Multi-scale water cycle predictions using the community WRF-Hydro modeling system

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Acknowledgements

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- CUAHSI
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- USBR WaterSmart & Dam Safety Programs
- Colorado Water Conservation Board
- Texas Dept. of Environmental Quality & Texas A&M U.

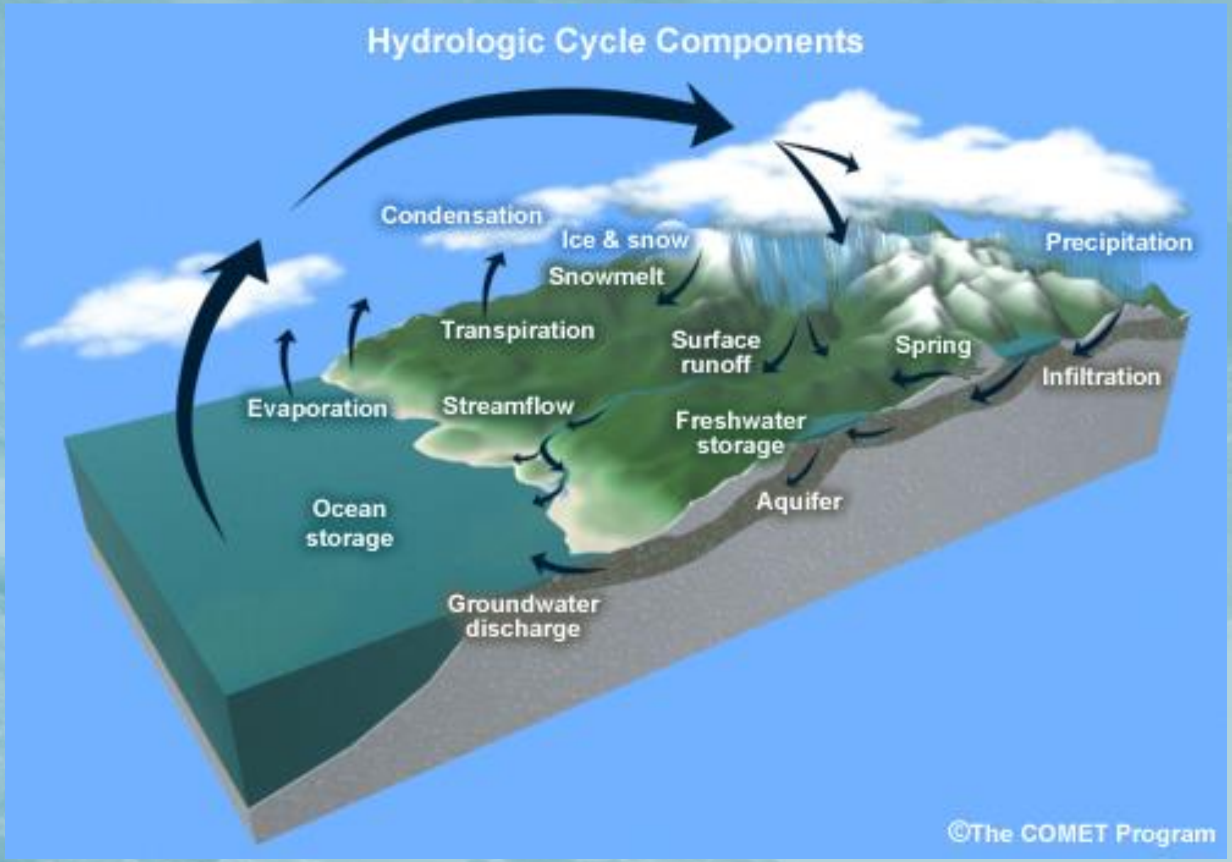
Purpose & Outline

Purpose: Provide a update of multi-scale water cycle modeling capabilities using the community WRF-Hydro system and description of recent prediction applications

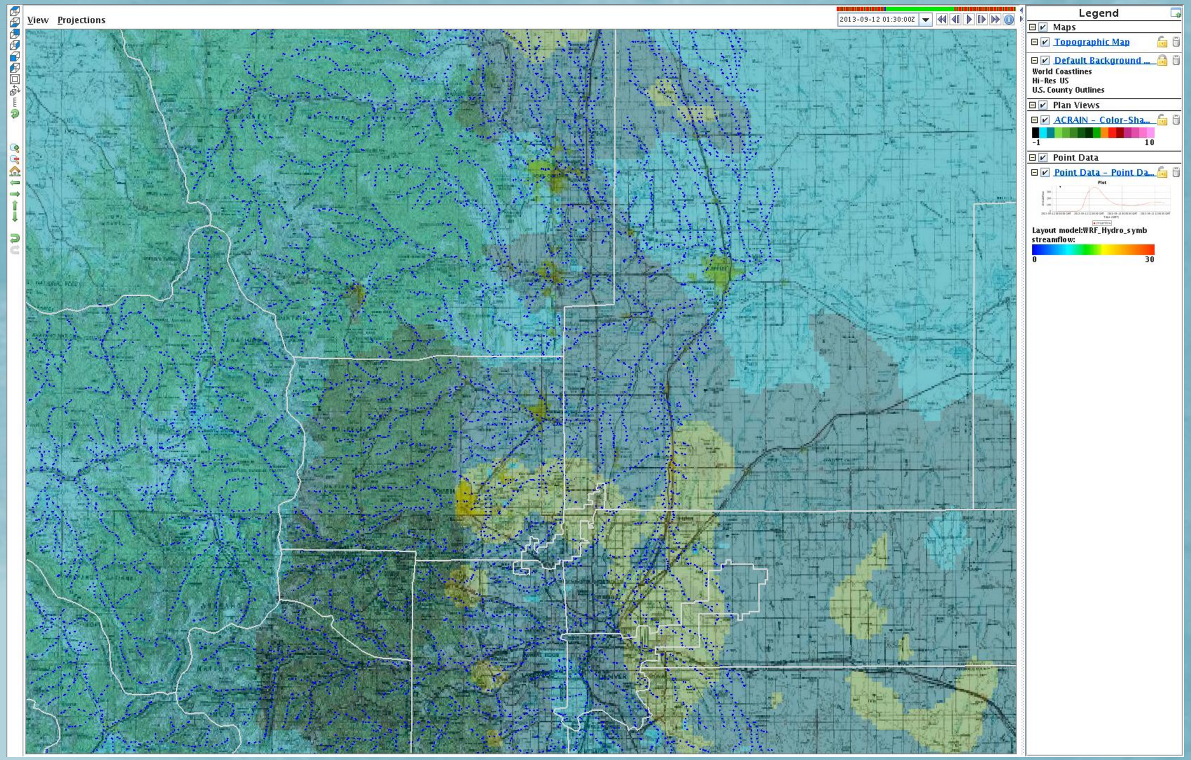
Outline:

1. Background – complete water cycle predictions
2. Brief WRF-Hydro System Update
3. Applications to flood simulation and prediction
4. CONUS-NFIE Implementations for National Streamflow Prediction

Water Cycle Modeling and Prediction within the WRF-Hydro System:



Great Colorado Flood of 11-15 Sept. 2013

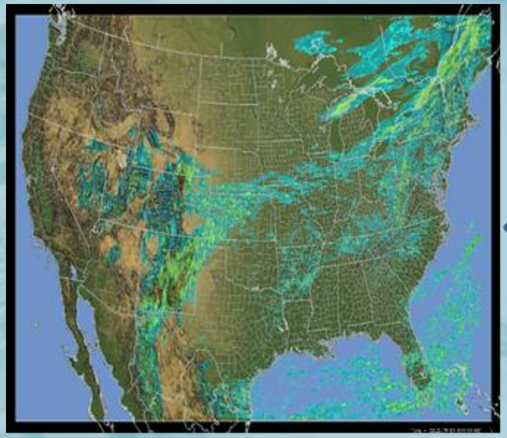


Accumulated Precipitation (shaded colors)
100m gridded streamflow (points)

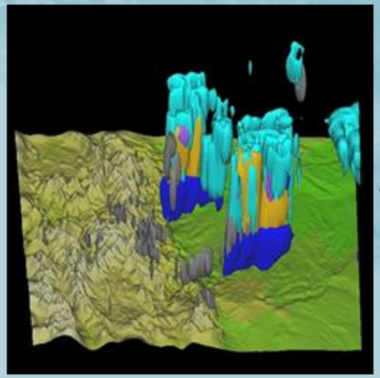
Overarching WRF-Hydro System Objectives

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

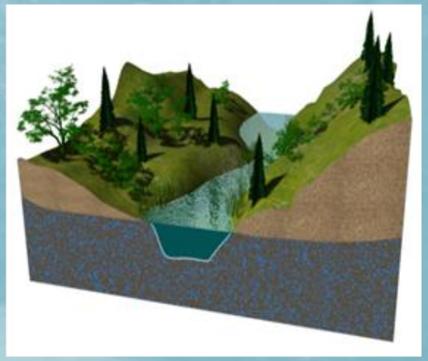
1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as <u>precipitation, soil moisture, snowpack, groundwater, streamflow, inundation</u>
2. 'Accurate' and 'reliable'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

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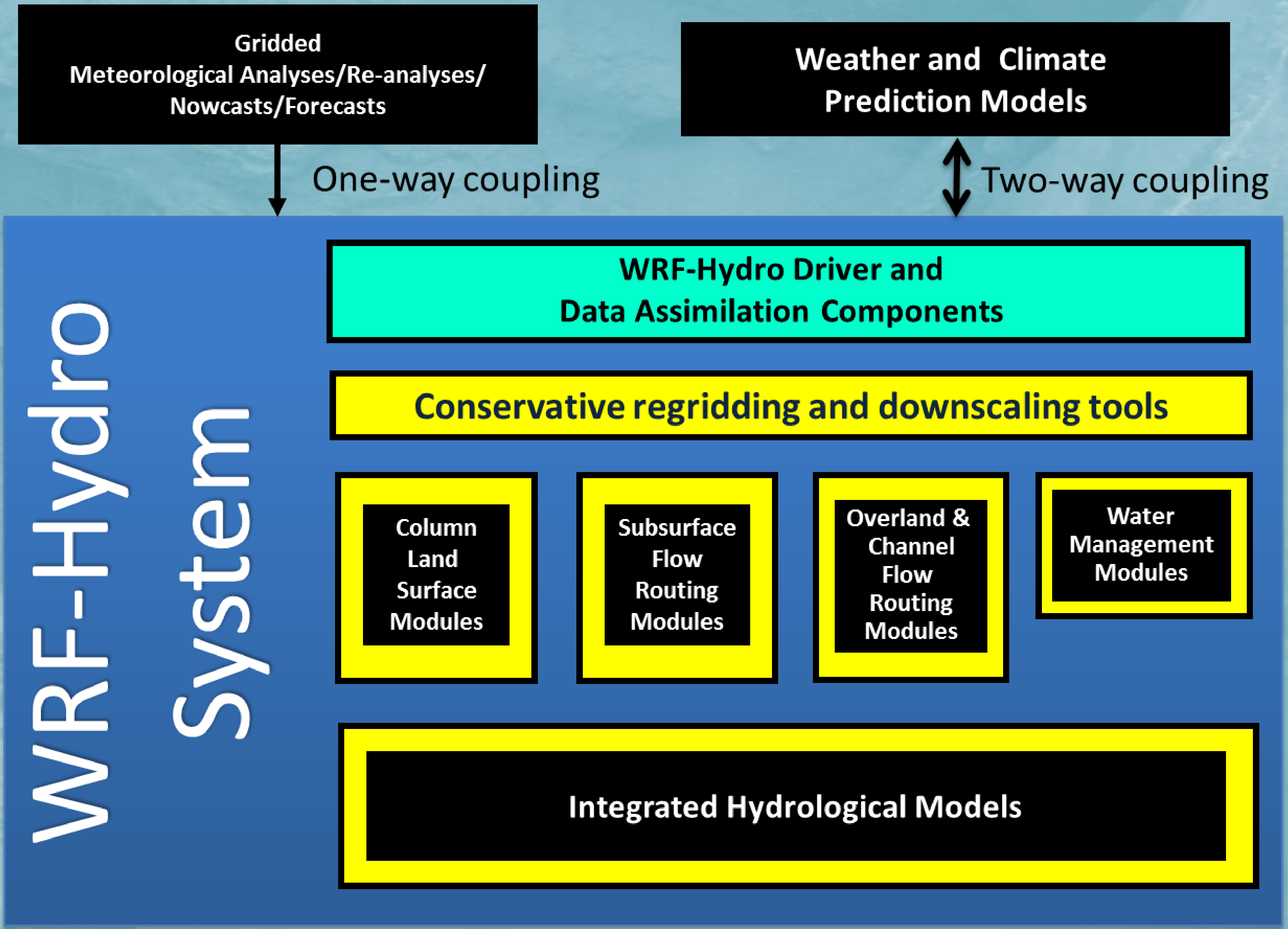

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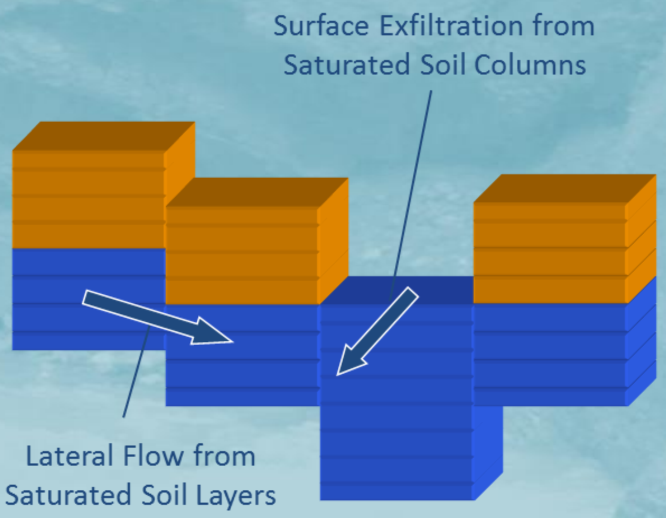
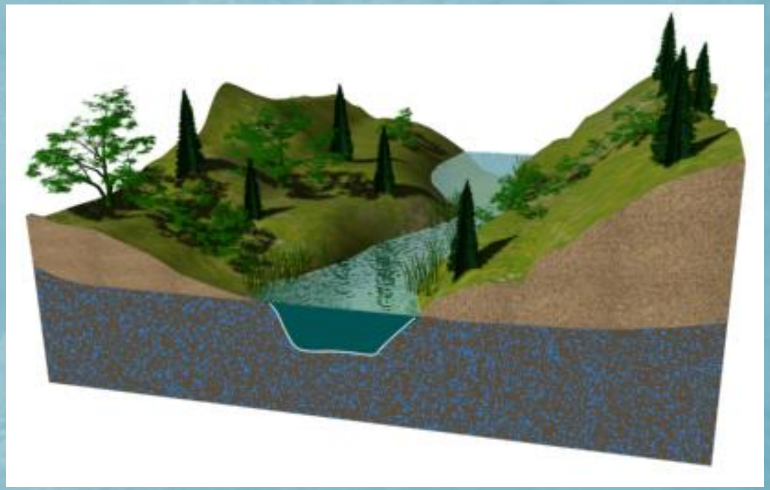
Version 2.2 physics components:

- physics-based runoff processes

Overland Flow -
Diffusive wave
Kinematic*
Catchment aggregation*



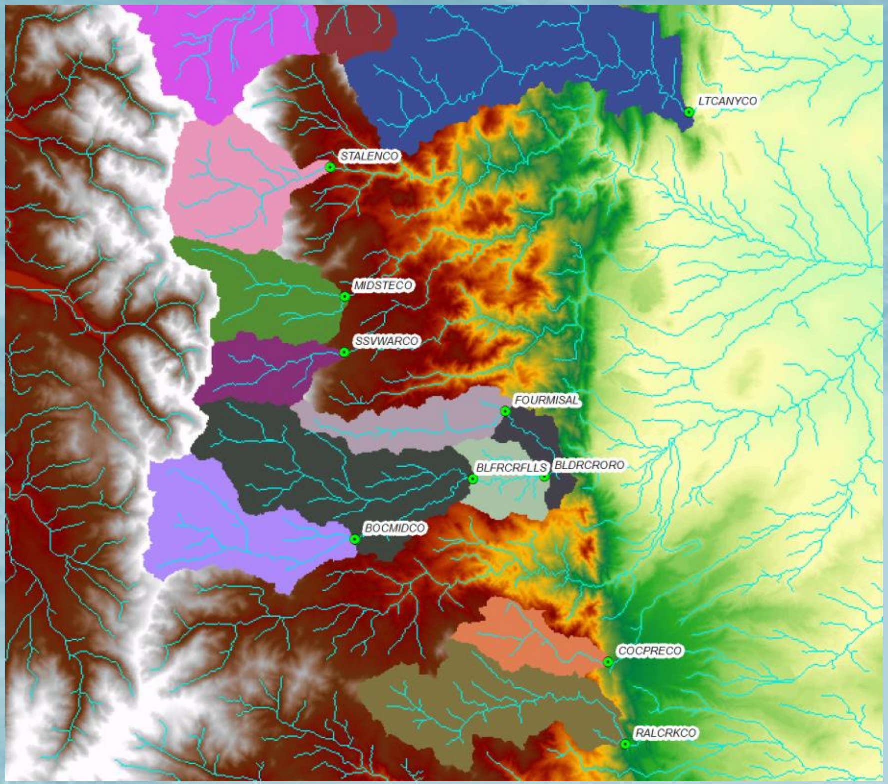
Groundwater Flow –
Boussinesq flow
Catchment aggregation*

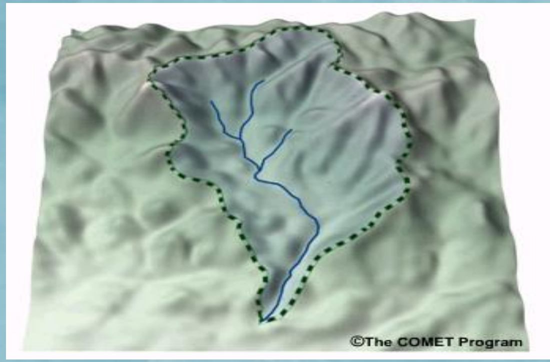


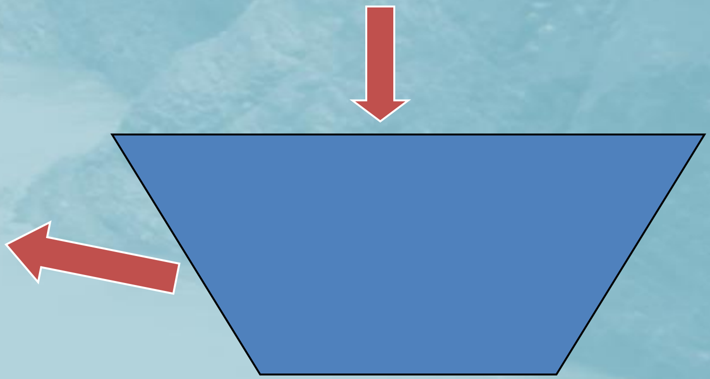
Channel Flow –
Diffusive wave
Kinematic*
Reach-based Muskingam*

