Phase 2 Salish Sea Modeling Results

in support of the Puget Sound Nutrient Source Reduction Project

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Environmental Assessment Program

March 27th, 2025

Ecology's Salish Sea Modeling Team

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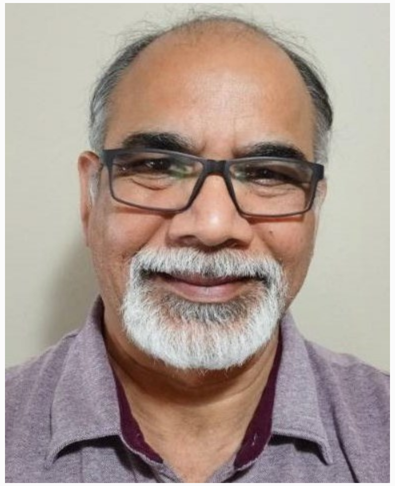


Anise Ahmed

Teizeen Mohamedali

What we plan to cover

1. Context/Summary of Findings

2. Phase 2 Optimization Scenarios

   Pause for Q&A

3. Model Updates and Performance

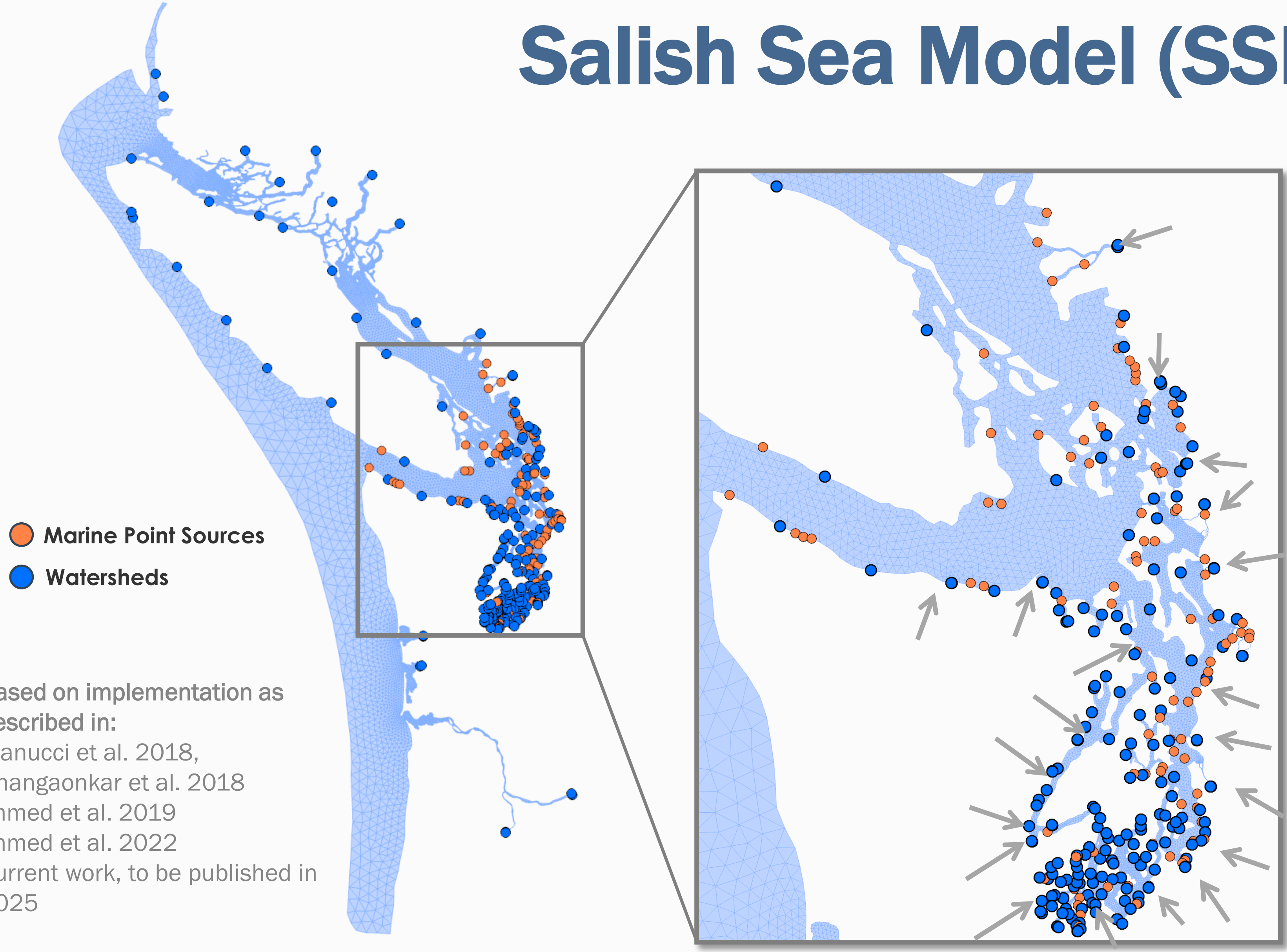
   Final Q&A

Context/ Summary of Findings

Photo courtesy: Eyes over Puget Sound, MMU, ECY

Algal bloom in Henderson Inlet, 9/16/2014

Salish Sea Model (SSM)



Based on implementation as described in:
Bianucci et al. 2018,
Khangaonkar et al. 2018
Ahmed et al. 2019
Ahmed et al. 2022
Current work, to be published in 2025

