Dissolved Oxygen Criteria Attainment in Chesapeake Bay: Where Has It Improved Since 1985?

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Part 1 of 2

ITAT Monthly Meeting
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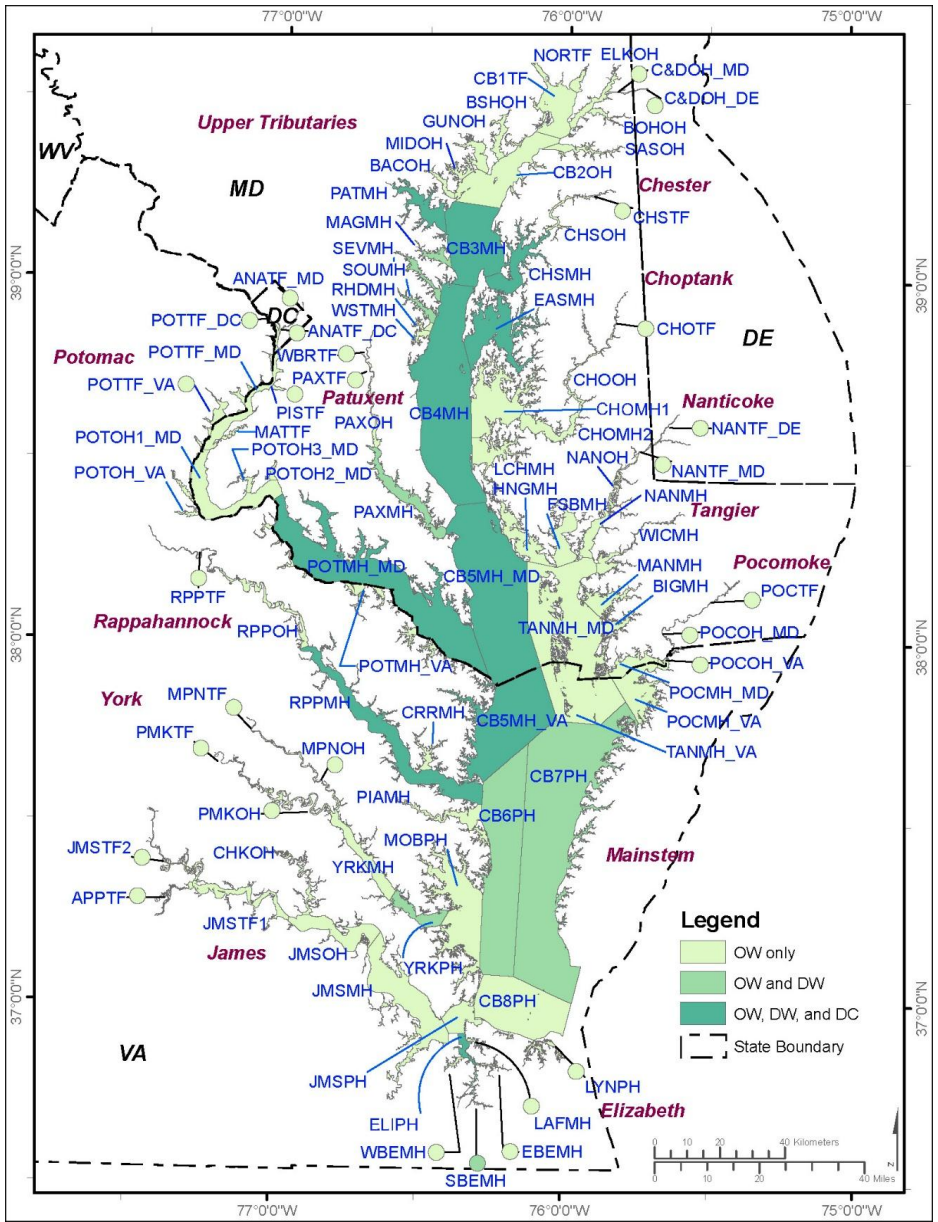
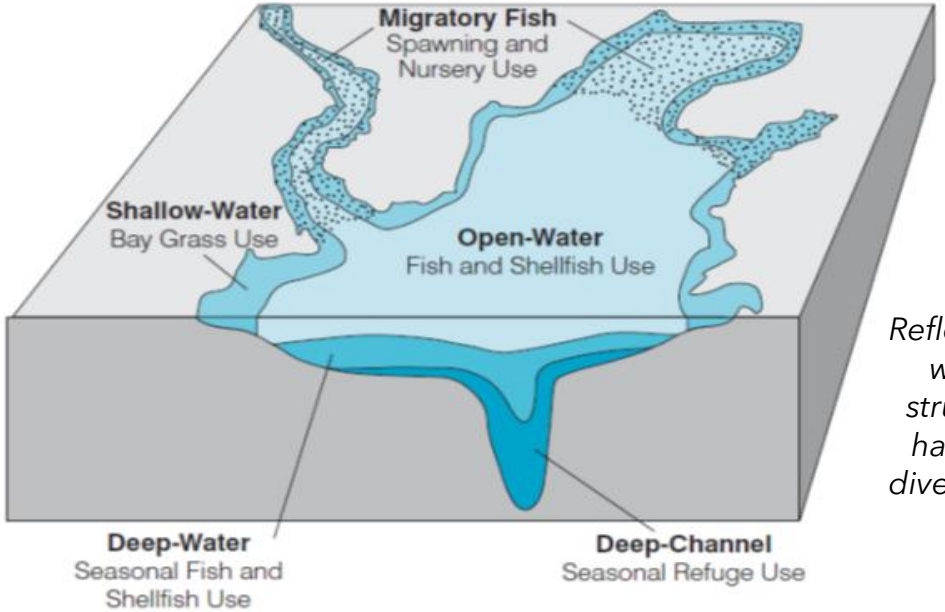
Introduction

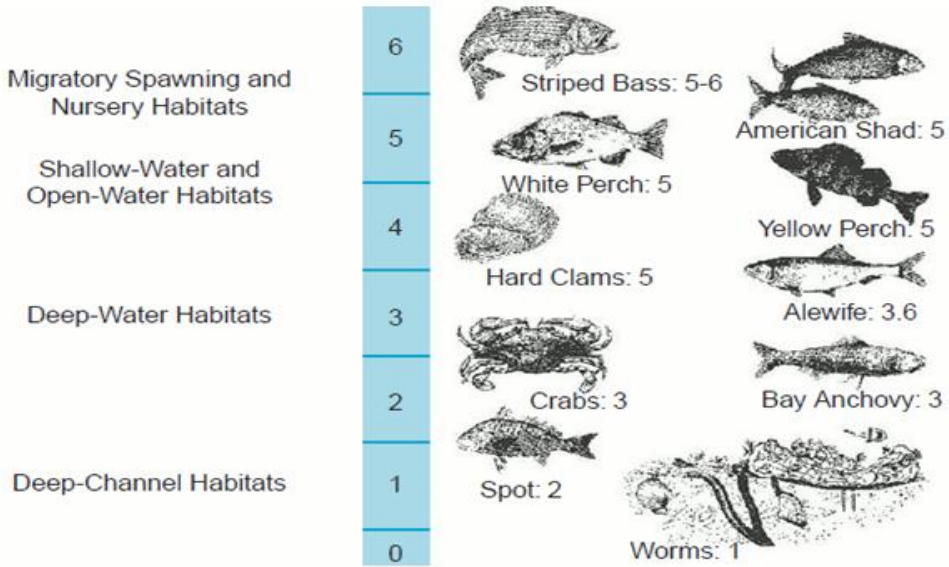
- One of the largest estuaries in the world.
- Provides essential habitats and economic benefits.
- Longstanding water quality issues due to nutrient pollution:
  - Algal blooms
  - Poor water clarity
  - **Low dissolved oxygen (DO)**
- Water quality standards (WQS) criteria developed for DO, water clarity/SAV, and chlorophyll-a.

Bay Segments and Designated Uses





Reflecting seasonal water-column structure and the habitat needs of diverse aquatic life.



WQS Criteria

Criteria	Designated Use	Threshold	Applicable Segments
Dissolved Oxygen	Migratory Fish Spawning & Nursery (MSN)	30-day mean, February-May	73
	Open Water (OW)	30-day mean, June-September	92
	Deep Water (DW)	30-day mean, June-September	18
	Deep Channel (DC)	Instantaneous, June-September	10
Chlorophyll-a	Open Water (OW)	Chlorophyll-a concentrations	7
SAV and/or Water Clarity	Shallow Water (SW)	Segment-specific water clarity and bay grass acreage goals	79

Note: The attainment indicator uses a subset of the complete accounting for the water quality criteria to ESTIMATE the attainment of water quality standards.

Objective

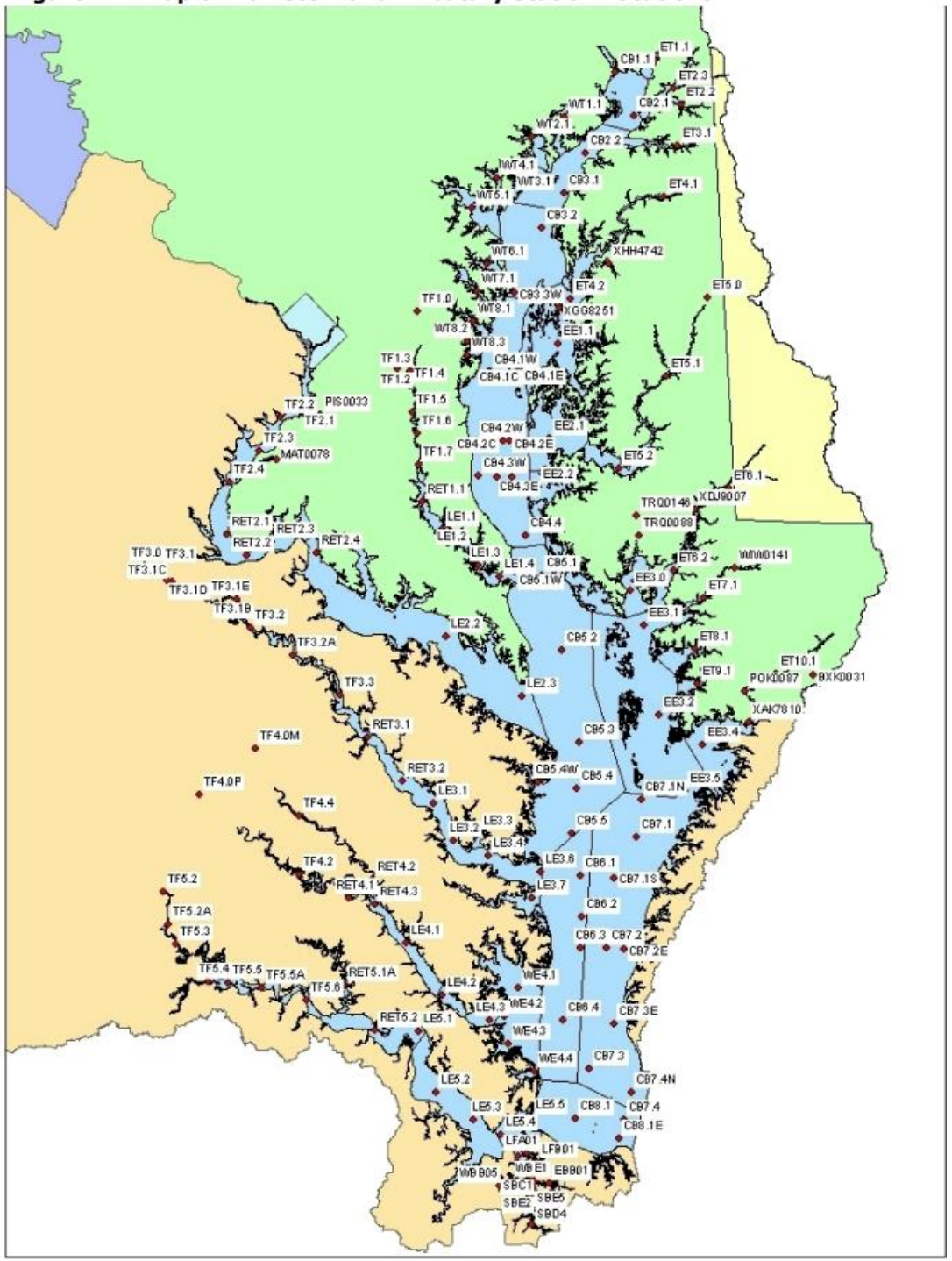
To provide updated information on the status and trends of DO criteria attainment in the Bay and help address a critical management question, i.e., ***where has the DO criteria attainment improved since 1985***?

