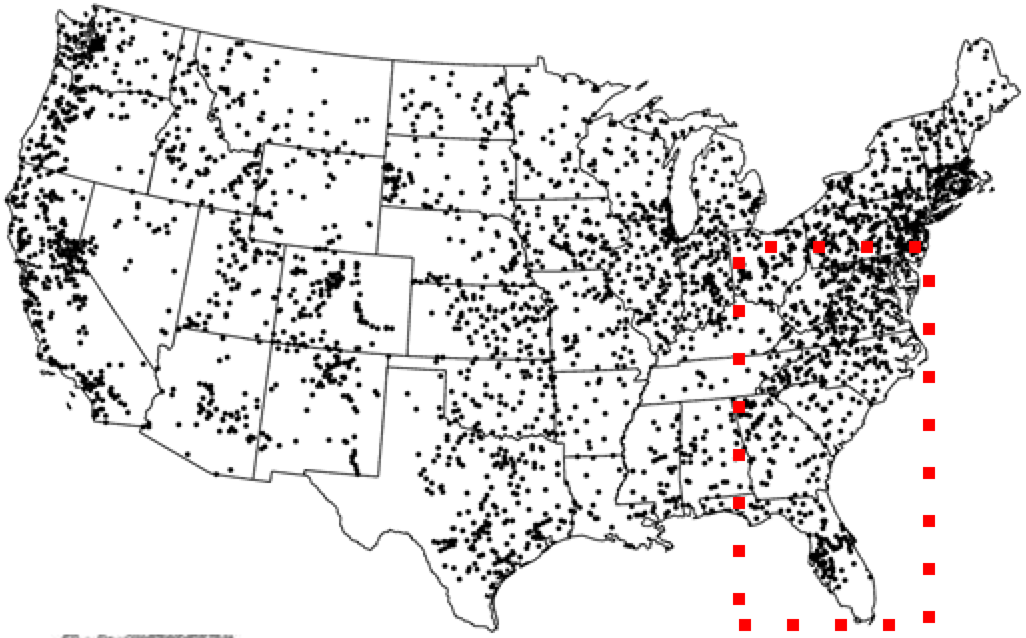
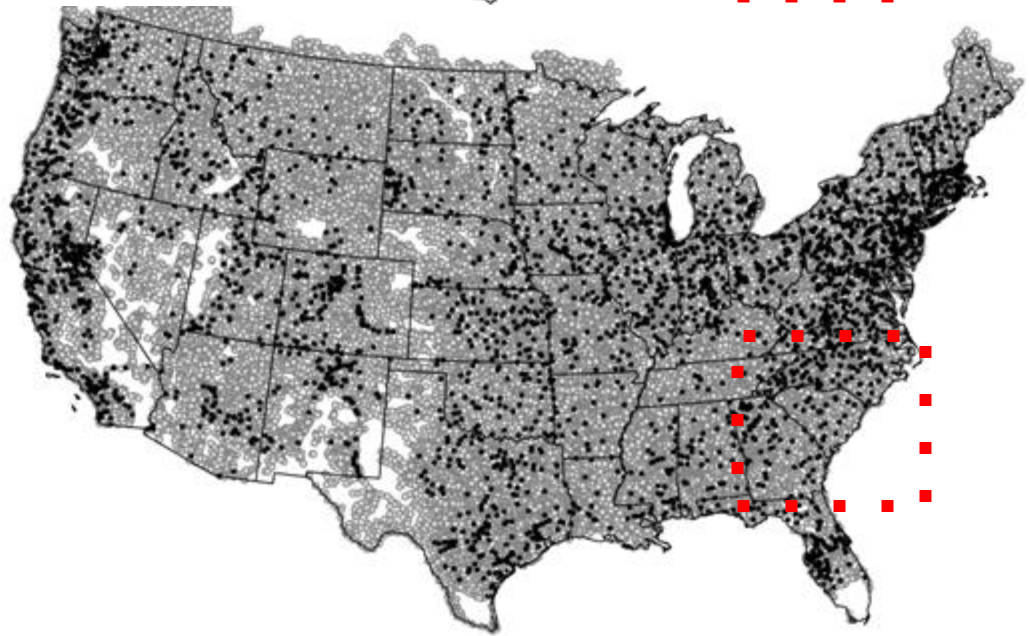
Data-Driven Hydrological Drought Onset, Duration and Intensity Forecasts for the Conterminous United States: Developing and Testing an Operational Tool to Enhance Drought Early Warning

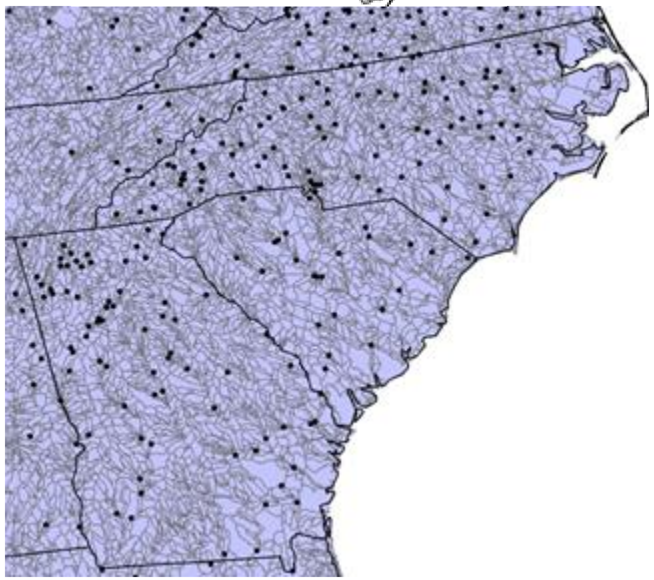
Presenter: John Hammond, Research Hydrologist, U.S. Geological Survey, MD-DE-DC Water Science Center.

Project scientists: Hayley Corson-Dosch, Jeremy Diaz, Phillip Goodling, Scott Hamshaw, Aaron Heldmyer, Ryan McShane, Jesse Ross, Roy Sando, Caelan Simeone, Leah Staub, David Watkins, Michael Wieczorek, Kendall Wnuk, Jacob Zwart.

BLUF: Streamflow drought forecasting tools coming soon







First version:

- Weekly-scale streamflow percentile forecasts with 1-13 week lead time
- Public facing webmap with tabular forecasts provided via AWS S3 link
- ~3,200 gaged locations across the conterminous U.S. *(sites with complete record 1981-2020)*

Second version:

- Improvements to gaged forecasts to account for more human flow regulations, enhanced treatment of meteorological forecasts
- State / river basin level summaries and API data access
- Forecasts also provided for an additional ~60,000 ungaged locations (based on USGS + NOAA National Hydrologic Geospatial Fabric)
- Addition of a retrospective set of ungaged area predictions 1981-2020

Presentation overview

1. What is hydrological drought and how do we identify it?
2. Forecasting streamflow drought across the conterminous U.S. at gaged locations
3. Including reservoirs in streamflow drought models
4. Ungaged area forecasts and historical predictions
5. National groundwater drought modeling

What is hydrological drought?

Hydrological drought is "a lack of water in the hydrological system, displaying as abnormally low flow in rivers and streams, and as abnormally low levels in lakes, reservoirs, and groundwater."

Hydrological drought impacts: widespread and recurring

Depending on your water use type, management constraints, and location, different ways of defining drought may be more useful than others.

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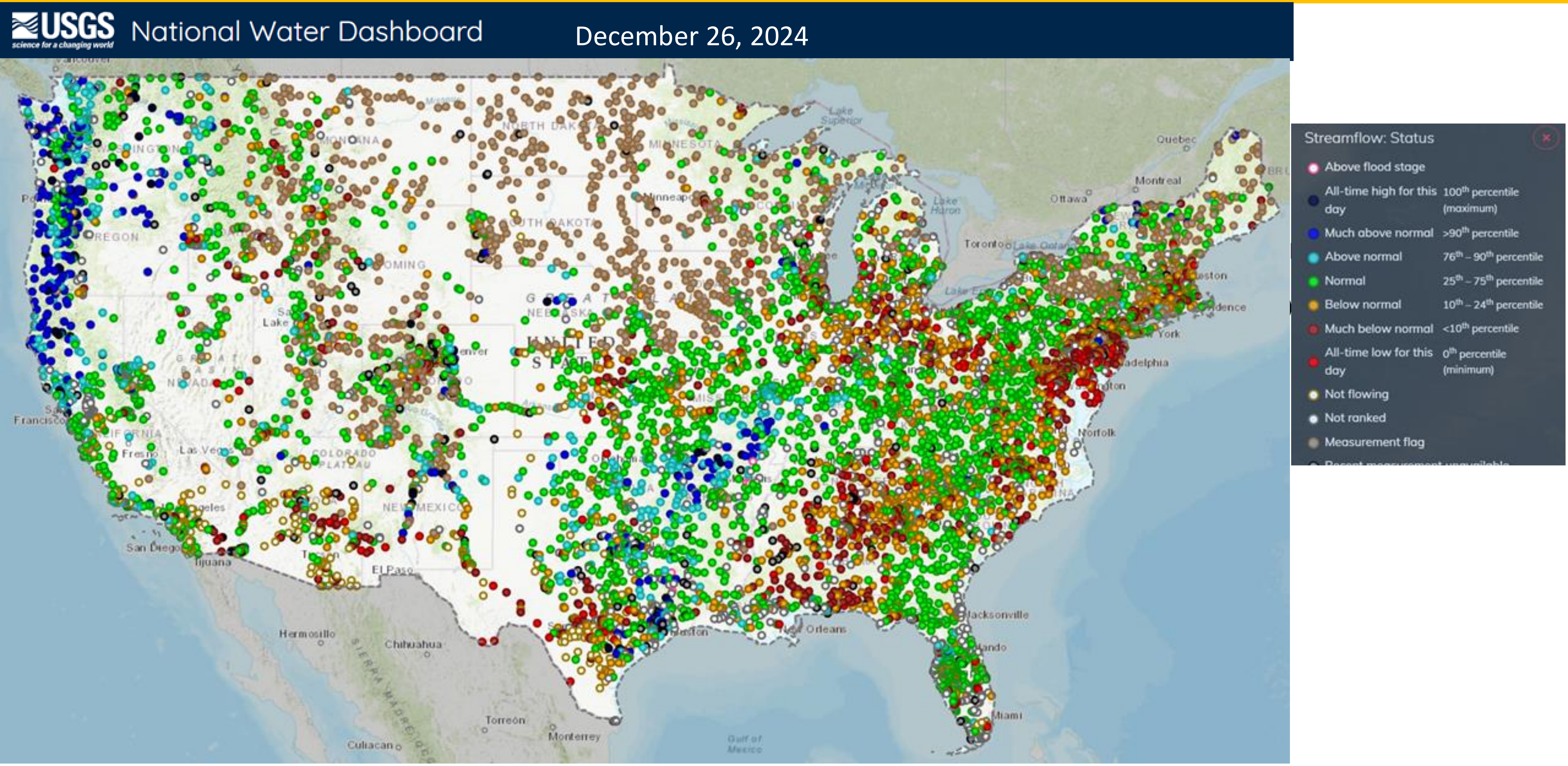
Identifying hydrological droughts: a focus on streamflow drought



Drought prediction project objectives:

- **Define drought** in generalized, relevant ways for multiple stakeholder groups.
- **Apply data-driven models** to determine feasibility of forecasting drought onset, duration and severity weeks to months in advance.
- **Improve methods** for drought prediction in heavily regulated areas.
- **Assess performance** and compare with existing national-scale physically-based models.
- **Prototype** operational drought assessment and forecast tools that communicate predictions + uncertainty.

NIDIS

Jan. - Oct. 2022
Listening Sessions

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Stakeholder Needs

Daily or weekly operational model

Estimate forecast uncertainty

Spatial coverage for entire basin

Short-term to seasonal forecasts

Include water use

Drought Prediction and Water Availability: A Report on the 2022 USGS-NIDIS National Listening Session Series | Drought.gov

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General modelling approach

3,200 streamflow gages with 40-year record

(Simeone, 2022)

+

Static *(land cover, human activity, etc.)* and time-varying attributes *(meteorology, soil moisture, antecedent streamflow)* aggregated in common geospatial fabric

(Wieczorek and others, 2023)

0, 1, 2, 3, 4, … and 13 week forecasts

Regression
(exact percentile)

- Boosted regression trees [lightGBM]
- Long short-term memory neural networks (LSTMs) [NeuralHydrology]

Classification
(in or out of drought)

- Boosted regression trees [lightGBM]
- LSTMs [NeuralHydrology]

Shared Evaluation Metrics

Existing physically-based models

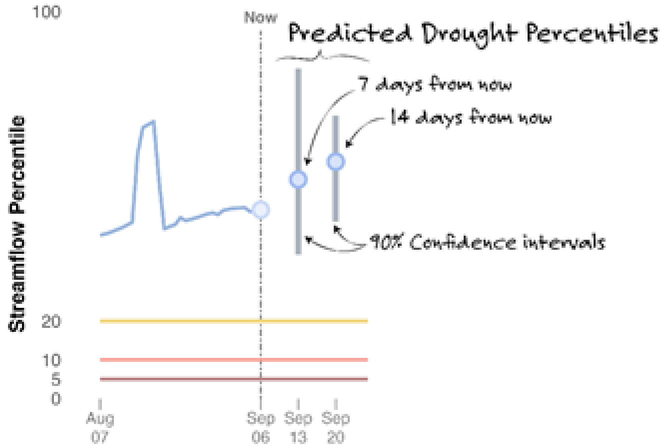
Conterminous U.S. streamgages with long-term, complete records:

3,200 USGS streamflow gages with nearly complete 1981-2020 daily record

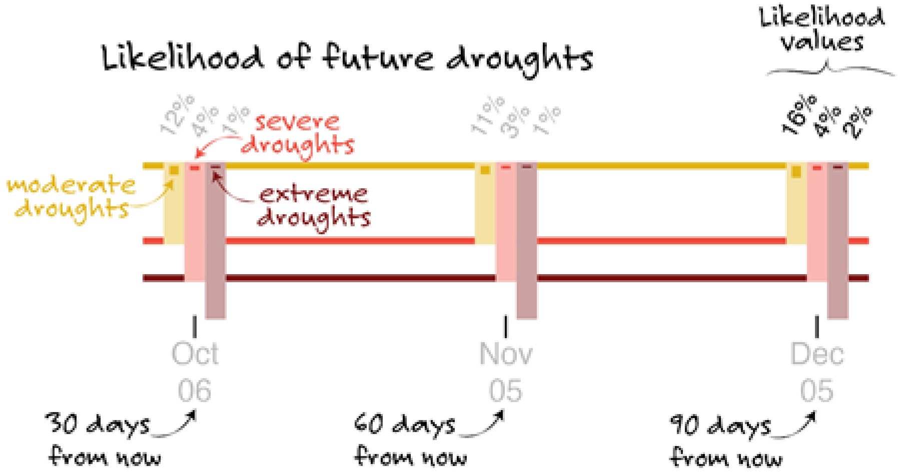
Modeling methods

Modelling approaches used:

Streamflow percentile modeling (regression):
Modeling streamflow percentiles for 7 and 14 days into the future.

