Estimates of confidence in the impact of regulatory nutrient reductions on Chesapeake Bay water quality: *results of a multiple model analysis*

Marjy Friedrichs and Ike Irby

Virginia Institute of Marine Science, College of William & Mary

1. Marjy – CHAMP: new 5 year NOAA project
2. Ike – results of WQS assessment using an alternative estuarine model

Predicted impacts of climate change on the success of alternative management actions in the Chesapeake Bay

Using multiple models in support of hypoxia decision-making

CHAMP: Chesapeake Hypoxia Analysis and Modeling Program
September 2016 – September 2021
NOAA CSCOR funded ($1.4M)

CHAMP PIs:

Marjorie Friedrichs (VIMS)
Lewis Linker (CBP/EPA)
Gary Shenk (CBP/USGS)
Ray Najjar (PSU)
Hanqin Tian (Auburn)
Eileen Hofmann (ODU)

CHAMP goals

Use multiple models in Chesapeake scenario-forecast modeling system:

- To predict the impacts of future (i) climate change and (ii) anthropogenic nutrient inputs on hypoxia
- To predict the future effectiveness of various nutrient reduction scenarios in reducing hypoxia

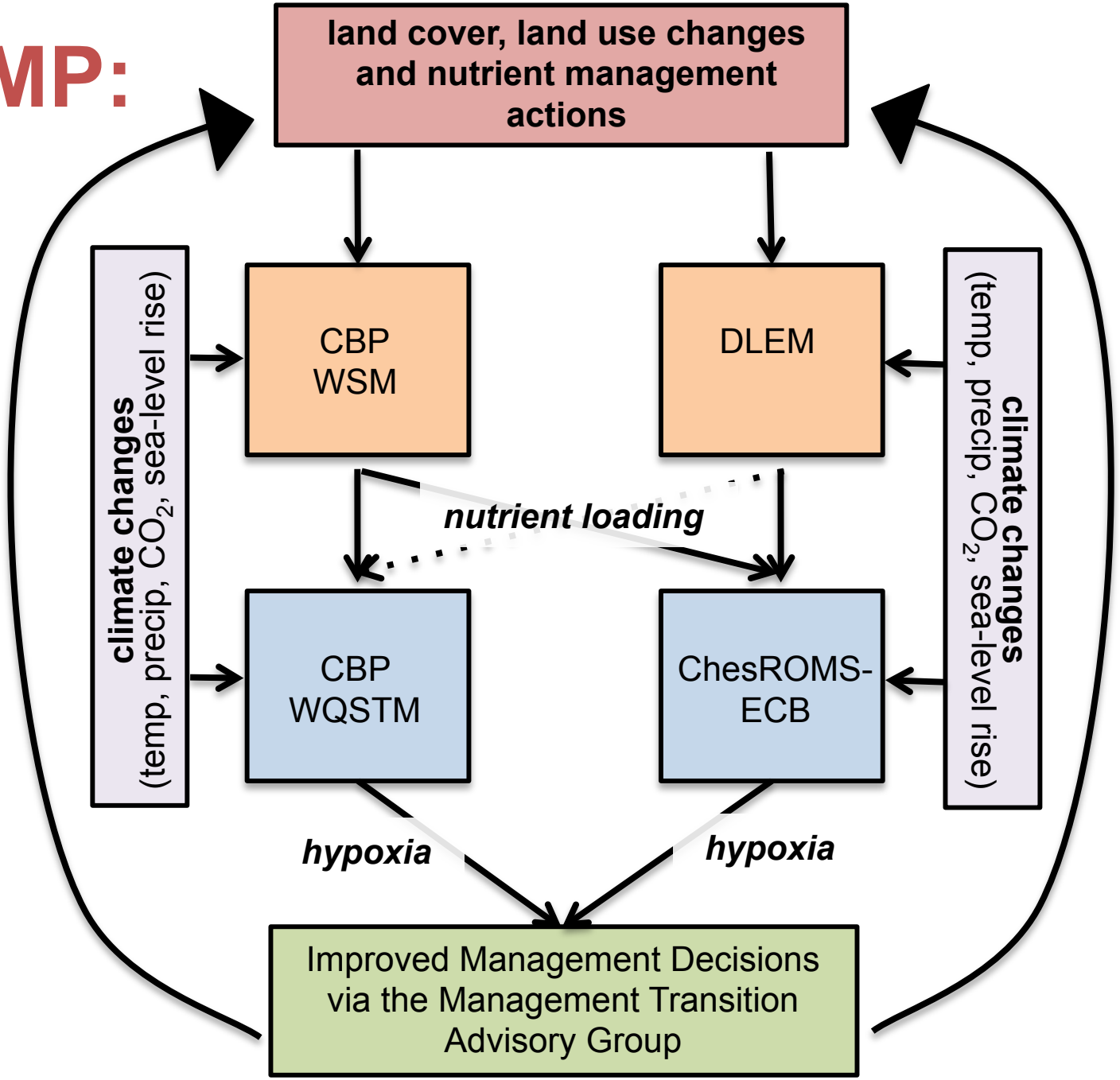
CHAMP goals

Use multiple models in Chesapeake scenario-forecast modeling system:

- Multiple climate and land use projections
- Two watershed models (CBP WSM and DLEM)
- Two estuarine models (CBP WQSTM and ChesROMS-ECB)

→ Realistic hindcasts (1985-2016)
→ Future simulations (2017-2050)

CHAMP:


land cover, land use changes and nutrient management actions
climate changes (temp, precip, CO_2, sea-level rise)
CBP WSM
DLEM
climate changes (temp, precip, CO_2, sea-level rise)
nutrient loading
CBP WQSTM
ChesROMS-ECB
hypoxia
hypoxia
Improved Management Decisions via the Management Transition Advisory Group

Evaluating confidence in the impact of regulatory nutrient reduction on Chesapeake Bay water quality

… and a look forward at the impact of climate change

I. Irby
Ph.D. Advisor - M. Friedrichs
Ph.D. Committee - C. Friedrichs, R. Hood, R. Najjar, C. Hershner

CBP Modeling Workgroup Meeting
December 2016

Motivation

- Would another model, compared to the CBP WQ Model, forced with the TMDL nutrient reduction, predict a similar degree of improvement in water quality?

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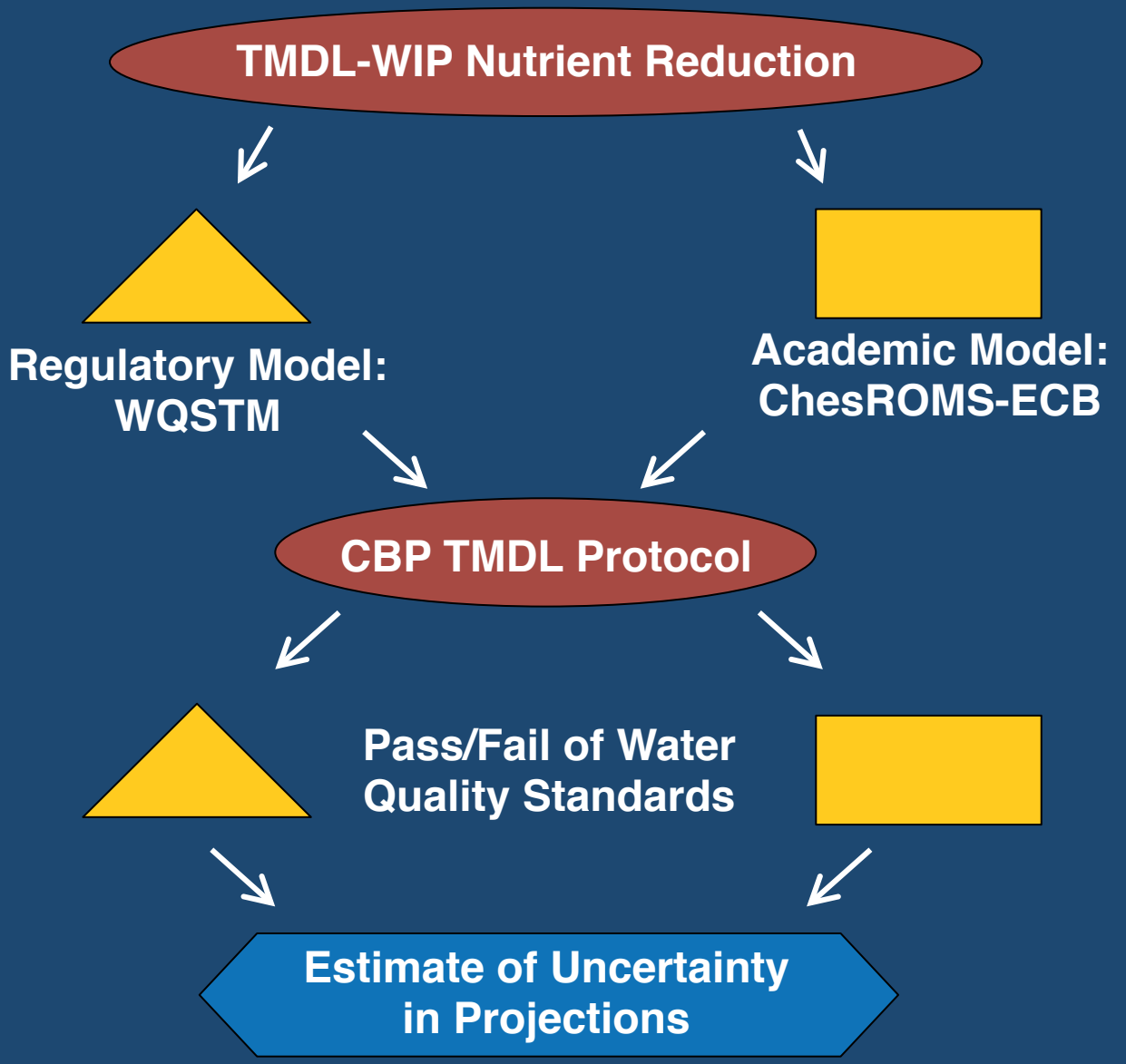
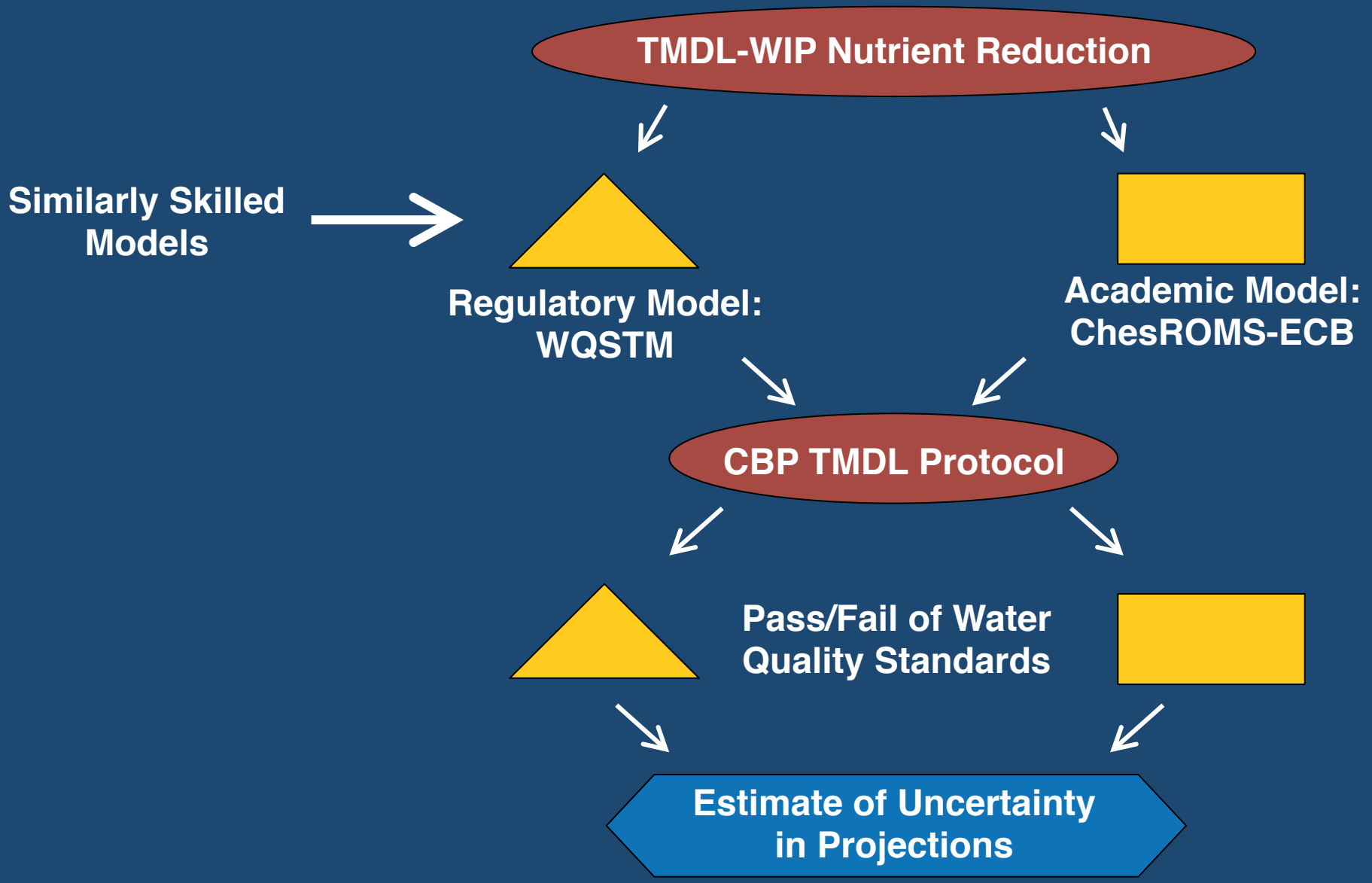
- Would another model, compared to the CBP WQ Model, forced with the TMDL nutrient reduction, predict a similar degree of improvement in water quality?

- Where, when, and why are the models' projections most and least similar, lending high and low confidence?

Methods


TMDL-WIP Nutrient Reduction
Regulatory Model:
WQSTM
Academic Model:
ChesROMS-ECB
CBP TMDL Protocol
Pass/Fail of Water
Quality Standards
Estimate of Uncertainty
in Projections

