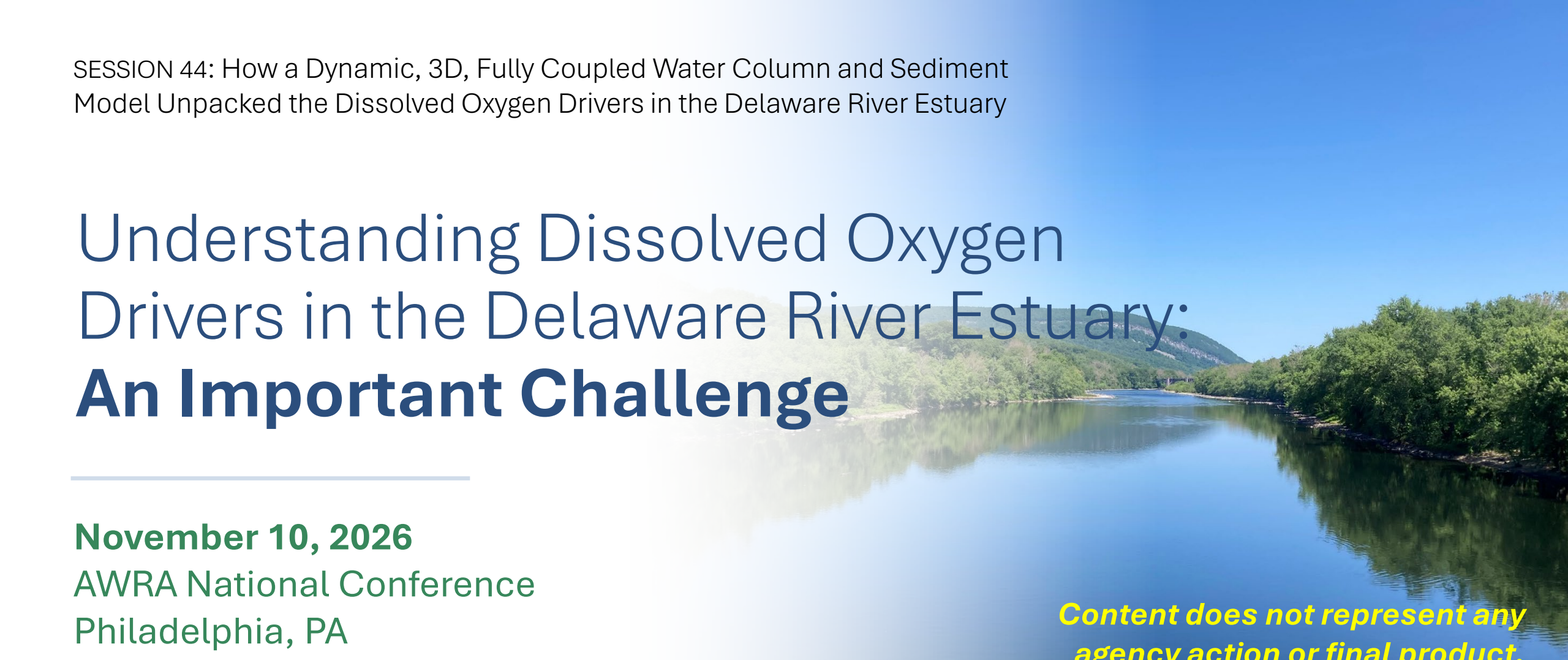
SESSION 44: How a Dynamic, 3D, Fully Coupled Water Column and Sediment Model Unpacked the Dissolved Oxygen Drivers in the Delaware River Estuary

Understanding Dissolved Oxygen Drivers in the Delaware River Estuary: **An Important Challenge**



November 10, 2026
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Philadelphia, PA

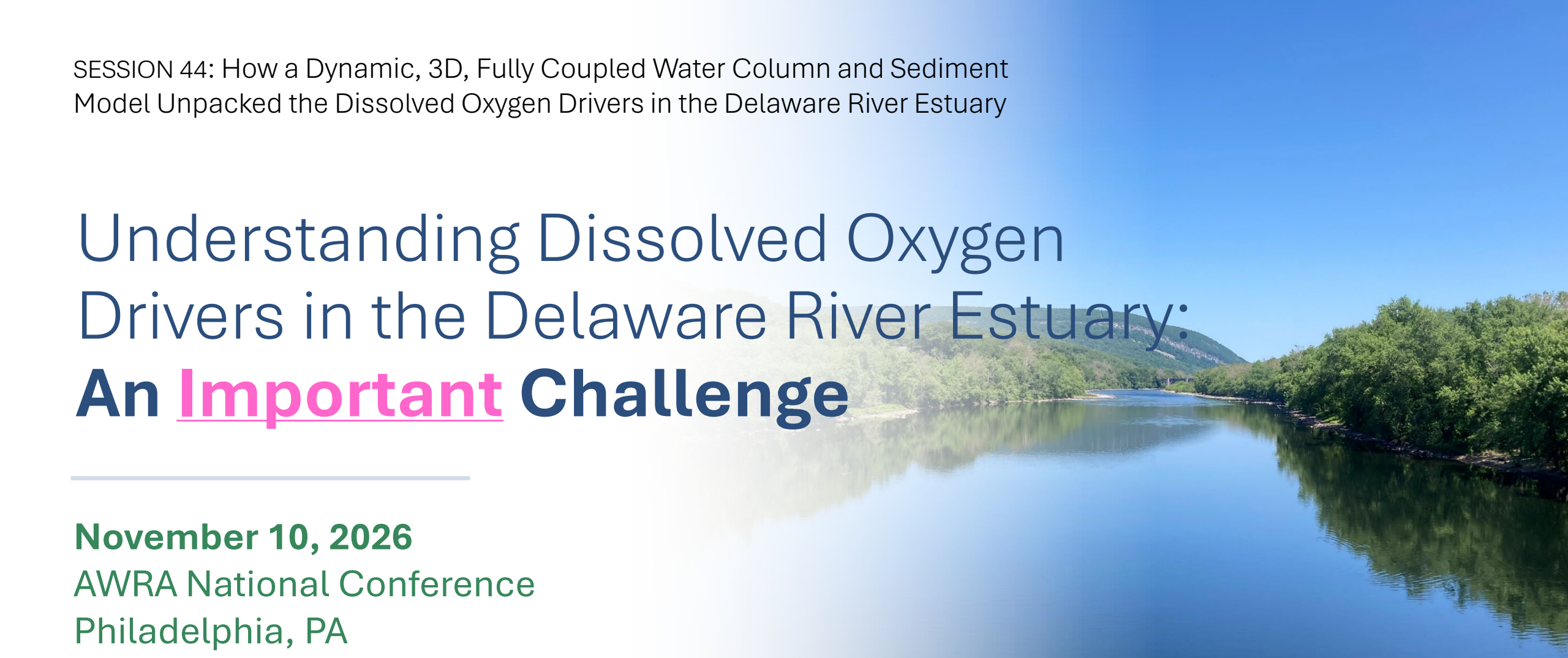
Content does not represent any agency action or final product.

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Joey Fogarty, Ph.D.
Matt Amato, Ph.D.
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The Delaware River Estuary spans from the Atlantic Ocean to Trenton, NJ

- **133 River Miles** from Mouth of Delaware Bay (RM = 0) to **head-of-tide at Trenton, NJ** ★
- Pennsylvania, New Jersey, and Delaware border the Delaware River Estuary (DRE)
- **Intakes** provide **drinking water for millions** of people in Philadelphia and New Jersey
- The DRE supports a **diverse aquatic ecosystem**, including migratory and resident fish, oyster fisheries, and endangered species from Atlantic sturgeon to whales

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Dissolved oxygen (DO) **supports the diverse aquatic life** of the Delaware River Estuary

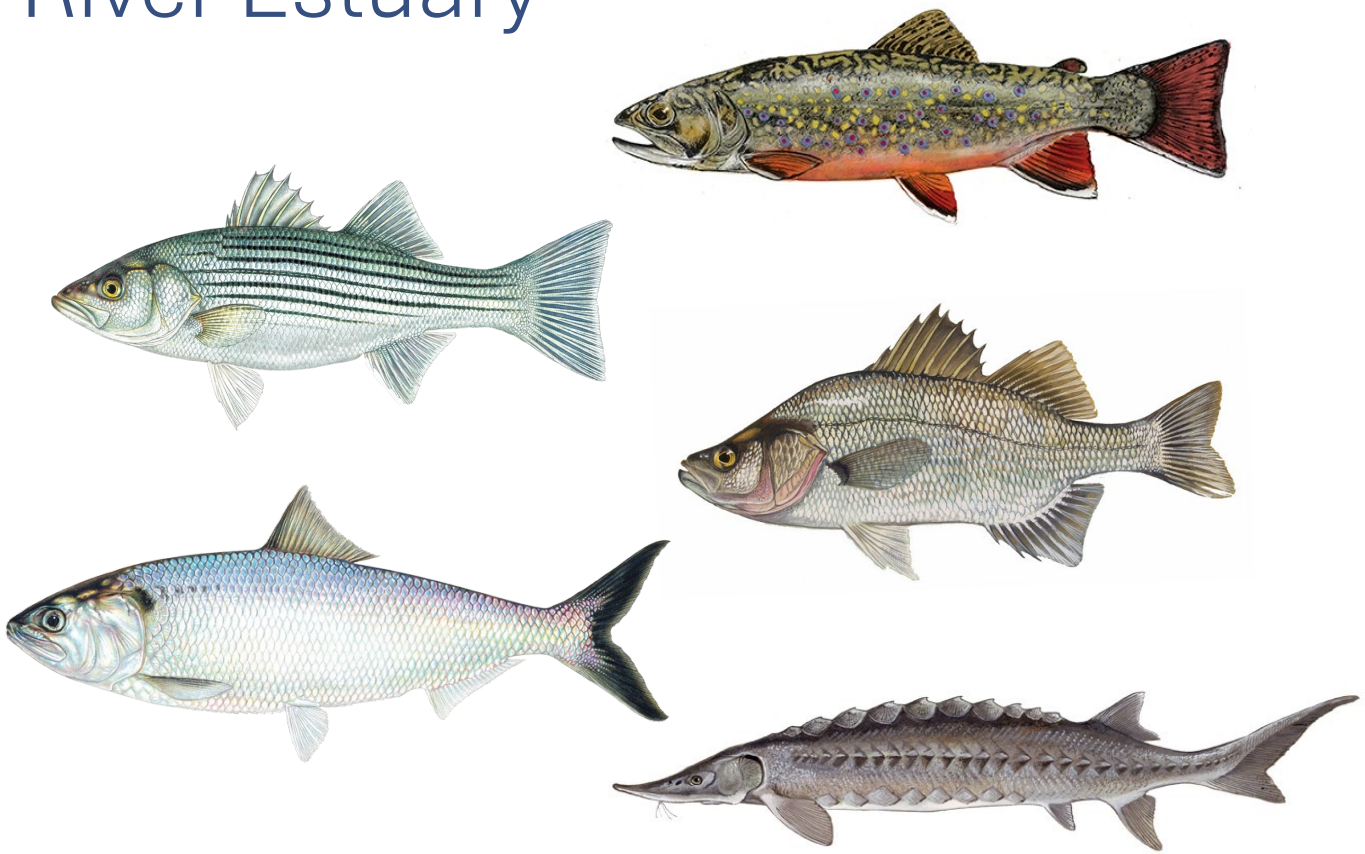






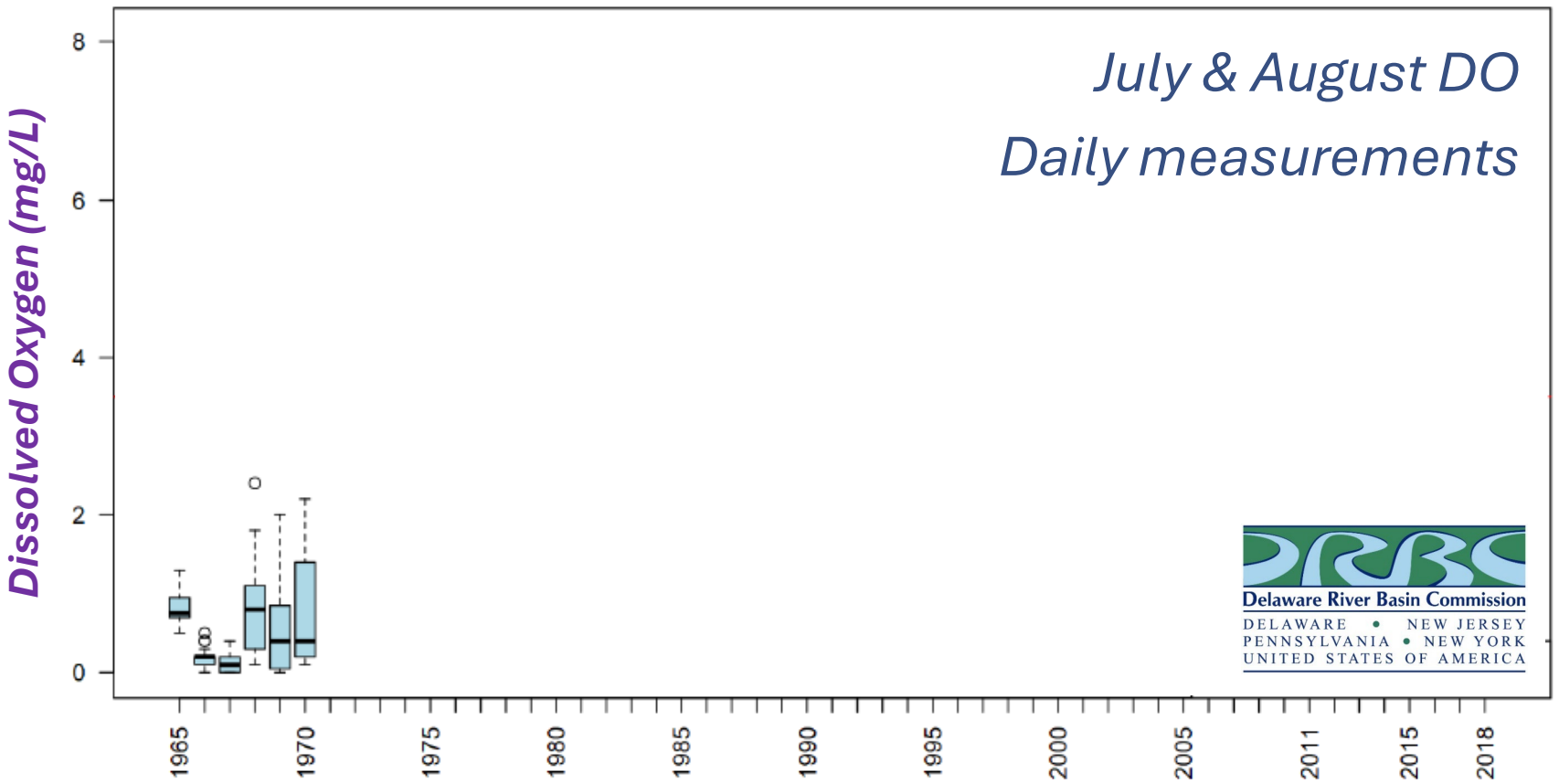
Image credits: maine.gov, DNREC, Haskins Shellfish Research Laboratory, NPS, John Whyte of the Ontario B.A.S.S. Nation, DNREC, OnWater, CA DFW

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In the Philadelphia urban corridor, **summer DO was close to zero** in the 1960s



USGS gage, Delaware River at Ben Franklin Bridge (River Mile 100)





The DRBC was established in 1961 to manage the Basin's shared water resources

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The Delaware River Basin Commission (DRBC)'s broad responsibilities include:

- Water supply
- Drought management
- Flood loss reduction
- **Water quality (Pollution control)**
- Watershed management
- Regulatory review (Permitting)
- Outreach and education
- Recreation

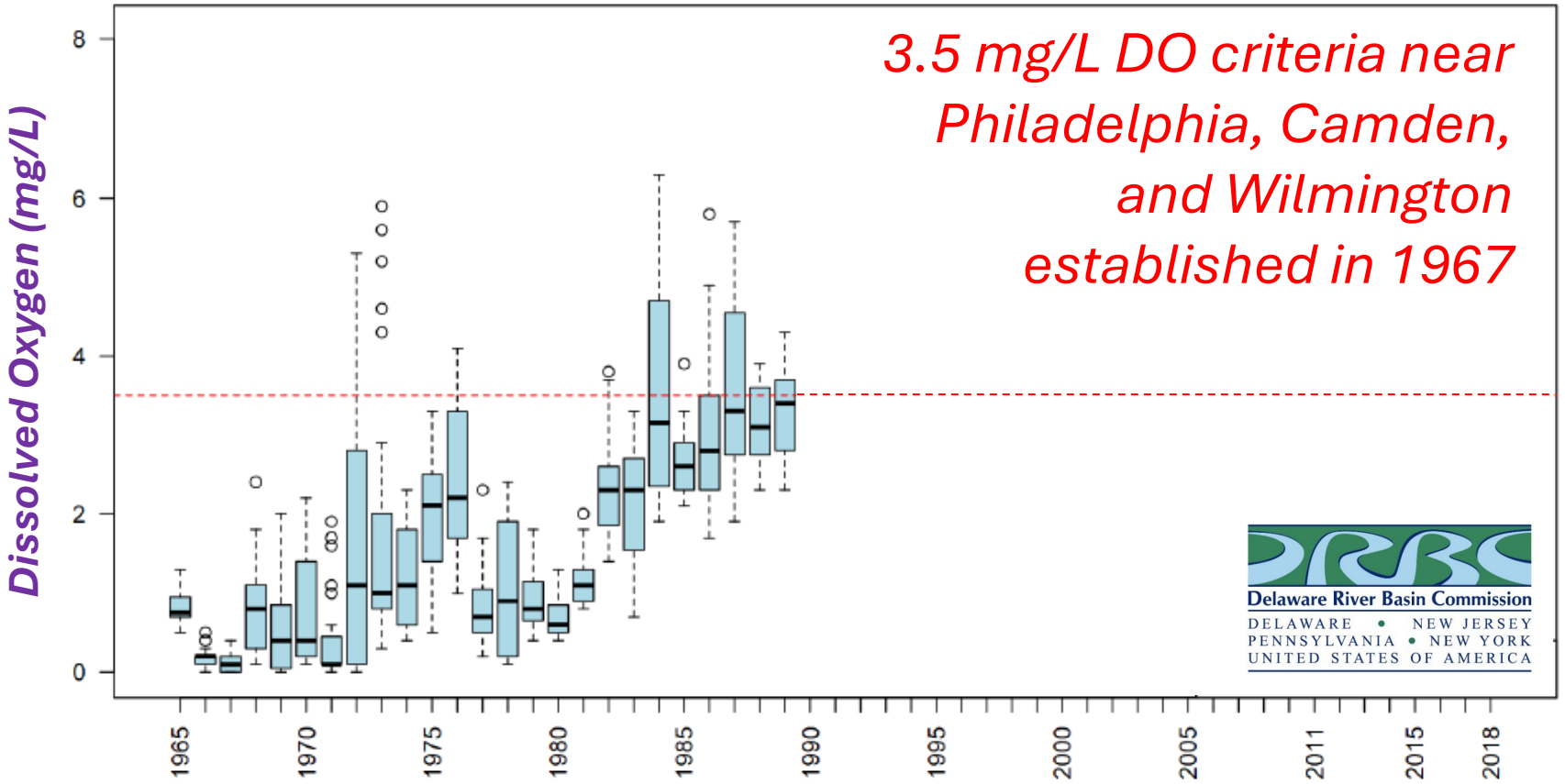
- Water quality includes:
  - Establishing water quality standards
  - Monitoring and assessment
  - Load reductions
- DRBC's first water quality regulations (1967) included **dissolved oxygen criteria**
- CBOD* wasteload allocation followed in 1968

** Carbonaceous biochemical oxygen demand*

Summer DO levels steadily increased
after CBOD wasteload allocation in 1968



USGS gage, Delaware River at Ben Franklin Bridge (River Mile 100)



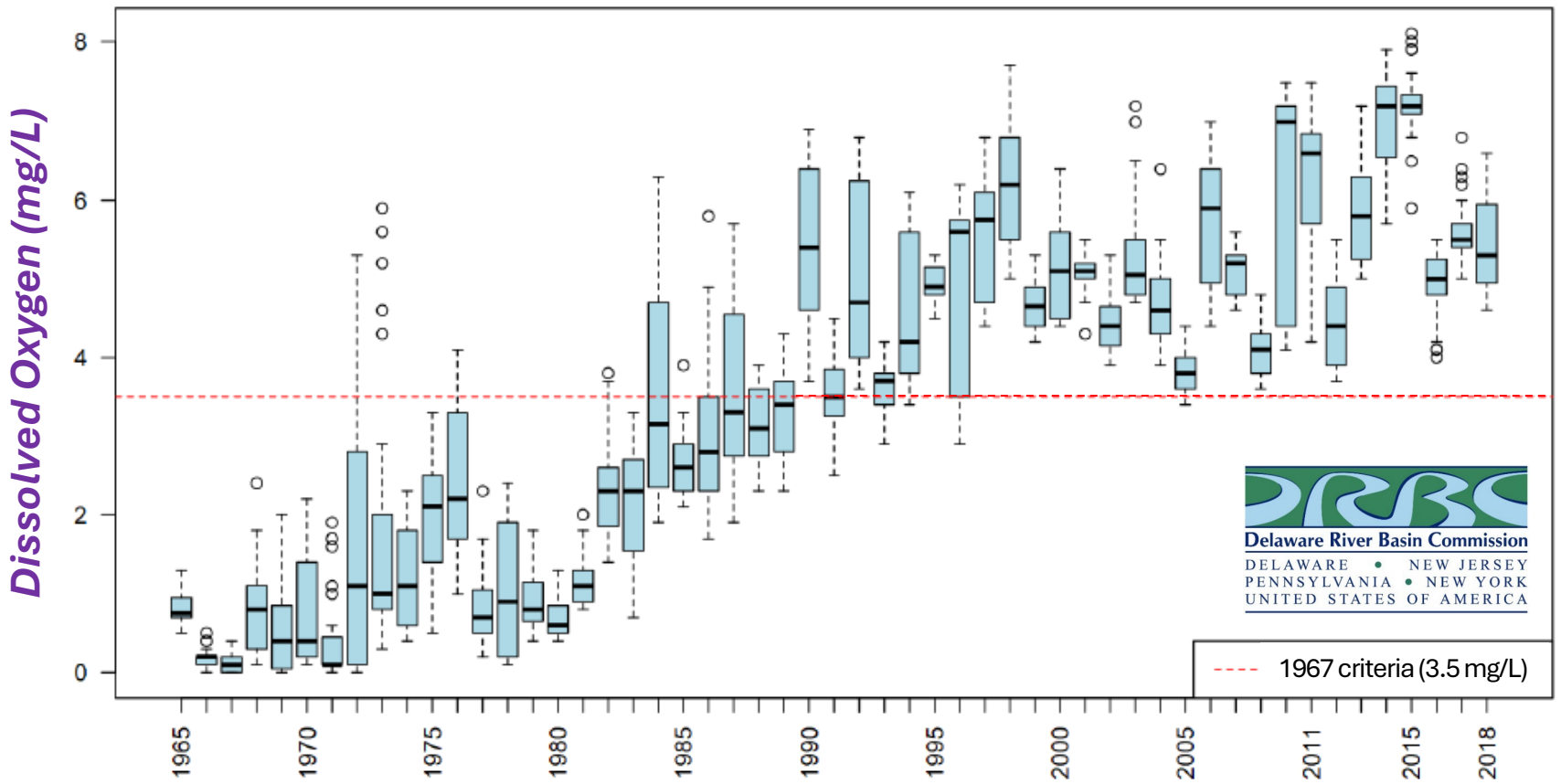
3.5 mg/L DO criteria near Philadelphia, Camden, and Wilmington established in 1967

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Since the mid-1990s, DO in the urban estuary **consistently meet water quality criteria**



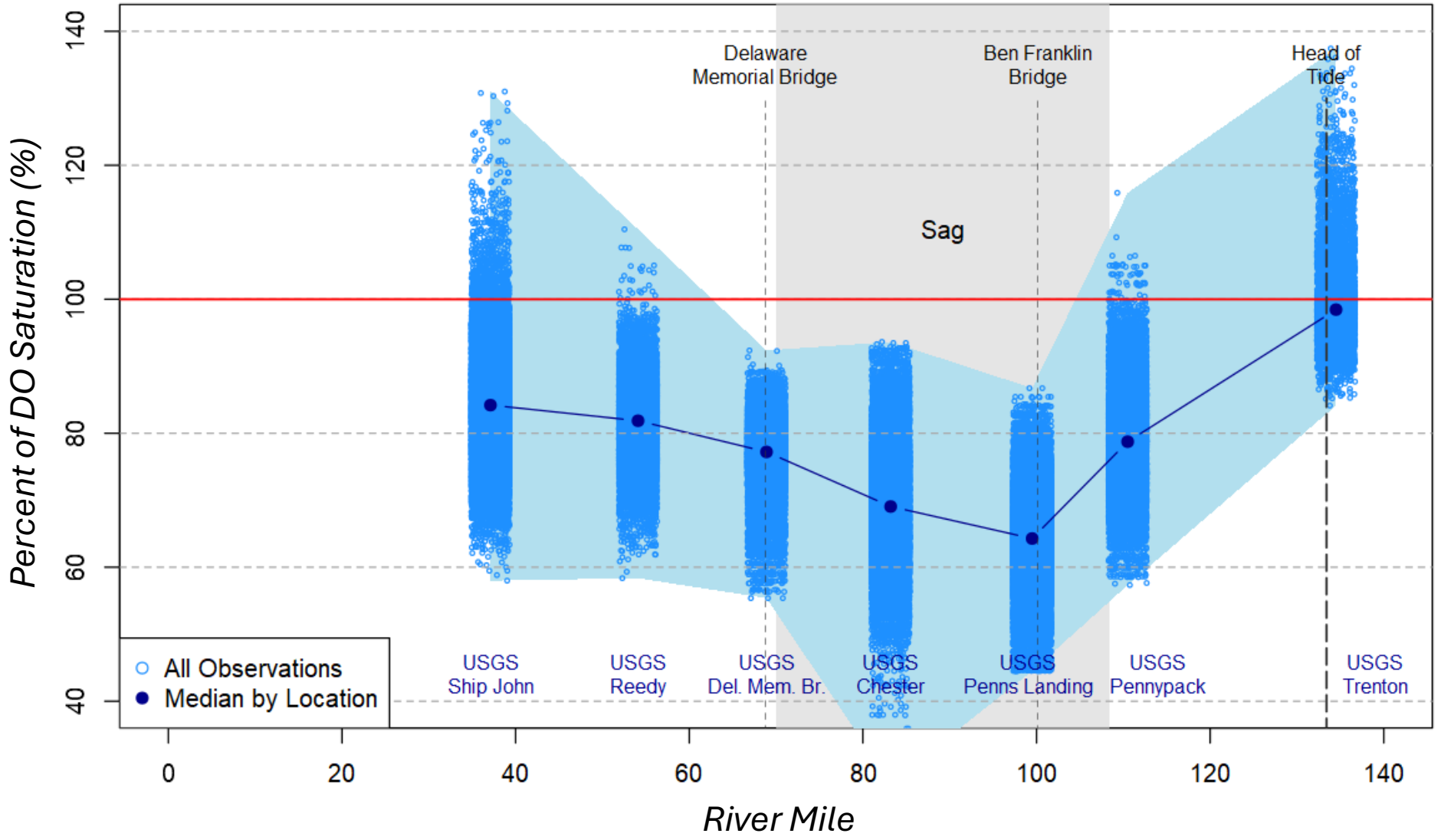
USGS gage, Delaware River at Ben Franklin Bridge (River Mile 100)



However, **a "DO sag" persists** in the urban Estuary

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Continuous Daily USGS Measurements
July and August, 2023–2025



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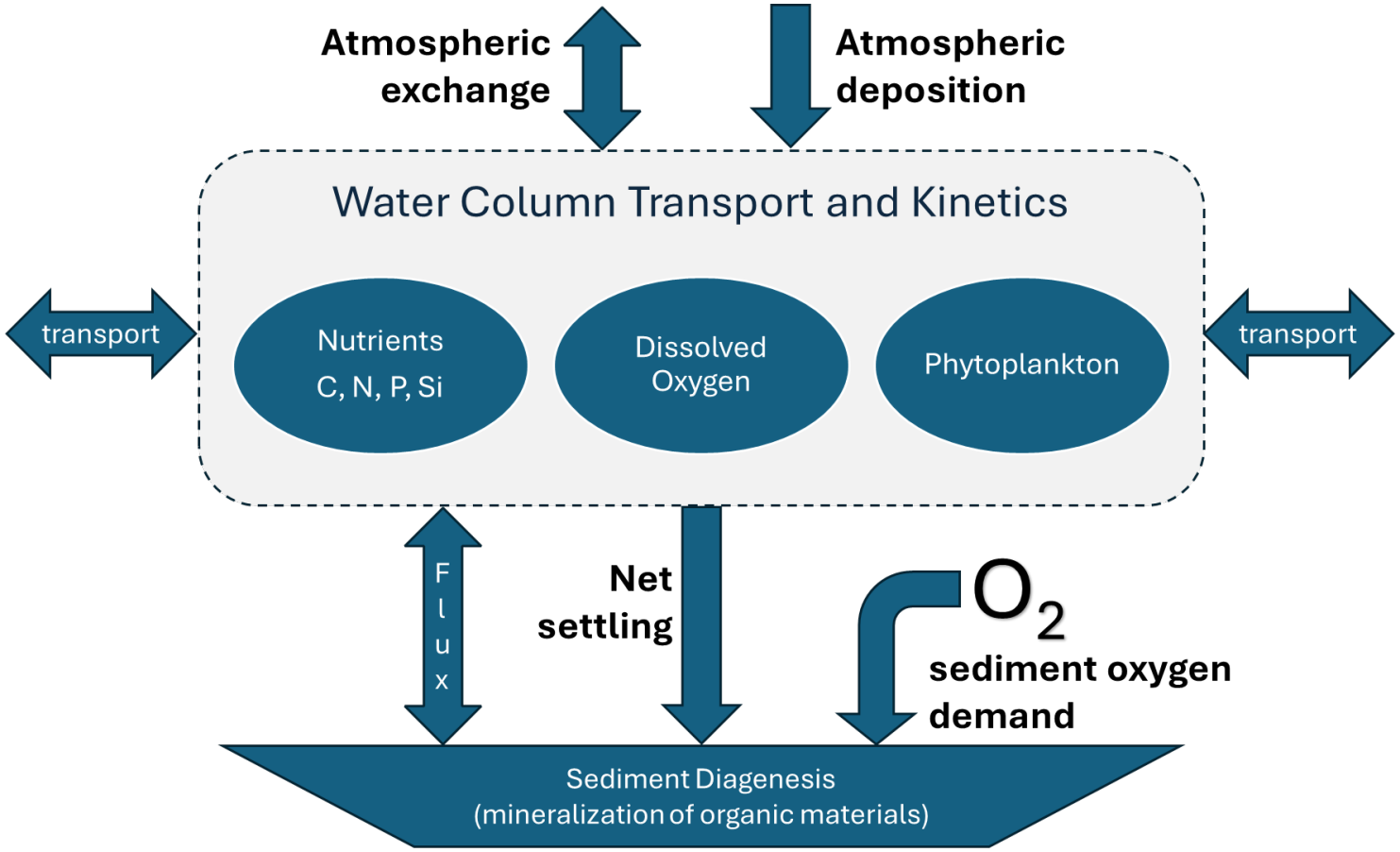
THE CHALLENGE

Relate changes in **loading conditions** to **dissolved oxygen levels** throughout the Delaware River Estuary

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THE APPROACH

3D hydrodynamic and water quality model



PRIMARY DO SOURCES

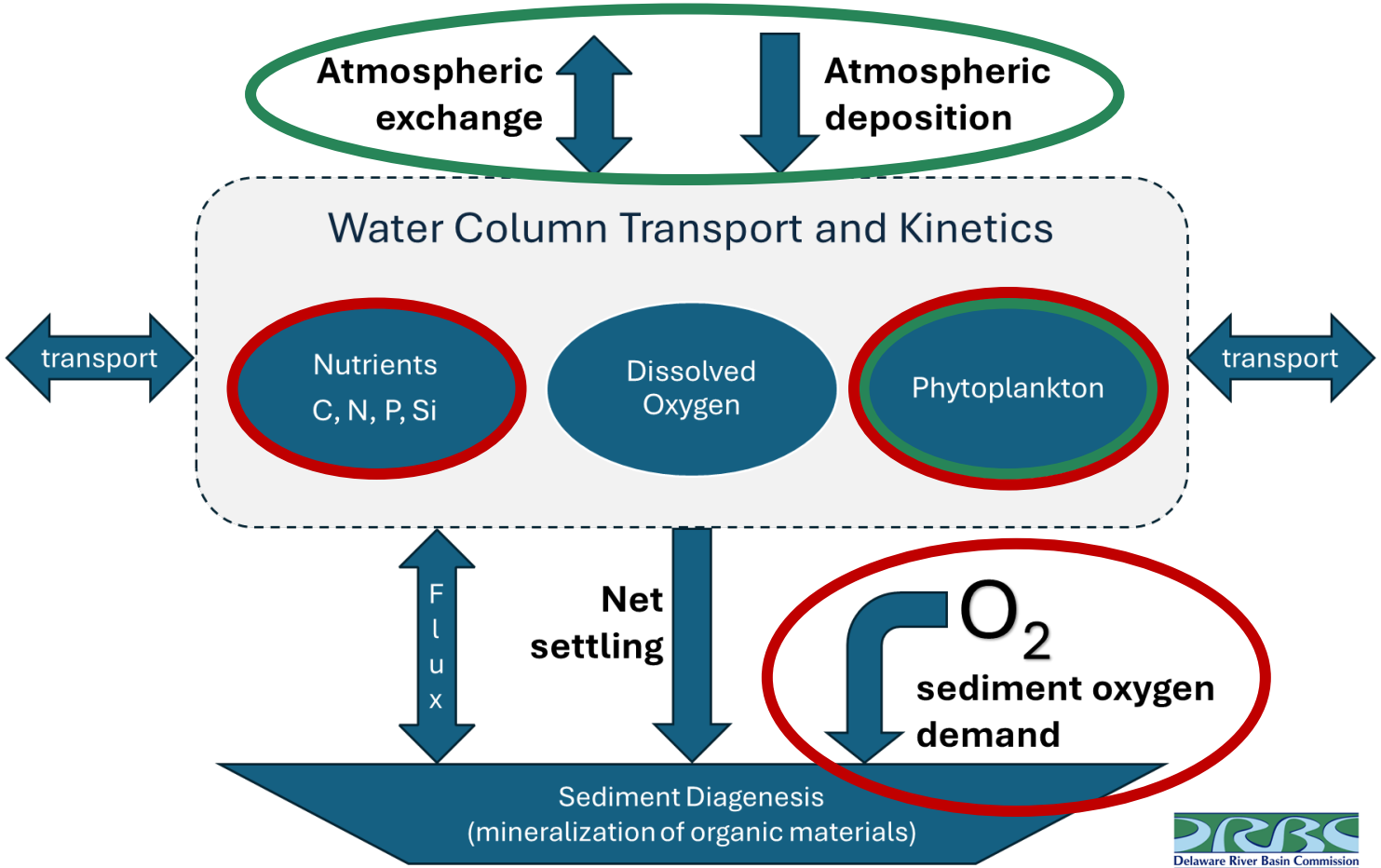
- Oxygen gas exchange with atmosphere
- Photosynthesis

PRIMARY DO SINKS

- Decay of organic carbon (CBOD)
- Oxidation of ammonia to nitrate (NBOD)
- Decay of organic matter in sediment layer (sediment oxygen demand, SOD)
- Respiration of phytoplankton and aquatic vegetation

THE APPROACH

3D hydrodynamic and water quality model



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THE CHALLENGE

Relate changes in **loading conditions** to **dissolved oxygen levels** throughout the Delaware River Estuary (DRE)

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~~Understanding Dissolved Oxygen Drivers in the Delaware River Estuary: An Important Challenge, Sarah Beganskas~~