193 river and streams

- Rivers and streams entering Salish Sea waters and the Pacific Ocean

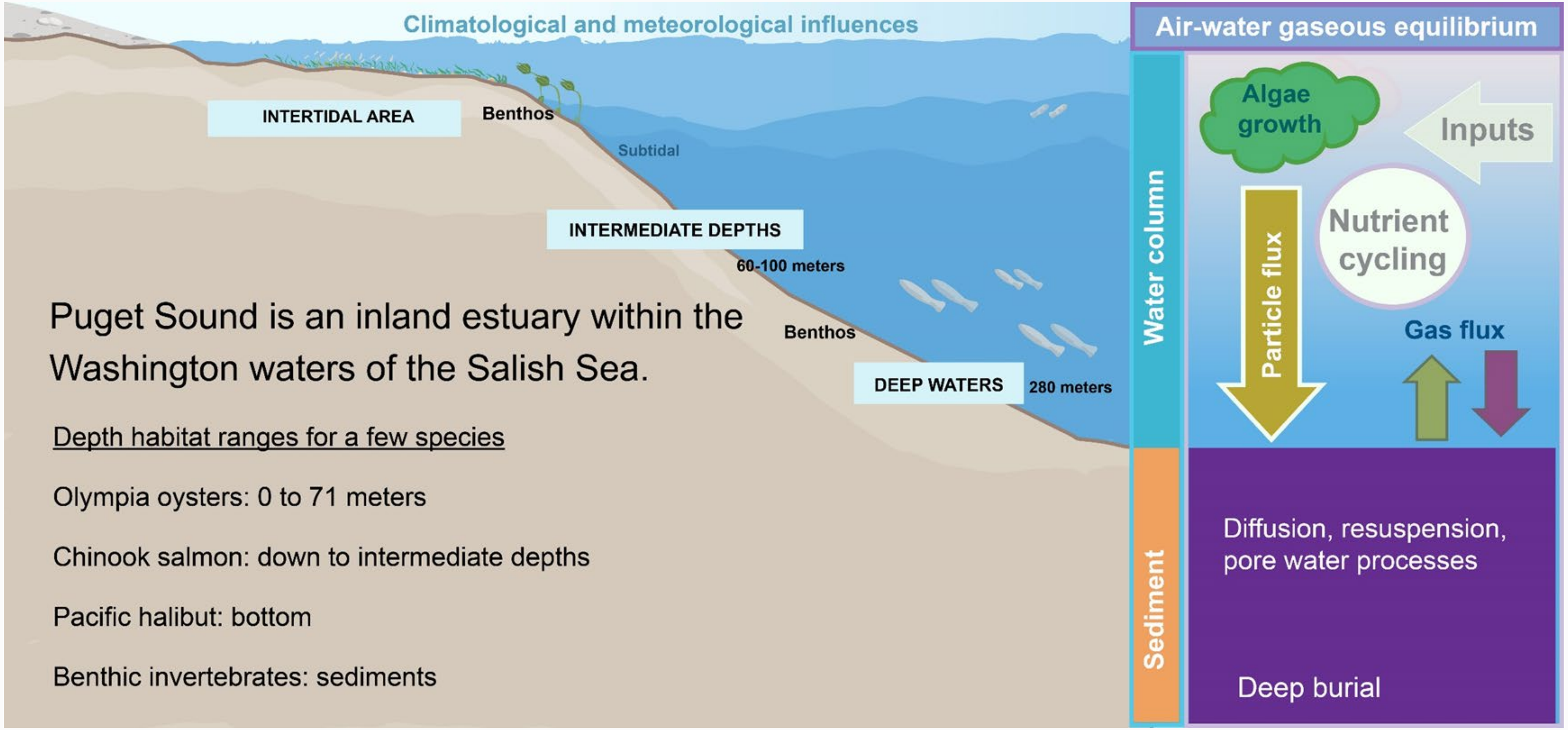
99 marine point sources

- All facilities with marine outfalls
- 78 U.S. WWTPs
- 9 Canadian WWTPs
- 10 industrial facilities

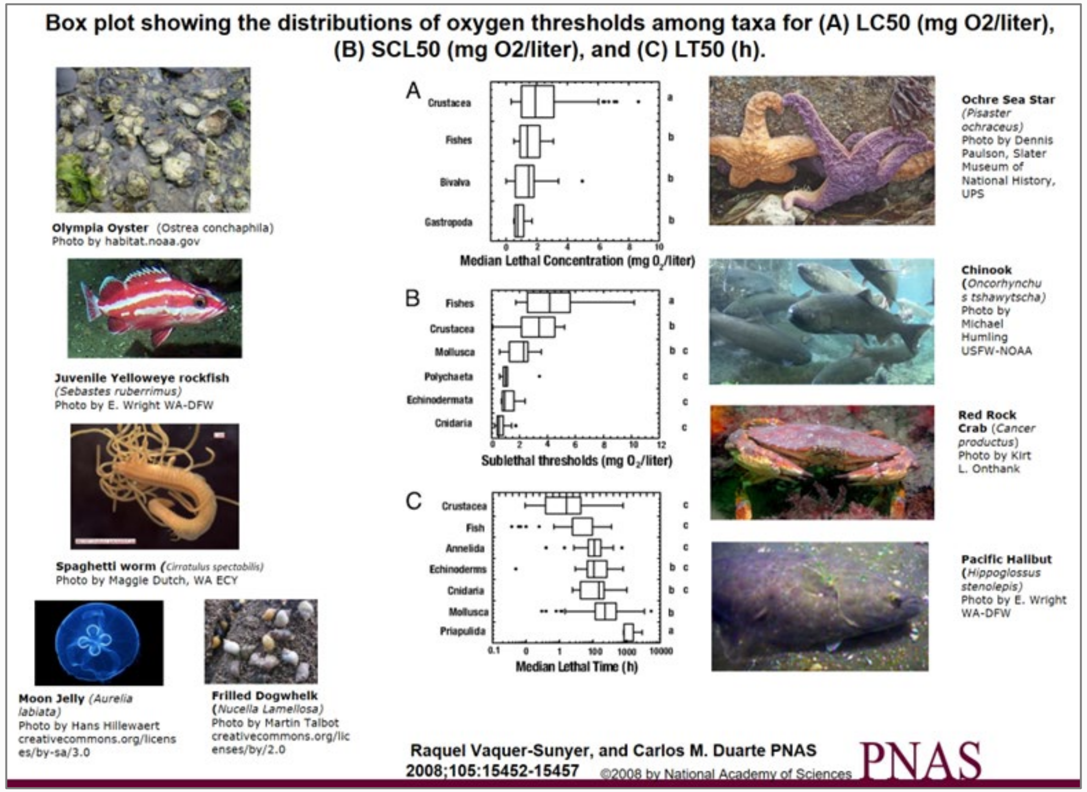
UMass Dartmouth | Woods Hole Oceanographic Institution | Pacific Northwest National Laboratory | Department of Ecology State of Washington