- Extended our prior assessment to the latest 2020–2022 period.
- Focused on the comparison of trends among 13 tidal systems.
- Developed a “report card” summary for attainment trends.

Data & Methods

CBP Water Quality Database (1985-2022)

- DO concentrations
- Water temperature
- Salinity

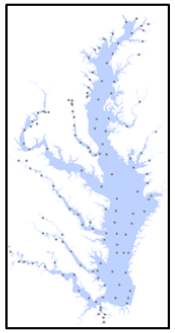


Attainment Deficit (AD)

- **Attainment indicator and attainment deficit (AD)** aimed at providing temporally and spatially consistent assessments over time.
- **Attainment indicator (binary)**: 0 (non-attainment) or 1 (in attainment) for each segment-DU-criterion combination (n = 291).
- **Attainment deficit (AD)** digresses away from the indicator's binary nature by quantifying the amount of space-time violation.
  - **0% = best possible condition** (minimum WQ requirements are met for protecting aquatic life in the defined zones).
  - **-100% = the worst possible condition** (complete non-compliance).
  - **Note:** For AD, an improving trend indicates progress toward attainment, a declining trend indicates degradation, and neither trend means that the required water quality standards are met.

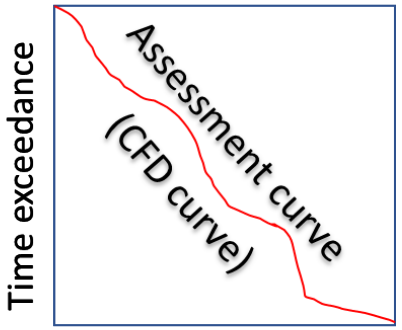
Attainment Deficit (AD)

Assessment Analysis of Monitoring Data[1]



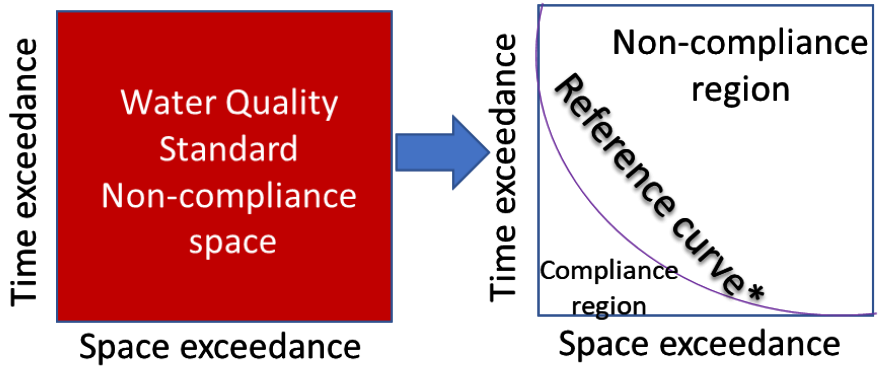
CBP WQ Monitoring Network

Data collection, spatial interpolation, and ranking of attainment results



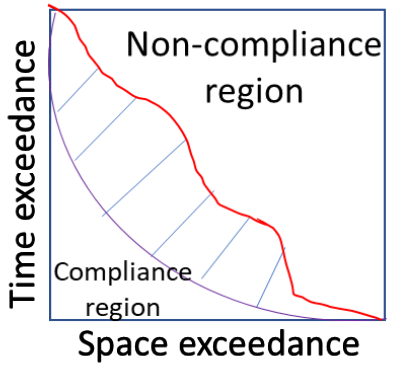
[1] USEPA (2003), Tango and Batiuk (2013)

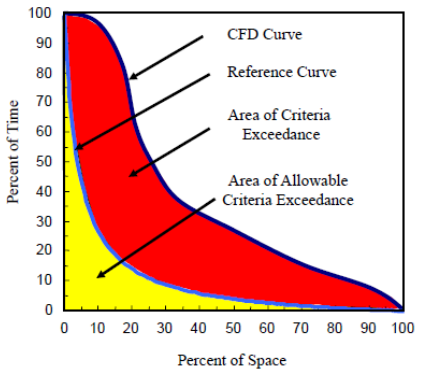
Compliance Decision Framework[2]



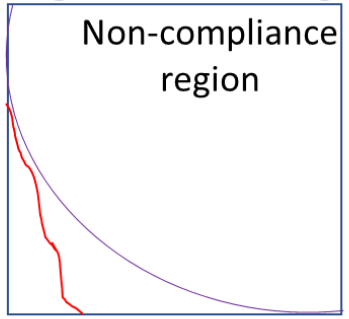
[2] USEPA (2003), Batiuk et al. (2009)

*Reference curve: Allowable non-compliance threshold

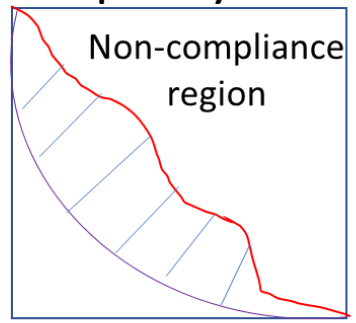




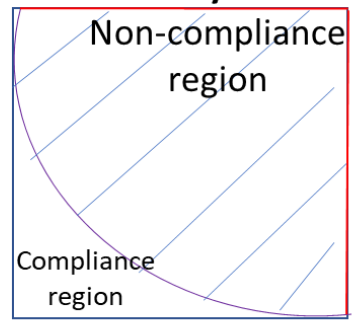
Example I.
Segment is attaining



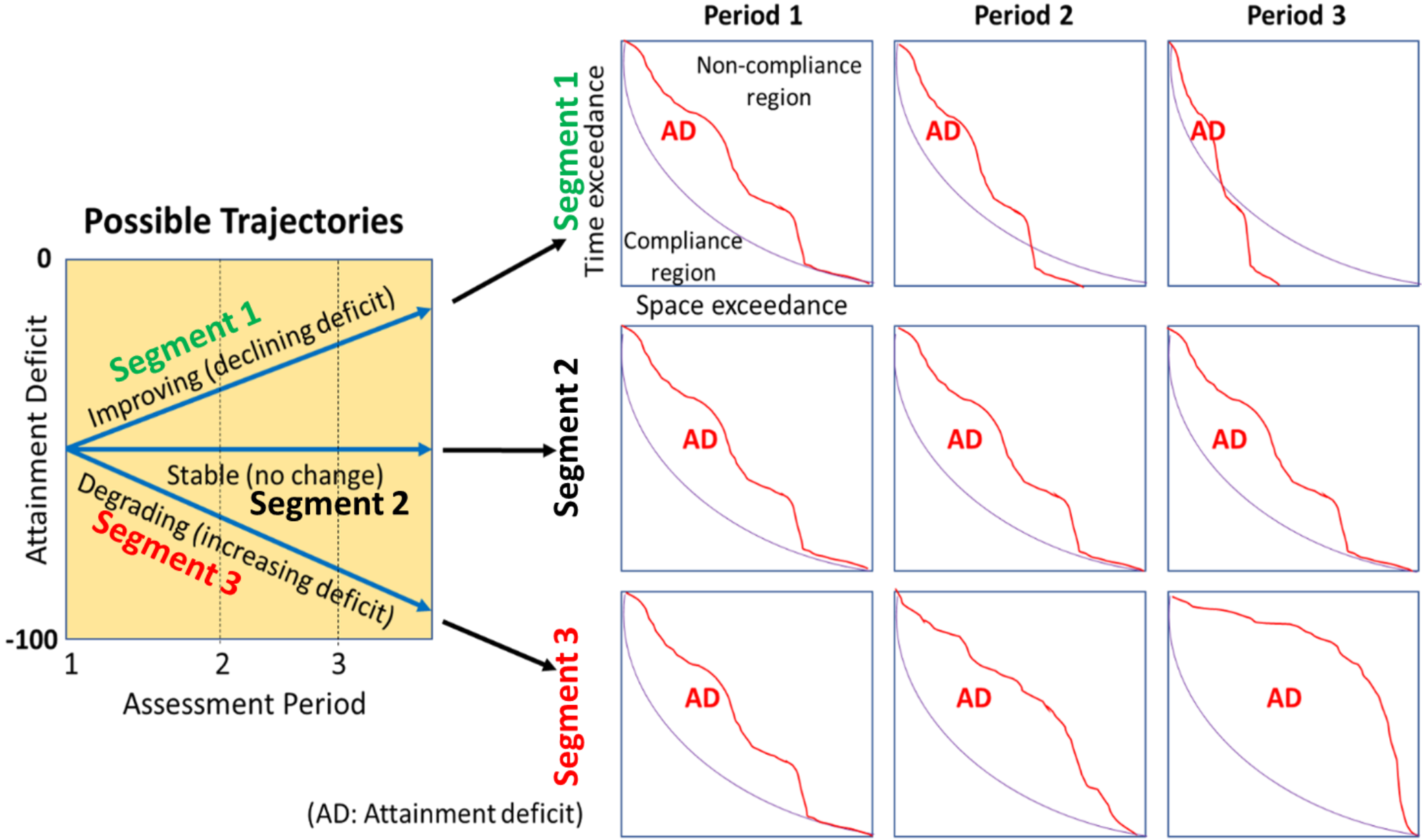
Example II.
Segment is partially not attaining



Example III.
Segment is entirely not attaining



Attainment Deficit (AD)



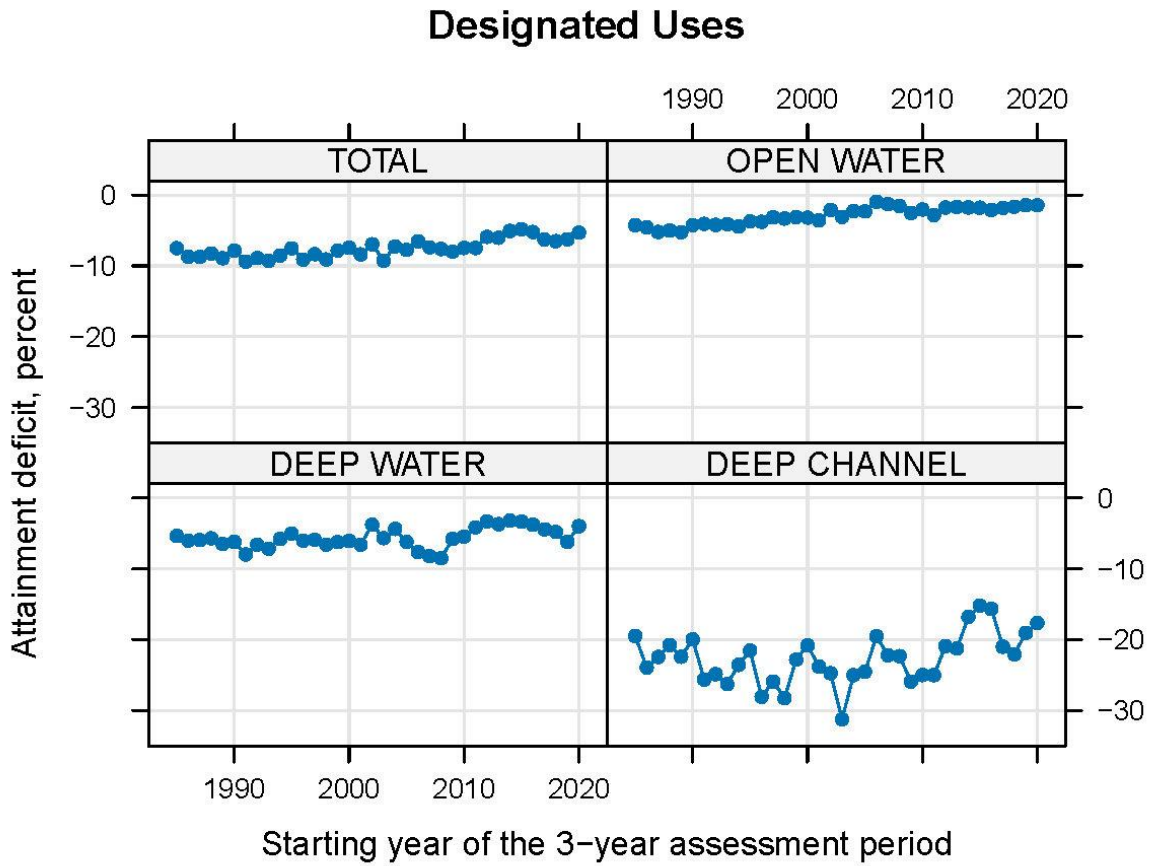
Attainment Deficit (AD)

- AD allows for better detection of temporal trends, particularly segments that have always been out of attainment and therefore categorized as “no trend” under the binary approach.
- For AD, individual segments’ scores were weighted via surface area and summed to obtain the aggregated score for each DU or tidal system.
  a) Segments vary in size over four orders of magnitude,
  b) The surface area of each segment does not change with time or designated use.

