Climate Change and the Challenge of Meeting Open Water DO Water Quality Standards Attainment

Criteria Assessment Protocol Workgroup

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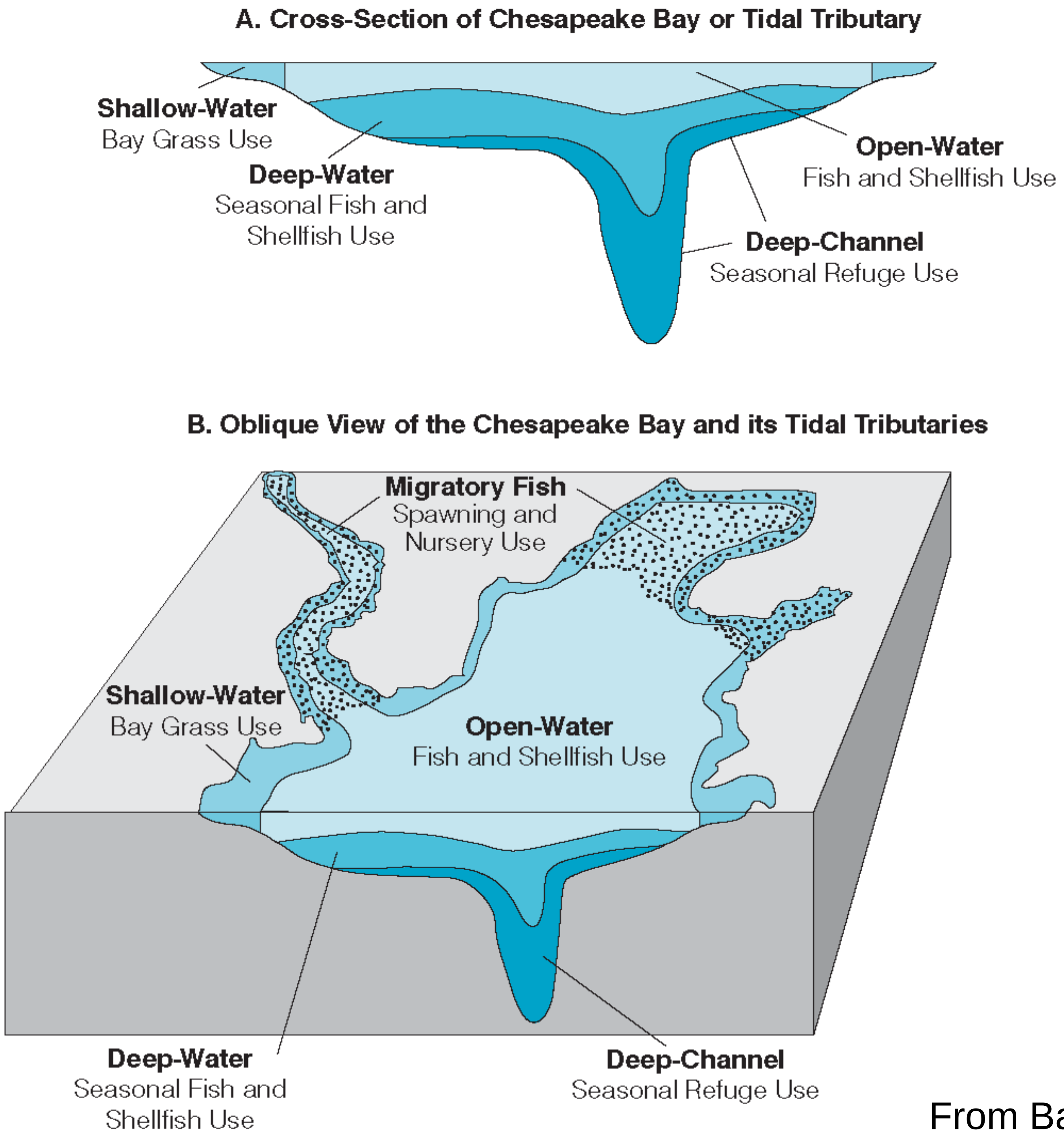
Lew Linker and the CBPO Modeling Team

linker.lewis@epa.gov

The ongoing CBP challenge is to develop and track Watershed Implementation Plans (now at WIP3s and counting) that will achieve Chesapeake water quality standards to support living resources. Current additional challenges are to account for climate change and cobenefits.



From Batiuk (2003)

Table VI-1. Chesapeake Bay dissolved oxygen criteria.

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use	7-day mean ≥ 6 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum ≥ 5 mg liter^{-1}	Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species.	
	Open-water fish and shellfish designated use criteria apply		June 1 - January 31
Shallow-water bay grass use	Open-water fish and shellfish designated use criteria apply		Year-round
Open-water fish and shellfish use	30-day mean ≥ 5.5 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species.	Year-round
	30-day mean ≥ 5 mg liter^{-1} (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean ≥ 4 mg liter^{-1}	Survival of open-water fish larvae.	
	Instantaneous minimum ≥ 3.2 mg liter^{-1}	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean ≥ 3 mg liter^{-1}	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean ≥ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum ≥ 1.7 mg liter^{-1}	Survival of bay anchovy eggs and larvae.	
	Open-water fish and shellfish designated-use criteria apply		October 1 - May 31
Deep-channel seasonal refuge use	Instantaneous minimum ≥ 1 mg liter^{-1}	Survival of bottom-dwelling worms and clams.	June 1 - September 30
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31

[1] At temperatures considered stressful to shortnose sturgeon (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

From Batiuk (2003)

Components of Climate Change on Tidal DO

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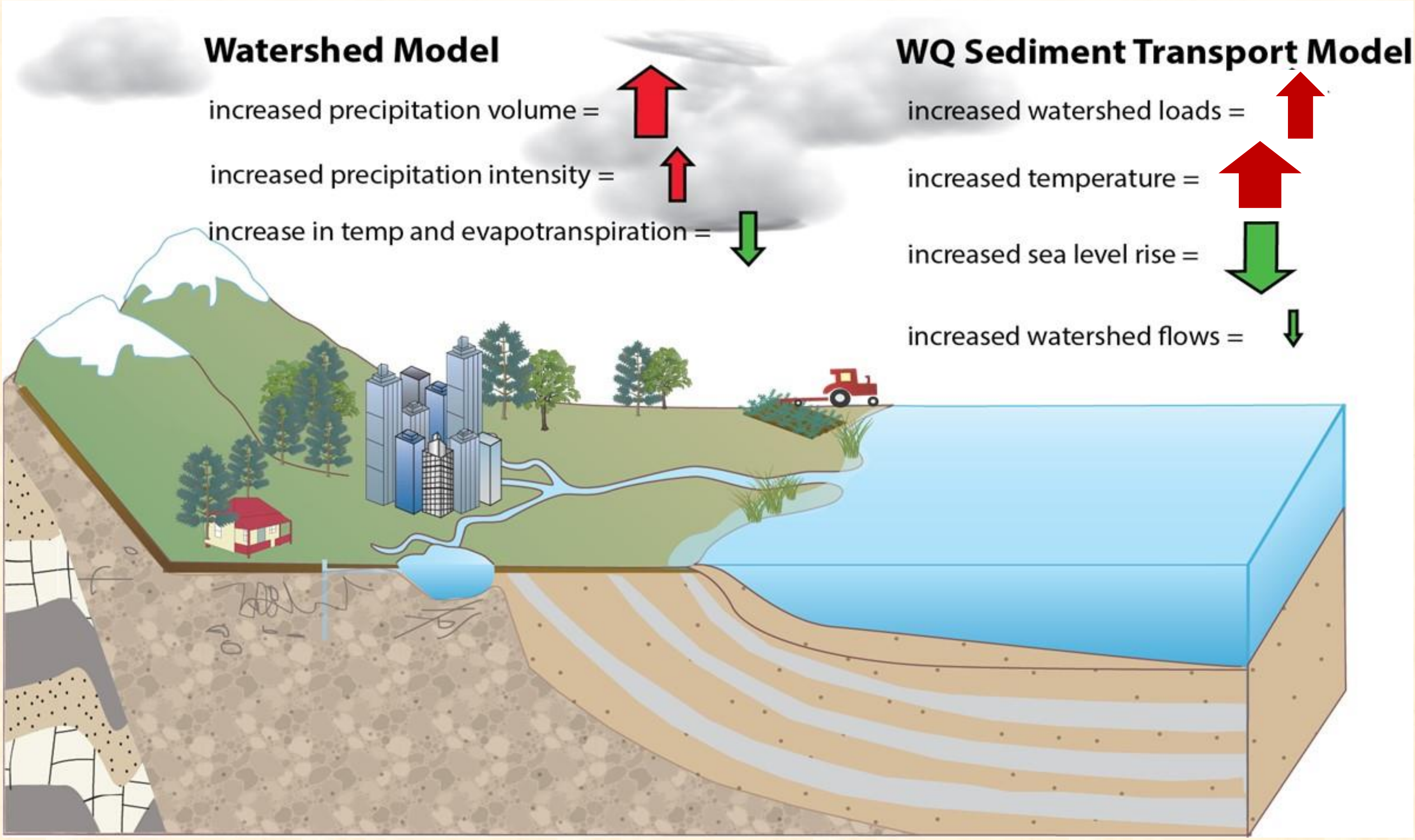

