (CLM/WRF lake model)
  - Full lake accounting
    - Evaporation
    - Ice formation
    - Inflows/outflows
    - Simple management
  - Coupling to FVCOM (GLERL)

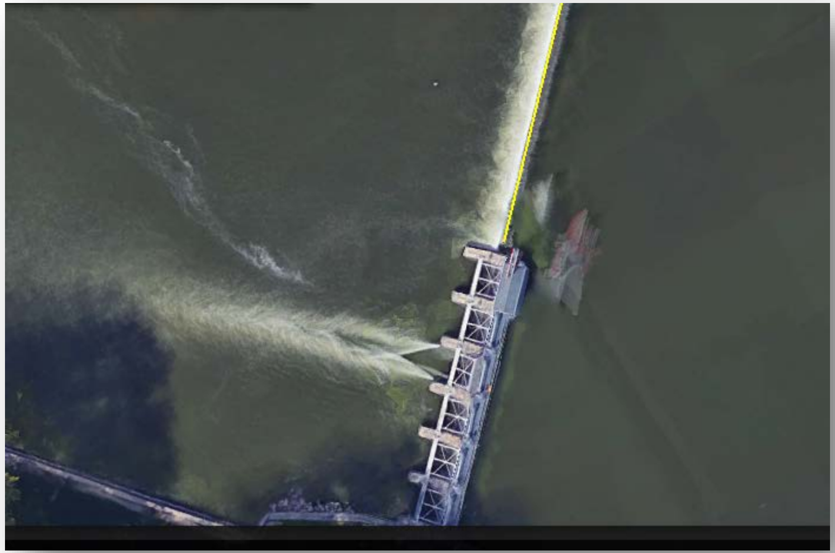
Lakes & Reservoirs in WRF-Hydro

- Level-pool storage
- Multiple discharge modes

3 ‘passive’ discharge mechanisms:

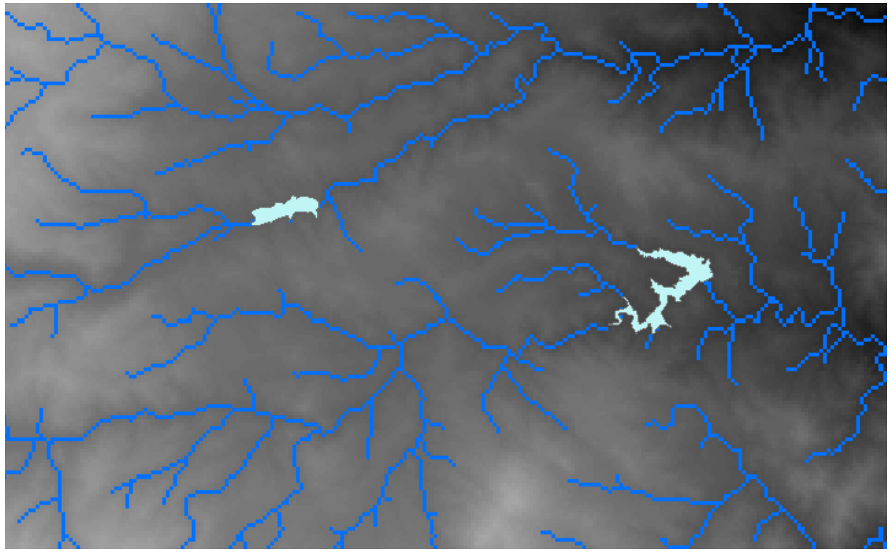
- Orifice flow
- Spillway flow
- Direct Pass-through
- ΔS= I – O (to include surface fluxes)





