Overview of the WRF-Hydro Modeling System

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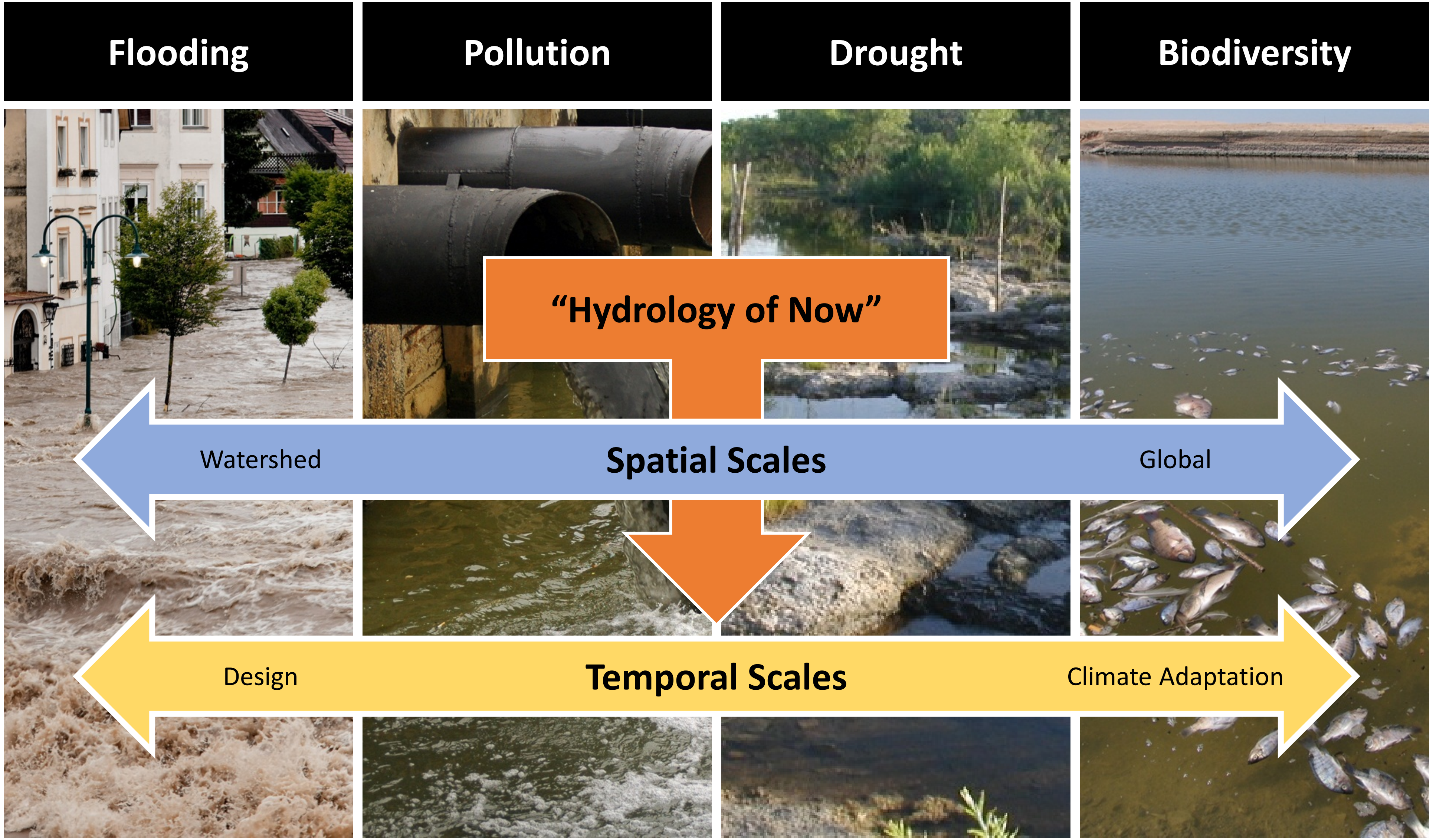
National Center for Atmospheric Research

Motivation: An Array of Water Issues



Scientific Imperative for WRF-Hydro

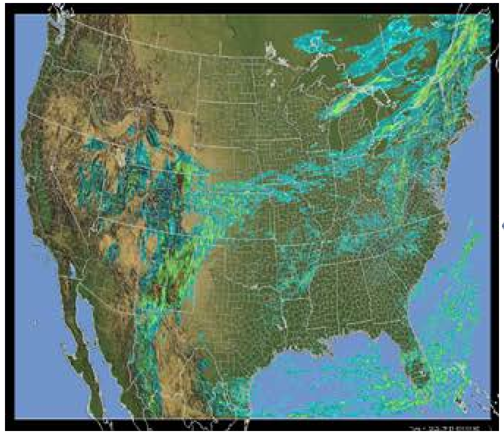
Addressing water cycle prediction questions:

1. What is the ‘coupled-system’ predictability of *extreme hydrological events* and how does physical process representation impact the lead-time dependence of forecast skill? How do horizontal routing processes impact the partitioning of water and energy at the land-atmosphere interface?
2. How does organization of fine-scale heterogeneity impact boundary layer exchange and atmospheric circulation features?
3. How will eco-hydrologic processes evolve under various disturbance mechanisms such as landscape and climatic change?
4. How do we build a framework for ‘total water prediction’ (e.g., NOAA-National Water Model)

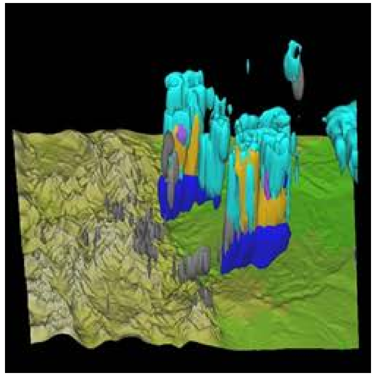
Overarching WRF-Hydro System Objectives

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

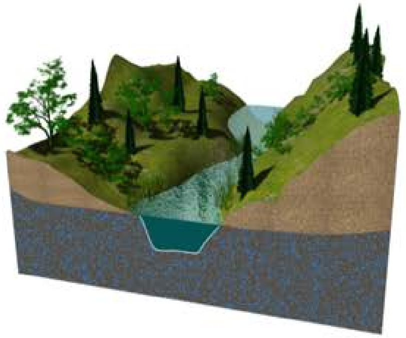
1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as <u>precipitation, soil moisture, snowpack, groundwater, streamflow, inundation</u>
2. 'Accurate' and 'reliable' 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



1-10's km

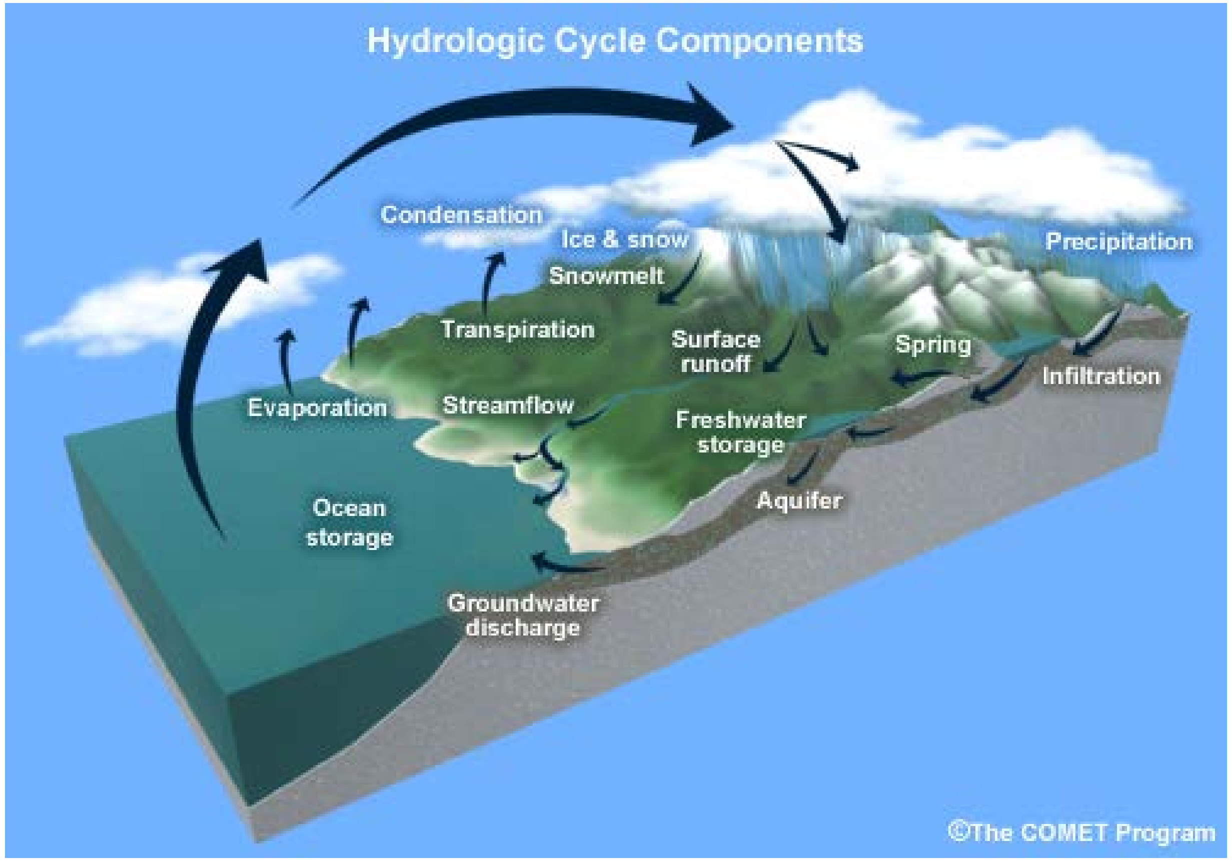


100's m - 1's km

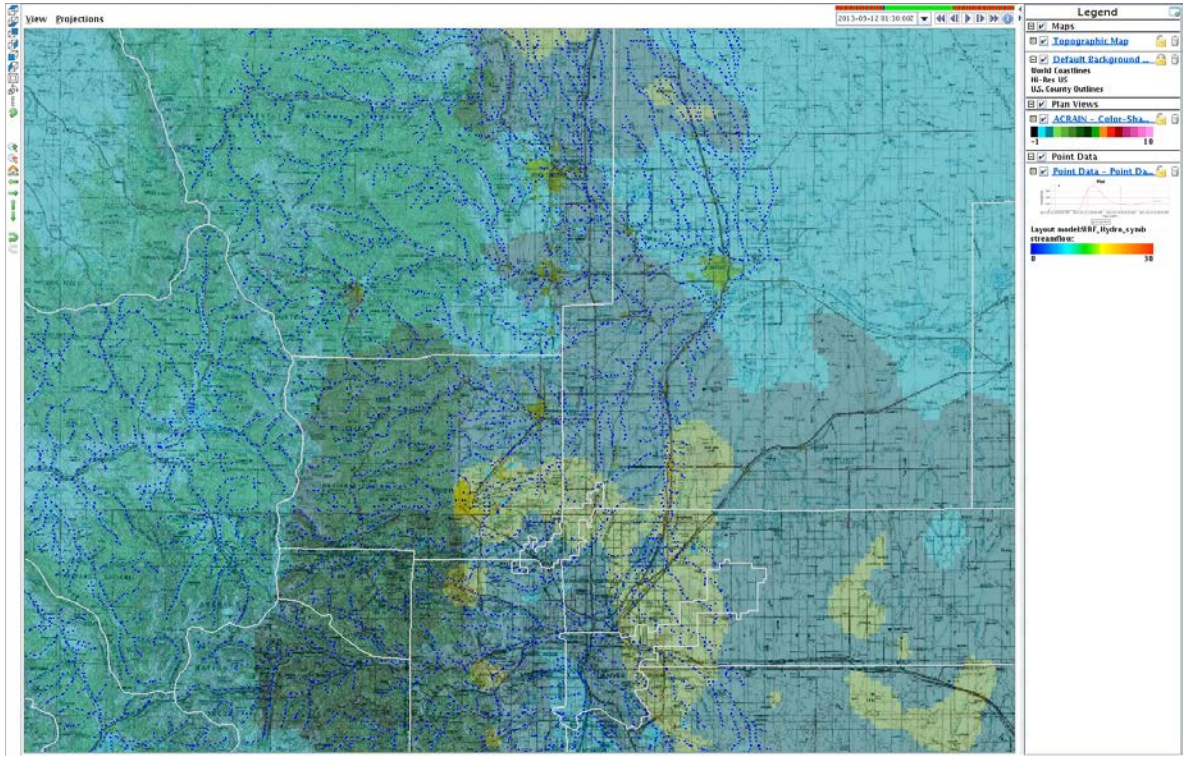


1-10's m

Water Cycle Modeling and Prediction within the WRF-Hydro System



Colorado Flood of 11-15 Sept. 2013

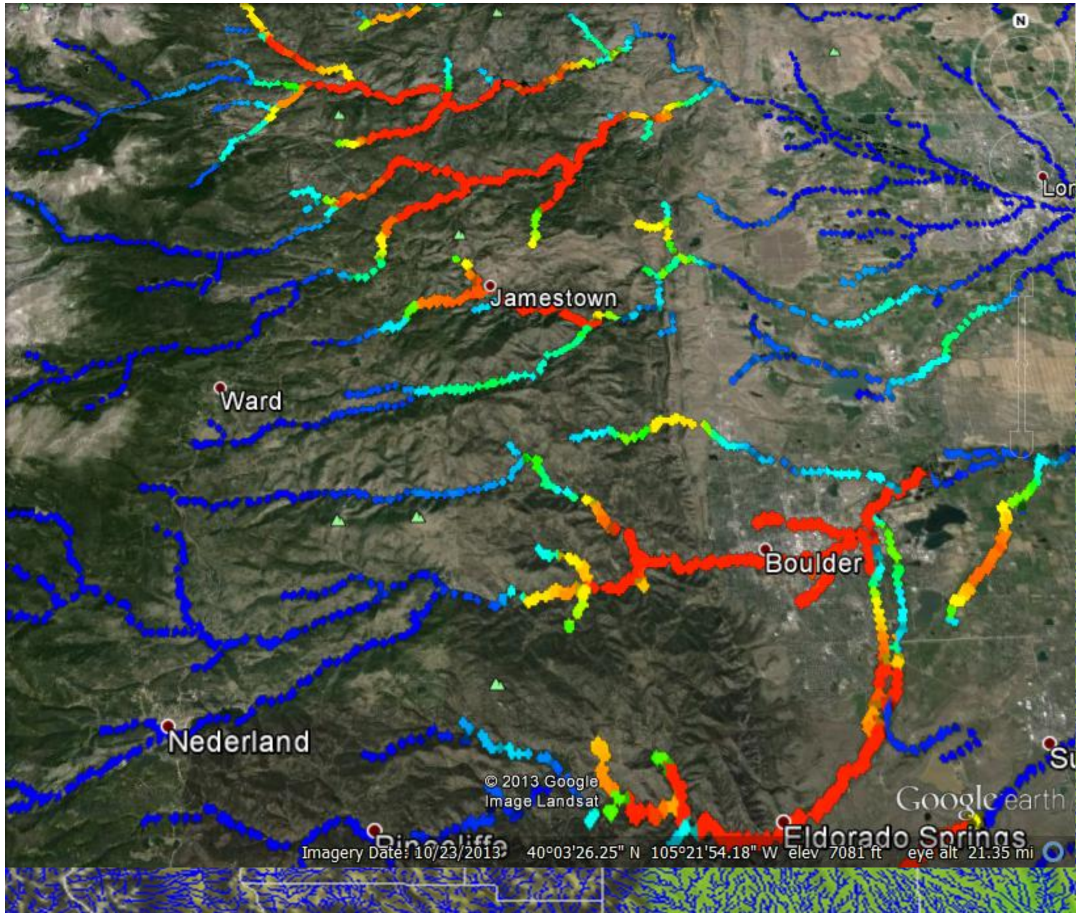


Accumulated Precipitation (shaded colors)
100m gridded streamflow (points)

