Report to the Water Quality Advisory Committee

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Liaison to DRBC Expert Panel

November 3, 2021

60 years 1961–2021

Delaware River Basin Commission
DELAWARE • NEW JERSEY
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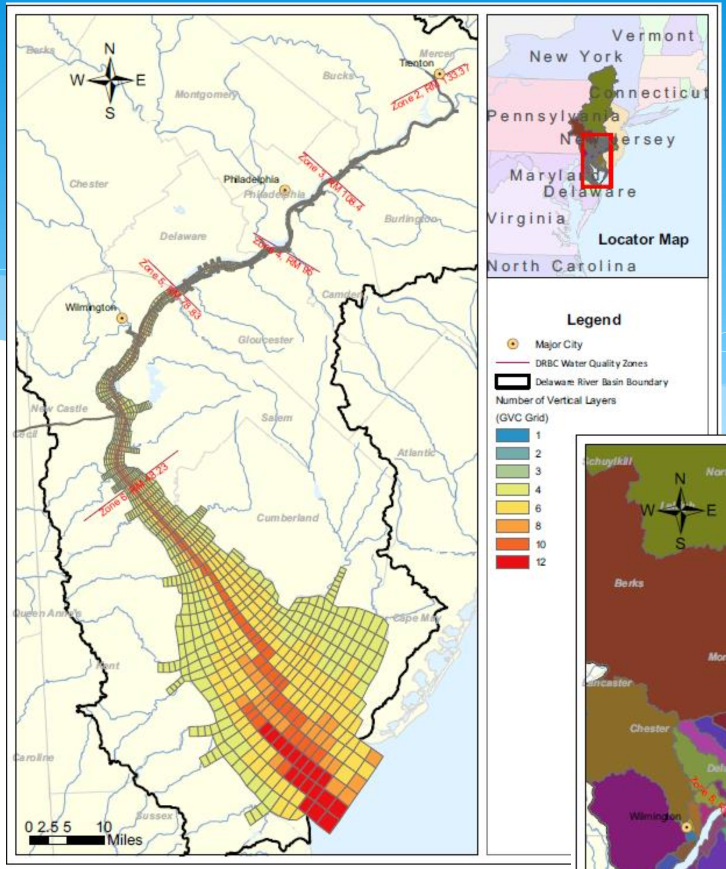
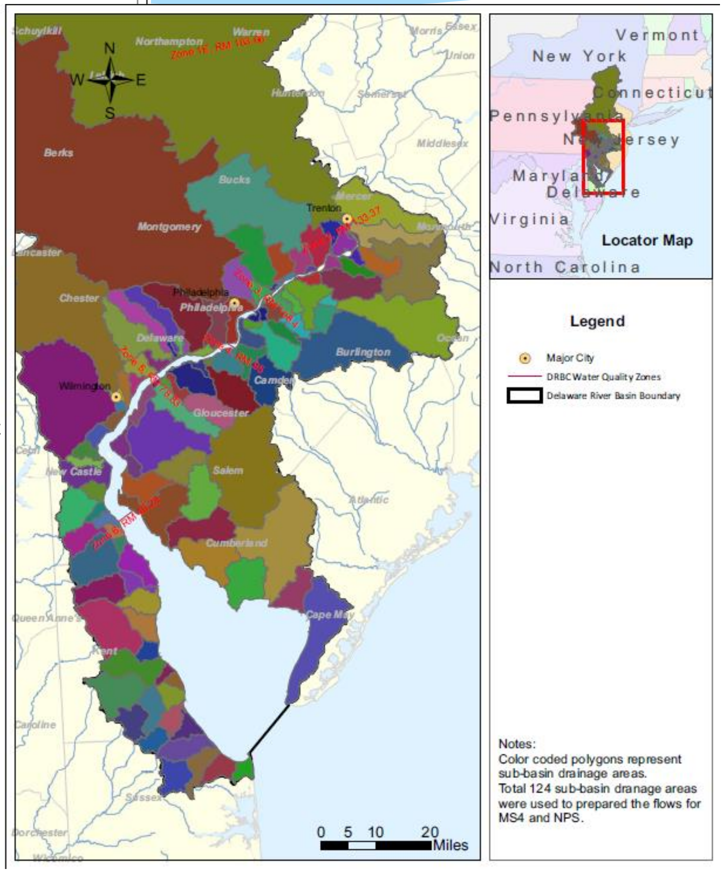
DRBC Expert Panel Members

Name	Organization	Service
Carl Cerco	U.S. Army Corps of Engineers (Retired)	Panel Members
Bob Chant	Rutgers University	
Steve Chapra	Tuffs University	
Tim Wool	U.S. EPA Region 4	
Vic Bierman	LimnoTech	Consultant to DRBC
Scott Hinz	LimnoTech	

Purpose and Goal

- Purpose:
  - To determine appropriate levels of source controls, especially in relation to dissolved oxygen
- Goal:
  - To develop a eutrophication model for the Delaware Estuary and Bay
    - technically sound
    - utilizing the current state of the science
    - within a timeframe established by the Commission





Modeling Approach

Develop linked hydrodynamic and water quality model

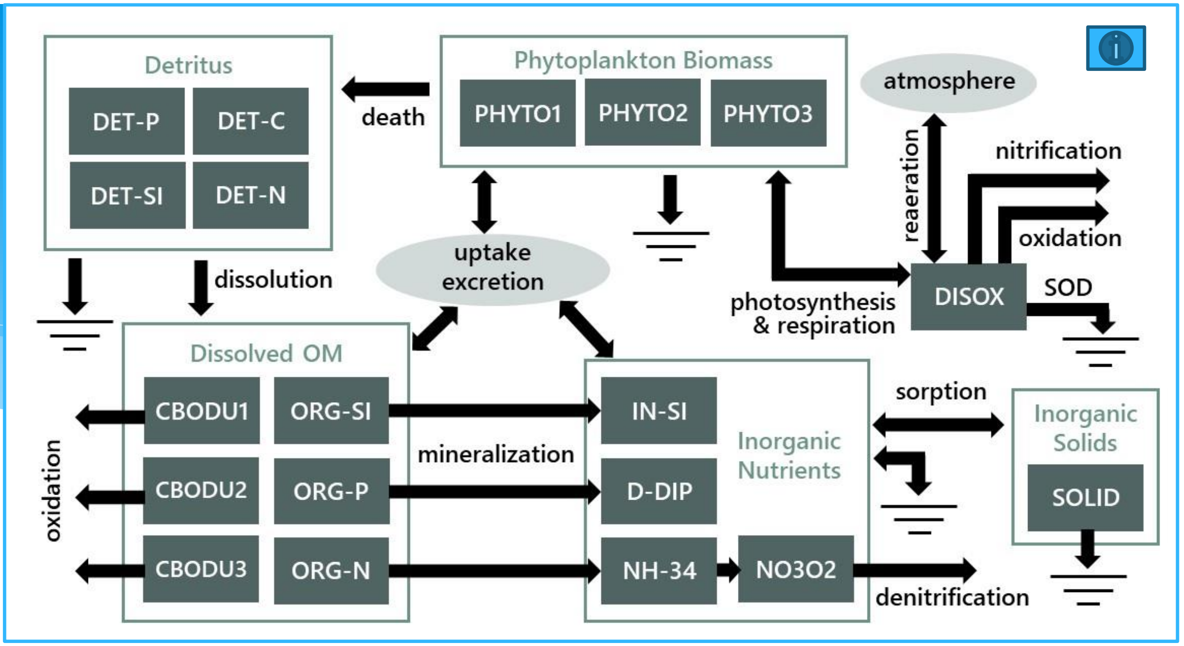
- Environmental Fluid Dynamics Code (EFDC)
- Water Quality Analysis Simulation Program (WASP8.x)

Develop flow and concentration inputs (boundary conditions)

- Intensive monitoring period 2018-2019
- Historical data, primarily 2012

Calibrate linked model

- Tributaries, point sources, stormwater, air deposition, CSOs, etc.
- Develop methodologies and submodels as needed to assign boundaries



Delaware Estuary Eutrophication Model Kinetics

Conduct forecast simulations with calibrated model

- Develop baseline (design) conditions and future scenarios
- Determine pollutant reductions required to achieve varying levels of ambient dissolved oxygen

State Variables and Processes Applied to Delaware Estuary Model

Dissolved Constituents

Gases
- **DISOX: dissolved oxygen**

Inorganic Nutrients
- NH-34: ammonia nitrogen
- NO3O2: nitrate nitrogen
- D-DIP: inorganic phosphate
- IN-SI: inorganic silica

Organic nutrients
- CBODU1: ultimate CBOD from stream
- CBODU2: ultimate CBOD from PS
- CBODU3: refractory CBOD
- ORG-N: dissolved organic nitrogen
- ORG-P: dissolved organic phosphorus
- ORG-SI: dissolved organic silica

Particulate Constituents

Phytoplankton Biomass
- PHYTO1: spring marine diatom community
- PHYTO2: summer freshwater diatom community
- PHYTO3: summer marine diatom community

Detritus
- DET-C: detrital carbon
- DET-N: detrital nitrogen
- DET-P: detrital phosphorus
- DET-SI: detrital silica

Other Solids
- TOTDE: particulate detrital organic material (dw)
- SOLID: inorganic solid

Major Processes Simulated

Chemical Processes
- **Oxidation of CBOD**
- **Nitrification of ammonia to nitrate**
- Dissolution and Mineralization
- **Sediment oxygen demand**

Physical Processes
- Settling
- **Reaeration (influx and efflux)**
- Sorption

Biological Processes
- **Photosynthesis**
- **Respiration**
- Phytoplankton growth and death
- Uptake

ears
1–2021
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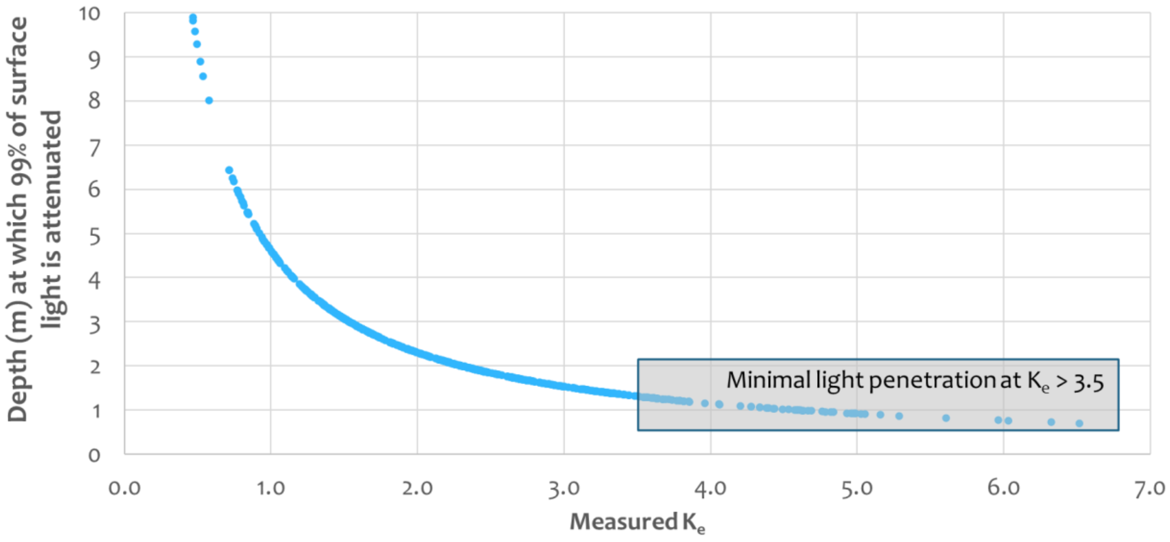
Key Accomplishments since October 2020

- Developed significant model improvements
  - Light extinction formulation
  - Reaeration formulation
- Prepared external loading inputs
- Developed fully operational 2D (horizontal) and 3D (10-layer) WASP models for Delaware Estuary
  - More than 300 2D runs performed
  - Approx 230 3D runs performed
- Calibrated global kinetics

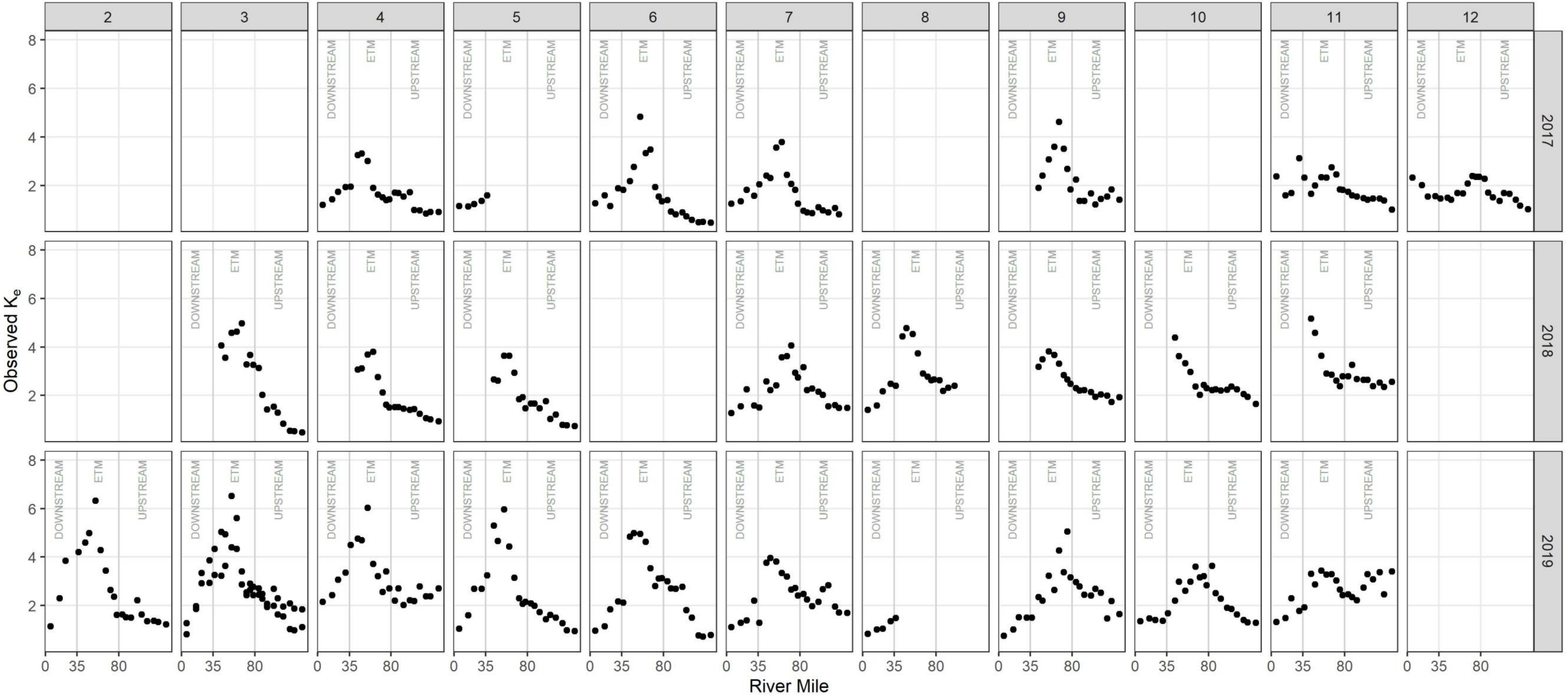
Light Extinction

- Light extinction refers to how quickly light is attenuated in the water column
  - Critical for algal growth!
  - Often poorly characterized in models
  - Light limitation is extremely important in the Delaware Estuary
  - LE tends to be site-specific
- Ke is related to:
  - Scattering (solids)
  - Absorption (color)
  - Self-shading (phytoplankton)
- Complicated by ETM in Delaware Estuary

Theoretical Ke vs. attenuation

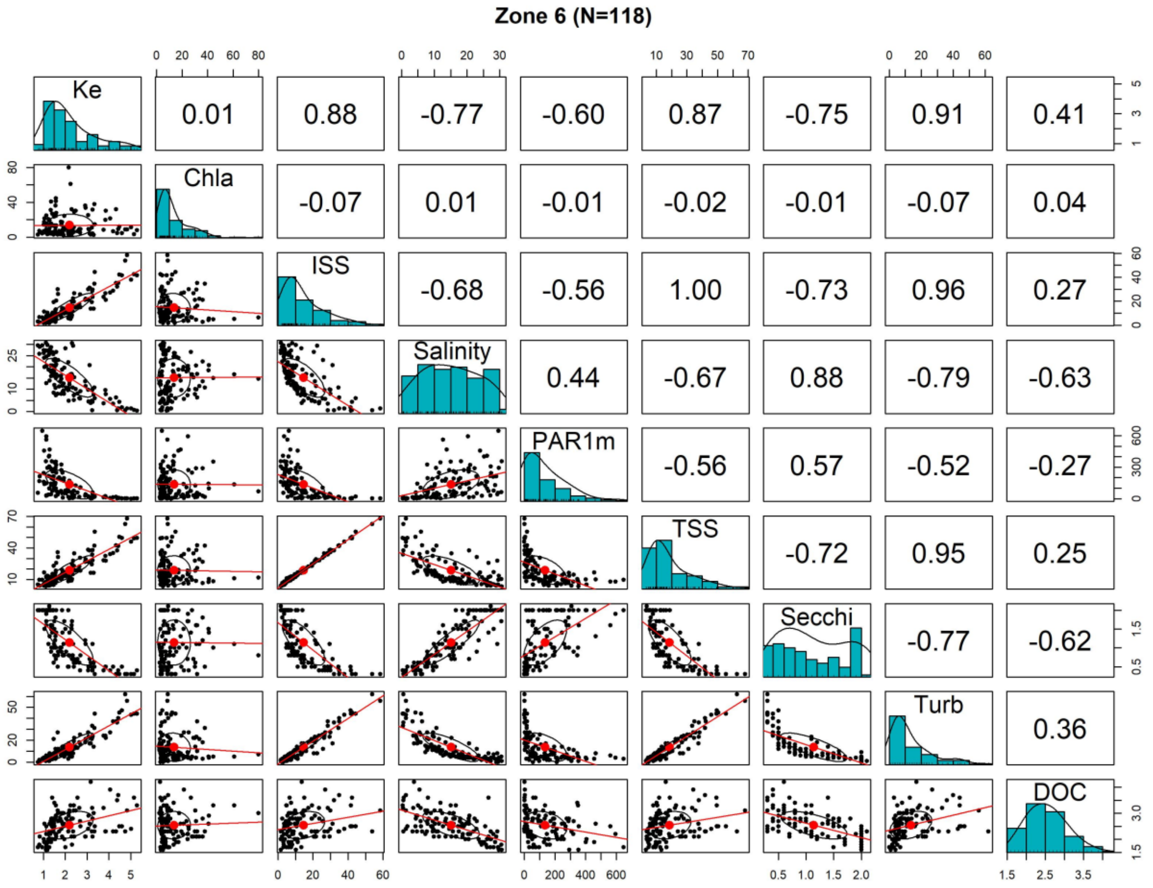


Light Extinction Data 2017-2019

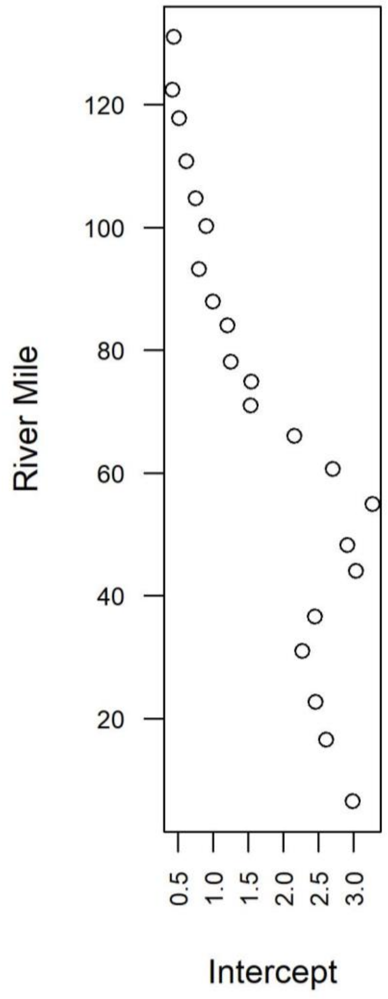


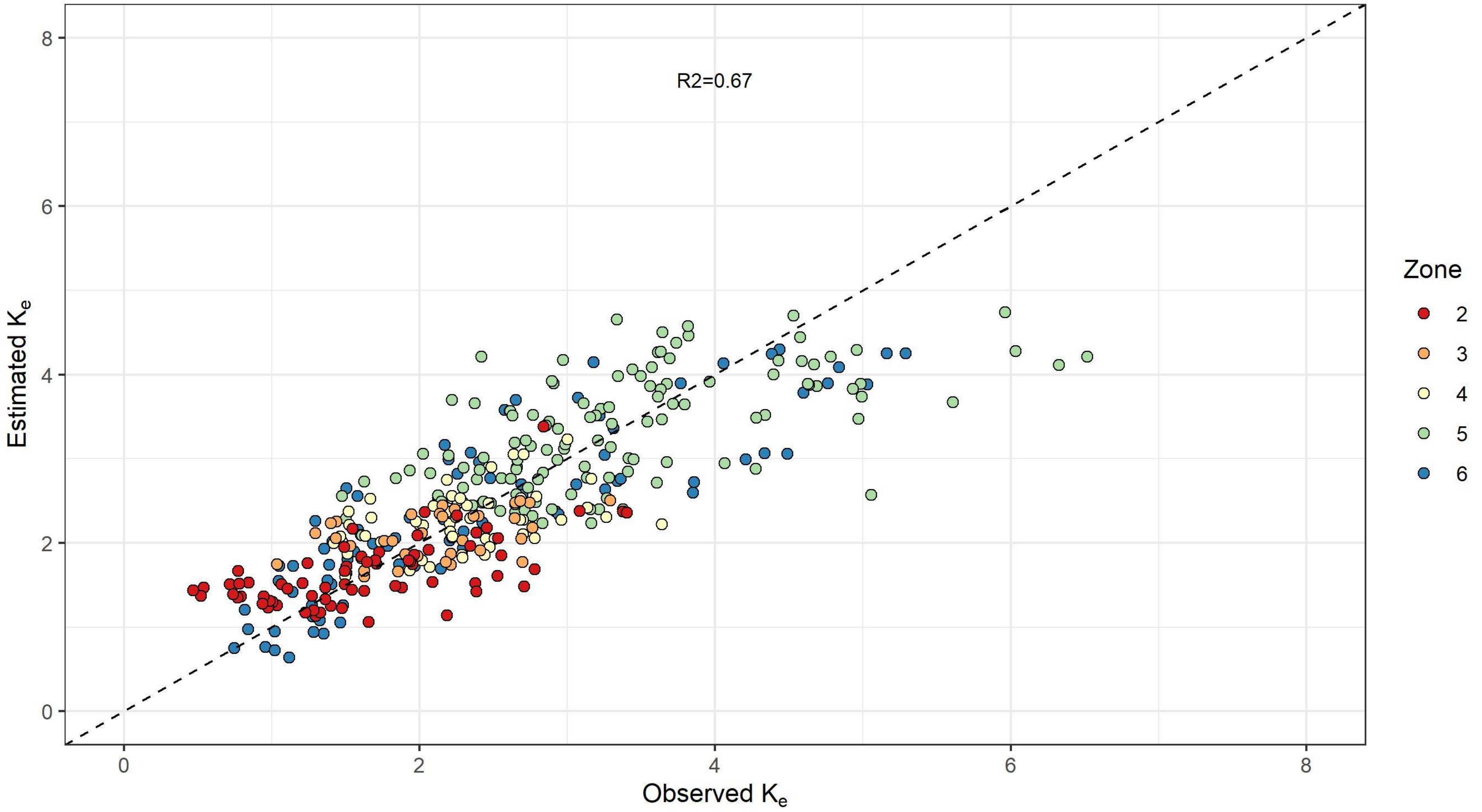
Data to Knowledge: Light Extinction

- It all starts with DATA!
  - PAR measurements 2017-2019
- Insights applied to re-formulation
  - ETM disrupts relationships
    - Data outside ETM used for fitting
    - More dynamic outside of the saline zones
    - More predictive for lower Ke values
  - Salinity used as surrogate for solids in Bay
- Intercept can be estimated as f(RM)