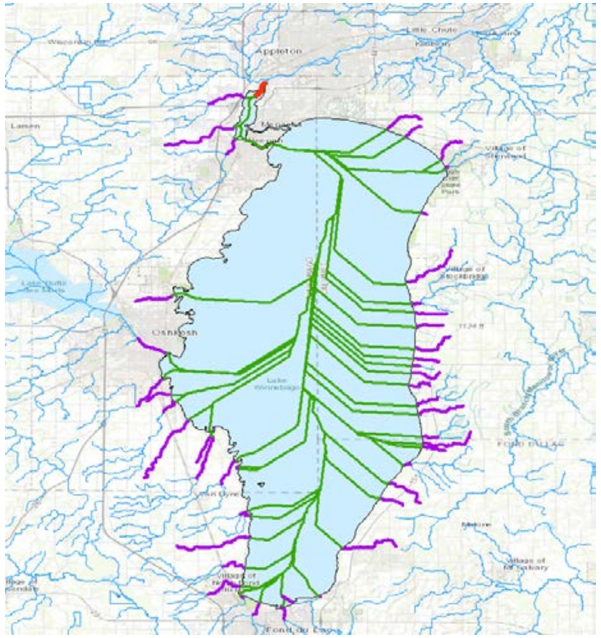
Lakes in Gridded Routing

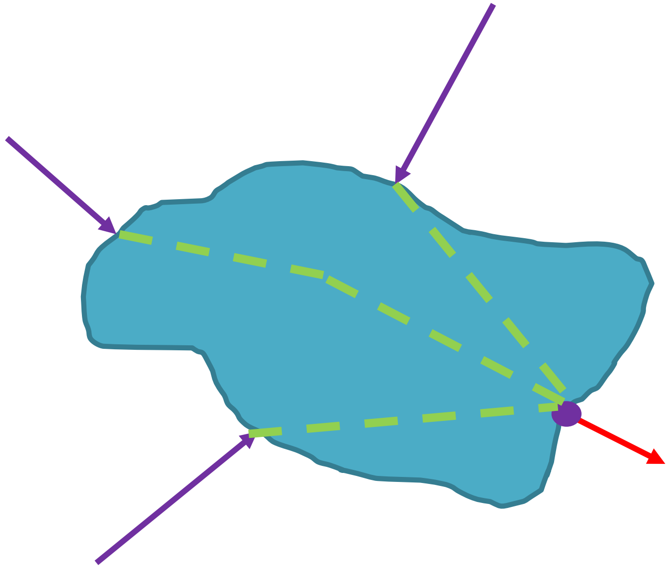
- Lakes are defined on the fine grid (in the Fulldom file 'LAKEGRID' var.)
- Channel pixels under lakes are erased
- Model identifies pixels as 'inflow' or 'outflow'; only 1 outflow pixel allowed
- Level-pool performed on outflow pixel



Lakes in NWM (Reach-Based)

