Overview of the WRF-Hydro Modeling System

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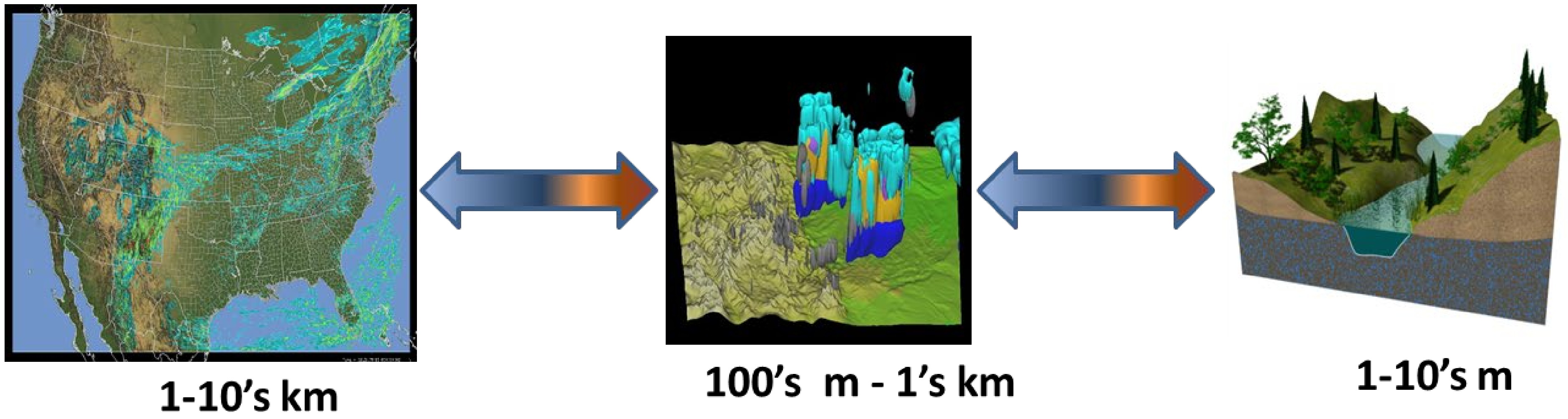
National Center for Atmospheric Research

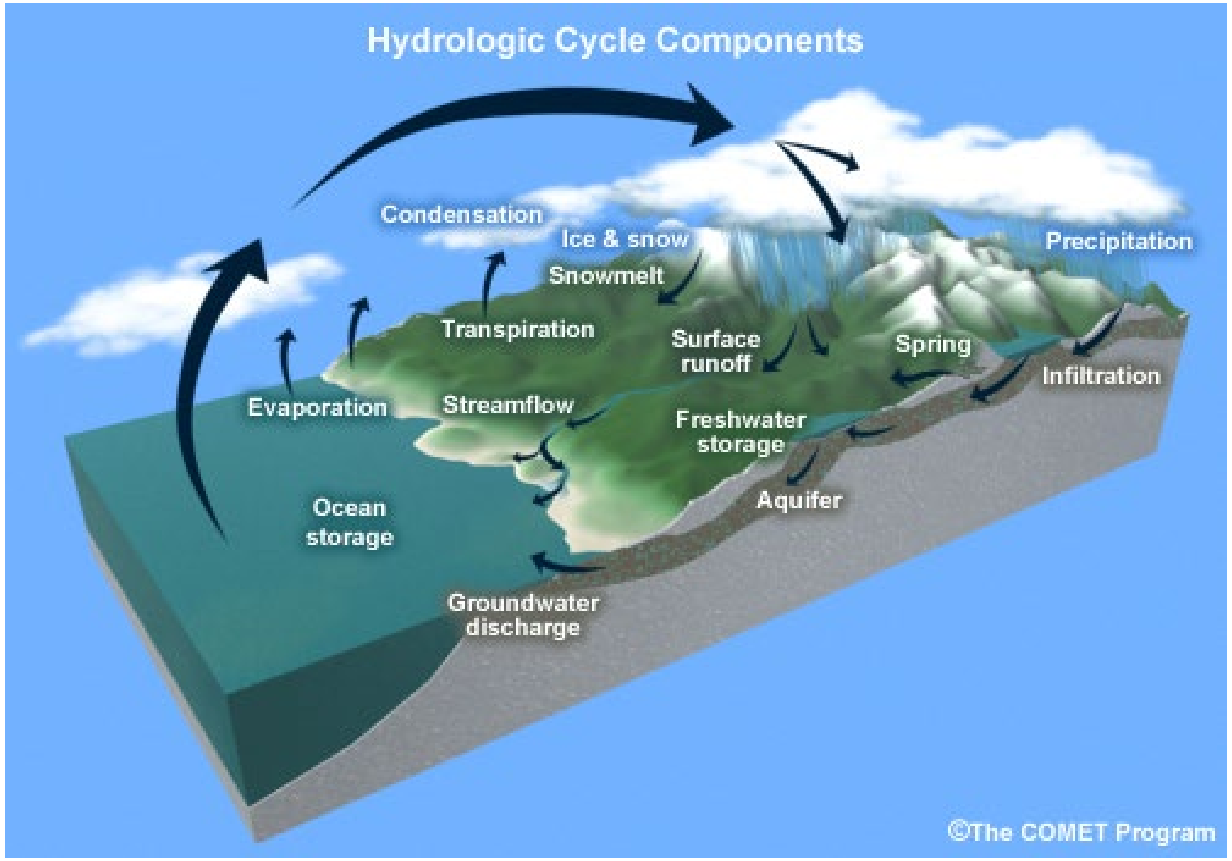
Overarching WRF-Hydro System Objectives

A community-based, supported coupling architecture designed to provide:

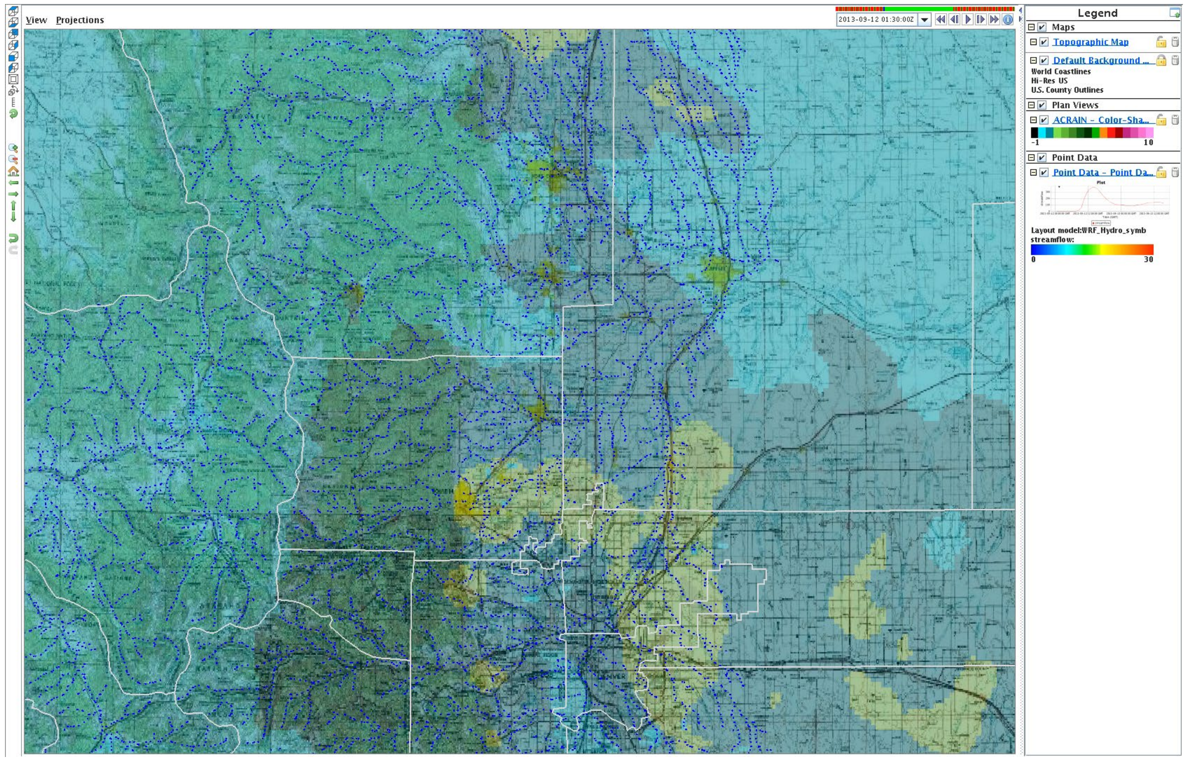
1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as <u>precipitation, soil moisture, snowpack, groundwater, streamflow, inundation</u>
2. ‘Accurate’ and ‘reliable’ streamflow prediction across scales (from 0-order headwater catchments to continental river basins & minutes to seasons)
3. A robust framework for land-atmosphere coupling studies



Water Cycle Modeling and Prediction within the WRF-Hydro System



Colorado Flood of 11-15 Sept. 2013

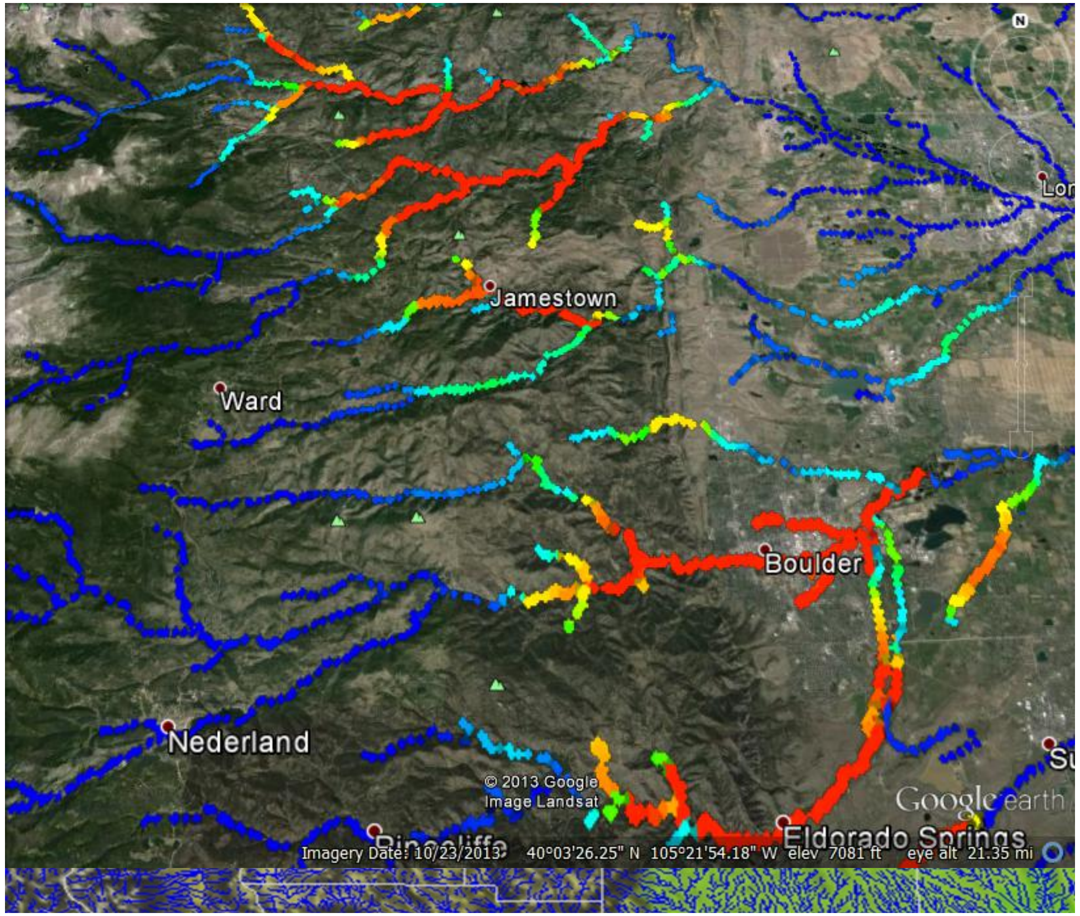


Accumulated Precipitation (shaded colors)
100m gridded streamflow (points)

1. Forecasts of water everywhere all the time

Current efforts are demonstrating the feasibility of Operational Quantitative Streamflow Forecasting (QSF):

- NSSL-FLASH, WRF-Hydro, LISFLOOD (UK), RAPID
- Spatial resolutions > 100m better
- Allows cycling from QPE and forecasting from QPN/QPF
- Emphasis on 0-6 hr gap

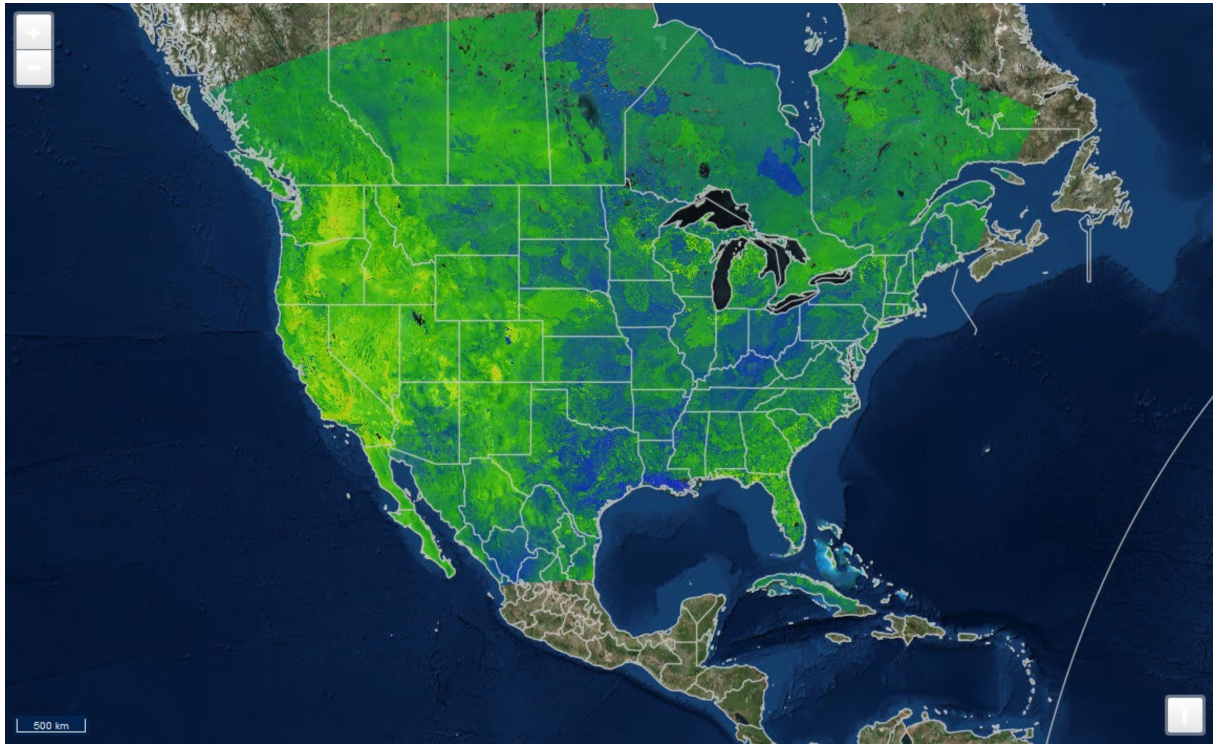


Moving Beyond Point Flow Forecasts

1. Forecasts of water everywhere all the time

The NOAA National Water Model

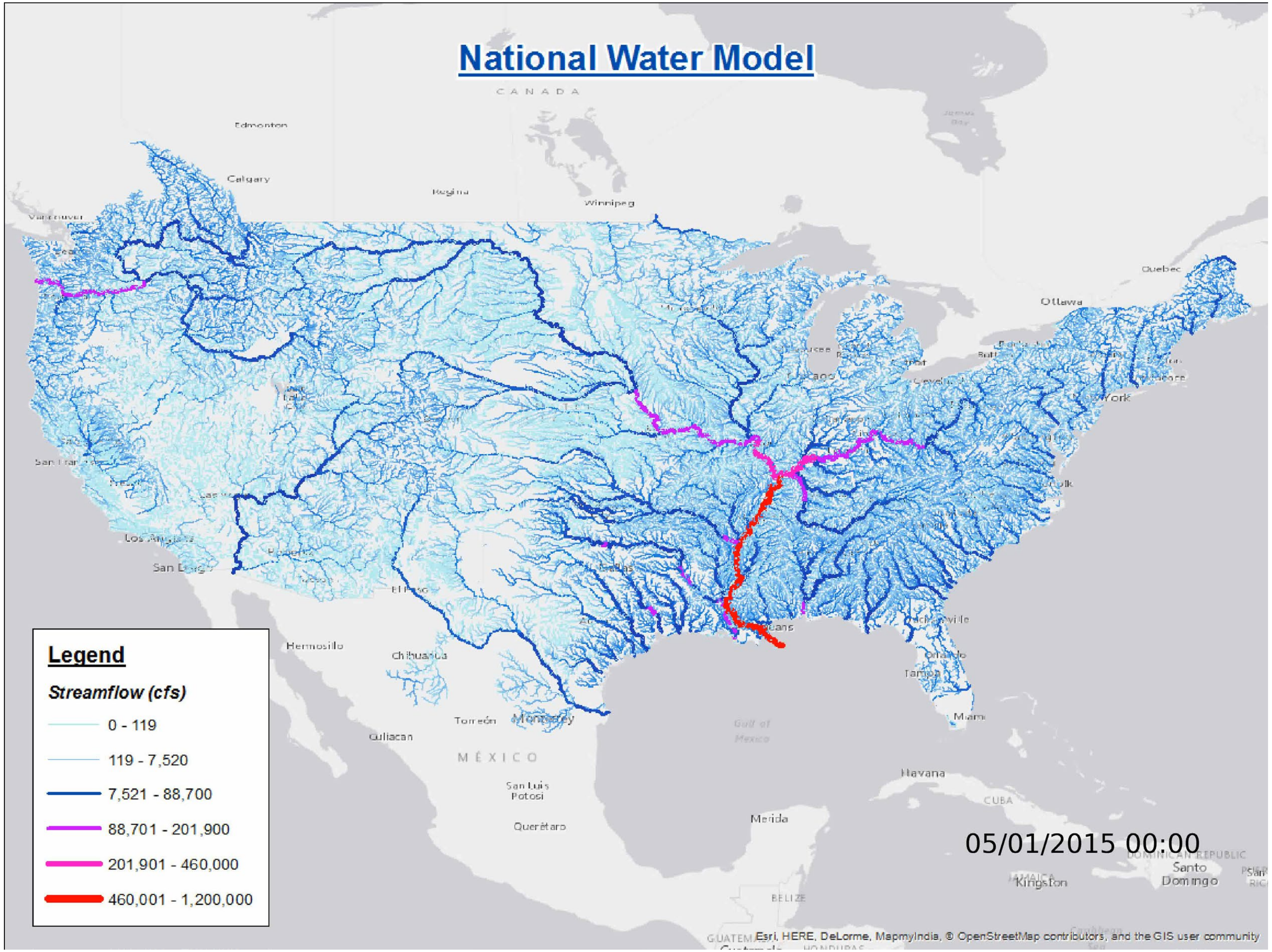
Snow Water Equivalent (SNEQV): Oct. 23, 2018



Total Column % Saturation ("SOILSAT"): Oct. 23, 2018

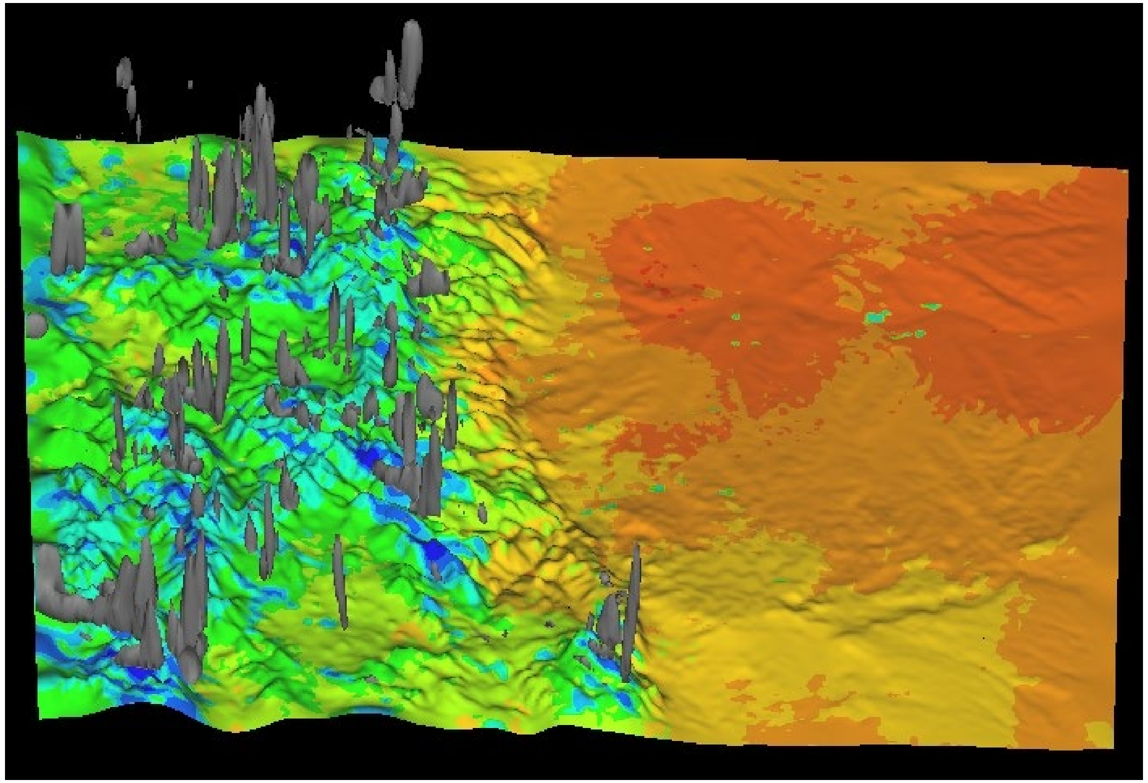
1. Forecasts of water everywhere all the time