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

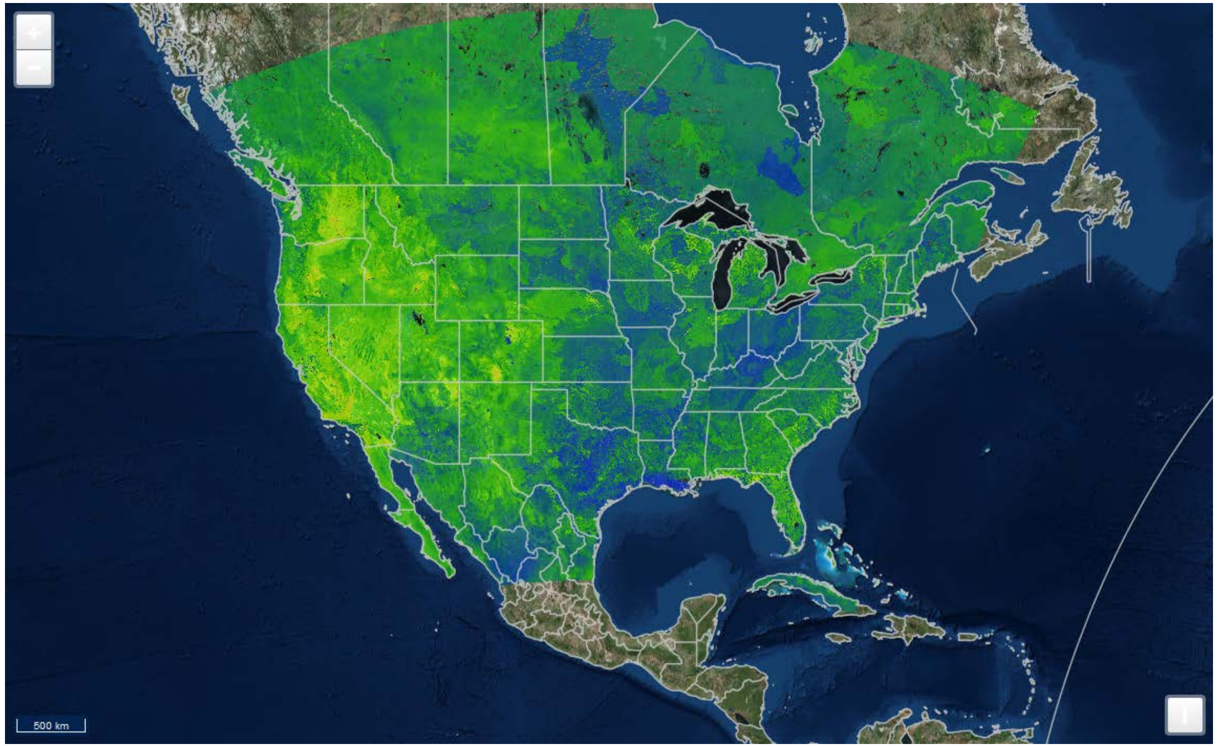


Moving Beyond Point Flow Forecasts

1. Forecasts of water everywhere all the time

The NOAA National Water Model

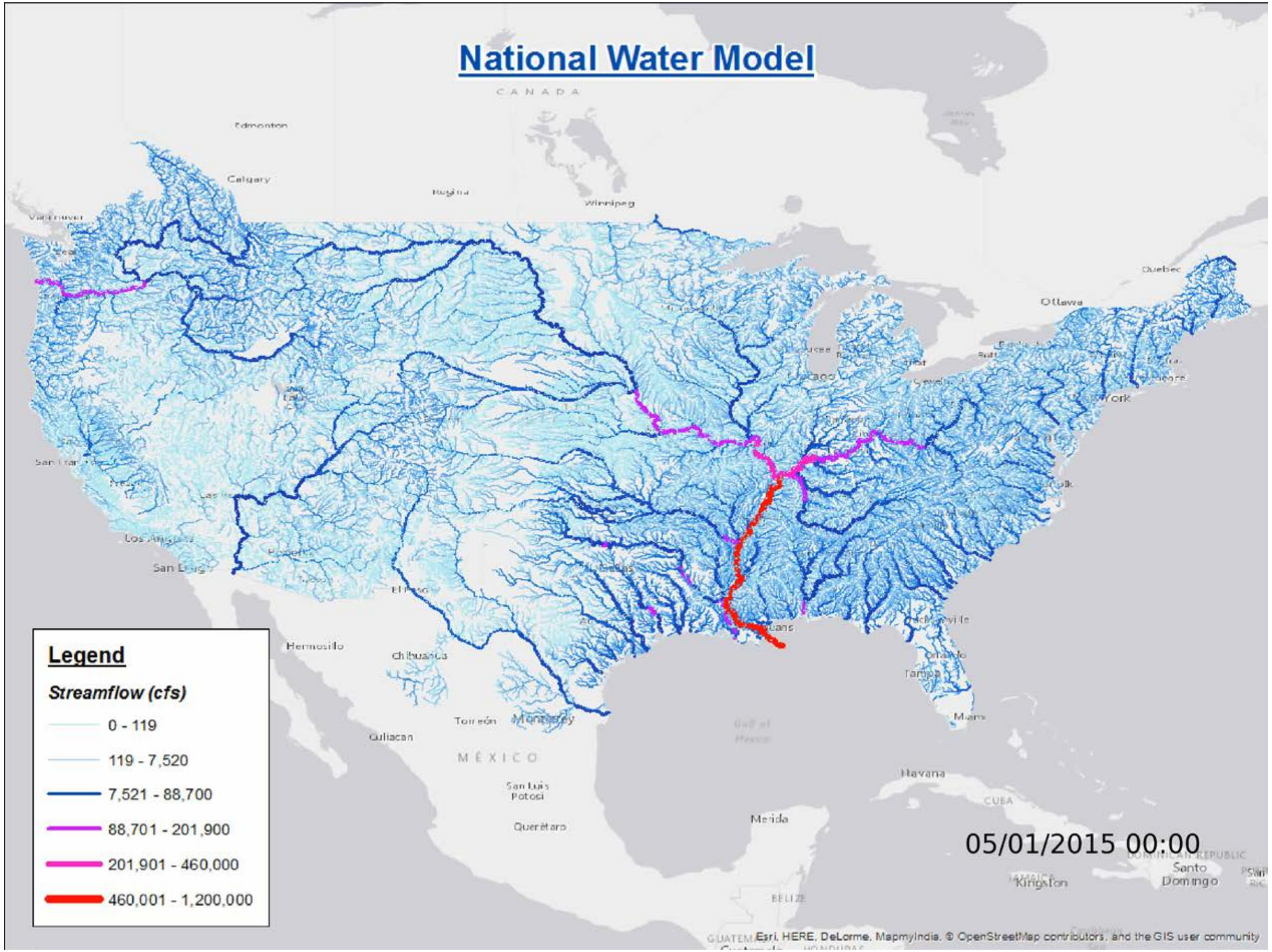
Snow Water Equivalent (SNEQV): Oct. 23, 2018



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

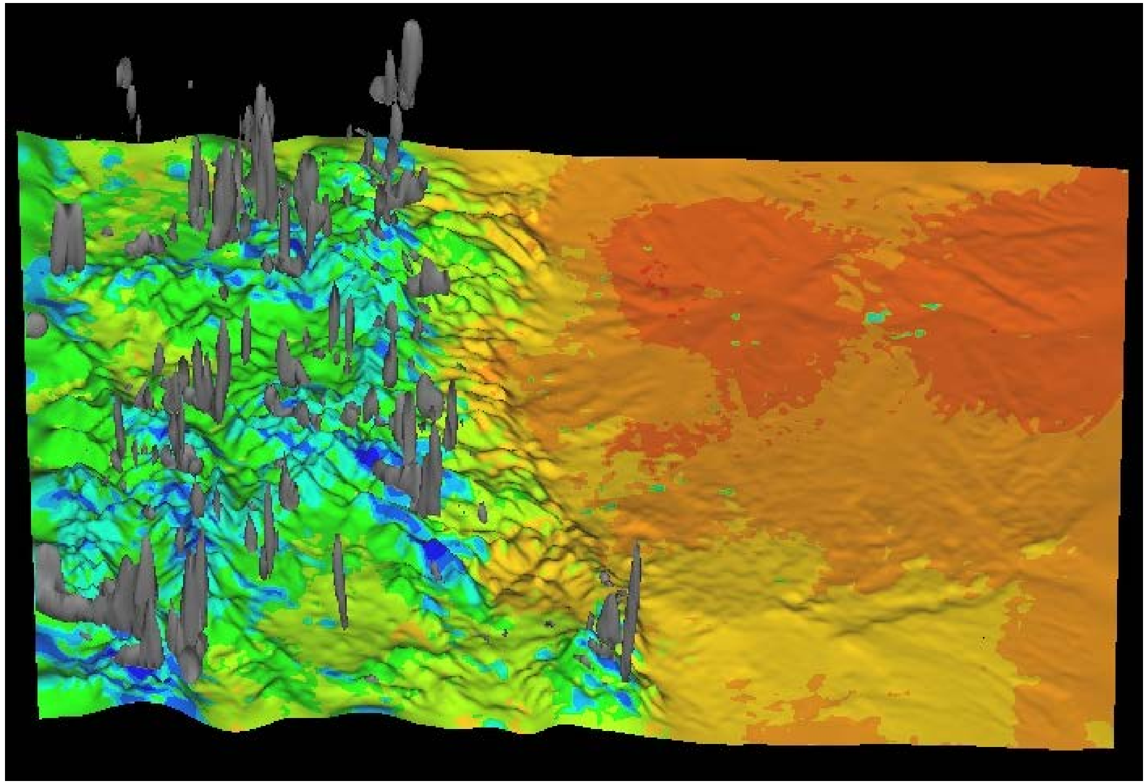
1. Forecasts of water everywhere all the time

The NOAA National Water Model

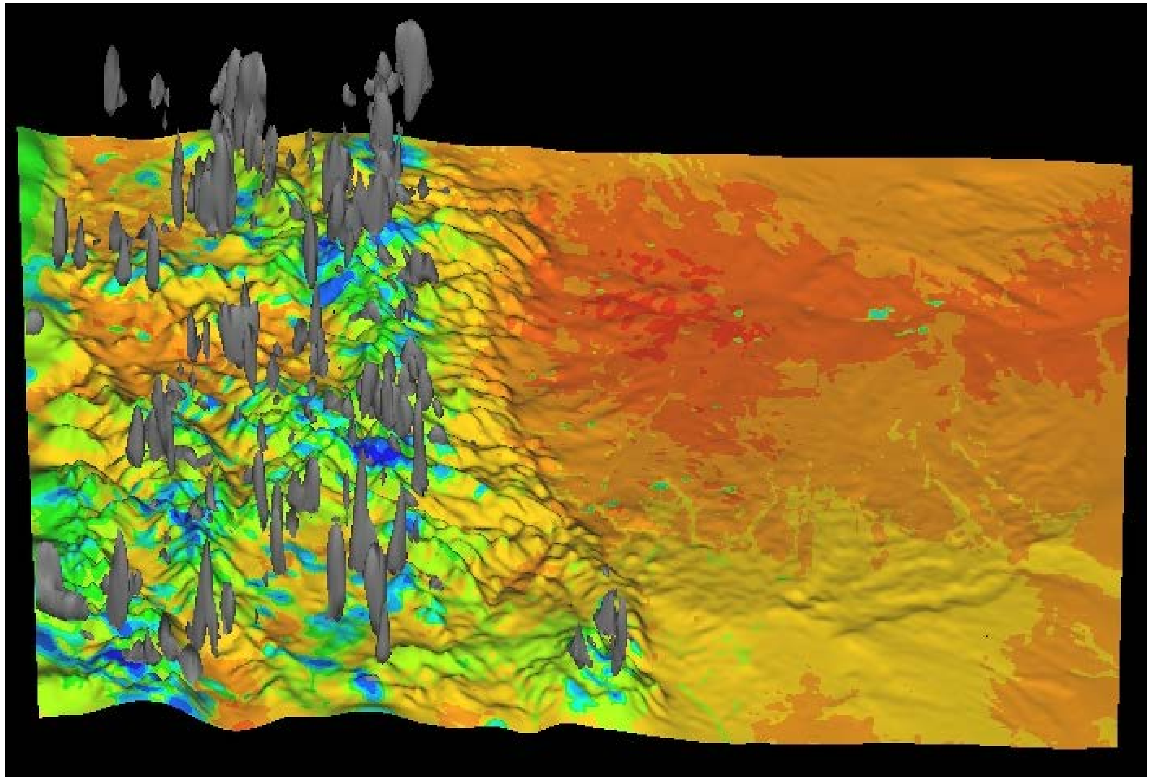


2. Coupled system flux predictions

FRNG_1km_cloudwater_tskin_NARR_7_18_2004_1800z



FRNG_1km_cloudwater_tskin_WRF-Hydro_rtg_7_18_2004_1800z



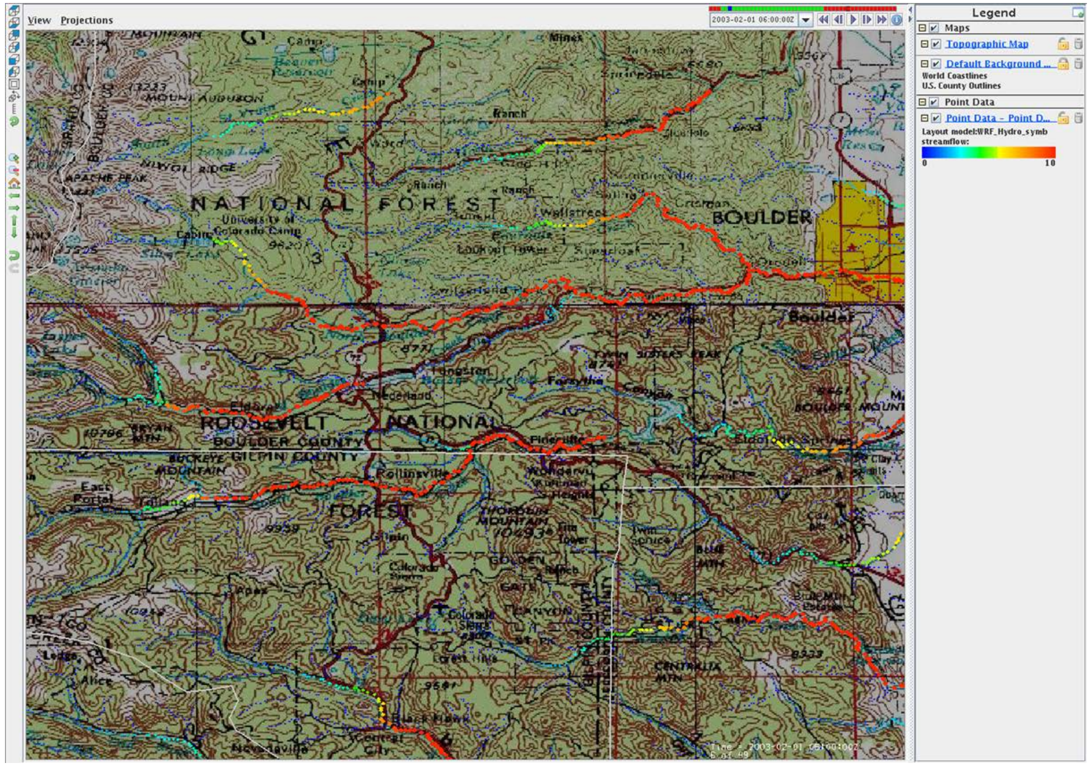
Variability in surface fluxes are strongly coupled to convective initiation and cloud formation. Complex, non-linear feedback require coupled system representation