WRF-Hydro v2.2 Physics Components:

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

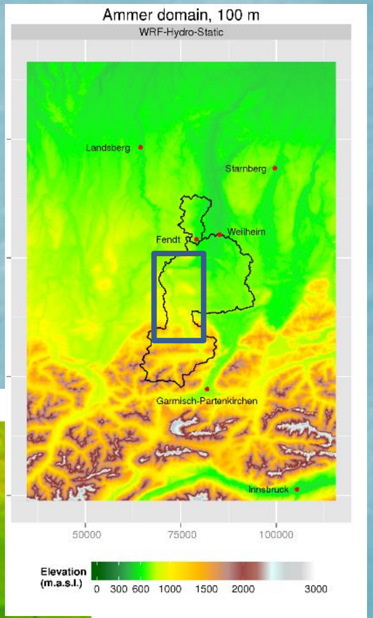


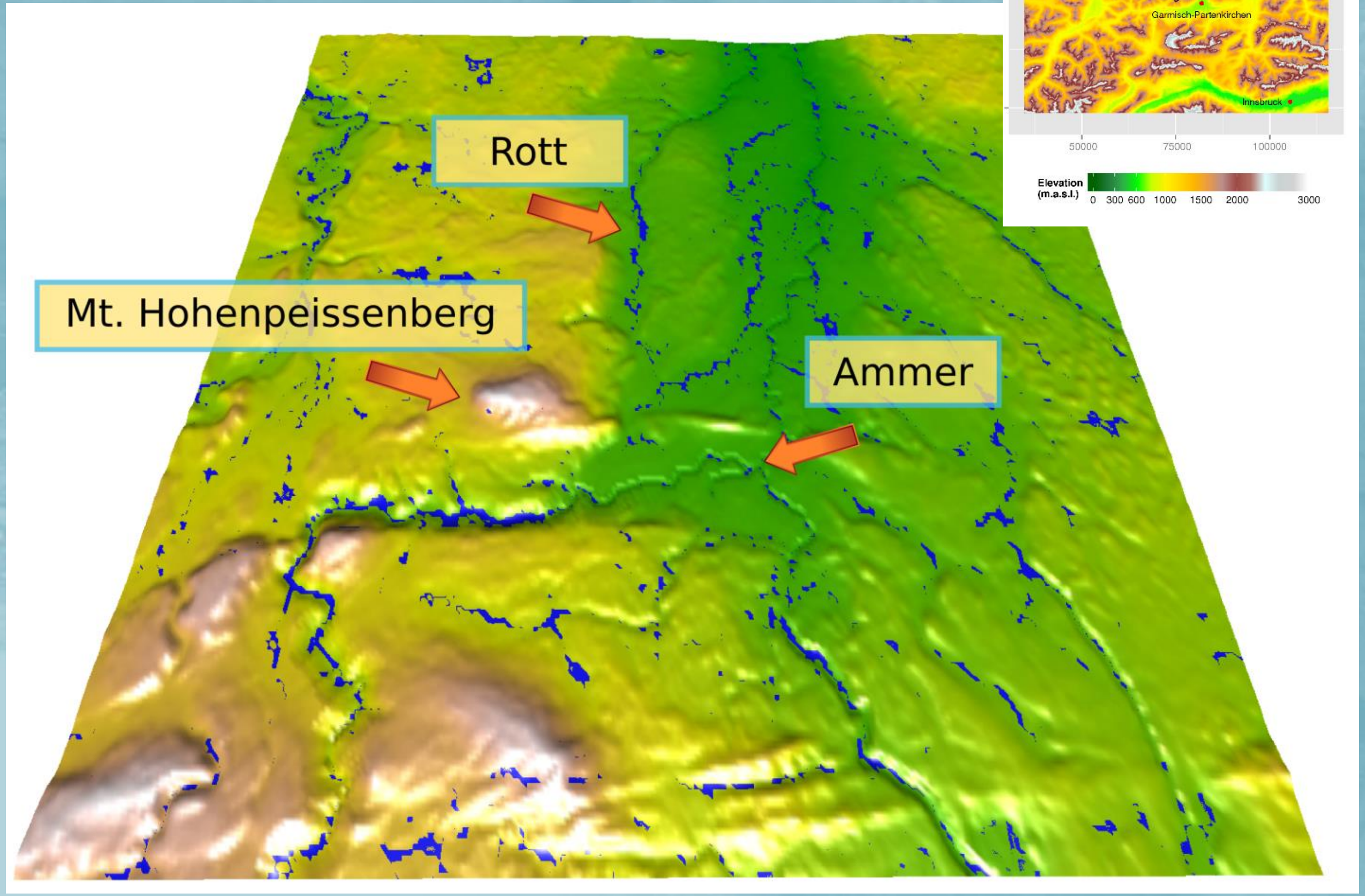




WRF-Hydro v2.2 Physics Components:

- Subsurface routing:
  - 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

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/silvaculture

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

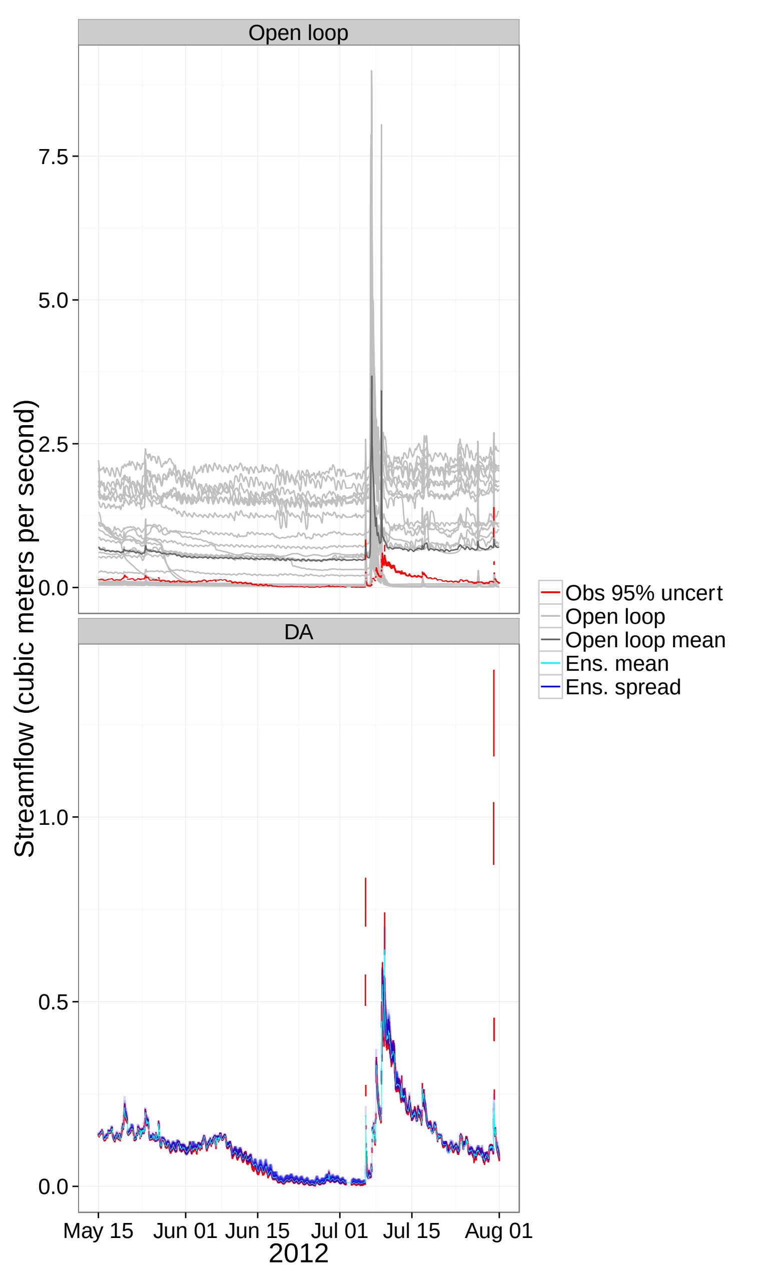
Data Assimilation with WRF Hydro

Current capabilities

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

Future capabilities

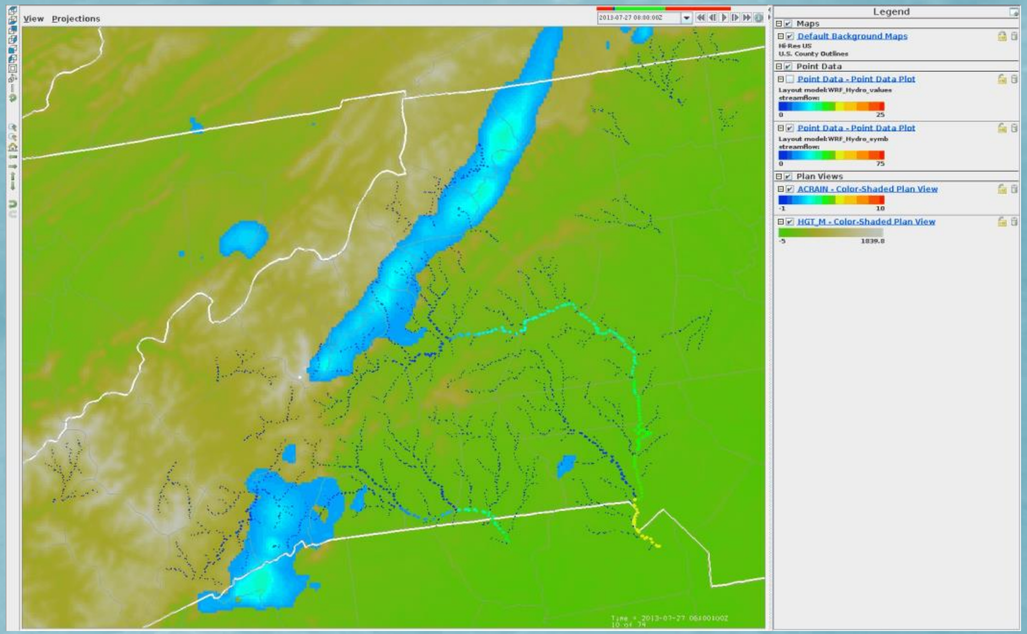
- Variational DA and/or nudging:
  - Faster & computationally cheaper for large-scale applications.
  - Variational DA not rank-deficient
- Other kinds of DA (hybrid, MLEF, …)
- Bias-aware filtering / Two-stage bias estimation (Friedland, 1969; Dee and de Silva, 1998; De Lannoy et al., 2007)



‘WRF-Hydro’ Process Permutations and System Features:

- ~180 possible ‘physics’ component configurations for streamflow prediction:
  - 3 up-to-date column physics land models (Noah, NoahMP, CLM)
  - 3 overland flow schemes (Diffusive Wave, Kinematic Wave, Direct basin aggregation)
  - 4 lateral/baseflow groundwater schemes (Boussinesq shallow-saturated flow, 2d aquifer model, Direct Aggregation Storage-Release: pass-through or exponential model
  - 5 channel flow schemes: Diffusive wave, Kinematic Wave, RAPID-Muskingam for NHDPlus, Custom Network Muskingam/Muskingam Cunge

- Simple level-pool reservoir with management
- DART, filter-based hydrologic data assimilation



Ensemble Flood Forecasting in the Southeast U.S. with WRF-Hydro
***2014 WRF User’s Workshop*, K. Mahoney (NOAA-ESRL)**

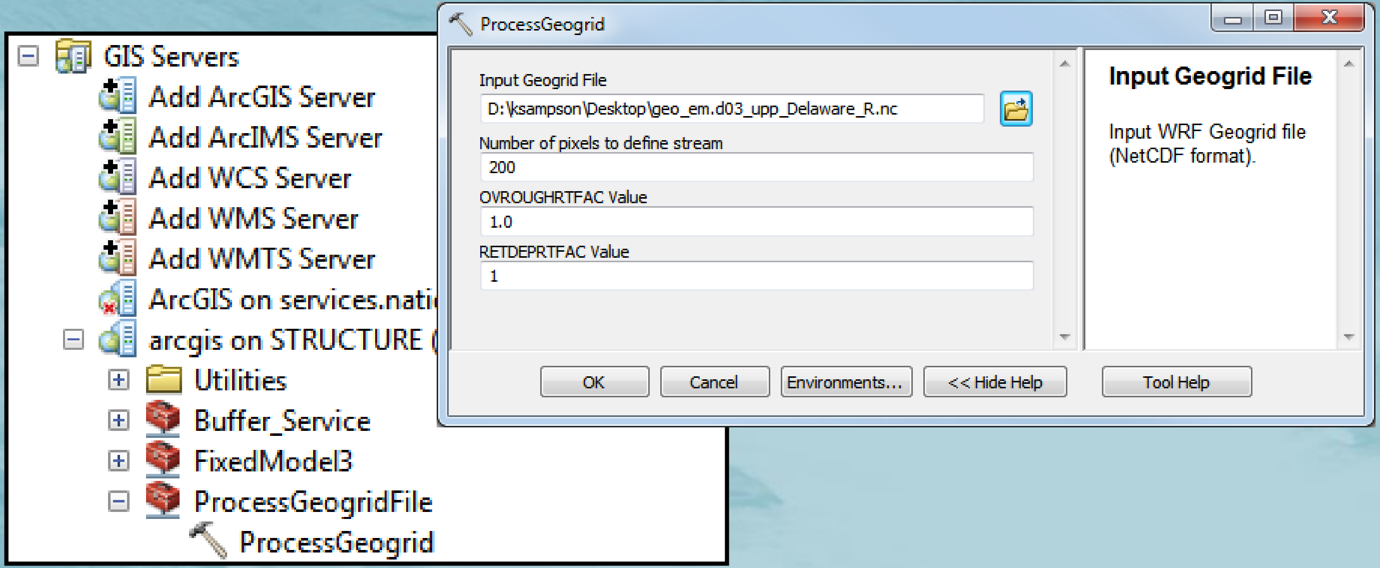
‘WRF-Hydro’ Software Features:

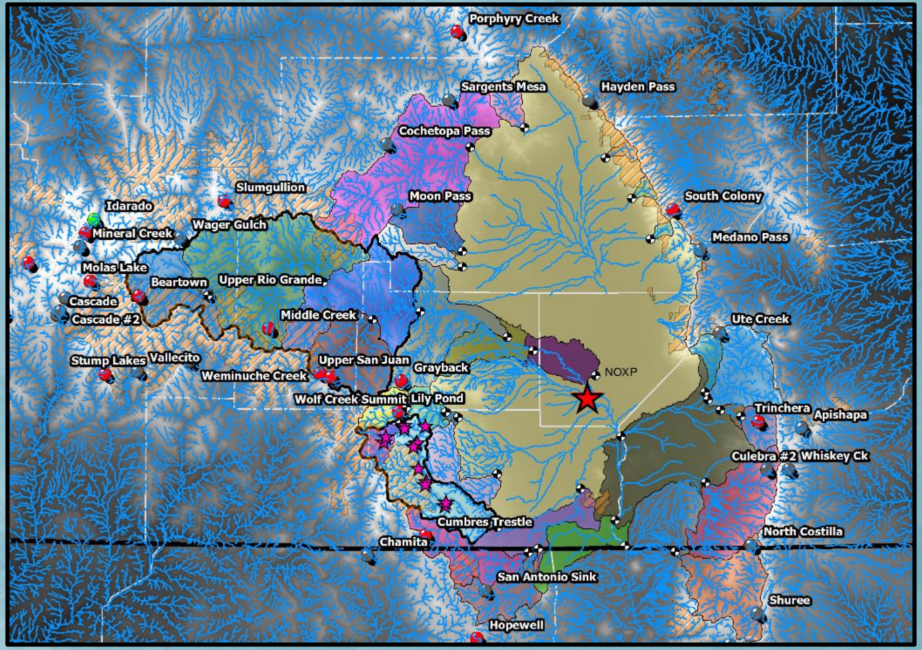
- Modularized F90/95 (and later)
- Coupling options are specified at compilation and WRF-Hydro is compiled as a new library in WRF when run in coupled mode
- Physics options are switch-activated though a namelist/configuration file
- Options to output sub-grid state and flux fields to standards-based 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)

Wei Yu (RAL) – lead engineer

WRF-Hydro Setup and Parameterization: Python Pre-Processing Toolkit: K. Sampson - developer

