07/07/2020

Fine-scale Chesapeake Regional Hydrologic Model (CRHM)

Modeling Workgroup Quarterly Meeting – July 2020

Gary Shenk[1], Gopal Bhatt[2], Jeffery Chanat[1], Joseph Zhang[3]

[1] USGS, [2] Penn State, [3] VIMS – Chesapeake Bay Program Office

Presentation Outline

1. Overview – Gary Shenk
2. CRHM 2020 – Gopal Bhatt
3. Hydro-Ecological Analysis – Jeff Chanat
4. SCHISM Estuarine Modeling – Joseph Zhang

Motivation

- TMDL
  - WQGIT interested in spatial accuracy of the TMDL model
  - Effective and efficient WIPs
  - Multiple STAC recommendations to refine spatial scale of TMDL model
    - Modeling beyond 2025
    - Watershed model review
    - BMP targeting
- CBP-identified science needs for fine-scale hydrology to develop living resource and habitat models in the watershed
- ICPRB, SRBC, and DEQ water supply modeling

Motivation

- CBP-identified science needs for fine-scale hydrology to develop living resource and habitat models in the watershed

Chesapeake Regional Hydrologic Model 2020

- Downscaling Phase 6 dynamic model to the NHD scale
- Purpose
  - Provide input to living resources models
  - Develop new calibration metrics
  - Expand and revise data sets
  - Test strategies for 2023 model

Motivation

- TMDL
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Chesapeake Regional Hydrologic Model 2023

- NHD-scale land and river simulation

- Purpose
  - Emphasize nutrient and sediment production areas
  - Determine local effects of groundwater
  - Incorporate management action effects on hydrology

CRHM-related presentations

2020 model

2023 building blocks

CRHM-related presentations

2020 model

- 10:20 Gopal Bhatt
  - Downscaling method
- 10:35 Jeff Chanat
  - Evaluation
- 10:50 Joseph Zhang
  - Estuarine linkage

2023 building blocks

- 11:20 Peter Claggett
  - Landscape characterization
- 11:40 Isabella Bertani
  - NHD-scale input data
- 12:00 Art DeGaetano
  - Climate effects on IDF curves
- 12:30 Gary Shenk
  - CAST vs observations
- 1:00 Jesse Bash
  - Future atmospheric deposition estimates

Chesapeake Regional Hydrologic Model (CRHM 2020 Version)

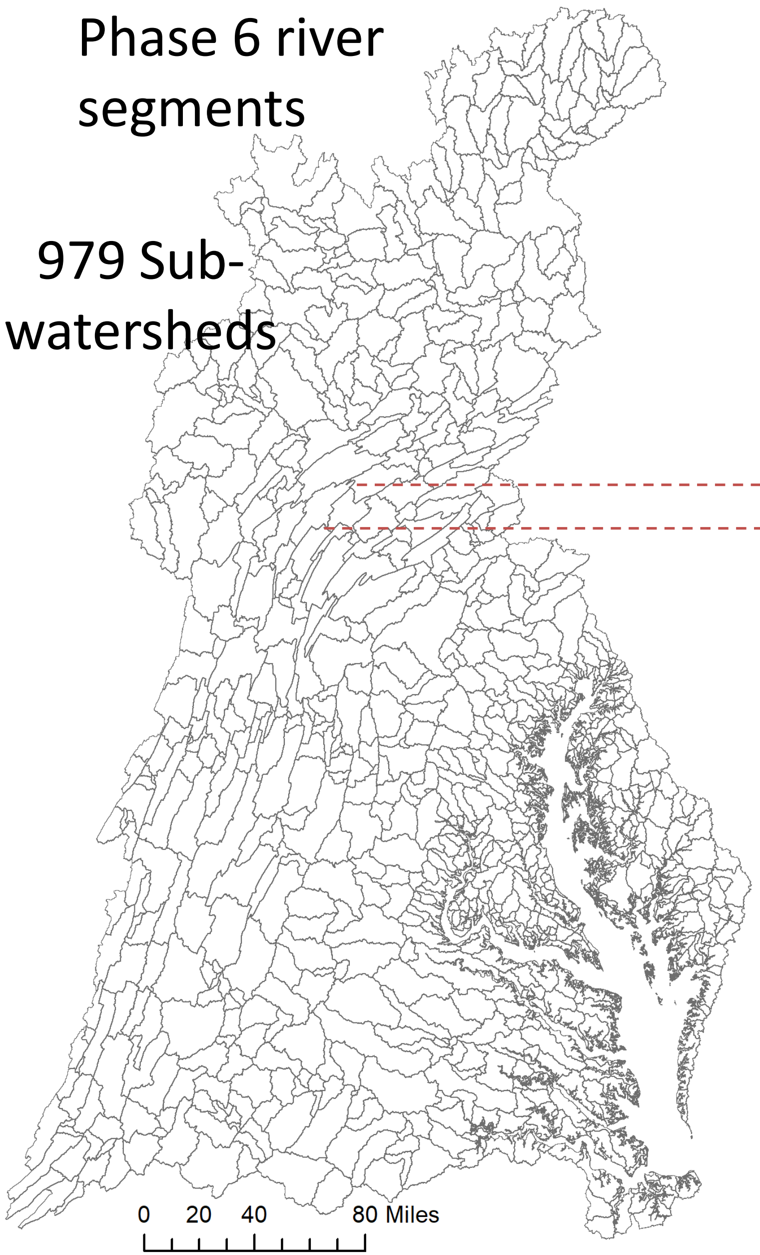
Gopal Bhatt[1], Lewis Linker[2], Gary Shenk[3], Isabella Bertani[4], Cuiyin Wu[5], Peter Claggett[3], Jeffery Chanat[3]

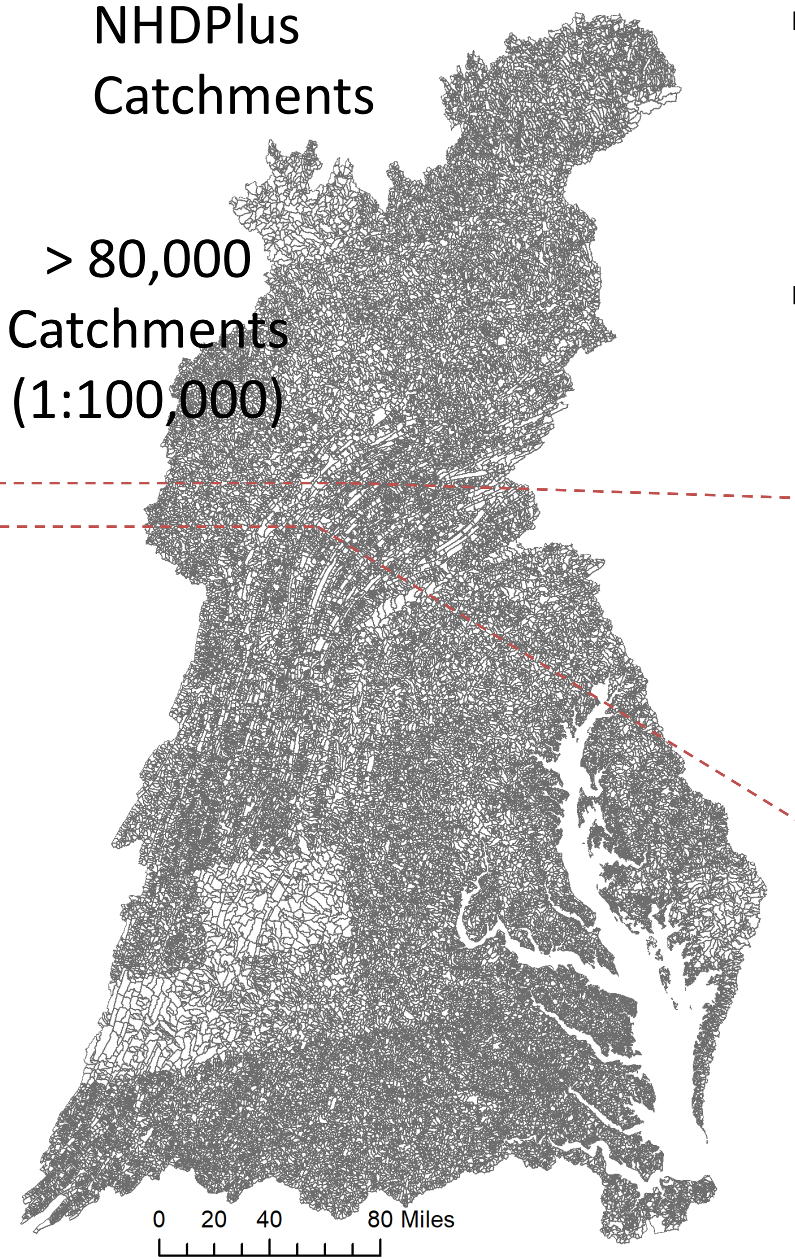
[1] Penn State, [2] US EPA, [3] USGS, [4] UMCES , [5] CRC – Chesapeake Bay Program Office

Elements of CRHM 2020 Version

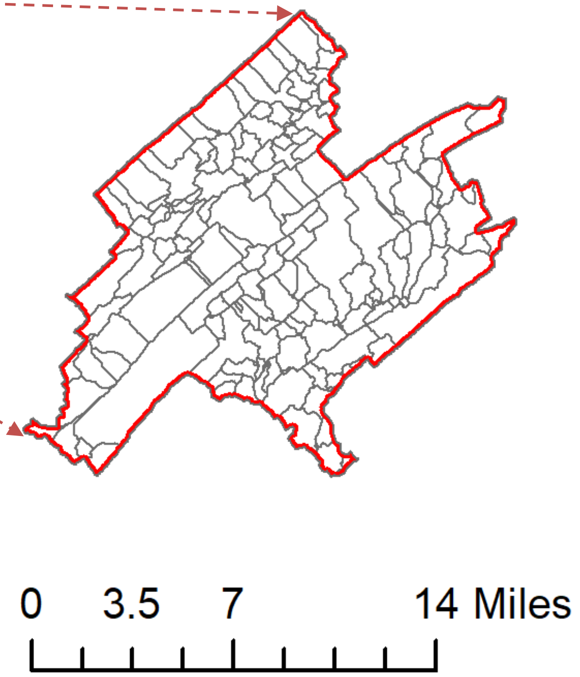
- CBP Phase 6 (county scale) land simulation for finer NHDplus V2 1:100,000 scale stream hydrology
- Refinements throughout 2020 – *2 to 3 Versions*
  - Version 1 has been completed
- Better understanding of data needs and operational details

Scale – Phase 6 vs. CRHM 2020



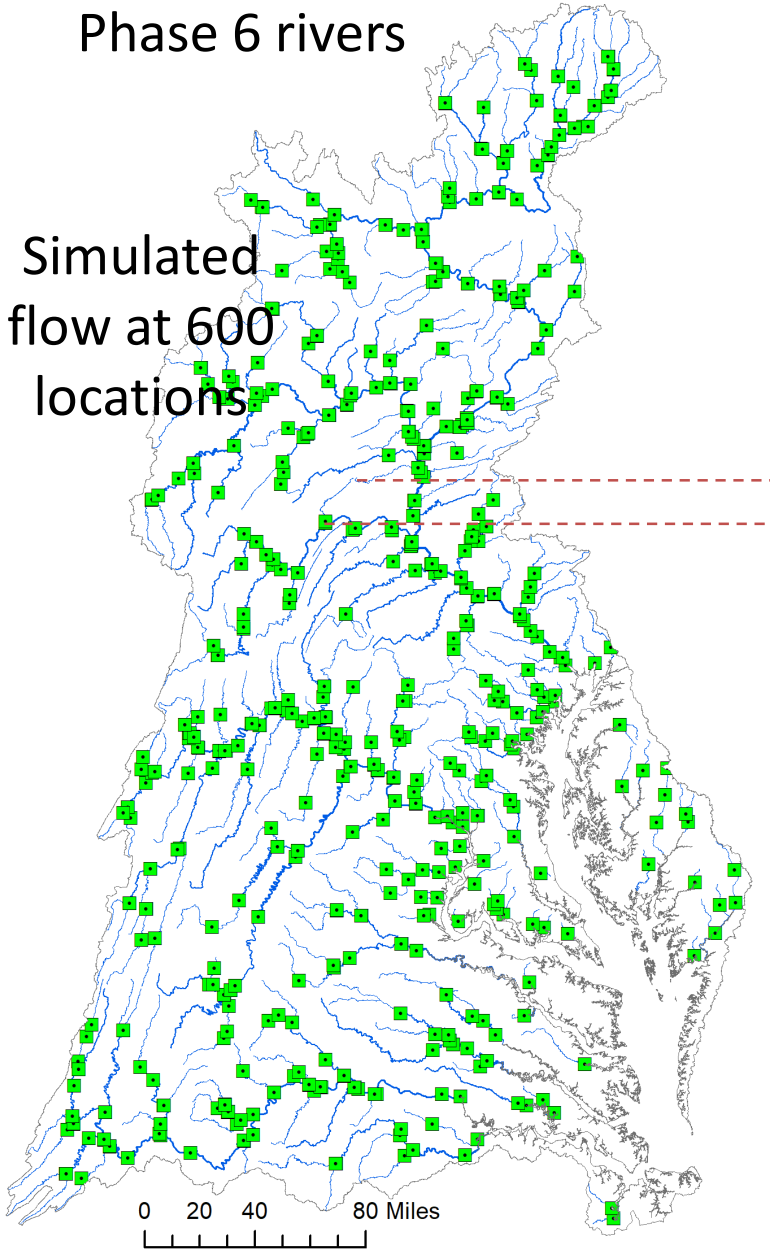


- Simulation at NHD catchments would be considerably finer scale than that of Phase 6 (approx. 80x)
- Ability to represent watershed characteristics at finer scale

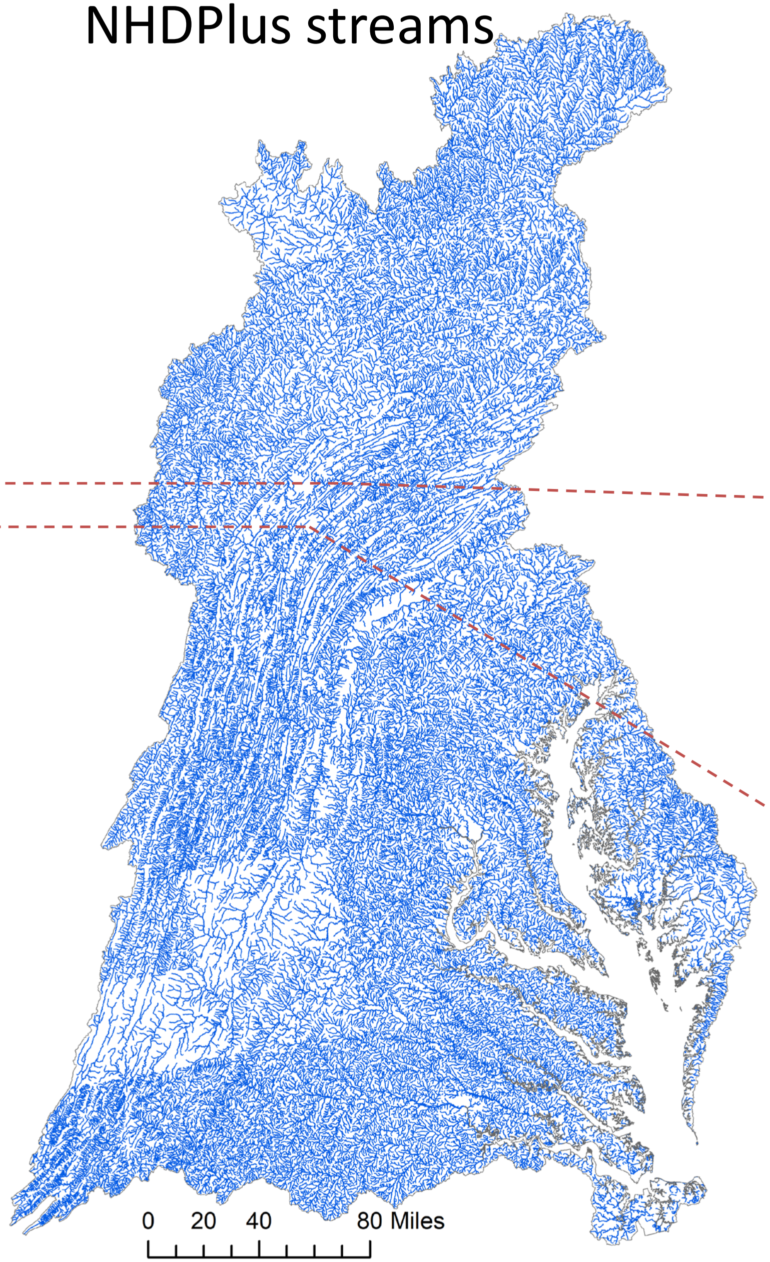


Scale – Phase 6 vs. CRHM 2020

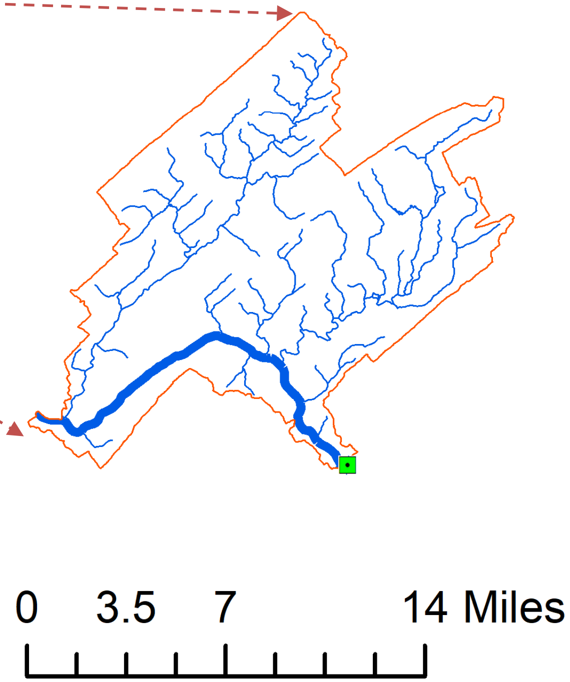
Phase 6 rivers



NHDPlus streams

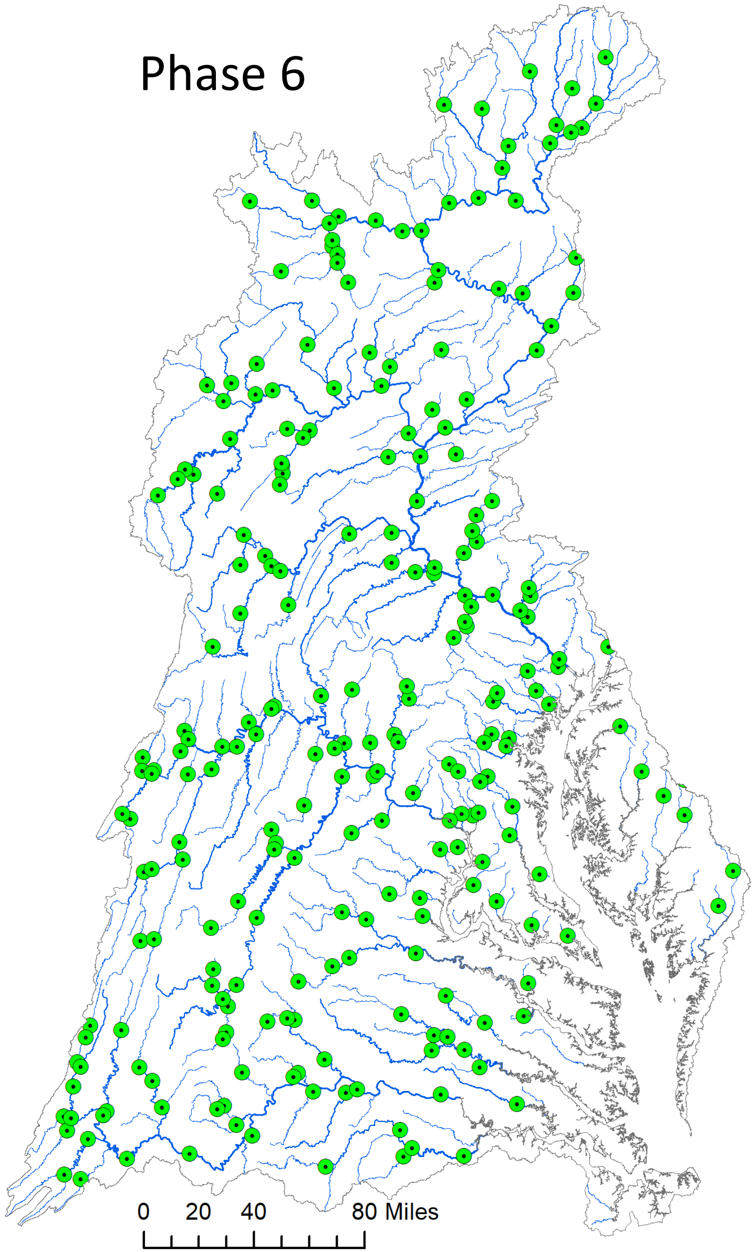


- Model outputs of riverine fluxes (streamflow timeseries) at finer scales



Streamflow Monitoring Data – Model Calibration & Evaluation

Cuiyin Wu, CRC | CBPO



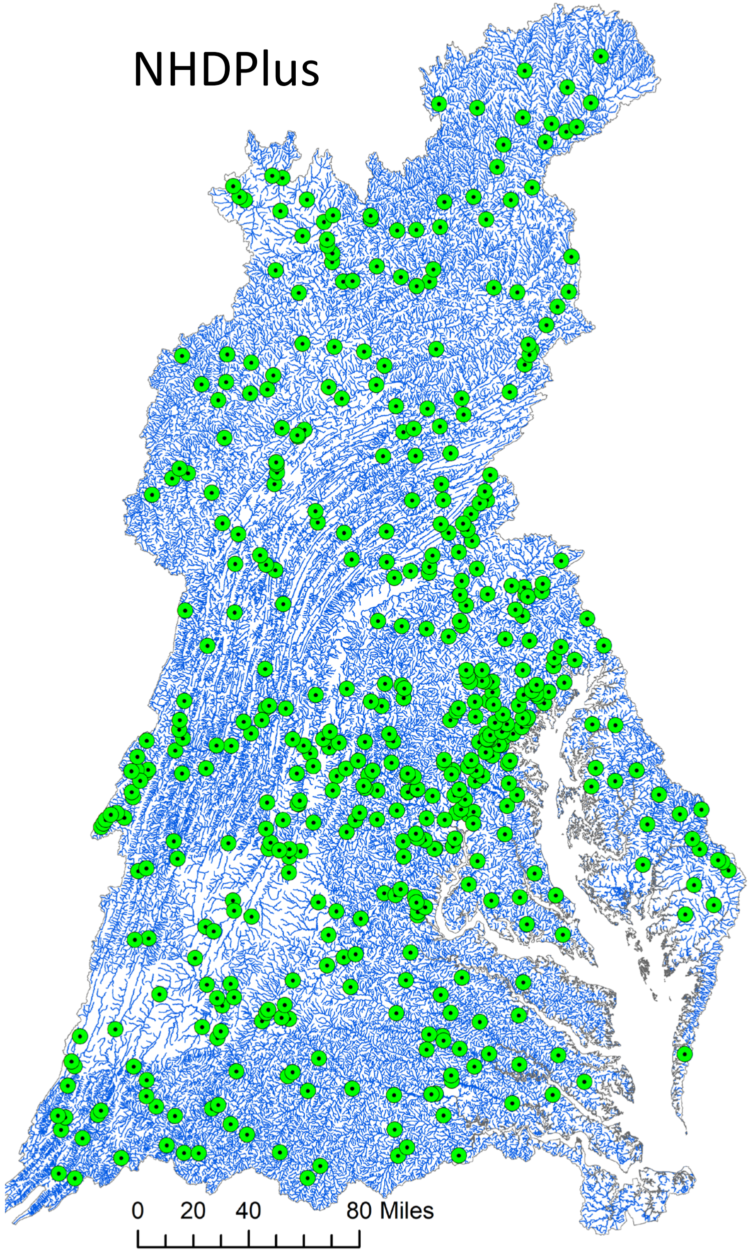


Table: Feasible **flow** calibration stations

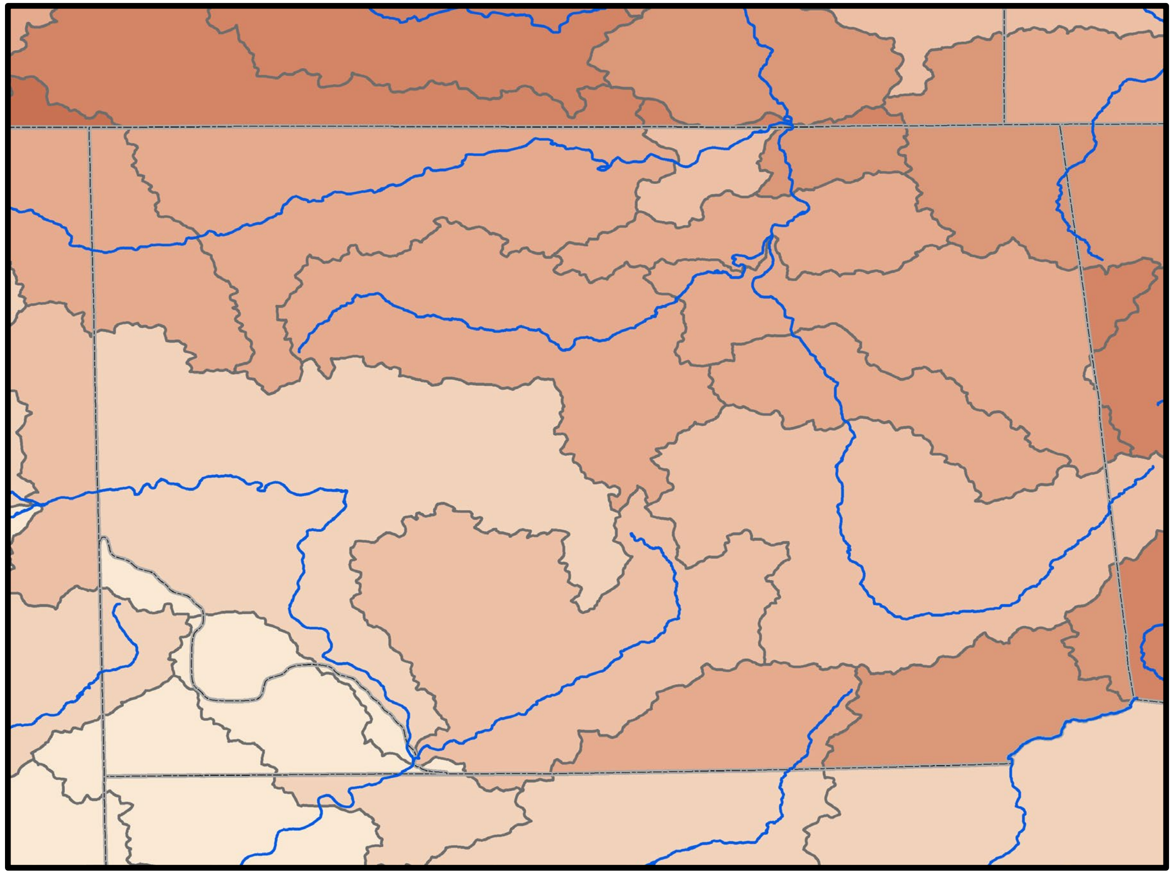
Major Basins	Phase 6	NHD
Eastern Shore	7	23
James	40	52
Patuxent	7	14
Potomac	68	141
Rappahannock	8	12
Susquehanna	101	159
Western Shore	7	49
York River	8	17
Total	247	**467**