Understanding **Physical** Impacts on DO in the DRE, Li Zheng

Understanding **Biological** Impacts on DO in the DRE, Joseph Fogarty

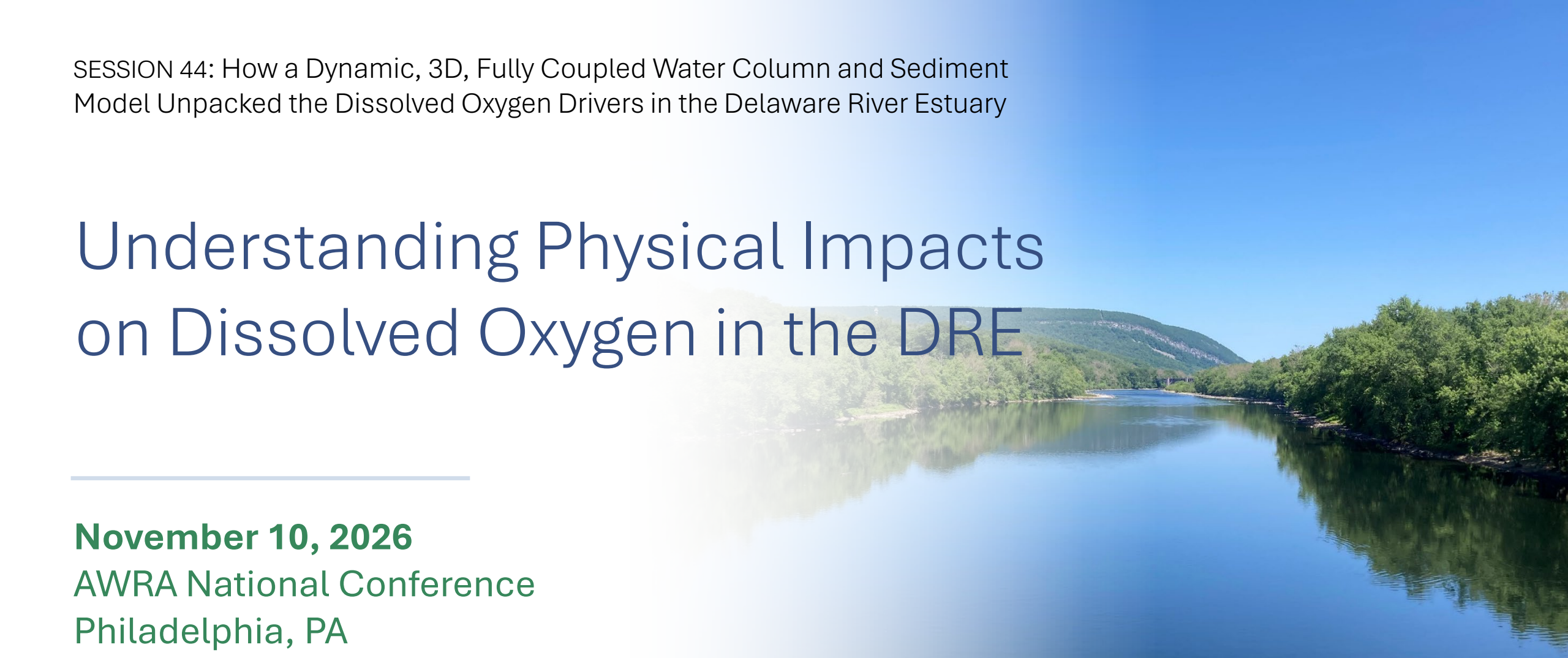
Quantifying **Sediment Processes** and Their Impacts on DO in the DRE, Matthew Amato

A Novel Quantification of the DO Budget in the DRE and its **Implications for Water Quality Management**, Thomas Amidon

Joint Q+A Session, All

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Understanding Physical Impacts on Dissolved Oxygen in the DRE



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Hydrodynamic Model
Environmental Fluid Dynamics Code (EFDC)

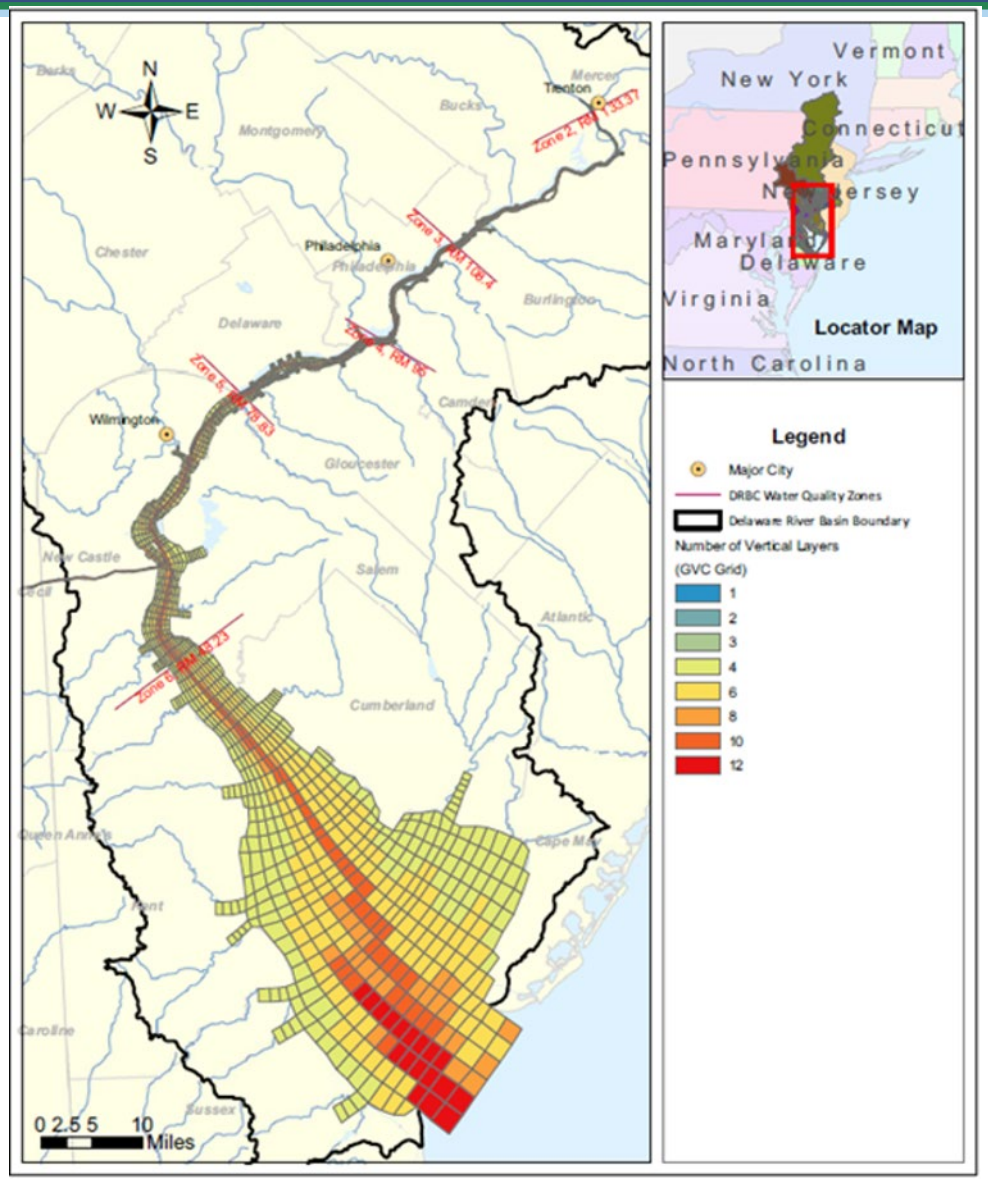
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Model domain

- From the head of the tide on the Delaware River at Trenton to the mouth of the Delaware Bay
- C&D Canal
- Inflow from
  - 33 major tributaries
  - 71 major point source discharges
  - 14 aggregated CSO locations

Numerical grid

- Horizontal cell: 1,876
- Vertical layer: 10 in navigation channel
- Total segments: 11,490



Integration of the EFDC with the Water Quality Model

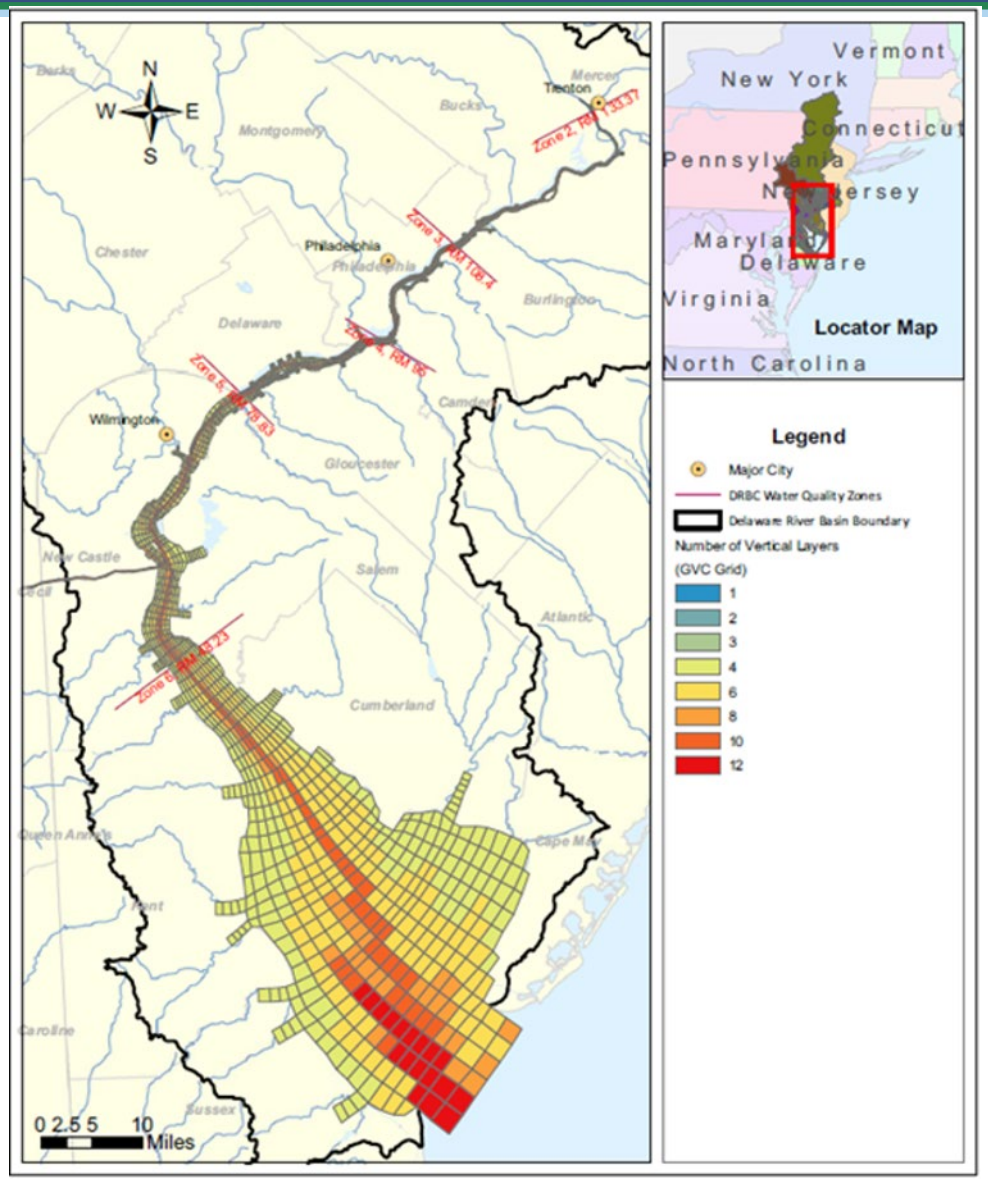
Water Quality Simulation Program (WASP)

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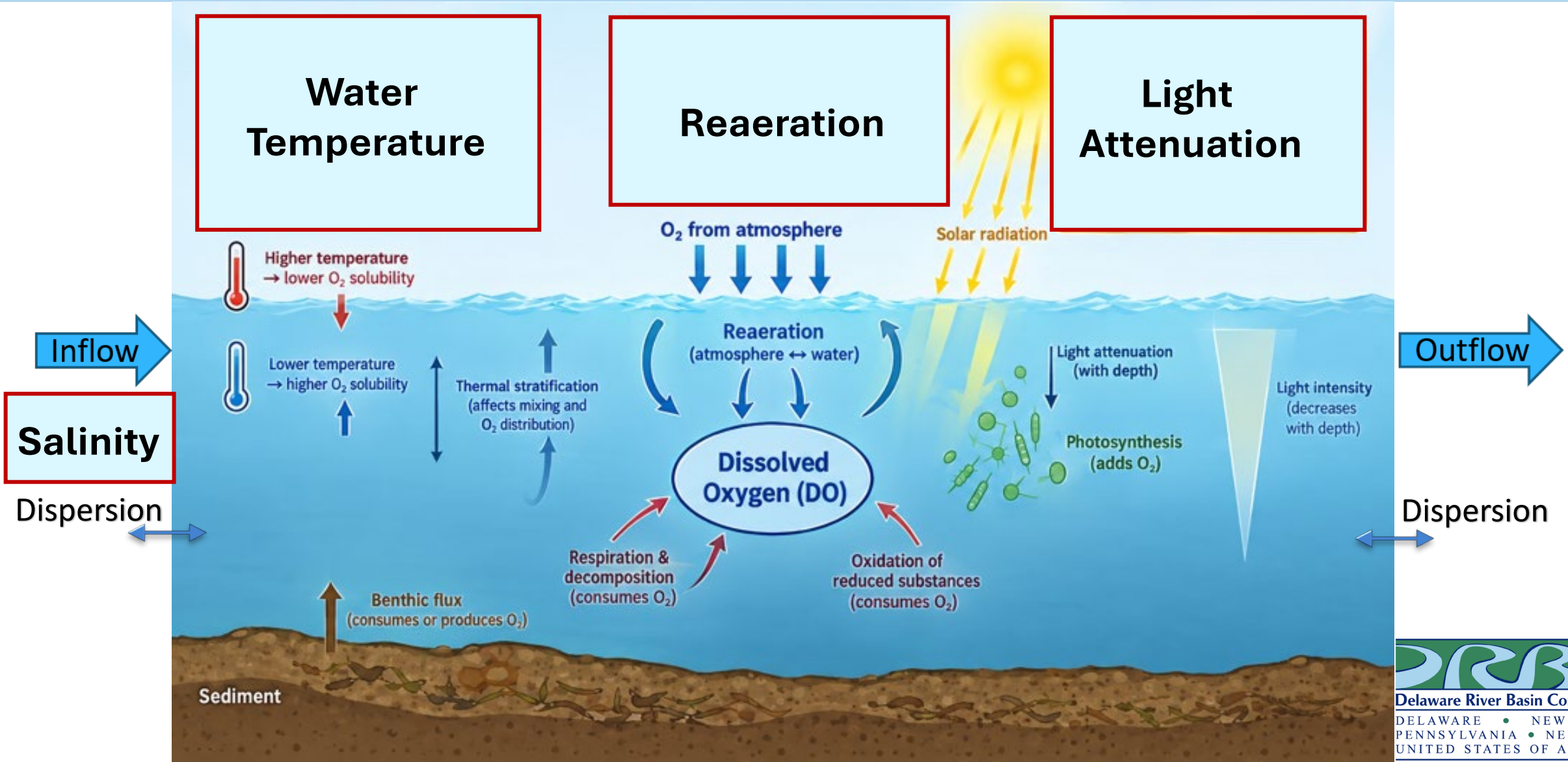
EFDC outputs to WASP inputs

- Water volume
- Current velocity
- Water temperature
- Salinity
- Mixing coefficient
- Turbulent kinetic energy dissipation rate

EFDC and WASP share the same model grid



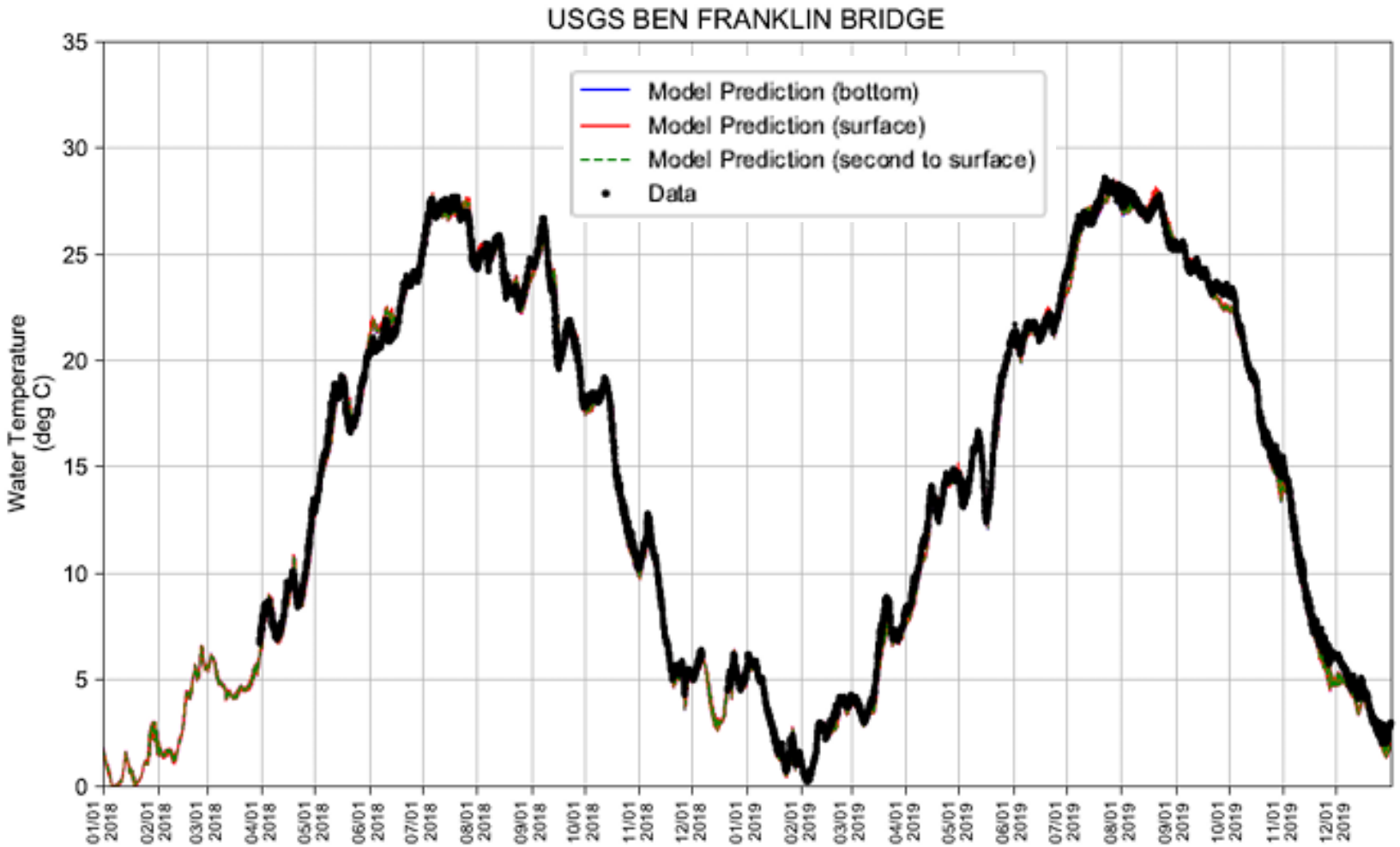
Physical Processes affecting Dissolved Oxygen (DO)

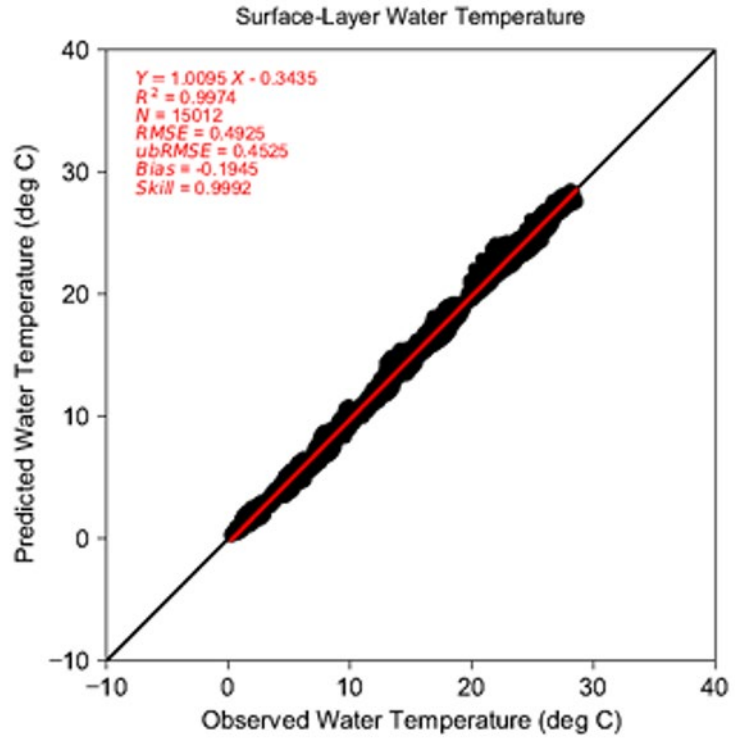


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The Model Tracks Temperature Seasonal Variation Well

at USGS Ben Franklin Bridge (2018 – 2019)

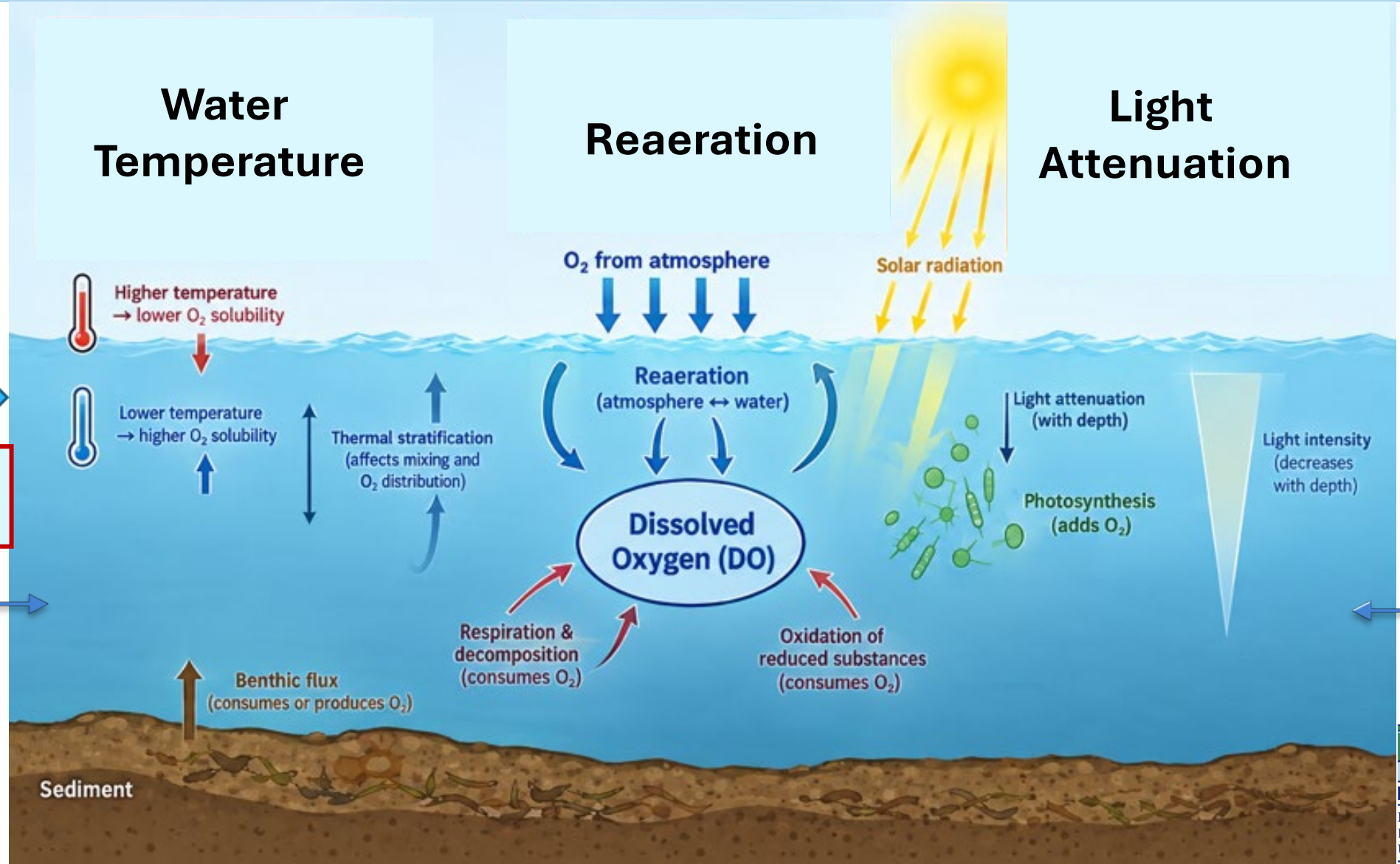




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Physical Processes affecting Dissolved Oxygen (DO)



Inflow

Salinity

Dispersion

Outflow

Dispersion

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The model now more accurately captures salinity dynamics upstream

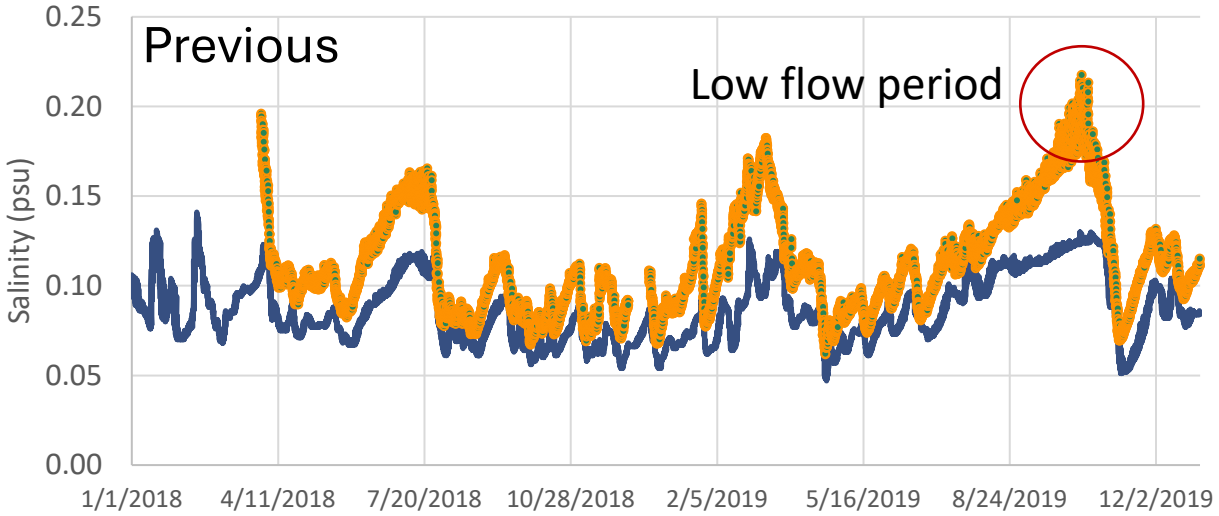
Salinity from point dischargers

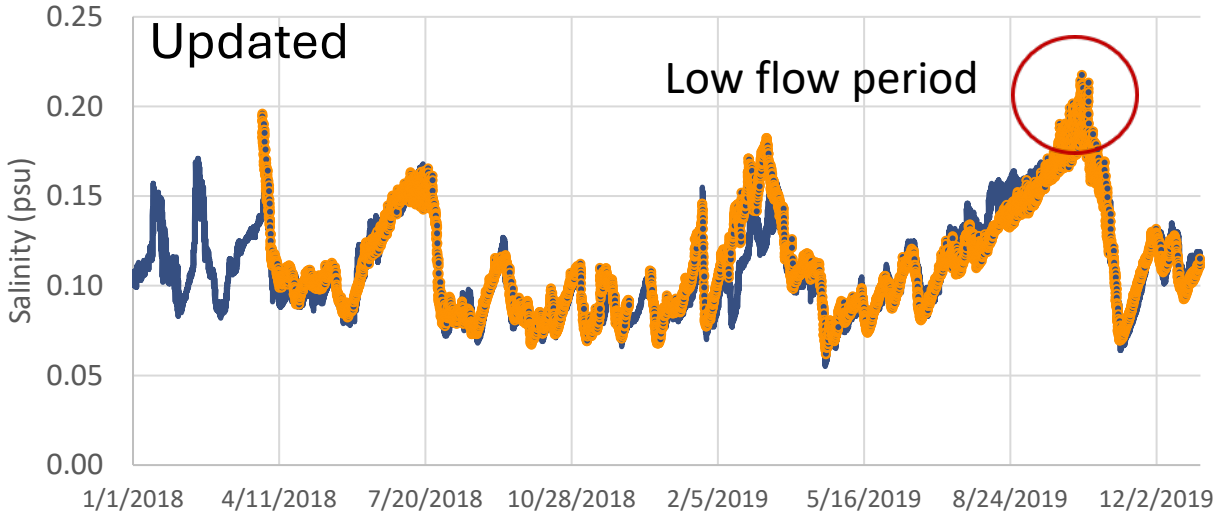
- Previous: zero
- Updated: spatial and temporal constants

Salinity at tributary boundaries

- Previous: Use Trenton/Schuylkill
- Updated: Tribs U/S of Schuylkill use DRBC data

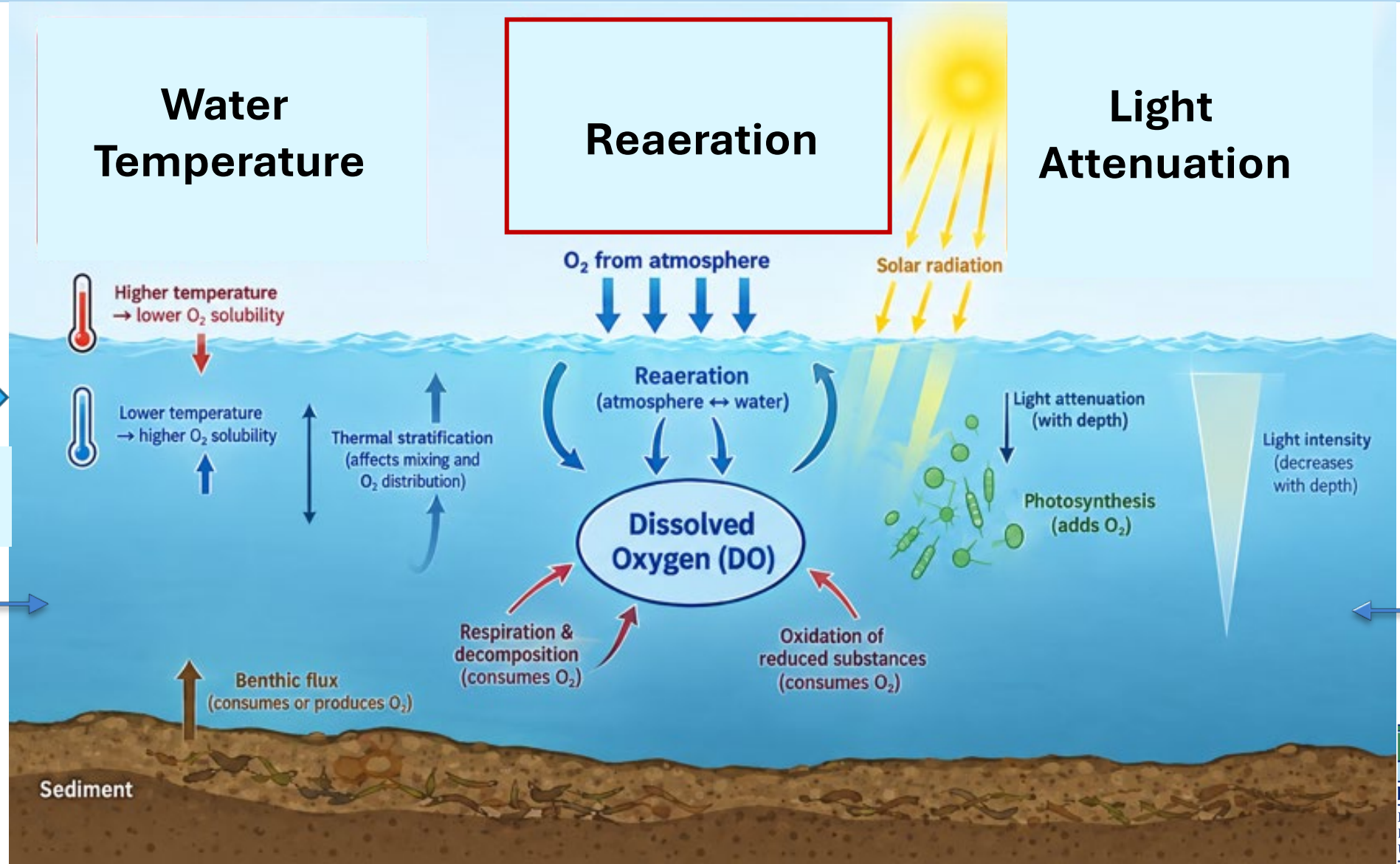
Ben Franklin Bridge (RM 100.1)





Salinity - Data Salinity - Model

Physical Processes affecting Dissolved Oxygen (DO)



Inflow

Salinity

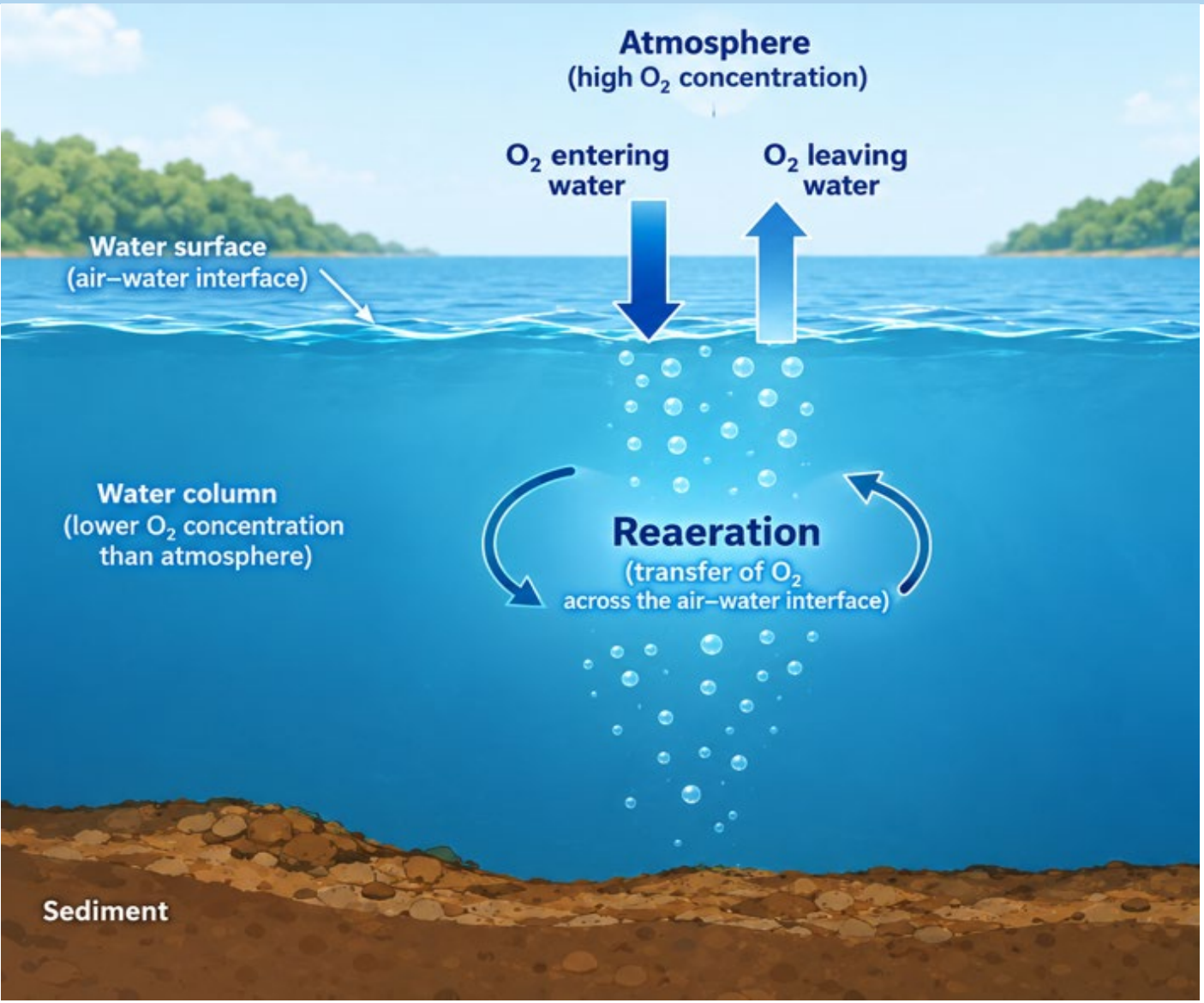
Dispersion

Outflow

Dispersion

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Reaeration – A Key Physical Process Affecting DO



Common Representation

$$\frac{dO_2}{dt} = k_2(O_{2,\text{sat}} - O_2)$$

where:

- O_2 = dissolved oxygen concentration
- $O_{2,\text{sat}}$ = saturation concentration at water temperature
- k_2 = reaeration coefficient (depends on wind, turbulence, and temperature)