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

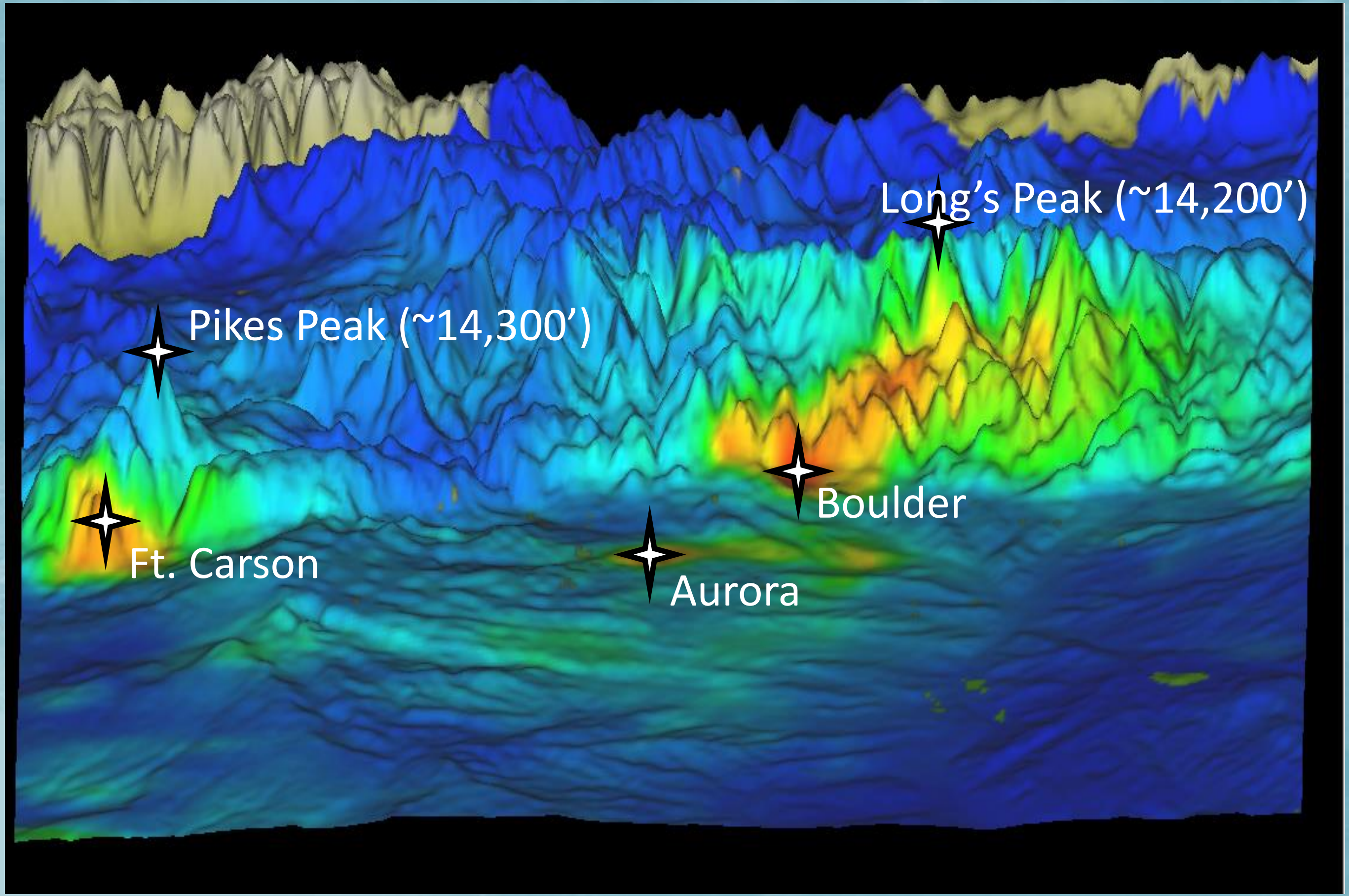




Outputs: topography, flowdirection, watersheds, gridded channels, river reaches, lakes, various parameters

Forcing data supported:

- NLDAS, NARR analyses
- QPE products: MPE, StgIV, NCDC-served, dual-pol, Q3/MRMS, gauge analyses
- NOAA QPF products: GFS, NAM, RAP, HRRR, ExREF
- Nowcast (NCAR Trident/TITAN)
- NOHRSC SNODAS

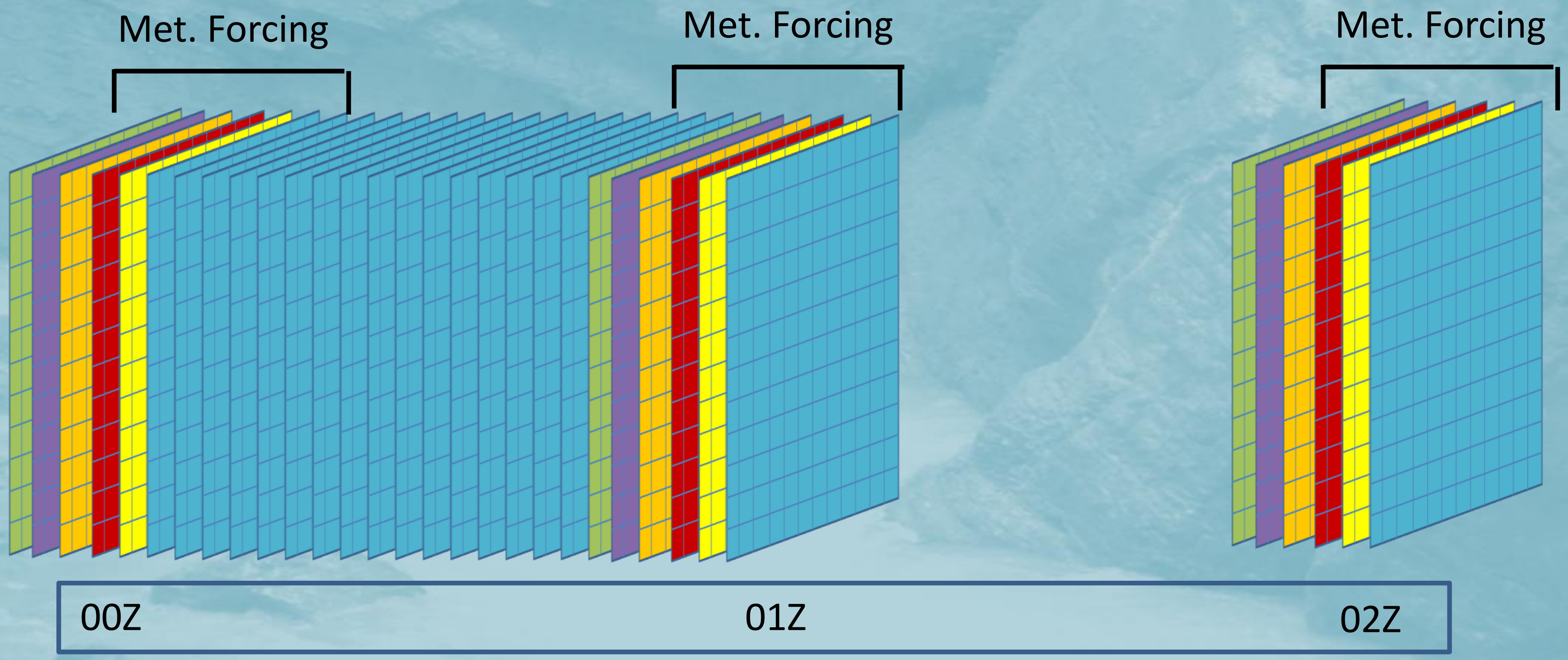


Regridded MPE precipitation during the 2013 Colorado Floods
Unidata IDV display

- ESMF/ncl regridding tools

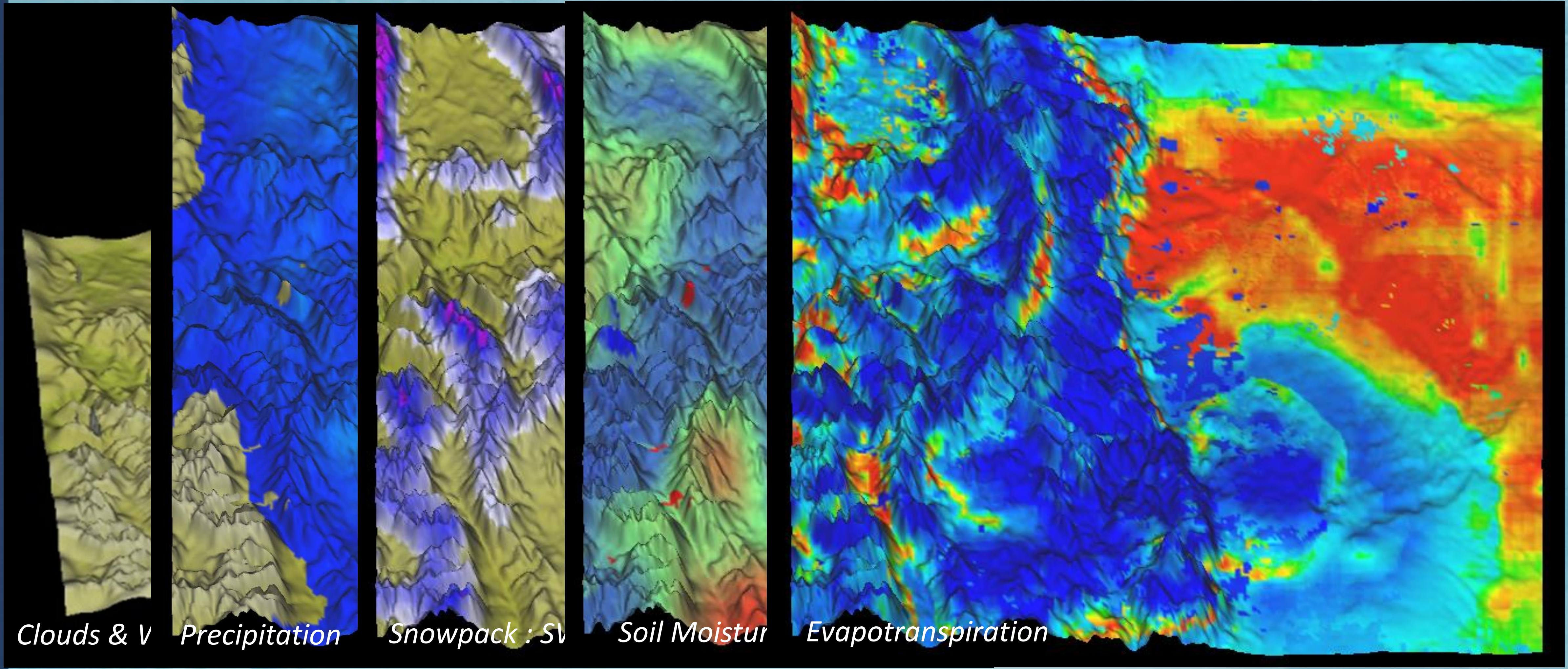
Input Forcing Data Requirements:

- Data Requirements:
  - Forcing Input: Forecast Example…



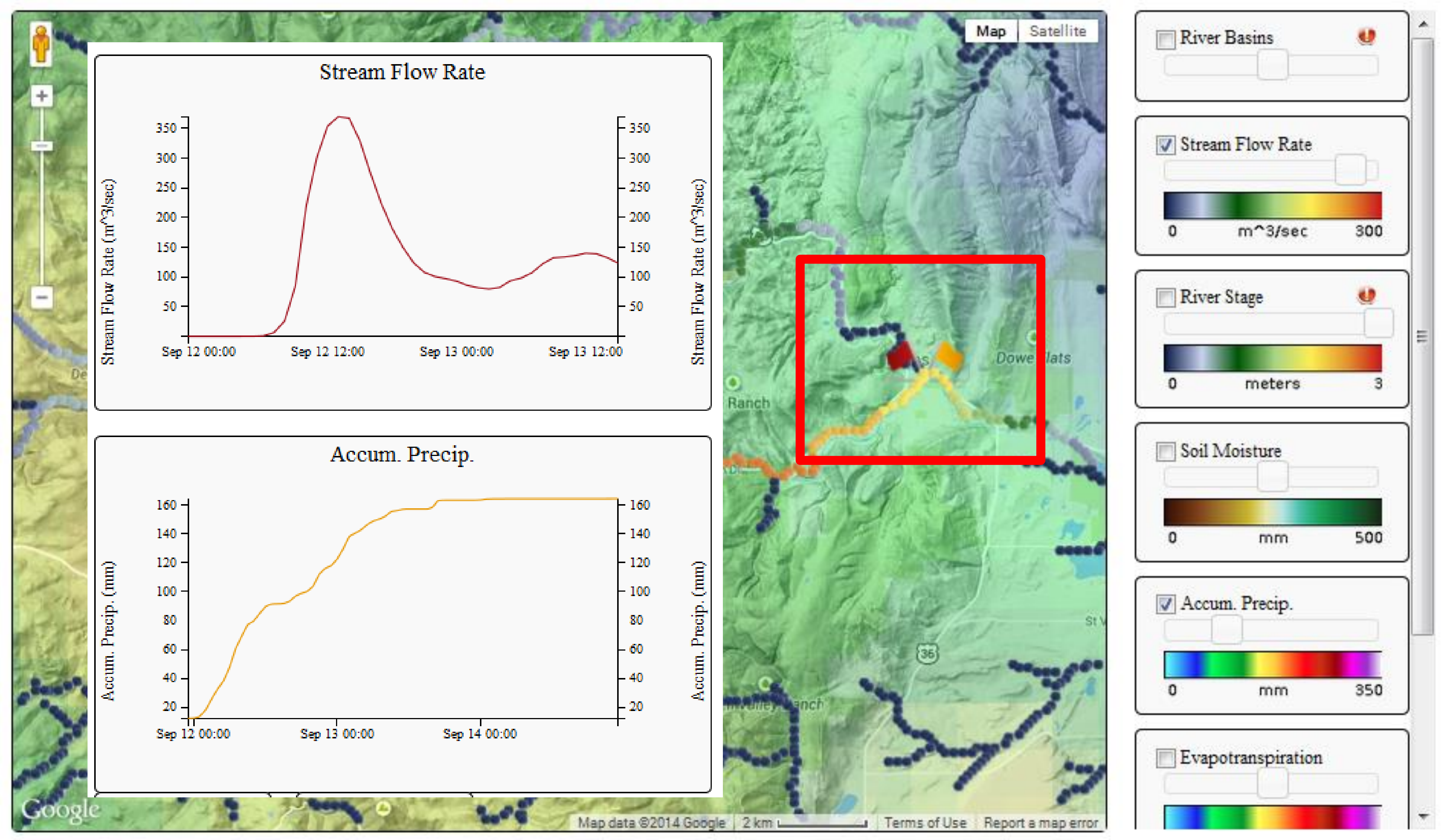
WRF-Hydro output products: Forecasts of water cycle components

Maps of precipitation, soil moisture, ET, snowpack, inundation depth, groundwater depth, streamflow



Unidata IDV display

Visual forecast products…Web map service interfaces: GoogleMaps/Earth , ESRI ArcGIS, OpenLayers



GoogleEarth, GoogleMaps. ArcGIS WMS display

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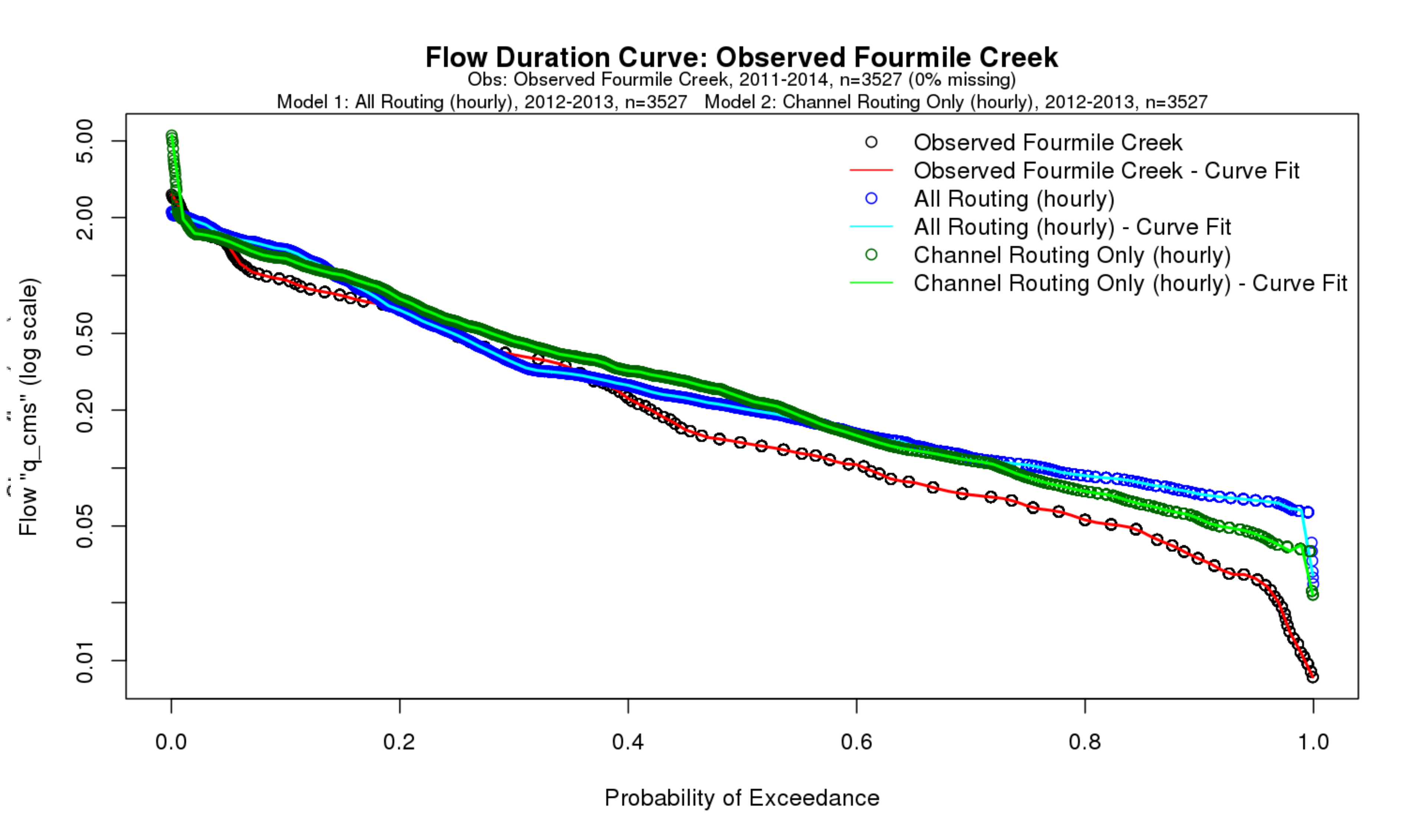
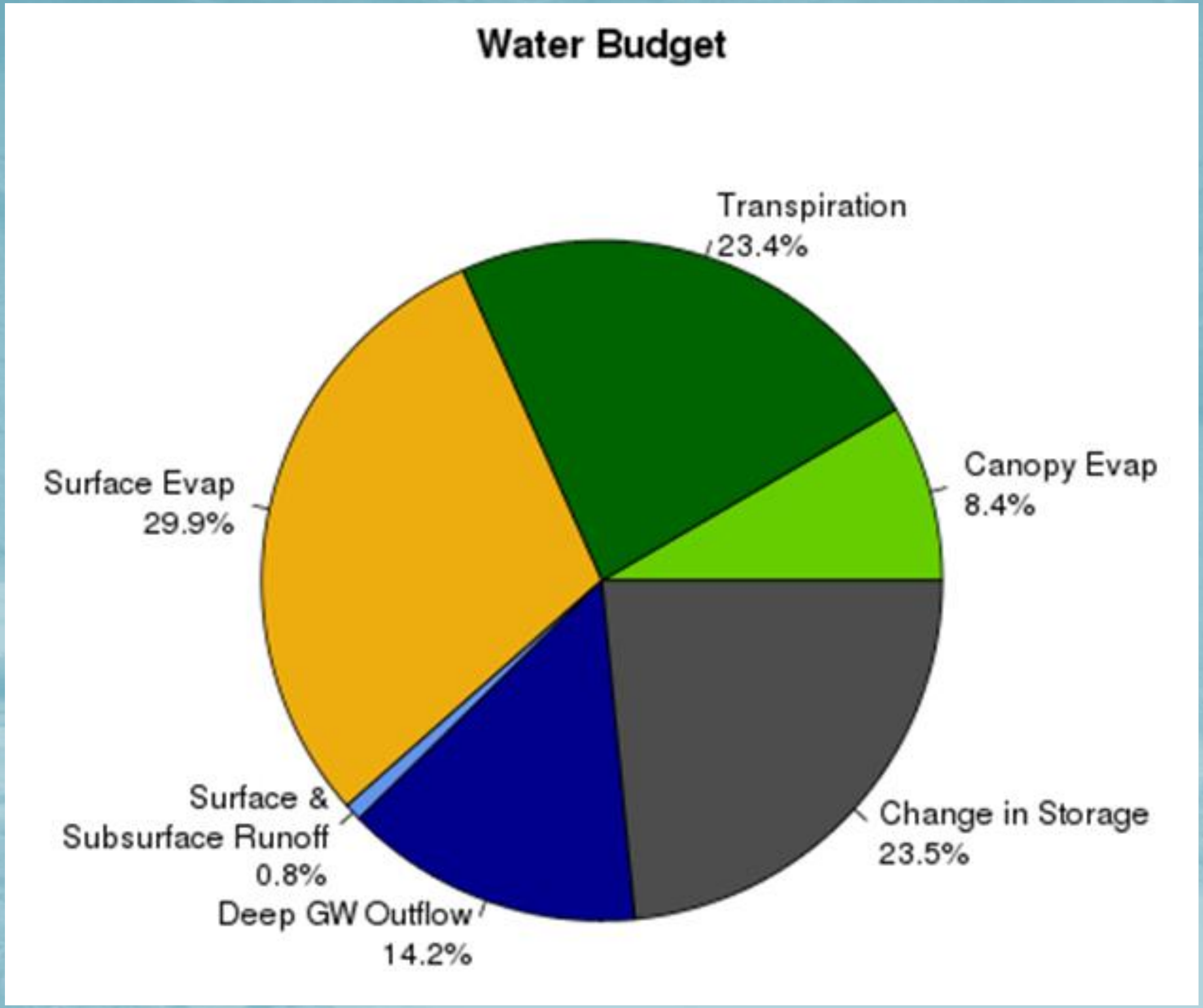
Plotting and Analyzing Data in R: The 'Rwrfhydro' package