Stations with flow data during 1985 to 2019

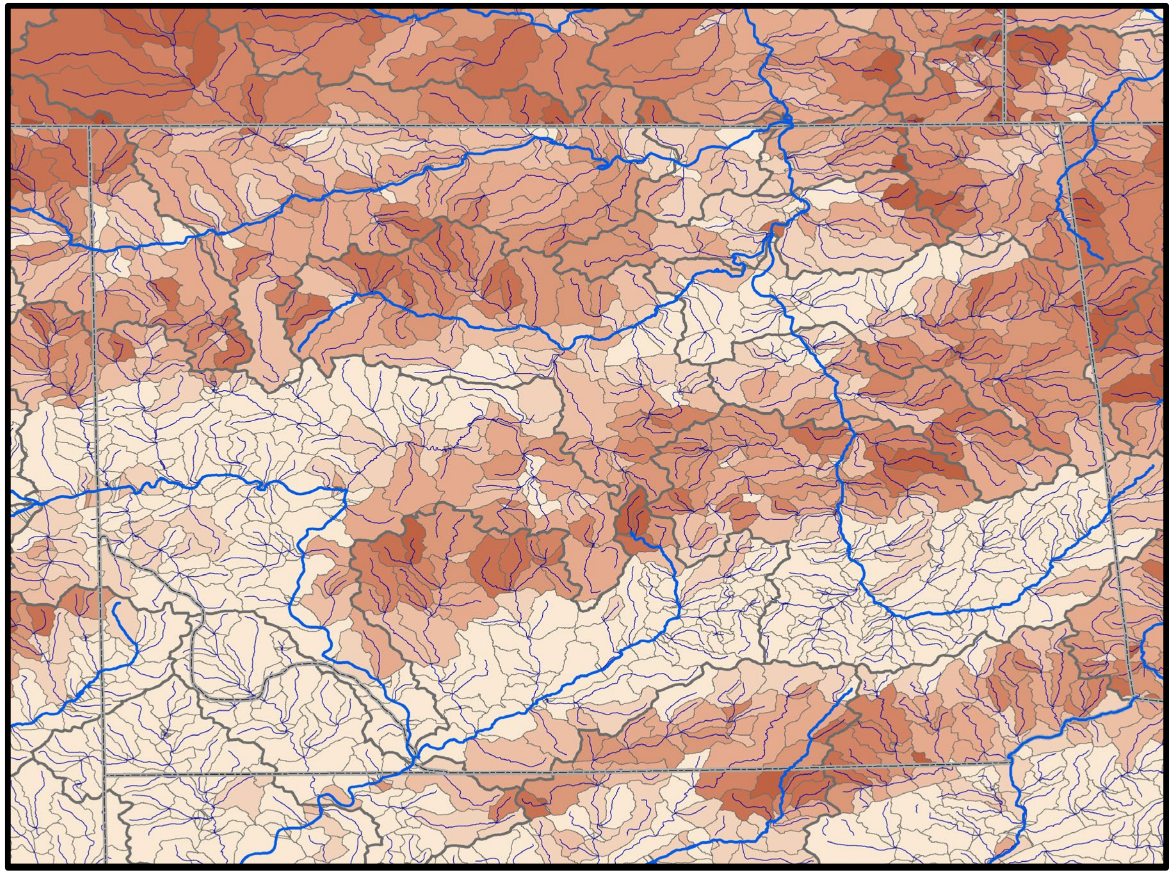
Methods and Results – CRHM 2020 Version 1

"Downscaling" of Phase 6 hydrology to NHD catchments based on the composition of land cover data

Land Segment → River Segments



Land Segment → NHDplus Catchments



County/Land Segment

Percent Cropland

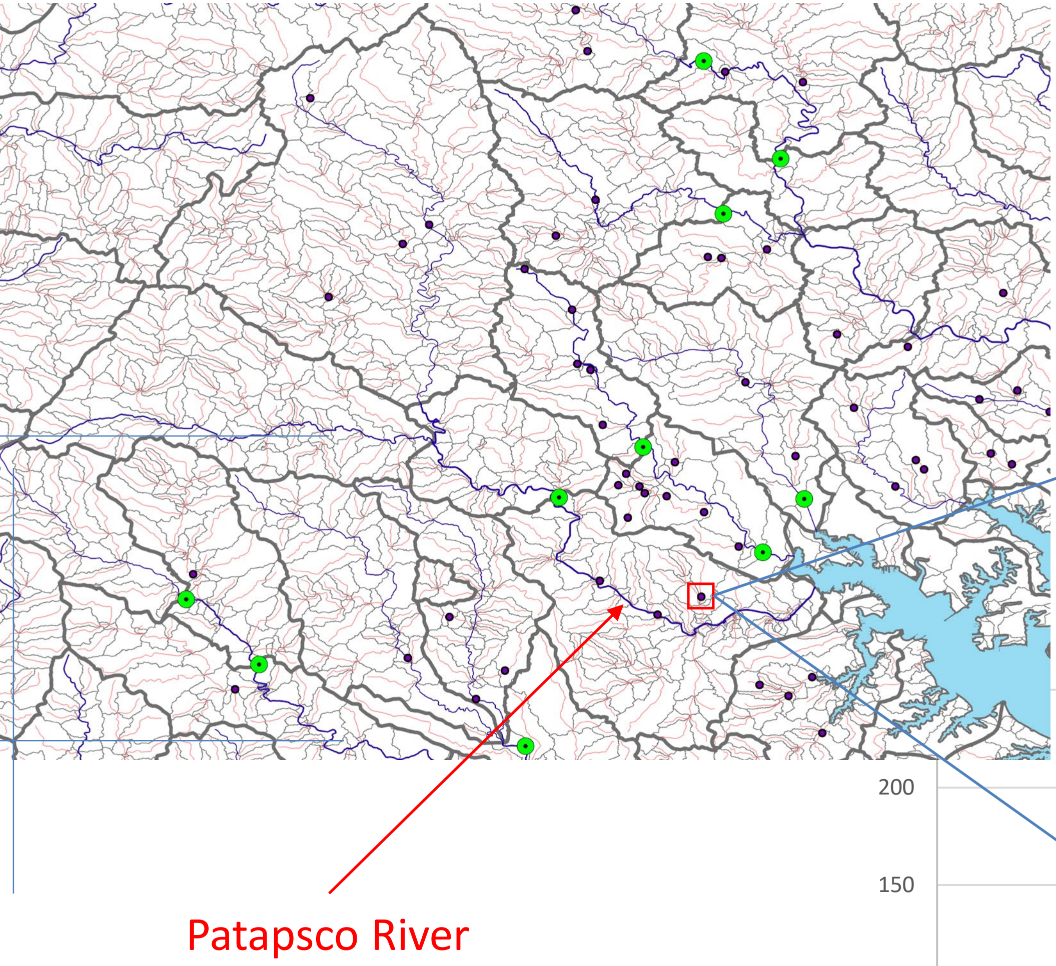
0% - 3%
4% - 9%
10% - 17%
18% - 26%
27% - 35%
36% - 45%
46% - 55%
56% - 66%
67% - 80%
81% - 100%

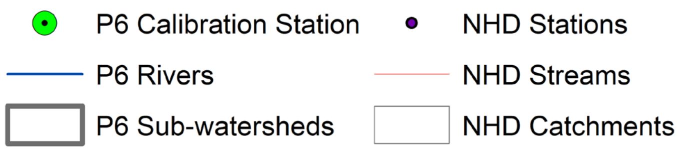
Methods and Results – CRHM 2020 Version 1

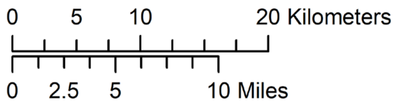
- Limitations of the current approach
  - Point-source (Wastewater & CSO) discharges
  - Surface water withdrawals (water supply and irrigation)
  - Spatial variability in rainfall and meteorology
  - Flow routing through small streams
  - Spatial variability in watershed properties

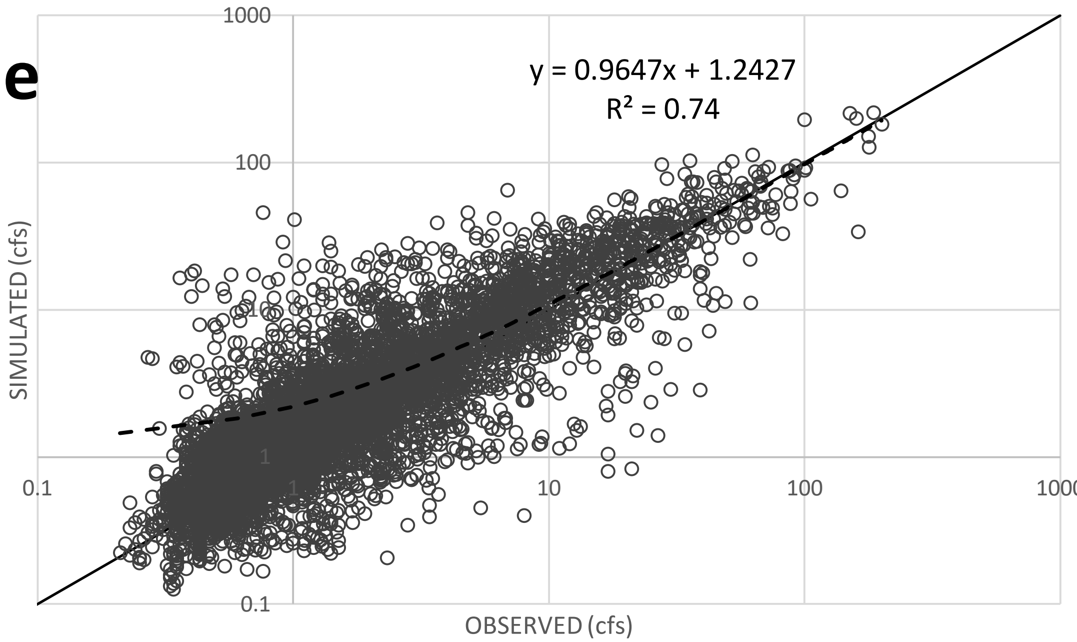
+ other minor issues such as static land cover, exclusion of water land use, etc.

Downscaled streamflow at NHDplus scale

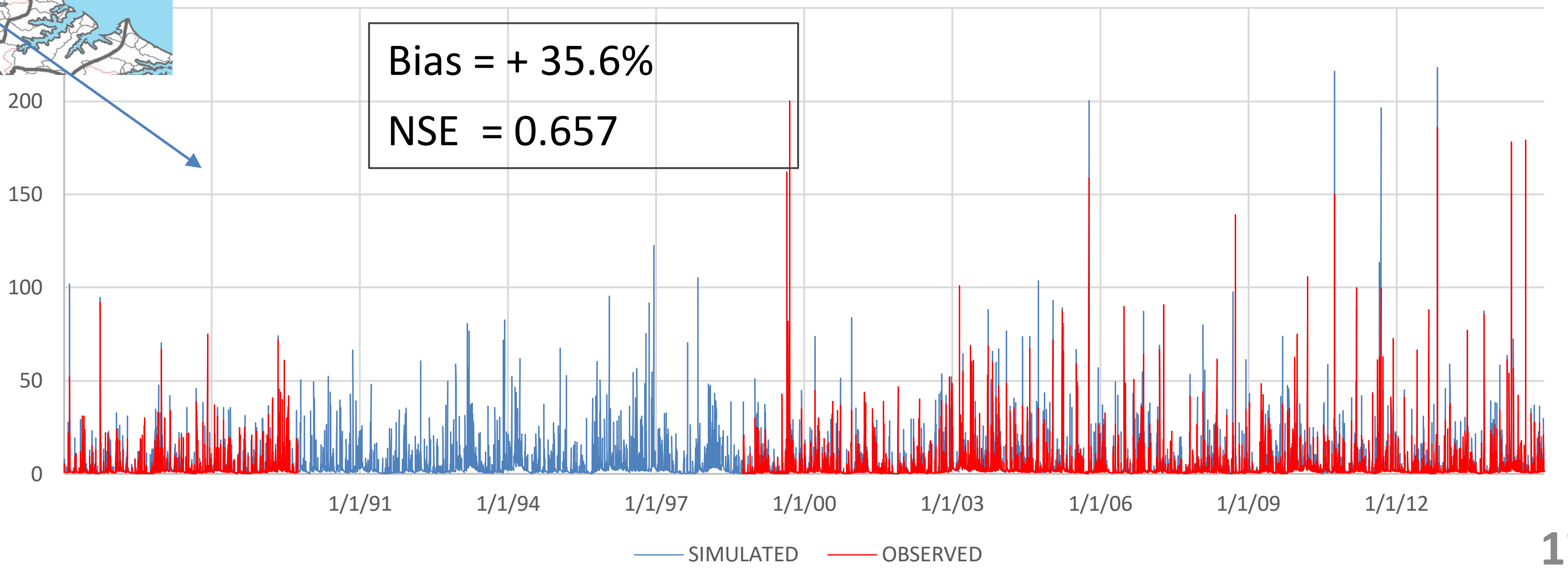






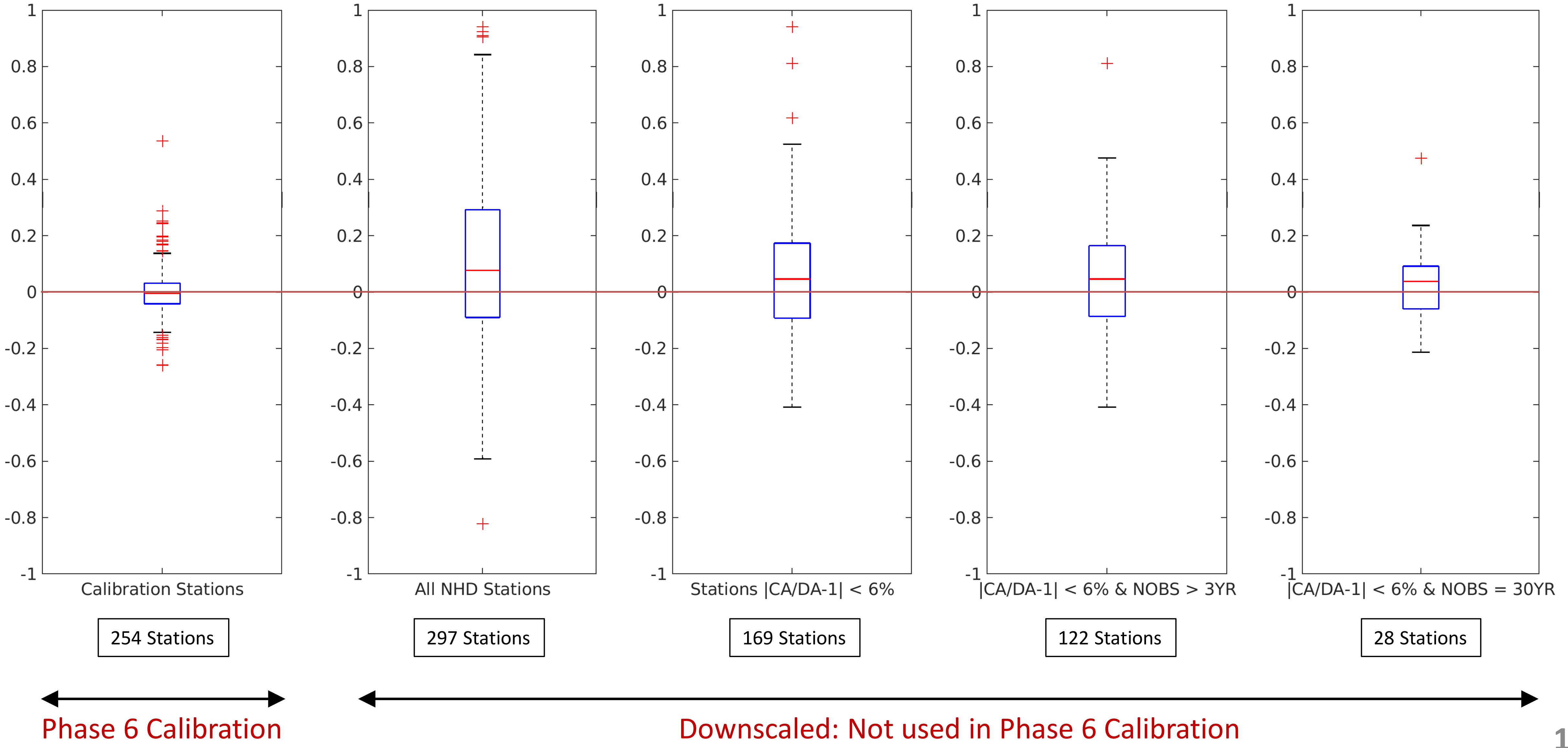


DAILY FLOW (cfs): USGS 01589100 EAST BRANCH HERBERT RUN AT ARBUTUS, MD; **DA = 2.47 mi^2; Flow = 3.6 ft^3/s**



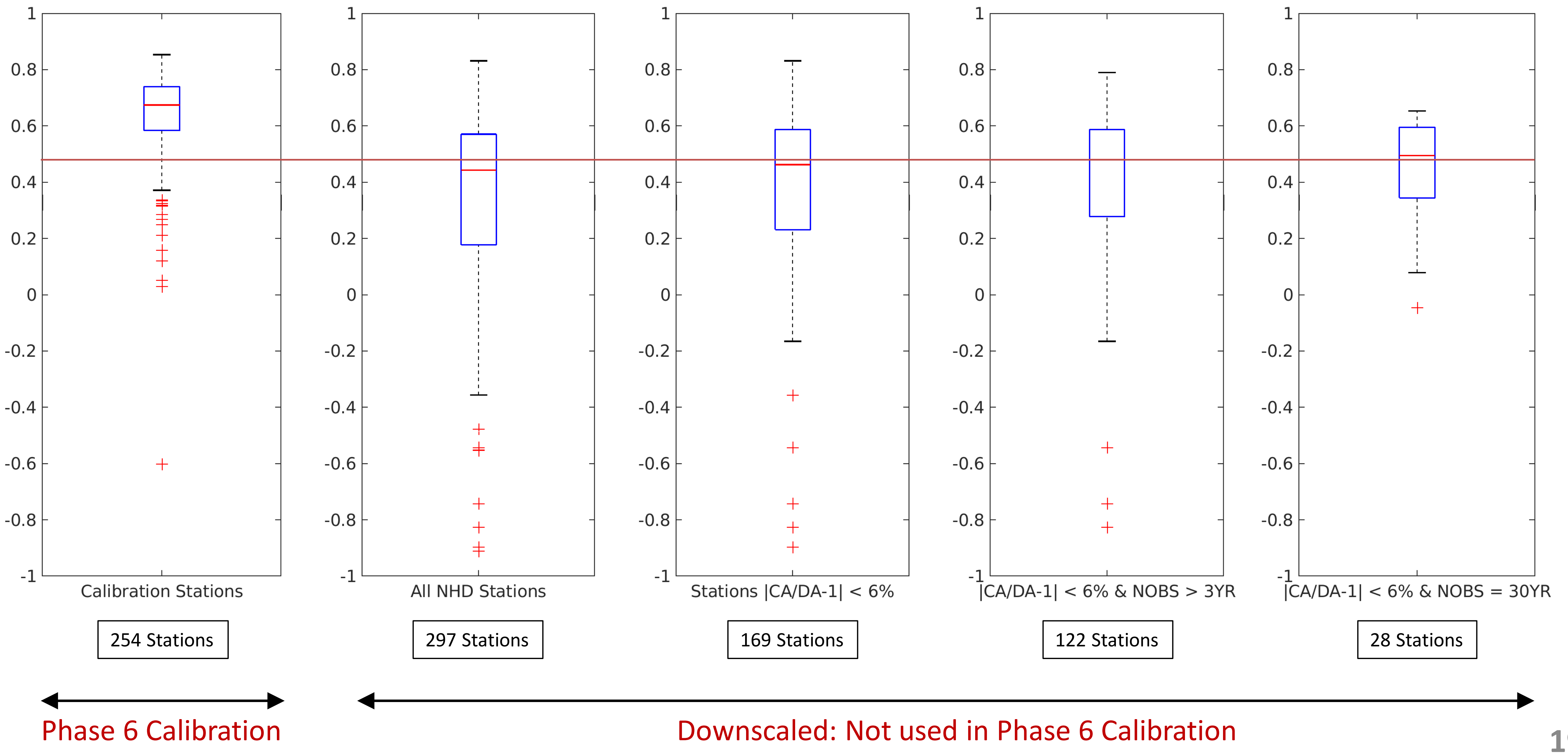
Bias in simulated streamflow

Bias closer to 0 is better



Nash Sutcliffe Efficiency (NSE) of simulated daily streamflow

NSE closer to 1 is better



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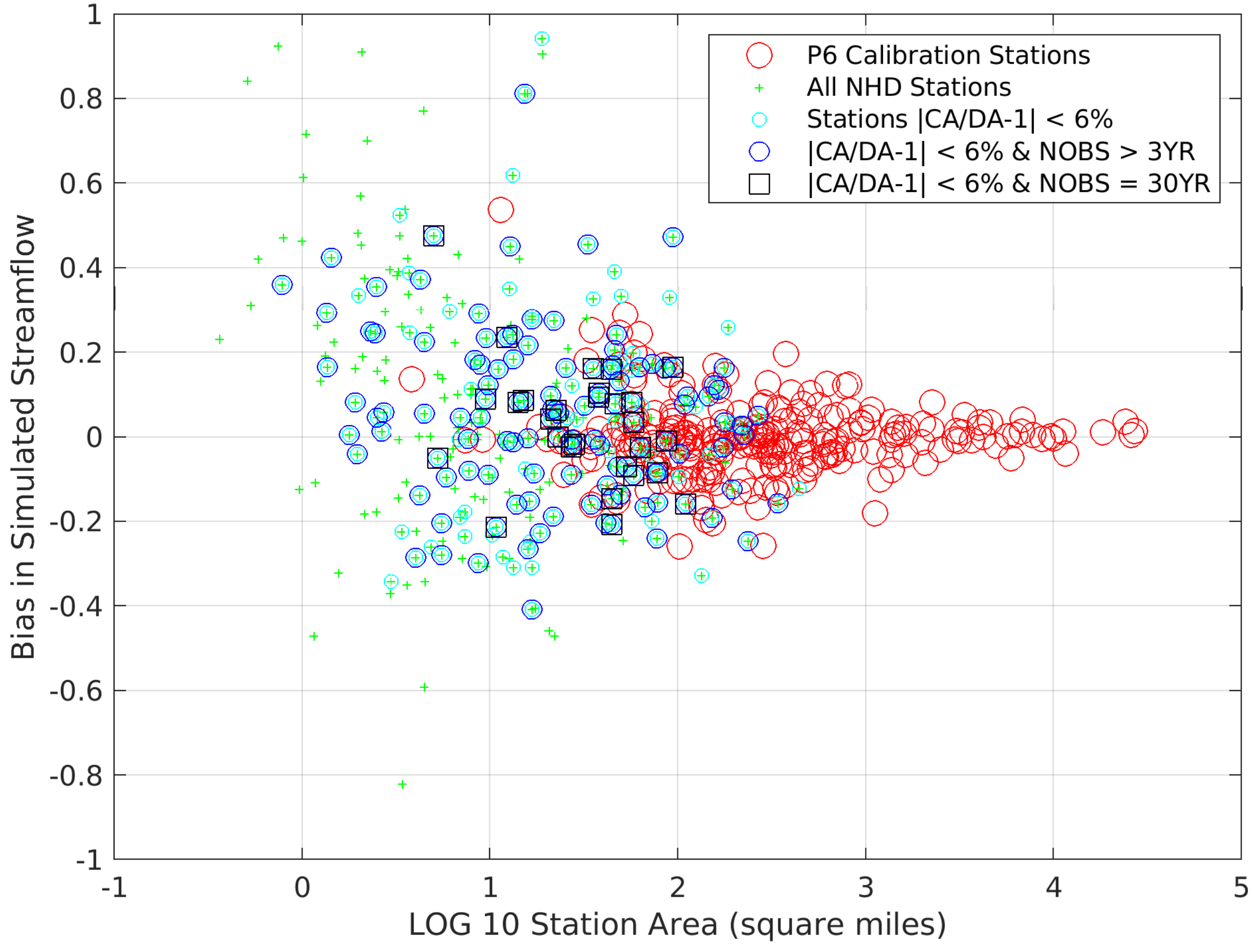
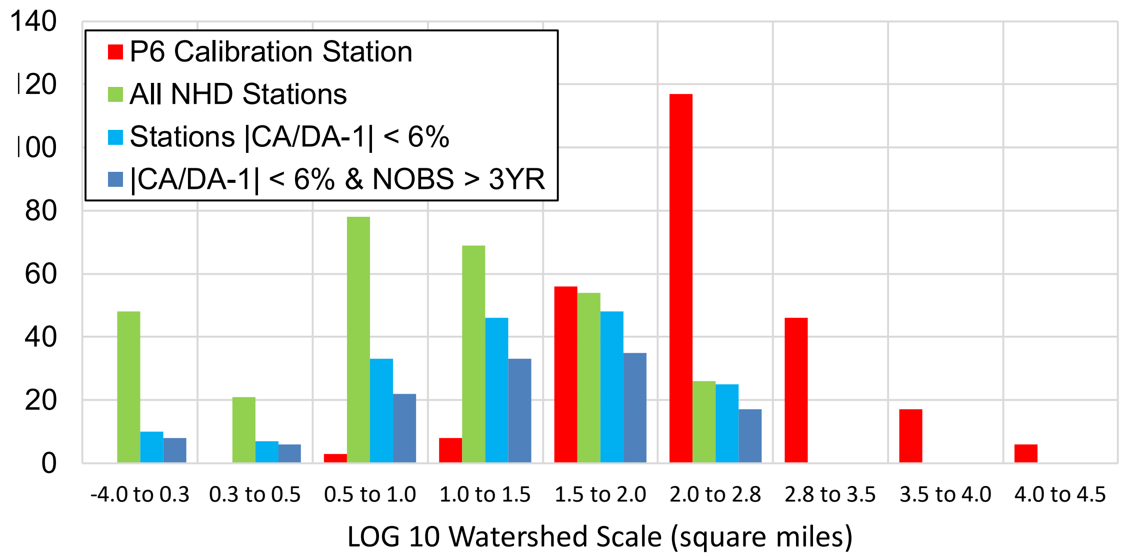
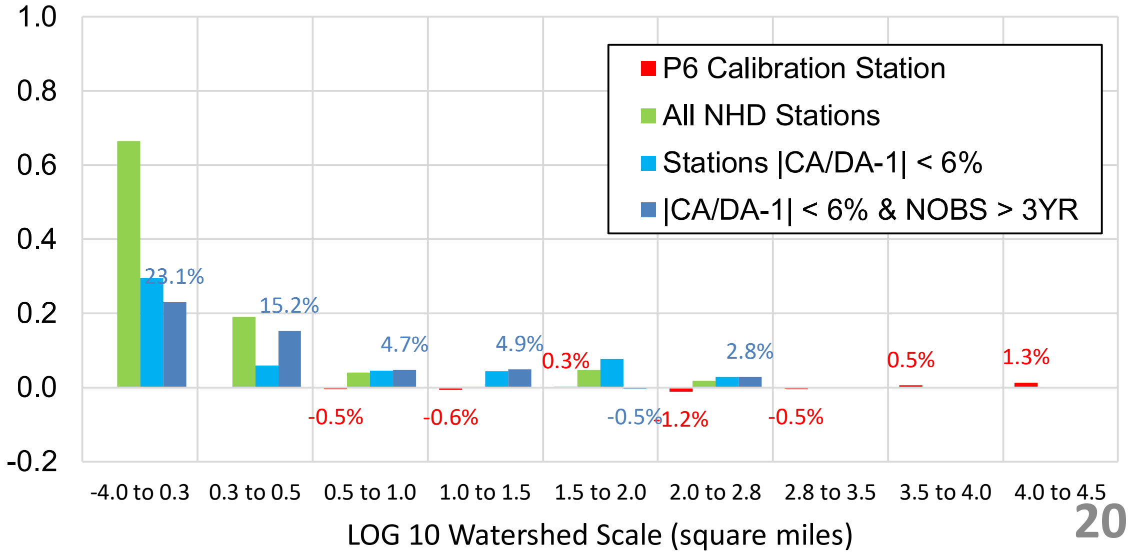


Number of Stations



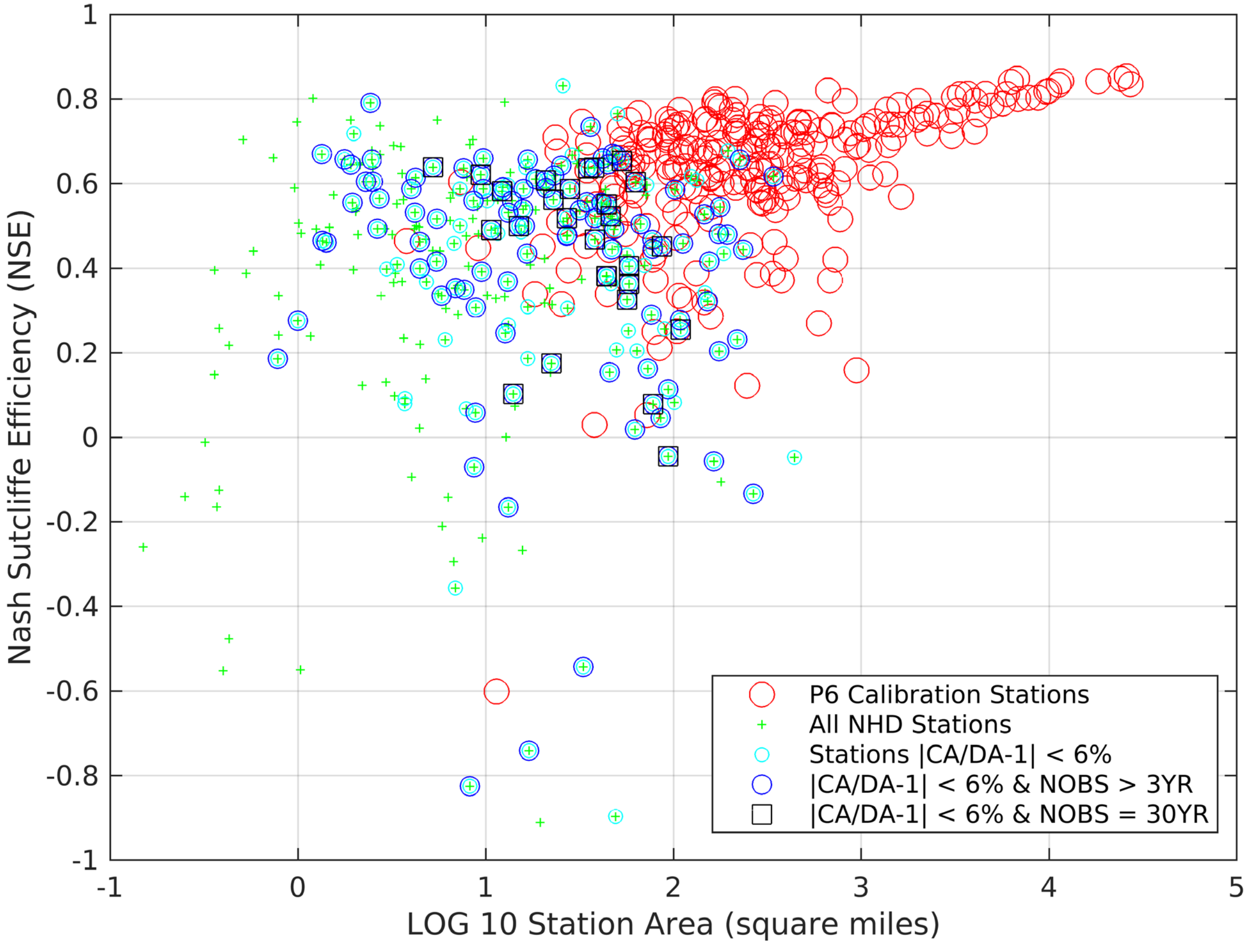
Median Bias in simulated streamflow



“downscaled” streamflow had degradation in biases with watershed scale/size but it showed comparable skill at P6 watershed scale.

