WRF-Hydro/NoahMP Applications in Real-time, Operational Hydrologic Forecasting

D. Gochis, D. Yates, A. Dugger, K. Sampson, R. Rasmussen, Y. Zhang, R. Cabell, A. RafieeiNasab, M. Casali, J. Grim, A. Mazrooei, M. McAllister, A. Gaydos, F. Chen, C. He, R. Apolafia-Rosenzweig, T. Schneider, E. Towler, I. Srivastava, N. Omani, T. Enziminger, T. Eidehamer, J. Kim, E. Dougherty, S. Rasmussen….J. McCreight, L. Read, L. Karsten, W. Yu, P. Valayumkunnath, K. Fitzgerald, B. Kahzaei, R. Saddiq

Research Applications Lab

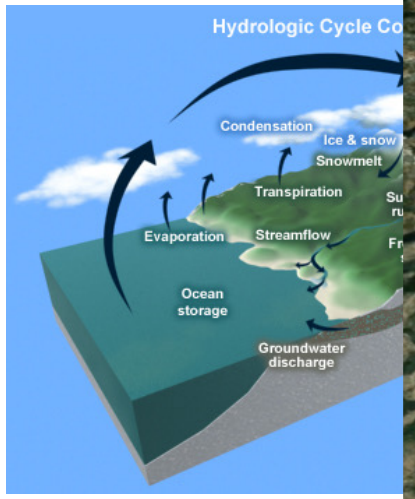
May 23, 2023

Outline:

1. **WRF-Hydro System Description**
2. Recent developments and applications
3. Science Highlight
4. New Evolutions

Advancing Multi-scale Water Cycle Predictions:

- Conceptual Framework: Linking the Water Cycle Across Scales…



Hydrologic cycle is a f
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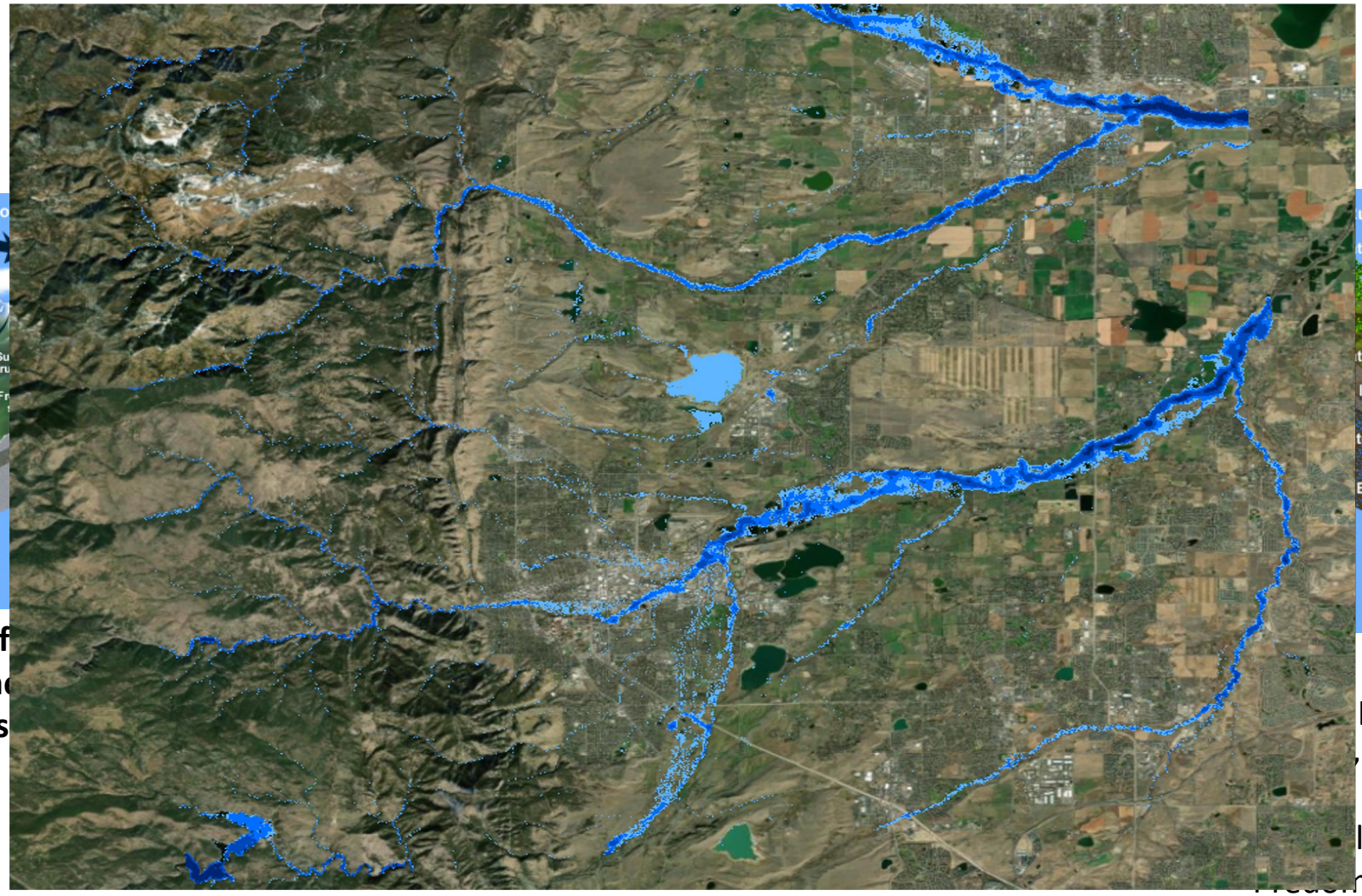
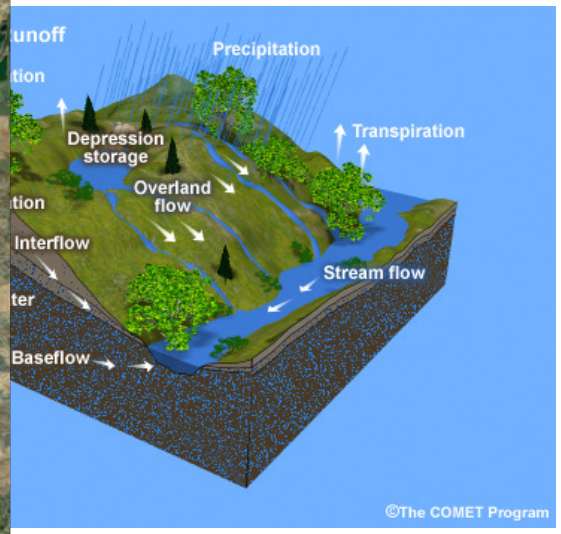
systems and…the bas



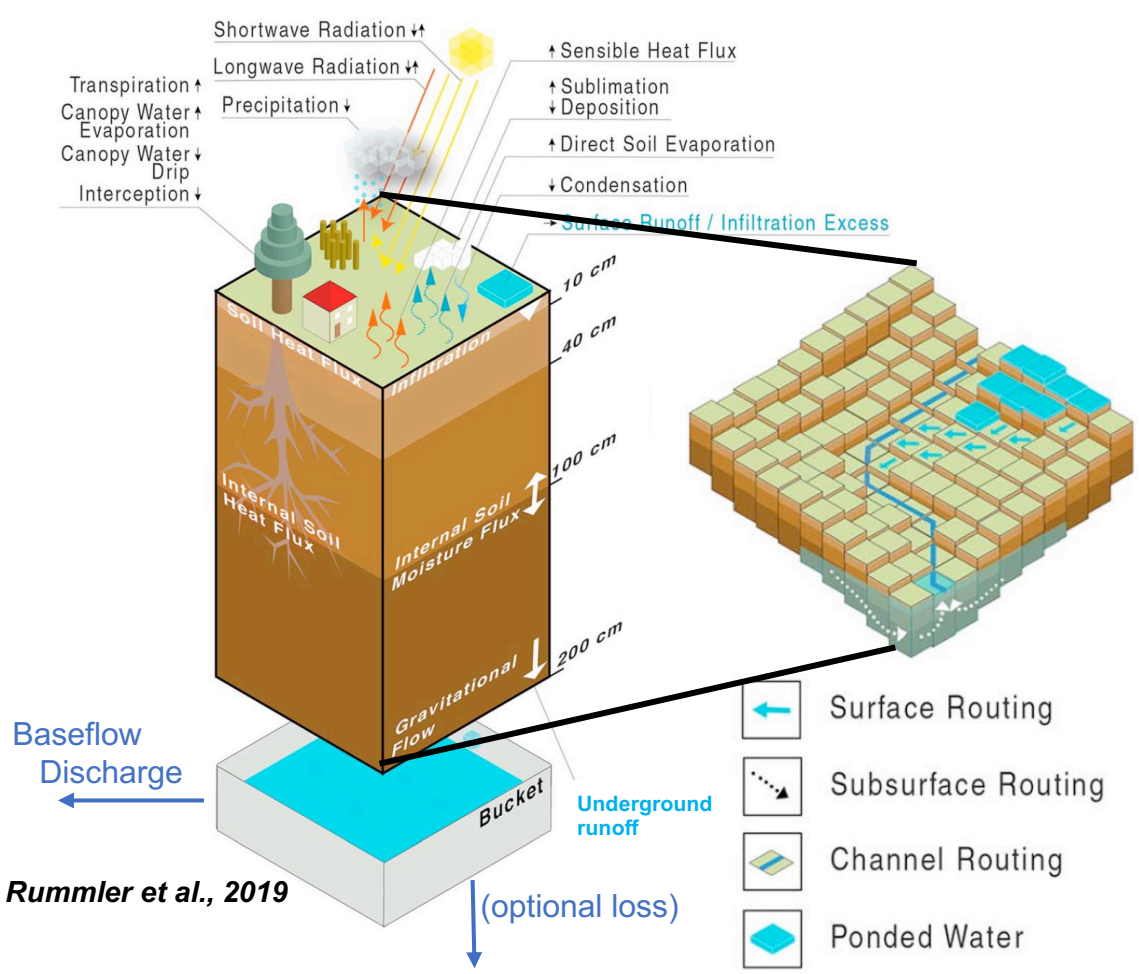
K. Sampson, M. Casalli



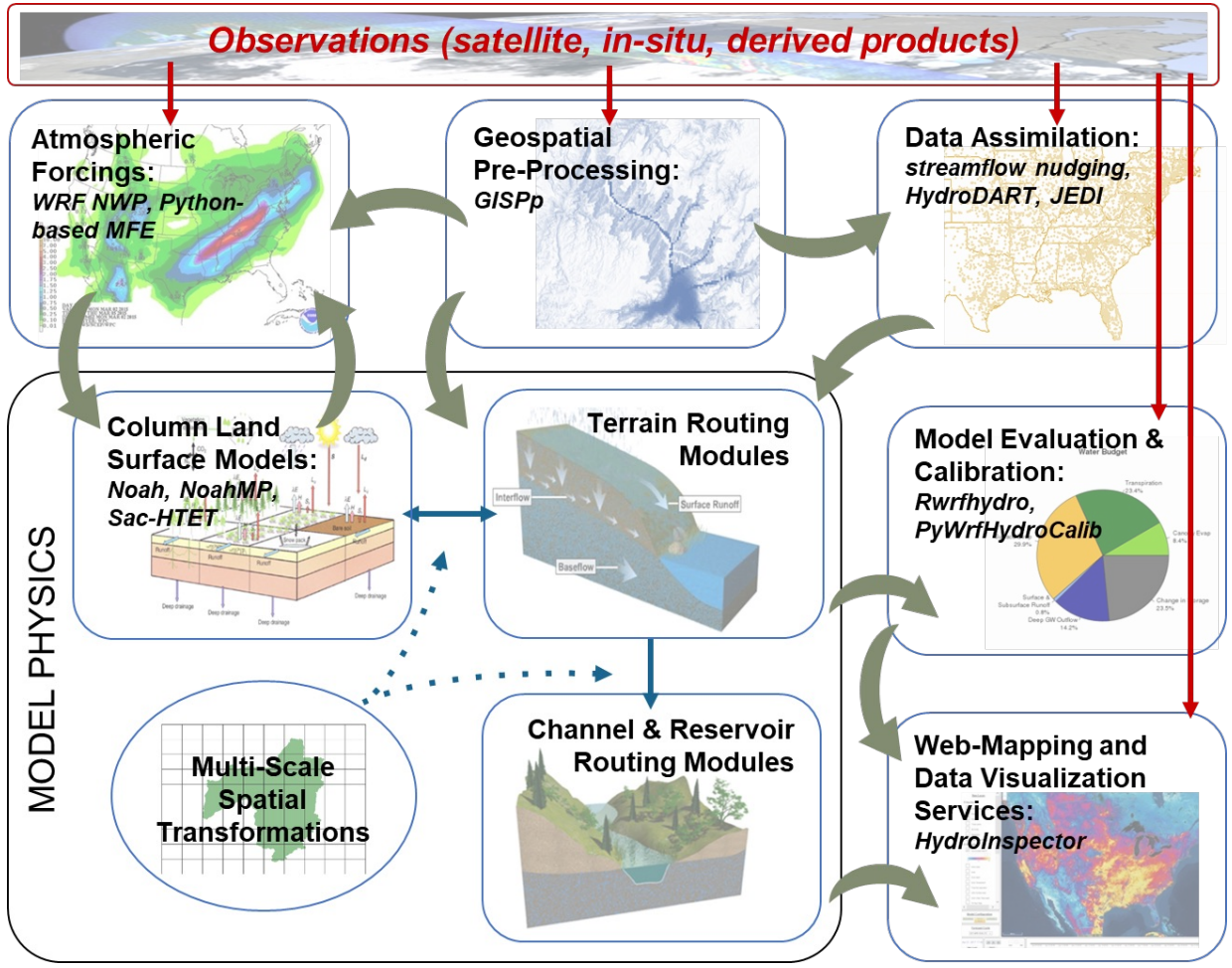
process drivers….
, distribution and availability of