Data & Methods

- **Trend Analysis**
  - Modified Mann-Kendall for accounting for auto-correlation; Sen slope for measuring the rate of change.
    - Long-term trends (1985–2022).
    - Short-term trends (2006–2022).
  - Non-parametric Pettitt test for change-point detection.

Overall DO Attainment Trends



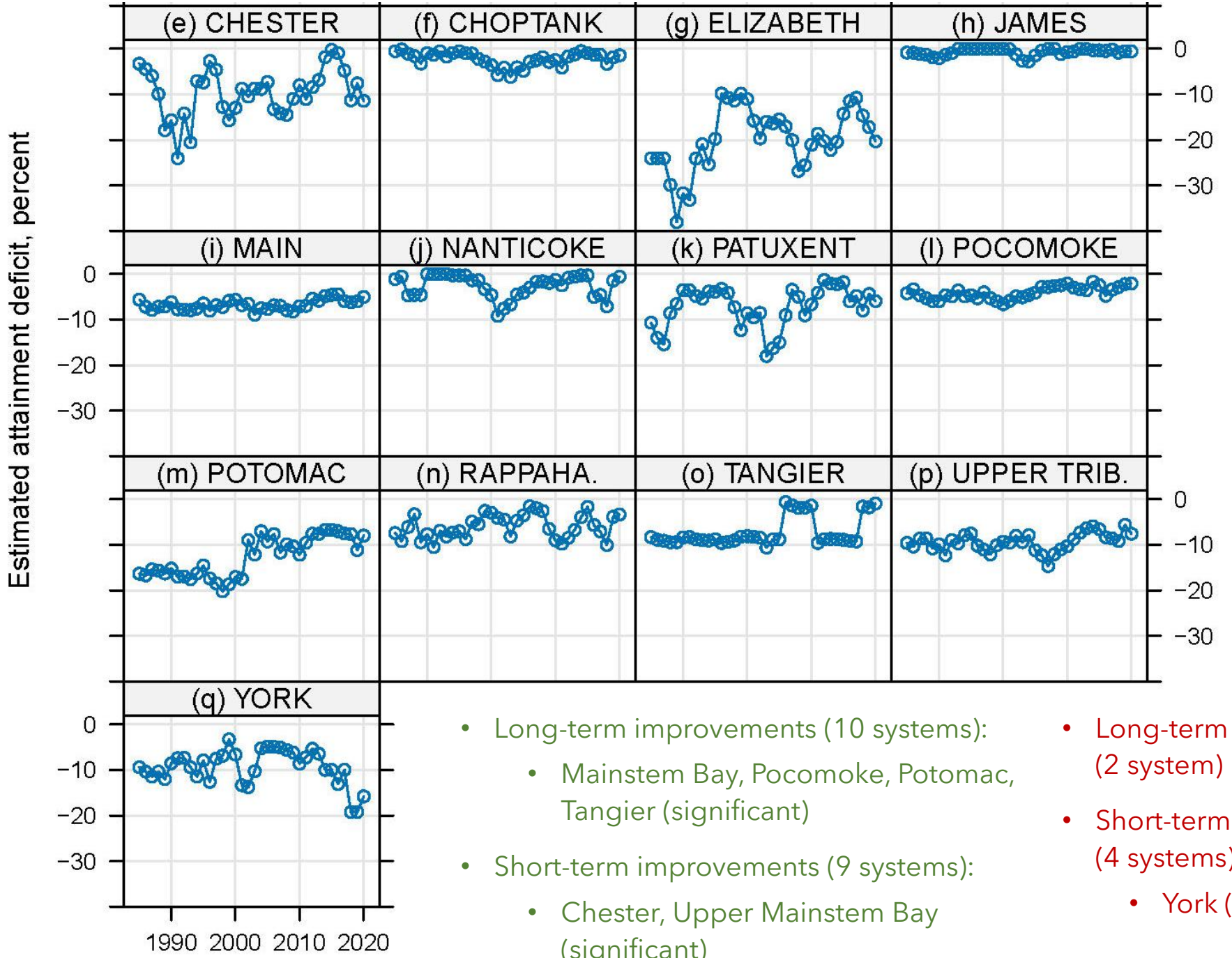
- Improvement observed from 1985 to 2022.
- **Long-term (LT) trend**: 0.10%/year improvement ($p < 0.05$).
- **Short-term (ST) trend**: 0.15%/year improvement ($p = 0.13$).

Trends by Designated Use

Subgroup	Initial deficit (1985–1987), percent	Current deficit (2020–2022), percent	Change point (3-year period)		Long-term trend, percent/year		Short-term trend, percent/year	
Overall Attainment								
TOTAL	-7.5	-5.3	2003–2005	***	0.10	***	0.15	–
Designated Uses								
Open water (OW)	-4.3	-1.4	2001–2003	***	0.11	***	0.004	–
Deep water (DW)	-5.4	-4.0	2008–2010	***	0.06	–	0.20	–
Deep channel (DC)	–19.5	-17.6	2011–2013	***	0.11	–	0.39	***

- **Open Water (OW)**: Significant LT improvement (0.11%/year).
- **Deep Water (DW)**: Improving, but not statistically significant.
- **Deep Channel (DC)**: Significant ST improvement (0.39%/year).
- **Chang Points**: OW (2001–2003) occurred earlier than DW (2008–2010) & DC (2011–2013), suggests varying responses of different depths.

Trends by Tidal System

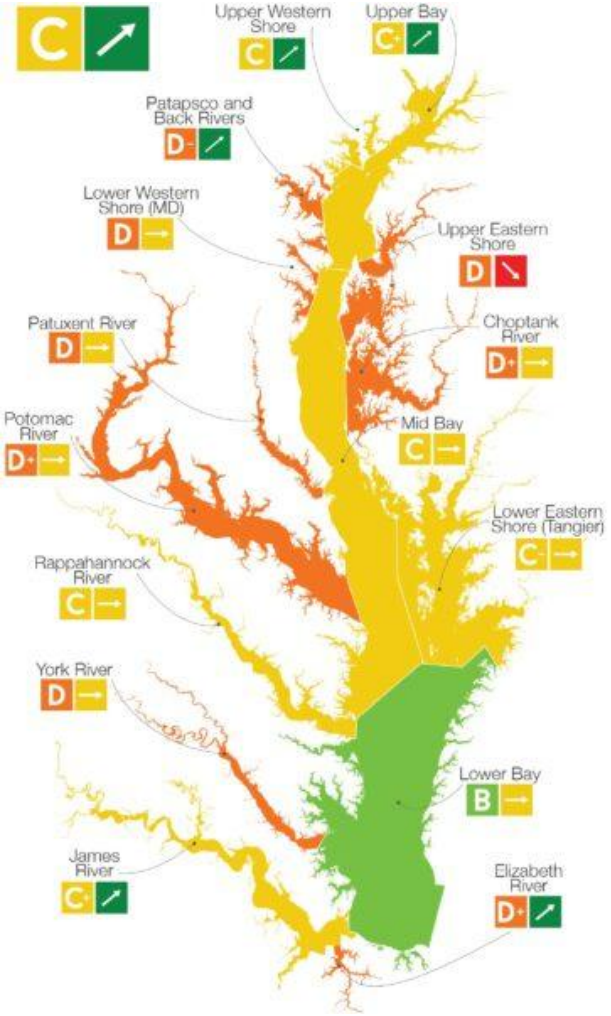


- Long-term improvements (10 systems):
  - Mainstem Bay, Pocomoke, Potomac, Tangier (significant)
- Short-term improvements (9 systems):
  - Chester, Upper Mainstem Bay (significant)

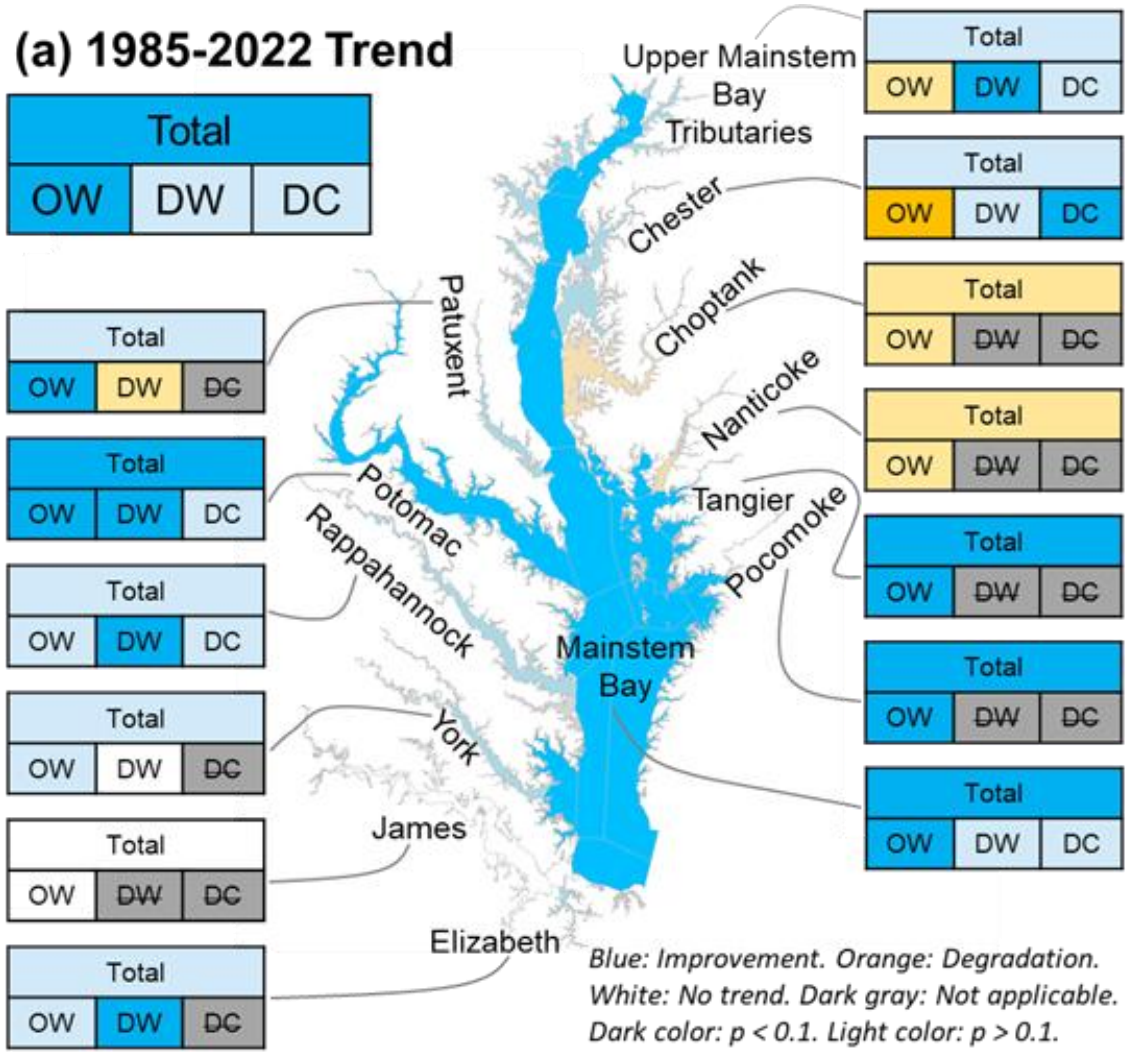
- Long-term degradation (2 system)
- Short-term degradation (4 systems)
  - York (significant)

Trends by Tidal System and DU

- **Report Card Summary Approach**
  - Inspired by UMCES Chesapeake Bay Report Card.
  - Focused on DO criteria assessment.
  - Visual representation of trends across 13 tidal systems.
  - Helps prioritize areas for targeted management in terms of WQS.