Nash Sutcliffe Efficiency (NSE) of simulated daily streamflow

NSE closer to 1 is better



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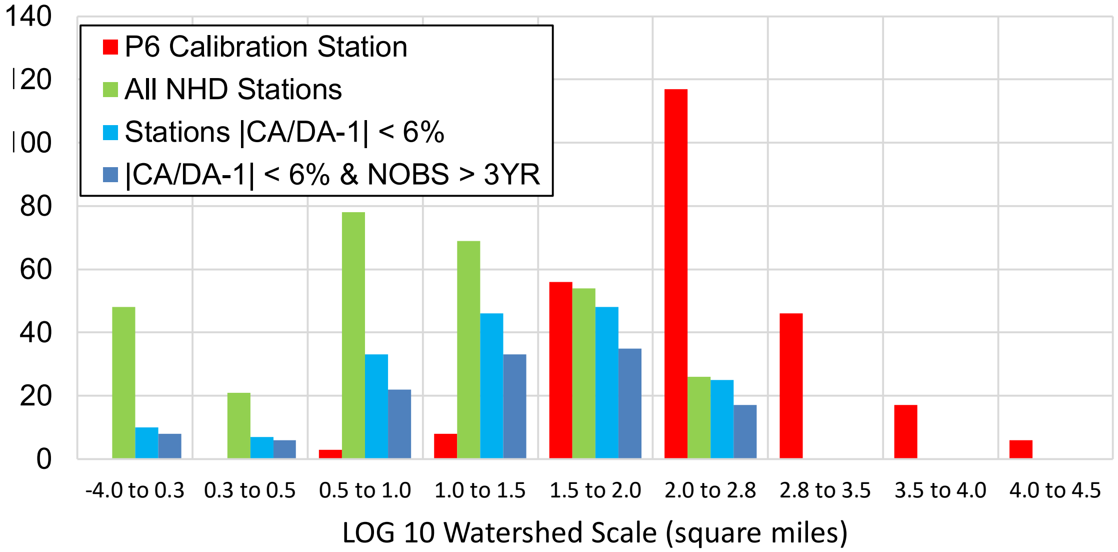
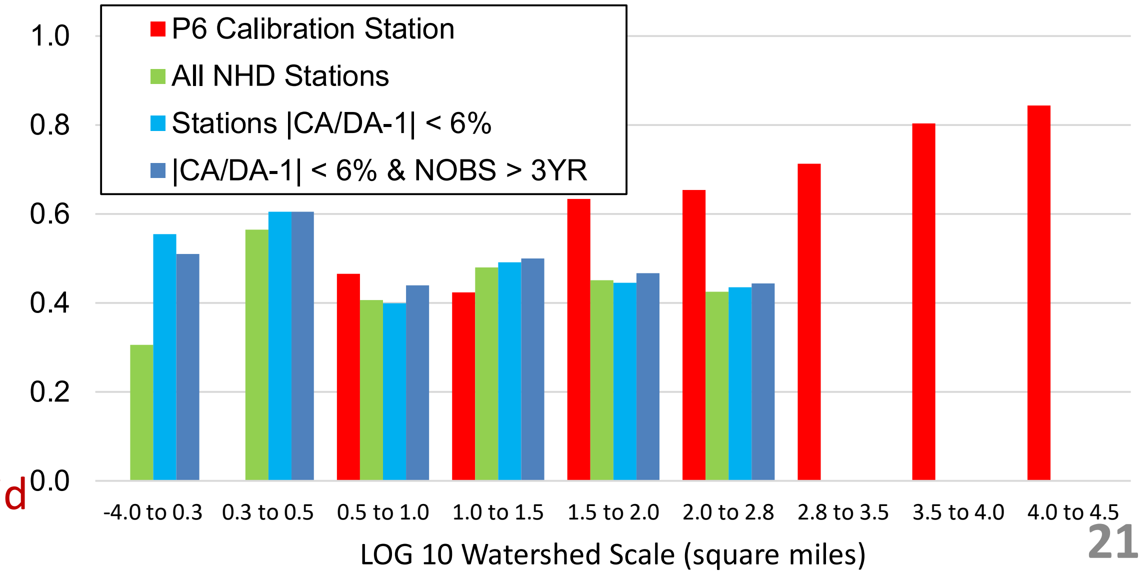


NSE of simulated daily streamflow



Although "downscaled" streamflow had an overall lower NSE but it did not show significant degradation in model skill with "downscaling".

Summary and Next Steps

- CBPO Watershed Modeling Team is working on CRHM 2020 at NHDplus (1:100,000) scale.
  - early results were presented
- Potential lines of investigations:
  - Variability in rainfall and temperature between P6 and NHD Scales
  - Diversions
  - Empirical relationships between land use parameters that defines their water budget
  - Other watershed characteristics (e.g., topography, soil hydraulic properties)

Predicting ecological flow statistics using the CBP Phase-6 hydrologic model

- Streamflow is among the “master variables” that constrains the ecological characteristics of stream ecosystems (Poff and Zimmerman, 2010)
- Recent CB example: Influence of changes in spring high flows on fish community life-history strategies, Potomac mainstem (Hitt et al., 2019)
- How well does the Chesapeake P6 hydrologic sub-model predict daily streamflow statistics of ecological relevance?

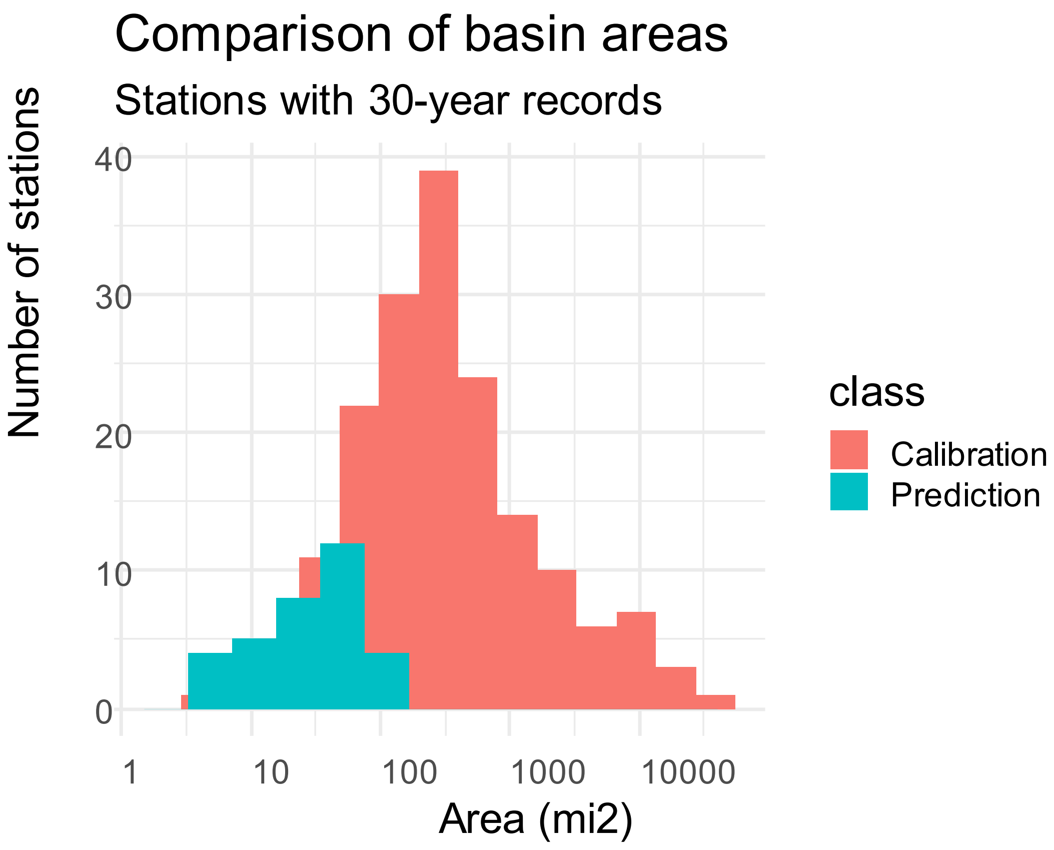
Statistics considered today

- Drawn from statistics linked by Carlisle et al. (2017) to impairment of benthic invertebrate communities in three EPA level-3 ecoregions dominant in CB watershed.
  - *Northeast, Eastern Highlands, Eastern Coastal Plain*

Abbreviation	Description	Units
mhSpr	Period-of-record (POR) average of the time series of maximum daily flows occurring in the months of March, April, and May (area-normalized)	cfs/mi^2
ra5	POR average of the percentage of days per year that hydrograph is rising ($Q_{Dt = i+1} > Q_{Dt = i}$)	percent
fl1	POR average of the number of instances per year that daily flow drops below the POR 10^{th} percentile of daily flows	count
ma1	POR mean annual flow (area-normalized)	cfs/mi^2

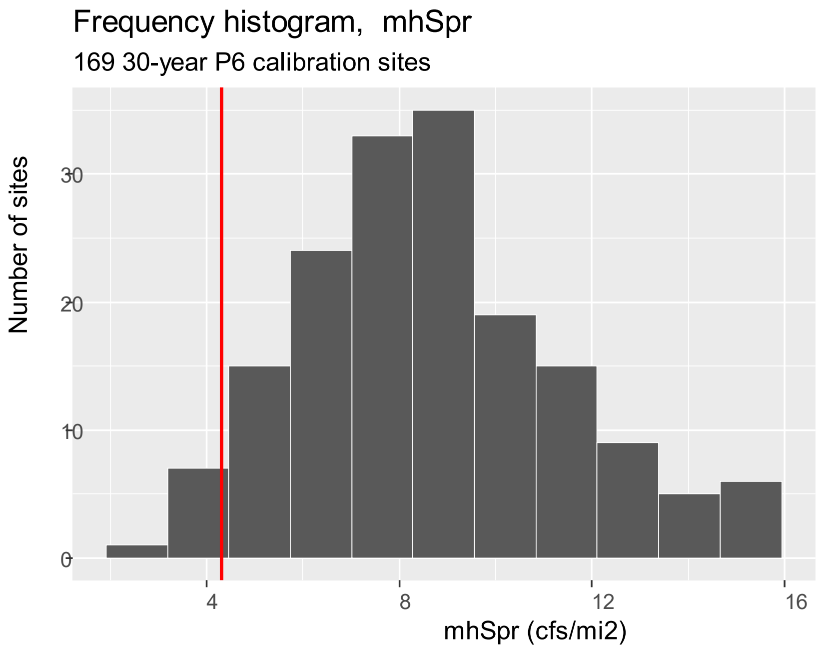
Data considered

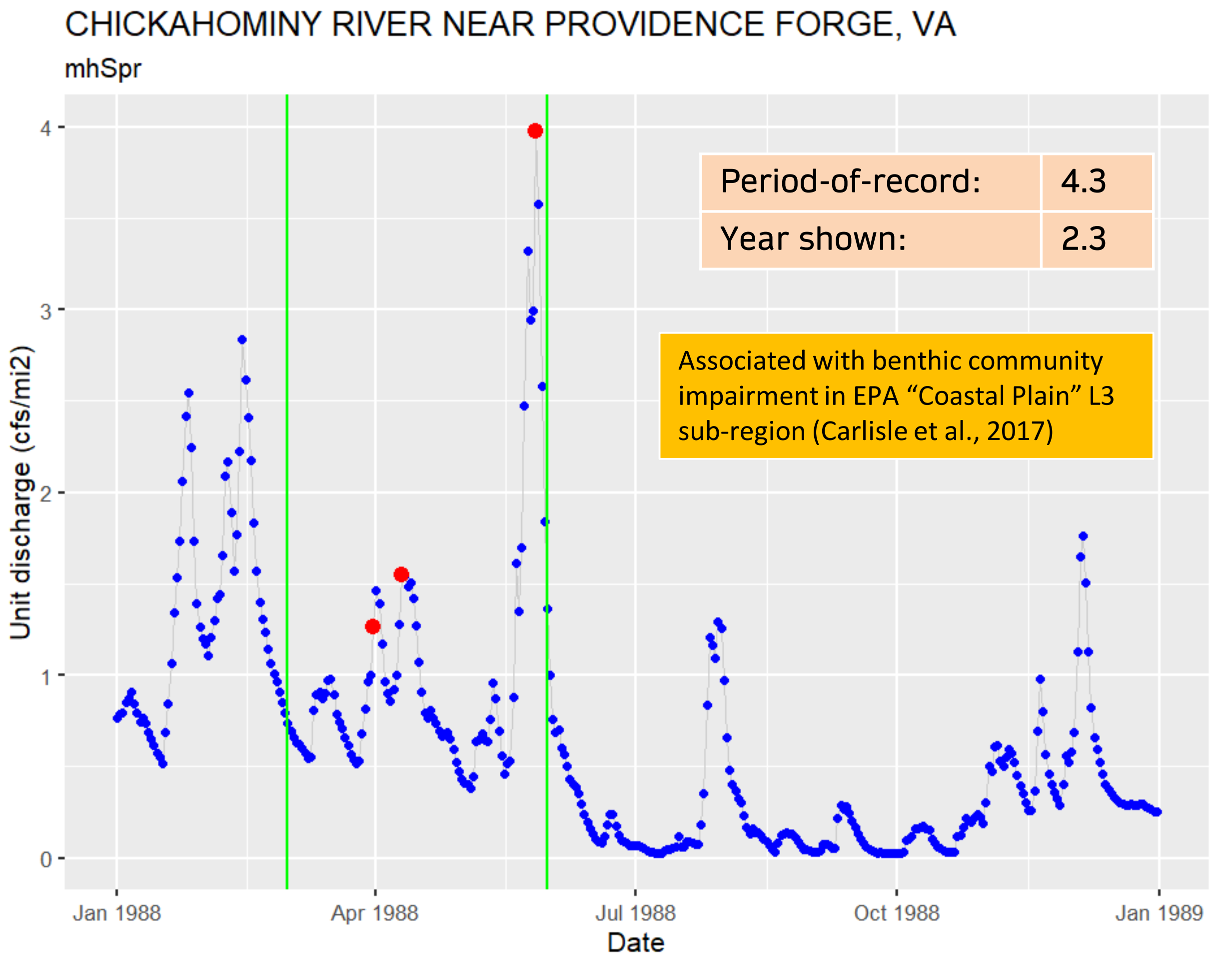
- Observed/simulated daily time series for sites *having an unbroken 30-year record (CY 1985-2014)*
  - "Calibration": 169 sites used for P6 hydrologic sub-model calibration
  - "Prediction": 30 smaller sites, accessible through NHD "down-scaling"
- Evaluate ability to represent site-to-site differences in POR averages, not ability to represent change over time at individual sites



Mean annual spring high flows

Average of March, April, May maximum daily flows (cfs/mi^2)

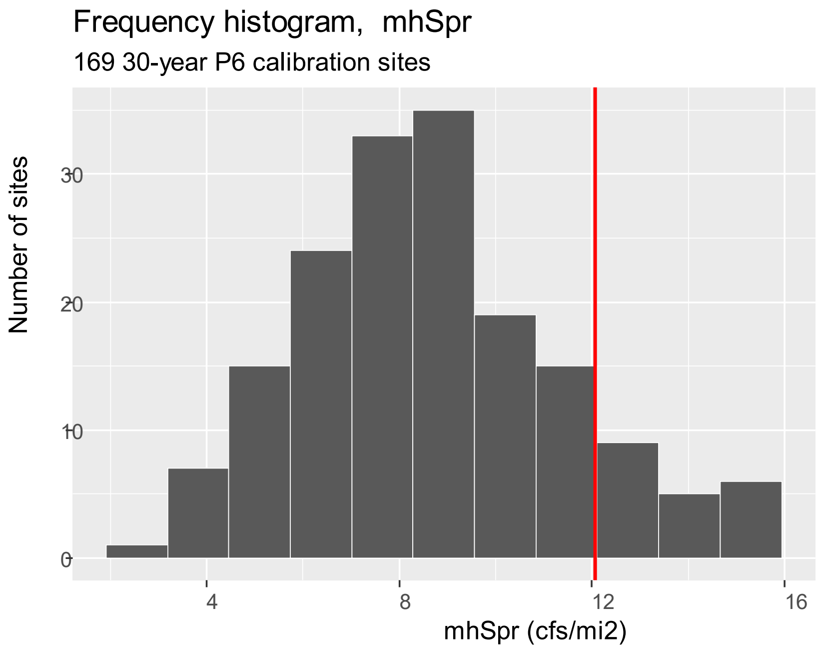


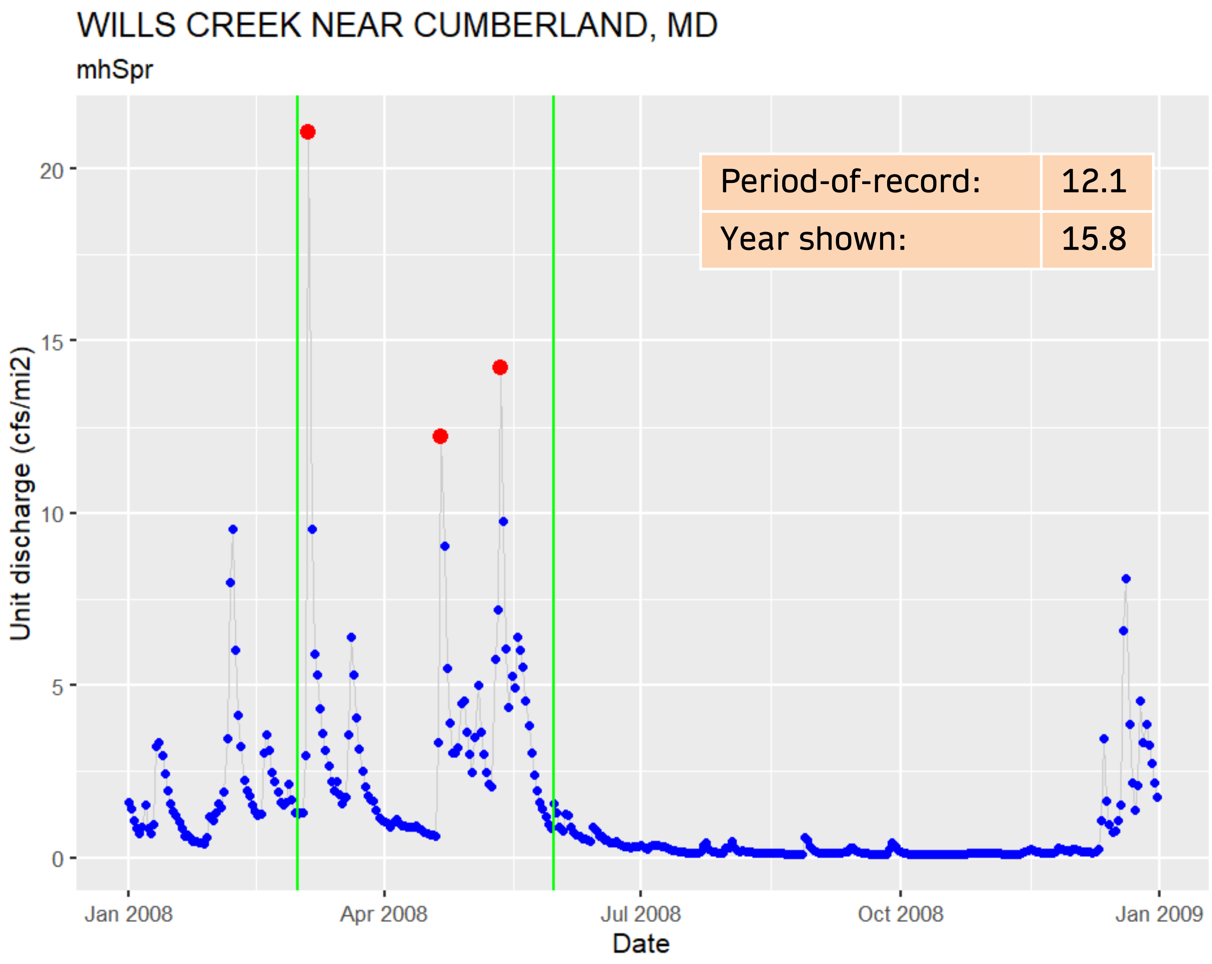


Provisional results, not for citation or publication

Mean annual spring high flows

Average of March, April, May maximum daily flows (cfs/mi^2)





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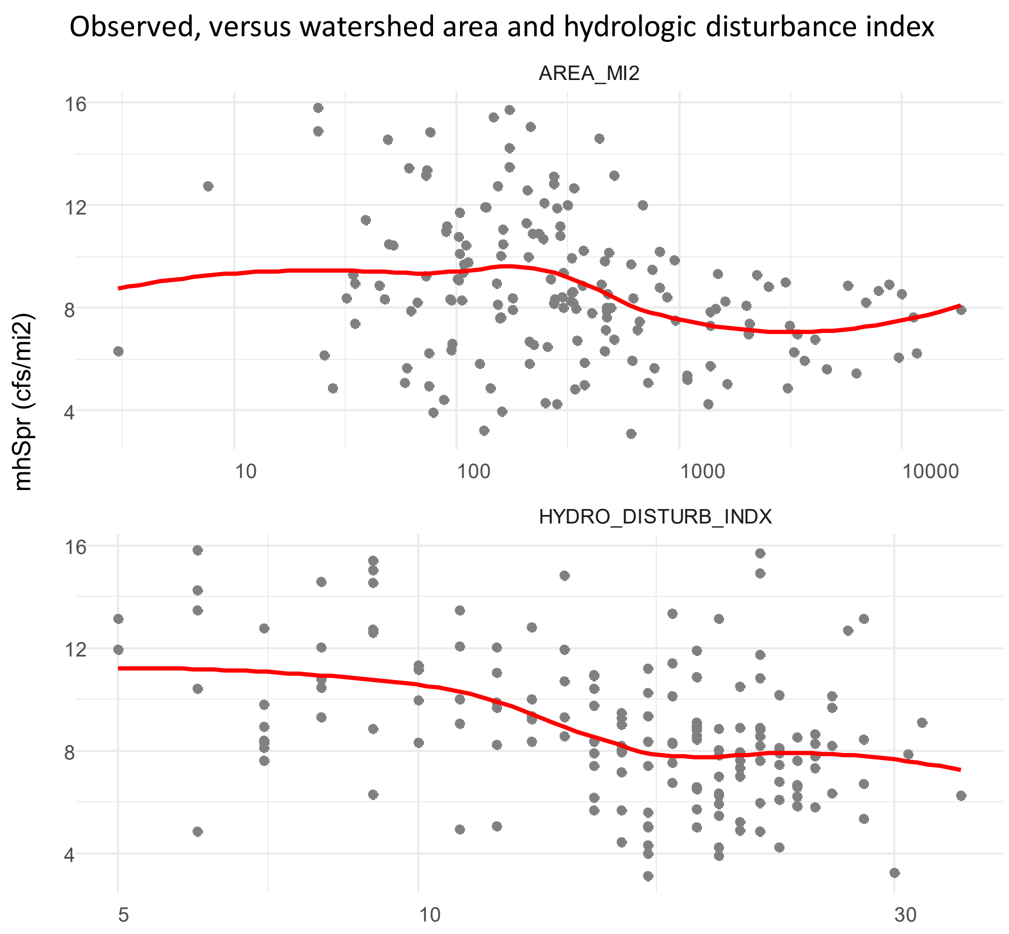