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

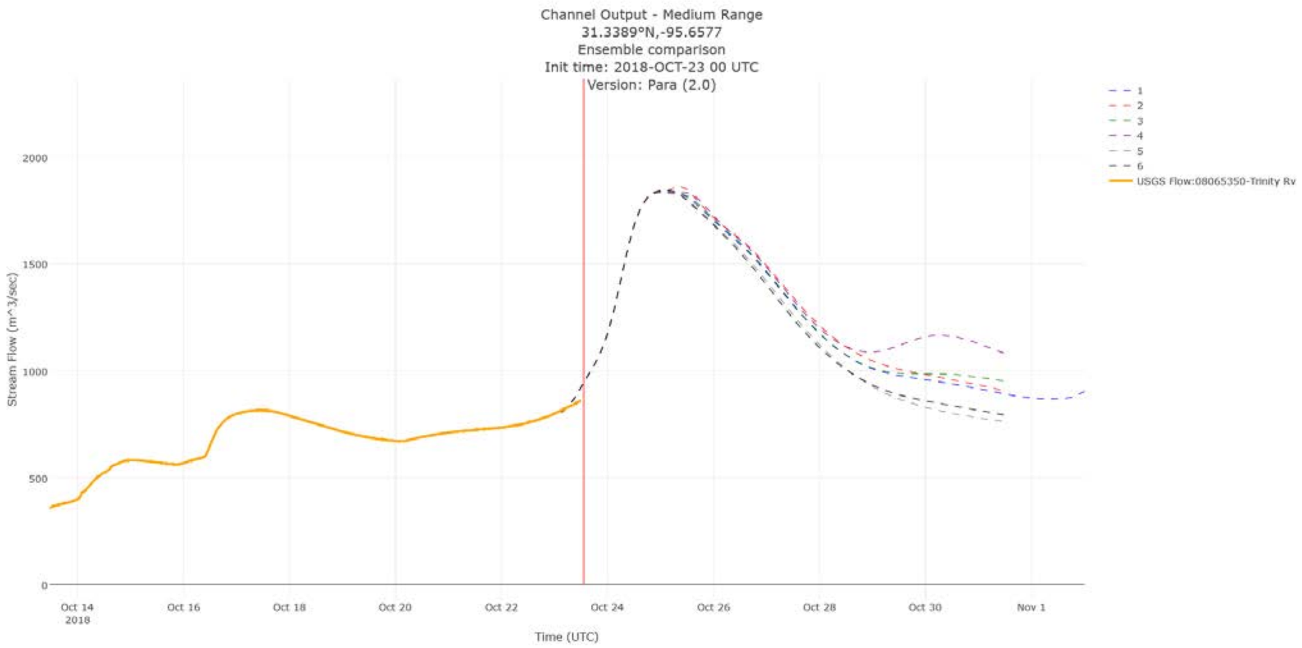
Quantify analysis and forecast uncertainty to provide meaningful risk guidance

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

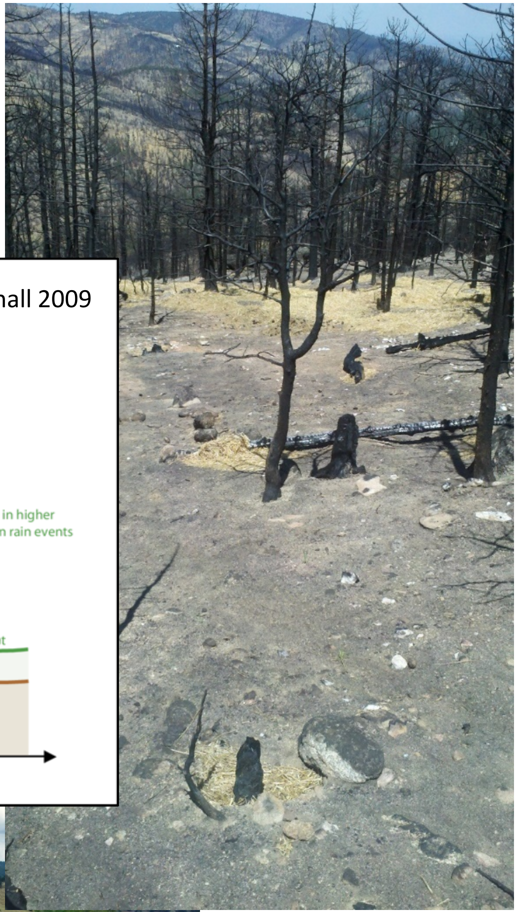


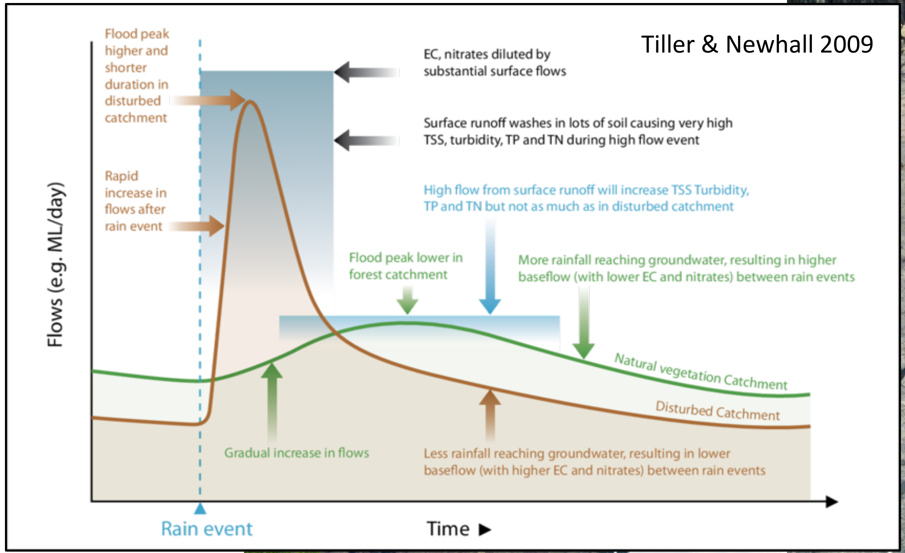
5. Hydro-system dynamics

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***



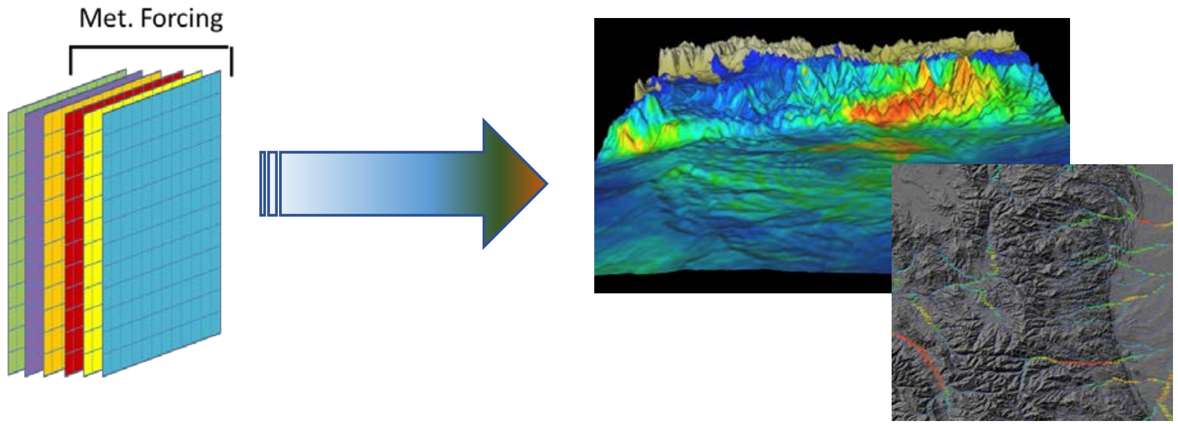


WRF-Hydro System Specifics

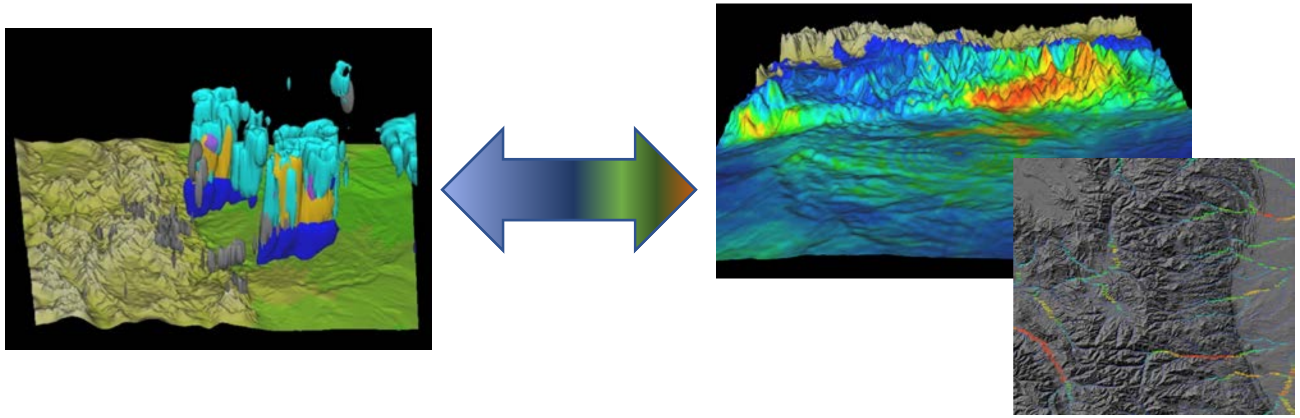
WRF-Hydro Operating Modes

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

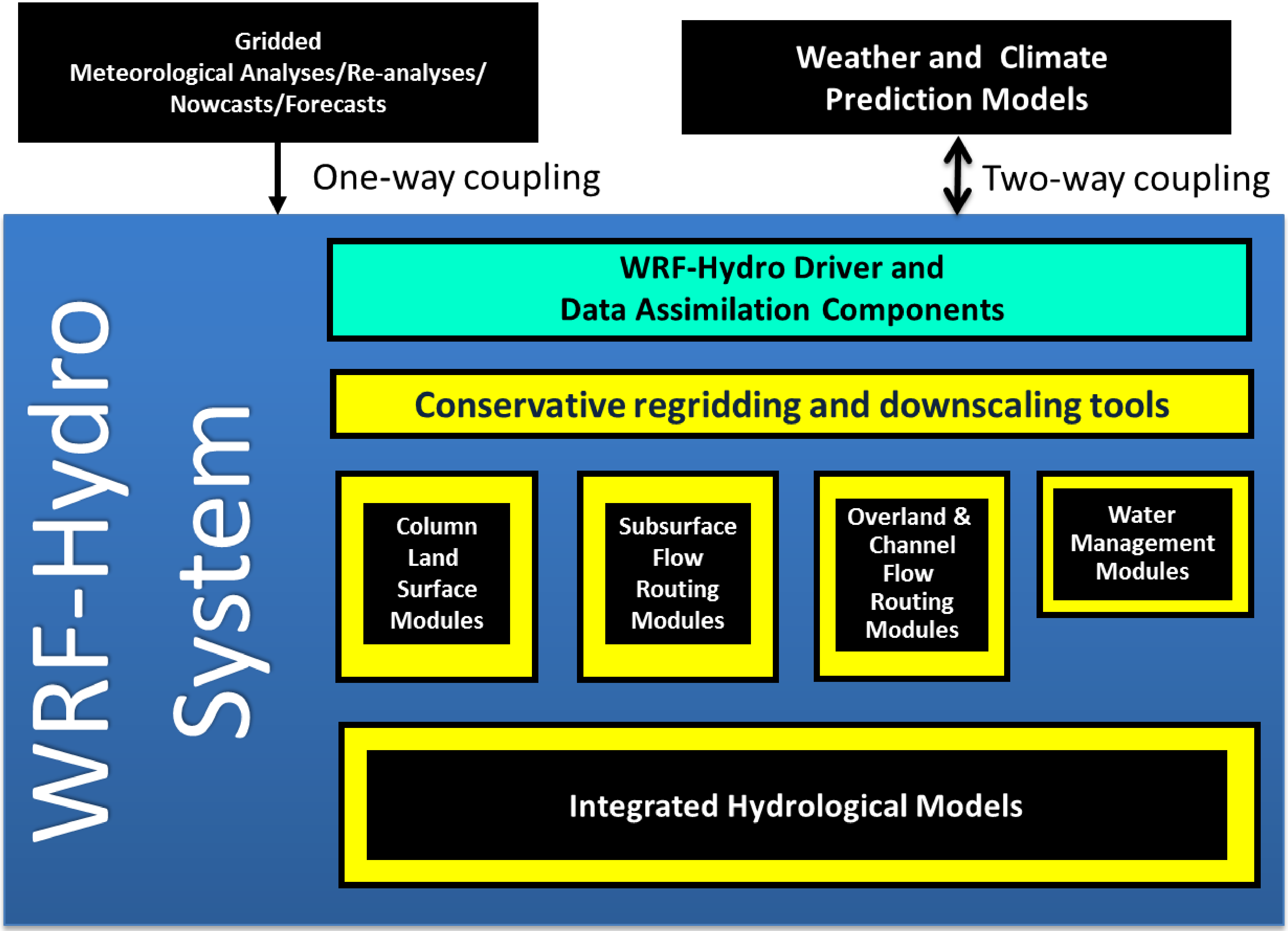
One-way (“uncoupled”) →



Two-way (“coupled”) ↔

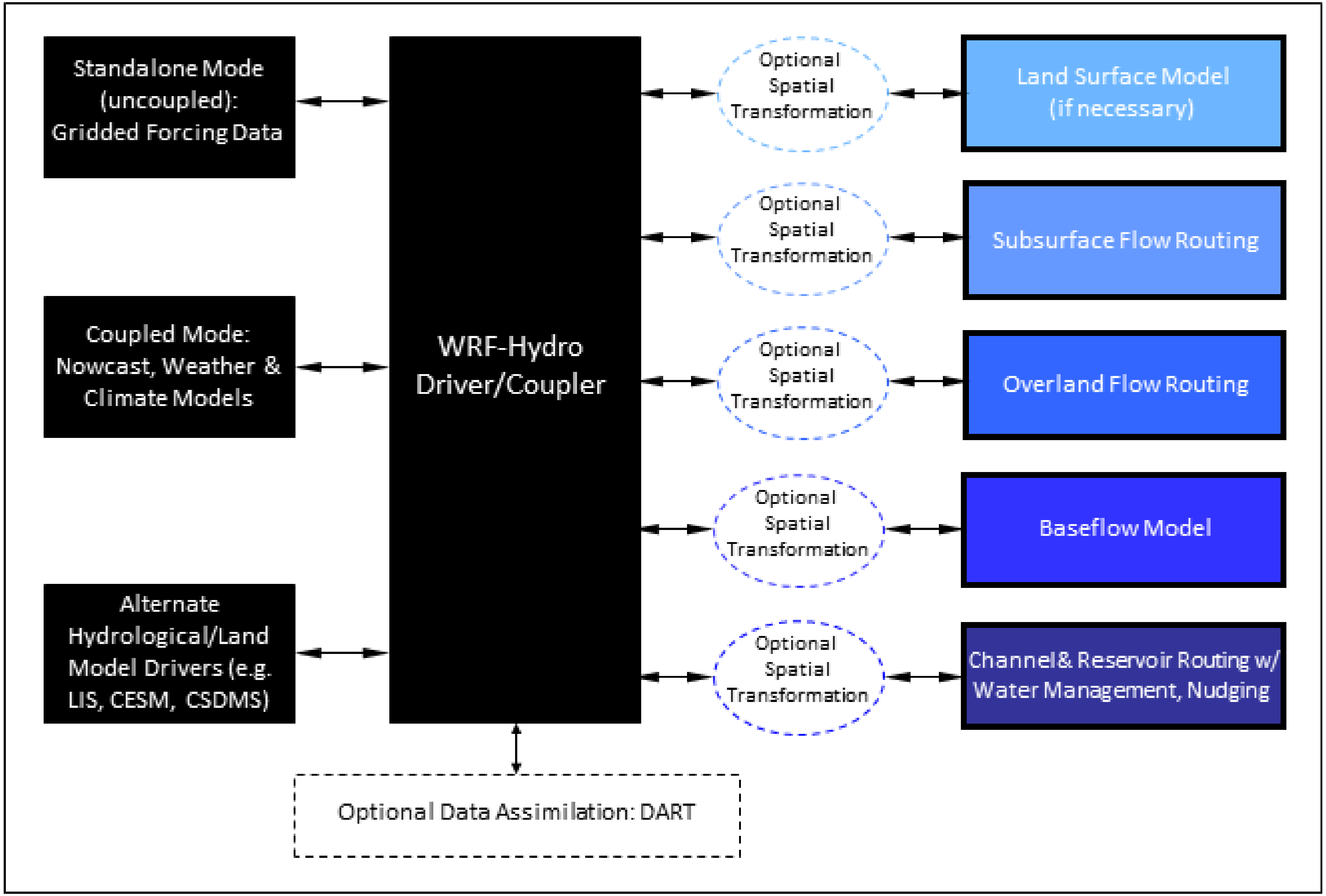


- <u>Uncoupled mode</u> critical for spinup, data assimilation and model calibration
- <u>Coupled mode</u> critical for land-atmosphere coupling research and long-term predictions
- Model forcing and feedback components mediated by WRF-Hydro:
  - Forcings: T, Press, Precip., wind, radiation, humidity,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



Gridded Meteorological Analyses/Re-analyses/ Nowcasts/Forecasts
Weather and Climate Prediction Models
One-way coupling
Two-way coupling
WRF-Hydro System
WRF-Hydro Driver and Data Assimilation Components
Conservative regridding and downscaling tools
Column Land Surface Modules
Subsurface Flow Routing Modules
Overland & Channel Flow Routing Modules
Water Management Modules
Integrated Hydrological Models