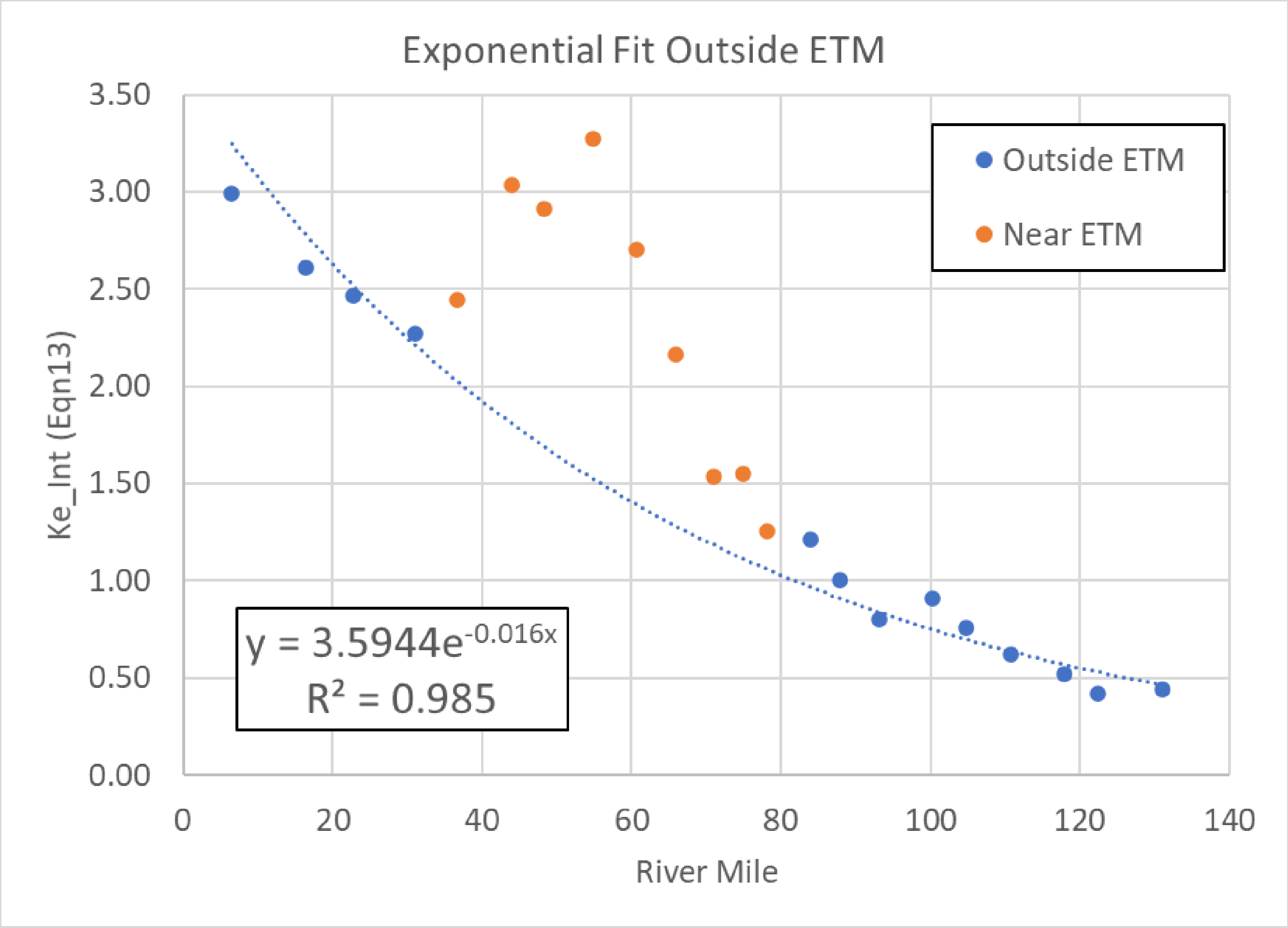


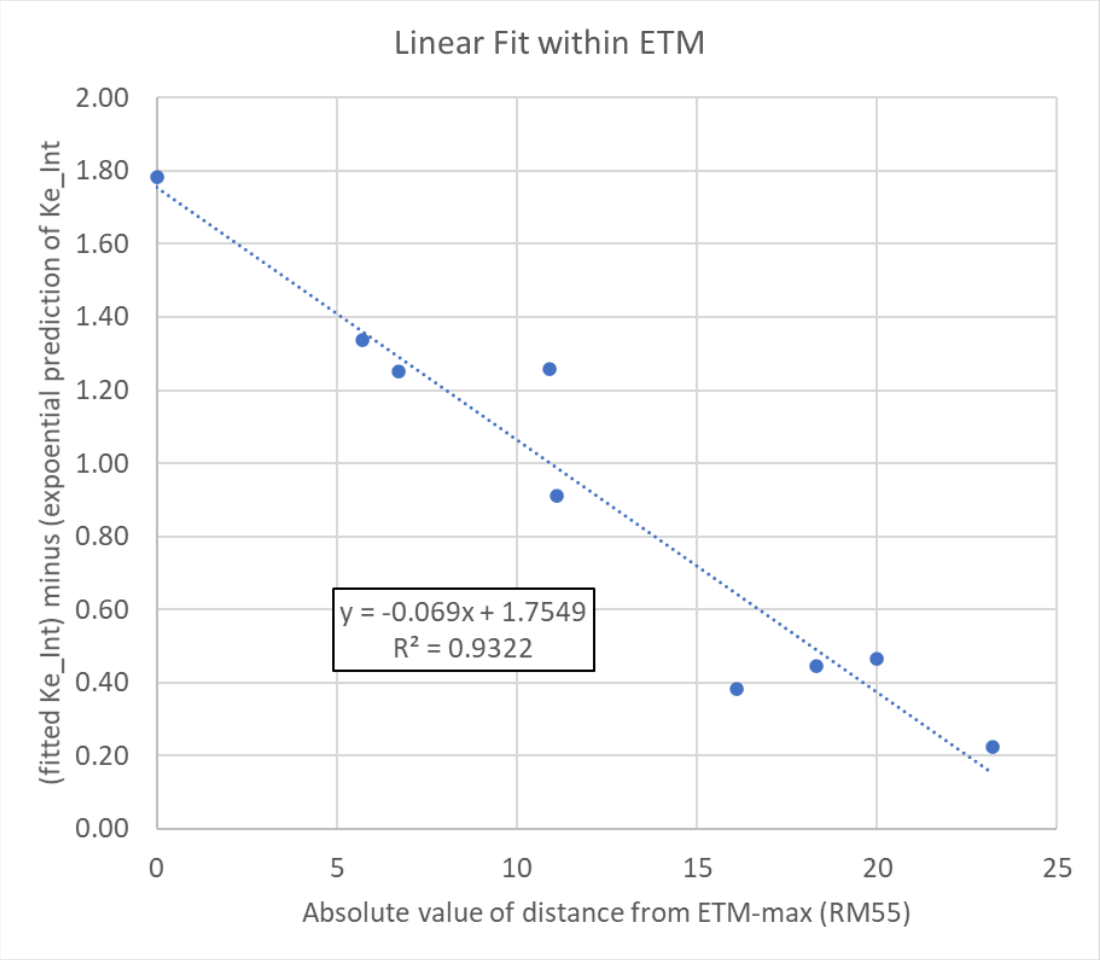
#	Type	K_e=	Data for Coefs	Data for Ints	R^2
13	Linear	Ke_int+(0.345*DOC)+(0.014*Chla)-(0.097*Sal)	Salinity: <RM 35 Chla, DOC:RM 0-35, 80-131	Site-specific Intercepts	0.67



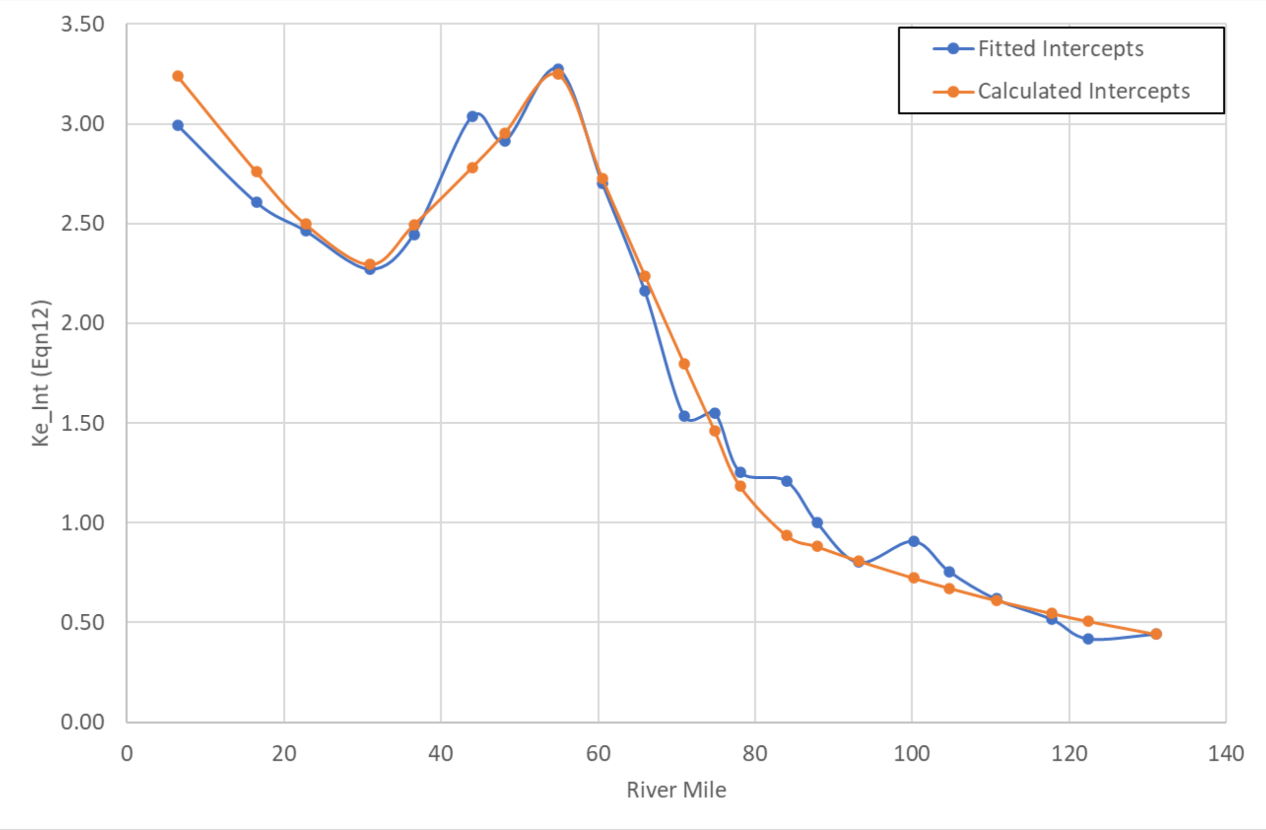


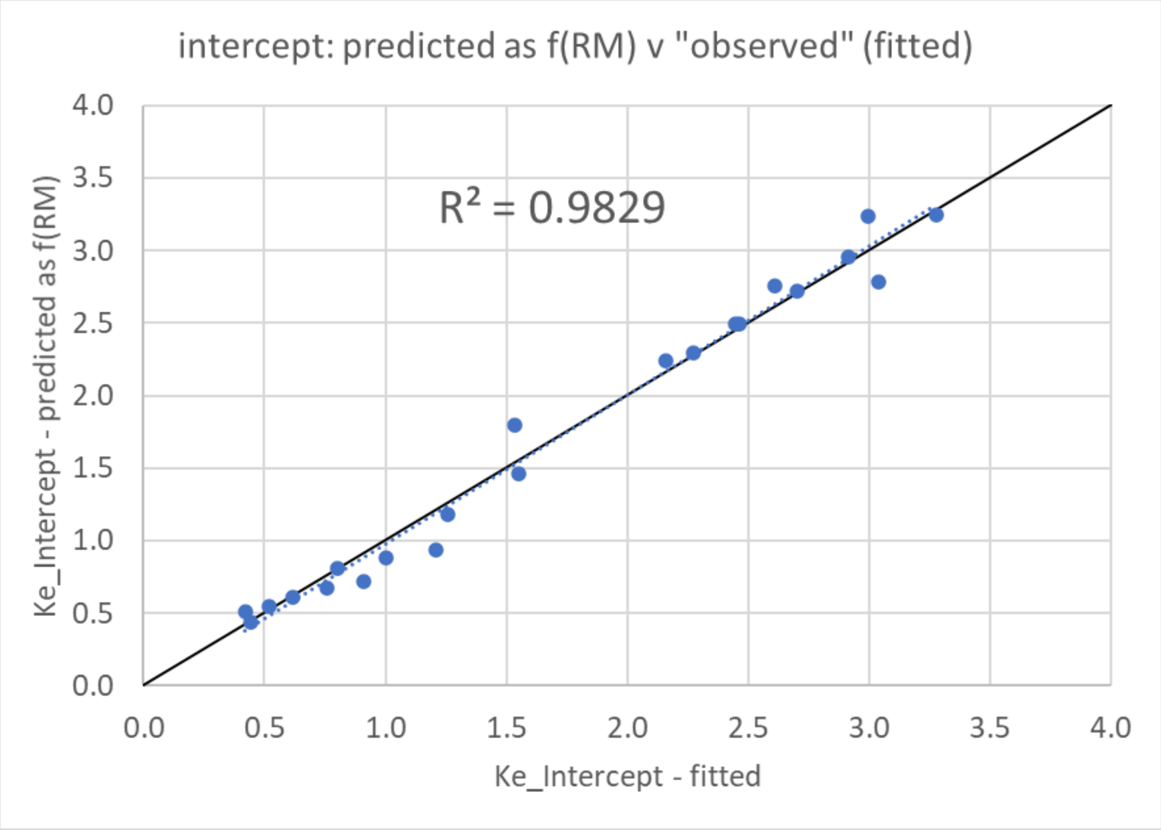
Basis for Calculating Intercept as f(RM)





Prediction Fitness:
Intercepts as f(RM) vs “observed” (fitted)





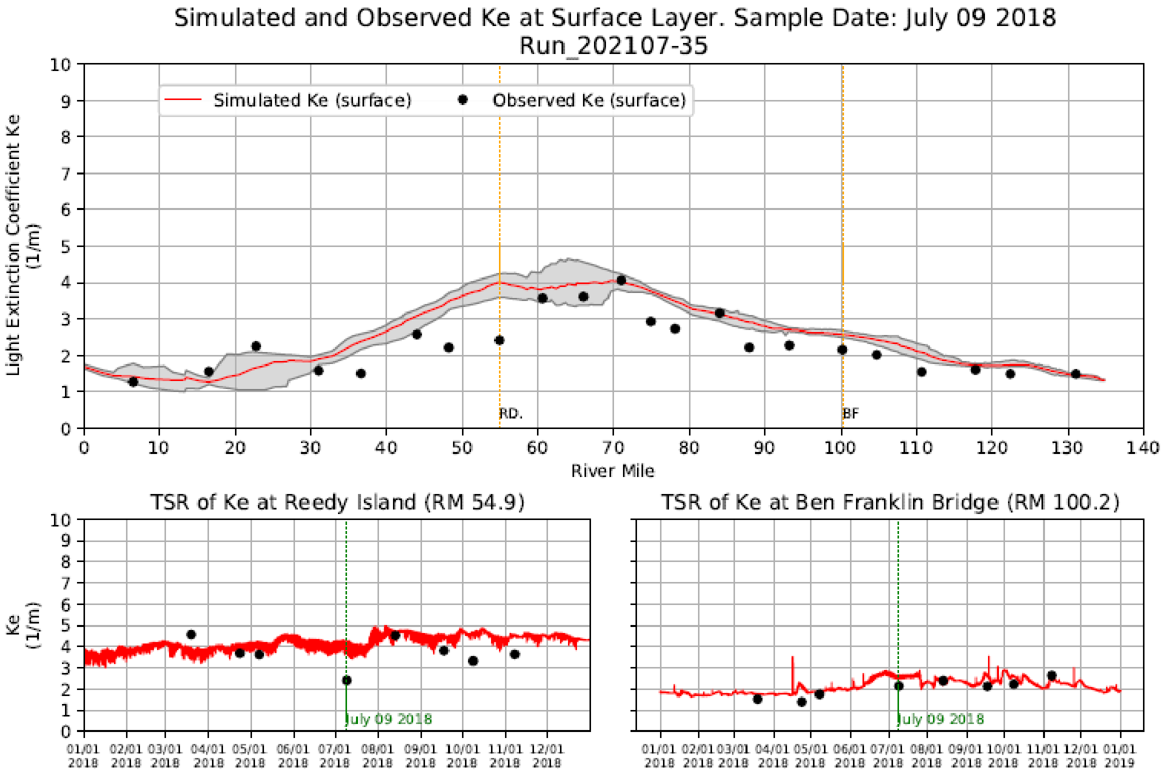
New Light Extinction Formulation

- Adopted linear regression as f(DOC, chl-a, salinity) that utilizes spatially variable intercept
  - Coefficients for salinity fitted using data downstream of ETM Zone
  - Coefficients for chl-a, and DOC fitted using data outside ETM Zone
- Used expression of intercept as f(RM) to calculate intercepts along the

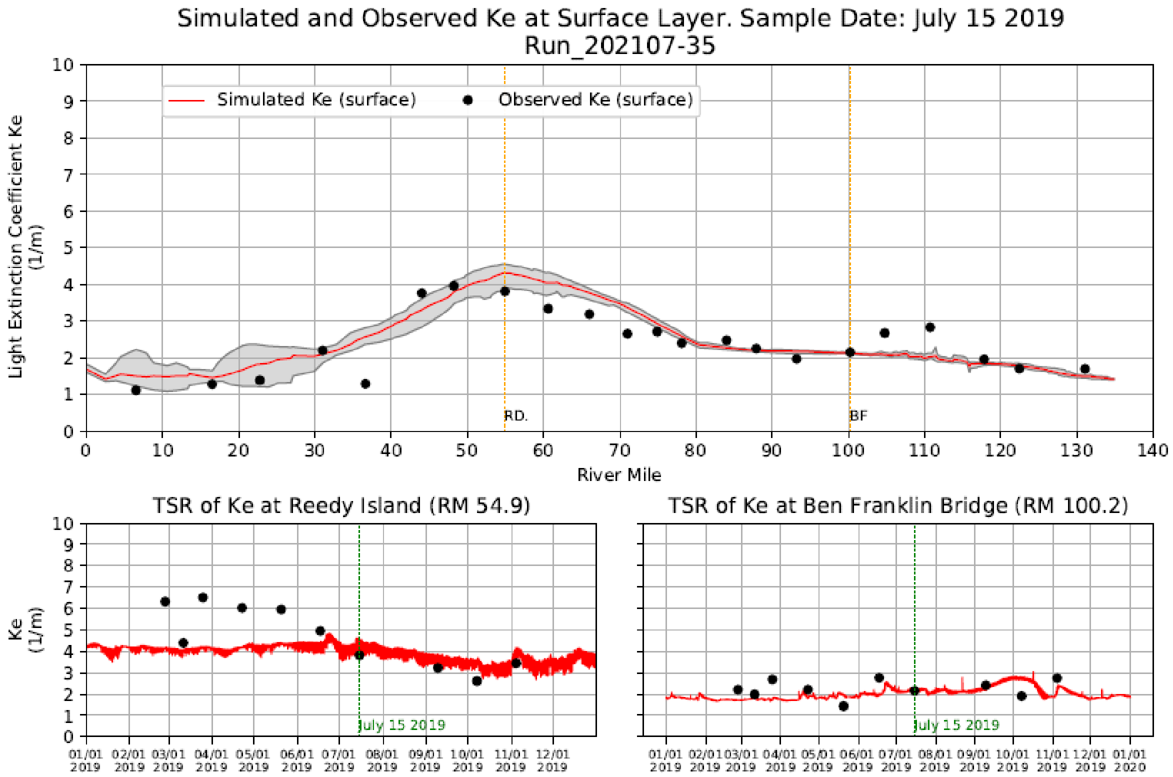
$$Ke = Ke_{Int} + (0.014 \times Chla) + (0.345 \times DOC) - (0.097 \times Salinity)$$

$$Ke_{Int}\ as\ f(RM) = 3.5944 \times e^{(-0.016*RM)} + Max[0, (1.7549 - 0.069 \times ABS(54.9 - RM))]$$

Model-Data Comparison for Ke



Simulated and Observed Light Extinction Coefficient Ke
Model results from 07/09/2018 were used in this analysis.



Simulated and Observed Light Extinction Coefficient Ke
Model results from 07/15/2019 were used in this analysis.