Methods


TMDL-WIP Nutrient Reduction
Similarly Skilled Models
Regulatory Model: WQSTM
Academic Model: ChesROMS-ECB
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Pass/Fail of Water Quality Standards
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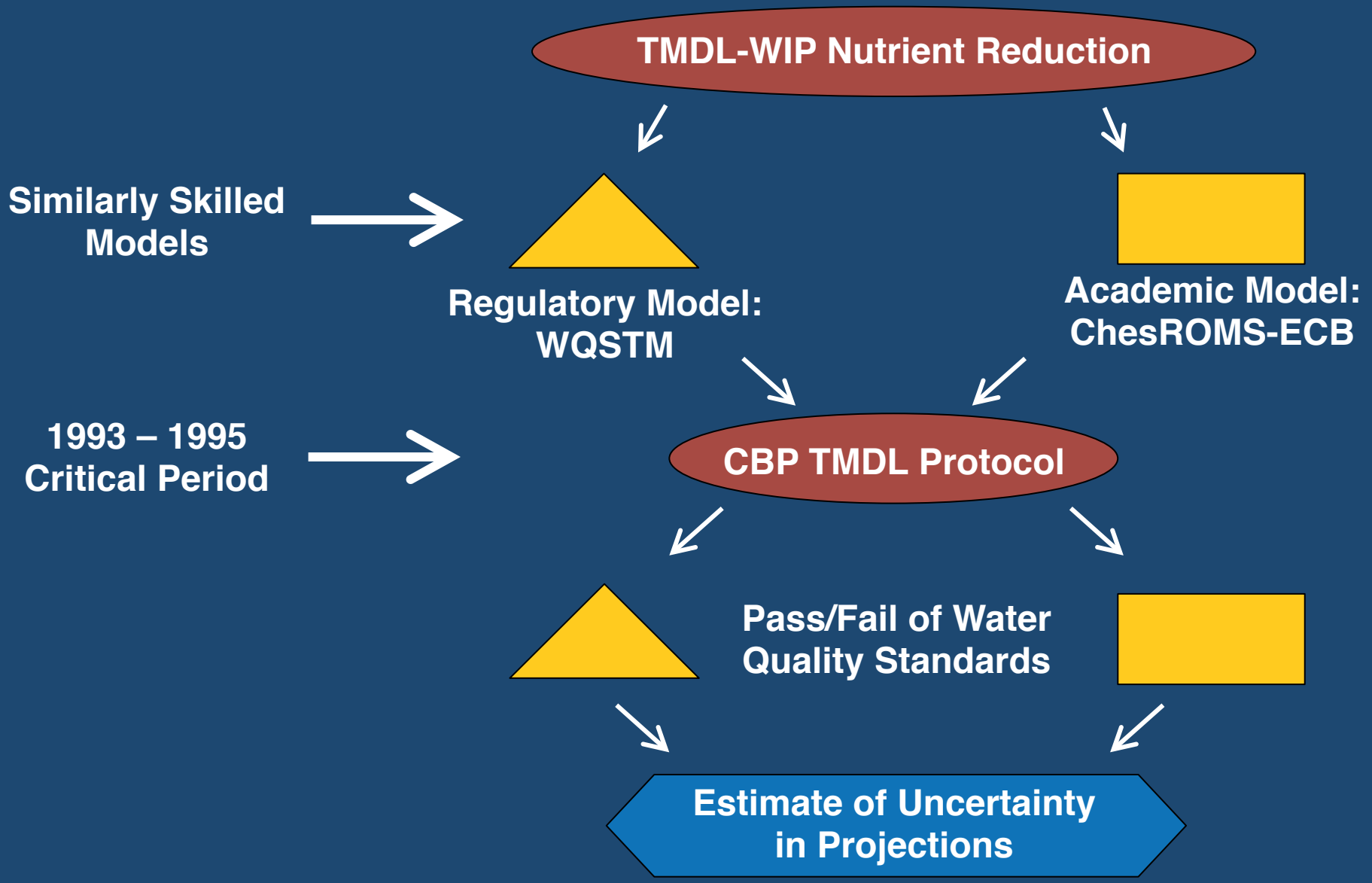
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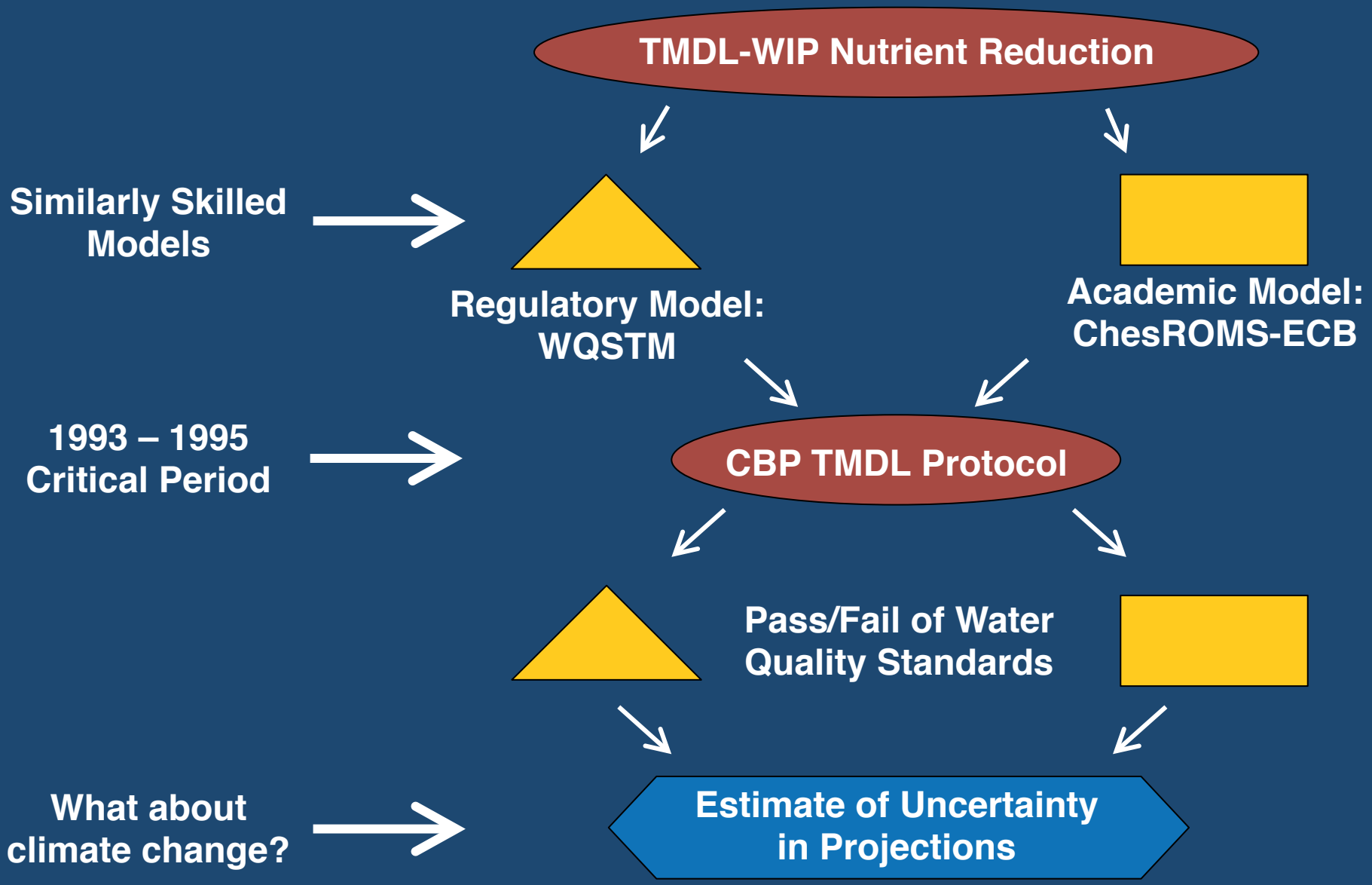
Methods


TMDL-WIP Nutrient Reduction
Similarly Skilled Models
Regulatory Model: WQSTM
Academic Model: ChesROMS-ECB
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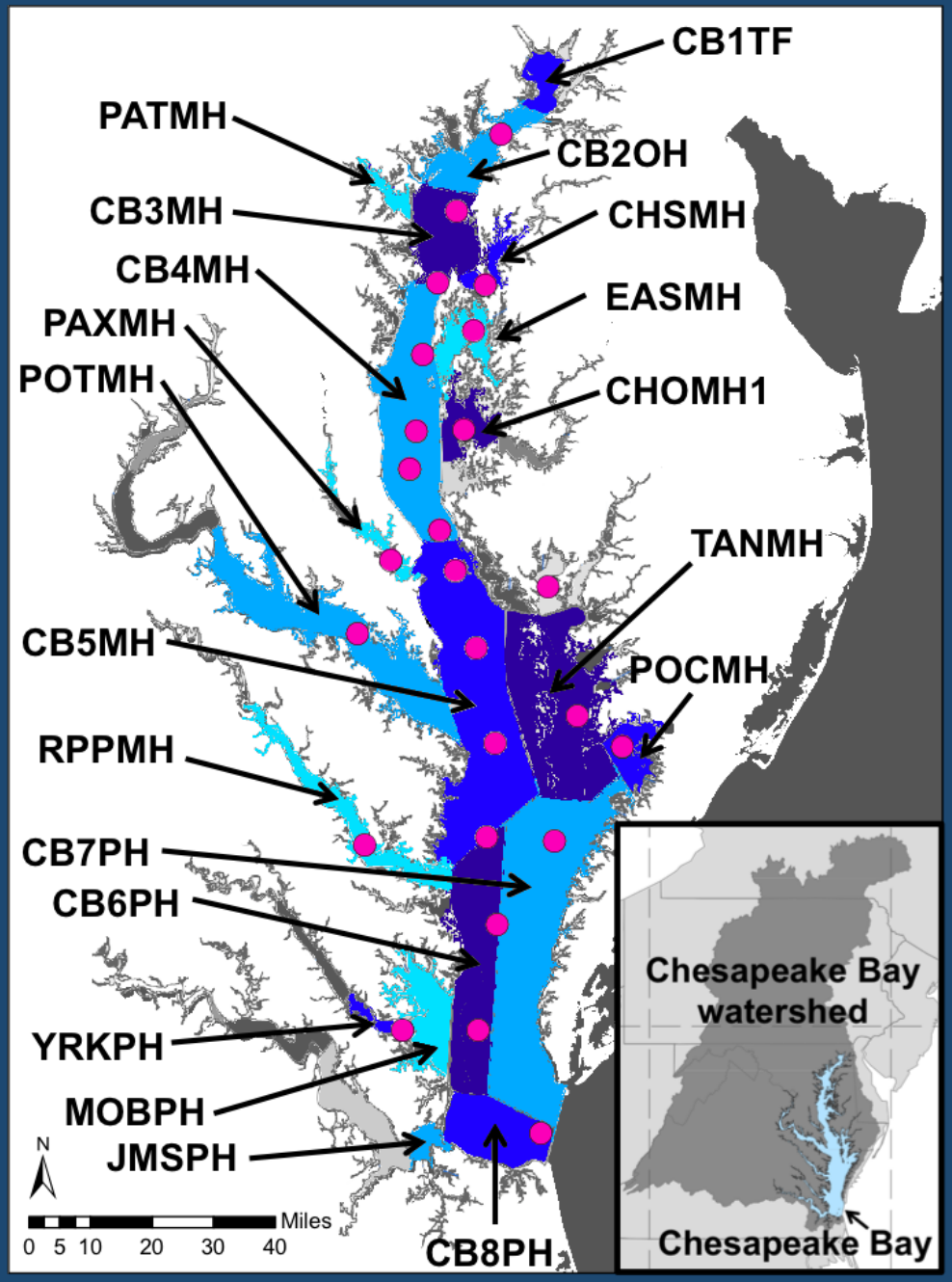
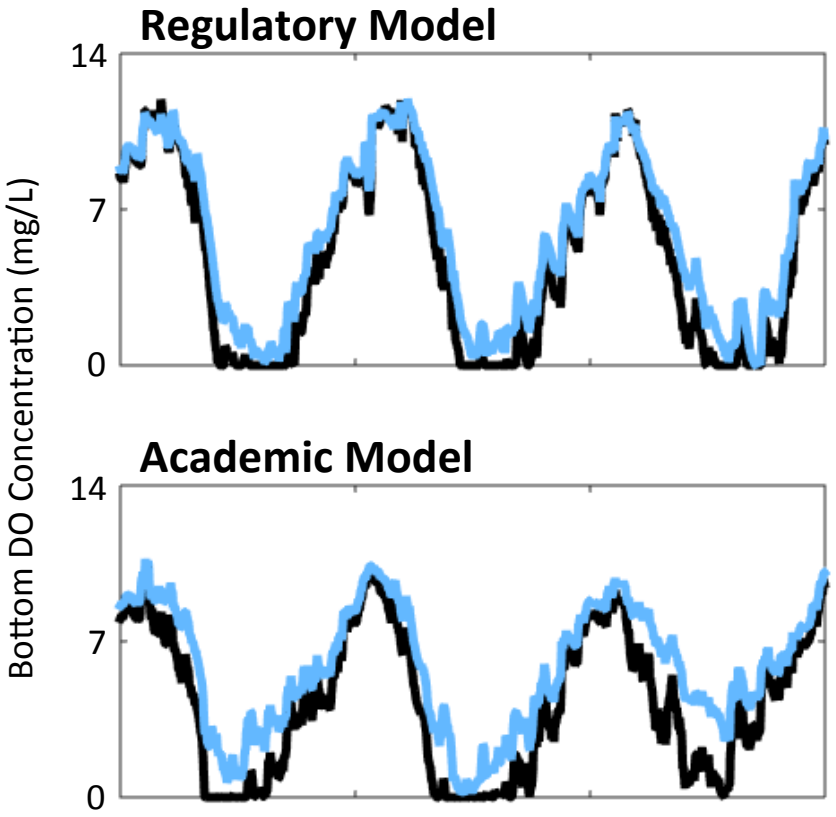
Pass/Fail of Water Quality Standards
What about climate change?
Estimate of Uncertainty in Projections

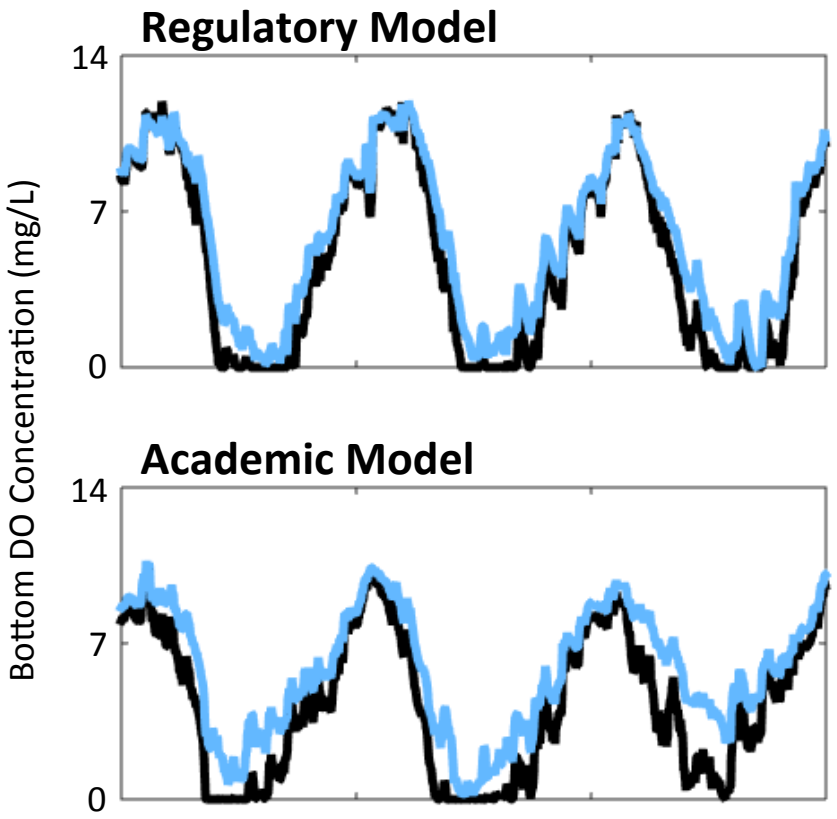

CB1TF
PATMH
CB2OH
CB3MH
CHSMH
CB4MH
EASMH
PAXMH
POTMH
CHOMH1
TANMH
CB5MH
POCMH
RPPMH
CB7PH
CB6PH
YRKPH
MOBPH
JMSPH
CB8PH
N
Miles
0 5 10 20 30 40
Chesapeake Bay watershed
Chesapeake Bay

Time series of bottom DO at CB4.3C



Time series of bottom DO at CB4.3C

- Both models simulate an increase in bottom DO concentrations as a result of nutrient reduction