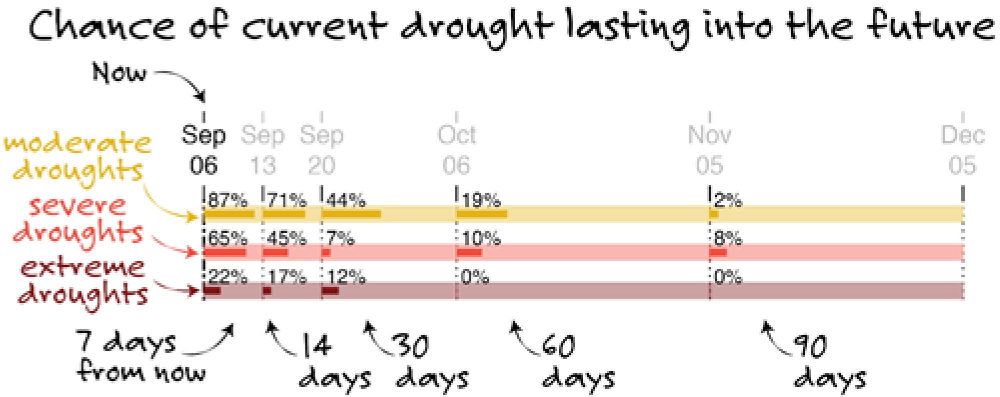


Drought likelihood modeling (classification):
Modeling the likelihood that streamflow percentiles will be below an intensity threshold in N-days. N-day periods modeled = 7, 14, 30, 60, 90. Models developed for three drought intensities:



<u>Drought intensity classes used:</u>
<20th percentile = National Drought Monitor, ***Moderate Drought***
<10th percentile = National Drought Monitor, ***Severe Drought***
<5th percentile = National Drought Monitor, ***Extreme Drought***

Drought duration modeling (classification): Modeling the likelihood that if a drought continues from the prior day, or was to start today, that it would last another N-days. Models developed for three different drought intensities and for 7-90 day periods.



Model inputs extracted for each site

Time variable area-weighted watershed mean values:

Variable	Units	Source	Reference
Minimum Temperature	°C	gridMET	(Abatzoglou, 2013)
Maximum Temperature	°C		
Precipitation	mm		
Evapotranspiration (Reference - grass)	mm		
Standardized Precipitation Evapotranspiration Index (SPEI)	unitless		
Snow Water Equivalent (SWE)	mm	NASA NSIDC	(Broxton and others, 2019)
Soil Moisture (0-10 mm depth)	kg/m²	NASA NLDAS	(Mitchell, 2004)
Soil Moisture (10-40 mm depth)	kg/m²		
Soil Moisture (40 – 100 mm depth)	kg/m²		
Observed streamflow	mm/d	USGS	(USGS, 2023)
Precipitation (7 + 14-day ensemble forecasts)	mm	GEFS	(Zhou et al., 2022)
Mean temperature (7 + 14-day ensemble forecasts)	°C		
Precipitation (1,2,3 month ensemble forecasts)	mm	NMME CFSv2, SUBX, ECMWF	(Kirtman et al., 2014), SubseasonalClimateUSA github
Mean temperature (1,2,3 month ensemble forecasts)	°C		
Monthly maximum surface water extent (DSWE C2)	%	Landsat	(Jones et al., 2022)
Monthly irrigation, public supply water use	Mgpd	USGS	(Martin et al., 2023) revised version

Baseline data available through yesterday.

Continued experimentation, including meteorological forecast datasets.

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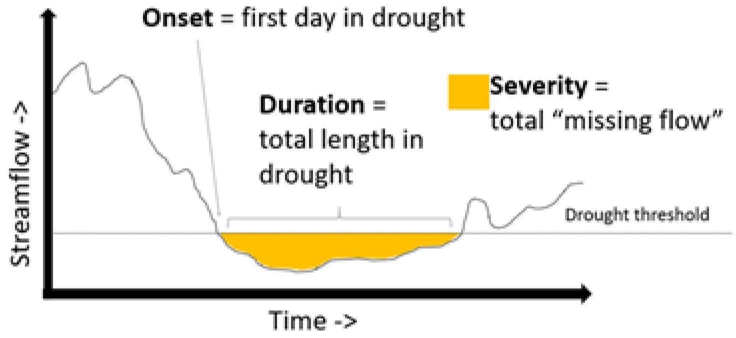
Static watershed attributes: degree of regulation, topography, land cover etc.

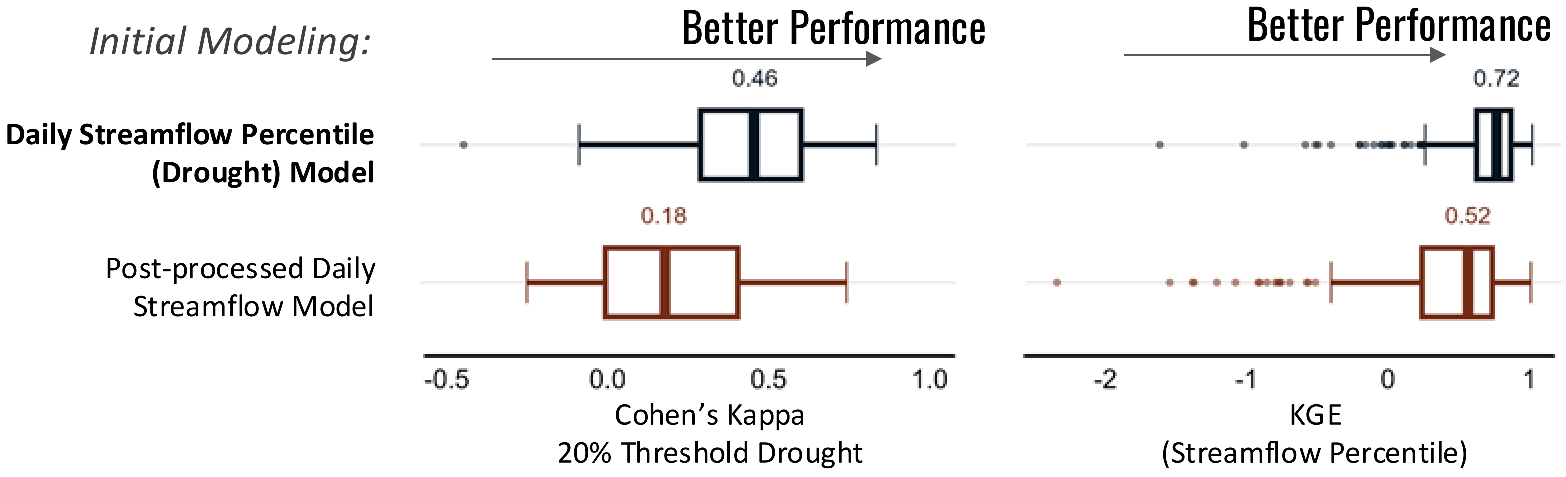
Prediction of Streamflow Drought using Neural Networks

- Key components of streamflow drought events:



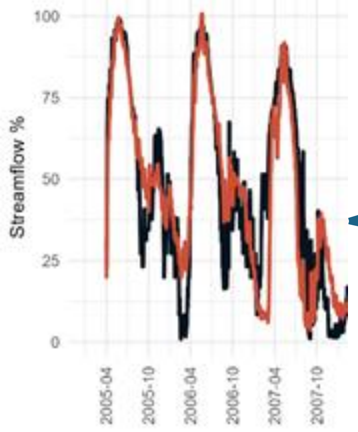
- Predict streamflow or streamflow *drought*?

Initial Modeling:



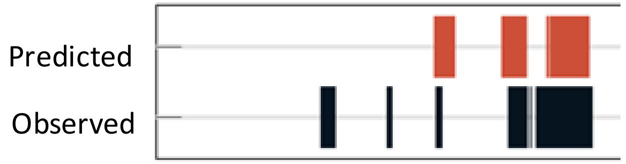
- Modeling Approach:

LSTM Model → *Model Output (Target variable)*: Daily streamflow percentile →



Forecasting (Operational) → Streamflow Drought Conditions (Onset, Intensity)

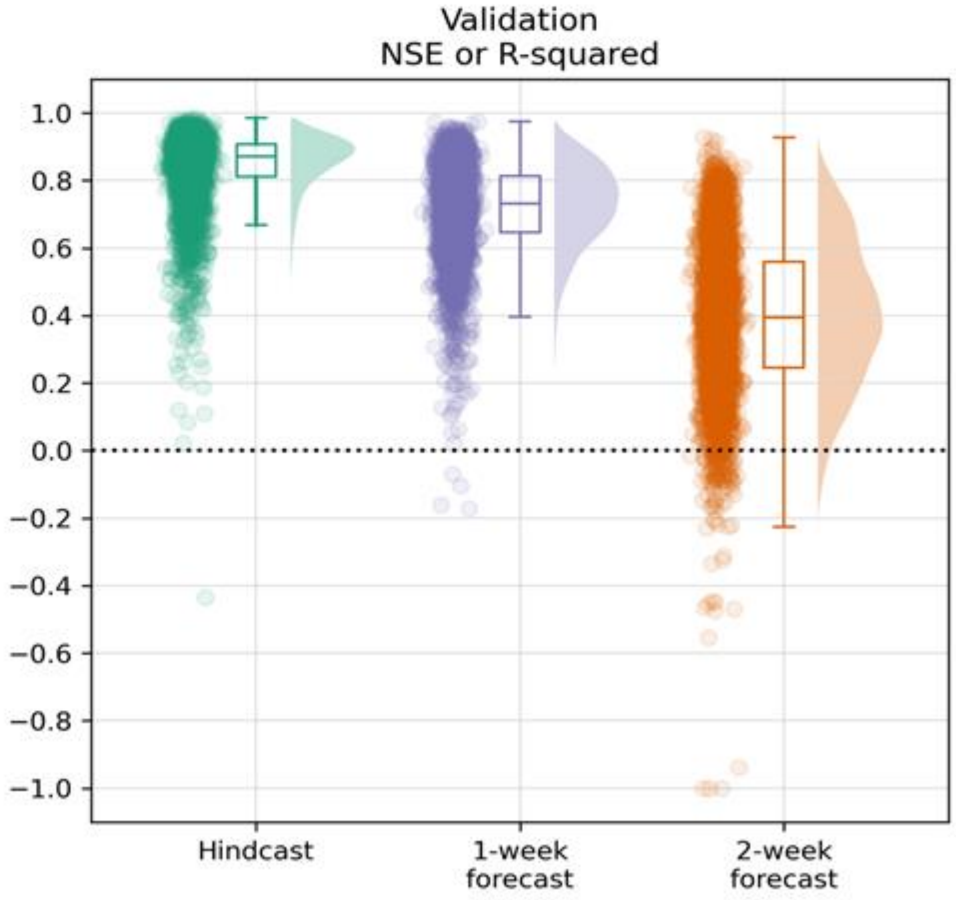
Hindcasting (Retrospective) → Streamflow Drought Events (Onset, Duration, Severity)

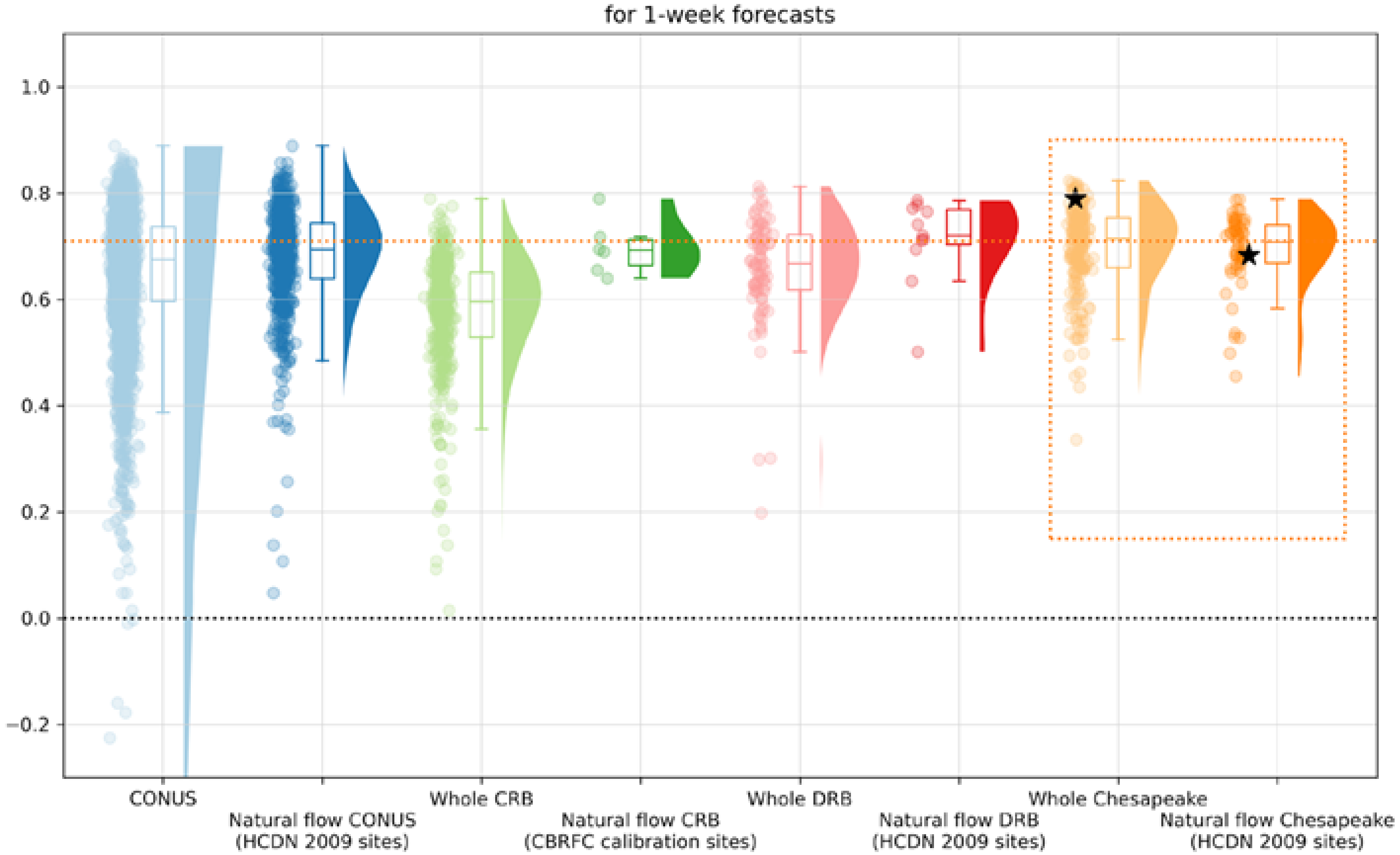


Streamflow drought modeling for regions across the United States

- **Early results** for a single, nationally trained model
- Performance higher for shorter lead times and less regulated locations