Conventional options for k_2

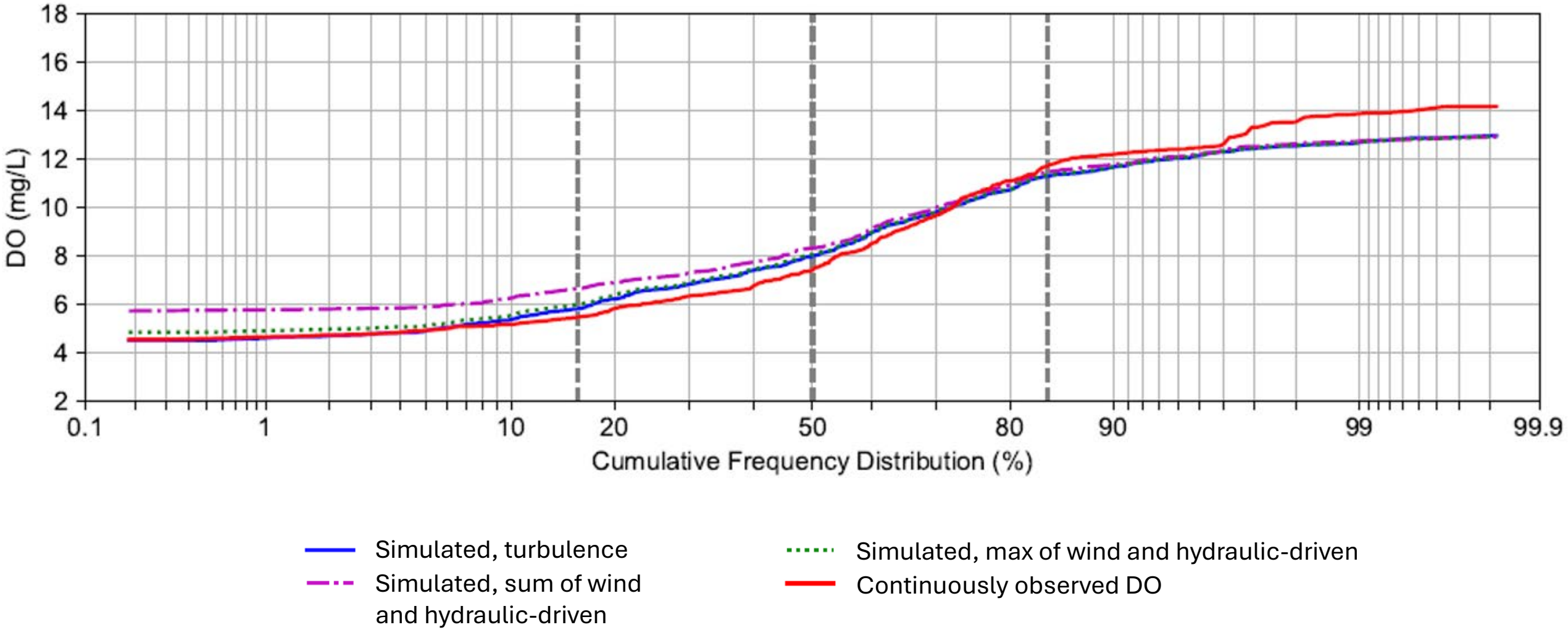
- Wind-driven for lakes or bays
- Hydraulic-driven reaeration for rivers & streams

Enhanced approach

- Utilize turbulent energy dissipation rate at air-water interface (Zappa et al. 2007)

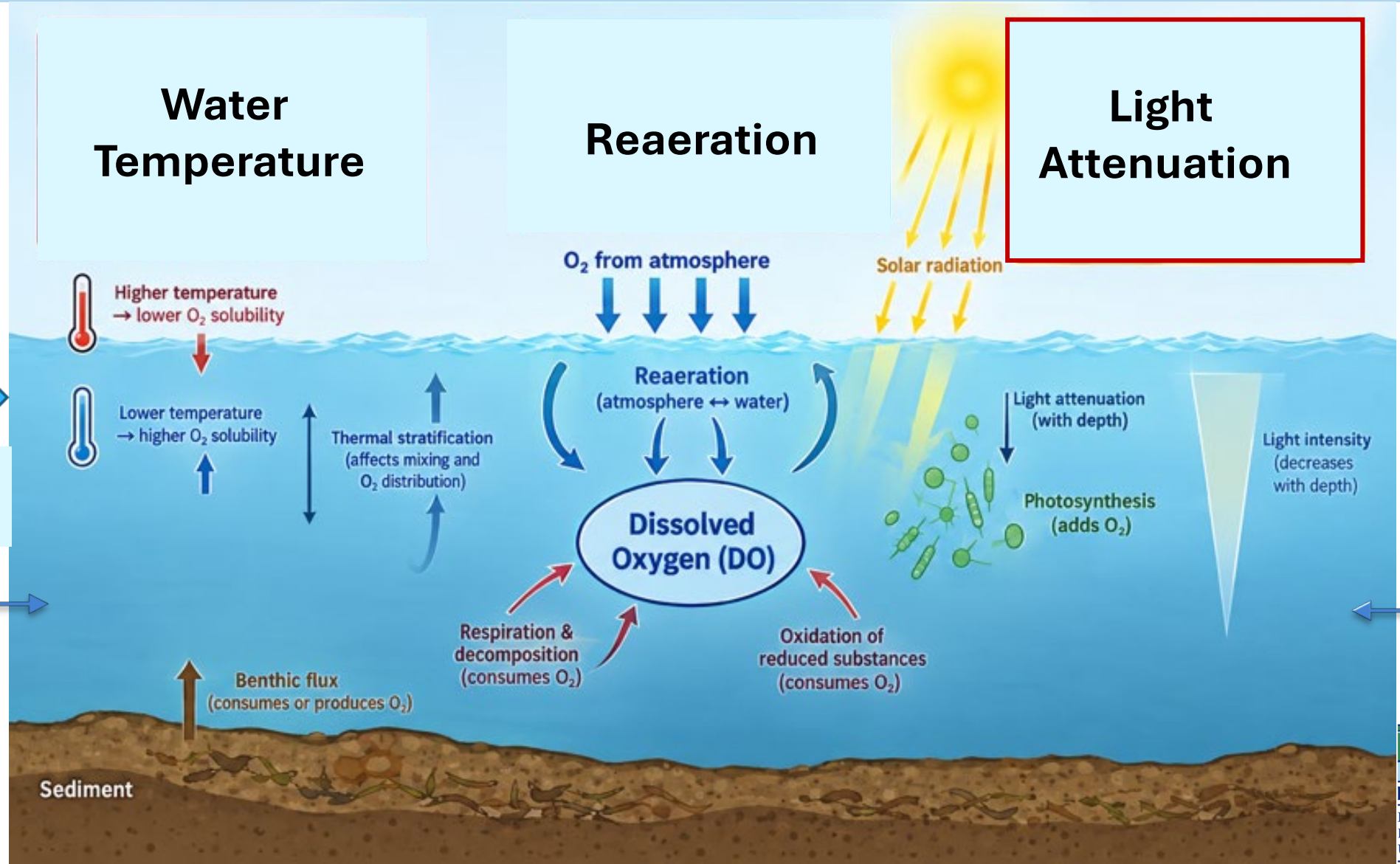
Comparison of Reaeration Coef. Approaches

Using DO at USGS Ben Franklin Bridge (2018 – 2019)



Zheng et al. (2024). Modeling Eutrophication Processes in the Delaware River Estuary: Three-Dimensional Water Quality Model. (DRBC Report No. 2024-5).

Physical Processes affecting Dissolved Oxygen (DO)



Inflow

Salinity

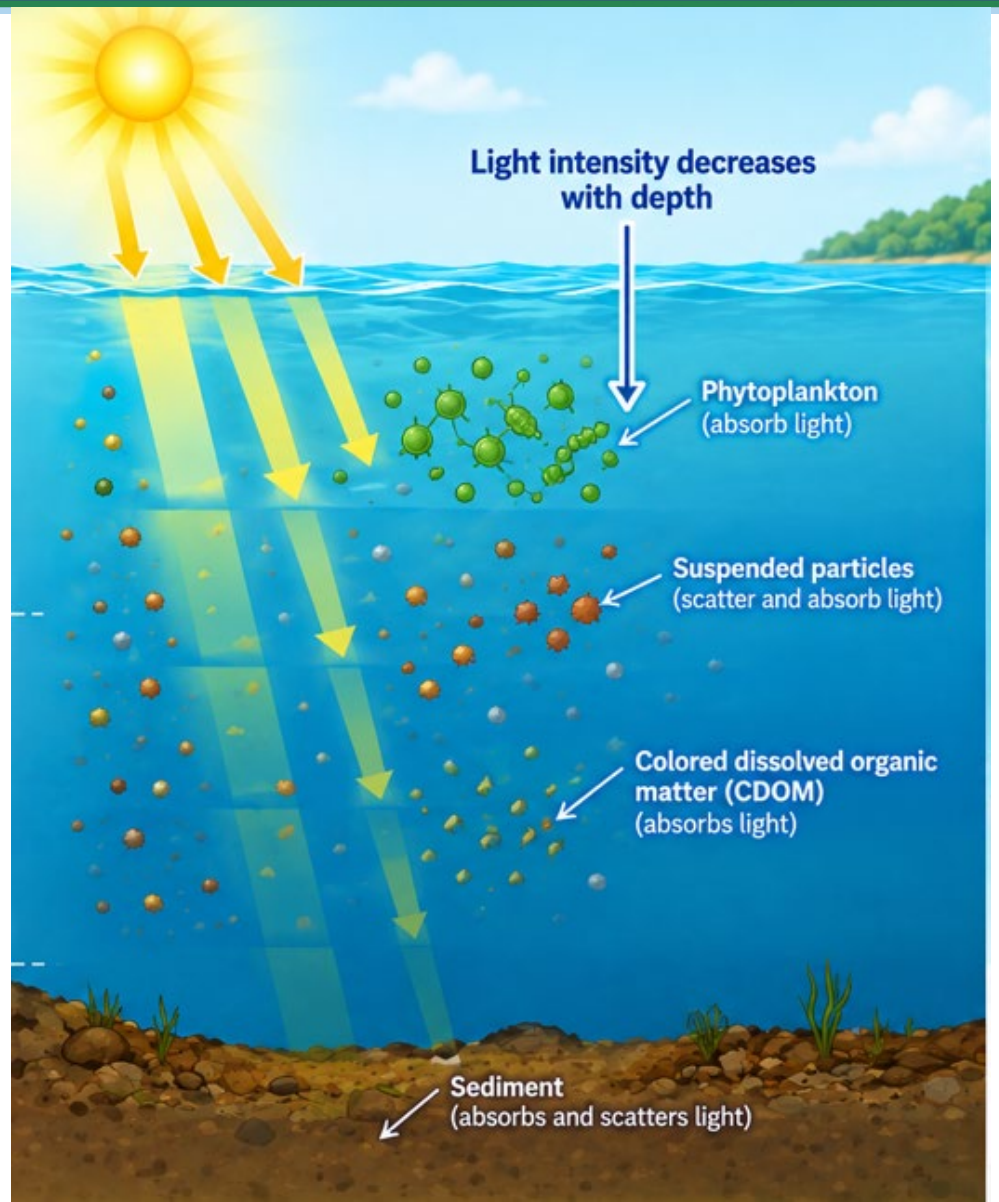
Dispersion

Outflow

Dispersion

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Light Attenuation – A Key Physical Process Affecting DO



Self-shading by phytoplankton

Scattering by suspended particles

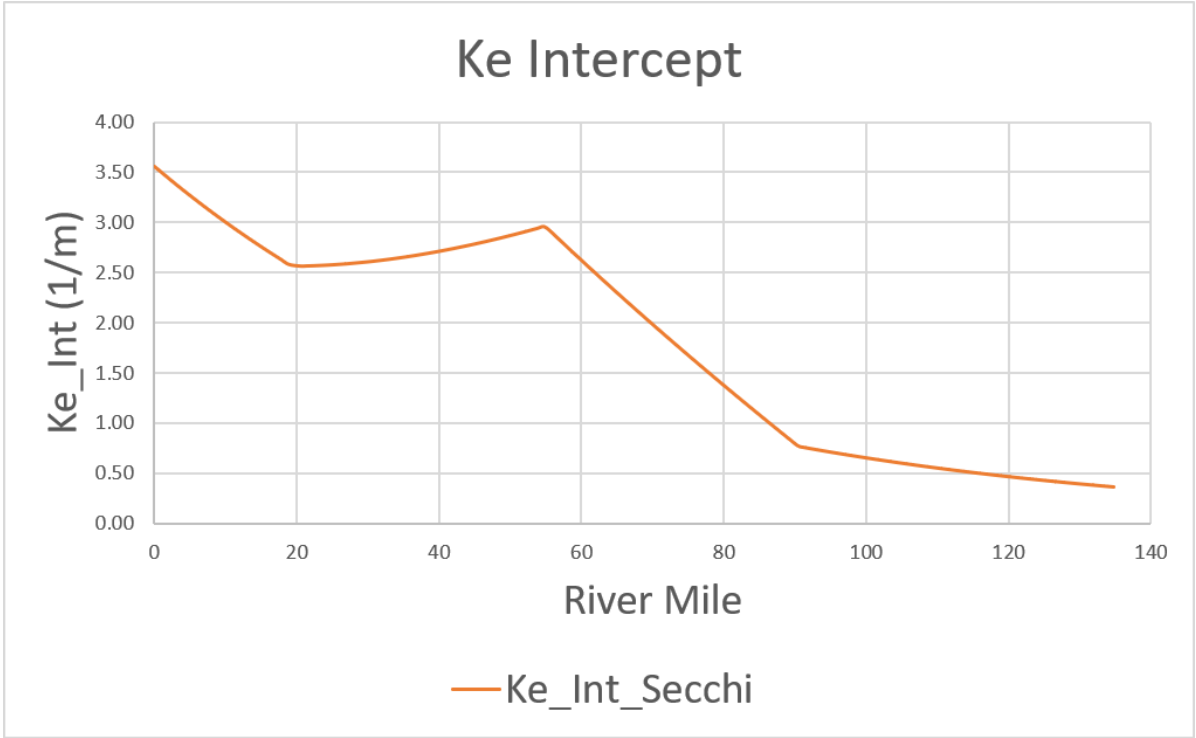
Absorption by colored dissolved substances

Light Attenuation Coefficient K_e

- Ke formulation based on Secchi depth data
  - Use salinity as a surrogate for suspended solids

$$Ke = Ke_{Int} + (0.009 \times Chla) + (0.253 \times DOC) - (0.097 \times Salinity)$$

self-shading absorption scattering



- Intercept formulation:

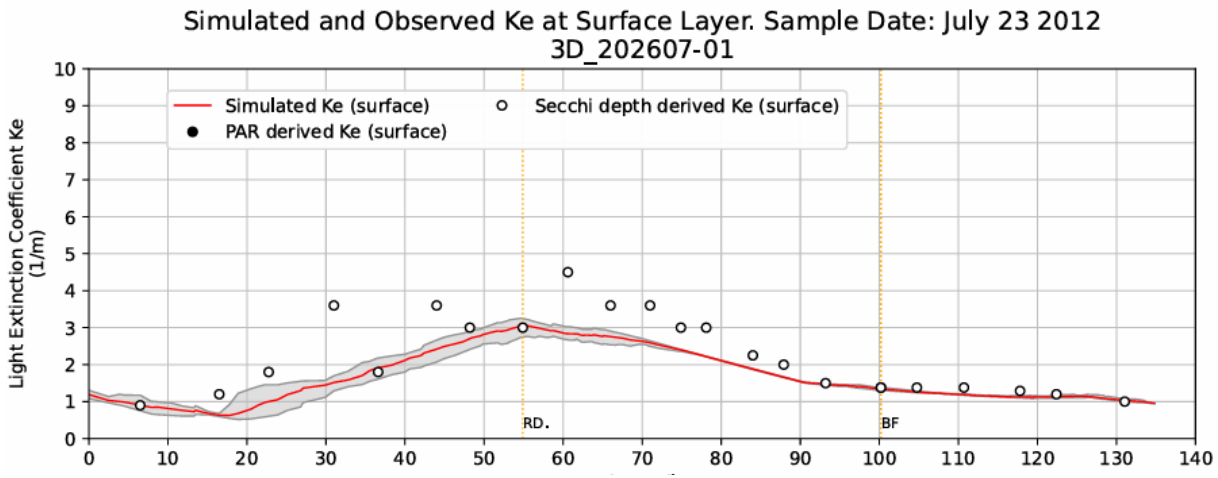
$$Ke_{Int}\ as\ f(RM) = 3.558 \times e^{(-0.017 * RM)} + Max\left[0, \left(1.563 - 0.044 \times ABS(54.9 - RM)\right)\right]$$

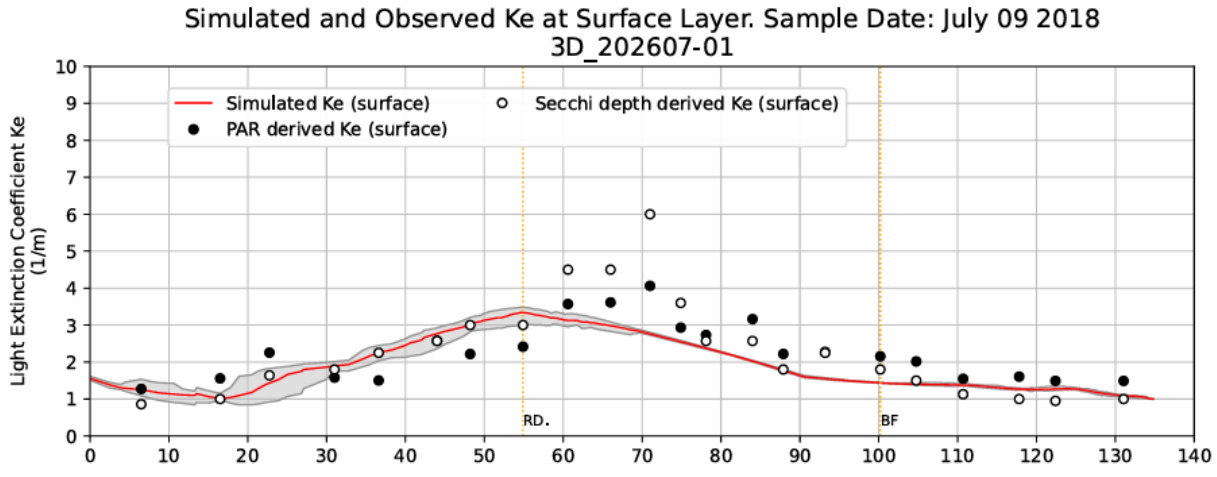
RM: river mile

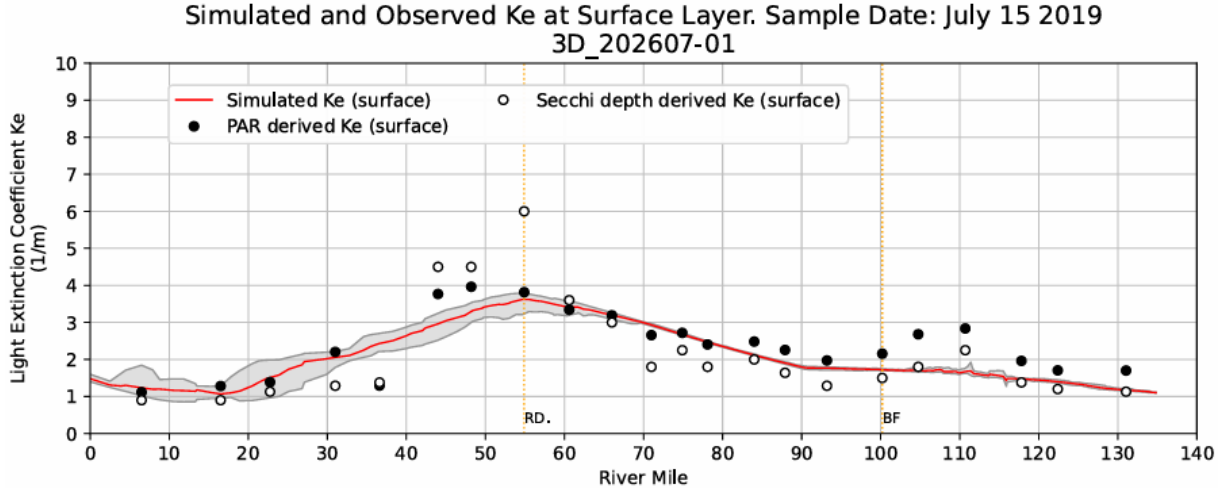
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Comparisons of Simulated and Observed Ke at Surface Layer on July 2012, 2018, and 2019

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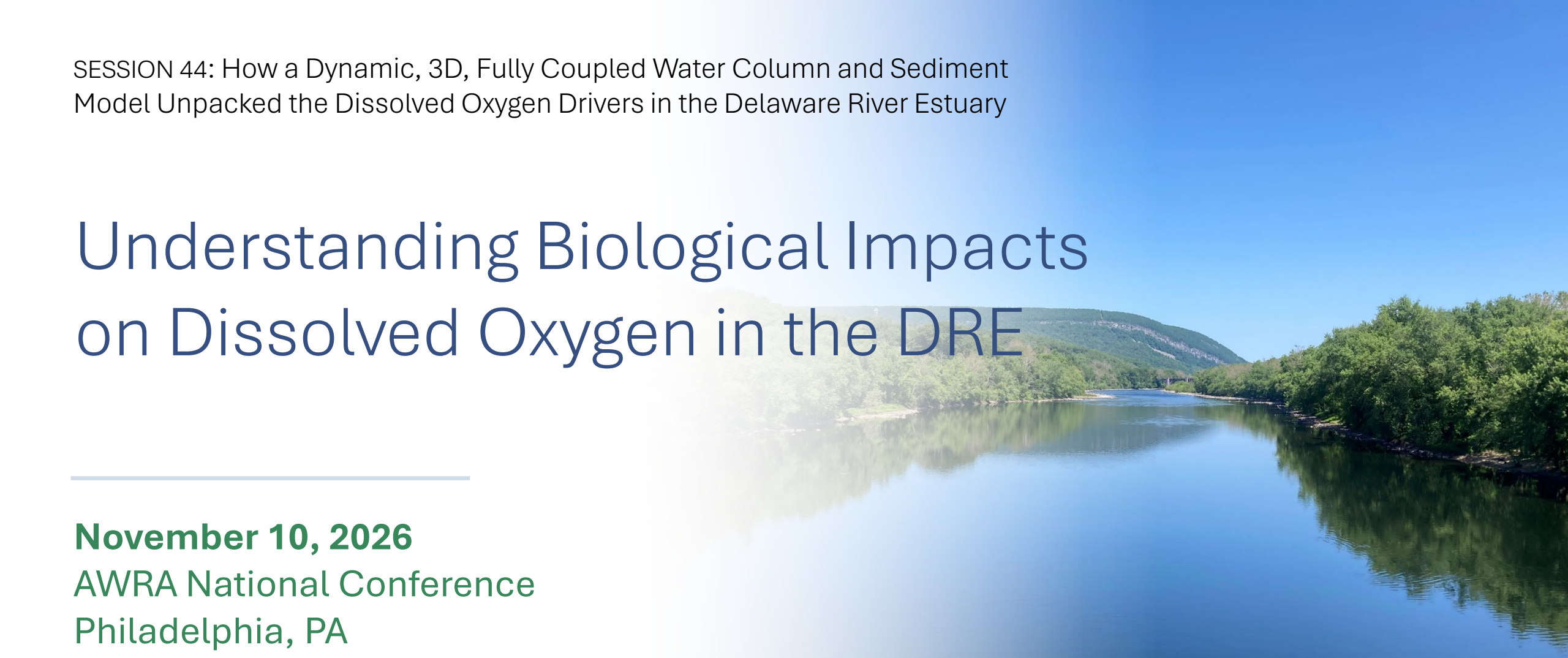


Summary

- Adopted EFDC to simulate flow, water temperature, salinity, and mixing characteristics
- Fine-tune salinity prediction in the urban area to support algal simulation
- Enhanced reaeration simulation using turbulent kinetic energy dissipation rate
- Developed a site-specific formulation for light attenuation coefficient
- Model performance indicated these physical processes that impact dissolved oxygen in DRE were simulated properly

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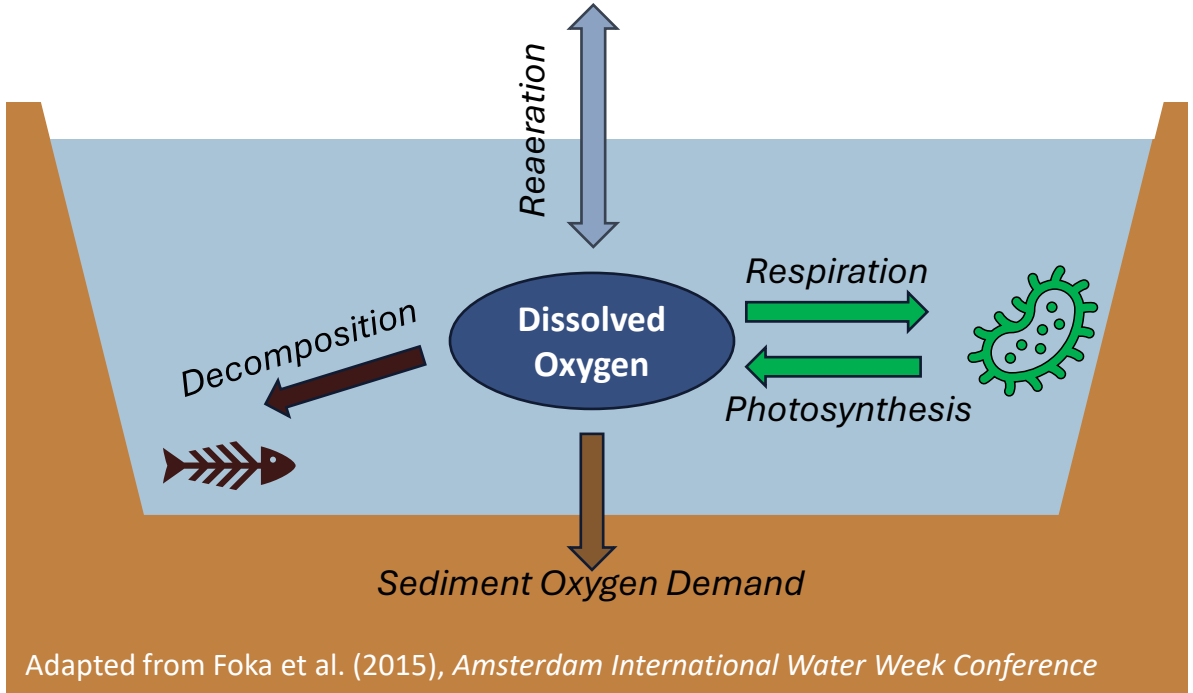
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Getting DO Right Means **Getting Phytoplankton Right**

- Unfortunately: modeling algal kinetics is **difficult**
- Although many DO processes are represented in our model, phytoplankton is a **major part** of the DO budget

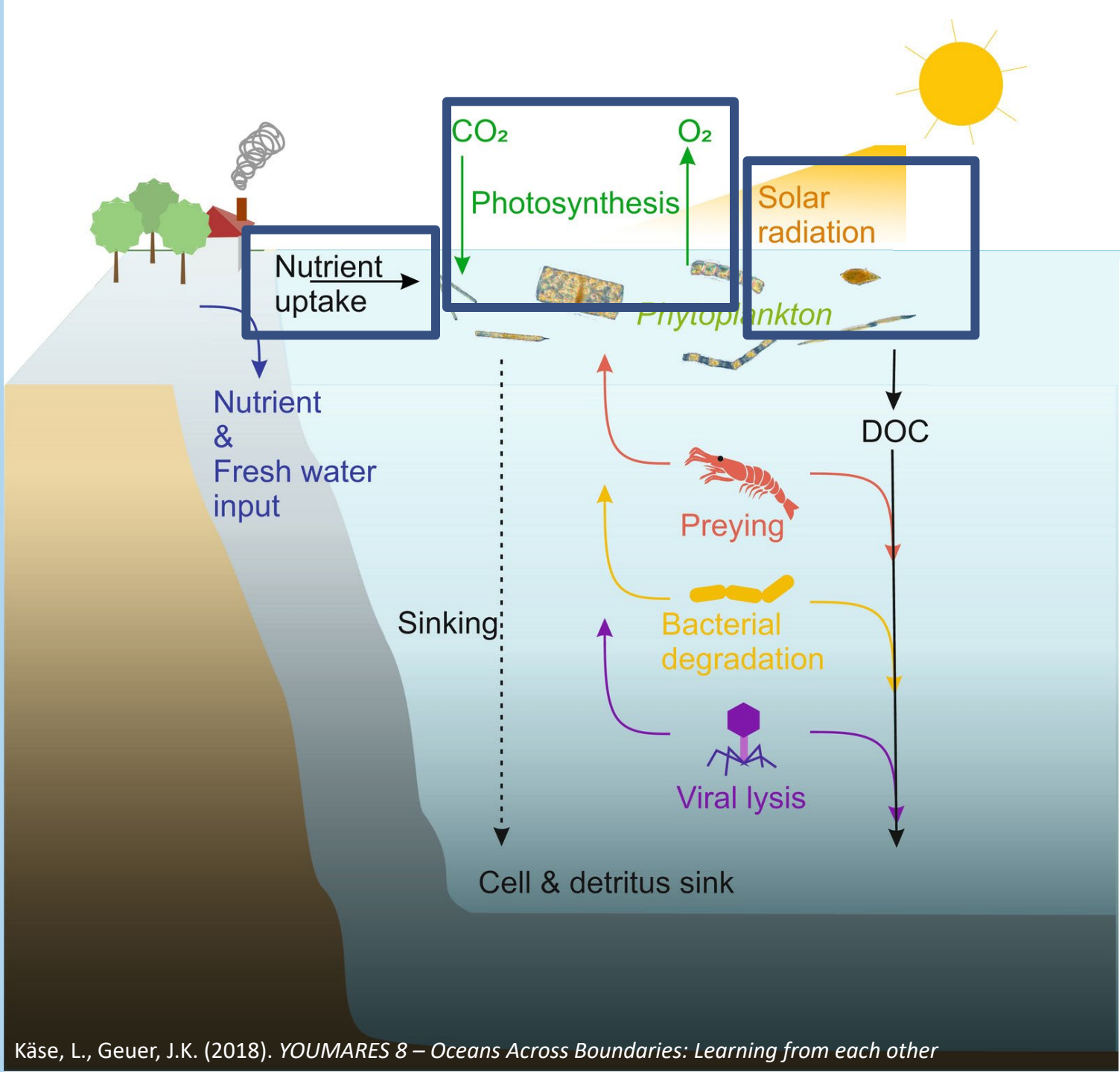


Adapted from Foka et al. (2015), *Amsterdam International Water Week Conference*

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How did we parameterize phytoplankton in our model?

- Light Limitation
- Nutrients
- Growth Kinetics



Käse, L., Geuer, J.K. (2018). *YOUMARES 8 – Oceans Across Boundaries: Learning from each other*

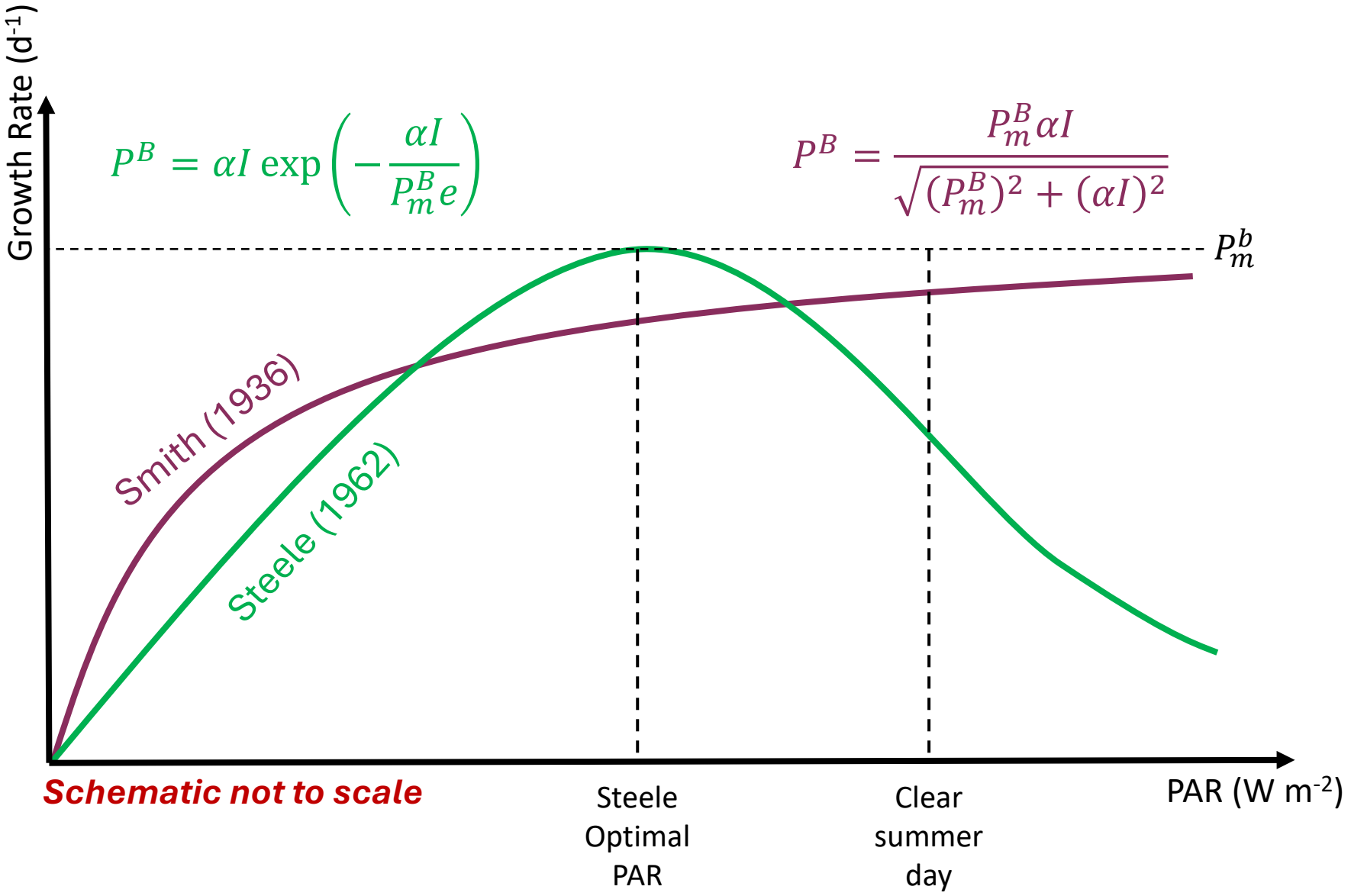
Our Model was Updated to **Remove Photoinhibition**

- **Photoinhibition**: a light-induced reduction in the photosynthetic capacity of algae
- Degree of photoinhibition is affected by **external** factors (temperature, nutrients) and **internal** factors (properties of the algal species)
- When modeling algal response to light, if photoinhibition is included in the model, one must set an **"optimal" PAR**
  - What does that look like?...



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Our Model was Updated to **Remove Photoinhibition**



Variable	Parameter
P^B	Primary productivity per unit chlorophyll biomass
I	Irradiance
α	Slope of the light saturation curve at low light levels
P_m^B	Specific photosynthetic rate at optimal illumination, i.e., the assimilation number

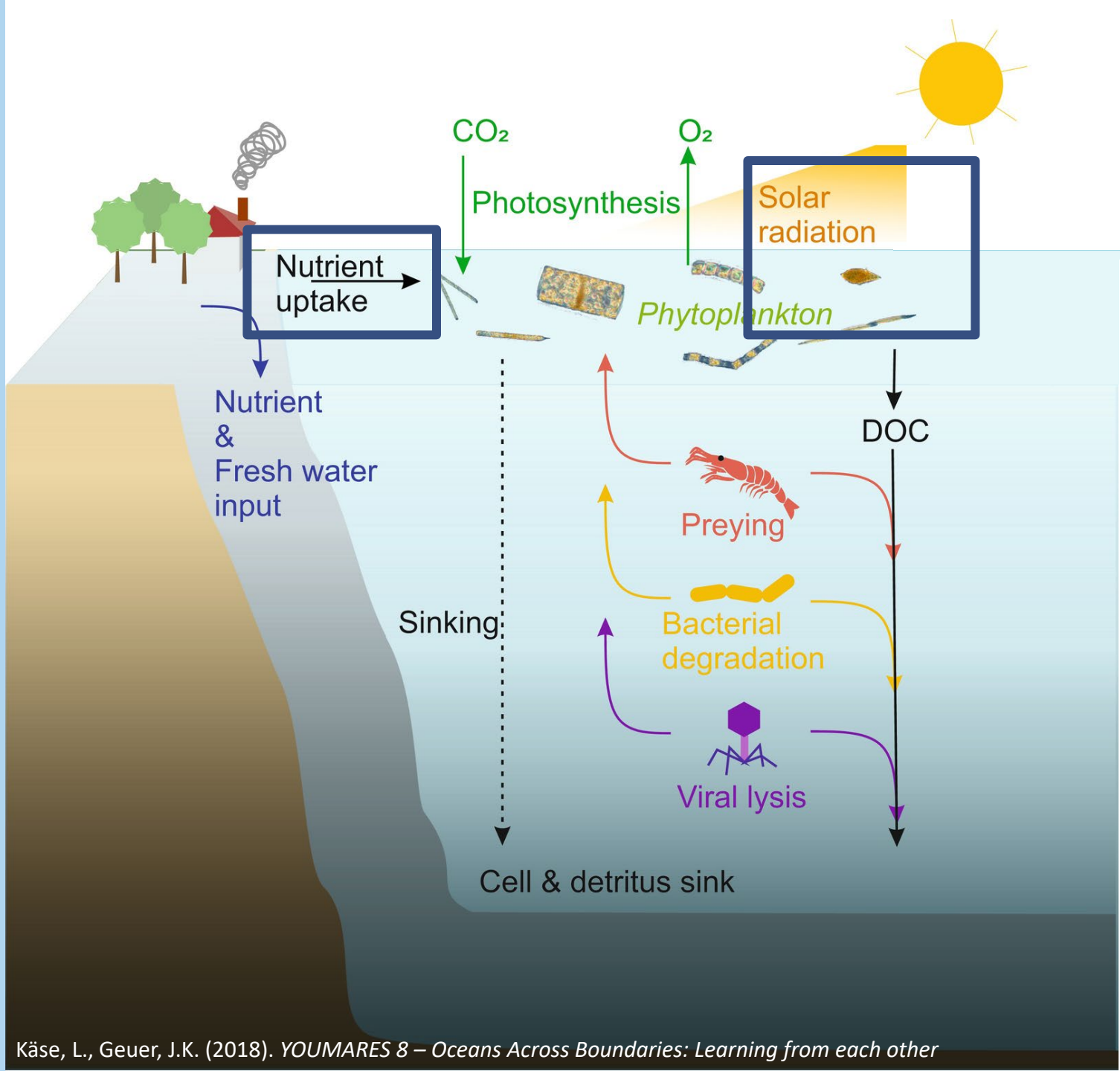
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How did we parameterize phytoplankton in our model?