Reaeration Formulation – Mass Transfer Coefficient

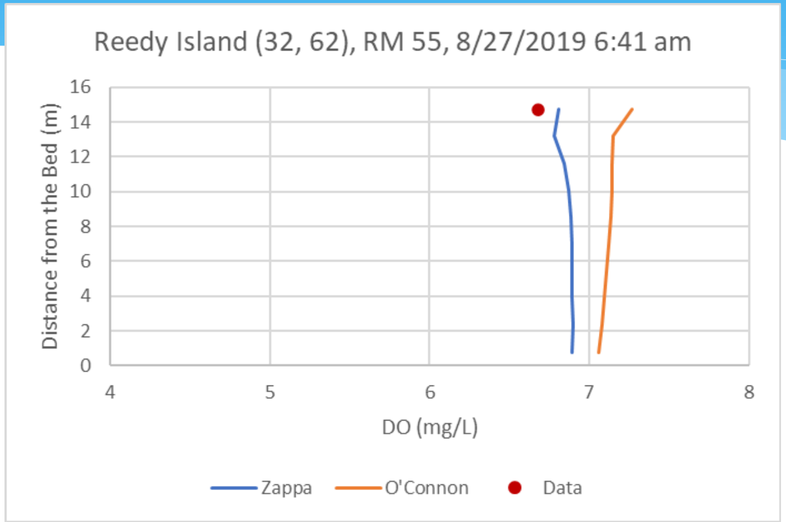
- Reaeration – rate of DO transfer at surface
  - Driven by gradient and mass transfer coefficient
  - Significant contribution to DO gain in tidal river
- Existing WASP options
  - Covar (1976), O'Connor-Dobbins (1958), Churchill (1962), Owens (1964)
  - Estimate mass transfer coefficient at air-water interface using mean water velocity, water depth, and wind speed
  - Developed for river & stream environments
- Vertical resolution testing revealed need for more accurate reaeration formulation
  - Existing WASP methods cannot capture energy characteristics at the air-water interface
  - Zappa et al. (2007) – estimates mass transfer coefficient using turbulent energy dissipation rate at air-water interface
    - Include the effects of both hydraulic and wind
    - Dissipation rate is thereby calculated from hydrodynamic model

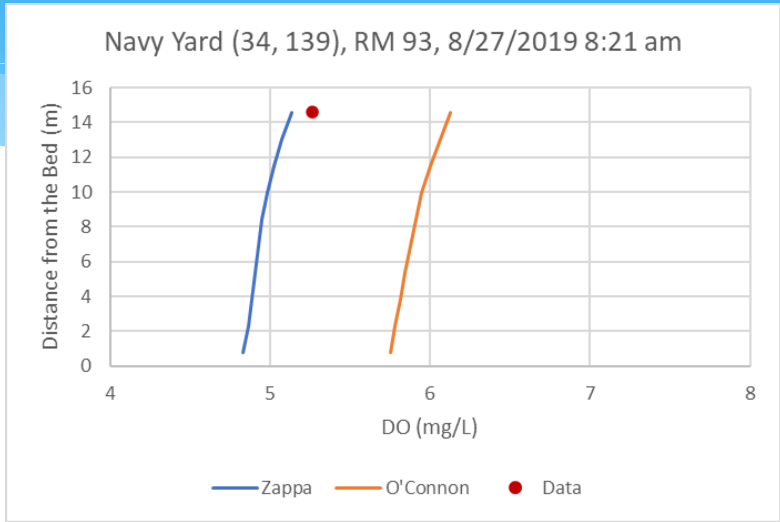
Longitudinal & Vertical Plots of DO

Old (O'Connor) and New (Zappa) Methods

Vertical DO profile

In the Bay

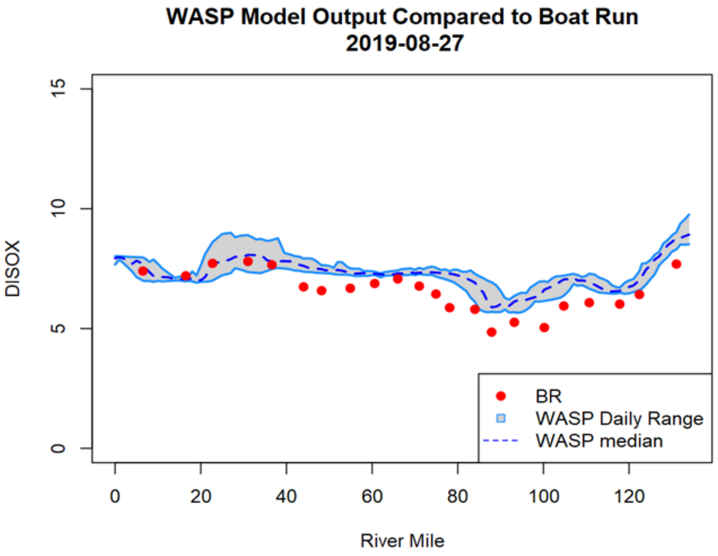


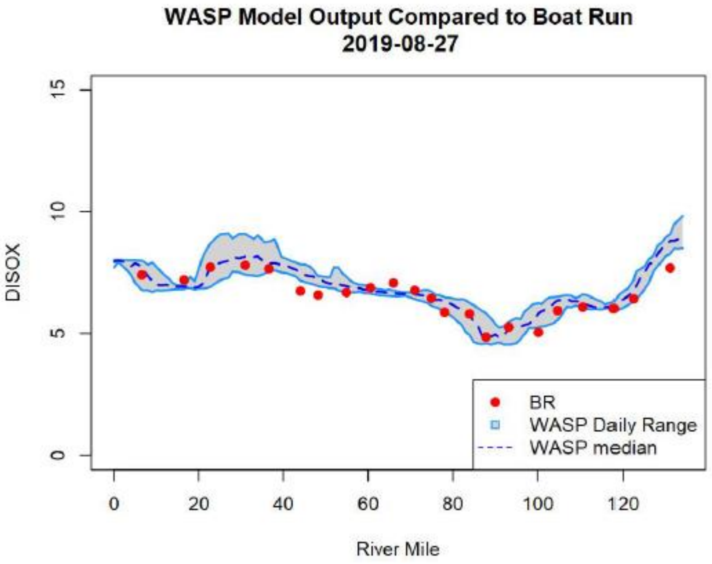


Vertical DO profile

Tidal river

August 2019 boat-run comparison with O'Connor approach

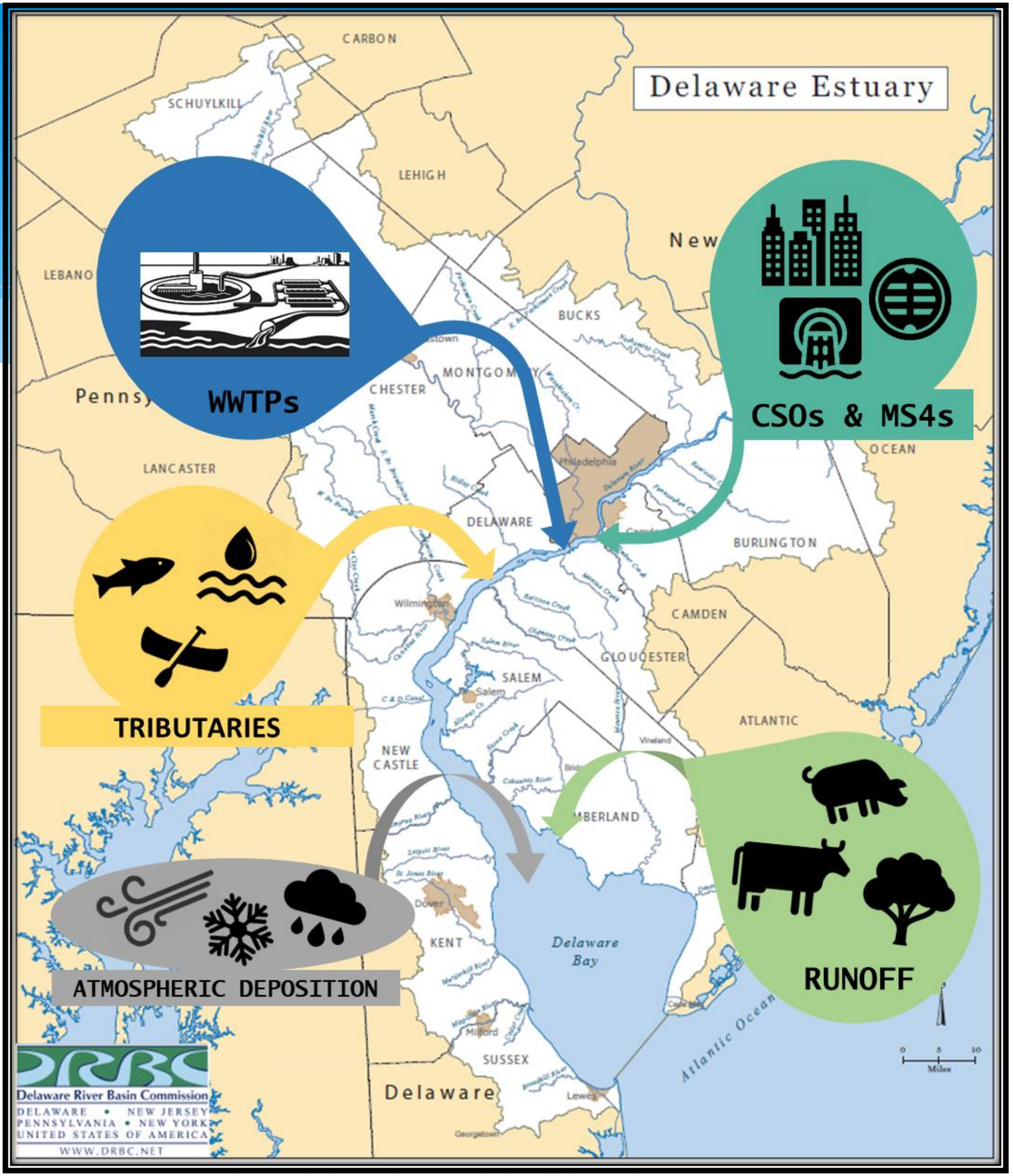




August 2019 boat-run comparison with Zappa approach

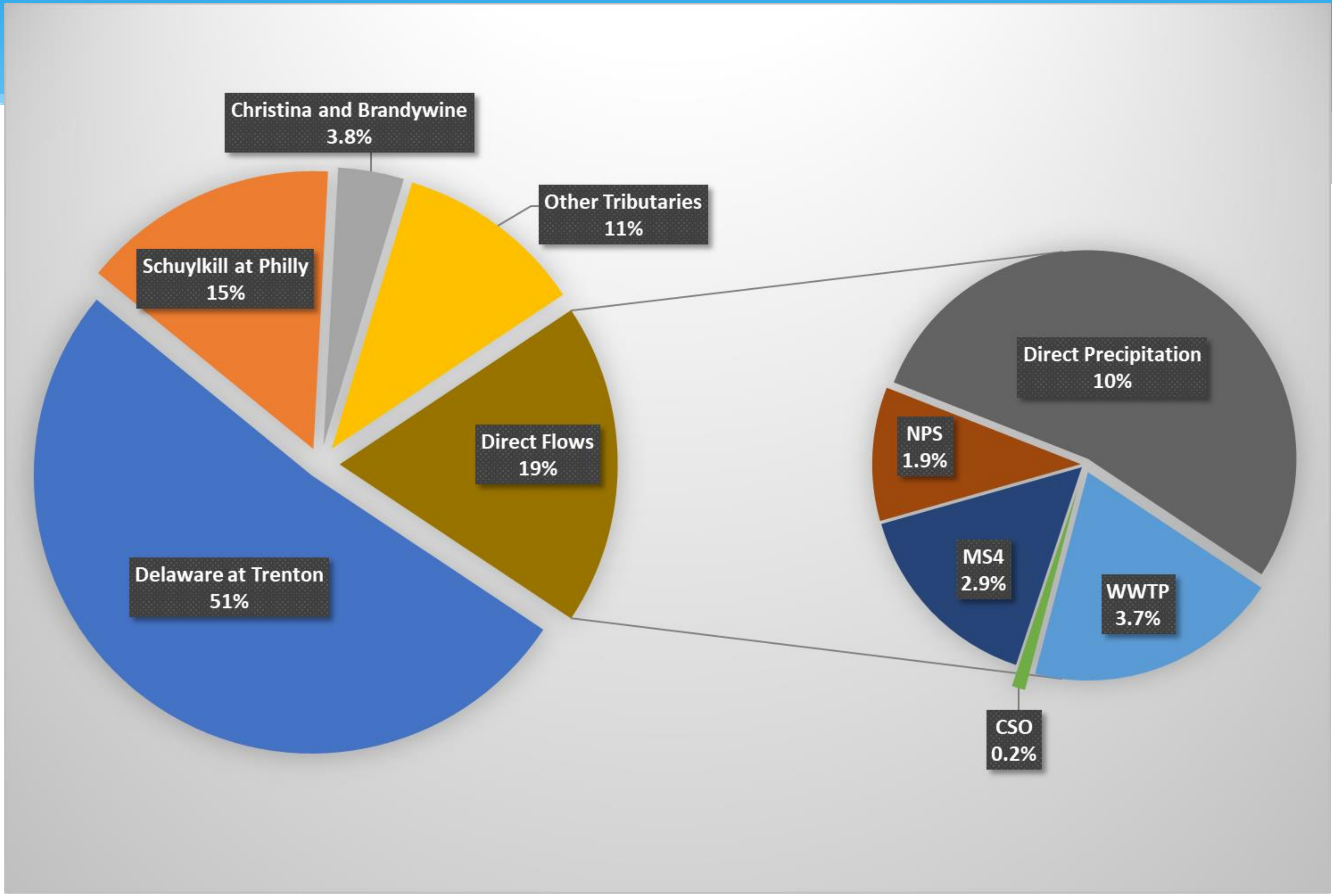
Characterization of External Loads

- Tributary Loads
  - Delaware River at Trenton (Zone 1)
  - Schuylkill River
  - 31 other tributaries
- Direct Basin Loads
  - Wasteloads: WWTPs, CSOs, MS4
  - Nonpoint Source (runoff outside MS4)
  - Wet/Dry deposition onto water surface



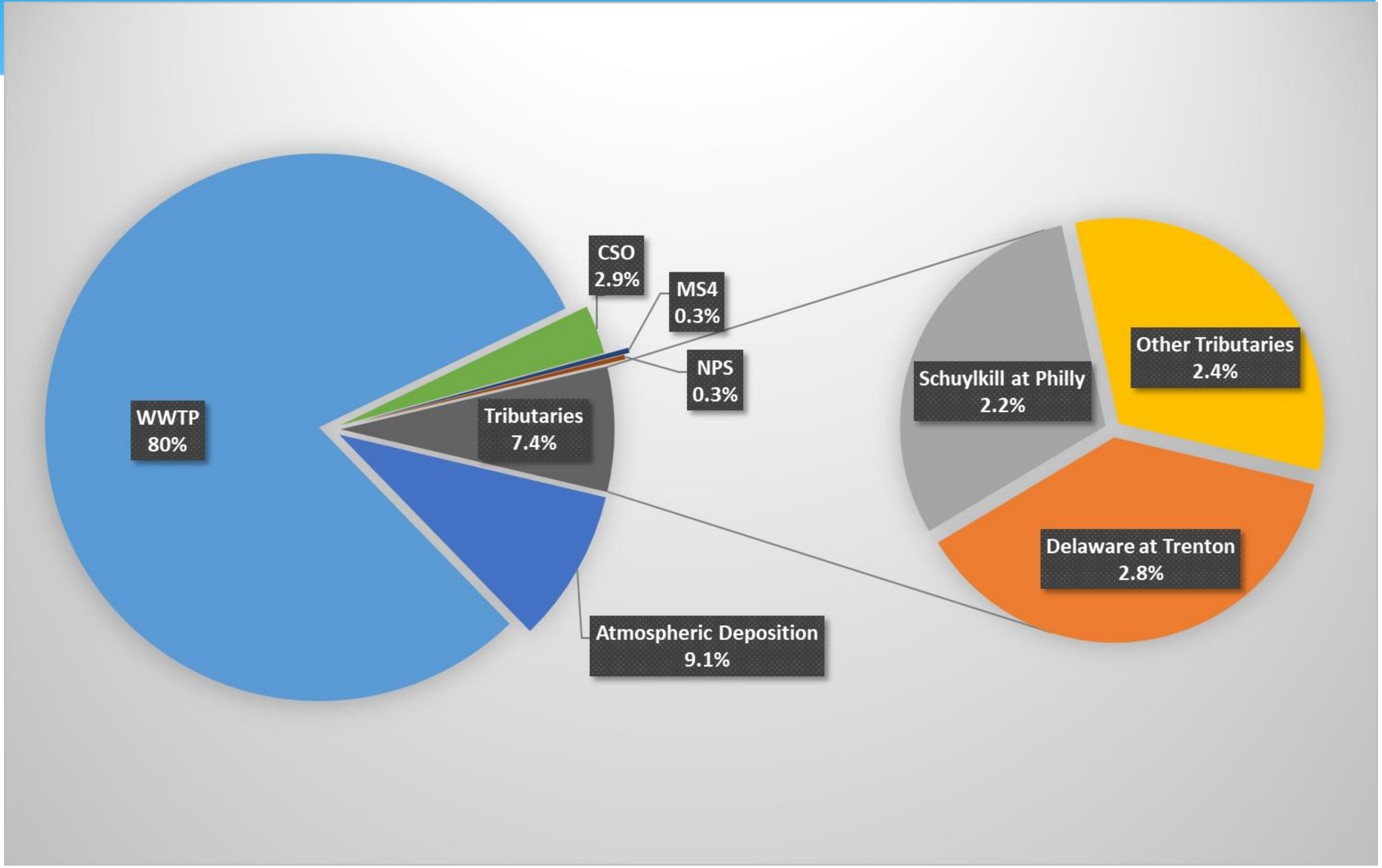
Water Inflows

- ~80% of water delivered to estuary through 33 modeled tributaries
- ~10% of water from direct precipitation



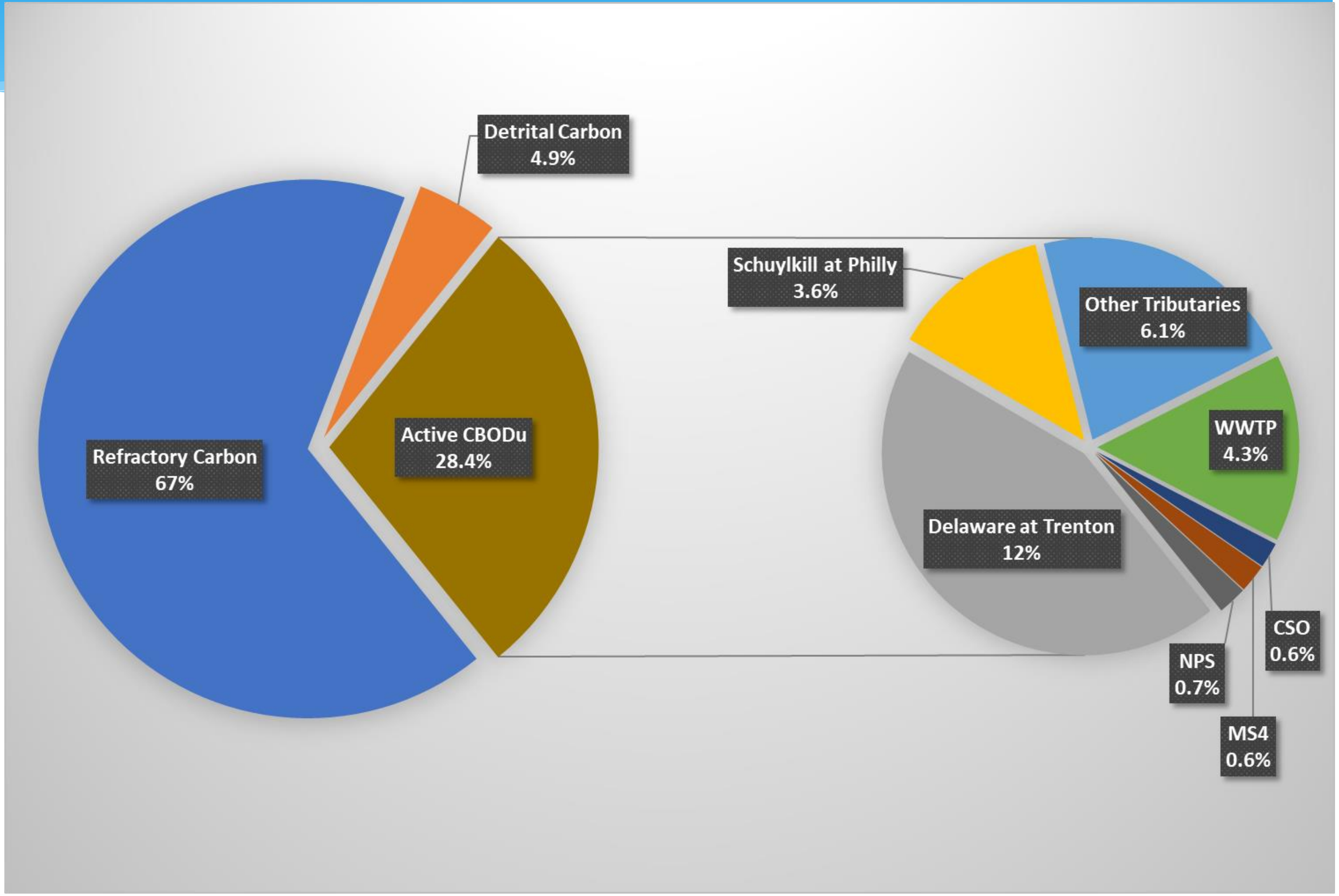
Ammonia-Nitrogen

- ~80% of ammonia load to estuary is from treated wastewater
- ~10% from atmospheric deposition and NPS
- Nitrification impact
  - Ammonia is oxidized to nitrate
  - Significant oxygen demand



Carbon

- Refractory CBODu
  - 73% average from tributaries
  - 45% average from treatment plants
- Active CBOD
  - 15% from treated wastewater
  - 78% from tributaries
- Decay rates
  - 0.087/d from wastewater
  - 0.033/d from tributaries
  - 0.01/d for refractory



Calibration Strategy

- Calibration period: 2018 ~ 2019
  - 2012 under development
- Principal data used for comparison with model predictions
  - DRBC monthly boat-run survey with grab samples
  - USGS continuous measurement
- Approach
  - Use a 2D depth-averaged model as surrogate for calibration testing
  - Spatial plots, time series plots, 1-1 plots, and cumulative frequency distributions used to compare predicted and observed
  - Coefficients ground-truthed when possible and benefitted from vast experience of Expert Panel
  - Component analyses used to drive calibration
  - Phytoplankton output compared based on growth seasons of three communities

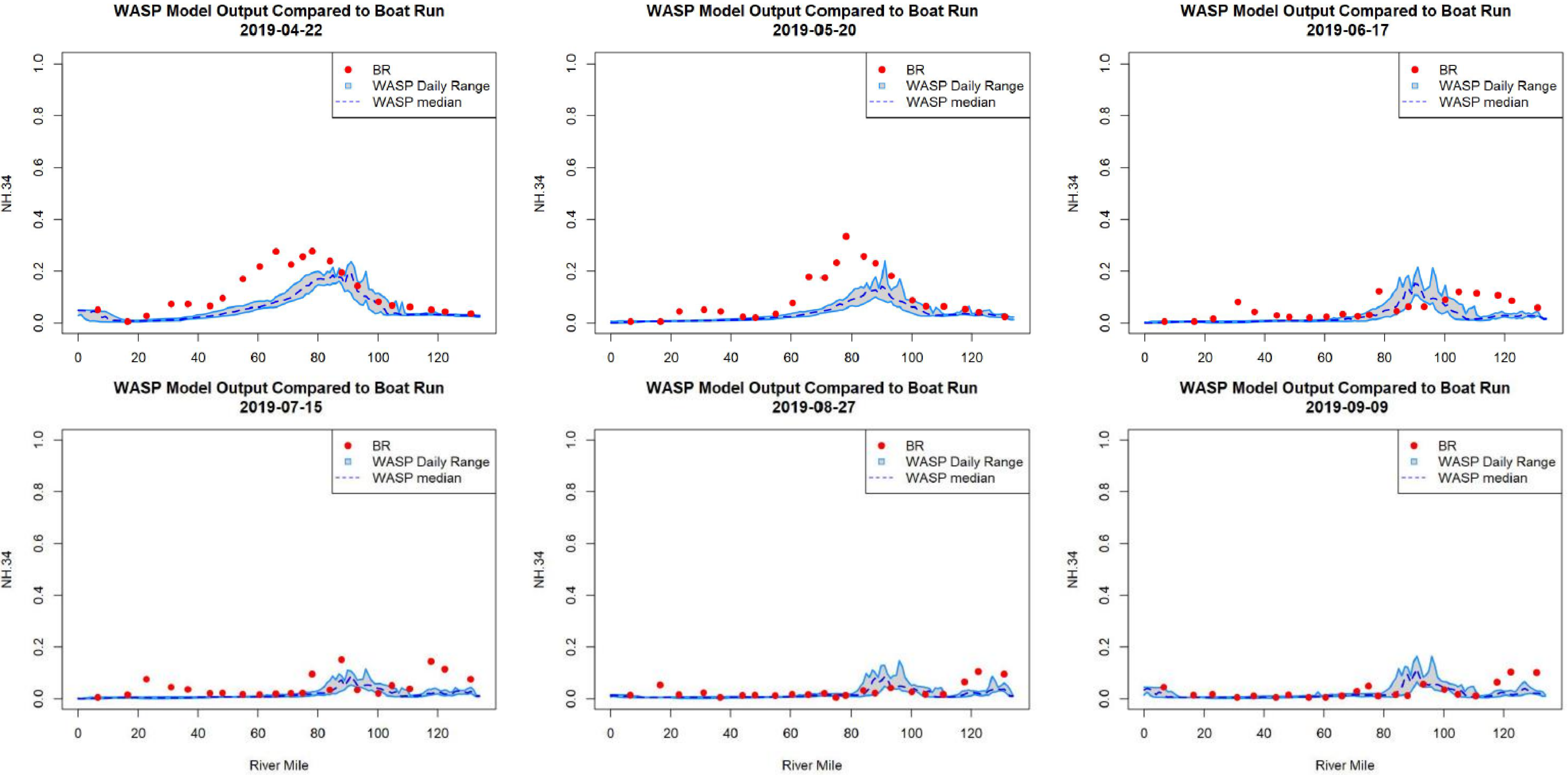
Key Parameters
(final values may change during ongoing calibration)