SSM was developed by PNNL in collaboration with WA Ecology, funded by EPA

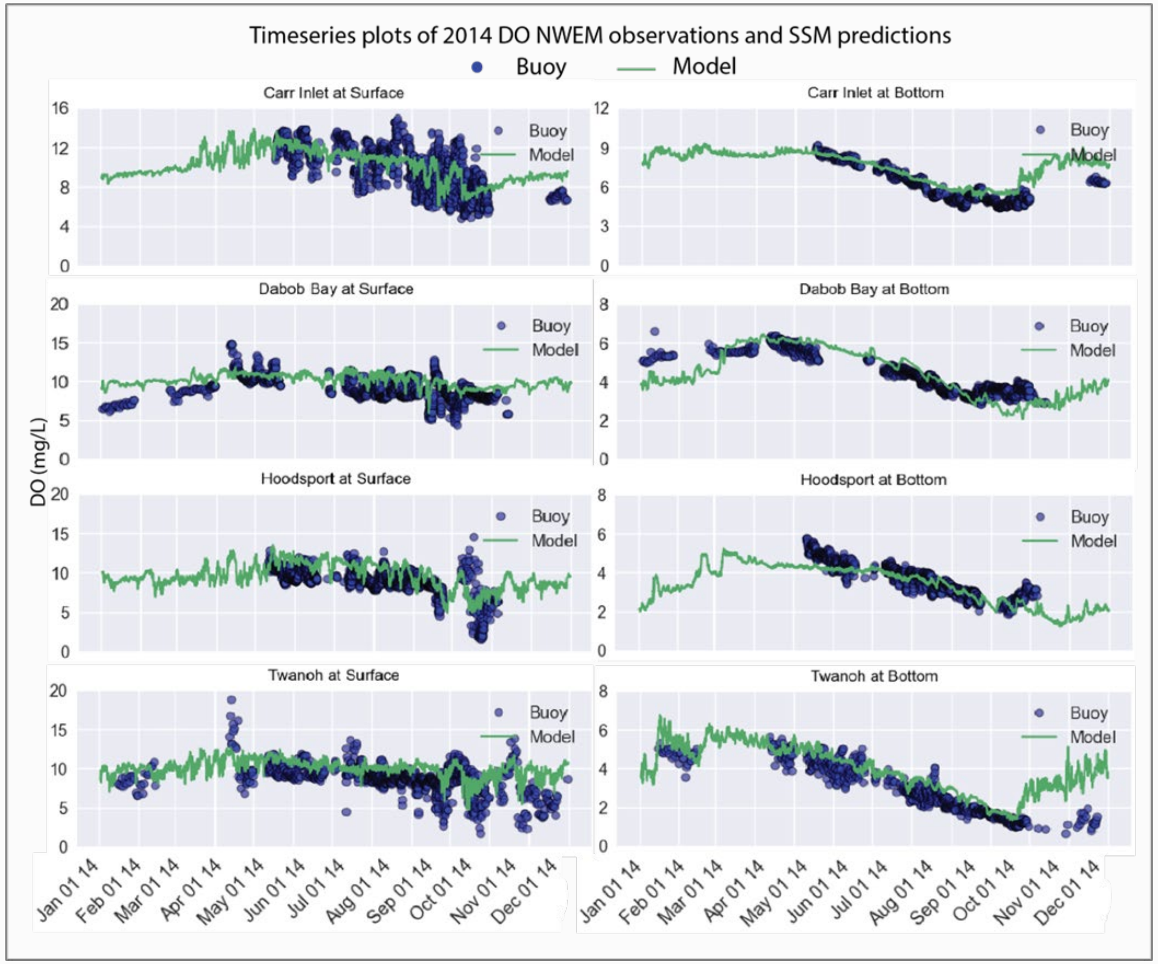
Biogeochemical Modeling



Salish Sea Model was developed for regulatory use



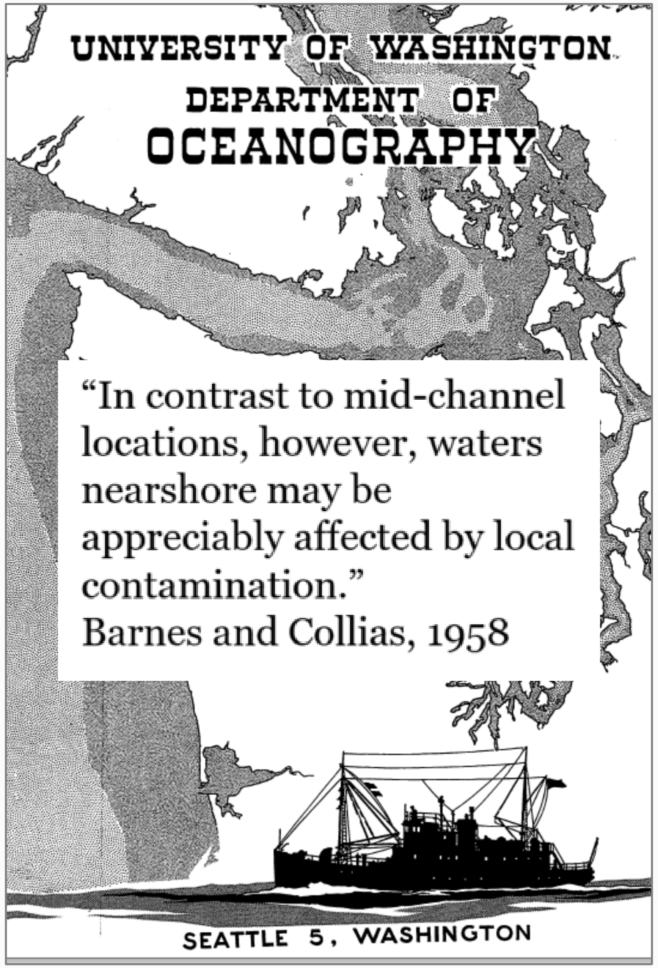
Large variability in biological response. Washington