lved with landscape patterns
inantly responsible for
flooding impacts

WRF-Hydro Community Model Ecosystem

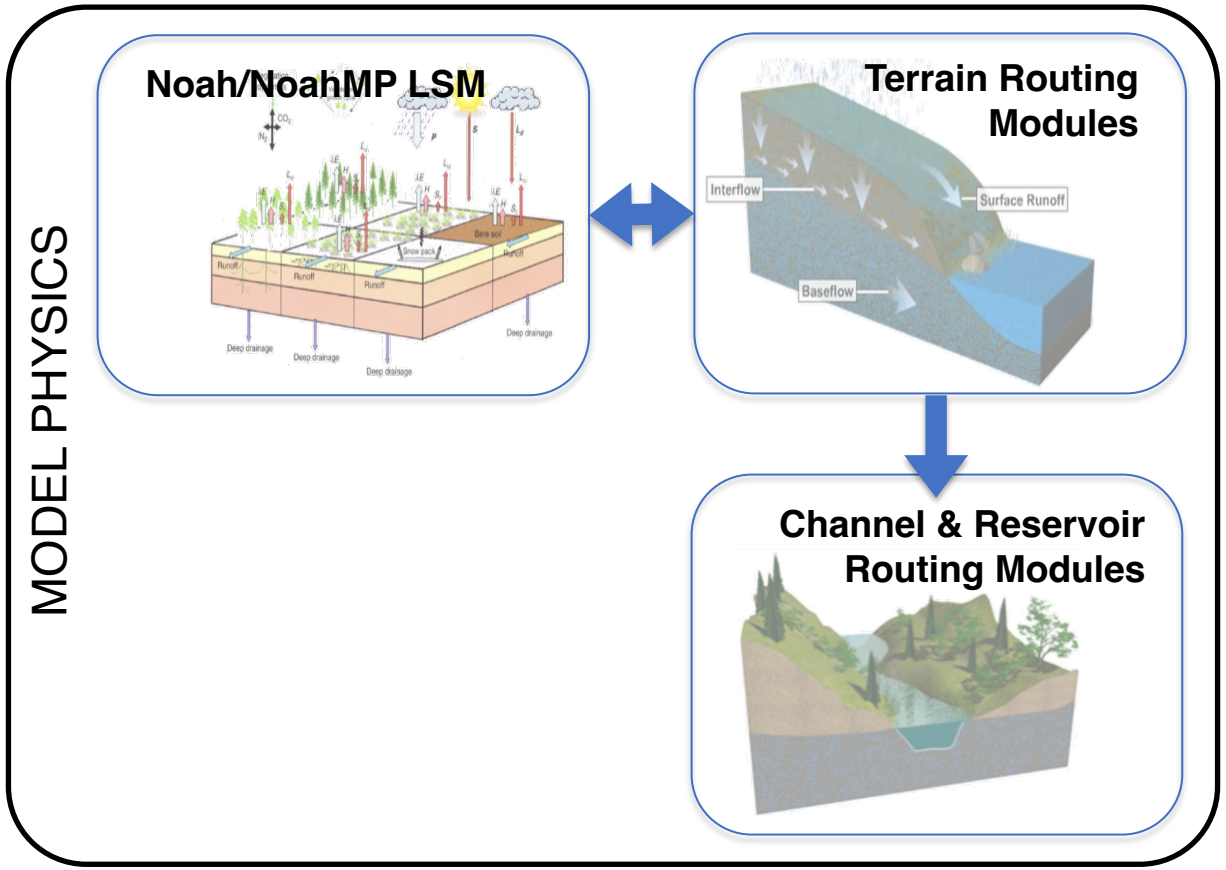


Rummler et al., 2019

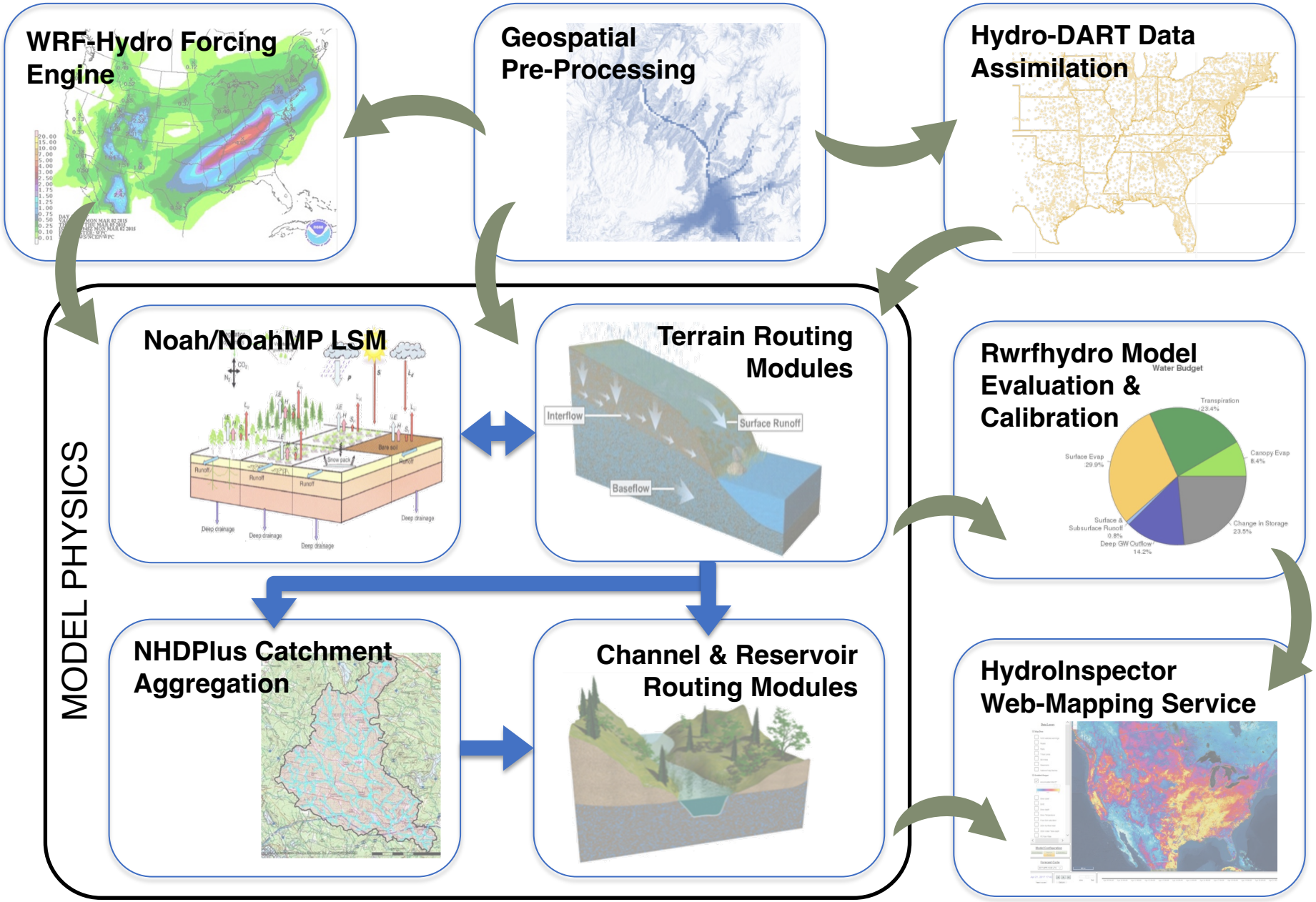


- State of the art column land surface physics
- Dynamic, hyper-resolution terrestrial overland, sub-surface and channel routing
- Multi-spatial framework support
- Interfaced with modern data assimilation systems (DART, JEDI)

WRF-Hydro Base Configuration



Full WRF-Hydro Ecosystem



WRF-Hydro V5.x Physics Components

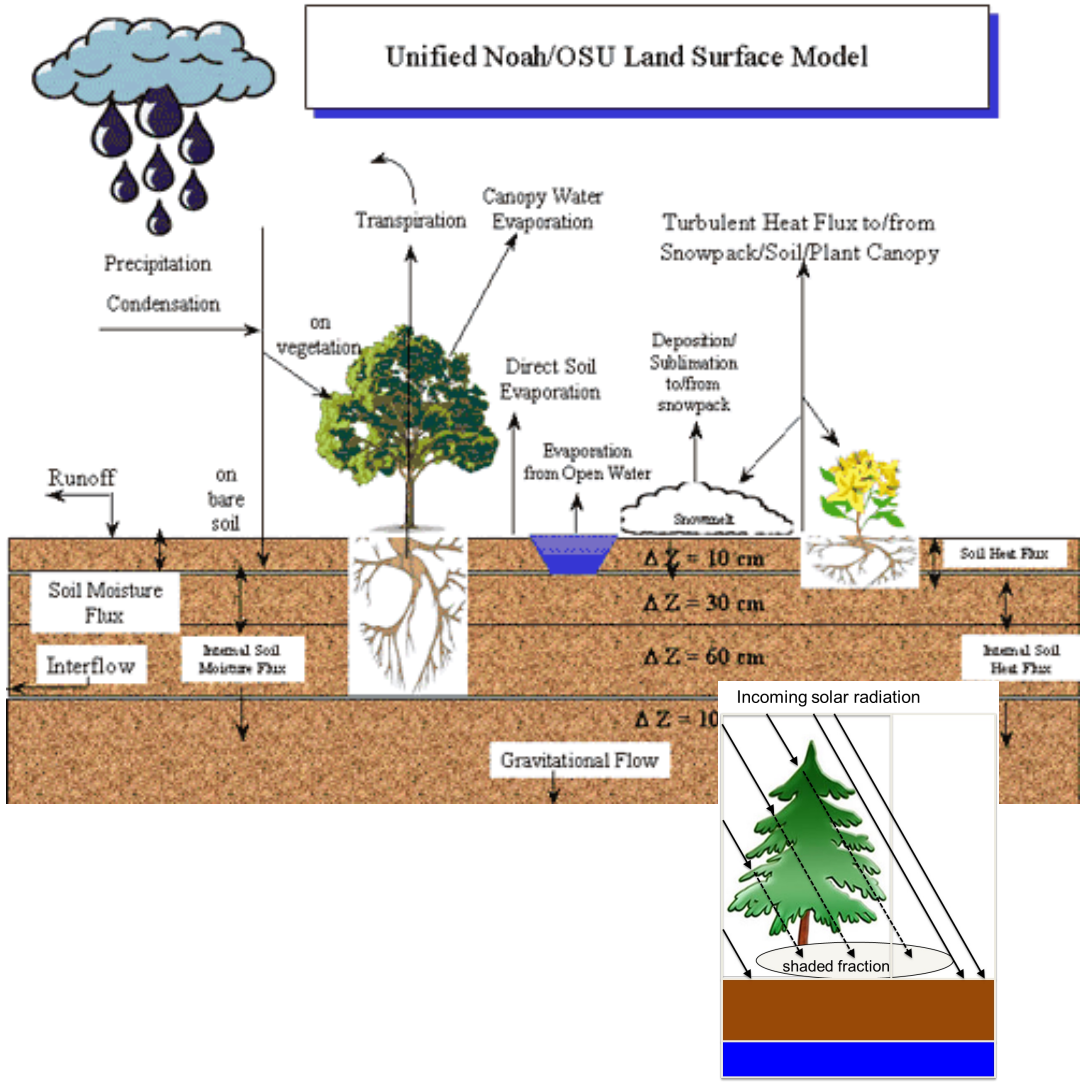
NoahMP Column Physics:

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. Snow/soil diffusion solution (2 options)
12. Canopy interception, evaporation, sloughing, drip
13. Sublimation/evaporation
14. Lower soil boundary condition (2 options)

No wind scouring/re-distribution yet.