The NOAA National Water Model

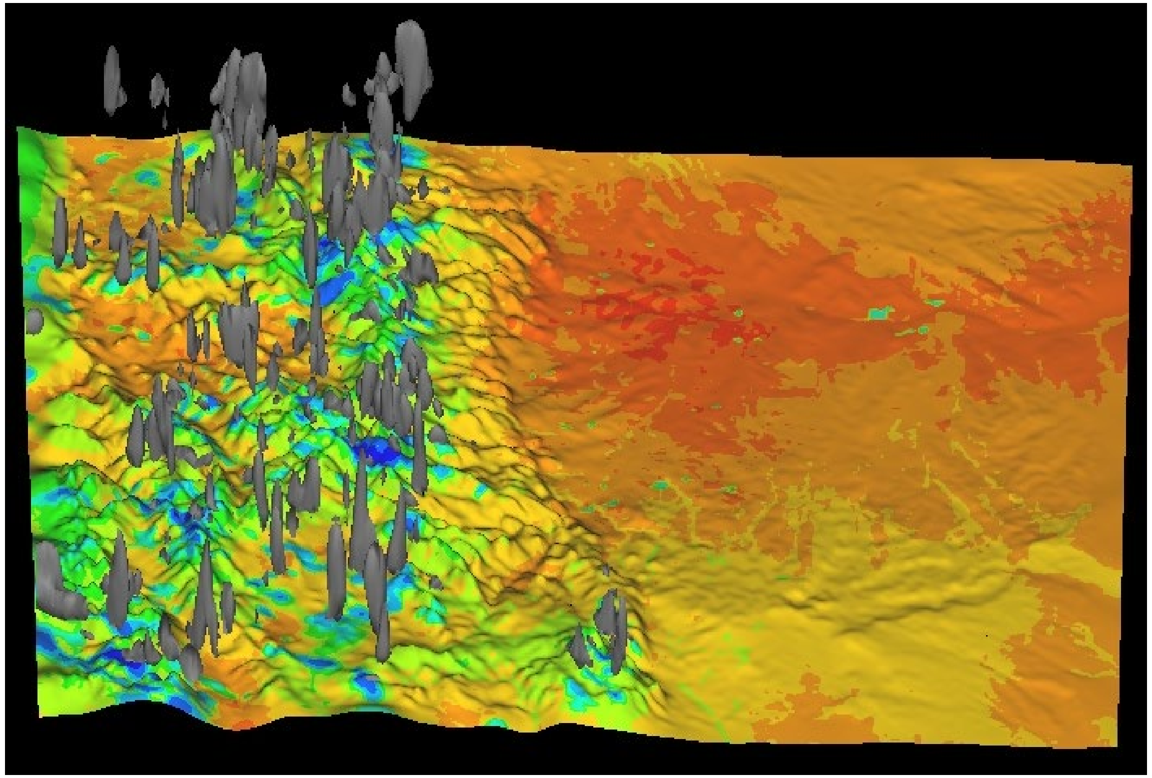


2. Coupled system flux predictions

FRNG_1km_cloudwater_tskin_NARR_7_18_2004_1800z



FRNG_1km_cloudwater_tskin_WRF-Hydro_rtg_7_18_2004_1800z



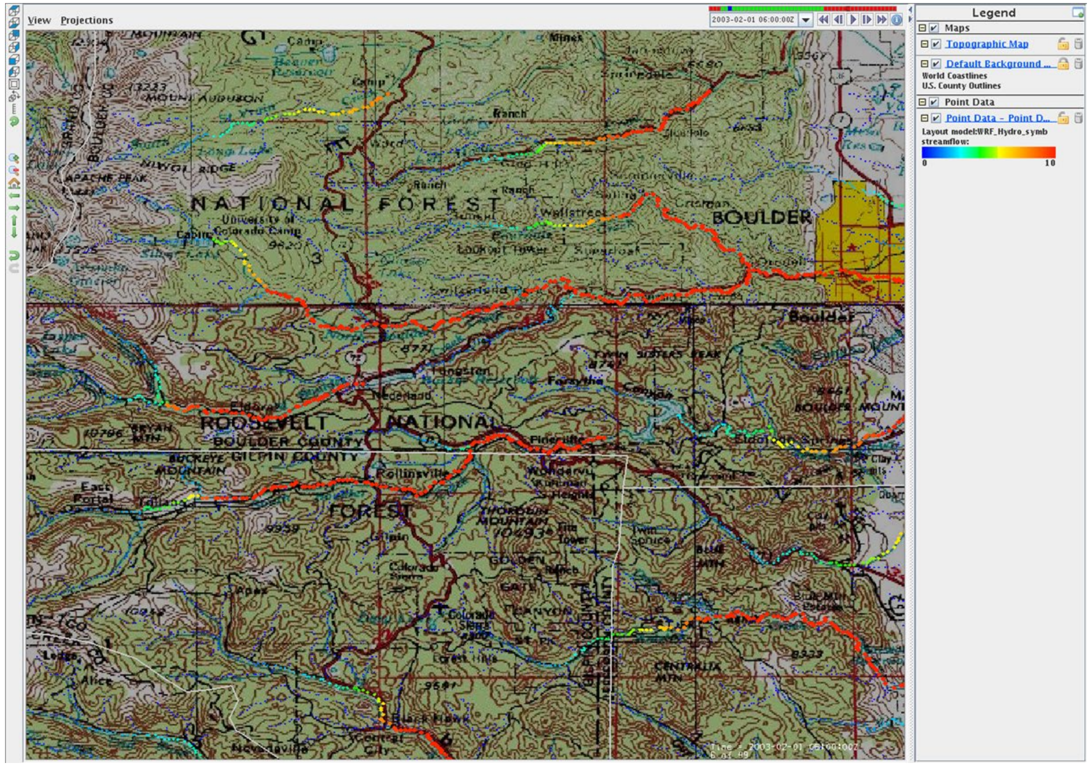
Variability in surface fluxes are strongly coupled to convective initiation and cloud formation. Complex, non-linear feedback require coupled system representation

3. Moving beyond natural flows towards explicit accounting of infrastructure

Including the control effects of and impacts on infrastructure:

- Dams and reservoirs (passive and actively managed)
- Overbank storage and attenuation
- Diversion structures, headgates
- Levees, dikes
- Failures of infrastructure (exceeding design capacity)

*** Needs Infrastructure & Operations Data Standards**



Design storm streamflow capture by Barker Reservoir and Gross Reservoirs. Colorado Front Range

4. Probabilistic framework for meaningful risk forecasting

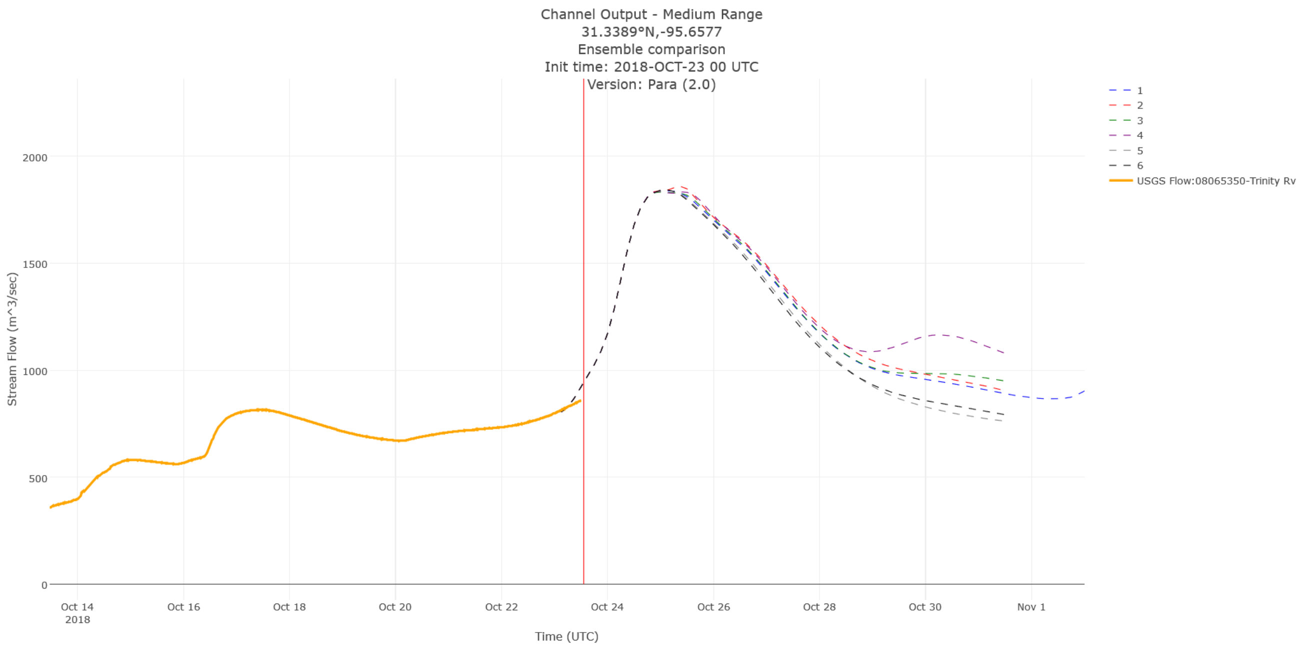
Quantify analysis and forecast uncertainty to provide meaningful risk guidance

Provide forecasters and decision makers with probabilities of:

- Locations and time of rapid river stage increase
- Duration of high waters and inundation

Requires maximizing the utility of High Performance Computing (HPC)

MRF Texas Flooding Oct. 23, 2018

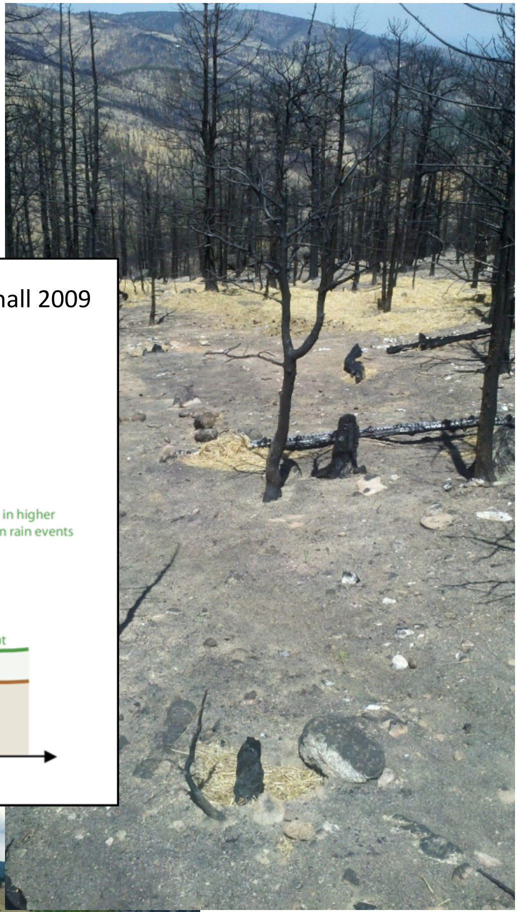


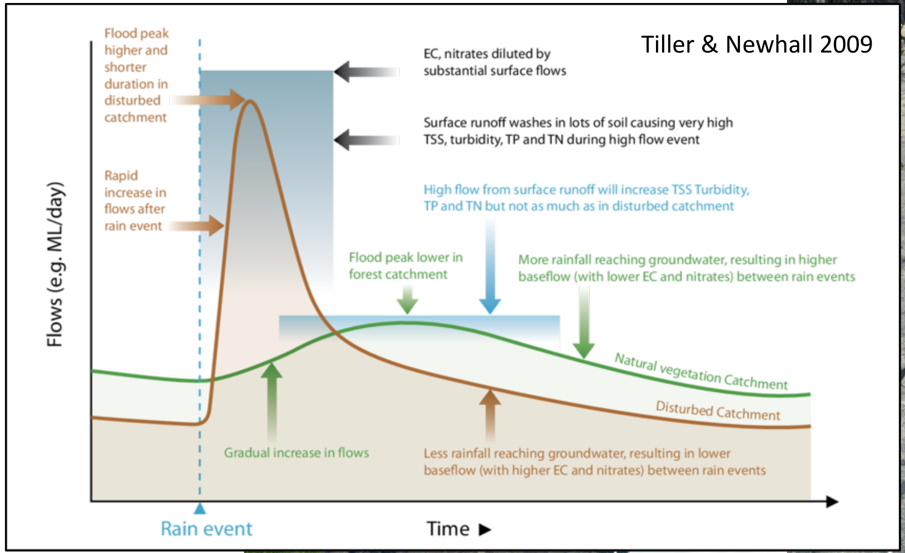
5. Hydro-system dynamics

Improving representation of landscape dynamics essential to flood risks:

- Geomorphological:
  - Bank stability
  - Sediment transport/deposition
  - Debris flows
- Land cover change due fire, urbanization, ag/silviculture

**** Needs: improved channel, soils and land cover geospatial data***



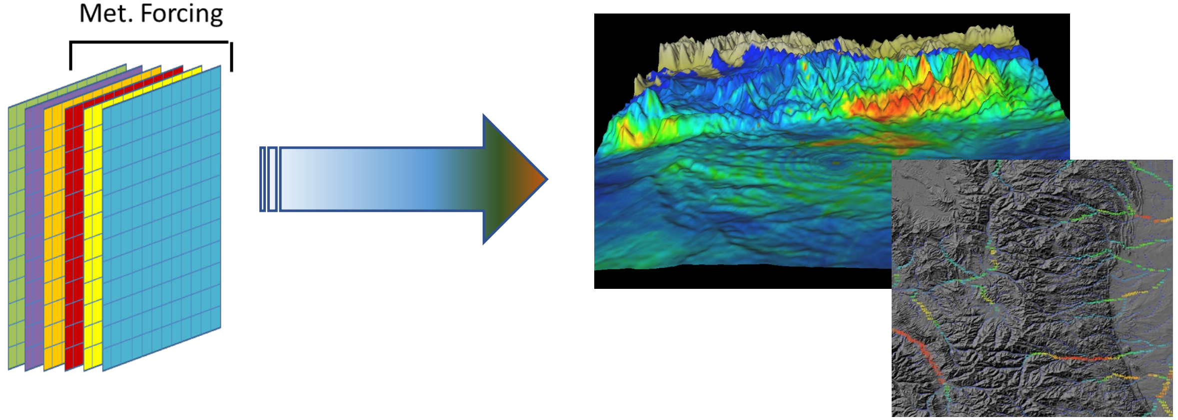


WRF-Hydro System Specifics

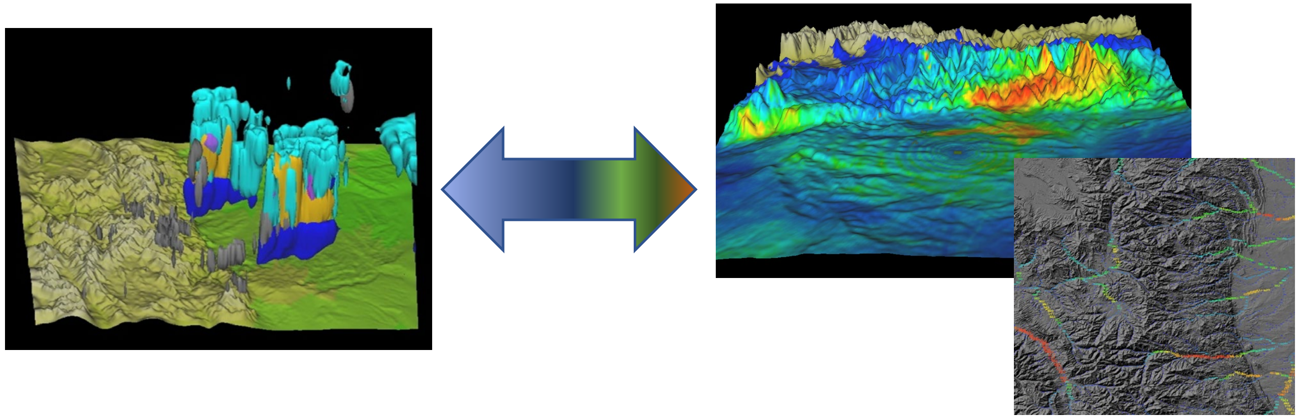
WRF-Hydro Operating Modes

WRF-Hydro operates in two major modes: coupled or uncoupled to an atmospheric model

One-way ("uncoupled") →

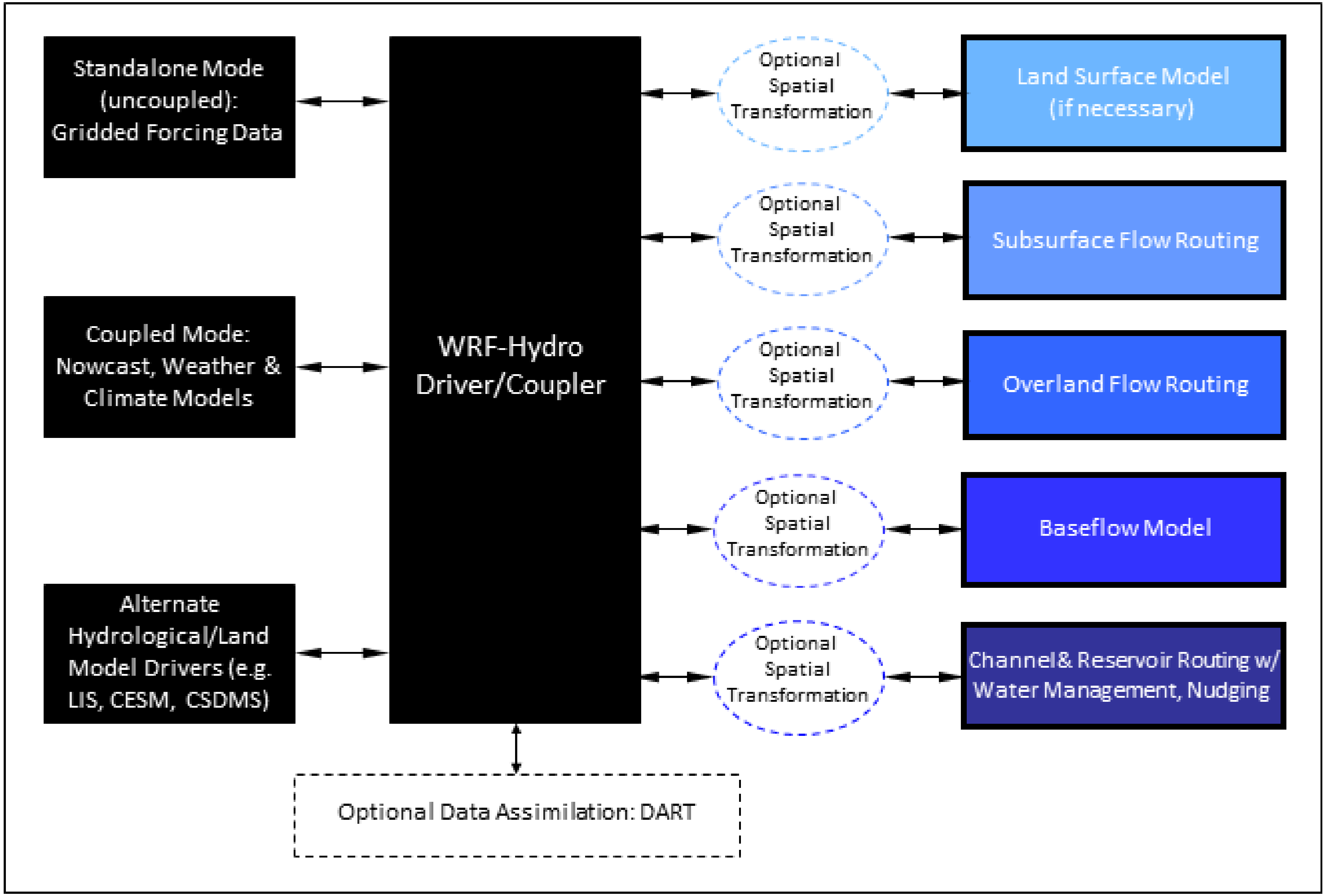


Two-way ("coupled") ↔



- <u>Uncoupled mode</u> critical for spinup, data assimilation and model calibration
- <u>Coupled mode</u> critical for land-atmosphere coupling research and long-term predictions
- Model forcing and feedback components mediated by WRF-Hydro:
  - Forcings: T, Press, Precip., wind, radiation, humidity, BGC-scalars
  - Feedbacks: Sensible, latent, momentum, radiation, BGC-scalars

WRF-Hydro Modular Calling Structure



WRF-Hydro System-Level Coupling Capabilities

Completed:

- Stand-alone, “Un-coupled” (1-d Noah & NoahMP land model driver)
- Coupled with the Weather Research and Forecasting Model (WRF-ARW)
- NOAA/NEMS (NOAA Environmental Modeling System, NUOPC)
- Coupled with LIS (WRF-Hydro v5.0, LISv7.2)
- Coupled into DART

In Progress:

- Coupling with PARFLOW integrated surface water / groundwater model (Col. School of Mines)

WRF-Hydro Software Features

- Modularized Fortran
- Coupling options are specified at compilation and WRF-Hydro is compiled as a new library in WRF when run in coupled mode
- Physics options are switch-activated though a namelist/configuration file
- Options to output sub-grid state and flux fields to standards-based netcdf point and grid files
- **Fully-parallelized** to HPC systems (e.g. NCAR supercomputer) and "good" scaling performance
- Ported to Intel, IBM and MacOS systems and a variety of compilers (pg, gfort, ifort)

WRF-Hydro Physics Components Overview

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.