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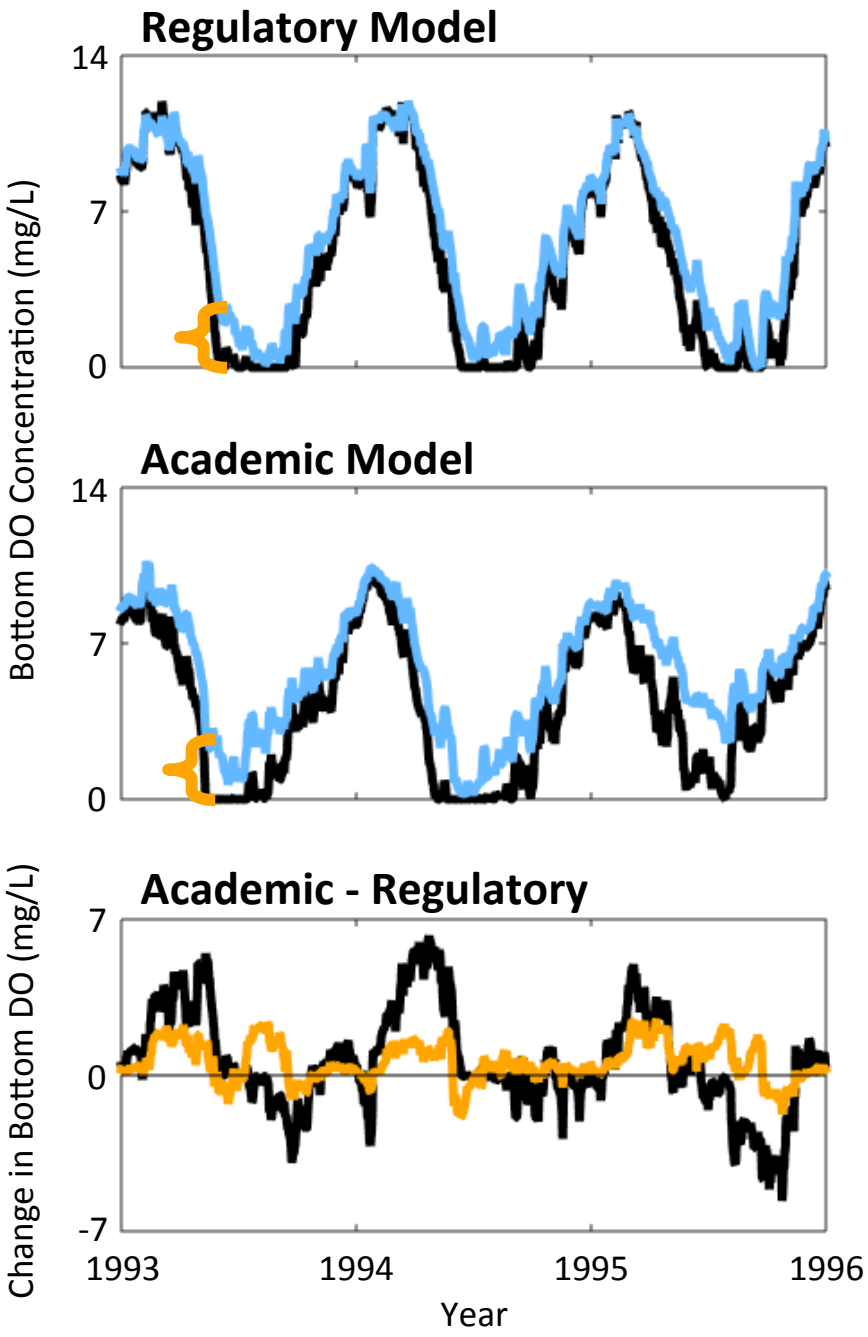
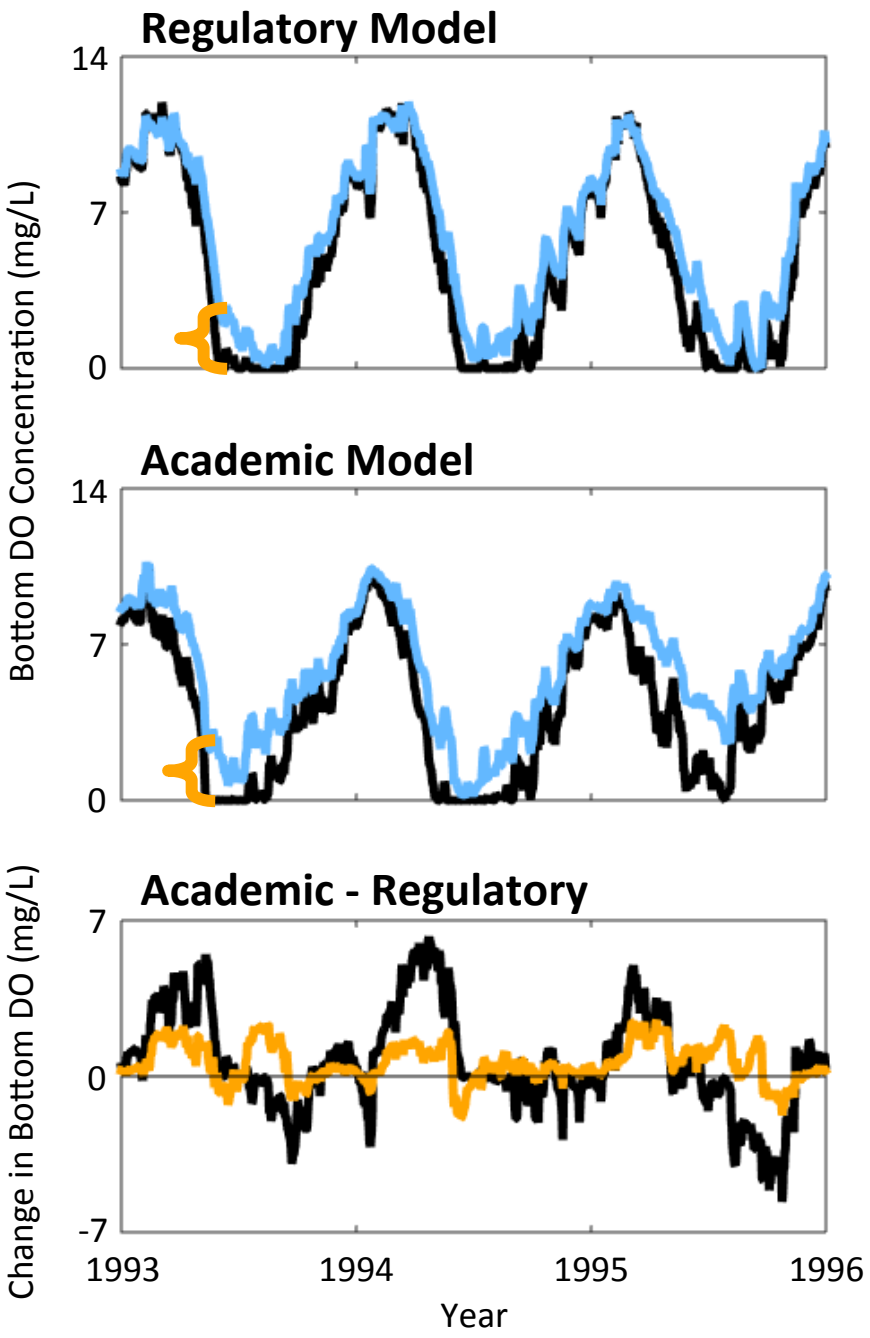
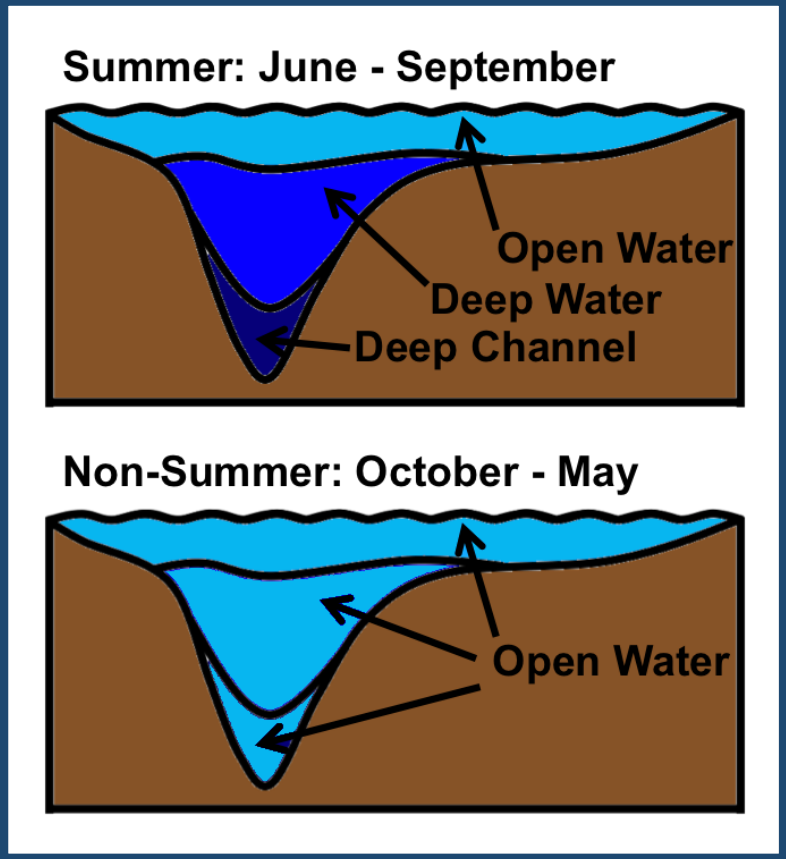


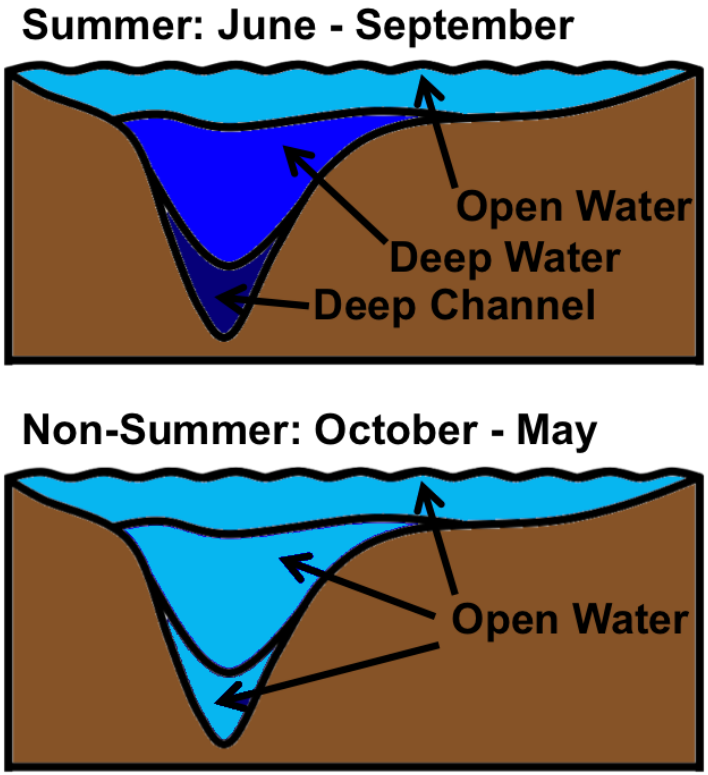
Time series of bottom DO at CB4.3C

- Both models simulate an increase in bottom DO concentrations as a result of nutrient reduction
- The difference between the models is larger than the difference between the simulated impact of nutrient reduction



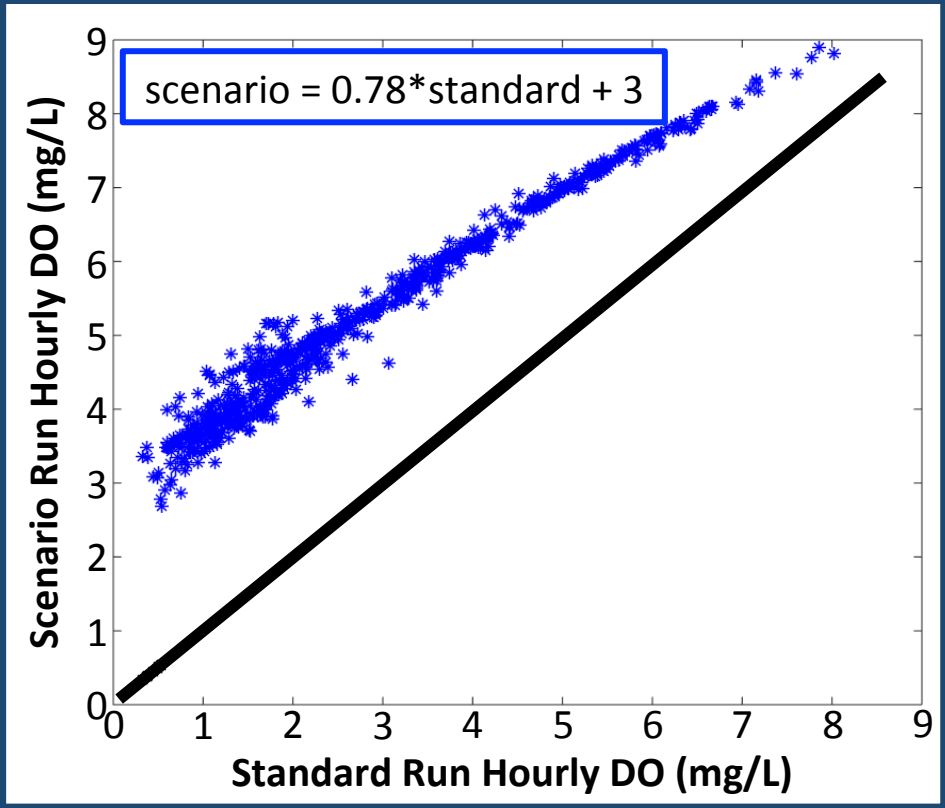


CBP Habitats examined (Designated Uses)



CBP Habitats examined (Designated Uses)

CBP Regression method



Water Quality Standards

Designated Use	Dissolved Oxygen Criteria	Rationale	Timeframe
Open Water	30-day mean ≥ 5.5 mg/L (tidal habitats with salinity ≤ 0.5 PSU)	Protects growth of tidal-fresh juvenile and adult fish as well as threatened/ endangered species	Year-round
	30-day mean ≥ 5.0 mg/L (tidal habitats with salinity ≥ 0.5 PSU)	Protects growth of larval, juvenile, and adult fish and shellfish as well as threatened/endangered species	
	7-day mean ≥ 4.0 mg/L	Protects survival of open water fish larvae	
	Instantaneous minimum ≥ 3.2 mg/L	Protects survival of threatened/ endangered sturgeon species	
Deep Water	30-day mean ≥ 3.0 mg/L	Protects survival and recruitment of Bay anchovy eggs and larvae	June 1 – September 30
	1-day mean ≥ 2.3 mg/L	Protects survival of open water juvenile and adult fish	
	Instantaneous minimum ≥ 1.7 mg/L	Protects survival of Bay anchovy eggs and larvae	
	Open Water criteria apply		October 1 – May 31
Deep Channel	Instantaneous minimum ≥ 1.0 mg/L	Protects survival of bottom-dwelling worms and clams	June 1 – September 30
	Open Water criteria apply		October 1 – May 31

Similarity Table

Similarity in Attainment of Water Quality Standards

Segment	Deep Channel	Deep Water	Open Water Summer	Open Water 8
CB1TF			96 : 4 : 0	98 : 2 : 0
			96 : 4 : 0	98 : 2 : 0
CB2OH			94 : 6 : 0	98 : 2 : 0
			95 : 5 : 0	98 : 2 : 0
PATMH	95 : 5 : 0	87 : 13 : 0*	95 : 5 : 0	97 : 3 : 0
	95 : 5 : 0	93 : 7 : 0	95 : 5 : 0	97 : 3 : 0
CB3MH	93 : 7 : 0*	91 : 9 : 0*	96 : 4 : 0	97 : 3 : 0
	89 : 9 : 2	90 : 10 : 0	96 : 4 : 0	97 : 3 : 0
CHSMH	73 : 11 : 16	79 : 18 : 3	96 : 4 : 0	98 : 2 : 0
	94 : 6 : 0	88 : 12 : 0	96 : 4 : 0	98 : 2 : 0
CB4MH	88 : 9 : 3	79 : 16 : 5	95 : 5 : 0	95 : 5 : 0
	93 : 7 : 0*	84 : 15 : 1	96 : 4 : 0	96 : 4 : 0
EASMH	88 : 10 : 2	87 : 12 : 1	96 : 4 : 0	97 : 3 : 0
	96 : 4 : 0	88 : 12 : 0*	96 : 4 : 0	97 : 3 : 0
CHOMH1			94 : 6 : 0*	98 : 2 : 0
			93 : 7 : 0	98 : 2 : 0
PAXMH		92 : 8 : 0	95 : 5 : 0	98 : 2 : 0
		90 : 10 : 0*	92 : 8 : 0*	98 : 2 : 0
CB5MH	97 : 3 : 0	88 : 11 : 1	96 : 4 : 0	97 : 3 : 0
	98 : 2 : 0	94 : 6 : 0	96 : 4 : 0	98 : 2 : 0
TANMH			93 : 7 : 0	98 : 2 : 0
			94 : 6 : 0	98 : 2 : 0
POTMH	98 : 2 : 0	92 : 8 : 0	96 : 4 : 0	98 : 2 : 0
	98 : 2 : 0	95 : 5 : 0	96 : 4 : 0	98 : 2 : 0
POCMH			96 : 4 : 0	98 : 2 : 0
			96 : 4 : 0	98 : 2 : 0
RPPMH	97 : 3 : 0	91 : 9 : 0	96 : 4 : 0	98 : 2 : 0
	97 : 3 : 0	87 : 13 : 0*	96 : 4 : 0	98 : 2 : 0
CB6PH		94 : 6 : 0	93 : 7 : 0	98 : 2 : 0
		96 : 4 : 0	94 : 6 : 0	98 : 2 : 0
CB7PH		96 : 4 : 0	90 : 10 : 0*	98 : 2 : 0
		96 : 4 : 0	93 : 7 : 0	98 : 2 : 0
YRKPH		96 : 4 : 0	96 : 4 : 0	98 : 2 : 0
		94 : 6 : 0	93 : 7 : 0	98 : 2 : 0
MOBPH			93 : 7 : 0	98 : 2 : 0
			92 : 8 : 0	98 : 2 : 0
JMSPH			95 : 5 : 0	98 : 2 : 0
			95 : 5 : 0	98 : 2 : 0
CB8PH			96 : 4 : 0	98 : 2 : 0
			95 : 5 : 0	98 : 2 : 0