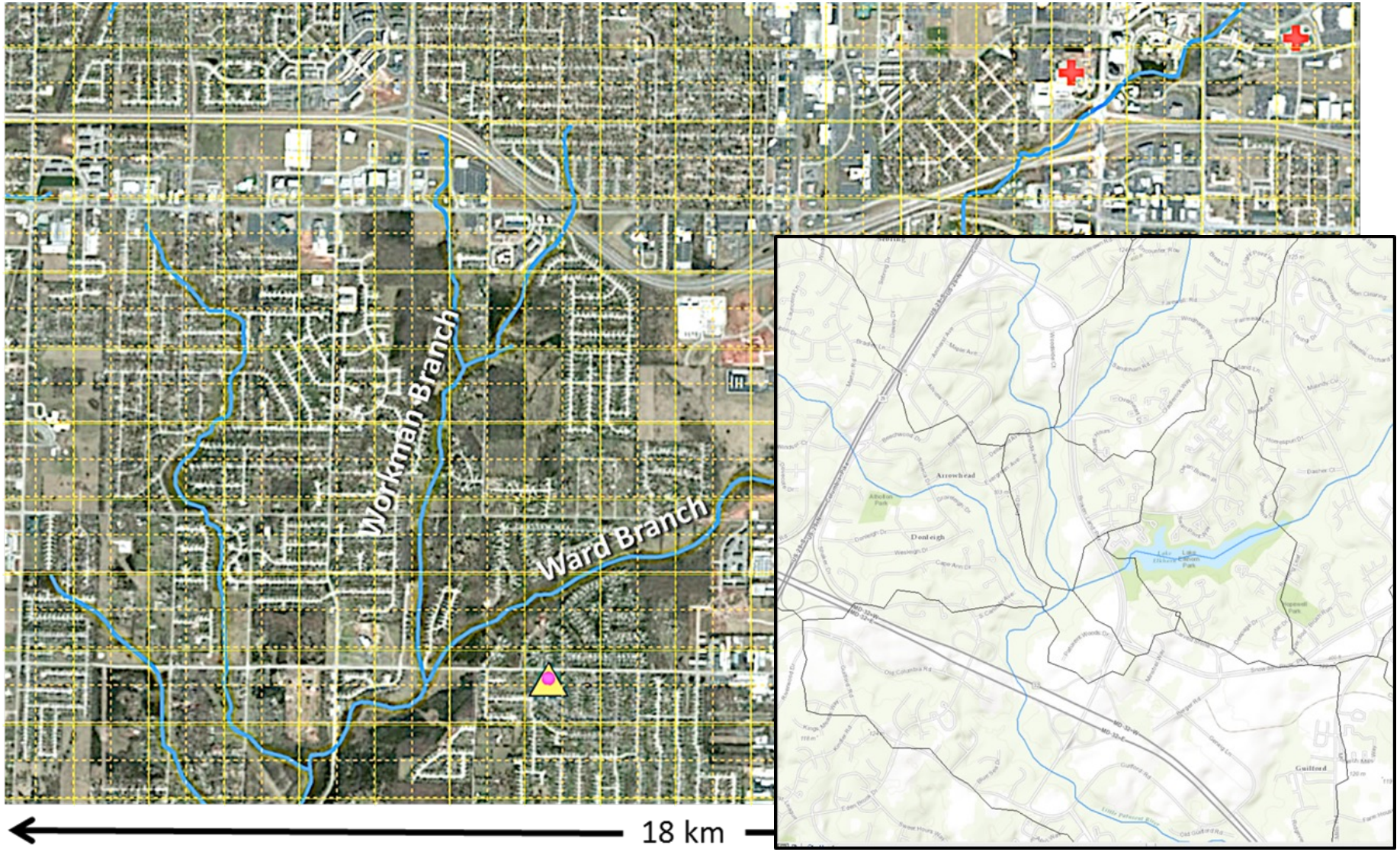
Total of ~50,000 permutations can be used as multi-physics ensemble members



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

WRF-Hydro Multi-scale Modeling Framework

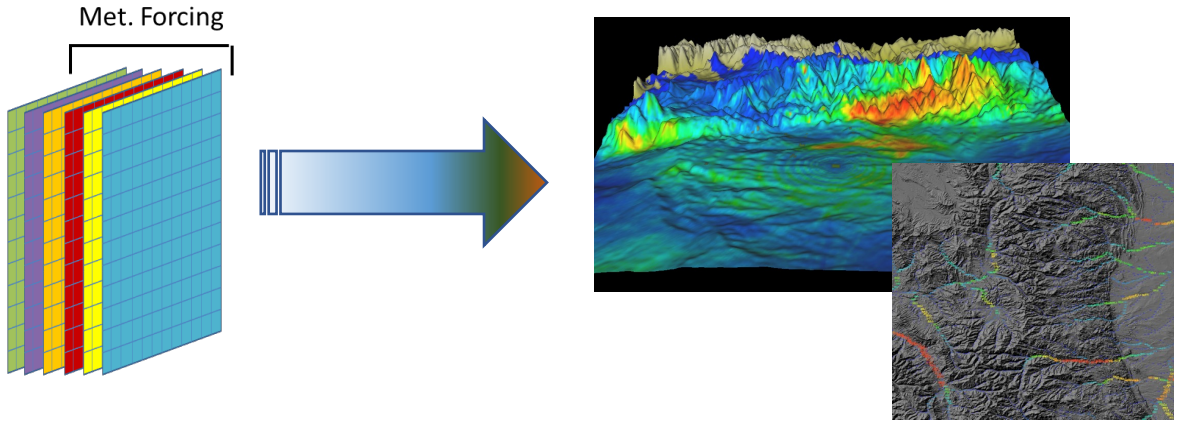
- Multi-scale aggregation/disaggregation:



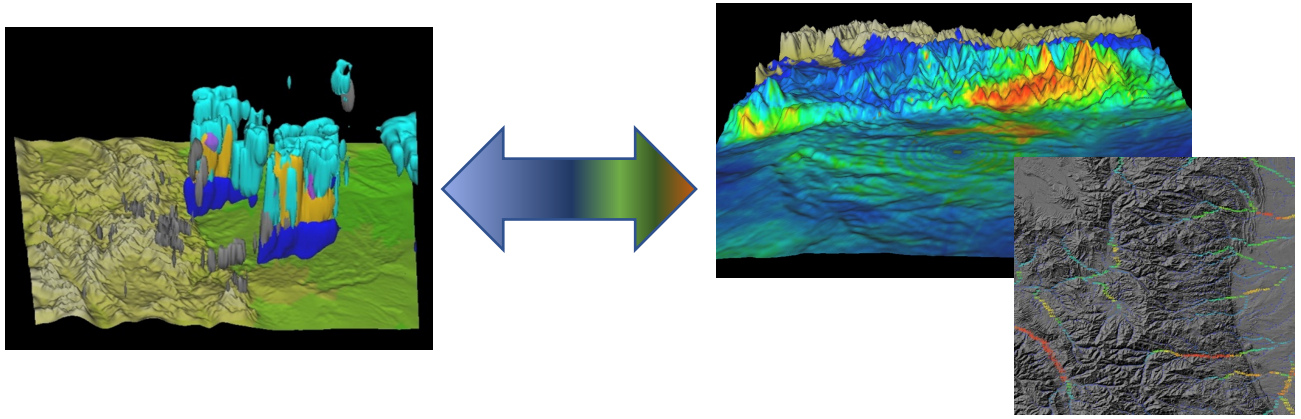
WRF-Hydro Operating Modes

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

One-way ("uncoupled") →



Two-way ("coupled") ↔



- Uncoupled mode critical for spinup, data assimilation and model calibration
- Coupled mode 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

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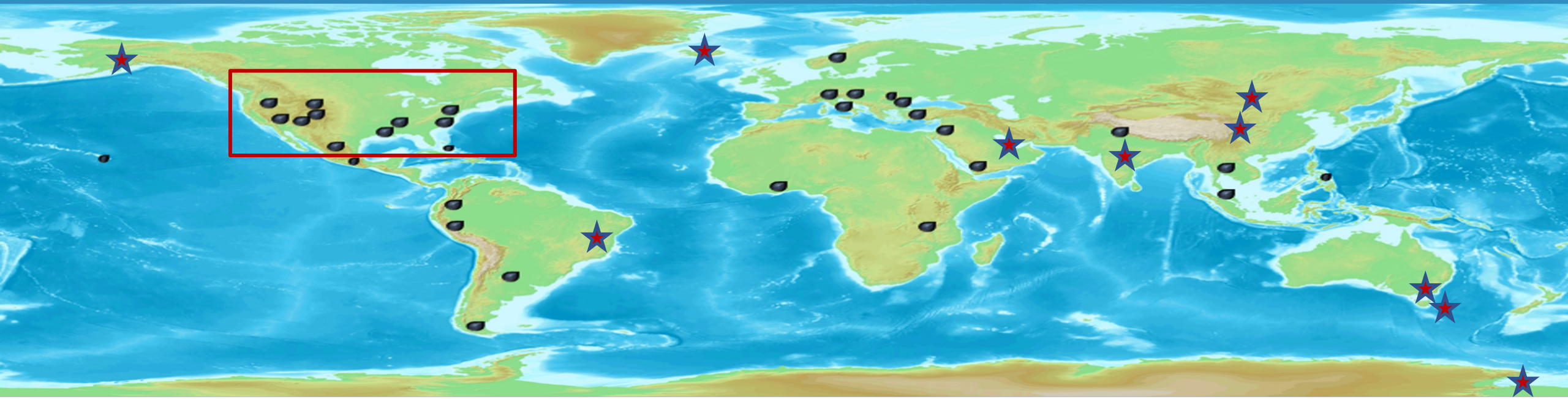
WRF-Hydro Applications Around the Globe



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)

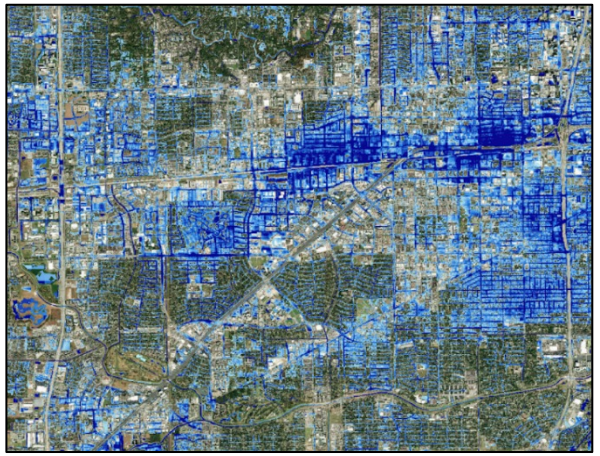
Diagnosing the Impacts of Disturbed Landscapes on Hydrologic Predictions

- 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

Community WRF-Hydro Development & Application Timeline



2003 Inception

2006 World Bank: Romania

2011 N. American Monsoon

2013 Real-time Colorado Floods (STEP)

2014 Israel & Turkey Flood Forecasting

2016 U.S. NWS National Water Model v1.0

2016-2019 Colorado ASO gap-filling radar & in situ forecast impact studies

2016-2020 Multiple European/African Applications (Alps, Italy, Norway, Nigeria)

2017 v1.1 NWM

2018 v1.2 NWM

2018 v2.0 NWM

2018-2019 Real-time RELAMPAGO Forecasting

2020 v2.1 NWM

2021 Real-time ASO assim. (CA)

2021 Iceland Hydropower

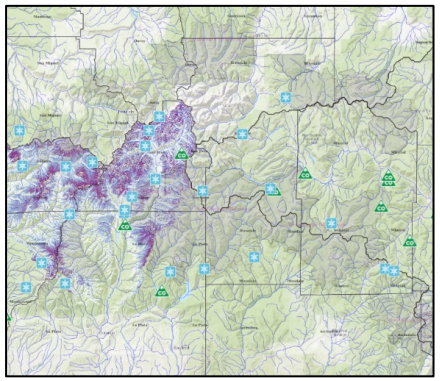
2022 UFS/WRF-Hydro Coupling

2023 USGS National Water Census v1

2023 v3.0 NWM

2023 UAE National Forecast System

2024 USDM



Major Research & Operational Deployments:

- **NOAA NWM (7 years)**
- **NOAA UFS/RRFS**
- **NOAA JEDI**
- **USGS National Water Census (new)**
- **U.S. Drought Monitor (new)**
- **State of Colorado seasonal water supply forecast**
- **State of California seasonal water supply forecast**
- Landsvirkjun/Iceland Hydropower forecast
- NASA/LIS water temperature forecasting
- **UAE National Forecast**
- U.S. DoT
- NSF/CSDMS EarthScape