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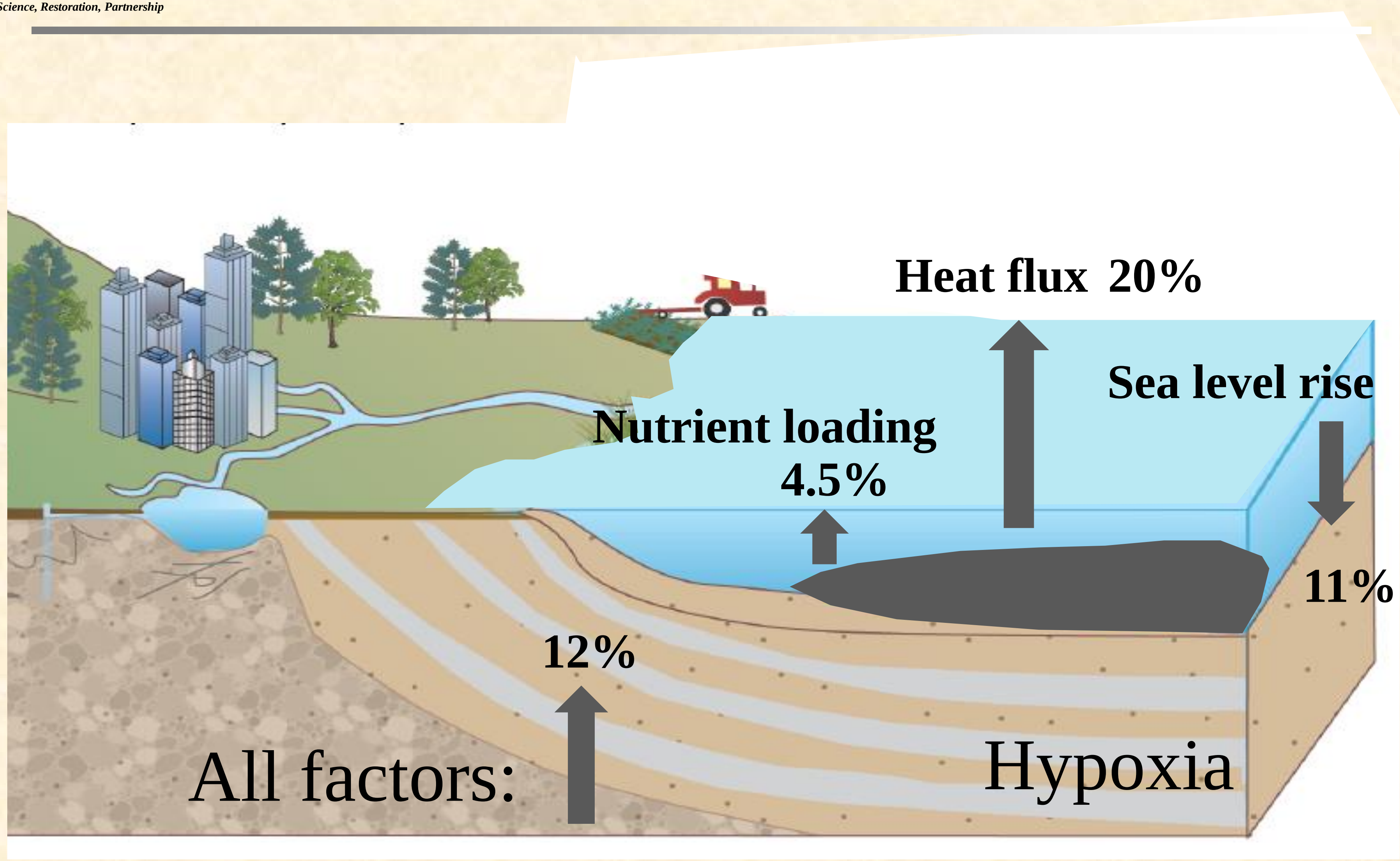
Elements of Hypoxia Volume Change: 1995 - 2025



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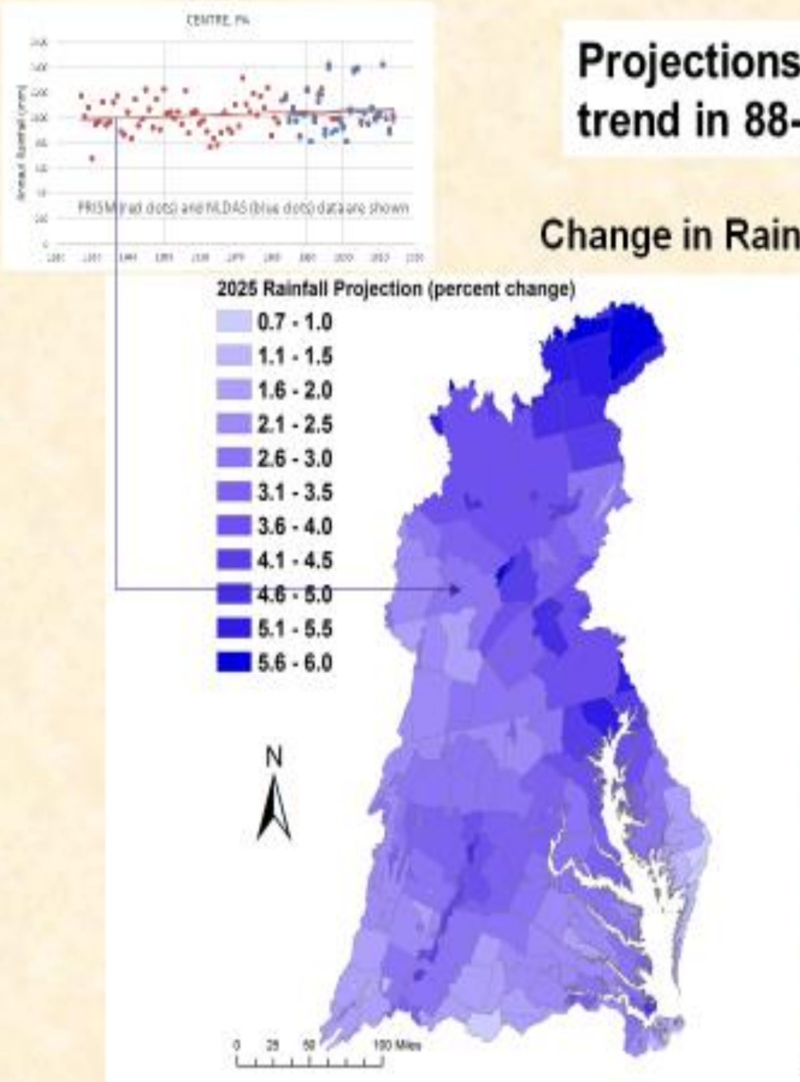
Precipitation Volume Increasing

Projections of rainfall increase using trend in 88-years of annual PRISM[1] data



Change in Rainfall Volume 2021-2030 vs. 1991-2000

Major Basins	PRISM Trend
Youghiogheny River	2.1%
Patuxent River Basin	3.3%
Western Shore	4.1%
Rappahannock River Basin	3.2%
York River Basin	2.6%
Eastern Shore	2.5%
James River Basin	2.2%
Potomac River Basin	2.8%
Susquehanna River Basin	3.7%
Chesapeake Bay Watershed	**3.1%**

[1] Parameter-elevation Relationships on Independent Slopes Model

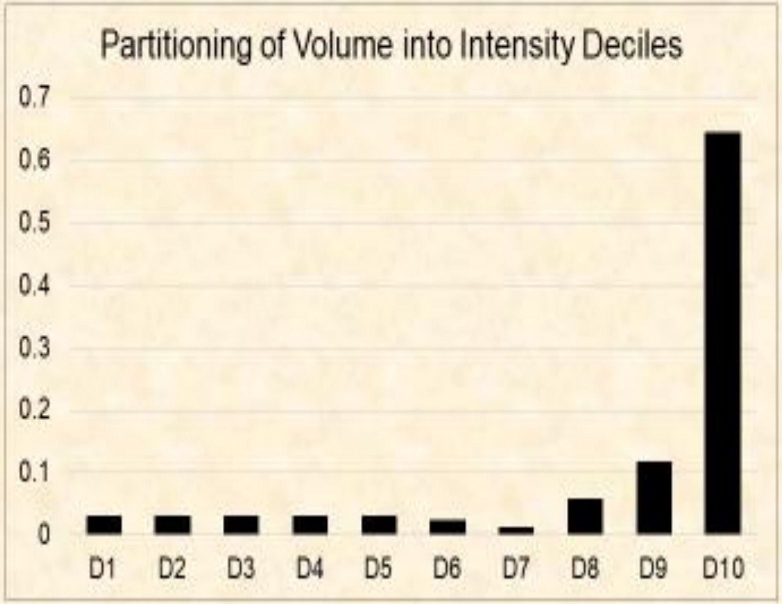
The 1991 – 2000 period of hydrology & nutrient loads is the basis of decisions in the Chesapeake TMDL.

There are 30 years between 1995 and 2025.

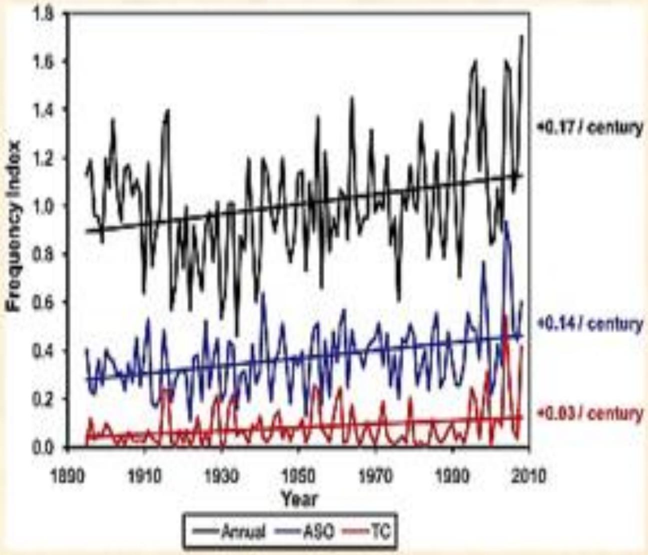
Long term mean precipitation increased 3.1% and temperature by 1° C.

Rainfall Intensity Increasing

Observed trend of more precipitation volume in higher intensity events based on a century of observations.

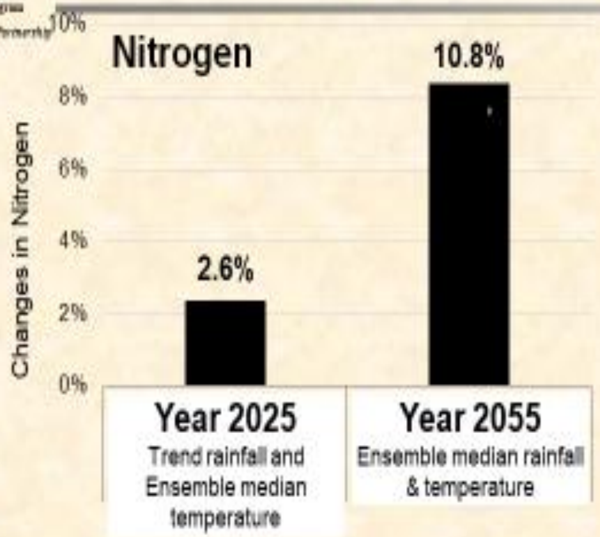


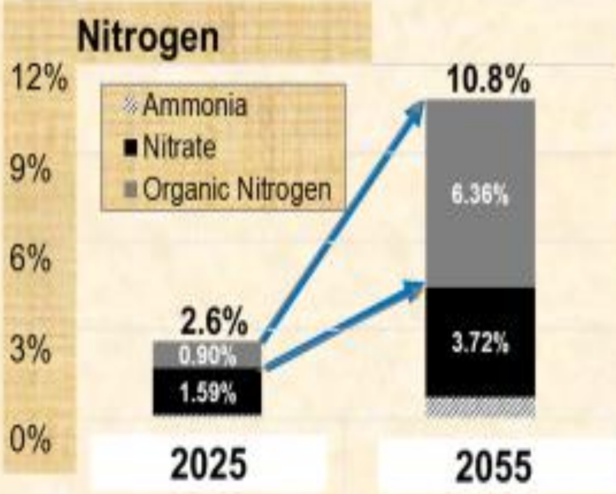
Source: Groisman et al., 2004



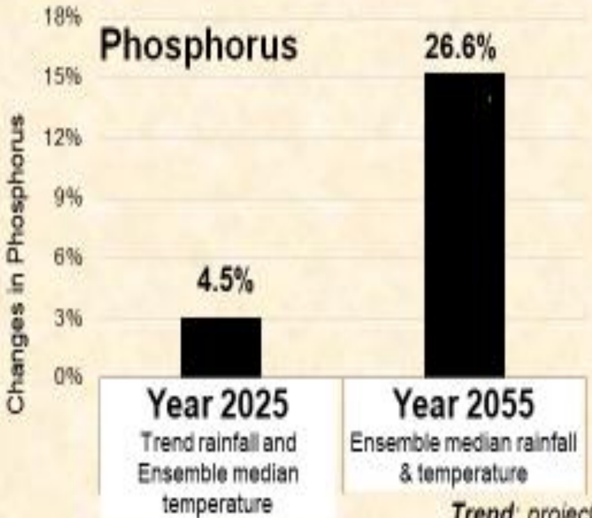
National average heavy precipitation event index (HPEI) for the entire year (annual, black), for August through October (ASO, blue), and for heavy events associated with tropical cyclones (TC, red). [Kunkel et al., 2010]