Streamflow Hydrographs

Flow Duration Curves

Plotting and Analyzing Data in R: The 'Rwrfhydro' package



Water Budget Analyses

Statistical Evaluation Metrics

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Plotting and Analyzing Data in R: The 'Rwrfhydro' package

MODEL 1:

	nse	nselog	cor	rmse	rmsenorm	bias	mae	errcom	errmaxt	errfdc
ts	0.86	0.81	0.95	0.17	6.52	18.7	0.1	NA	NA	0.06
daily	0.87	0.81	0.96	0.16	7.08	19	0.1	-0.07	-0.64	0.06
monthly	0.95	0.87	1	0.08	8.01	18.8	0.06	0	0	NA
yearly	NA	NA	NA	0.07	NA	18.7	0.07	1	2	NA
max10	0.09	0.07	0.57	0.43	25.56	15.3	0.05	NA	NA	NA
min10	-34.59	-7.31	0.51	0.05	181.74	186.9	NA	NA	NA	NA

MODEL 2:

	nse	nselog	cor	rmse	rmsenorm	bias	mae	errcom	errmaxt	errfdc
ts	0.68	0.72	0.88	0.26	9.77	22.2	0.13	NA	NA	0.07
daily	0.79	0.71	0.92	0.21	9.03	23.5	0.12	0.2	-0.41	0.08
monthly	0.92	0.85	0.98	0.1	9.7	24	0.08	-0.5	-0.4	NA
yearly	NA	NA	NA	0.08	NA	22.2	0.08	-2	-2	NA
max10	-0.82	0.05	0.39	0.6	36.19	10.1	0.05	NA	NA	NA
min10	-108.28	-8.11	0.24	0.08	318.47	224.9	NA	NA	NA	NA

Water Budget Analyses

Statistical Evaluation Metrics

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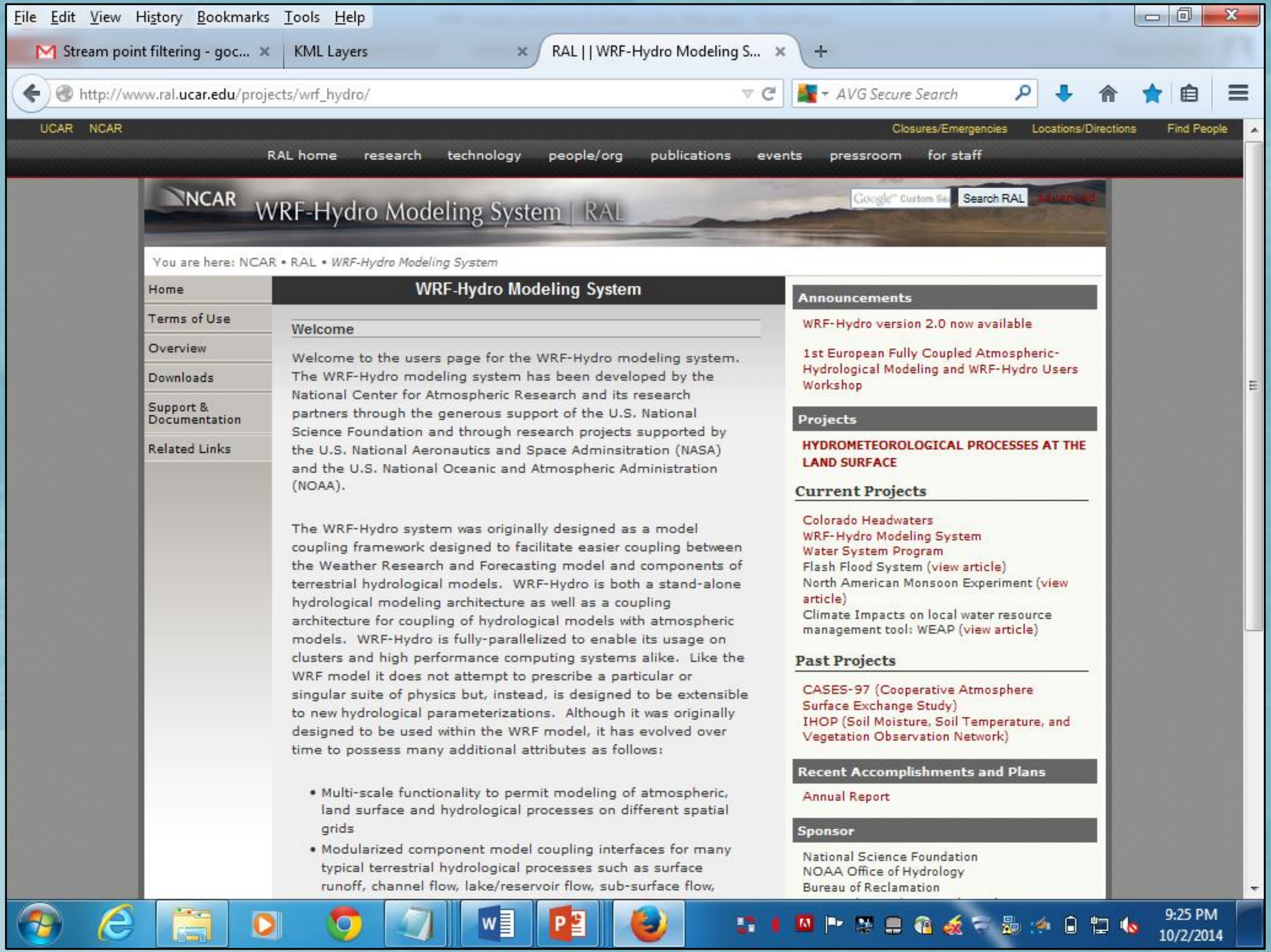
WRF-Hydro Support Services

- Web Page:
  - Code distribution (GIT repository)
  - Documentation (v2, 120 pages)
  - Test cases (coupled and uncoupled)
  - Script Library (file prep, reformatting, viz)
  - ArcGIS preparation tools
  - Email help support (staff limited)
  - Next Training is May 4-7, 2015 in Boulder (sponsored by CUAHSI)



http://www.ral.ucar.edu/projects/wrf_hydro/

Current WRF-Hydro Applications around the world:

1. Operational Streamflow Forecasting:
   - U.S. National Weather Service, National Water Center
   - Israeli Hydrological Service
   - State of Colorado-Upper Rio Grande River Basin (CWCB, NSSL)
   - NCAR-STEP Hydrometeorological Prediction Group
   - U. of Calabria reservoir inflow forecasting
2. Streamflow prediction research (U. Ankara, Arizona State U., Karlsruhe Inst. Tech.)
3. Diagnosing climate change impacts on water resources
   - Himalayan Mountain Front (Bierknes Inst.)
   - Colorado Headwaters (U. Colorado)
   - Bureau of Reclamation Dam Safety Group (USBR,NOAA/CIRES)
4. Diagnosing land-atmosphere coupling behavior in mountain-front regions of the U.S. and Mexico (Arizona State U., U. Arizona)
5. Diagnosing the impacts of disturbed landscapes on coupled hydrometeorlogical predictions
   - Western U.S. Fires (USGS)
   - West African Monsoon (Karlsruhe Inst. Tech)
   - S. America Paraná river (U. Arizona)
   - Texas Dust Emissions (Texas A&M U.)
   - Landslide Hazard Modeling (USGS)
6. Hydrologic Data Assimilation, WRF-Hydro/DART coupling

Recent Water Prediction Activities

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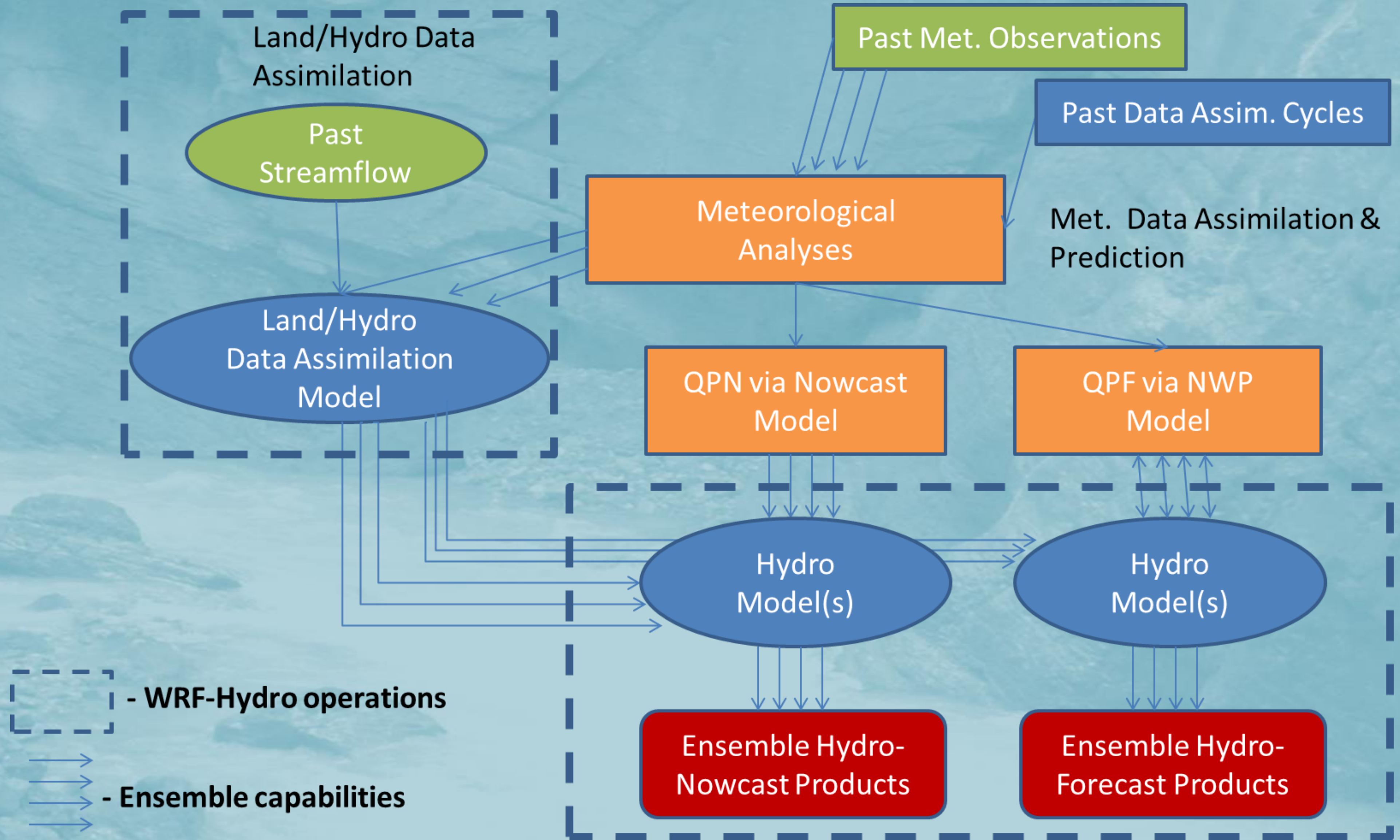
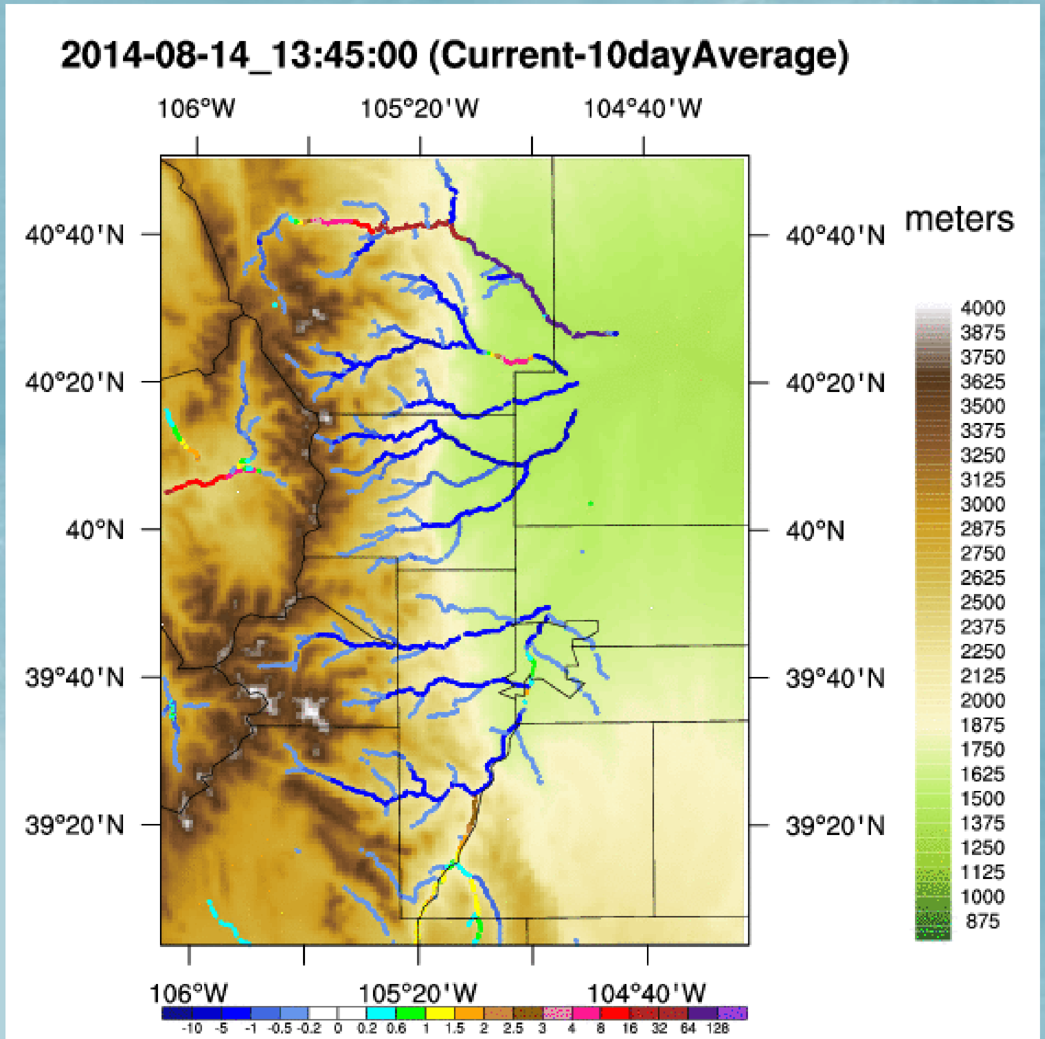
WRF-Hydro Within an Operational Forecasting Workflow:



1. Real-time High-Resolution, Spatially-Distributed Streamflow Prediction: NCAR STEP Program

Project Goals:

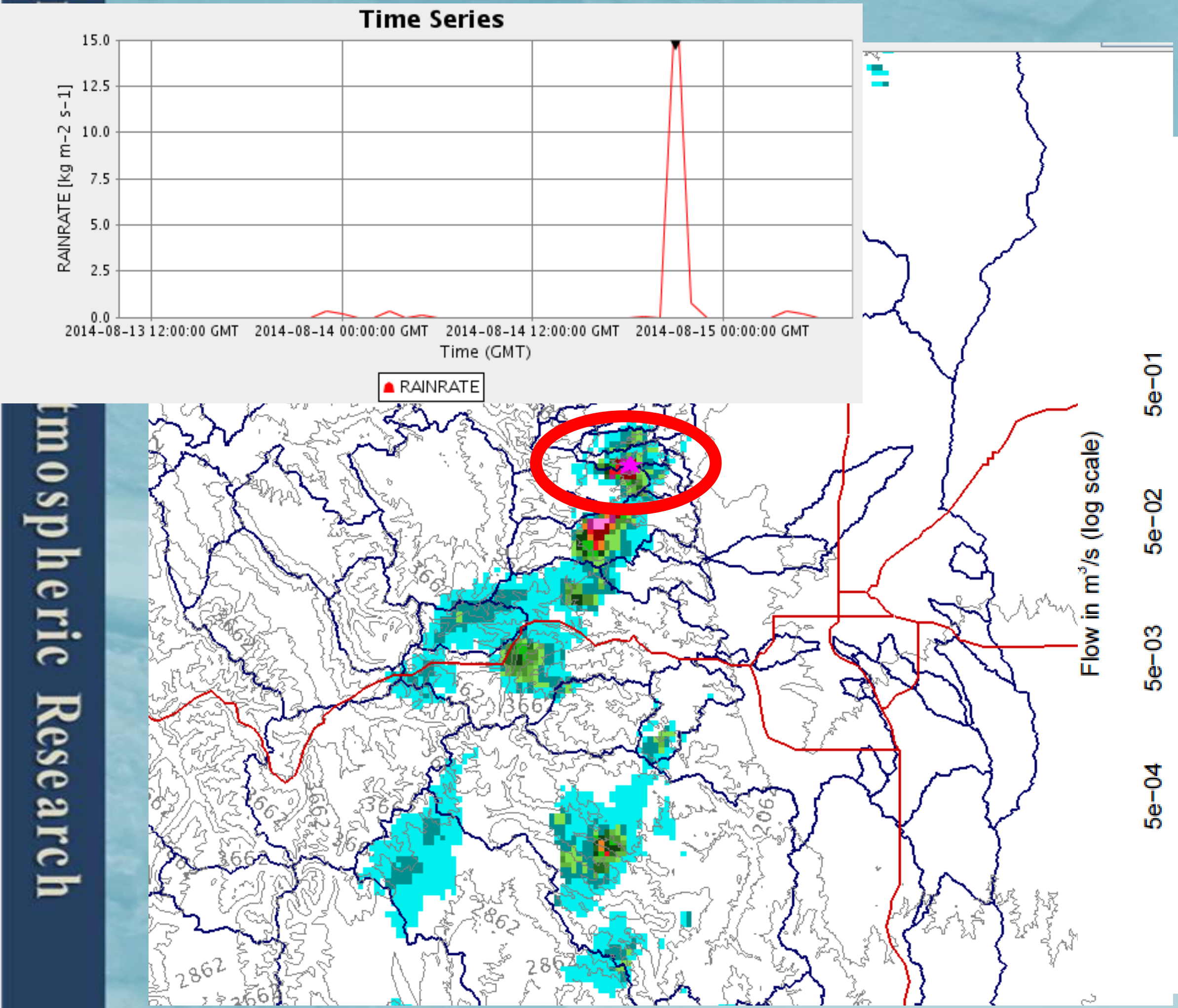
- Real-time 24/7 cycling of radar, nowcast and weather model forecasts into hydro model
- Spatial depiction of streamflow conditions at over 220k locations in the Front Range area
- Animated visualization products for qualitative assessment



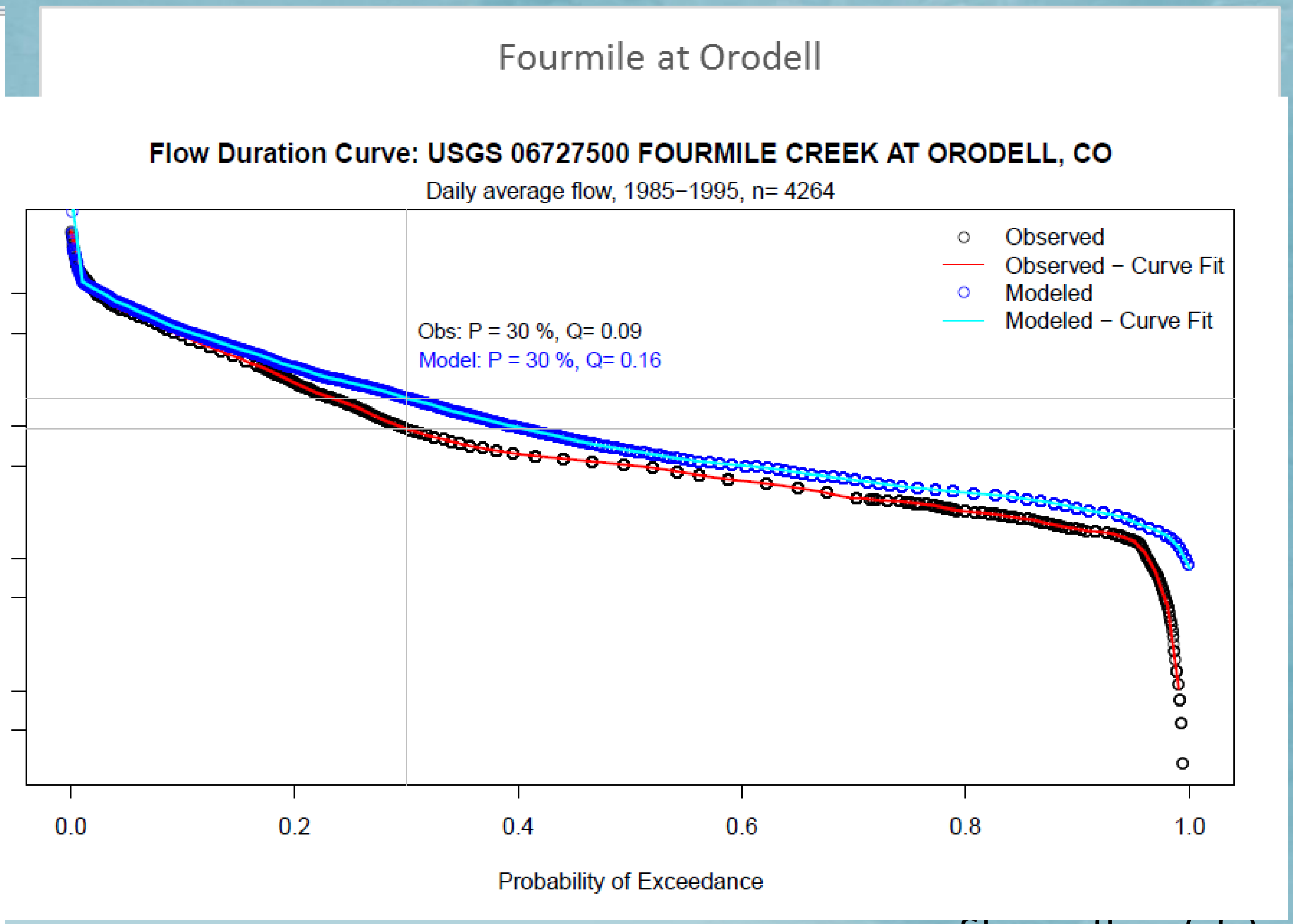
Real-time Aug. 14, 2014 streamflow anomaly

Science Highlights: Hydro Forecasting

- Status of Re-runs: MRMS Precipitation Forcing… Fourmile Canyon



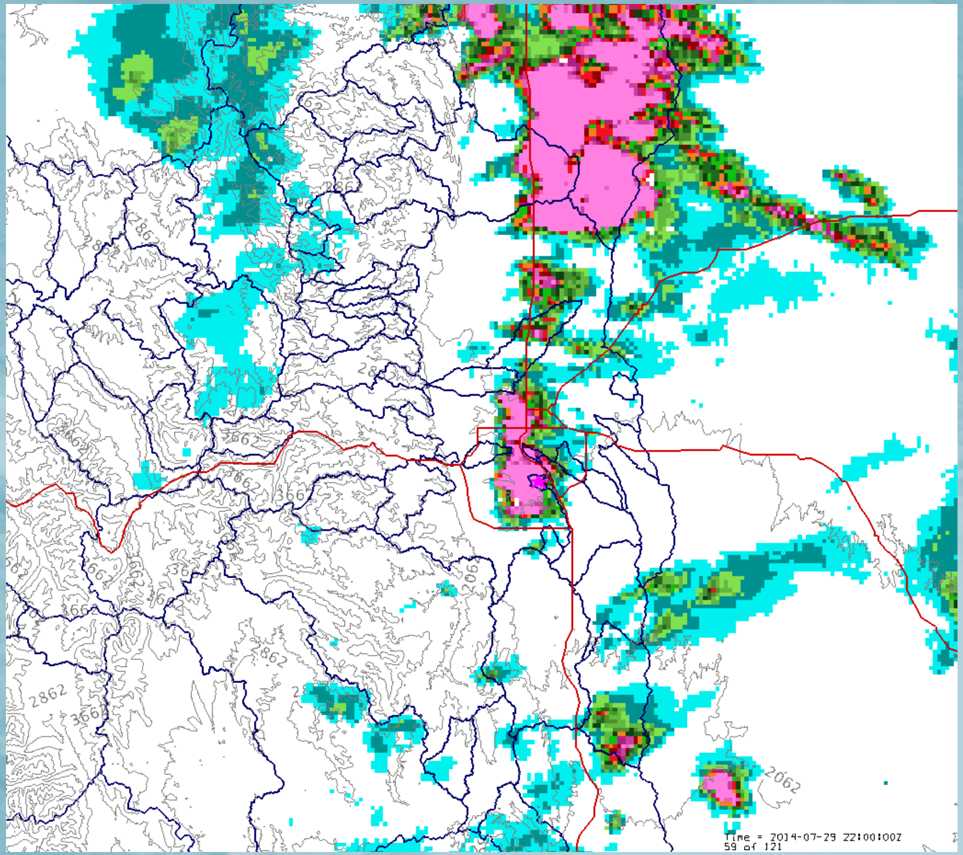
Precipitation Rate (mm/hr) Aug 14, 21Z



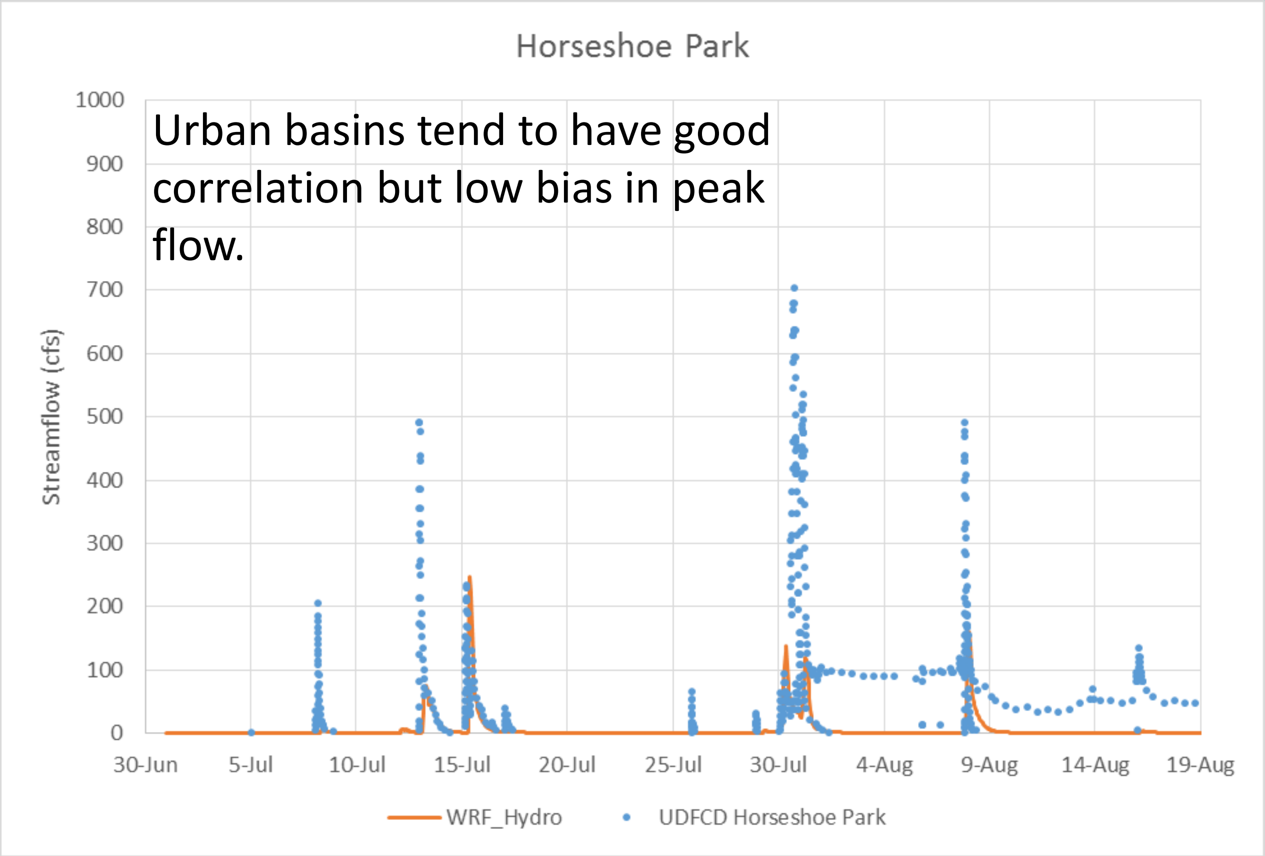
Streamflow (cfs)

Science Highlights: Hydro Forecasting

- Status of Re-runs: MRMS Precipitation Forcing… Urban basins show too little runoff production



Precipitation Rate (mm/hr)



Streamflow (cfs)

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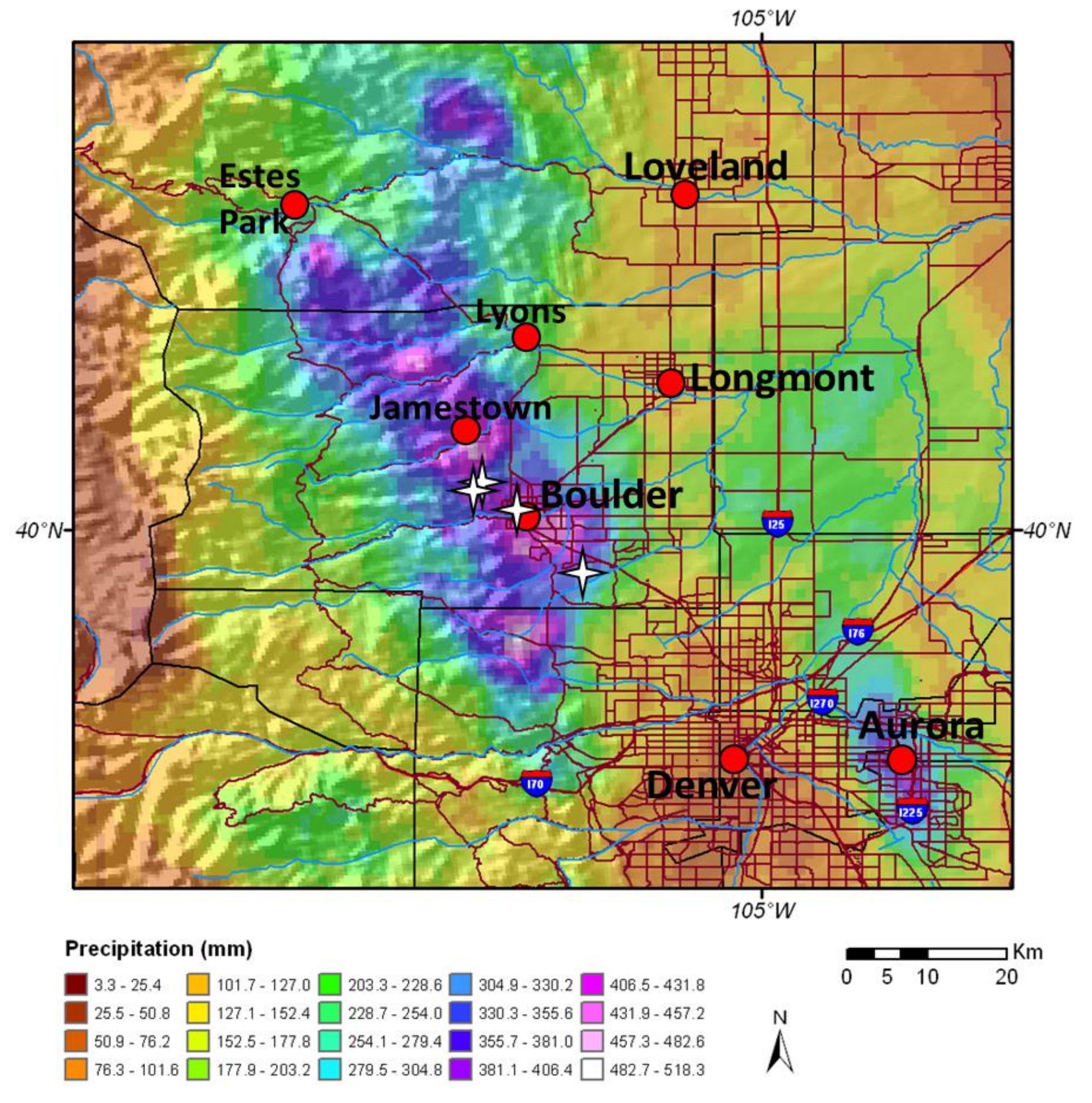
4. Impacts from the September 2013 Colorado Floods