- Chesapeake region among the most predictable in the country
- Whole Chesapeake region (including human impacted areas) on par to its natural flow subset
- Neighboring Delaware River Basin also has good predictability





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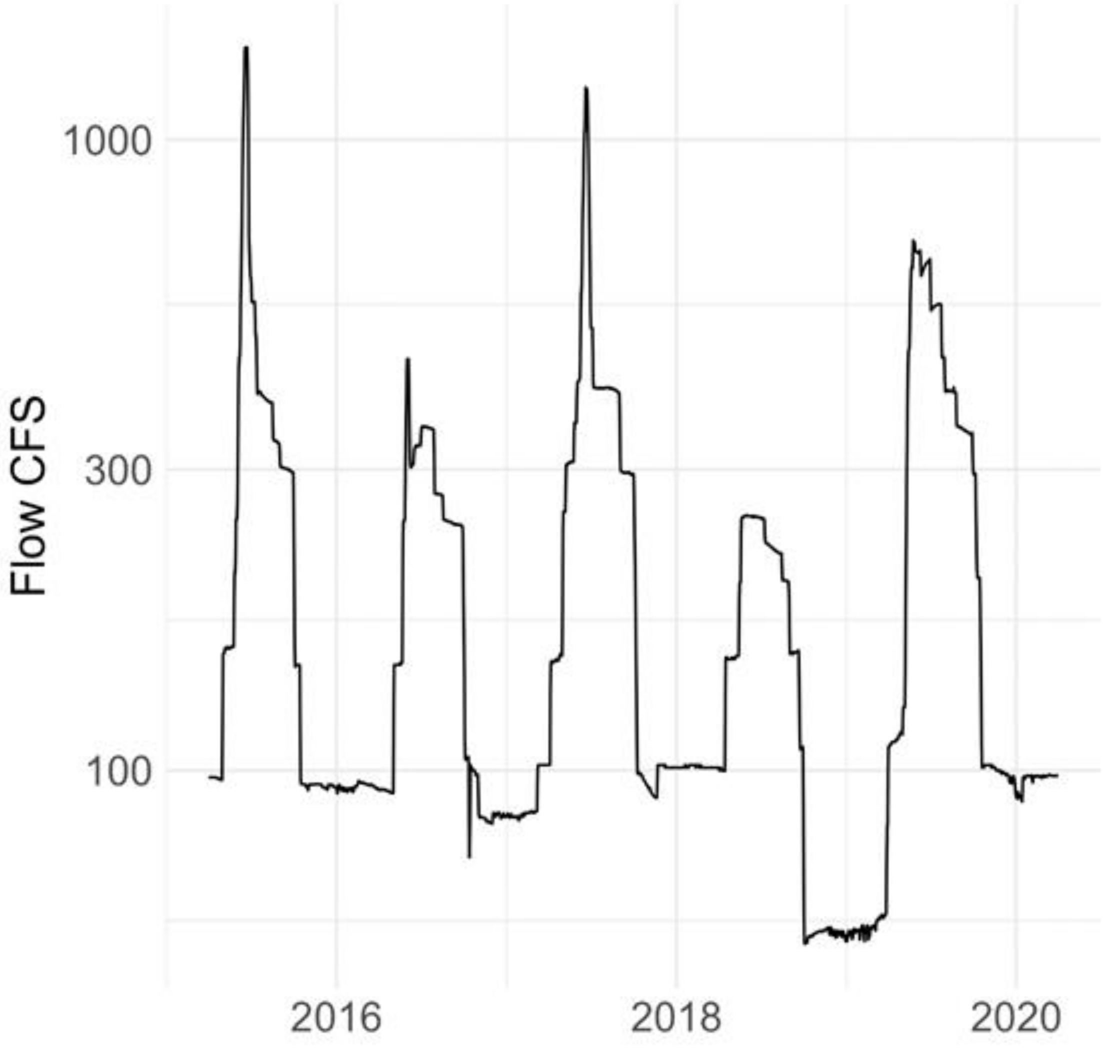
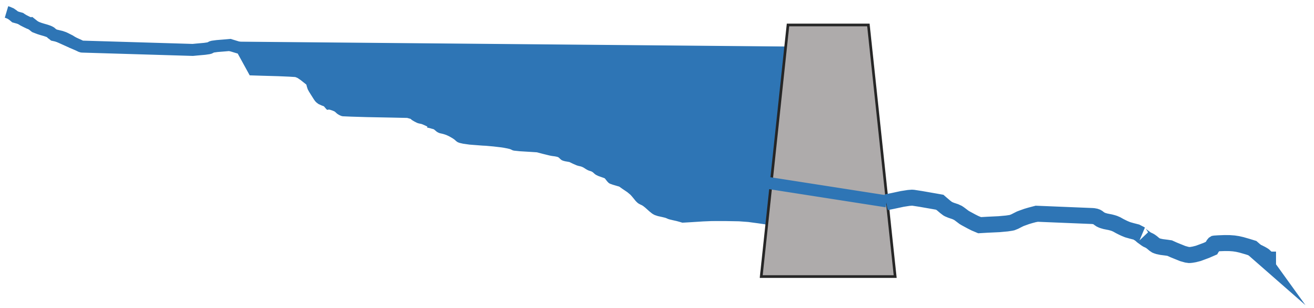
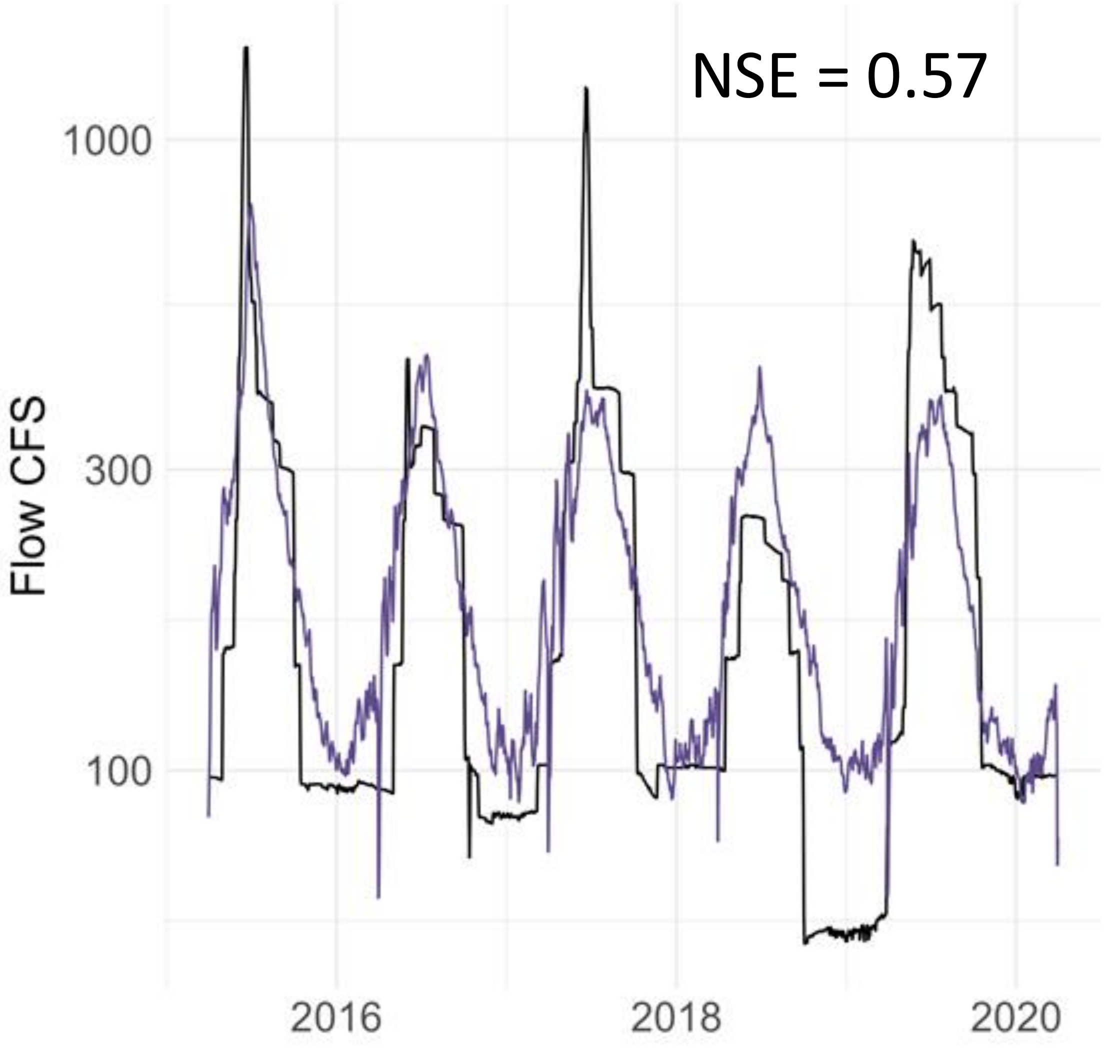
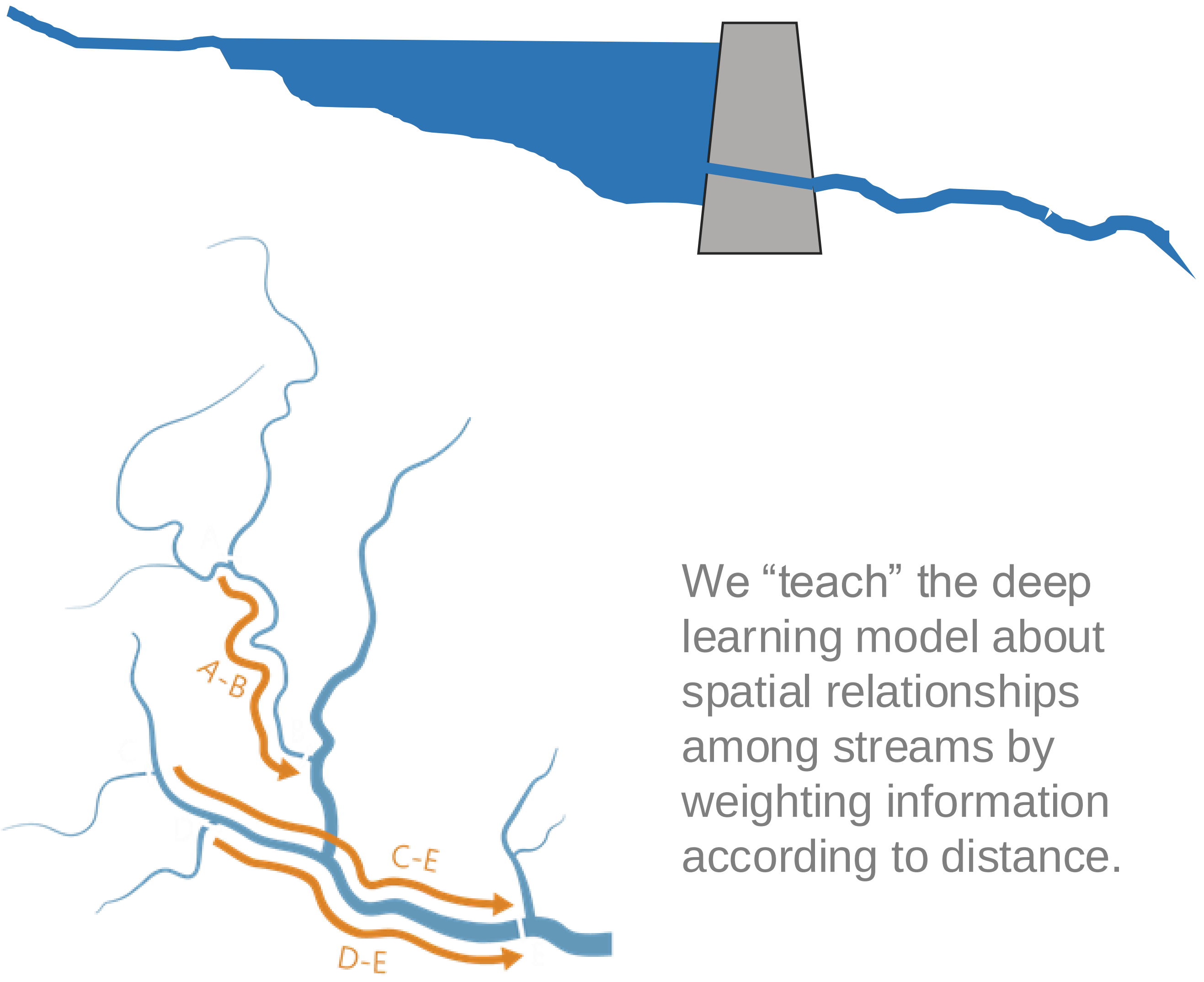
Streamflow drought modeling including reservoir operations