Removed photoinhibition

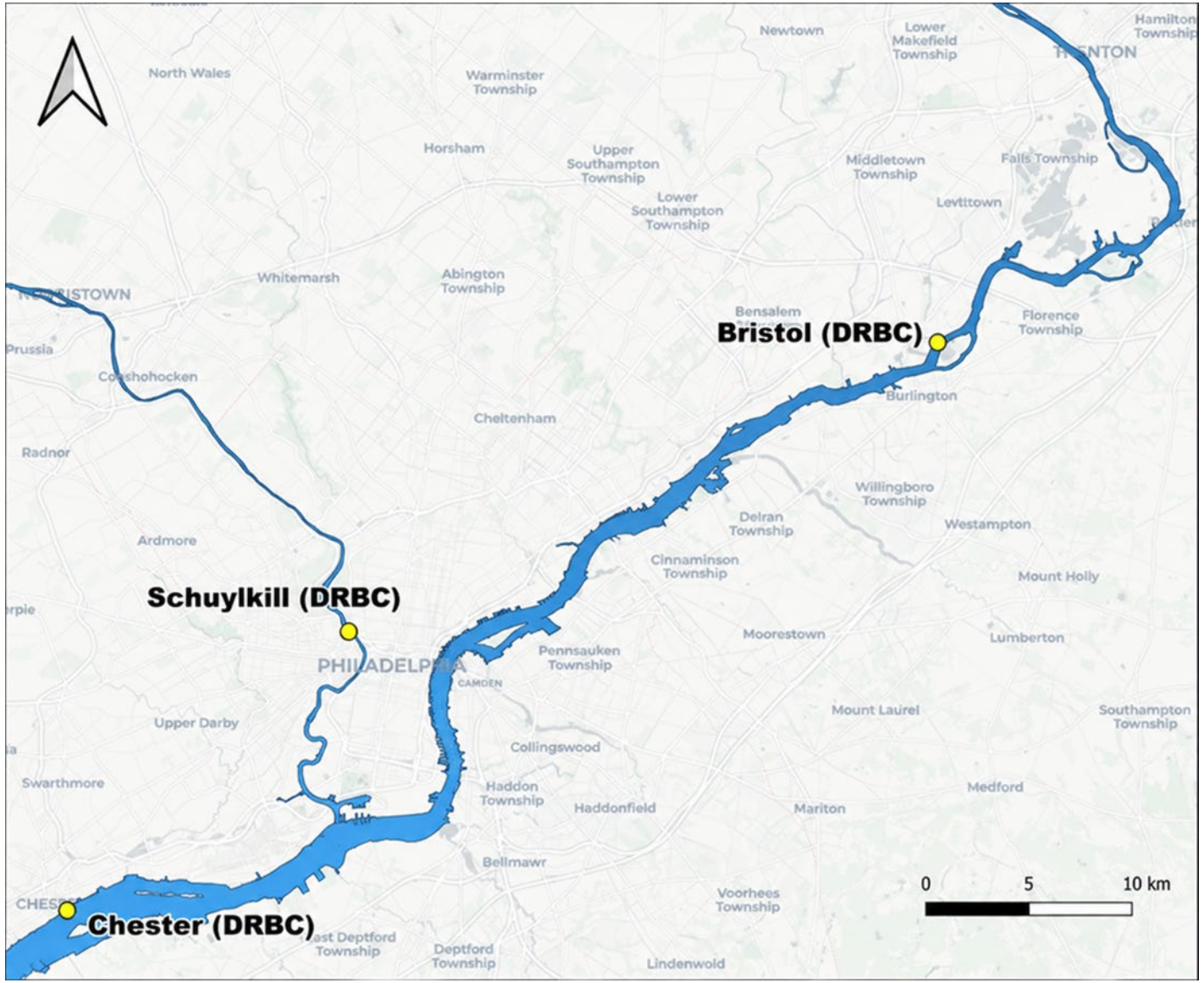
Nutrients

Growth Kinetics



Käse, L., Geuer, J.K. (2018). *YOUMARES 8 – Oceans Across Boundaries: Learning from each other*

Algal Composition Sampling Efforts



Monitoring Period	April – October 2024
Logger Locations	DRBC loggers: • Bristol (Zone 2) • Chester (Zone 4) • Schuylkill
Data collected	• Chlorophyll-a • Algal community composition (density, biovolume)

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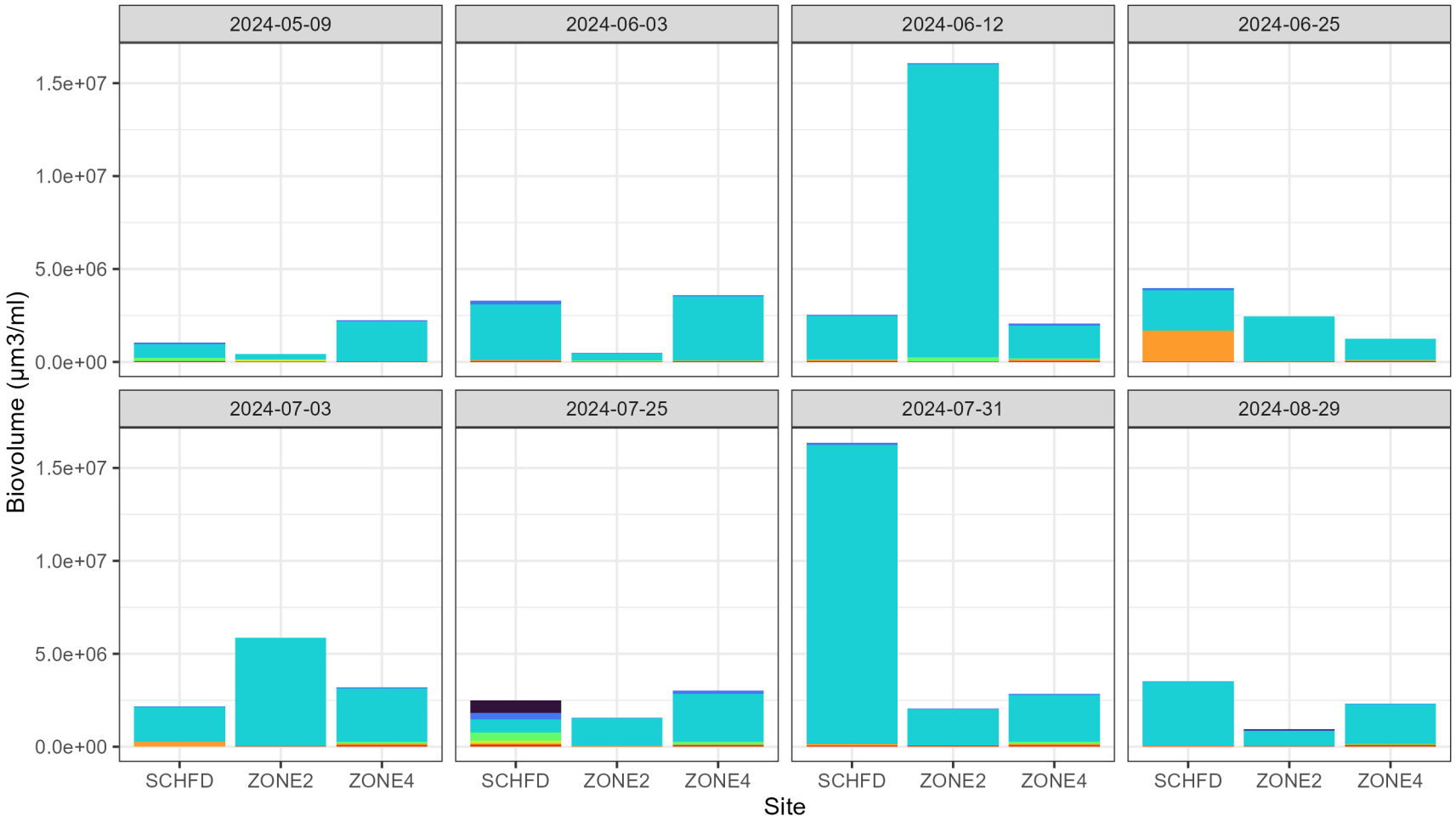
Algal Composition Analyses Summary

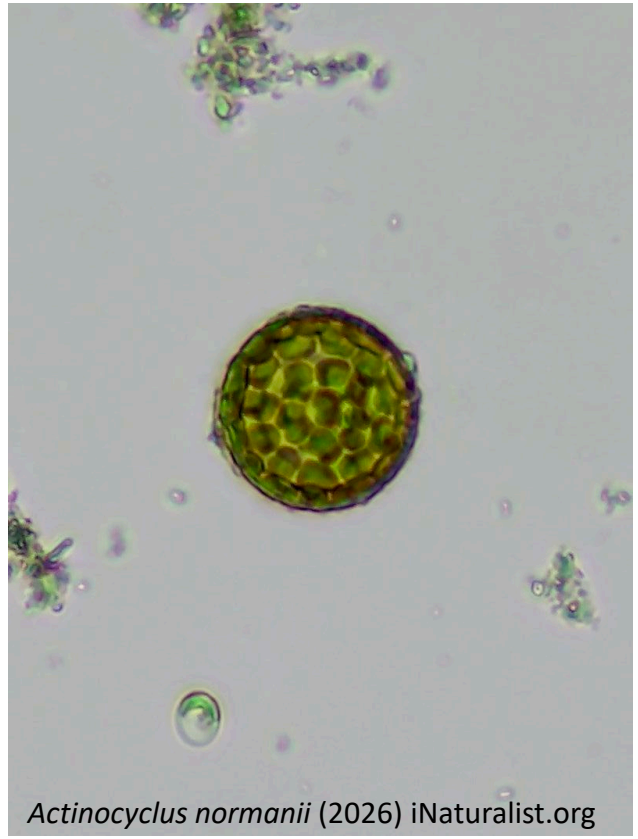
(Boat run samples 2019-2021, 2024)

		Season		
Location	RM	**Early Spring** (Mar – Apr)	**Late Spring** (May)	**Summer** (Jun – Sep)
Bay	<40	Diverse Diatom Community: *Thalassiosira levanderi* *Ditylum brightwellii*	Rare bloom: *Cyclotella choctawhatcheeana* *Thalassiosira eccentrica*	*Thalassiosira angulata* *Thalassiosira eccentrica* *Lithodesmium variabile*
ETM	~54.9	Little or no bloom	Rare bloom: *Actinocyclus normanii* *Stephanocyclus gamma* *Thalassiosira gessneri*	Little or no bloom
Freshwater	>74	Little or no bloom	Primary: *Actinocyclus normanii* Secondary: *Thalassiosira gessneri*	Primary: *Actinocyclus normanii* *Stephanocyclus gamma* Secondary: *Thalassiosira lacustris*

Phyto 1
Phyto 2
Phyto 3

Diatoms Dominate the Estuary





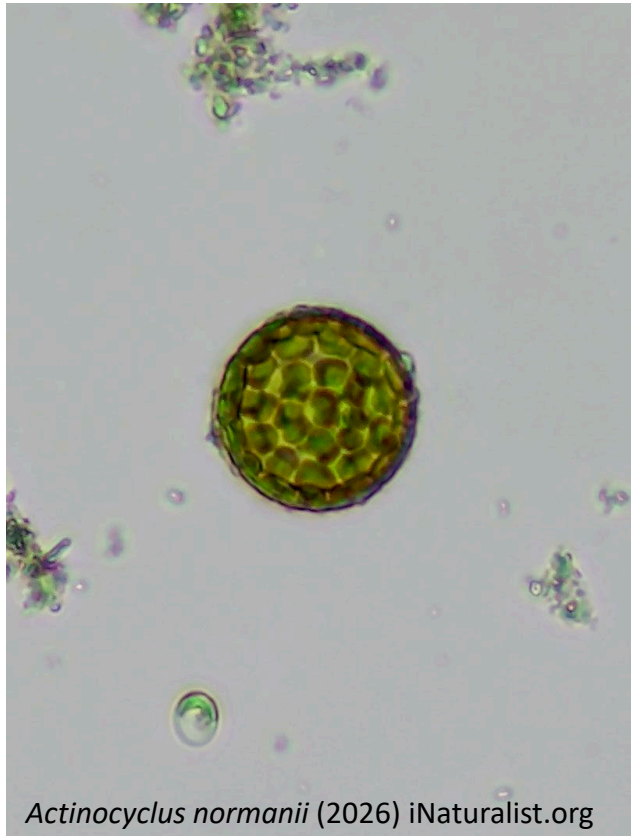
Actinocyclus normanii (2026) iNaturalist.org

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Diatoms Dominate the Estuary

Parameter	2024	2026	References
Half-saturation constant for Silica uptake [-]	0.20	0.10	Paasche (1986), *Marine Biology* Olsen and Paasche (1986), *British Phycological Journal* Conley et al. (1989), *Limnology and Oceanography*
Silica to carbon ratio [mg Si (mg $C^{)-1}$]	1.2	1.4	Brzezinski (1985), *Journal of Phycology* Chapra (2008), *Surface Water-Quality Modeling*
Salinity mortality threshold (fresh to saltwater) [ppt]	0.10	0.05	Potapova (2011), *The Diatom World*
Salinity level for half mortality (due to salinity toxicity) [ppt]	1.0	0.30	Potapova (2011), *The Diatom World*



Actinocyclus normanii (2026) iNaturalist.org

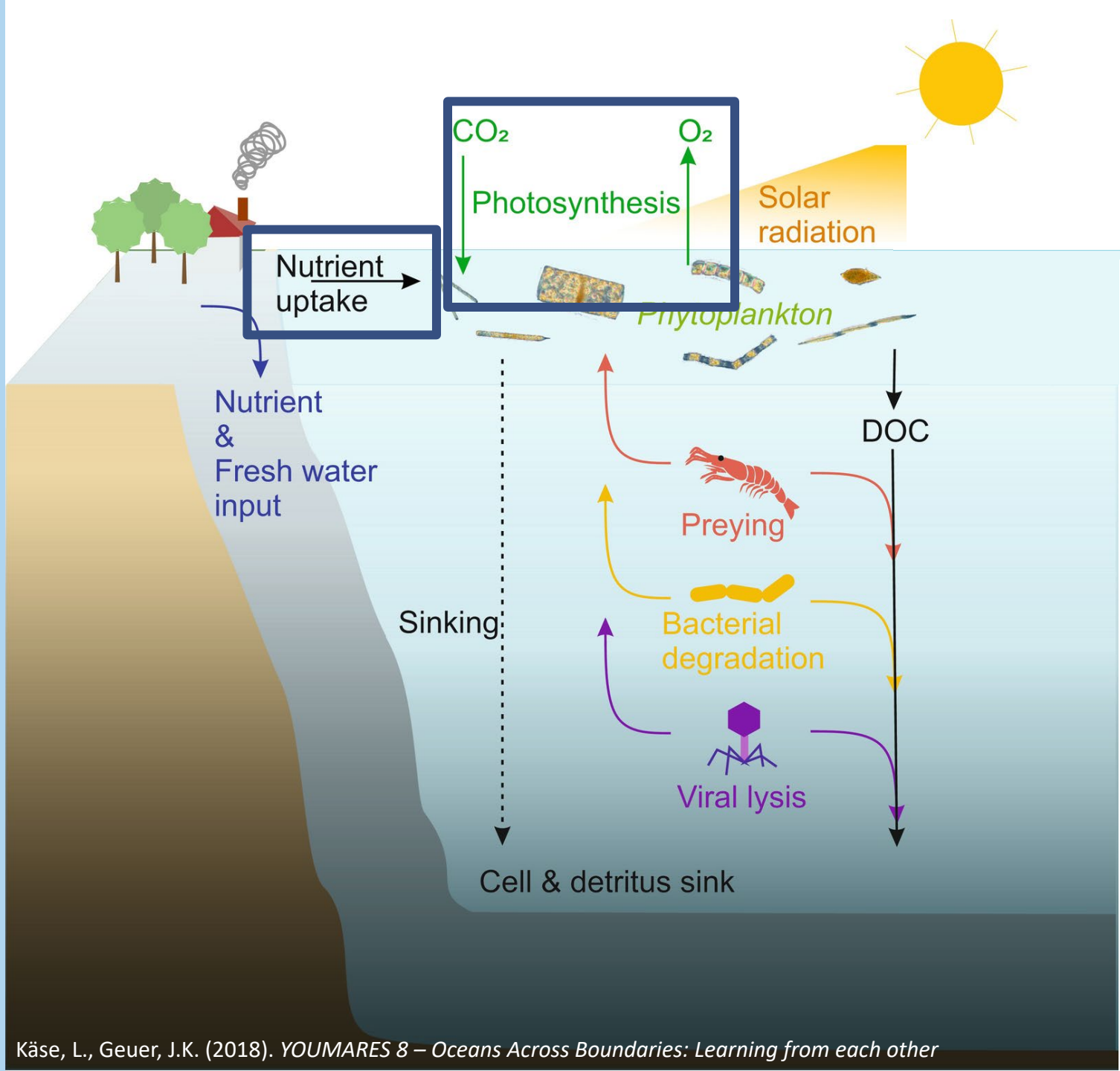
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How did we parameterize phytoplankton in our model?

Removed photoinhibition

Altered nutrient limitation, salinity toxicity, and stoichiometry

Growth Kinetics



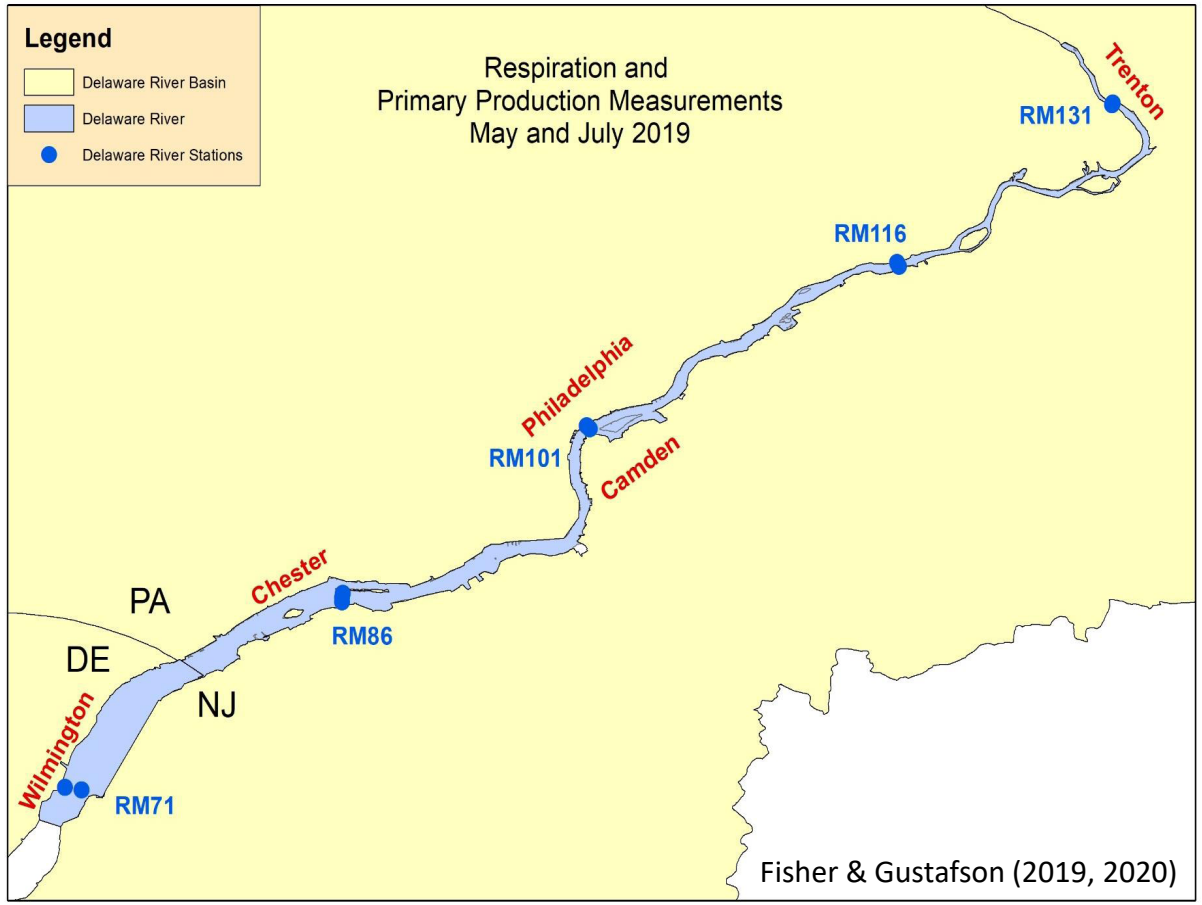
Käse, L., Geuer, J.K. (2018). *YOUMARES 8 – Oceans Across Boundaries: Learning from each other*

Validation of Phytoplankton Kinetics

- The DRBC collected algae data from five transects in 2018-2019 and had laboratory analyses performed to measure **primary productivity** and **respiration** rates
- In the model, our phytoplankton sink/source term (S) follows first-order kinetics

$$S = \frac{\mathrm{d}C_{alg}}{\mathrm{d}t} = (G - R - D - K)C_{alg},$$

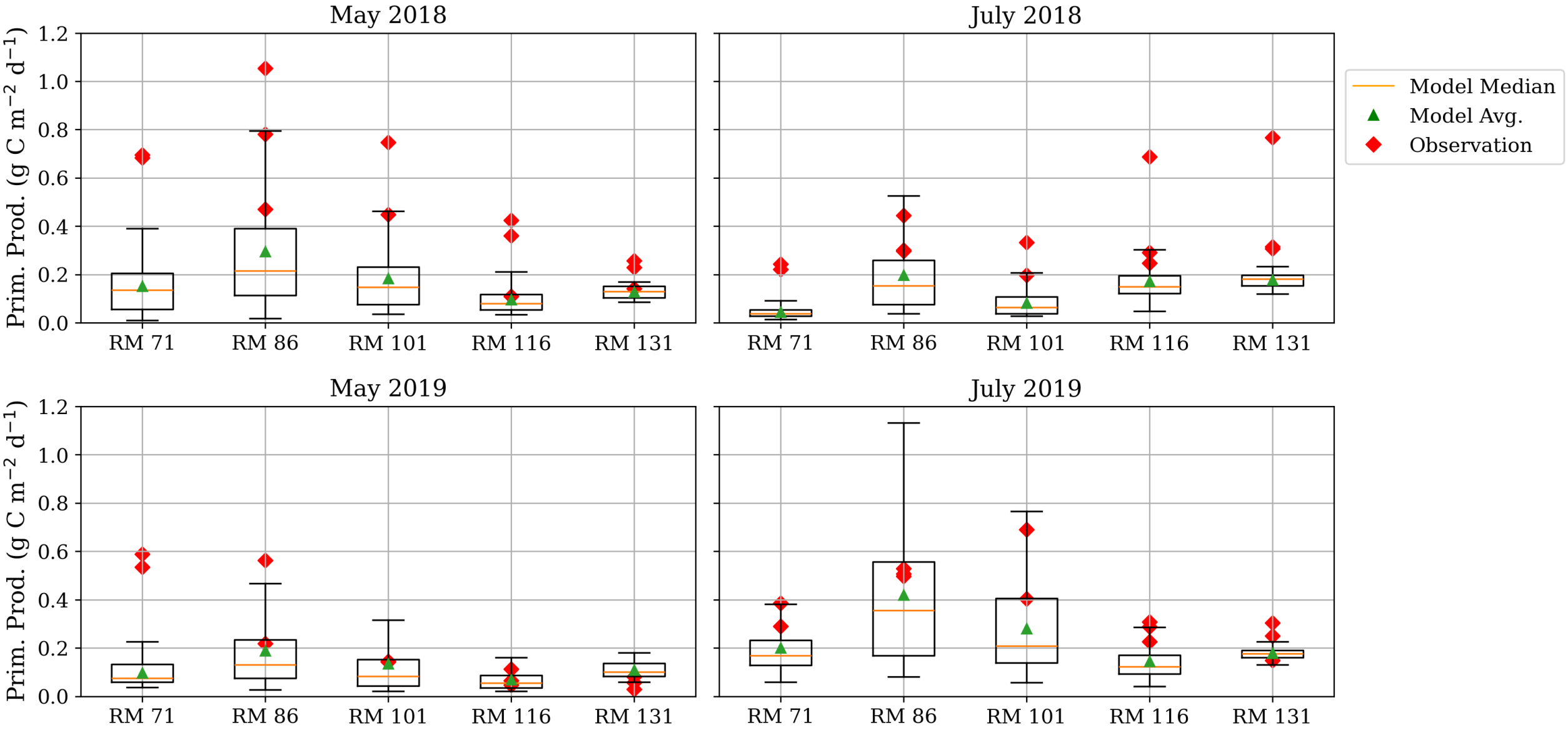
Variable	Parameter
C_{alg}	phytoplankton concentration [mg-C L^{-1}]
G	growth rate at 20°C (adjusted by temperature, light, and nutrient limitations) [d^{-1}]
R	respiration rate at 20°C (adjusted by temperature) [d^{-1}]
D	death rate [d^{-1}]
K	settling rate [d^{-1}]



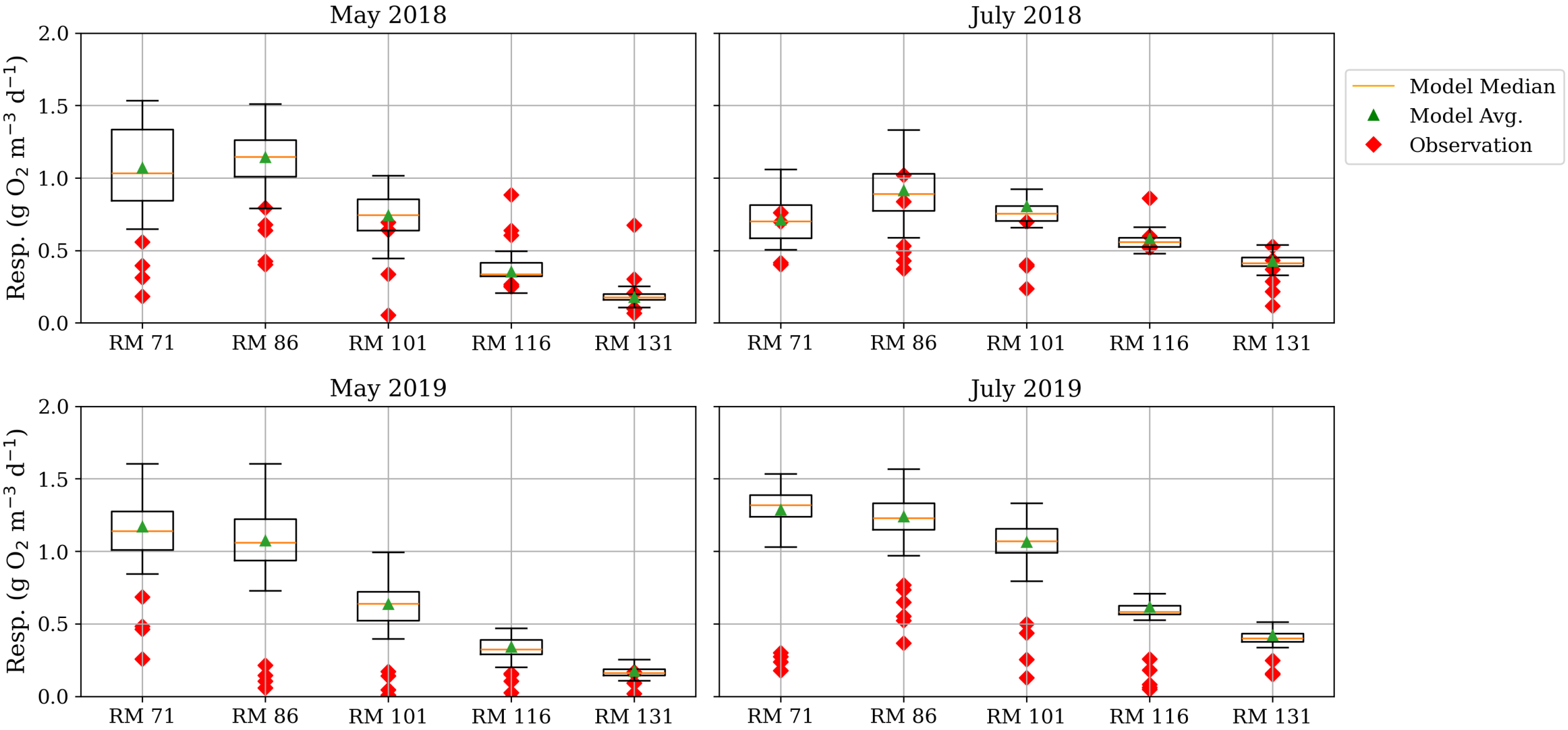
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$$\frac{dC_{alg}}{dt} = (\boldsymbol{G} - R - D - K)C_{alg}$$



$$\frac{dC_{alg}}{dt} = (G - \mathbf{R} - D - K)C_{alg}$$



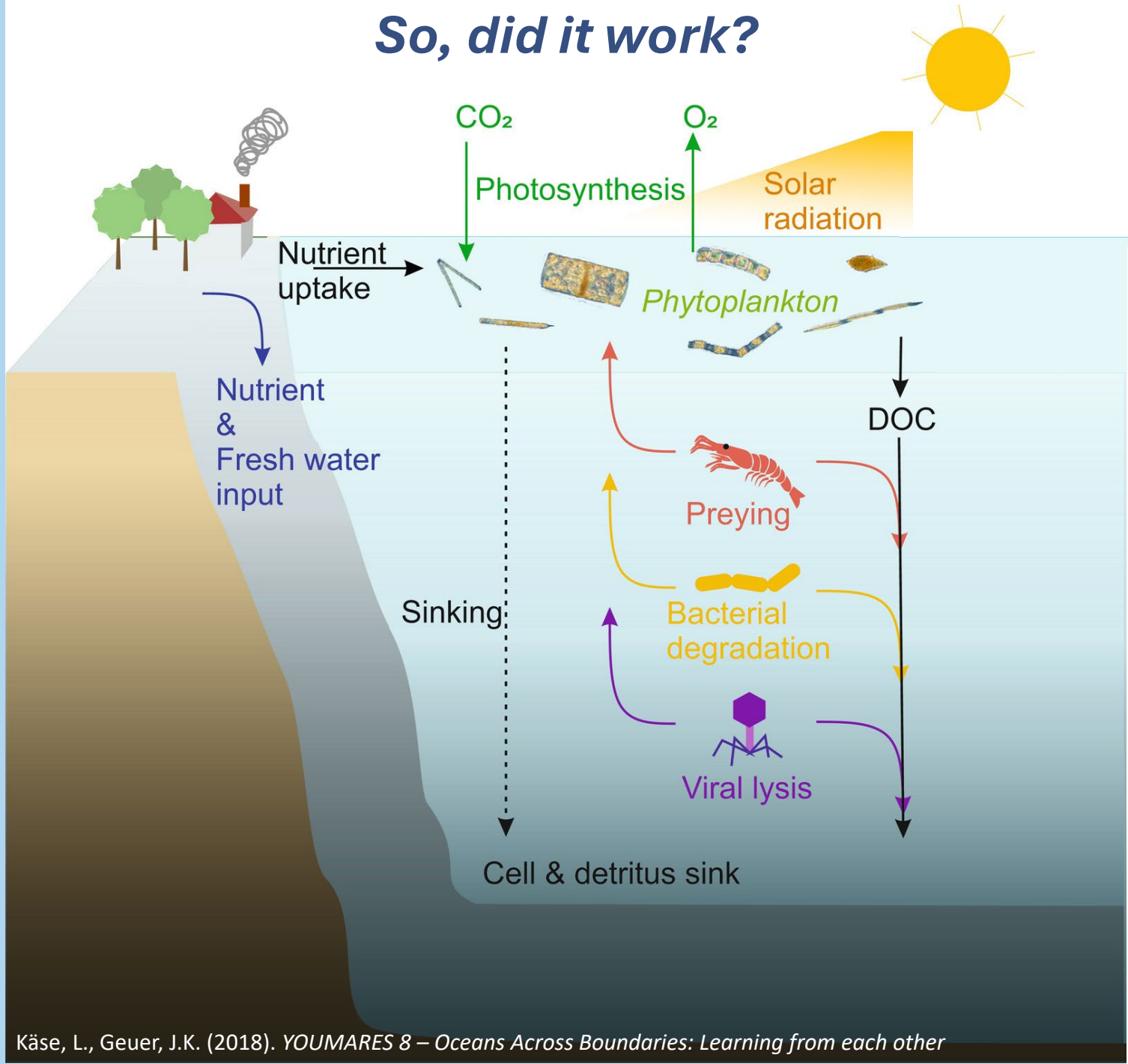
How did we parameterize phytoplankton in our model?

Removed photoinhibition

Altered nutrient limitation, salinity toxicity, and stoichiometry

Corroborated primary productivity and respiration measurements

So, did it work?



Käse, L., Geuer, J.K. (2018). *YOUMARES 8 – Oceans Across Boundaries: Learning from each other*

How did we parameterize phytoplankton in our model?