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)

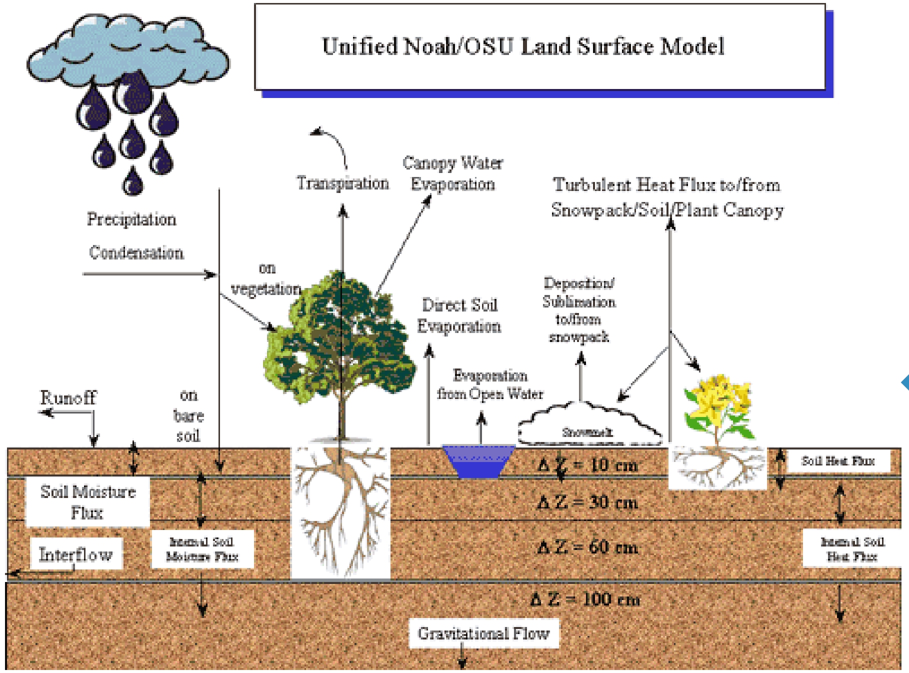
WRF-Hydro Software Features

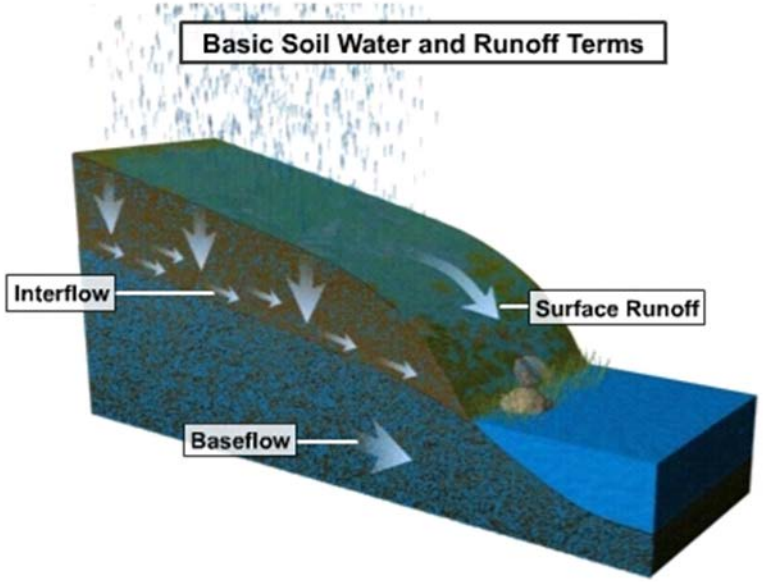
- Modularized Fortran
- Coupling options are specified at compilation and WRF-Hydro is compiled as a new library in WRF when run in coupled mode
- Physics options are switch-activated though a namelist/configuration file
- Options to output sub-grid state and flux fields to standards-based netcdf point 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

WRF-Hydro Physics

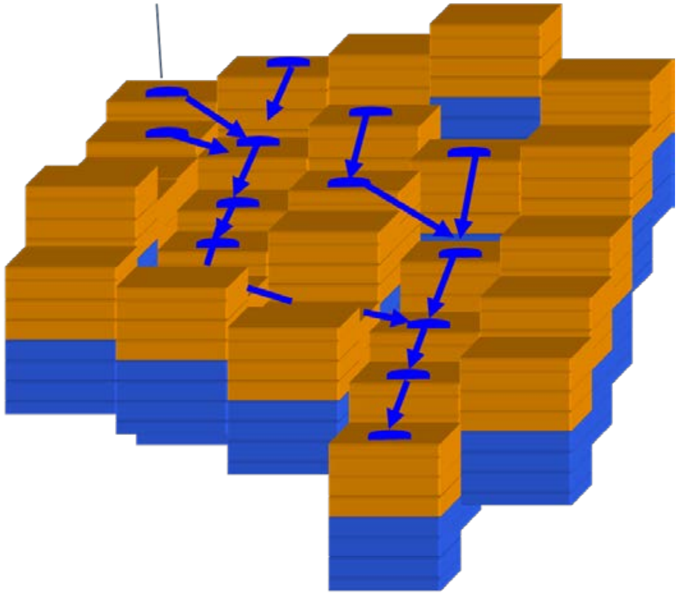
- Linking the column structure of land surface models with the ‘distributed’ structure of hydrological models in a flexible, HPC architecture
- Multi-scale process representation



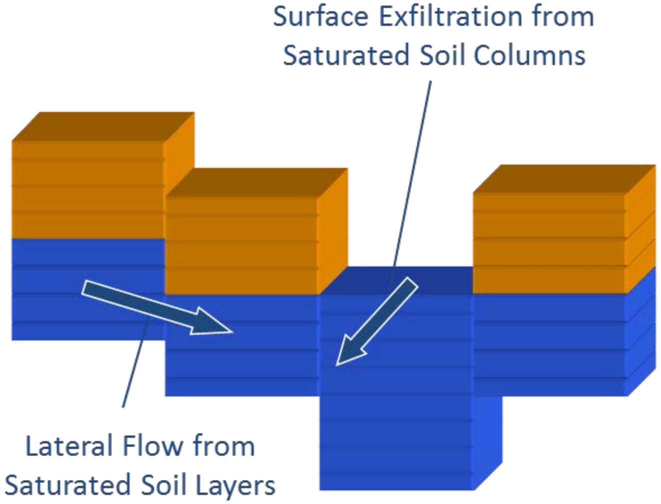


WRF-Hydro Physics Components

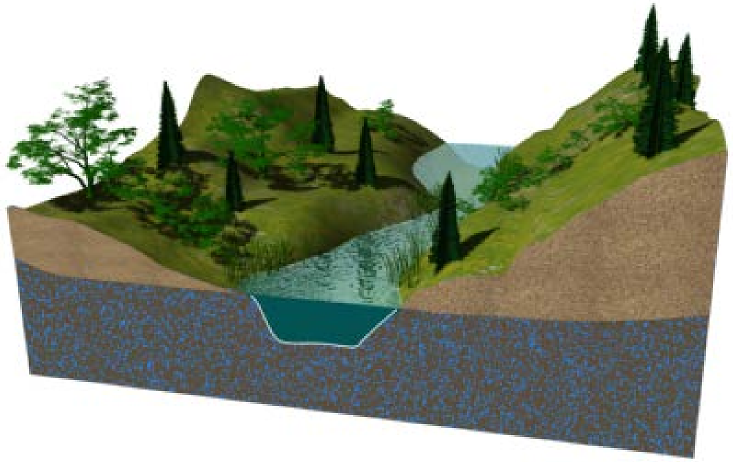
- Physics-based runoff processes



Overland Flow -
Diffusive wave
Kinematic*
Catchment aggregation*



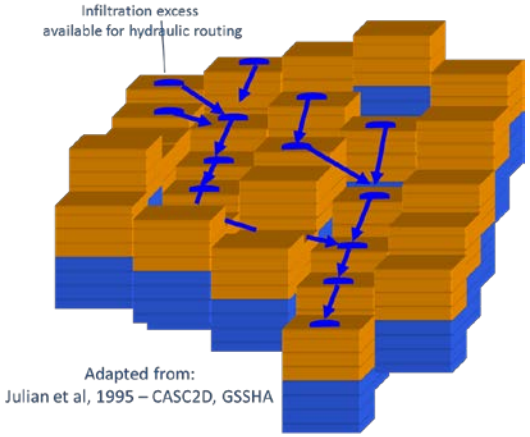
Groundwater Flow –
Boussinesq flow
Catchment aggregation*



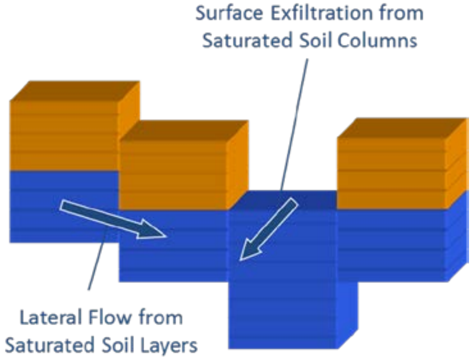
Channel Flow –
Diffusive wave
Kinematic*
Reach-based Muskingum*

Runoff and Routing Physics

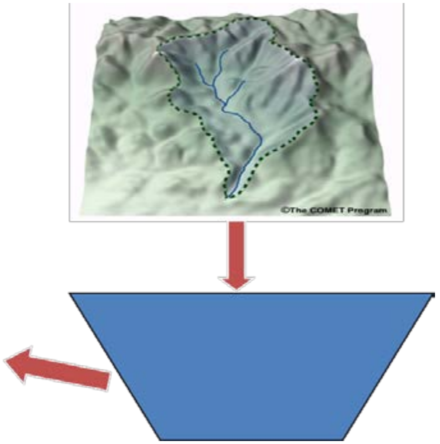
Overland Flow



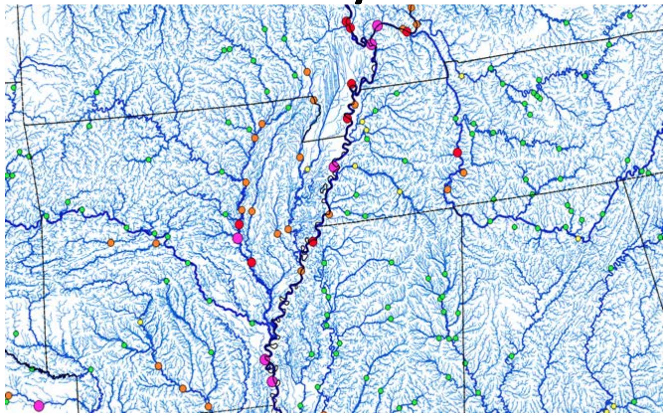
Lateral Subsurface Flow



Simplified Baseflow Parameterization

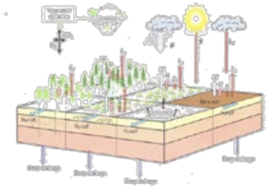
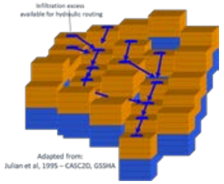
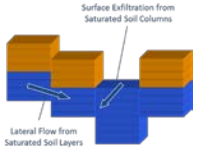
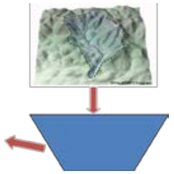
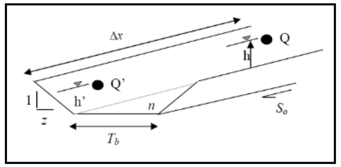
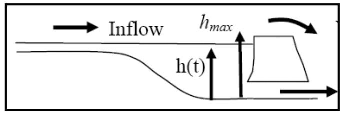


Channel Hydraulics



Simple Water Management

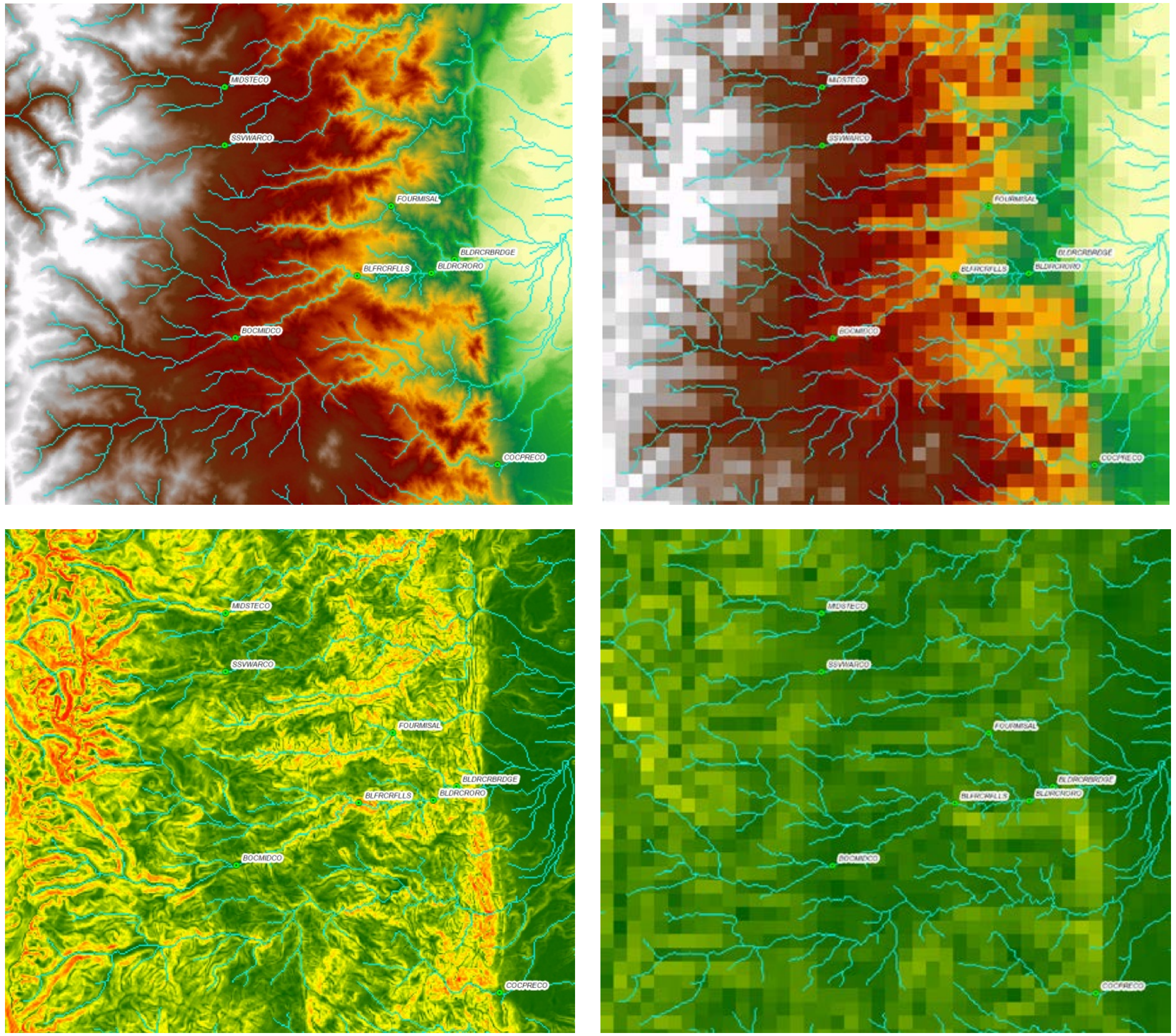
WRF-Hydro Physics Permutations

		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 Physics: Regular Grid Aggregation/Disaggregation