Parameters	Values
Nitrification Rate Constant @20 degree C (1/day)	0.6
Nitrification Temperature Coefficient	1.1
CBOD Decay Rate Constant @20 C (1/day)	0.033 / 0.087 / 0.01
Phytoplankton Maximum Growth Rate Constant @20 C (1/day)	4 / 3.75 / 4
Phytoplankton Carbon to Chlorophyll Ratio (mg C/mg Chl)	40 / 40 / 40
Phytoplankton Respiration Rate Constant @20 C (1/day)	0.03 / 0.03 / 0.03
Phytoplankton Death Rate Constant (Non-Zoo Predation) (1/day)	0.02 / 0.08 / 0.05
Phytoplankton Settling Velocity (m/day)	0.1 / 0.2 / 0.2
POM Settling Velocity (m/day)	*0.14 ongoing*
SOD and benthic fluxes of ammonia and phosphate	*Spatially variable ongoing*

Model-Data Comparisons

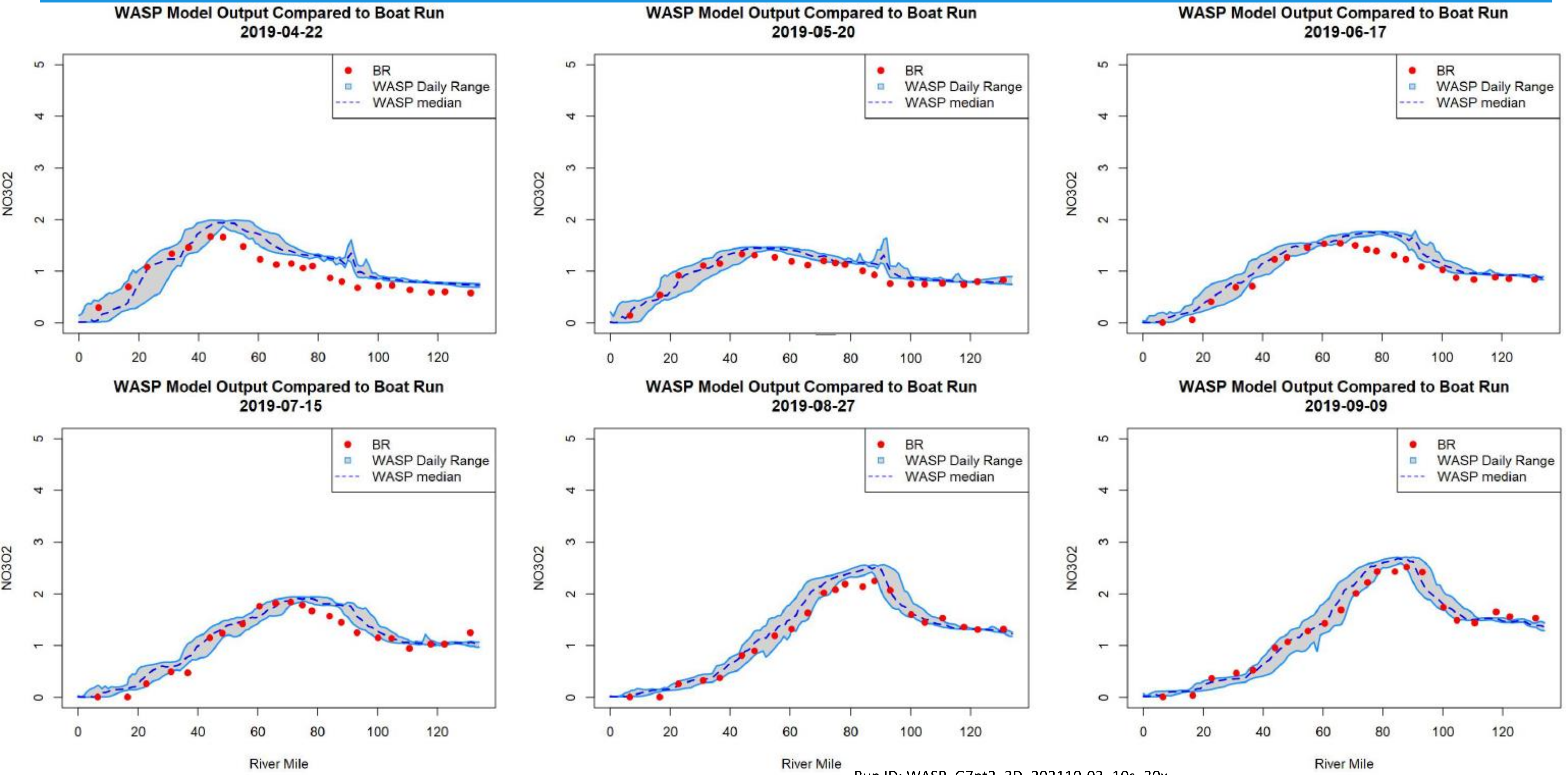
- Spatial plots during individual sampling events at boat-run stations
  - Ammonia nitrogen
  - Nitrate nitrogen
  - Total phosphorus
  - Dissolved organic carbon
  - Dissolved oxygen
- Phytoplankton
  - Conceptual model
  - Seasonal phytoplankton comparisons
- Model-data plots for individual boat run locations
  - Time series, 1-1 plots, cumulative frequency distribution, and statistics
- Comparison with continuous data at discrete locations
  - Time series, cumulative frequency distribution, and 1-1 plots
    - Reedy Island
    - Chester
    - Benjamin Franklin
    - Pennypack Woods

Model-Data Comparison of Ammonia Nitrogen at 22 Boat-Run Stations



Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Model-Data Comparison of Nitrate Nitrogen at 22 Boat-Run Stations



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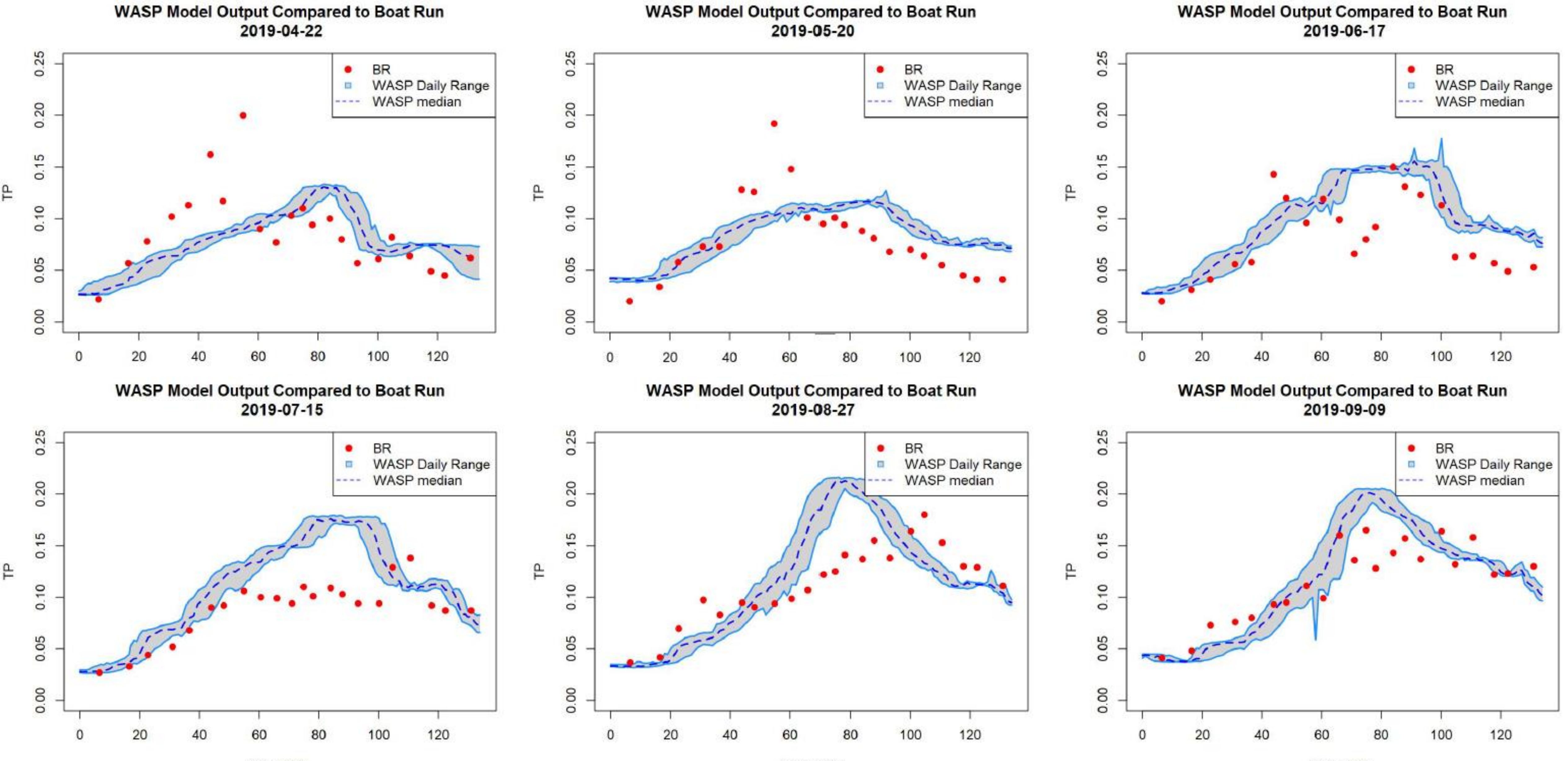
Model-Data Comparison of Total phosphorus at 22 Boat-Run Stations



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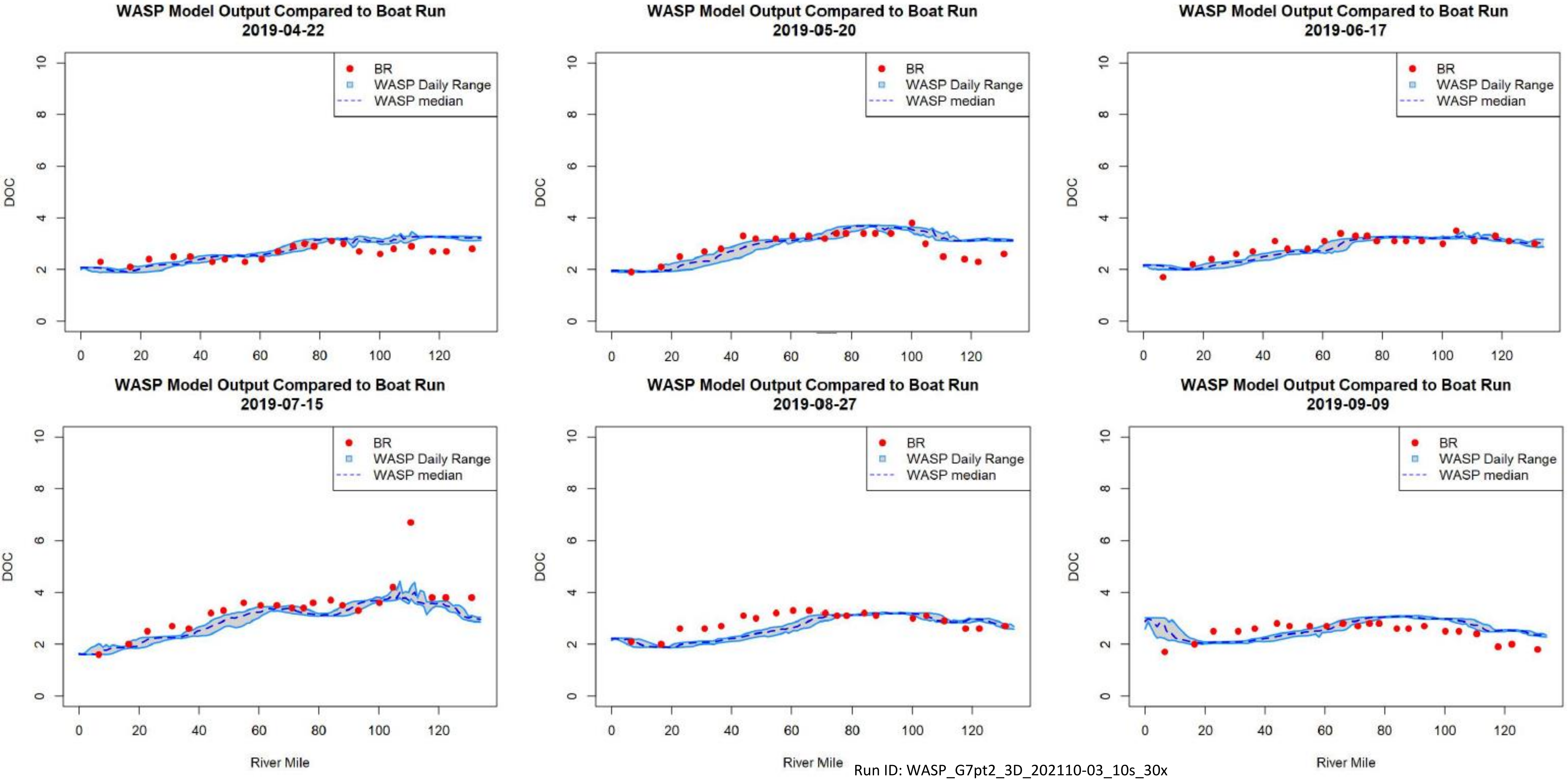
Model-Data Comparison of Dissolved Organic Carbon at 22 Boat-Run Stations



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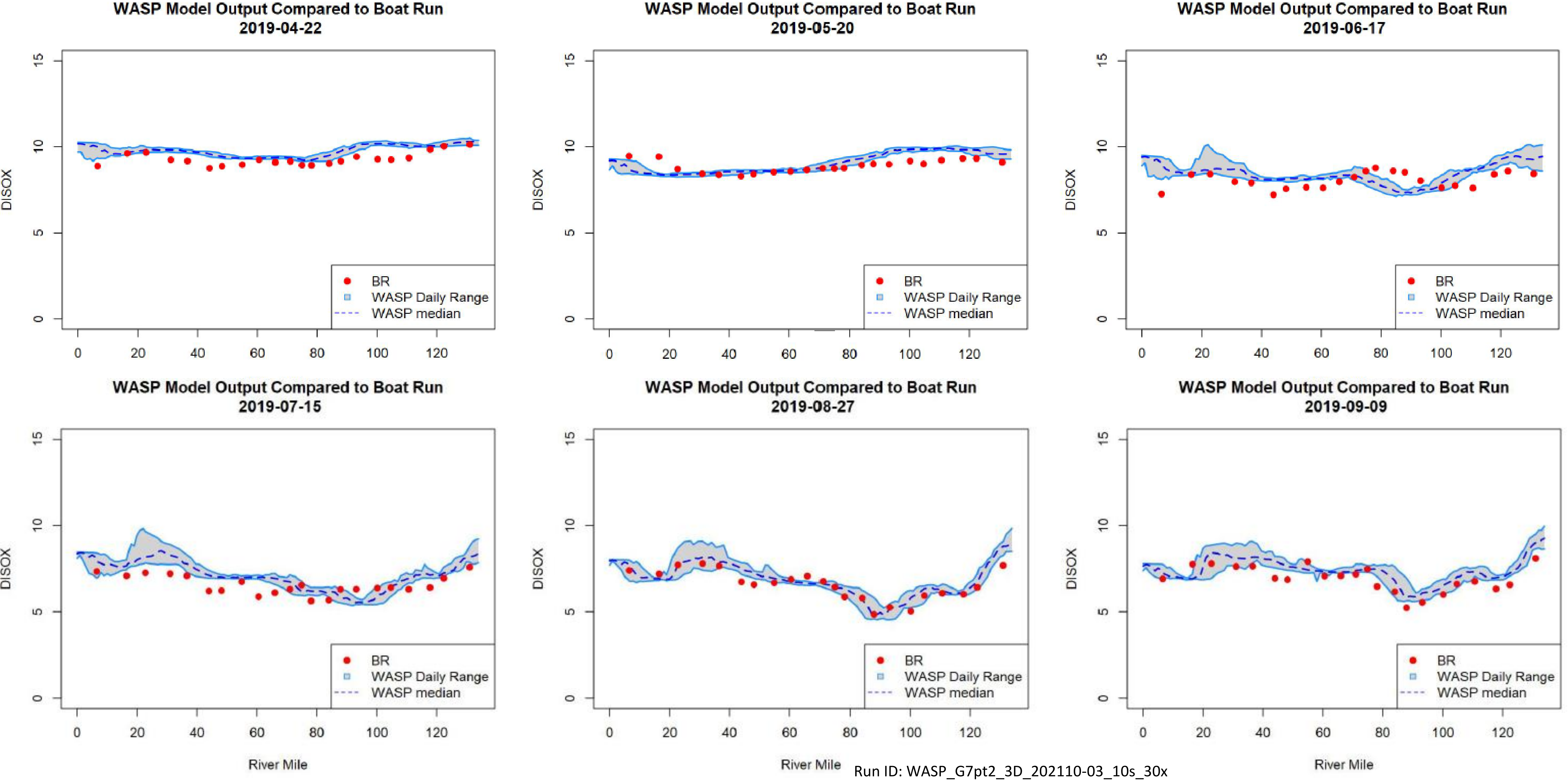
Model-Data Comparison of Dissolved Oxygen at 22 Boat-Run Stations



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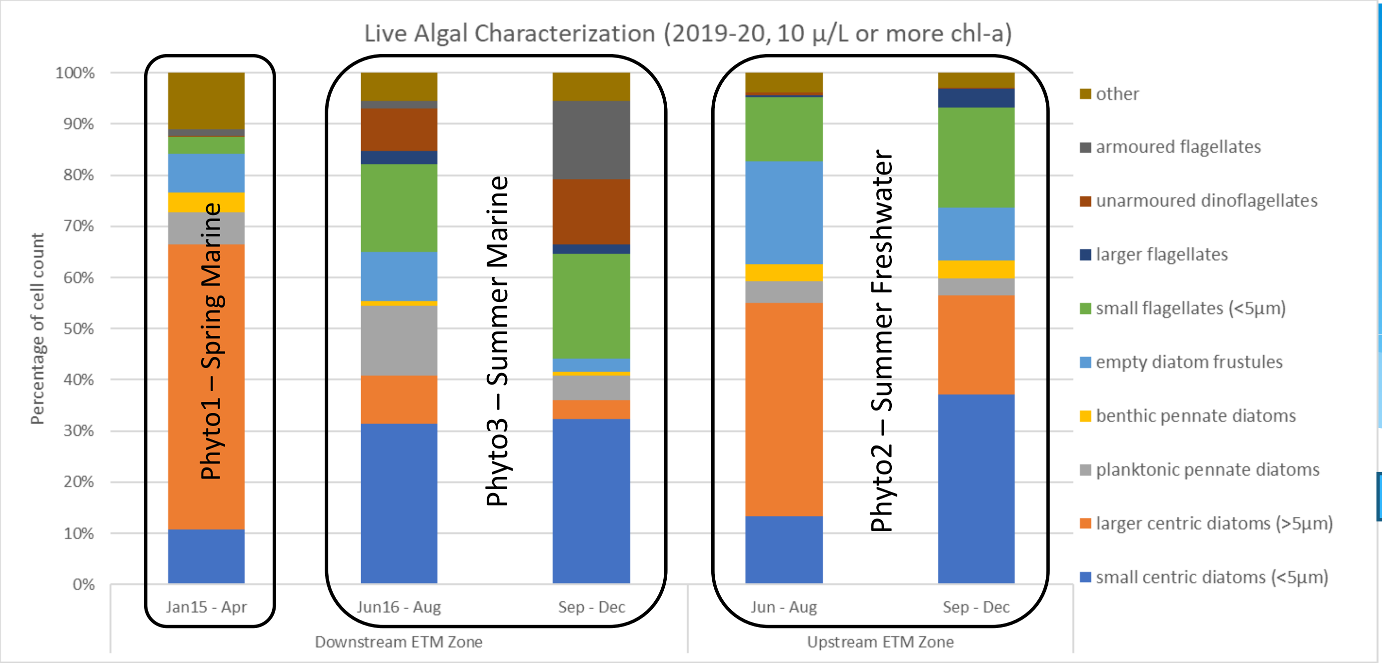
Phytoplankton Conceptual Model



Model SV	Phytoplankton Class ID	Description	Seasonal Peak	Geographic Peak
Phyto1	Spring Marine	Winter / Spring marine phyto community	Mid-Jan – mid-April	Elbow of Crossledge Shoal (RM 22.75)
Phyto2	Summer Freshwater	Summer freshwater phyto community	June – August	Eddystone (RM 84)
Phyto3	Summer Marine	Summer marine phyto community	Mid-June – August	Elbow of Crossledge Shoal (RM 22.75)

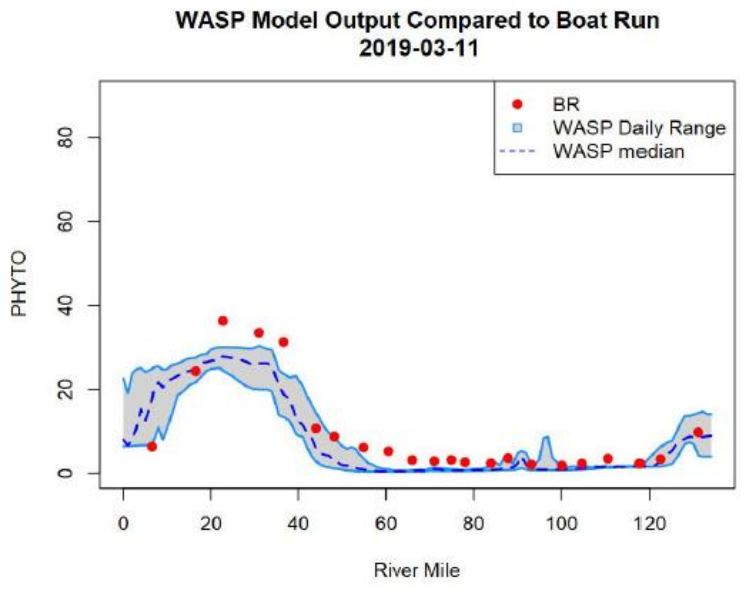
	Phyto1	Phyto2	Phyto3
Growing Season	1-Feb	15-Apr	16-Jun
	7-Apr	31-Aug	31-Aug
Peak Date	5-Mar	23-Jun	24-Jul
Median temp. on peak date, 2010-2019	3.2	24.8	27.9
Average daily temp over season, 2010-2019	4.3	22.5	26.3