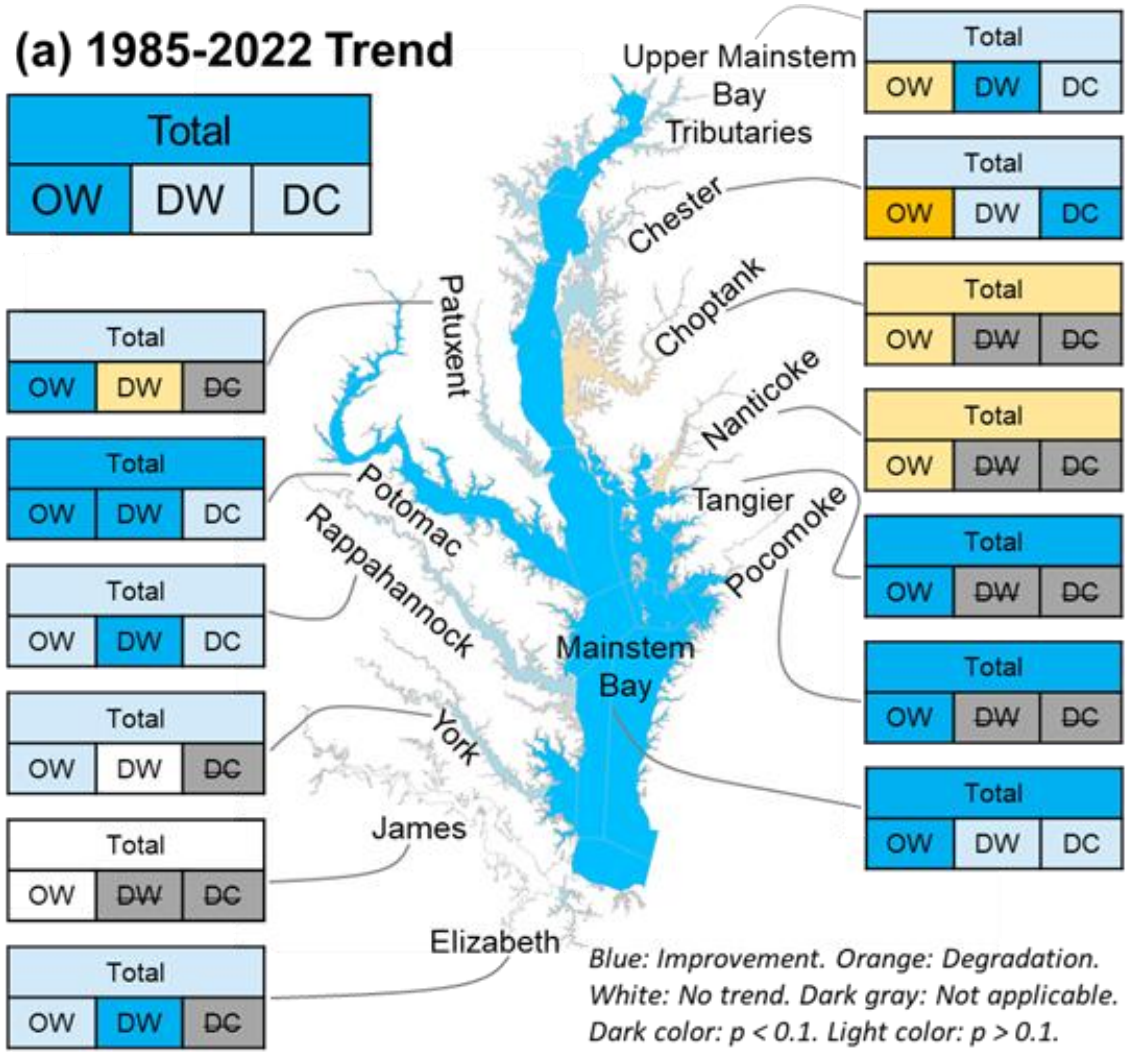


Trends by Tidal System and DU



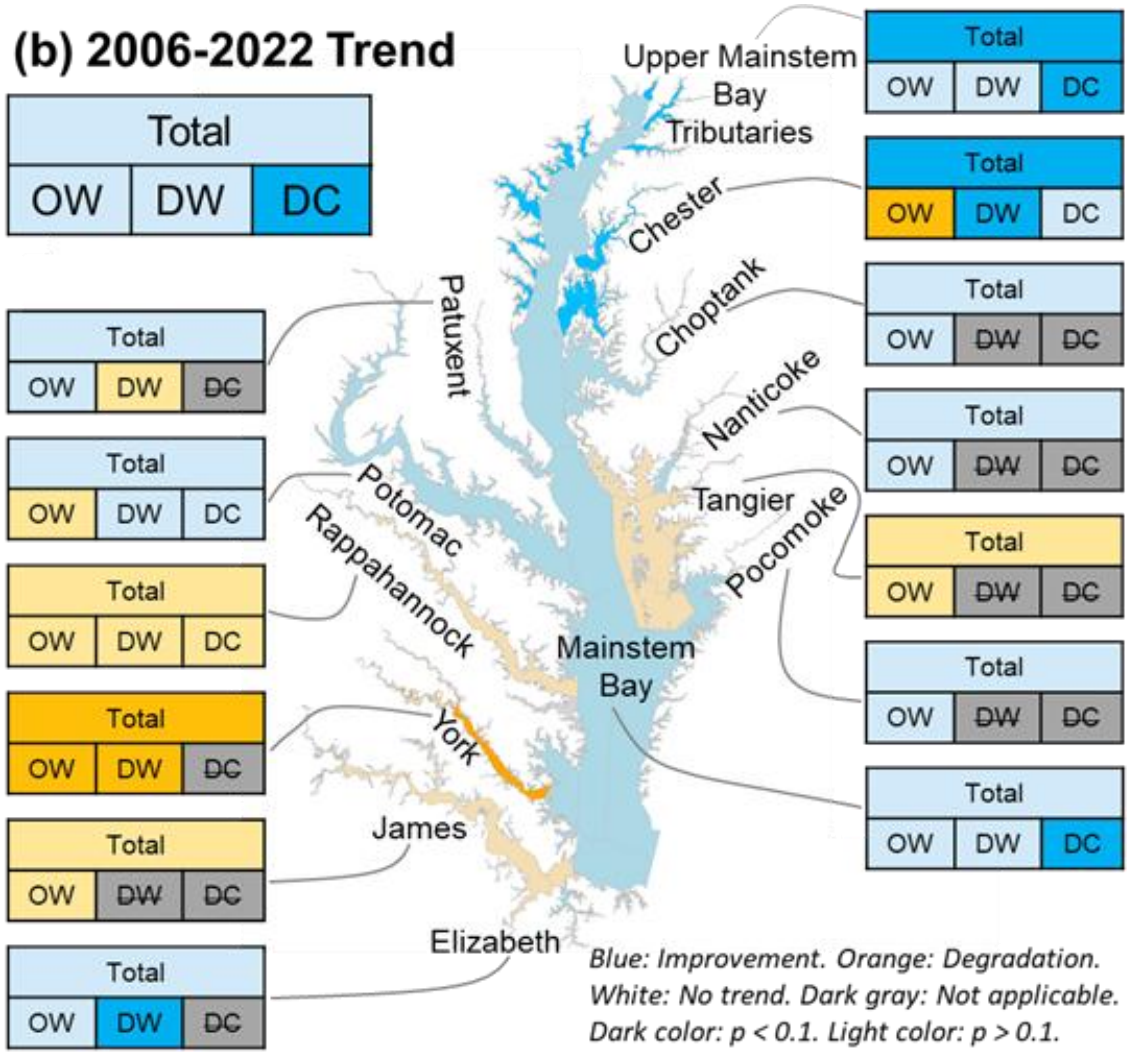
- A report card summary was produced to provide a concise depiction of the various trends for each system.
- Blue and orange shades indicate improving and degrading trends, respectively.
- Dark and light shades indicate statistically significant ($p < 0.1$) and insignificant ($p > 0.1$) trends, respectively.
- **Note:** Not all systems have DW or DC. Also, for a system with DW and/or DC, not all segments within that system contributes to its DW or DC trend.

Trends by Tidal System and DU



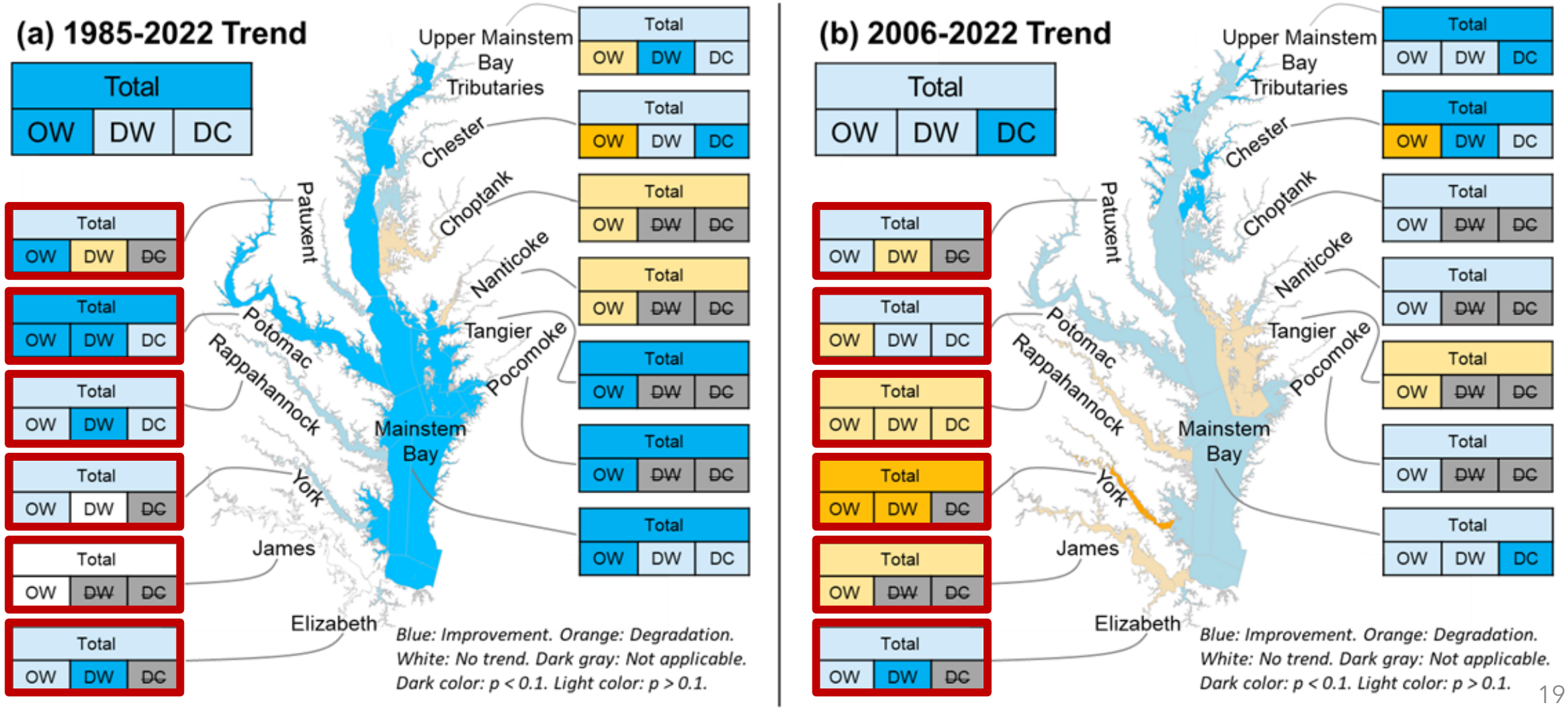
Long Term	OW	DW	DC
No. systems	13	8	5
Improvement (significant)	8 (5)	6 (4)	5 (1)
Degradation (significant)	4 (1)	1 (0)	0 (0)