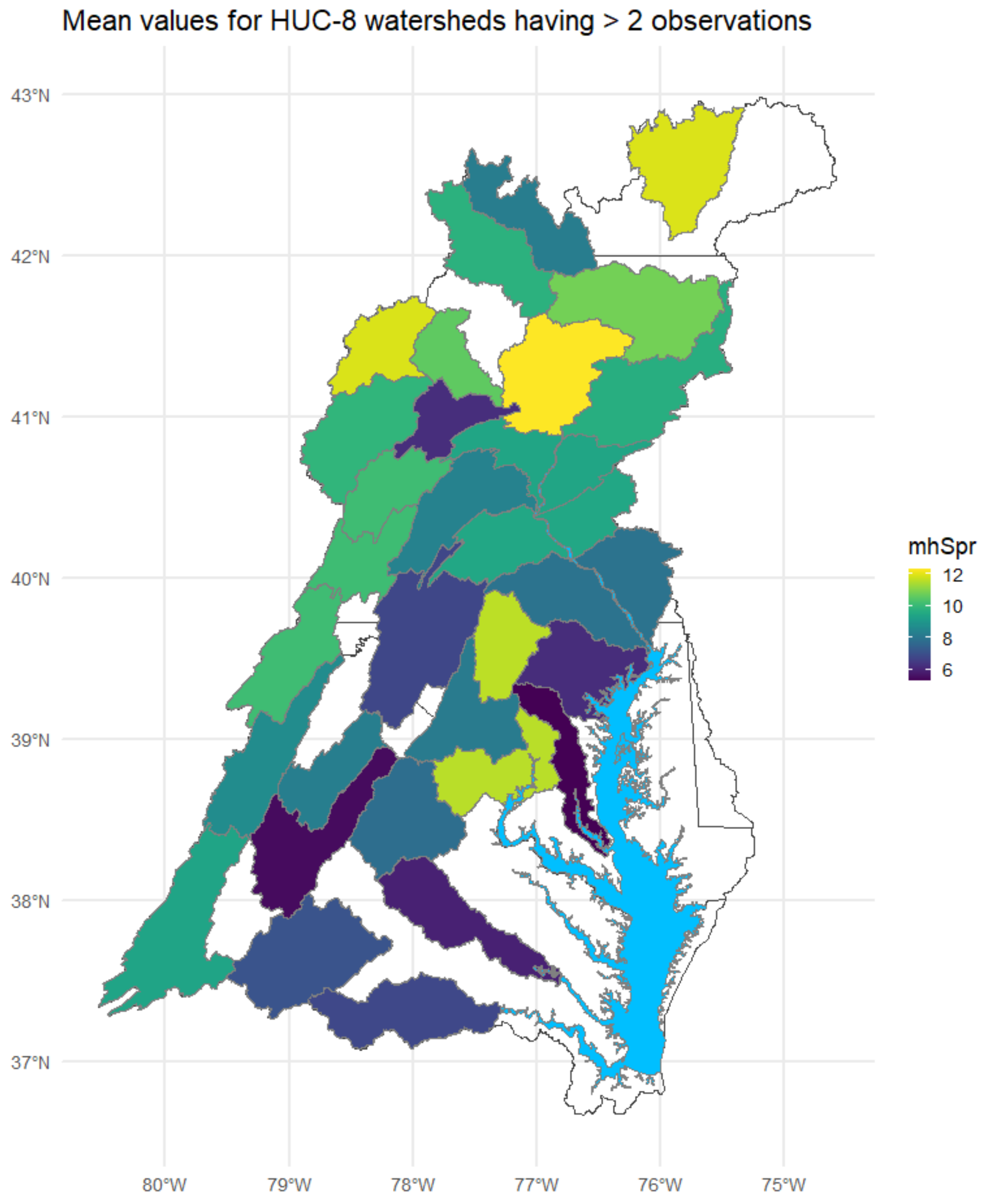

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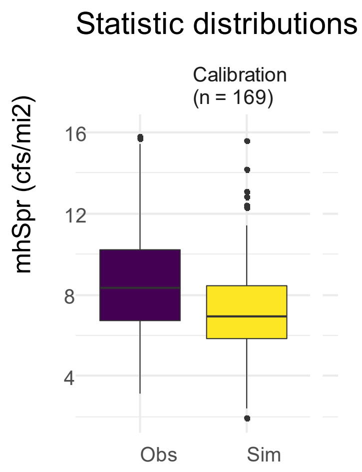
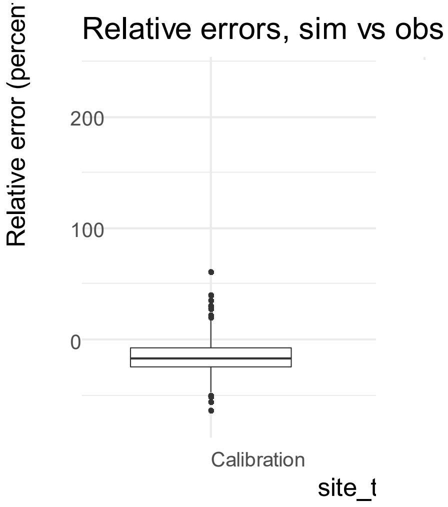
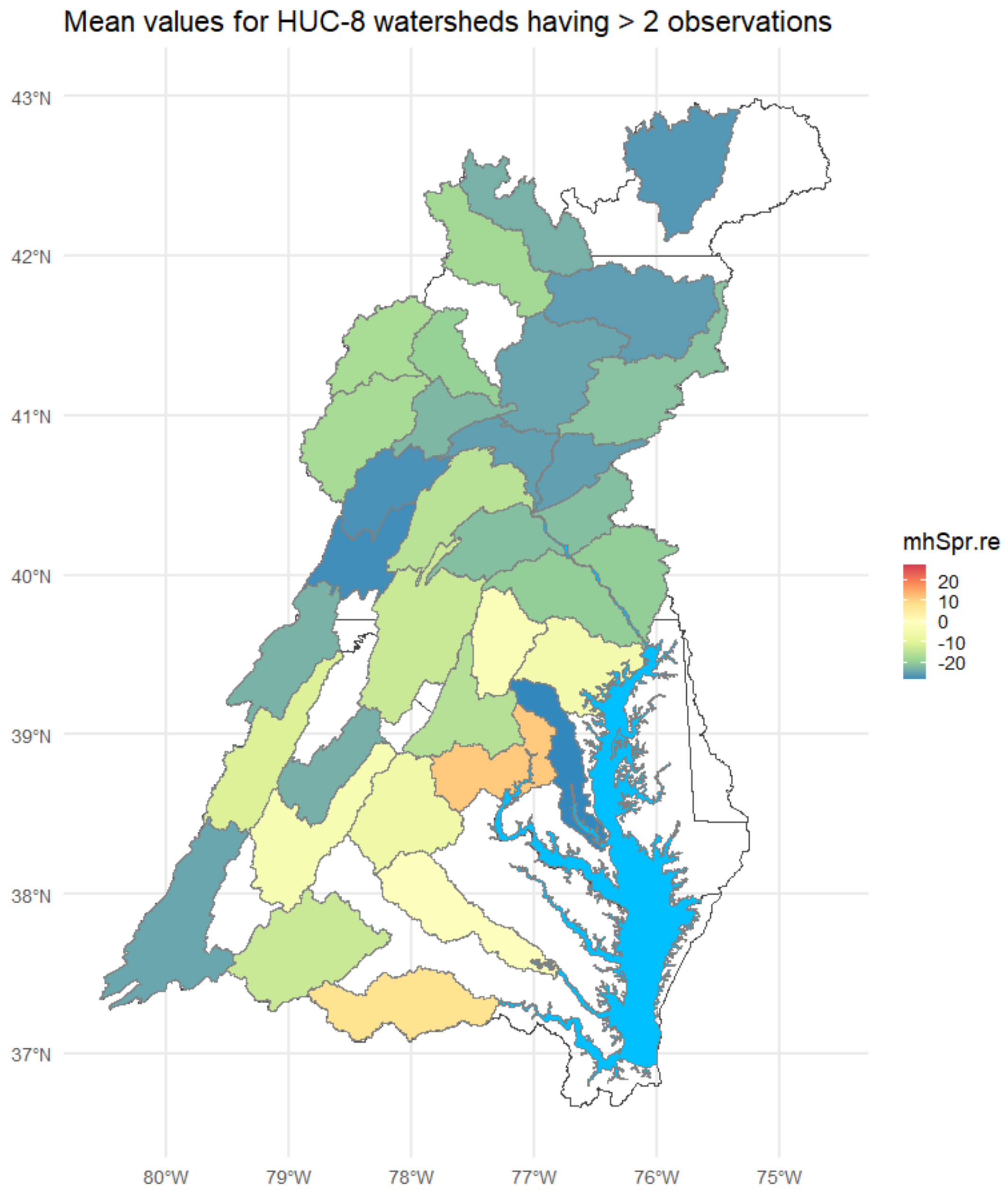
Mean annual spring high flows

- CBP P6 HM performance
  - Calibration







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Mean annual spring high flows

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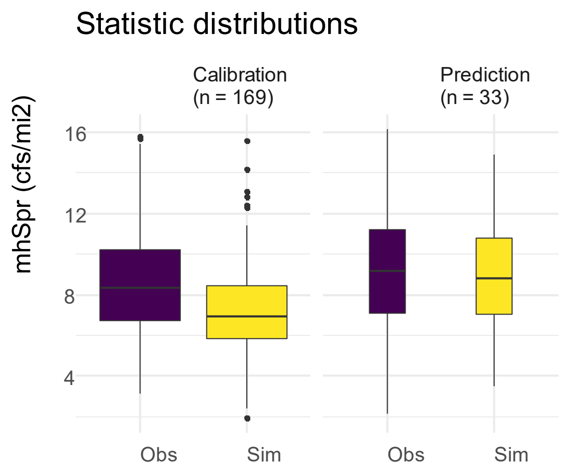

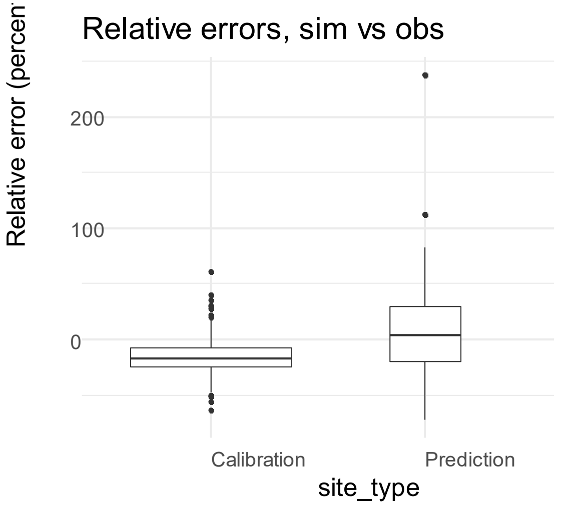

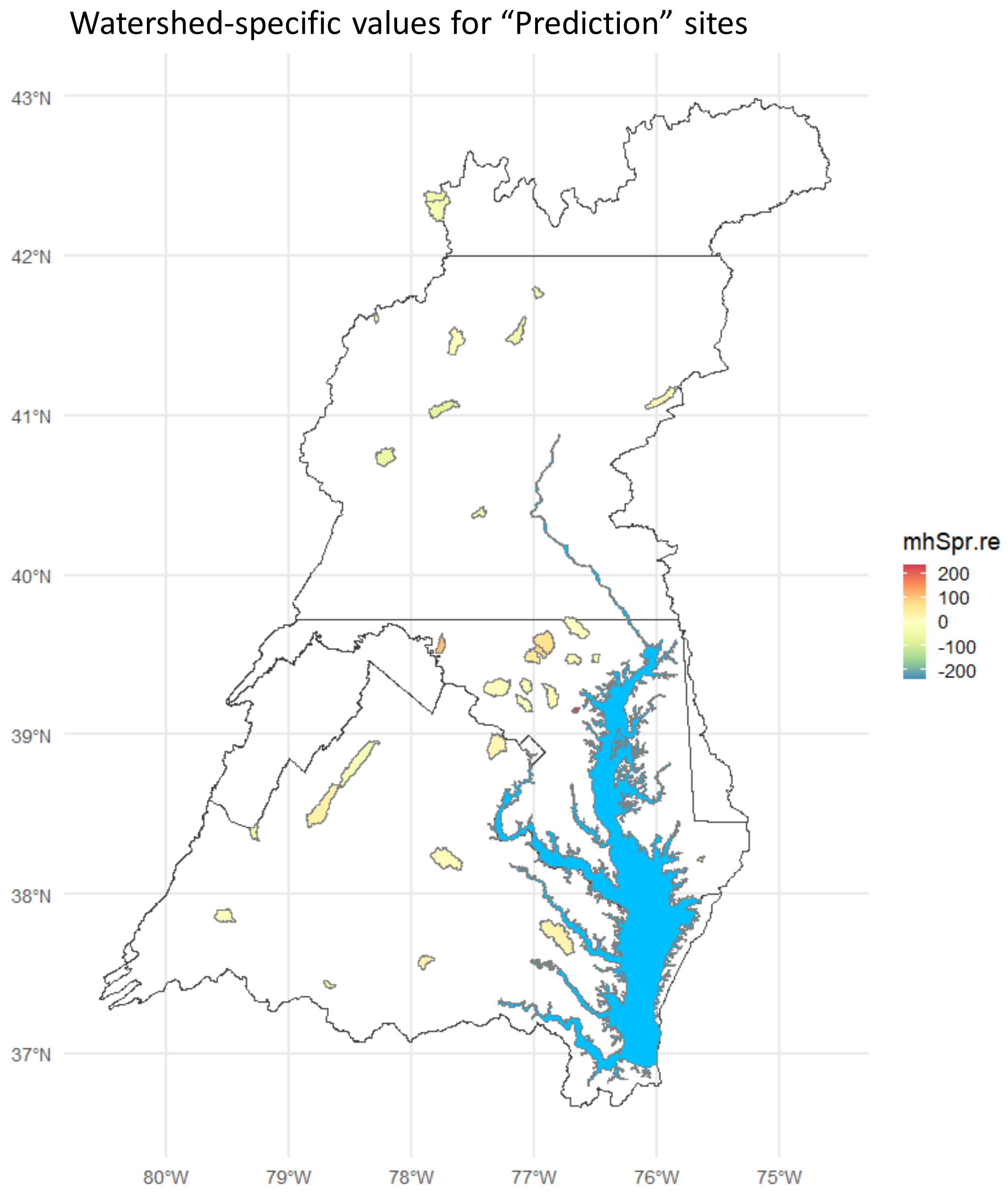

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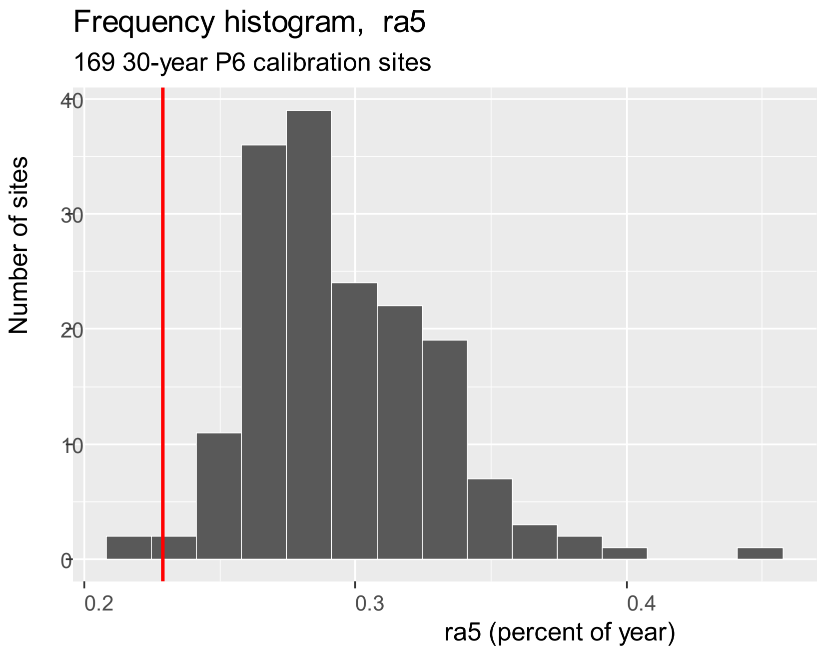
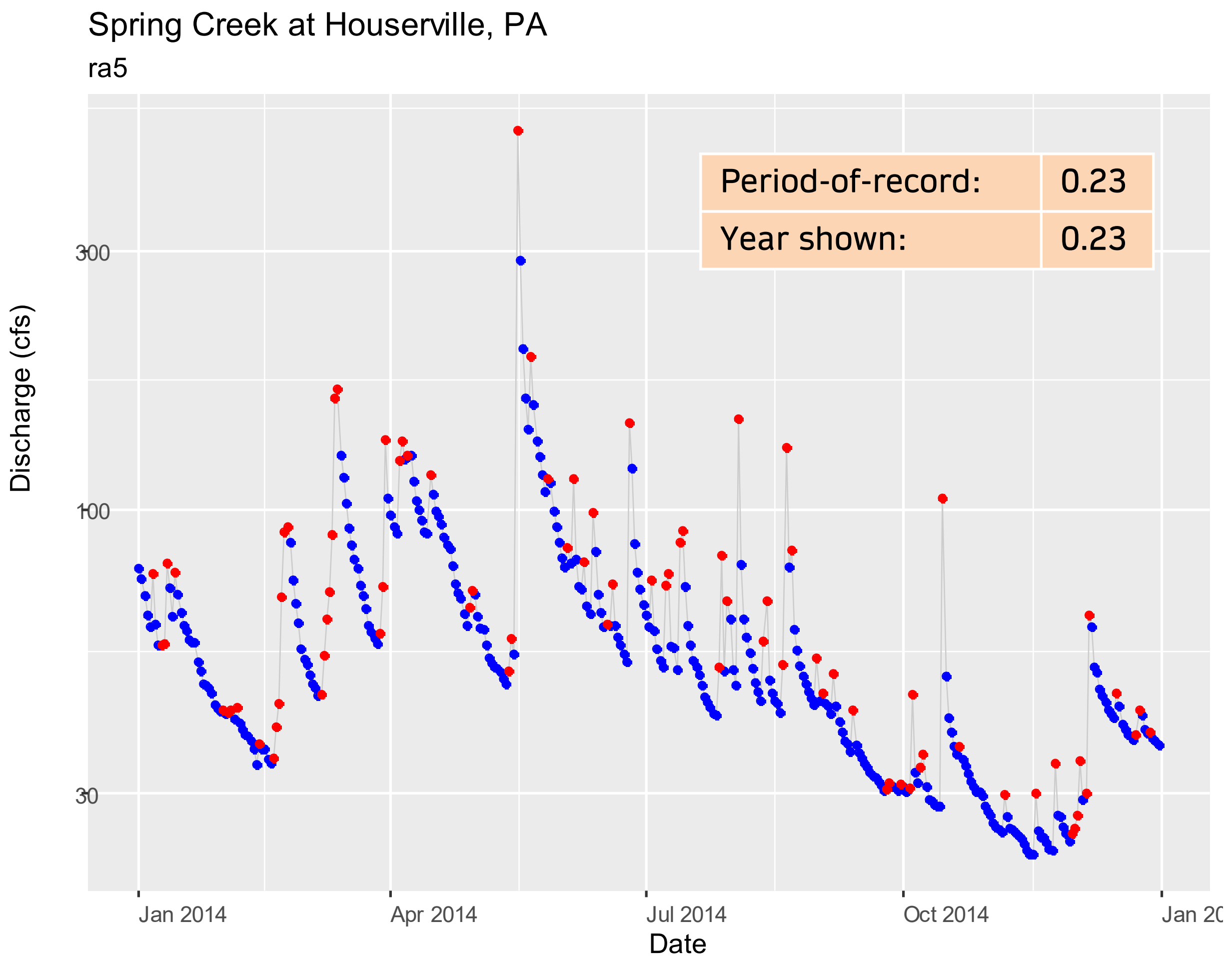
Percentage of days with increasing flows

Percentage of days when daily Q(i + 1) > Q(i)





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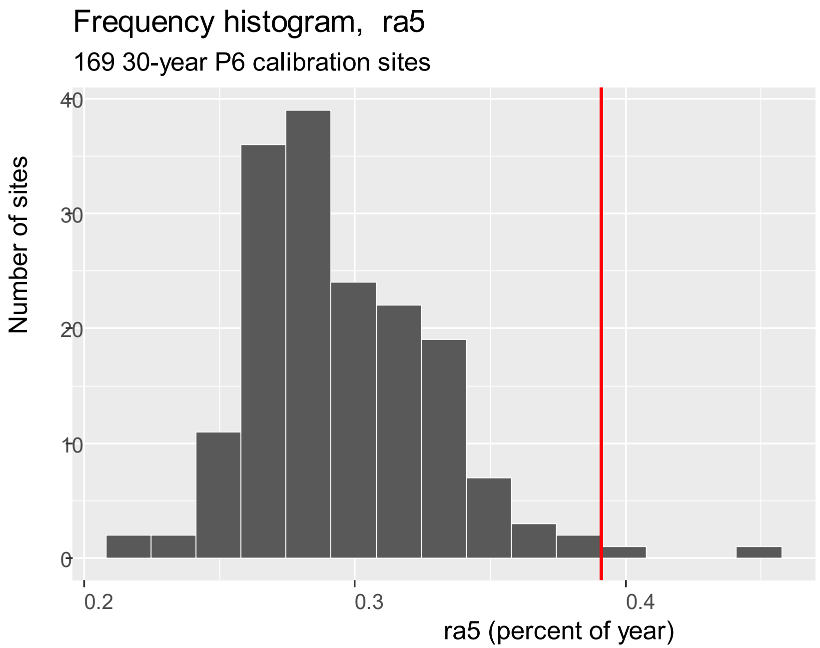

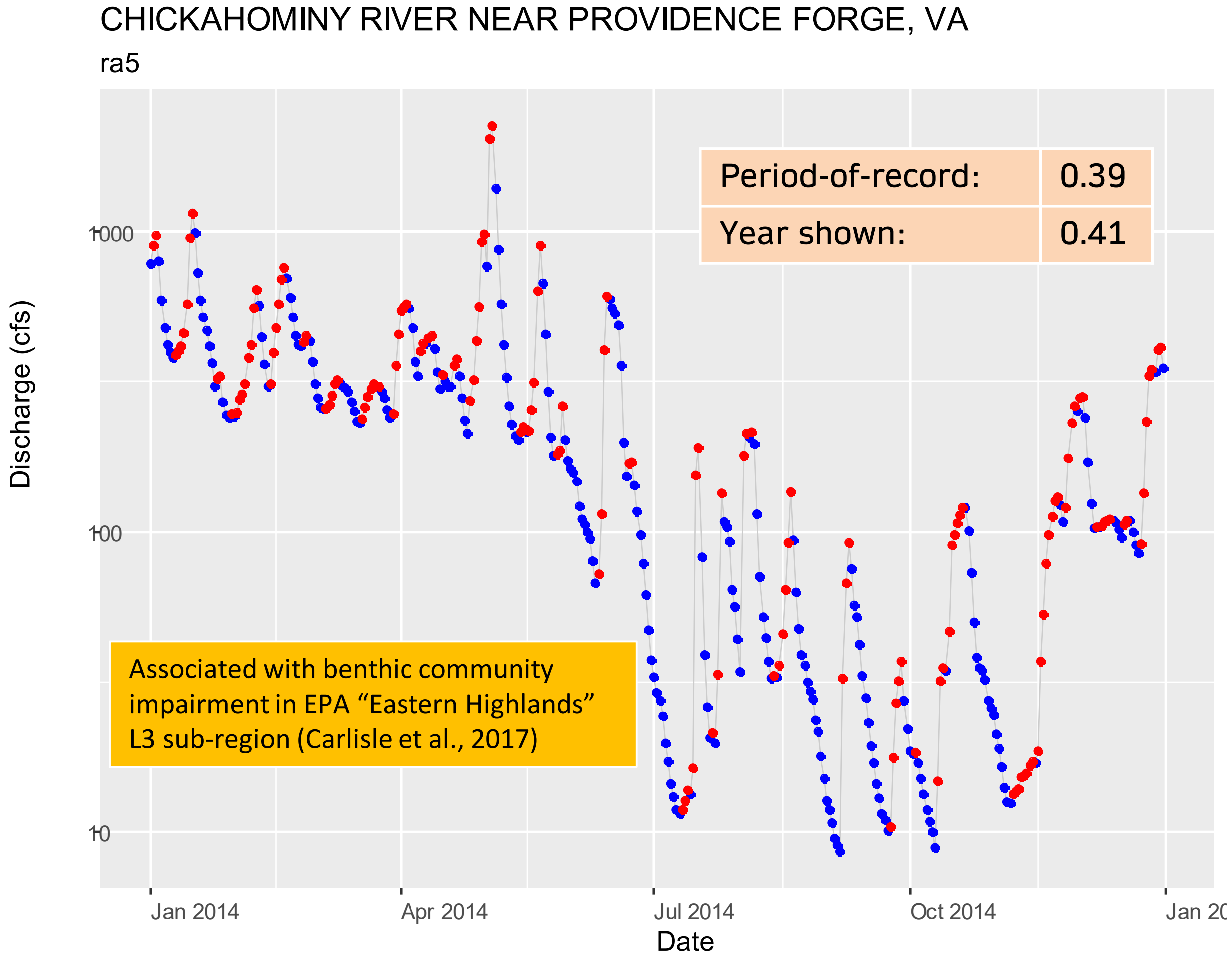

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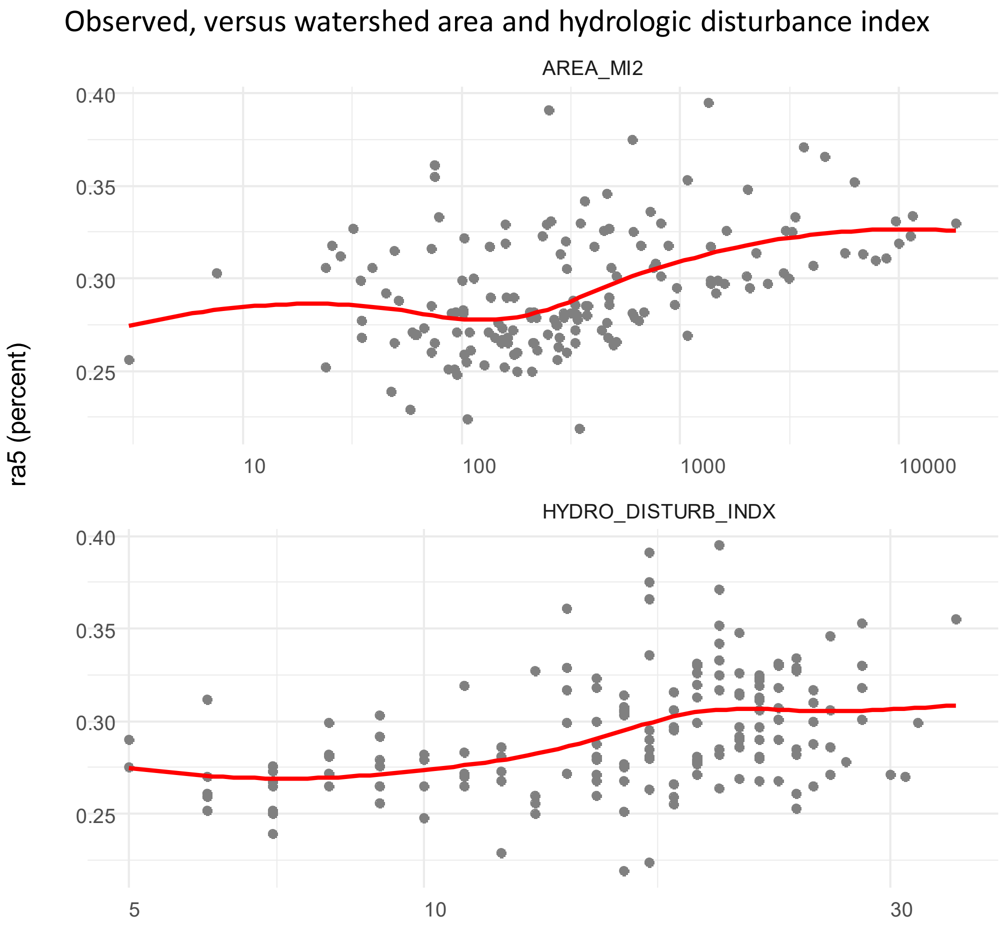