Multi-scale Modeling: WRF-Hydro as the NOAA National Water Model

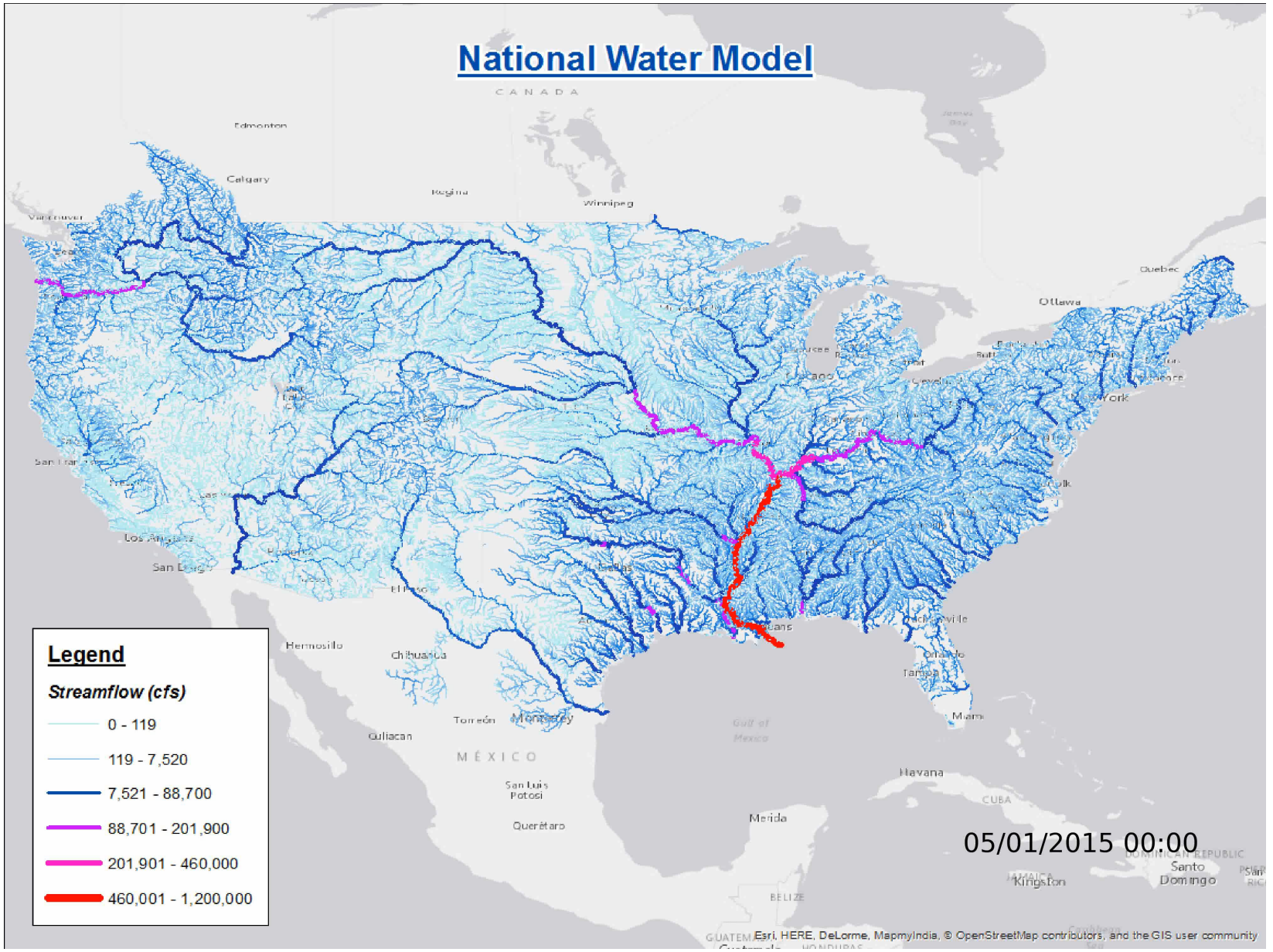
National Water Model:

Goals:

- Operational forecast streamflow guidance for currently *underserved locations*
- Fully *continuous, 24/7/365 analyses and forecasts* of the nation's surface water
- Seamlessly interface into an advanced *geospatial intelligence* framework
- Rapidly *infuse critical observation data*
- *Focus on flooding…NWS mission to protect lives and property*

Delivered:

- First-in-kind capability with respect to resolution, physics, operational cycling
- On time and under budget



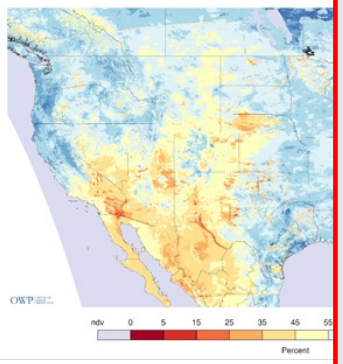
Acknowledge F. Salas, OWP

WRF-Hydro Applications: NOAA National Water Model v1.0-v3.0

v1.0

August 2016

Inaugural
water forecas
model, 1-km/
m CONUS
coverage, 2.7
reaches, strea



Soil Moistu

v1.1

May 2017

v1.2

March 2018

v2.0

June 2019

xpansion,
sembles,
d channel,
d analysis

Since v1.0 in 2016 the NWM has doubled in skill in 6 yrs according to bulk streamflow performance metrics:

- % bias: **from 31% to 68% of sites have %bias <= 20%**
- Hourly correlation: **from 18% to 52% of sites have cor >= 0.8**
- NNSE: **from 43% to 81% of sites have NNSE >= 0.6**

First ever standing forecast capabilities for:
Hawaii (v2.0), Puerto Rico/VI (v2.1)

V3.0 Expands to south-central Alaska with alpine glacier implementation

Read et al., 2023….channel routing performance
Hughes et al., 2023 (under review)….use of NWM as drought monitor
Cosgrove et al., 2023 (under review)…NWM program overview

2.1

h 2021

eat Lakes & PR/VI,
nagement modules

3.0

2023

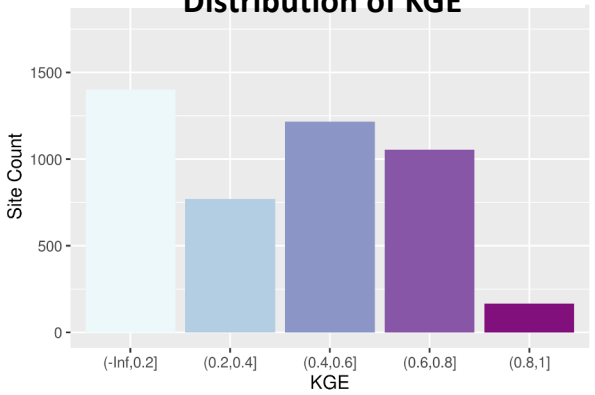
Expansion to Alaska, improved runoff, improved derived parameters, coastal coupling, glacier model implementation

Water Table Depth

Evapotranspiration – Plant/Crop Water Use

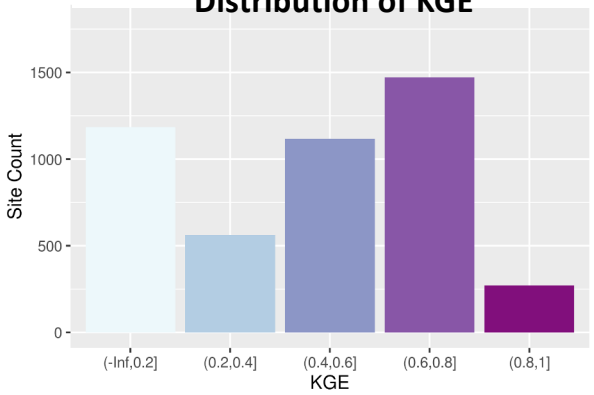
NWM v3.0 Retrospective Improvement: CONUS

v1.2



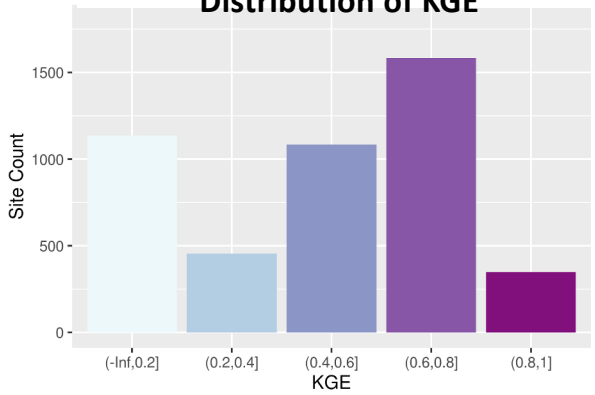
26% have KGE >= 0.6

v2.0



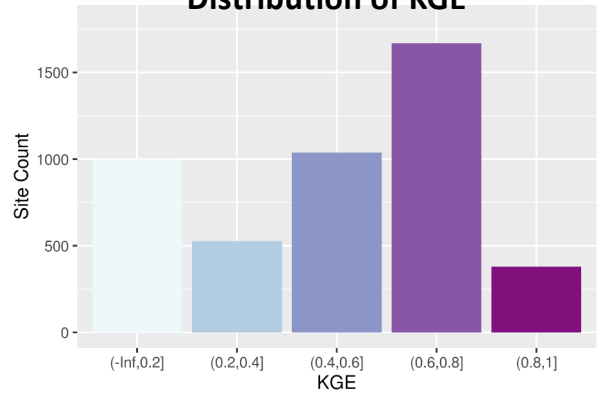
38% have KGE >= 0.6

v2.2



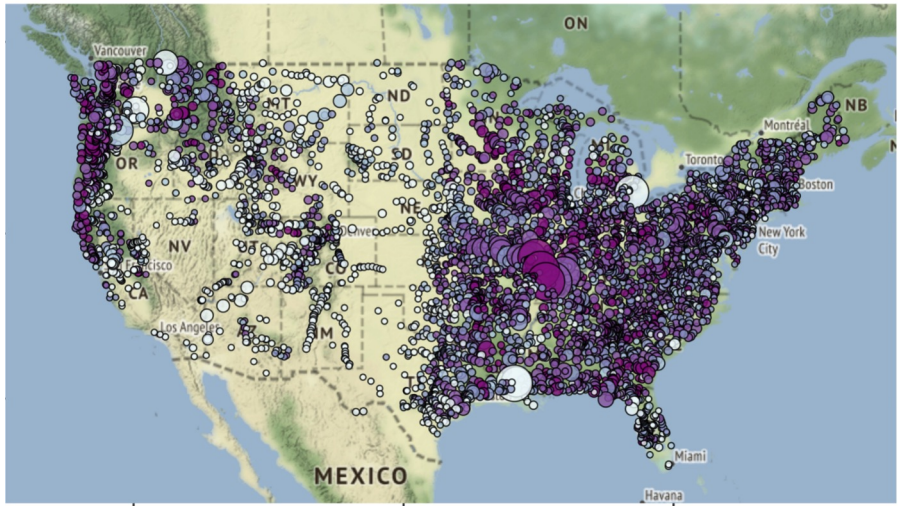
42% have KGE >= 0.6

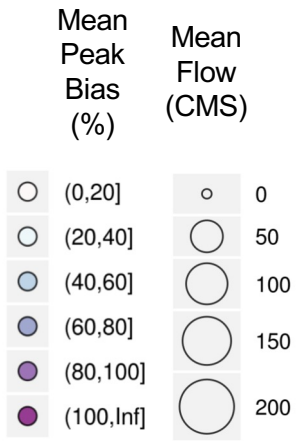
v3.0



44% have KGE >= 0.6

NWM v3.0 Streamflow KGE at USGS Gauges (WY 2014-2016, AORC Forcing)

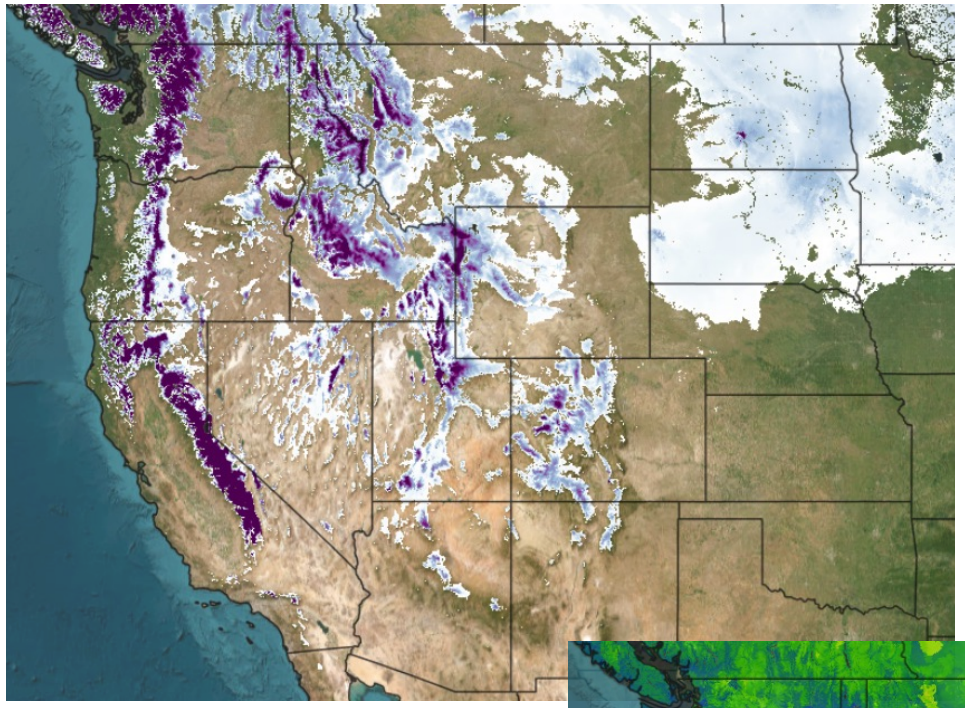




- **Streamflow KGE continues to improve at USGS gauged basins**
- **Simulation is for WY2014-2016 (validation period) and uses AORC forcing data**
- **No assimilation of streamflow or reservoir observations**