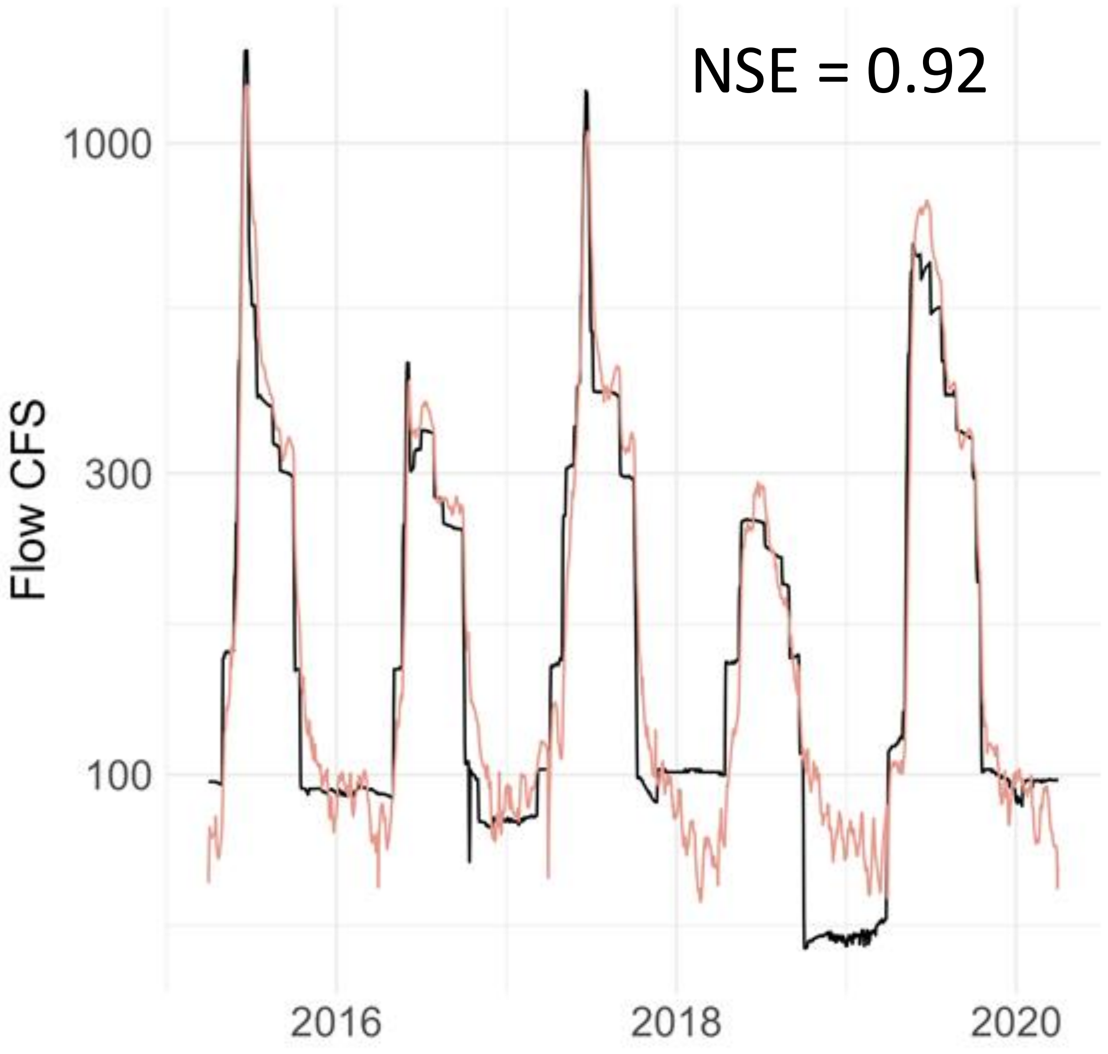
Streamflow drought modeling including reservoir operations

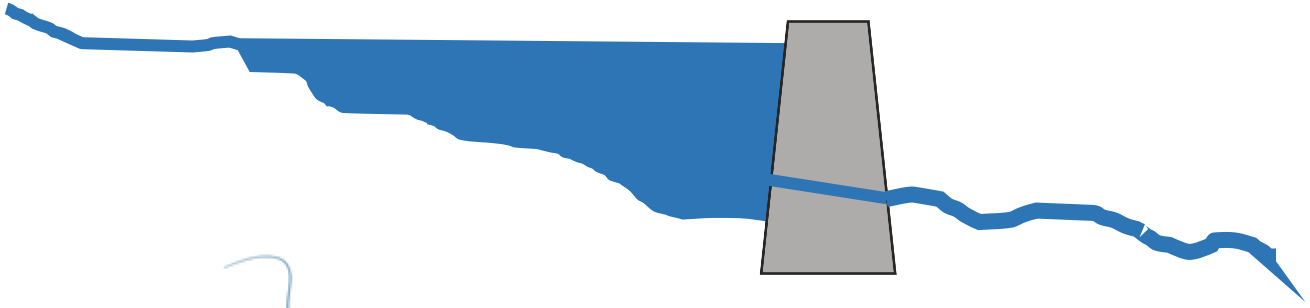




We "teach" the deep learning model about spatial relationships among streams by weighting information according to distance.

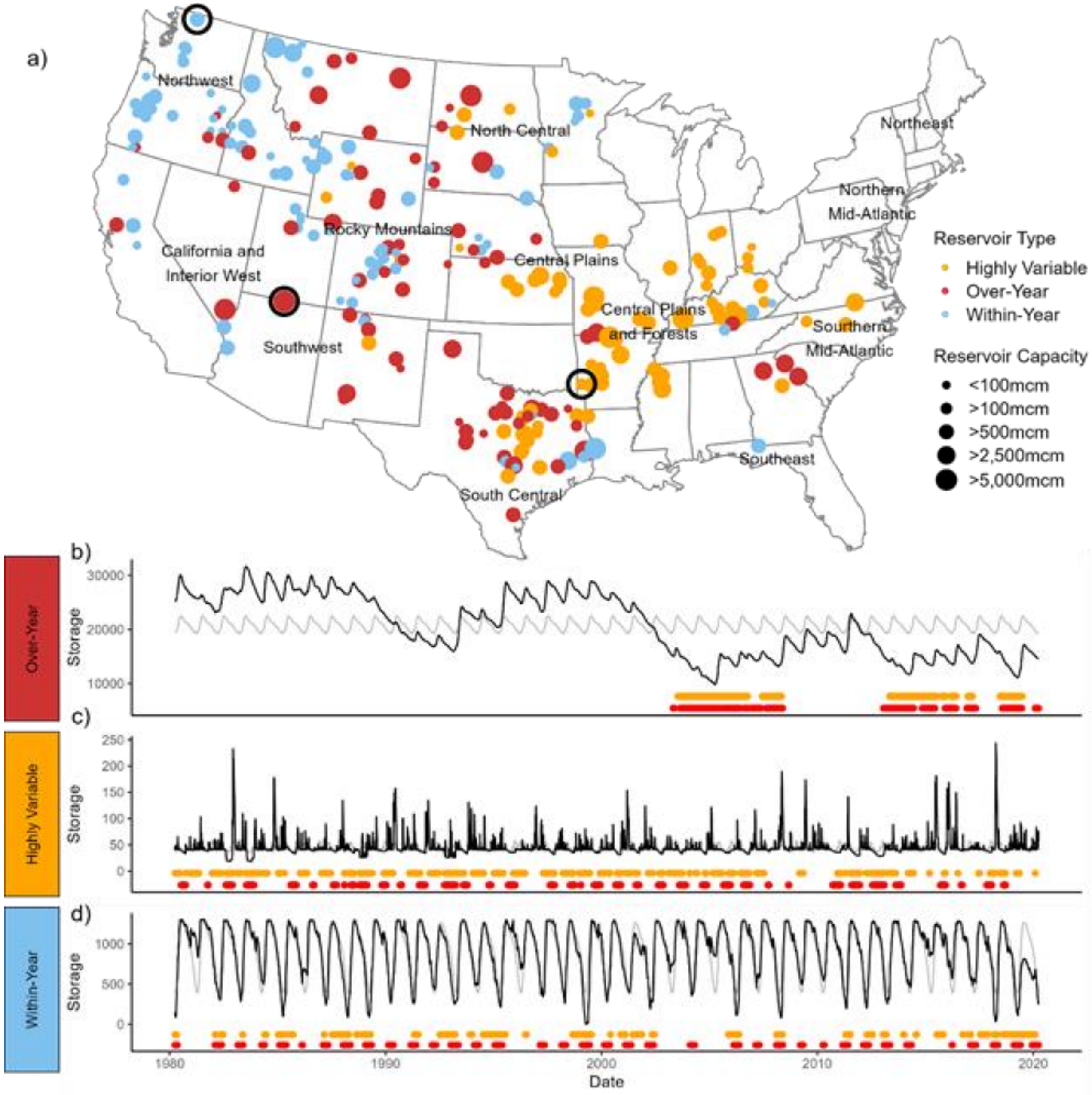
Streamflow drought modeling including reservoir operations





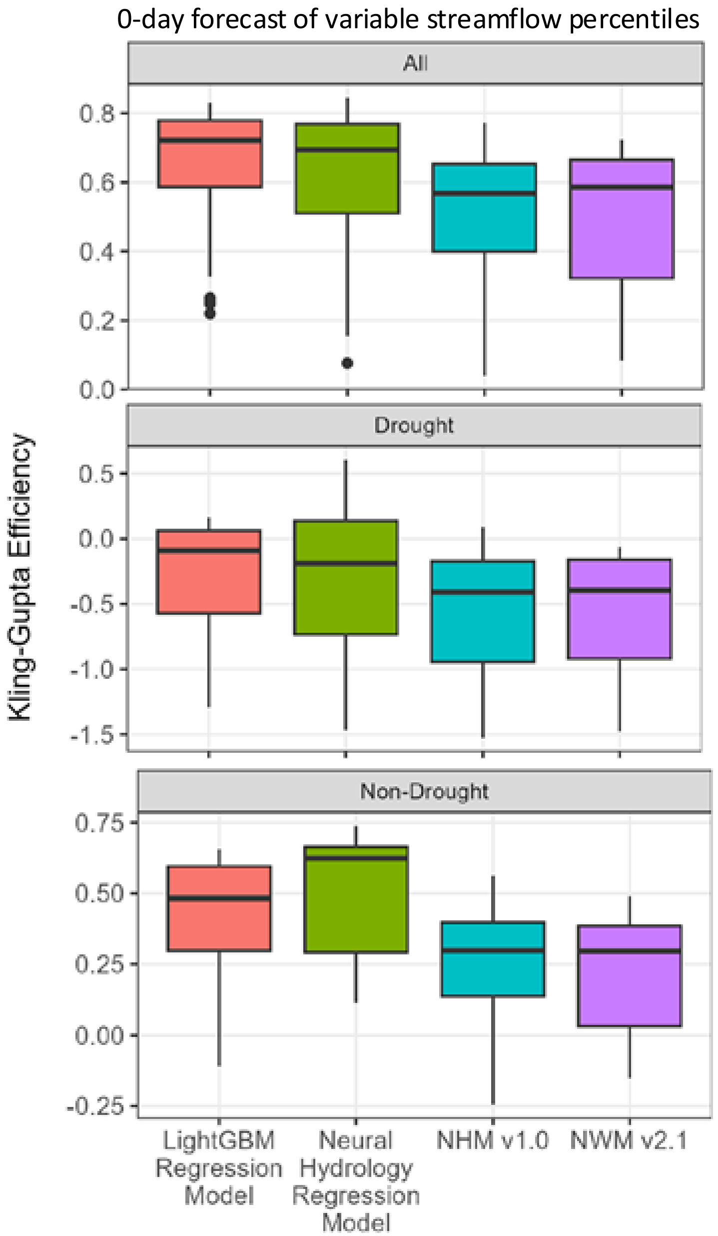
Reservoir information from ResOpsUS

Reservoirs and the ResOpsUS dataset



[ResOpsUS, a dataset of historical reservoir operations in the contiguous United States | Scientific Data]

Comparison to nationally available, physically-based models



Baseline (no antecedent streamflow) drought classification performance for 0-day forecast, for severe droughts (<10th %ile) for the period 1984-2016.

Four models evaluated:

- National Hydrologic Model (NHM, USGS, Precipitation Runoff Modeling System).
- National Water Model (NWM, NOAA, WRF-Hydro and Noah-MP).
- Tree-based models from this project.
- Neural network models from this project.

Baseline ML drought models show improvement upon existing national models in predicting departures from normal conditions.