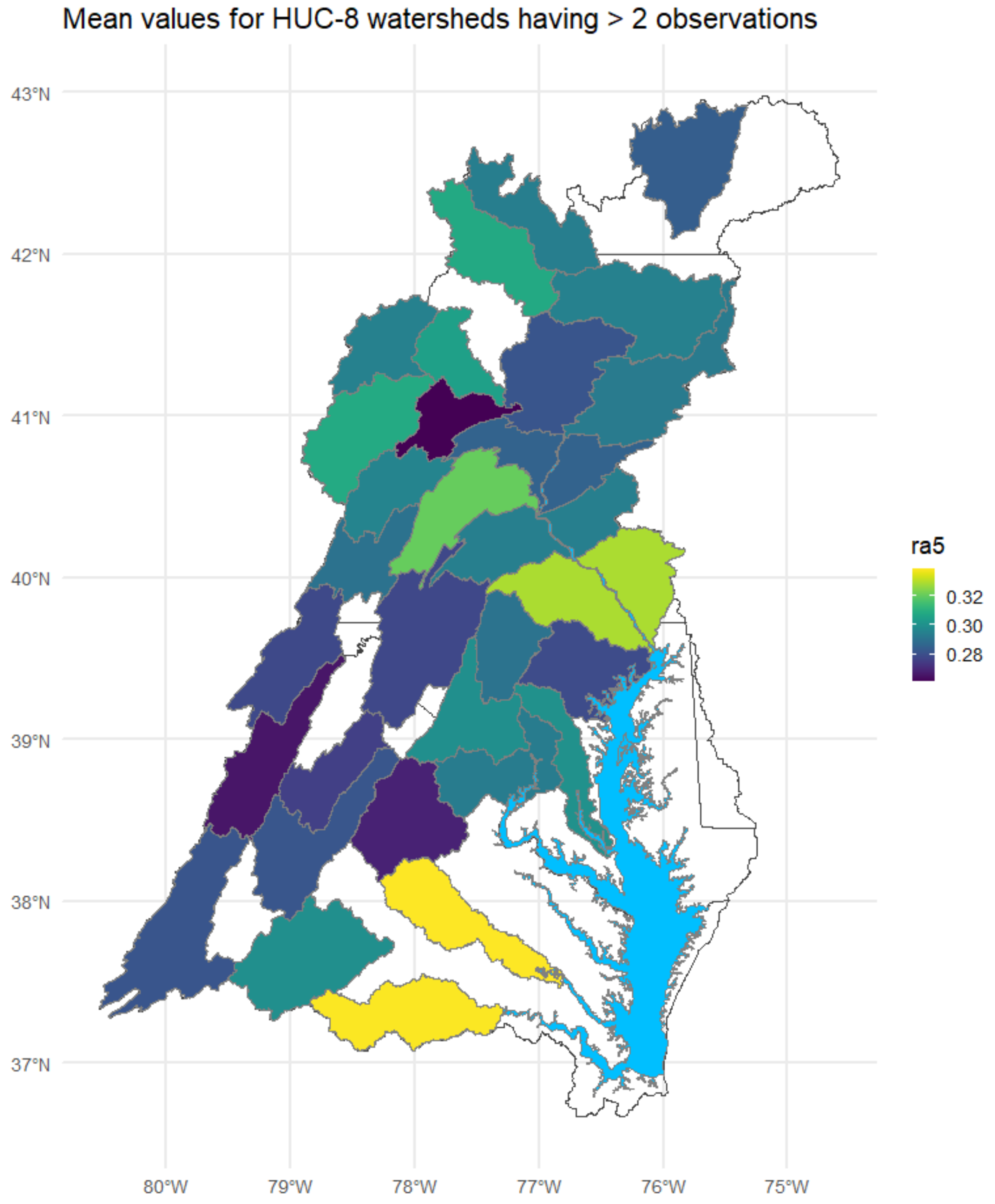

Percentage of days with increasing flows

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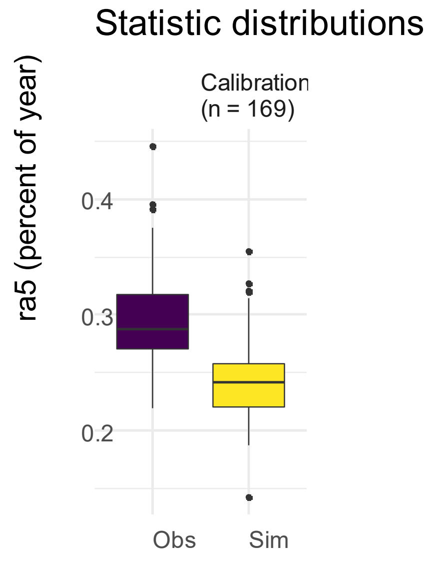
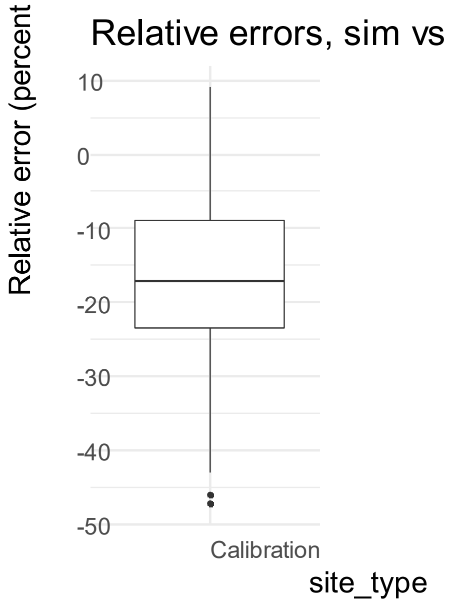
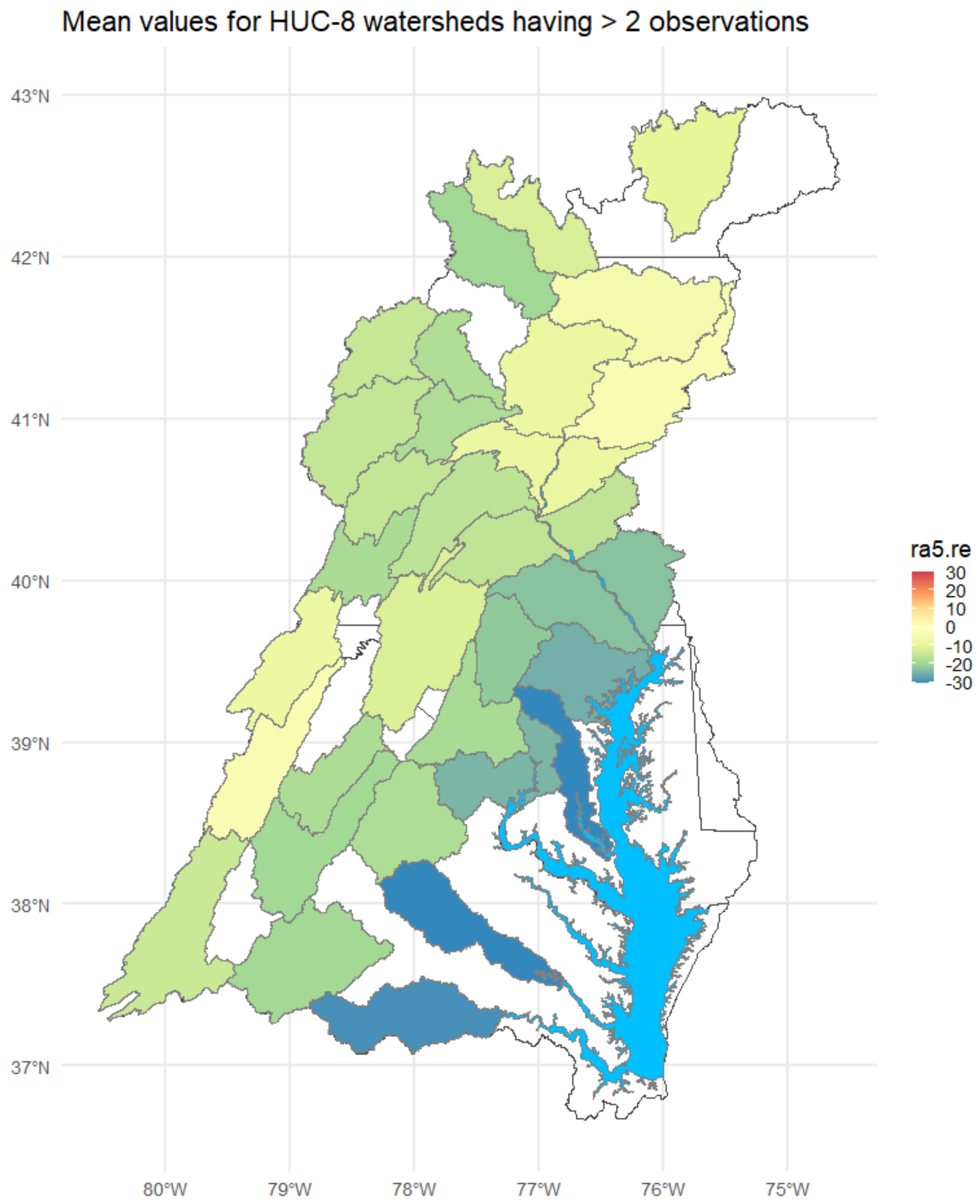
  - Calibration







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Percentage of days with increasing flows

- CBP P6 HM performance
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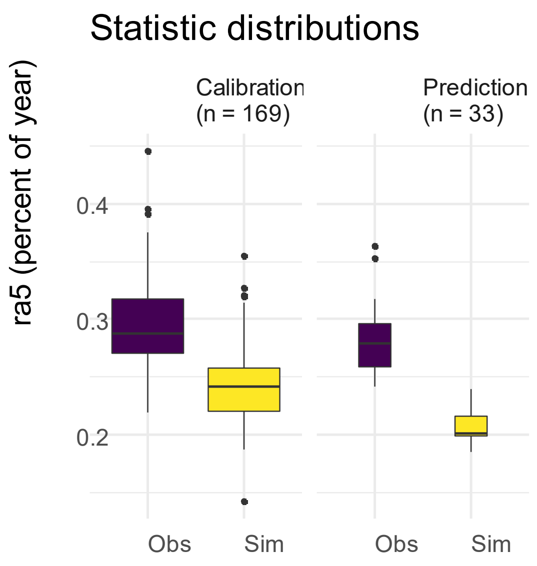
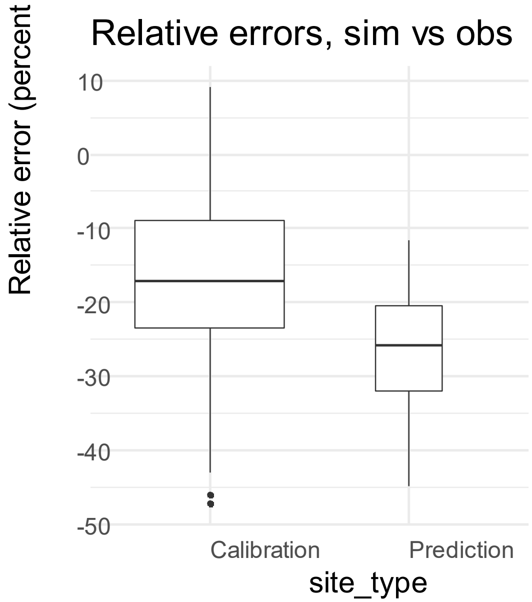
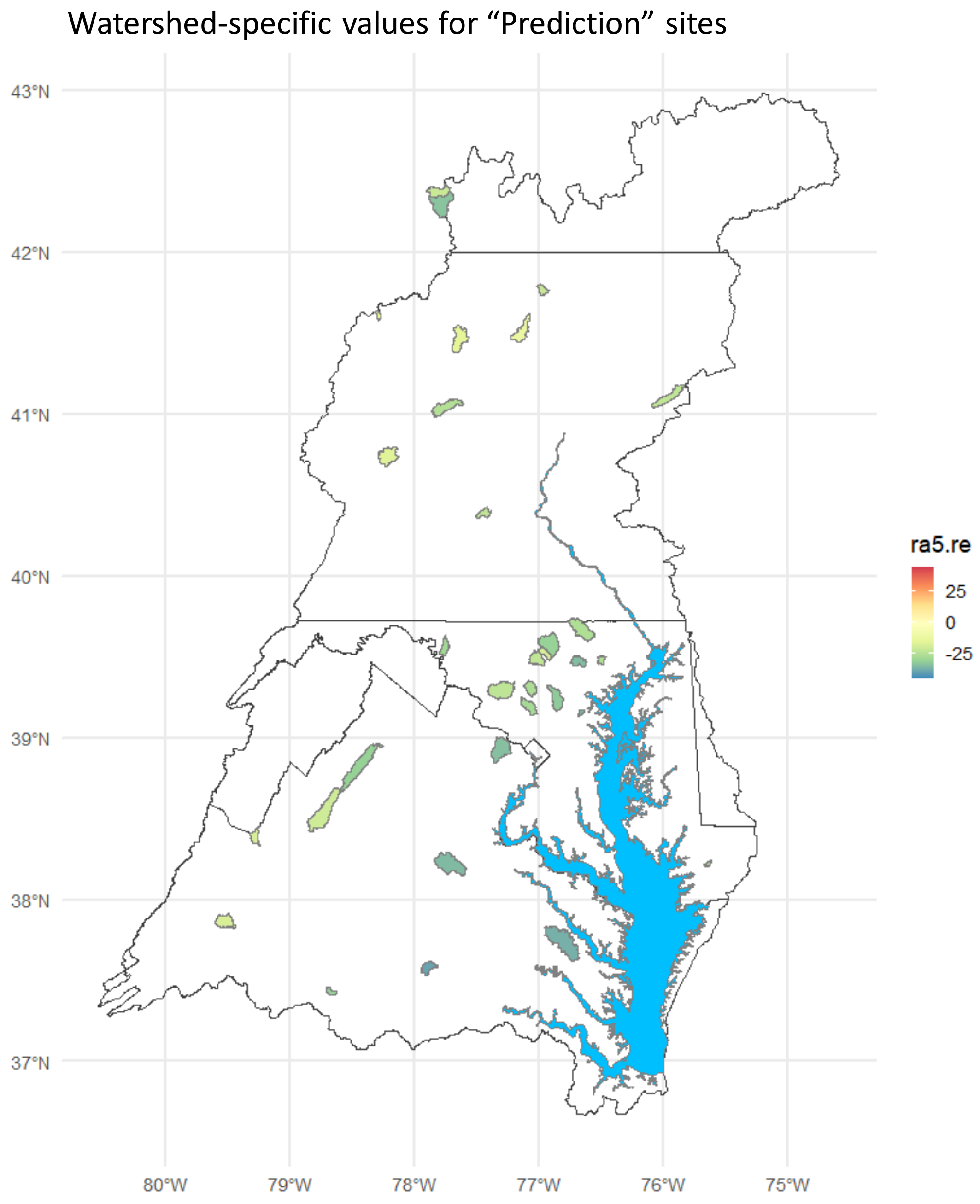


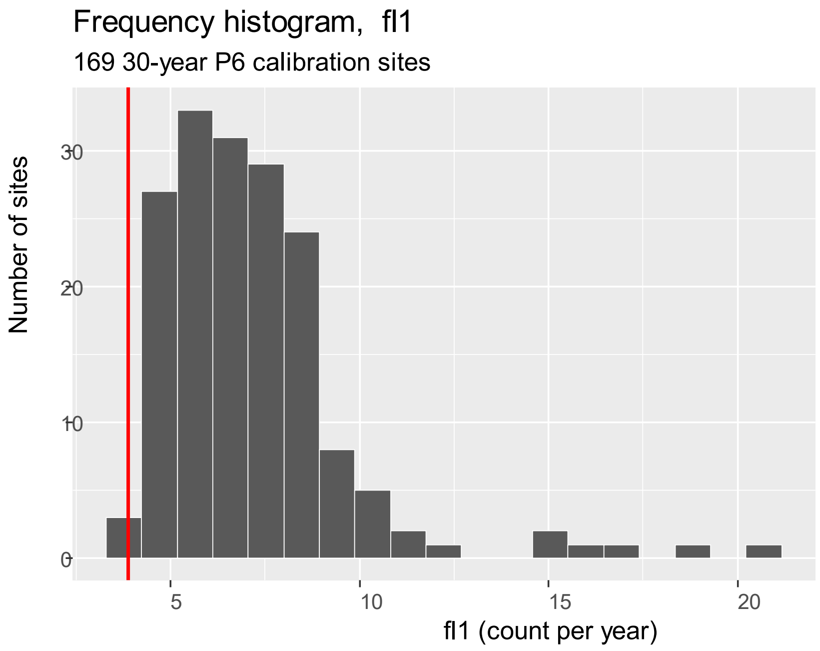


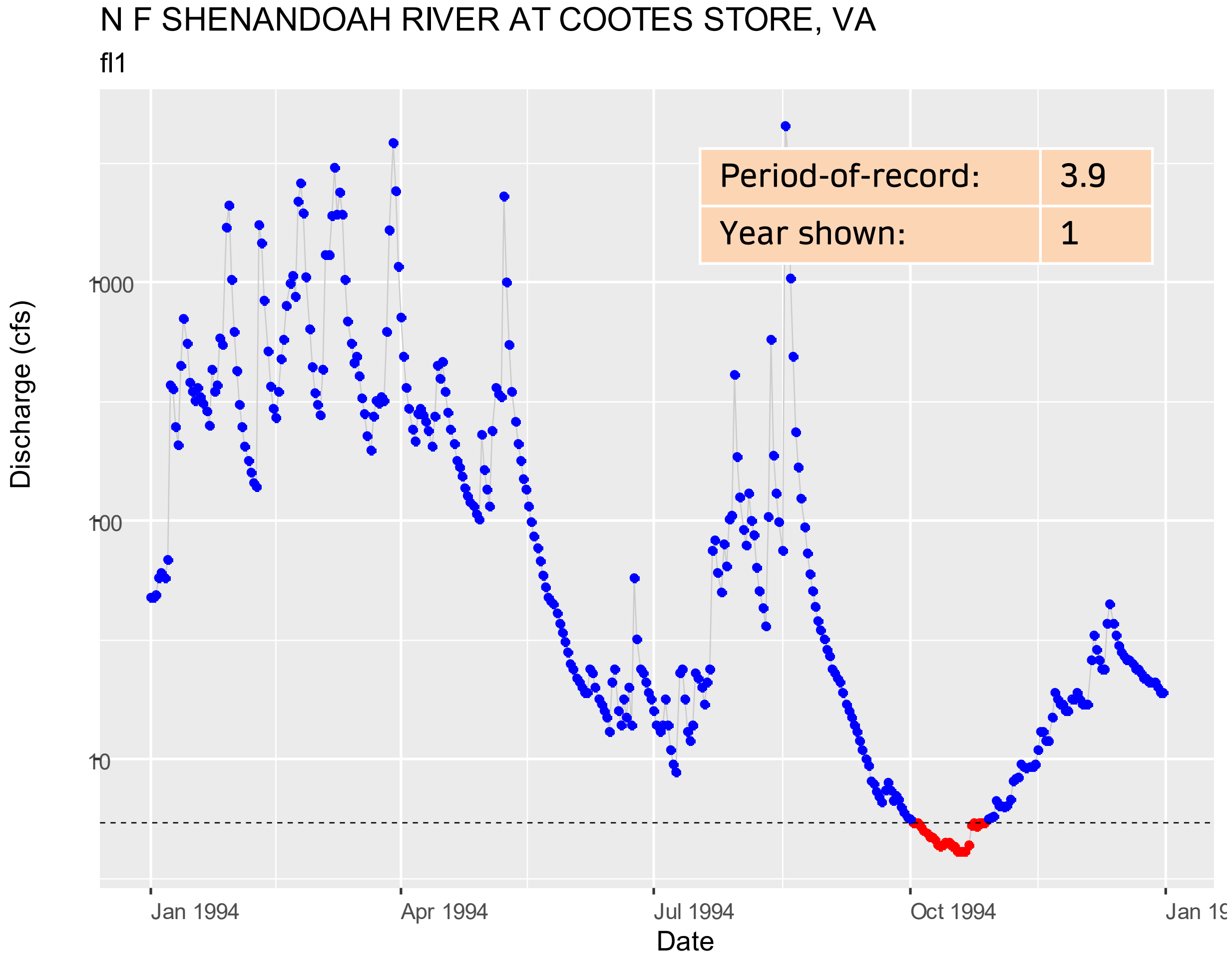


Provisional results, not for citation or publication

Number of excursions below long-term p10

Number of independent instances that Q drops below long-term 10th percentile for 1 day or more





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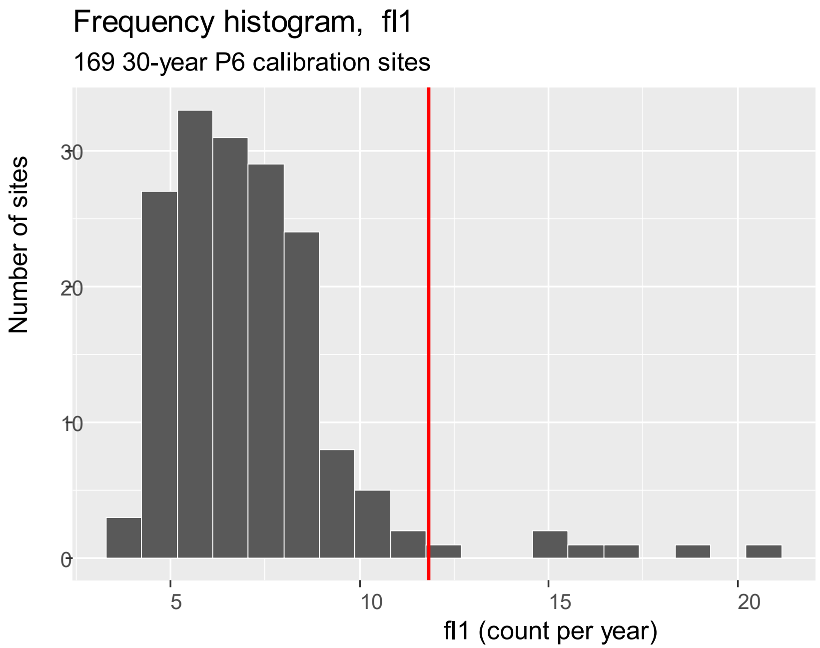

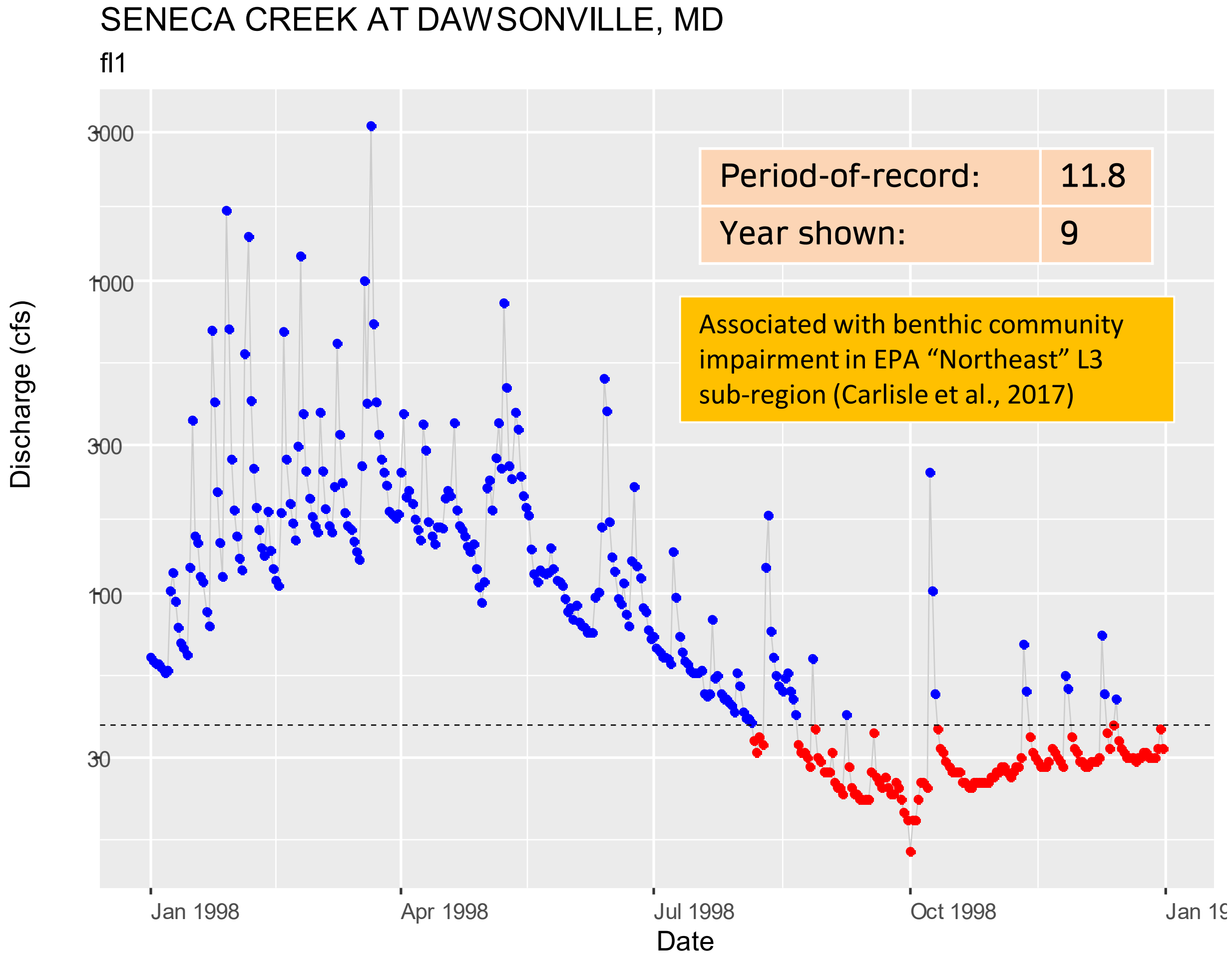

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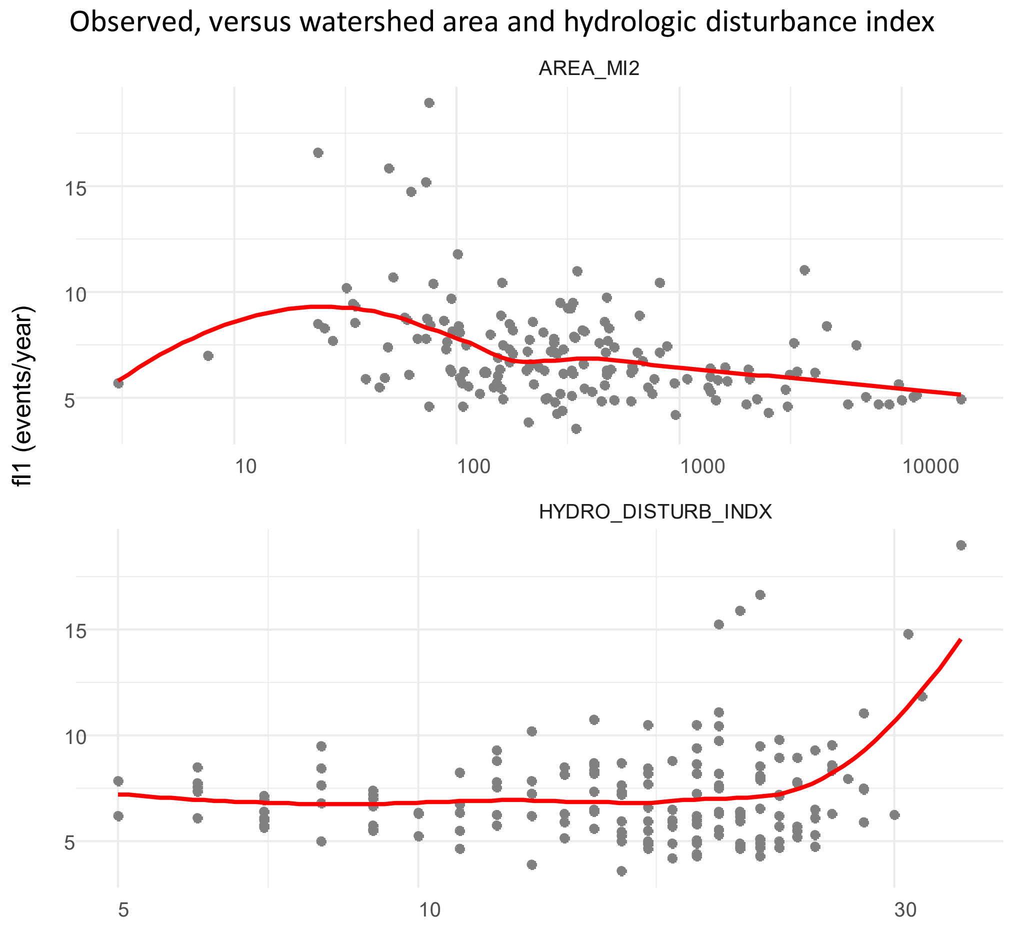
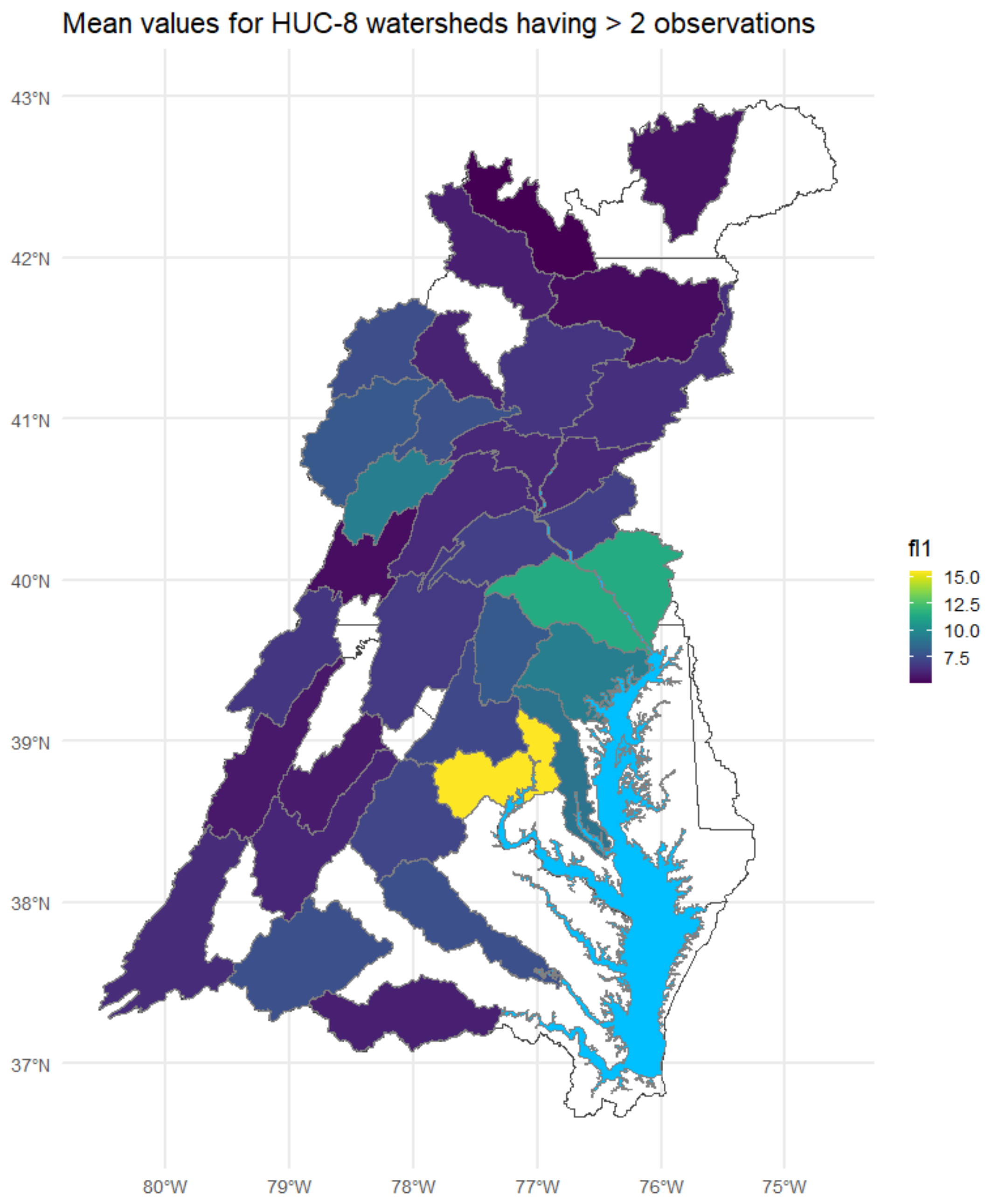
Number of excursions below long-term p10