Top: Regulatory Model
Bottom: Academic Model

Percent Agreement
100%
98 - 99%
95 - 97%
90 - 94%
< 90%

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CB2OH			94 : 6 : 0 95 : 5 : 0	98 : 2 : 0 98 : 2 : 0
PATMH	95 : 5 : 0 95 : 5 : 0	87 : 13 : 0* 93 : 7 : 0	95 : 5 : 0 95 : 5 : 0	97 : 3 : 0 97 : 3 : 0
CB3MH	93 : 7 : 0* 89 : 9 : 2	91 : 9 : 0* 90 : 10 : 0	96 : 4 : 0 96 : 4 : 0	97 : 3 : 0 97 : 3 : 0
CHSMH	73 : 11 : 16 94 : 6 : 0	79 : 18 : 3 88 : 12 : 0	96 : 4 : 0 96 : 4 : 0	98 : 2 : 0 98 : 2 : 0
CB4MH	88 : 9 : 3 93 : 7 : 0*	79 : 16 : 5 84 : 15 : 1	95 : 5 : 0 96 : 4 : 0	95 : 5 : 0 96 : 4 : 0
EASMH	88 : 10 : 2 96 : 4 : 0	87 : 12 : 1 88 : 12 : 0*	96 : 4 : 0 96 : 4 : 0	97 : 3 : 0 97 : 3 : 0
CHOMH1			94 : 6 : 0* 93 : 7 : 0	98 : 2 : 0 98 : 2 : 0
PAXMH		92 : 8 : 0 90 : 10 : 0*	95 : 5 : 0 92 : 8 : 0*	98 : 2 : 0 98 : 2 : 0
CB5MH	97 : 3 : 0 98 : 2 : 0	88 : 11 : 1 94 : 6 : 0	96 : 4 : 0 96 : 4 : 0	97 : 3 : 0 98 : 2 : 0
TANMH			93 : 7 : 0 94 : 6 : 0	98 : 2 : 0 98 : 2 : 0
POTMH	98 : 2 : 0 98 : 2 : 0	92 : 8 : 0 95 : 5 : 0	96 : 4 : 0 96 : 4 : 0	98 : 2 : 0 98 : 2 : 0
POCMH			96 : 4 : 0 96 : 4 : 0	98 : 2 : 0 98 : 2 : 0
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CB6PH		94 : 6 : 0 96 : 4 : 0	93 : 7 : 0 94 : 6 : 0	98 : 2 : 0 98 : 2 : 0
CB7PH		96 : 4 : 0 96 : 4 : 0	90 : 10 : 0* 93 : 7 : 0	98 : 2 : 0 98 : 2 : 0
YRKPH		96 : 4 : 0 94 : 6 : 0	96 : 4 : 0 93 : 7 : 0	98 : 2 : 0 98 : 2 : 0
MOBPH			93 : 7 : 0 92 : 8 : 0	98 : 2 : 0 98 : 2 : 0
JMSPH			95 : 5 : 0 95 : 5 : 0	98 : 2 : 0 98 : 2 : 0
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Similarity Table

- All but 6 have >95% agreement

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- Low agreement corresponds to disagreement in "red"

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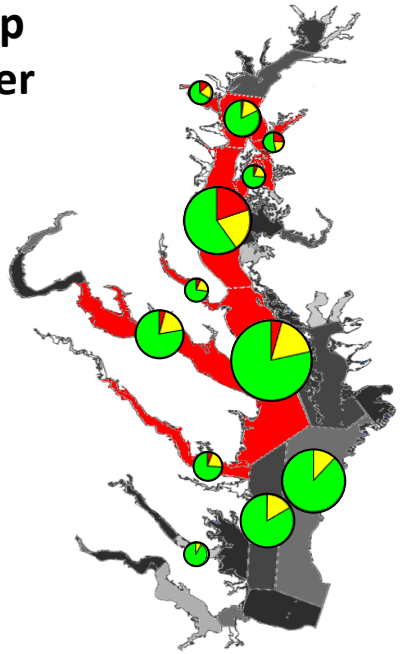
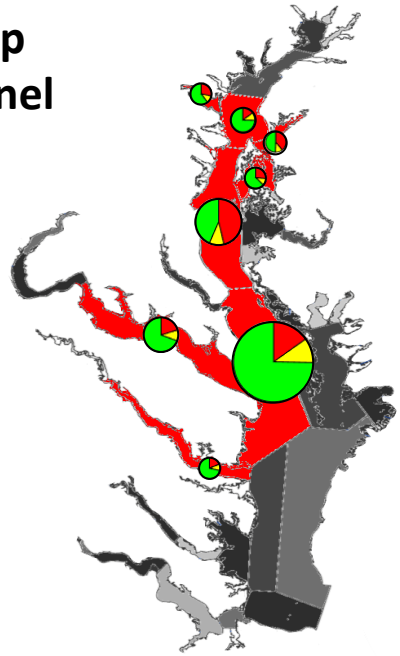
- Low agreement corresponds to disagreement in "red"
- Low agreement centered around similar location

1993 - 1995 Regulatory Academic

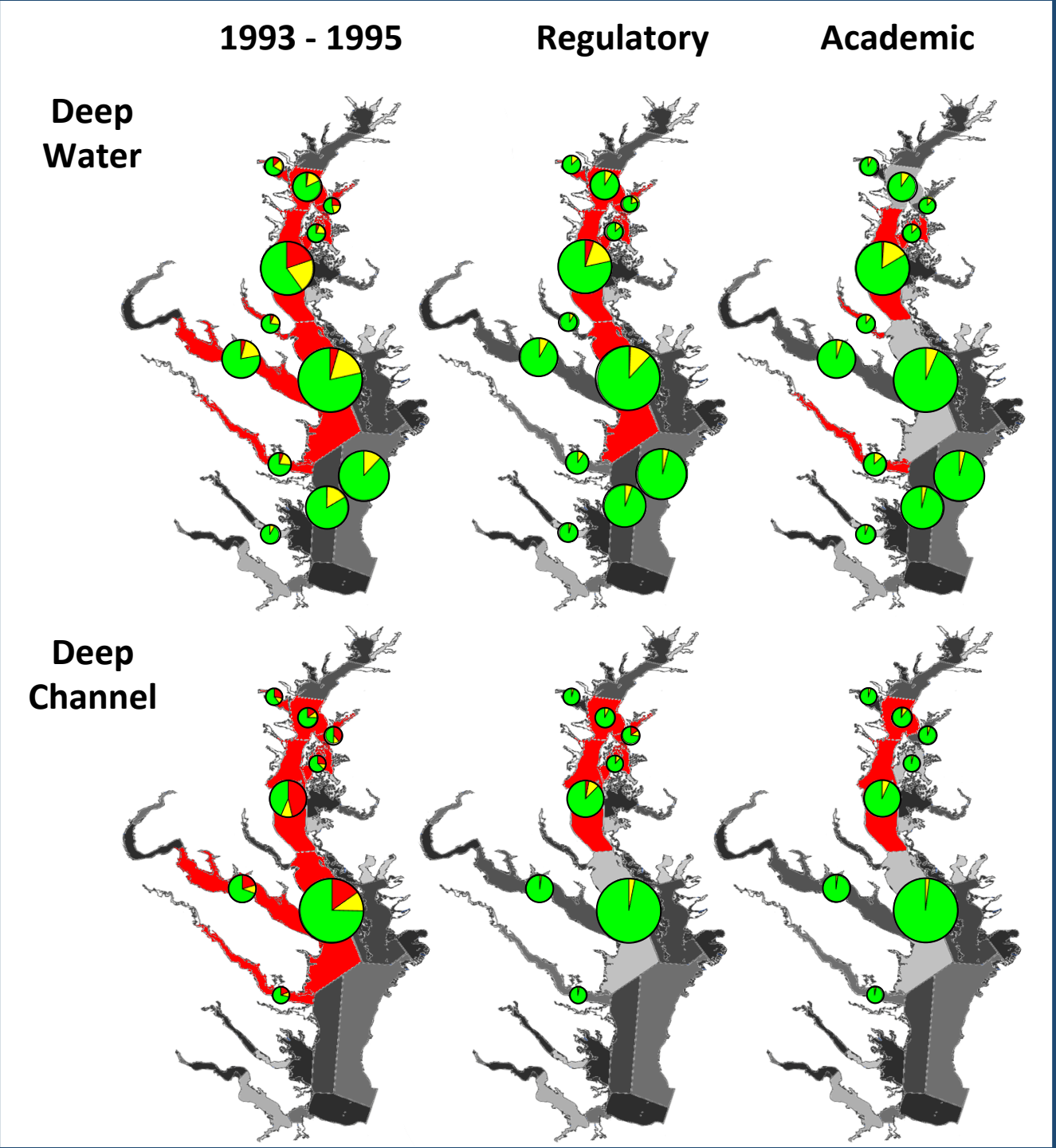
Deep Water



Deep Channel



Stoplight Analysis



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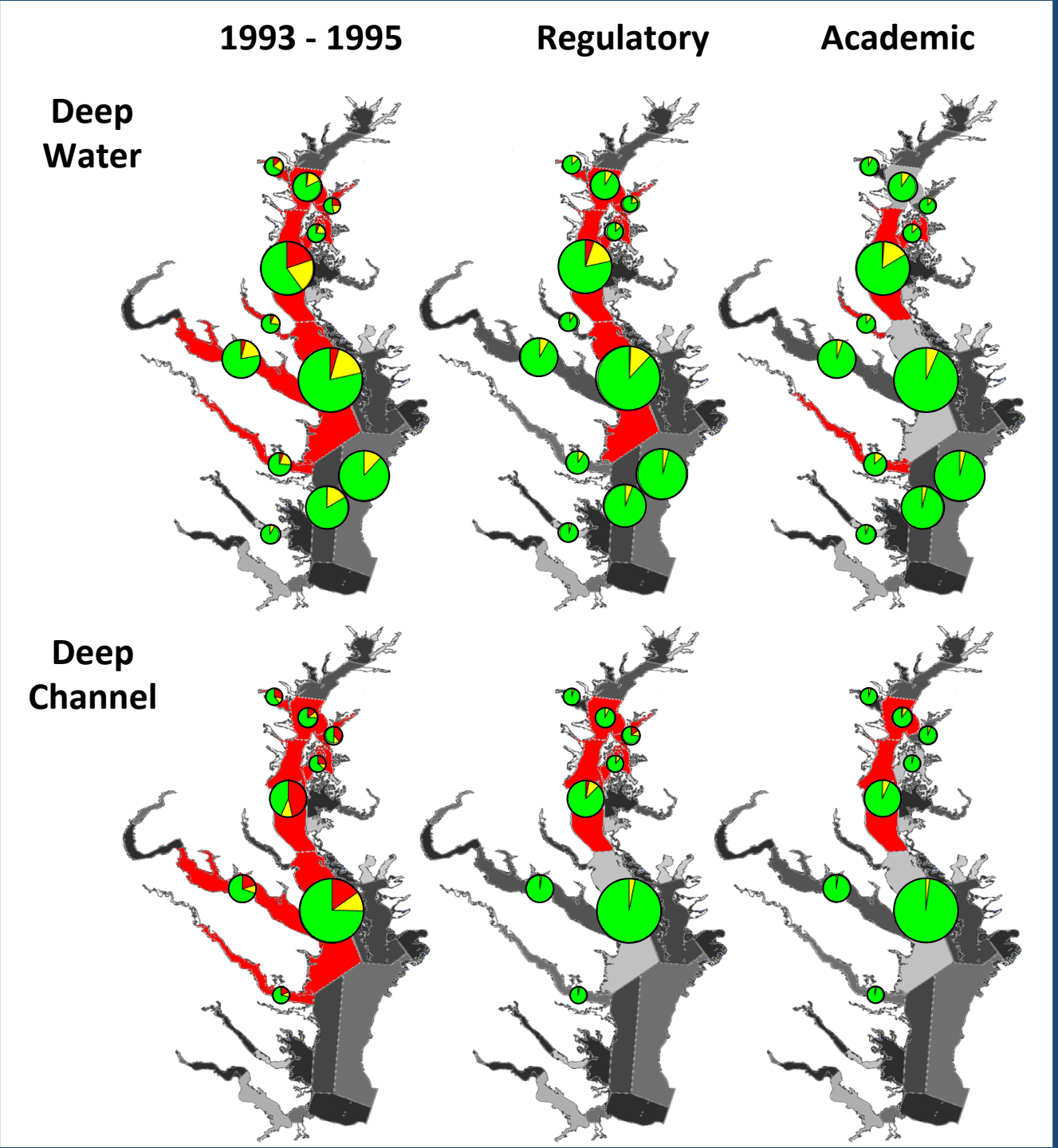
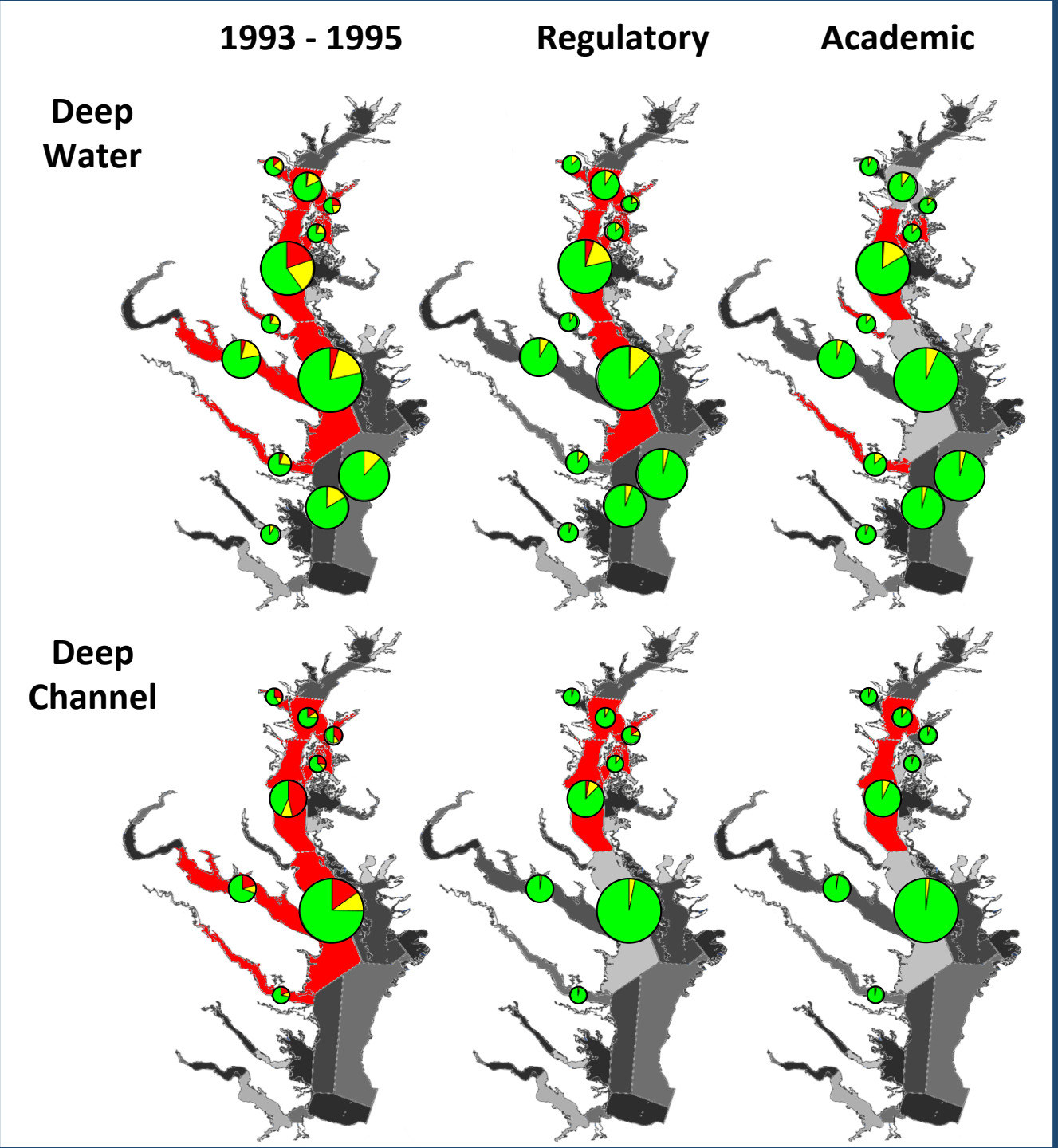