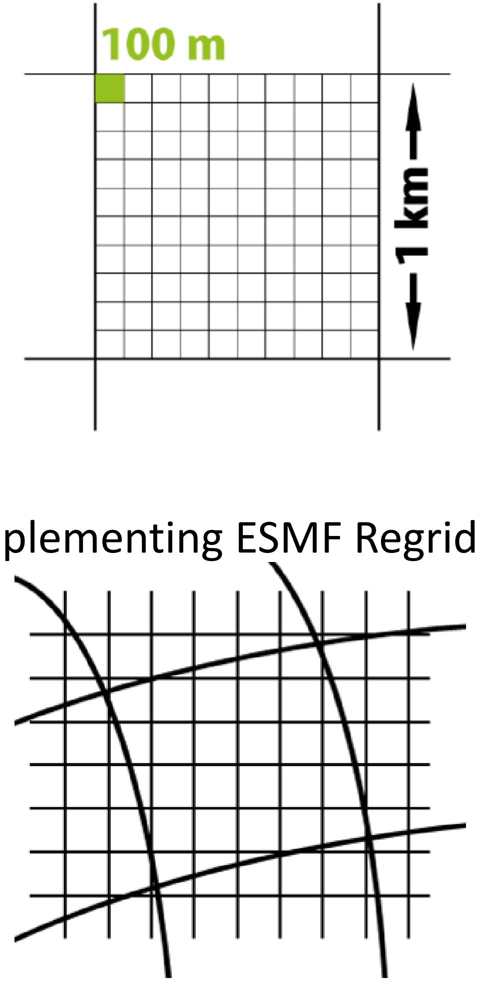
100m Terrain

1 km Terrain



Terrain slope (0-45 deg)

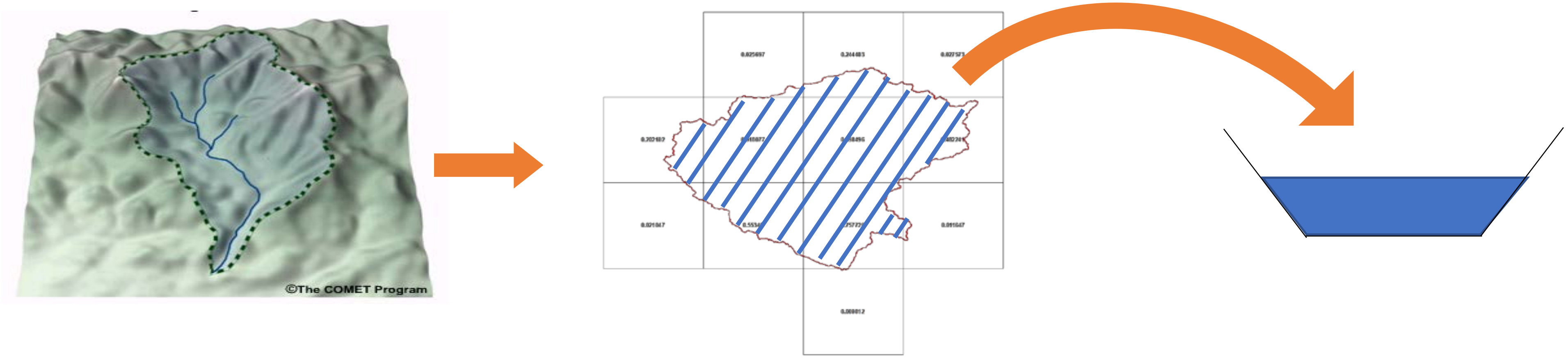
Current Regridding



Implementing ESMF Regridders

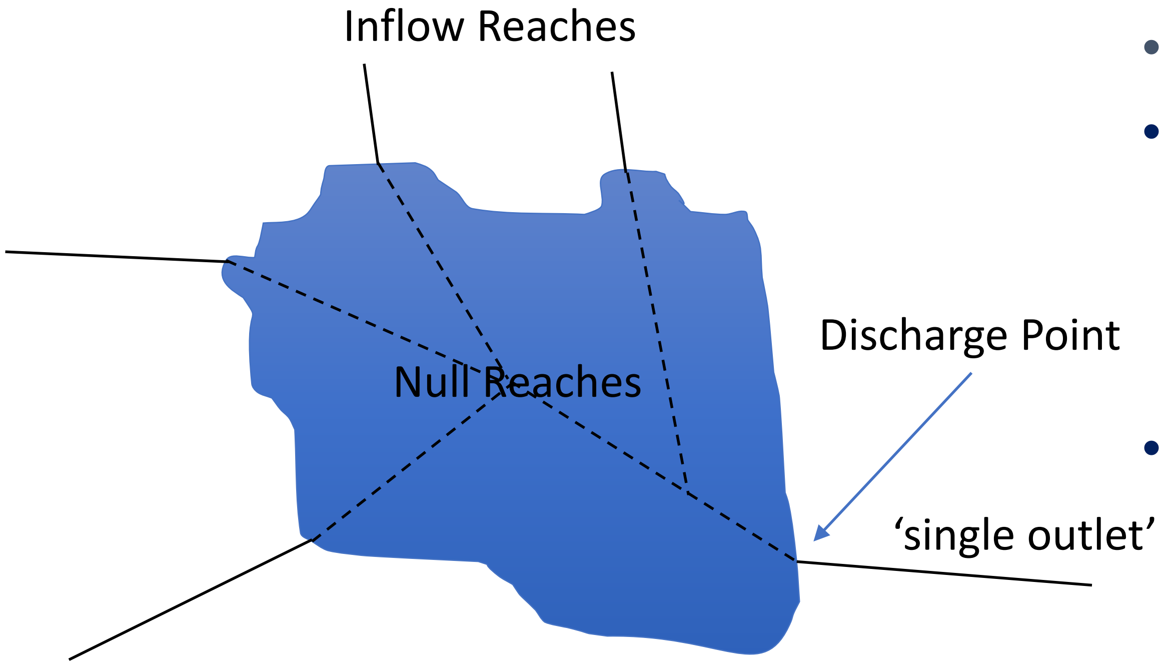
WRF-Hydro Physics: Unstructured “Catchment” Aggregation

- Optional conceptual “catchment” modeling support:
  - Benchmarking simple versus complex model structures
  - Enable very rapid “first-guess” forecasts with reduced runtime/computational demand
  - Discharge gets distributed to channel network for channel routing (e.g. NWM & RAPID coupling)



Runoff and Routing Physics: Lake/Reservoir Routing

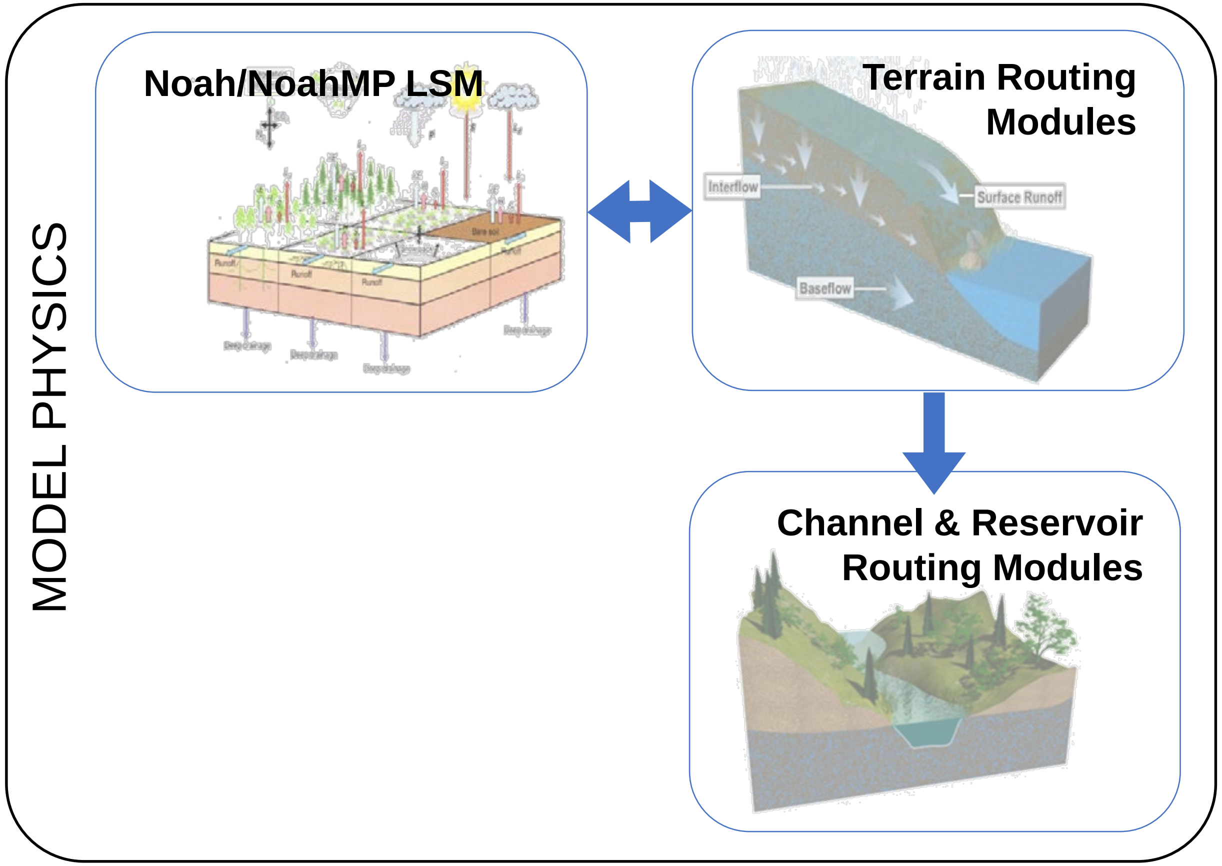
- Defined in GIS Pre-processing, integrated with channel hydrograph
- Specified spillway characteristics (length, height)



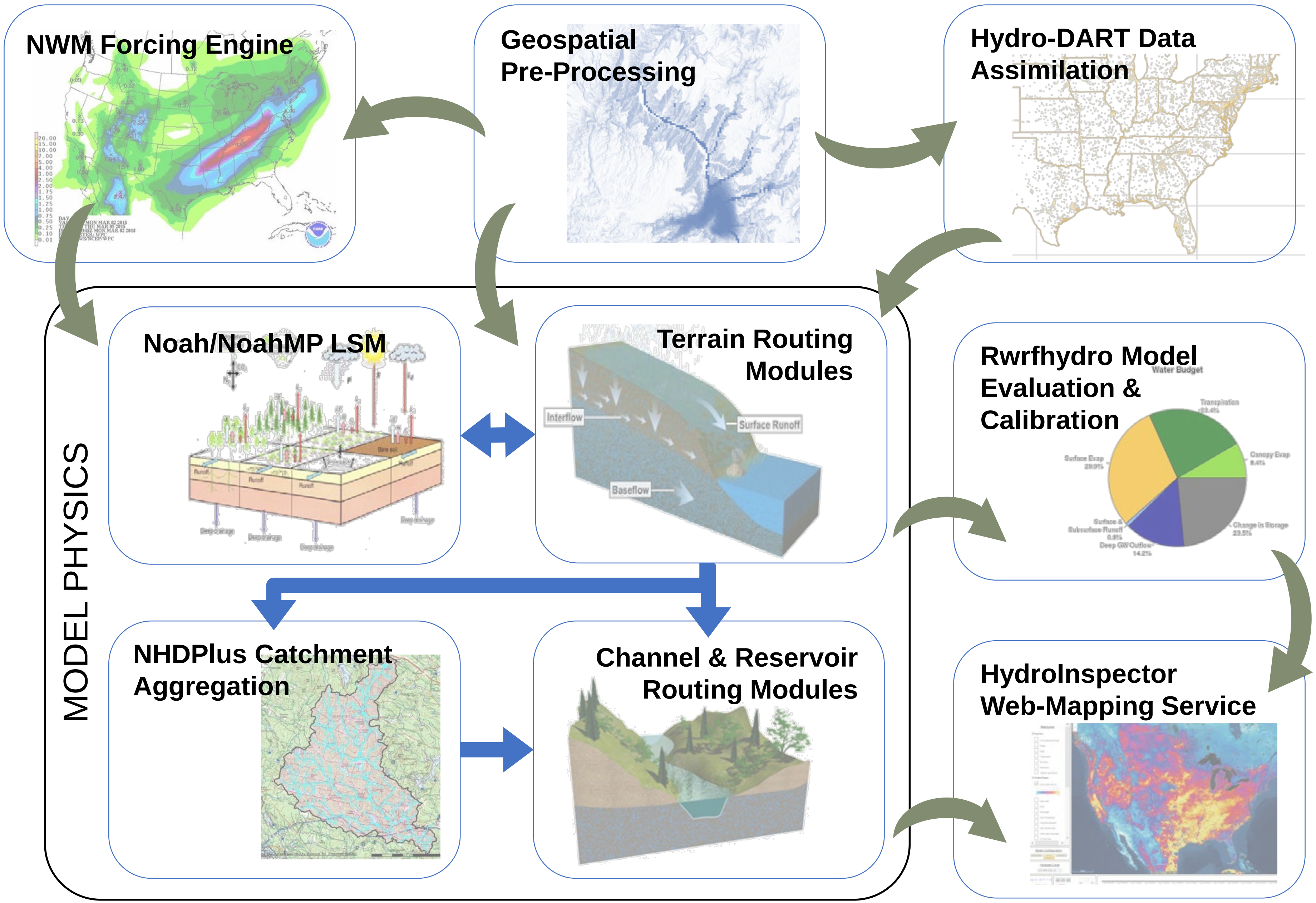
- Level Pool Scheme:
- 3 'passive' discharge mechanisms:
  - Orifice flow
  - Spillway flow
  - Direct Pass-through
- Development:
  - Basic thermodynamics (CLM/WRF lake model)
  - Full lake accounting
    - Evaporation
    - Ice formation
    - Inflows/outflows
    - Simple management
  - Coupling to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