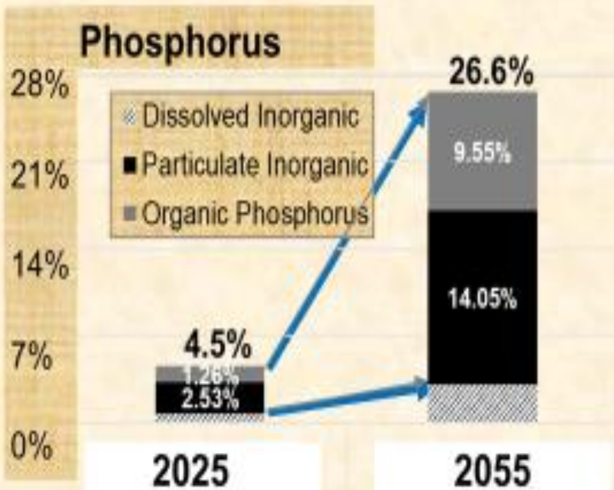
Summary of Changes in Nutrient Species Delivery





Arrows show relatively more increase in organic N & P or PIP compared to DIN or DIP.





The TN & TP loads are steadily increasing from 2025 to 2055 under climate change but there is a greater proportion of refractory N and P in the total N & P going forward.

Trend: projection of extrapolation of long-term trends
Ensemble: 31-member ensemble of RCP4.5 GCMs

Estimates of Climate Only and Climate and Land Use

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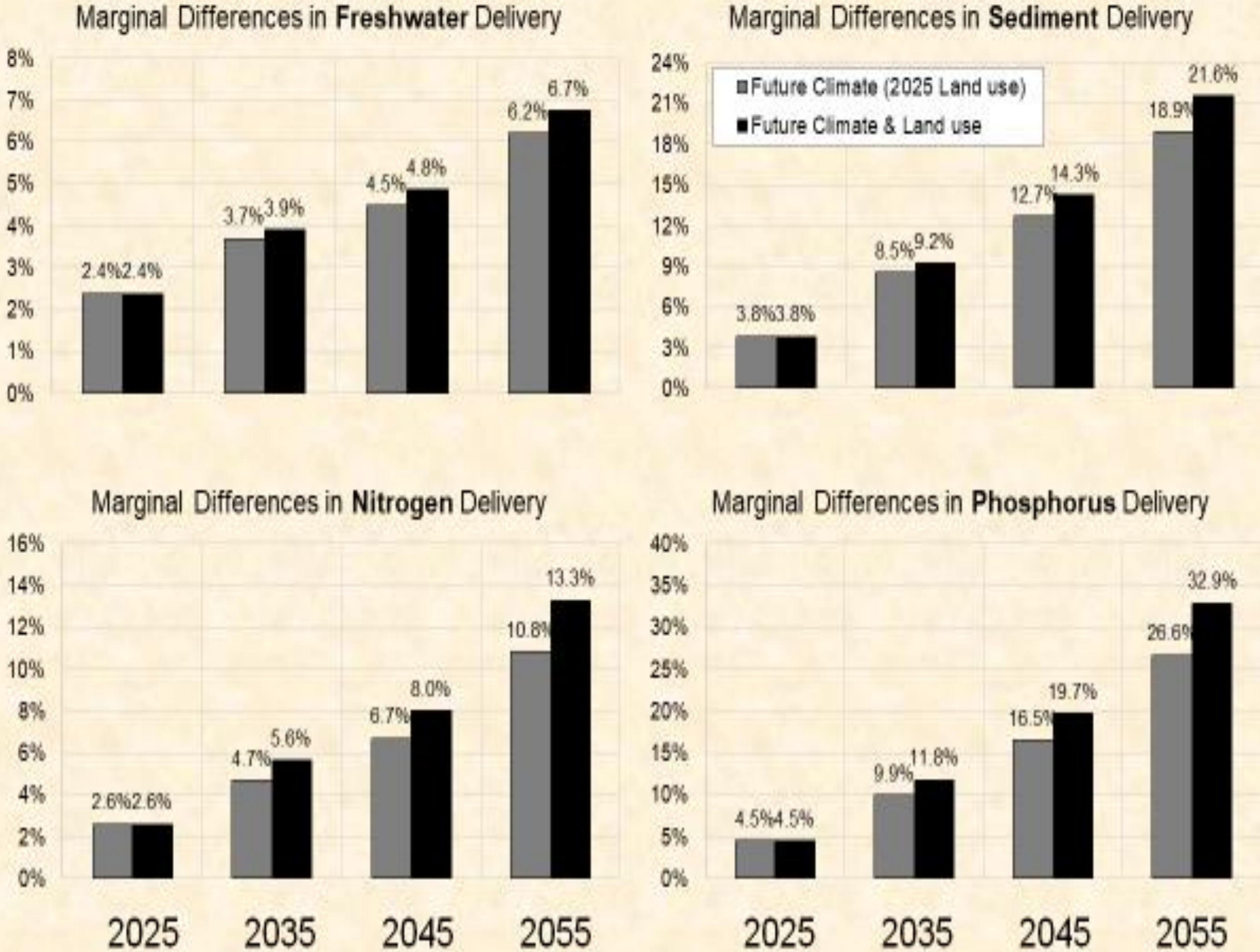

Grey bar = climate only   Black bar = Climate and Land Use

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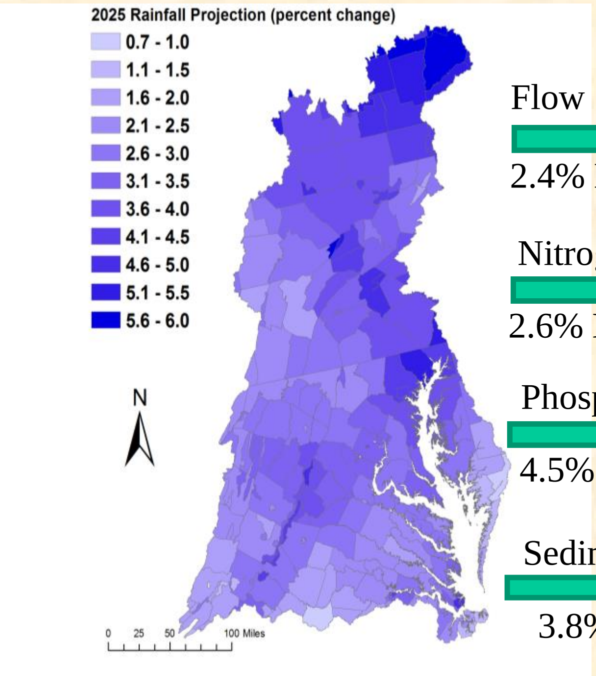
Elements of 2025 Climate Change in the Estuary



Phase 6 Watershed Model

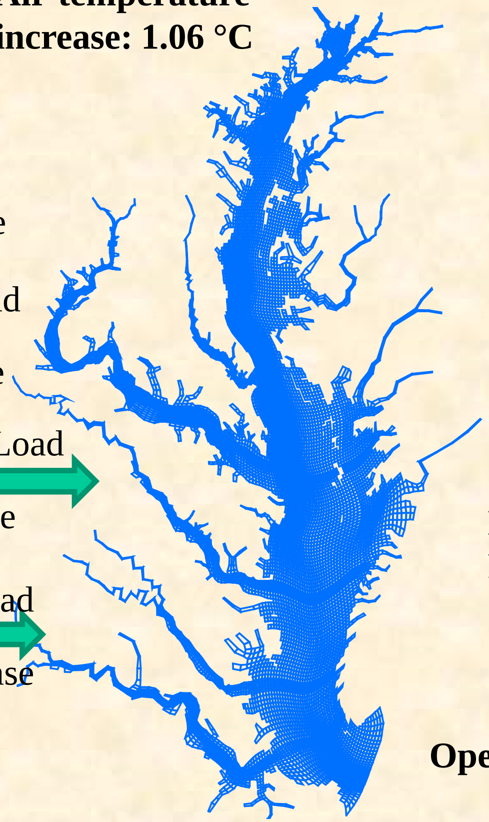
Flow
2.4% Increase

Nitrogen Load
2.6% Increase

Phosphorus Load
4.5% Increase

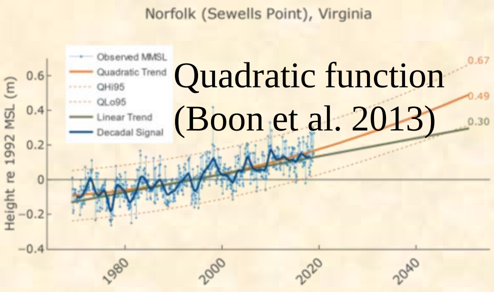
Sediment Load
3.8% Increase

Air-temperature increase: 1.06 °C

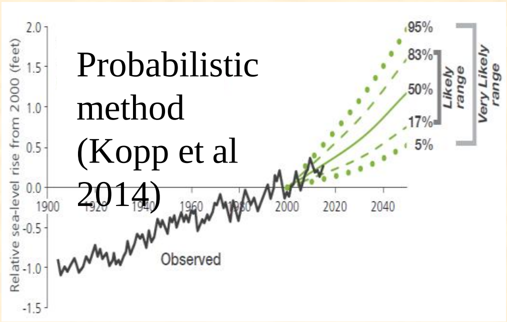


Model: CH3D-ICM
400m-1km Resolution

2025 Sea Level Rise: 0.22m



Quadratic function (Boon et al. 2013)