regulations strive for biological integrity and protection of most sensitive species.

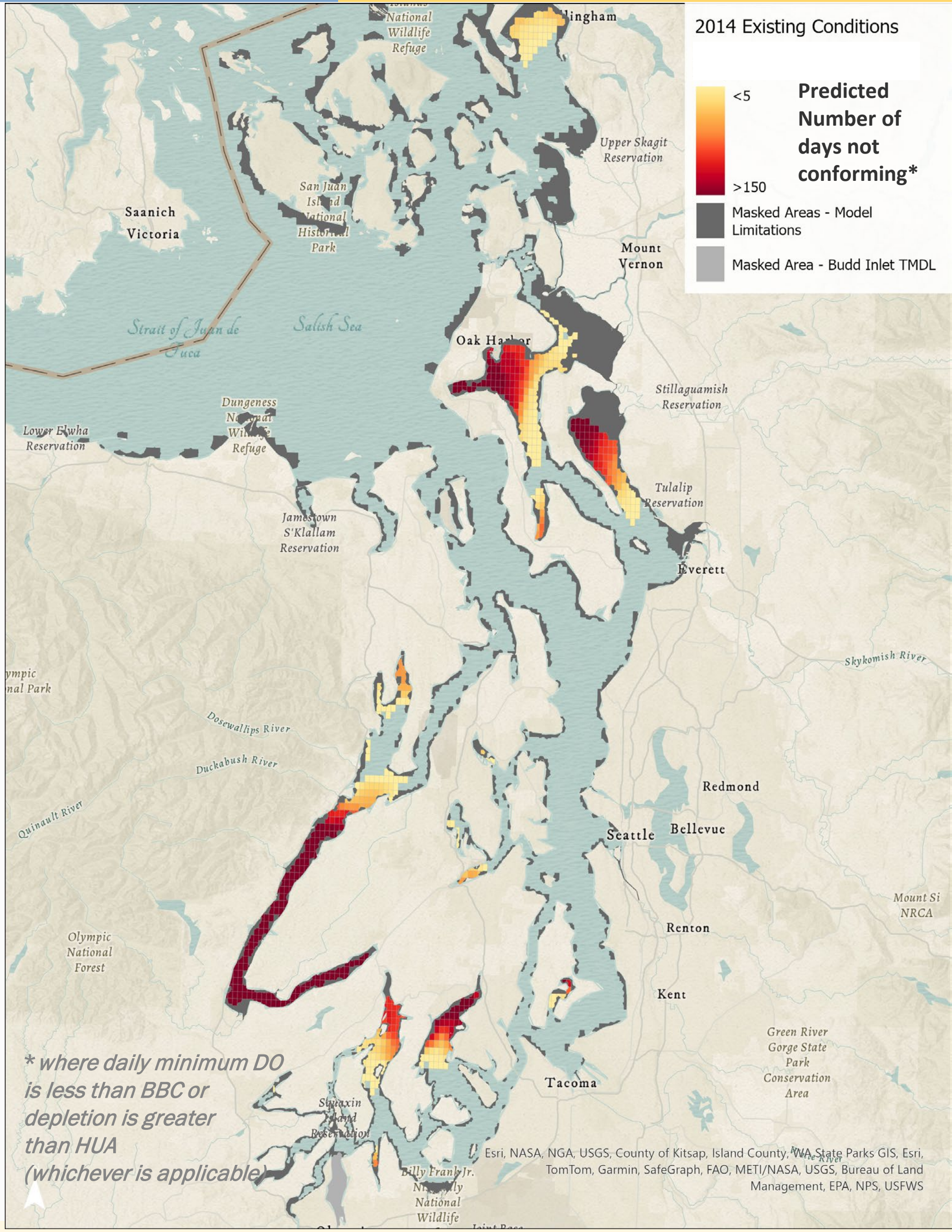


Predictions vs observations at surface and bottom layers
SSM vs UW/NOAA observations (2014)
Note: These obs were not used for calibration or statistical model evaluation