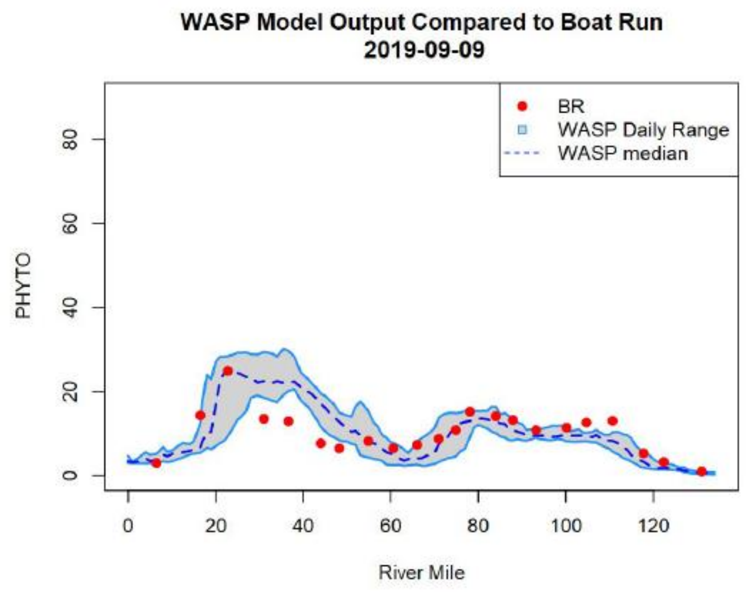
Model-Data Comparison of Total Phytoplankton at 22 Boat-Run Stations

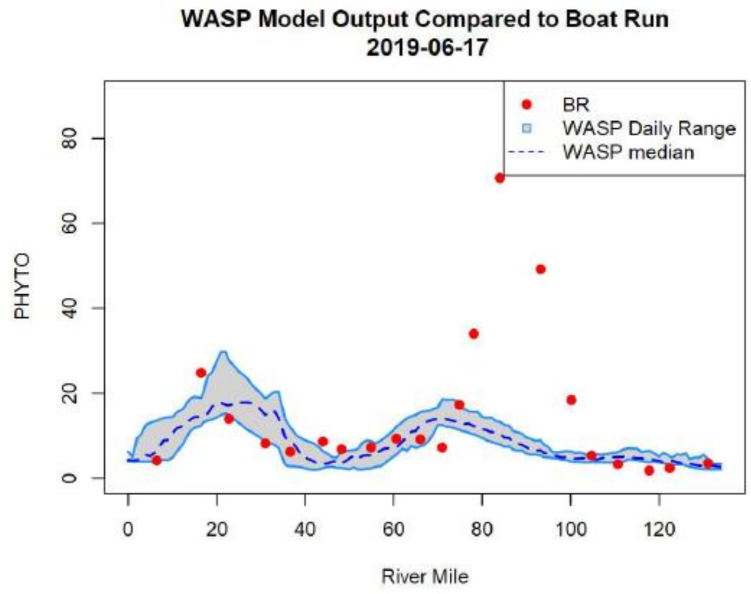
Spring growing season

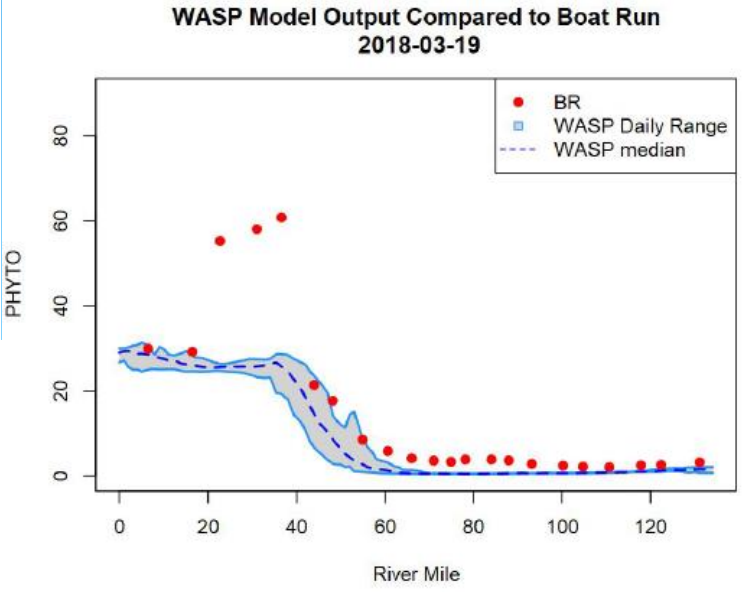
Summer growing season

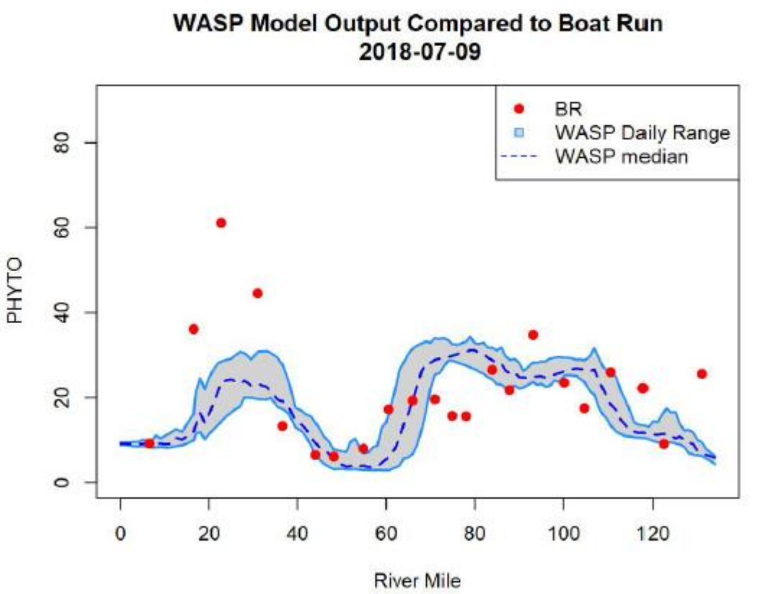
Summer growing season

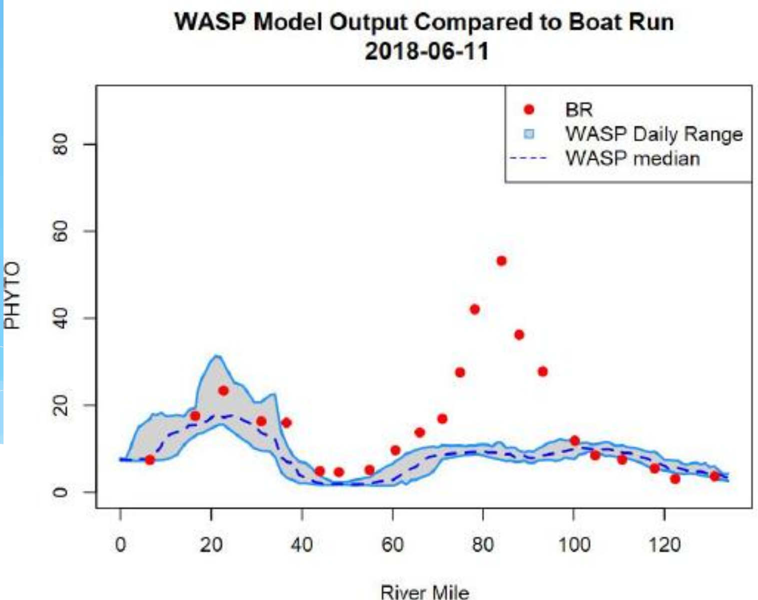




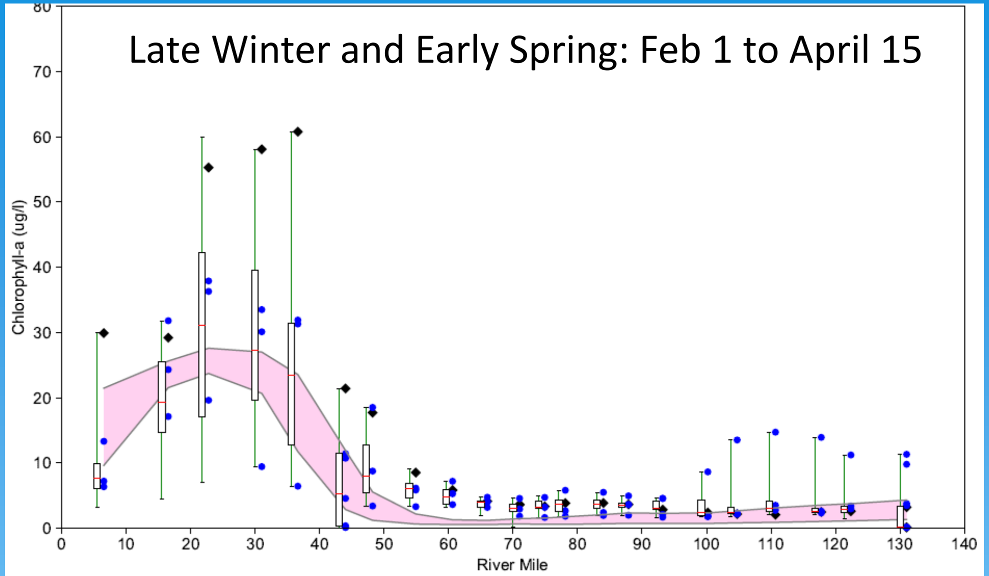


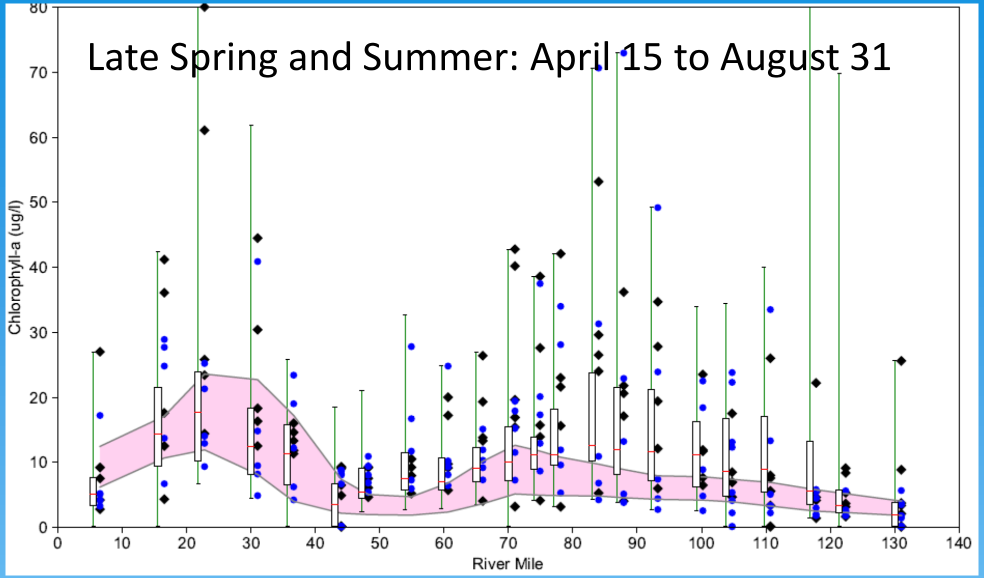


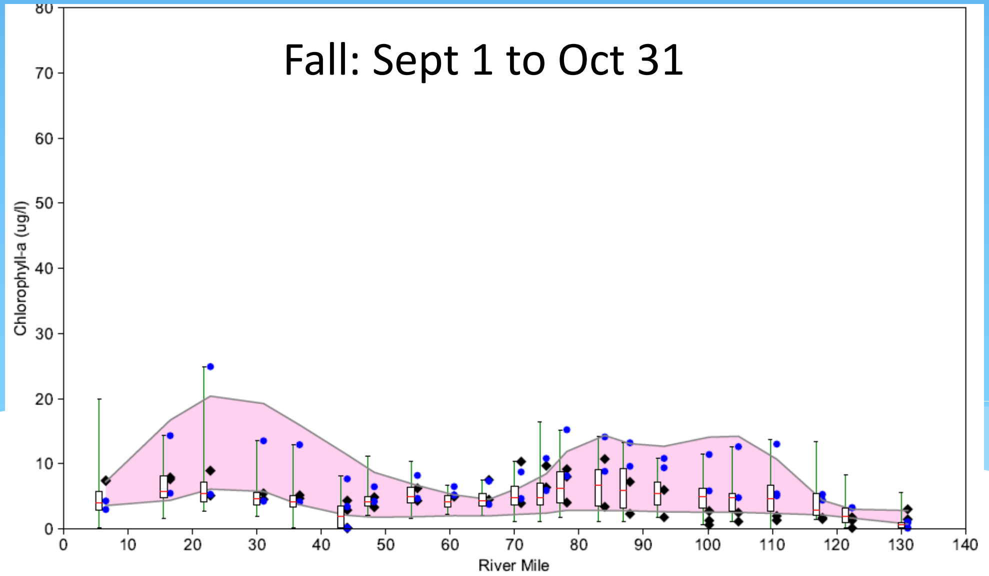


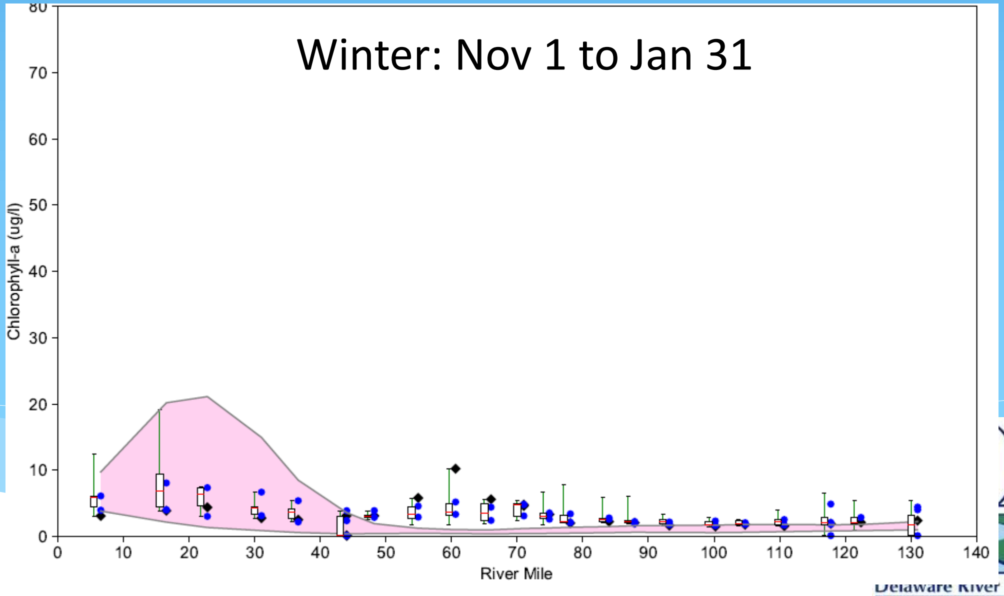


Seasonal Variation of PHYTO with Recent 10-year Data









◆ Data (2018) ● Data (2019)

The symbols next to the box represent data from 2018 and 2019
The shaded area represent model results between the 25 and 75 percentile.
The un-colored box was based on 10-year boat-run data.

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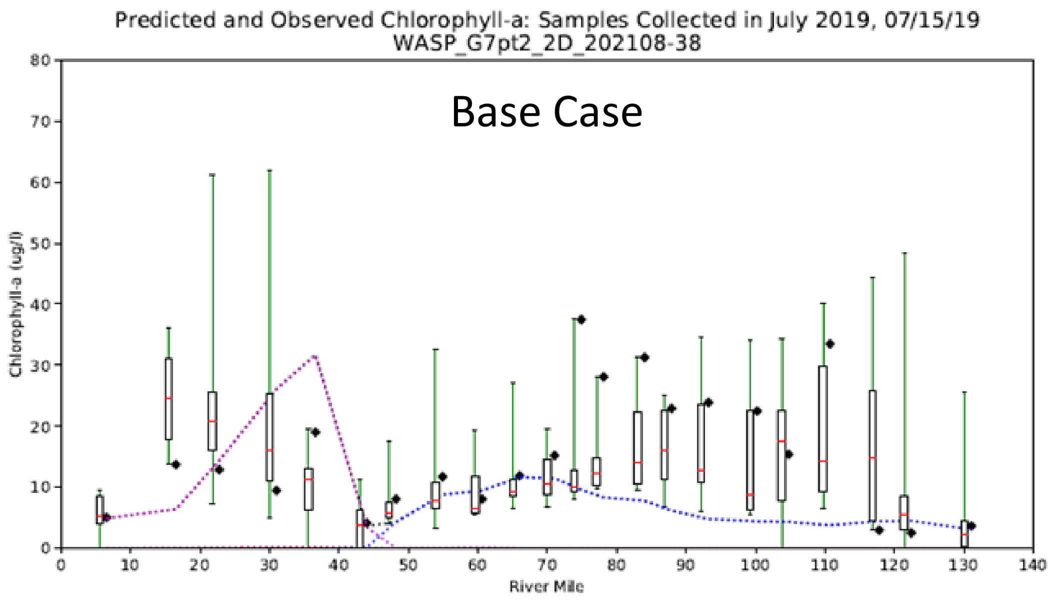
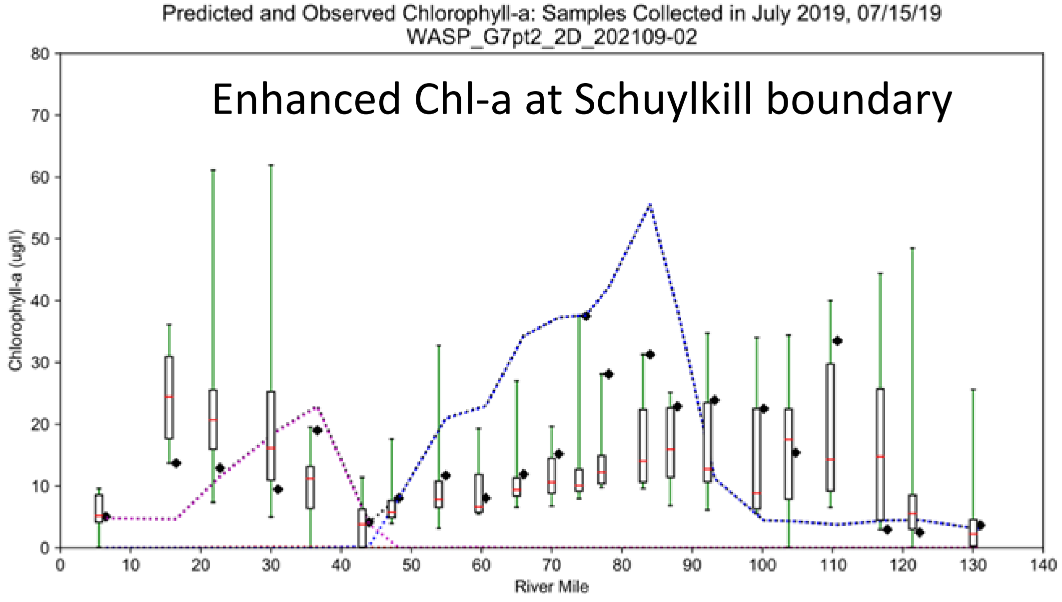
Phytoplankton Summary
(slide 1 of 2)

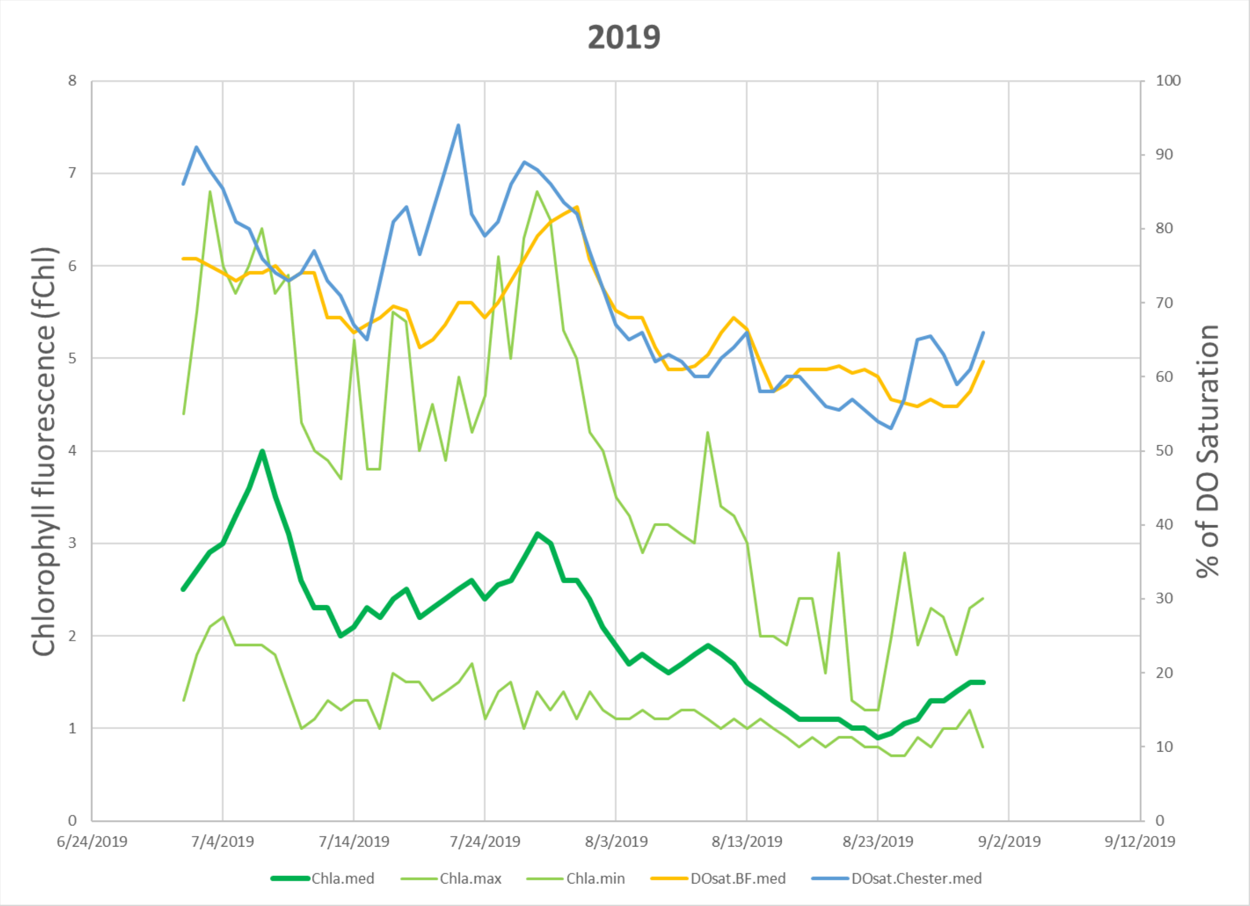
- Spatial and seasonal trends captured reasonably well
- Transient blooms in urban estuary are often missed
  - Not a calibration issue
  - Appear to be caused by bloom seed from tributaries





Phytoplankton Summary
(slide 2 of 2)