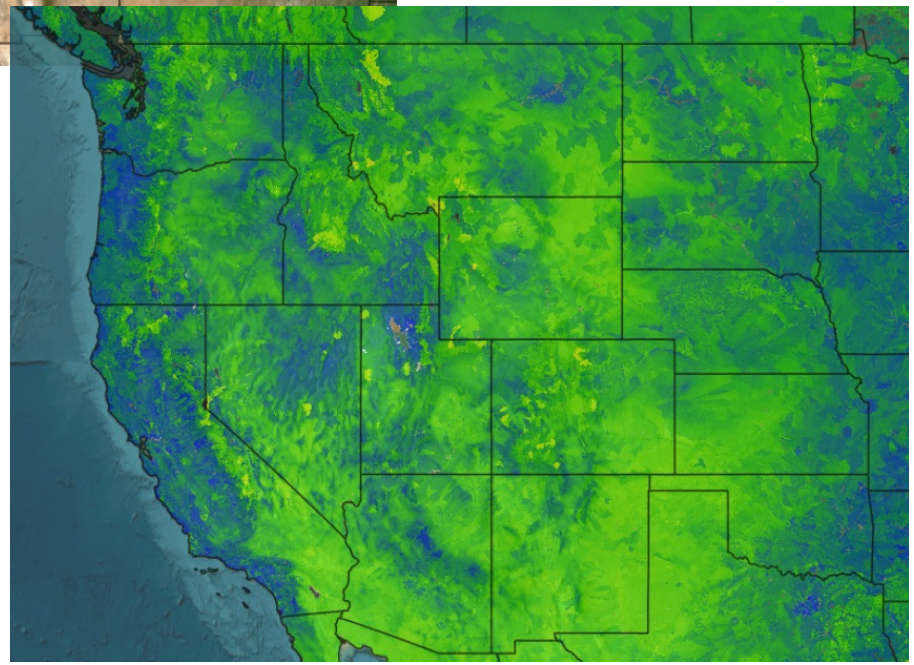
WRF-Hydro Applications: USGS National Water Availability Assessment (IWAA)

- **USGS Integrated Water Availability Assessment:**
  - AKA “Water Census”
  - Congressionally-mandated and officially reported to U.S. Congress
  - Documents trends and vulnerabilities in water resources
  - Looks at changes in full water budget
  - NCAR providing unique hydrologic modeling and future climate scenario capabilities



Peak Seasonal Snowpack

Soil Moisture

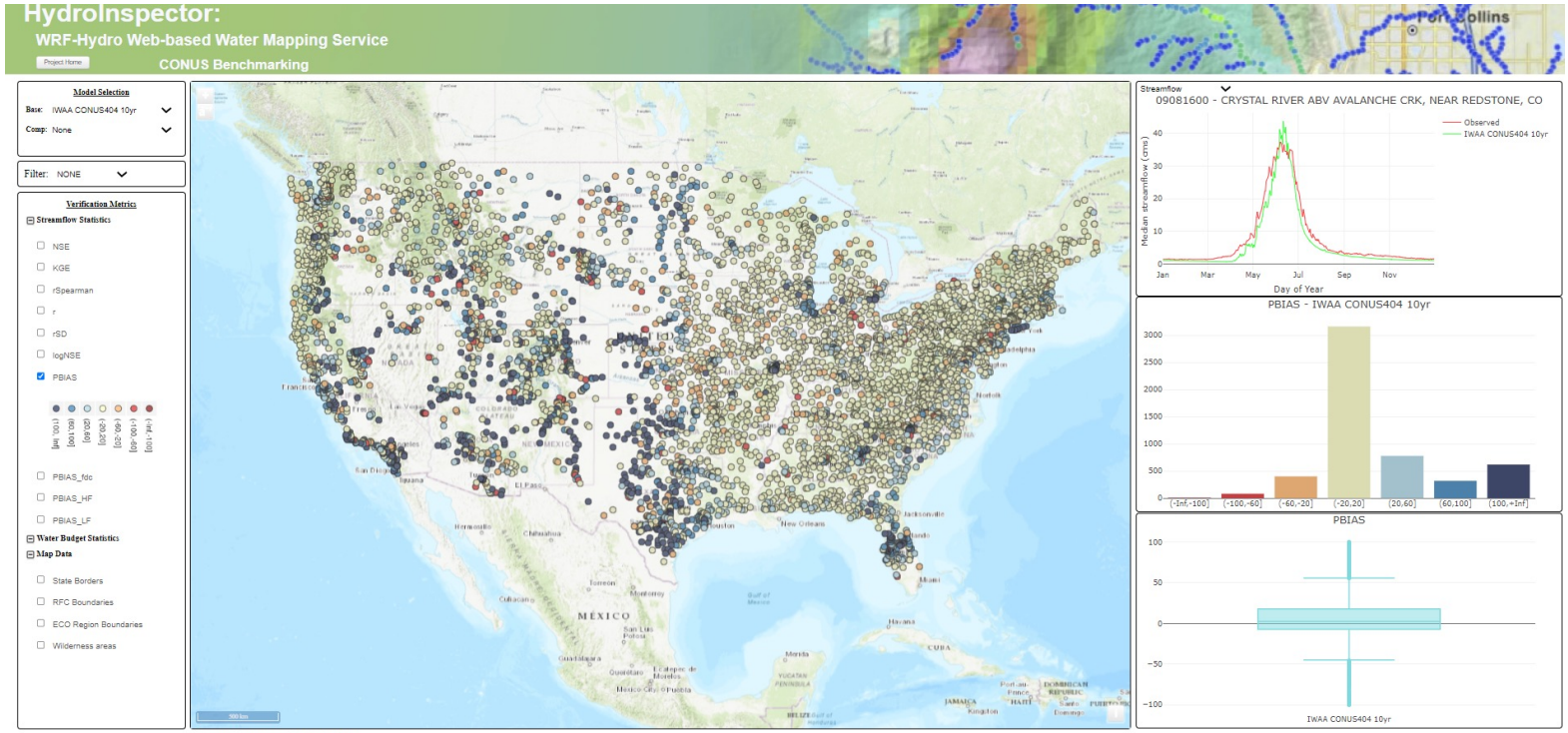


- **2024: U.S. Drought Monitor**

USGS National Water Availability Assessment (IWAA):

- National hydrologic model and water budget benchmarking:
  - Assess quality and veracity of current CONUS scale models of the nation's water resources
  - Created bias-adjusted version of CONUS-404 for water resources research & applications

- Highlight: WRF-Hydro has exceeded performance of both USGS National Hydrologic Model and CONUS-Parflow in overall simulation of streamflow across country (Tijerina et al., 2021; Towler et al., 2023)



***HydroInspector:* Web-mapping service for shared intercomparison of hydrologic models, forecasts and future scenarios**

Towler et al., 2023: HESS

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1. WRF-Hydro System Description
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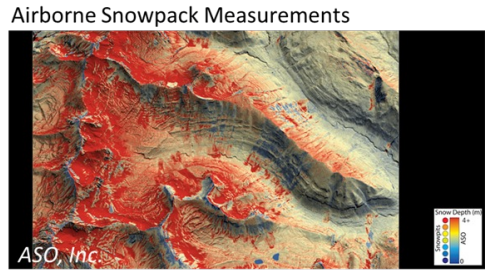
3. **Science Highlight: Assimilation of airborne-lidar snowpack observations into operational water supply forecasts**
4. New Evolutions

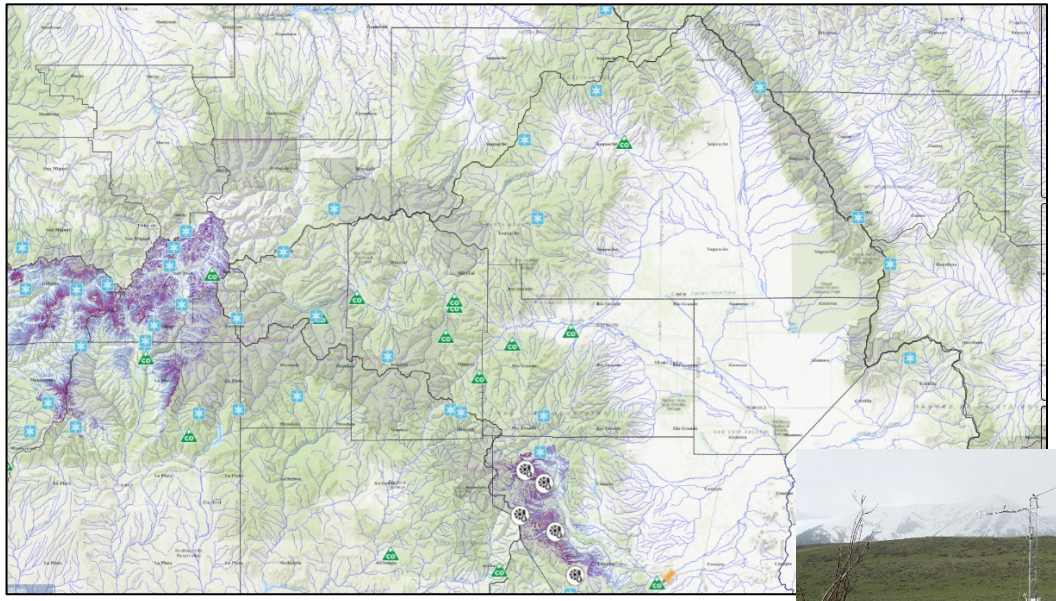
WRF-Hydro Science and Prediction Highlight: Improving Runoff and Water Supply Predictions in High Mountain Watersheds:

- CWCB-initiated multi-year effort spanning back to 2009 through present with expanding focus
- Embedded research efforts with focused hypotheses for improving forecasts

- Goals: Address observational and model deficiencies limiting skill of water resources predictions & projections
  - Improving and integrating water cycle observations in high mountain watersheds (in-situ stations, remotely sensed snowpack, gap-filling radars,)
  - Advance data assimilation methods in predictive models of water resources
  - Address shortcoming in process models of key water cycle variables (ET, snowpack ablation, runoff generation, sfc-water/gw interactions, alpine glaciers)

- Partners: *CWCB, Colorado Water Districts, WRF-Hydro & NoahMP Development Teams, ASO Inc., USGS, DOE, NSSL*





Gochis et al., 2016; Abolafia-Rosenzweig et al., 2022

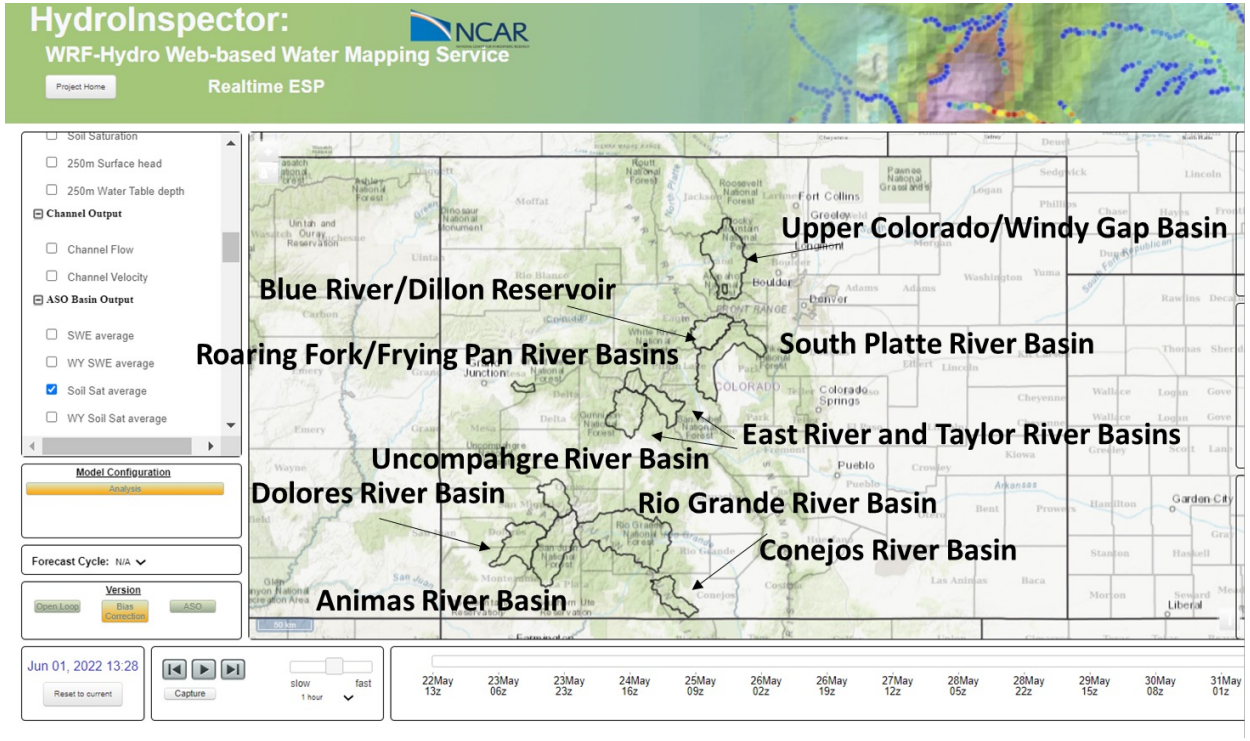
Snowmelt runoff forecasts with sparse data & increasing variability