Trends by Tidal System and DU

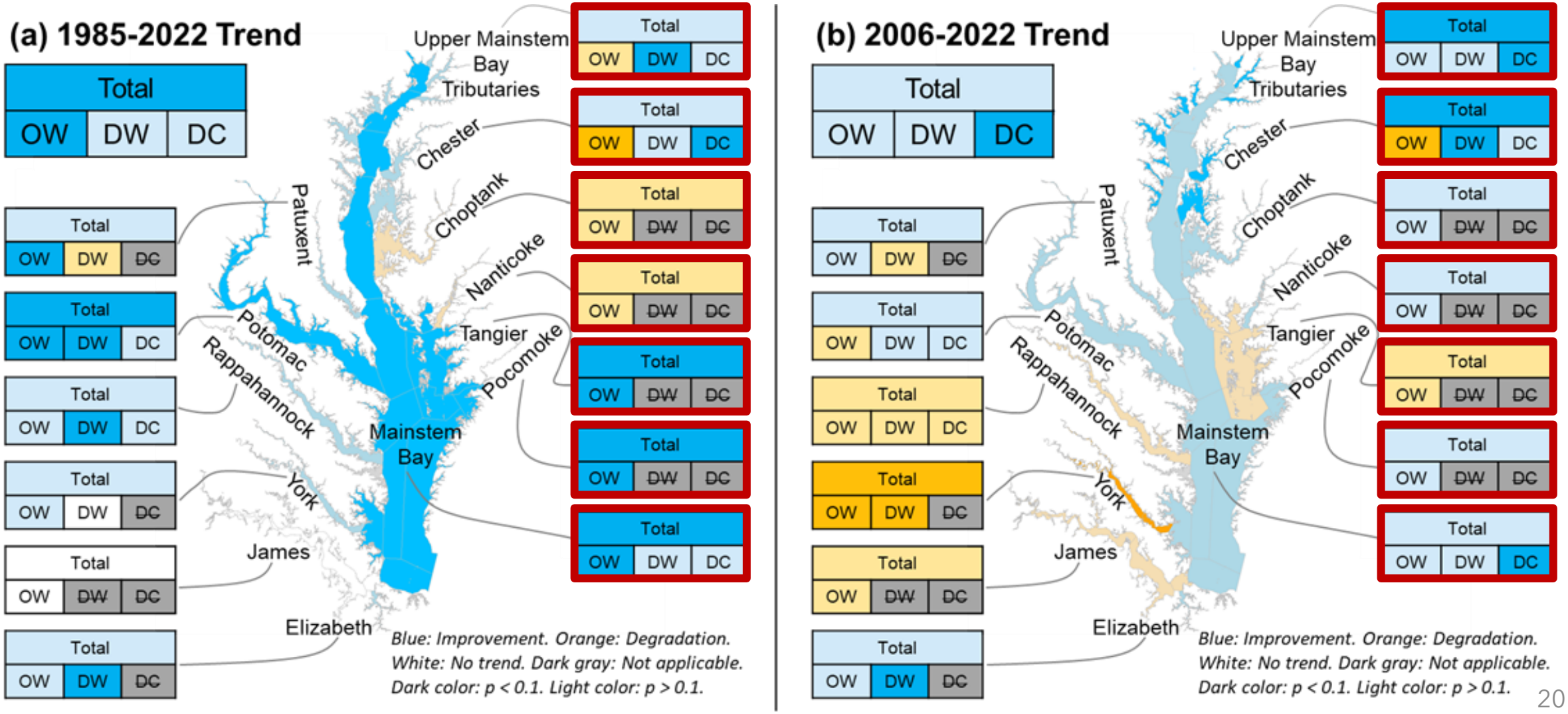


Short Tterm	OW	DW	DC
No. systems	13	8	5
Improvement (significant)	7 (0)	5 (2)	4 (2)
Degradation (significant)	6 (2)	3 (1)	1 (0)

Trends by Tidal System and DU



Trends by Tidal System and DU



Trends by Segment – visit Shiny apps

DU	Trend	Period	p<0.05	p<0.1	p<0.25	p<1.0	Segments with p<0.1
OW (n=92)	Improving	LT	8	**9**	12	23	CB6PH, CB7PH, JMSTF1, LCHMH, PAXMH, POCOH_MD, POCOH_VA, POTOH1_MD, SASOH,
	Improving	ST	11	**13**	16	24	ANATF_MD, CB2OH, CHOOH, CHOTF, LAFMH, LYNPH, NANTF_DE, NANTF_MD, POCOH_MD, POTOH1_MD, RHDMH, SOUMH, WBEMH,
	Degrading	LT	7	**11**	13	17	CHOMH1, CHOTF, CHSOH, CHSTF, PATMH, PAXTF, POCTF, POTMH_VA, POTTF_VA, WBRTF, WICMH,
	Degrading	ST	7	**8**	12	19	CB5MH_VA, CHKOH, CHSOH, EBEMH, SASOH, WBRTF, YRKMH, YRKPH,
DW (n=19)	Improving	LT	5	**6**	6	8	CB5MH_MD, EASMH, MAGMH, RPPMH, SBEMH, SOUMH,
	Improving	ST	4	**4**	6	11	CB5MH_VA, CHSMH, MAGMH, SBEMH,
	Degrading	LT	1	**1**	1	6	CB3MH,
	Degrading	ST	1	**1**	1	4	YRKPH,
DC (n=11)	Improving	LT	2	**2**	4	7	CB5MH_VA, CHSMH,
	Improving	ST	3	**4**	6	7	CB3MH, CB5MH_MD, EASMH, POTMH_MD,
	Degrading	LT	0	**0**	1	2	
	Degrading	ST	0	**0**	0	1	

https://wqs.chesapeakebay.net/wqs_attainment_deficit/
https://wqs.chesapeakebay.net/wqs_attainment_indicator/

Key Takeaways

- The overall attainment deficit showed improving trends in both long and short terms, which can be mainly attributed to OW and DC designated uses, respectively.
- Long-term and short-term trend slopes and p-values were quantified for 13 tidal systems. 10 and 9 systems had improvements in the long and short terms, respectively.
- A report card was produced to provide a concise depiction of the trends for the 13 systems and their DUs -- the first of its kind in the context of DO criteria assessment.

Management Implications

- While progress has been made, many systems and DUs lacked improvement, reflecting **response** (DO response to nutrient management) **and implementation gaps** (insufficient management practices) – as noted in the STAC CESR Report. Mixed results may reflect progress in reducing point sources and atmospheric deposition but lack of progress in nonpoint sources.
- Recovery may be hindered by **changing climates** (e.g., rising temperature).
- **Further research**, using advanced data analysis methods (e.g., GAM, SEM), is needed to better understand trends and change points in individual systems.
- **Long-term monitoring data**, though sparse in density, is crucial for understanding ecosystem changes.

Geography, trajectories, and controls of coastal water quality:
More rapid improvement in the shallow zone of the Chesapeake Bay

Qian Zhang [1,2], Rebecca Murphy [1,2], Richard Tian [1,2], Peter Tango [2,3]

[1] University of Maryland Center for Environmental Science

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Part 2 of 2

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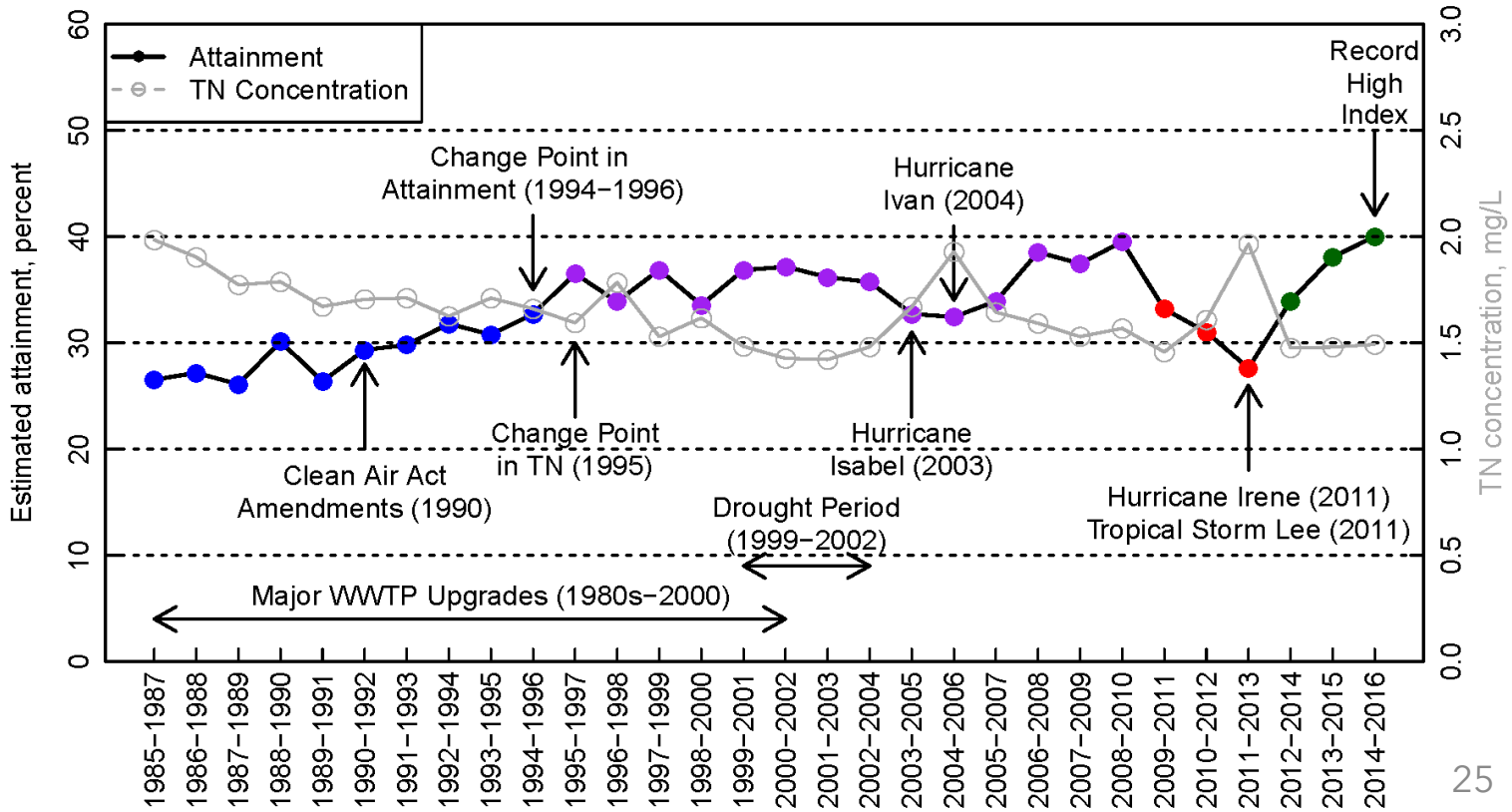
Introduction

Local Context

- In our previous work, the improvement in the attainment indicator (1985-2016) was statistically linked to the decline of TN input from the watershed, suggesting the effectiveness of nutrient control actions.