Stoplight Analysis

- Majority green for all segments and both models



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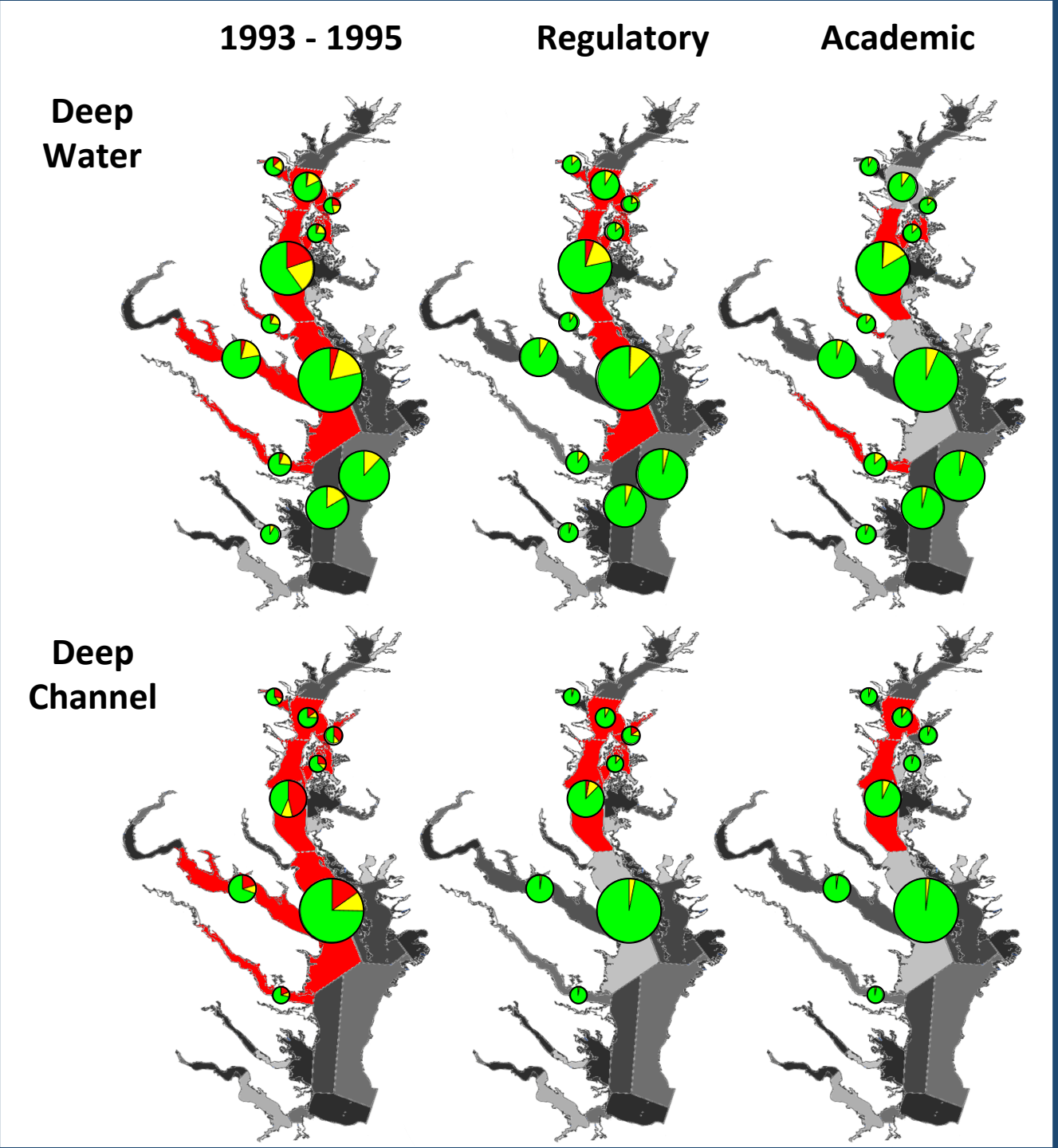
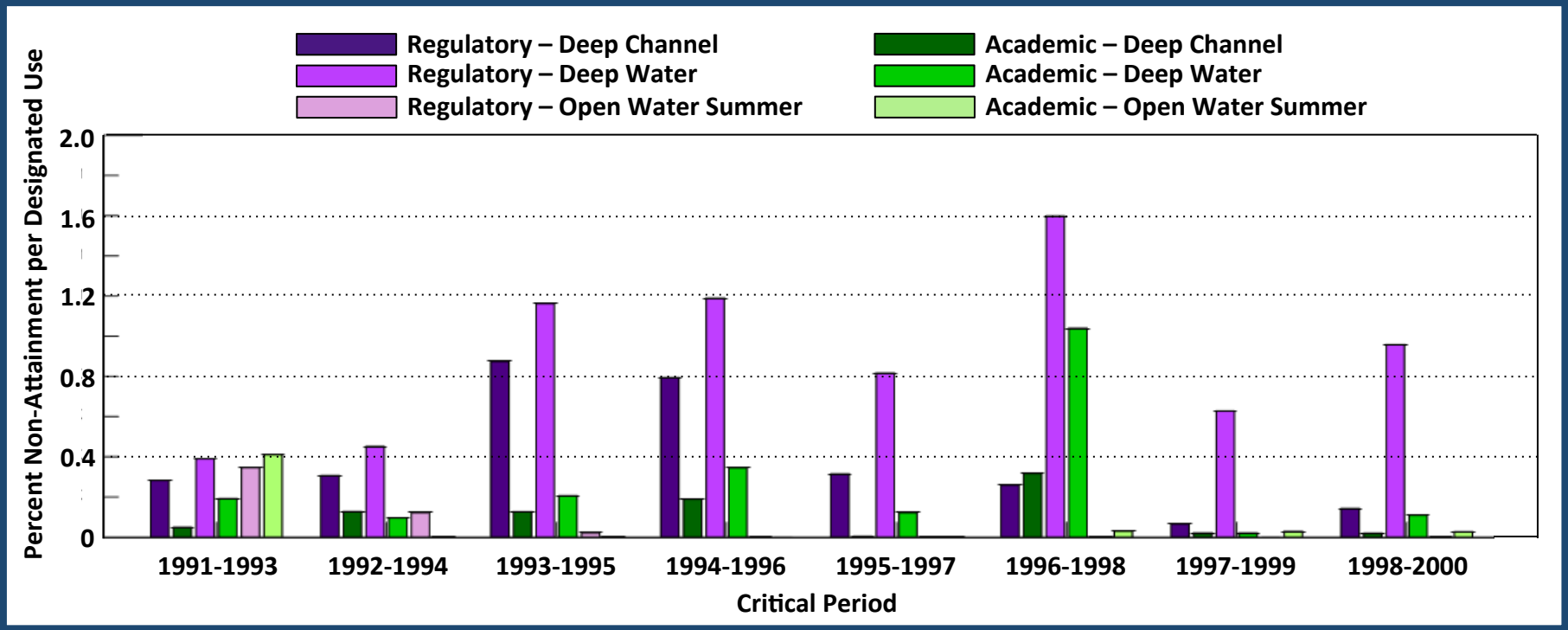


Stoplight Analysis

- Majority green for all segments and both models
- Large decreases in percent red from 1993-1995
- Spatial similarity is greater for Deep Channel than Deep Water

Impact of Choice of 3-Year Period (Critical Period)



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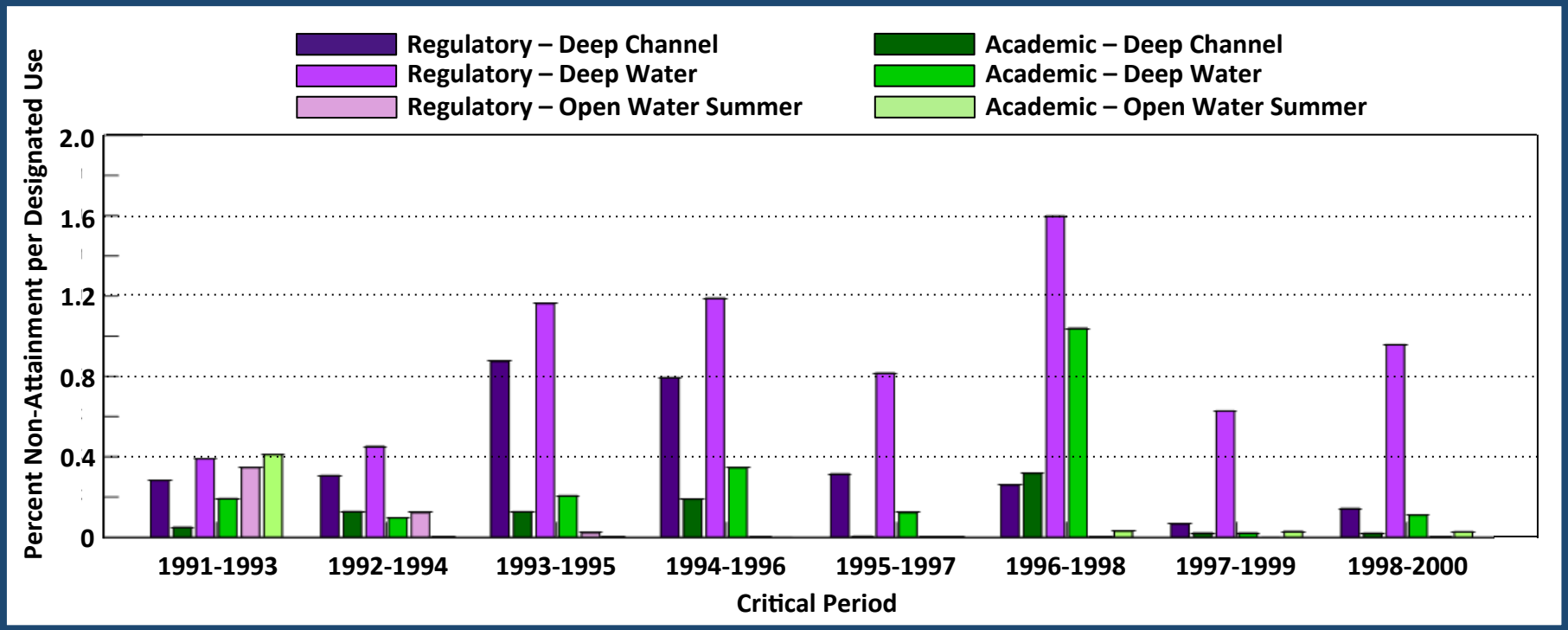

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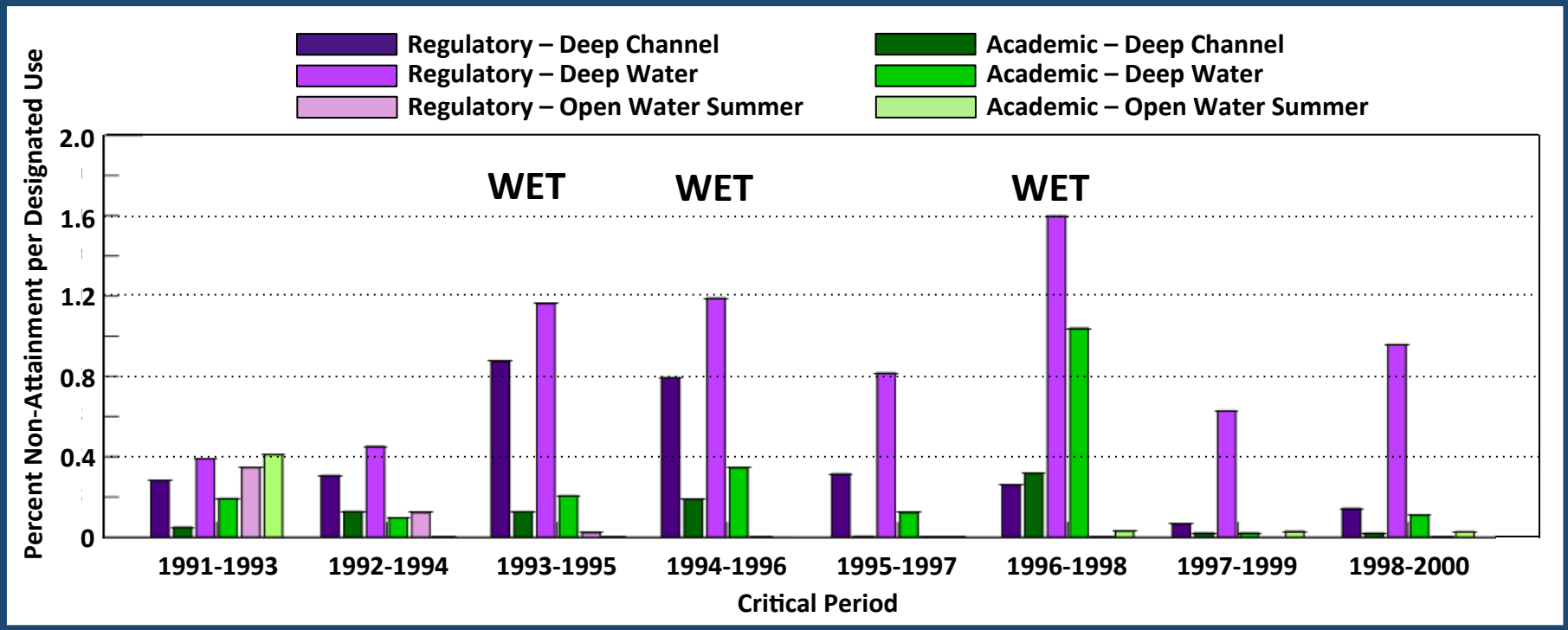

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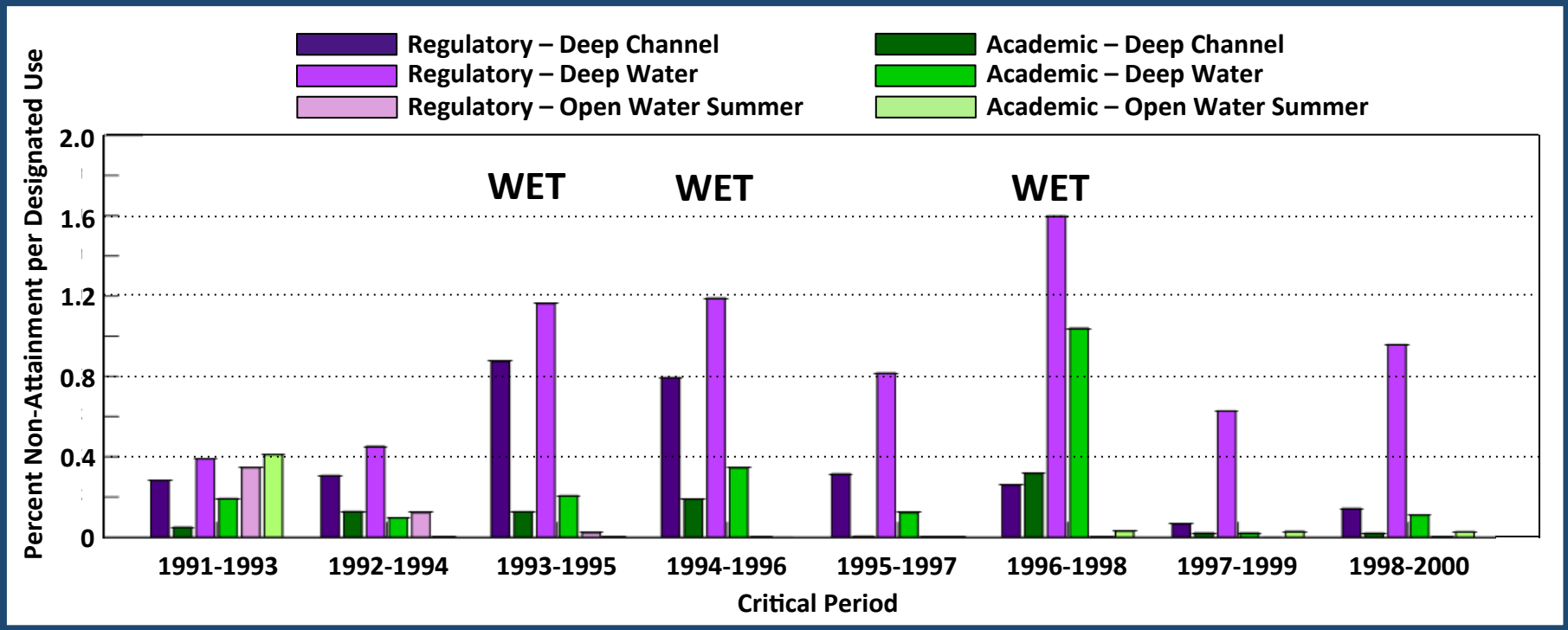