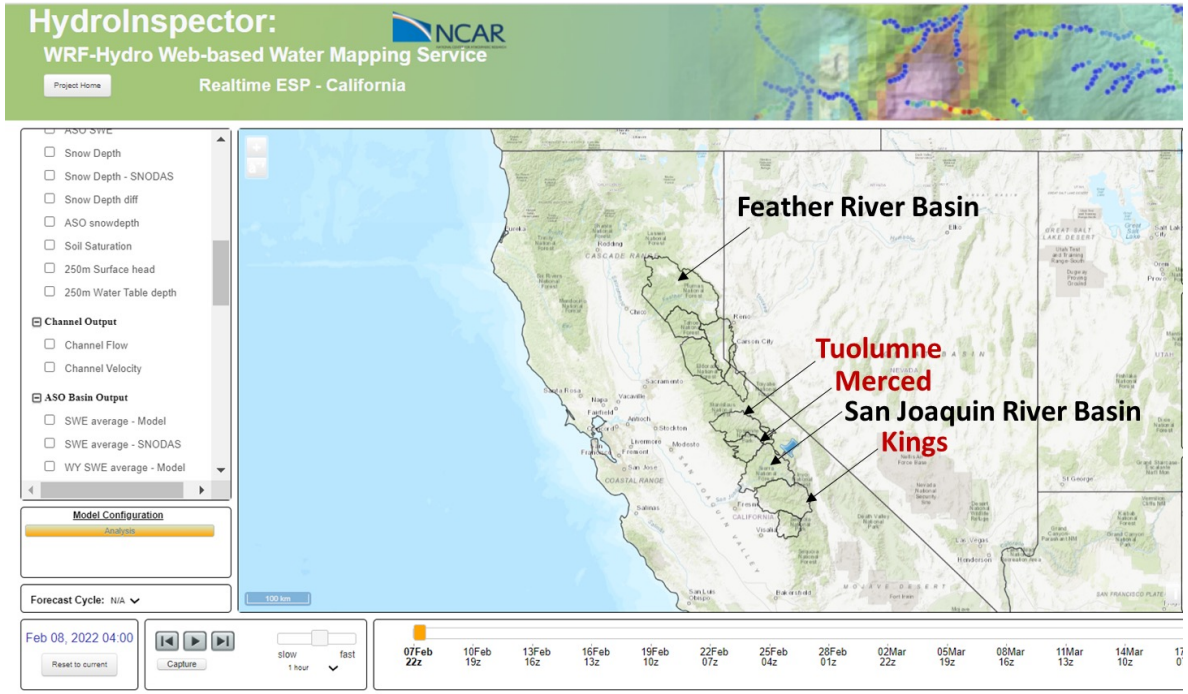
Elk Range
ASO Snow Depth
April 2019

Snow Depth (m)
0 5+

Water prediction for western water woes…: Transformative capabilities in seasonal prediction

Colorado: Colorado Airborne Snow Measurement Program (CASM):
Nascent effort to build statewide observation and prediction program



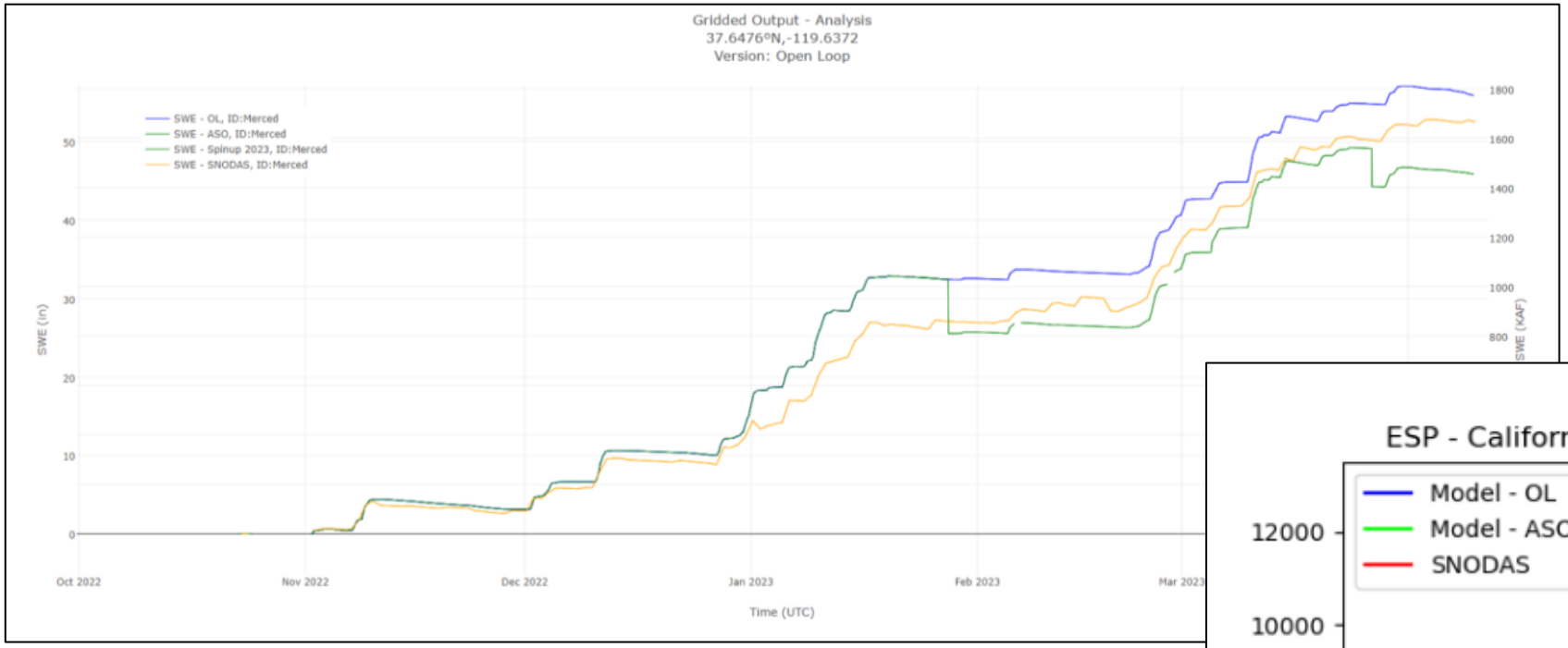


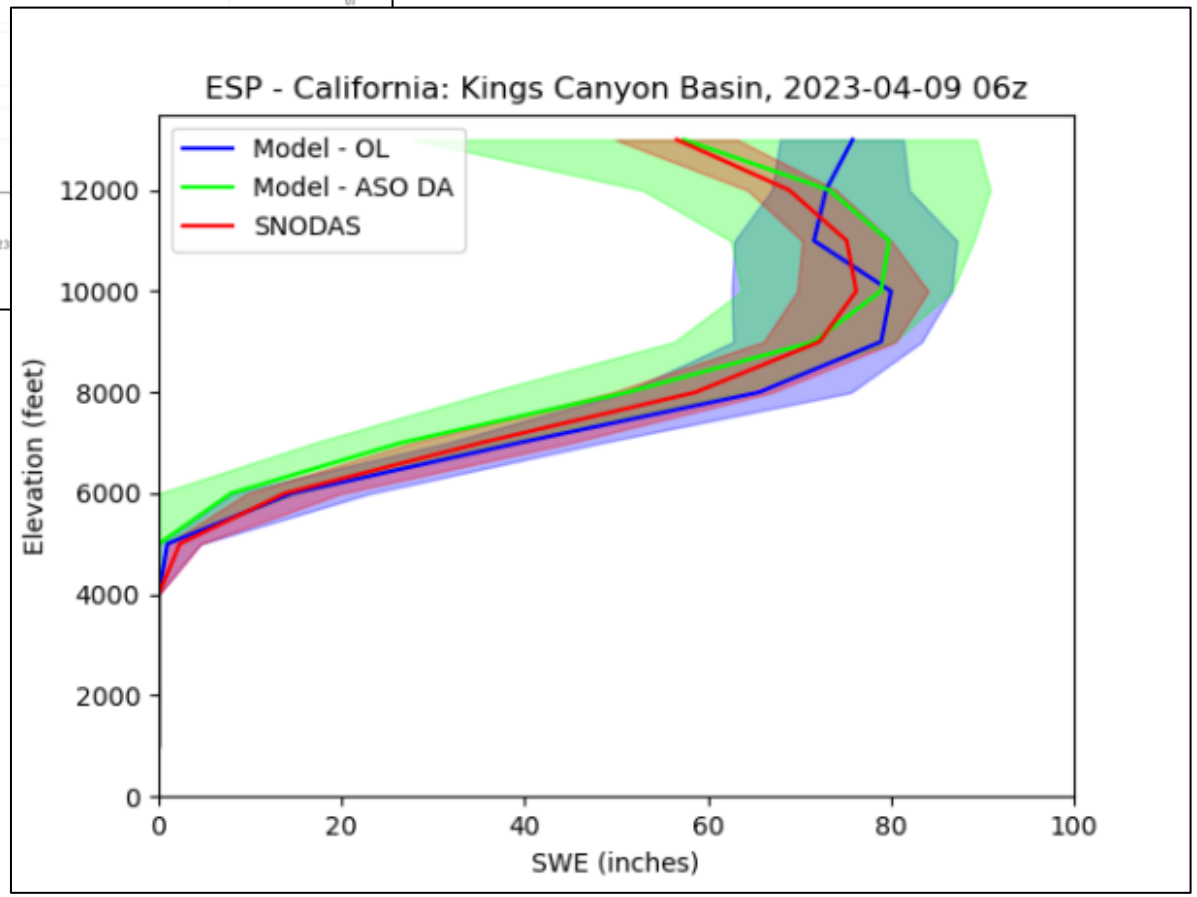
California: Dept. Water Resources funded Demonstration project…

Just got requested to fastrack double the number of forecast basins for this year by CADWR based on stakeholder demand for critical operational information

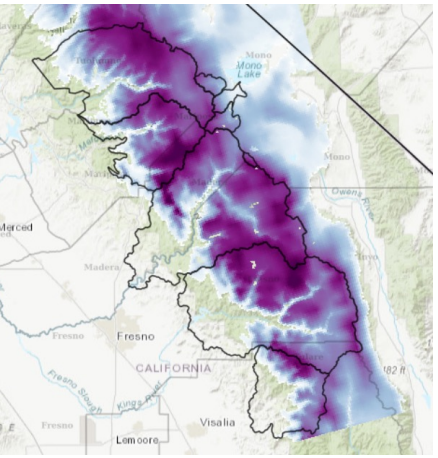
- Rapidly expanding domain of coverage for water supply forecast services