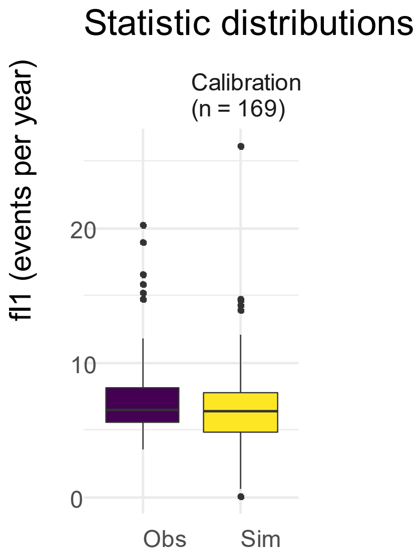


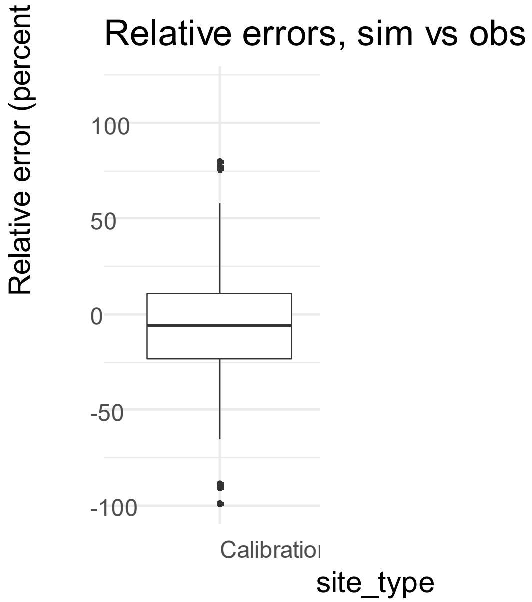


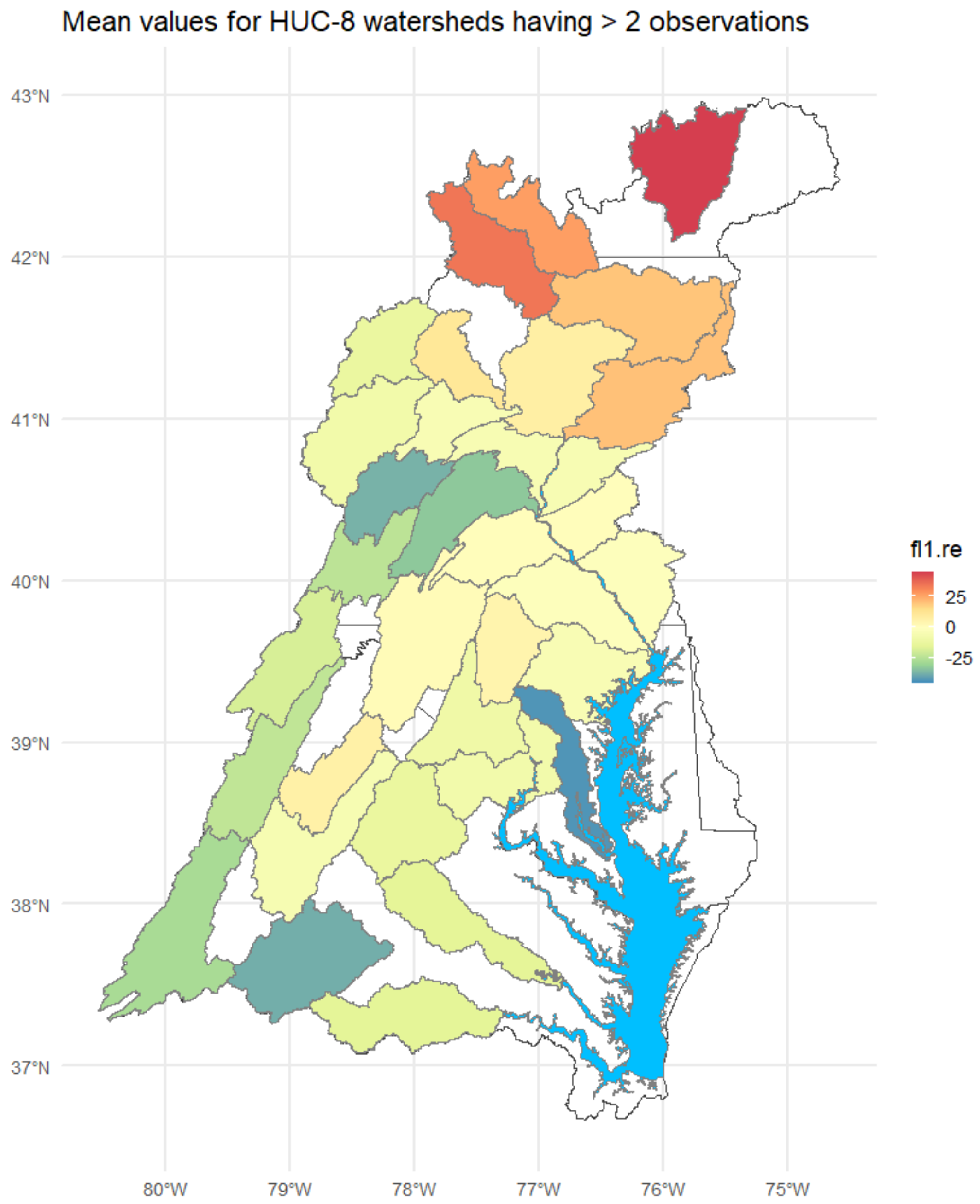
Provisional results, not for citation or publication

Number of excursions below long-term p10

- CBP P6 HM performance
  - Calibration



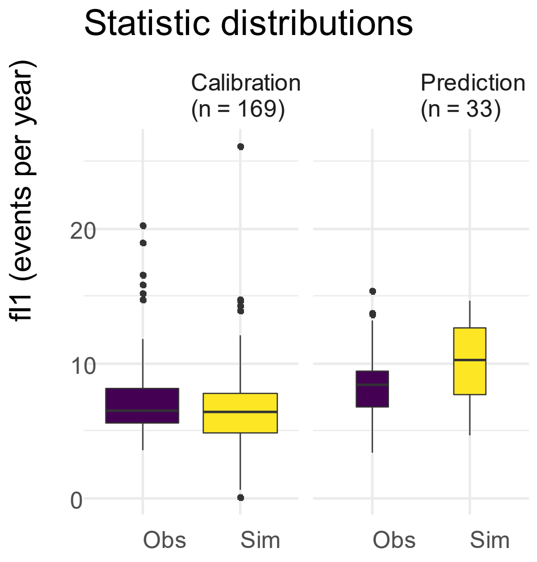


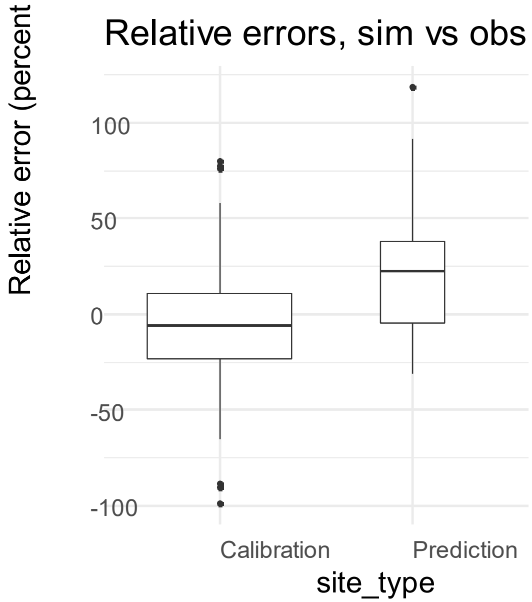


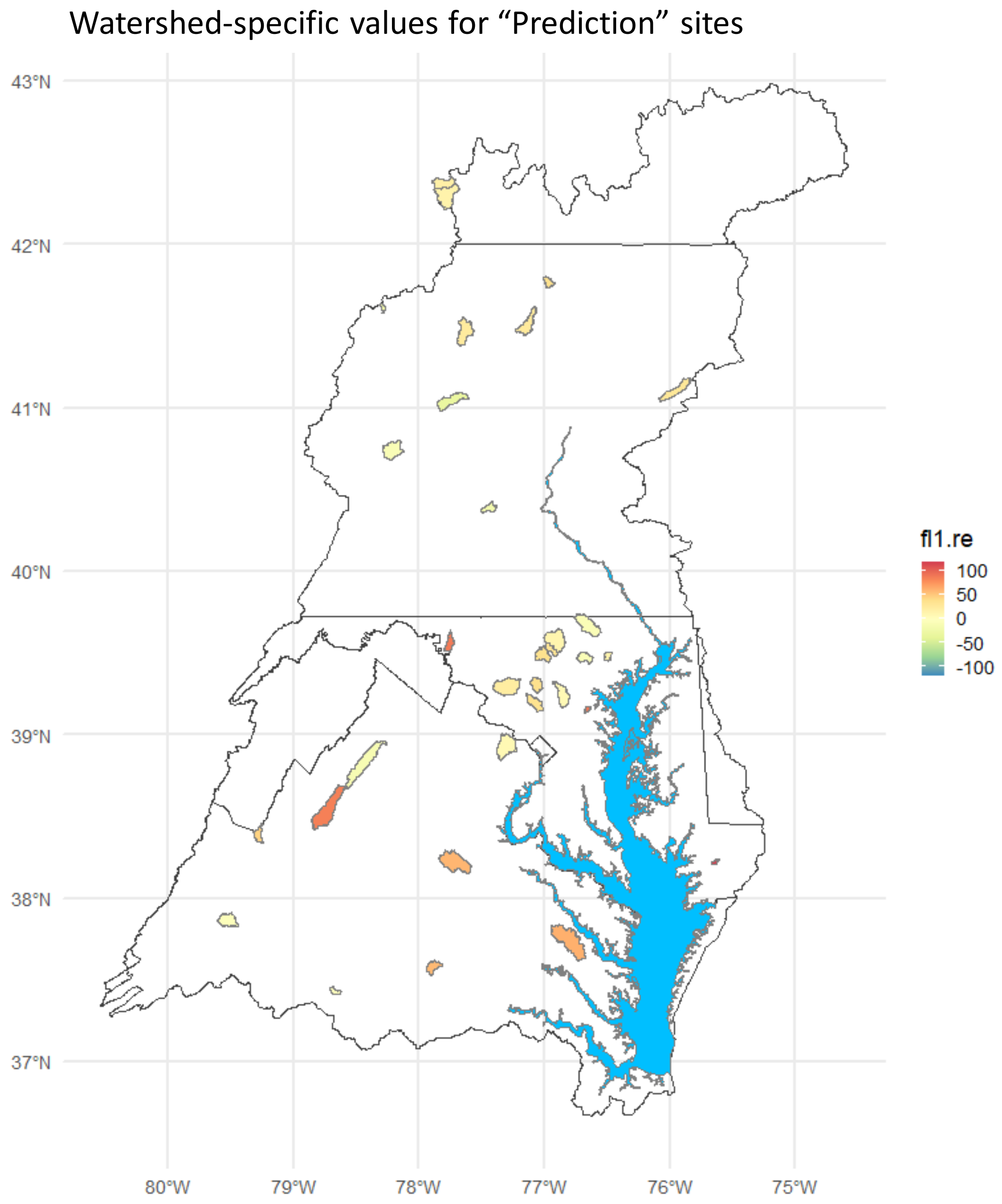
Provisional results, not for citation or publication

Number of excursions below long-term p10

- CBP P6 HM performance
  - Prediction







Provisional results, not for citation or publication

Conclusions

- For any daily hydrologic model, a calibration NSE = 1.0 will result in *perfect reproduction* of any flow statistic derived from daily flows. However, this performance is never attainable.
- Because of the place-specific complexity of rainfall-runoff processes underlying the shape of observed daily hydrographs, deviations from ideal model performance will be evident to different degrees for different ecological flow statistics.
- Such shortcomings would be evident in a lumped model for even a single gaged site, but are compounded in a spatially distributed model calibrated to many gages, such as the CBP P6 HSM.
- Combined, these observations make it difficult to set performance expectations for the CBP P6 HSM as an EFlows tool.

Recommendations

- Future CBP EFlows work should begin with developing the flexibility to calibrate the CBP P6 HSM *specifically* to any EFlows statistic of interest. Specific approaches include:
    1. Identify the strongest relations between individual elements of the current objective function vector (OFV) and EFlows statistic of interest, and re-calibrate P6 HSM to minimize *only* that element.
    2. Re-calibrate to EFlows statistic of interest, abandoning current gradient-based linkages between errors in specific OFV elements and HSPF parameters in favor of a more “naïve” machine-learning approach.
- Any such approach should also support the capability to constrain the model domain to specific sub-regions of the CB watershed.

Application of an unstructured-grid model in the Chesapeake prototype

Joseph Zhang[1], Nicole Cai[1], Gopal Bhatt[2], Lewis Linker[2], Jian Shen[1], and Harry Wang[1]

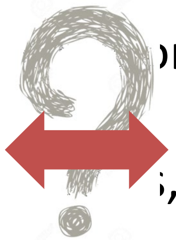
1. Virginia Institute of Marine Science
2. U.S. EPA Chesapeake Bay Program Office

Chesapeake Community Research Symposium 2020

Motivation

? Can high-resolution watershed prototype model (NHDplus) be effectively used by hi-res estuarine model?

? What are the impacts of hi-res watershed fc ... on the estuarine model?

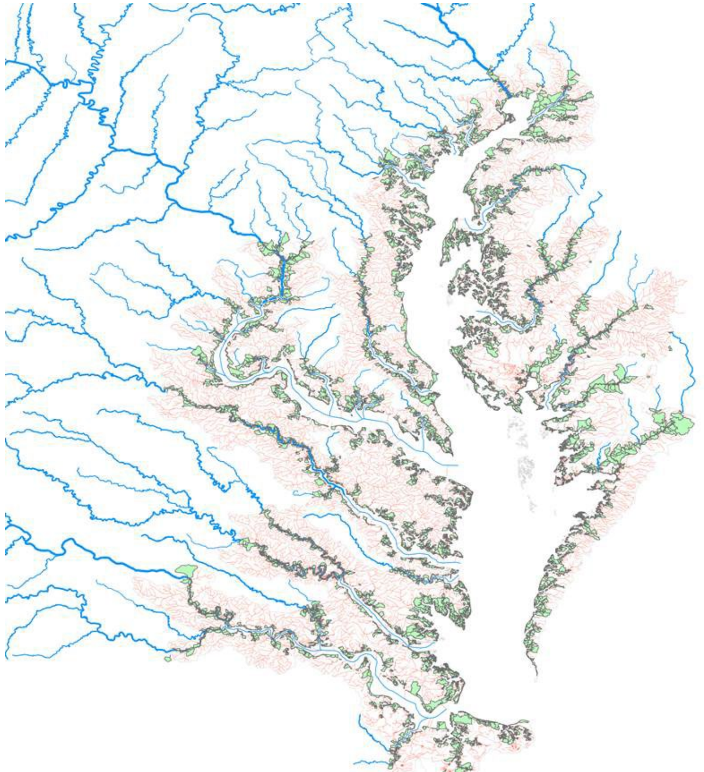


Hydrology ⟷ Hydrodynamics

? As we refine both watershed ... ne ..., wh ... way to adapt the linkage in space and time?

NHDplus segmentation (cf. Gopal's talk)

* Pink areas are NHDplus tidal streams, with delivery at green polygons
* Other discharges (non-tidal or tidal PS) are same as P6 (land-river segmentation)
* NHDplus segments are much finer than P6 (~80 times more)

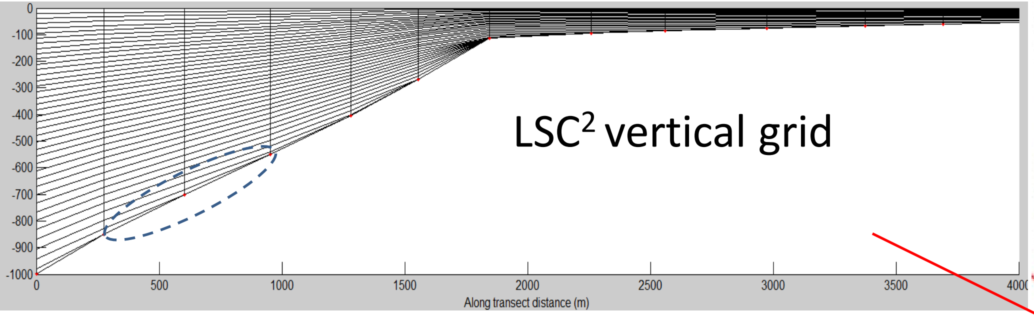


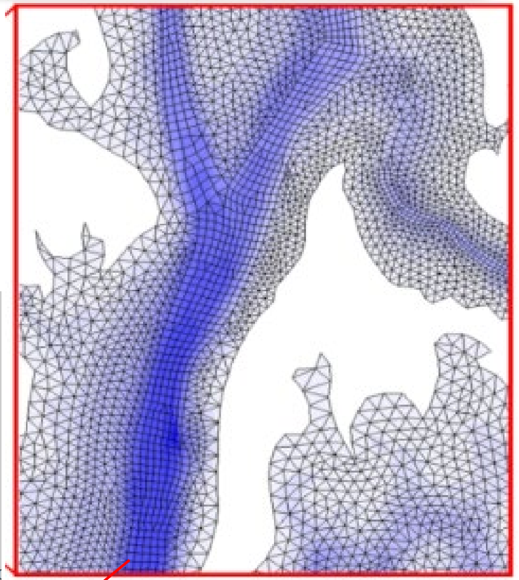
Overview

- SCHISM modeling system
- Approach to link new NHDplus outputs to SCHISM
- Proof-of-concept simulation of estuarine hydrodynamics and water quality using the high-resolution NHDplus: preliminary results
- Summary and future work

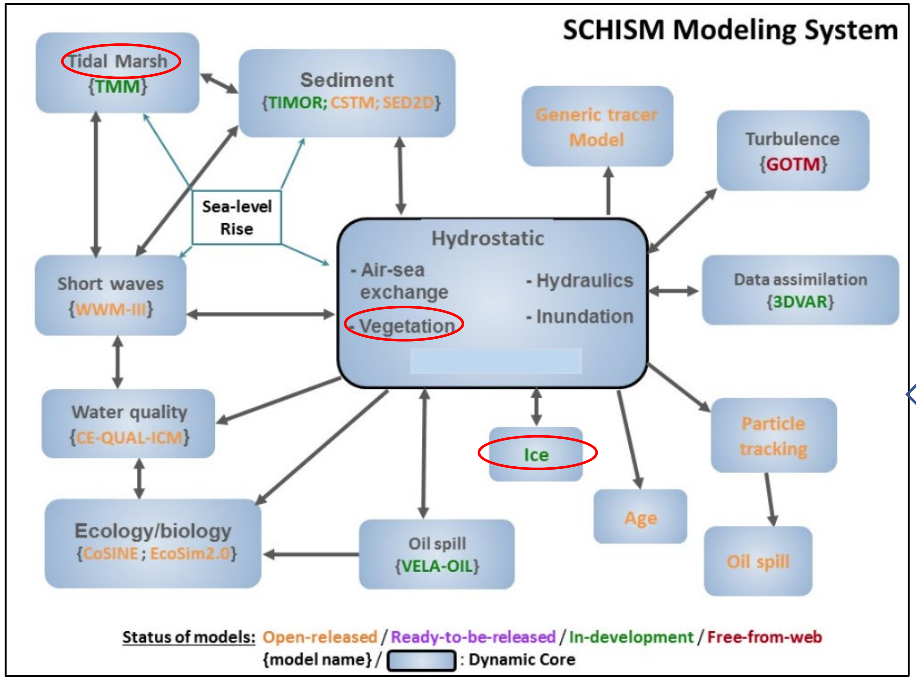
SCHISM: Semi-implicit Cross-scale Hydroscience Integrated System Model

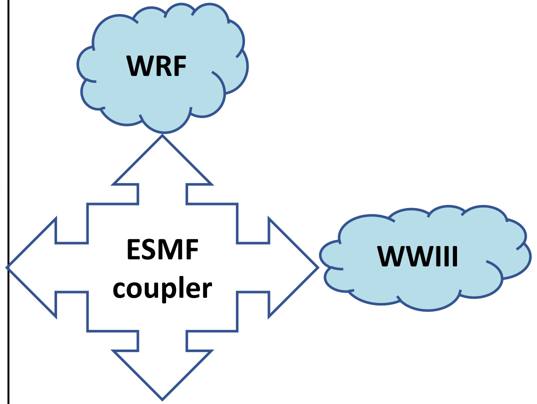
- Solves Navier-Stokes equations in hydrostatic form with Boussinesq approximation
- Galerkin finite-element and finite-volume approach: generic unstructured grids
- Semi-implicit time stepping: no mode splitting → large time step and no splitting errors
- Eulerian-Lagrangian method (ELM) for momentum advection → efficiency & robustness
- Major differences from SELFE v3.1
  - Apache license
  - Mixed grids (tri-quads)
  - LSC^2 vertical grid with shaved cells
  - Implicit TVD transport (TVD^2); WENO3; *all with monotonicity enforced*
  - Higher-order ELM with ELAD
  - Upwind biased momentum advection
  - Bi-harmonic viscosity
- The ultimate product is a seamless cross-scale model from creek to ocean, that allows for on-demand resolution





polymorphism





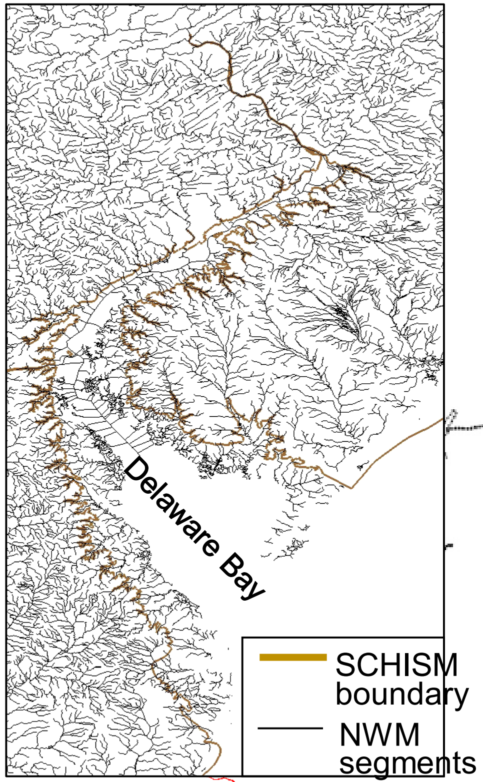
visit schism.wiki

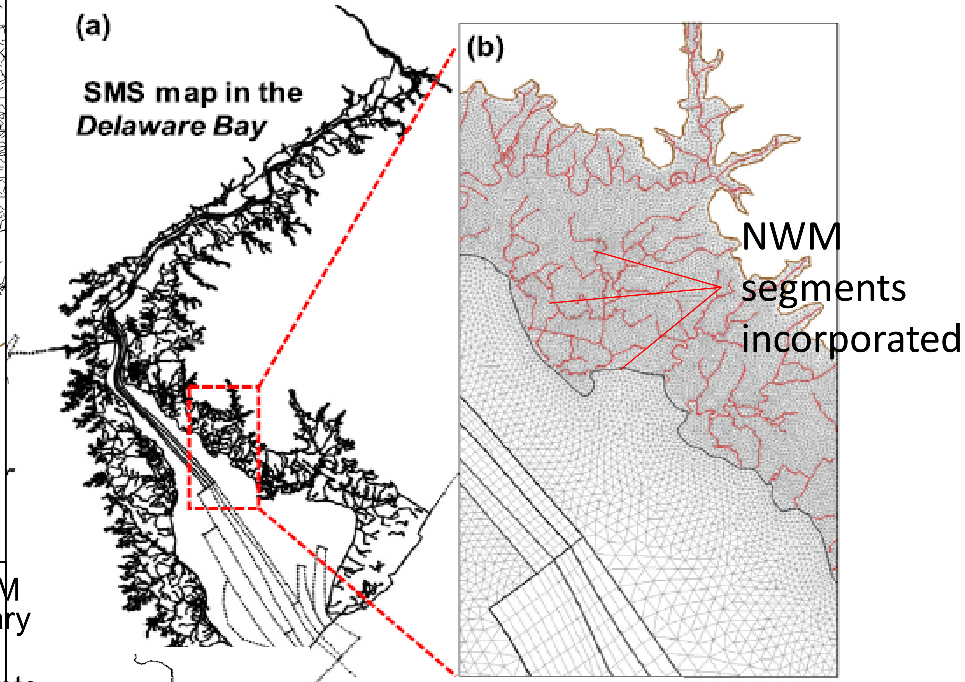
SCHISM

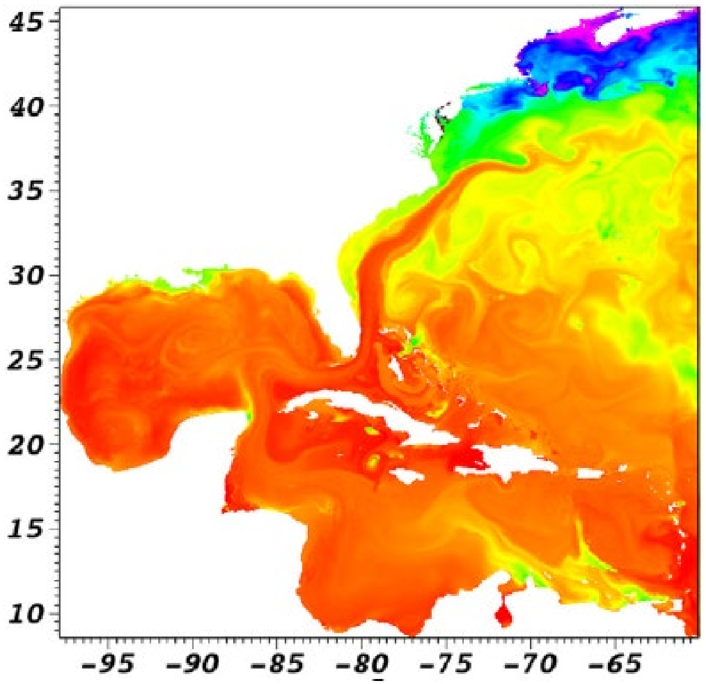
An example of cross-scale application: compound flooding