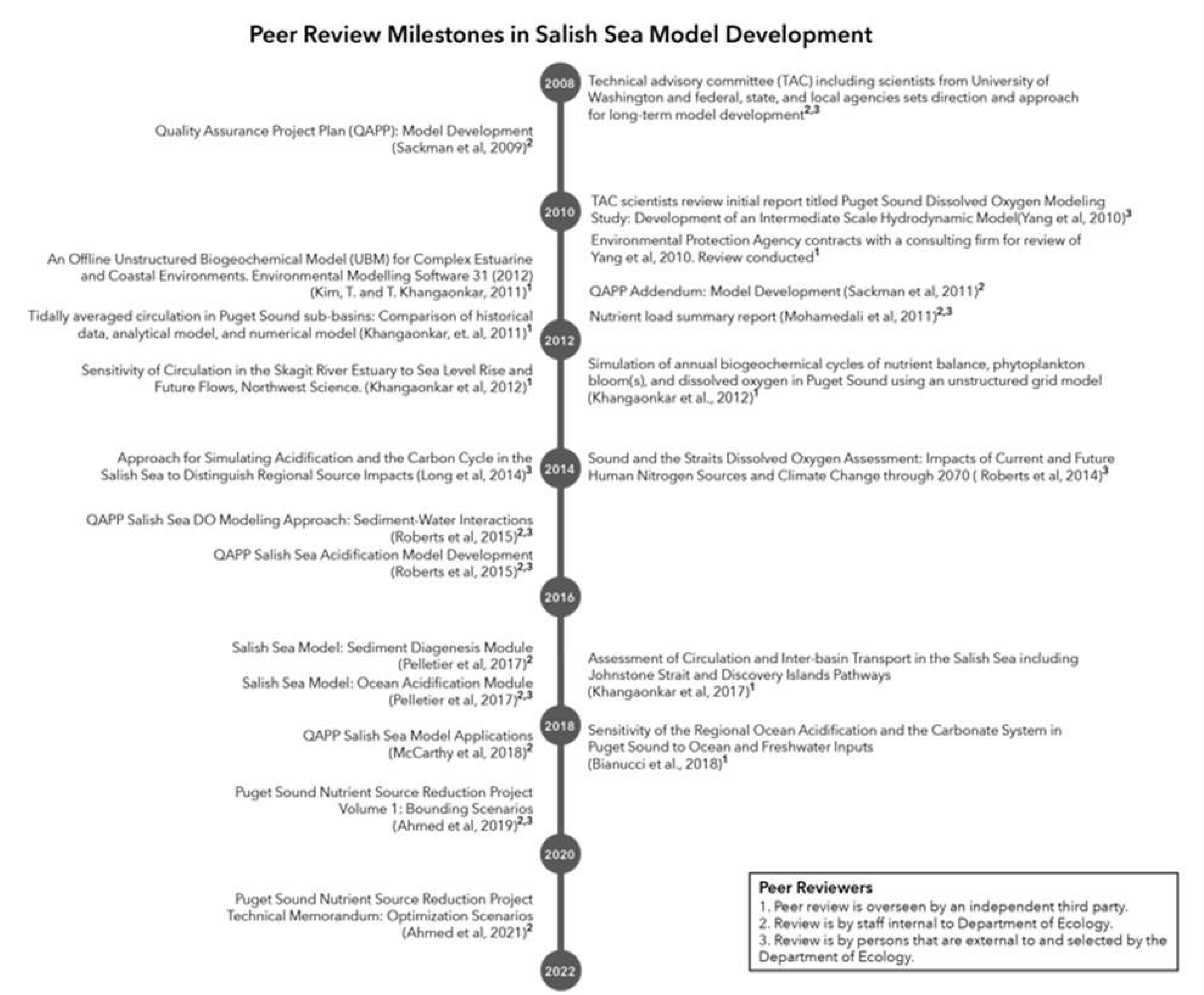
Embayments and terminal inlets are vulnerable to lower DO in bottom waters

- Human regional impacts from freshwater nutrient inflows are greatest in embayments
- Primarily due to restricted mixing and flushing





Clear and traceable science roots



Masked areas

Areas that are masked are not currently assessed for regulatory purposes:

- All intertidal and very shallow subtidal areas (same as BSR)
- Cells with ebb tide depths of 4 m or less that produce unrealistic low temperatures from heat flux calculations during winter
- Budd Inlet – covered by Budd Inlet TMDL

Key Findings

- Updates resulted in improved model skill.

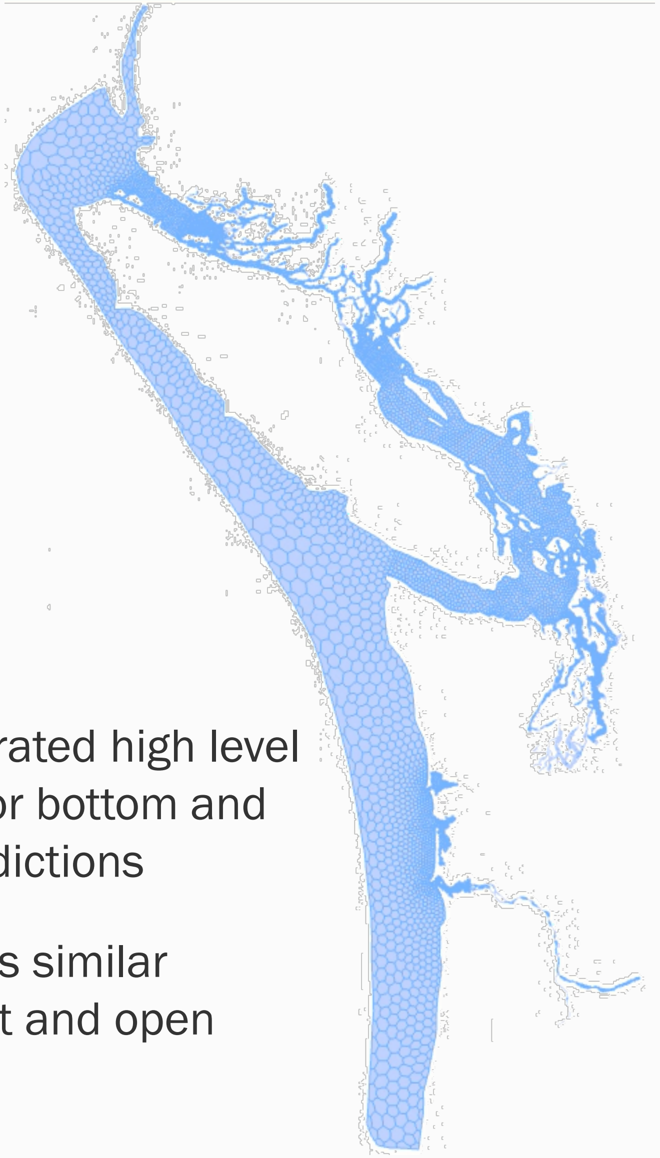
✓ Updated code and review of key parameters.