WRF-Hydro California ESP: 2023 Implementation

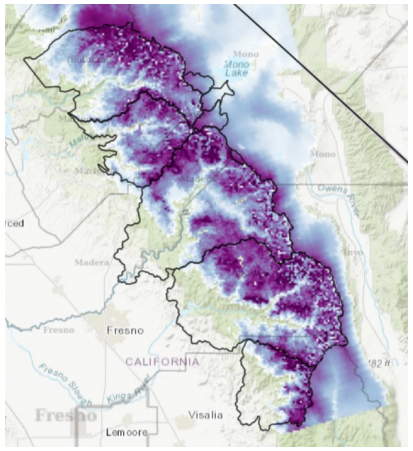




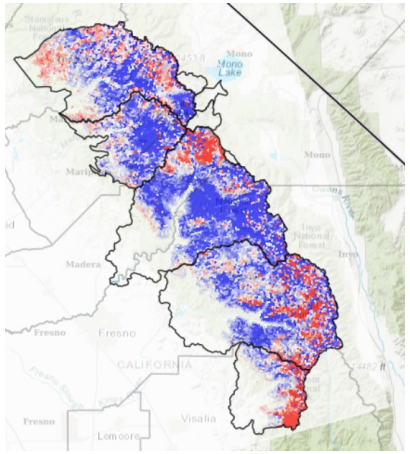
OpenLoop



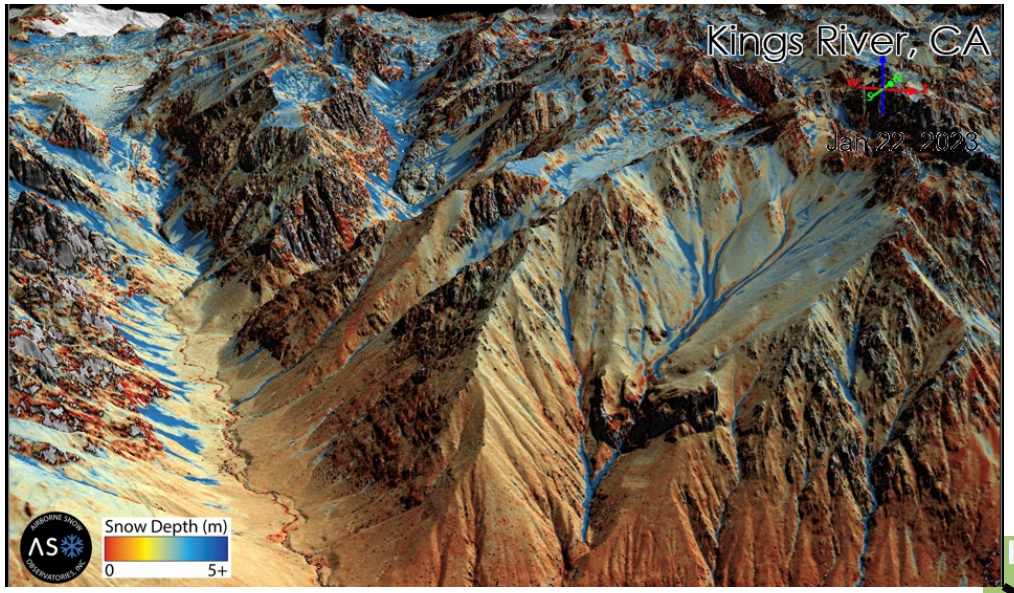
ASO-assimilated



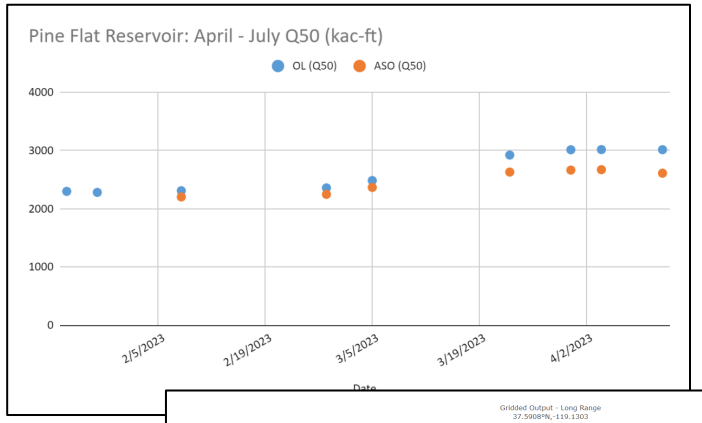
OL – ASO/WH

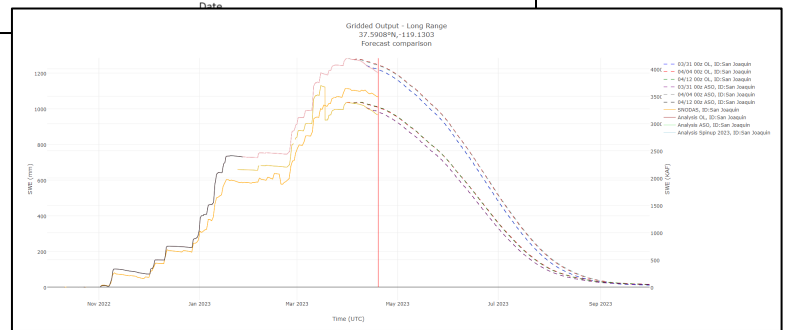


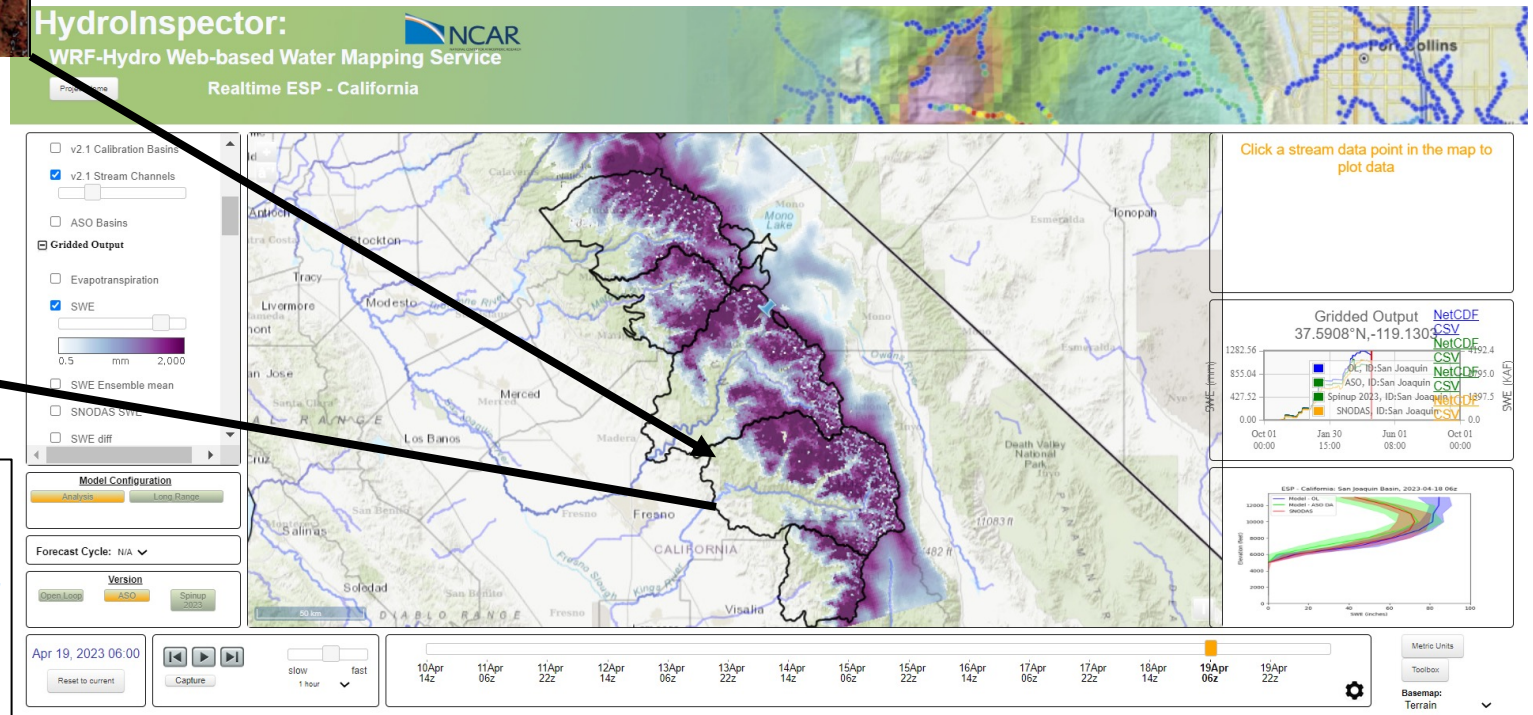
Water prediction for western water woes…: Transformative capabilities in seasonal prediction



- Rapidly assimilate new ASO surveys into WRF-Hydro
- Providing updated ensemble seasonal snowpack, runoff and peak flow forecasts multiple times/week
- Forecasts feed into California and Colorado water management models





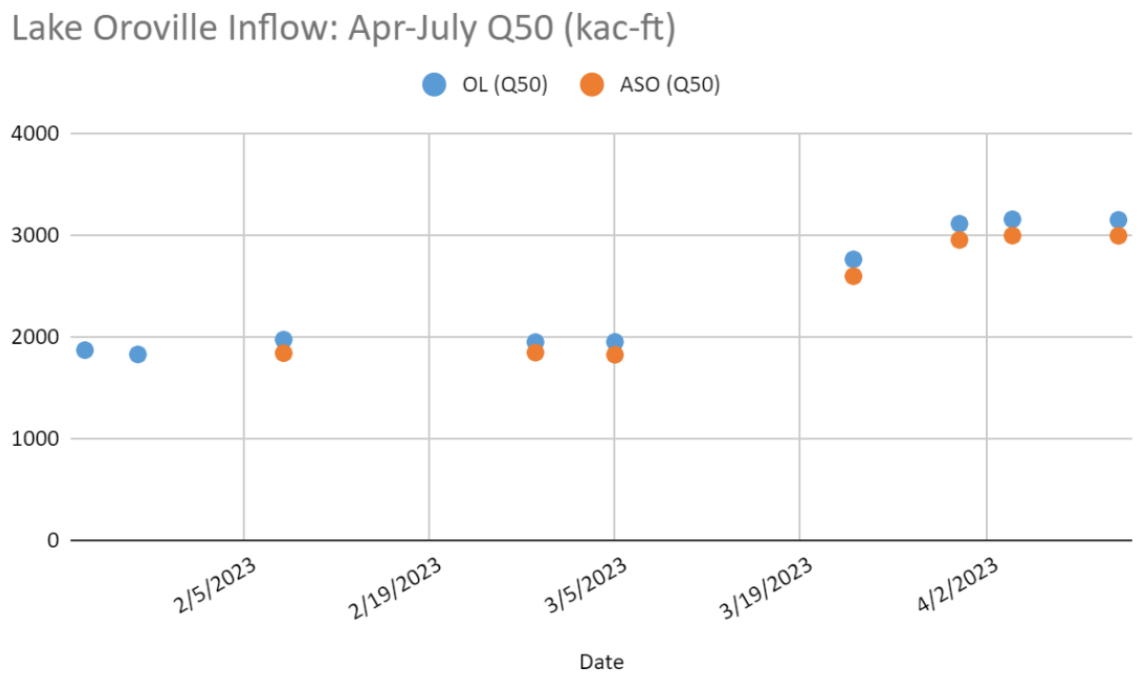


WRF-Hydro California ESP: 2023 Implementation

Basin-integrated Snow Water Equivalent:

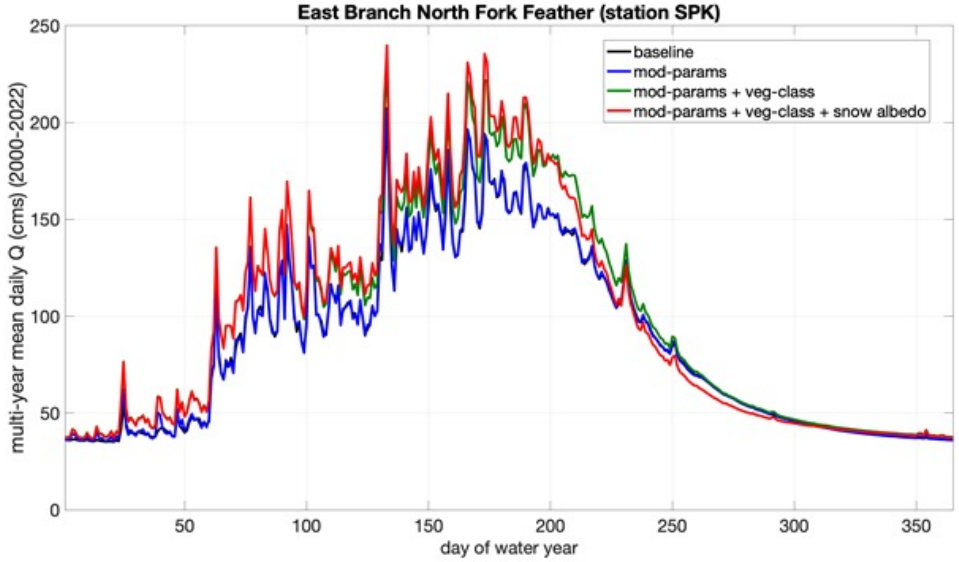
Tabulated values:

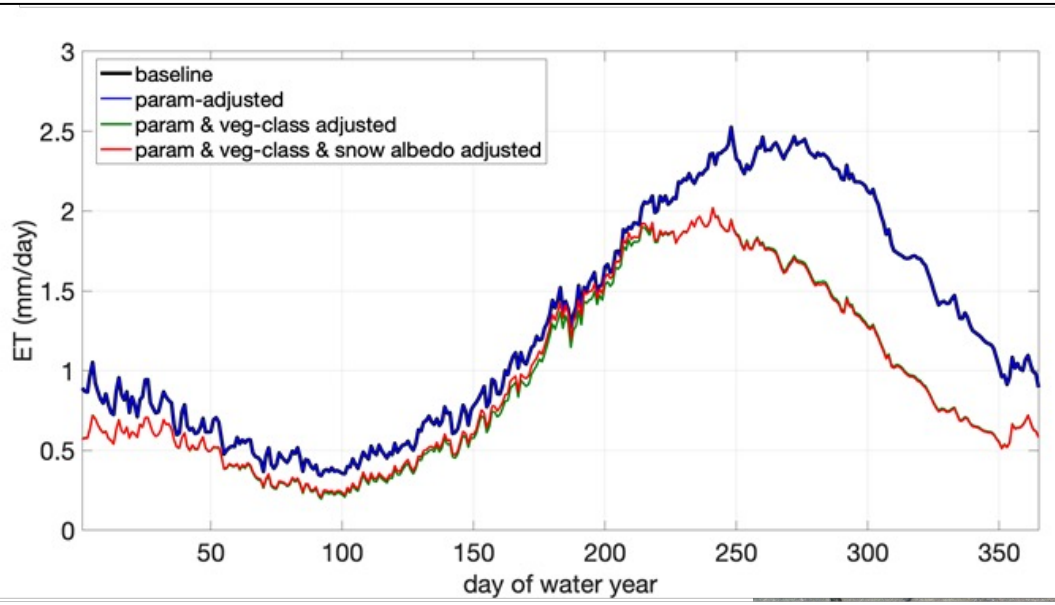
	Feather River			Tuolumne			Merced			San Joaquin			King's		
Date	OpenLoop	ASO	SNODAS	OpenLoop	ASO	SNODAS	OpenLoop	ASO	SNODAS	OpenLoop	ASO	SNODAS	OpenLoop	ASO	SNODAS
Jan. 24	2120	n/a	2333	1656	1367	1540	1036	n/a	830	2396	2155	1920	2178	n/a	2041
Jan. 28	2094	n/a	2313	`1639	1357	1554	1027	810	859	2380	2148	1920	2166	2087	2062
Feb. 6	2143	n/a	2463	1719	1432	1647	1068	850	894	2462	2226	1998	2220	2138	2134
Feb. 12	2097	1913	2409	1702	1416	1622	1060	844	935	2460	2226	2007	2211	2136	2173
Feb. 27	2295	2062	2923	2055	1657	1979	1273	1009	1087	2975	2625	2464	2748	2591	2559
Mar. 13	3091	2943	4142	2580	2276	2543	1604	1422	1469	3728	3491	3091	3452	3379	3319
Mar. 23	3072	3021	4095	2782	2458	2728	1733	1553	1563	4060	3246	3470	3873	3541	3695
April 1	3397	3242	4437	2920	2817	2593	1812	1632	1654	4192	3384	3641	4009	3682	3870
April 4	3348	3187	4556	2894	2572	2956	1797	1472	1675	4168	3366	3610	3994	3671	3864
April 12	3233	3067	4468	2847	2531	2927	1771	1454	1665	4119	3332	3597	3944	3639	3841
(all values in kac-ft)															