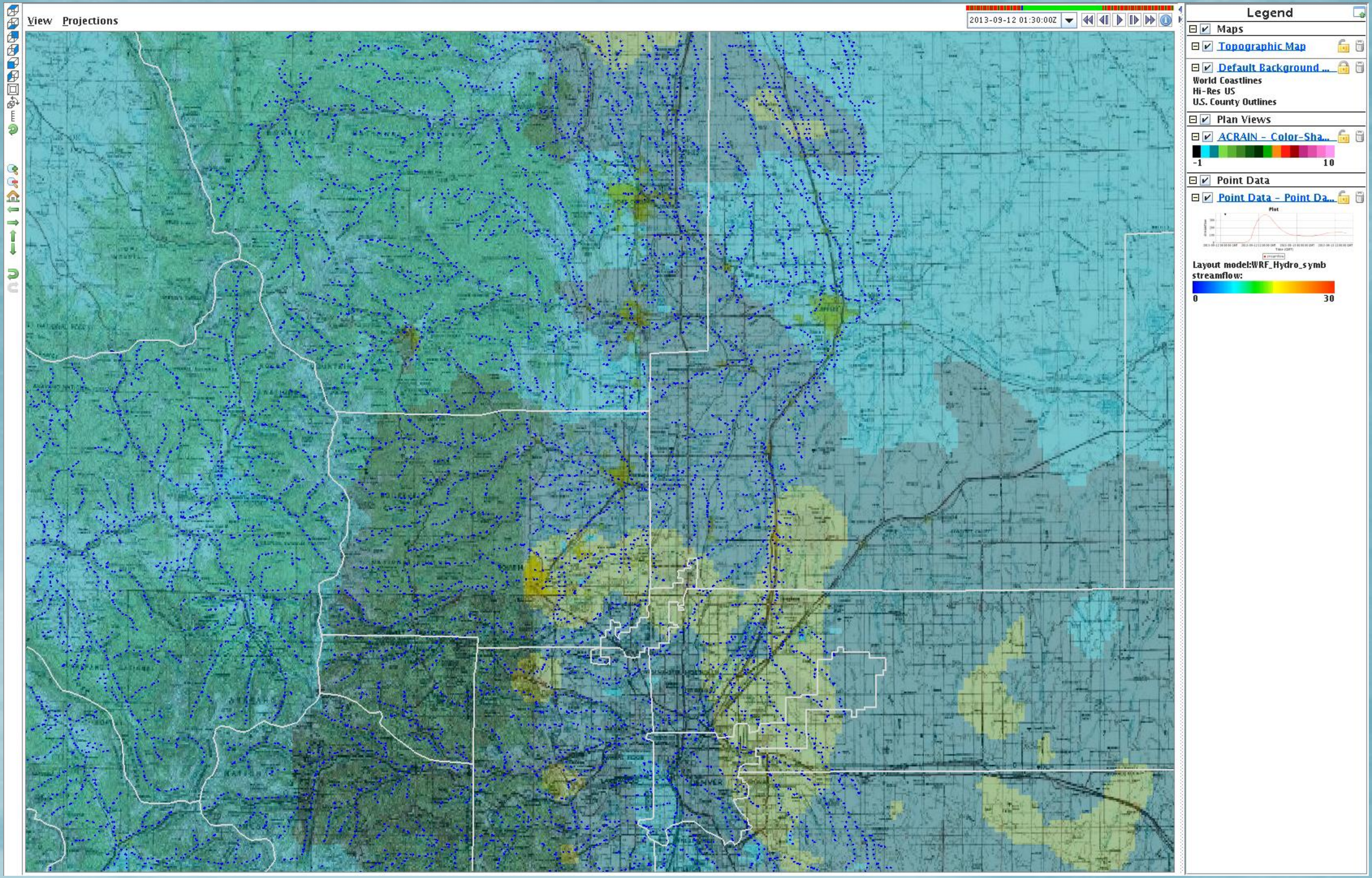
- 8 fatalities
- Flooding less than 1.0% probability widespread across several counties
- Communities completely evacuated
- 18 Counties declared fed. disasters
- > 450 mi road destroyed
- Water/wastewater infrastructure destroyed
- Measurement infrastructure destroyed
- > $2B damages
- No flood watch was issues on 9/11



Gochis et al., 2015 BAMS

Modeling the Sept. 2013 Floods:

WRF-Hydro simulated streamflow using NOAA radar-gauge observed rainfall



Streamflow in cms

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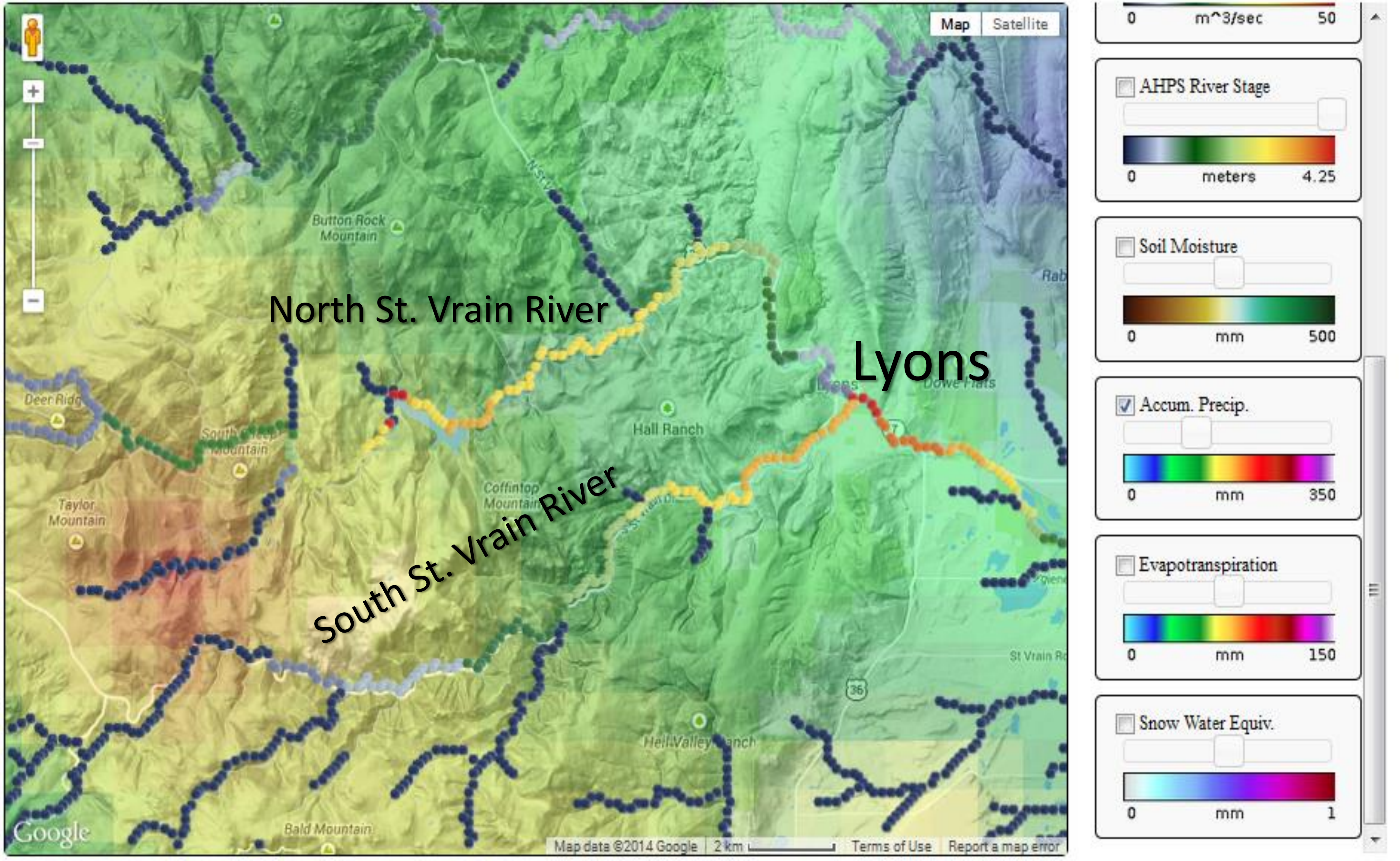

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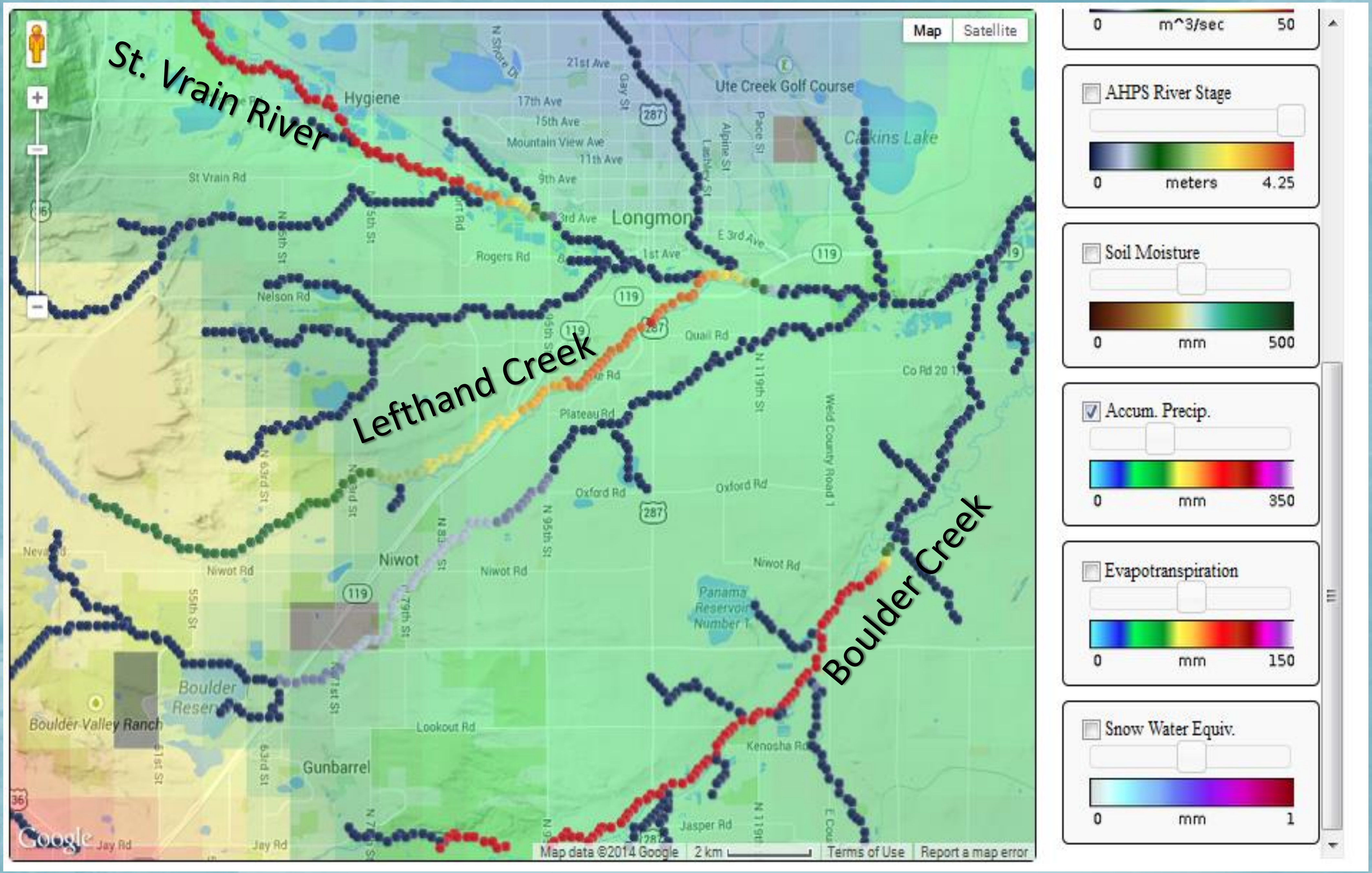

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Forecasted accumulated rainfall:

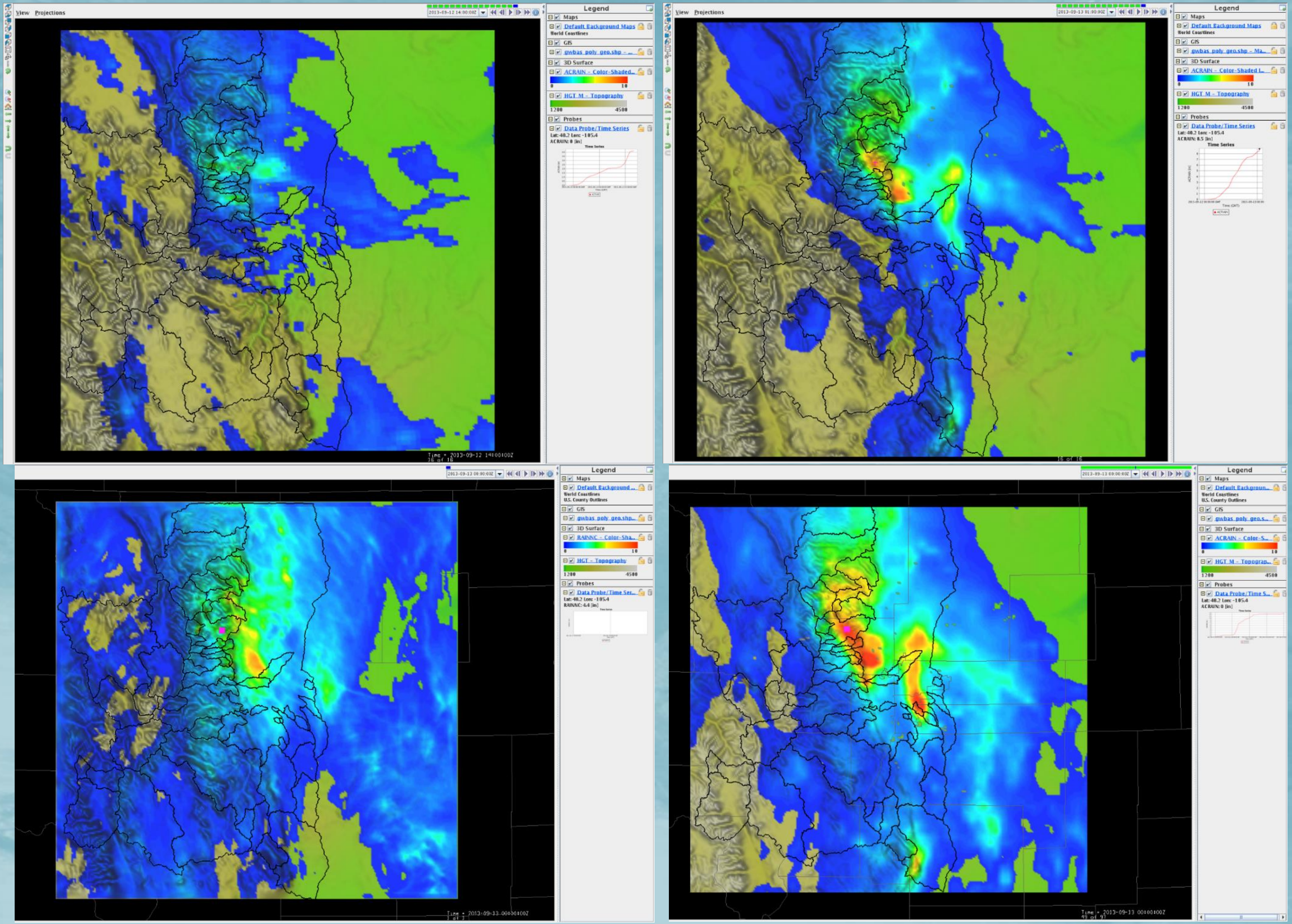
Uncoupled NOAA-ESRL HRRR:
15-hr
Initialized:
9/11 23z (1700 LT)