Probabilistic method (Kopp et al 2014)

Open boundary **T: + 0.95 °C; S: + 0.18 psu (Thomas et al., 2017)**

Estimated DO Change From Four Key Factors: 1995 to 2025

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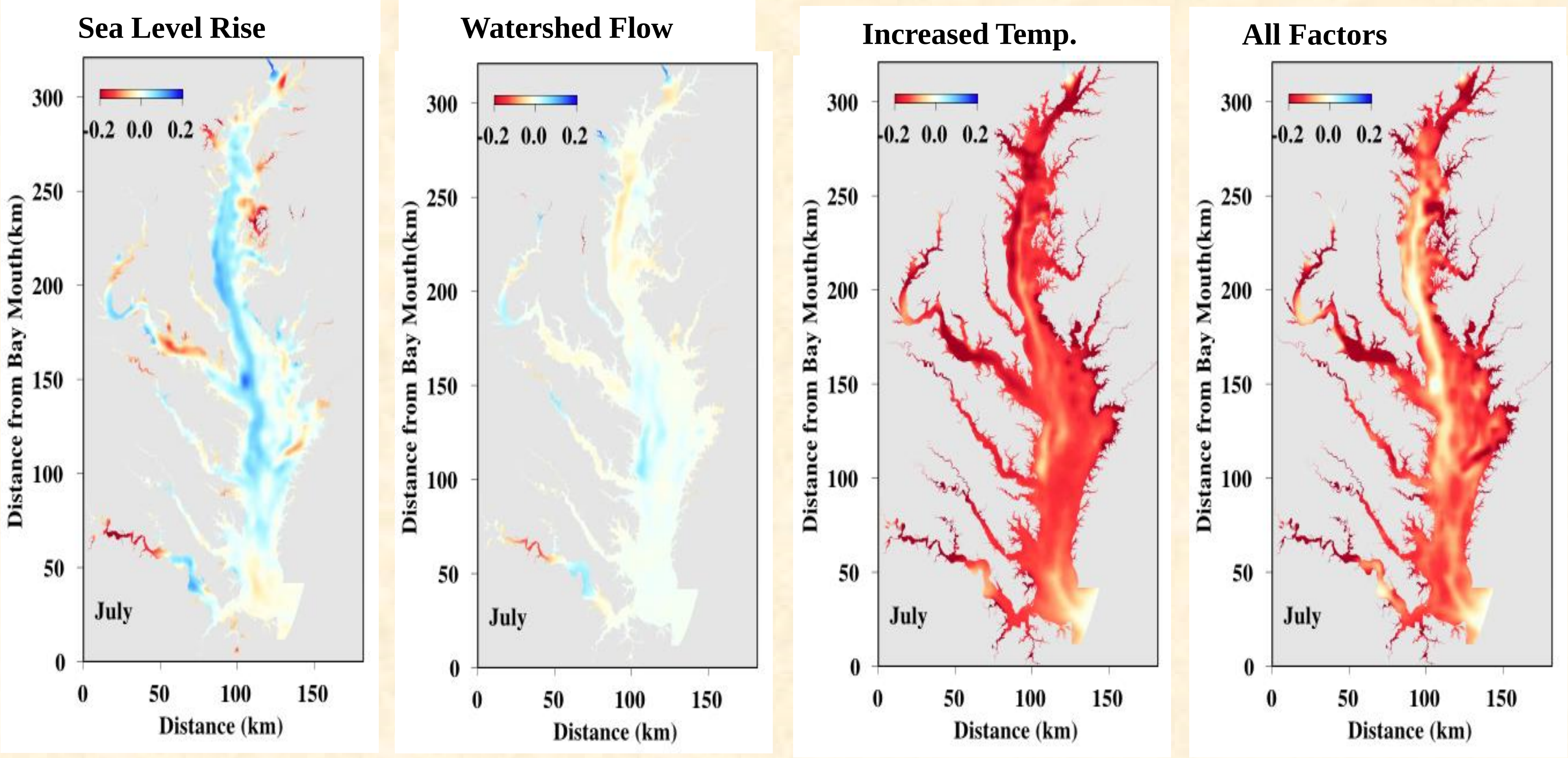
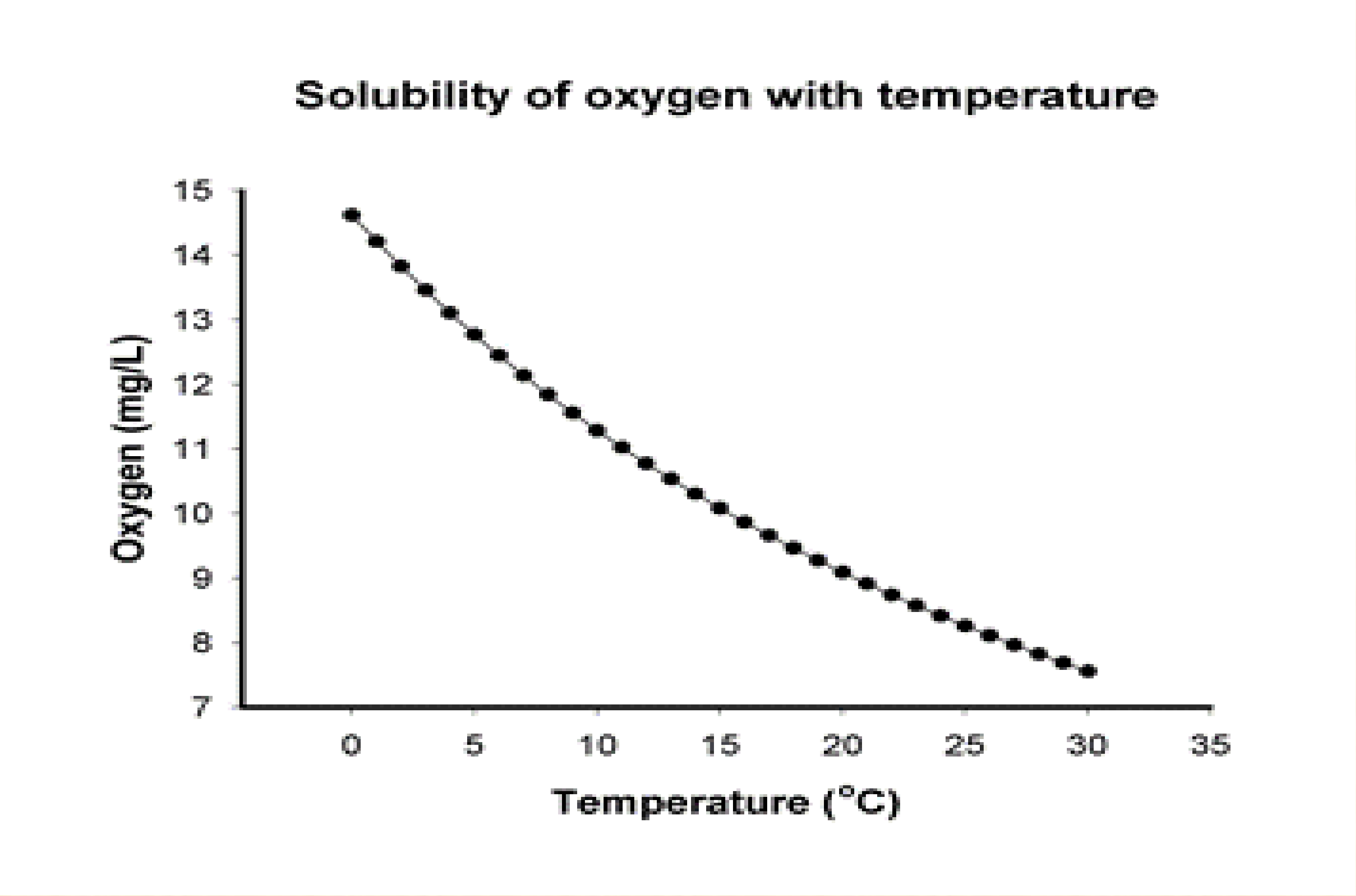
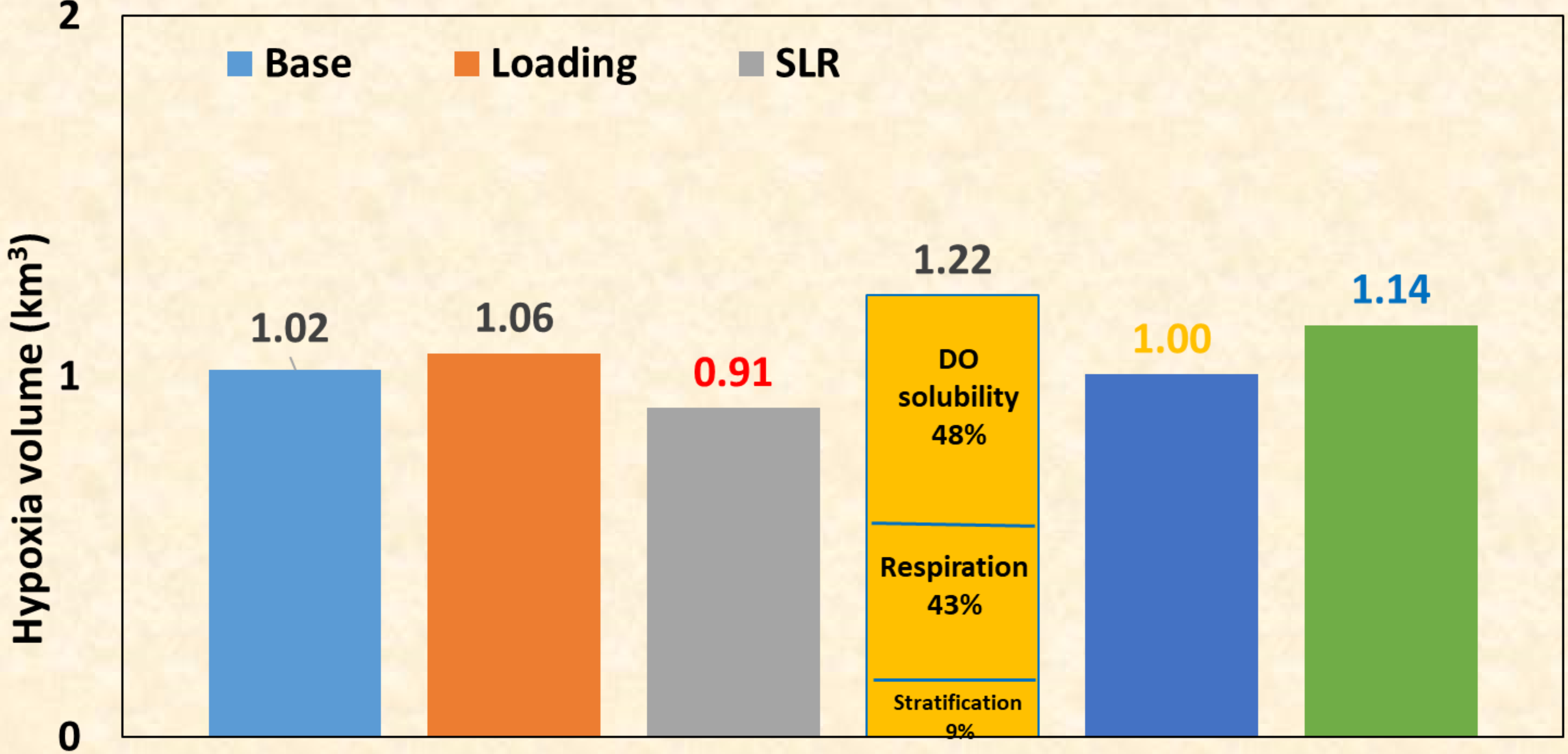
Keeping all other factors constant, sea level rise and increased watershed flow reduce hypoxia in the Bay, but the predominant influence are the negative impacts of increased water column temperature.