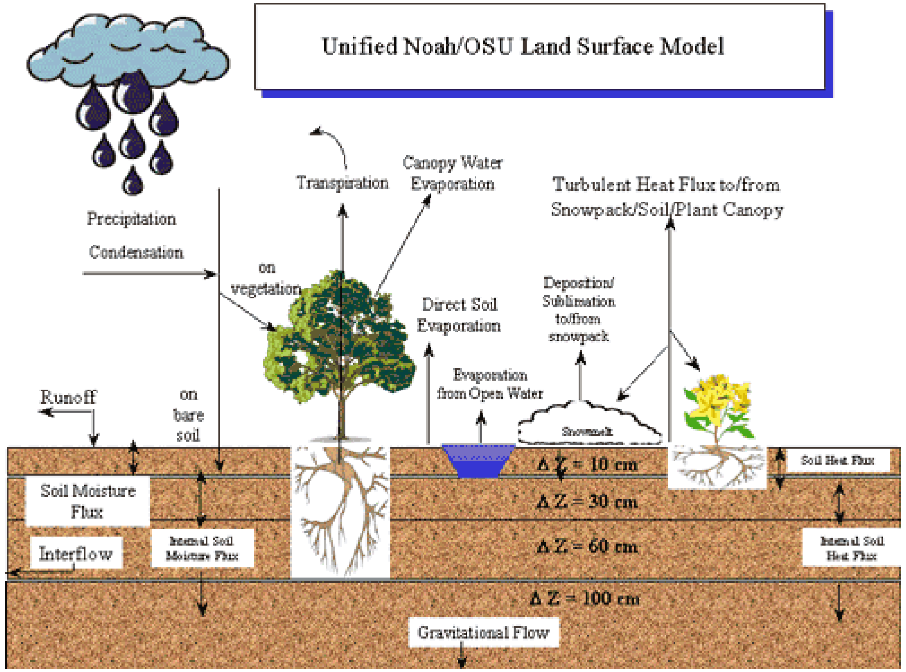
C. Required in meteorological models to describe indirect effect of land surfaces on climate through their contribution to changes in atmospheric composition

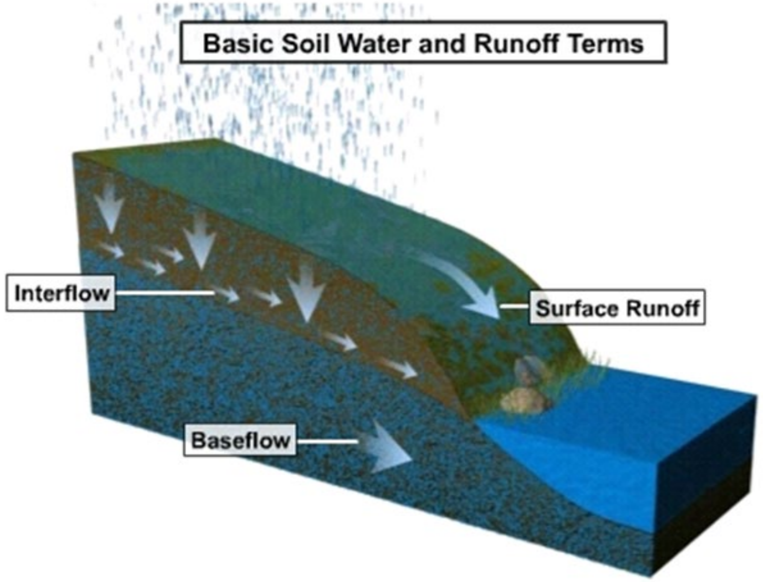
8. Area-average exchange of carbon dioxide (and possibly other trace gases).

Shuttleworth, 2011

Basic Concepts:

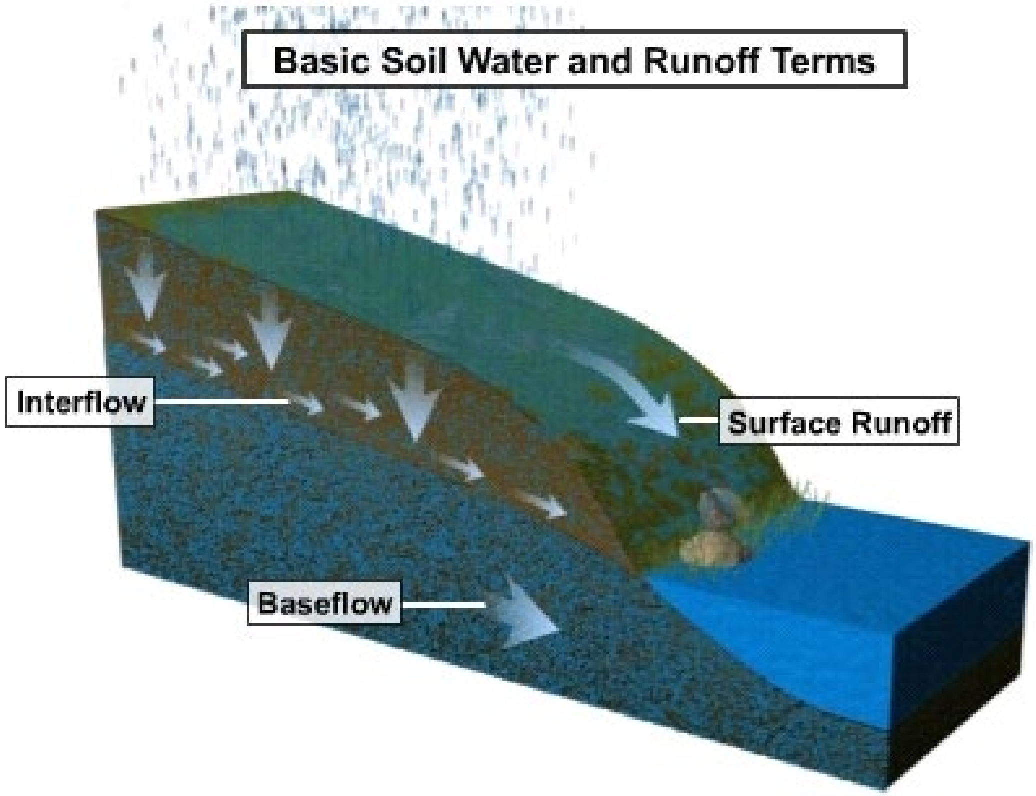
- Linking the column structure of land surface models with the ‘distributed’ structure of hydrological models in a flexible, HPC architecture….





'Moving Water Around': scale and process issues

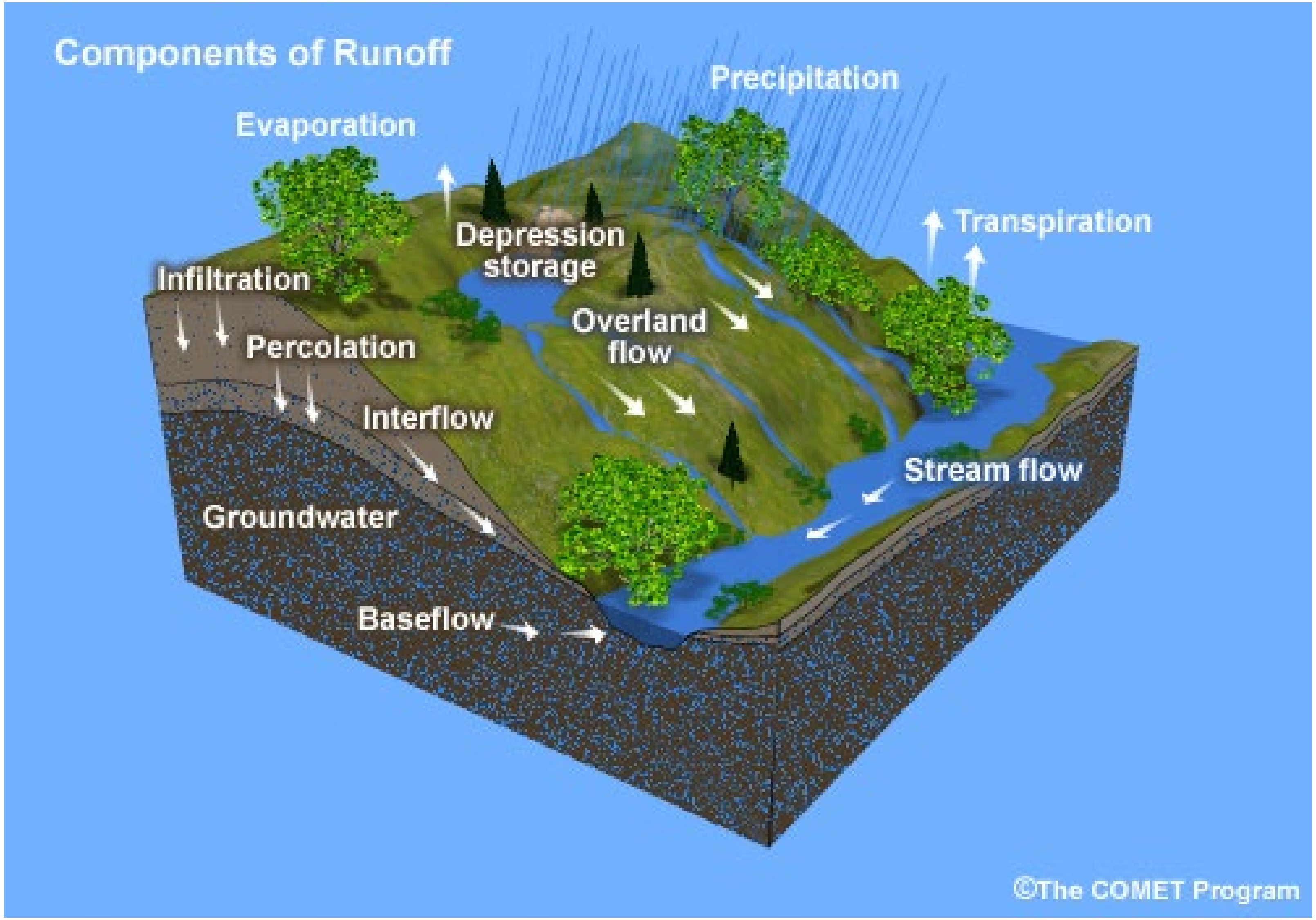
- Terrain features affecting moisture availability (scales ~1km)
  - Routing processes: the redistribution of terrestrial water across sloping terrain
    - Overland lateral flow (dominates in semi-arid climates)
    - Subsurface lateral flow (dominates in moist/temperate climates)
    - Shallow subsurface 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

WRF-Hydro V5.x Physics Components

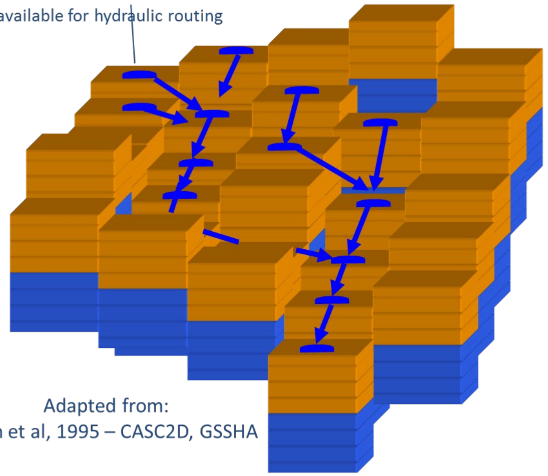
Goal…



WRF-Hydro V5.x Physics Components

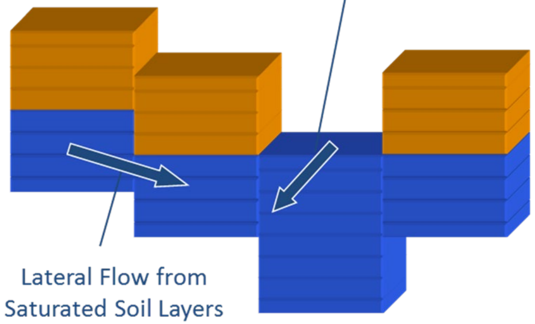
Runoff and Routing Physics:

Overland Flow

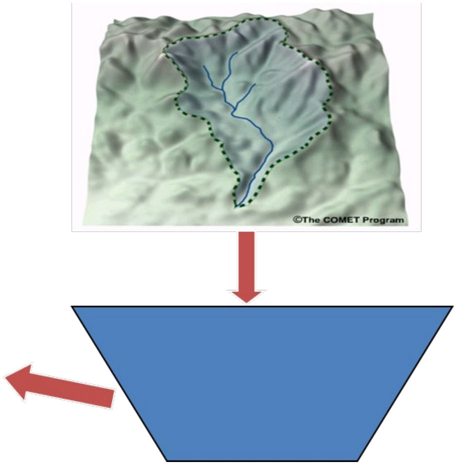


Adapted from:
Julian et al, 1995 – CASC2D, GSSHA

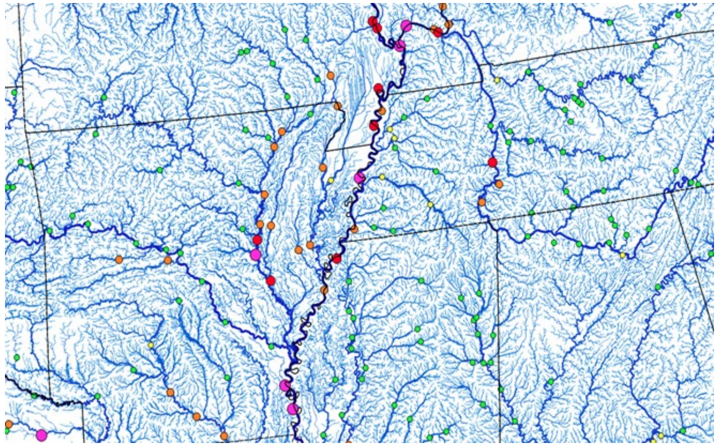
Lateral Subsurface Flow



Simplified Baseflow Parameterization

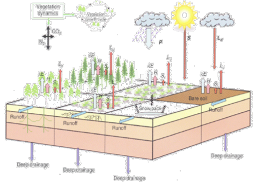
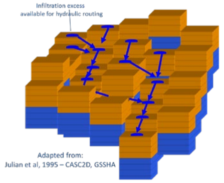
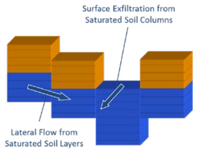
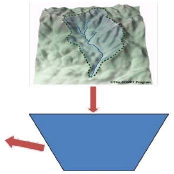
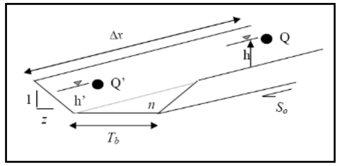
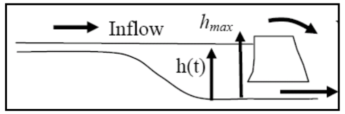


Channel Hydraulics



Simple Water Management

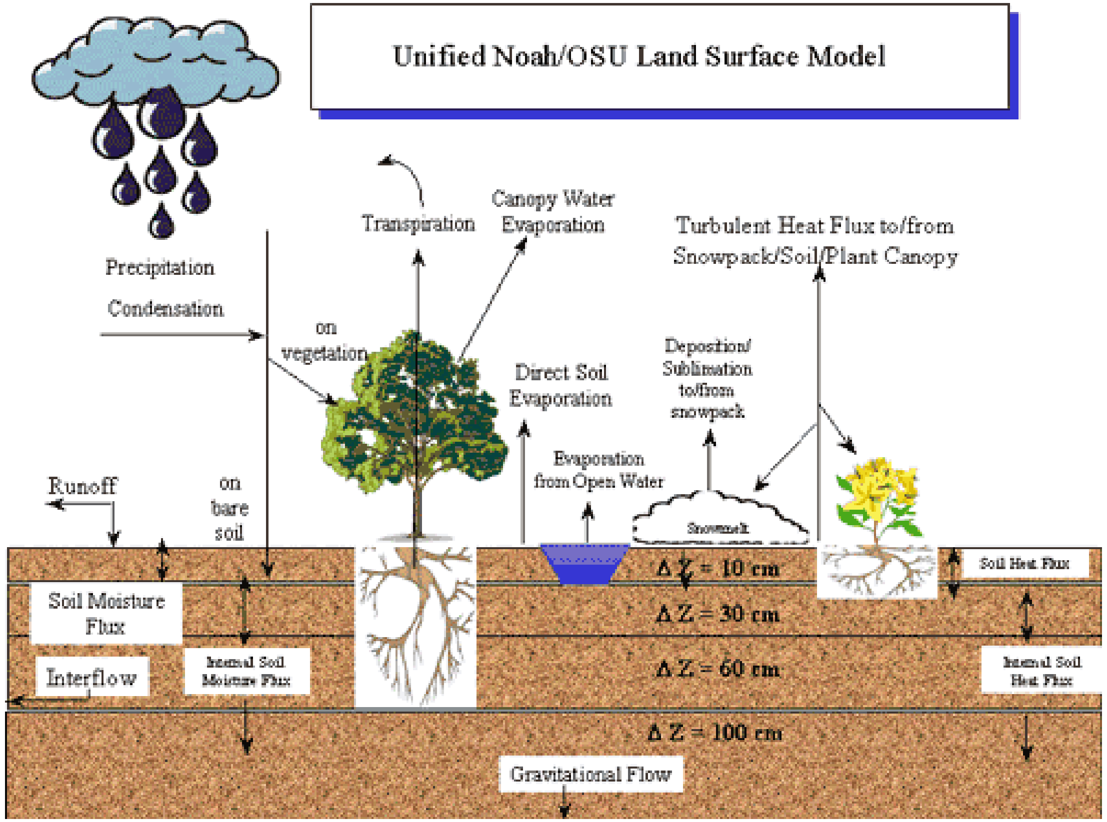
WRF-Hydro Physics Permutations

		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.x Physics Components

Current Land Surface Models:

- Column physics & land-atmosphere exchange



Noah LSM & Noah-MP

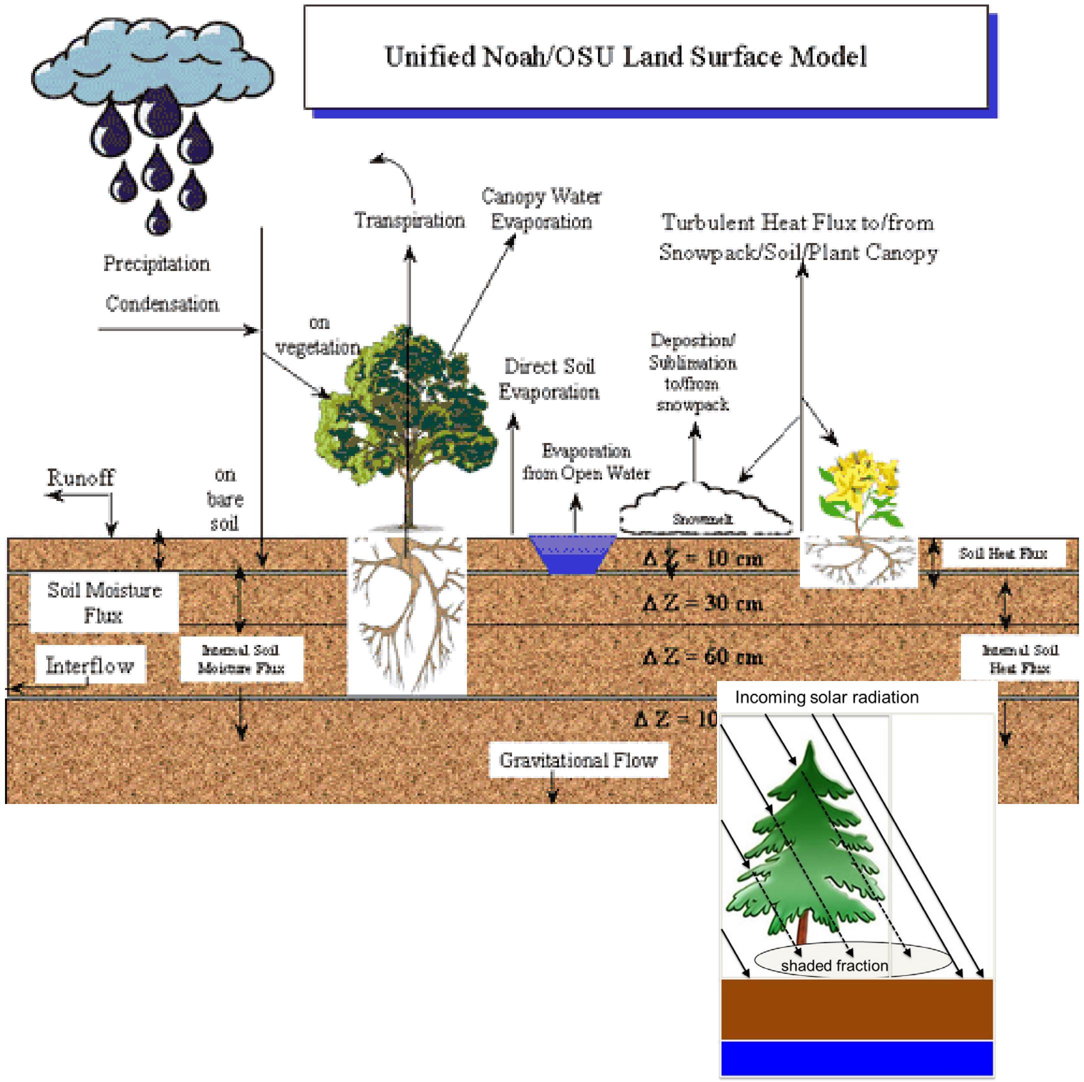
WRF-Hydro V5.x Physics Components

NoahMP Column Physics:

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



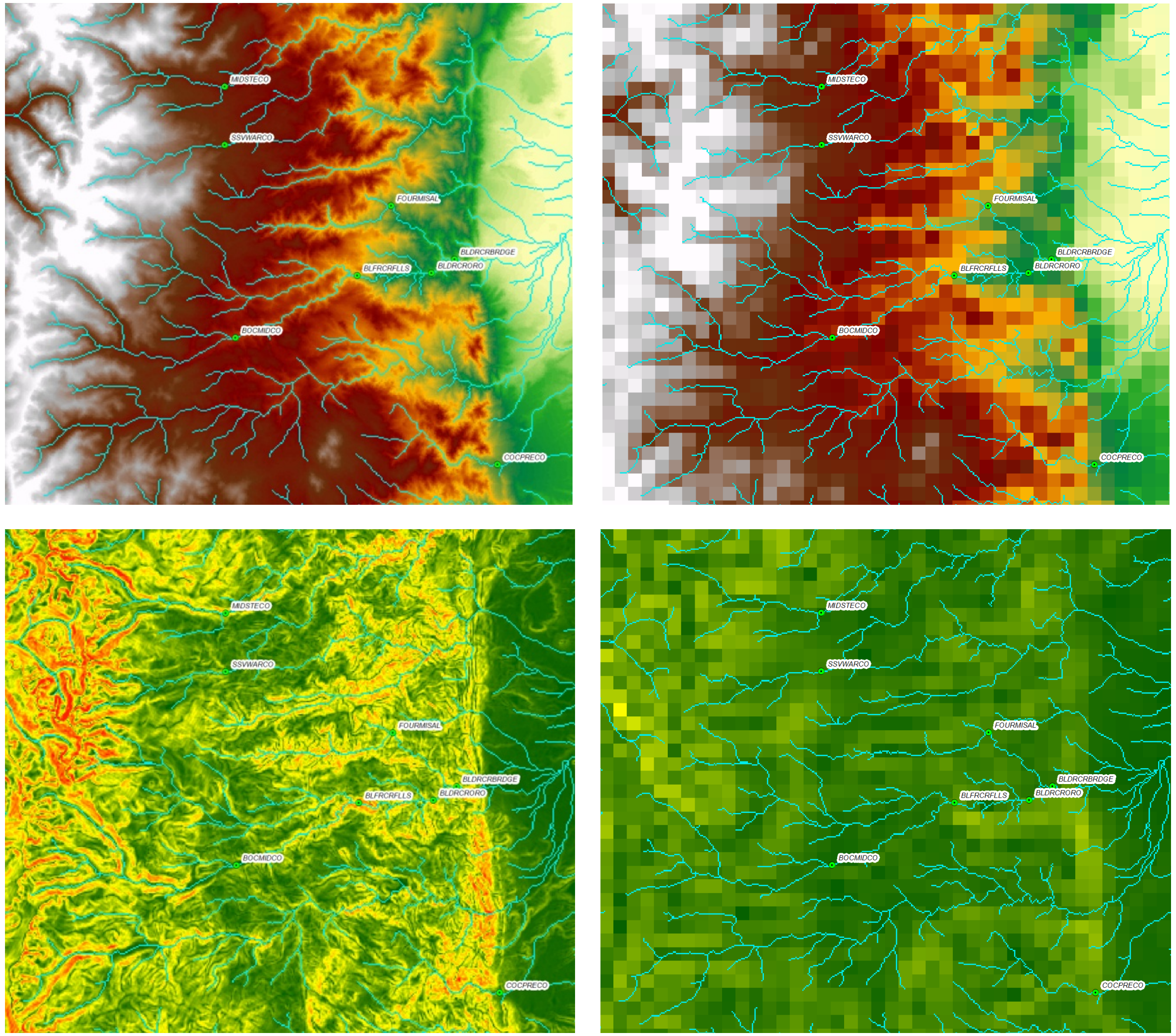
Noah/NoahMP development lead by M. Barlage and F. Chen, NCAR

WRF-Hydro V5.x Physics Components

- Multi-scale aggregation/disaggregation:

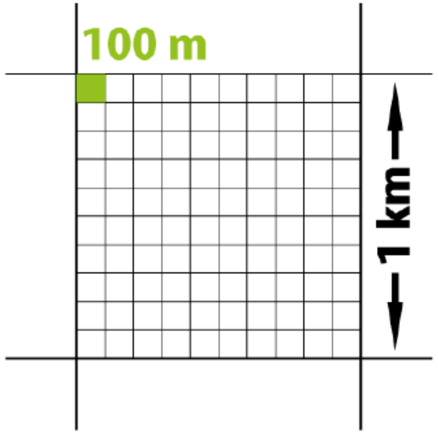
100m Terrain

1 km Terrain

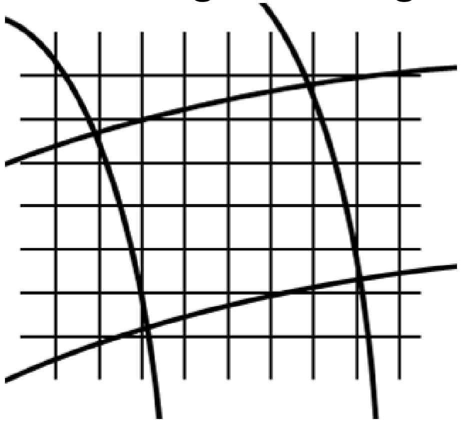


Terrain slope (0-45 deg)

Current ‘Regridding’

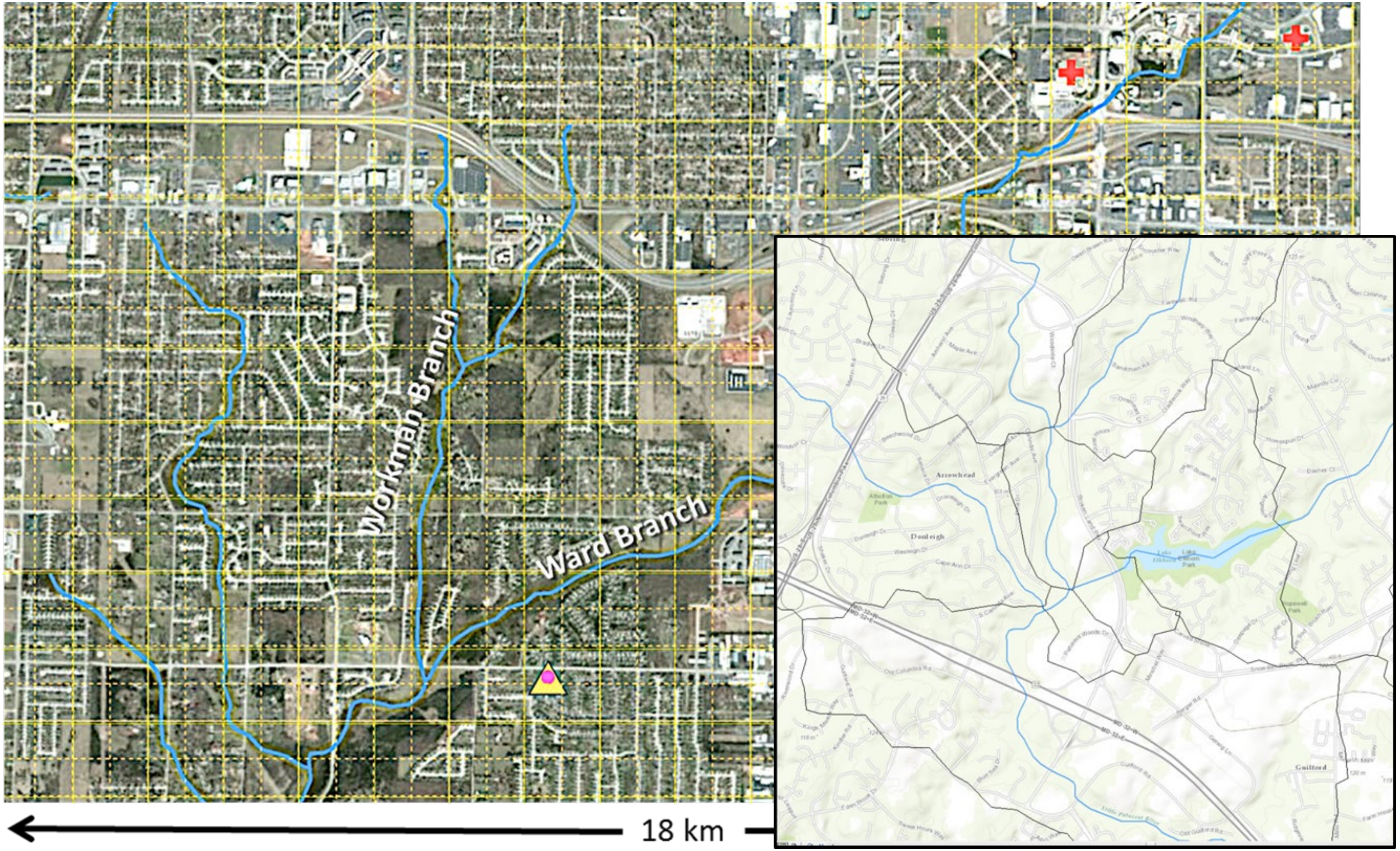


Implementing ESMF Regridders



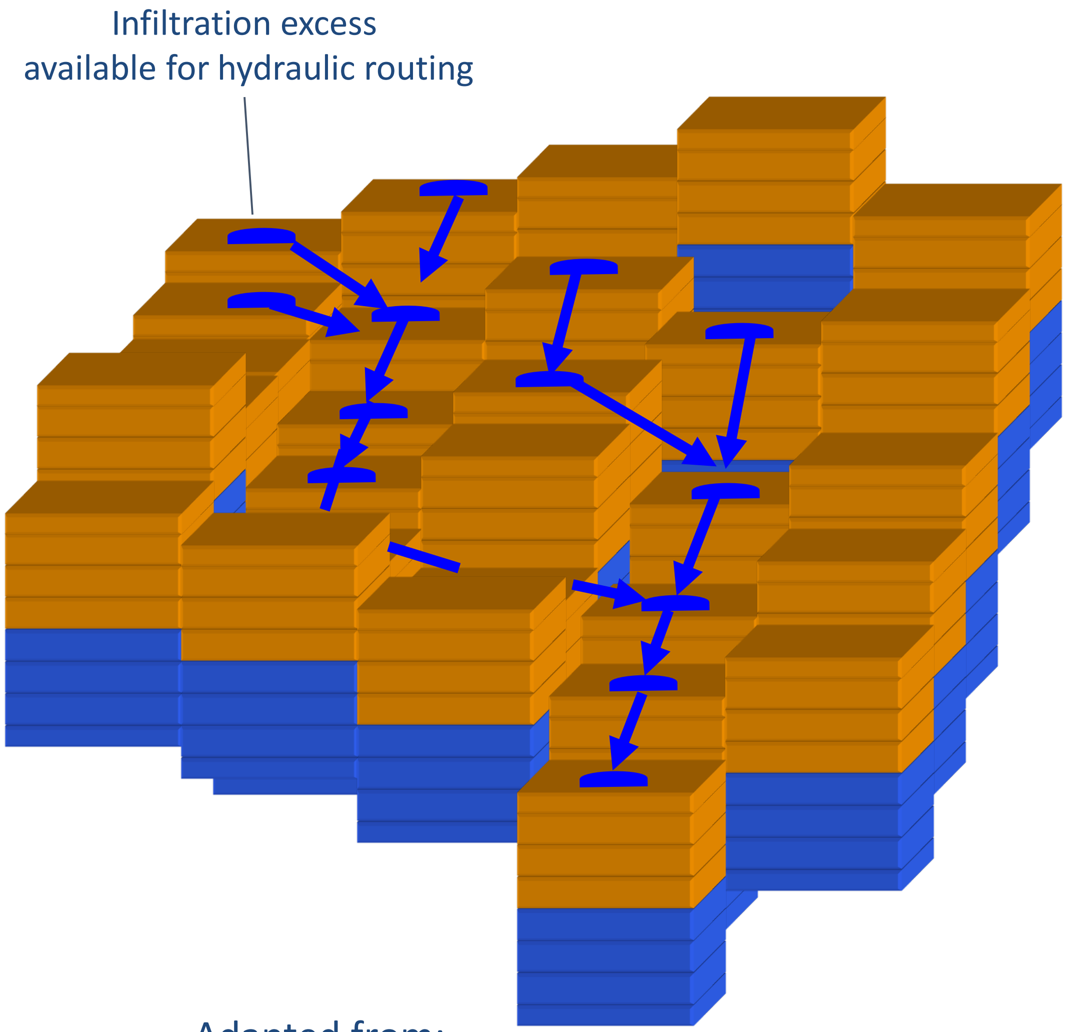
WRF-Hydro V5.x Physics Components

- Multi-scale aggregation/disaggregation:



Terrain Routing

Surface Routing



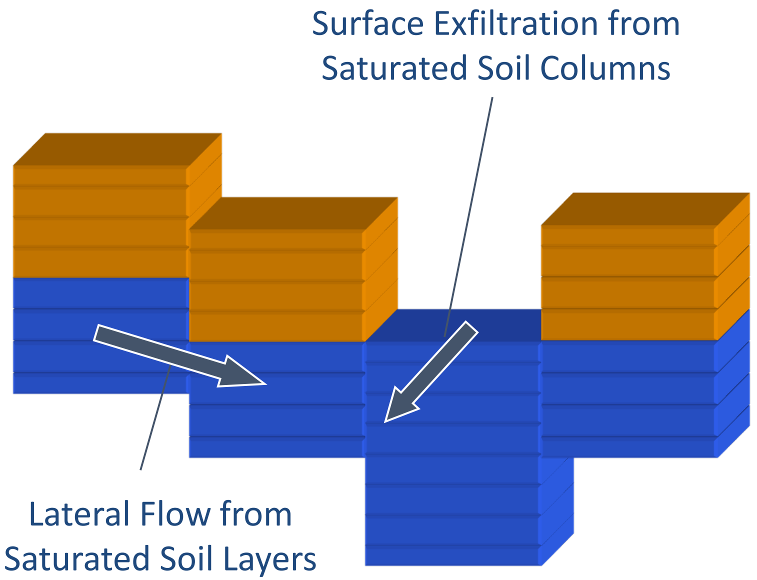
Adapted from:
Julian et al, 1995 – CASC2D, GSSHA

- 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

Subsurface Routing in v5



Adapted from:
Wigmosta et. al, 1994

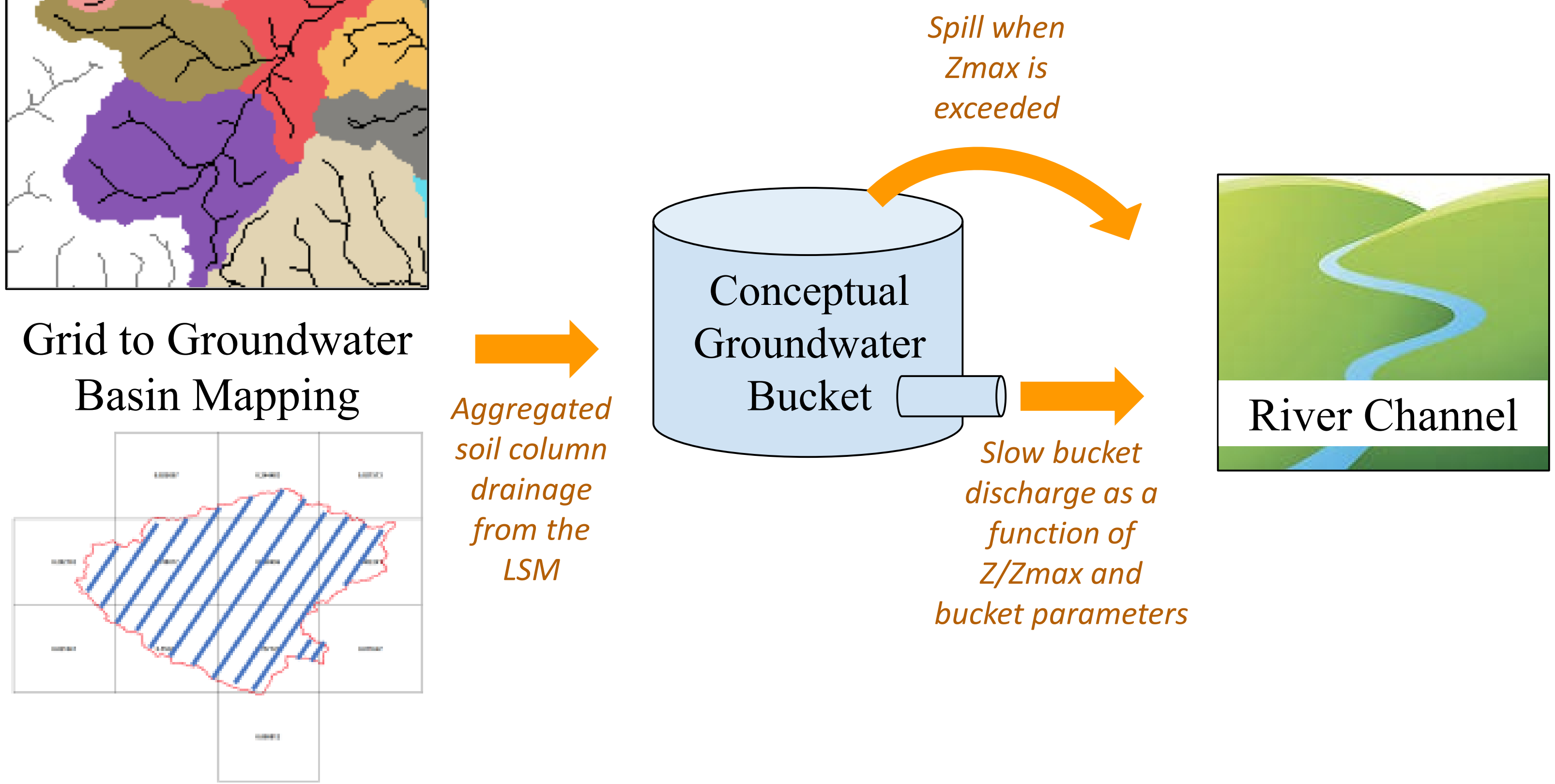
- Quasi steady-state, Boussinesq saturated flow model
- Exfiltration from fully-saturated soil columns
- Anisotropy in vertical and horizontal Ksat
- No ‘perched’ flow
- Soil depth is uniform