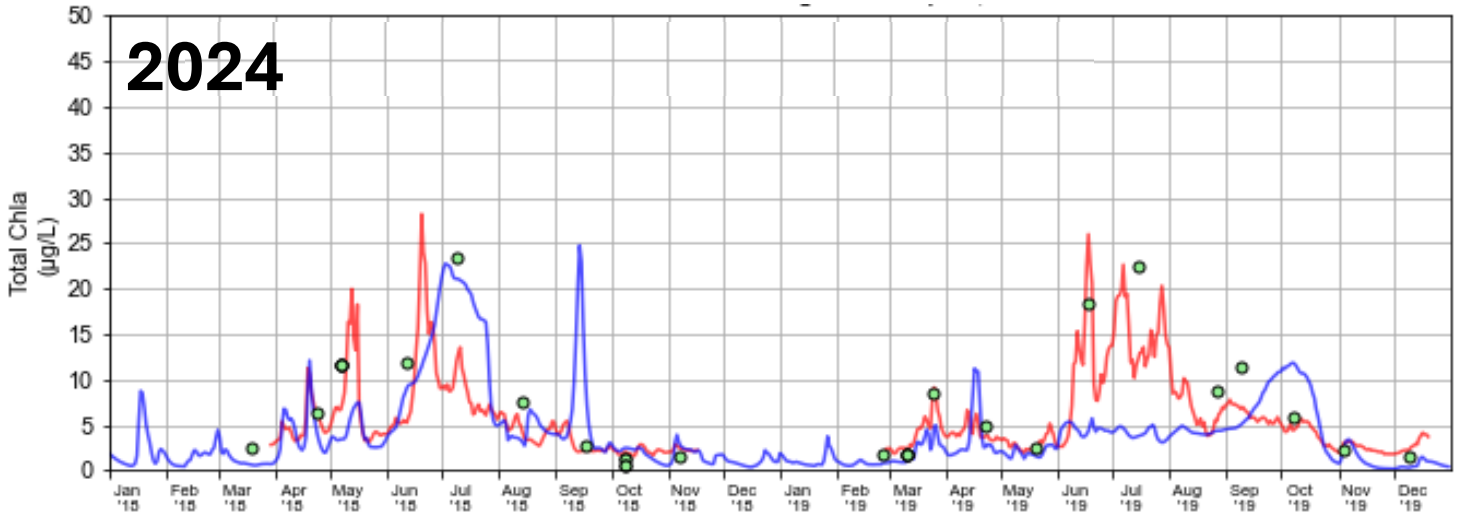
Removed photoinhibition

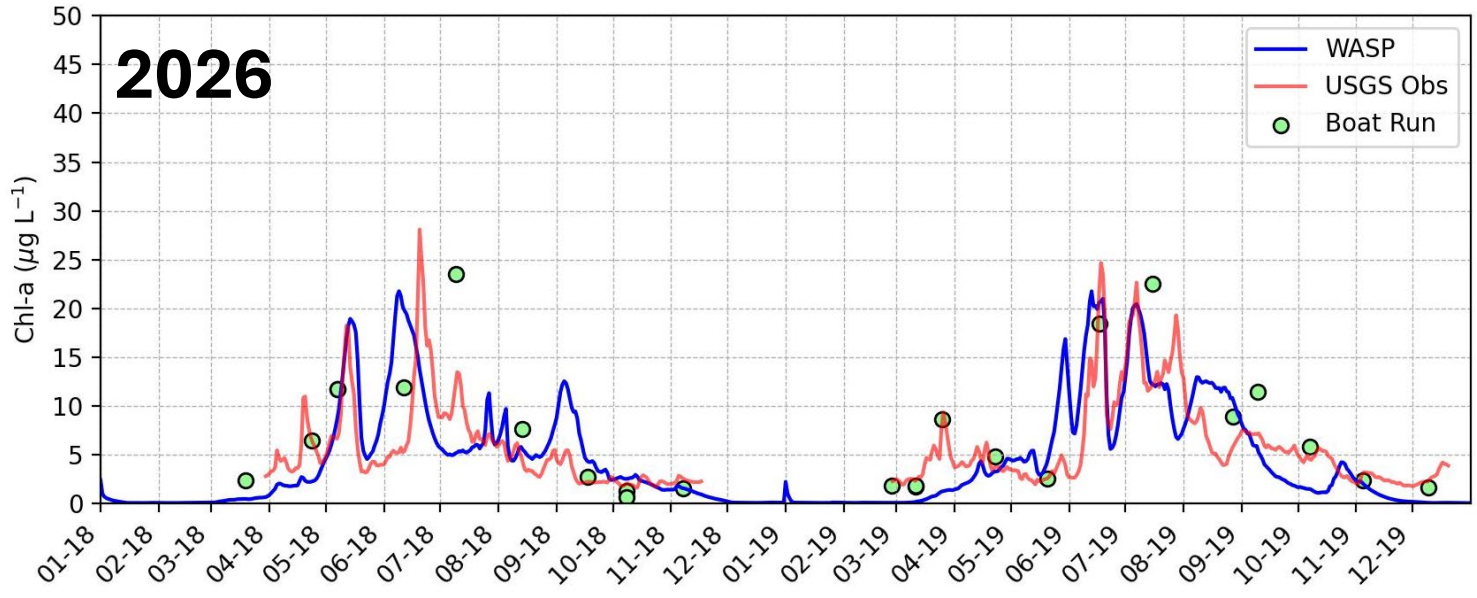
Altered nutrient limitation, salinity toxicity, and stoichiometry

Corroborated primary productivity and respiration measurements

So, did it work?

Simulated and Observed Chl-a at Ben Franklin Bridge Philadelphia, RM 100.1: 2018 to 2019





How did we parameterize phytoplankton in our model?

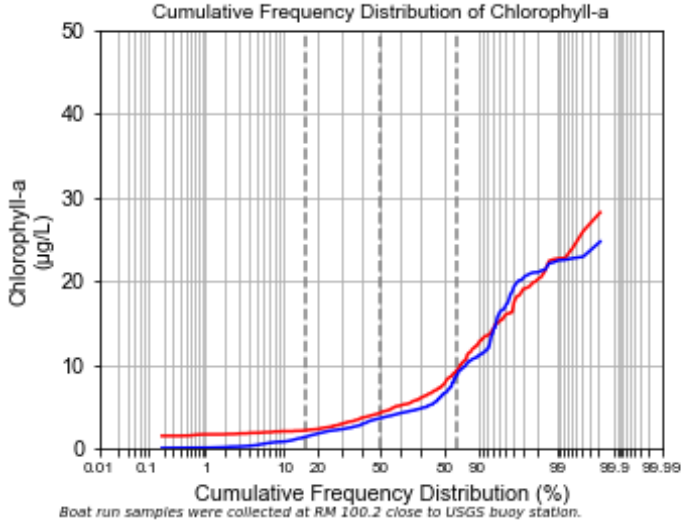
Removed photoinhibition

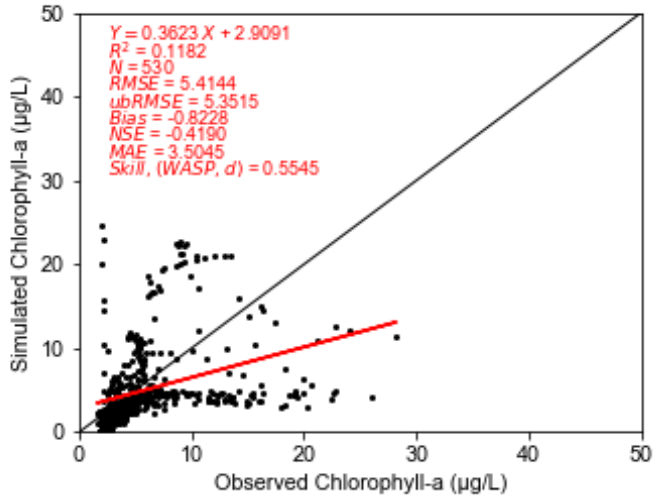
Altered nutrient limitation, salinity toxicity, and stoichiometry

Corroborated primary productivity and respiration measurements

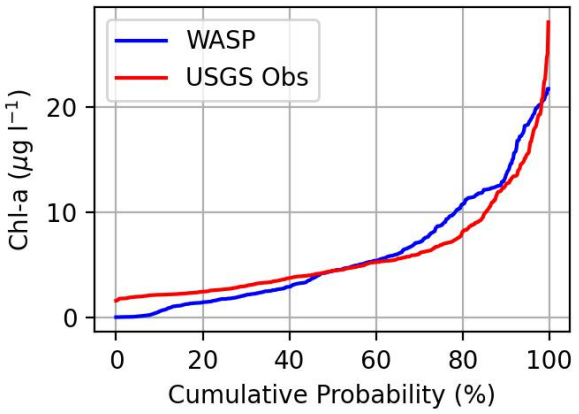
So, did it work?

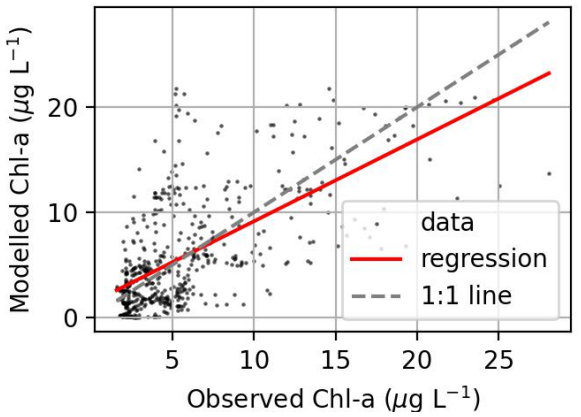
2024





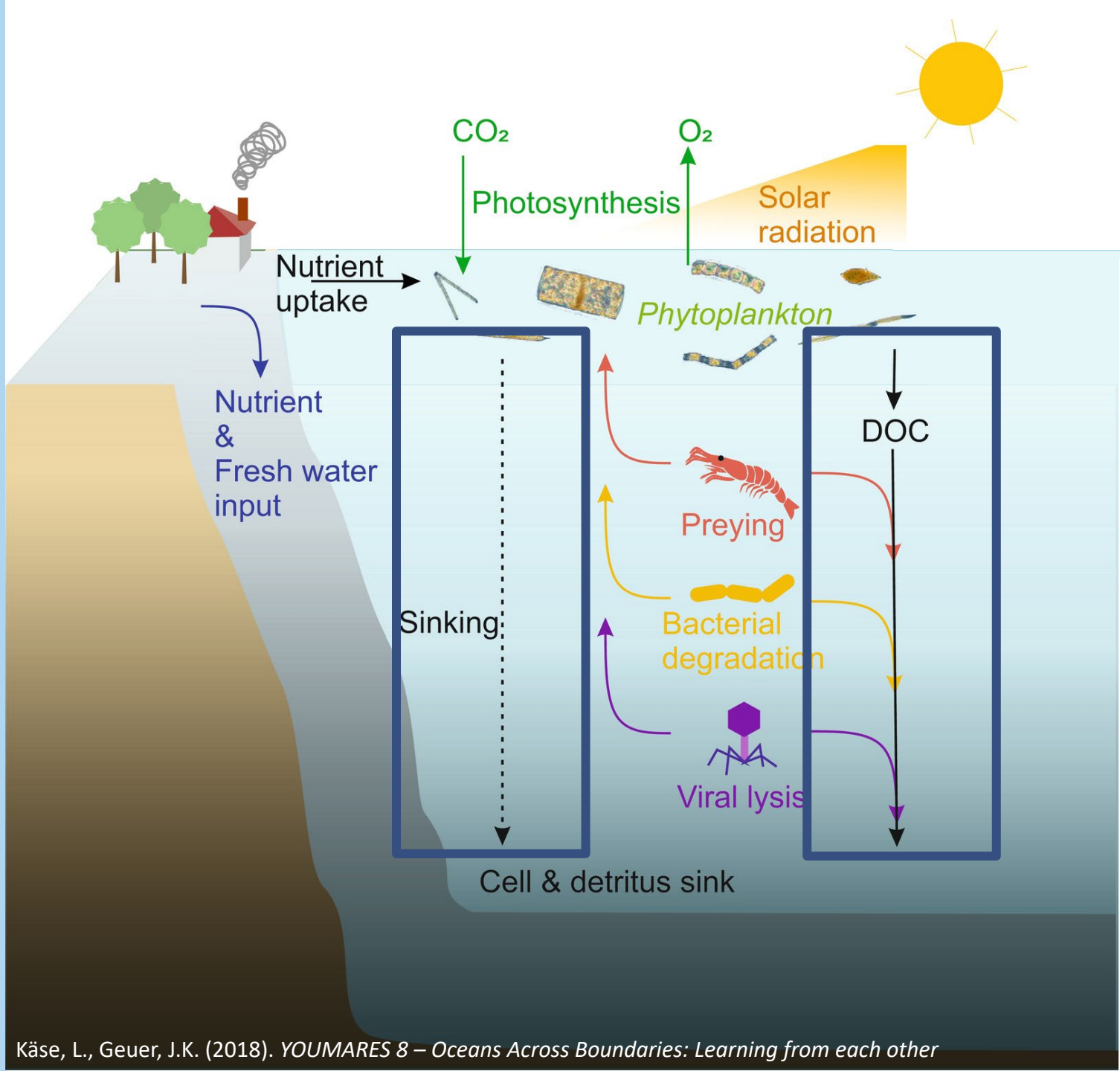
2026





R^2 = 0.42
y = 0.778x + 1.359
N = 530
RMSE = 4.22
ubRMSE = 4.22
Bias = 0.07
NSE = 0.11
Skill = 0.79
MAE = 3.08

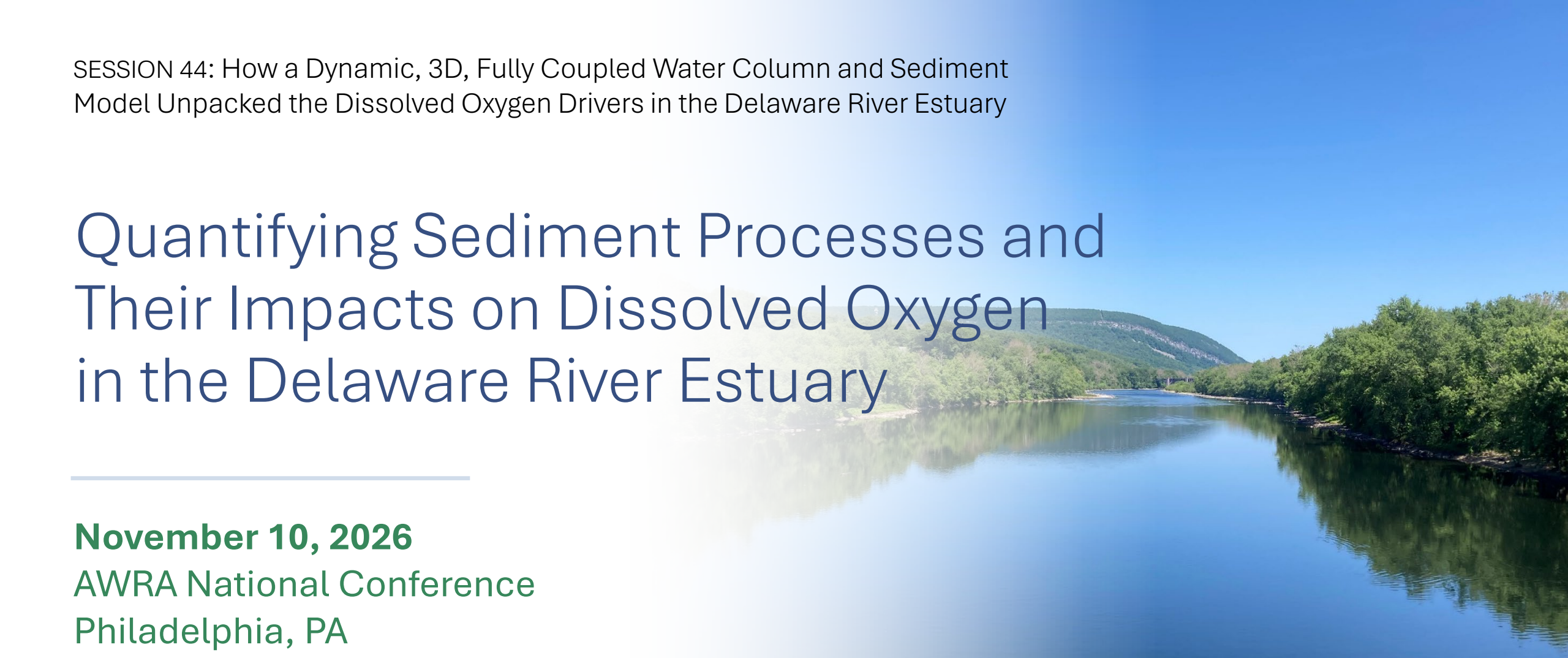
But what about the end of the phytoplankton life cycle?



Käse, L., Geuer, J.K. (2018). *YOUMARES 8 – Oceans Across Boundaries: Learning from each other*

SESSION 44: How a Dynamic, 3D, Fully Coupled Water Column and Sediment Model Unpacked the Dissolved Oxygen Drivers in the Delaware River Estuary

Quantifying Sediment Processes and Their Impacts on Dissolved Oxygen in the Delaware River Estuary



November 10, 2026

AWRA National Conference

Philadelphia, PA

Li Zheng, Ph.D.

Joey Fogarty, Ph.D.

Matt Amato, Ph.D.

Thomas Amidon, BCES

Sarah Beganskas, Ph.D.

Namsoo Suk, Ph.D.

Delaware River Basin Commission

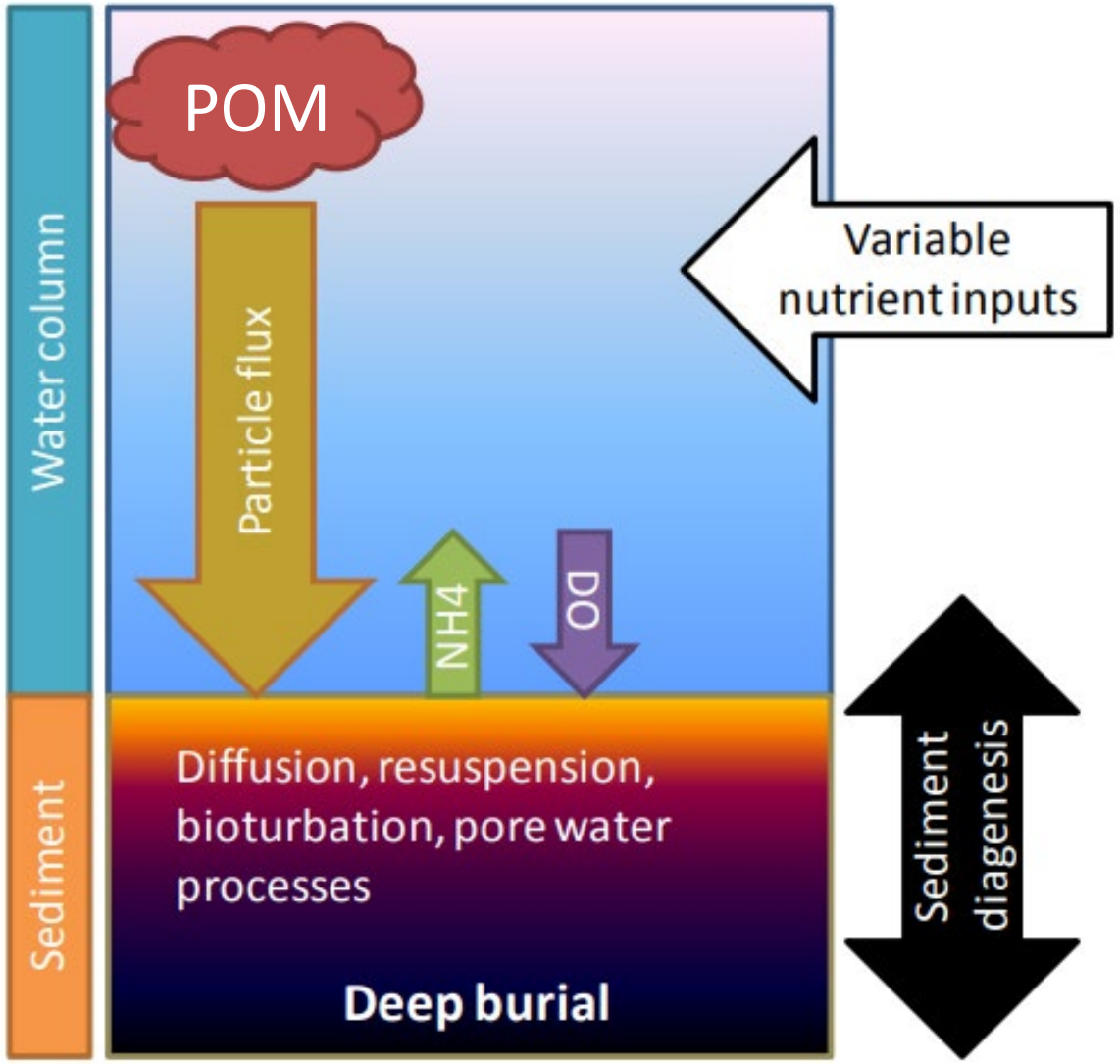
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Sediments play a key role in regulating dissolved oxygen and nutrient dynamics in the DRE

Sediment Diagenesis - the physical, chemical, and biological processes that transform particulate organic matter (POM) within bottom sediments



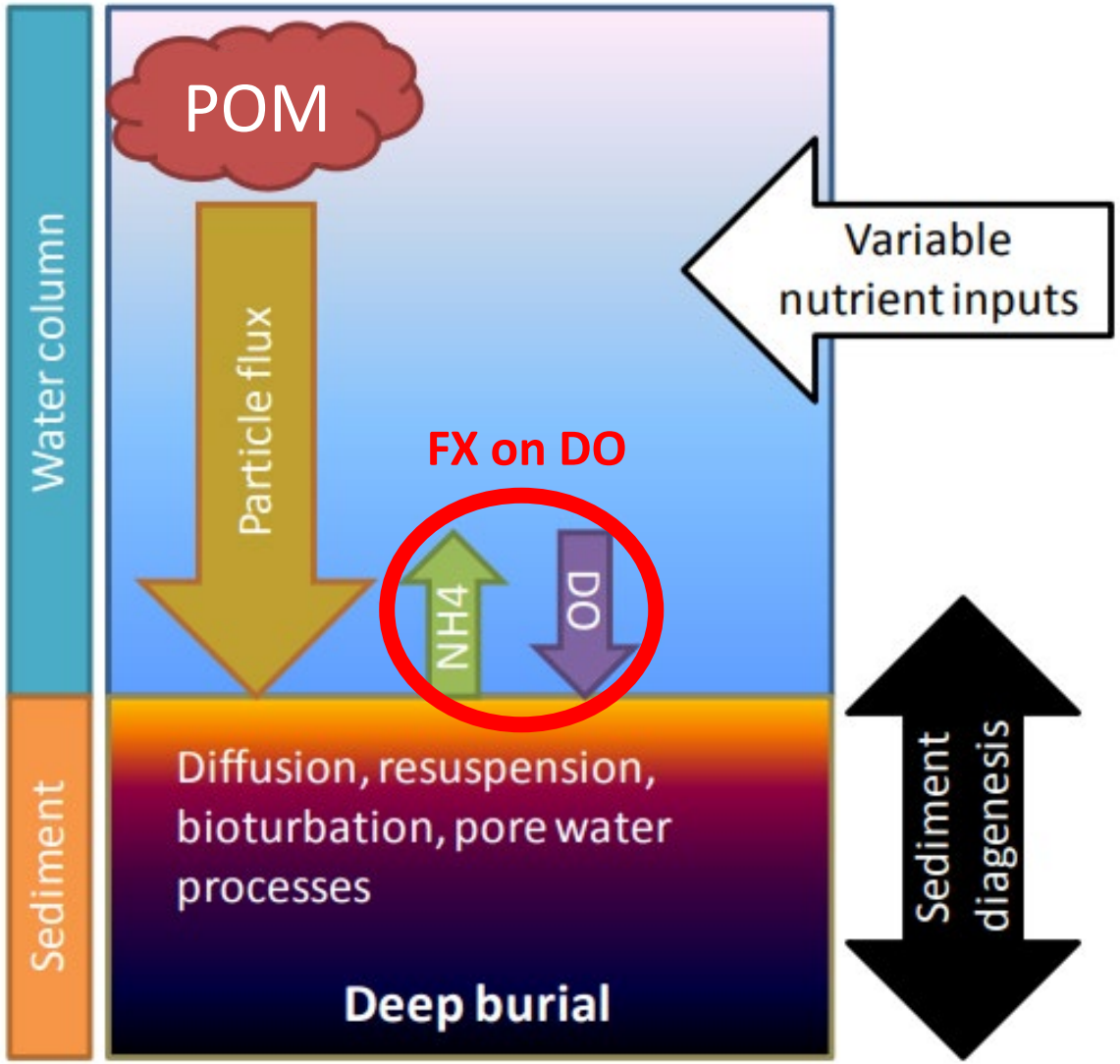
Adapted from Pelletier et al., 2024

Sediments play a key role in regulating dissolved oxygen and nutrient dynamics in the DRE

Sediment Diagenesis - the physical, chemical, and biological processes that transform particulate organic matter (POM) within bottom sediments

Impacts on Dissolved Oxygen

- Microbial Decomposition of Organic C
- Mineralization of Organic N into NH_4



Adapted from Pelletier et al., 2024

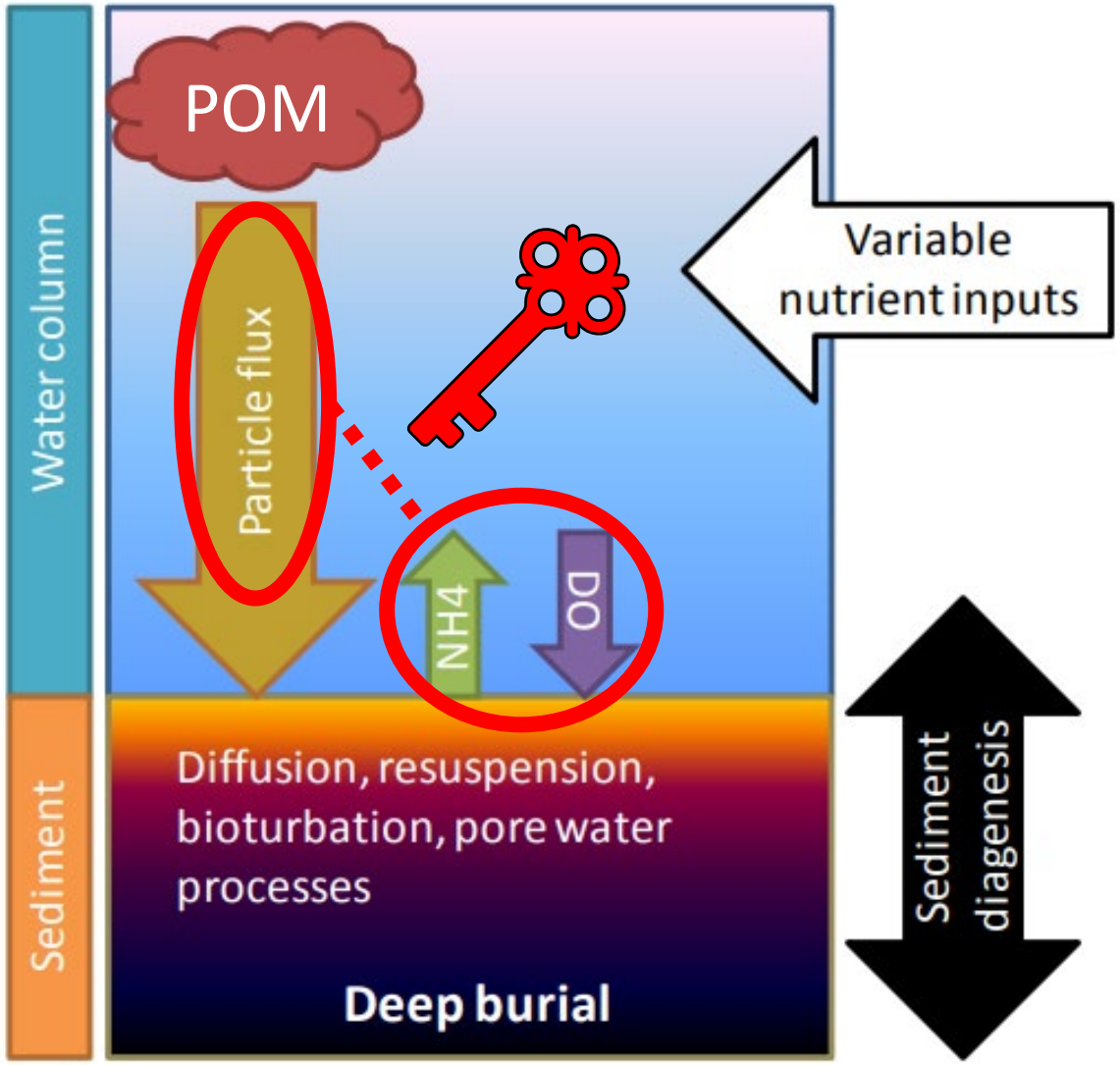
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Impacts on Dissolved Oxygen

- Microbial Decomposition of Organic C
- Mineralization of Organic N into NH_4

The key to modeling sediment diagenesis is capturing this settling flux of POM!!!

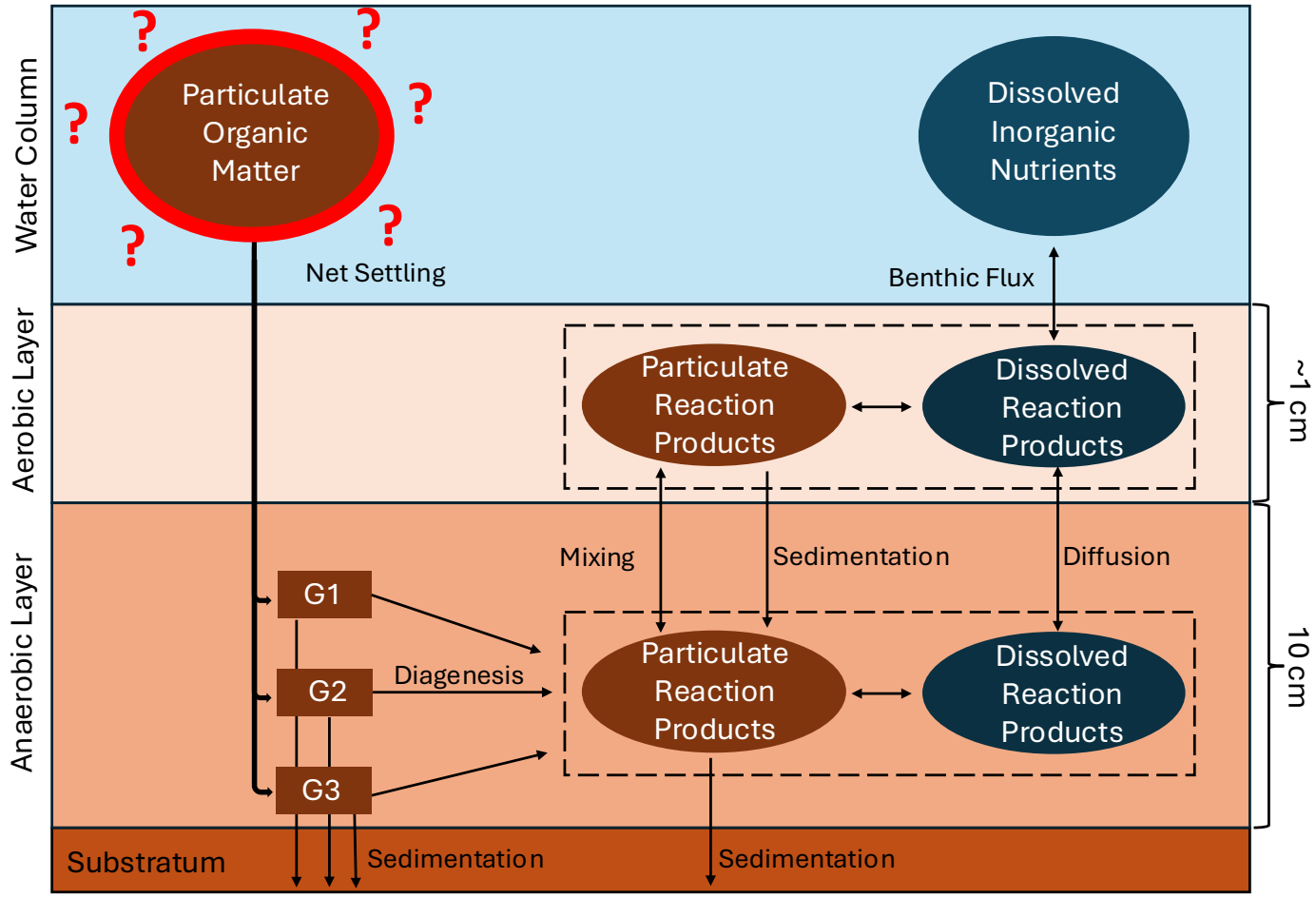


Adapted from Pelletier et al., 2024

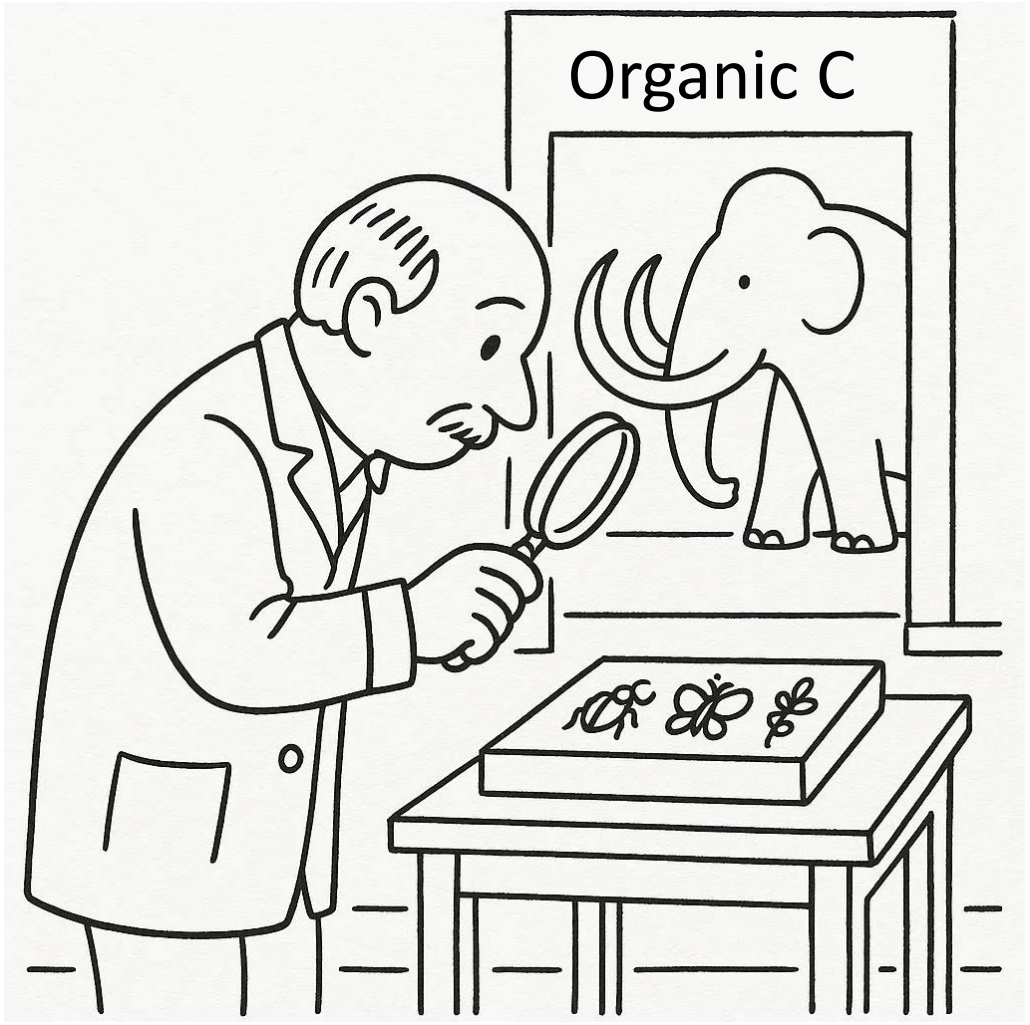
Under the Hood of a Sediment Diagenesis Model

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Sediment Diagenesis Model (Di Toro)



How to Get a Sediment Diagenesis Model Off the Ground 101



Based on Ivan Krylov's 1814 fable, "The Inquisitive Man"

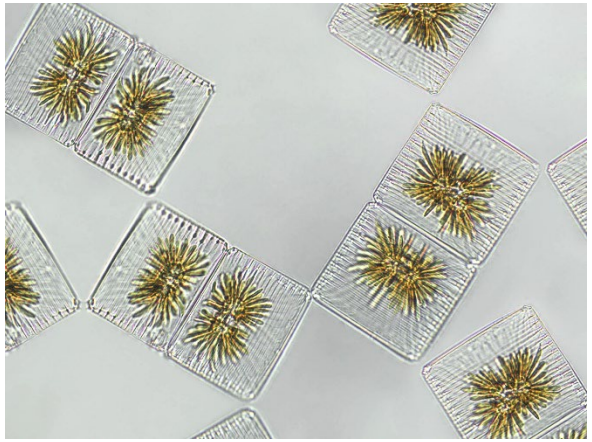
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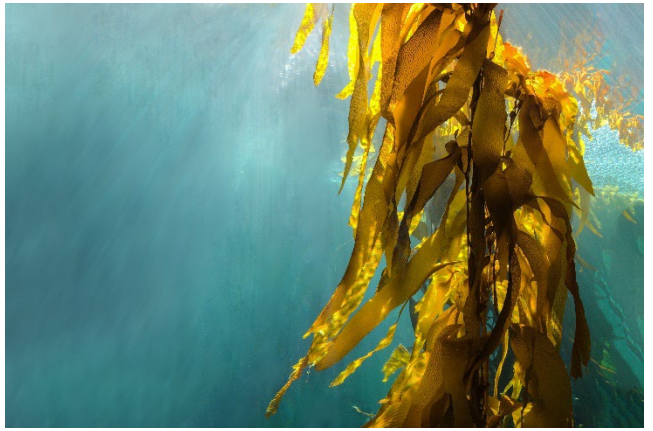
Where does the C come from?