The WRF-Hydro Workflow

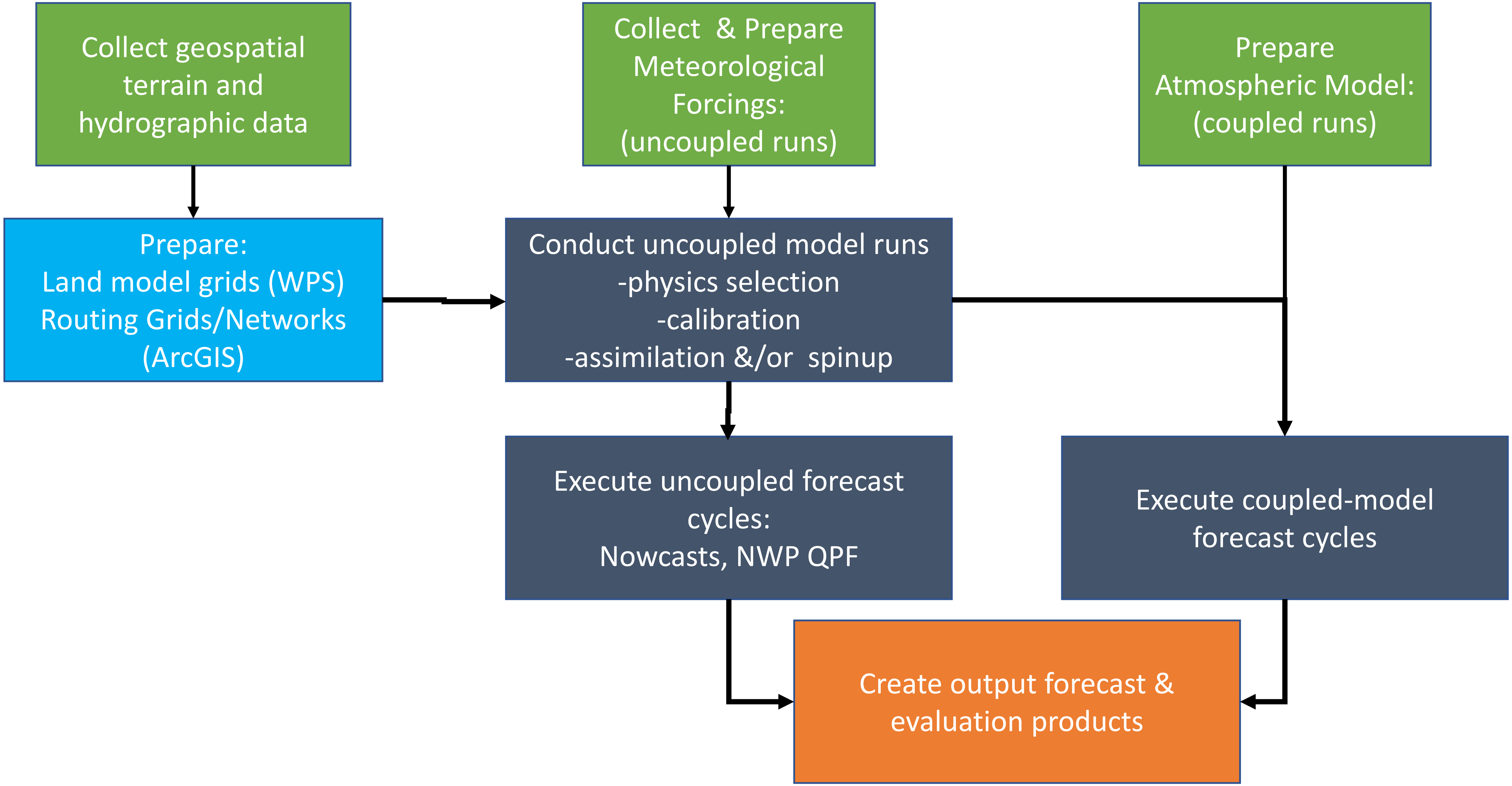
WRF-Hydro Base Configuration



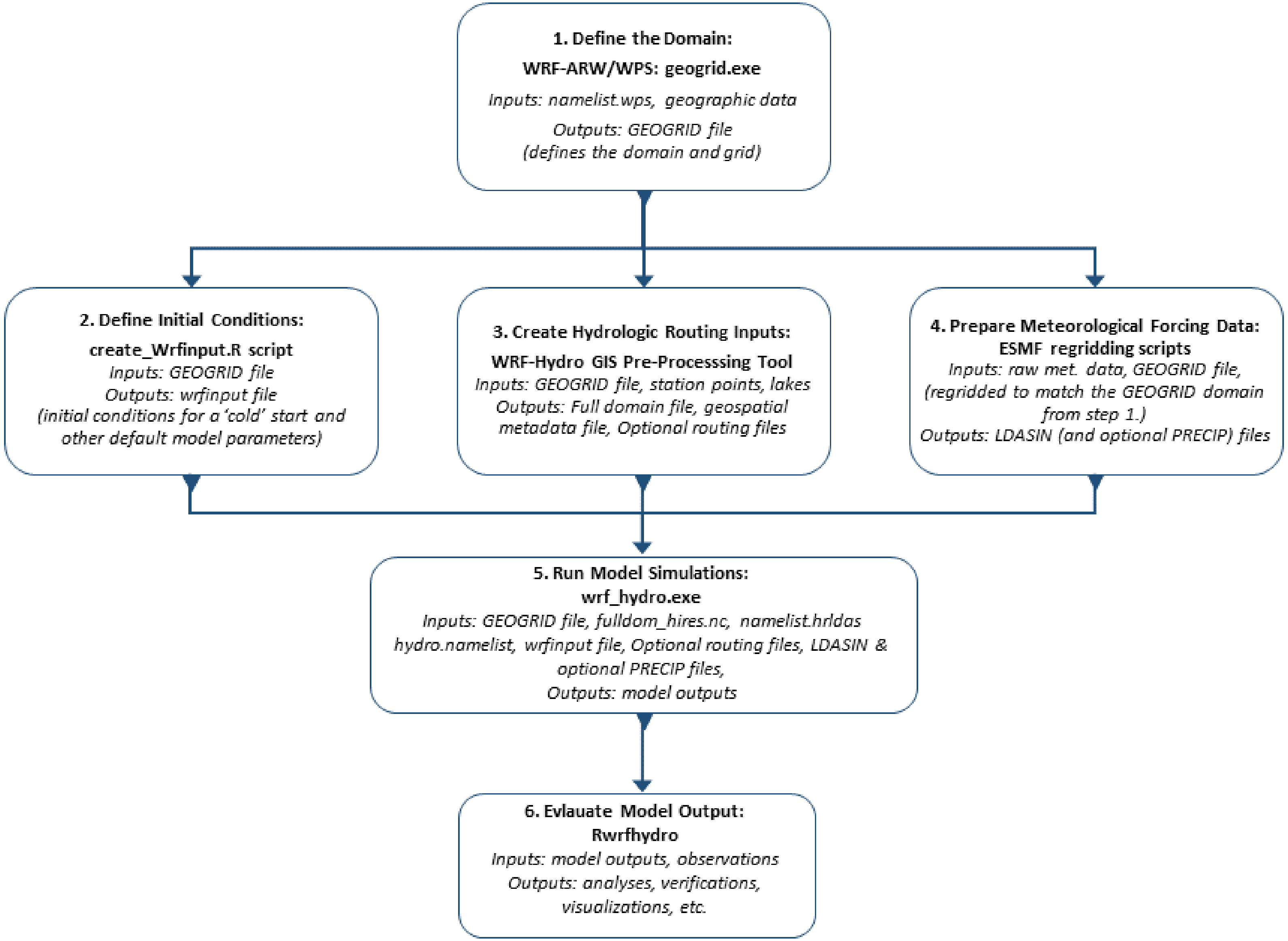
Full WRF-Hydro Ecosystem



WRF-Hydro Implementation Workflow



WRF-Hydro Workflow - custom geographical inputs



Model System Components

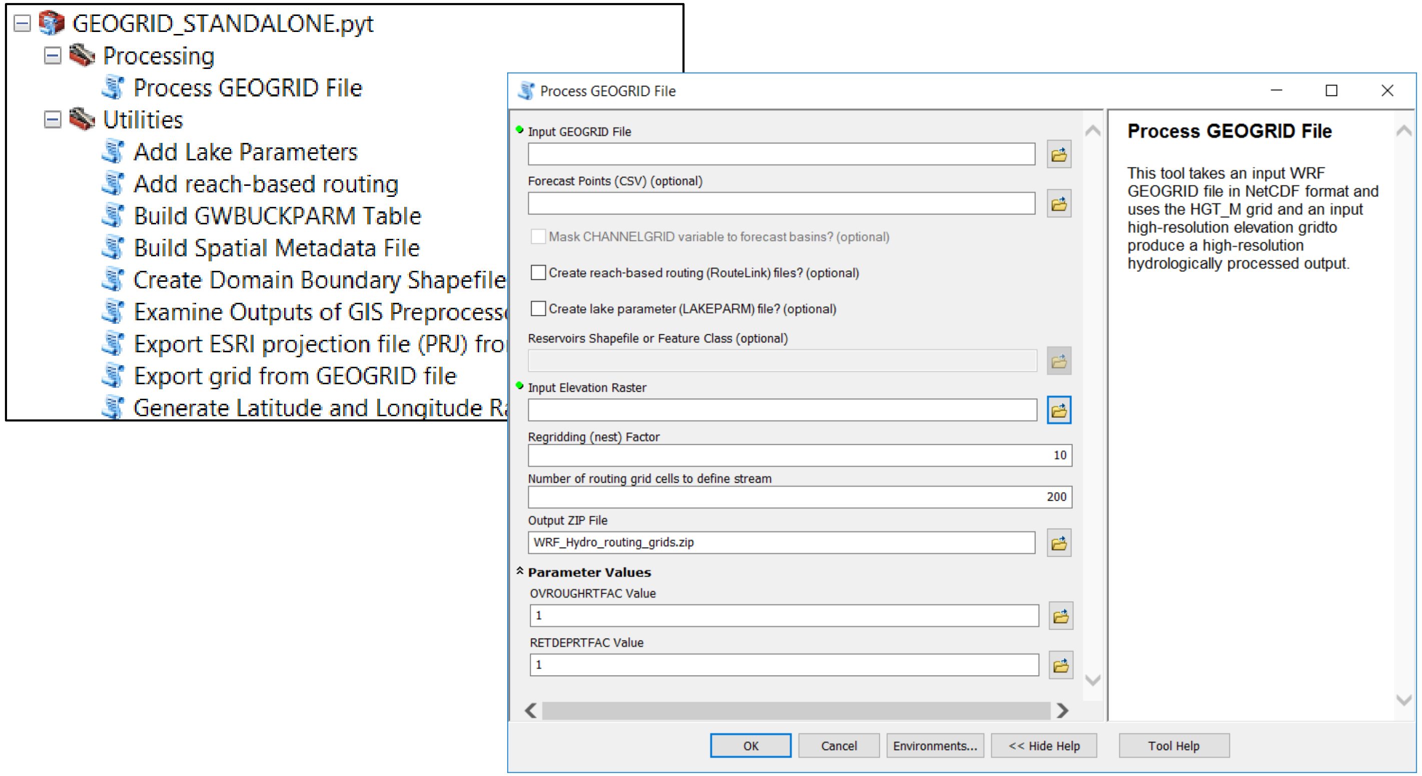
- **GIS Pre-Processor** – Physiographic data processing
- **ESMF Regridding Scripts** – Met. data pre-processing
- **Core WRF-Hydro Model** – Model physics
- **Rwrfhydro** – Analysis, verification, visualization
- **PyWrfHydroCalib** – Model calibration toolkit

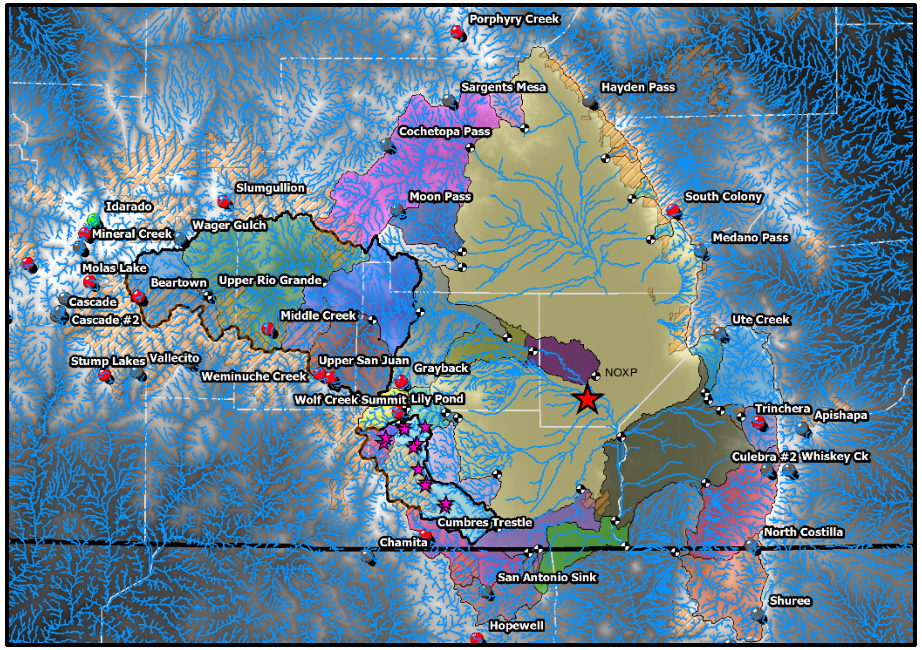
WRF-Hydro Setup and Parameterization: Python Pre-Processing Toolkit

K. Sampson - developer

https://github.com/NCAR/wrf_hydro_arcgis_preprocessor

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



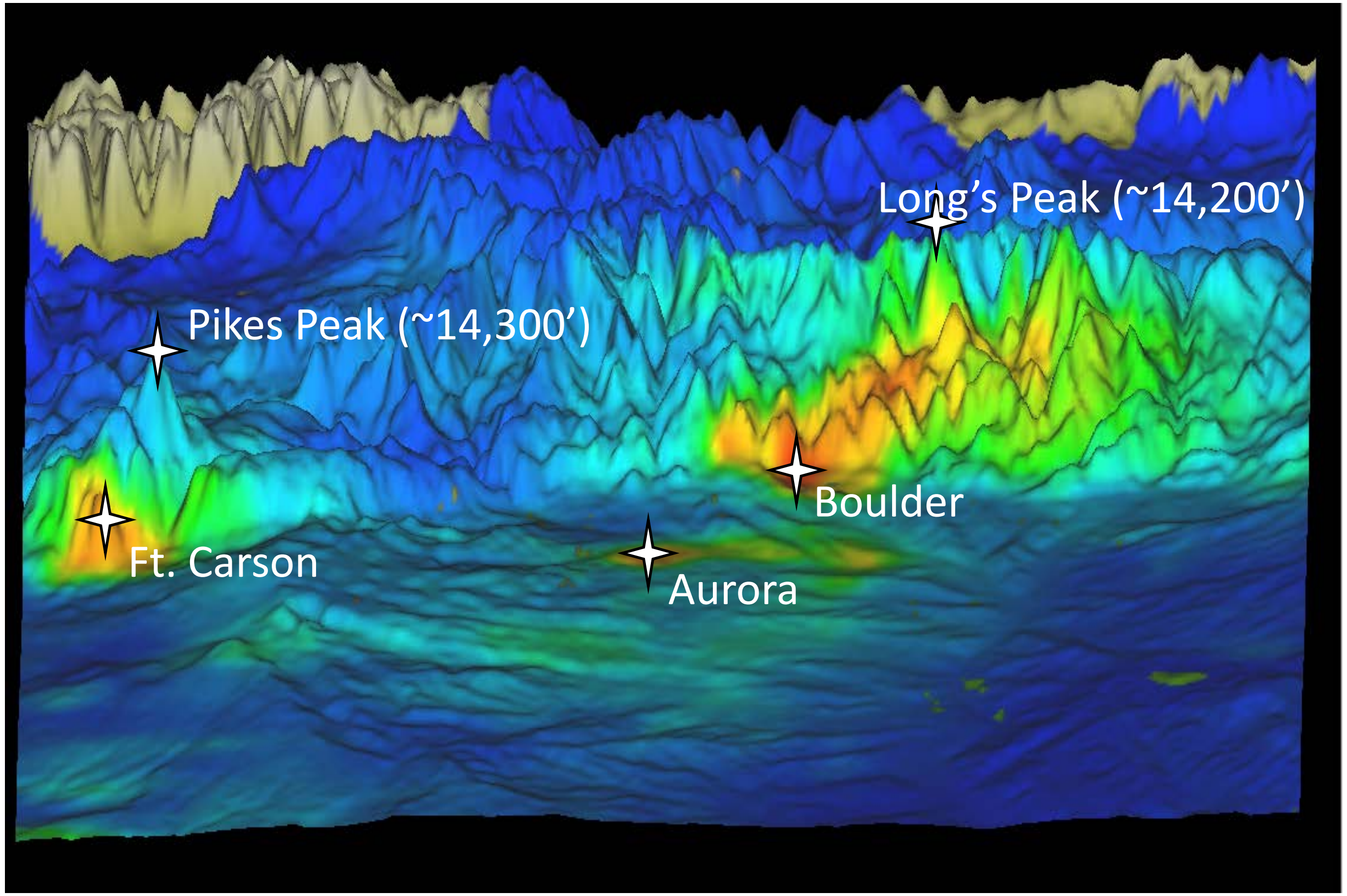


Outputs: topography, flowdirection, watersheds, gridded channels, river reaches, lakes, various parameters

Meteorological Forcing Engine – Used in NWM

L. Karsten - developer

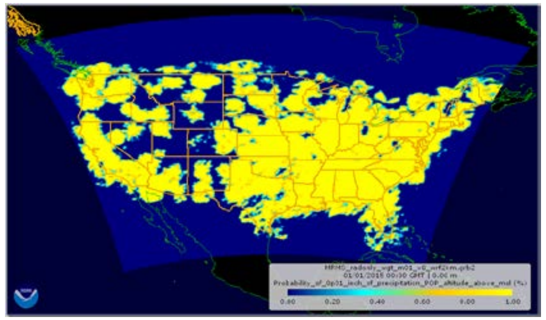
- NEW!!! Python-based code…
- NLDAS, NARR analyses
- QPE products: MPE, StgIV, NCDC-served, dual-pol, Q3/MRMS, gauge analyses, CMOPRH, TRMM, GPM
- NOAA QPF products: GFS, NAM, RAP, HRRR, ExREF
- Nowcast (NCAR Trident/TITAN)
- NOHRSC SNODAS
- ESMF regridding tools



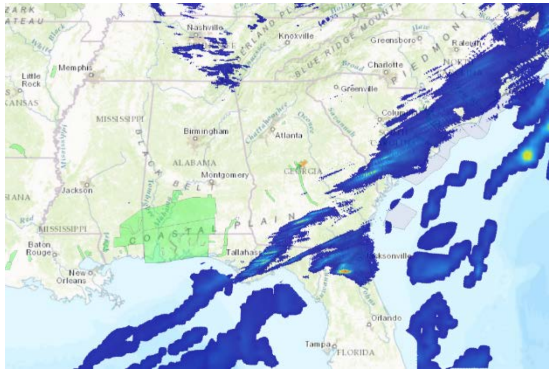
Regridded MPE precipitation during the 2013 Colorado Floods
Unidata IDV display