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

Runoff and Routing Physics: Deep Groundwater

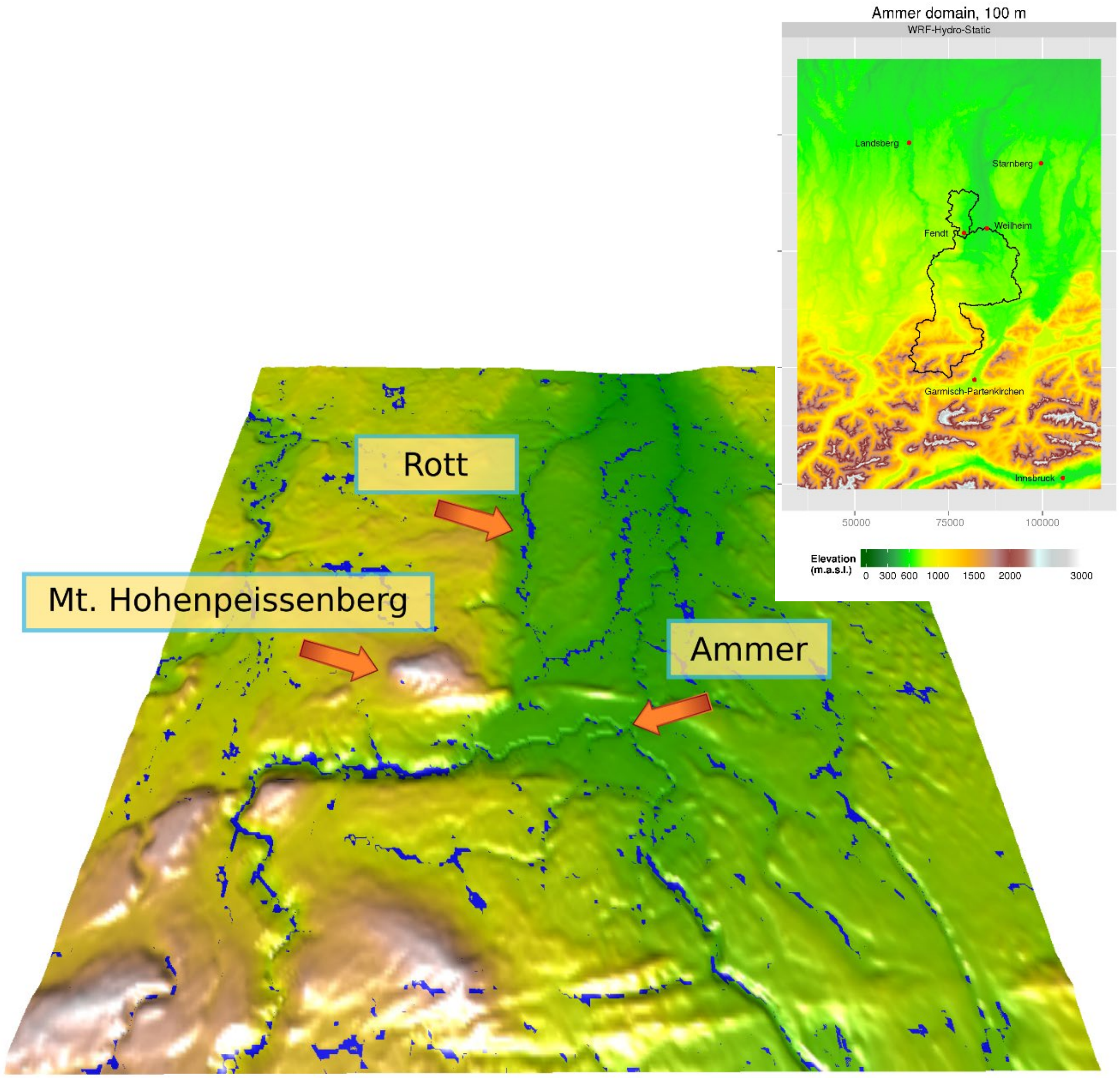
Conceptual groundwater baseflow "bucket" model:

- 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

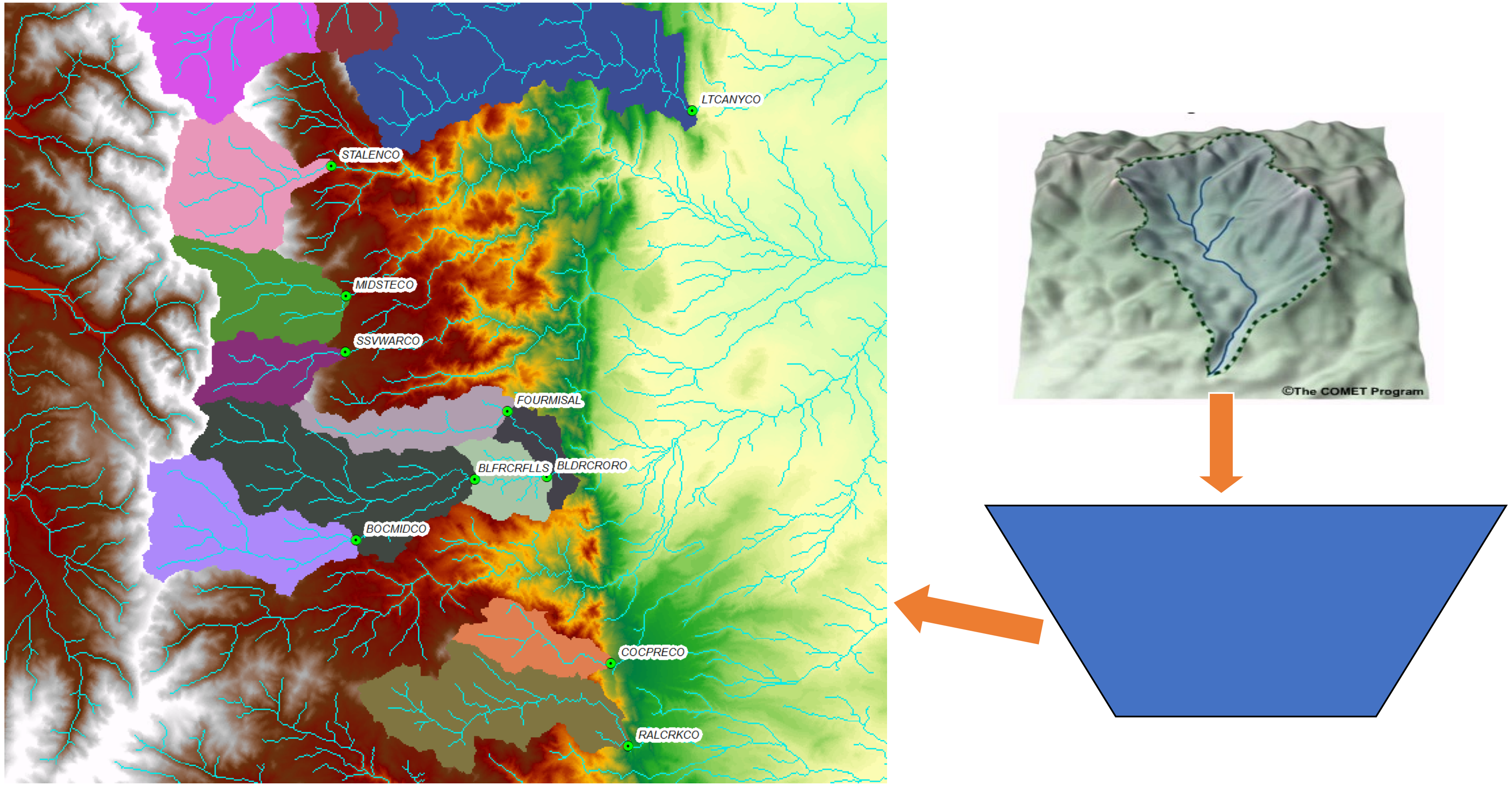


Surface ponded water from coupled groundwater in WRF-Hydro
B. Fersch, KIT, Germany

WRF-Hydro V5.x Physics Components

Optional conceptual 'Bucket' models:

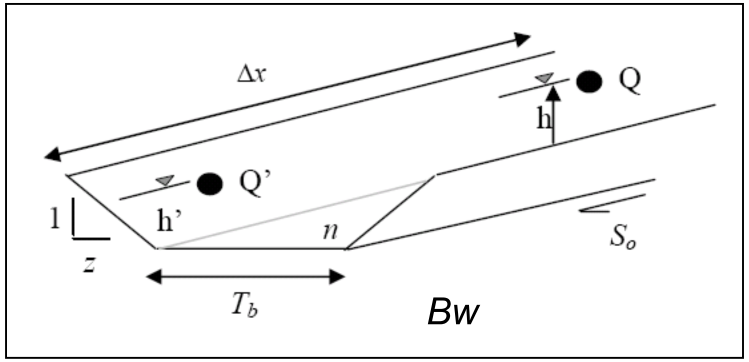
- Used for continuous (vs. event) prediction
- Simple pass-through or 2-parameter exponential model
- Bucket discharge gets distributed to channel network

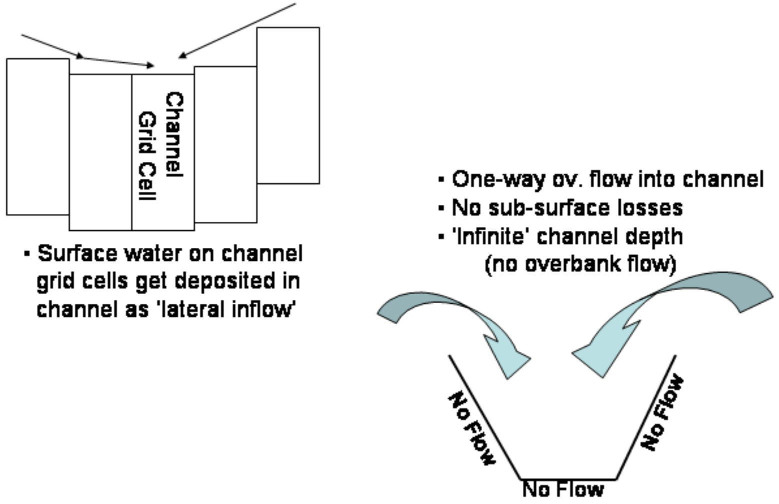


Channel Routing

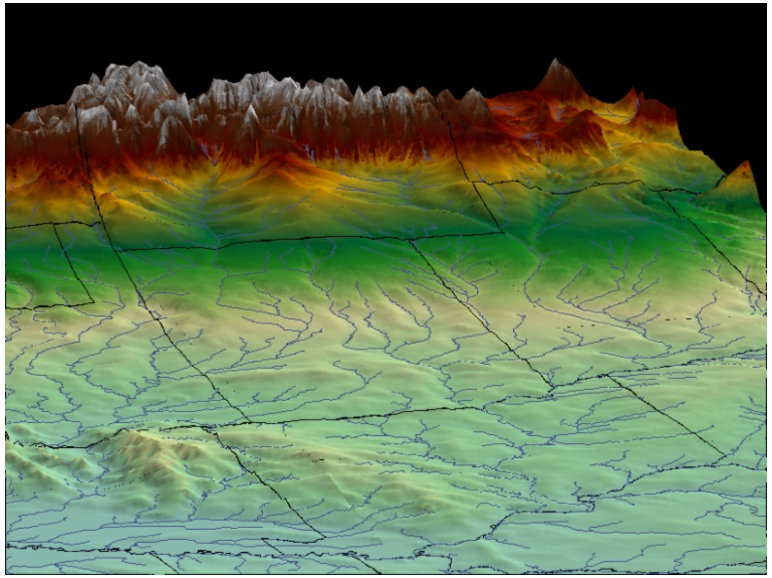
WRF-Hydro V5.x Physics Components

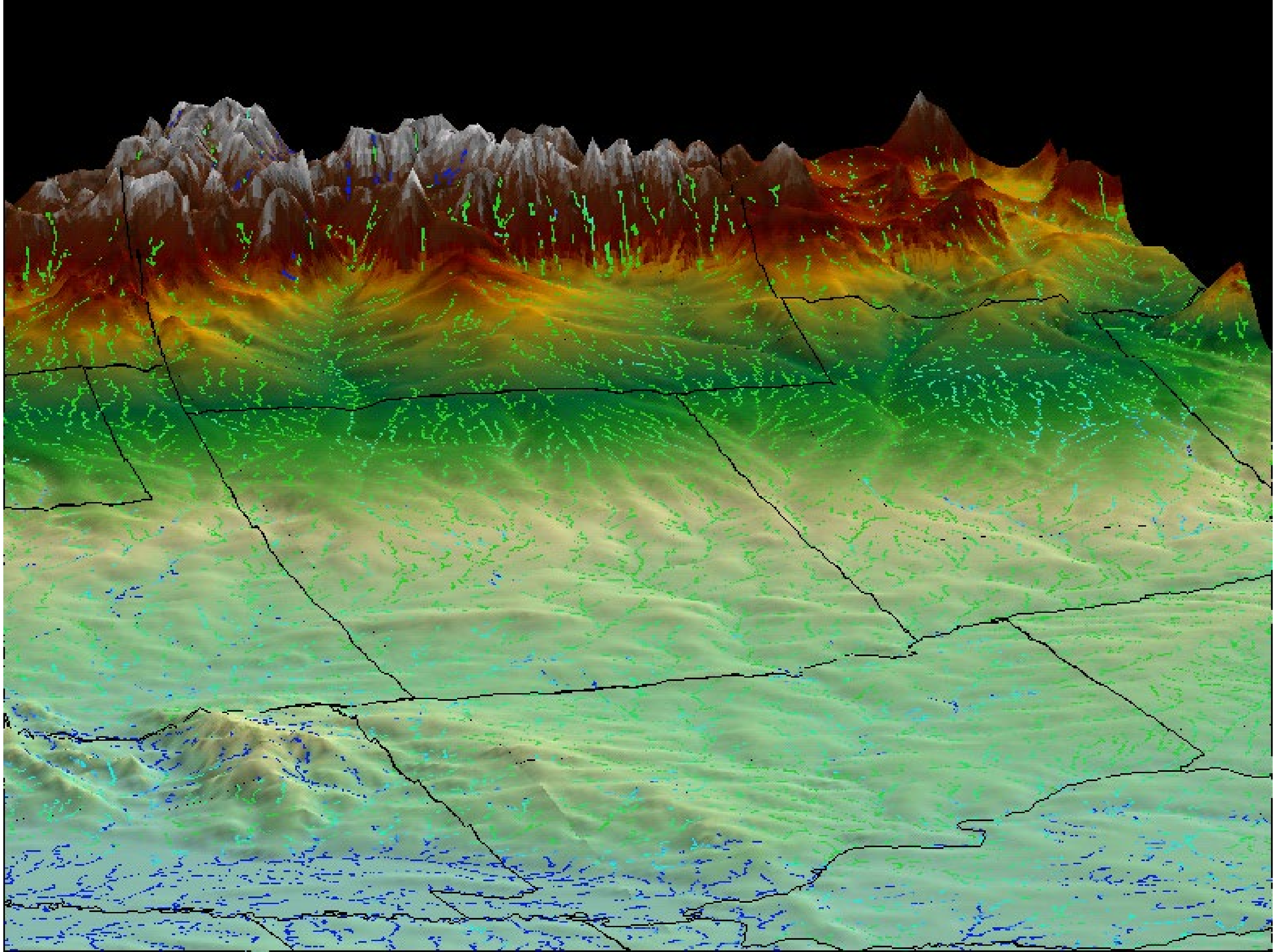
Channel routing: Gridded vs. Reach-based



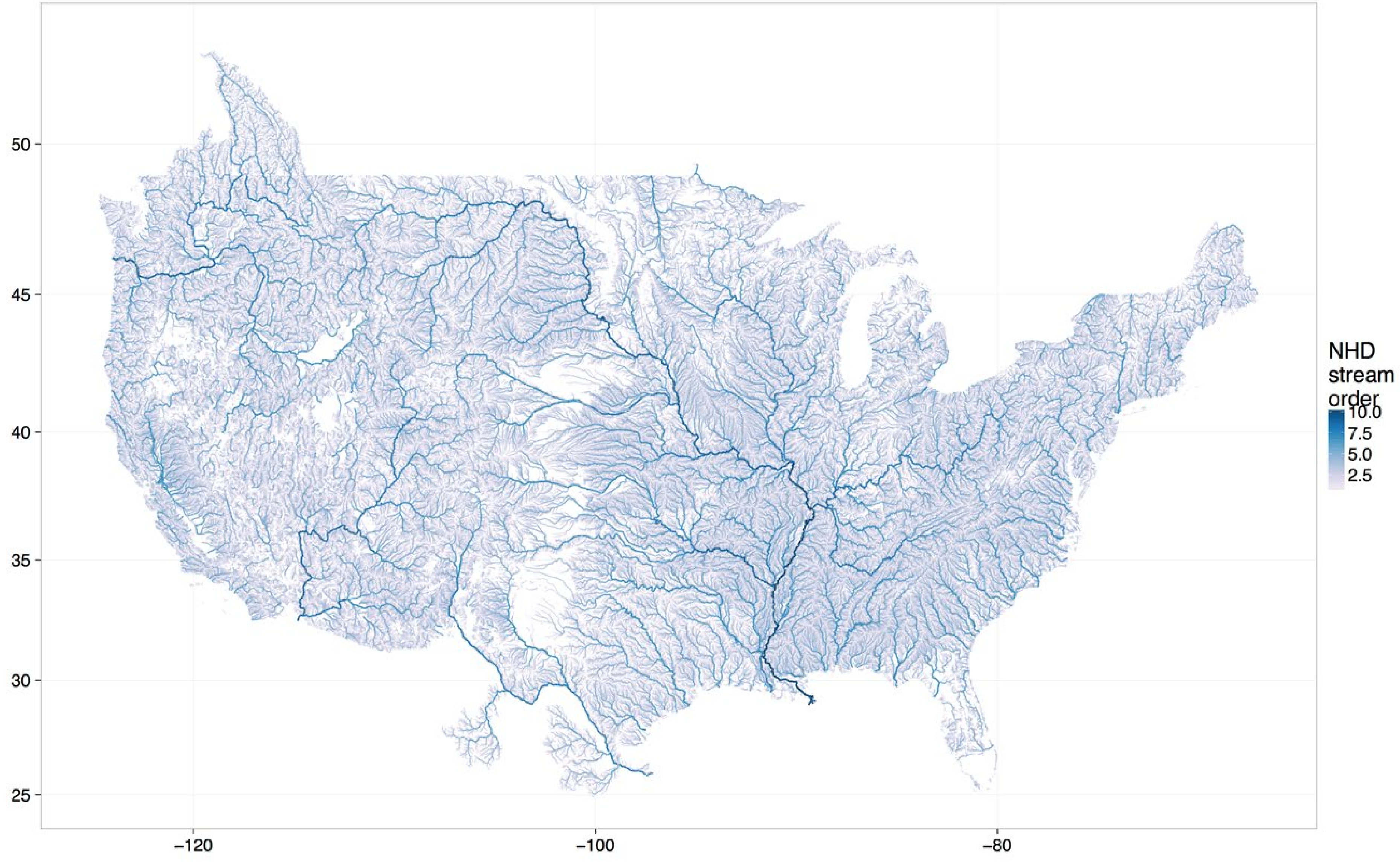


- Solution Methods:
  - Gridded: 1-d diffusive wave: fully-unsteady, explicit, finite-difference
  - Reach: Muskingum, Muskingum-Cunge *(much faster)*
- Parameters:
  - A priori function of Strahler order
  - Trapezoidal channel (bottom width, side slope)