Autochthonous (*internal*) sources: **phytoplankton**, SAV, periphyton

Allocthonous (*external*) sources: **tributaries, tidal marshes, atmospheric deposition**

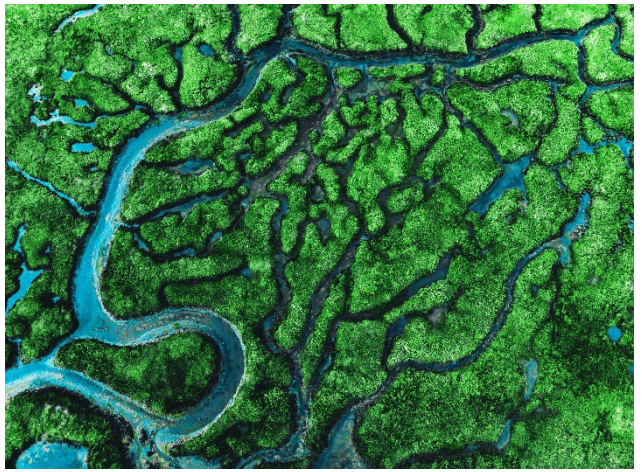
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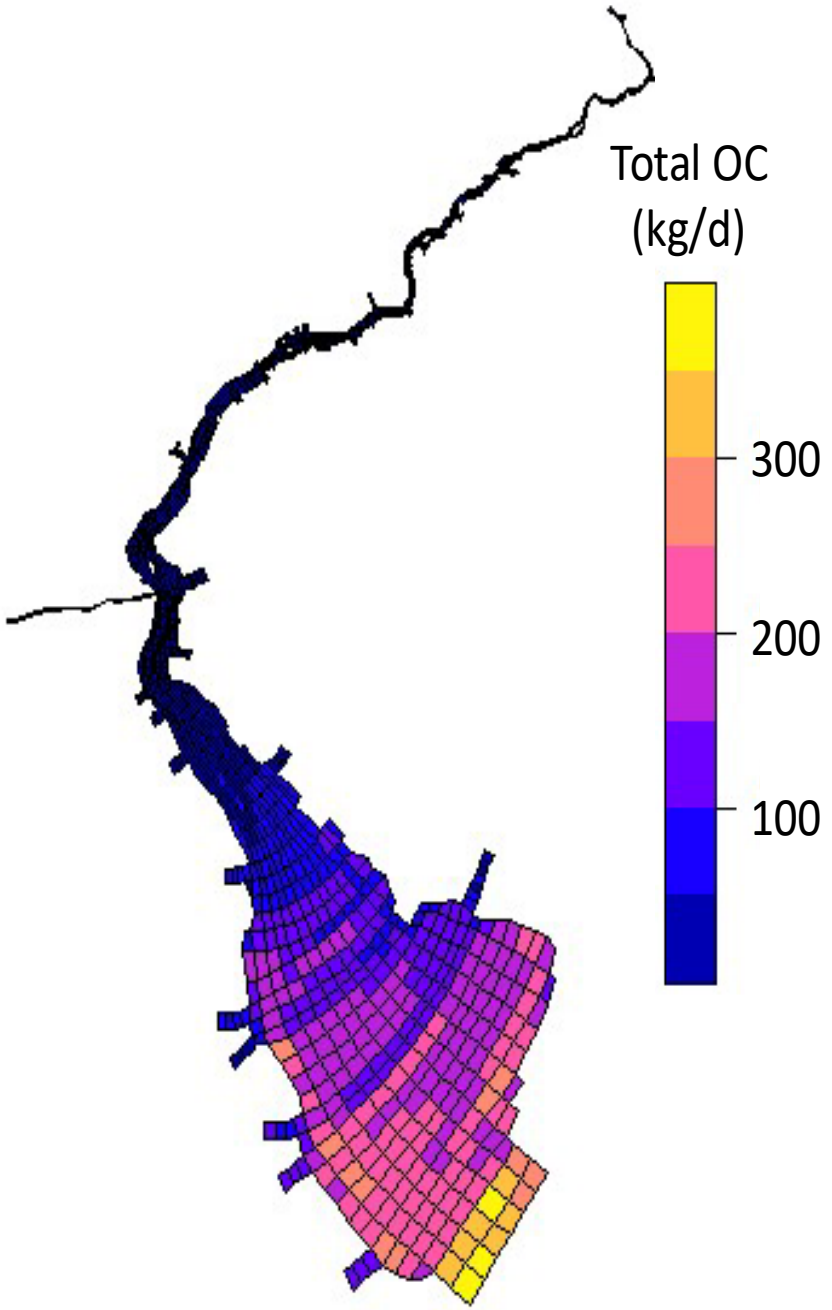


Atmospheric deposition determined from the surface area of our model grid

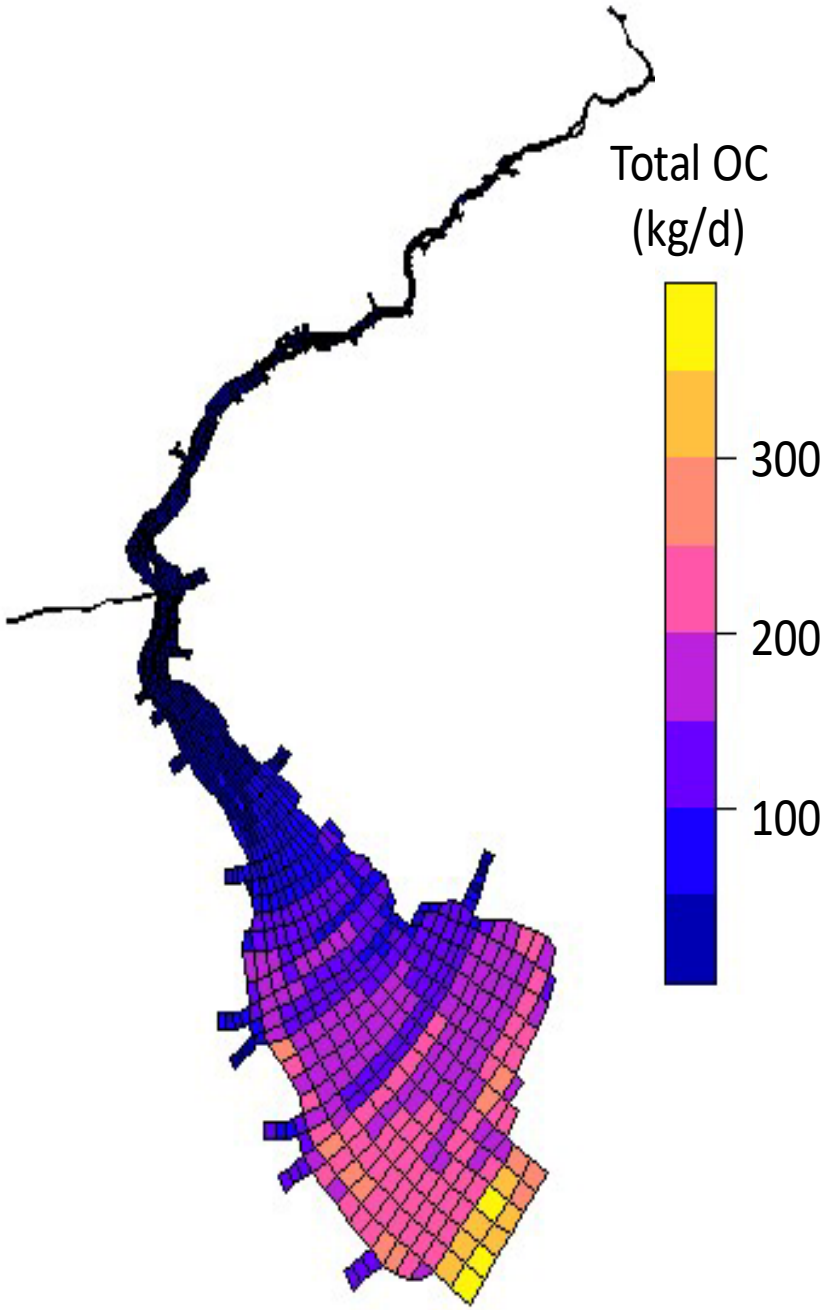
Assuming an annual atmospheric deposition rate of TOC is 11.3 g C/m2/yr for Chesapeake Bay Region (Velinsky et al., 1986)

Measurements suggest annual wet and dry deposition are approximately equivalent

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Atmospheric deposition accounts for ~35,000 kg POC/d

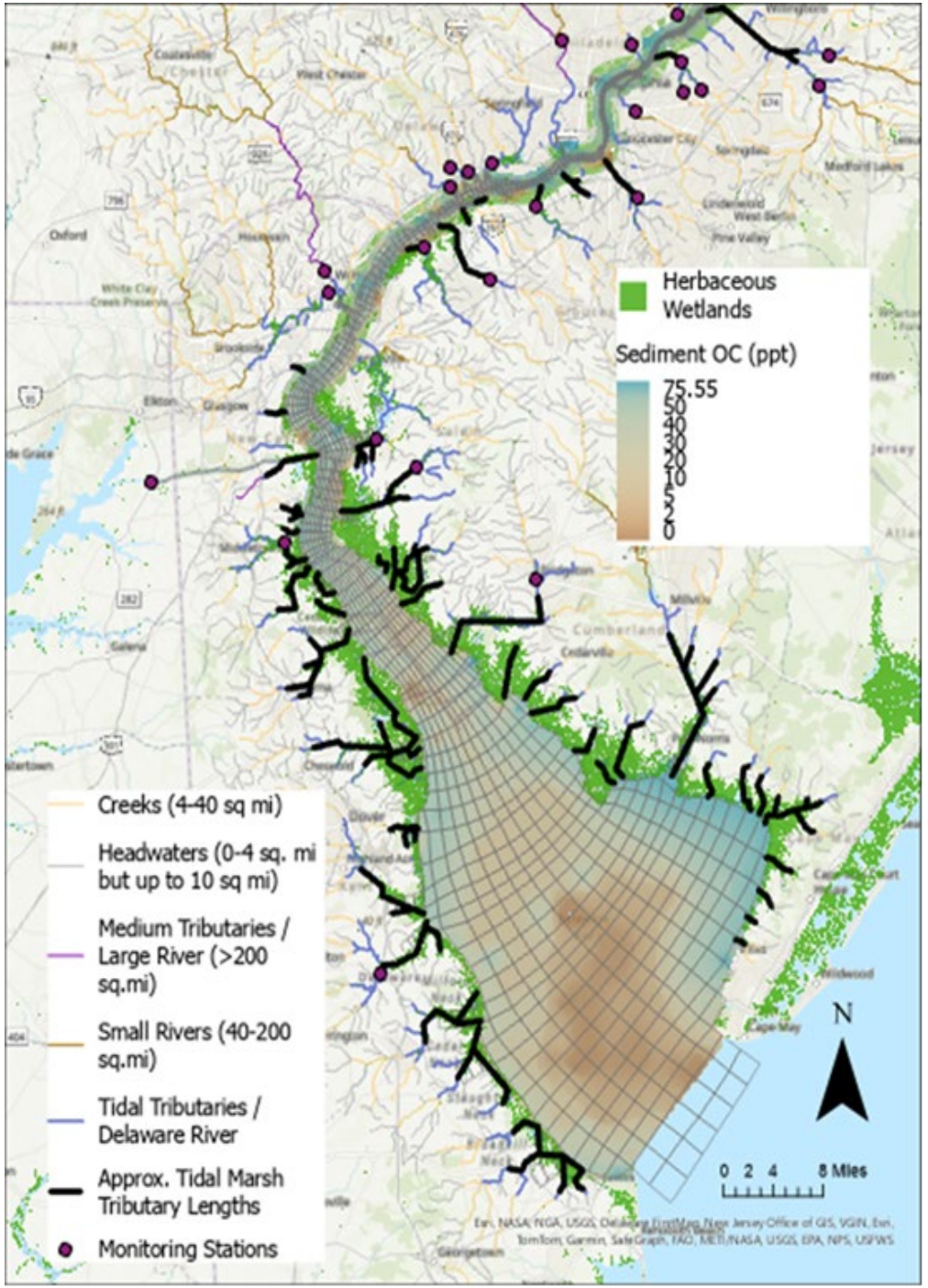


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Seasonal marsh loads were calculated proportional to marsh area

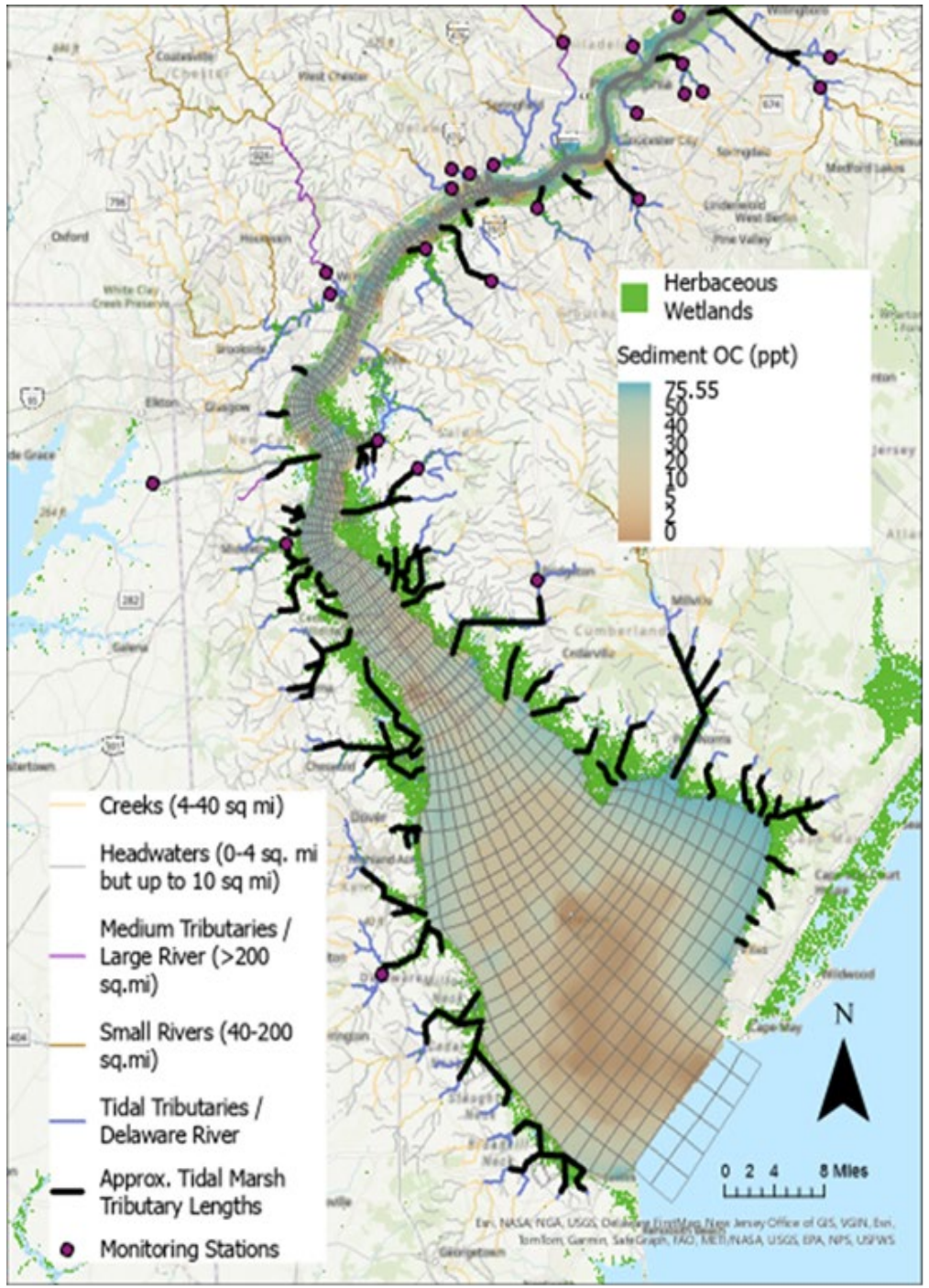
Season	DRE Marsh POC Exports (mg C/m²/d)
Winter	-33.9
Spring	220.6
Summer	274.8
Fall	43.5
Avg.	126.3

Based on literature estimates (Cifuentes, 1987; Roman and Daiber, 1989)

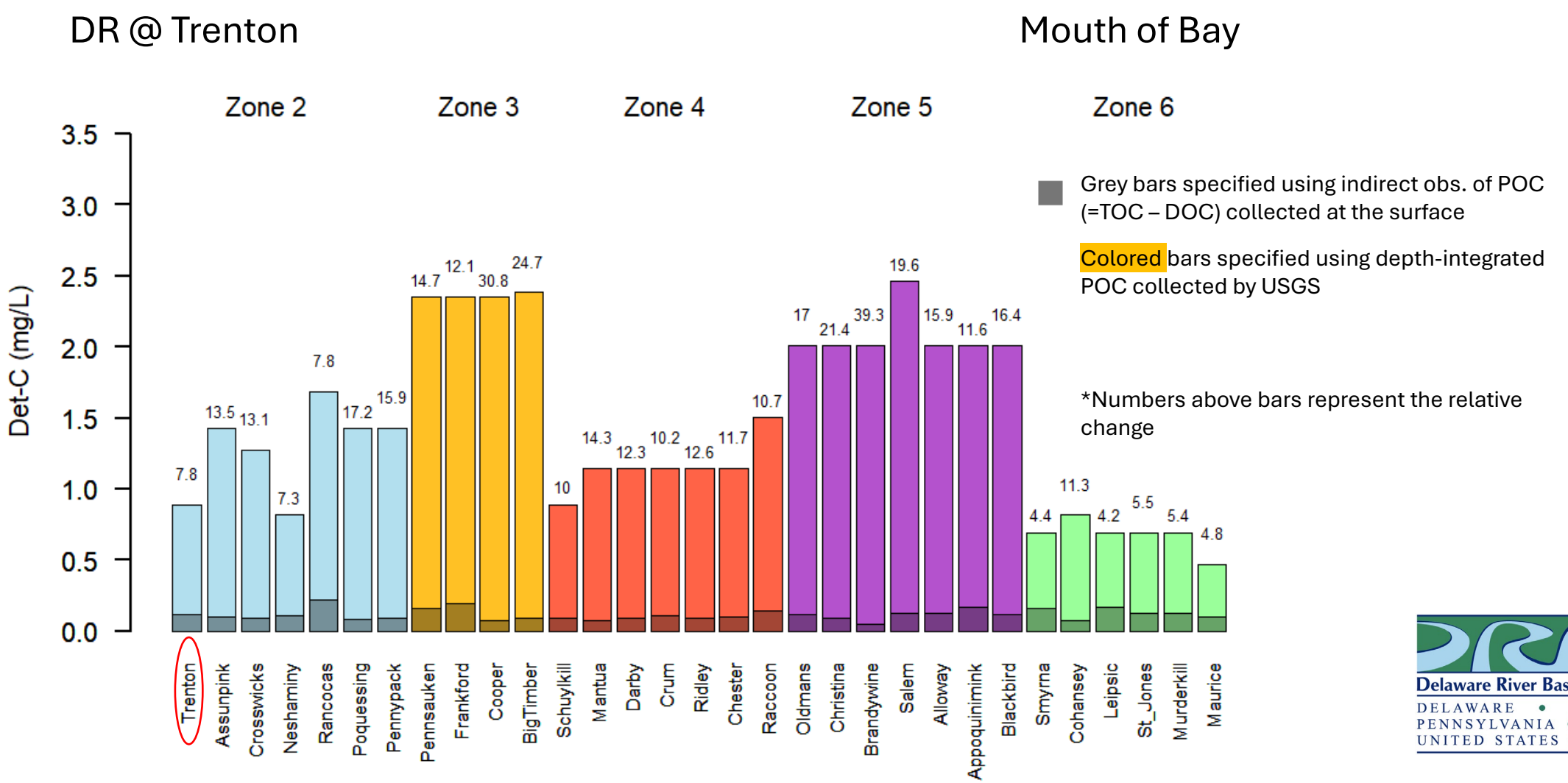


Tidal marshes contribute ~38,000 kg of particulate organic C per day to the DRE!

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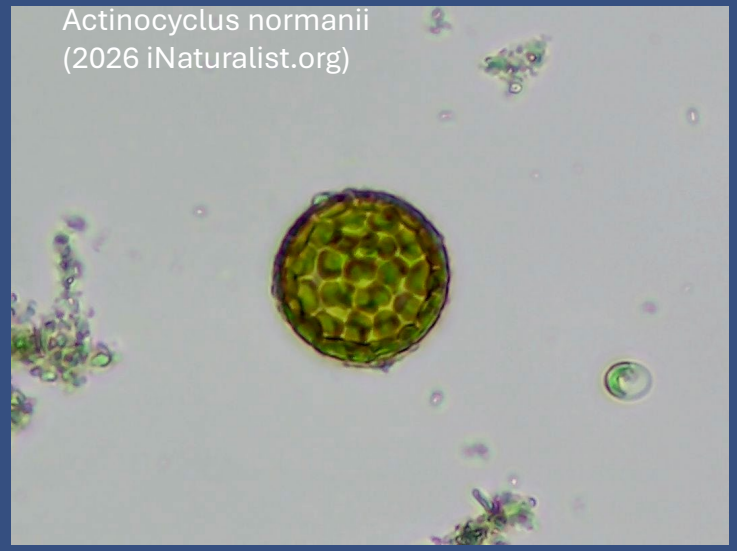
Tributaries contribute almost 80,000 kg of particulate organic C every day to the DRE



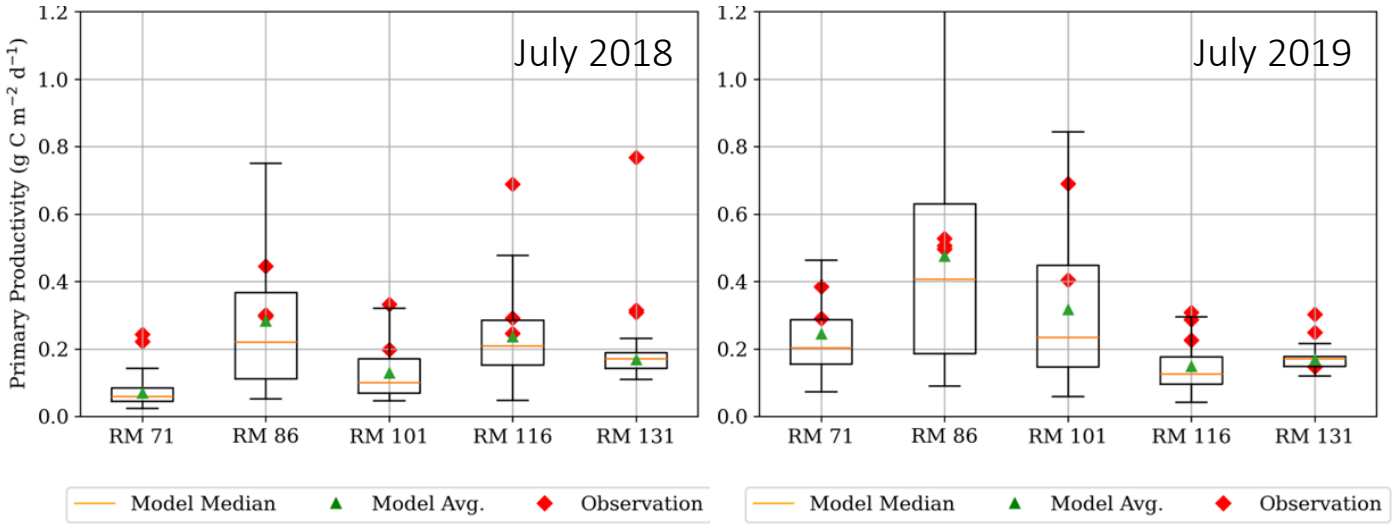
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Phytoplankton are the primary source of POC to the DRE (~395,000 kg/d)

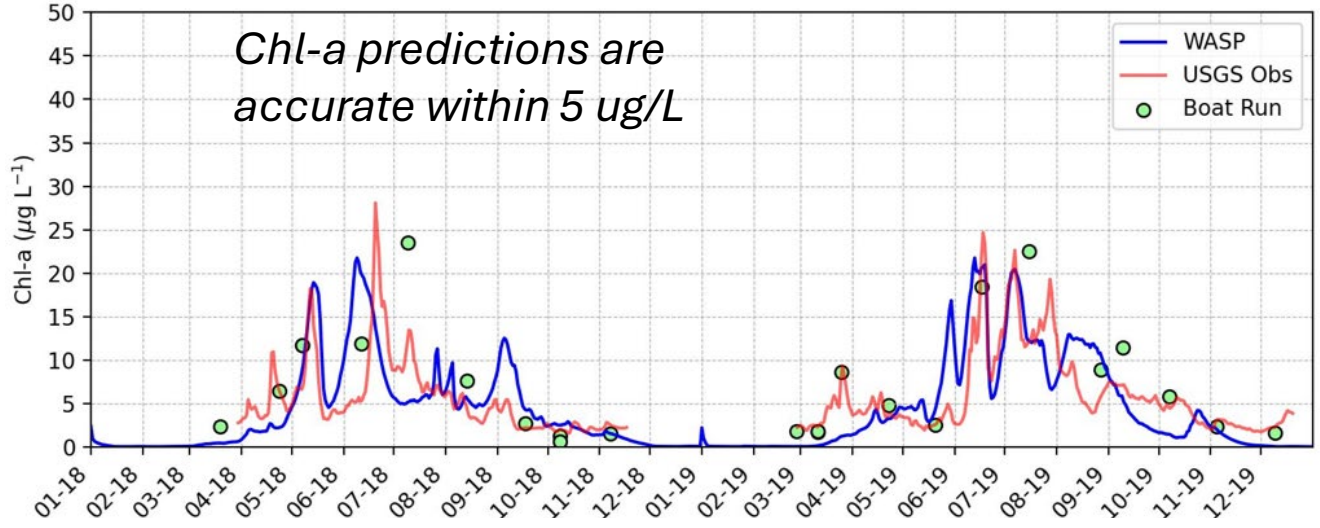
Based on model predictions of winter-marine, summer-marine and summer-fresh phytoplankton bloom dynamics



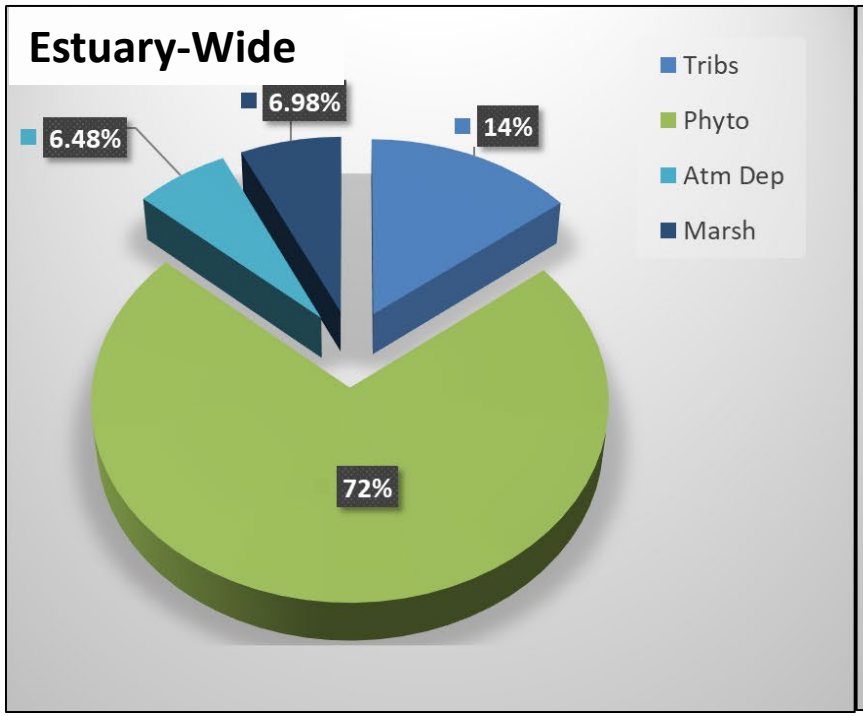
Algal Primary Productivity in the Tidal Delaware River

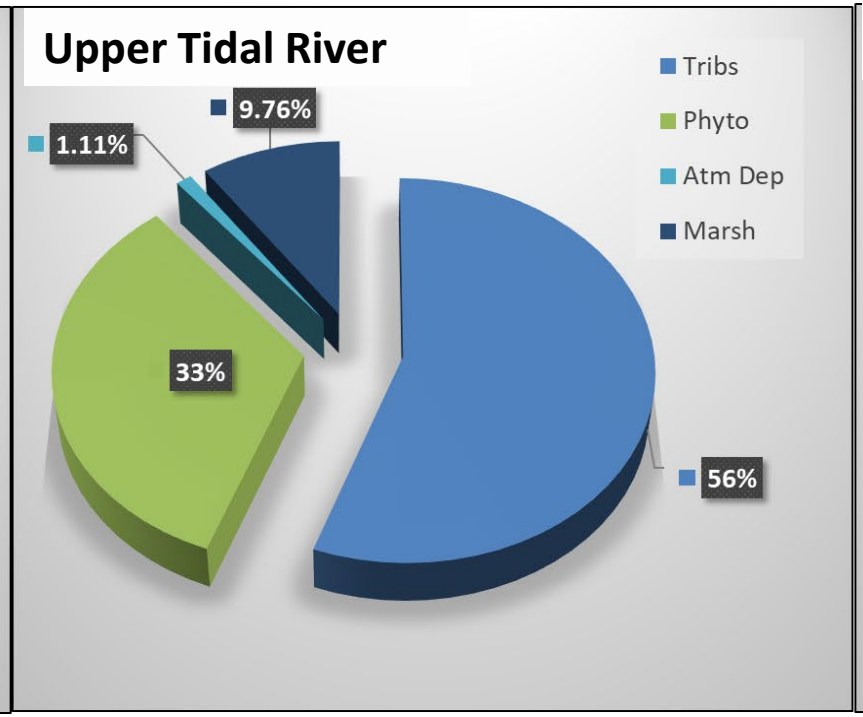


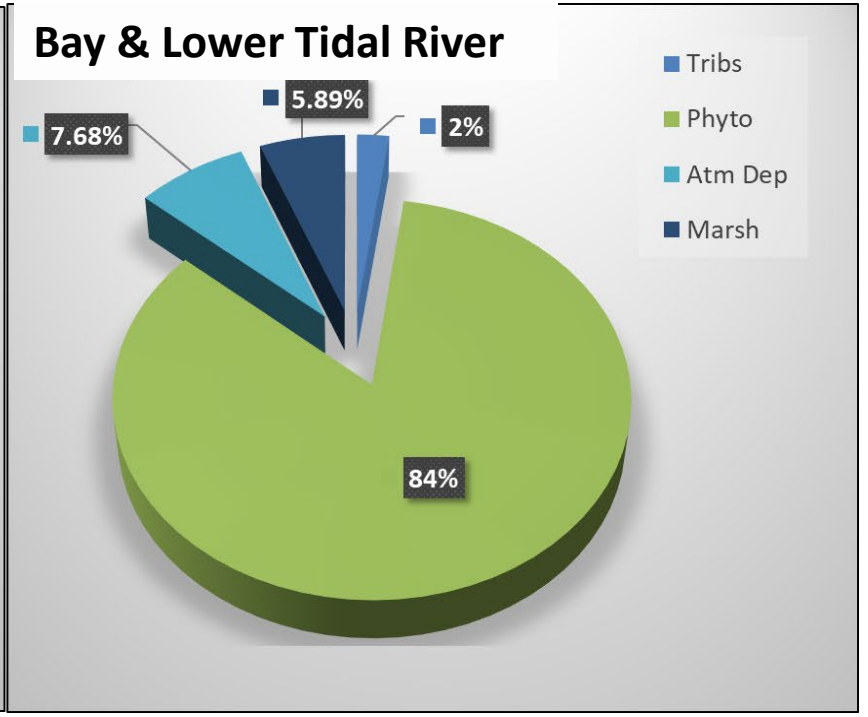
Simulated and Observed Chl-a at Ben Franklin Bridge Philadelphia, RM 100.1: 2018 to 2019



The origin of estuarine POC varies by region







In the bay, most POC is from internal algal production (due to the size of the bay!)

In the tidal river, external production is the primary source of POC

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Spatially Varying Net Settling Captures Estuary-Wide Sediment OC Trends

TOC (% weight)	Net Settling Velocity (m/d)	# of 2D Grid Cells
0 – 1%	0.125	448
1 – 2%	0.25	583
2 – 3%	0.5	431
> 3%	1.0	414

Sediment transport not simulated

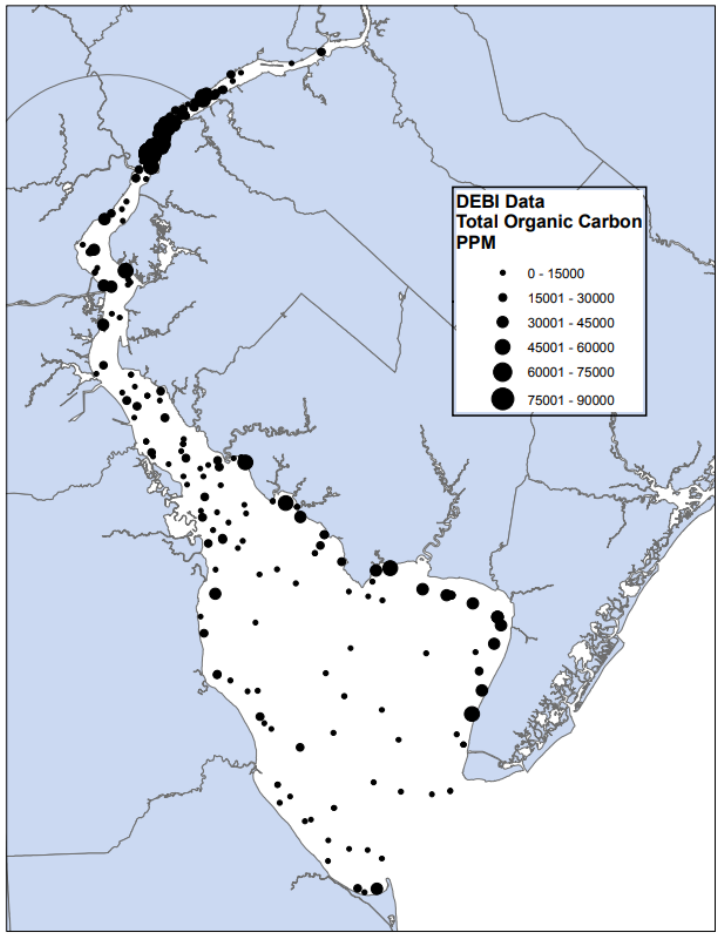
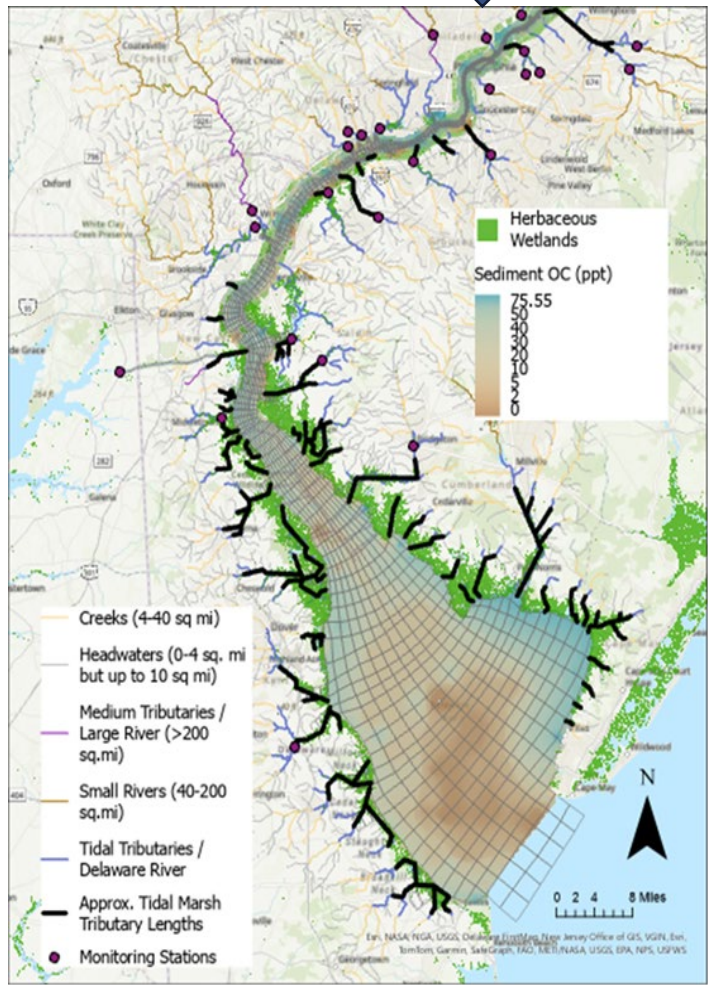


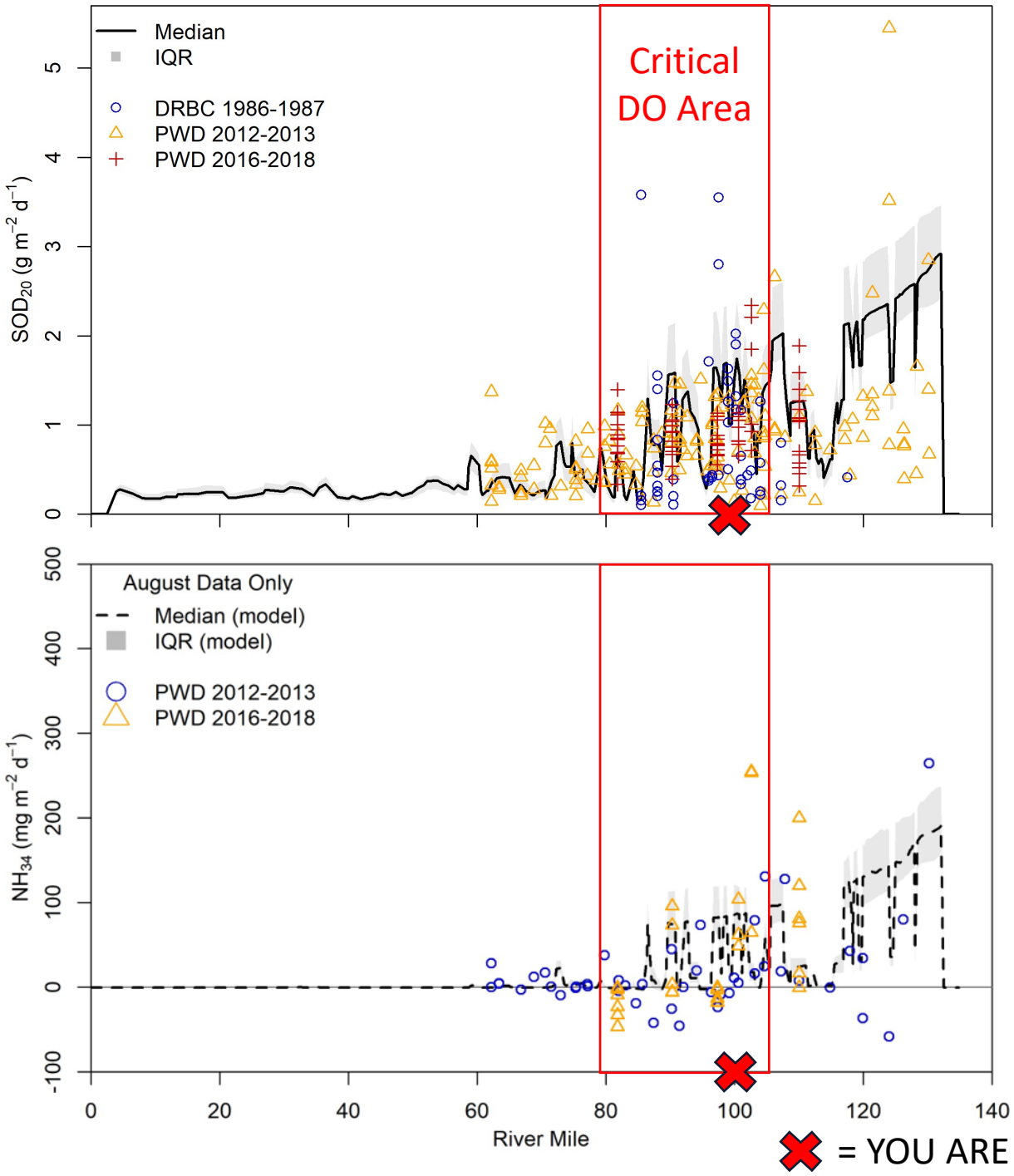
Figure 4.3.1 Total organic carbon concentrations in 2008 DEBI sediment samples.