Objective & Questions

Q1. What is the trajectory of the overall indicator scores over the last 37 years (i.e., 1985–2021), and how does the **trajectory** vary between the DZ and the SZ?

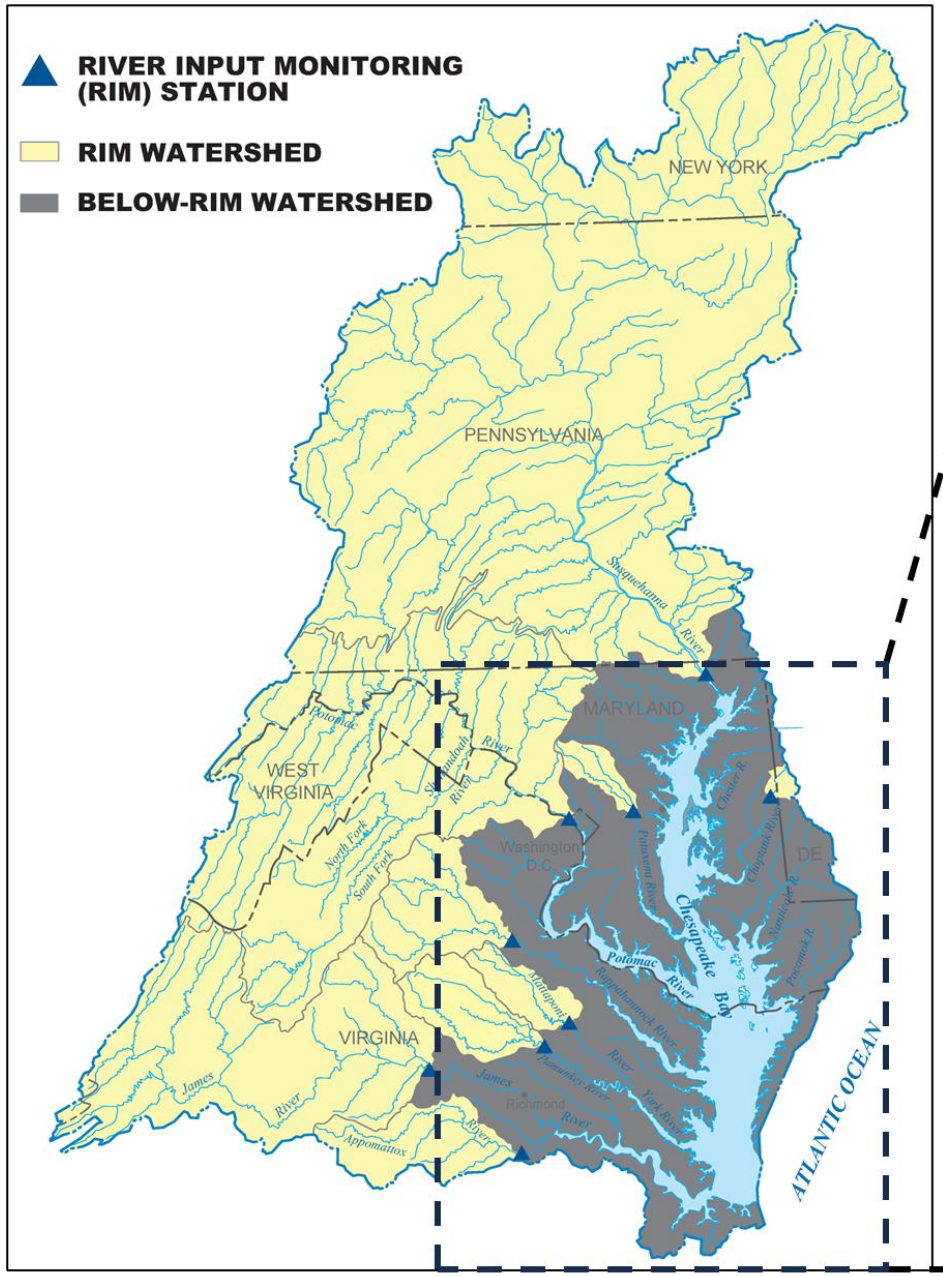
- *Hypothesis: WQS attainment has improved in both the DZ and the SZ after decades of nutrient reductions, but that response has been more rapid in the SZ due to its proximity to managed nutrient sources.*

Q2. What are the main drivers affecting the indicator, and how do the **drivers** differ between the DZ and the SZ?

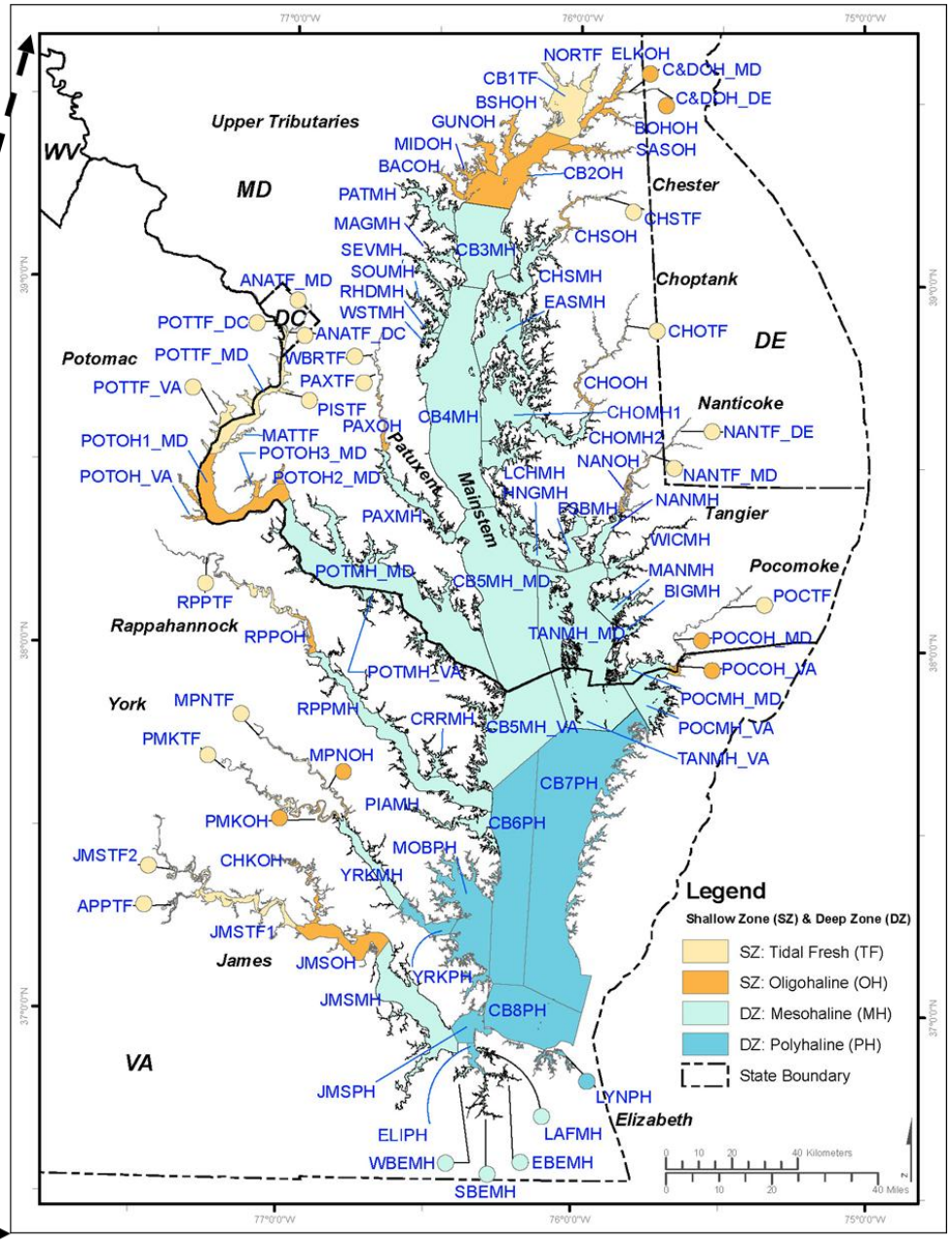
- *Hypothesis: Although the attainment indicator trajectory has been previously linked to the reduction in N load, it may have also been affected by other external and internal drivers.*

(Note: SZ = TF + OH; DZ = MH + PH)

(a) Chesapeake Bay Watershed



(b) Chesapeake Bay Tidal Segments



Data & Methods

- **Bay segmentation**
  - 92 management segments based on salinity, depth, and circulation.
- **Shallow Zone (SZ)**
  - Tidal fresh and oligohaline segments.
  - 47 segments; 142 segment-DU pairs.
  - 13% of total Bay area.
  - **Note:** Not equivalent to "< 2m" area.
- **Deep Zone (DZ)**
  - Mesohaline and polyhaline segments.
  - 45 segments; 147 segment-DU pairs.
  - 87% of total Bay area.

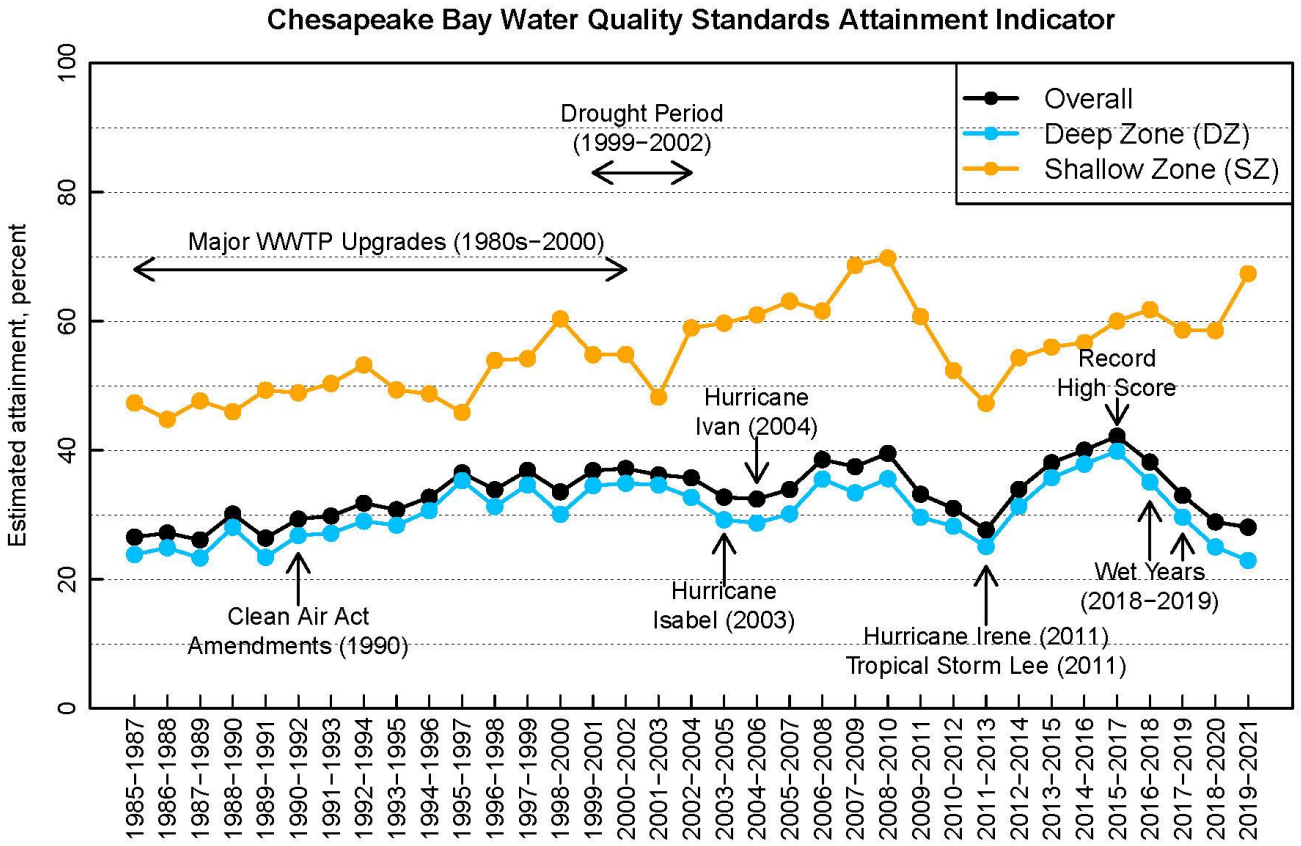
Data & Methods

- **Trend Analysis**
  - Modified Mann-Kendall test for accounting for autocorrelation.
  - Sen slope for measuring the rate of change.
- **Random Forest Modeling**
  - Identify key drivers of the attainment trajectories (overall, DZ, SZ).
  - Include external factors and internal factors.
  - Hyperparameter tuning for finding the optimal combination.
  - Optimal models determined using LOOCV.
  - SHapley Additive exPlanations (SHAP) for interpreting the effects.