Coupled WRF/WRF-Hydro model

Initialization:
9/11 00z

Valid: 9/12 07z

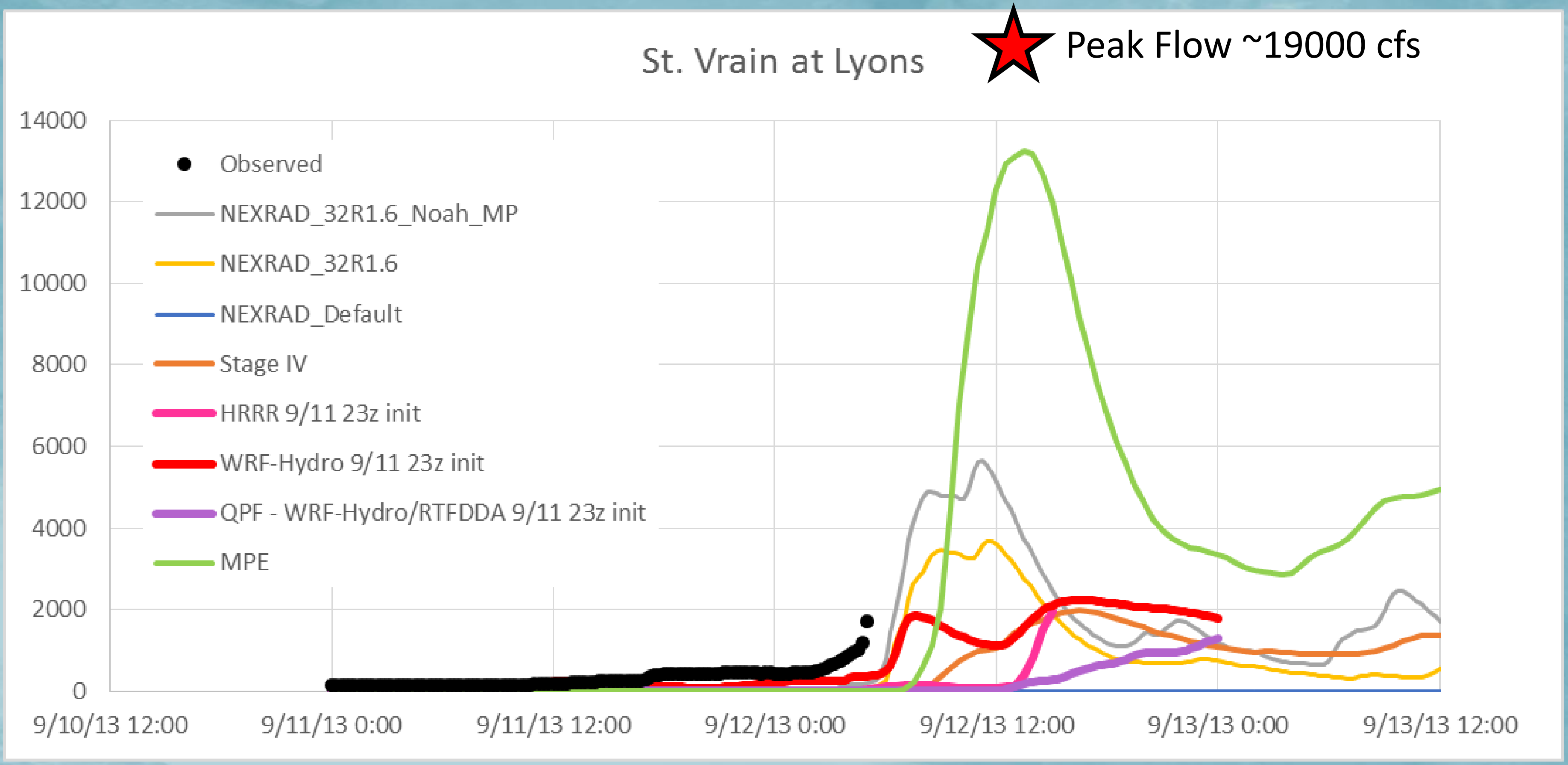
Forecast **NEXRAD QPE**

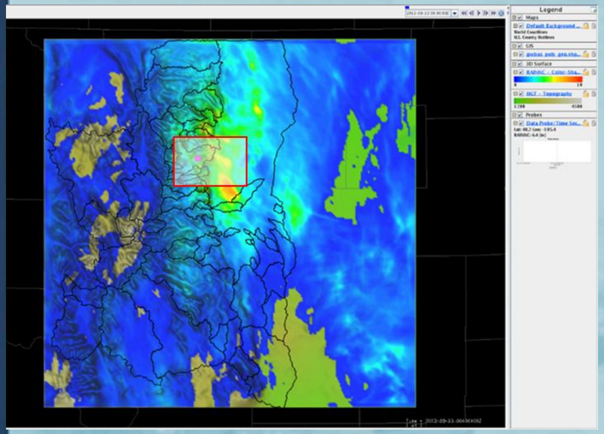


Forecasted streamflow coupled WRF/WRF-Hydro model

Initialization: 9/11 00z

Valid: 9/12 07z




Streamflow in cms

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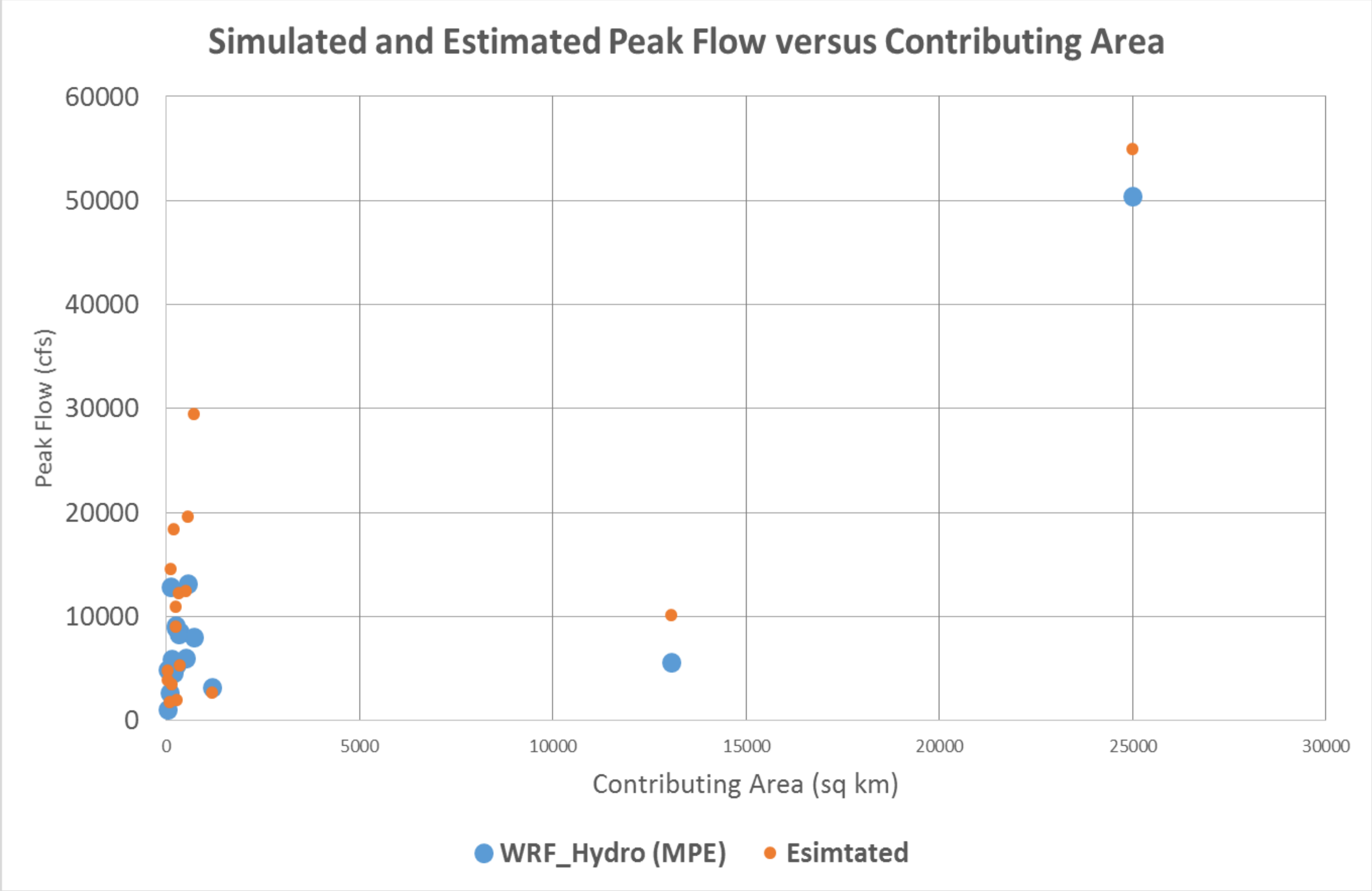
Simulated peakflow values from the WRF-Hydro model

Driven by: NOAA/MPE QPE



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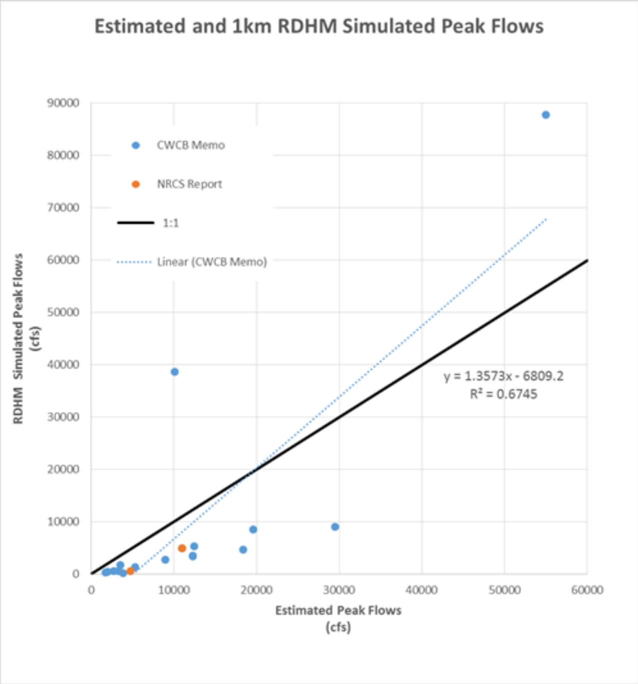
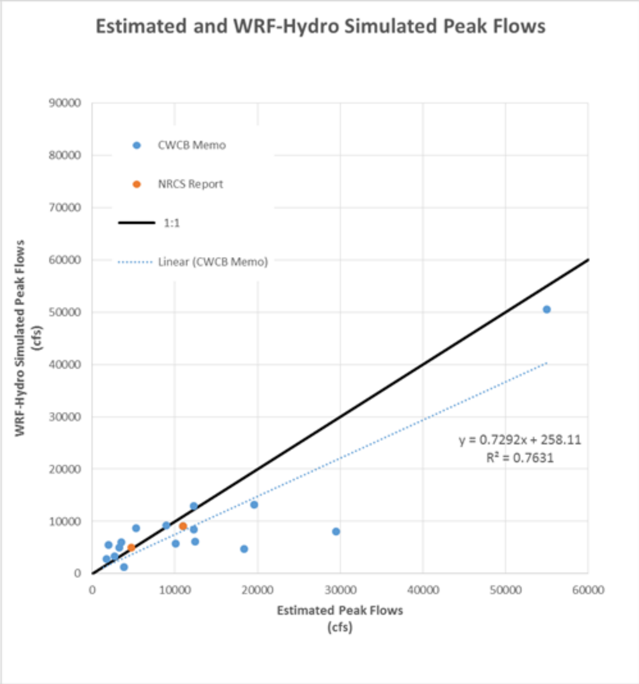
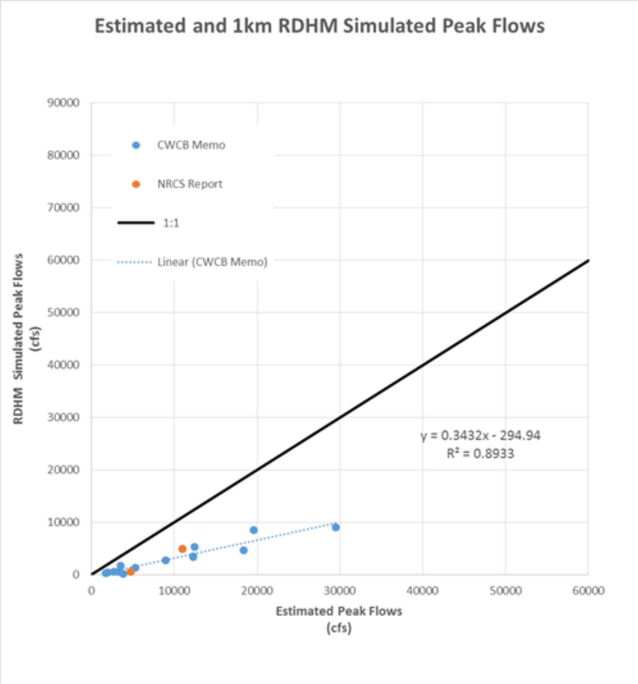
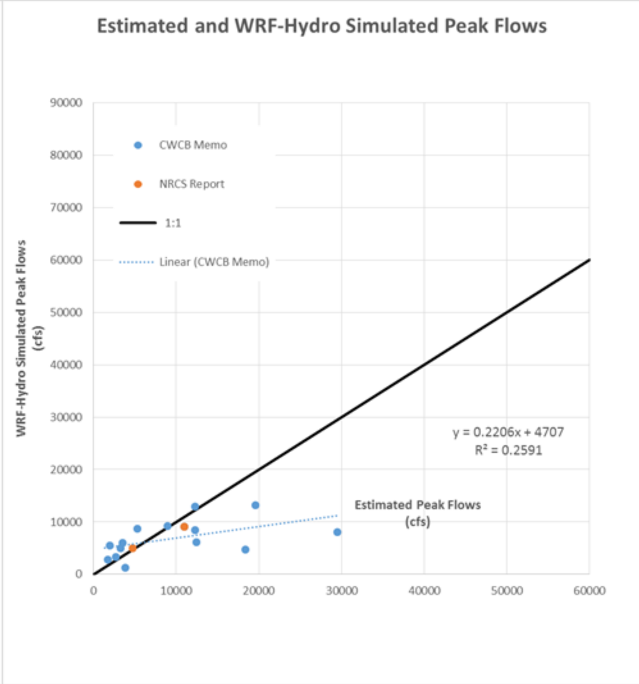
Simulated peakflow values from the WRF-Hydro model and the NOAA/OHD RDHM model

Driven by: NOAA/MPE QPE





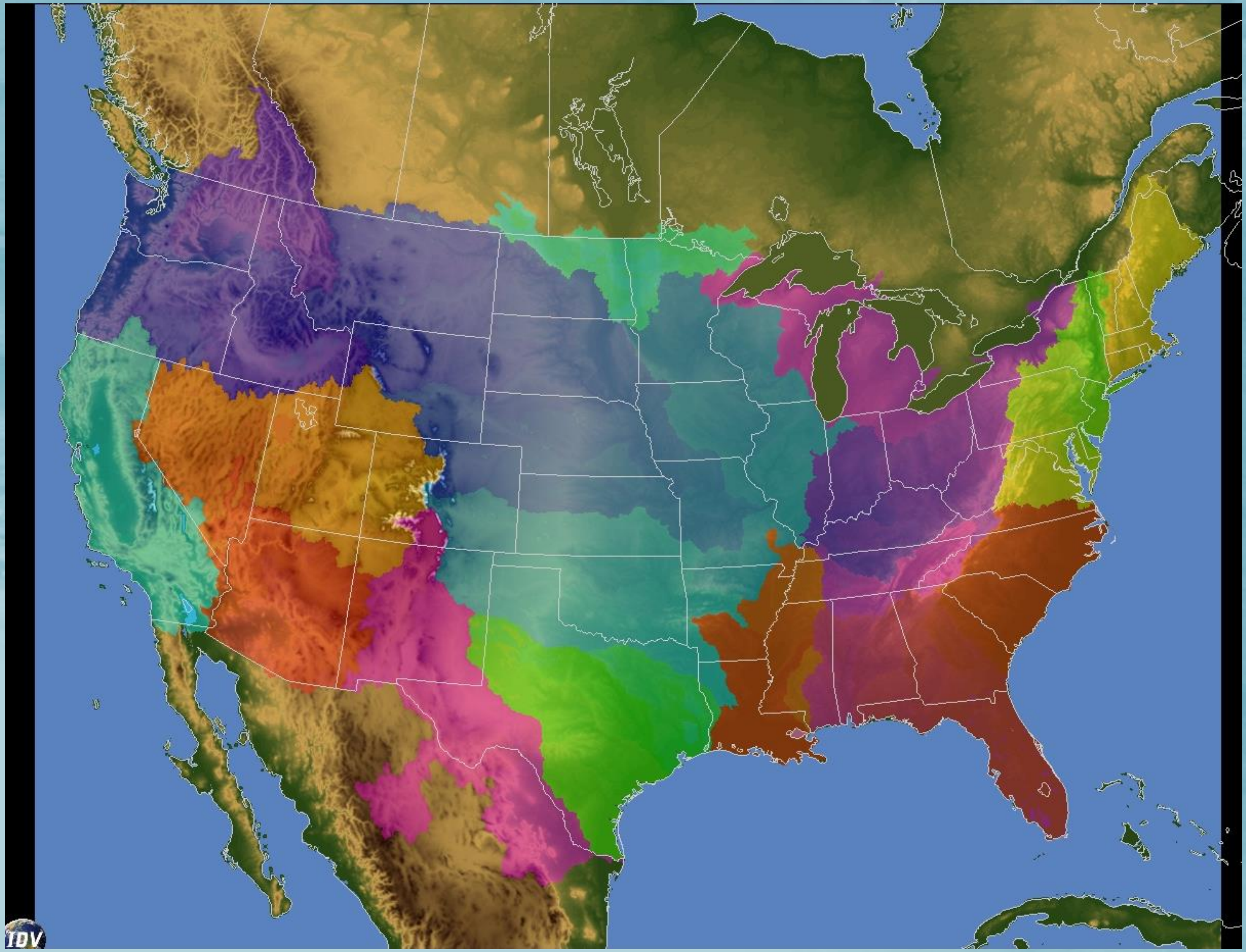




5. CONUS Domain Continuous Water Prediction

NFIE Default Set-up, Spin-up and Retrospective Analysis:

- NHDPlusV2-Encompassing Domain
- 3km NoahMP land model only:
  - No routing (to be done offline by RAPID)
  - No reservoirs
  - USGS land cover type
  - NRCS STATSGO soils
  - Climatological vegetation structure
- In progress: 5 year 2010-2014 continuous run
  - NLDAS2 forcing only with GFS background
- Goal: Quantify background model and forcing bias



- Problems:

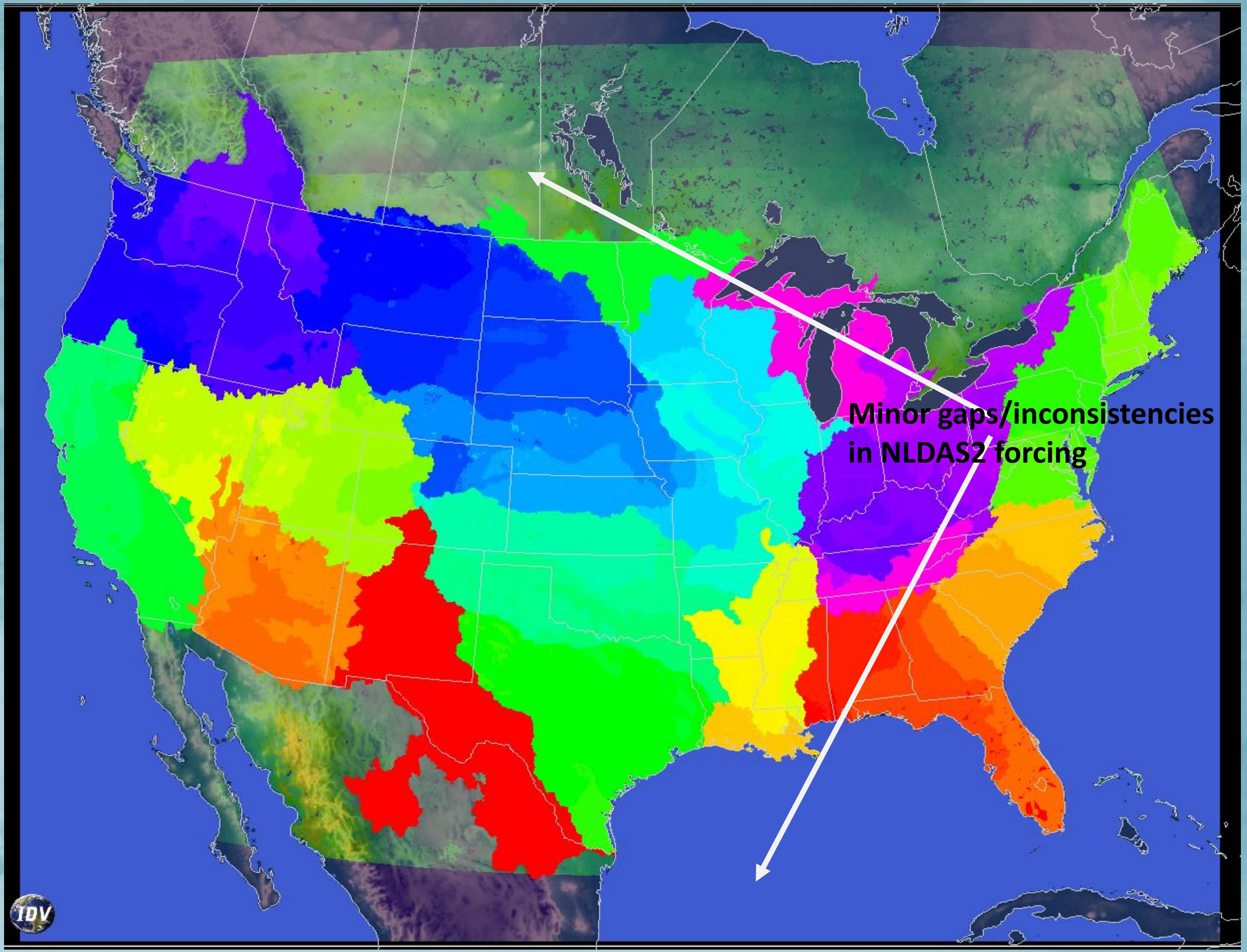
MRMS, HRRR (and NLDAS2) do not provide complete tributary coverage