Interpolation



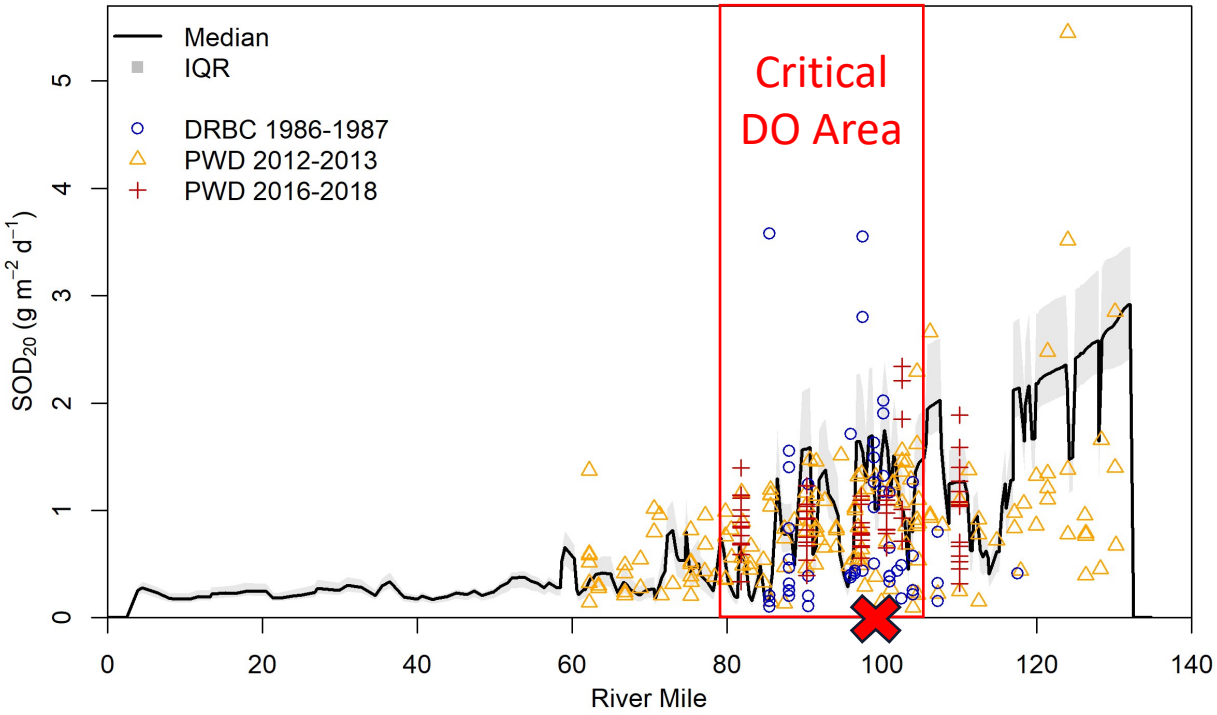
Interpolation

Characterizing the quantity and sources of POC was key to capturing the spatial impacts of sediments on DO

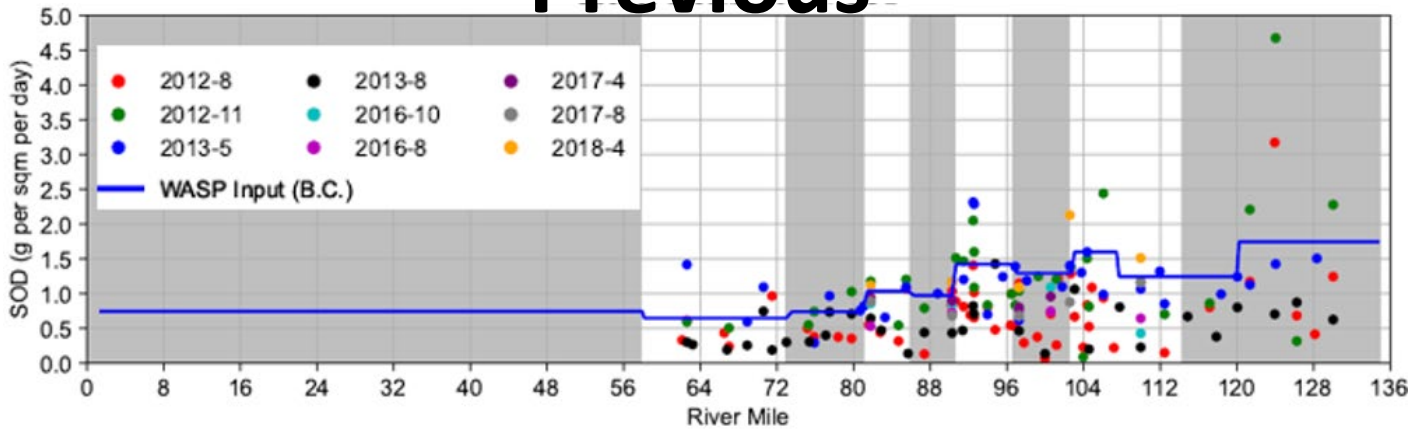


Implementing a dynamic sediment diagenesis model enabled….

- Better representation of sediment impacts on DO
- Enhanced capacity to predict DO load responses to future changes in water quality
- A more scientifically defensible framework for evaluating DO dynamics



Previous



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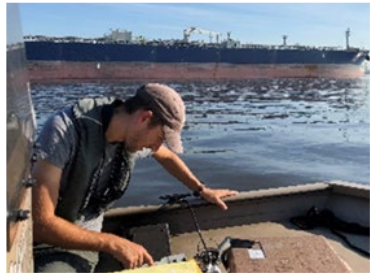


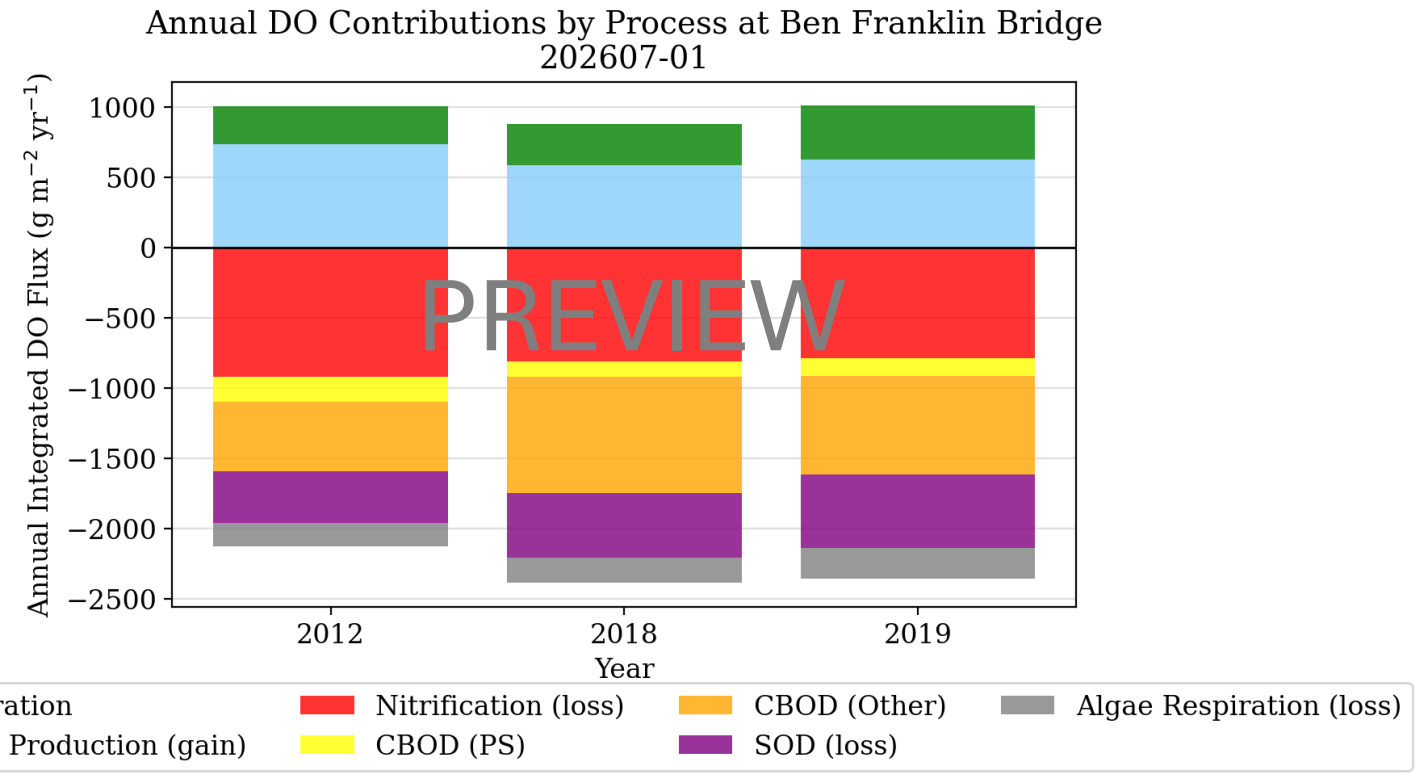
UP NEXT: A Novel Quantification of the Dissolved Oxygen Budget in the DRE and its Implications for Water Quality Management

Thomas Amidon, BCES



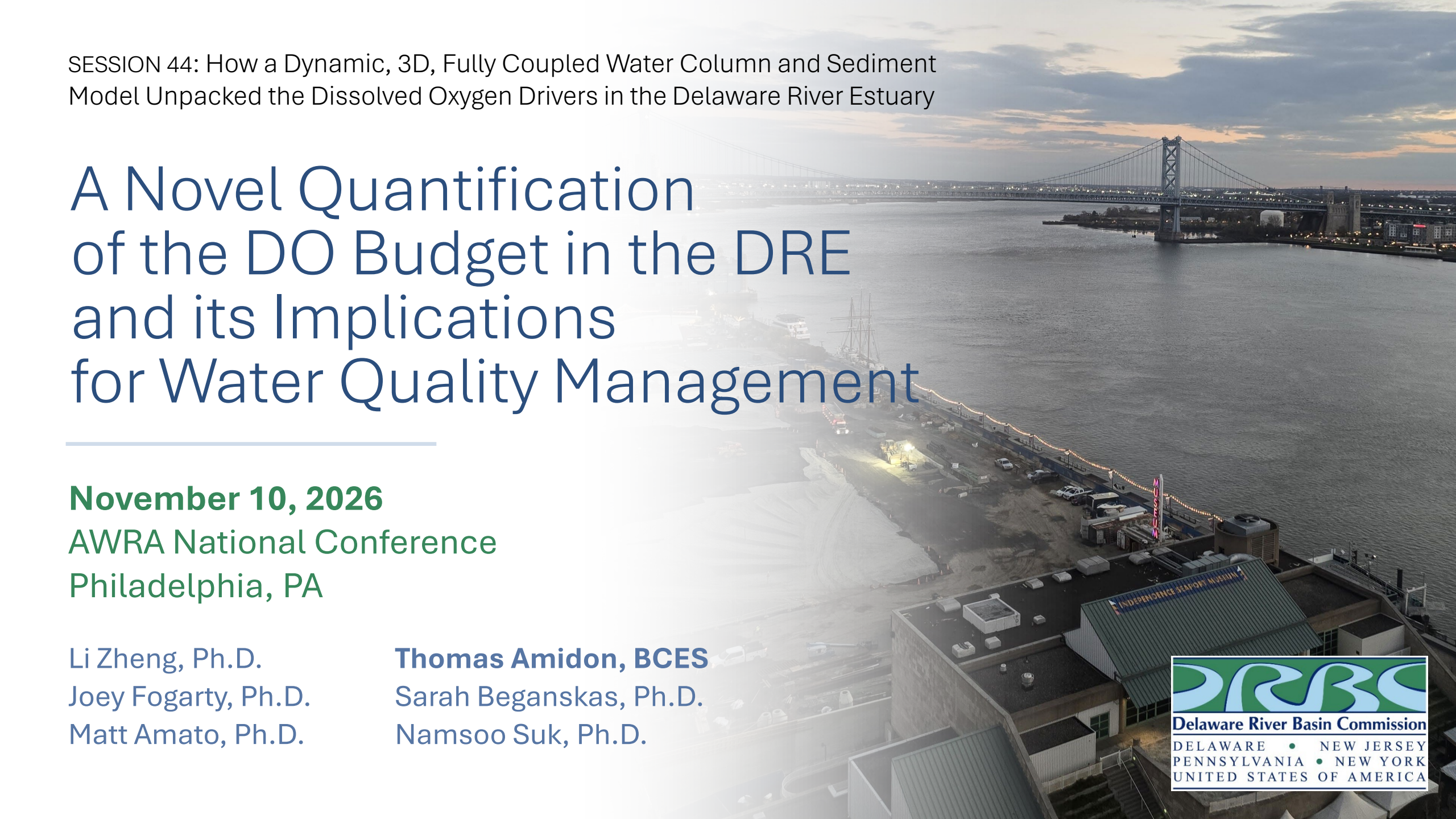






SESSION 44: How a Dynamic, 3D, Fully Coupled Water Column and Sediment Model Unpacked the Dissolved Oxygen Drivers in the Delaware River Estuary

A Novel Quantification of the DO Budget in the DRE and its Implications for Water Quality Management



November 10, 2026

AWRA National Conference

Philadelphia, PA

Li Zheng, Ph.D.

Joey Fogarty, Ph.D.

Matt Amato, Ph.D.

Thomas Amidon, BCES

Sarah Beganskas, Ph.D.

Namsoo Suk, Ph.D.

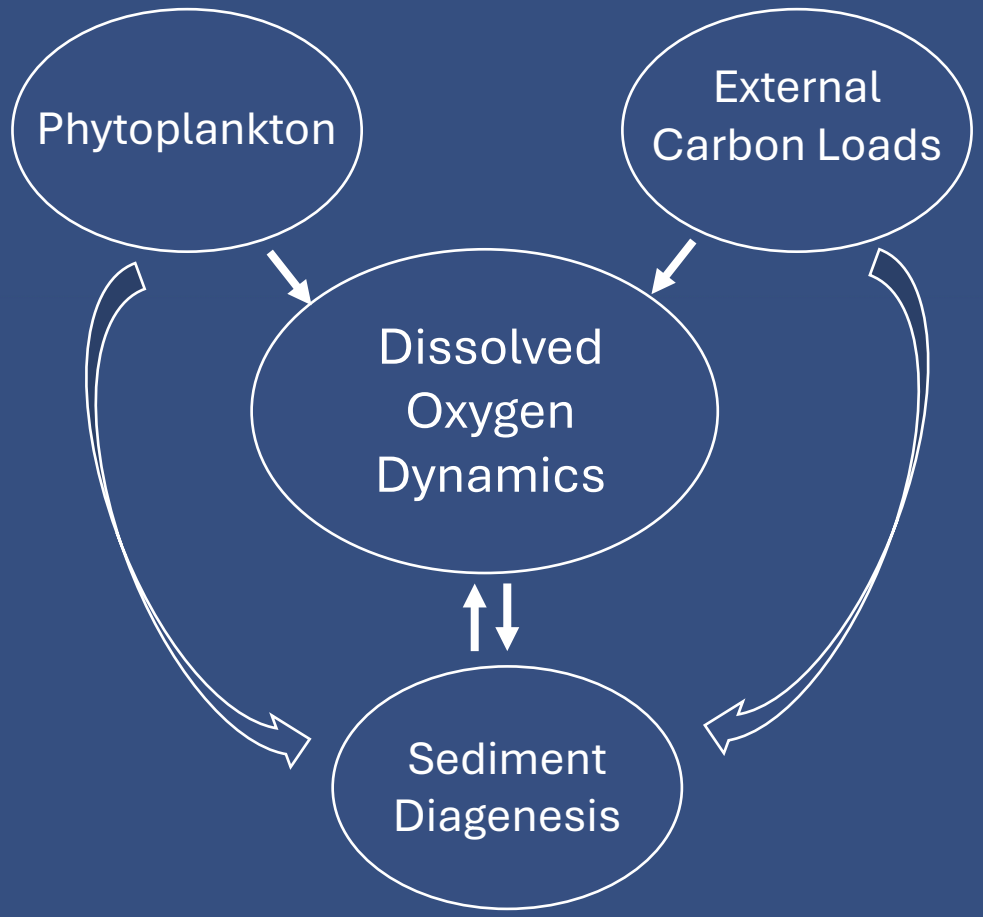
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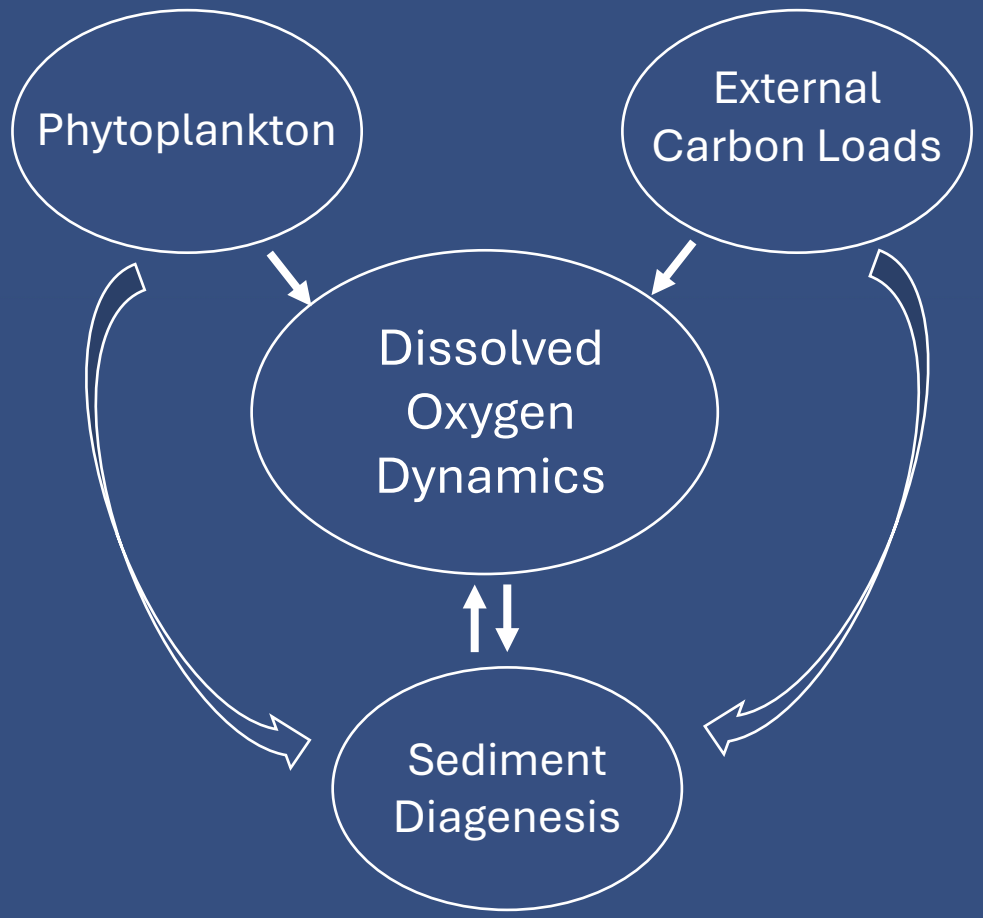
Enhanced DO Model



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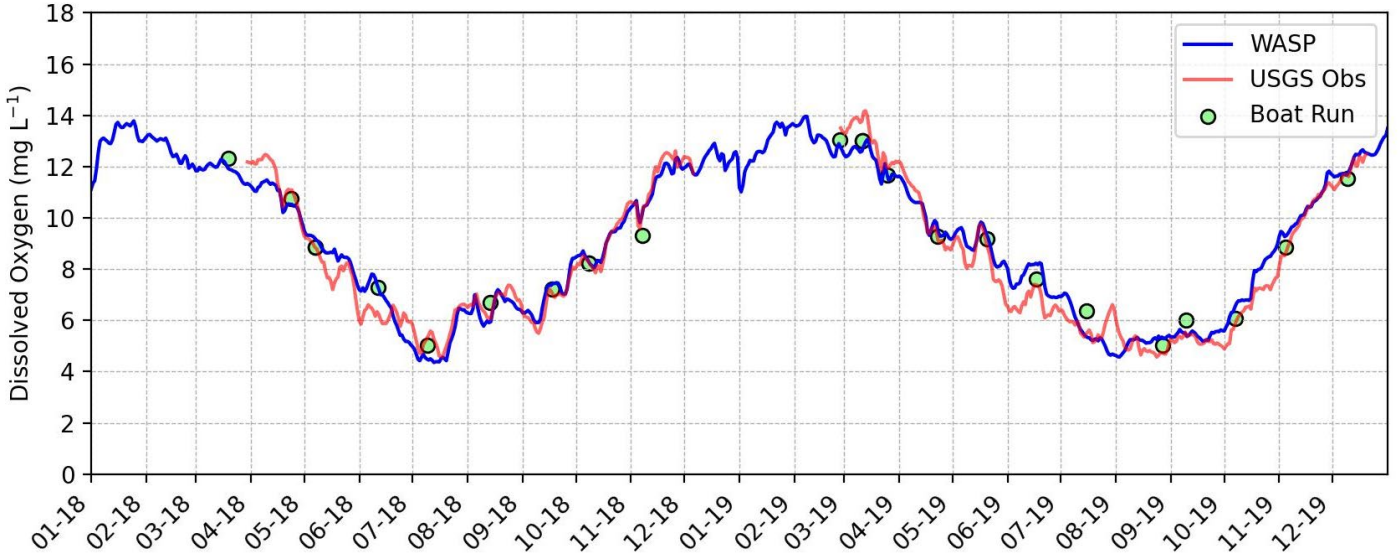
- Model enhancements performed by
  - DRBC staff and managers
  - Close coordination with Model Expert Panel
  - And MEP technical consultants
- How was the model improved?
  - Mechanistic sediment diagenesis
  - POC characterization
  - Kinetic refinements
    - Phytoplankton
    - Settling
    - CBOD characterization

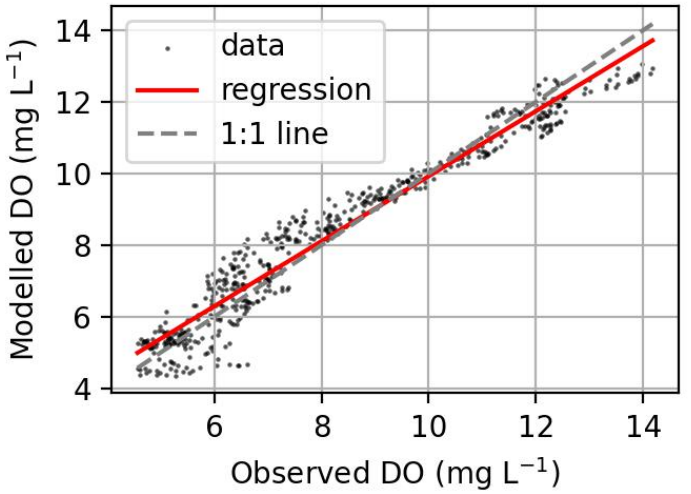
Enhanced DO Model



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Simulated and Observed Dissolved Oxygen at Ben Franklin Bridge Philadelphia, RM 100.1: 2018 to 2019

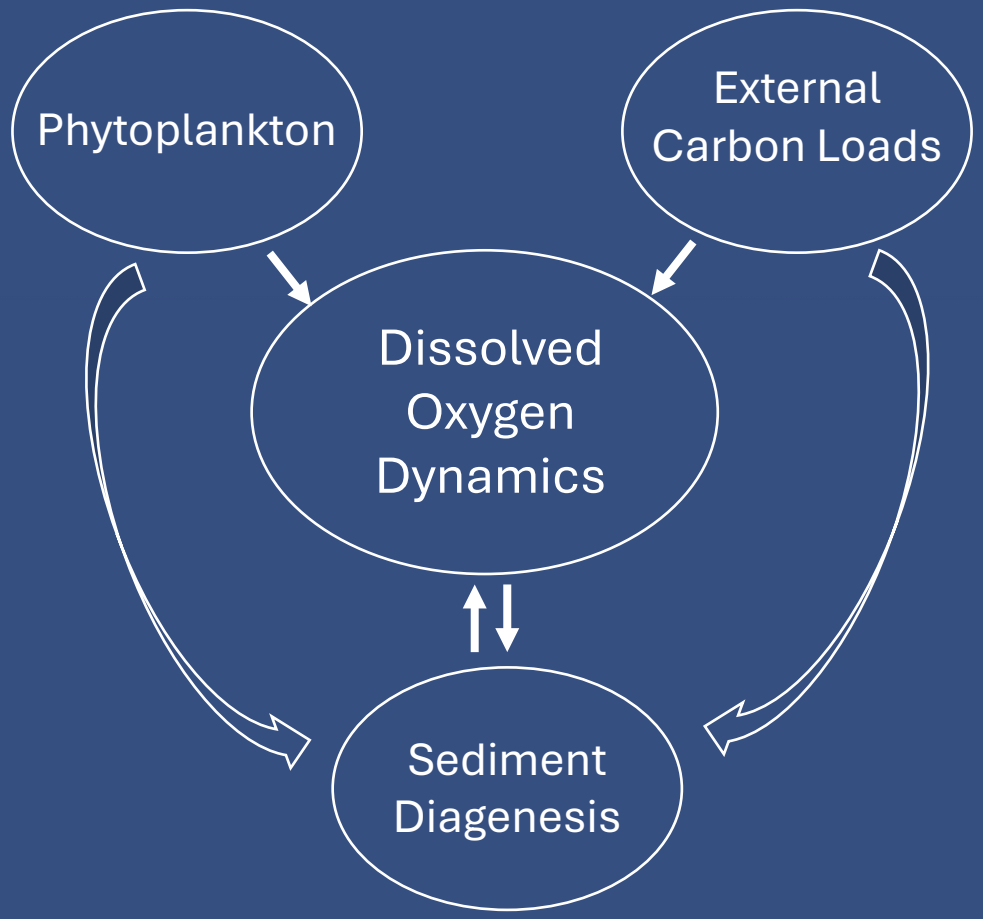




R^2 = 0.95
y = 0.908x + 0.845
N = 549
RMSE = 0.62
ubRMSE = 0.61
Bias = 0.09
NSE = 0.94
Skill = 0.98
MAE = 0.49

DO predictions are accurate within ~0.6 mg/L

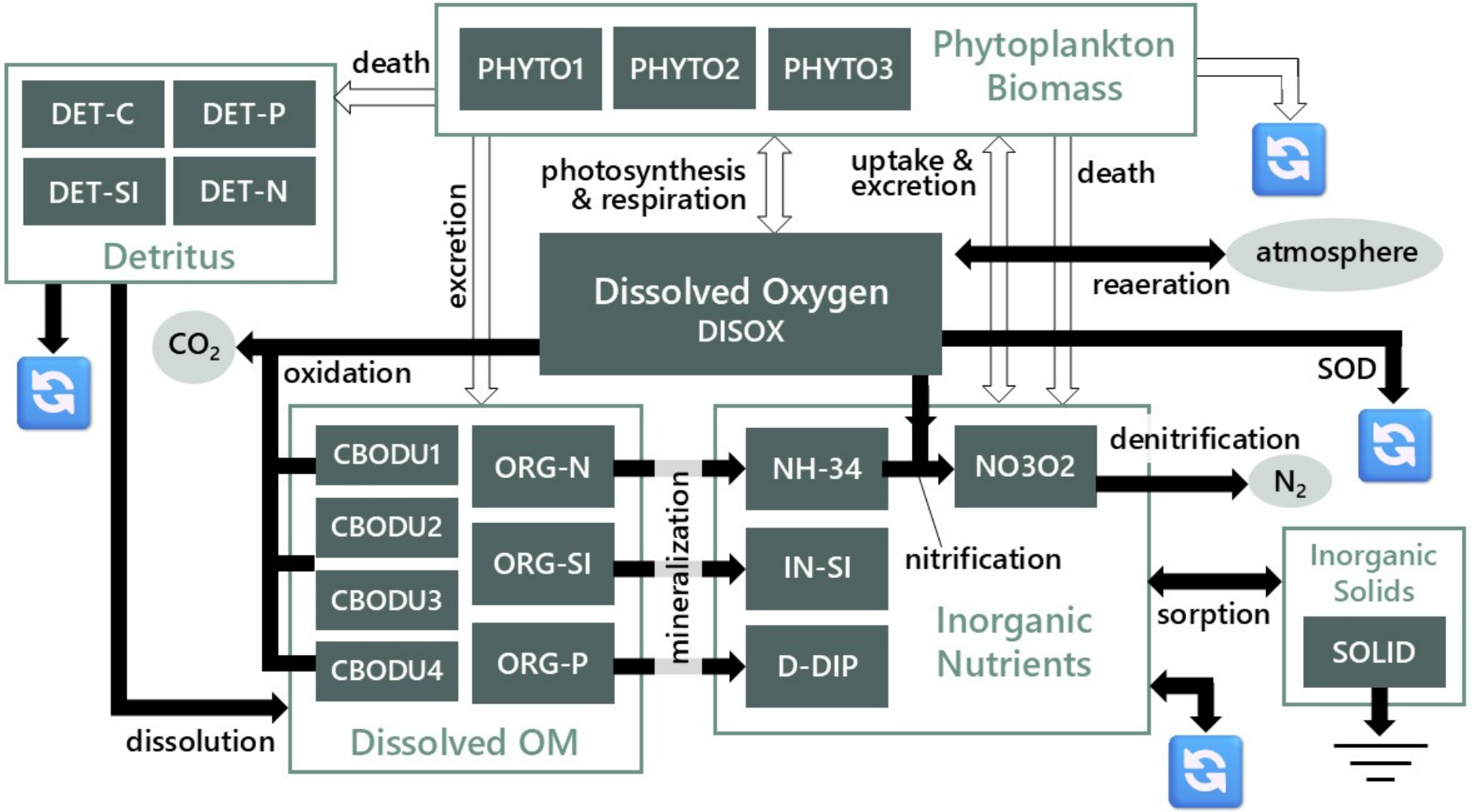
Enhanced DO Model



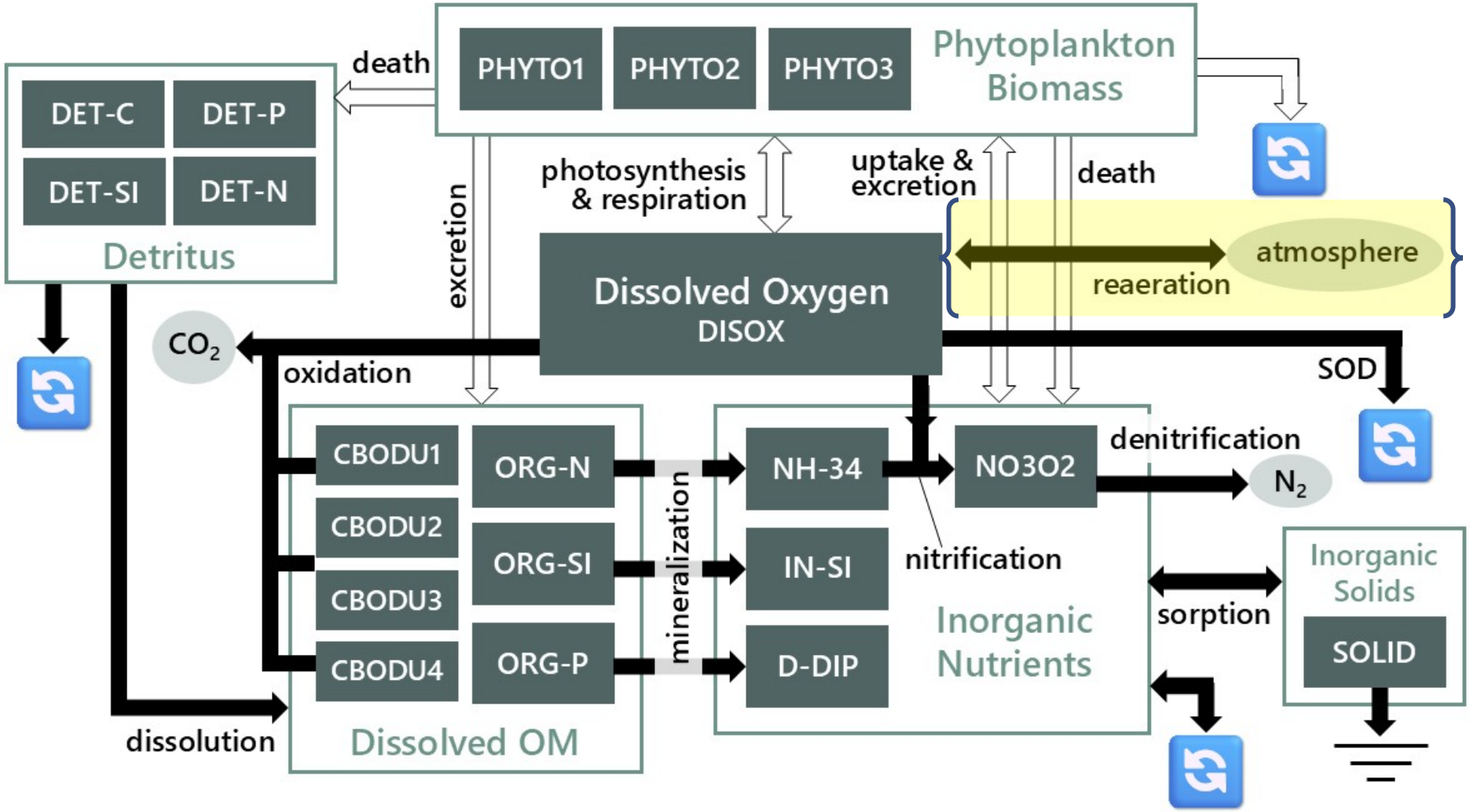
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- Model enhancement represents significant advance in the state of the art … but **why is this important**?
  - Directly links organic carbon and DO between water column and sediments
  - Result is a more constrained model with less uncertainty (“right for the right reasons”)
  - **Allows future scenarios to incorporate changes to sediment dynamics that impact dissolved oxygen**
- Model enhances understanding of DO conditions under different loading scenarios
  - **Suitable to determine loading conditions needed to achieve dissolved oxygen criteria**

So what are the processes that drive DO in the Delaware River Estuary?