✓ Improved initialization process

✓ Refined watershed inputs and the spatial distribution of these freshwater inflows

✓ Filling data gaps and improving inputs for some marine point sources

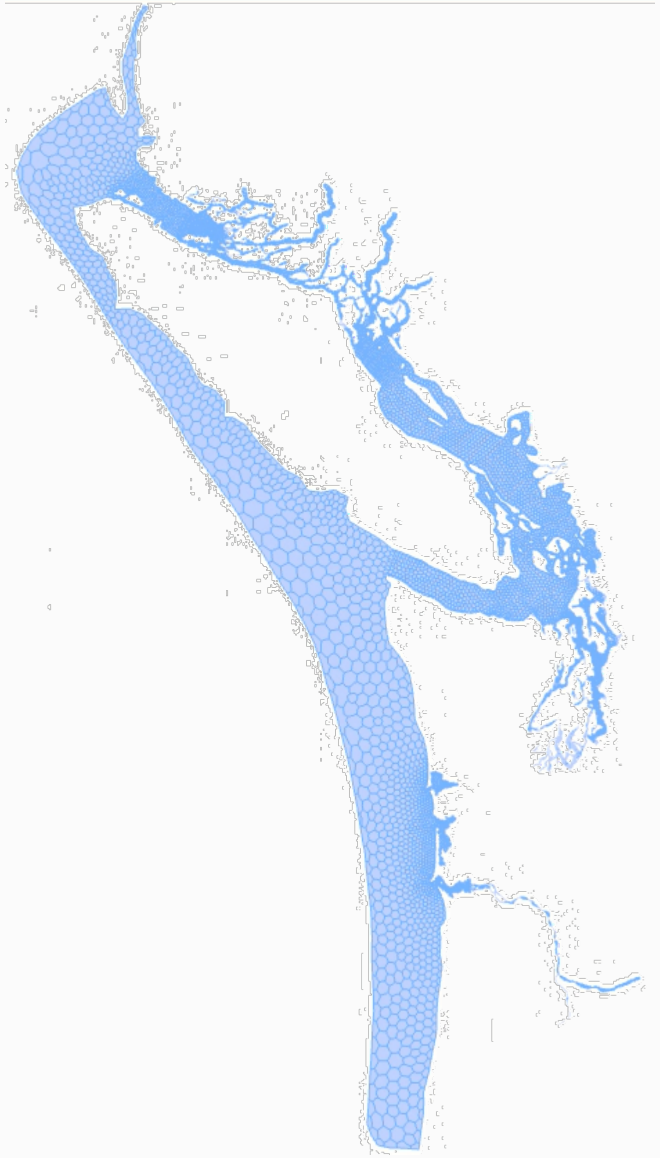
✓ Updates to tidal constituents at the open boundary



- The model demonstrated high level of skill particularly for bottom and middle layer DO predictions
- Level of model skill is similar between embayment and open channel stations

Key Findings

- Flushing analysis points to longest flushing times in Hood Canal. Restricted flushing also occurs in other embayment locations.
- Simulated key biogeochemical processes in Salish Sea waters compare well with independent datasets.
- Sediment oxygen demand can play a key role in oxygen consumption in shallow inlets in Puget Sound particularly during periods when waters experience reduced flushing.



Phase 2 Optimization (Opt2) Scenarios

Photo courtesy: Eyes over Puget Sound, MMU, ECY
Algal bloom in Carr Inlet 7/28/2014