			The overall attainment	The DZ attainment	The SZ attainment
External	Logarithm of streamflow discharge (logQ, Q in m^3/s)	Jan.–Dec.	RIM+BRIM	RIM+BRIM	RIM+$BRIM_{TF+OH}$
	Flow-weighted concentration of total nitrogen (TN FWC, in mg/L)	Jan.–Dec.	RIM+BRIM	RIM+BRIM	RIM+$BRIM_{TF+OH}$
	Flow-weighted concentration of total phosphorus (TP FWC, in mg/L)	Jan.–Dec.	RIM+BRIM	RIM+BRIM	RIM+$BRIM_{TF+OH}$
Internal	Surface water temperature (WTEMP, in °C)	June–Sep.	TF+OH+MH+PH stations	MH+PH stations	TF+OH stations
	Maximum density gradient (MaxG, in kg/m^4)	June–Sep.	TF+OH+MH+PH stations (mainstem)	MH+PH stations (mainstem)	TF+OH stations (mainstem)
	Secchi disk depth (Secchi, in m)	May–Nov.	TF+OH+MH+PH stations	MH+PH stations	TF+OH stations
	Surface chlorophyll-a concentration (Chla, in μg/L)	Mar.–Sep.	TF+OH+MH+PH stations	MH+PH stations	TF+OH stations

(Note: SZ = TF + OH; DZ = MH + PH)

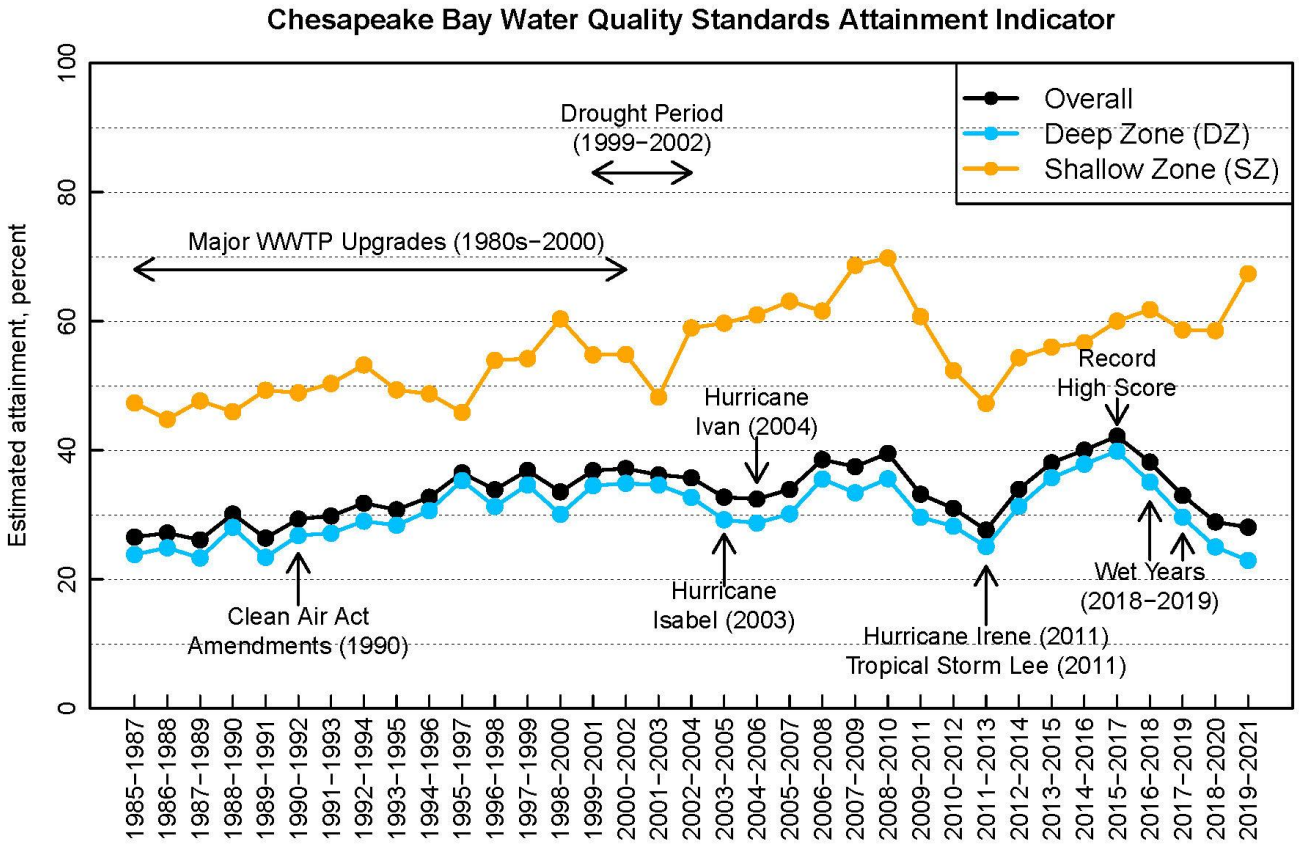
More rapid improvement in the SZ attainment than the DZ attainment



(Note: SZ = TF + OH; DZ = MH + PH)

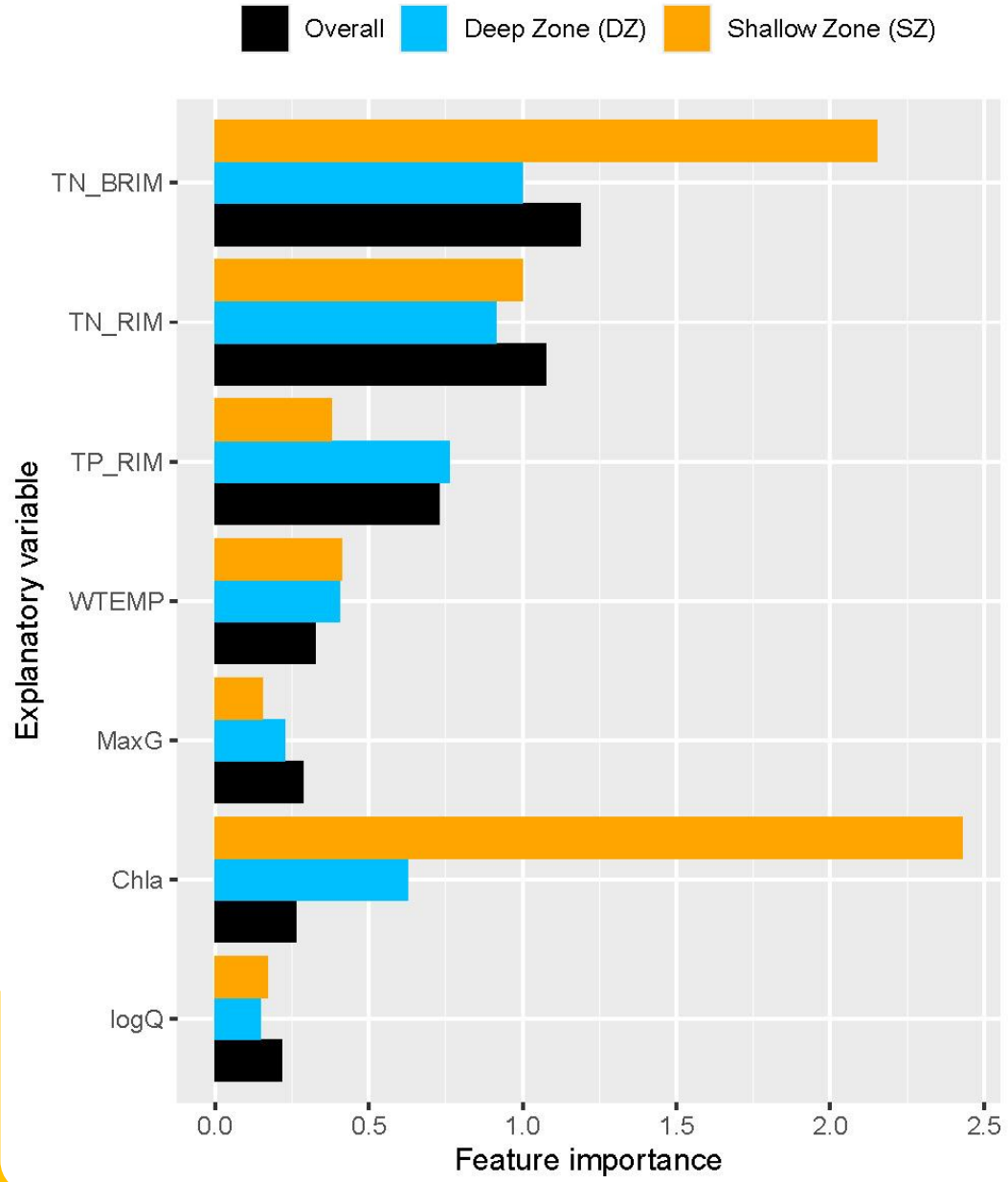
- **Overall attainment**: There has been a general increase since 1985, with a trend slope of 0.26%/year ($p < 0.05$).
- **DZ attainment**: The long-term trend slope is 0.21%/year ($p = 0.06$), with less variability in its trajectory.
- **SZ attainment**: The long-term trend slope is 0.49%/year ($p = 0.001$). SZ rebounded in the most recent assessment period - more rapid than DZ.