Dissolved oxygen solubility in water is sensitive to temperature. In the summer, surface DO in the mainstem Bay is typically about 8 mg/l. But in the coolest winter months the surface DO is about 12 mg/l, one third more than that of the summer concentration. Temperature increases also increase the consumption of oxygen by increased respiration and strengthen stratification.



Summer (Jun.-Sep.) Hypoxia Volume (<1 mg/l) 1991-2000 in the Whole Bay Under 2025 WIP3 Condition



Summer hypoxic (< 1 mg/l DO) estimates solely under conditions of a 1.03° C temperature increase (1.22 km3, Heat - amber bar) compared to the 2025 WIP3 scenario conditions without climate change (1.02 km3, Base – blue bar). Other bars are solely 2025 climate change nutrient loads (Loading, orange bar) solely 2025 sea level rise condition (SLR, grey bar, solely watershed 2025 increased flows (Flow, dark blue bar), and all 2025 climate change conditions combined (All, green bar).

Achievement of Open Water DO Water Quality Standard

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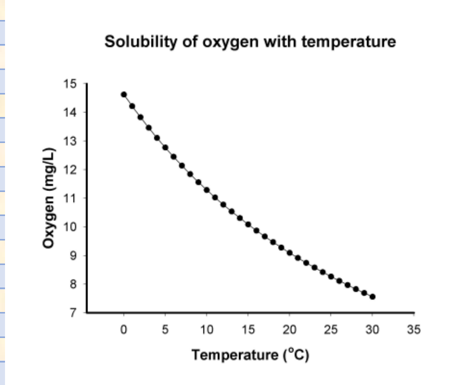
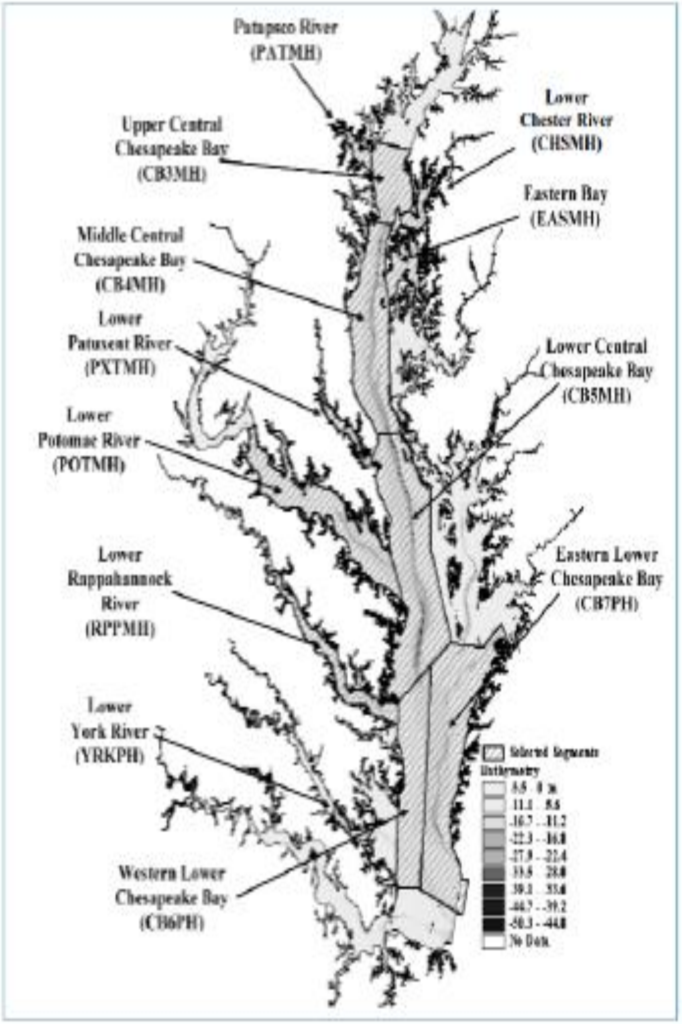
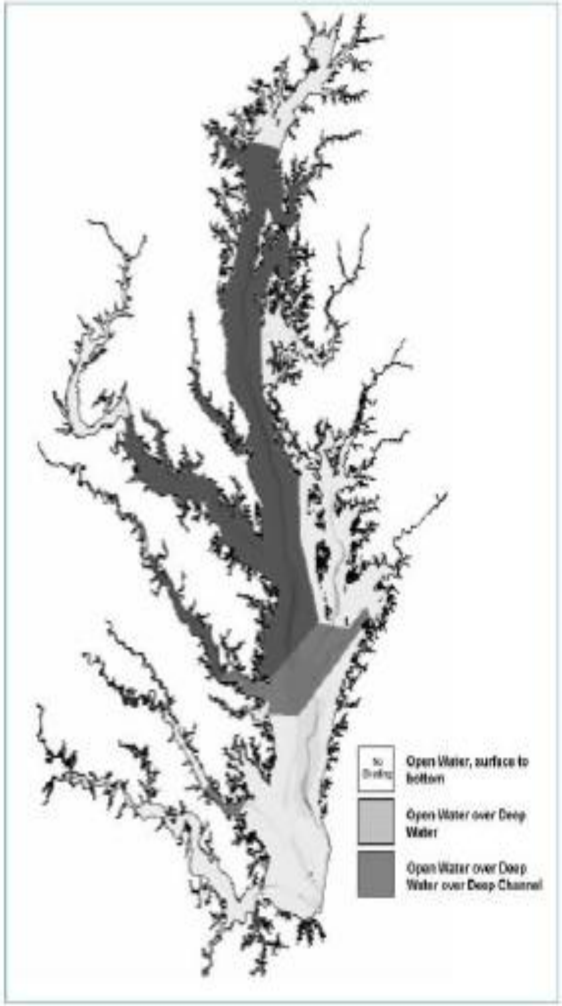
CB Segment	State	2025 Climate 2025 Land Use 204TN 14.0TP 1993-1995 DO Open Water	2035 Climate 2025 Land Use 208TN 14.6TP 1993-1995 DO Open Water	2035 Climate 2035 Land Use 209TN 14.7TP 1993-1995 DO Open Water	2045 Climate 2025 Land Use 212TN 15.4TP 1993-1995 DO Open Water	2045 Climate 2045 Land Use 213TN 15.7TP 1993-1995 DO Open Water	2055 Climate 2025 Land Use 220TN 16.7TP 1993-1995 DO Open Water	2055 Climate 2055 Land Use 222TN 17.1TP 1993-1995 DO Open Water
CB1TF	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CB2OH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CB3MH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CB4MH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CB5MH_MI	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CB5MH_VA	VA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CB6PH	VA	0.4%	**0.7%**	**0.8%**	**1.0%**	**1.1%**	**1.3%**	**1.4%**
CB7PH	VA	**1.1%**	**1.8%**	**1.9%**	**2.8%**	**2.9%**	**4.0%**	**4.1%**
CB8PH	VA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BSHOH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
GUNOH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
MIDOH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
BACOH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
PATMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
MAGMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
SEVMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
SOUMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
RHDMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
WSTMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
PAXTF	MD	**3.3%**	**3.4%**	**3.3%**	**4.3%**	**4.3%**	[illegible]	[illegible]
WBRTF	MD	**21.3%**	**28.6%**	**21.3%**	**43.6%**	**51.2%**	[illegible]	[illegible]
PAXOH	MD	**6.1%**	**9.5%**	**11.0%**	**10.7%**	**12.0%**	[illegible]	[illegible]
PAXMH	MD	0.0%	0.0%	0.0%	0.0%	0.0%	[illegible]	[illegible]
POTTF_DC	DC	**1.8%**	**2.6%**	**2.7%**	**3.0%**	**3.2%**	[illegible]	[illegible]
POTTF_MD	MD	**0.5%**	**0.6%**	**0.7%**	**2.0%**	**2.3%**	[illegible]	[illegible]
ANATF_DC	DC	**5.1%**	**6.0%**	**6.4%**	**8.6%**	**9.2%**	**10.6%**	**11.7%**
ANATF_MI	MD	**10.6%**	**16.4%**	**16.8%**	**24.7%**	**25.7%**	**29.8%**	**30.2%**
PISTF	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MATTF	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
POTOH1_M	MD	0.3%	0.5%	**0.5%**	**0.9%**	**0.9%**	**1.4%**	**1.5%**
POTMH_MI	MD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RPPTF	VA	0.0%	0.0%	0.0%	0.0%	0.0%	**1.7%**	**3.7%**
RPPOH	VA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RPPMH	VA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CRRMH	VA	**4.2%**	**5.6%**	**5.6%**	**7.1%**	**7.1%**	**8.9%**	**9.7%**
PIAMH	VA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MPNTF	VA	**16.6%**	**18.5%**	**18.1%**	**15.7%**	**16.2%**	**10.0%**	**11.0%**
MPNOH	VA	**3.6%**	0.3%	**9.8%**	0.0%	0.0%	0.0%	0.0%
PMKTF	VA	**8.9%**	**14.6%**	**10.0%**	**10.2%**	**10.2%**	**2.8%**	**3.3%**
PMKOH	VA	**2.9%**	**1.8%**	**5.3%**	-2.6%	-2.6%	-3.3%	-3.3%
YRKMH	VA	**2.3%**	**1.8%**	**4.5%**	**2.5%**	**3.2%**	**4.3%**	**5.3%**
YRKPH	VA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MOBPH	VA	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%
JMSTFL	VA	0.0%	**0.6%**	**0.5%**	**1.1%**	**1.2%**	**1.2%**	**1.4%**



https://www.chesapeakebay.net/content/publications/cbp_13218.pdf

Why are CB6 and CB7 acting so differently?