HRRR missing LW radiation

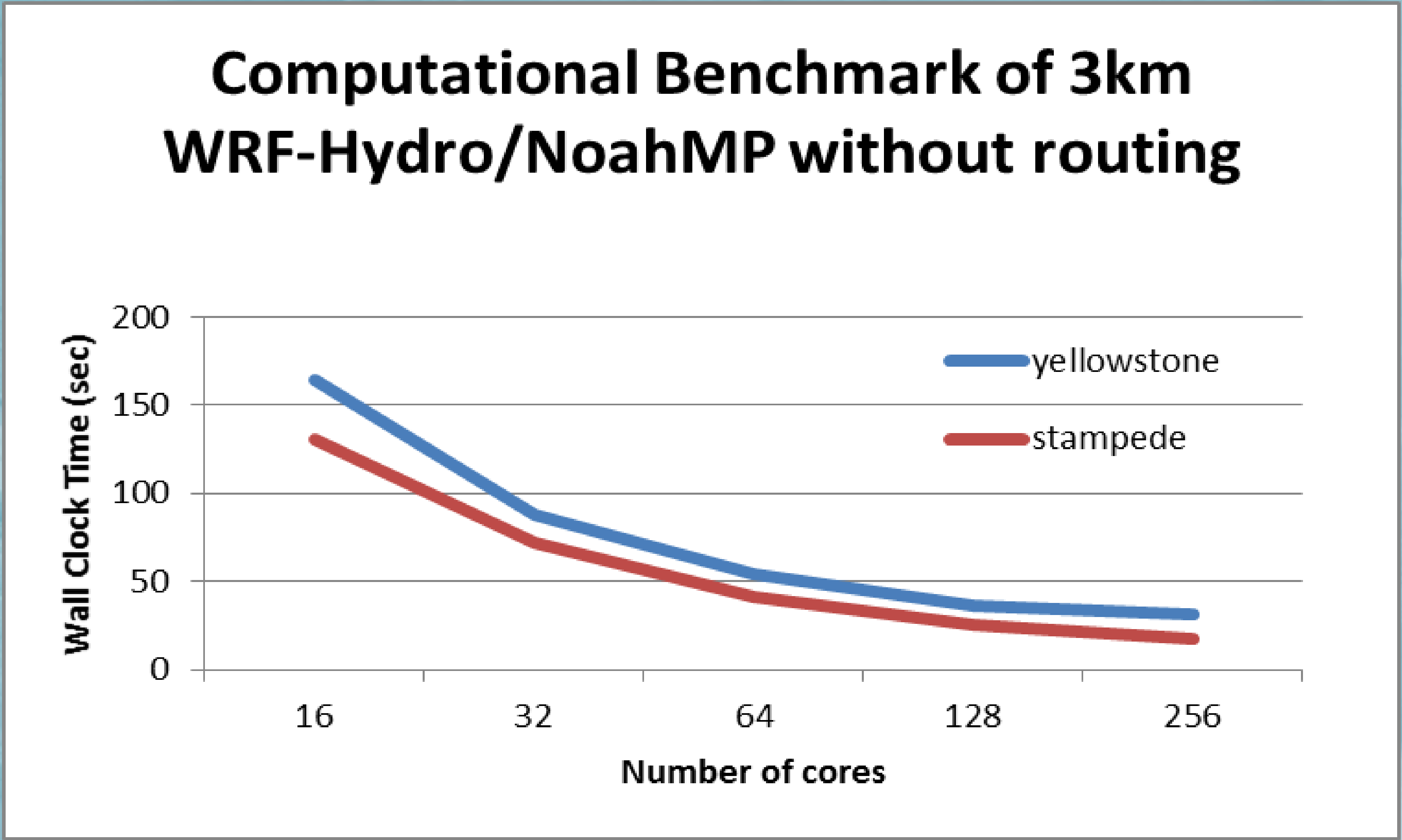
- Solutions:

Mosaic HRRR onto GFS (0.25 deg)

LW radiation will be added to HRRR output



Computational Performance of WRF-Hydro for CONUS implementations: 6-hour forecast, no routing, full NoahMP output



1-day Forecast on 128 cores
With full output takes
~ 10min.

NFIE Preparation Activities:

1. Thinning NoahMP model output (IN PROGRESS):
   - Reduce output to key water budget (state and flux) terms
   - Markedly improves runtime (up to 50%) and overall parallelization efficiency

2. Parallelizing WRF-Hydro forcing data regridding and re-formatting scripts (DONE)
   - Written in ncl
   - Utilizes ESMF regridders
   - Fully parallelized for fast performance (minimal contribution to total forecast execution time)
   - Processing all grids takes a few minutes depending on # of cores

3. Developing alternate 'RESEARCH' model configurations (IN PROGRESS):
   - w/ and w/out terrain routing
   - alternate land model specification (SAC-HTET if ready)
   - alternate land cover type and vegetation structure specification
   - alternate channel routing schemes (single executable w/ RAPID)
   - regional nest(s) with water management (mid-Atlantic/Northeast?)

4. Final Benchmarking

NFIE WRF-Hydro/RAPID Workflow

- Model Execution:

1. Collect Forcings:
   MRMS
   GFS&HRRR (anal. and frxsts)

2. Regridding forcings to WRF-Hydro Grid (ESMF regridders)

3. Cycle operational streamflow analyses (HRRR-met, MRMS precipitation)

3a. Create output analysis products

4. Cycle operational streamflow forecasts (HRRR-met, HRRR precipitation)

4a. Create output forecast products

NFIE Research Objectives and Opportunities:

Basic Research Questions:

1. How do various sources of error in CONUS domain hydrologic simulations scale with river basin size?
2. What are the fundamental land-surface controls on flood generation and how do those controls vary regionally? What roles do river management play?
3. How does the predictability of flood events scale with river basin size and forecast lead time?
4. Are predicted streamflow values sufficient for national domain inundation mapping inputs?
5. What is the role of seasonal vegetation dynamics in runoff production?

NFIE Research Objectives and Opportunities:

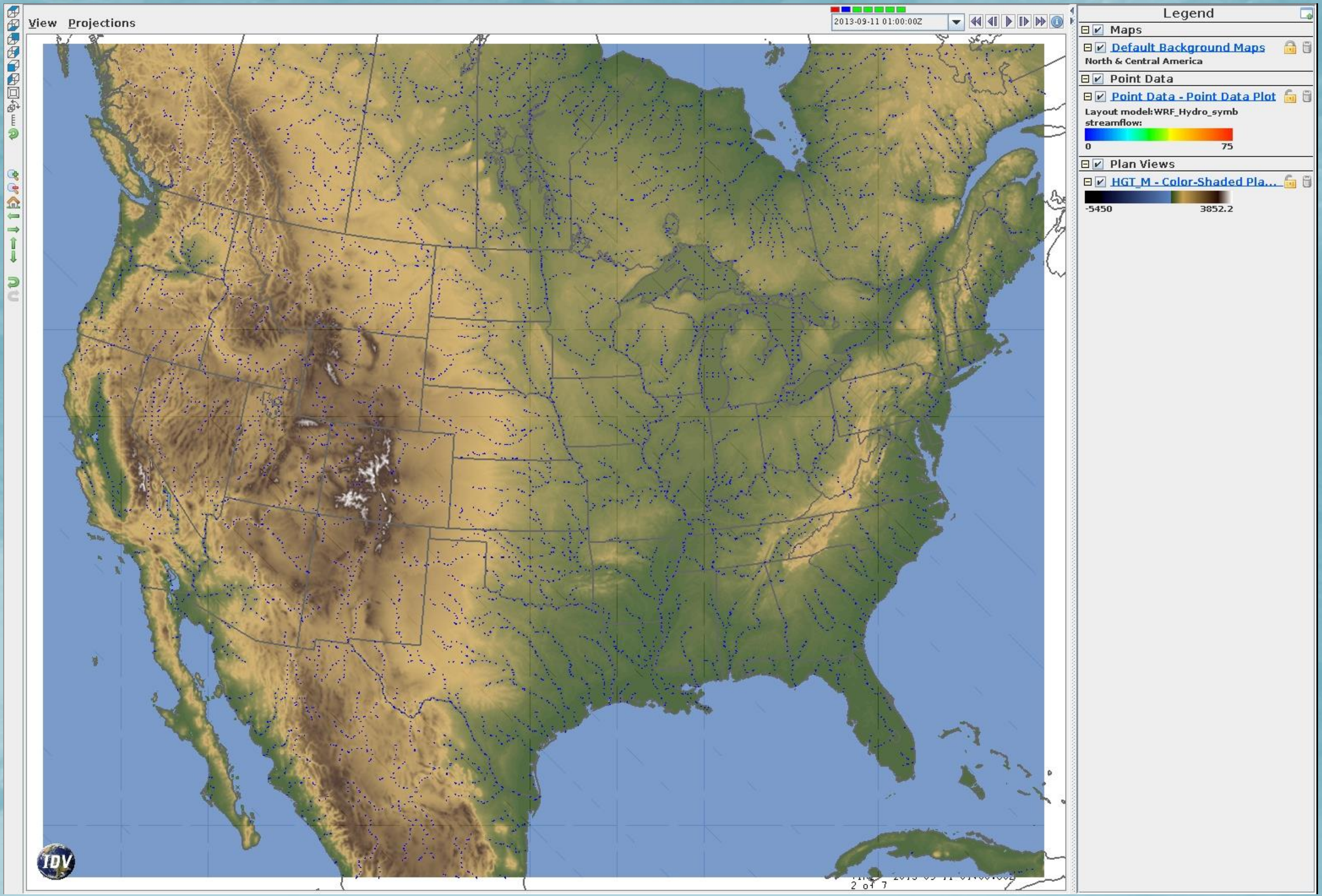
Prediction Research Questions:

1. How accurate are model forcings across the nation and what level of accuracy is need for flood prediction?
2. What are the computational requirements of various national domain configured models?
3. What are the most efficient/feasible way to implement a probabilistic flood prediction framework over CONUS domains?
4. What opportunities exist for improving flood forecasts through incorporation of hydrologic data assimilation?

The National Center for Atmospheric Research

Continental Domain Water Prediction

- **Initial tests…**
  - **Streamflow from cold start**
  - **250m channel pixels, 2nd order and higher filesize 575MB ea.**



CONUS+ 250m channel flow (thinned to 5th order and higher channels)

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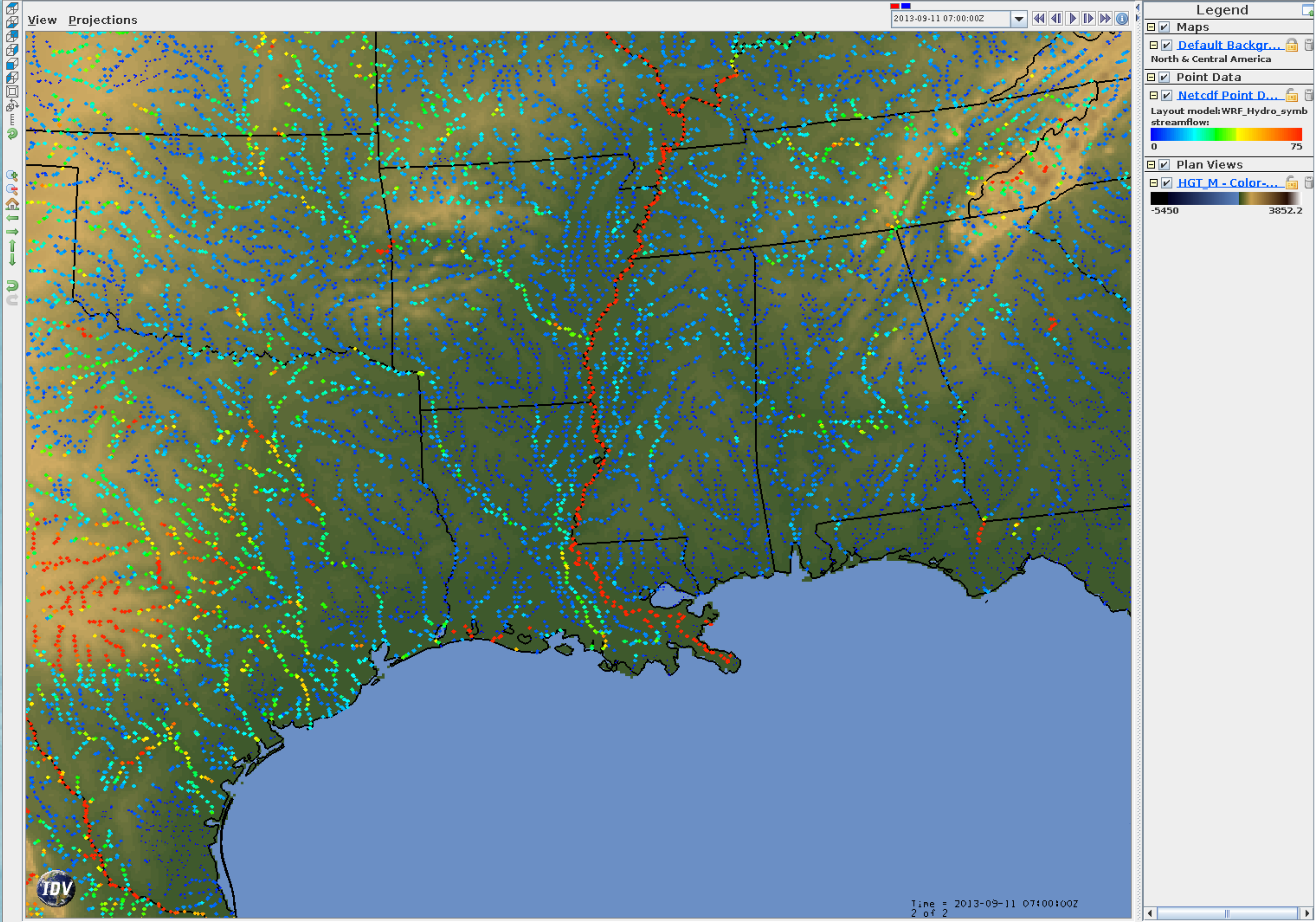
IDV images Regional Views



CONUS+ 250m channel flow (thinned to 4^{th} order and higher channels)

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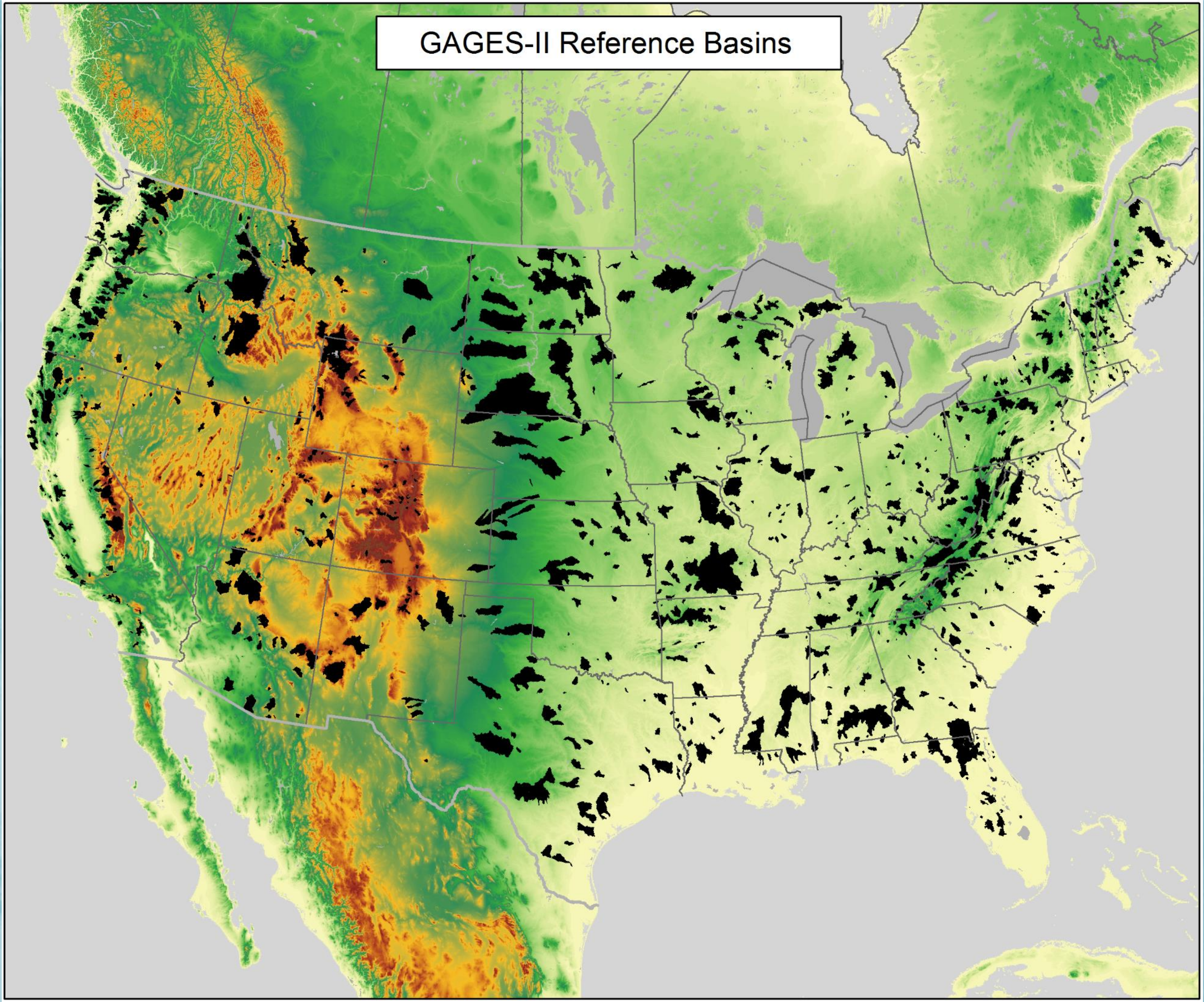
Benchmarking Stream Flow Measurement Sites



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End

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

Contributions:

NCAR Internal:

D. Gochis (Project Lead)

W. Yu (Lead Software Engineer)

D. Yates (Water Resources Lead)

K. Sampson (GIS Specialist)

J. McCreight (Post-doc)

A. Dugger (Post-doc)

M. Barlage (NoahMP Developer)

A. Wood (Advising Scientist)

M. Clark (Advising Scientist)

K. Ikeda (Data Analyst)

R. Rasmussen (Sr. Advising Scientist)

F. Chen (Sr. Advising Scientist)