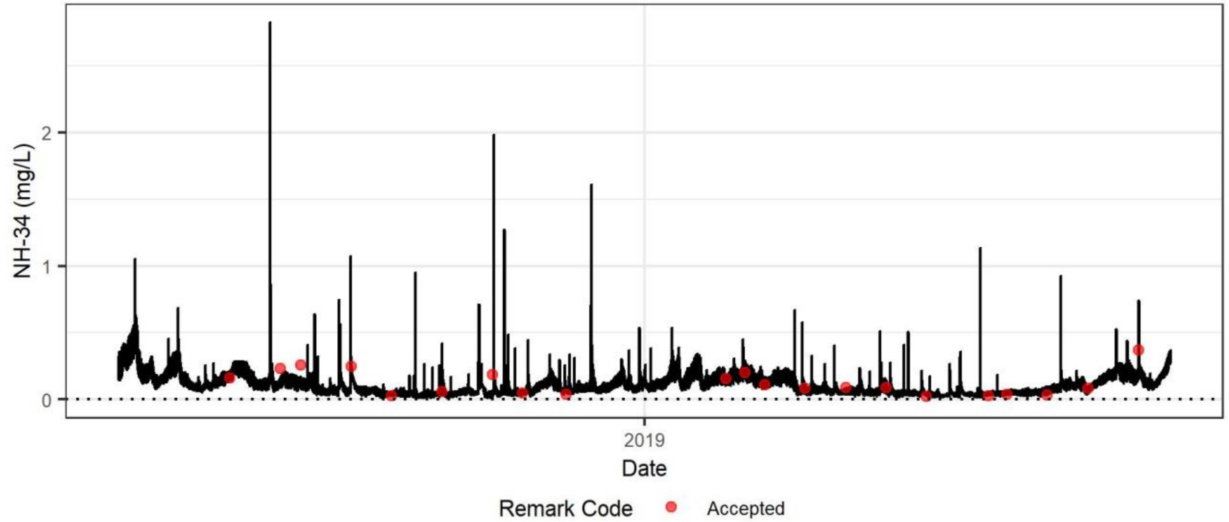
- The most critical DO events in urban estuary occur when phytoplankton does not bloom
  - Phytoplankton impact dissolved oxygen
    - Long time scale
      - Contributes to SOD (lower DO)
    - Short-term
      - Net increase from photosynthesis

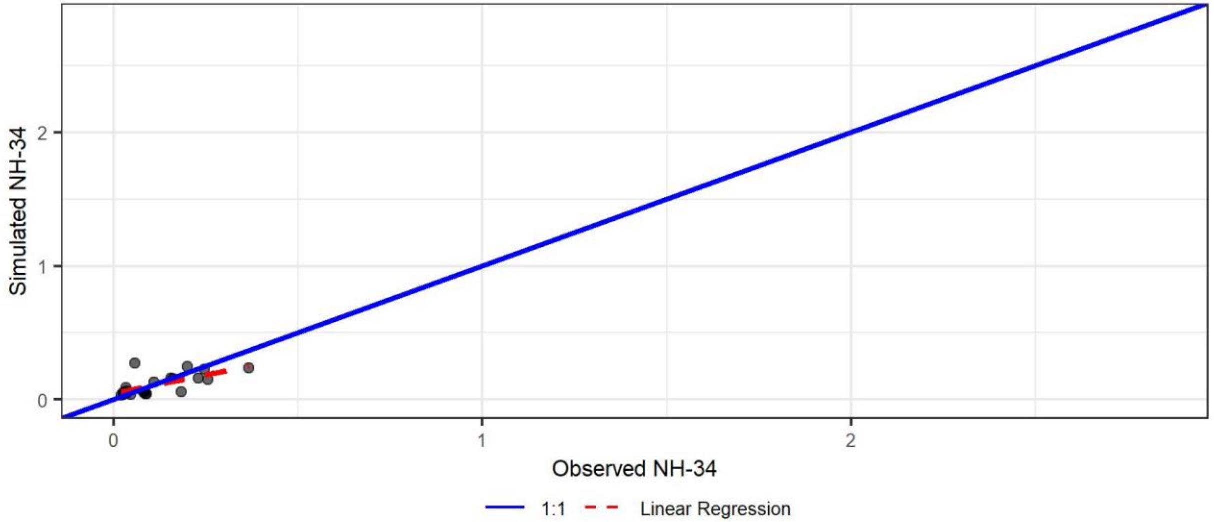


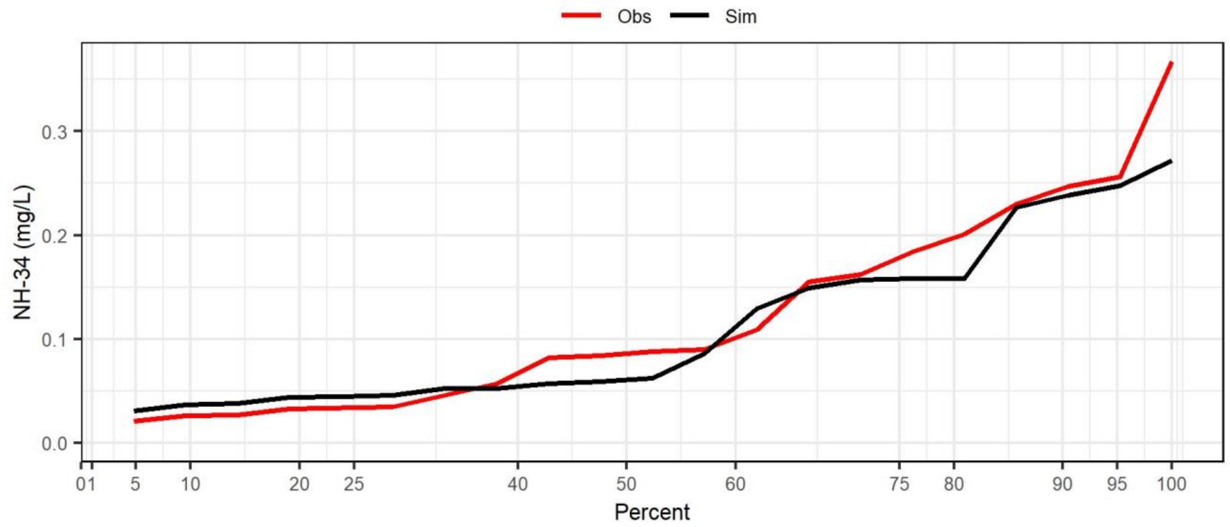
Ammonia Nitrogen at Boat-Run Station @ Benjamin Franklin Bridge

Benjamin Franklin Bridge (RM 100.2)

Parameter: NH-34







Dataset	10%	20%	50%	80%	90%	Average
OBS	0.03	0.04	0.09	0.20	0.25	0.121
SIM	0.04	0.04	0.06	0.16	0.24	0.112

GoF Metric	Value
Num Obs	21.0000
R2	0.4485
NSE	0.4126
RMSE	0.0719
NRMSE %	20.8000
d	0.8115

(Calib Station: 31DELRBC-WQX-892071; WASP Seg: 1281)

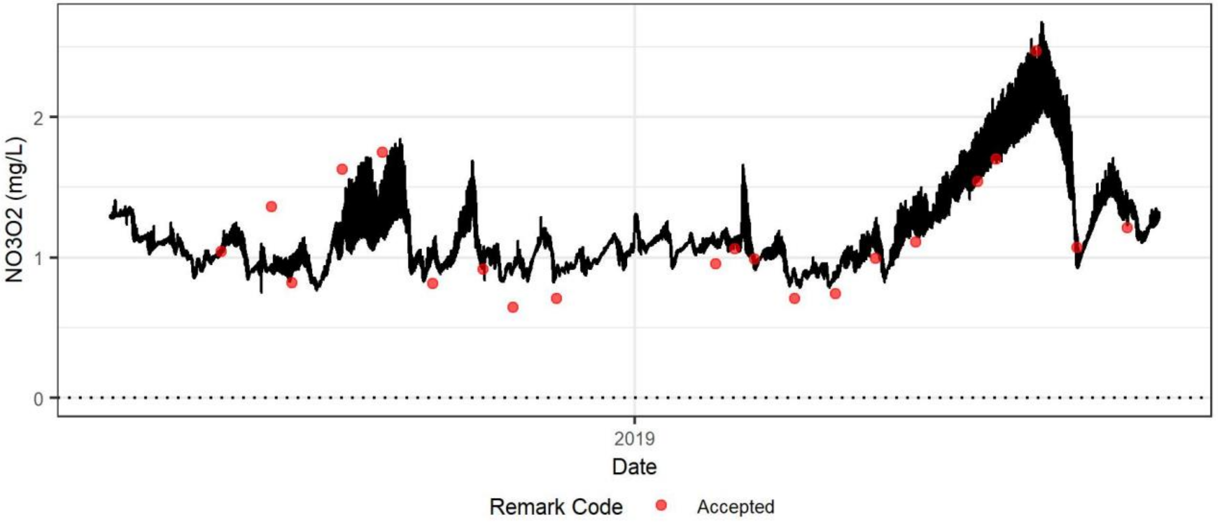
UNITED STATES OF AMERICA

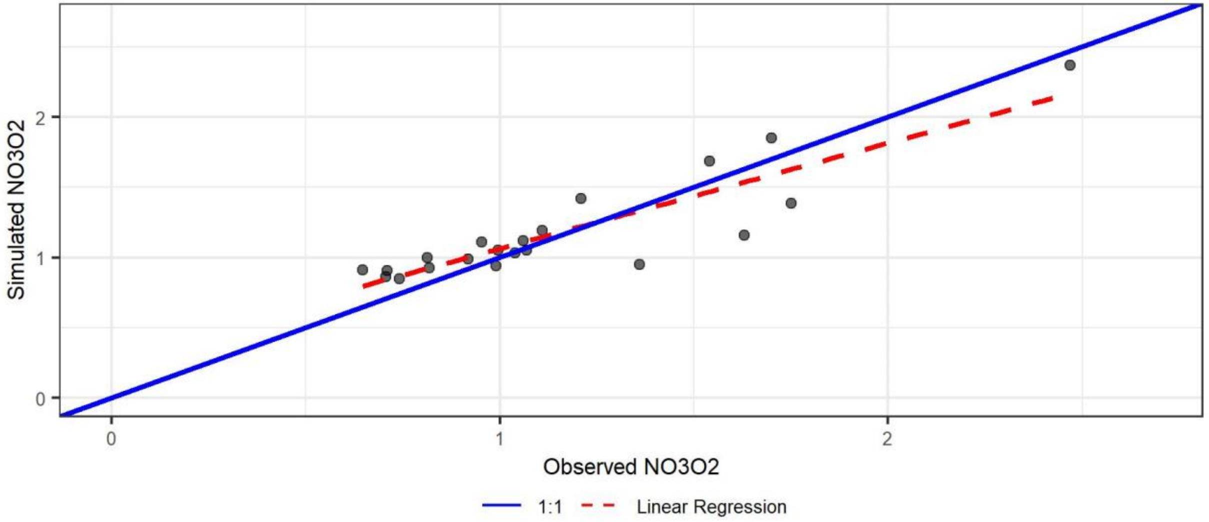
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

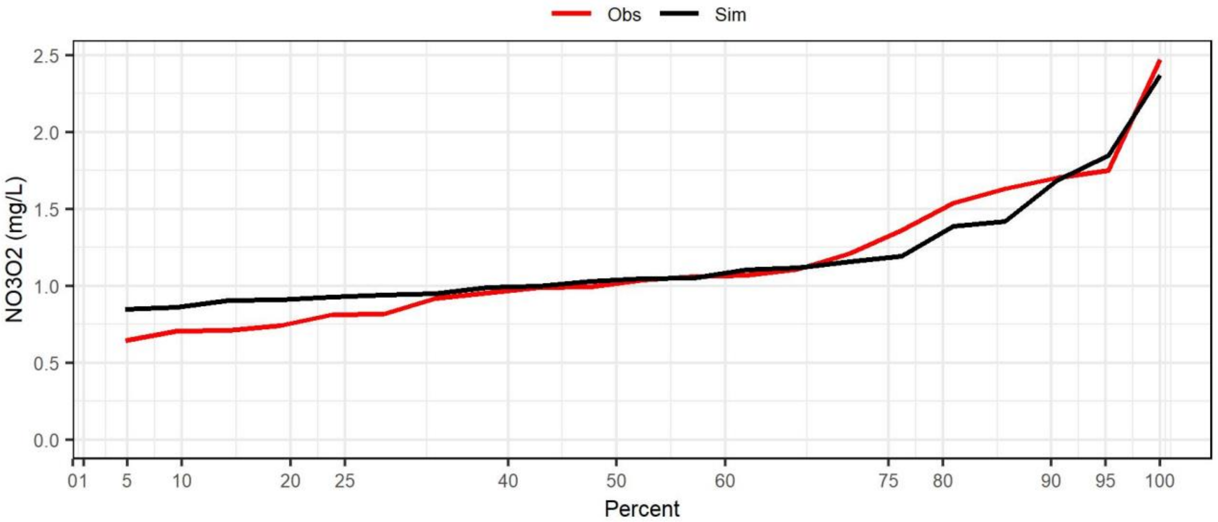
Nitrate Nitrogen at Boat-Run Station @ Benjamin Franklin Bridge

Benjamin Franklin Bridge (RM 100.2)

Parameter: NO3O2







Dataset	10%	20%	50%	80%	90%	Average
OBS	0.71	0.81	1.04	1.54	1.70	1.154
SIM	0.91	0.93	1.05	1.39	1.68	1.179

GoF Metric	Value
Num Obs	21.0000
R2	0.7940
NSE	0.7886
RMSE	0.2016
NRMSE %	11.1000
d	0.9353

(Calib Station: 31DELRBC-WQX-892071; WASP Seg: 1281)

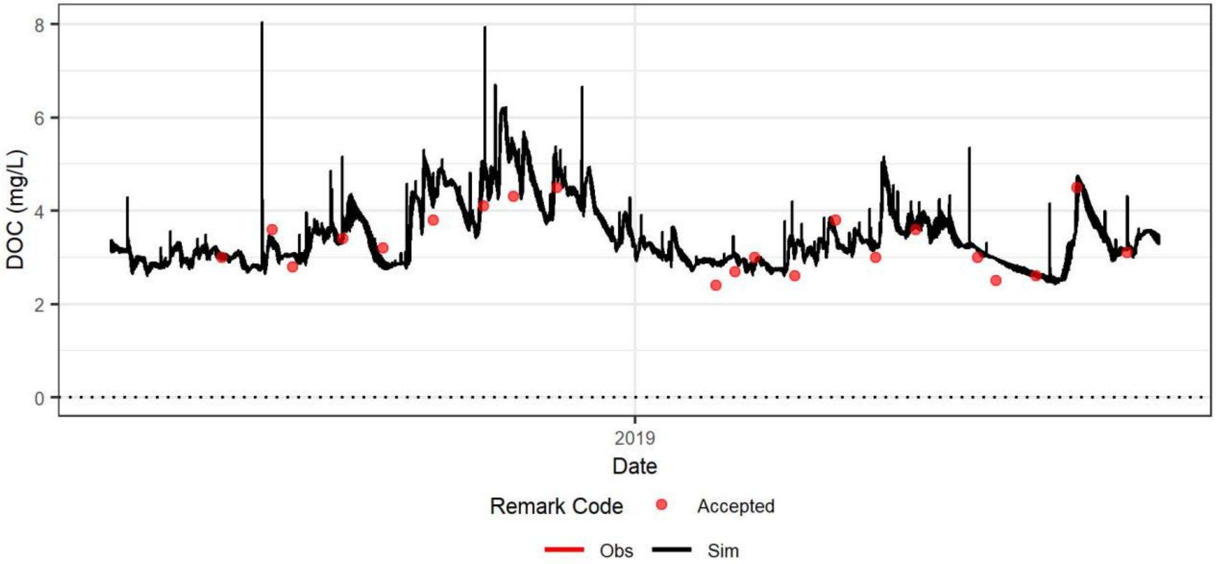
UNITED STATES OF AMERICA

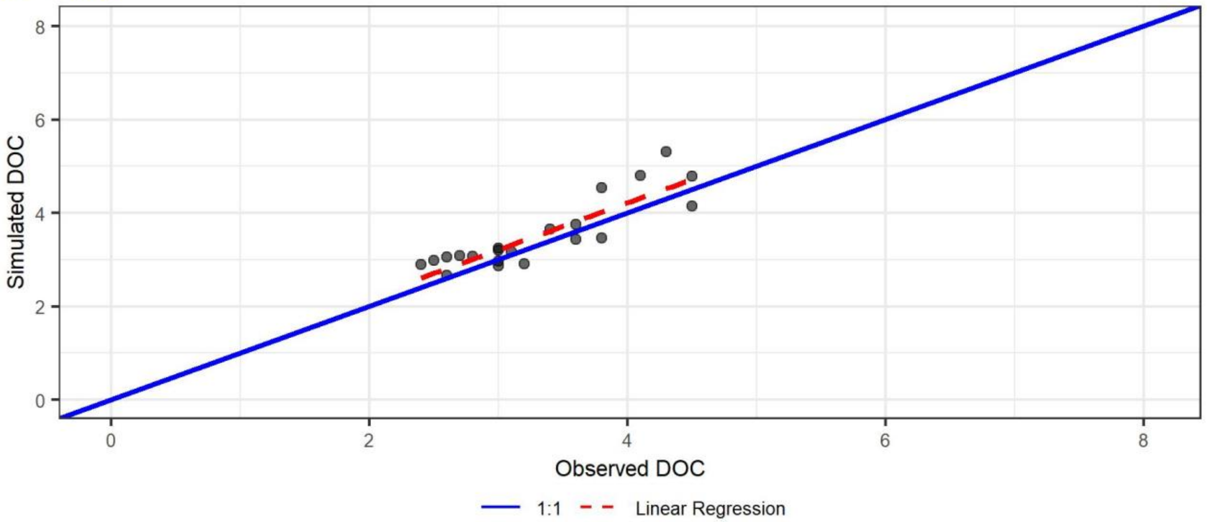
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

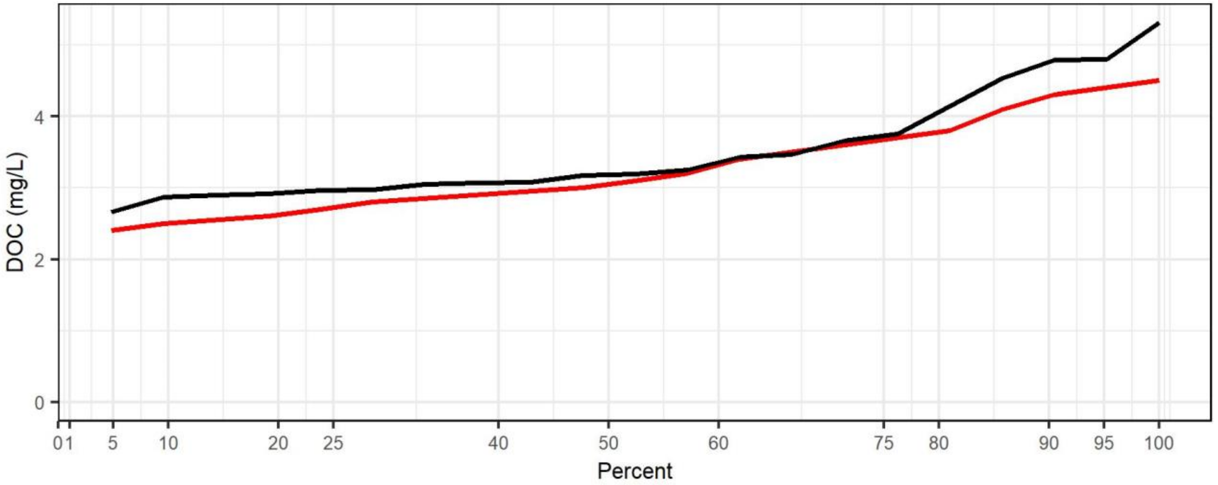
Dissolved Organic Carbon at Boat-Run Station @ Benjamin Franklin Bridge

Benjamin Franklin Bridge (RM 100.2)

Parameter: DOC







Dataset	10%	20%	50%	80%	90%	Average
OBS	2.6	2.70	3.1	3.80	4.30	3.310
SIM	2.9	2.97	3.2	4.15	4.79	3.524

GoF Metric	Value
Num Obs	21.0000
R2	0.7697
NSE	0.5854
RMSE	0.4135
NRMSE %	19.7000
d	0.9066

(Calib Station: 31DELRBC-WQX-892071; WASP Seg: 1281)

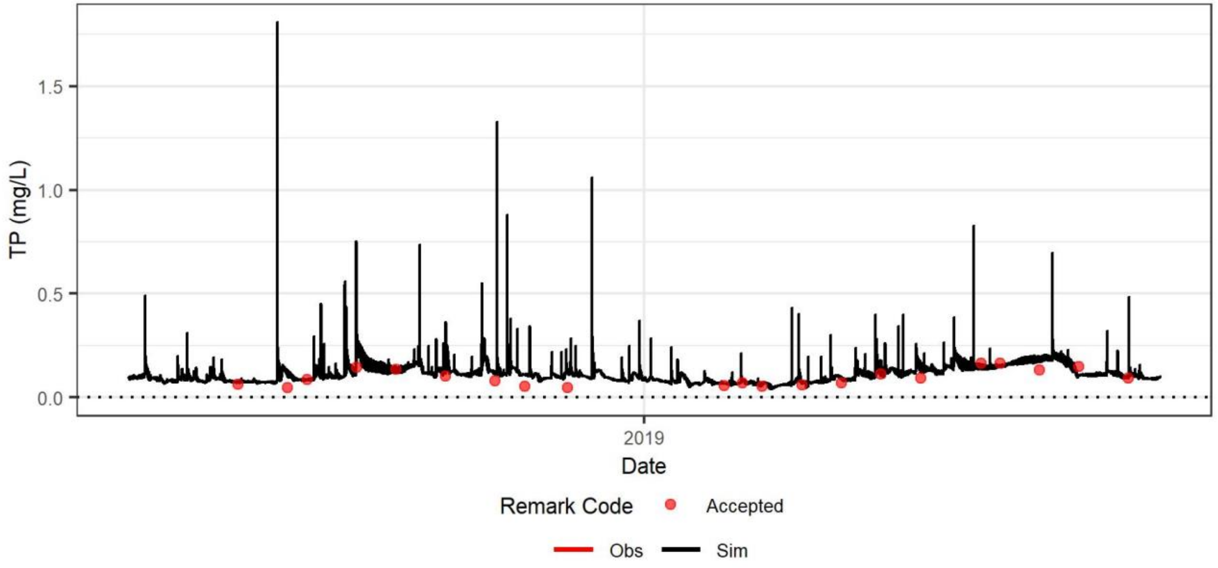
UNITED STATES OF AMERICA

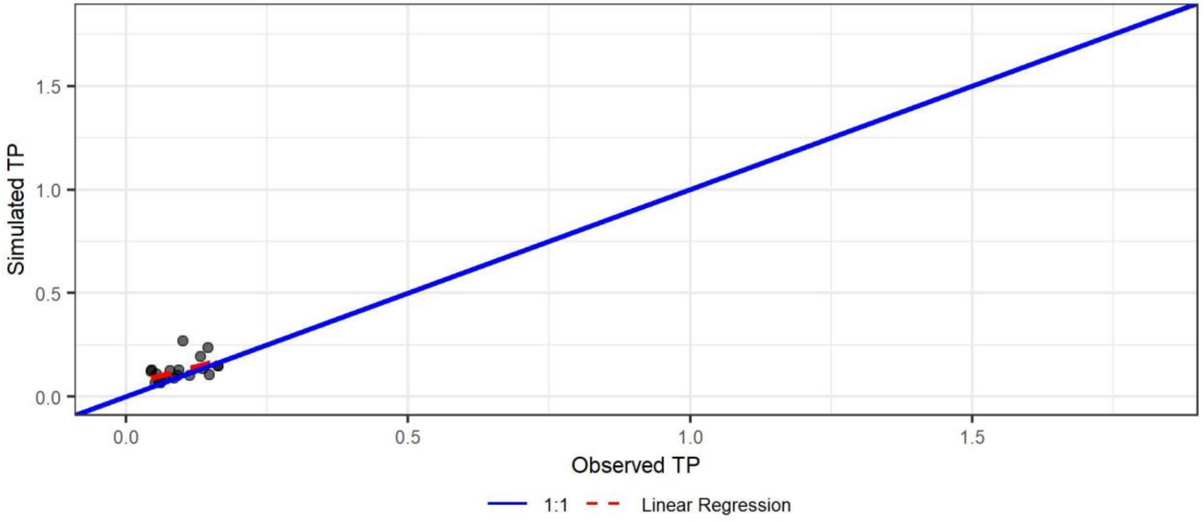
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