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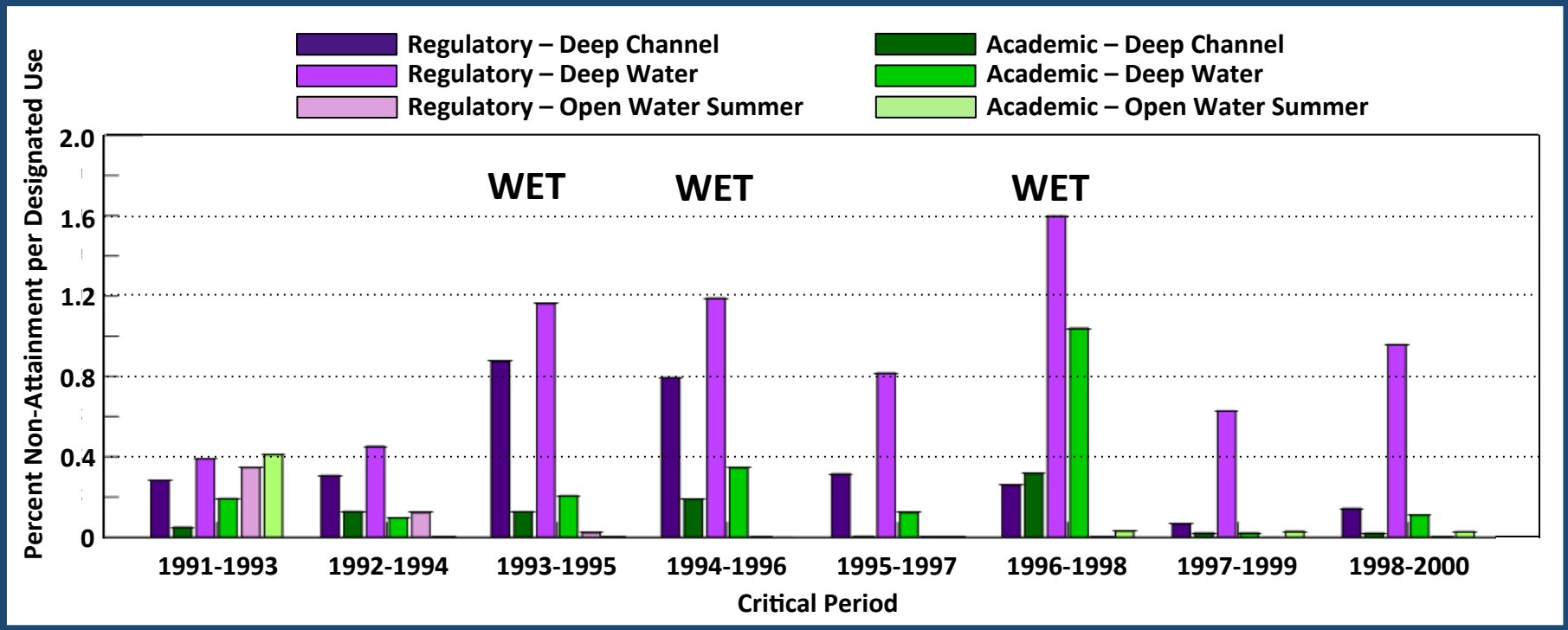


- Total percent non-attainment is consistently below 1.6%
  - Larger non-attainment for wet periods
  - Difference is ~1% across critical periods

Choice of Critical Period is not overly important*

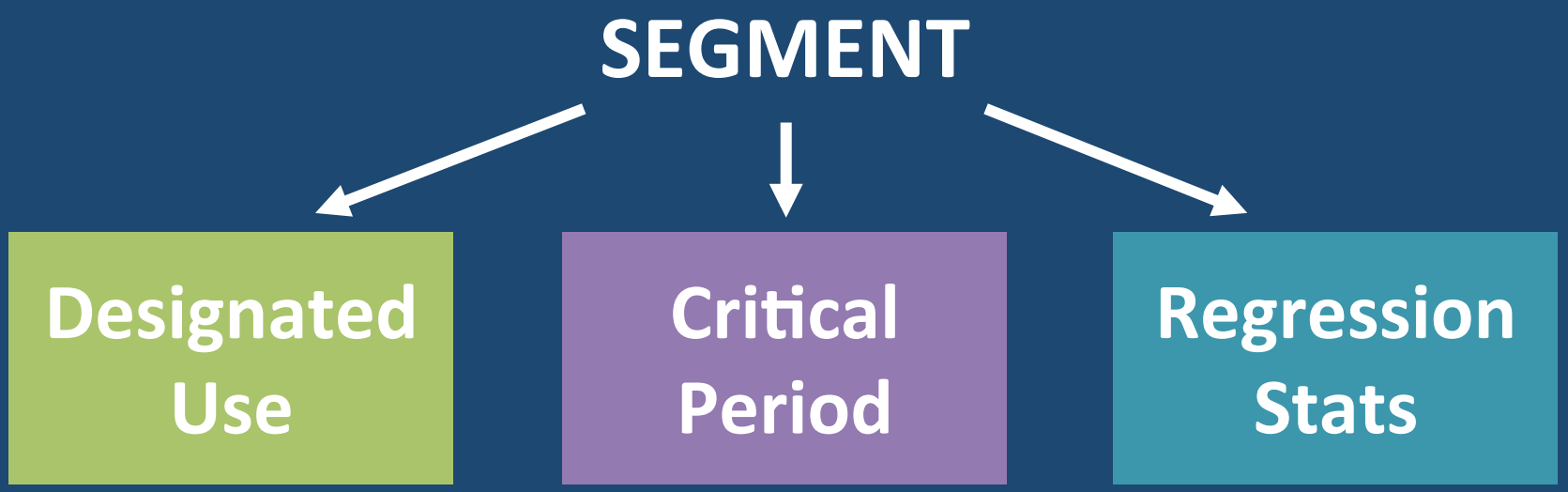
Confidence Index

Assess Confidence in the Impact of Nutrient Reduction on Water Quality

Confidence Index

SEGMENT

Confidence Index



Confidence Index

SEGMENT

Designated Use	Critical Period	Regression Stats
Average of Deep Channel, Deep Water, Open Water Summer, Open Water non-Summer	Difference between standard deviation's of each model for each designated use	Difference between the models' average Slope, Y-int, and Correlation across all designated uses

Confidence Index

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Rankings are relative and interpolated between 0 - 1

Confidence Index

Segment	Designated Use	Critical Period	Regression Statistics	Confidence Index
CB1TF	1	1	.55	.85
CB2OH	.93	1	.85	.95
PATMH	.80	.99	.69	.82
CB3MH	.83	.88	.87	.86
CHSMH	0	0	.62	0
CB4MH	.60	.86	.73	.69
EASMH	.70	.81	0	.39
CHOMH1	.93	.99	.73	.90
PAXMH	.78	.97	.90	.89
CB5MH	.73	.97	.89	.87
TANMH	.93	1	.90	.98
POTMH	.90	.97	.84	.92
POCMH	1	1	.86	.99
RPPMH	.87	.96	.80	.89
CB6PH	.87	.98	.83	.91
CB7PH	.87	.99	.79	.90
YRKPH	.78	.51	1	.74
MOBPH	.93	1	.95	1
JMSPH	1	1	.85	.98
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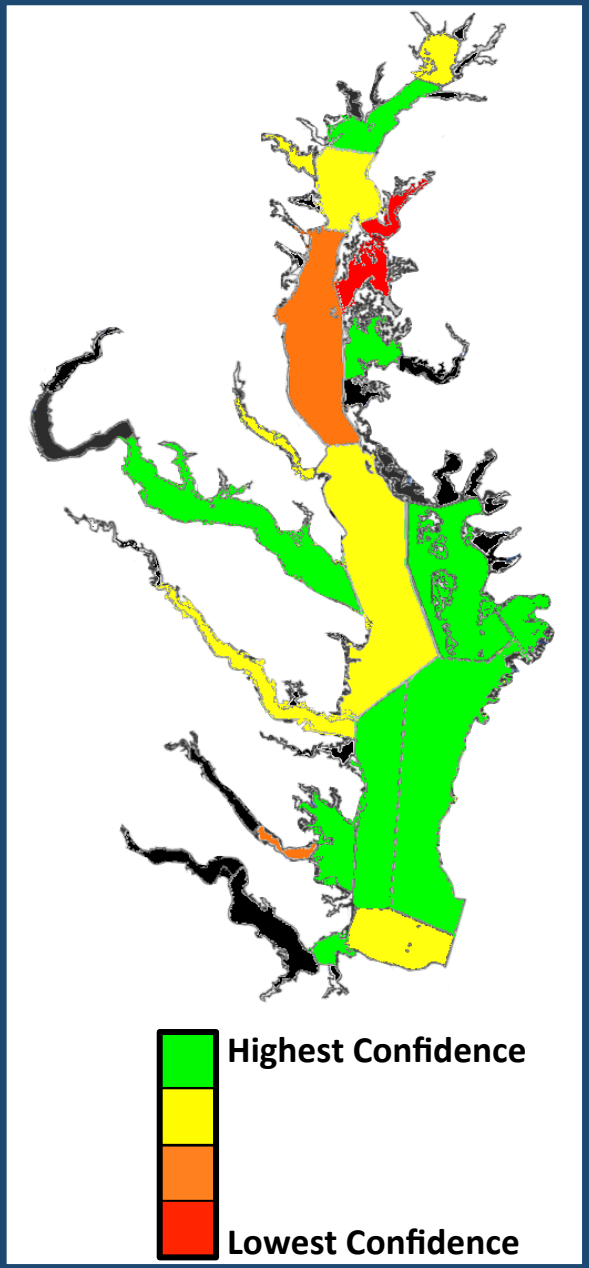

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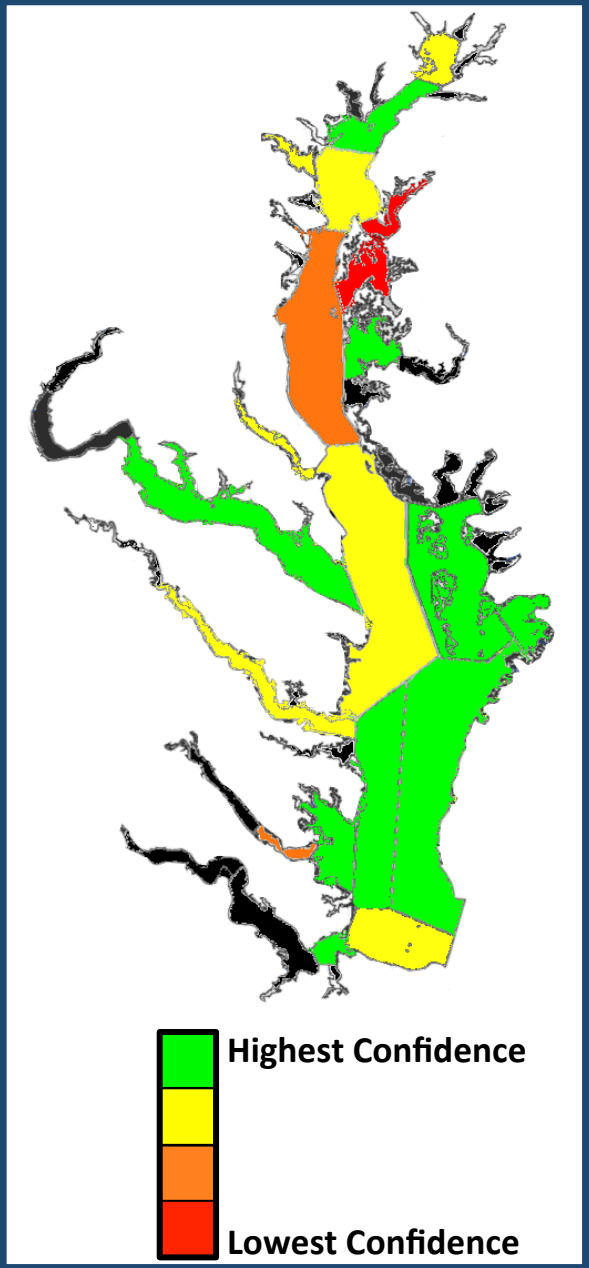

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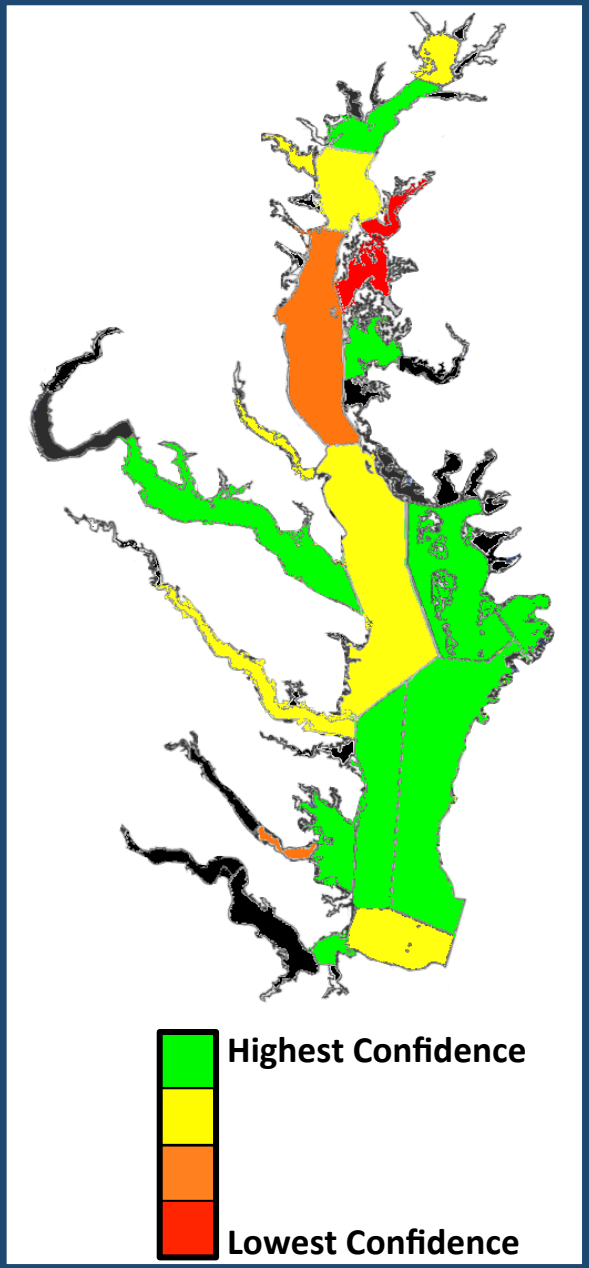

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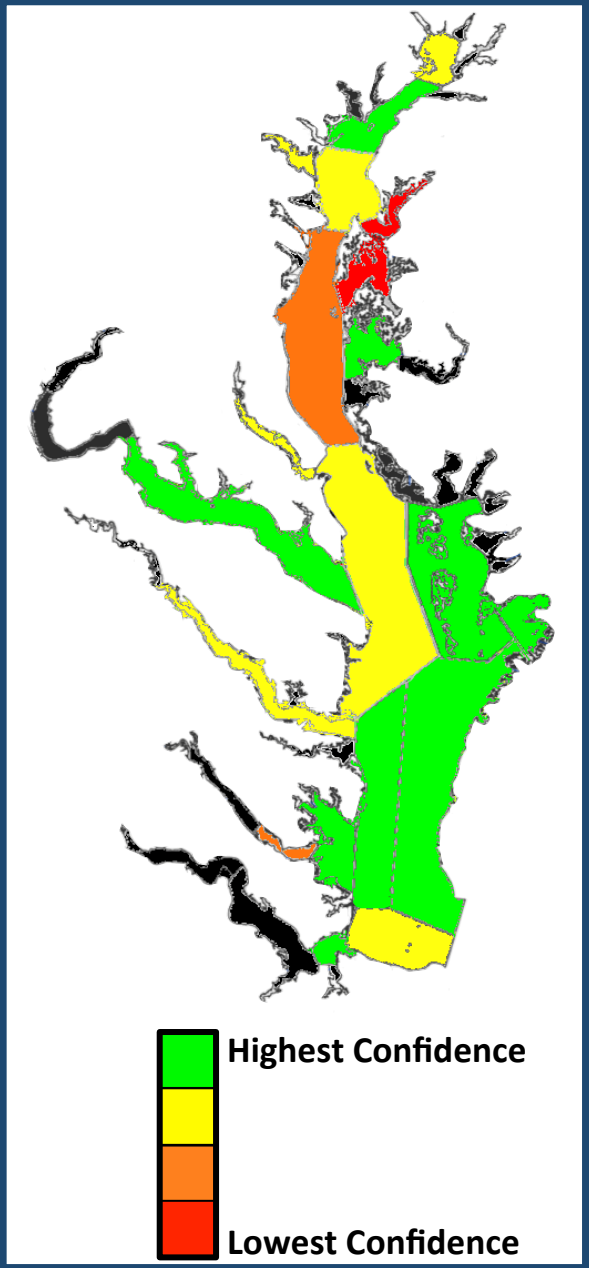