- Lakes are objects

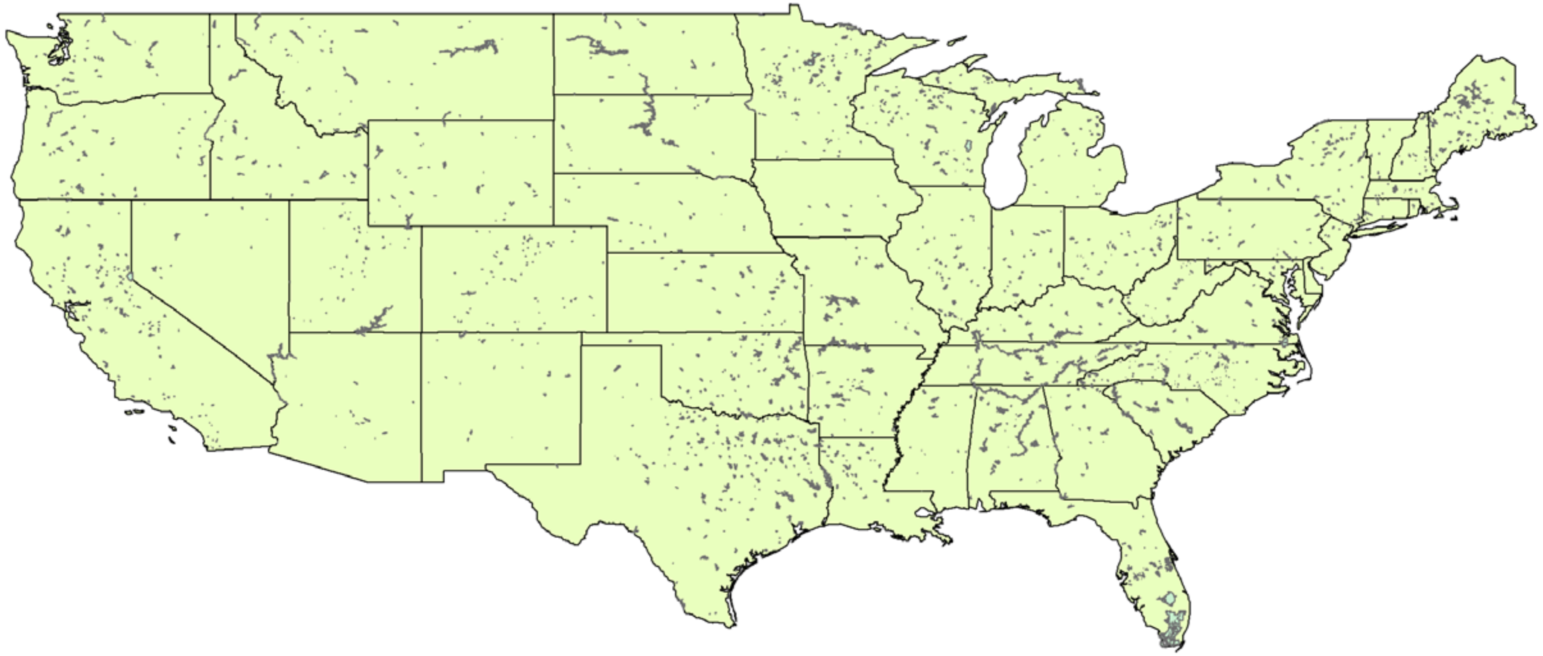




- **Why**: We can easily integrate with the flow network; vectorization speed.
- **Implications**: Lakes outflow at a single point; the lake ‘module’ is run independently.

National Water Model Reservoirs

- V1.2: 1,507 NHDPlus water bodies
- Specified spillway characteristics (length, height)



- Default reservoir configuration: Level-pool scheme with parameterized discharge:
  - orifice
  - spillway
- Discharge Options Under Development:
  - Fixed/constant value
  - Operating Curves
  - Downstream stream gauge data assimilation
  - Management schedule
- Future:
  - Diversions
  - Reservoir evaporation
  - Irrigation

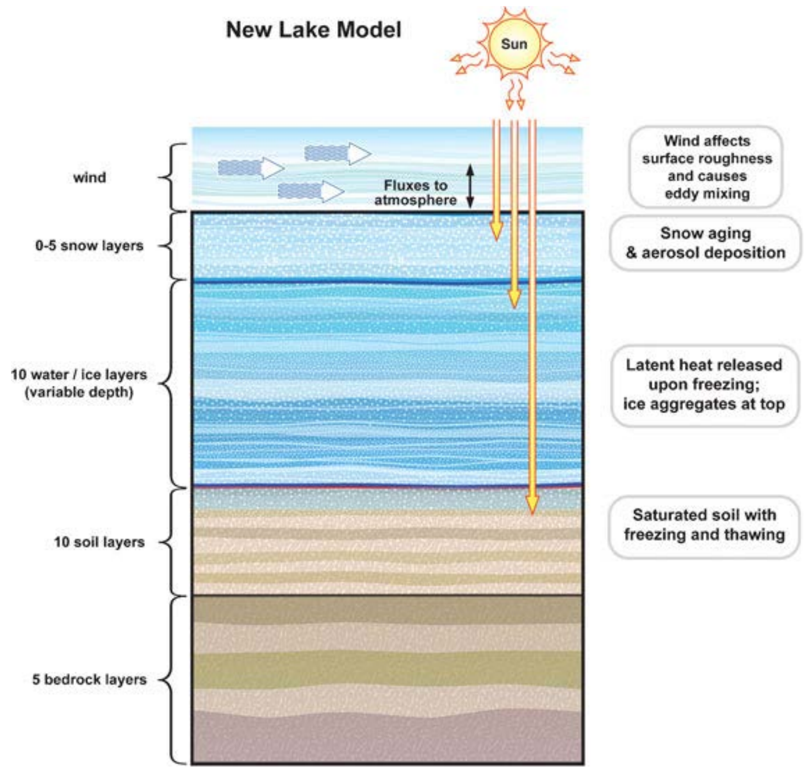
Ongoing Work Related to Lake Development