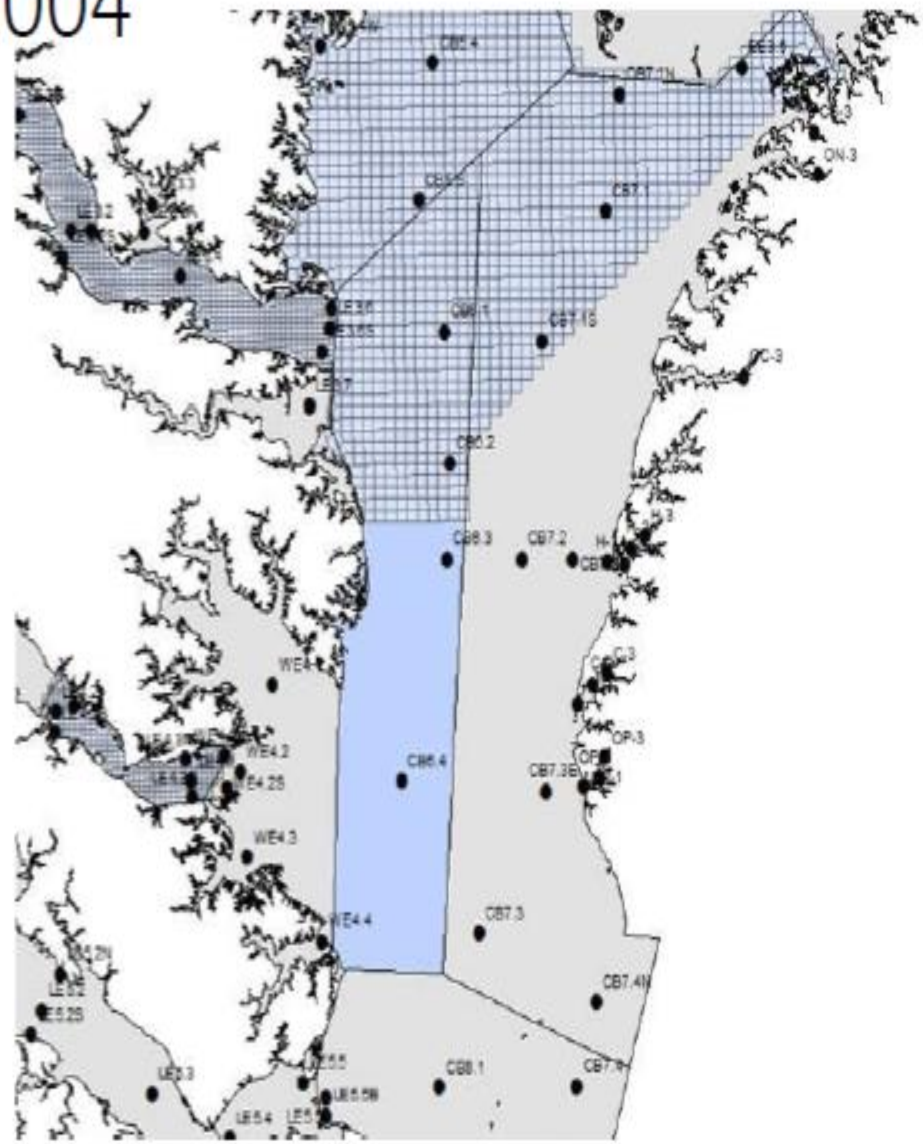


- 2003 Technical Support Document

"The delineation of the boundary was determined by examining maps of contemporary dissolved oxygen concentration distributions and the anecdotal historical dissolved oxygen concentration data record."

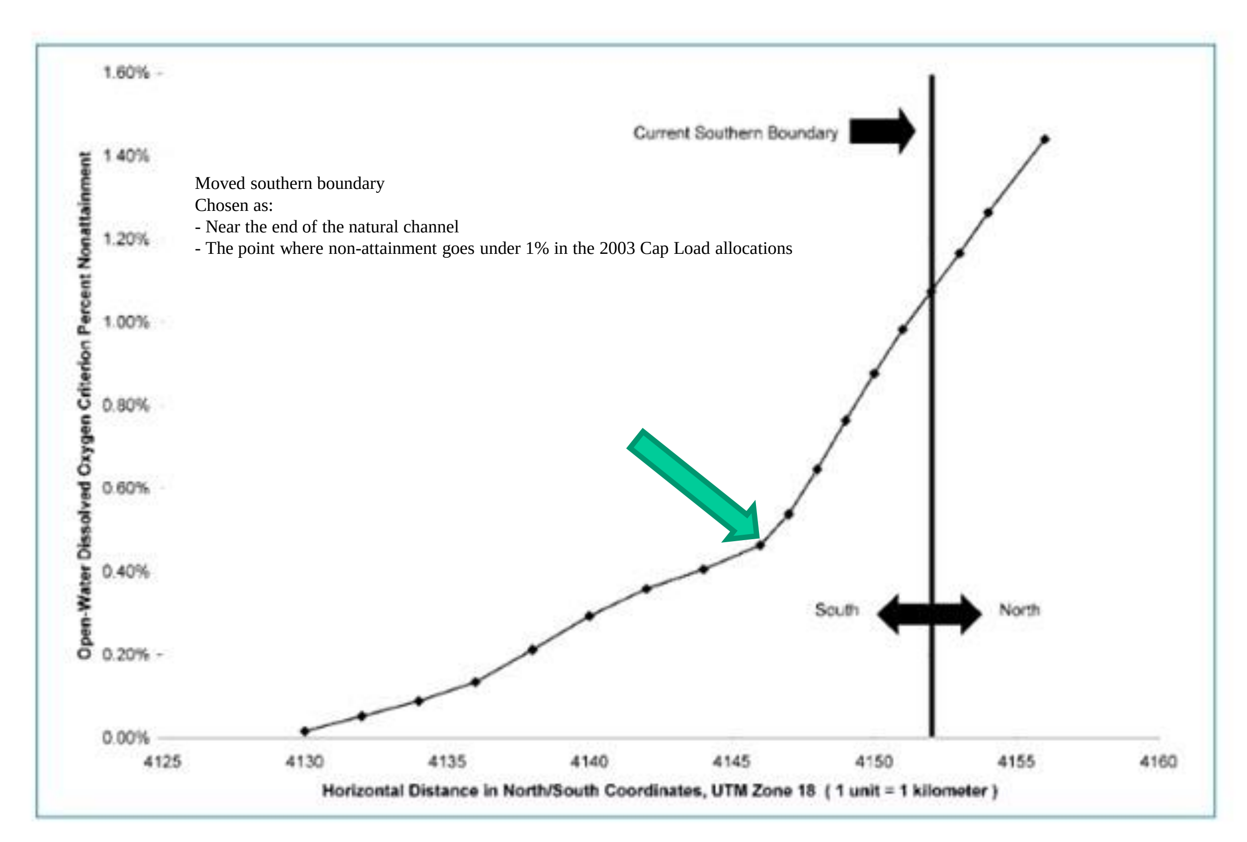
CB6 boundary moved in 2004

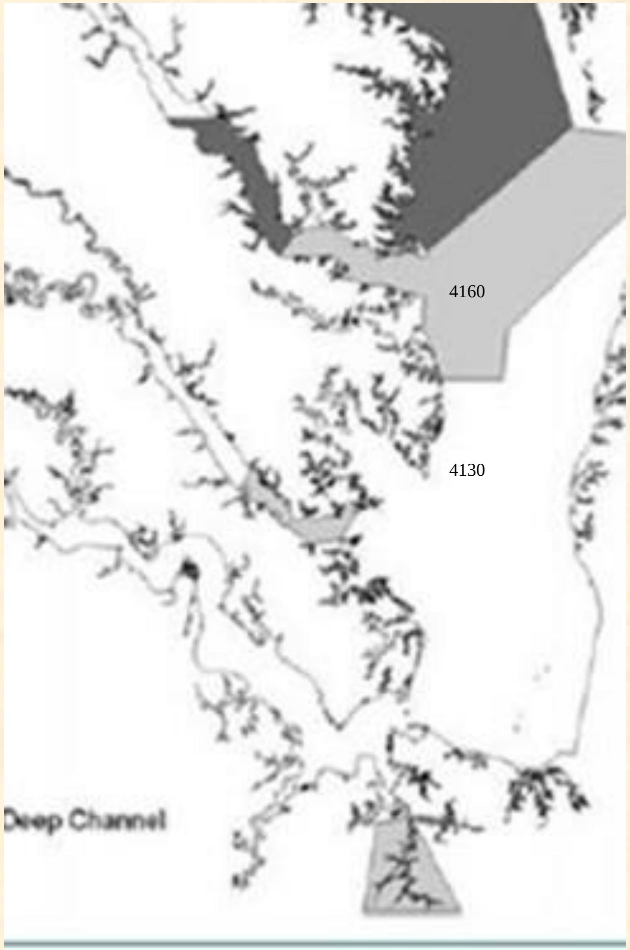
- Chosen as:
  - Near the end of the natural channel
  - The point where non-attainment goes under 1% in the 2003 Cap Load allocations