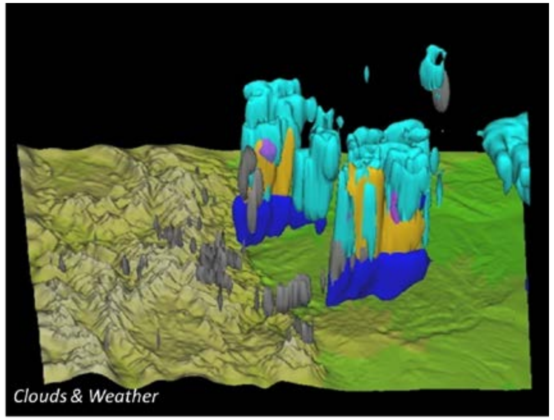
Meteorological Forcing Engine - NWM: Examples

Seasonally-varying MRMS RQI

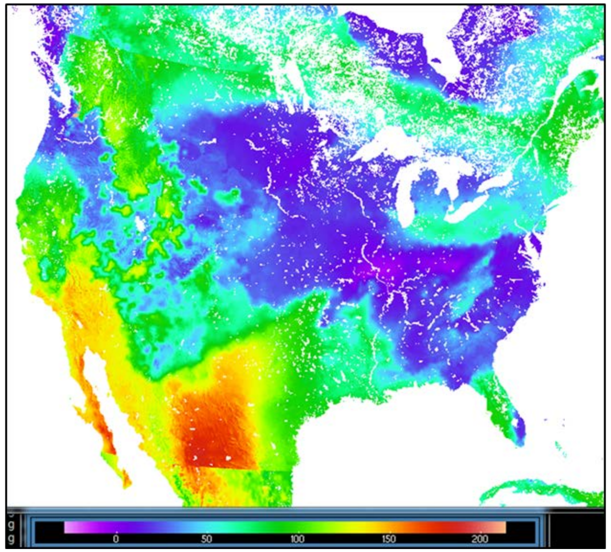


Blended MRMS-HRRR Precipitation

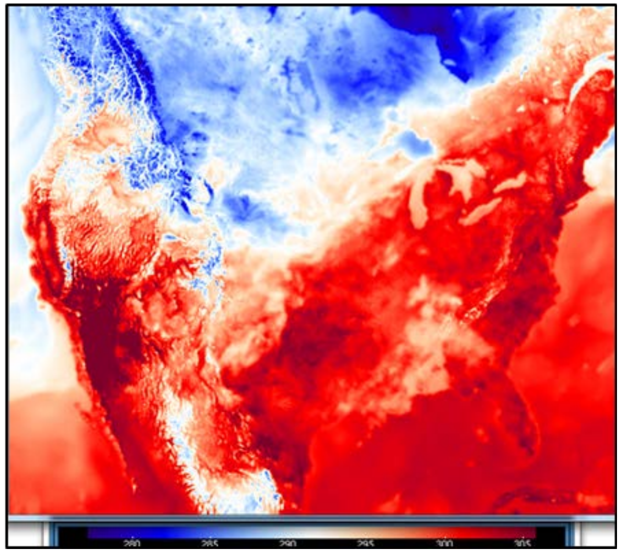




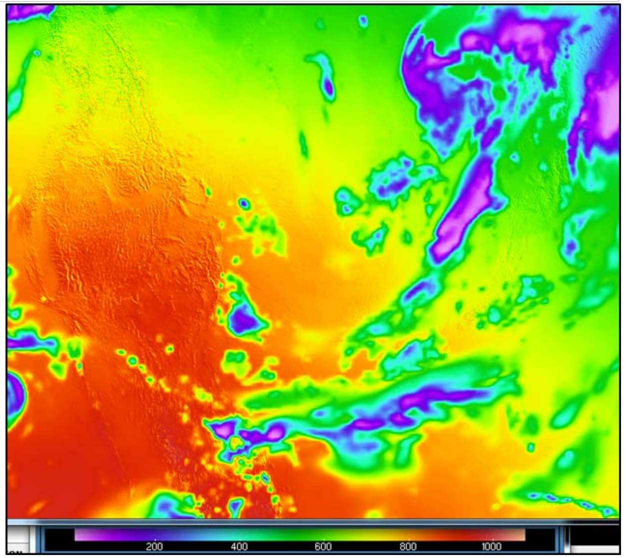
HRRR-RAP incoming longwave radiation



HRRR-RAP 2m Air Temperature



GFS – derived incoming shortwave radiation



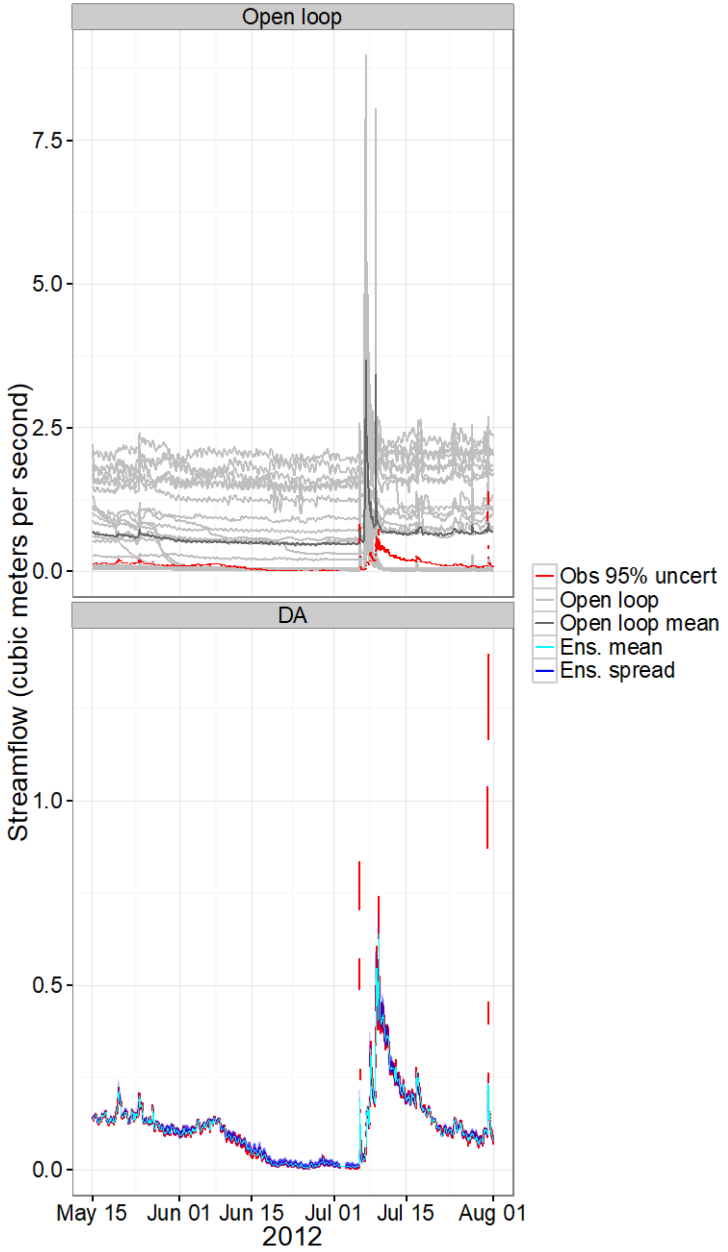
Data Assimilation with WRF-Hydro: HydroDART

Current capabilities

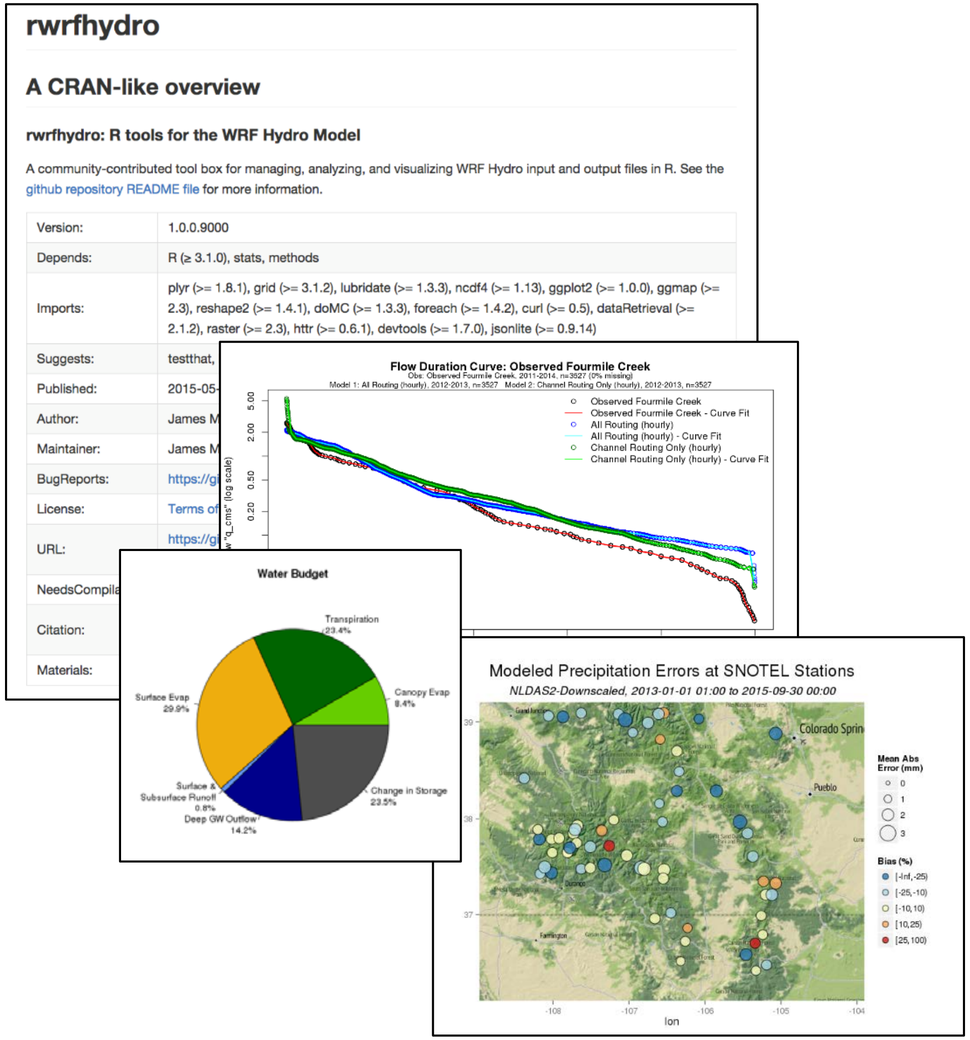
- Ensemble DA:
  - Offline WRF Hydro + DART = "HydroDART"
- Ensemble generation:
  - Initial state & parameter perturbation, ensemble runs

Future capabilities

- Variational DA and/or nudging:
  - Faster & computationally cheaper for large-scale applications.
  - Variational DA not rank-deficient
- Other kinds of DA (hybrid, MLEF, …)
- Bias-aware filtering / Two-stage bias estimation (Friedland, 1969; Dee and de Silva, 1998; De Lannoy et al., 2007)



Rwrfhydro: R package for hydrological model evaluation



Package Features:

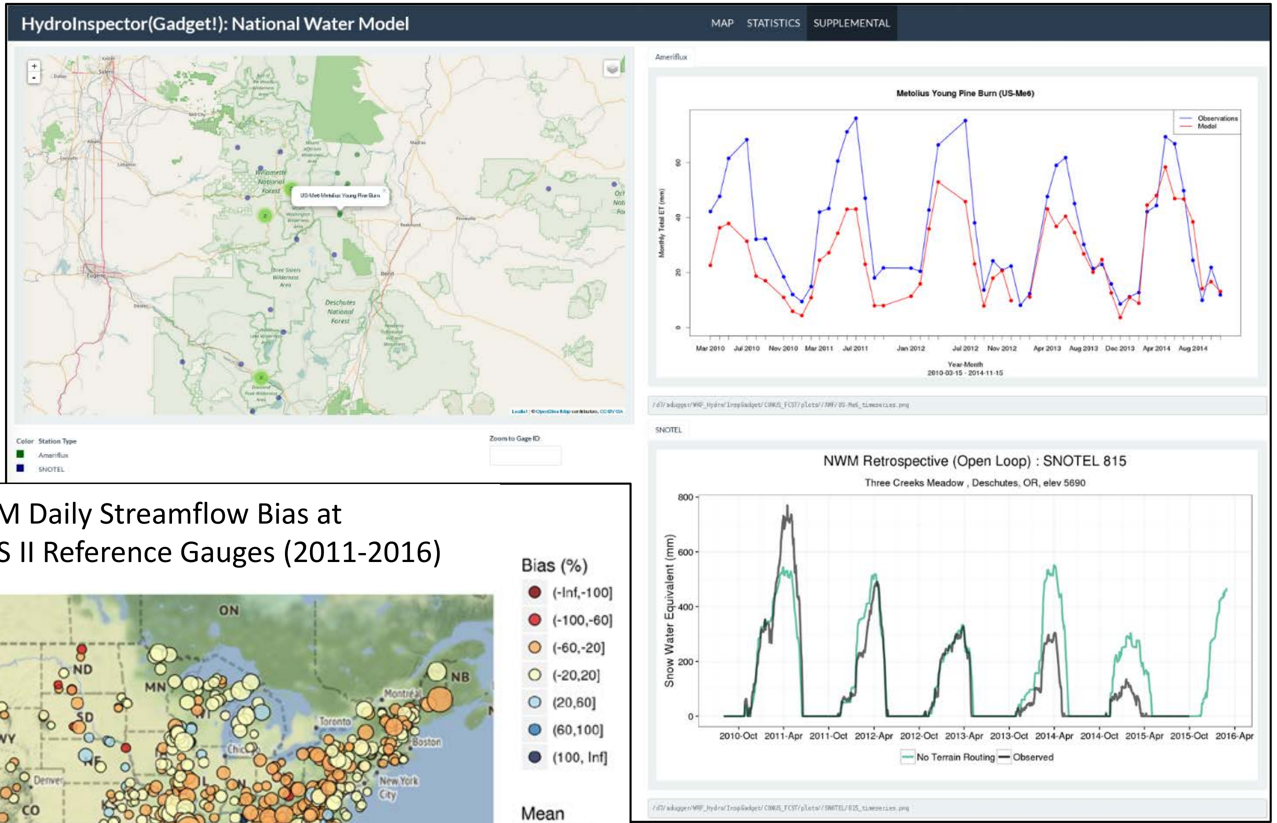
- Set of R tools to support WRF-Hydro pre- and post-processing
- Open source, community tool (and built from other community tools!)
- Full documentation and training vignettes
- Major Features:
  - Domain visualization
  - Remote sensing & geospatial data prep
  - Regridding capabilities (ESMF)
  - Output post-processing
  - Observation data acquisition and processing
  - Model output evaluation and visualization (Shiny integration)
  - Generally model agnostic

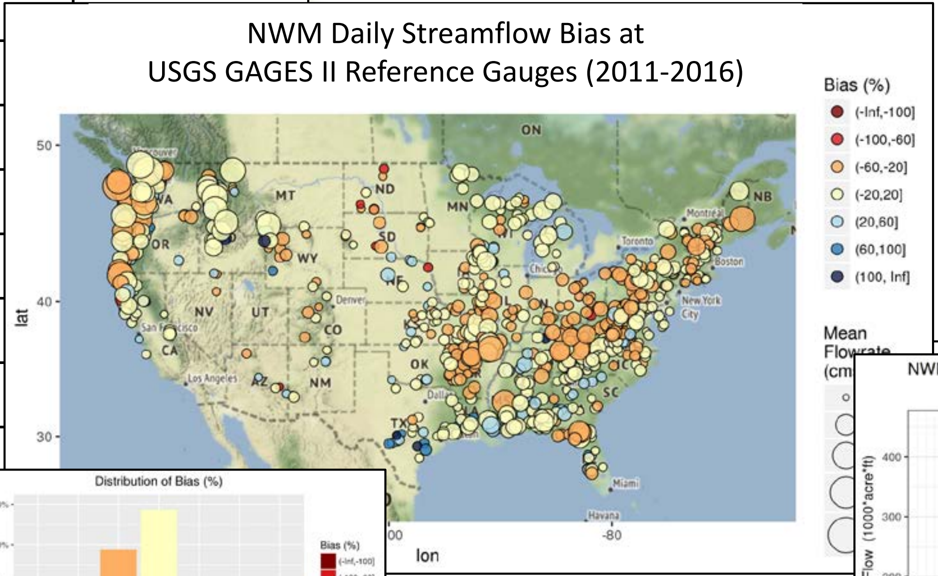
https://github.com/NCAR/rwrfhydro

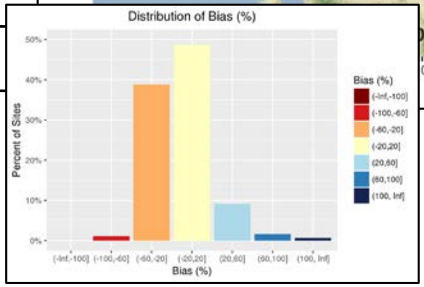
Rwrfhydro: R package for hydrological model evaluation