Implementation of 1-dimensional lake model

- Account for ice formation, rainfall, and evaporation fluxes over lakes.
- Adapt the WRF/CLM-LISSS lake scheme

Reservoir Operations

- Use observed lake outflows to assimilate flow/lake levels in managed reservoirs
- Machine learning to develop rule curves

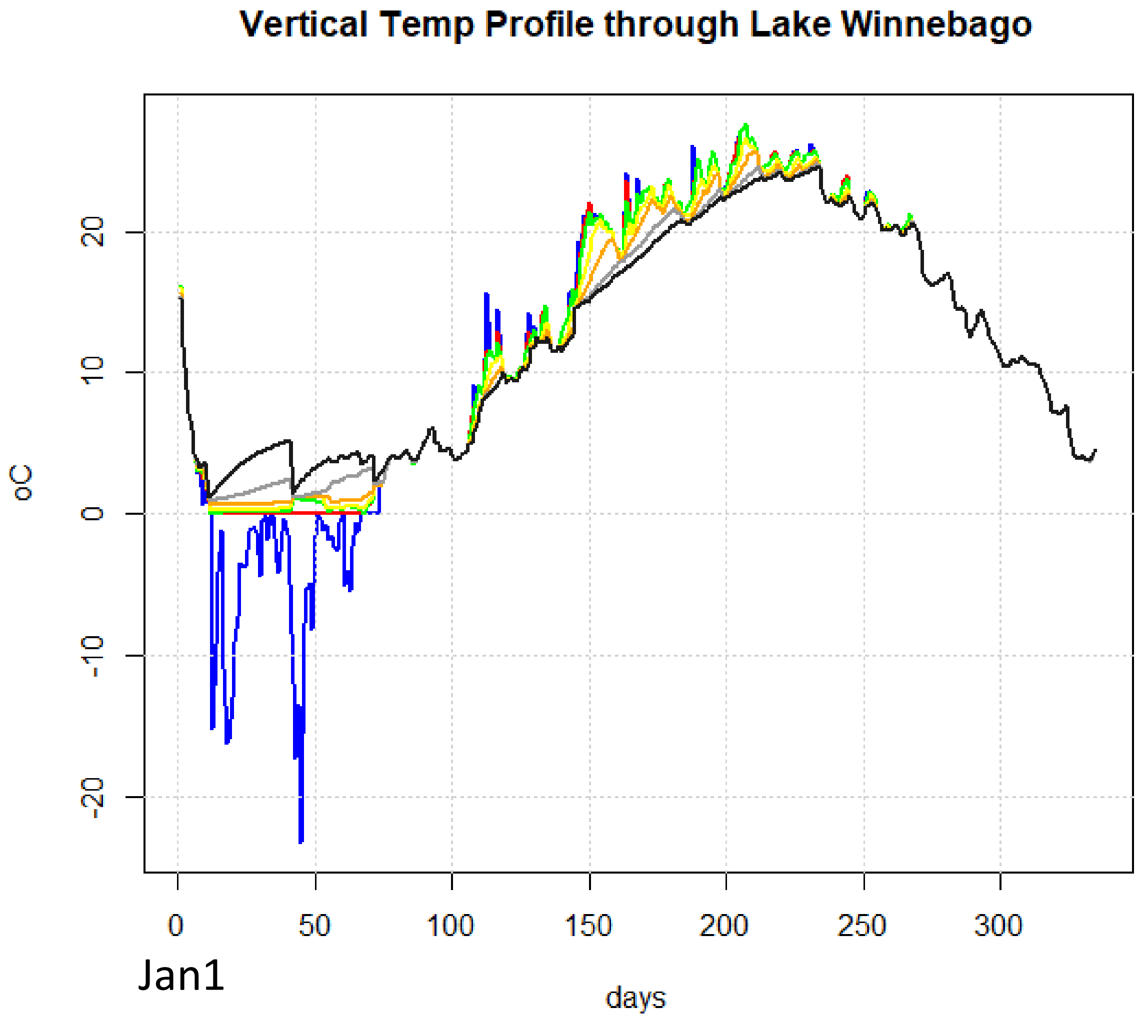


Borrowed from Subin et al. 2012

Ongoing Work Related to Lake Development

Implementation of 1-dimensional lake model

Surface (0.1m)
2m
4m
6m
8m
10m



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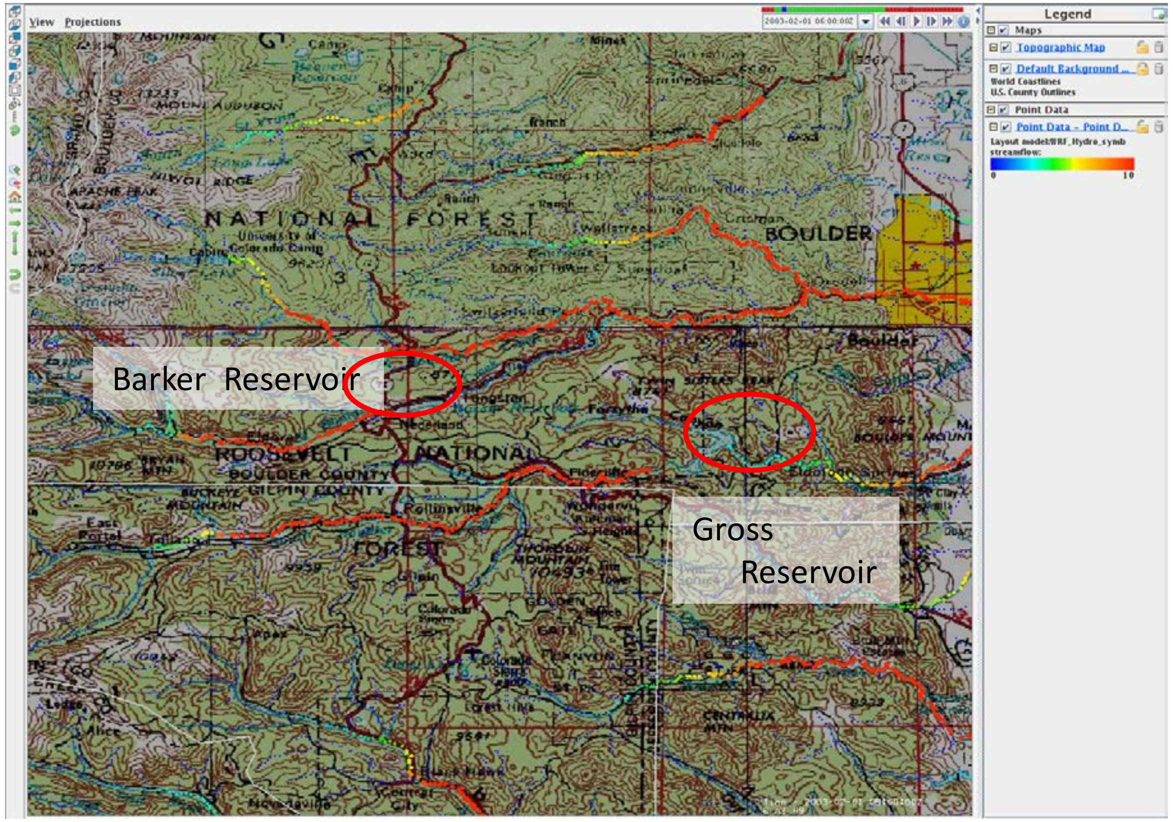
Reservoir Level-Pool Routing: Key Settings & Parameters

Parameter/Setting	Description	Scale/File	Estimate
Runtime Settings			
route_lake_f	Path to lake parameter file (if provided, lake model will be active)	hydro.namelist	Landscape/event
Parameters			
LAKEGRID or NHDWaterbodyComID	Location of lake object (gridded) ID of waterbody (NWM)	Routing grid (Fulldom) Route_Link	Landscape/event
LkArea, LkMxE	Lake geometry	LAKEPARM.nc file	Area: derived from NHDPlus or provided; LkMxE derived from elevation grid
WeirC, WeirL, WeirE	Lake weir properties (constitutes “uncontrolled flow”)	LAKEPARM.nc file	WeirE from elevation grid; coeff and length defaults
OrificeC, OrificeA, OrificeE	Lake orifice properties (constitutes “controlled flow”)	LAKEPARM.nc file	OrificeE from elevation grid; coeff and area are defaults