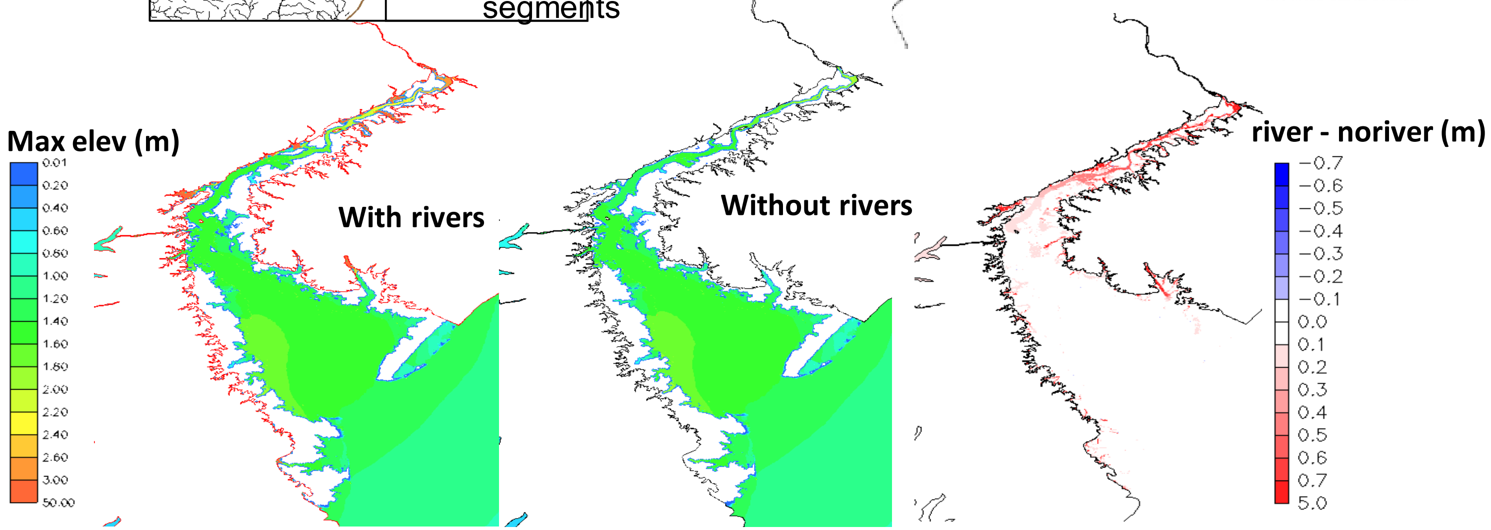
- Use a large domain for storm surge; boundary @ 10m above MSL (so include part of watershed)
- Driven by National Water Model (NWM) outputs
- Resolve Gulf Stream to get baroclinic response right during storms
- Efficient seamless creek-to-ocean 3D-2D capability in to capture compound flooding in Bay and watershed
- All major estuaries/bays in east coast and GoMex resolved down to 20m
- Will serve multiple purposes, including WQ and morphology

Ye et al. (2019); Zhang et al. (2020)



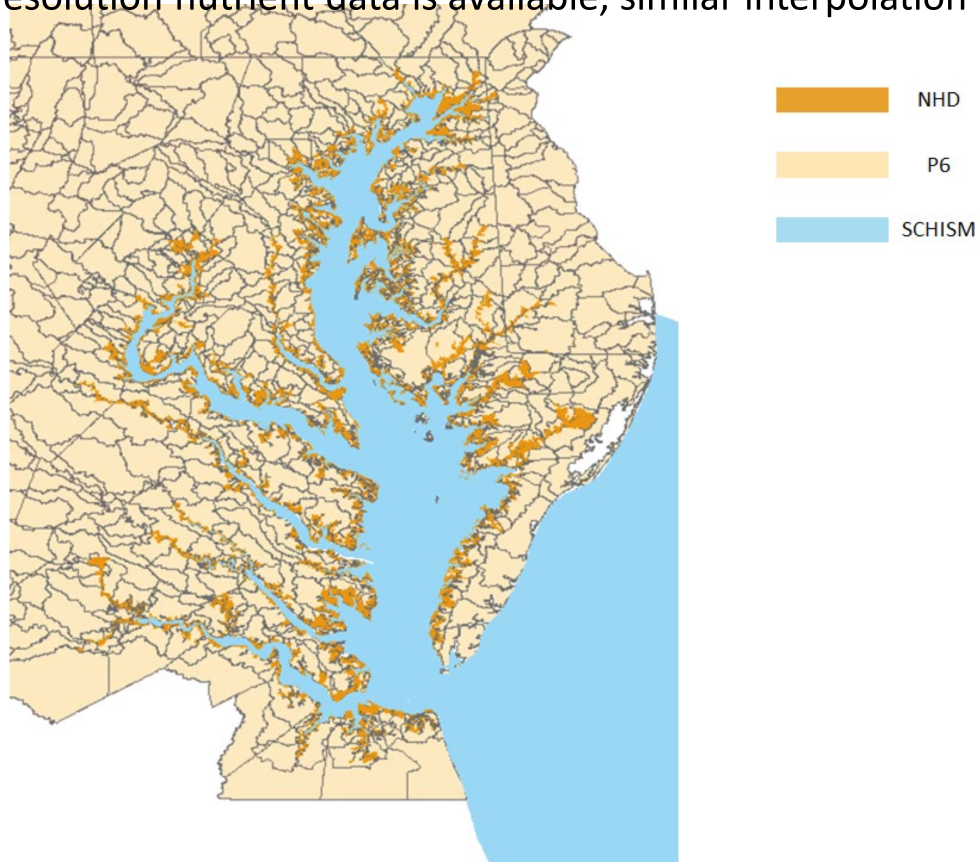


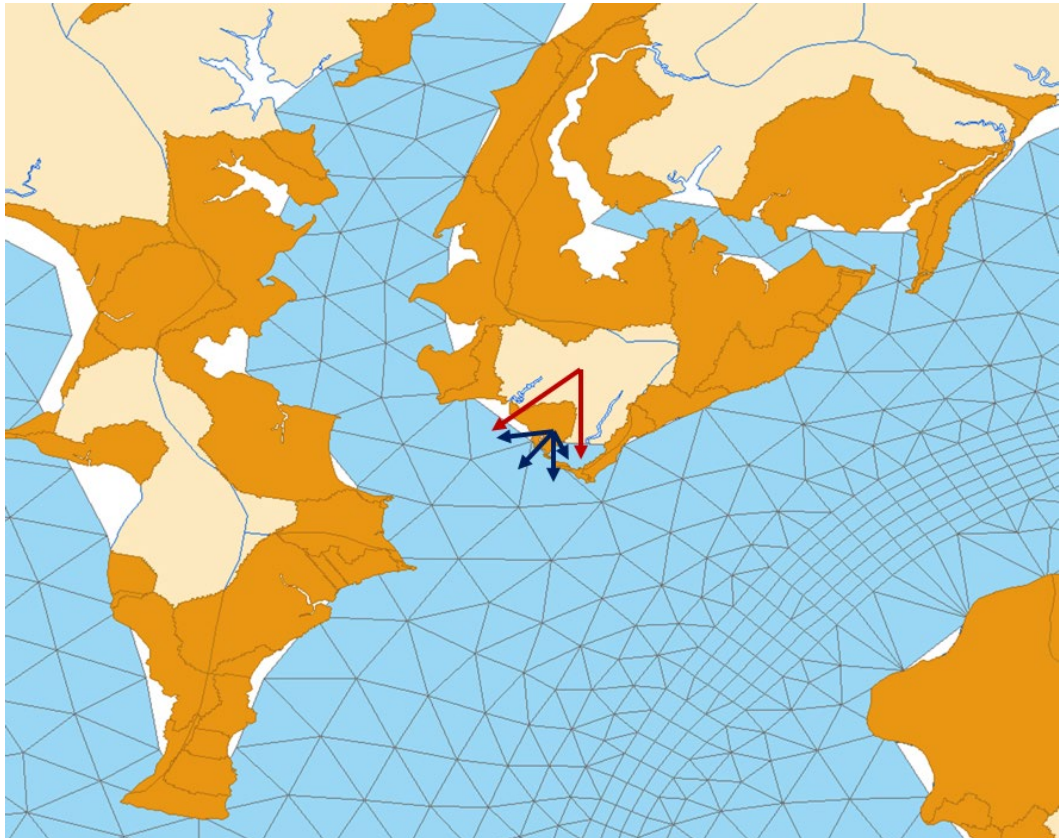




New algorithm for linking hydrology to SCHISM

1) For hydrologic segments that touch SCHISM's land boundary, split the loading evenly to number of boundary elements adjacent to the segment
2) For hydrologic segments that do not touch SCHISM's land boundary, find the nearest land boundary element and assign the flow to it (there are different options for this)
3) The final flow is the sum from NPS/PS and NHDplus segments, using the interpolation procedure in 1-2
4) Further fine tuning may be desirable
5) There is no nutrient loading data from NHDplus yet; use P6 loadings and try to reconcile the flow and nutrient (not easy!)
6) Once high resolution nutrient data is available, similar interpolation procedure may be used

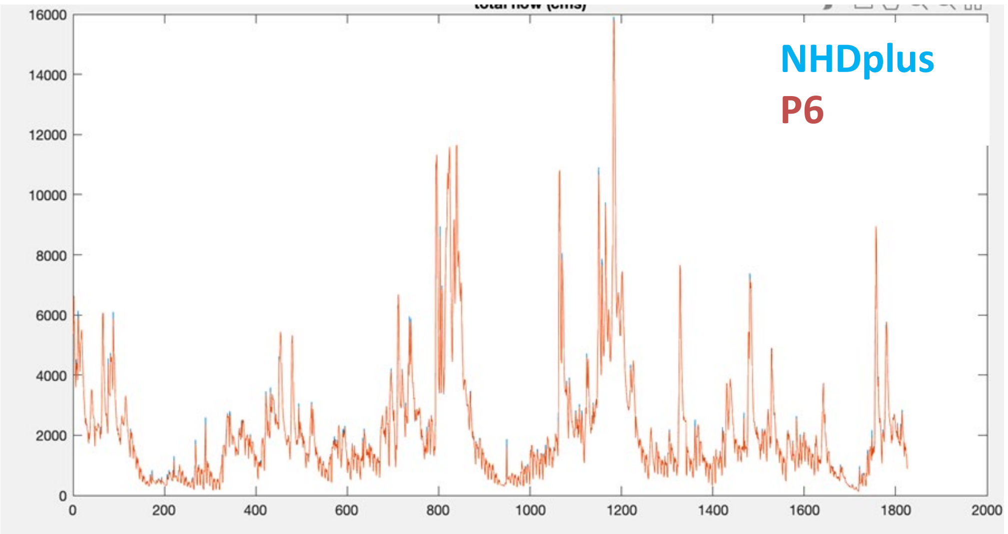




Cross check against P6

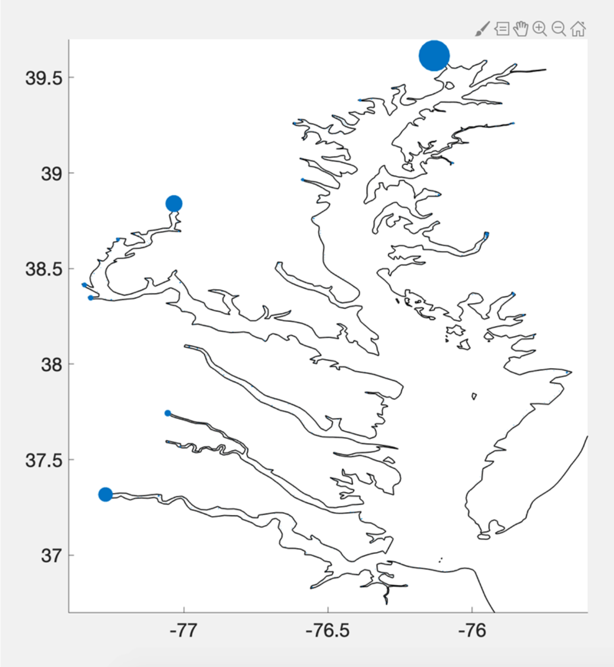
- Total flow from all rivers is consistent between P6 and NHDplus
- Nutrient conversion is trickier: notice that there are some discrepancies between the old and new as we tried to reconcile the old nutrient loadings with new flow inputs
  - The approach used has implications for WQ results

Total flow

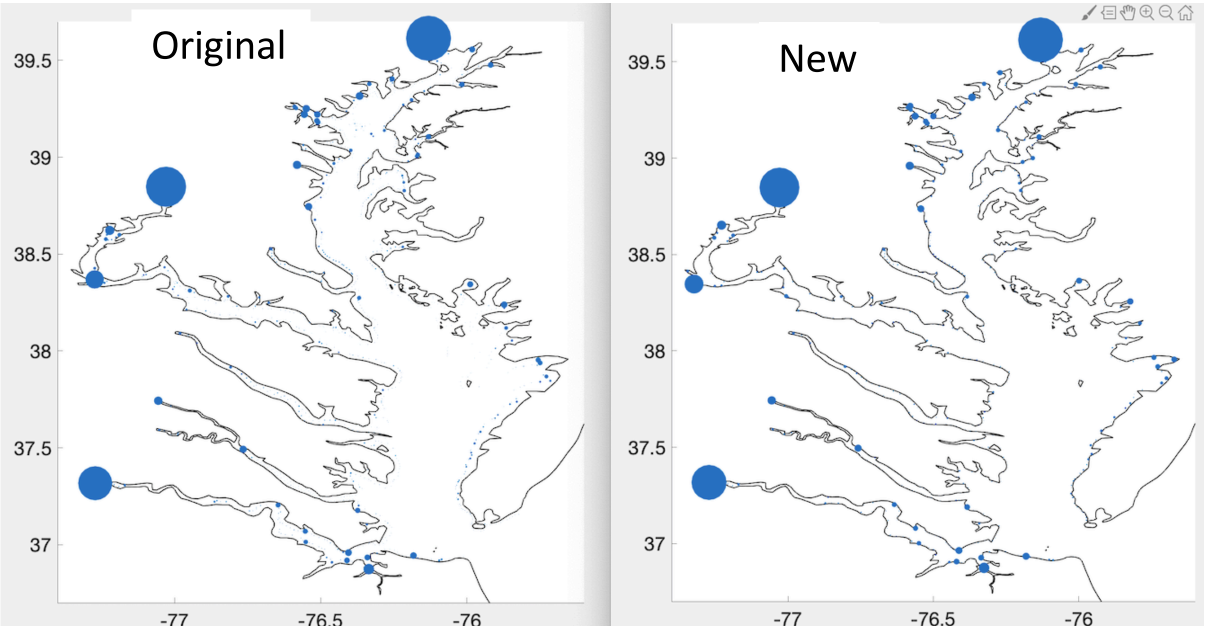


Days from Jan 1, 1991

Averaged flow



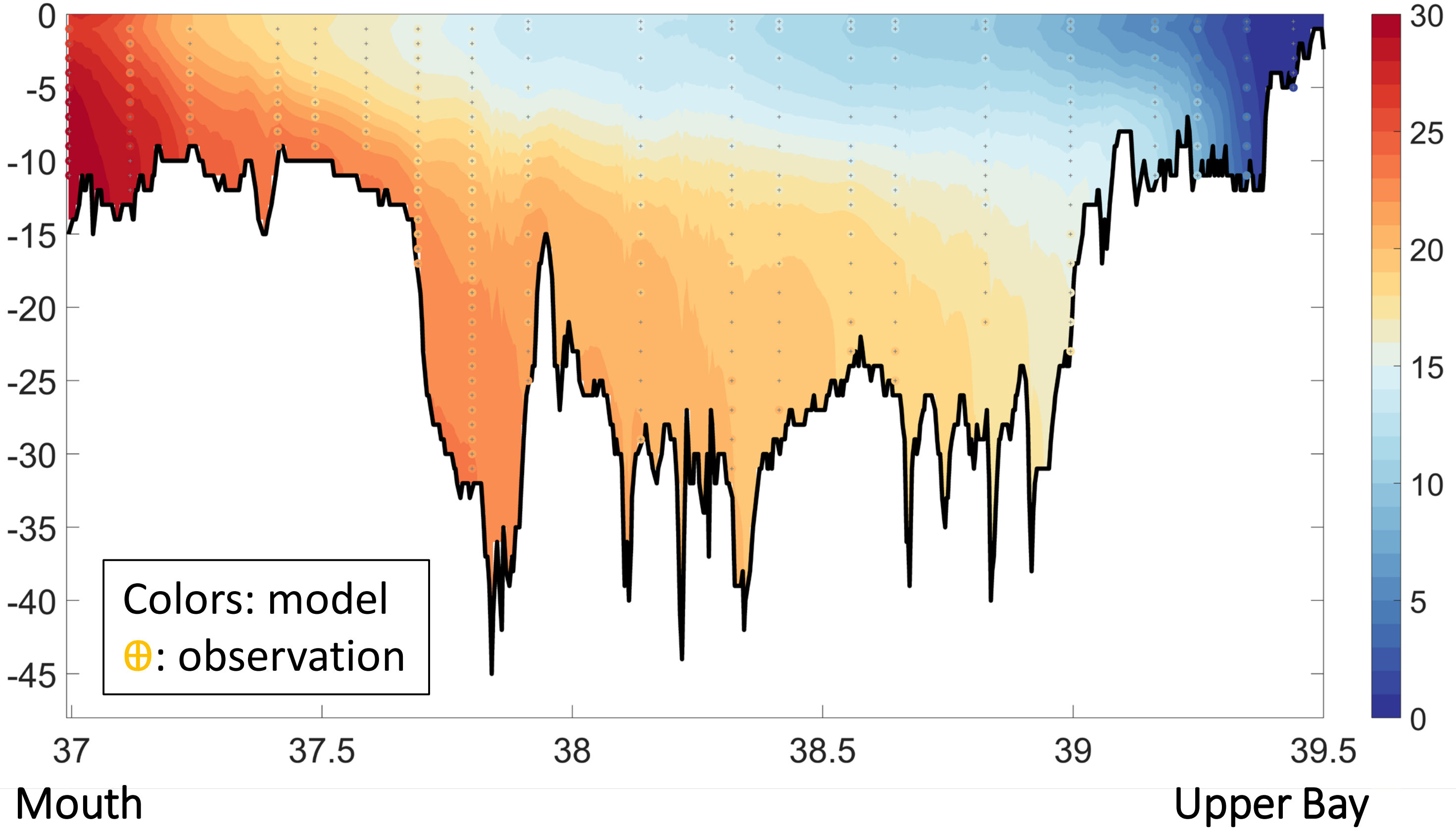
Averaged PO4



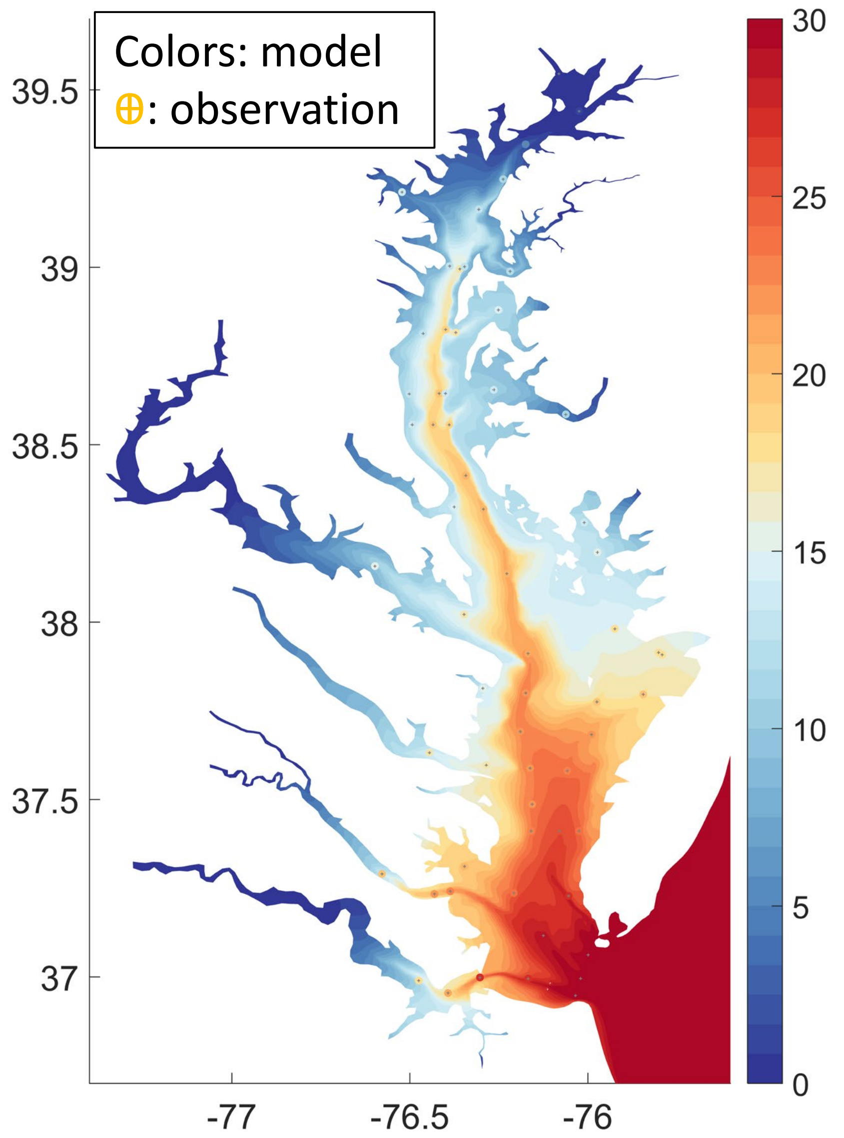
Model validation

* Model setup follows Ye et al. (2018) (cf. Nicole's and Dan's talks)
    * Whole Bay + tributaries with resolution from 7km to 100m
    * Non-smoothed bathymetry
    * Flexible vertical grid LSC^2
* The model skill for hydro part is very close to that with P6 (Ye et al. 2018)
* Model skill is generally high (averaged RMSE~2PSU)

5-year average (1991-1995) salinity, along main channel

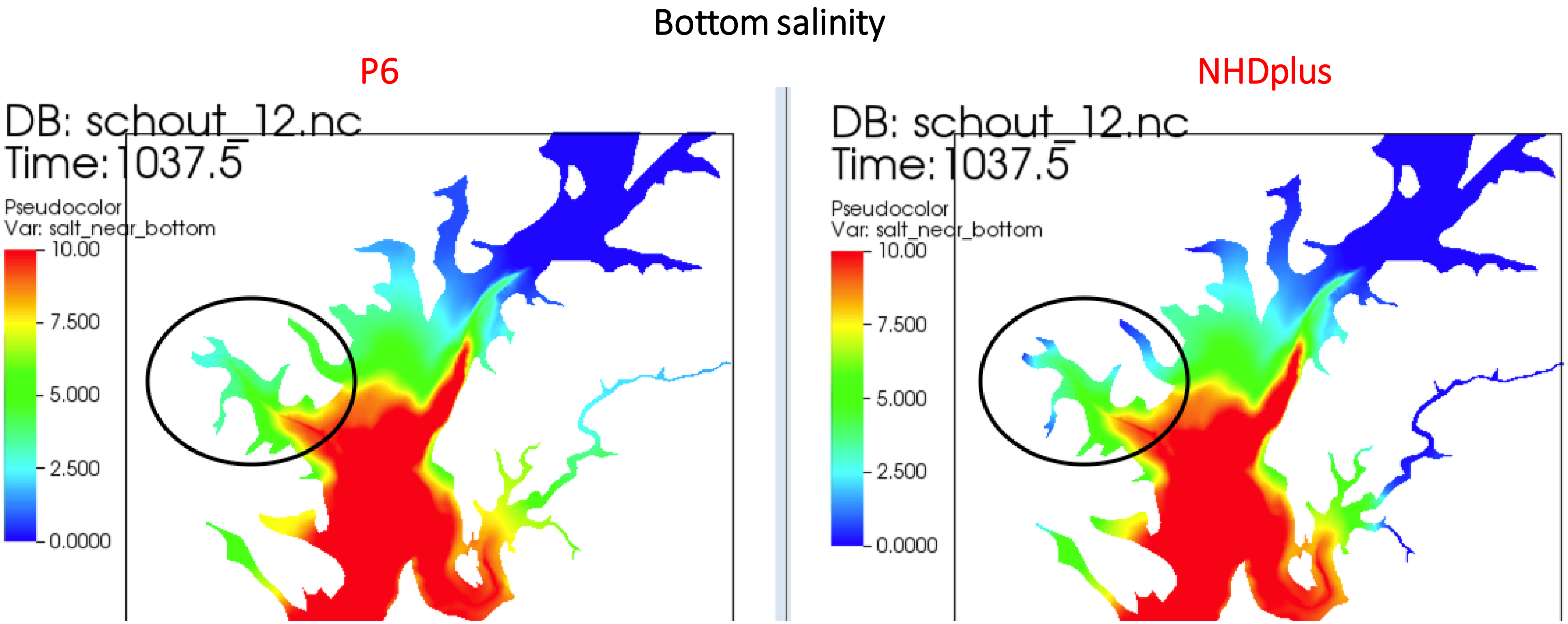


Bottom salinity (PSU)