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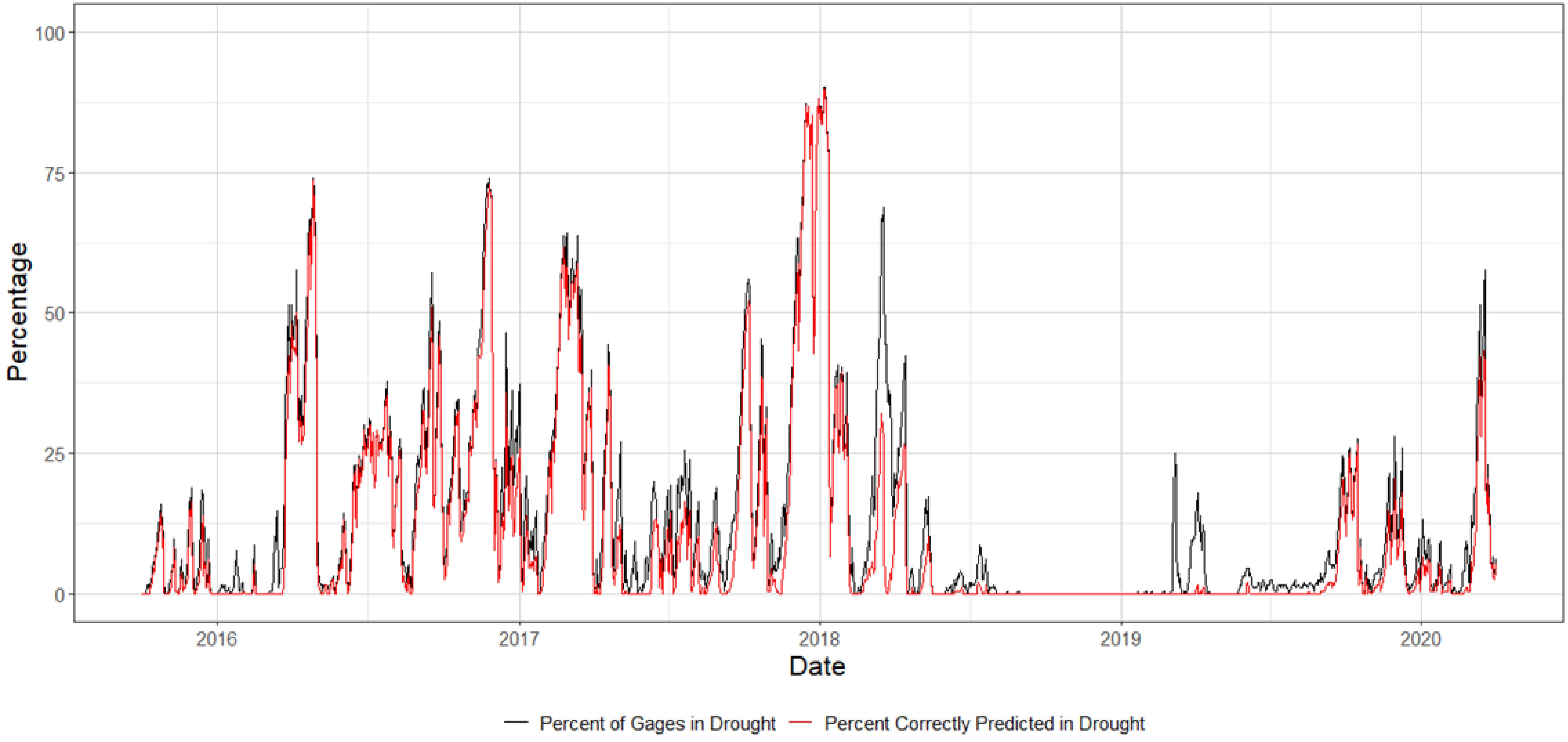
Matching patterns of drought in the Chesapeake Bay Watershed



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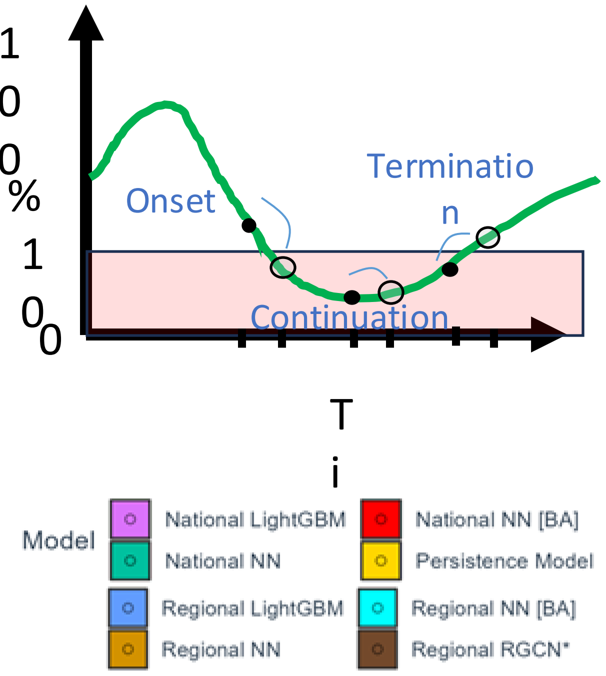
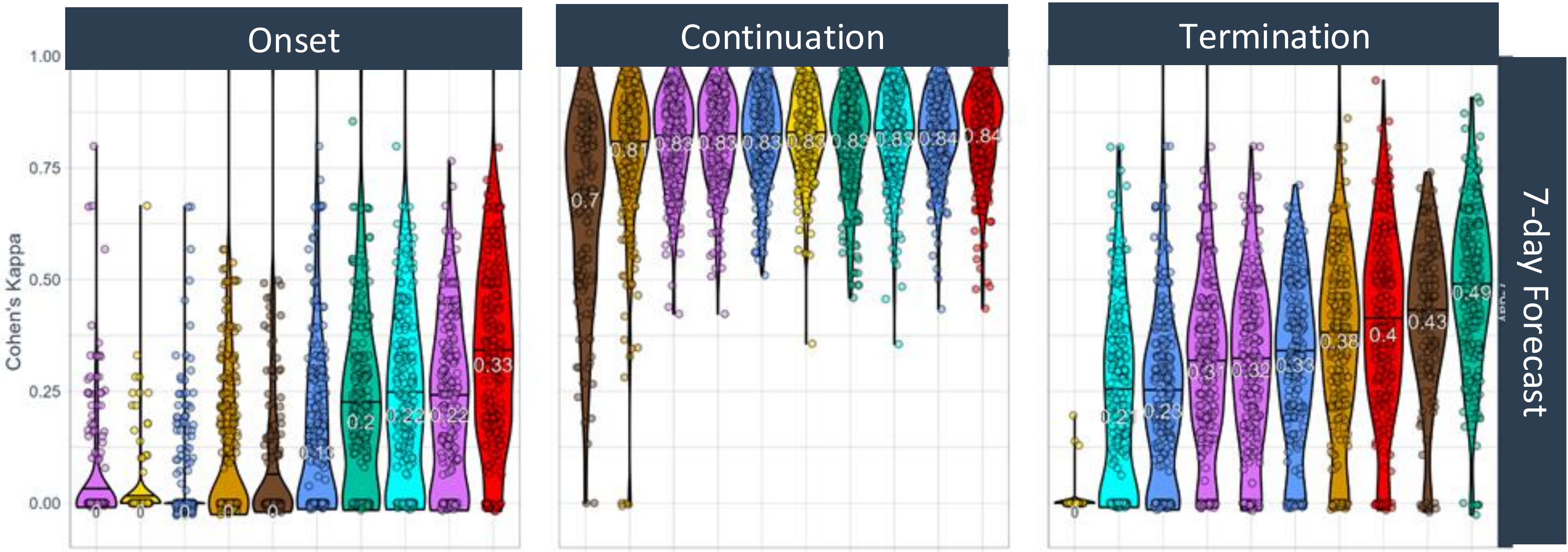
Modeling different components of drought





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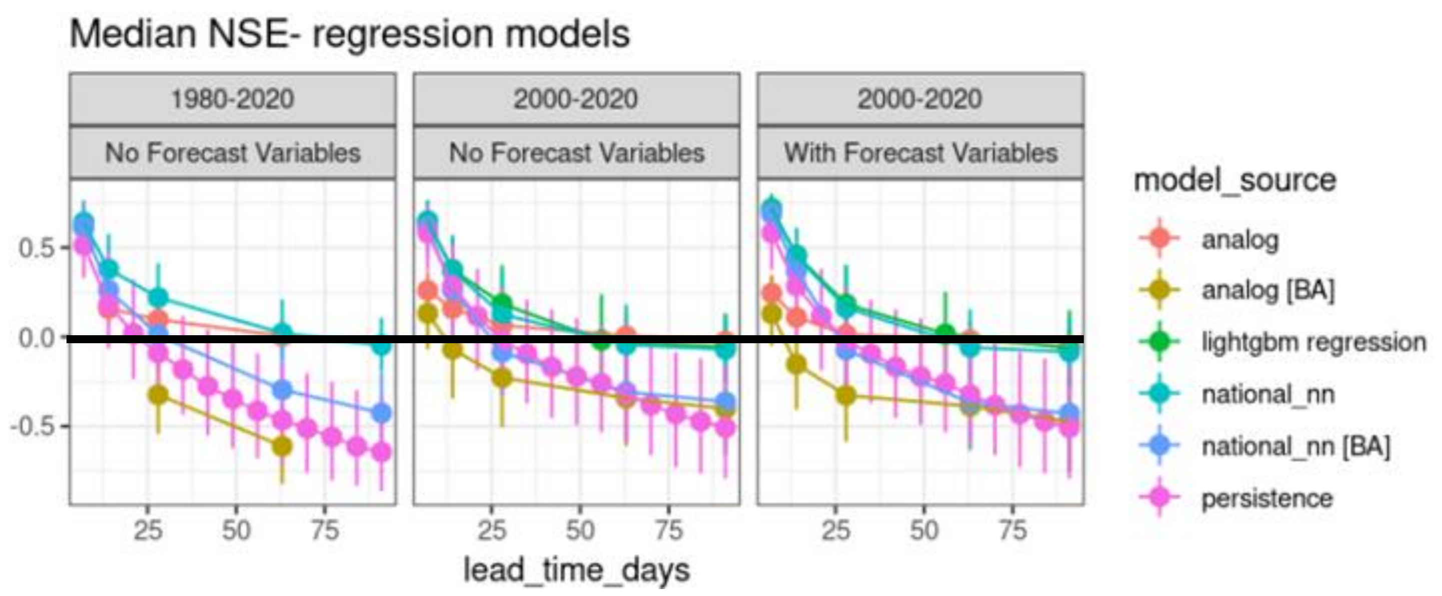
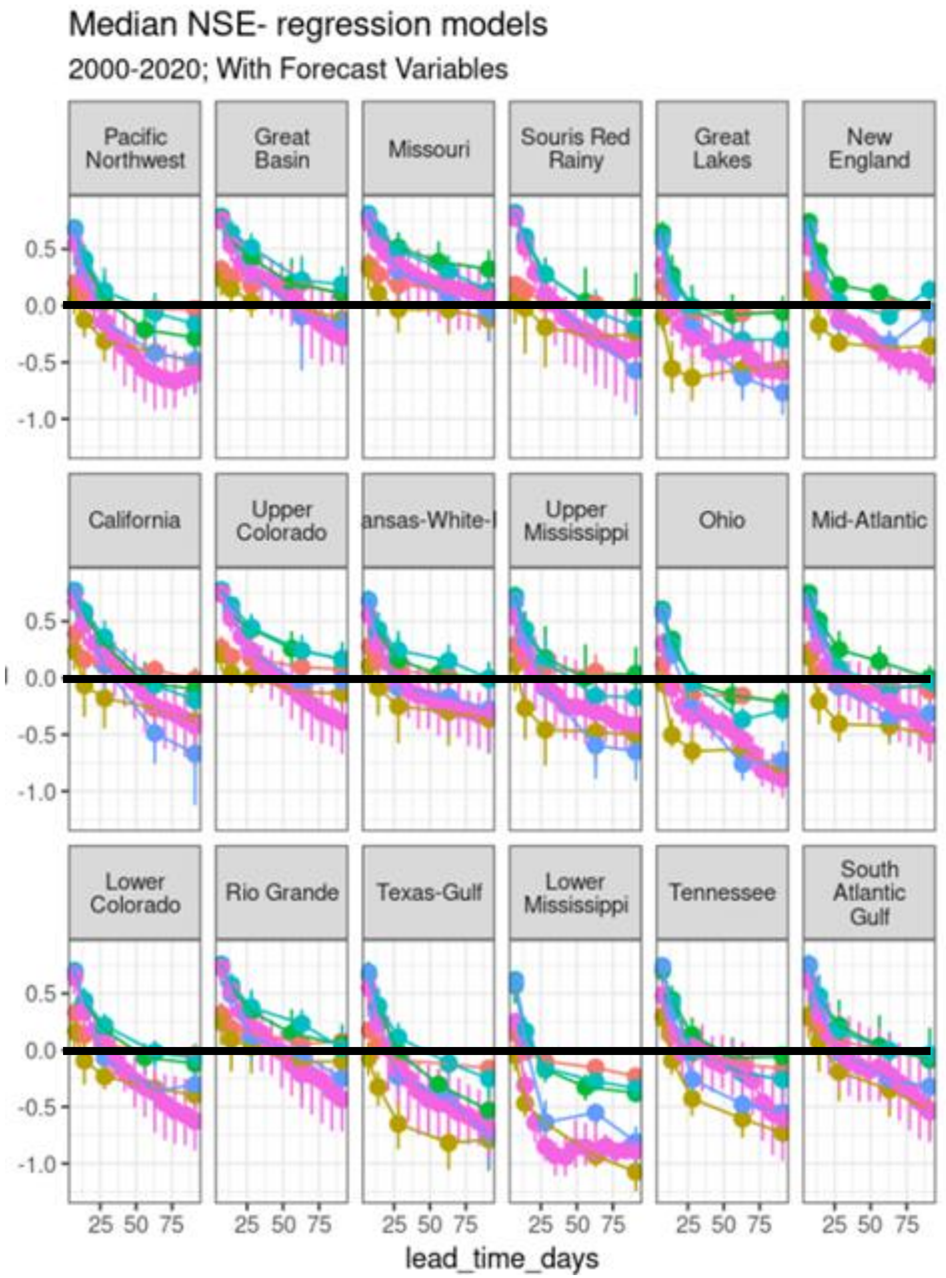
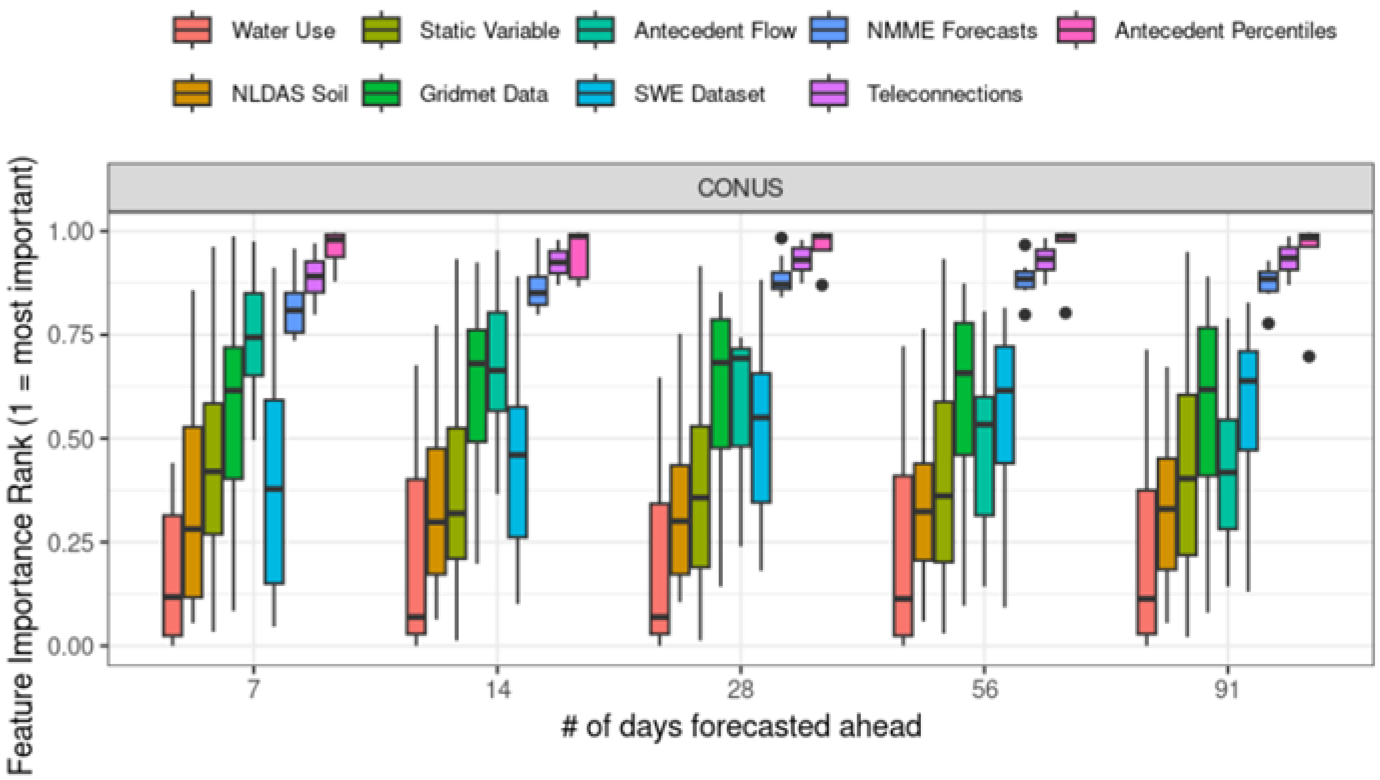
Declining model accuracy with increasing lead time: room for improvement