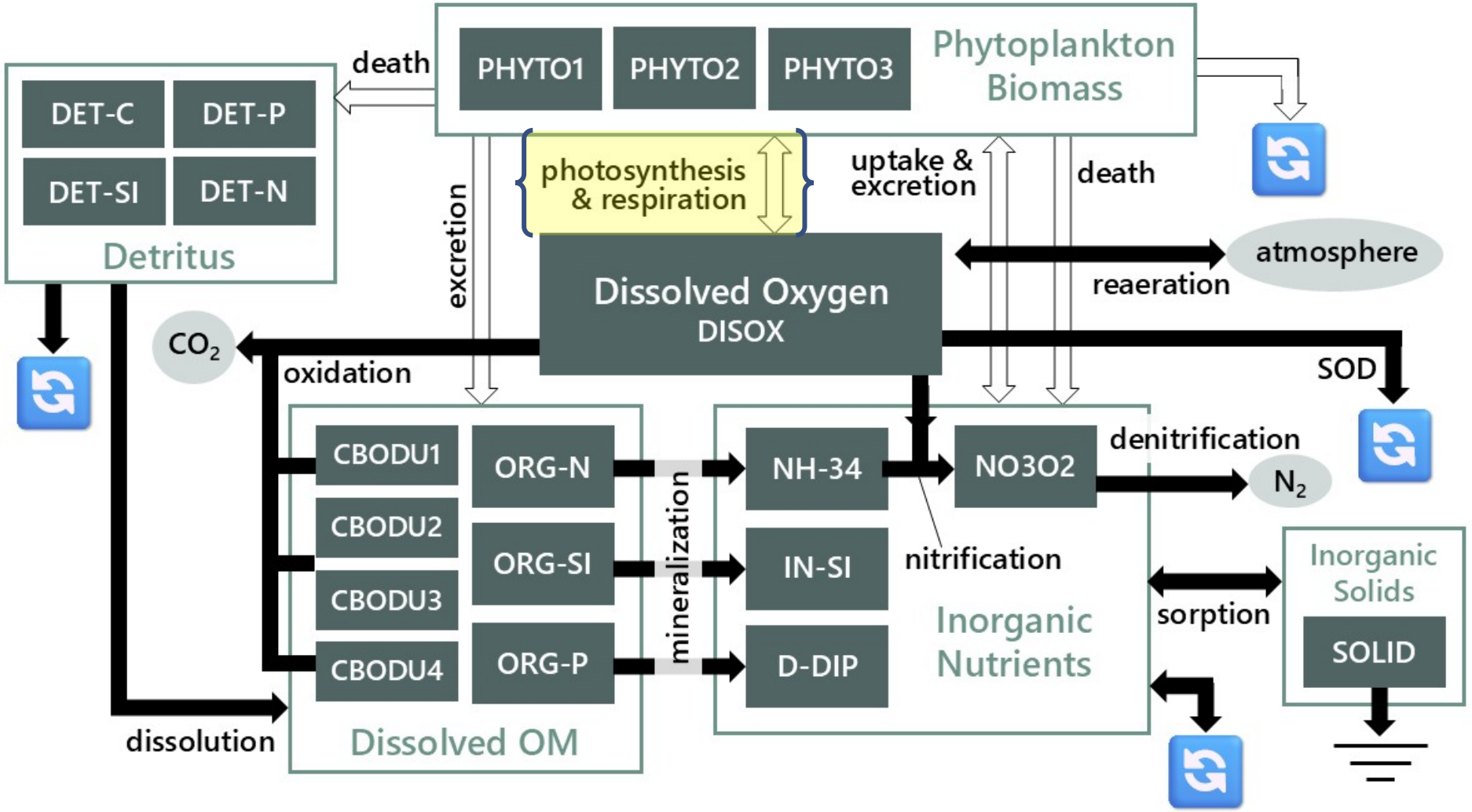


So what are the processes that drive DO in the Delaware River Estuary?



Reaeration

So what are the processes that drive DO in the Delaware River Estuary?

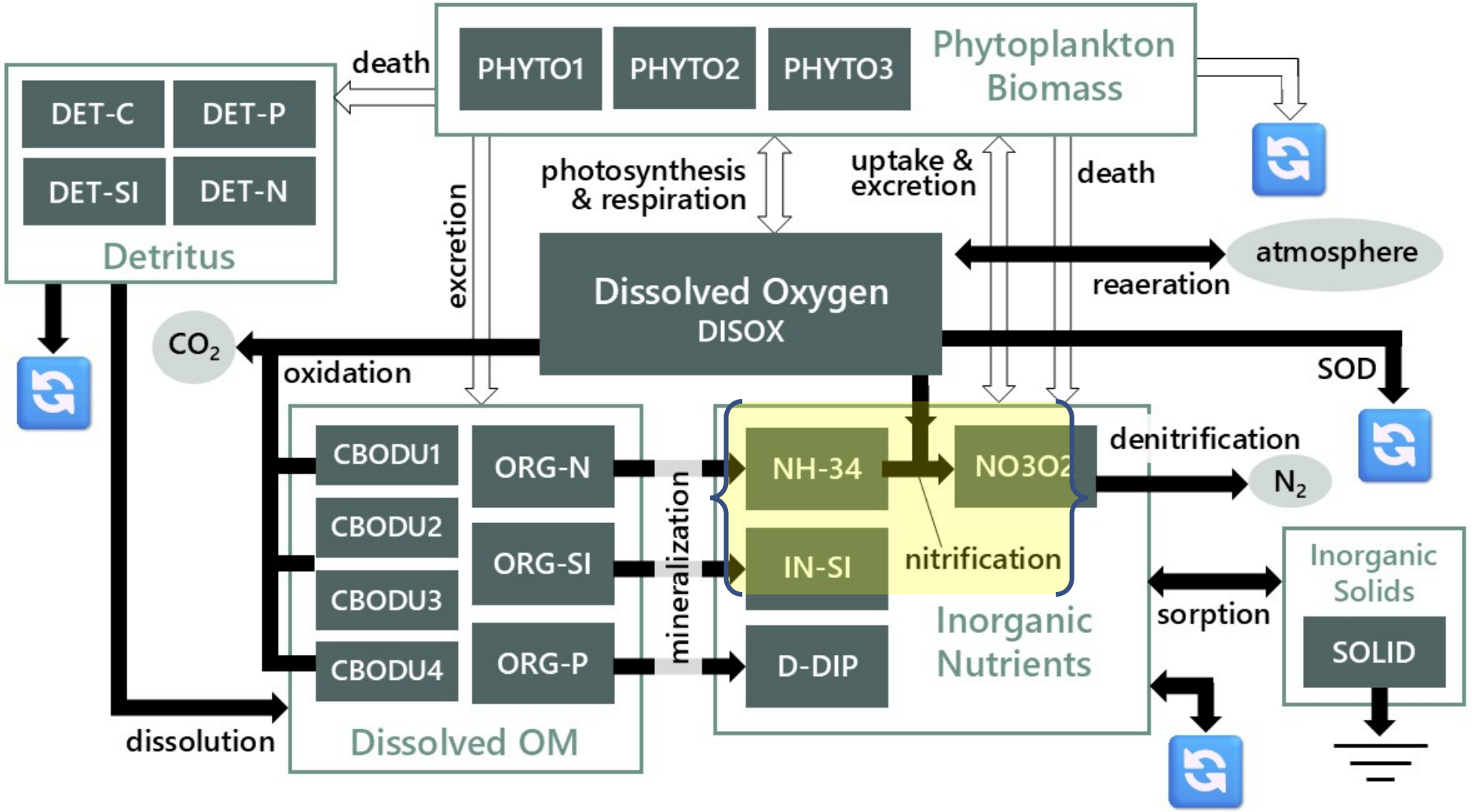


Reaeration

Photosynthesis

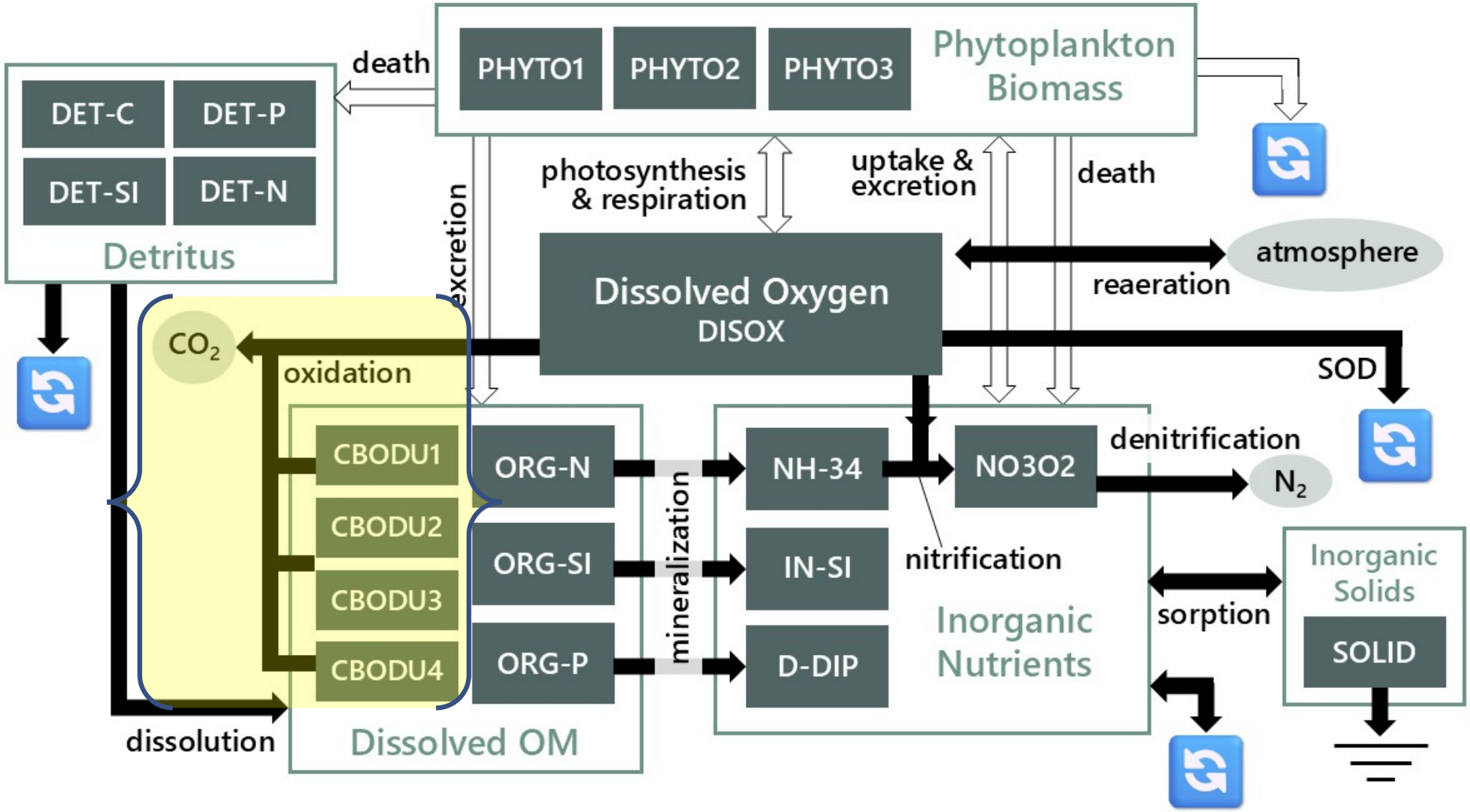
Respiration

So what are the processes that drive DO in the Delaware River Estuary?



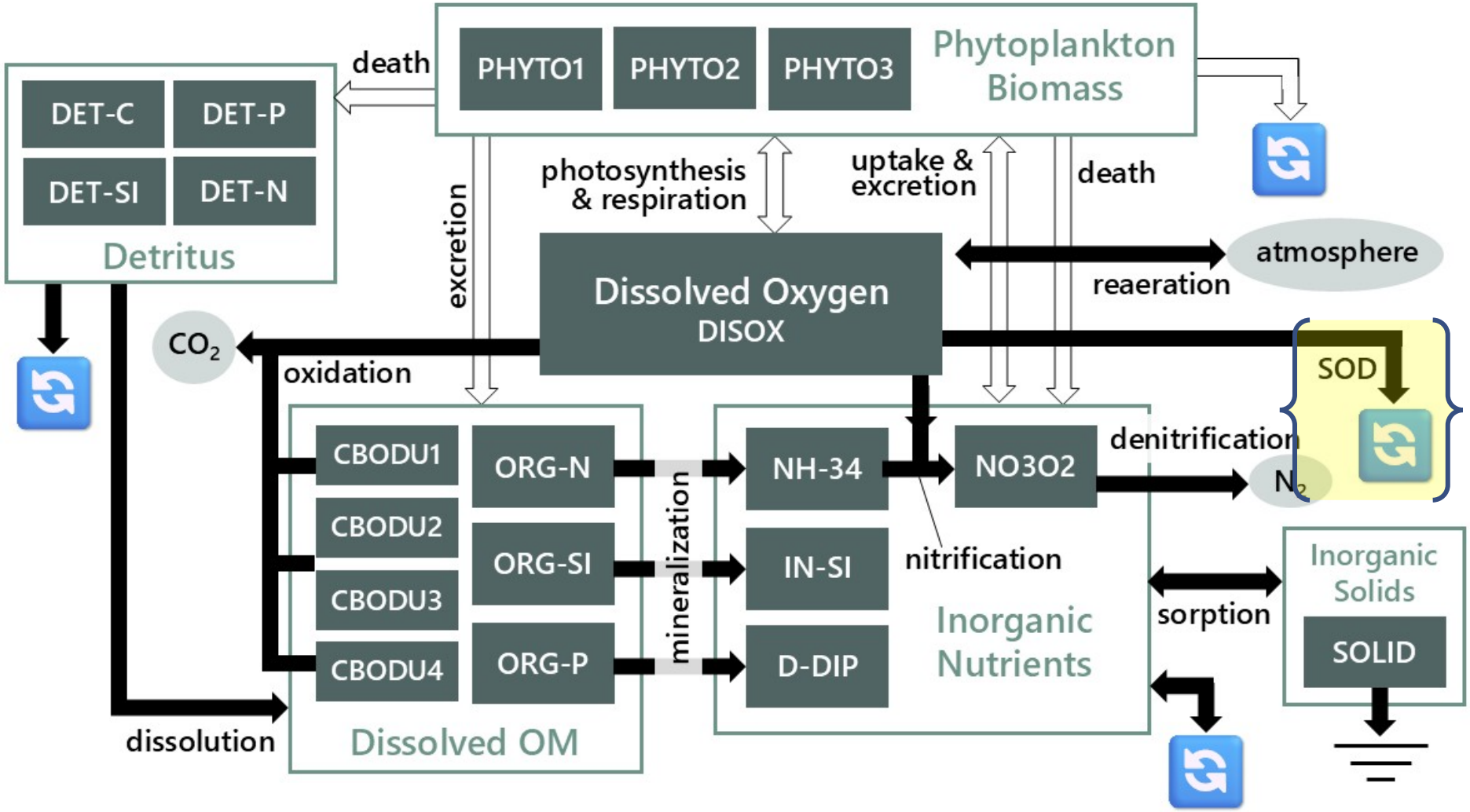
- Reaeration
- Photosynthesis
- Respiration
- Nitrification

So what are the processes that drive DO in the Delaware River Estuary?



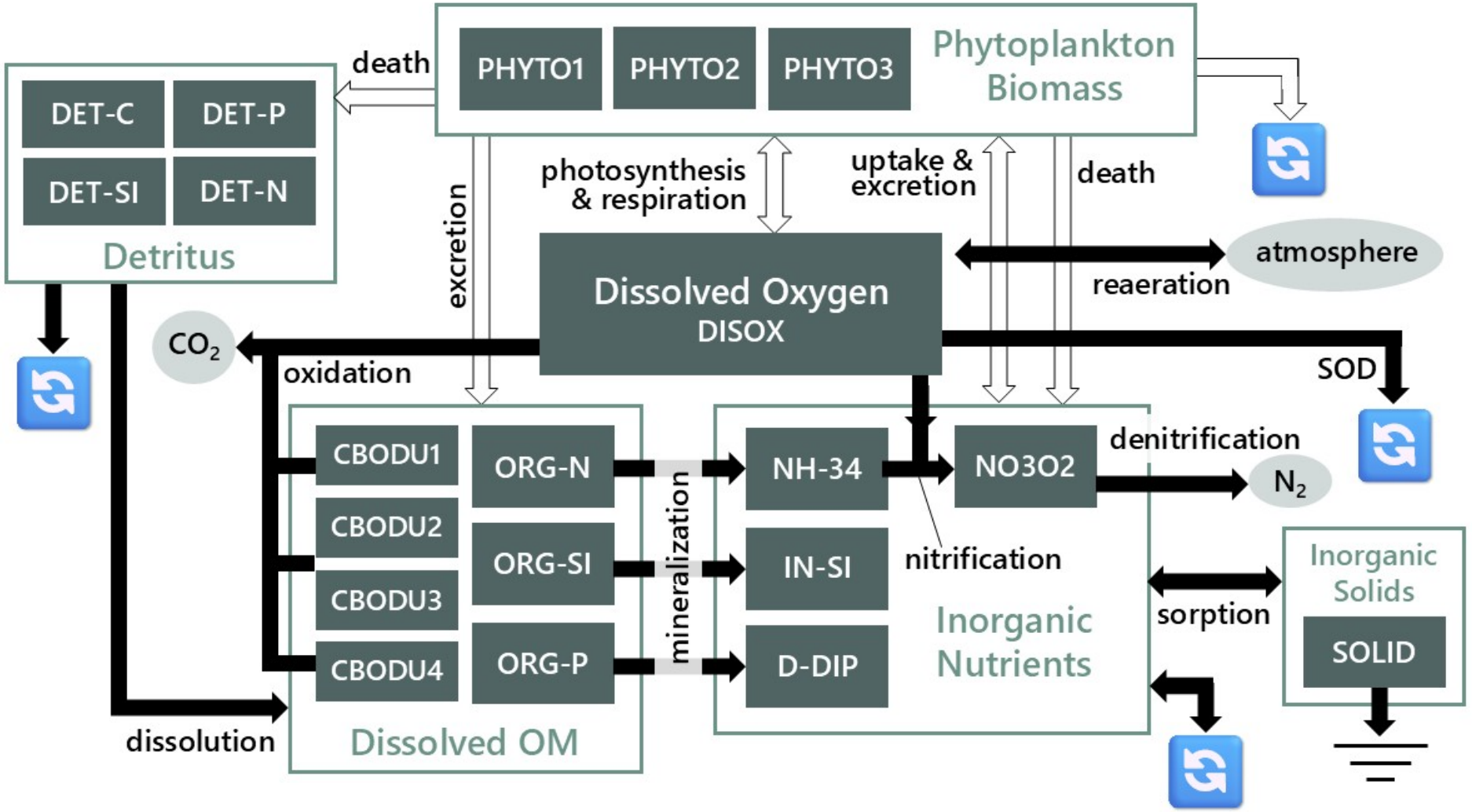
- Reaeration
- Photosynthesis
- Respiration
- Nitrification
- CBOD decay

So what are the processes that drive DO in the Delaware River Estuary?



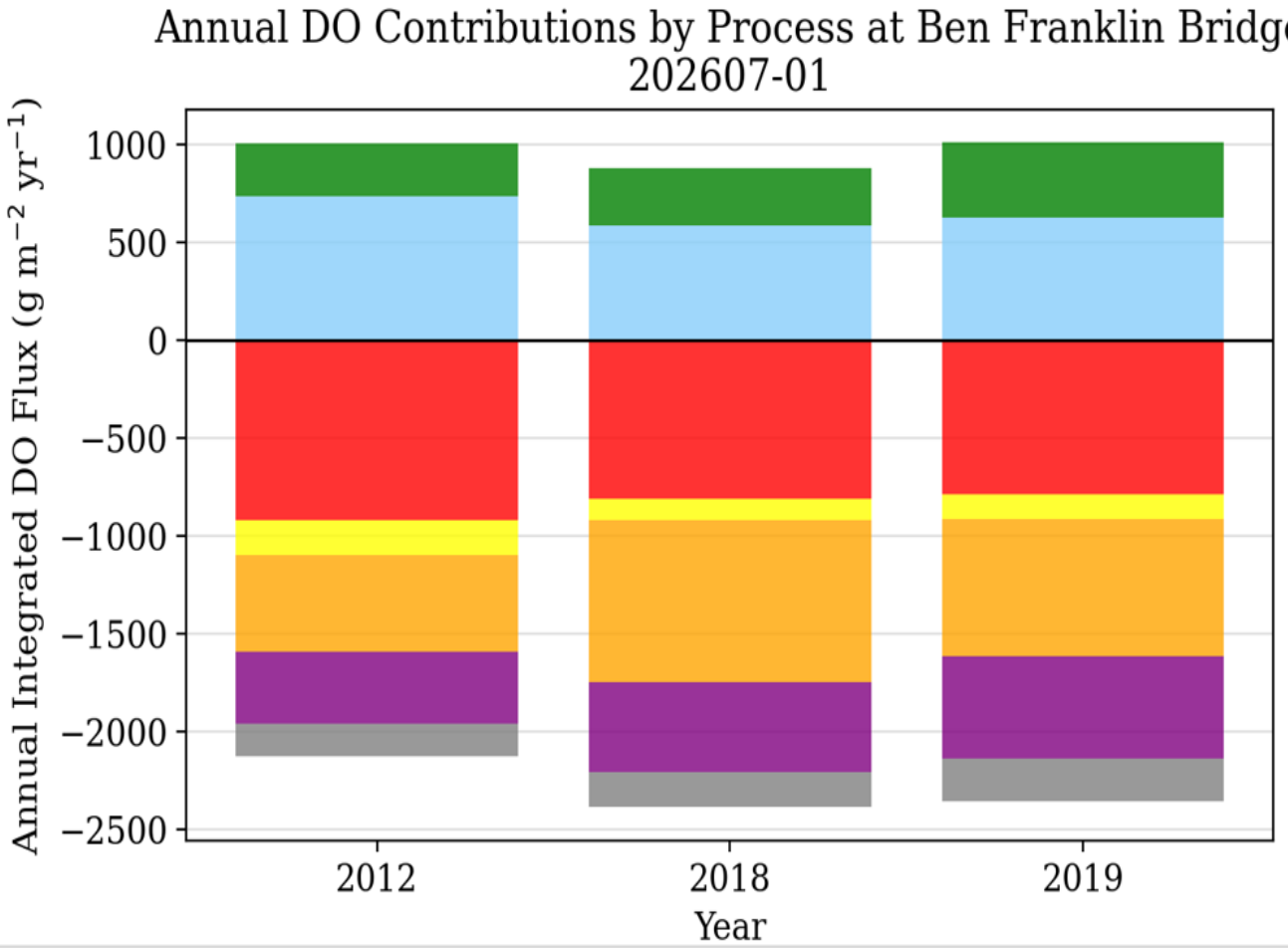
- Reaeration
- Photosynthesis
- Respiration
- Nitrification
- CBOD decay
- SOD

So what are the processes that drive DO in the Delaware River Estuary?



- Reaeration
- Photosynthesis
- Respiration
- Nitrification
- CBOD decay
- SOD

So what are the processes that drive DO in the Delaware River Estuary?

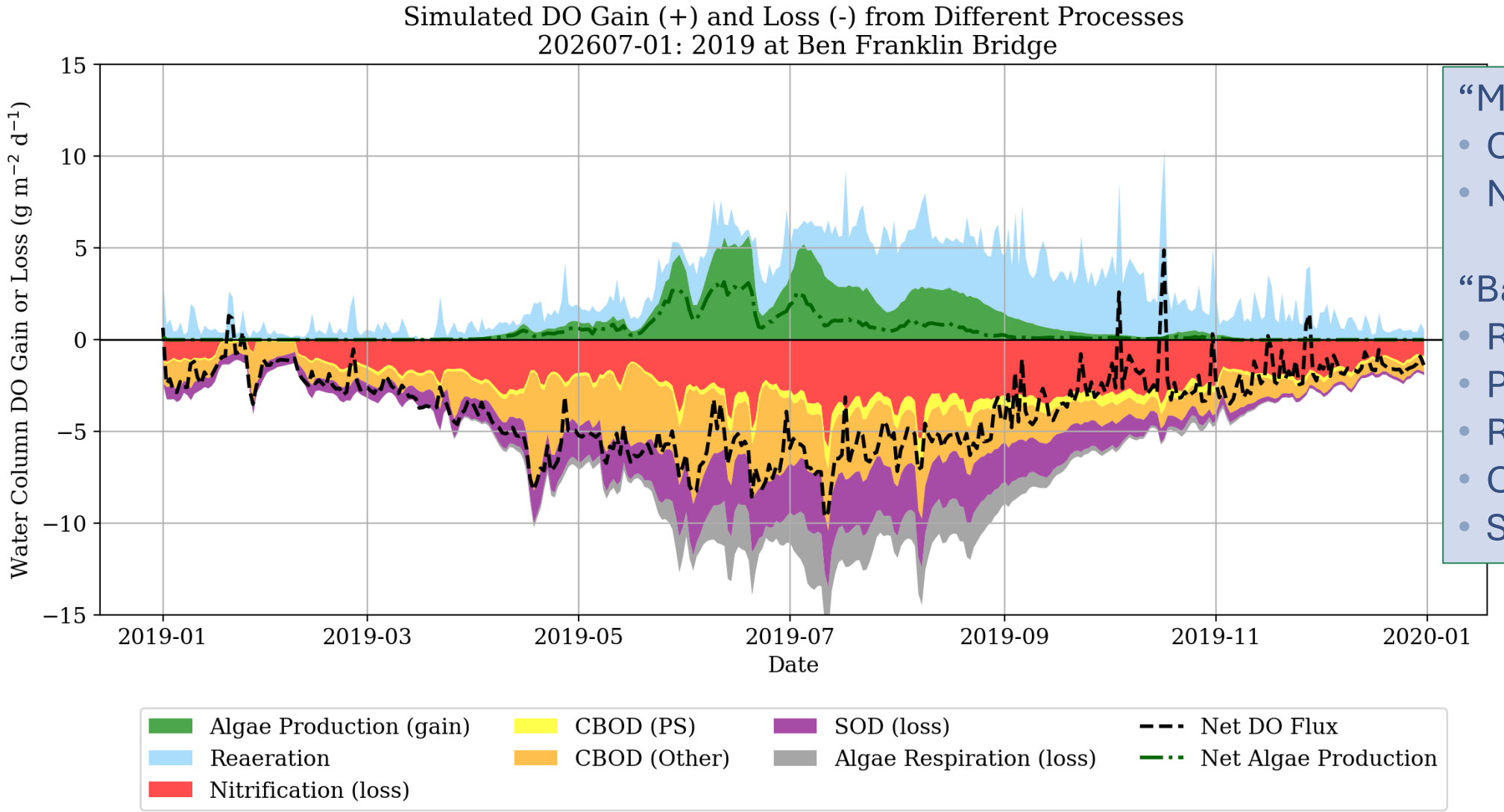


So many questions!

- Which of these sources are manageable?
- What does this look like during times when DO is lowest?
- What does this look like at other locations?

*Note: transport is not shown

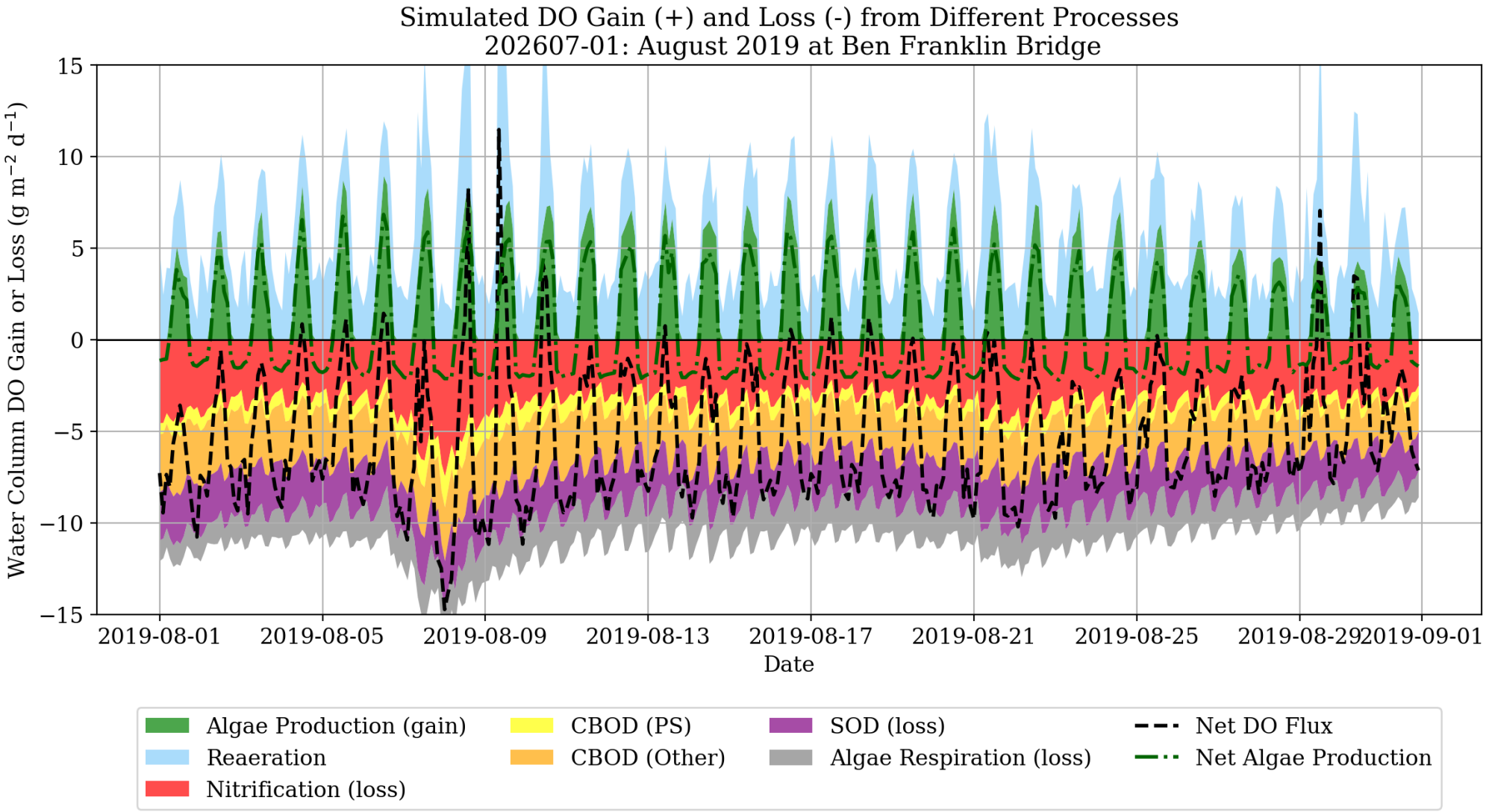
Let’s zoom in on our favorite location over the course of a whole year …



“Manageable”
- CBOD (PS)
- Nitrification

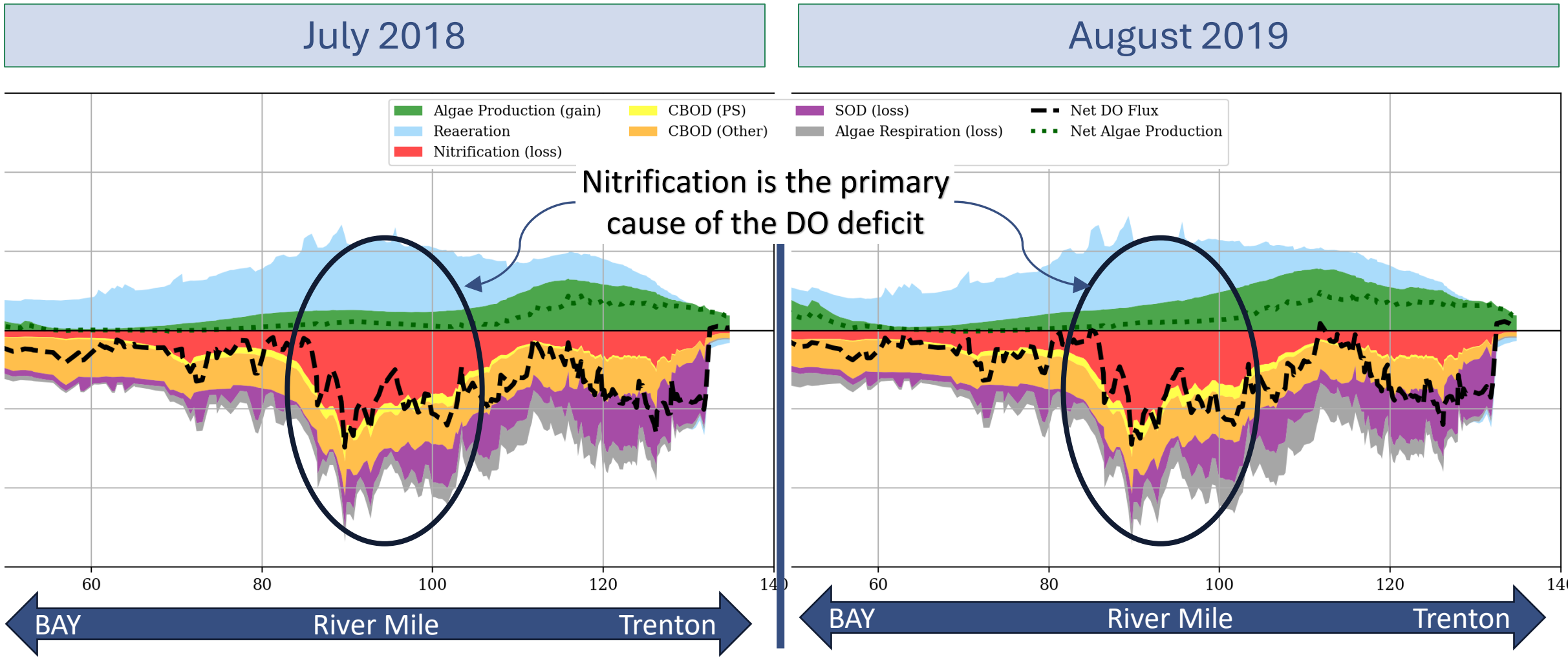
“Background”
- Reaeration
- Photosynthesis
- Respiration
- CBOD (Other)
- SOD

Same location, same year … let's zoom in on one month when DO was lowest



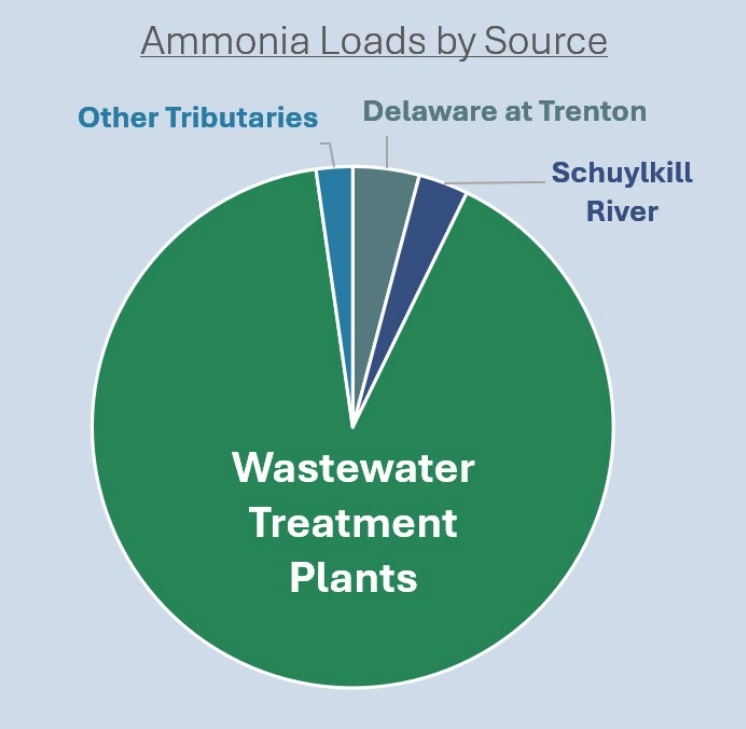
During periods when the Net DO Flux is lowest, it is nitrification that is driving those episodes.

What happens when we look at the entire tidal river during months when DO was lowest …



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What can we glean from our analysis of dissolved oxygen components?



- The three most important processes affecting DO in the estuary are:
  - Decay of CBOD
  - Nitrification of ammonia
  - Atmospheric reaeration
- Background processes comprise a significant portion of dissolved oxygen drivers
  - Reaeration in a high energy system
  - Phytoplankton in a light-limited system
  - Particulate carbon delivered by large tributaries
- Nitrification is primarily responsible for the “sag” observed between Philly and Chester
  - Caused principally by ammonia from municipal wastewater

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Better science +

More and better data +

Kinetic refinements =

A much better model!

DRBC Water Resource Modeling Team

https://www.nj.gov/drbc/programs/quality/designated-use.html