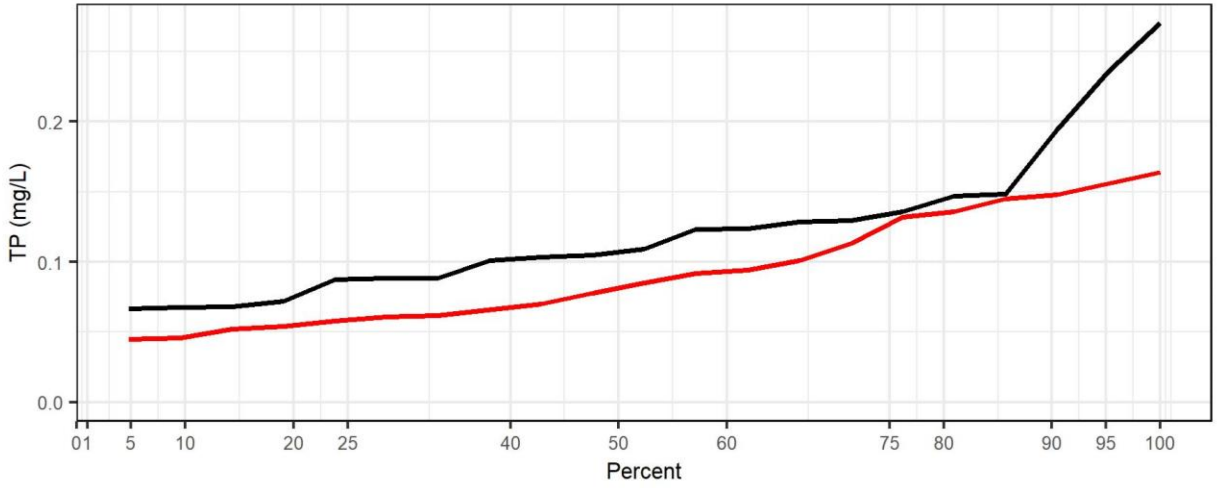
Total Phosphorus at Boat-Run Station @ Benjamin Franklin Bridge

Benjamin Franklin Bridge (RM 100.2)

Parameter: TP







Dataset	10%	20%	50%	80%	90%	Average
OBS	0.05	0.06	0.09	0.14	0.15	0.094
SIM	0.07	0.09	0.11	0.15	0.19	0.124

GoF Metric	Value
Num Obs	21.0000
R2	0.2668
NSE	-1.0006
RMSE	0.0551
NRMSE %	46.3000
d	0.6235

(Calib Station: 31DELRBC-WQX-892071; WASP Seg: 1281)

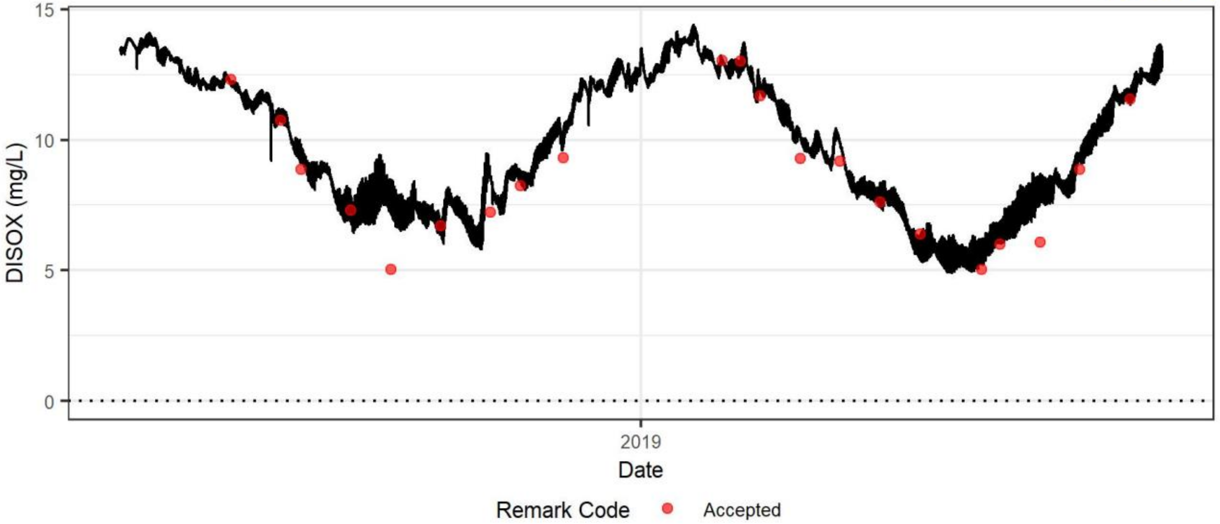
UNITED STATES OF AMERICA

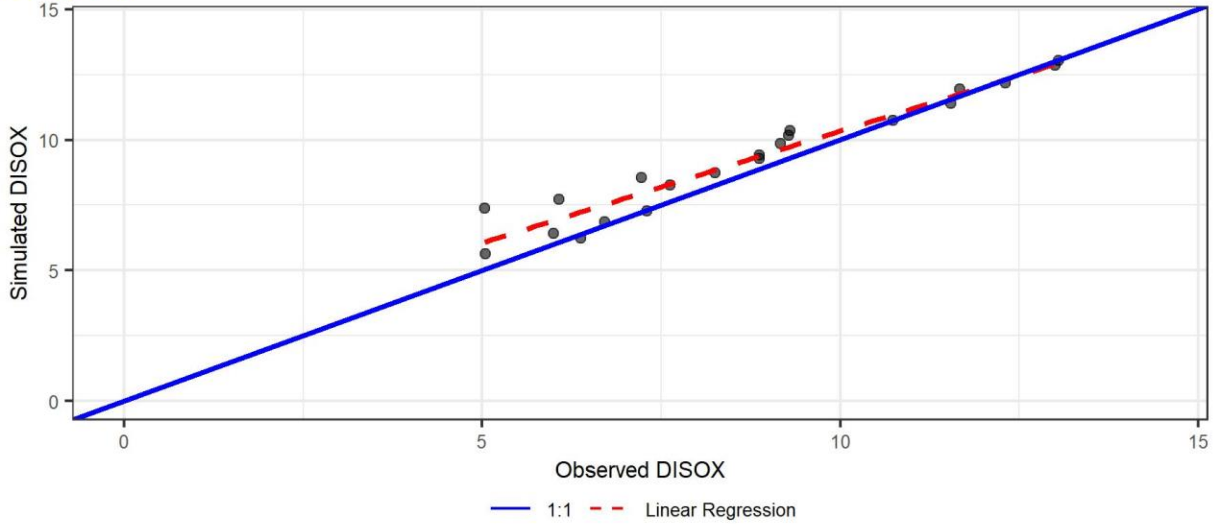
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

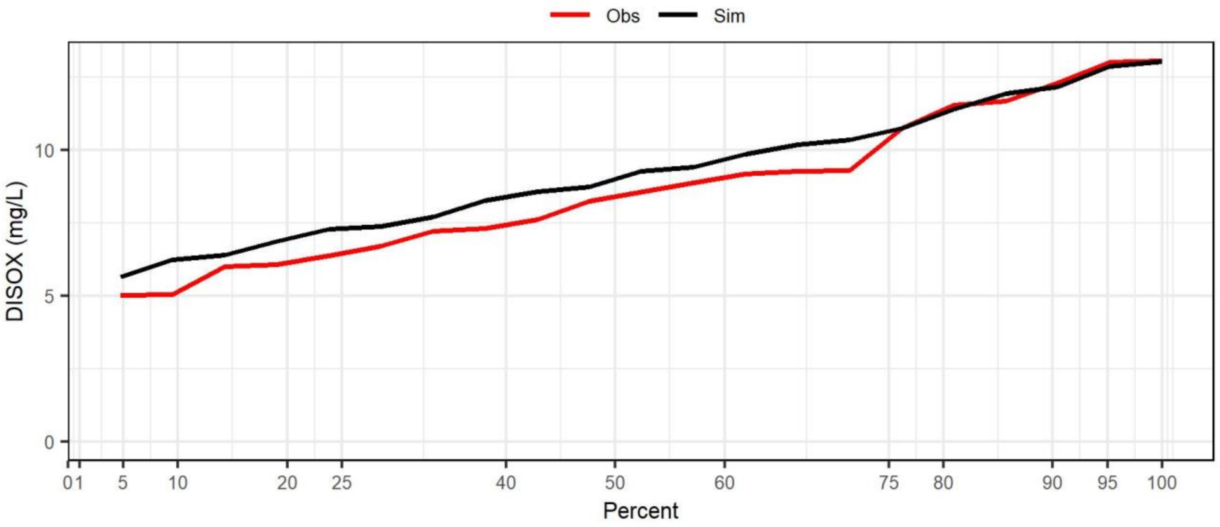
Dissolved Oxygen at Boat-Run Station @ Benjamin Franklin Bridge

Benjamin Franklin Bridge (RM 100.2)

Parameter: DISOX







Dataset	10%	20%	50%	80%	90%	Average
OBS	6.00	6.38	8.87	11.55	12.31	8.735
SIM	6.41	7.29	9.28	11.40	12.18	9.255

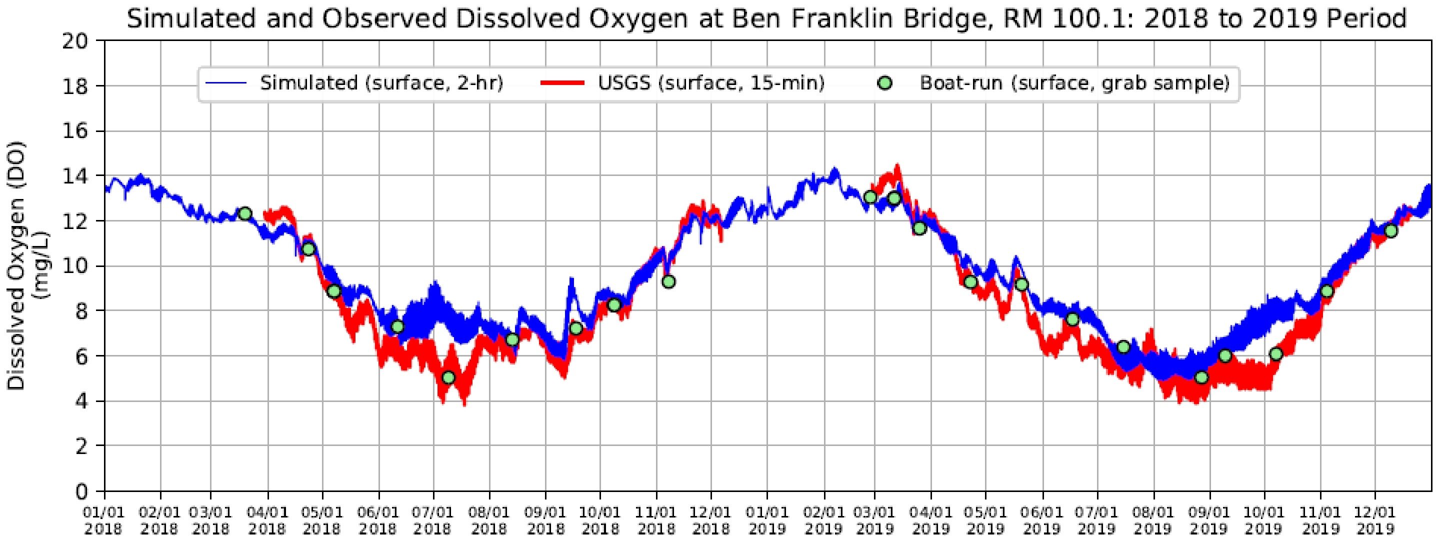
GoF Metric	Value
Num Obs	21.0000
R2	0.9415
NSE	0.8891
RMSE	0.8234
NRMSE %	10.3000
d	0.9686

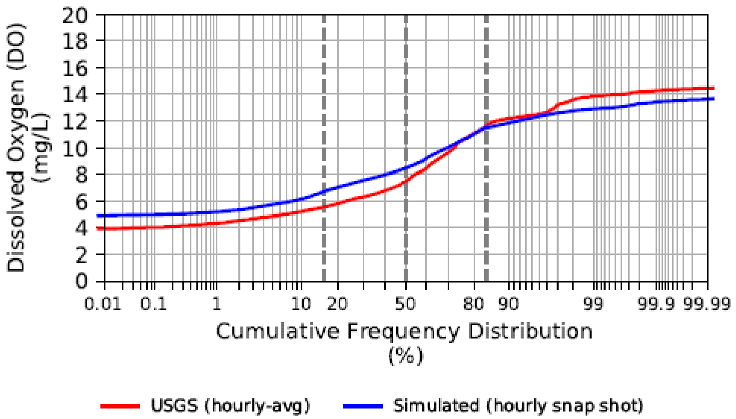
(Calib Station: 31DELRBC-WQX-892071; WASP Seg: 1281)

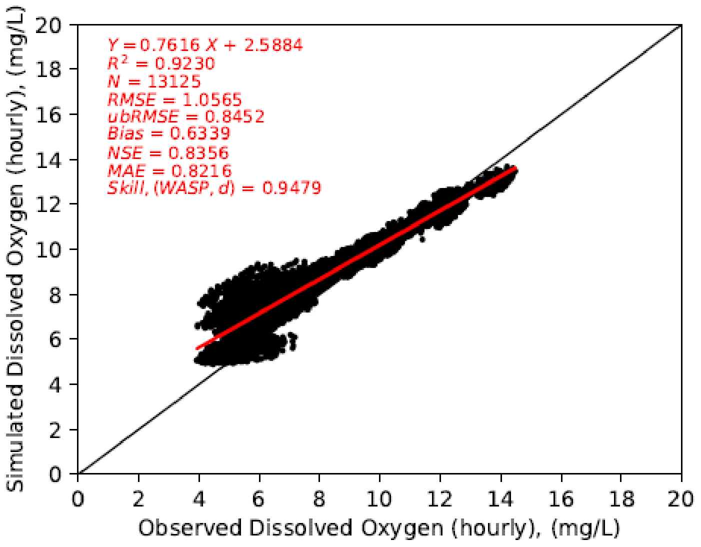
UNITED STATES OF AMERICA

Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Dissolved Oxygen at USGS Station @ Benjamin Franklin Bridge







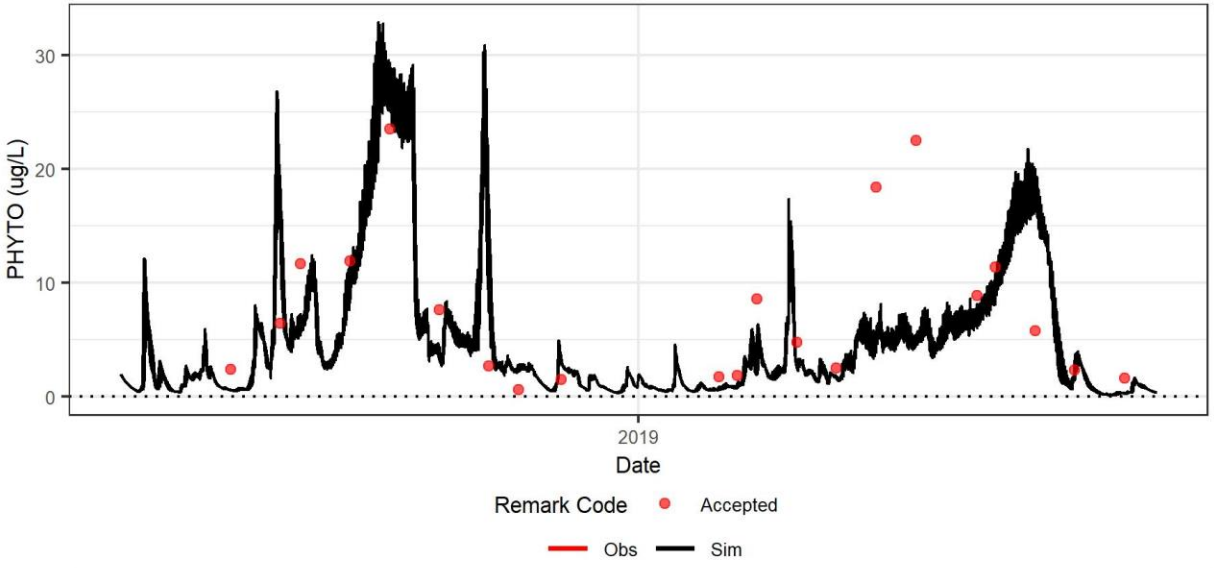
Simulated and Observed Dissolved Oxygen at Ben Franklin Bridge, RM 100.1

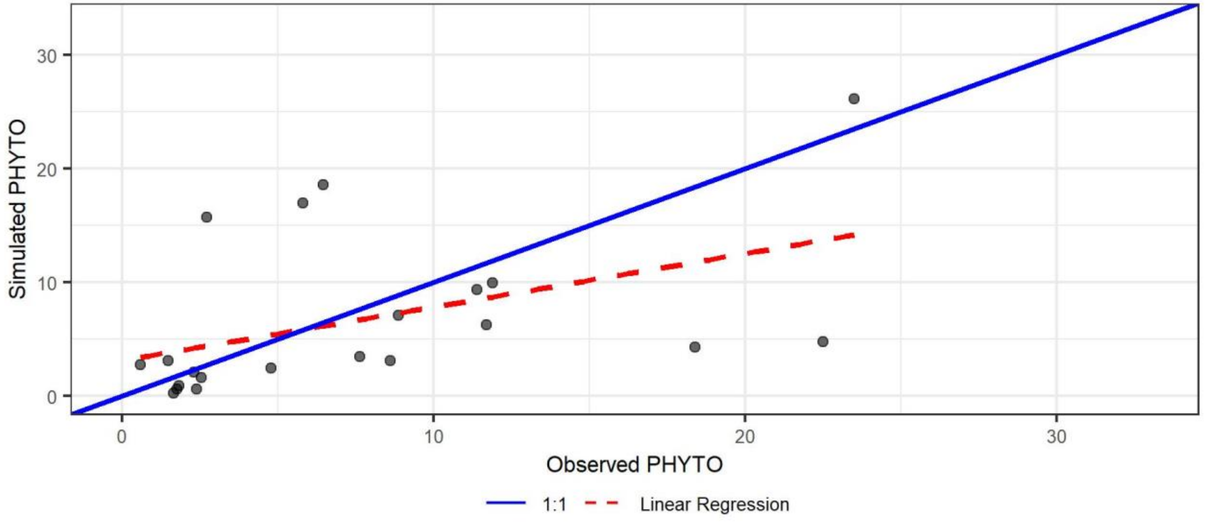
Boat run samples were collected at RM 100.2 close to USGS station.
USGS (01467200) 15-min continuous data were used in this analysis.
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

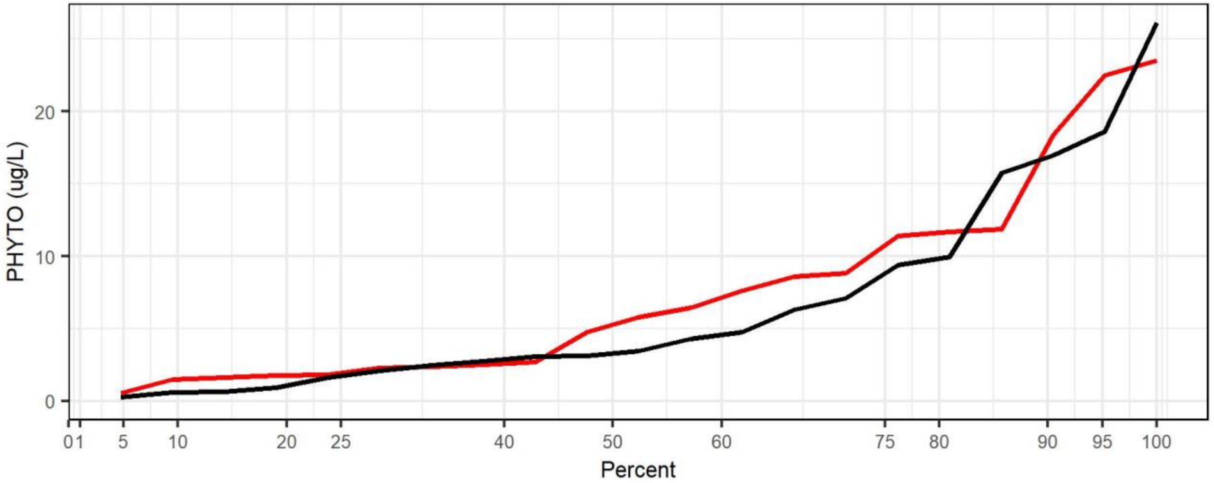
Phytoplankton at Boat-Run Station @ Benjamin Franklin Bridge

Benjamin Franklin Bridge (RM 100.2)

Parameter: PHYTO

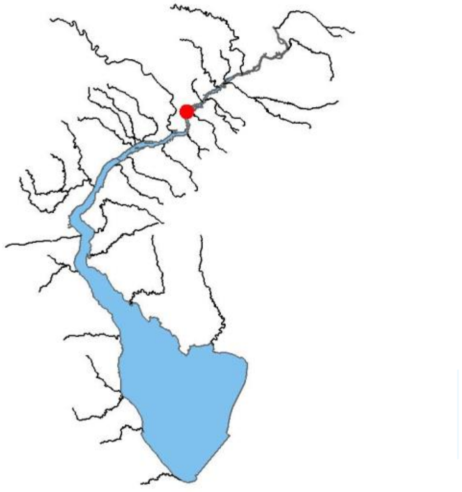






Dataset	10%	20%	50%	80%	90%	Average
OBS	1.64	1.83	5.81	11.70	18.40	7.561
SIM	0.63	1.64	3.47	9.95	16.98	6.686

GoF Metric	Value
Num Obs	21.0000
R2	0.2107
NSE	-0.1264
RMSE	7.1410
NRMSE %	31.2000
d	0.6927