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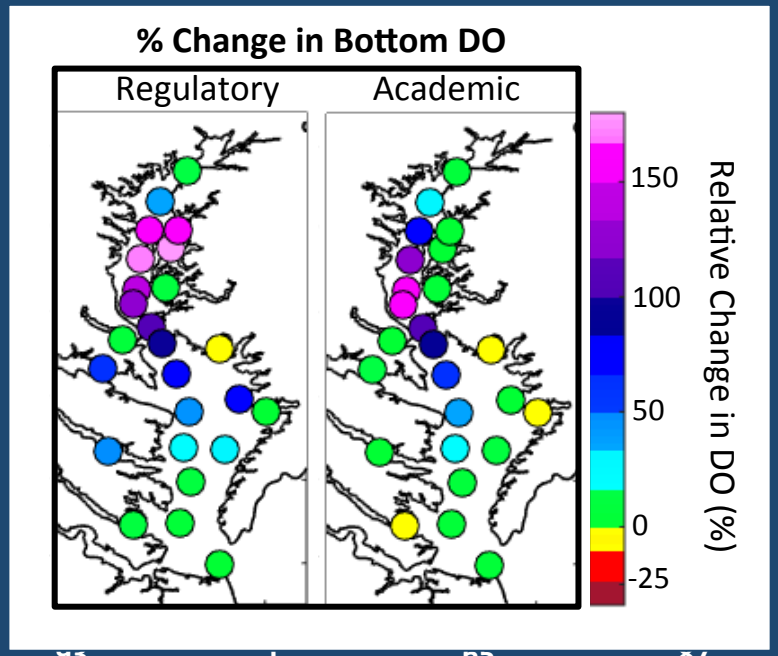

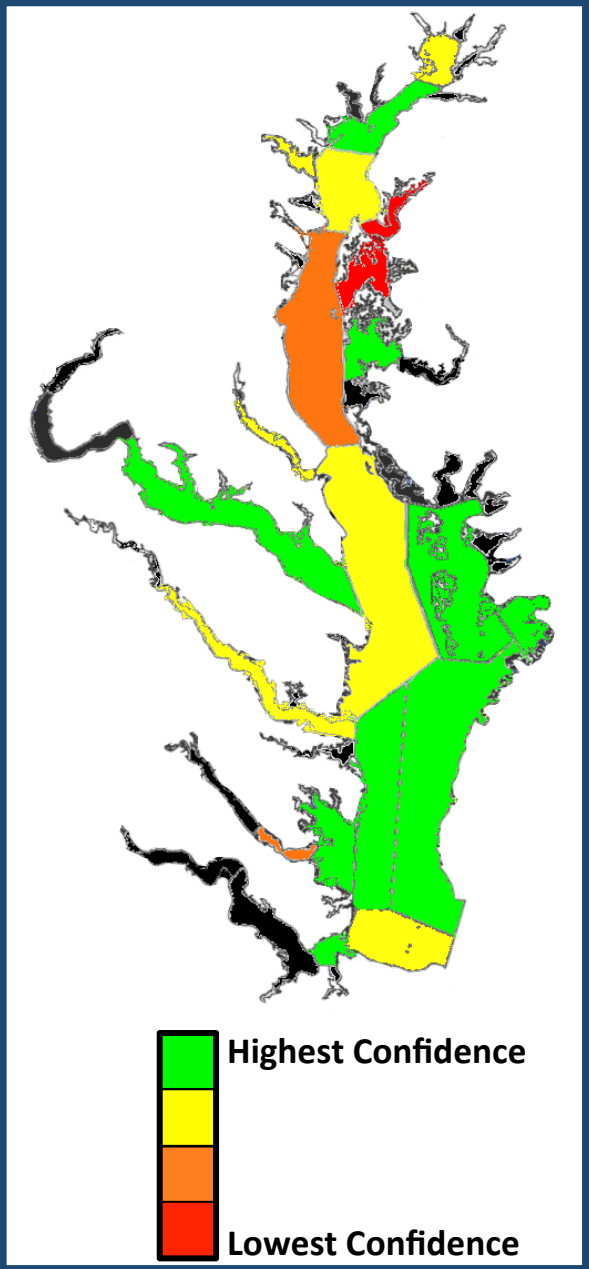

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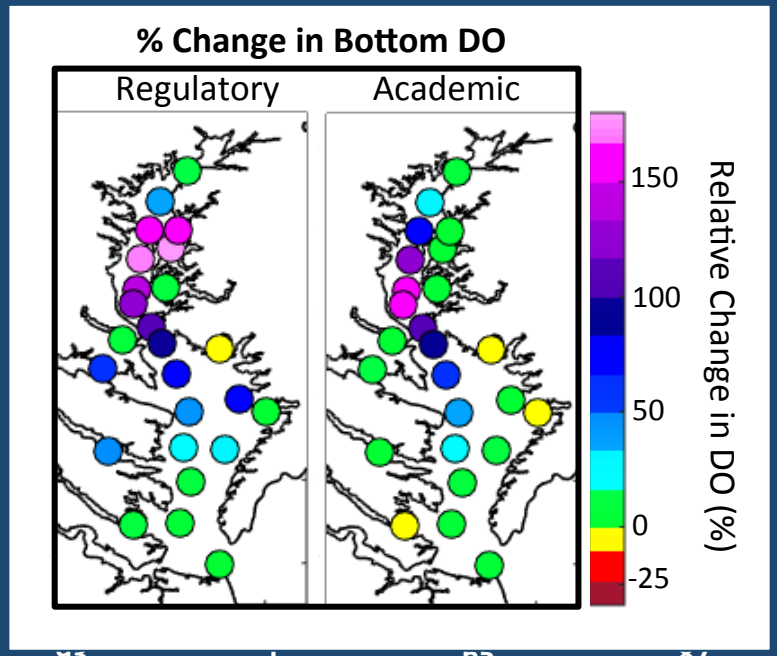

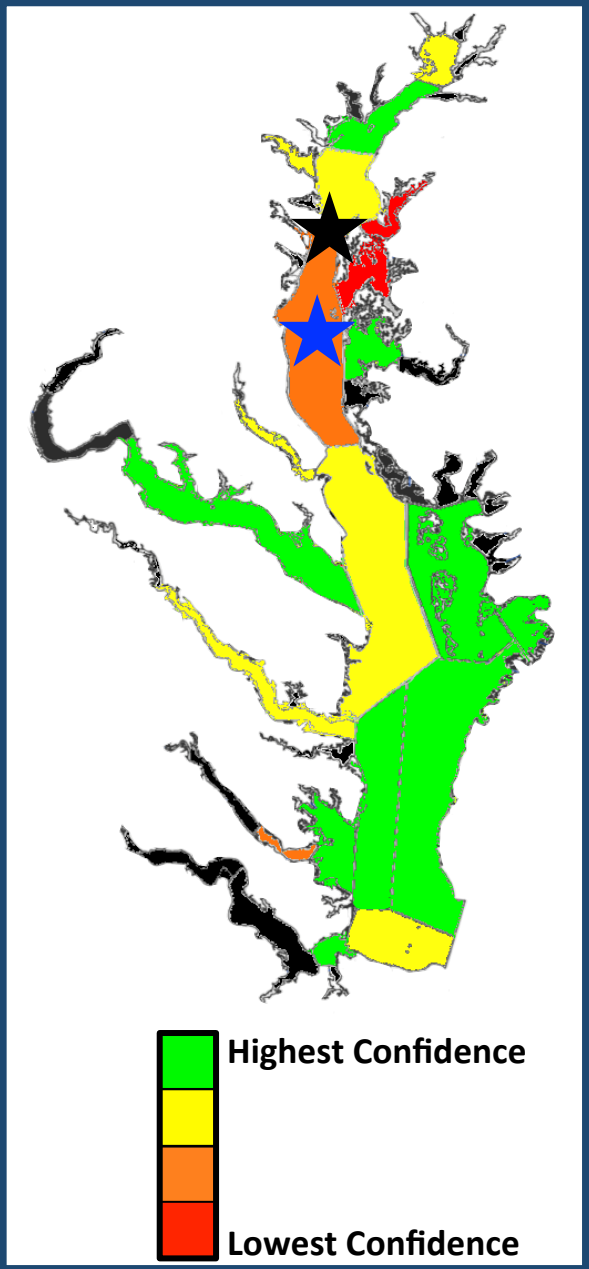

Part 1 Conclusions

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- Choice of 3-Year Period does not have a significant impact
- Greatest source of uncertainty is in the regression statistics used to project future DO concentrations
- Models disagree most in the Chester and Eastern Rivers
  - CB4MH is segment of most concern… but overall, the high confidence is great news!

2050 Climate Change?

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Academic Model

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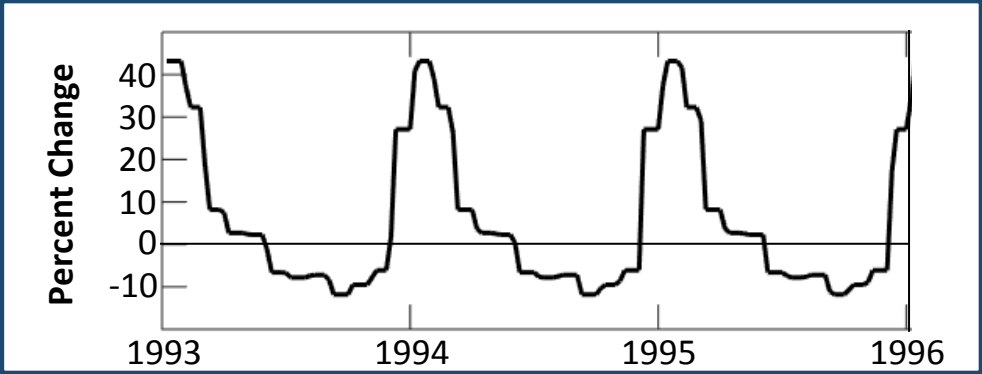
- Fresh water flow

2050 Climate Change?

Academic Model

- Fresh water flow



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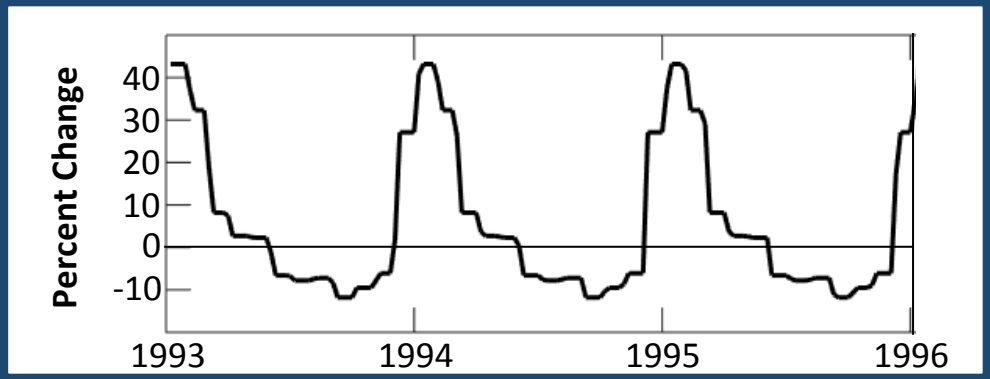

~10% annual increase

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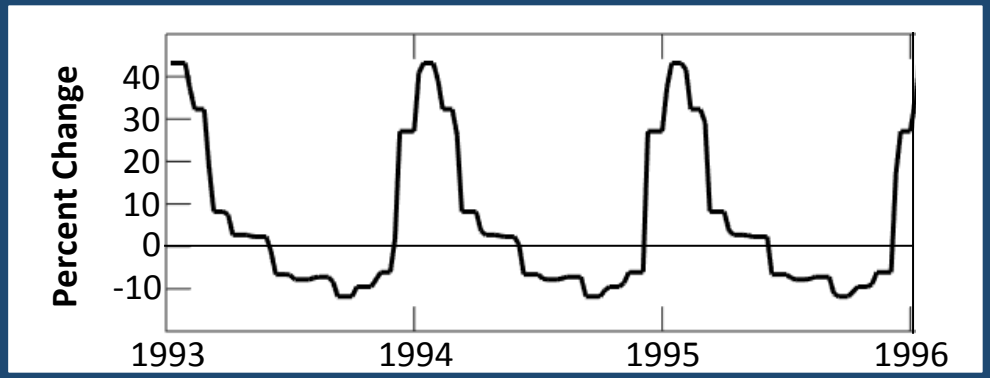
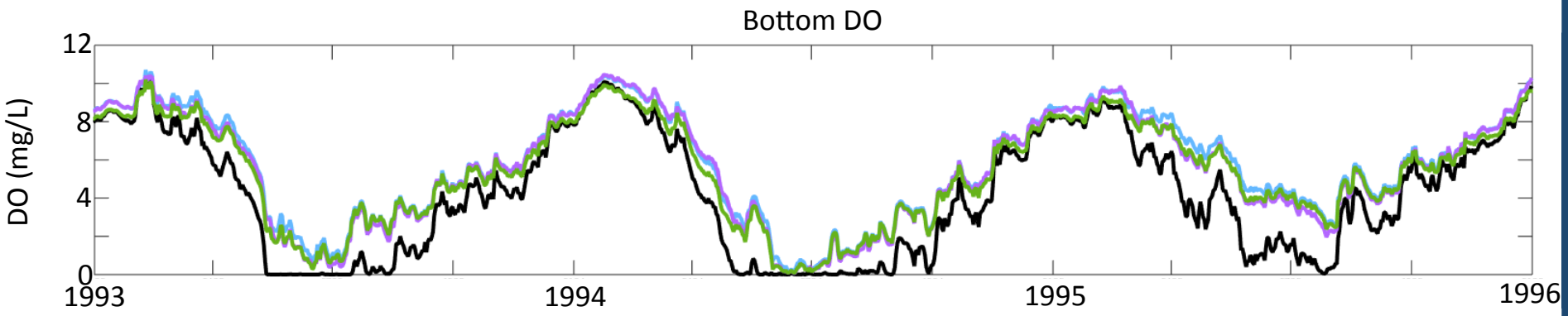


~10% annual increase

- Temperature increase
  - 1.75°C flat increase across time and space

Bottom DO - Station CB4.3C



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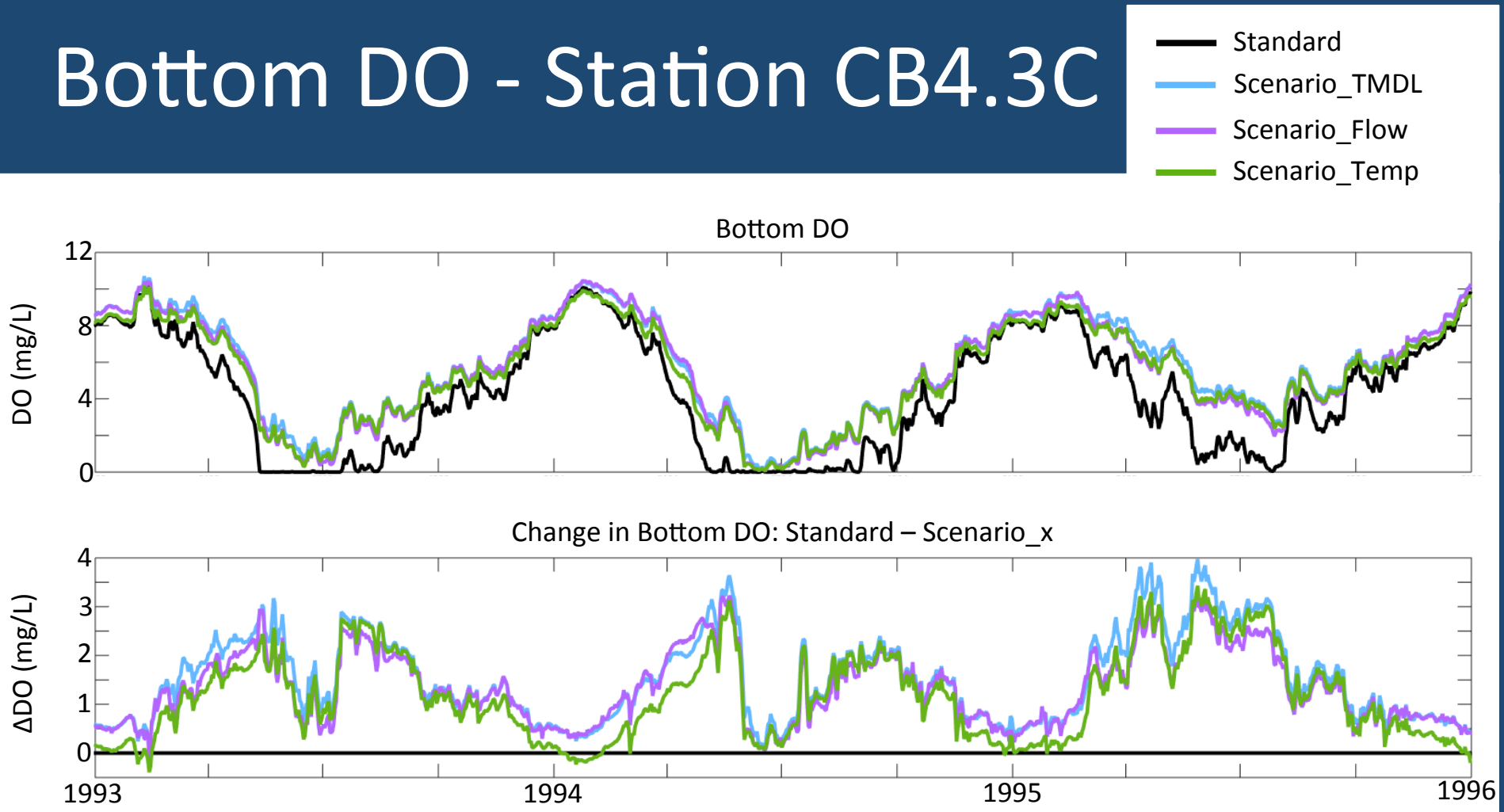