https://www.chesapeakebay.net/content/publications/cbp_13270.pdf

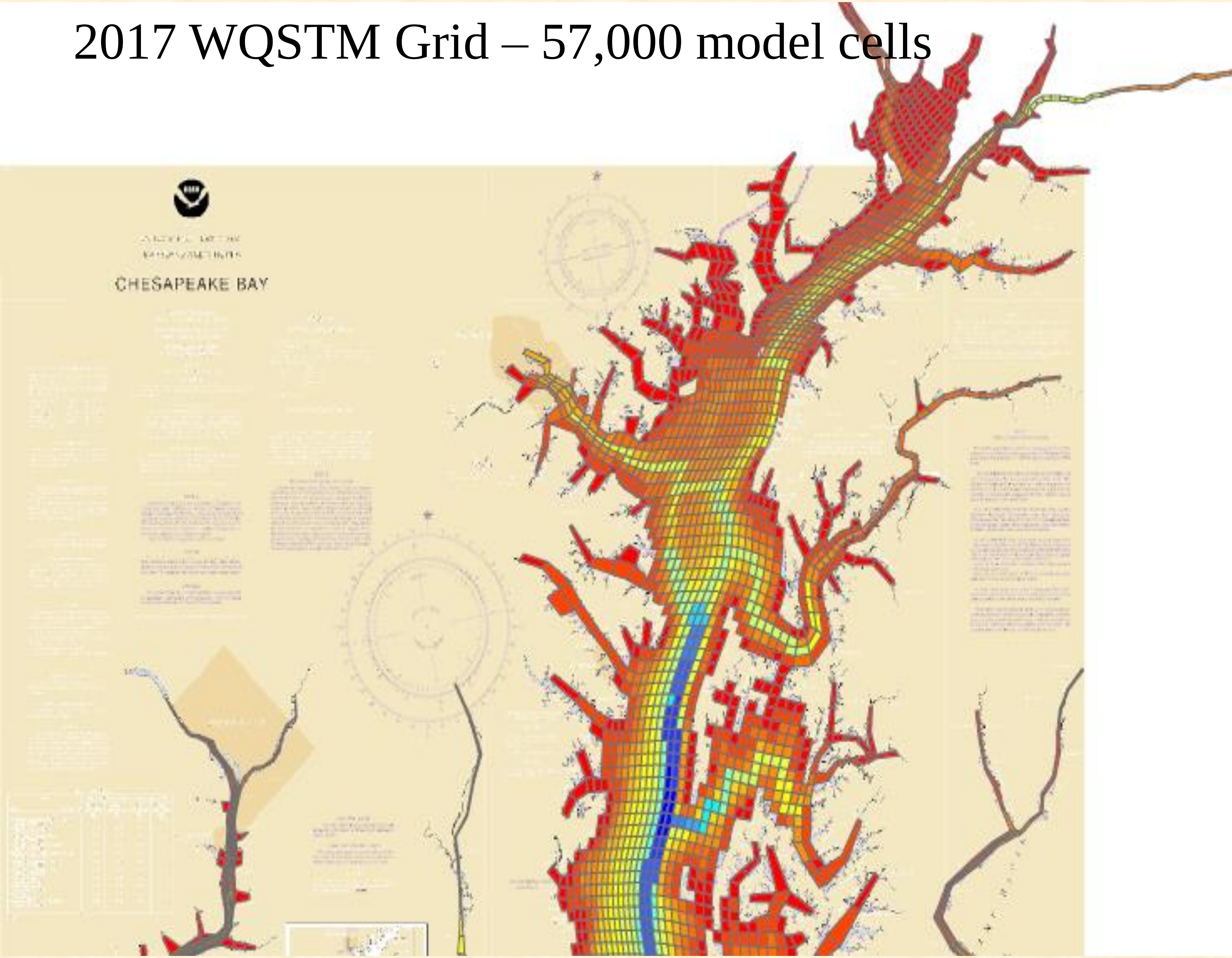
2004 Addendum to 2003 Technical Support Document





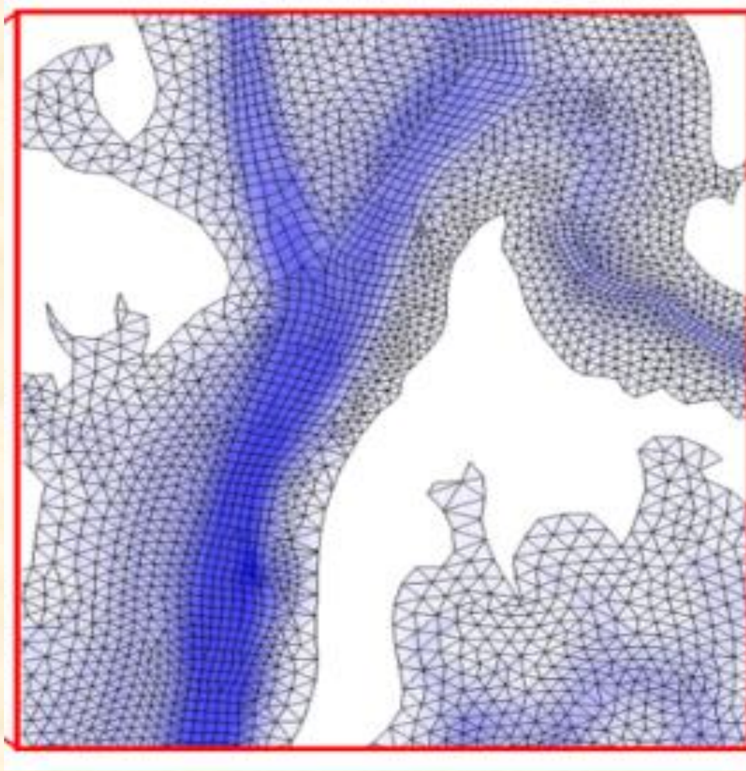
https://www.chesapeakebay.net/content/publications/cbp_13270.pdf

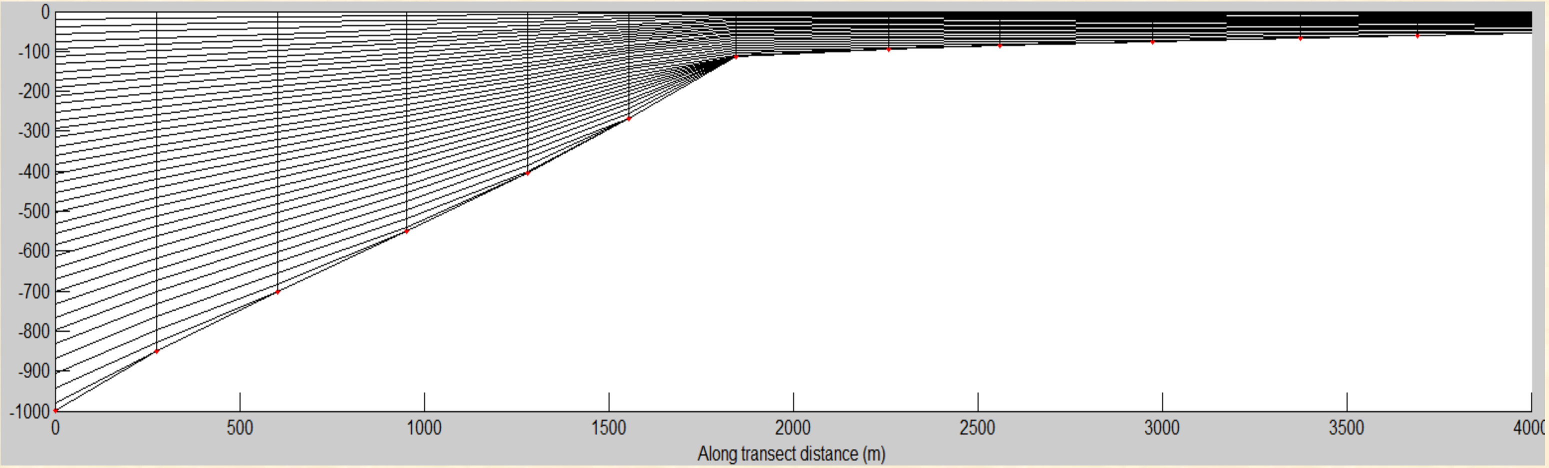
2017 WQSTM Grid – 57,000 model cells



Next Generation Bay Model

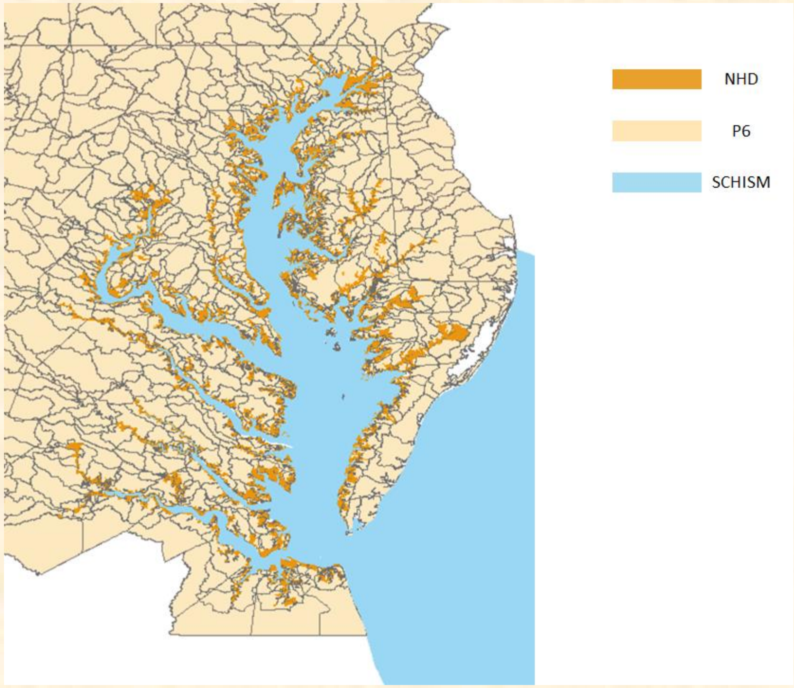
- Fine scale unstructured grid
- A multiple model implementation based on the CMAQ (Airshed Model) multiple model approach.