Phases of Scenario Development

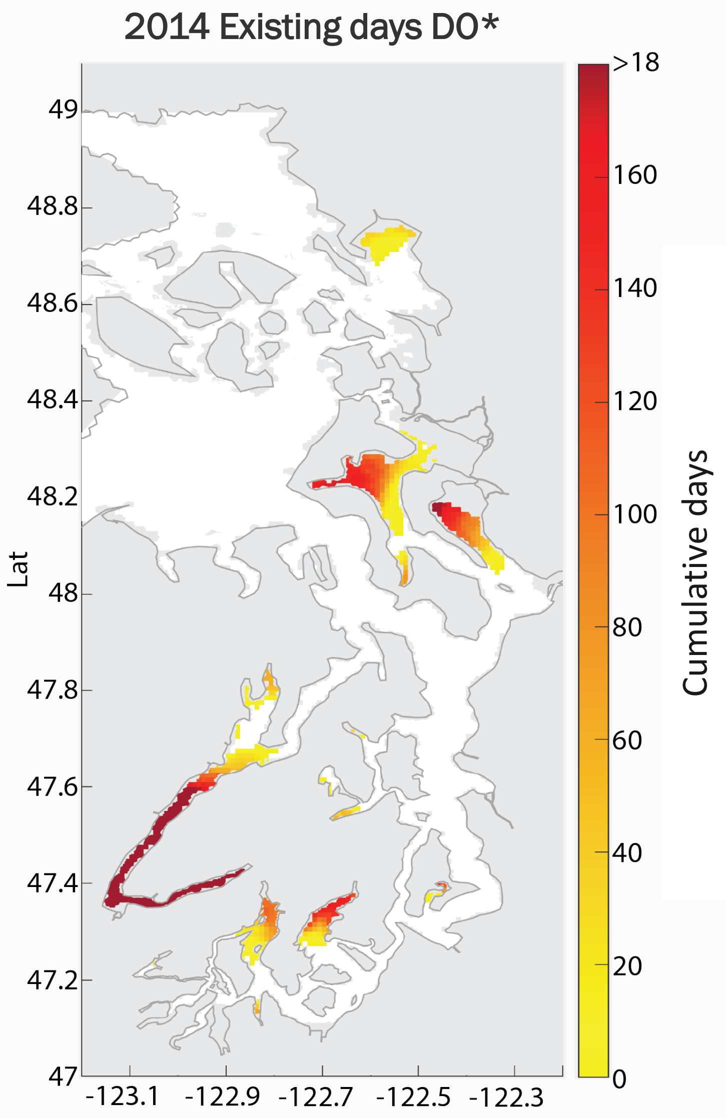
Bounding Scenarios 2019	Optimization Phase 1 Scenarios 2021	Optimization Phase 2 Scenarios 2025
Evaluated anthropogenic impact on DO, and improvement with BNR based on WWTP size (all, large, med)	Watershed and WWTP reductions by region, annual vs. seasonal BNR, future growth scenarios	More refined watershed and WWTP reduction frameworks to meet WQ standards

Collaboration and feedback from nutrient forums have informed the development of scenarios over time

Opt2 Scenarios

How much DO levels improve when nutrients from watersheds and WWTPs are reduced?

- All scenarios were run for model year 2014
- Watershed reductions involved all forms of nitrogen and organic carbon
- WWTP reductions involved DIN and CBOD
- Evaluated change in the magnitude (concentration), extent (area) and duration (days) **where daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)**



Opt2 Scenarios

What was not changed in scenarios:

- Loads from Canadian facilities
- Loads from industrial marine point sources
- Magnitude of flows from watersheds and marine point sources (i.e. hydrodynamics remained the same)
- Ocean boundary conditions
- Meteorological conditions

Biological Nitrogen Removal (BNR)

- Treatment of wastewater to remove nitrogen
- Different BNR levels based on dissolved inorganic nitrogen (DIN) effluent concentrations:
  - BNR 3 mg/L
  - BNR 5 mg/L
  - BNR 8 mg/L
- All BNR treatment levels paired with a CBOD effluent concentration of 8 mg/L
- Varied BNR treatment levels by season/months:

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
cool			warm			hot			warm	cool	

Opt2 Scenarios

Goal: To identify the optimal combination of watershed and WWTP reductions starting from Opt1 Scenarios