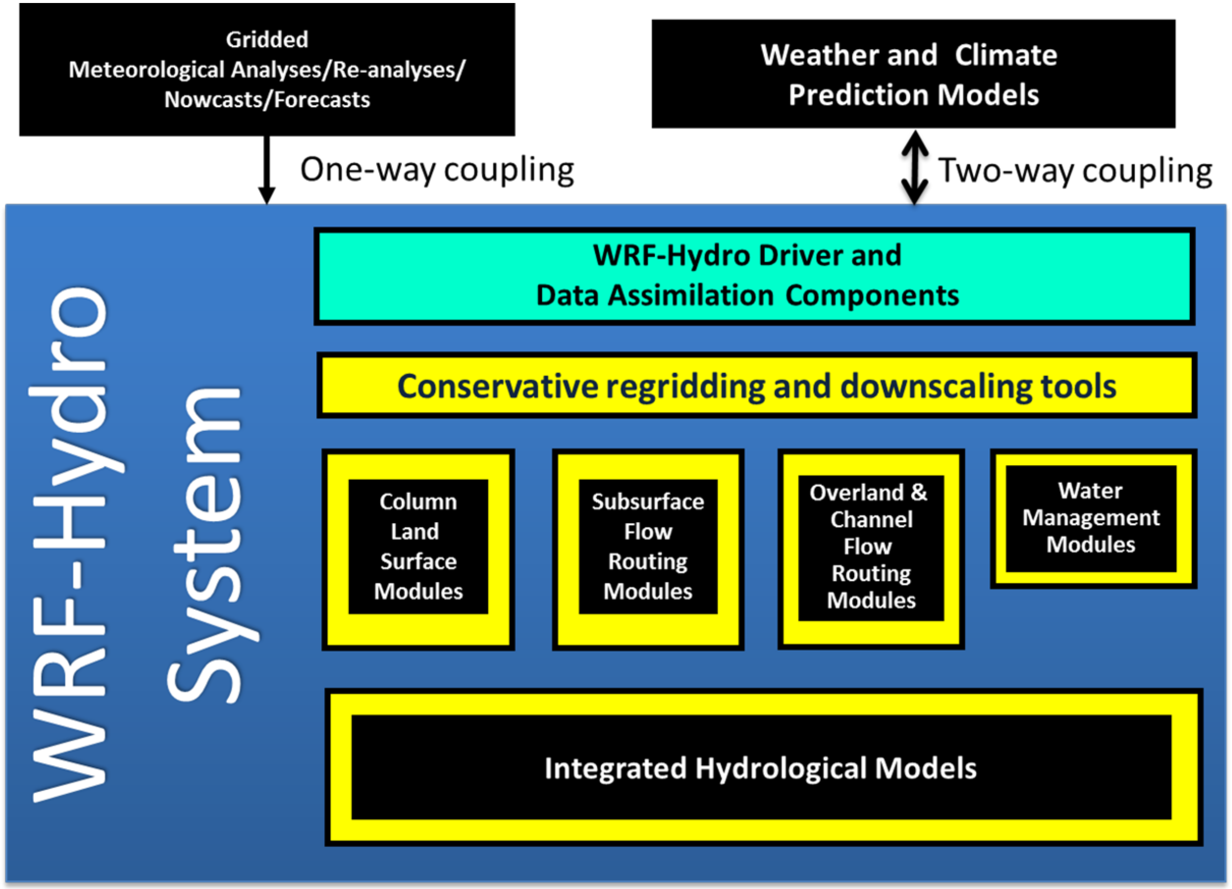
WRF-Hydro V5.0 Physics Components

Implementing lakes and reservoirs in WRF-Hydro

Visualization of lake impacts



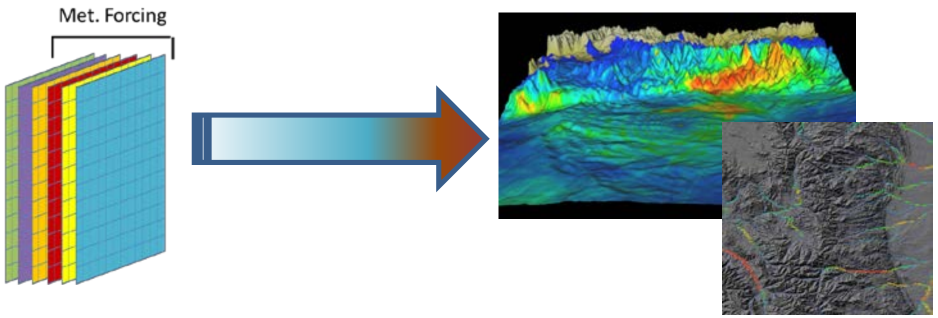
WRF-Hydro Model Architecture



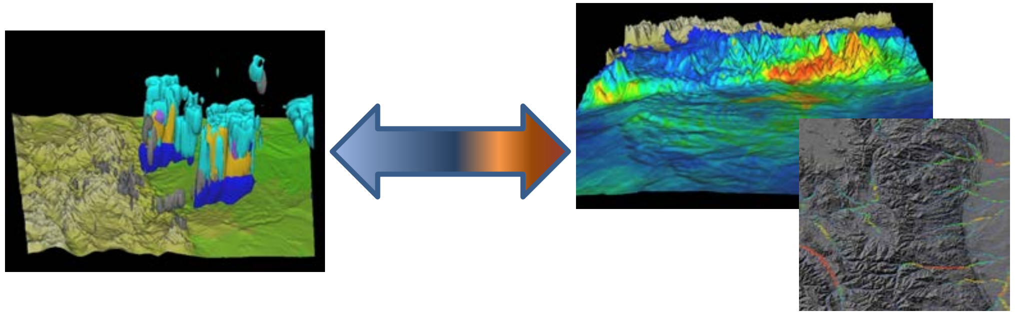
- Model physics components….
- Multi-scale components….
  - Rectilinear regridding
  - ESMF regridding
  - Downscaling

WRF-Hydro Model Architecture

One-way (‘uncoupled’) →



Two-way (‘coupled’) ↔



- Modes of operation..1-way vs. 2-way
- Model forcing and feedback components:
  - Forcings: T, Press, Precip., wind, radiation, humidity, BGC-scalars
  - Feedbacks: Sensible, latent, momentum, radiation, BGC-scalars

Routing Options

Type	When/Why To Use	Benefits	Drawbacks
Subsurface Routing			
SUBRTSWCRT	When local topography is important to flow processes or your fluxes/states of interest	Allows lateral water movement between cells, better representing convergence/divergence patterns (e.g., water converging into a valley) and residence times	More computationally expensive
Overland Flow Routing			
OVRTSWCRT	When fast surface flow processes are of interest/importance (e.g., flood forecasting vs. water supply forecasting)	Better represents local ponding and re-infiltration; required to capture land runoff directly to channels and lakes	More computationally expensive
Channel Routing			
CHANRTSWCRT	When you want streamflow in the channel		
Muskingham- **Reach** channel_option = 1	When you want an approximate solution as efficiently as possible (e.g., over a large domain or with limited compute resources)	Computationally cheap and fast	Limited to uniform fluxes/states per reach (not ideal if reaches are long); no backwater effects
Muskingham-Cunge-**Reach** channel_option = 2	When you want an approximate solution as efficiently as possible (e.g., over a large domain or with limited compute resources)	Computationally cheap and fast; more “stable” in terms of propagating flow one-way down the channel	Limited to uniform fluxes/states per reach (not ideal if reaches are long); no backwater effects
Diffusive Wave- **Gridded** channel_option = 3	When you need a more precise/accurate local solution and have sufficient compute resources (e.g., small or high-resolution domains, conditions where hydraulic processes are important)	Captures backwater flow; provides higher spatial detail on channel flow (e.g., every channel grid cell); only option that allows (limited) water fluxes from land to lake	More computationally expensive, can be sensitive to parameters and internal time steps

WRF-Hydro®
MODELING SYSTEM

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