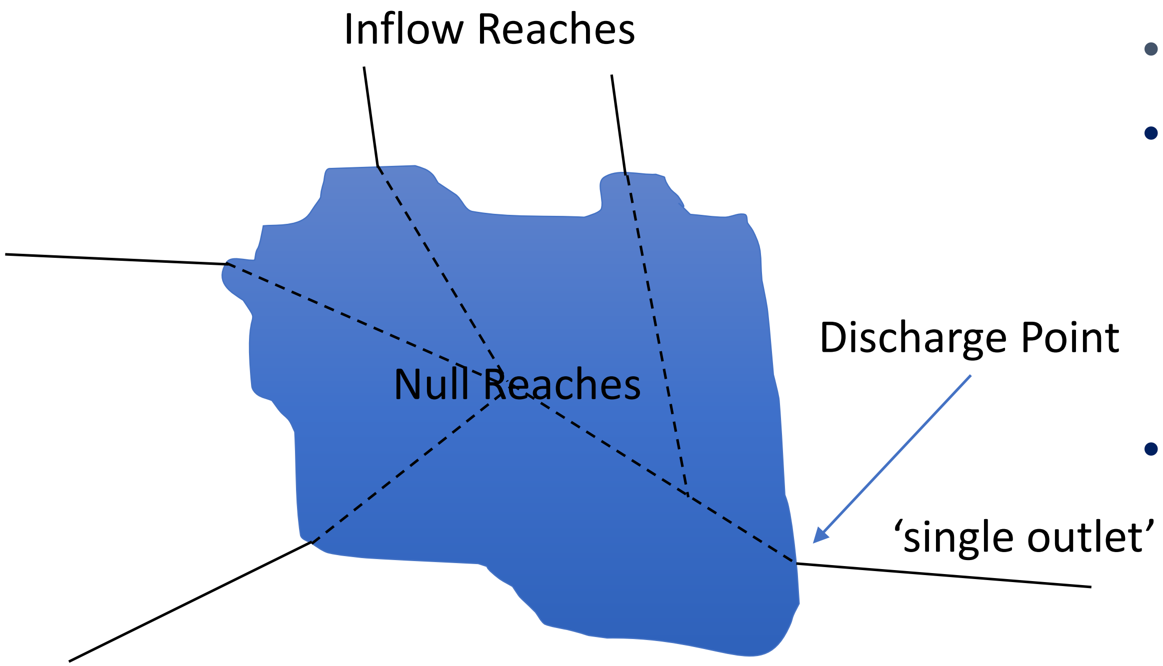
NHDPlus Reach Channel Network



Lakes & Reservoirs

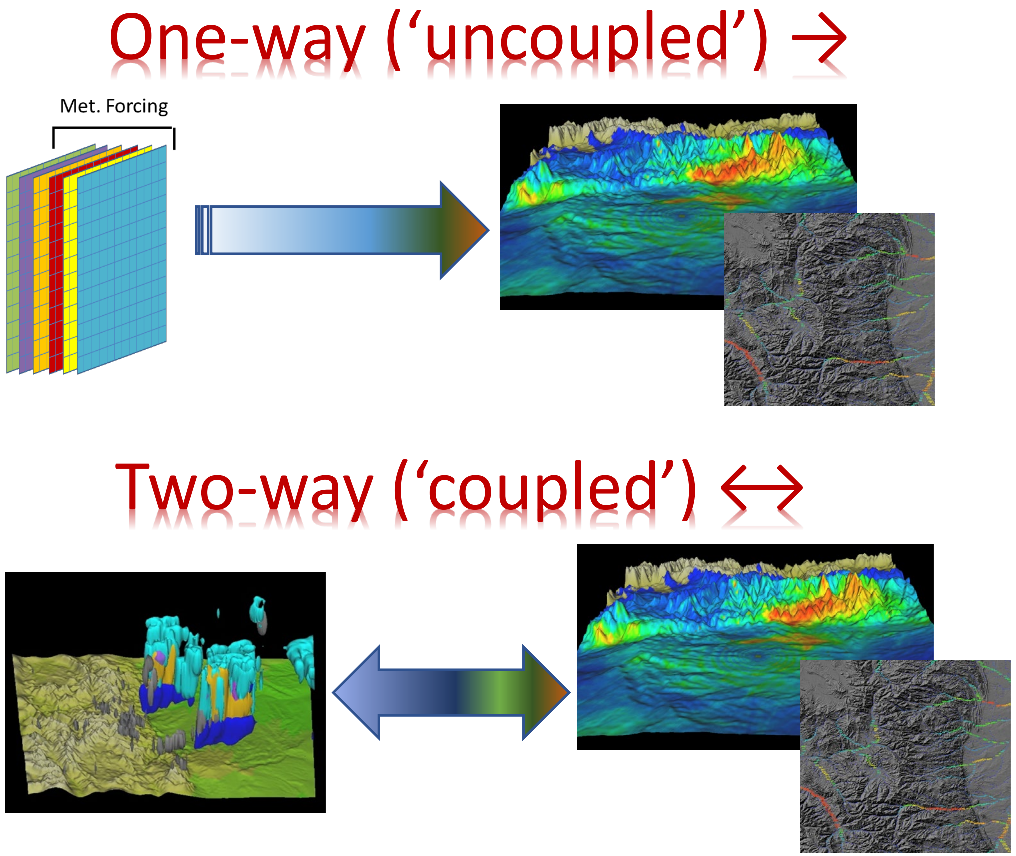
WRF-Hydro V5.x Physics Components : Lake/Reservoir Represenation

- 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)

WRF-Hydro Model Architecture



- 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

Model Parallelization

Data Grids:

- Three Data Grids

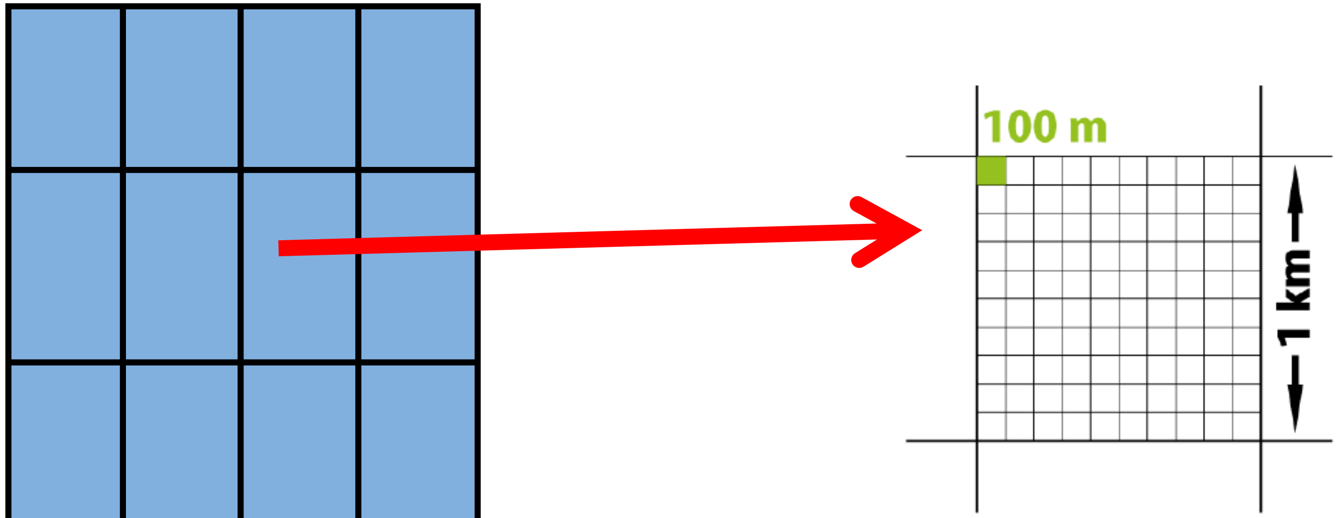
  Land Grids: (ix,jx), (ix,jx, n_soil_layer)

  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:

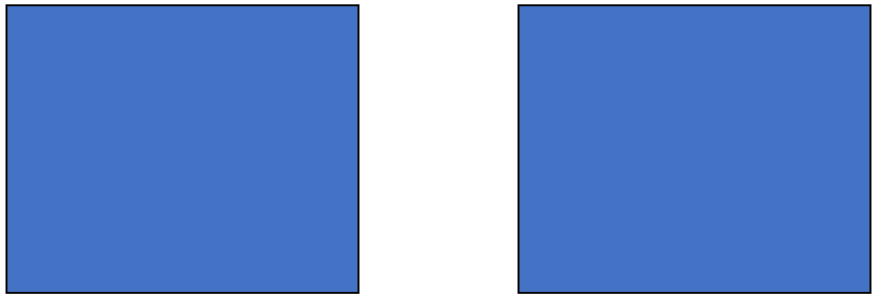


Land grid

Land routing grid cell: regridding

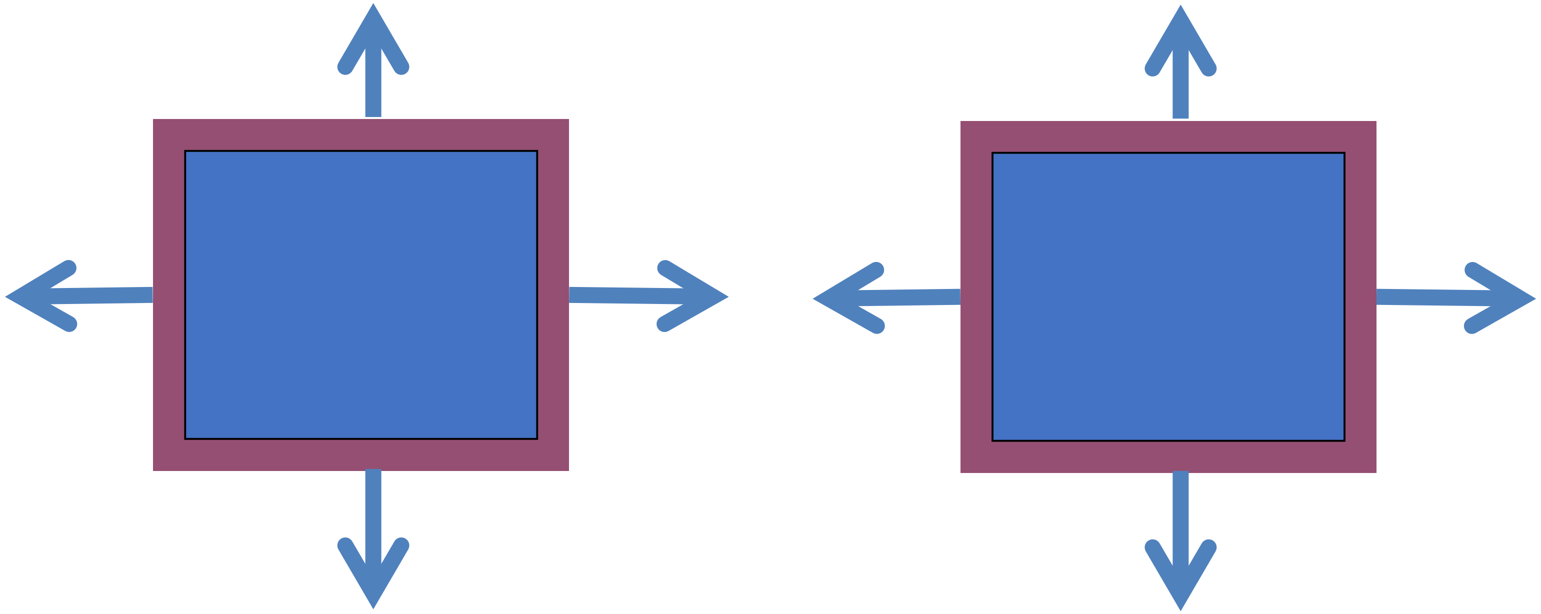
One CPU: Land grid, land routing grid cell, and channel routing nodes.

Distributed memory communications land grid:



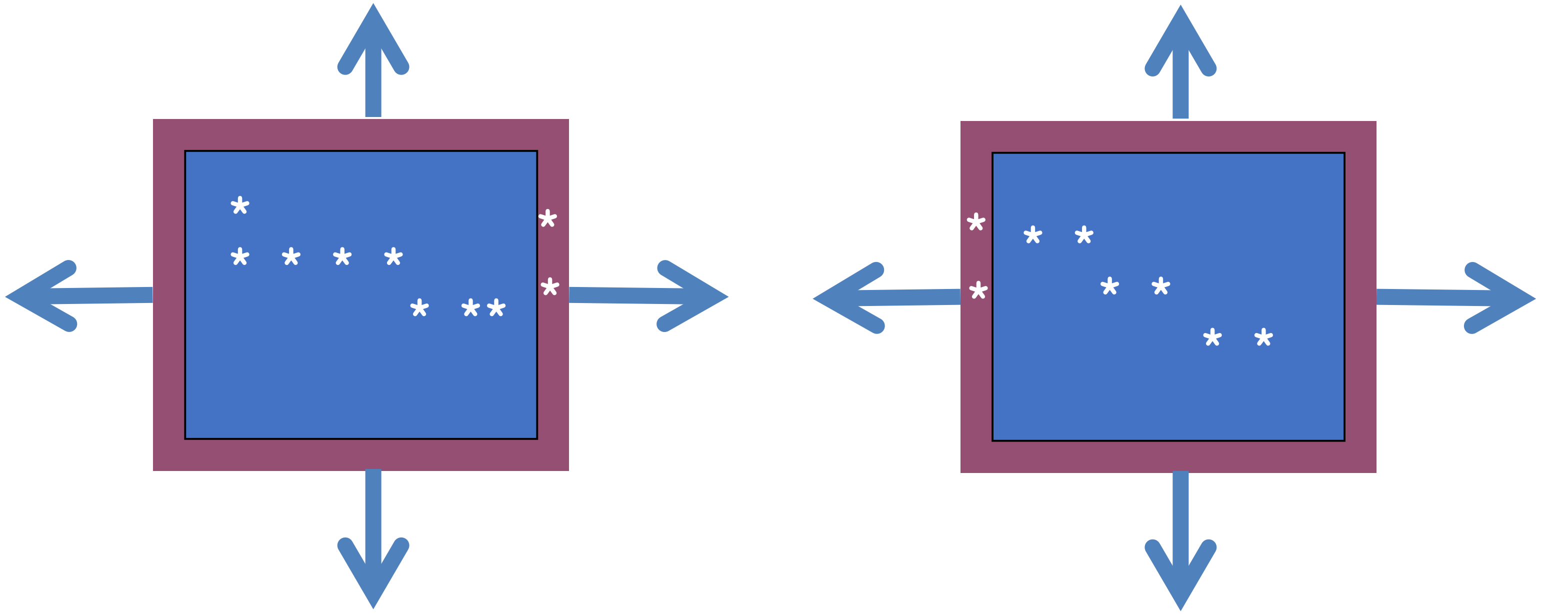
Stand alone columns require no memory communication between neighbor processors

Distributed memory communications land routing grid:



Lateral routing DOES require memory communication between neighbor processors

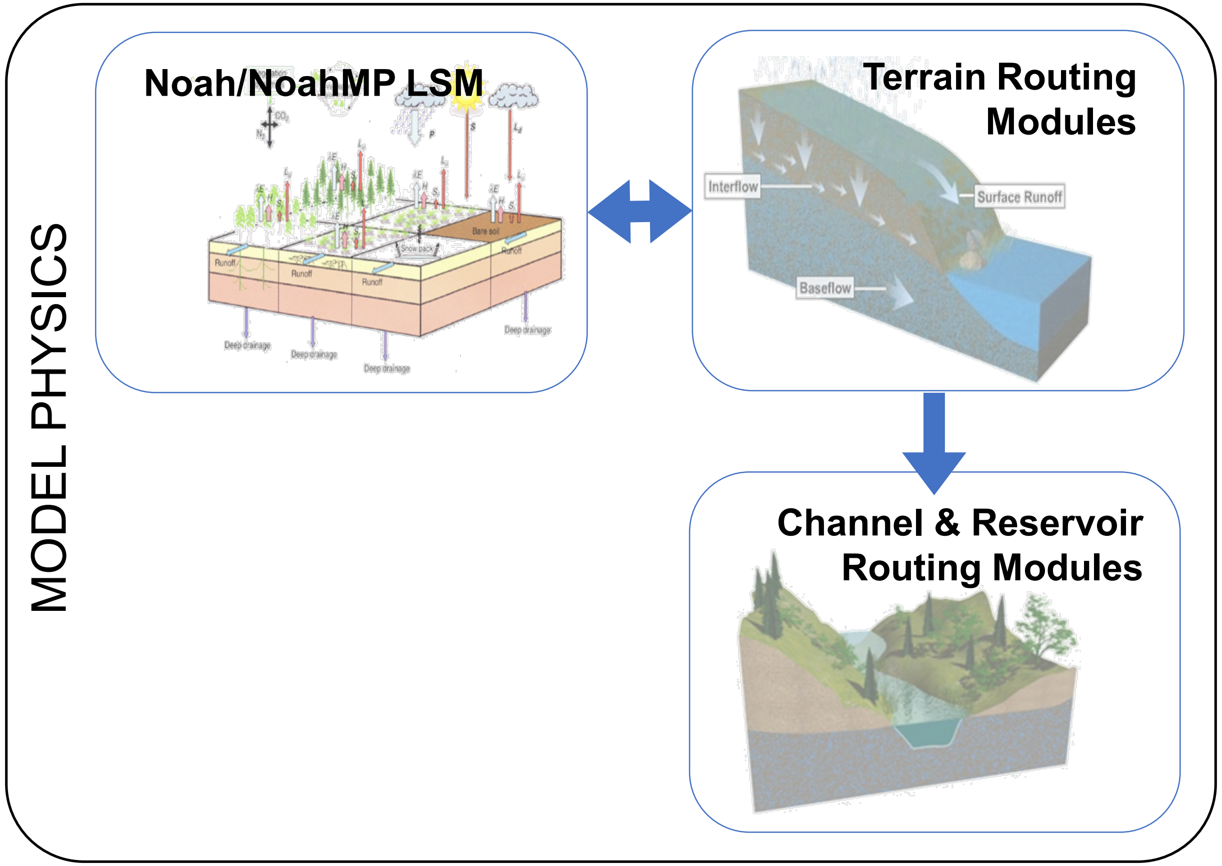
Distributed memory communications channel routing:



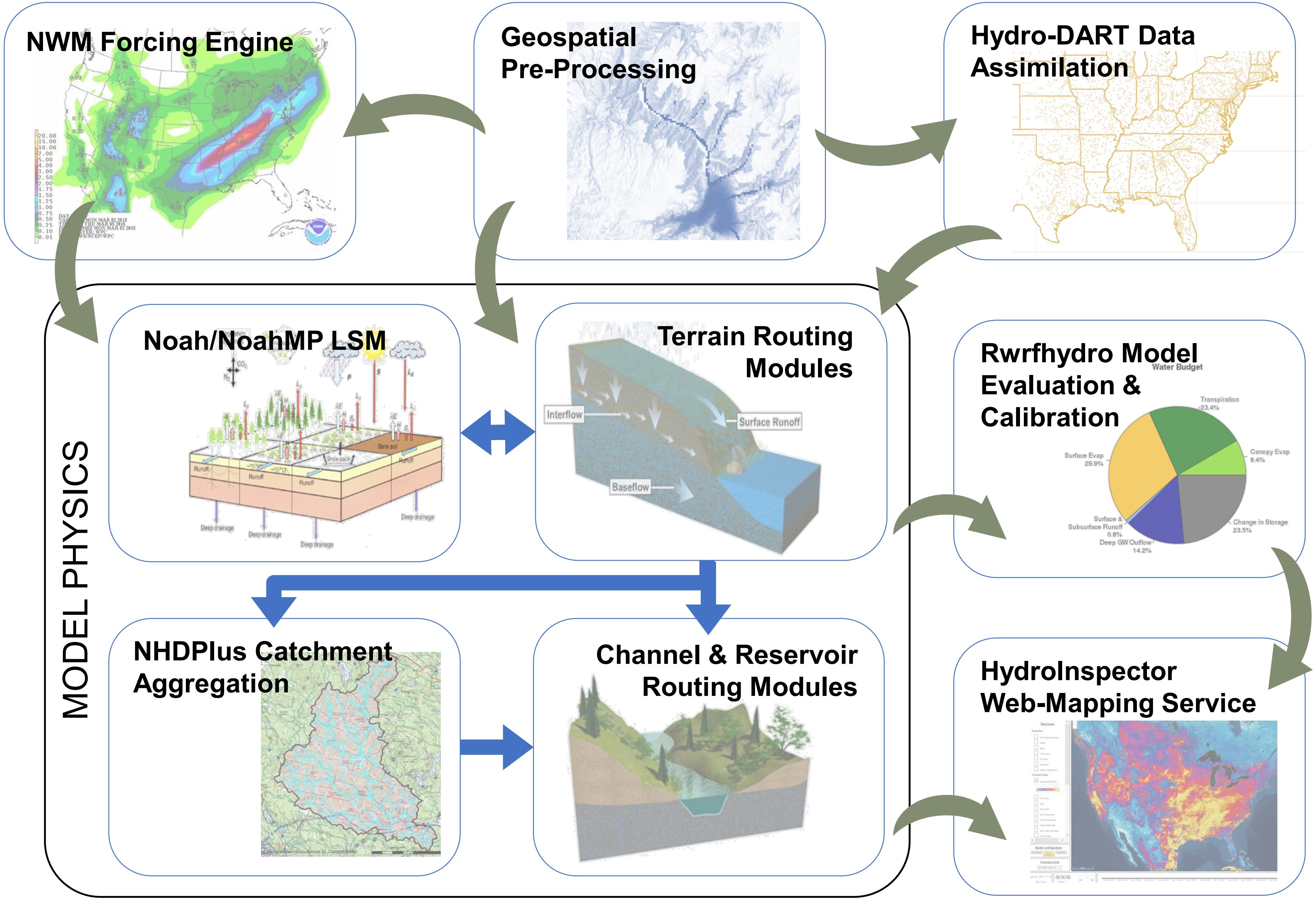
Lateral channel routing DOES require memory communication between neighbor processors, although the arrays are reduced to the sparse matrix of the channel elements