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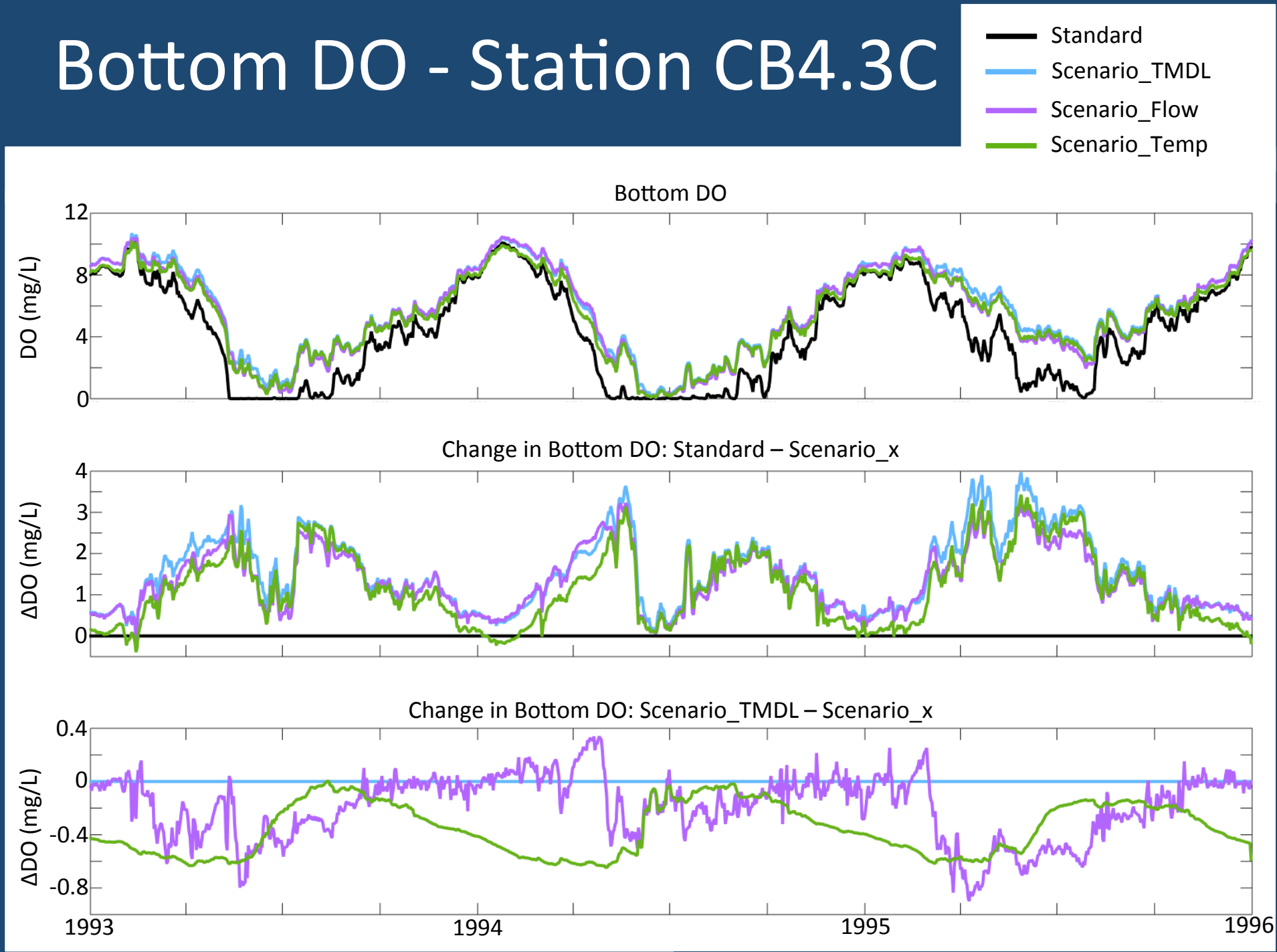

Fresh water flow impact on failure of water quality standards

	Deep Channel			Deep Water		
	TMDL	FLOW	Δ	TMDL	FLOW	Δ
PATMH	0	0	0	0	0	0
CB3MH	2	2	0	0	0	0
CHSMH	0	0	0	0	0	0
CB4MH	0	1	+1	1	3	+2
EASMH	0	0	0	0	1	+1
PAXMH				0	0	0
CB5MH	0	0	0	0	0	0
POTMH	0	0	0	0	0	0
RPPMH	0	0	0	0	1	+1
CB6PH				0	0	0
CB7PH				0	0	0
YRKPH				0	0	0

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	Deep Channel			Deep Water		
	TMDL	FLOW	Δ	TMDL	FLOW	Δ
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CHSMH	0	0	0	0	0	0
CB4MH	0	1	+1	1	3	+2
EASMH	0	0	0	0	1	+1
PAXMH				0	0	0
CB5MH	0	0	0	0	0	0
POTMH	0	0	0	0	0	0
RPPMH	0	0	0	0	1	+1
CB6PH				0	0	0
CB7PH				0	0	0
YRKPH				0	0	0

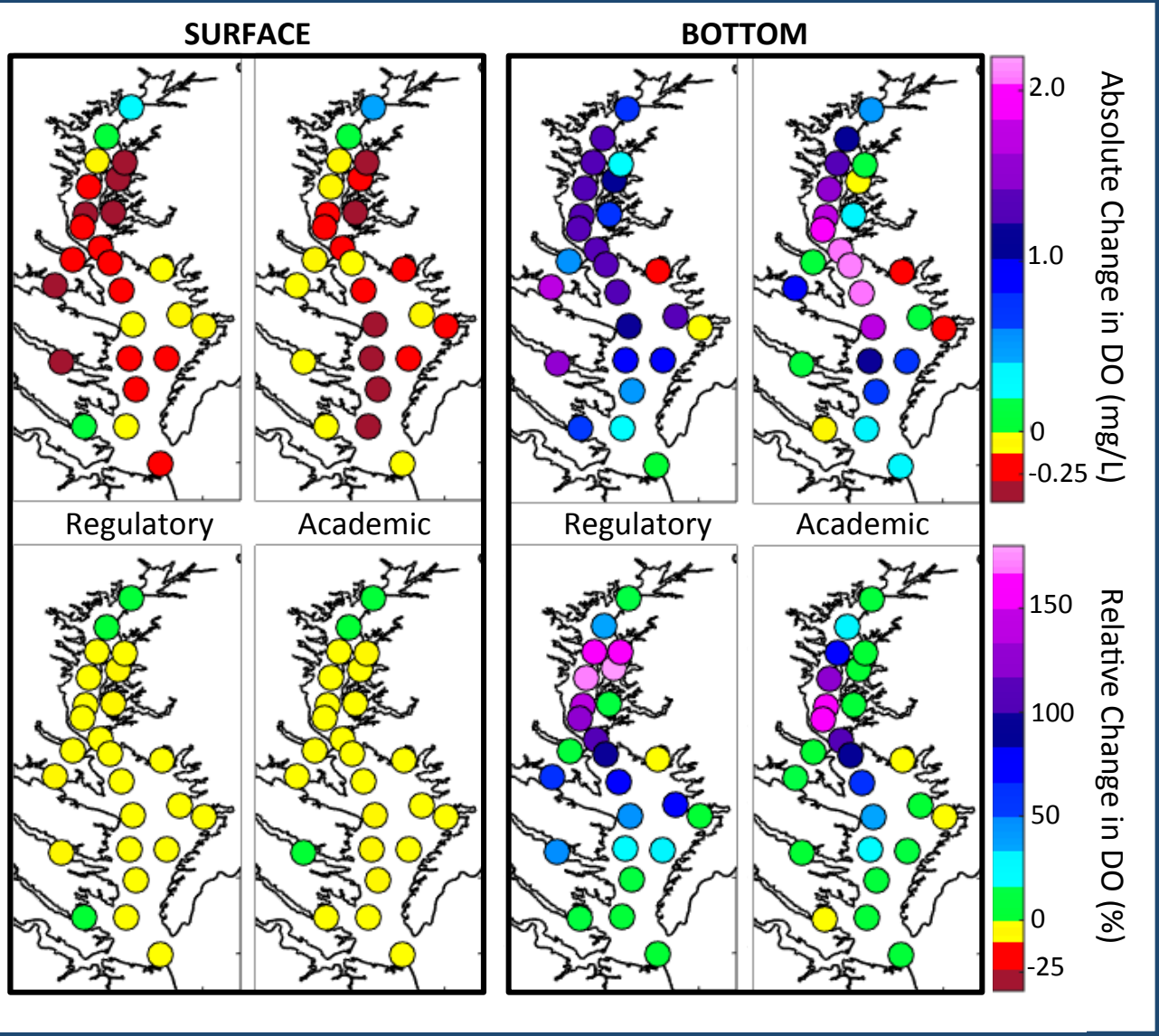
Part 2 Conclusions

- **While the impact of climate change on absolute DO concentrations may be small, the impact on attainment of water quality standards may be significant**

Thank You

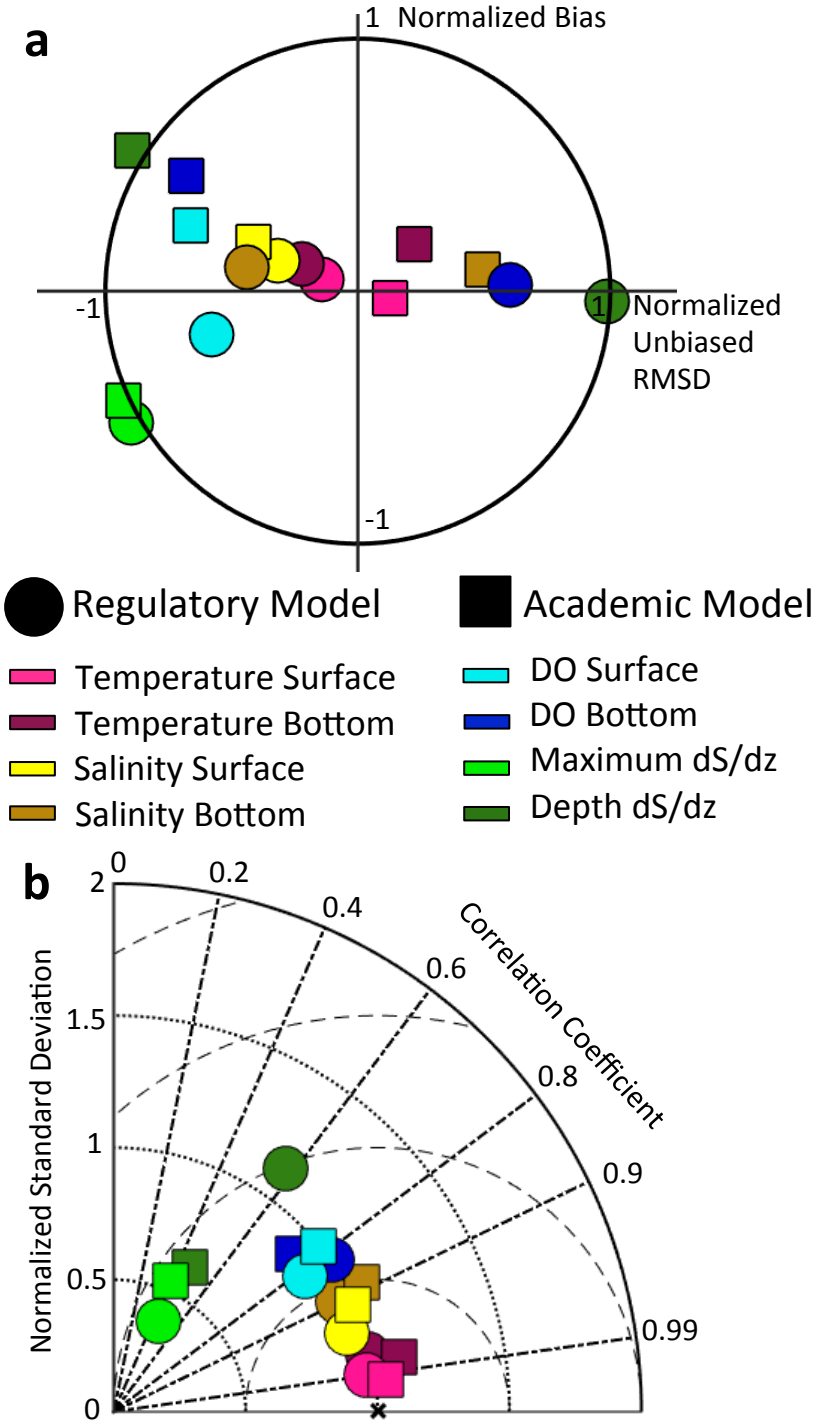
- M. Friedrichs
- R. Tian & G. Shenk – Chesapeake Bay Program
- A. Ross & R. Najjar – Penn State
- VIMS BioCOM Lab

1993 – 1995 Average Summer Results of Nutrient Reduction



- Both exhibit similar impact at the surface
- At depth, the Academic Model simulates a larger absolute increase in DO
- At depth, both models simulate a similar relative increase
- Max increase is further north in the Regulatory model

Designated Use	Segment	Variance
Deep Water	CB4MH	7%
	PATMH	7%
Deep Channel	CB4MH	2%
	EASMH	2%
	CHSMH	16%


a
1 Normalized Bias
-1
1
-1
Normalized
Unbiased
RMSD
Regulatory Model
Academic Model
Temperature Surface
Temperature Bottom
Salinity Surface
Salinity Bottom
DO Surface
DO Bottom
Maximum dS/dz
Depth dS/dz
b
0
0.2
0.4
0.6
0.8
0.9
0.99
Correlation Coefficient
Normalized Standard Deviation
2
1.5
1
0.5
0

Segment	Station(s) used in Confidence Index Regression Stats				
CB1TF	CB1.1				
CB2OH	CB2.1	CB2.2			
PATMH	WT5.1				
CB3MH	CB3.1	CB3.2	CB3.3C		
CHSMH	ET4.2				
CB4MH	CB4.1C	CB4.2C	CB4.3C	CB4.4	
EASMH	EE1.1				
CHOMH1	EE2.1				
PAXMH	LE1.1	LE1.2	LE1.3	LE1.4	
CB5MH	CB5.1	CB5.2	CB5.3	CB5.4	CB5.5
TANMH	EE3.1	EE3.2			
POTMH	RET2.4	LE2.2	LE2.3		
POCMH	EE3.3	EE3.4			
RPPMH	RET3.2	LE3.2	LE3.4	LE3.6	
CB6PH	CB6.1	CB6.2	CB6.3	CB6.4	
CB7PH	CB7.1	CB7.2	CB7.3	CB7.4	
YRKPH	LE4.2	LE4.3			
MOBPH	WE4.1	WE4.1			
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