- Distribution of performance across entire nation 3000+ gages.
- Dots are median performance, bars are the 25th – 75th percentile range.

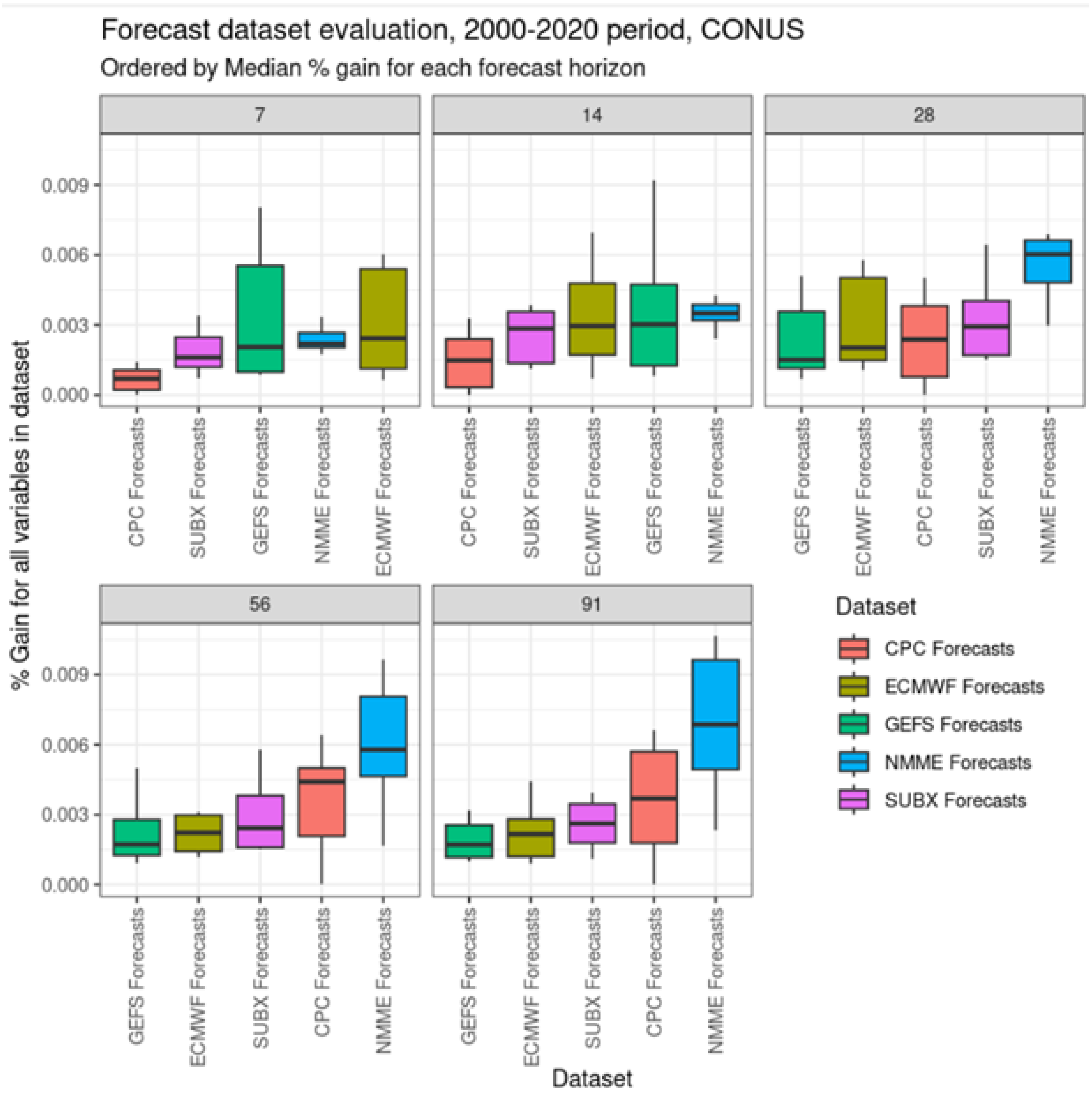


Why our models predict what they do



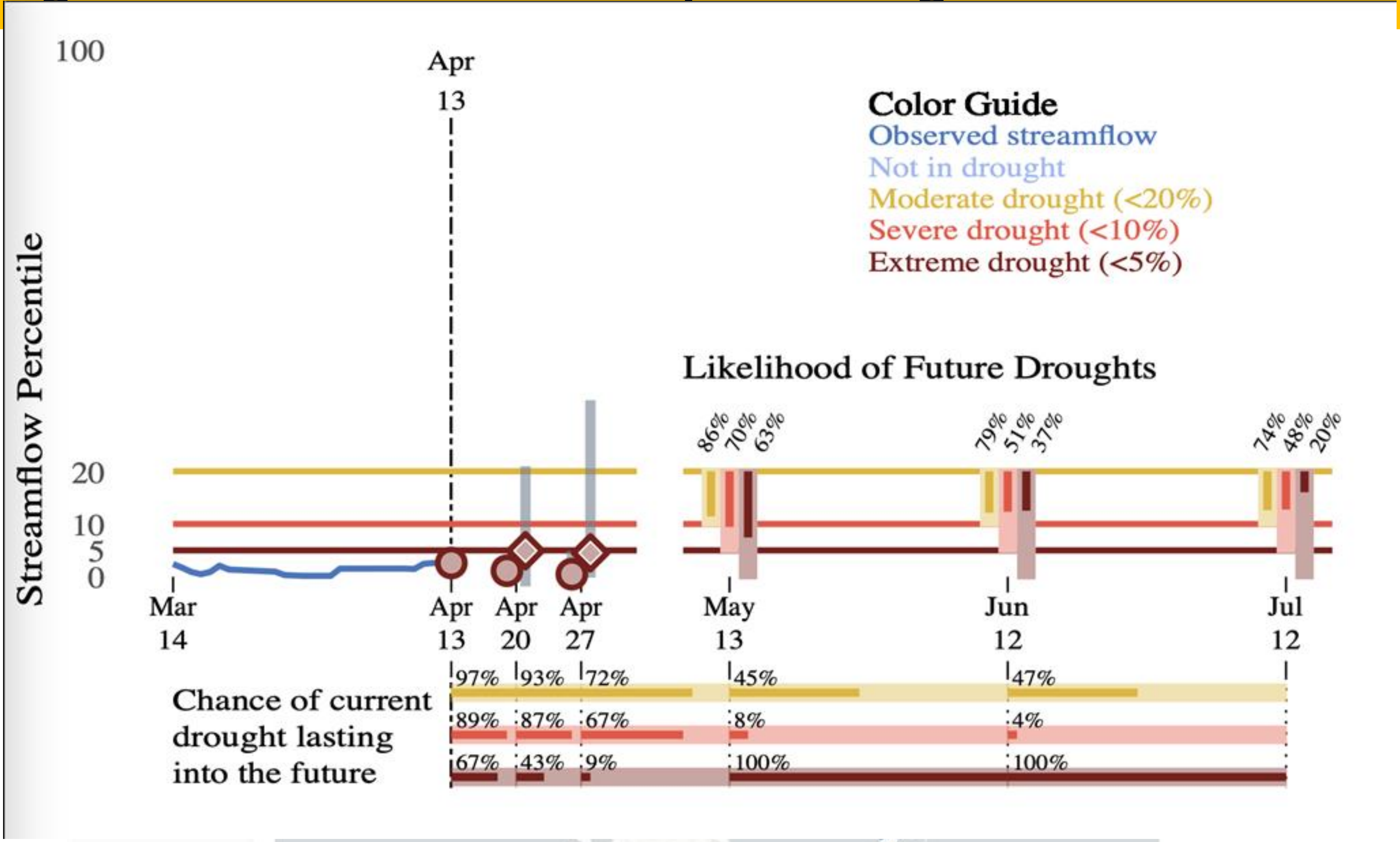
- Antecedent streamflow is our most important predictor
- Climate teleconnections (ENSO, PDO, AMO etc.) provide valuable drought prediction information
- The most useful meteorological forecasts we tested are from the North American Multi-Model Ensemble CFSv2 dataset

Which forecast products are most important?



- The utility of different forecast products varies by the lead time of the forecast

Prototyping tools to assess and anticipate drought conditions



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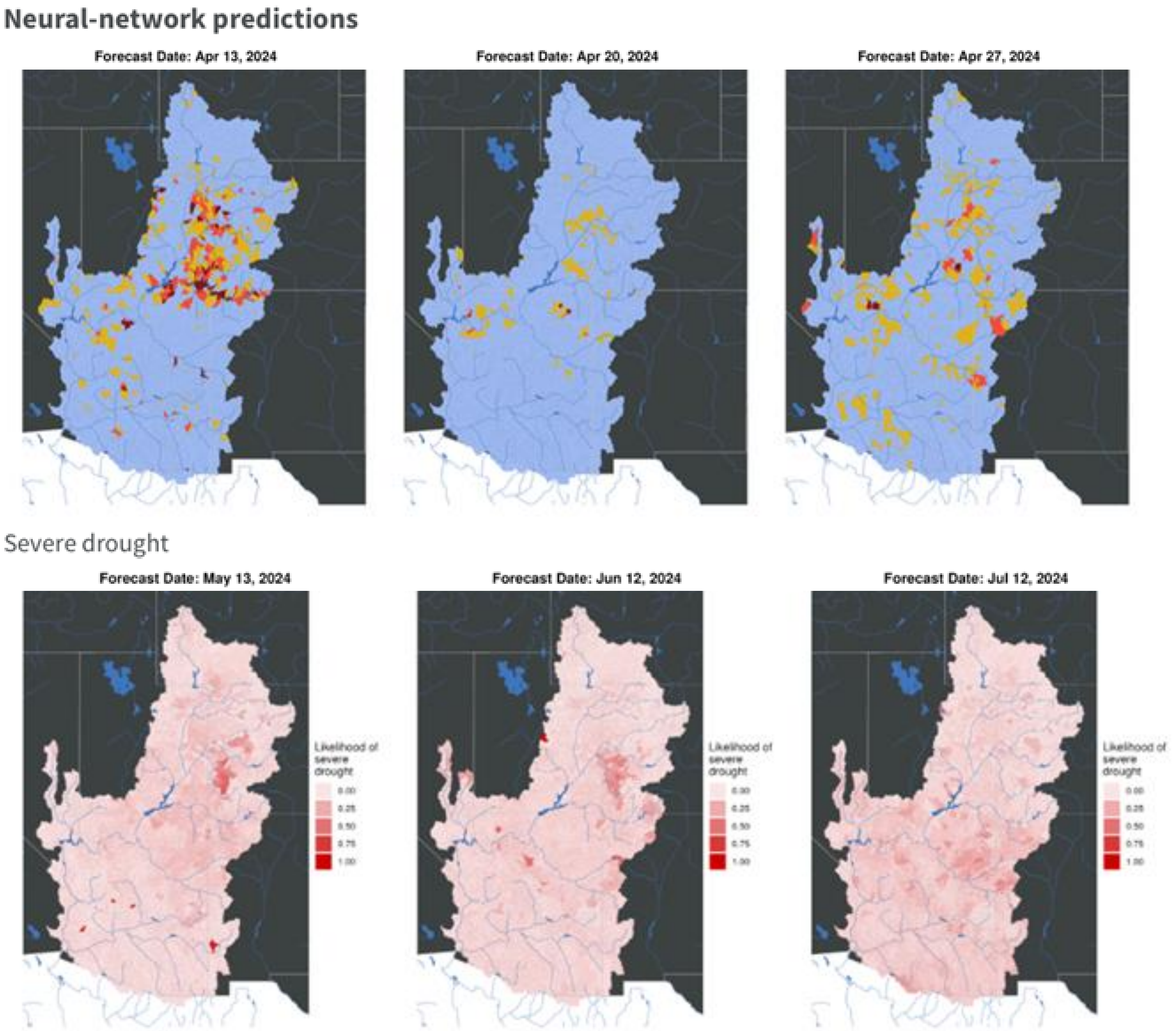
https://internal.wma.chs.usgs.gov/drought/#close