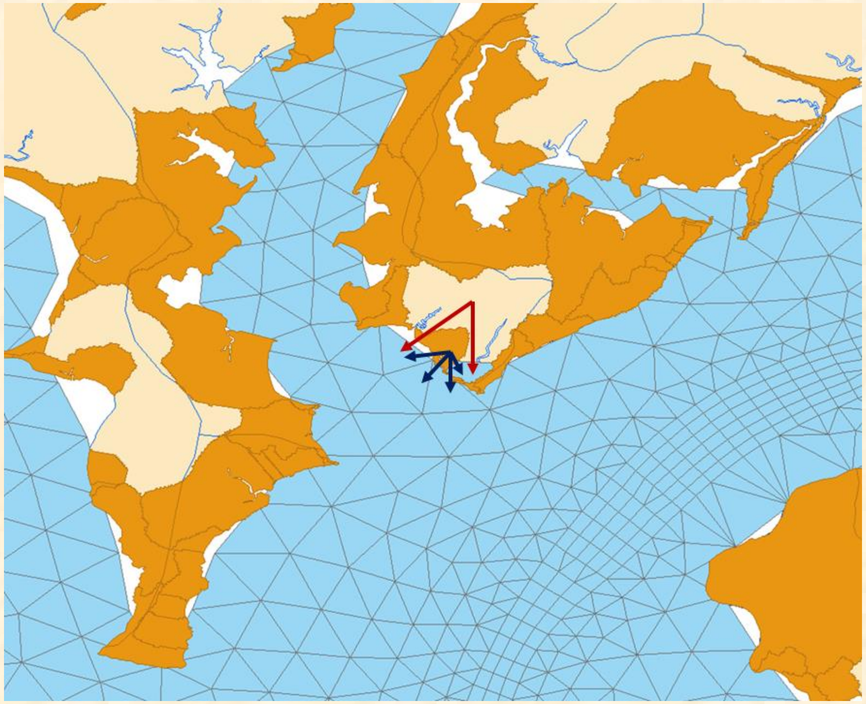




Prototype for Linking High Resolution Watershed Model to SCHISM

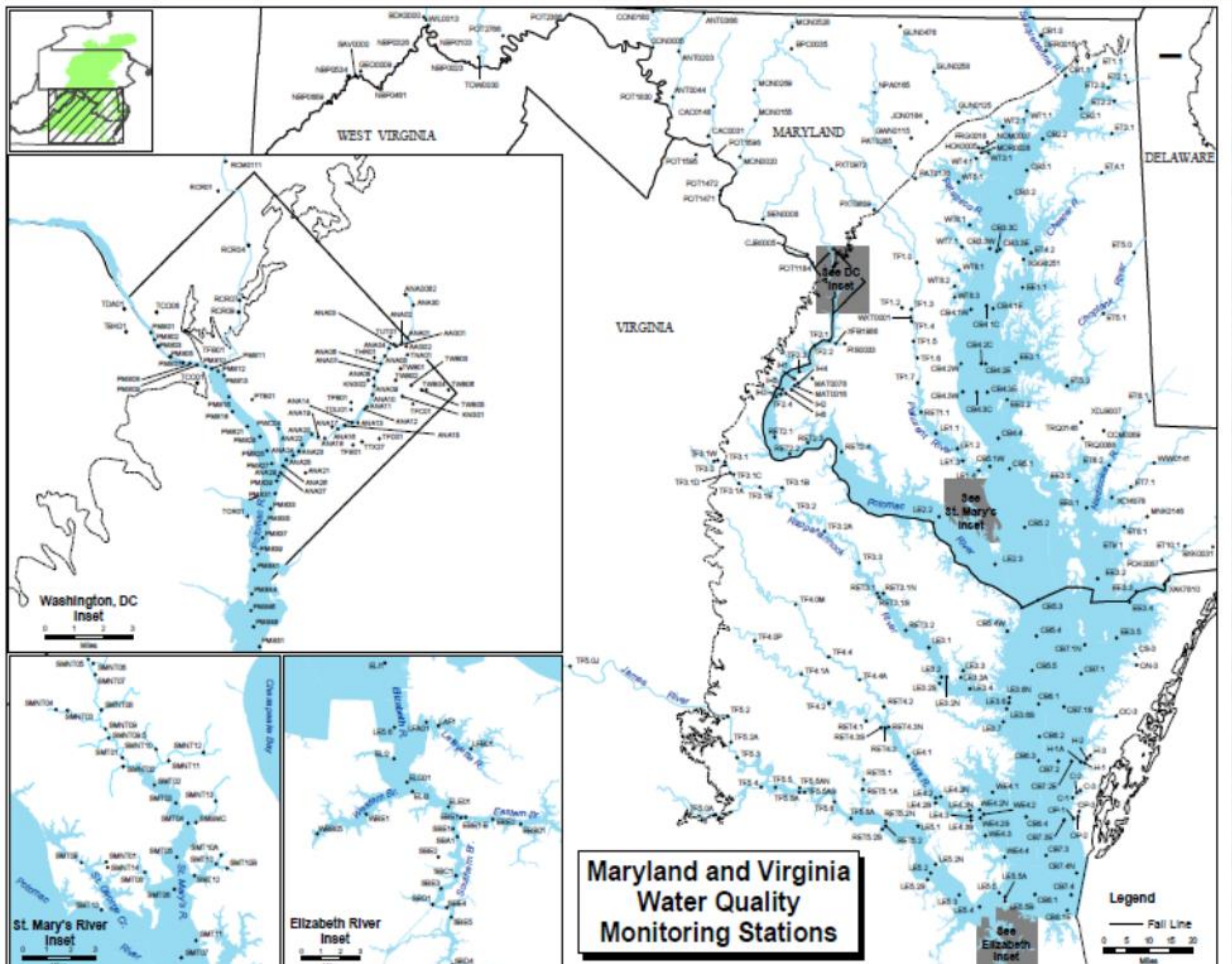
1) For hydrologic segments that touch SCHISM's land boundary, split the loading evenly to number of boundary elements adjacent to the segment
2) For hydrologic segments that do not touch SCHISM's land boundary, find the nearest land boundary element and assign the flow to it (there are different options 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



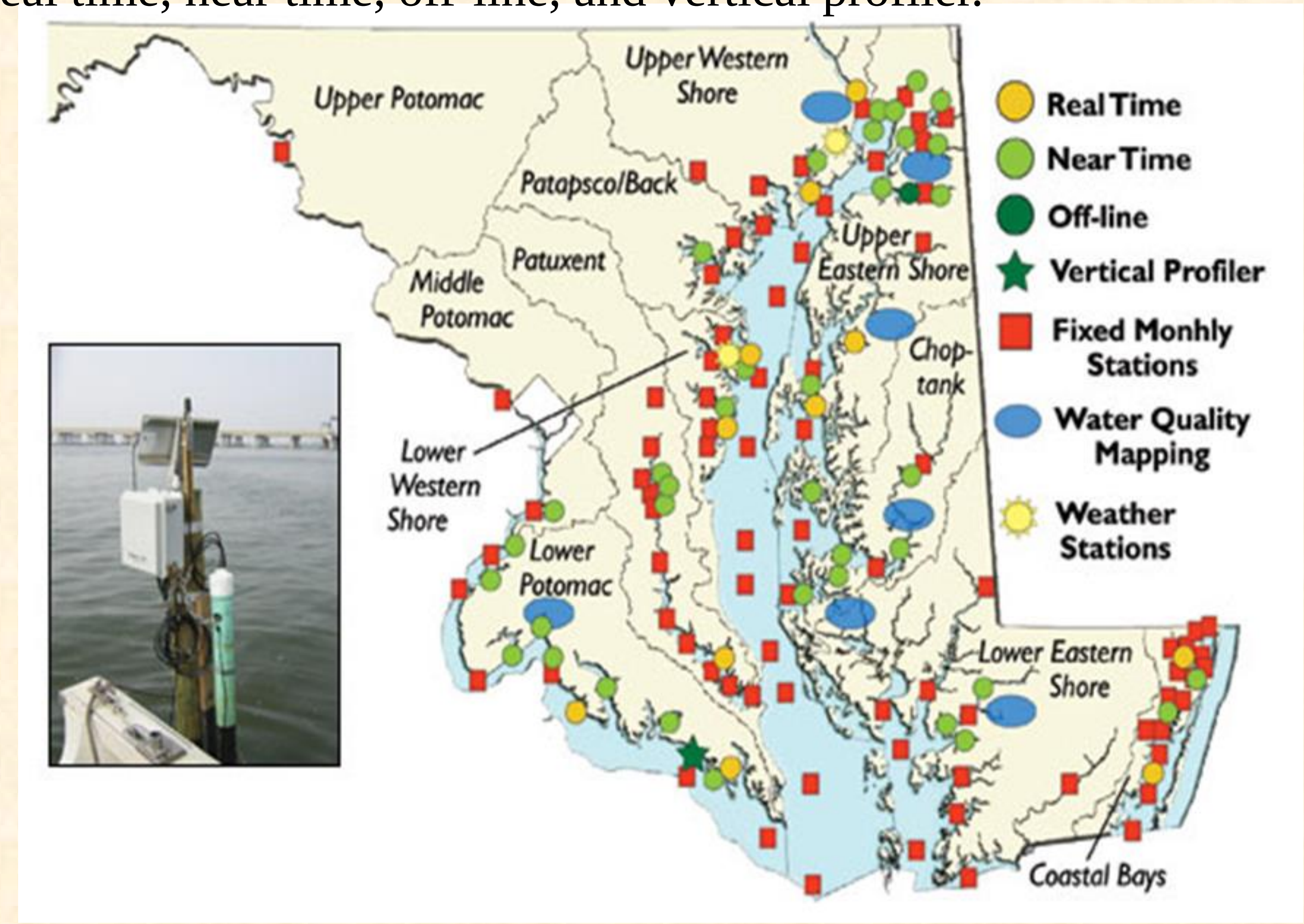


Source: CCRS 2020, Application of an unstructured-grid model in the Chesapeake prototype, Joseph Zhang, Nicole Cai1, Gopal Bhatt, Lewis Linker, Jian Shen, and Harry Wang

Chesapeake Bay Monitoring Stations



Maryland Shallow Water Monitoring Program stations. Continuous monitoring stations shown as yellow-orange or green symbols for real time, near time, off-line, and vertical profiler.



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CBP Partnership Decision

The Modeling Workgroup recommended, and the WQGIT agreed, that Open Water designated uses not be considered for the current climate change allocation decisions.

Key Points:

The Chesapeake Bay open-water dissolved oxygen (DO) water quality standard is based on protection of living resource habitat. The Chesapeake Bay TMDL is based on attainment of the summer open water monthly mean criteria of 5 mg/l (5.5 mg/l in tidal fresh waters), which was established to protect the growth of larval, juvenile, and adult fish and shellfish.

Under climate change conditions the average annual temperature is estimated to increase by 1° C over the three-decade period between the hydrology used for the Chesapeake TMDL (1991-2000) and the year 2025. By 2055 the average temperature is estimated to increase by 2° C for the 60 years between 2055 and 1995 (CBPO, 2020). Climate change temperature increases in Chesapeake tidal waters are inevitable over the next half-century, are global in origin, and are beyond CBP management and control.

Challenges in maintaining achievement of an open-water DO water quality criteria of 5 mg/l in all open-water designated uses at all times will inevitably increase throughout the next half-century. This is particularly true in the shallow water portions of the open-water DO designated uses of the Bay, which are generally defined as those areas less than 2 meters in depth as well as the main Bay segments of CB6PH and CB&PH which use an open-water DO criteria for their entire depth.

Key Points (*continued*):

The minimum depth represented in the 2017 Water Quality and Sediment Transport Model (WQSTM), used for the current assessment of climate change risk to tidal water quality standards, is 2 meters. Consequently, the depth of nearshore areas is inaccurately represented. Until now, the WQSTM was sufficient for open-water DO assessment, but in a changing climate with increasing temperatures the WQSTM simulation is unsuitable for shallow waters. .

Nevertheless, assessment of open-water DO climate risk is needed in shallow water. Going forward, a new estuarine model system is required which can: 1) simulate shallow water at a finer scale, 2) allow for an unstructured model grid to fit complicated shorelines, 3) simulate wetting and drying of the intertidal region, 4) project tidal wetland and SAV migration with sea level rise, 5) estimate SAV response to climate change, 6) assess living resource cobenefits, and 7) in general provide a state-of-the-art assessment of the important interface between land and water in the Chesapeake estuary.

The estuarine model approach for shallow water described in the STAC Report on CBP Modeling in 2025 and Beyond (2019) outlines the direction needed for a sufficient simulation of open-water DO in shallow Chesapeake waters under climate change conditions.