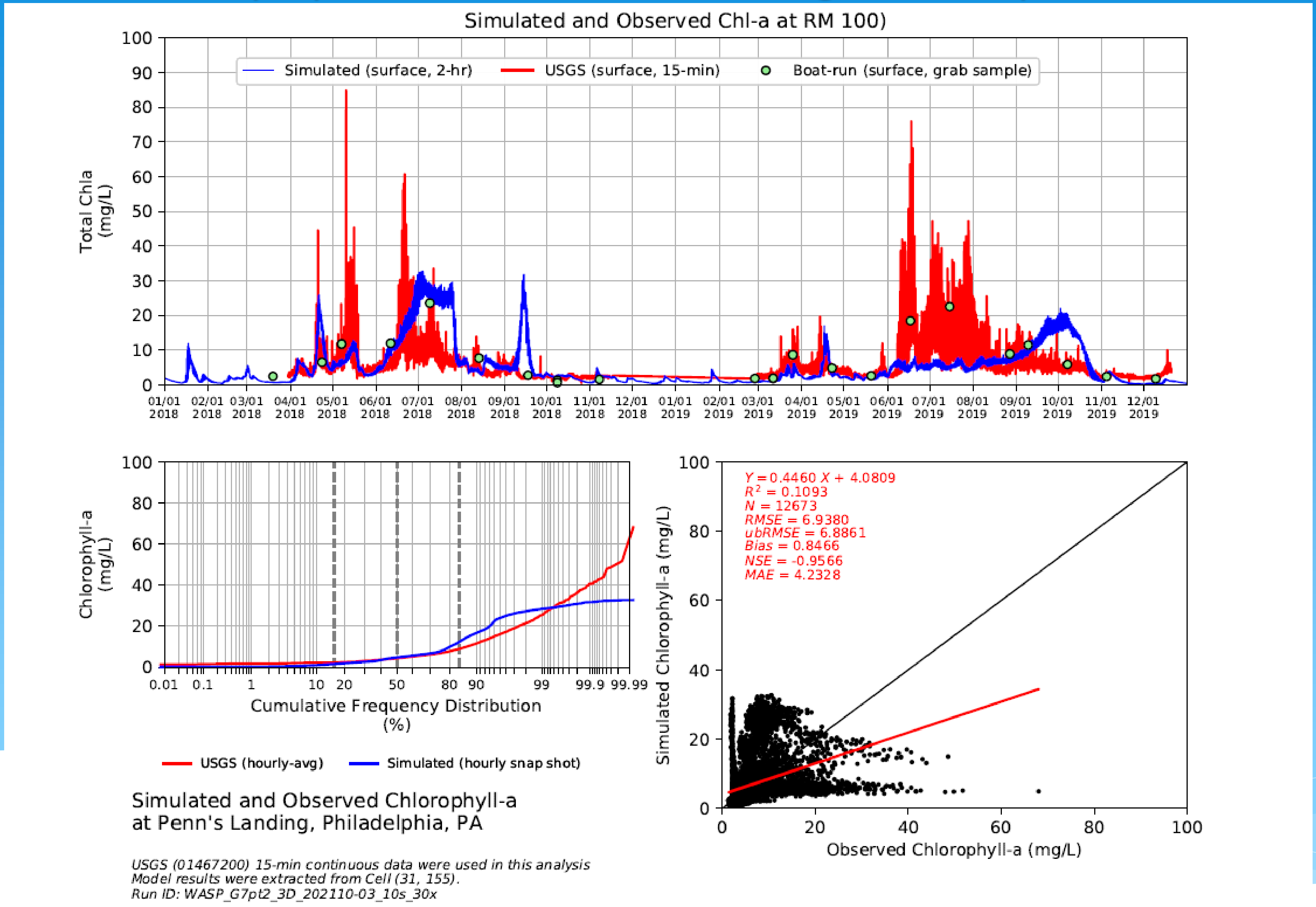


(Calib Station: 31DELRBC-WQX-892071; WASP Seg: 1281)

UNITED STATES OF AMERICA

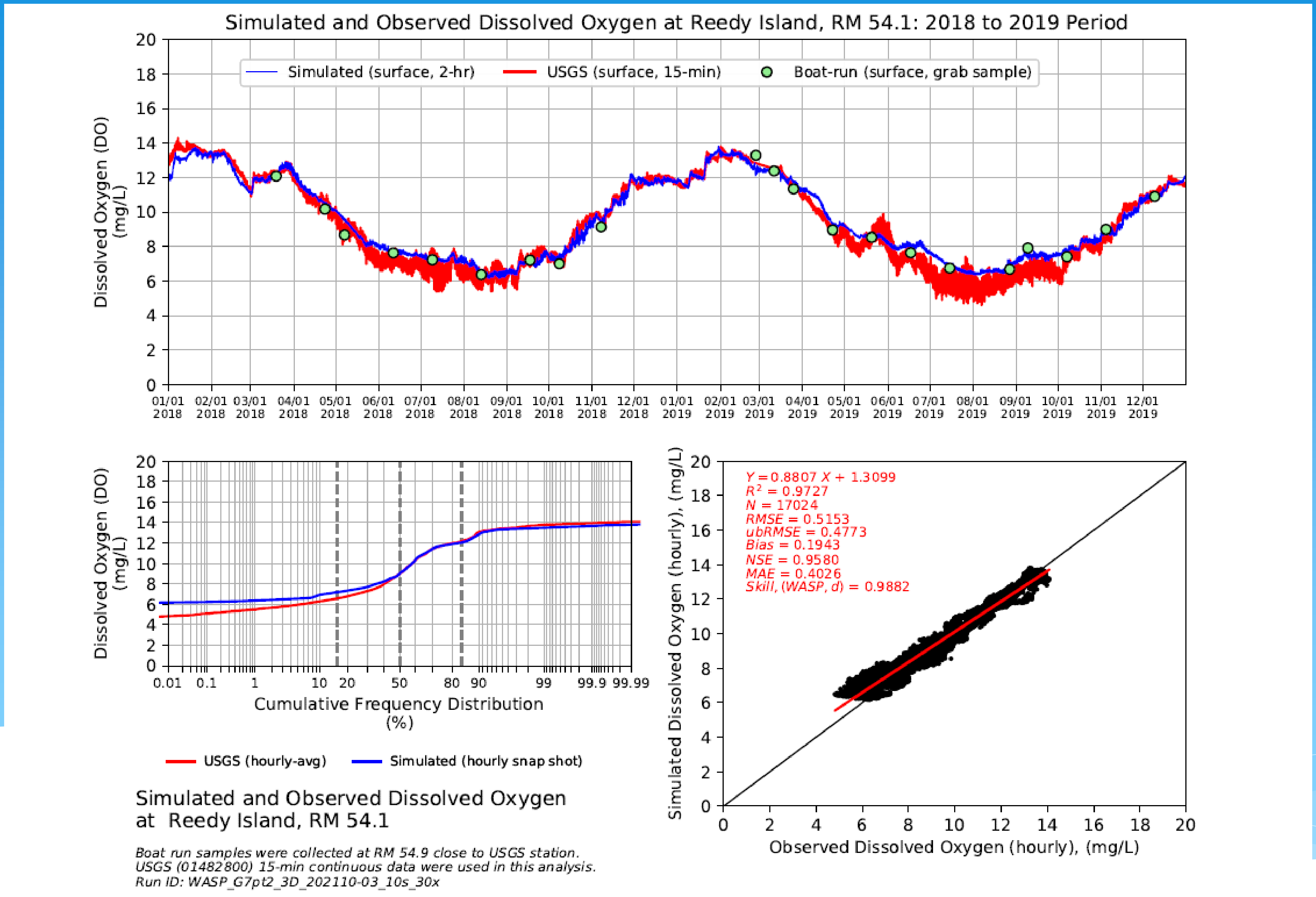
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Phytoplankton at Penn's Landing, Philadelphia



Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Dissolved Oxygen at USGS Station @ Reedy Island



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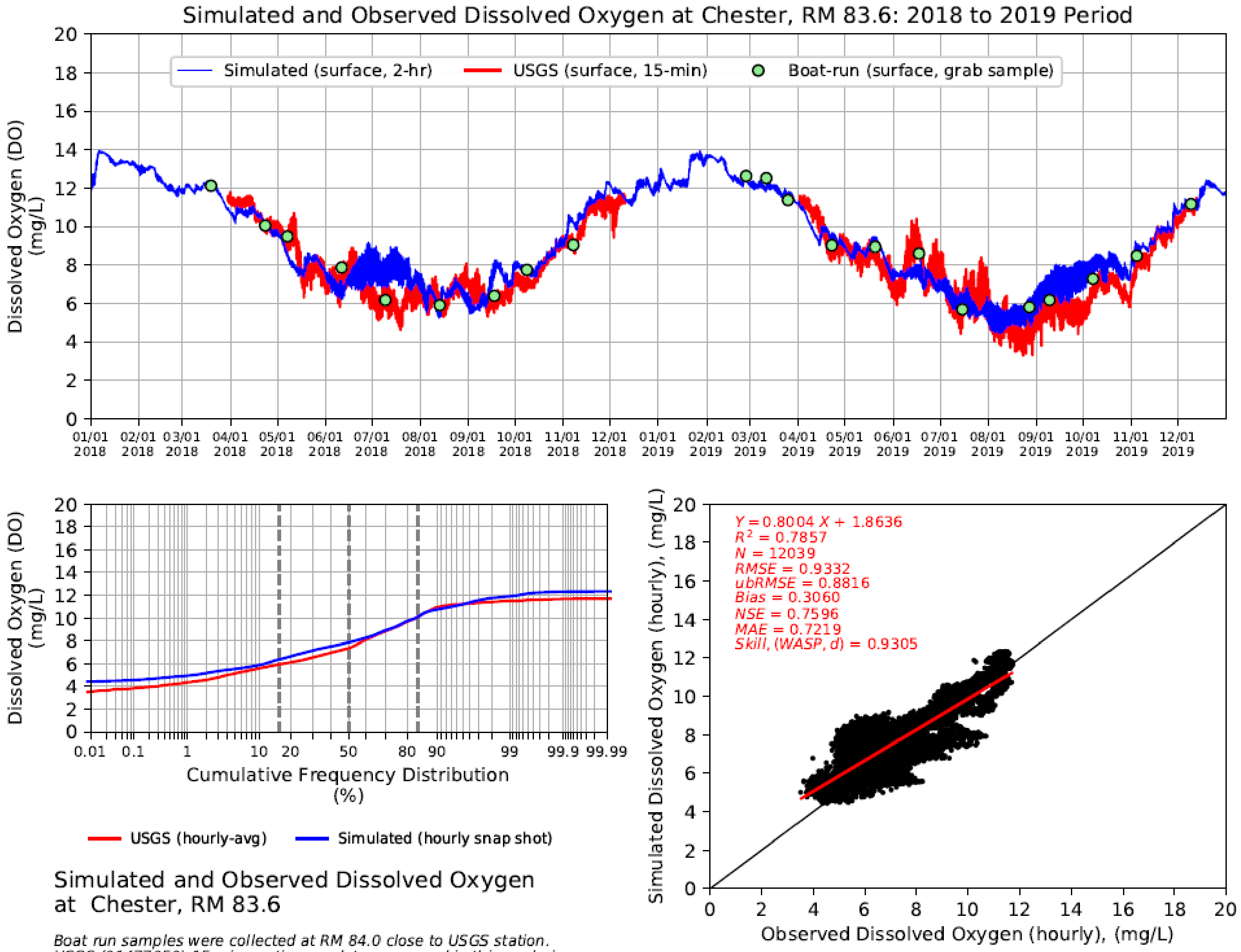
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Dissolved Oxygen at USGS Station @ Chester



Simulated and Observed Dissolved Oxygen at Chester, RM 83.6

Boat run samples were collected at RM 84.0 close to USGS station.
USGS (01477050) 15-min continuous data were used in this analysis.
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

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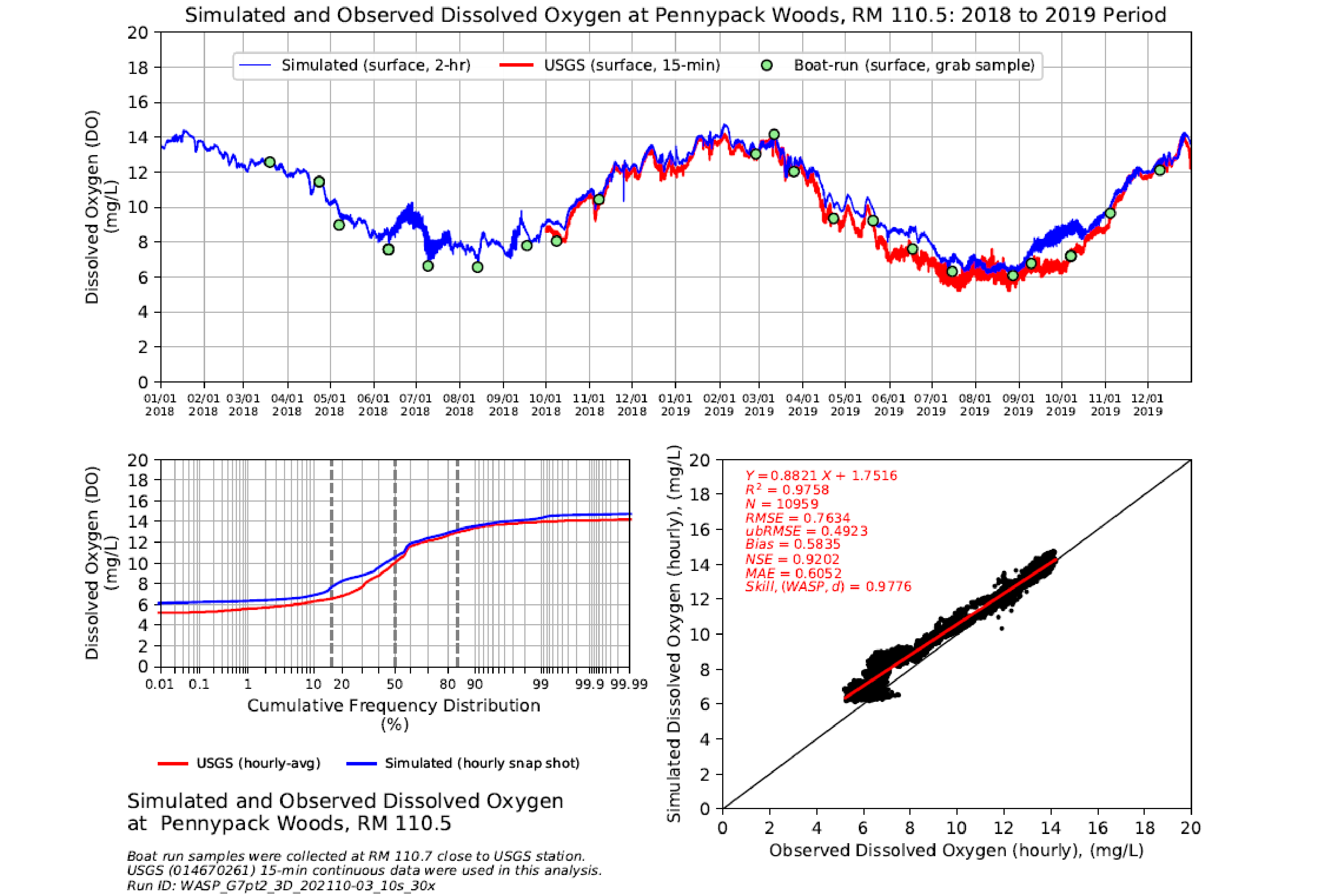
Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Dissolved Oxygen at USGS Station near Pennypack Woods



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Run ID: WASP_G7pt2_3D_202110-03_10s_30x

Dissolved Oxygen Component Analysis

- ❑Diagnostic plots of DO gain and loss along navigation channel on monthly basis
- ❑Identify the contributions to DO from processes involved

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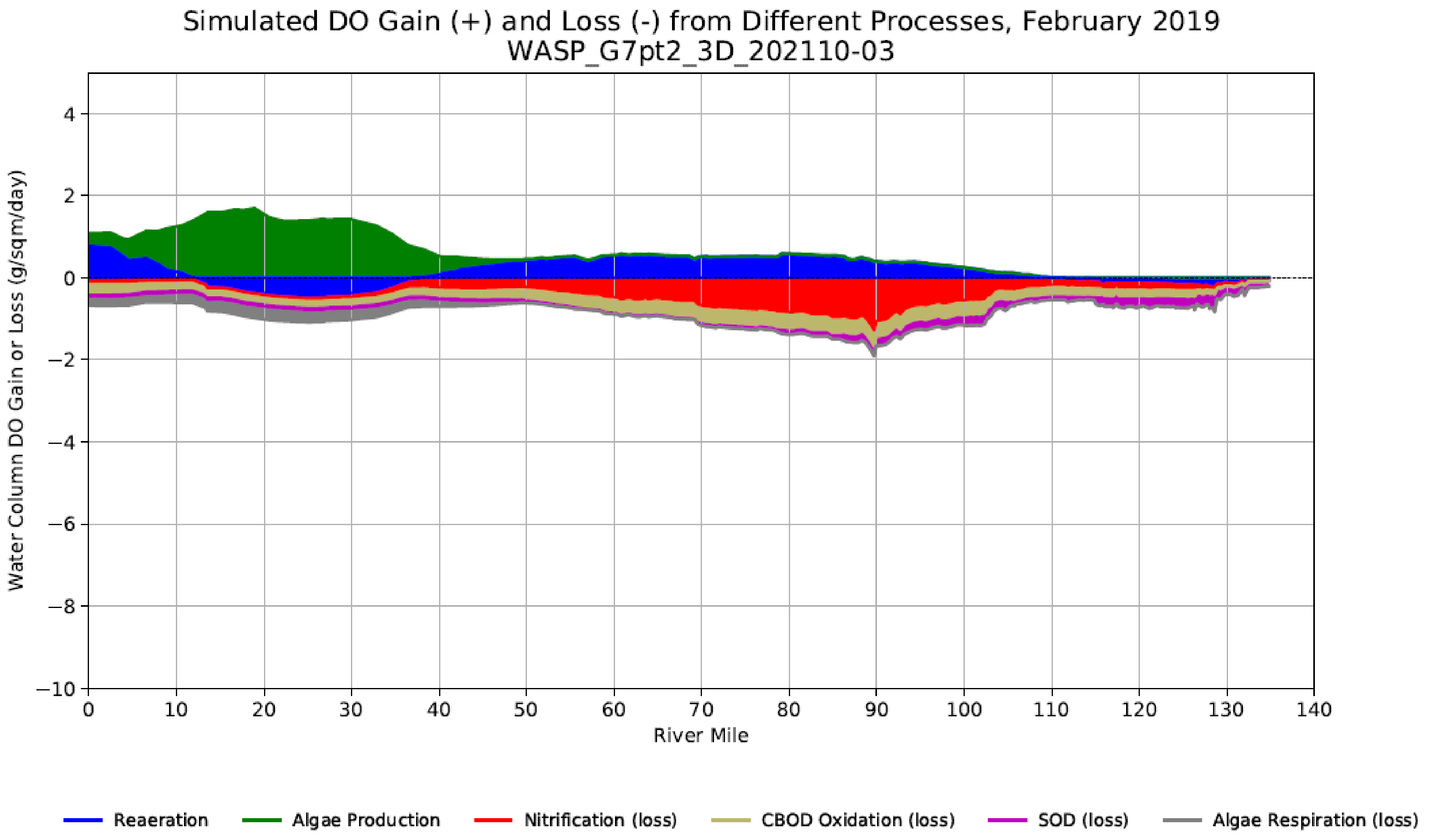
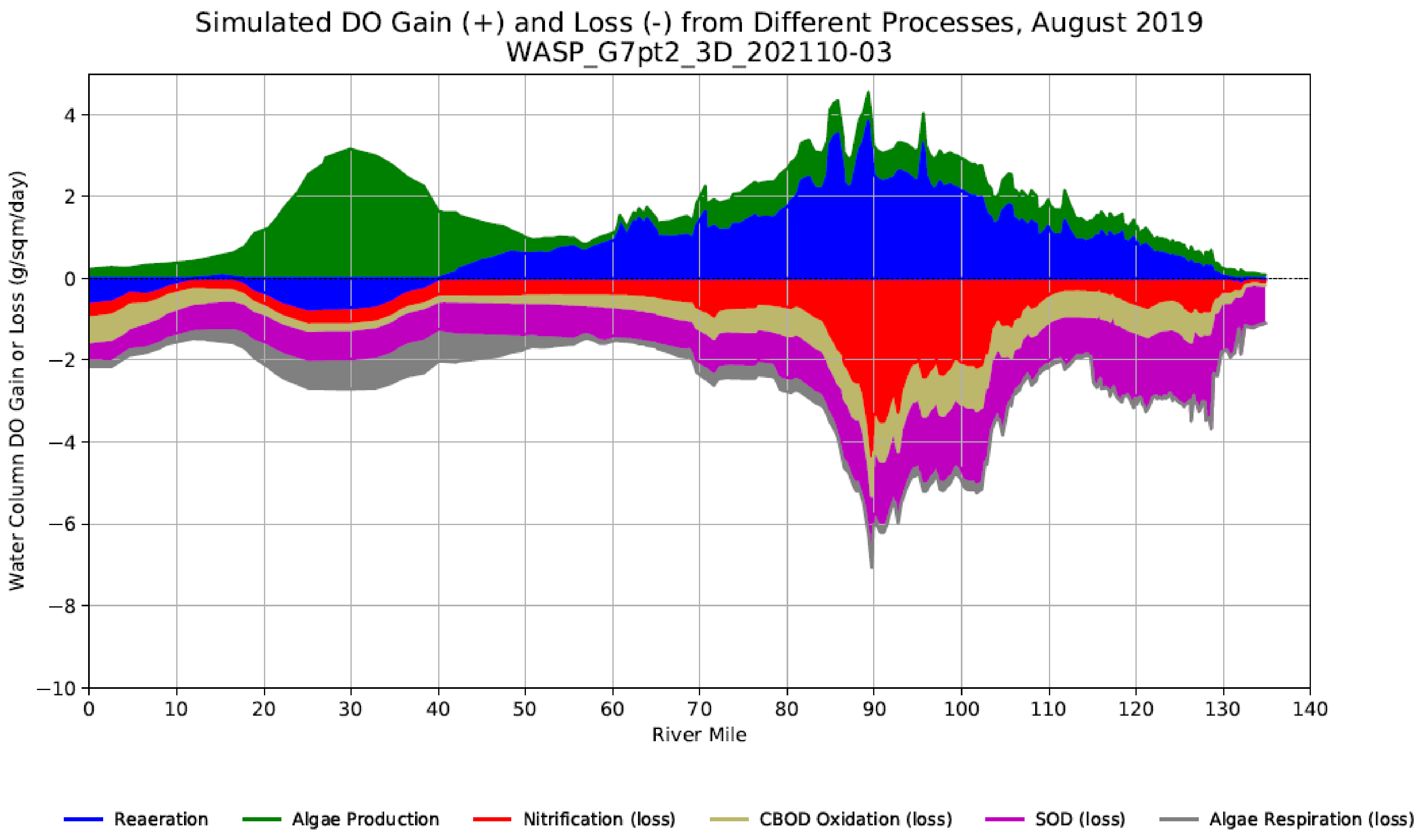
Longitudinal Profile of DO Gain/Loss along Navigation Channel – Entire Water Column



Longitudinal Profile of DO Gain/Loss along Navigation Channel, February 2019

Note: Total DO gain or loss over entire water column was calculated.
model results were averaged over the entire month. Gain or Loss rates were stacked.

Longitudinal Profile of DO Gain/Loss along Navigation Channel – Entire Water Column



Longitudinal Profile of DO Gain/Loss along Navigation Channel, August 2019

Note: Total DO gain or loss over entire water column was calculated. model results were averaged over the entire month. Gain or Loss rates were stacked.

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Summary of Calibration Status

- Near final calibration of global kinetics
  - Light extinction submodel represents a significant improvement
- Phytoplankton conceptual model captures broad temporal and spatial trends
  - Individual bloom events in urban estuary not captured
  - This appears to be related to characterization of tributary boundaries not kinetics
- Refine benthic fluxes to better capture DO and inorganic nutrients
- ~2 months of remaining effort anticipated

Preliminary Findings

- Major processes controlling dissolved oxygen
  - Production: reaeration and photosynthesis
  - Consumption: nitrification, SOD, and CBOD oxidation
- Low dissolved oxygen in the urban estuary driven by several factors
  - Nitrification is the most important driver and is centered in the urban estuary
  - SOD is an important secondary driver throughout the estuary
  - Low flows and high temperatures, as expected, exacerbate low DO
  - Photosynthesis from phytoplankton tempers low DO events

Path Forward

- Complete calibration of benthic fluxes (oxygen and nutrients)
  - Extensive benthic dataset collected by PWD
  - Explore dynamic simulation of sediment diagenesis
- Finish model setup and calibration (as needed) for 2012
  - 2012 captures a wider and more typical hydrologic range
- Develop baseline and future scenarios