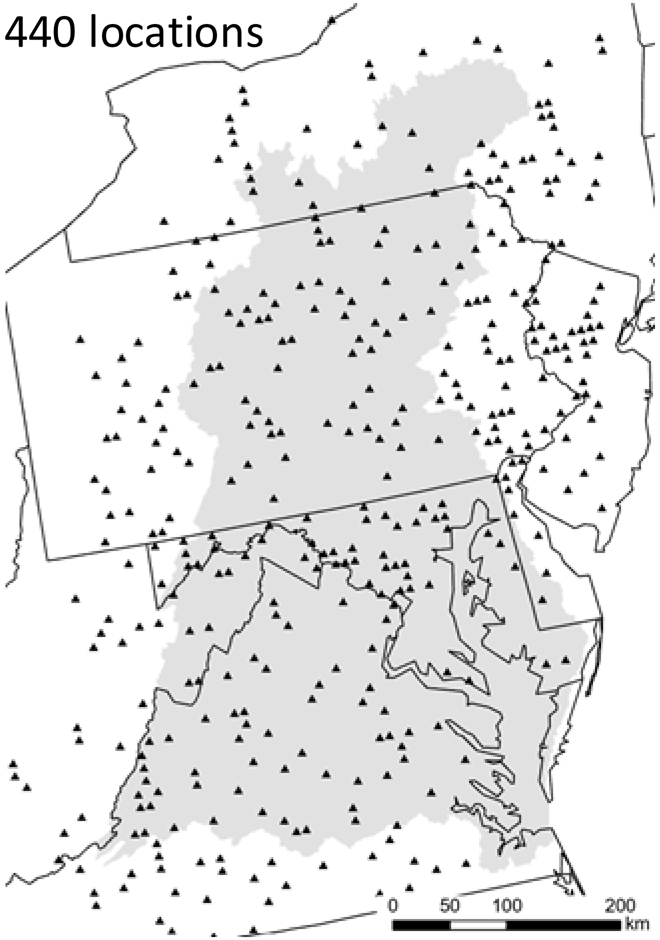
Ungaged area modeling



How have water quality and ecosystem response varied during hydrological drought?

Streamgages with 40+ years continuous, complete record

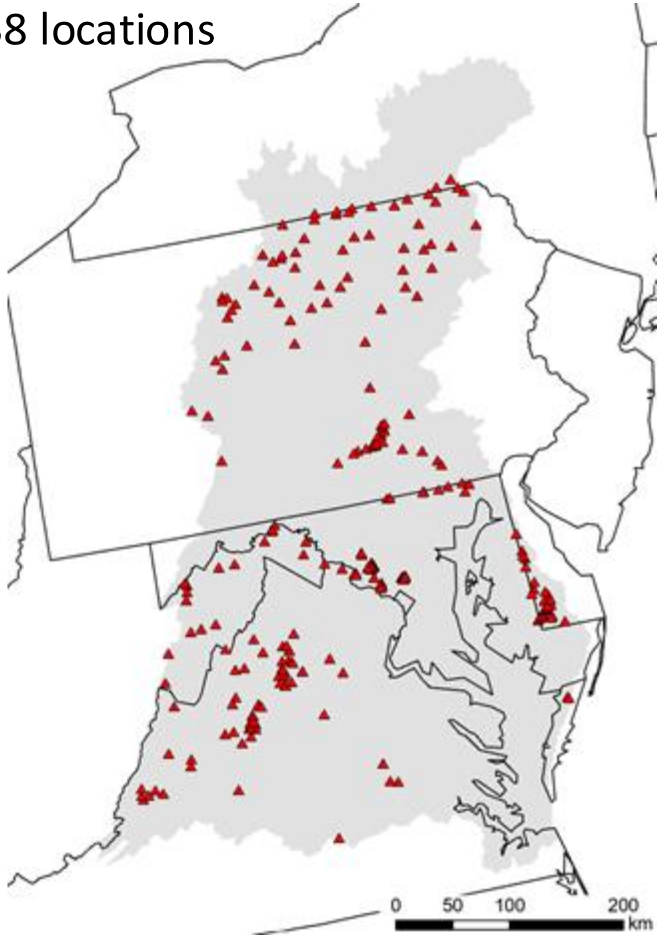
440 locations



20 or more measurements through time and within 25 km of a streamgage

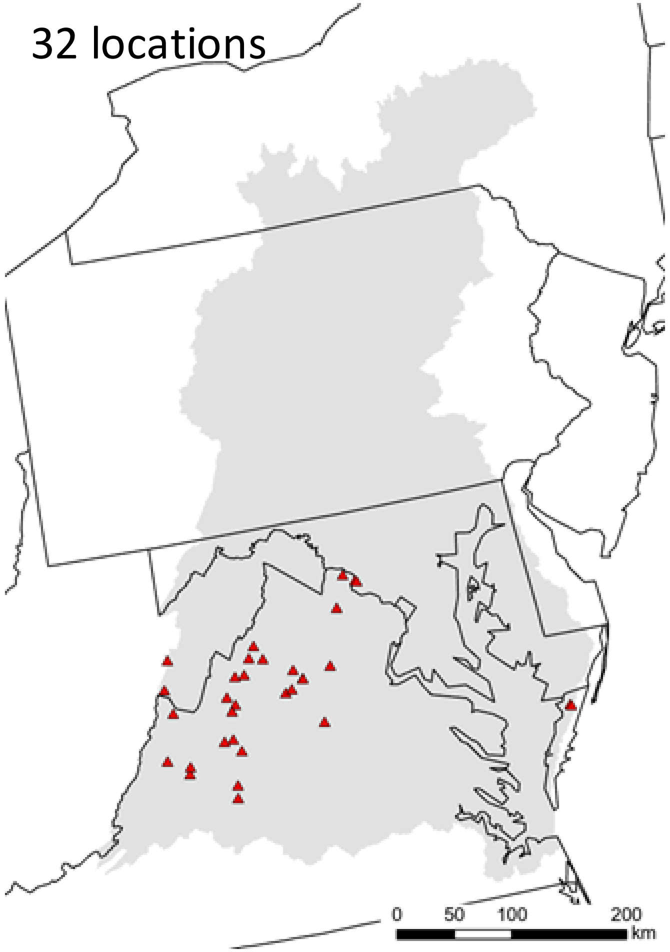
Dissolved Oxygen, Stream Temperature, Specific Conductivity, 1985-2020

238 locations



Basin-wide Index of Biotic Integrity (BIBI), 1985-2020

32 locations



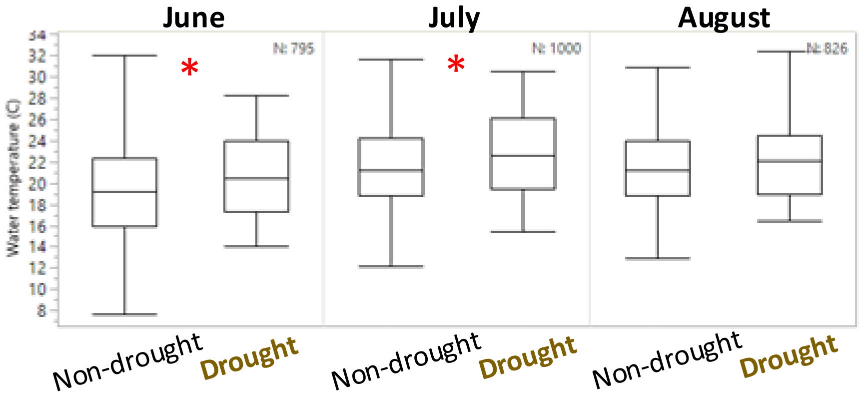
Streamflow Drought Metrics for Selected United States Geological Survey Streamgages

Attribution of benthic macroinvertebrate sampling data to NHDPlus V2 and NHDPlus HR catchments within the Chesapeake Bay Watershed

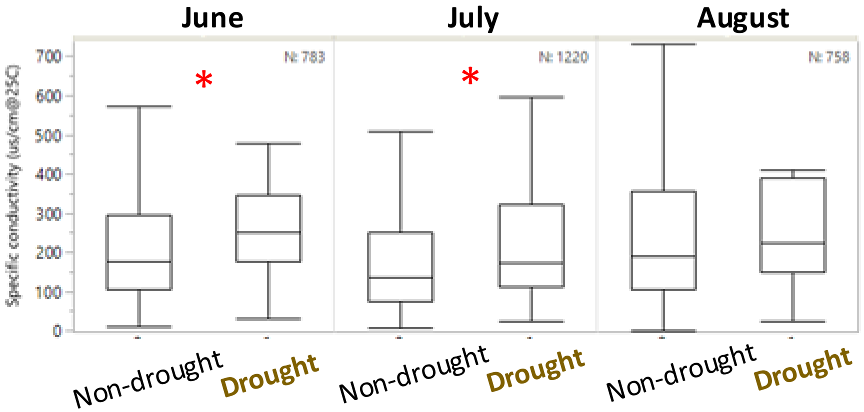
QW and biological metrics during hydrological drought

Drought defined using 10% streamflow percentile threshold corresponding to severe drought category

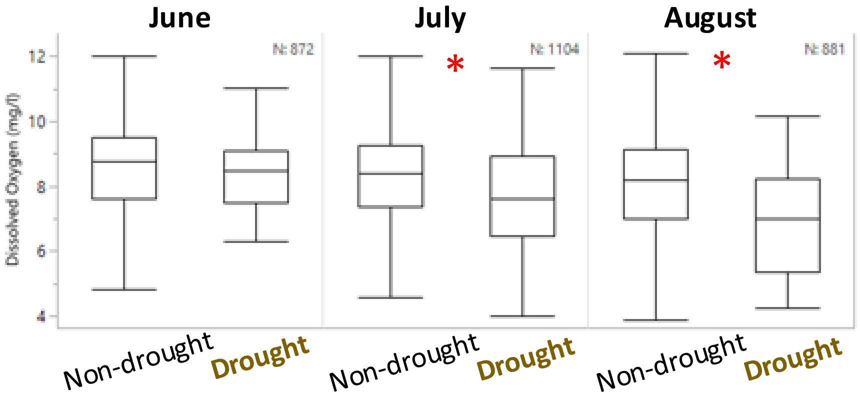
Higher stream temperatures during drought



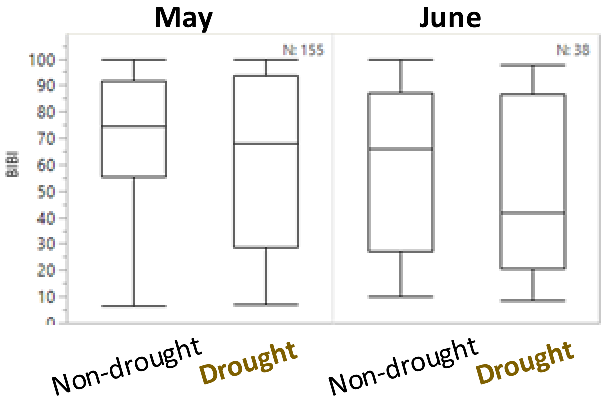
Higher specific conductivity during drought



Lower dissolved oxygen during drought



Lower biological integrity during drought



* *significantly different at alpha 0.05 using Mann Whitney test*

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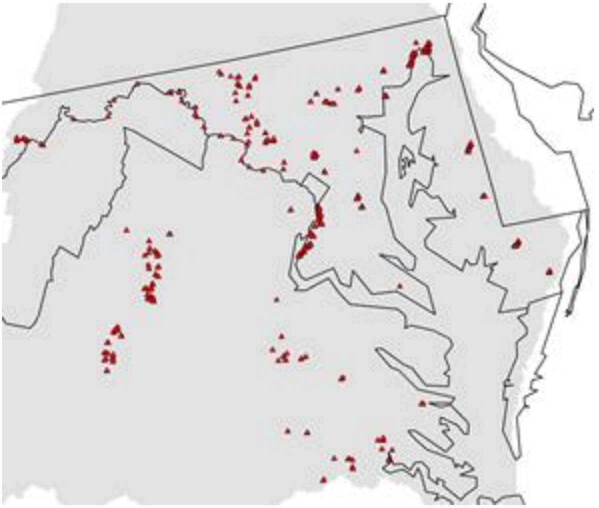
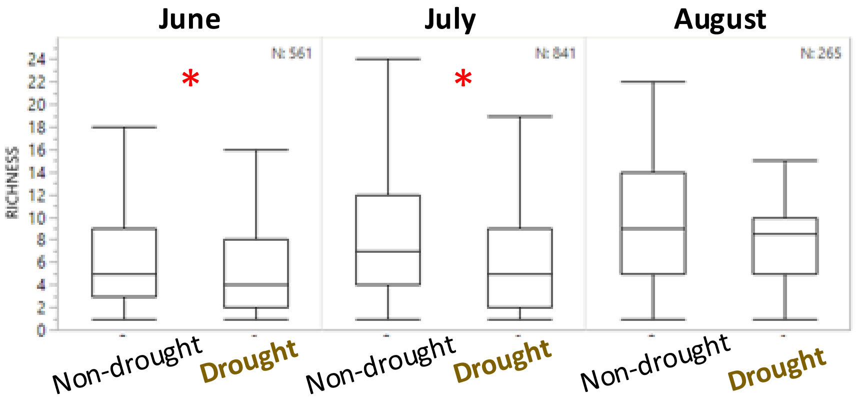
Biological metrics during hydrological drought