Impact of NHDplus flow on tributaries

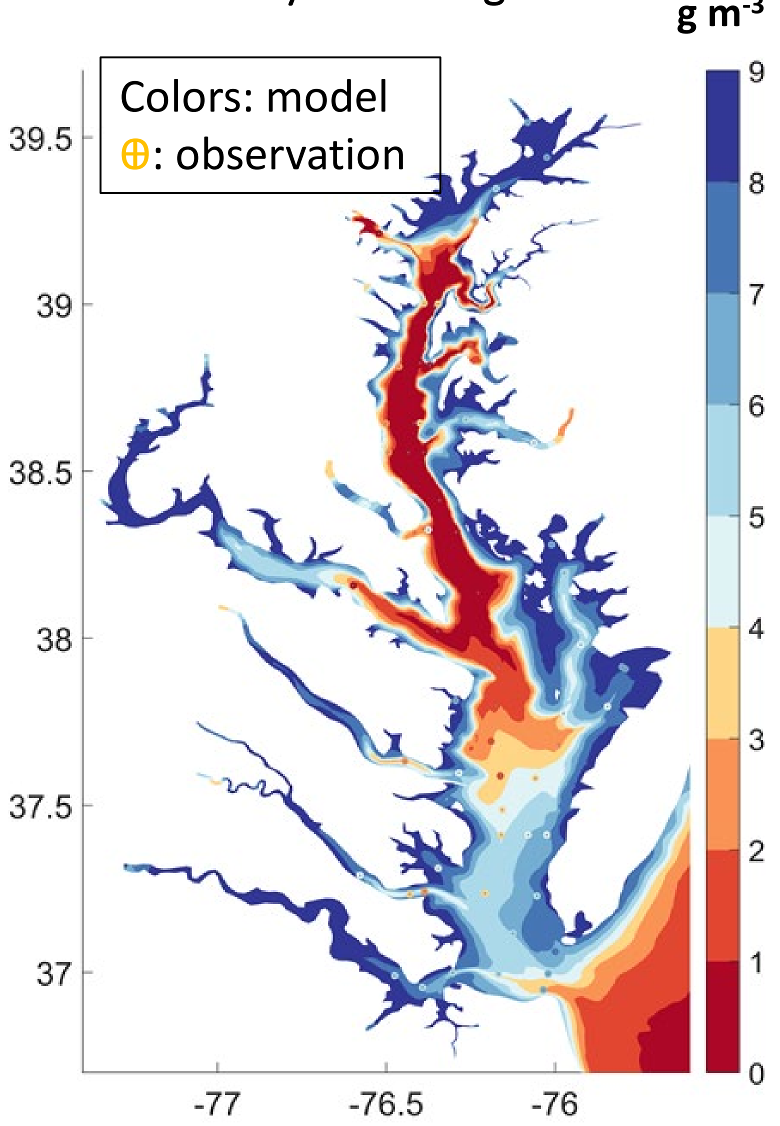
* Did not significantly affect the dynamics in main stem of the Bay
* The finer resolution in NHDplus flow allows us to better capture salinity gradients in tributaries and sub-tributaries
* Needs to further validate the model in those systems



Validation of DO

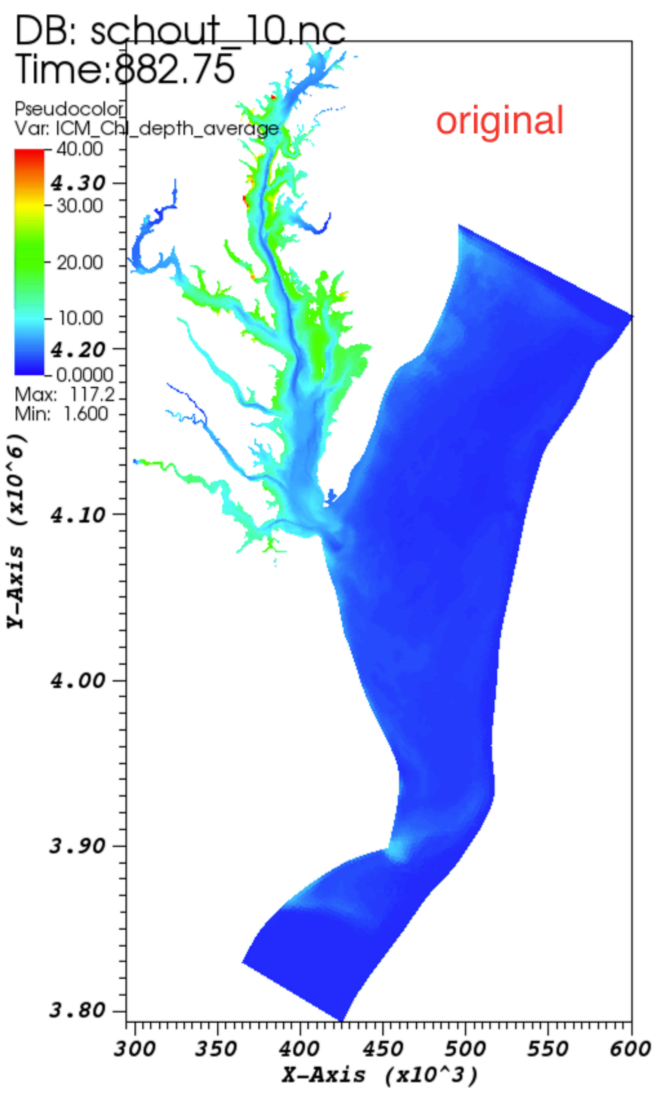
* With NHDplus flow + P6 nutrient inputs, area of hypoxia is similar in upper bay but increases in middle bay region (e.g. CB5.4)
* Overall, the results are reasonable
* Discrepancies in tribs: more productions there (e.g. Potomac River) contribute to more DO consumption
* Results are preliminary, as the nutrient inputs are derived from P6

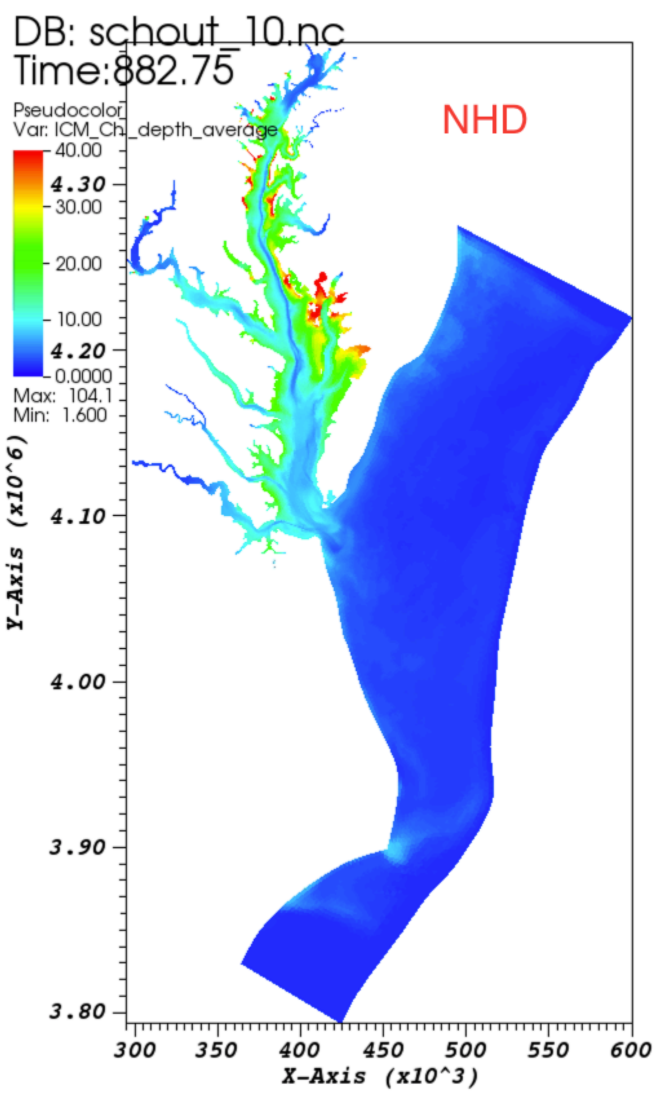
5-year averaged bottom DO from July 1st to Aug 31st



Impact on ecosystem (preliminary)

Chl-a (depth-averaged)

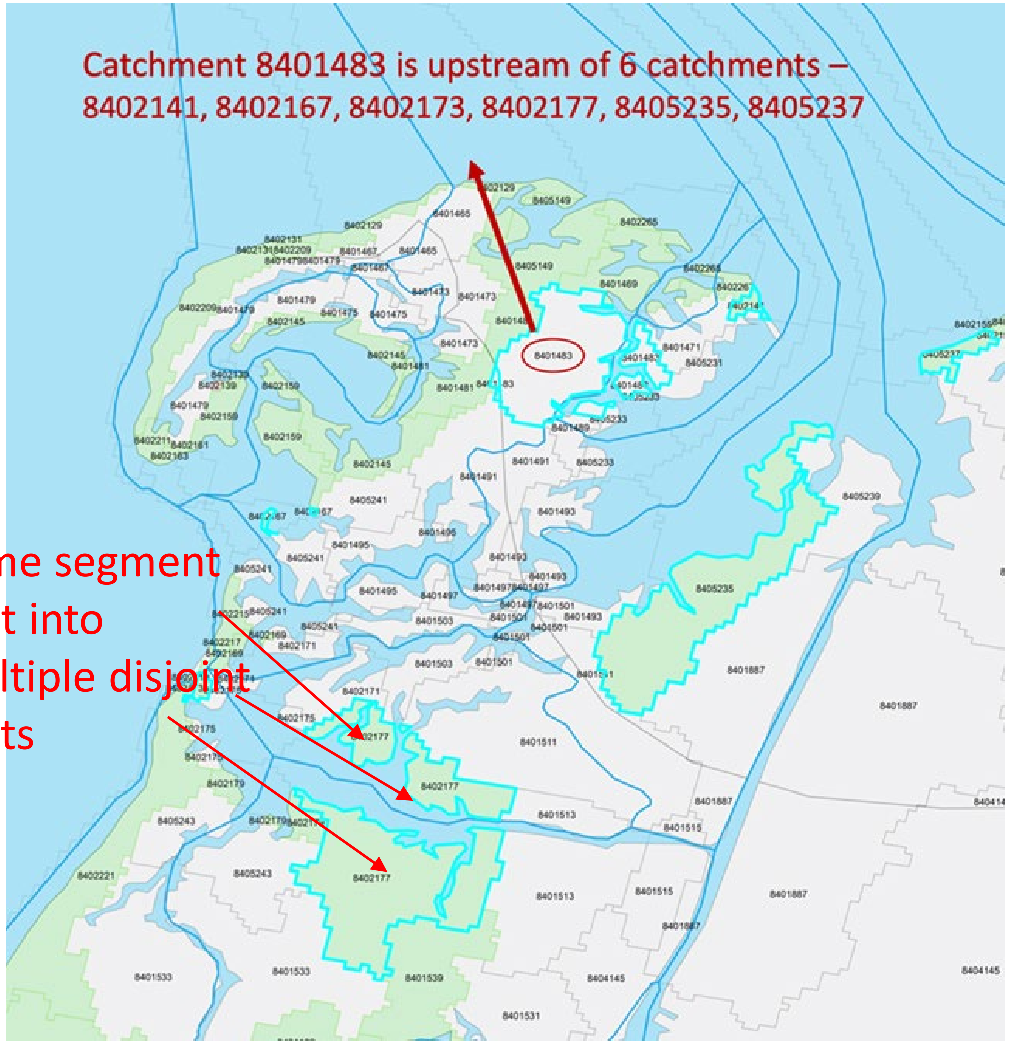




- Higher nutrient concentrations drive larger production and more severe hypoxia
  - But sensitivity to the details of coupling strategy is high
- The model needs to be recalibrated with new, consistent nutrient inputs with NHDplus
- These differences highlight the challenges of using high-resolution inputs
  - Ecosystem response often exhibits high sensitivity, especially in small confined systems
  - High-resolution observation in those systems can help

Summary

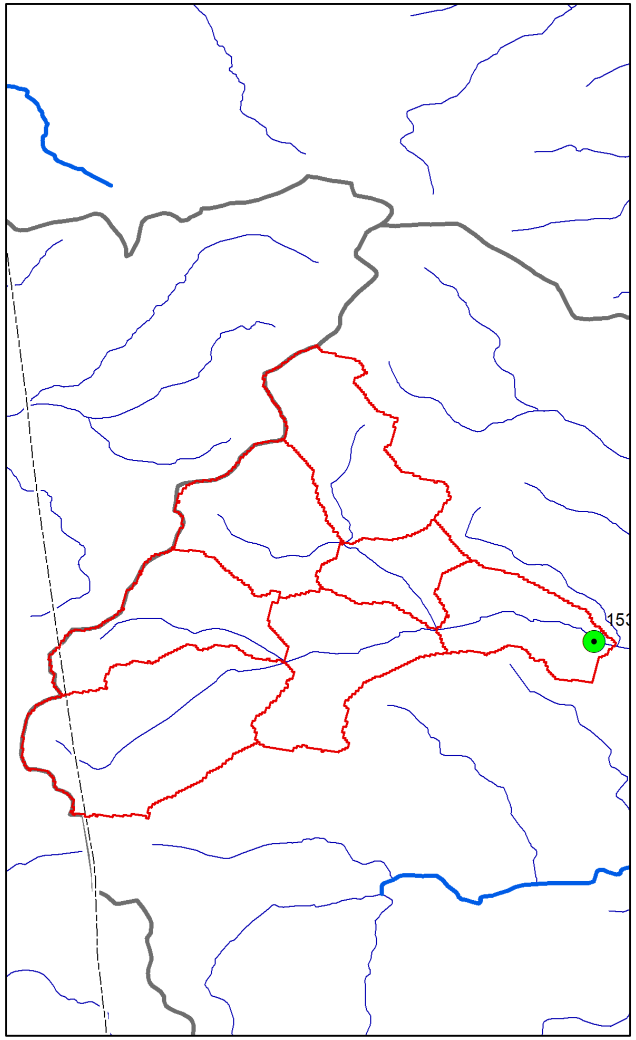
- We have tested the coupling between a hi-res 3D estuarine hydrodynamic-WQ model and a hi-res hydrologic model prototype (NHDplus)
    - The 3D estuarine hydrodynamic model is very robust
- Impact on estuarine circulation is mostly expected
    - Results are similar to P6 in the main stem of the Bay
    - Results in tributaries and sub-tributaries generally show higher salinity gradients
- Impact on WQ needs to be further explored
    - Nonlinear responses are expected especially in smaller systems
- Challenges and future work
    - ? Refinement of linkage strategy: what do you mean by ‘nearest element’?
    - ? Odd cases (e.g. multi-part disjoint segments)
    - ? How to distribute nutrient loadings under high resolution to better capture localized effects?
    - ? How to adapt the coupling strategy as the watershed model evolves in the future?



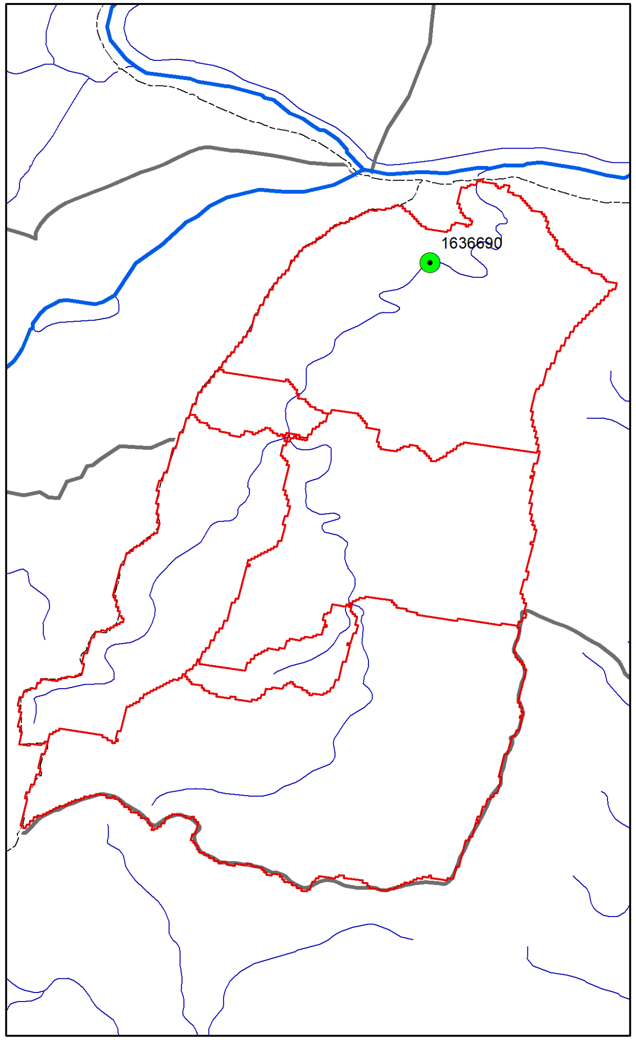
Additional Slides

Chesapeake Bay Program
Science. Restoration. Partnership.

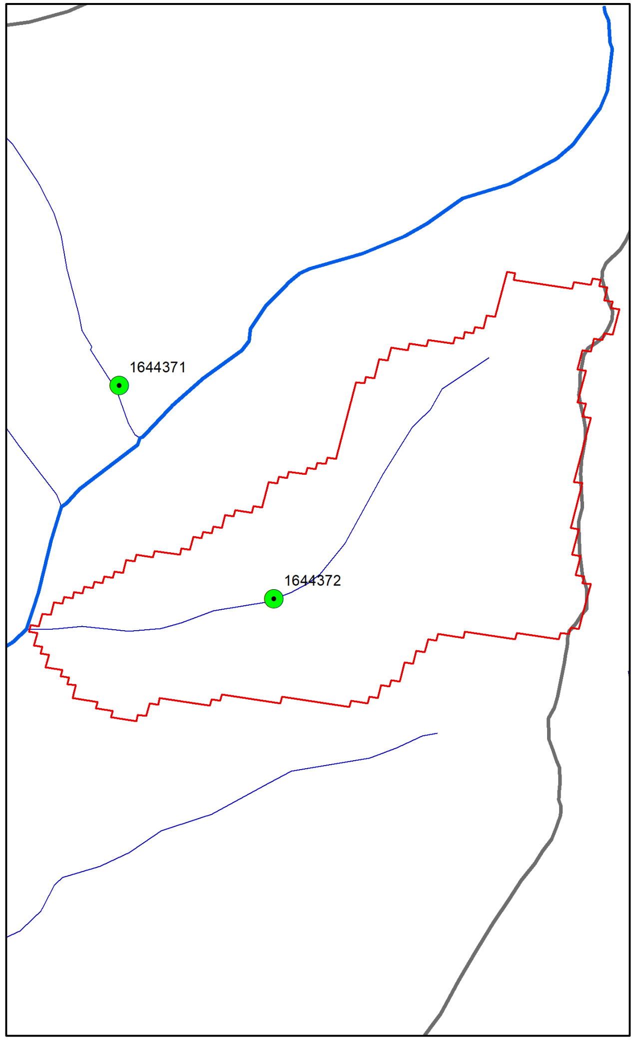
Alignment of the streamflow station with the NHD catchments



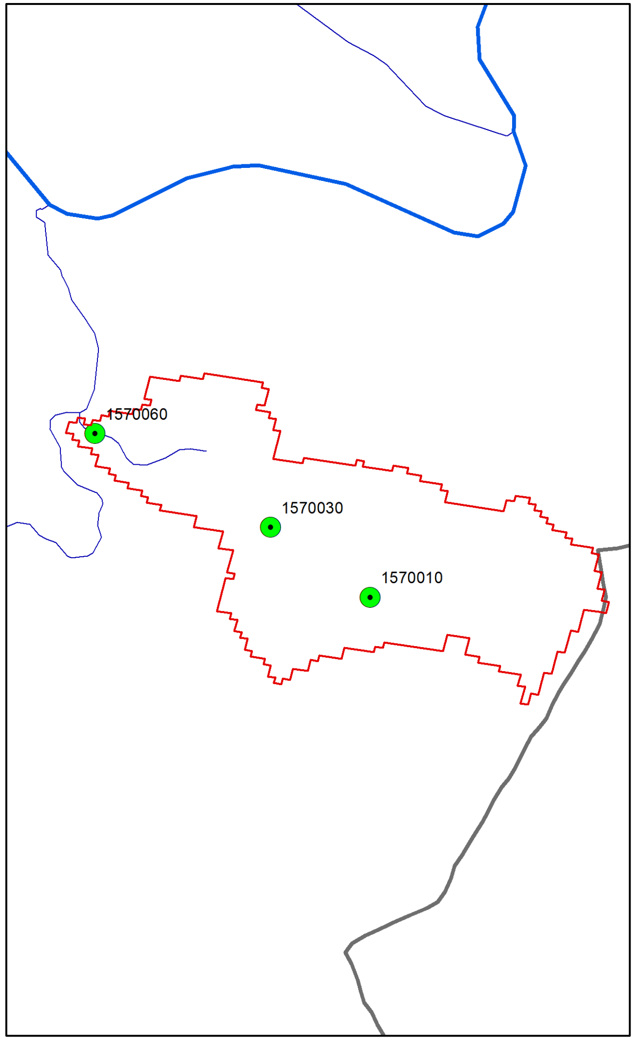
Good Alignment
CA = 1.01 x DA



Not So Good Alignment
CA = 1.10 x DA

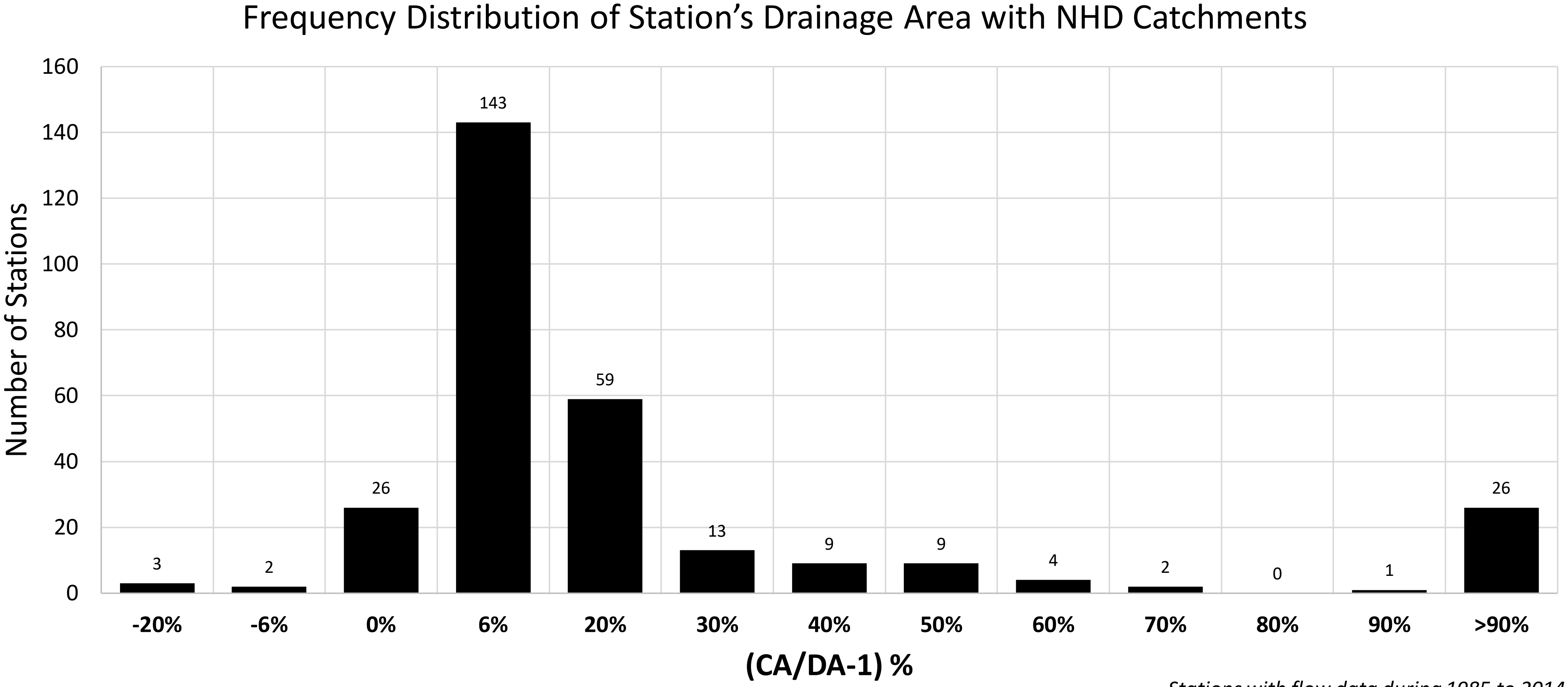


Poor Alignment
CA = 2.17 x DA



Unresolved Issue
CA = 0.43 x DA

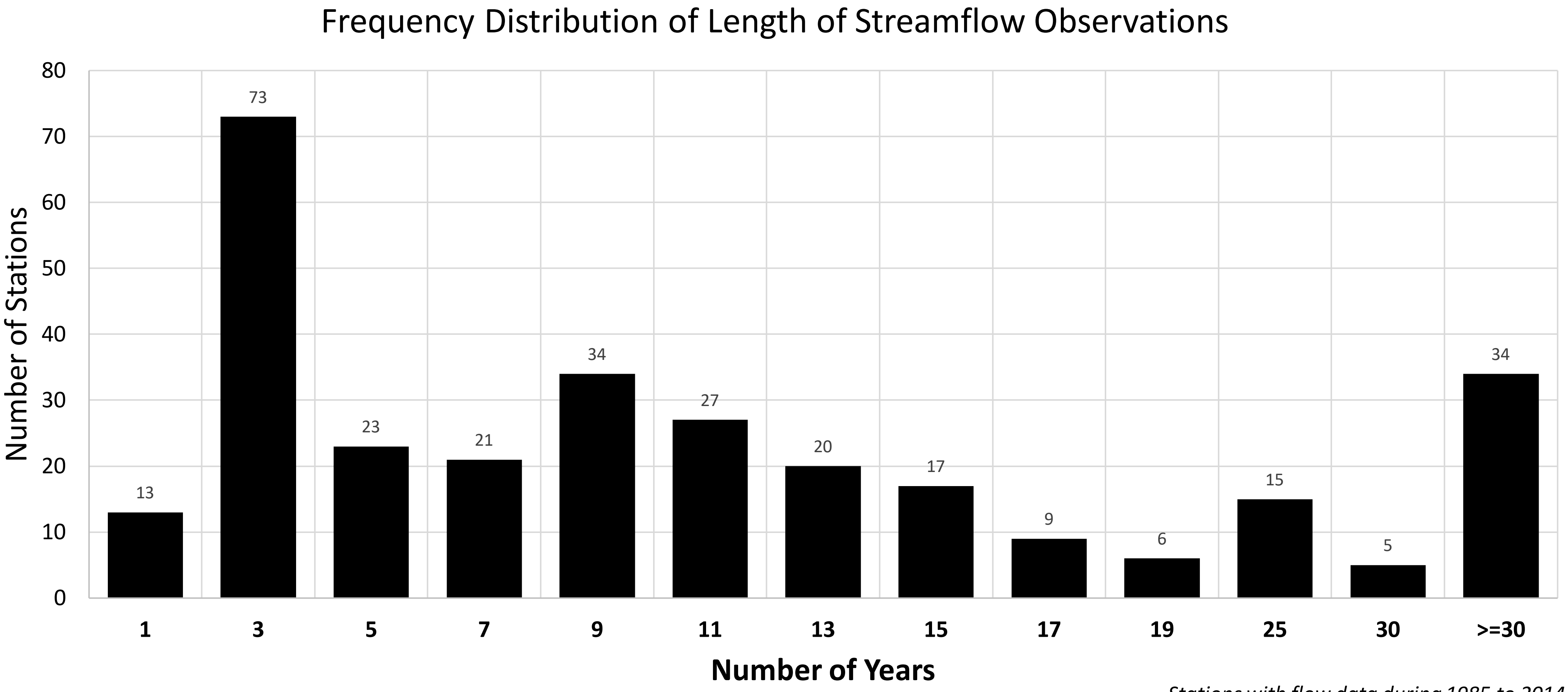
Alignment of NHD Catchments and USGS Stations (not used in Phase 6)



Stations with flow data during 1985 to 2014

169 out of 297 new stations have Catchment Area (CA) within ±06% of the station's Drainage Area (DA)
193 out of 297 new stations have Catchment Area (CA) within ±10% of the station's Drainage Area (DA)

Length of Streamflow Observation for USGS Stations (not used in Phase 6)



Stations with flow data during 1985 to 2014

86 out of 297 new stations have less than 3-years of streamflow observations

34 out of 297 new stations have complete 30-years (1985-2014) of streamflow observations