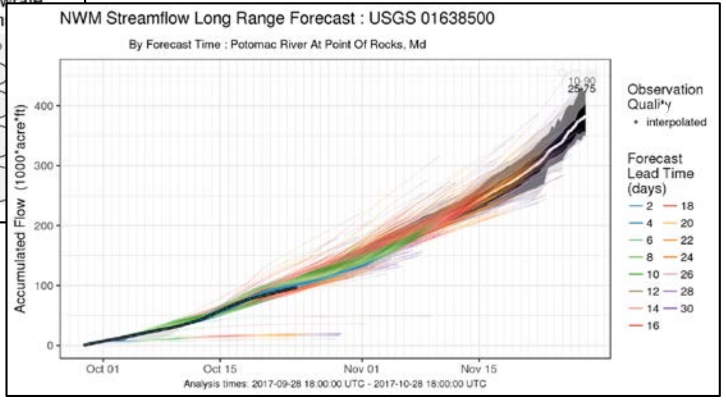
Observations Ingested for Model Evaluation in Rwrfhydro:

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







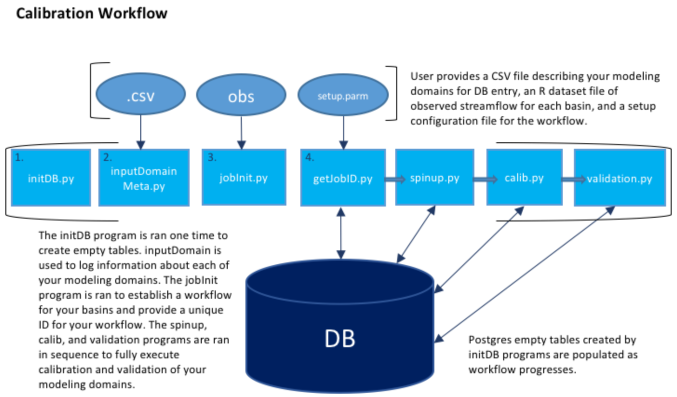


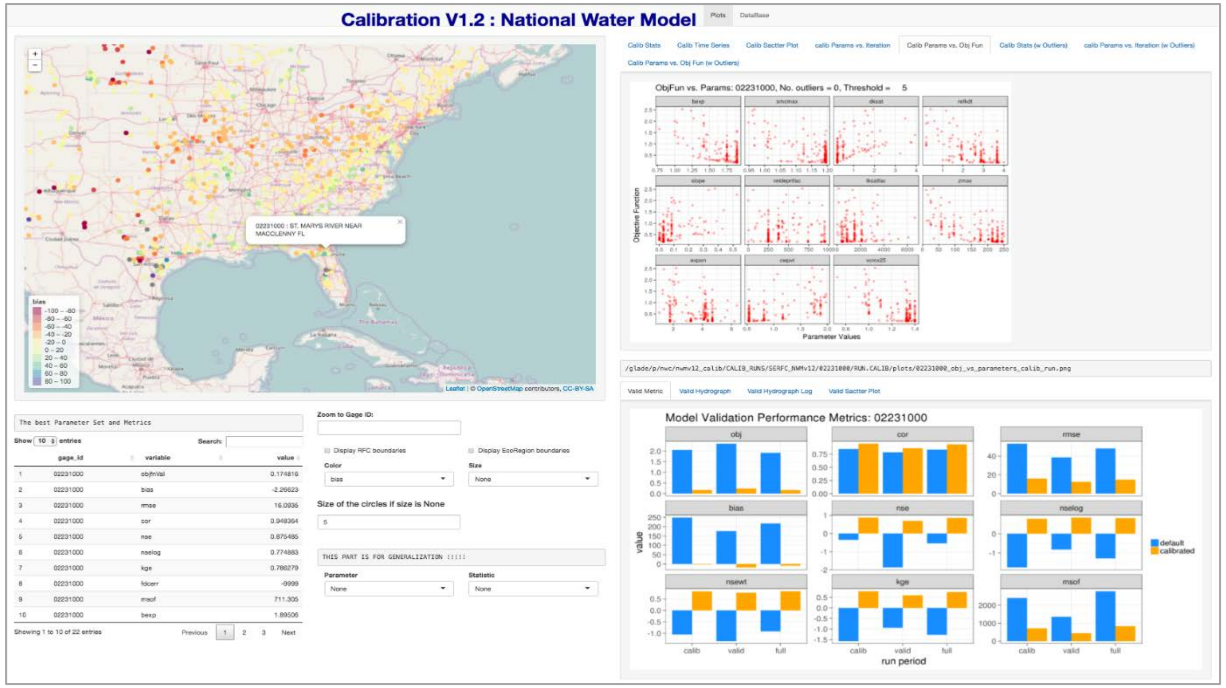
https://github.com/NCAR/rwrfhydro

PyWrfHydroCalib: Python + R package for model calibration

- Domain subsetting tools
- Parameter sensitivity analysis
    - Distributed Evaluation of Local Sensitivity Analysis (DELSA) methodology (Rakovec et al. 2014)
- Calibration:
    - Dynamically Dimension Search (DDS) algorithm (Tolson, B. A., and C. A. Shoemaker: 2007)
    - Split sample calibration/validation
    - Multiple criteria monitoring (NSE, RMSE, % bias, correlation, KGE, MSOF)
    - Automated Rwrfhydro-NWM workflow

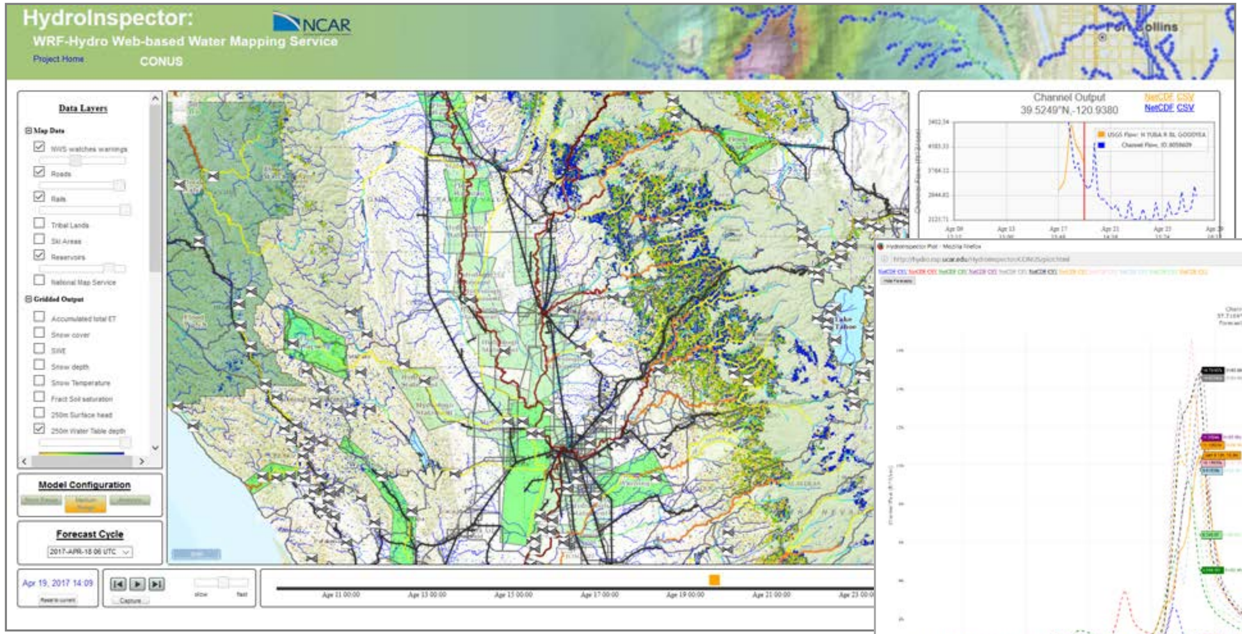
Automated workflow using Python and R interacting with a MySQL database (PyNWMCalib)



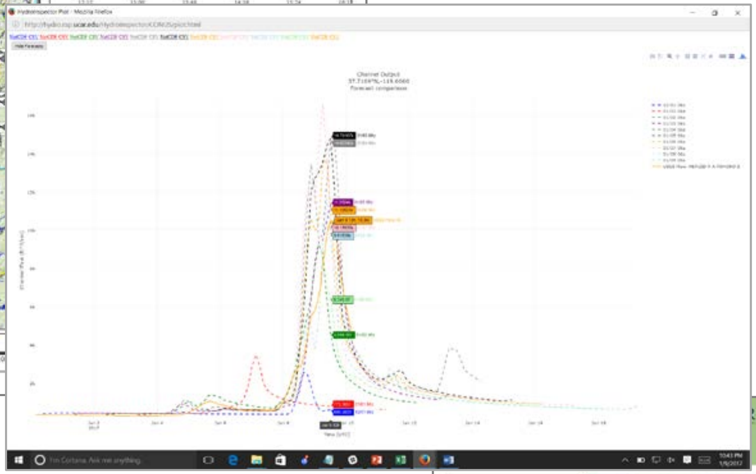


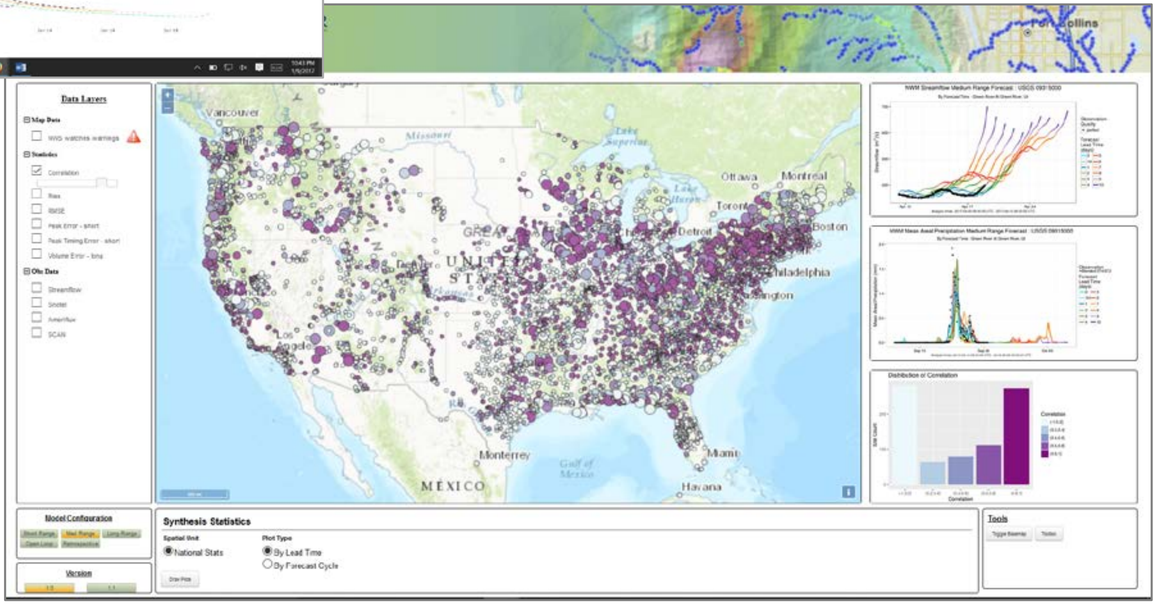
L. Karsten, A. RafieeiNasab, A. Dugger,

HydroInspector: Model Visualization and Communication



Saturated soils from snowmelt leading into an atmospheric river event in California overlaid with road and rail infrastructure, plus an interactive hydrograph of the time-lagged ensembles.





Saturated soils from snowmelt leading into an atmospheric river event in California overlaid with road and rail infrastructure, an interactive hydrograph of the time-lagged ensembles, a snapshot of the NWM verification viewer.

A. Gaydos, A. RafieeiNasab, A. Dugger, K. Sampson

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:

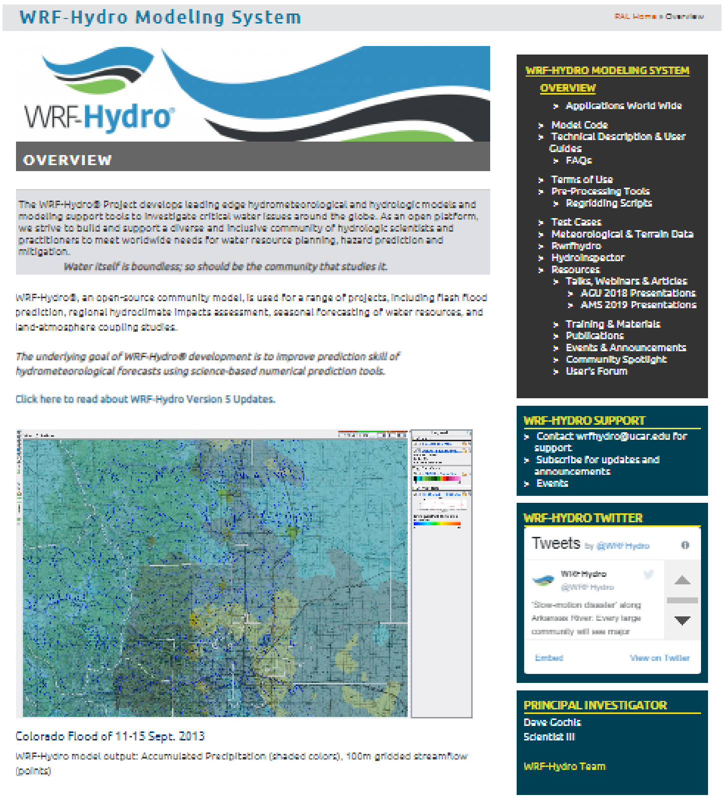
- Improved WRF-Hydro website & internet presence
- Helpdesk support
- New & increased volume of documentation, user guides, FAQs
- New test cases (standalone & coupled)
- Github repository
- Containerization of pre-processing tools & model run environment --> lowers barrier of entry

Online Training Suite:

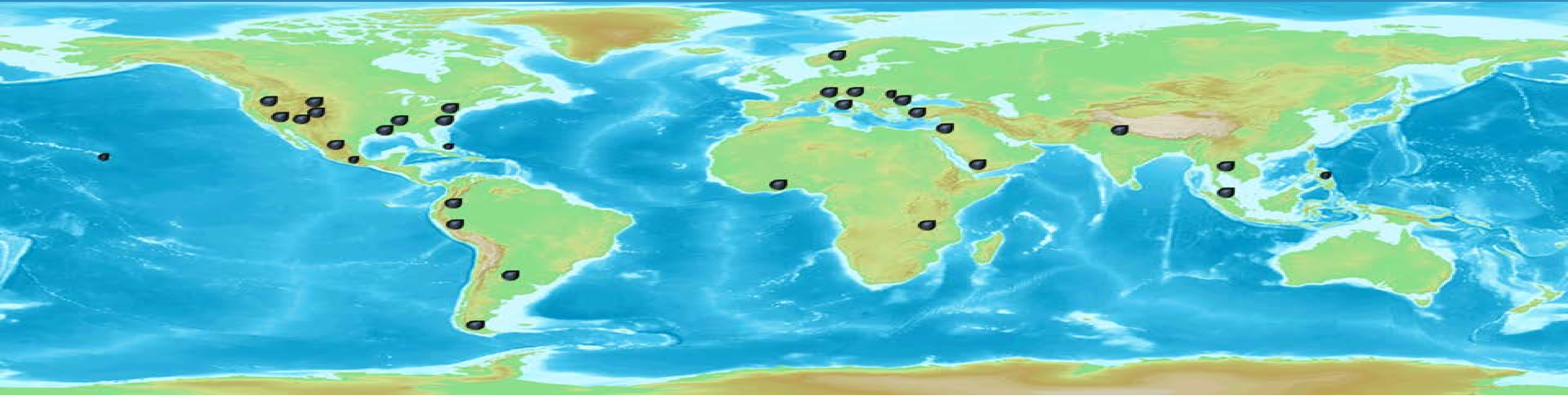
- YouTube video demo (w/ Spanish translation)
- Self-contained training modules using Docker & Jupyter Notebooks

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 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)

WRF-Hydro MODELING SYSTEM

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