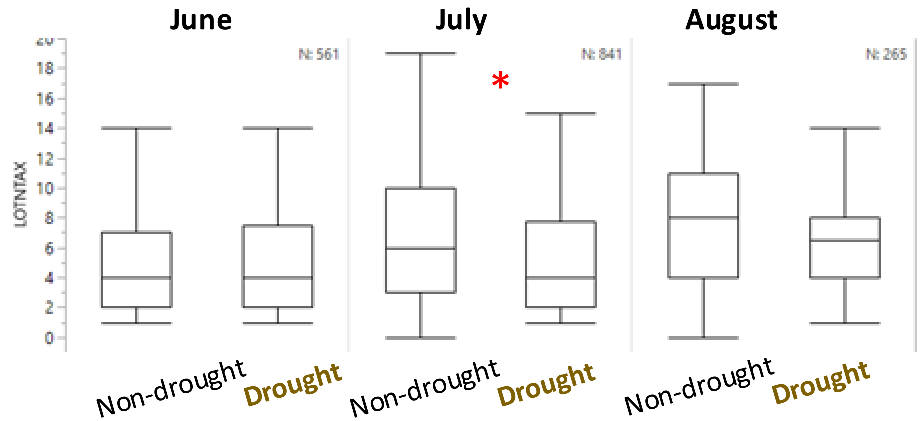
181 locations



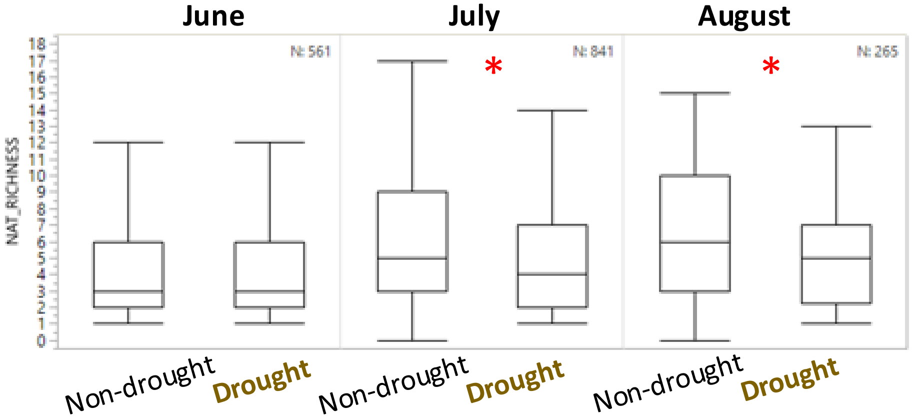
Lower species richness during drought



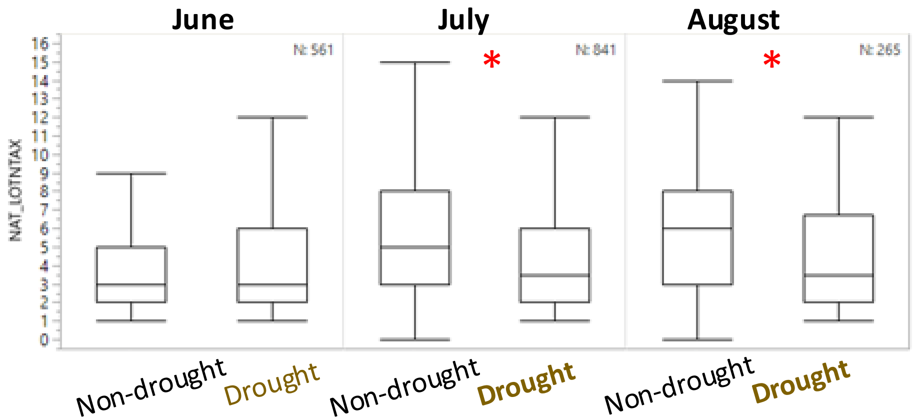
Fewer lotic species during drought



Lower native species richness during drought



Fewer native lotic species during drought



RICHNESS	Total number of species represented in the sample
NAT_RICHNESS	Total number of native species represented in the sample
LOTNTAX	Number of lotic taxa
NAT_LOTNTAX	Number of native lotic taxa

[Community metrics from inter-agency compilation of inland fish sampling data within the Chesapeake Bay Watershed]

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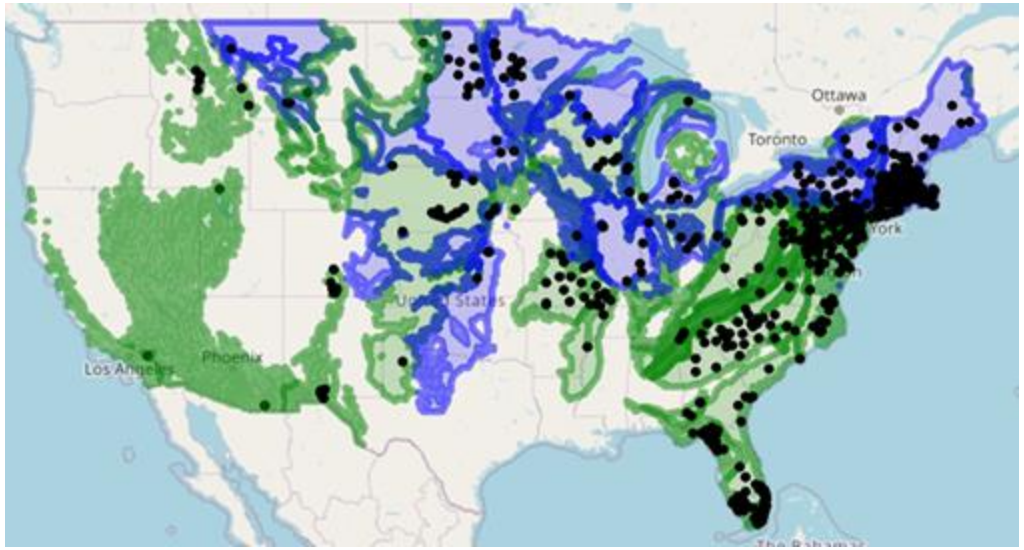
Monthly groundwater drought modeling

~2,300 well locations with complete data across CONUS (2001-2020)

Unconfined wells within principal or secondary aquifers, removing uncorrelated wells or wells with strong trends



~754 well locations in 35 primary or secondary aquifers (2001-2020)

Approach:

- Models using meteorology, SWE, soil moisture, antecedent water levels, forecasted meteorology 1-3 months ahead.
- Forecast monthly GW percentiles 1 to 12 months ahead.
- Made a ‘persistence’ model for comparison that assumes the same percentile exists for the following month.

Monthly groundwater drought modeling

All **unconfined** well groundwater data timeseries with **known*** aquifer

Is there a strong monotonic trend?

yes → **Discard well** – not suitable to forecast drought given GW pumping etc not captured by current model inputs.

no ↓

For each national aquifer

Are there more than 3 wells? → no

yes ↓

Are all the wells similar in groundwater percentiles, above a threshold of correlation or timeseries distance? → no

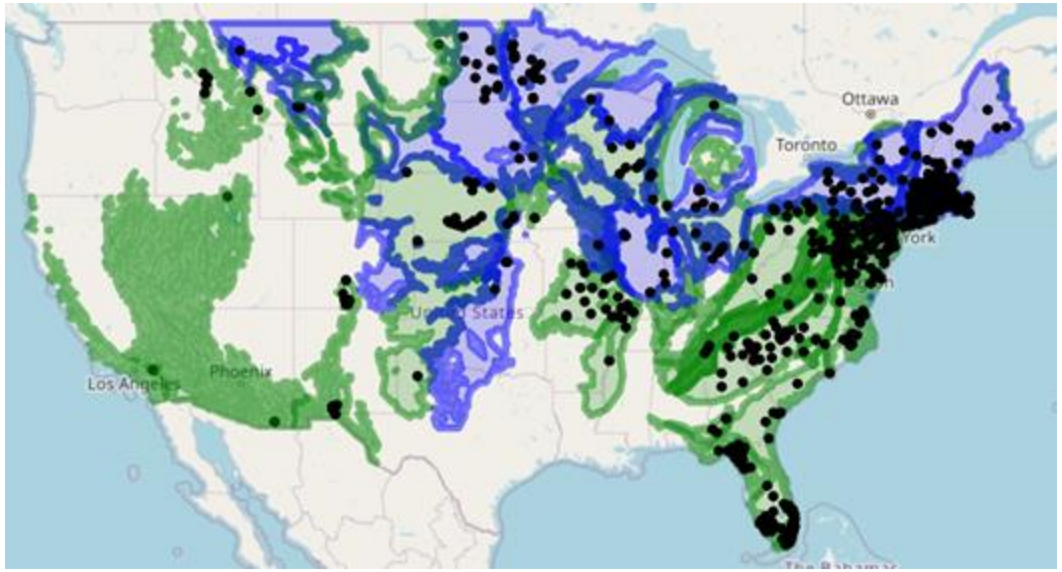
yes ↓

Are there more than 3 wells? → no

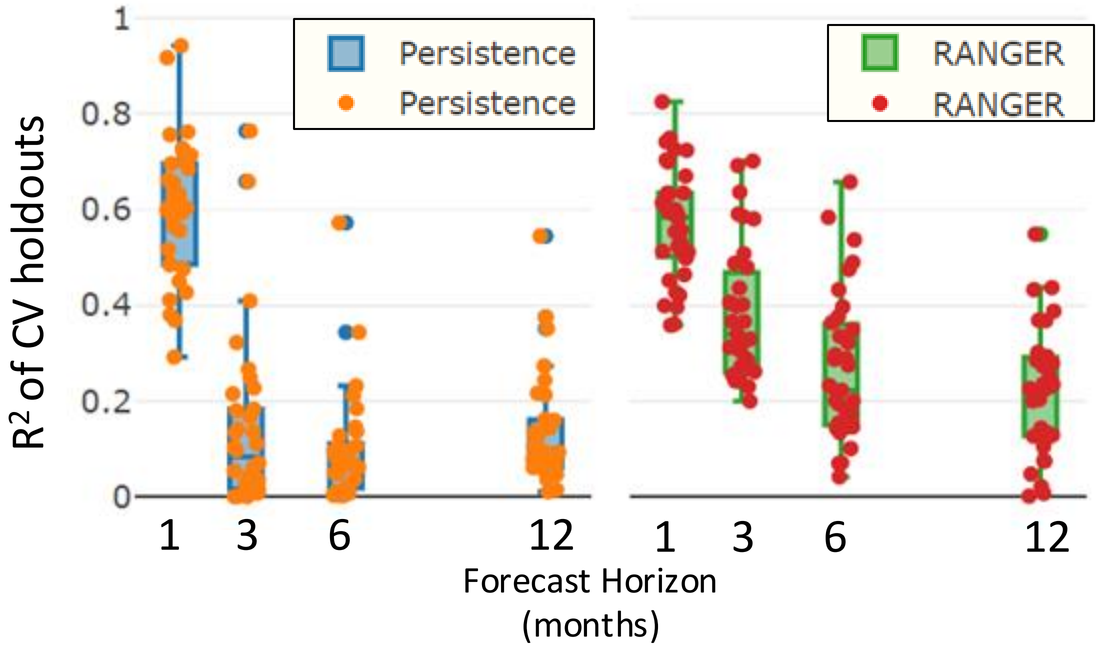
Train model on pooled well data,

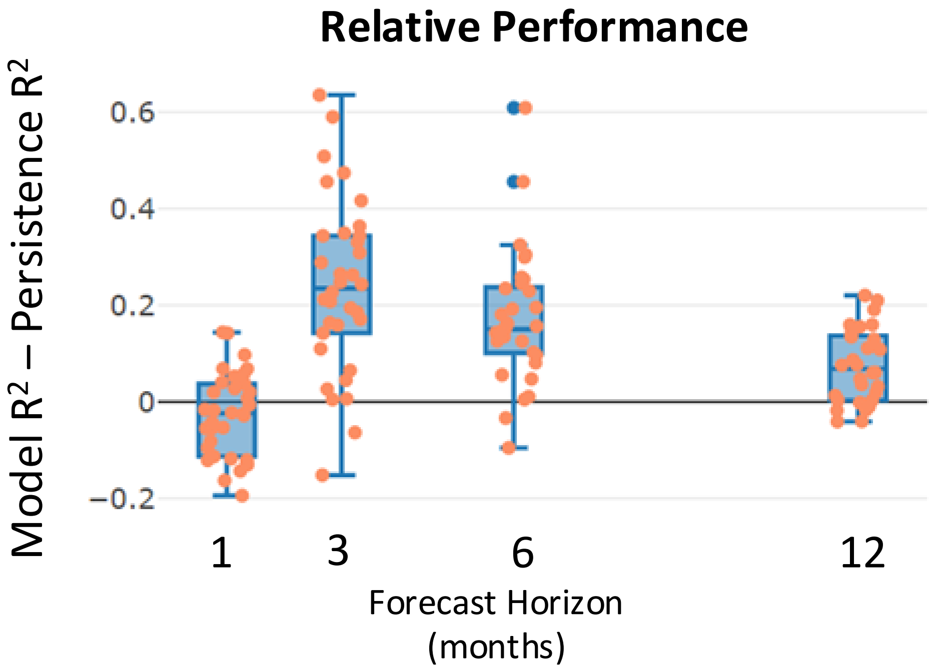
Is performance "good enough"? → no

Report drought forecasts



An initial assessment of GW percentile models





Looking Ahead

Additional model inputs

- **Historical hydroclimatology:** using historical traces to provide range of predictions weighted by forecast meteorology
- **Maximum monthly Surface Water Extent:** Landsat collection 2
- **Daily reservoir storage and outflow where available:** USBR and USACE, estimated reservoir outflow for reservoirs without long-term observations

Continuing work

- **New few months:**
  - Compilation of technical info supporting prototypes and for publications
  - Refinement of GW drought modeling approach
  - Soliciting feedback on CONUS prototype
  - Continuing focused user testing
- **End of FY25:**
  - Release of CONUS streamflow drought prediction tool for gaged areas (v1.0)
- **End of FY26:**
  - Updated models and ungaged areas (v2.0)

Questions?

Hydrological drought during summer 2022 on the border of Maine and New Hampshire

John Hammond, jhammond@usgs.gov

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