The WRF-Hydro Workflow

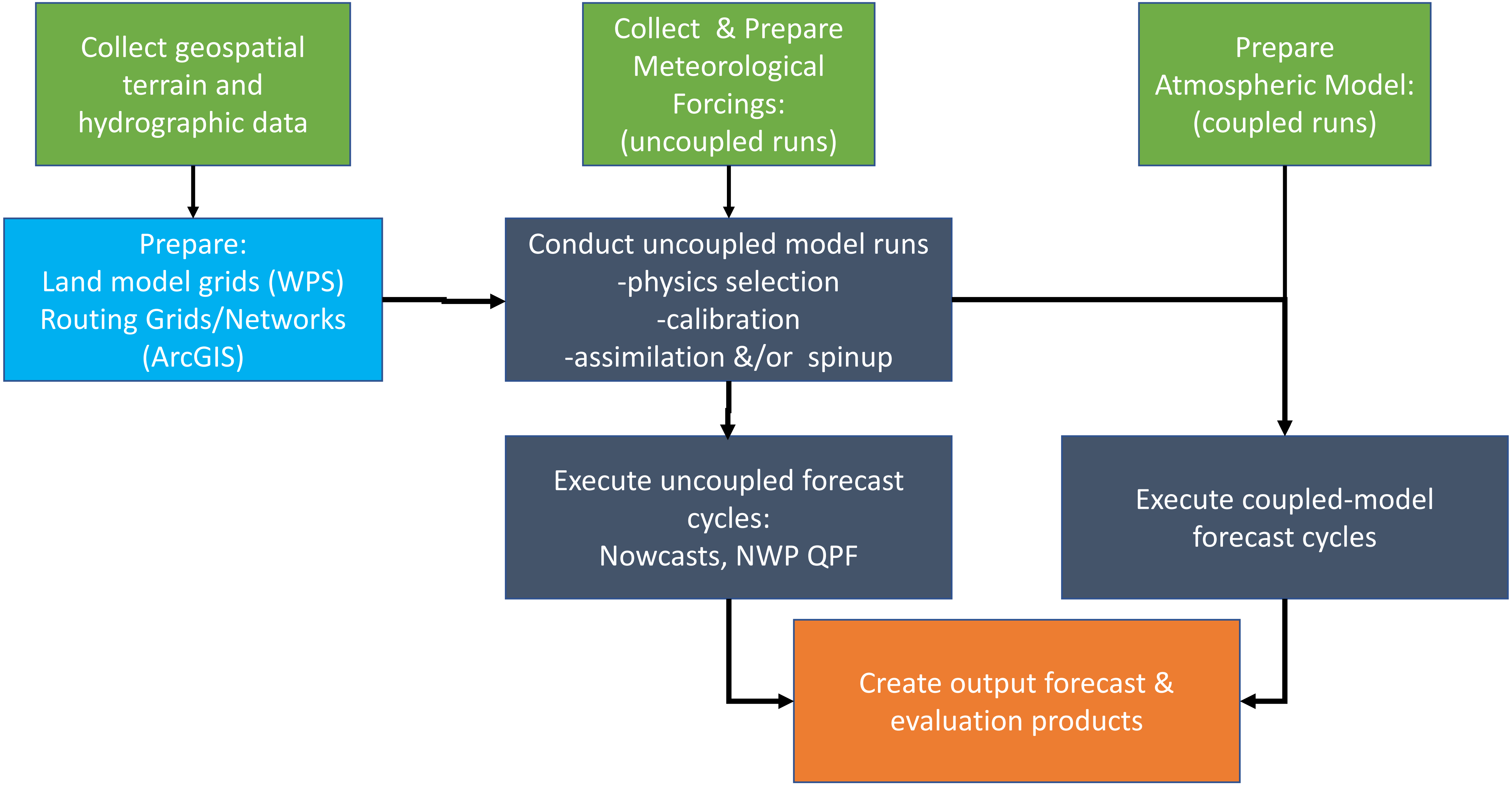
WRF-Hydro Base Configuration



Full WRF-Hydro Ecosystem



WRF-Hydro Implementation Workflow

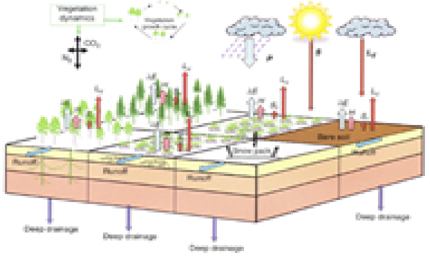


Input Files

WRF-Hydro Physics Components - Input Files

Meteorological Forcing Files:
*.LDASIN_DOMAINX.nc
*.PRECIP_FORCING.nc
wrfout_d0x_*

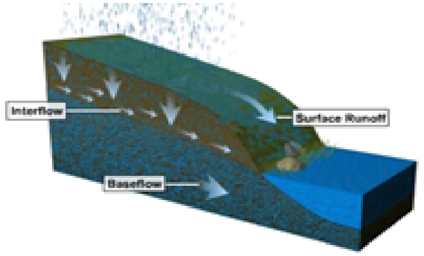
Column Land Surface Models



Input + Parameter Files:
geo_em.d0x.nc
wrfinput_d0x.nc
GENPARM.TBL
MPTABLE.TBL [MP]
SOILPARM.TBL
VEGPARM.TBL [N]
soil_properties.nc [MP]

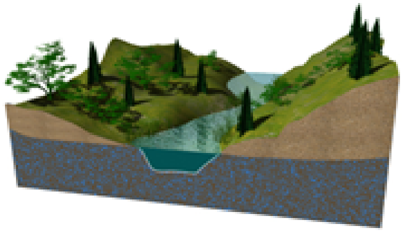
2- way
Coupling

Terrain Routing Modules



Input + Parameter Files:
Fulldom_hires.nc
hydro2dtbl.nc (or HYDRO.TBL)

Channel & Reservoir Routing Modules



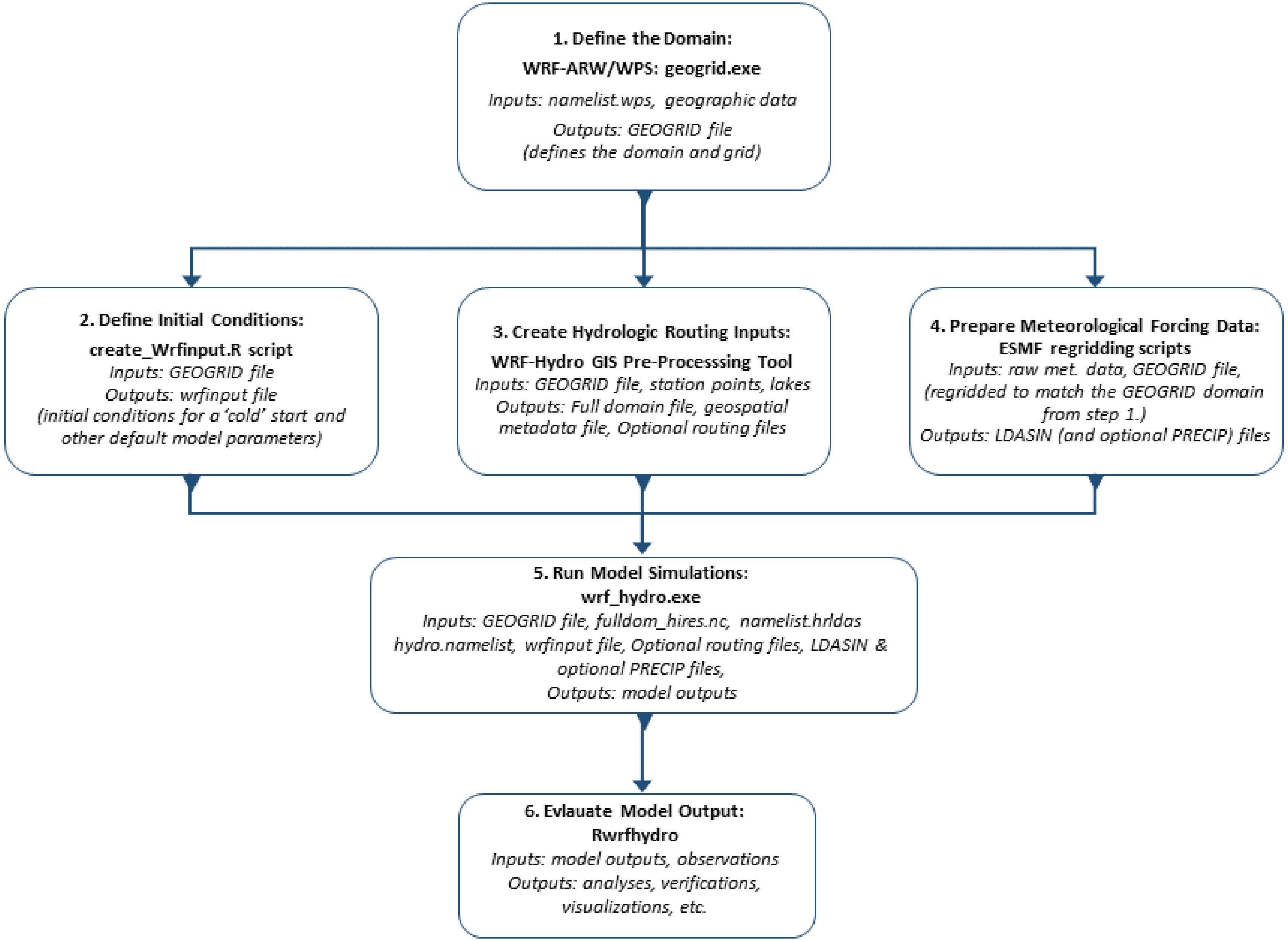
Input + Parameter Files:
Channels:
Fulldom_hires.nc [G]
CHANPARM.TBL [G]
Route_Link.nc [R,U]
Streamflow Nudging:
nudgingParams.nc [U]
*.usgsTimeSlice.ncdf [U]
Lakes + Reservoirs:
LAKEPARM.nc [G,U]
Groundwater:
GWBASINS.nc [G,R]
GWBUCKPARM.nc
spatialweights.nc [U]

Key:
Land Surface Model (LSM):
N - Noah
MP - Noah-MP

Model Channel Configurations:
U - User defined mapping (NWM)
R - Reach based
G - Gridded

WRF-Hydro input and parameter files organized by model physics component.
See the Key for files specific to a certain land model or channel configuration.

WRF-Hydro Workflow - custom geographical inputs



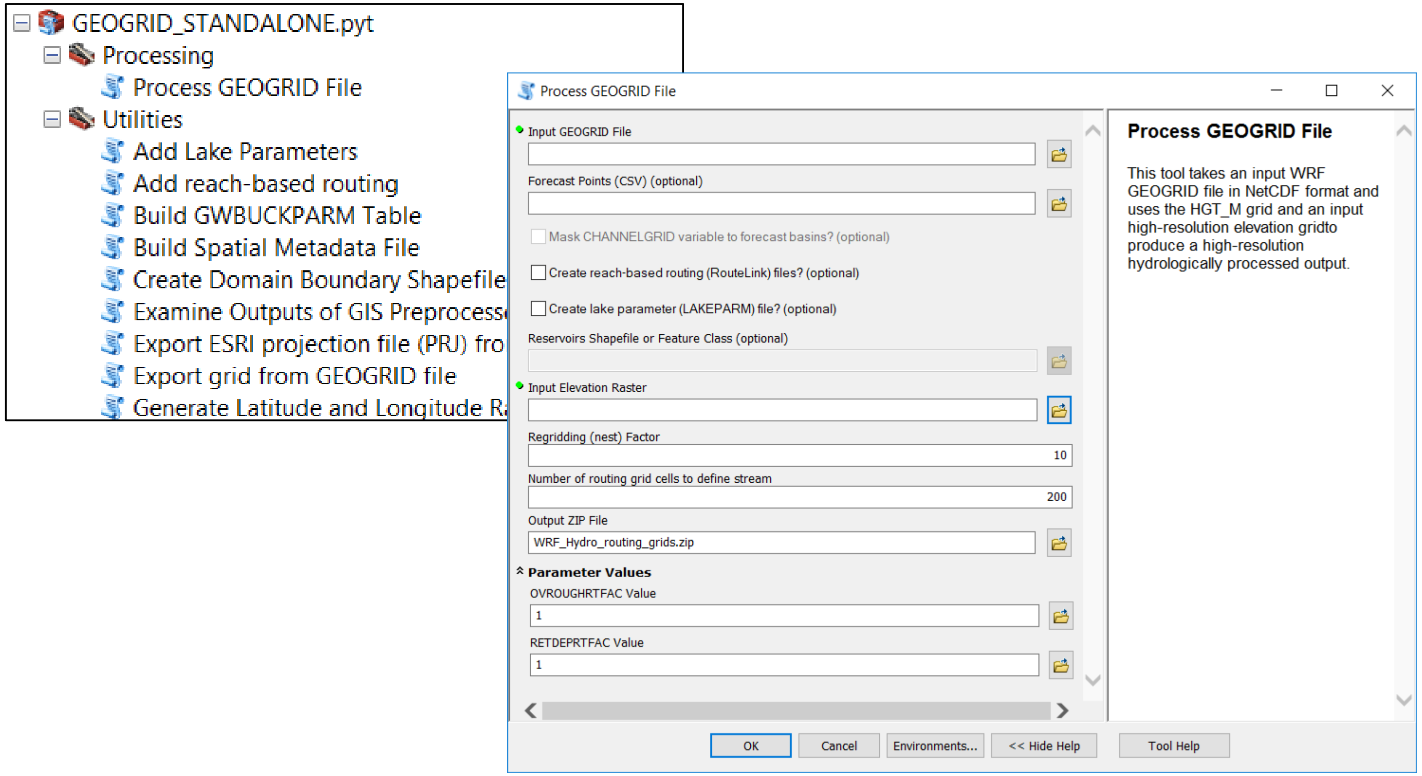
Model System Components

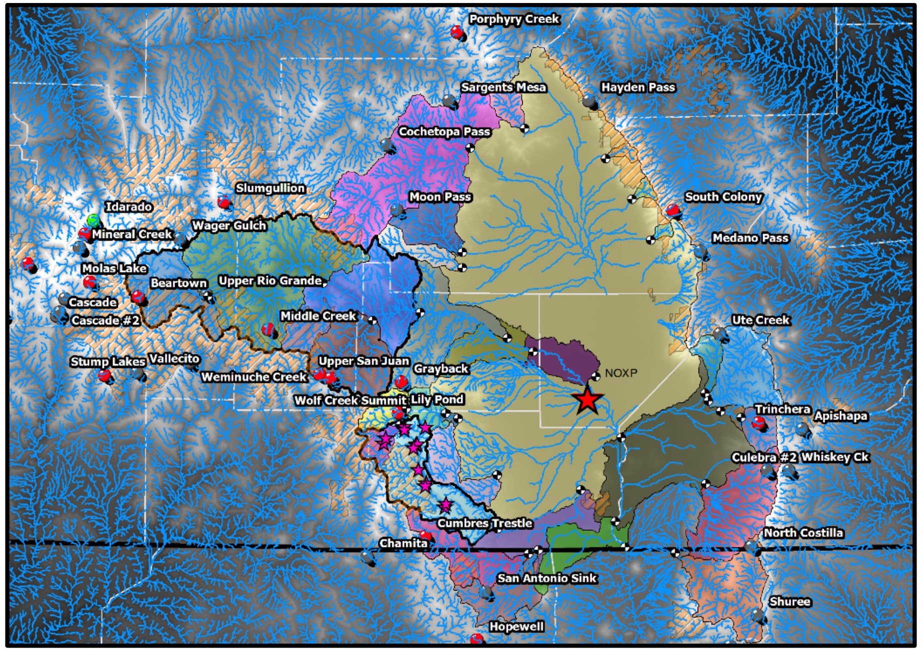
- **GIS Pre-Processor** – Physiographic data processing
- **ESMF Regridding Scripts** – Met. data pre-processing
- **Core WRF-Hydro Model** – Model physics
- **Rwrfhydro** – Analysis, verification, visualization
- **PyWrfHydroCalib** – Model calibration toolkit

WRF-Hydro Setup and Parameterization: Python Pre-Processing Toolkit

- Python-based scripts
- ESRI ArcGIS geospatial processing functions
  - Support of multiple terrain datasets
    - NHDPlus, Hydrosheds, EuroDEM

https://github.com/NCAR/wrf_hydro_arcgis_preprocessor

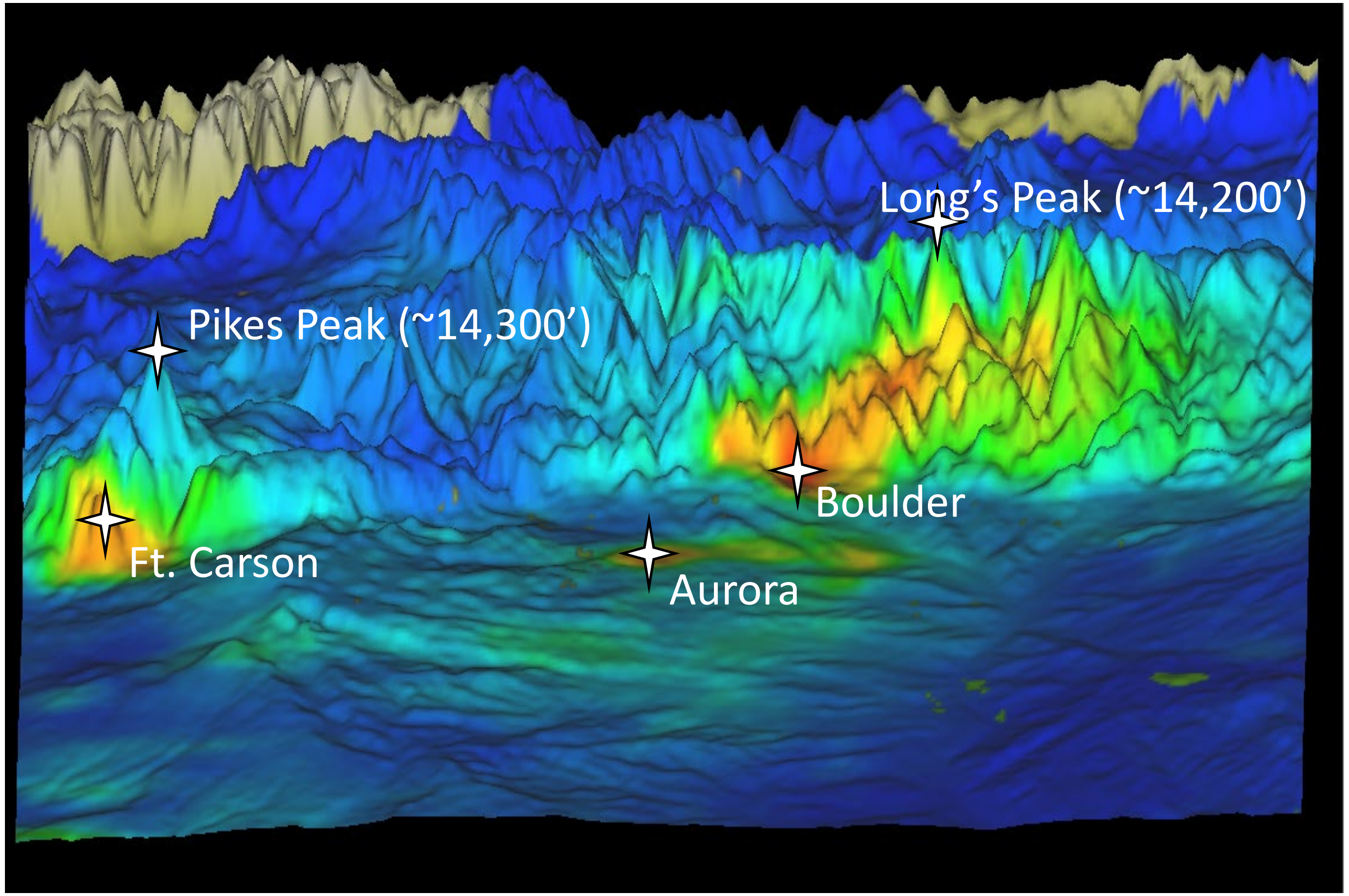




Outputs: topography, flowdirection, watersheds, gridded channels, river reaches, lakes, various parameters

Meteorological Forcing Engine – Used in NWM

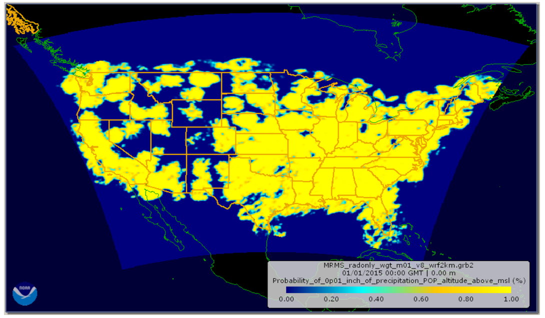
- Python-based code…
- NLDAS, NARR analyses
- QPE products: MPE, StgIV, NCDC-served, dual-pol, Q3/MRMS, gauge analyses, CMOPRH, TRMM, GPM
- NOAA QPF products: GFS, NAM, RAP, HRRR, ExREF
- Nowcast (NCAR Trident/TITAN)
- NOHRSC SNODAS
- ESMF regridding tools