More rapid improvement in the SZ attainment than the DZ attainment



(Note: SZ = TF + OH; DZ = MH + PH)

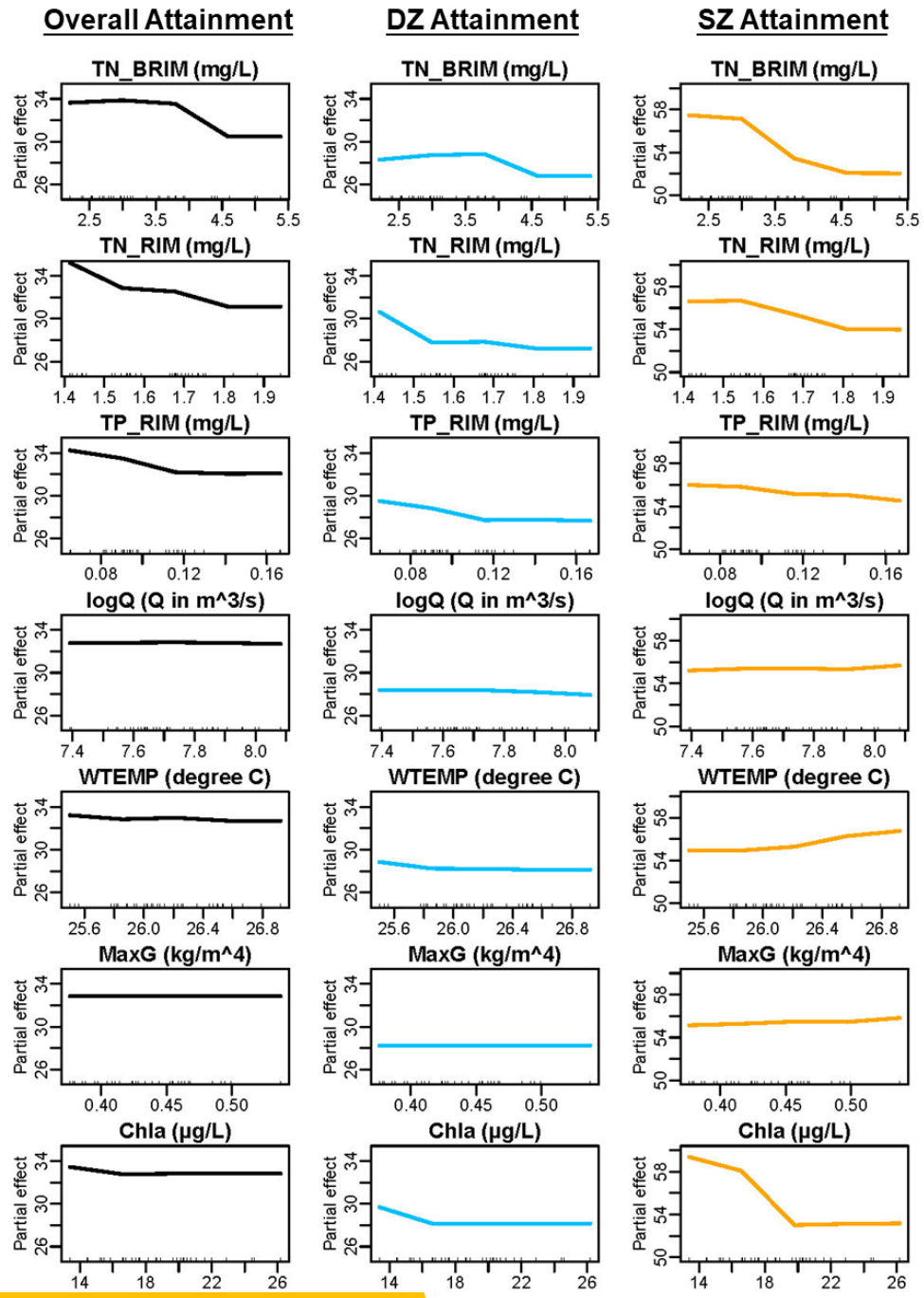
- Long-term improvements in the DZ and the SZ have both contributed to the long-term improvement in the overall indicator, but the more rapid response in the SZ has been masked by DZ.
- The **DZ trajectory** has been dominated by DO attainment.
- The **SZ trajectory** has been affected by both DO and water clarity/SAV, with the latter having a stronger impact.



Differential controls of DZ and SZ attainment

- **Overall attainment**: It has been more heavily affected by external drivers (i.e., TN_BRIM, TN_RIM, and TP_RIM) than internal drivers (i.e., WTEMP, MaxG, Chla).
- **SZ attainment**: TN_BRIM, TN_RIM, and TP_RIM are among the most important variables, but Chla ranks the highest. This may reflect the role of Chla (proxy of phytoplankton abundance) in modulating SAV/water clarity (e.g., shading) and DO (e.g., respiration, decomposition).

(Note: SZ = TF + OH; DZ = MH + PH)

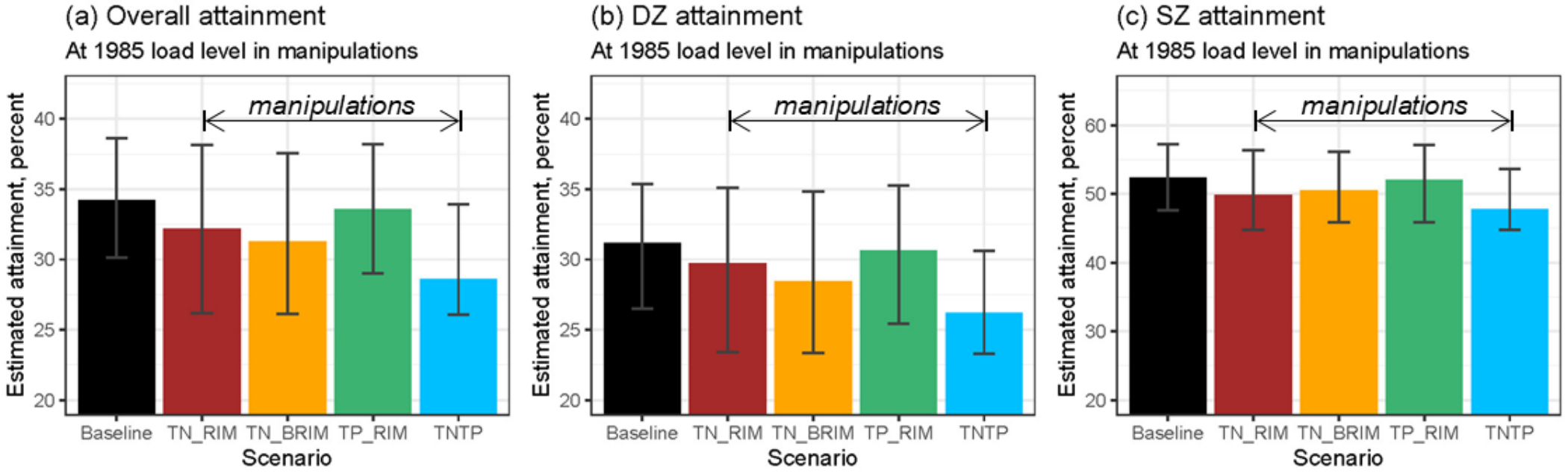


- **Overall attainment**: A higher attainment score corresponds to conditions of low TN_BRIM, low TN_RIM, and low TP_RIM, as well as low WTEMP and low MaxG. Thus, reductions in nutrient loads would improve attainment, whereas warming and stratification would degrade it.
- **DZ attainment**: Effects are generally similar to the overall attainment, but the negative effect of WTEMP is more evident.
- **SZ attainment**: The effects of the external drivers are also negative but more pronounced, potentially reflecting the proximity to managed nutrient sources. WTEMP has a positive effect, which reflect (a) an increase in DO attainment due to enhanced photosynthesis and/or (b) an increase in SAV/water clarity attainment due to enhanced SAV growth.

(Note: SZ = TF + OH; DZ = MH + PH)

Scenario analyses stressed the effects of nutrient load reductions

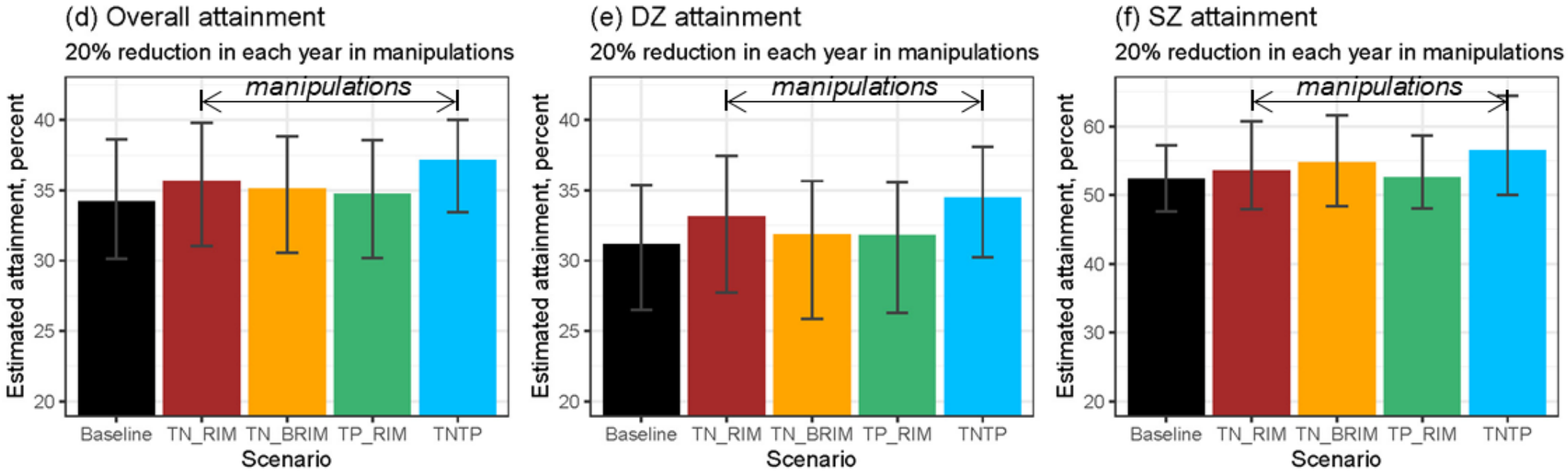
- **<u>1st scenario</u>**: If nutrient load levels were held at 1985 levels, the overall, DZ, and SZ attainments would all decline relative to baseline conditions. The worst scores would occur if TN_BRIM, TN_RIM, and TP_RIM were not managed.



(Note: SZ = TF + OH; DZ = MH + PH)

Scenario analyses stressed the effects of nutrient load reductions

- **<u>2nd scenario</u>**: Lowering nutrient load levels by 20% each year would lead to improvements in the overall, DZ, and SZ attainments. The best scores would occur if TN_RIM, TN_BRIM, and TP_RIM were reduced simultaneously.



(Note: SZ = TF + OH; DZ = MH + PH)

Key Takeaways

Q1. What is the trajectory of the overall indicator scores over the last 37 years (i.e., 1985–2021), and how does the trajectory vary between the DZ and the SZ?

- Water quality improved in **both the DZ and the SZ**, but the SZ improved at a faster rate than the DZ.
- Due to the dominance of the DZ segment, the overall attainment trajectory is similar to the DZ attainment.
- DZ and SZ showed differential responses: **A slow response in the DZ** (dominated by the signal of DO) vs. **a more rapid response in the SZ** (dominated by signals of DO and water clarity/SAV).

(Note: SZ = TF + OH; DZ = MH + PH)

Key Takeaways

Q2. What are the main drivers affecting the indicator, and how do the drivers differ between the DZ and the SZ?

- The trajectory of the overall attainment has been affected by **mainly external drivers** (i.e., reductions in TN and TP loads) and, **to a lesser extent, internal drivers** (i.e., water temperature and stratification).
- **Nutrient load reductions** improved water quality, **whereas internal drivers like warming and stratification** hindered progress, which are consistent with findings from many prior studies.
- Scenario analyses demonstrate the importance of **managing both nitrogen and phosphorus loads** for better water quality outcomes.

(Note: SZ = TF + OH; DZ = MH + PH)

Management Implications

- **Geographical targeting crucial for effective management:**
  - Both the DZ and the SZ have shown improvements, but the SZ has recovered more rapidly, reflecting the positive impacts of nutrient mitigation actions on SAV and DO in the low-salinity regions.
- **Nutrient reduction effects vs. climate effects:**
  - The attainment trajectory has been more affected by external drivers than internal drivers. Nutrient load reductions would improve the score, but warming temperature and stratification would degrade the score.
  - Similar results also observed in other coastal areas (e.g., Tampa Bay, Baltic Sea, Bohai Sea), emphasizing the importance of nutrient load reductions while highlighting the negative impacts of changing climate.

(Note: SZ = TF + OH; DZ = MH + PH)

Thank you!

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