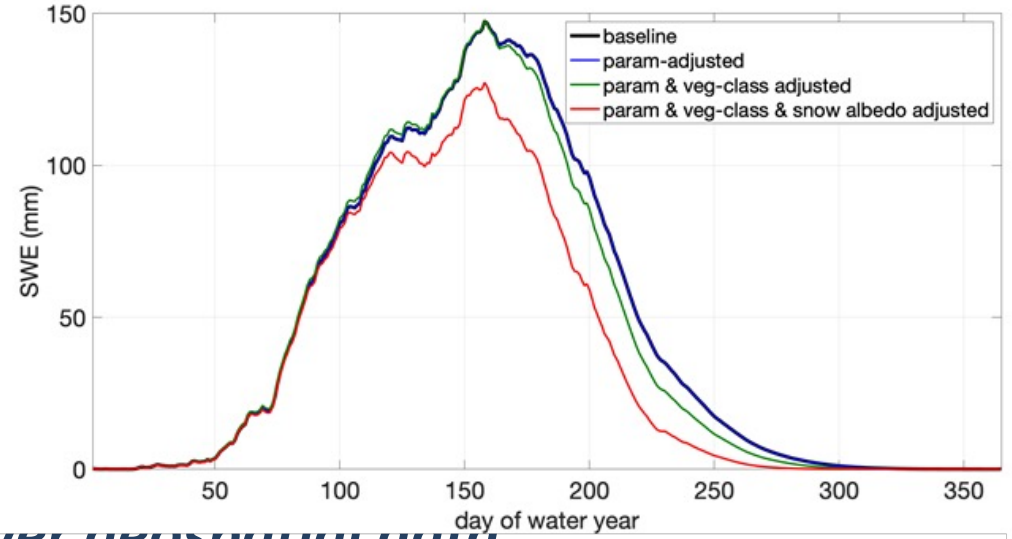


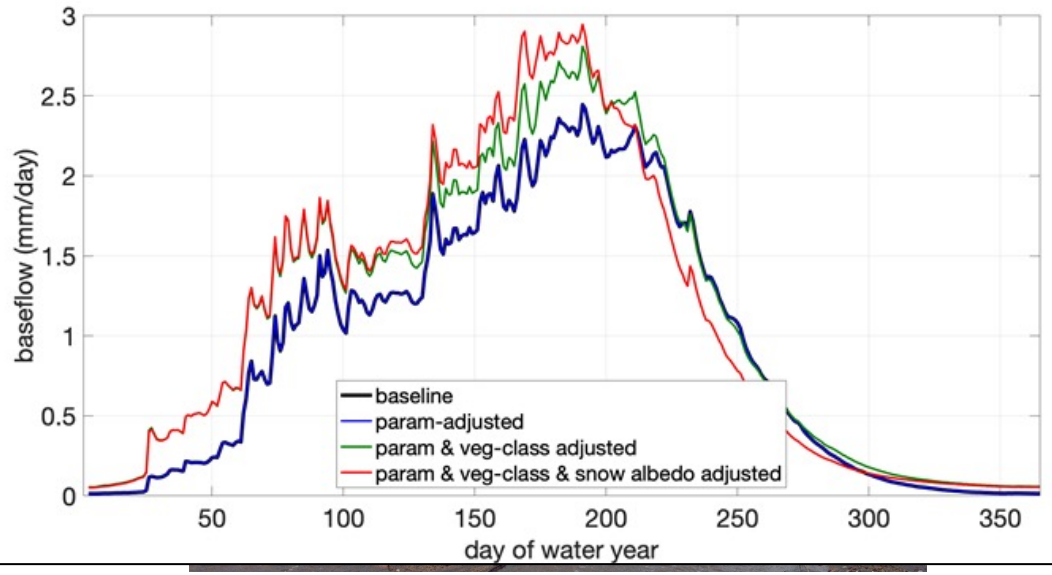
Lake Oroville				*Apr. 1 - Jul. 31*		
Forecast Date	**Mean**	**Q90**	**Q75**	**Q50**	**Q25**	**Q10**
Jan. 24, 2023 (OL)	2058	1230	1450	1867	2326	3313
Jan. 24, 2023 (ASO)	n/a	n/a	n/a	n/a	n/a	n/a
Jan. 28, 2023 (OL)	2019	1210	1396	1825	2318	3314
Jan. 28, 2023 (ASO)	n/a	n/a	n/a	n/a	n/a	n/a
Feb. 8, 2023 (OL)	2095	1220	1405	1970	2452	3486
Feb. 8, 2023 (ASO)	1999	1146	1306	1838	2377	3356
Feb. 27, 2023 (OL)	2090	1231	1478	1946	2572	2865
Feb. 27, 2023 (ASO)	1975	1139	1378	1843	2459	2701
Mar. 5, 2023 (OL)	2256	1486	1695	1948	2725	2882
Mar. 5, 2023 (ASO)	2123	1367	1559	1822	2587	2753
Mar. 23, 2023 (OL)	2927	2378	2515	2759	3392	3675
Mar. 23, 2023 (ASO)	2765	2222	2355	2594	3222	3506
Mar. 31, 2023 (OL)	3158	2688	2806	3109	3460	3821
Mar. 31, 2023 (ASO)	2996	2530	2646	2950	3286	3649
Apr. 4, 2023 (OL)	3150	2681	2846	3153	3421	3734
Apr. 4, 2023 (ASO)	2988	2524	2691	2993	3256	3568
Apr. 12, 2023 (OL)	3130	2734	2858	3147	3315	3626
Apr. 12, 2023 (ASO)	2973	2587	2701	2991	3160	3458

Hydro-disturbance representation: Dixie/Paradise Fire Complex, CA (CADWR)









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cover geospatial data

Abolafia-Rosenzweig, Dugger, Gochis, He

WRF-Hydro: New Evolutions & Opportunities

Current Evolutions of WRF-Hydro:

1. Integration of advanced Data Assimilation: Linking WRF-Hydro/NoahMP to both DART and JEDI for improved understanding and prediction of terrestrial hydrology (STEP, NOAA)
2. Explicit, physics-based groundwater modeling: 3 separate funded efforts in BMI-based model coupling (USGS-MODFLOW, Parflow, Miguez-Macho)
3. Expanded representation of explicit, terrestrial hydrology in coupled weather/climate prediction: RELAMPAGO, UFS, USGS
4. Alpine glacier contributions to hydrologic predictions: NWM v3.0 AK domain, Iceland implementation, upcoming USGS AK application (NOAA, NPS)
5. Enhance linkages to water resources management and allocation models: (WEAP, Riverware): Idaho DWR, Utah DWR, USGS
6. Coupling to coastal models: Coastal/estuary inundation modeling with SCHISM/ADCIRC and USGS models: (U.S. State Dept./NOA, NOAA, USGS)

Cross-cutting Opportunities:

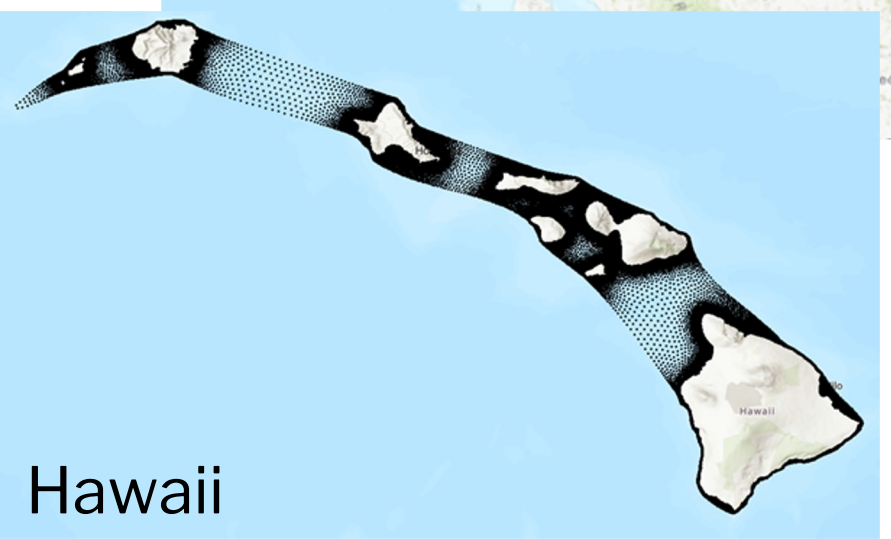
1. Expand WRF-Hydro methodologies into MPAS using enhanced physics and standards-based coupling interfaces (STEP)
2. Link with CTSM for longer-term spatially-explicit hydroclimate/BGC/water quality applications…(USGS)
3. Disturbance Hydrology: Link to NCAR Remote Sensing Initiative…requires rapid update and use of real-time, evolving products (CADWR, USGS)

Thank you

WRF-Hydro Team

NWM v3.0 Total Water Level Domain Coverage

TWL output is masked at depths greater than 5 meters offshore, extends to 10 meter topographic height inland

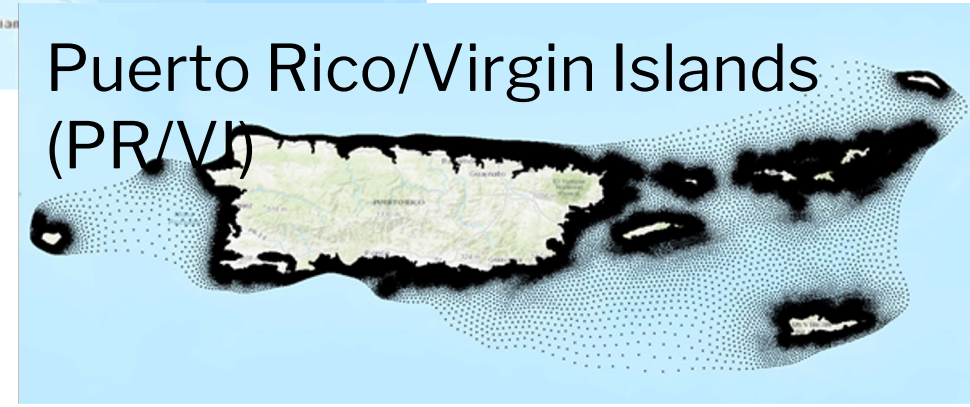


<u>Average Resolution</u>

Atlantic Coast: 75 m

Pacific Coast: 50 m

PR-VI and HI: 30 m

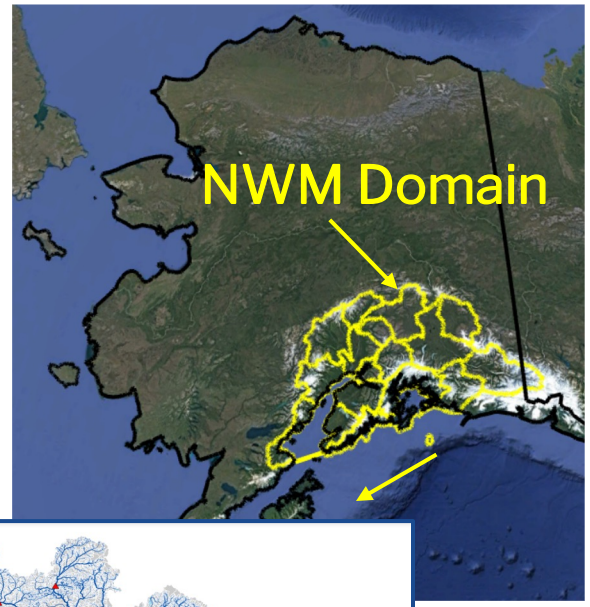


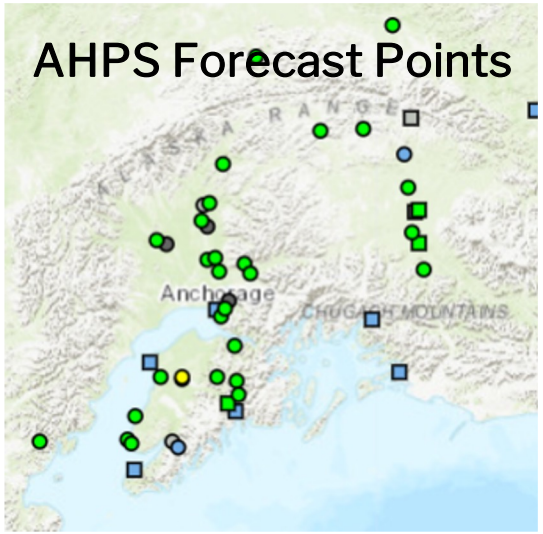
NWM v3.0: New Alaska Domain

Overarching Goal: Provide complementary and first-time hydrologic guidance for Alaska's Cook Inlet, Copper River Basin and Prince William Sound Regions

NWM Alaska Summary

- Close coordination with Alaska Pacific RFC
  - Assimilation of APRFC glacial dam lake (GDL) outflow forecasts
  - Customized model and forcing configurations
- Guidance for 390k stream reaches complements RFC AHPS sites
- Total water level guidance for AK coast in Version 4.0 of the model





Dense network of NWM hydrologic guidance