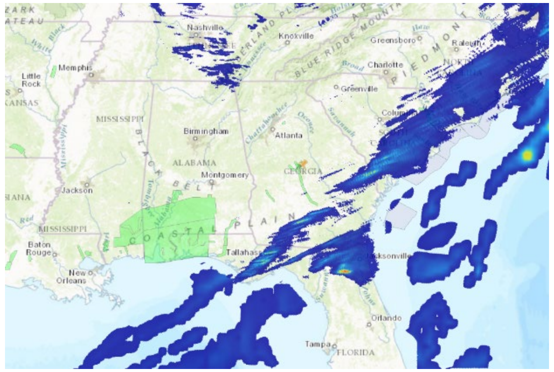
Regridded MPE precipitation during the 2013 Colorado Floods
Unidata IDV display

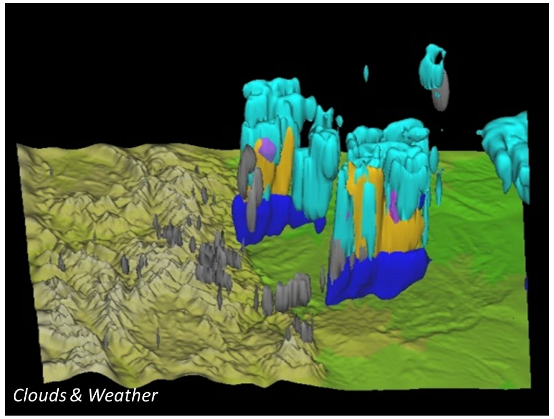
Meteorological Forcing Engine - NWM: Examples

Seasonally-varying MRMS RQI

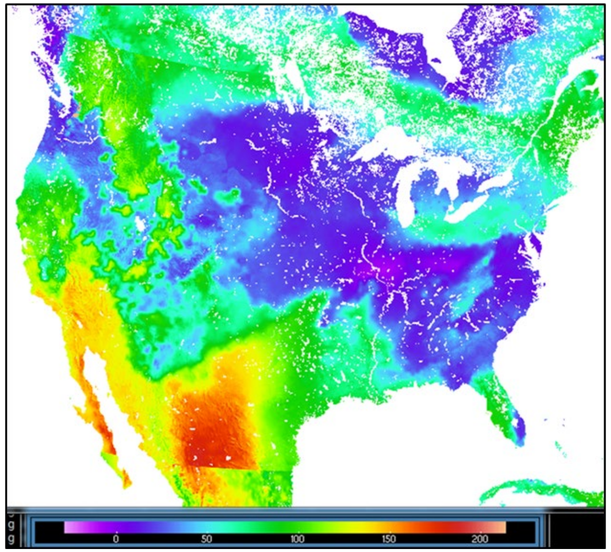


Blended MRMS-HRRR Precipitation

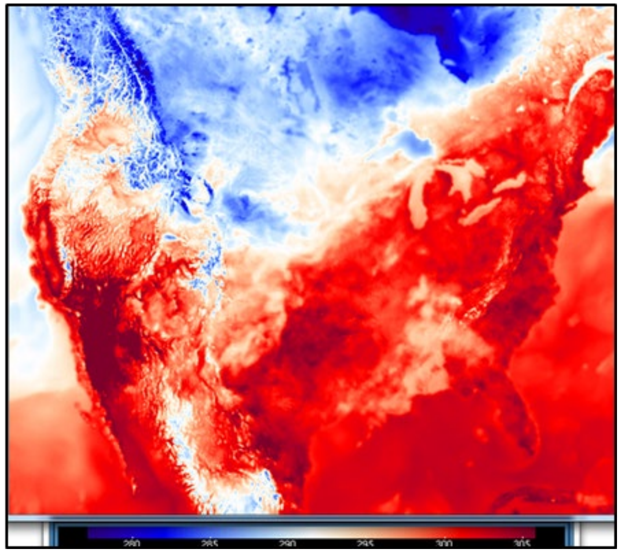




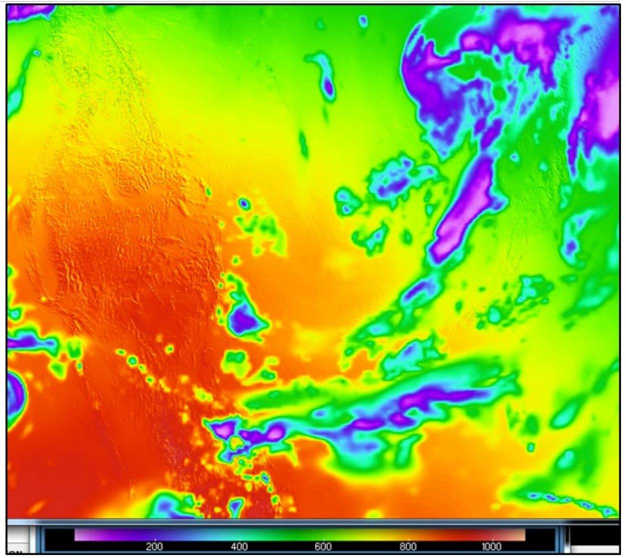
HRRR-RAP incoming longwave radiation



HRRR-RAP 2m Air Temperature



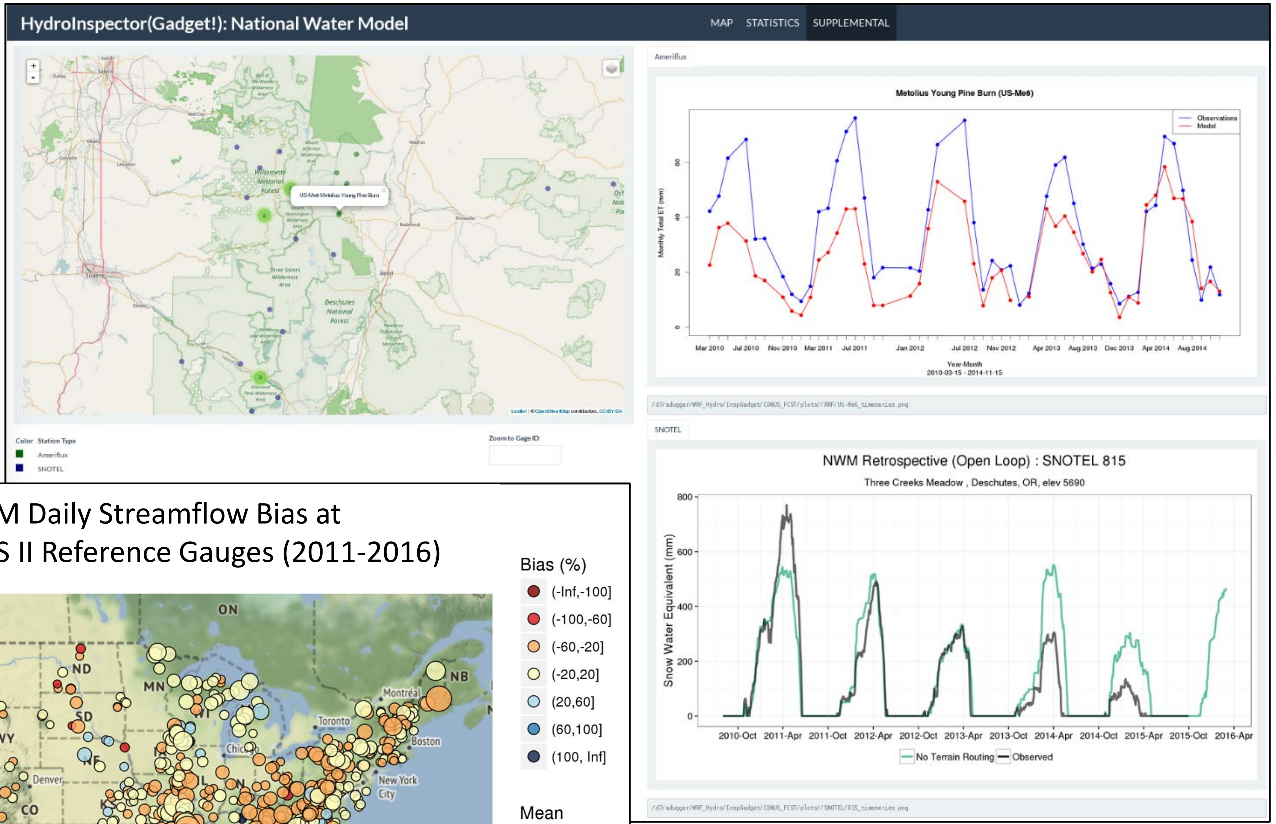
GFS – derived incoming shortwave radiation

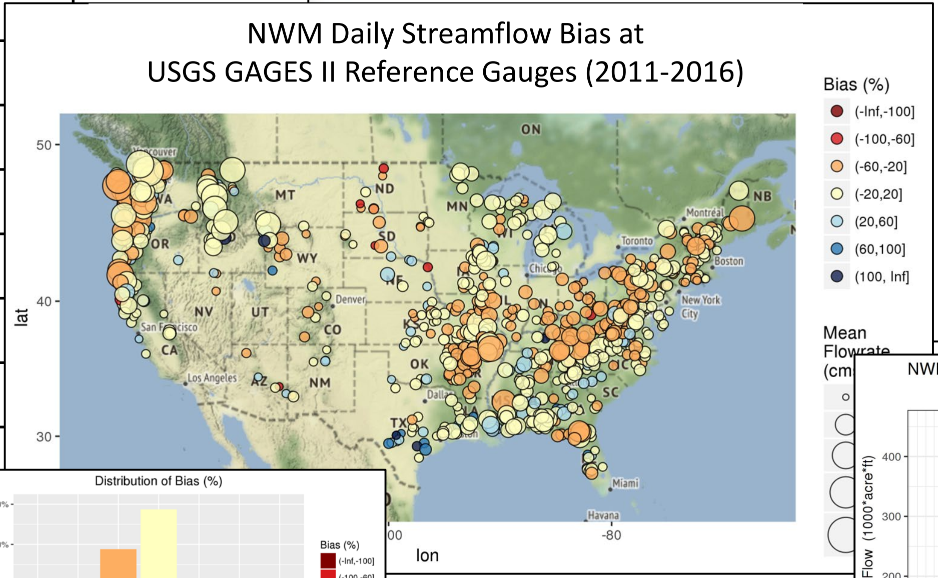


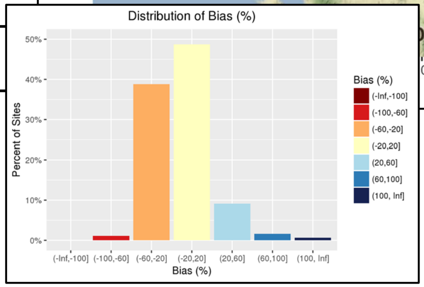
Rwrfhydro: R package for hydrological model evaluation

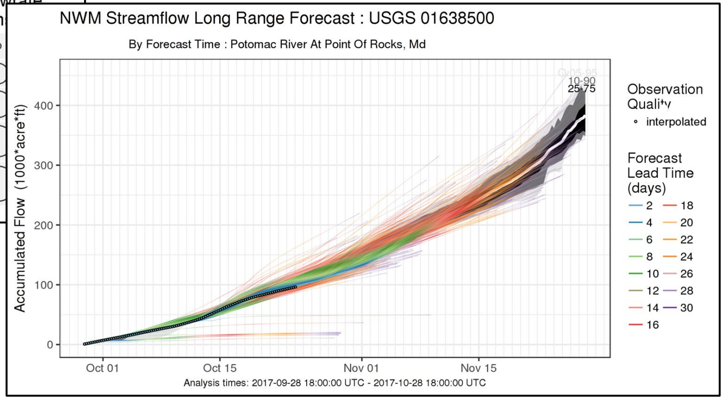
Observations Ingested for Model Evaluation in Rwrfhydro:

Variable	Dataset	Data type/format
Climate: precipitation, temperature, humidity, pressure, wind speed	GHCN	point obs
	USCRN	point obs
	HADS	point obs
	SNOTEL	point obs
Snow: SWE, fSCA, albedo	SNOTEL	point obs
	SNODAS	raster
	MODIS	raster
Soil Moisture: volumetric soil moisture by layer	SCAN	point obs
	USCRN	point obs
	ISMN	point obs
Energy: ET, skin temperature, albedo	Ameriflux	point obs
	MODIS	raster
Streamflow: flowrate, celerity	USGS	point obs
	CO & CA DWR	point obs









https://github.com/NCAR/rwrfhydro

WRF-Hydro Software Ecosystem

- Ecosystem overview: https://github.com/NCAR/wrfHydro
- Model: https://github.com/NCAR/wrf_hydro_nwm_public
  - Public, community model, with version control system
  - Contributing guidelines, conventions, license, code of conduct
  - Python-based (pytest) testing framework (Python API)
- Python API: https://github.com/NCAR/wrf_hydro_py
- Docker containers: https://github.com/NCAR/wrf_hydro_docker
  - Standard portable environments for working with the model
- Continuous Integration with Travis on Github (Docker + Python)
- "Discontinuous integration" at scale (cheyenne)
  - Large jobs, compilers with licenses
- ARC GIS preprocessing toolbox: https://github.com/NCAR/wrf_hydro_arcgis_preprocessor
- Analysis tool box: https://github.com/NCAR/rwrfhydro
- Training: https://github.com/NCAR/wrf_hydro_training

Community Engagement, Support & Training

Community resources:

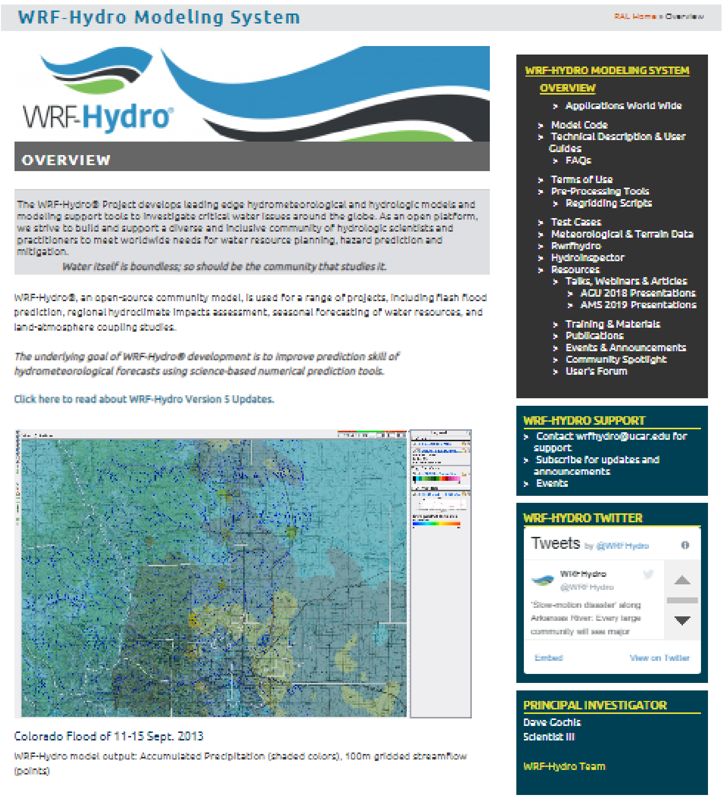
- Improved WRF-Hydro website & internet presence
- Helpdesk support
- New & increased volume of documentation, user guides, FAQs
- New test cases (standalone & coupled)
- Github repository
- Containerization of pre-processing tools & model run environment --> lowers barrier of entry

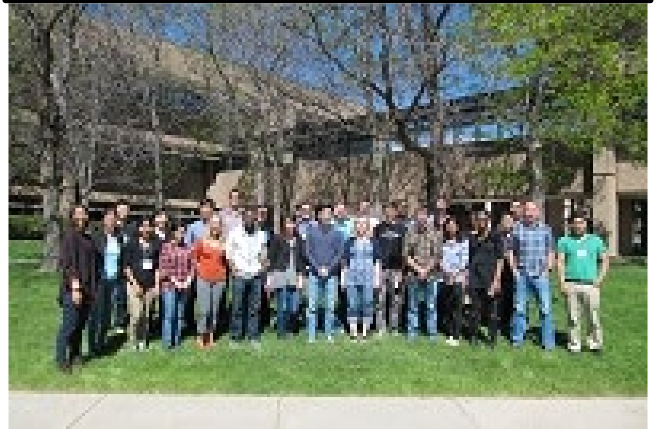
Online Training Suite:

- YouTube video demo (w/ Spanish translation)
- Self-contained training modules using Docker & Jupyter Notebooks

New lines of Communication & Support:

- Email listserv
- Online contact form + helpdesk ticketing system
- Online user forum - (users helping users)
- Twitter @WRFHydro
- Community spotlight
  - Users, research, & contributions to WRF-Hydro Community

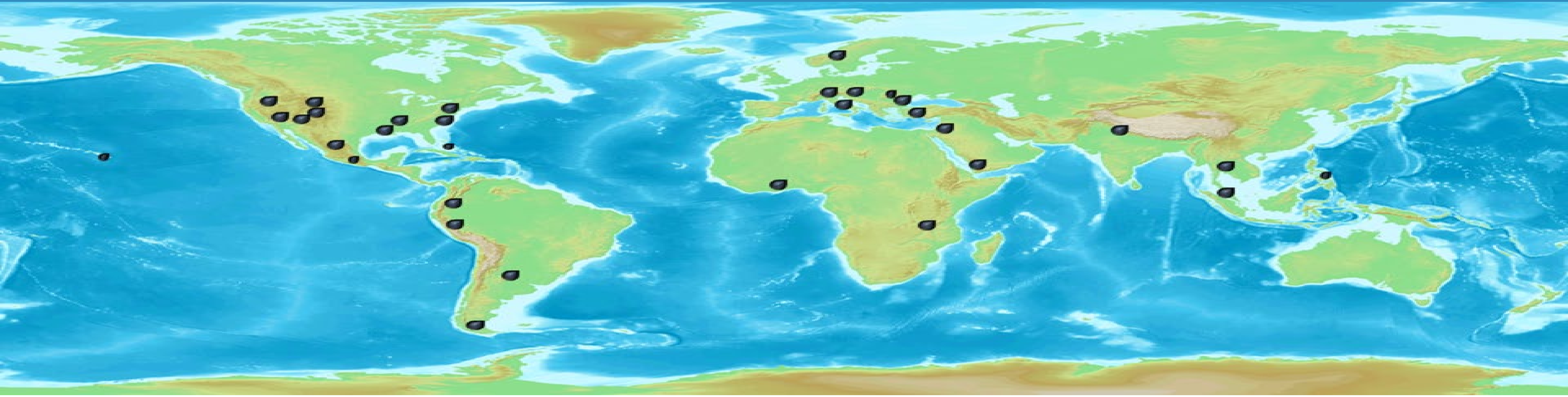




WRF-Hydro MODELING SYSTEM

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

WRF-Hydro Applications Around the Globe



Operational Streamflow Forecasting

- U.S. National Weather Service National Water Model (NOAA/NWS, National Water Center, USGS, CUAHSI)
- Israel National Forecasting System (Israeli Hydrological Service)
- State of Colorado Upper Rio Grande River Basin Water Supply Forecasting (Colorado Water Conservation Board, NOAA/NSSL)
- NCAR-STEP Hydrometeorological Prediction (NCAR)
- Italy reservoir inflow forecasting (Univ. of Calabria)
- Romania National Forecasting System (Baron)

Streamflow Prediction Research

- Flash flooding in Black Sea region of Turkey (Univ. of Ankara)
- Runoff production mechanisms in the North American Monsoon (Ariz State Univ.)
- Streamflow processes in West Africa (Karlsruhe Inst. Tech.)

Coupled Land-Atmosphere Processes

- Diagnosing land-atmosphere coupling behavior in mountain-front regions of the U.S. and Mexico (Arizona State Univ., Univ. of Arizona)
- Quantifying the impacts of winter orographic cloud seeding on water resources (Wyoming Board on Water Resources)
- Predicting weather and flooding in the Philippines, Luzon Region (USAID, PAGASA, AECOM)
- RELAMPAGO in Argentina (Univ. of Illinois Urbana-Champaign, NCAR)

Diagnosing Climate Change Impacts on Water Resources

- Himalayan Mountain Front (Bierknes Inst.)
- Colorado Headwaters (Univ. of Colorado)
- Bureau of Reclamation Dam Safety Group (USBR, NOAA/CIRES)
- Lake Tanganyika, Malawi, Water Supply (World Bank)
- Climate change impacts on water resources in Patagonia, Chile (Univ. of La Frontera)

Coupling WRF-Hydro with Coastal Process Models

- Italy-Adriatic sea interactions (Univ. of Bologna)
- Lower Mississippi River Valley (Louisiana State University)
- Integrated hydrological modeling system for high-resolution coastal applications (U.S. Navy, NOAA, NASA)

Diagnosing the Impacts of Disturbed Landscapes on Hydrologic Predictions

- Western U.S. Fires (USGS)
- West African Monsoon (Karlsruhe Inst. Tech)
- S. America Parana River (Univ. of Arizona)
- Texas Dust Emissions (Texas A&M Univ.)
- Landslide Hazard Modeling (USGS)

Hydrologic Data Assimilation:

- MODIS snow remote sensing assimilation for water supply prediction in the Western U.S. (Univ. of Colorado, Univ. of California Santa Barbara, NSIDC, NCAR)
- WRF-Hydro/DART application in La Sierra River basins in southeast Mexico (Autonomous National University of Mexico)