INITIAL SCENARIOS

Step 1: find "best" watershed framework

Pair 8 Watershed Frameworks with a single WWTP Framework

Step 2: find "best" WWTP framework

Pair 8 WWTP Frameworks with the "best" Watershed Framework

Evaluate "best" combination framework

Evaluate DO under "best" Watershed Framework with "best" WWTP Framework

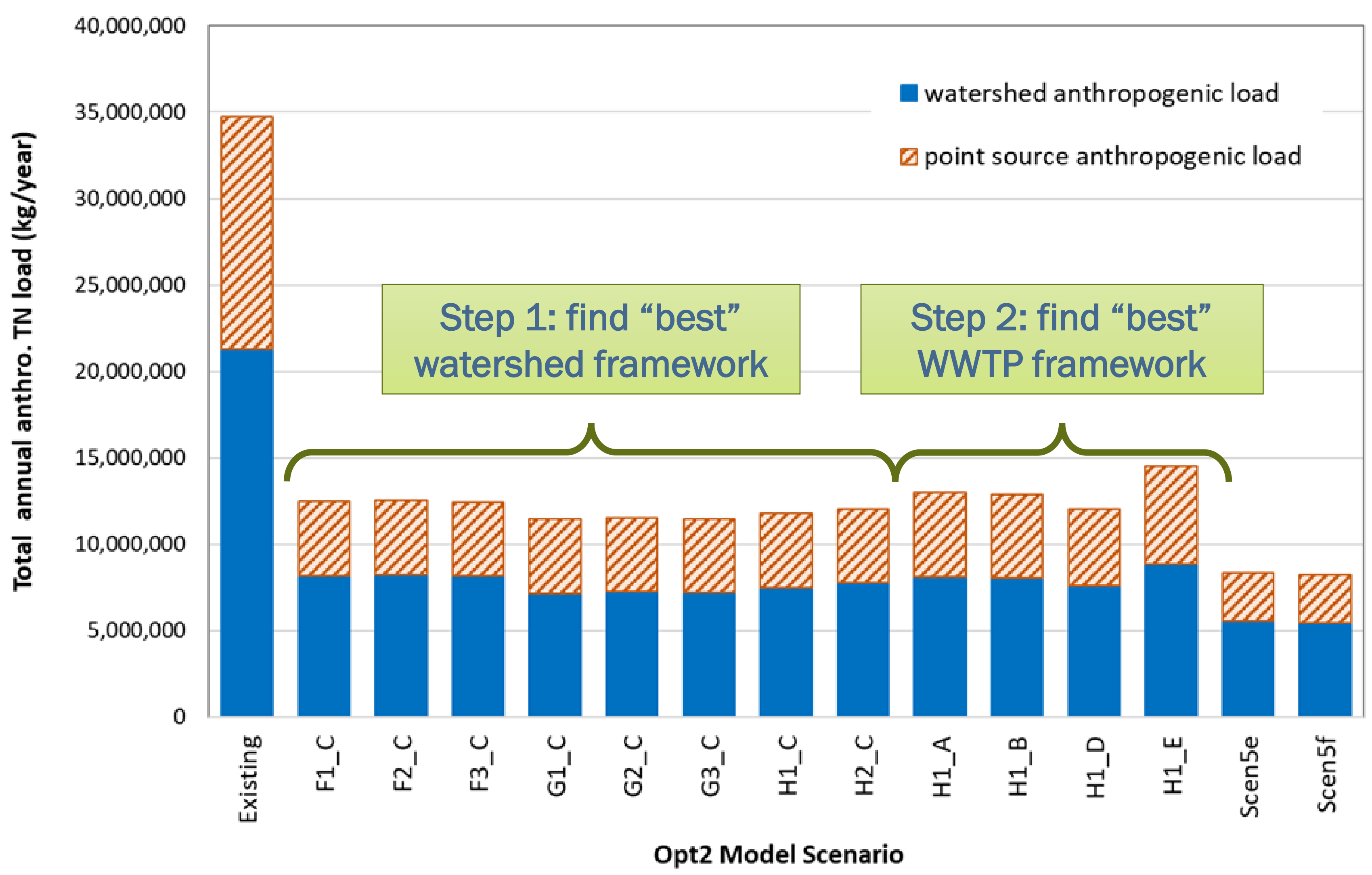
REFINED SCENARIOS

Step 3: refine combined scenario further

Refine nutrient reductions to address remaining areas where DO depletions are still greater than HUA

Step 1 & 2

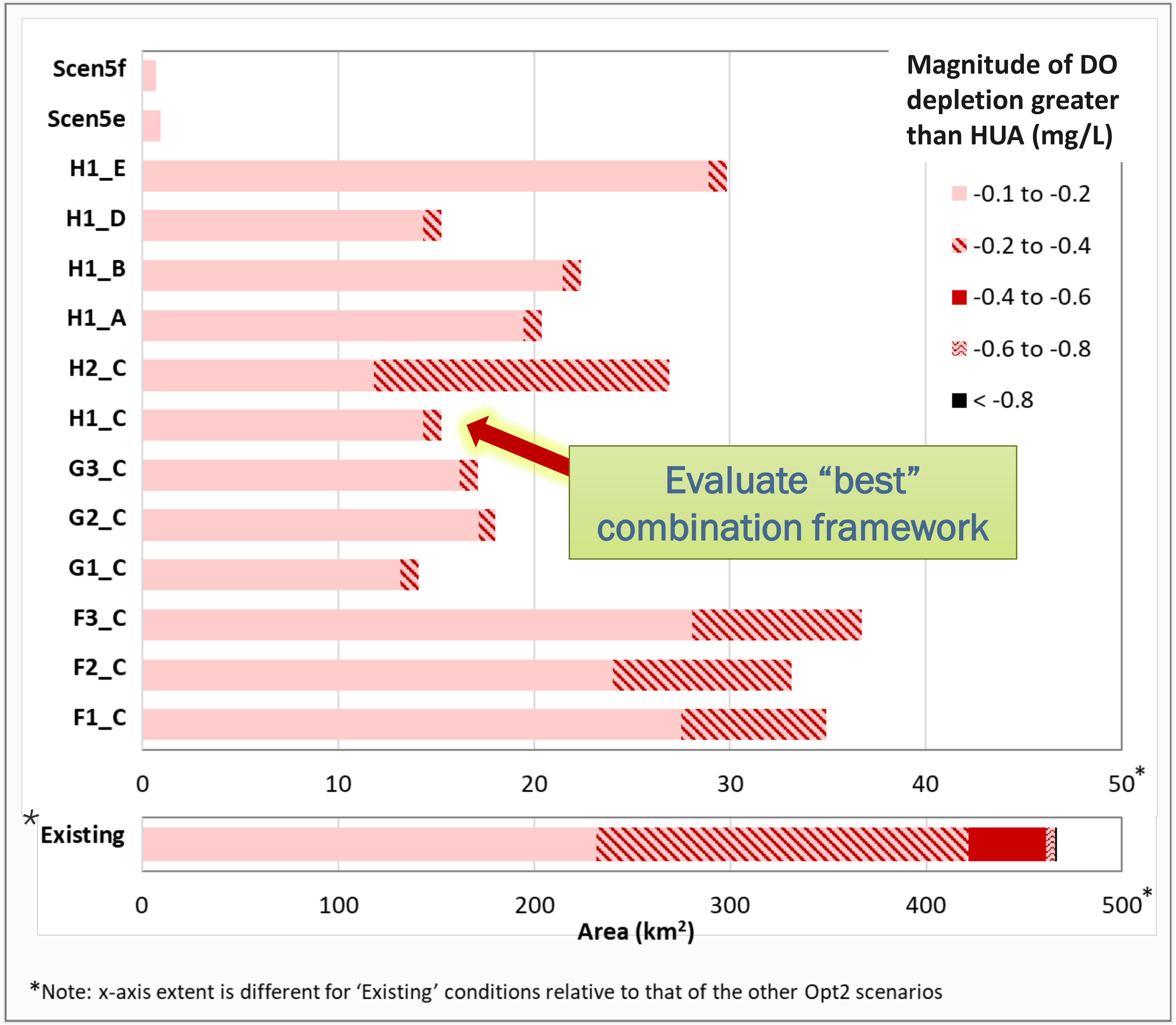
- Watershed anthropogenic reductions ranged from 58-74%
- WWTP anthropogenic reductions ranged from 58-79%



Best Combo Scenario

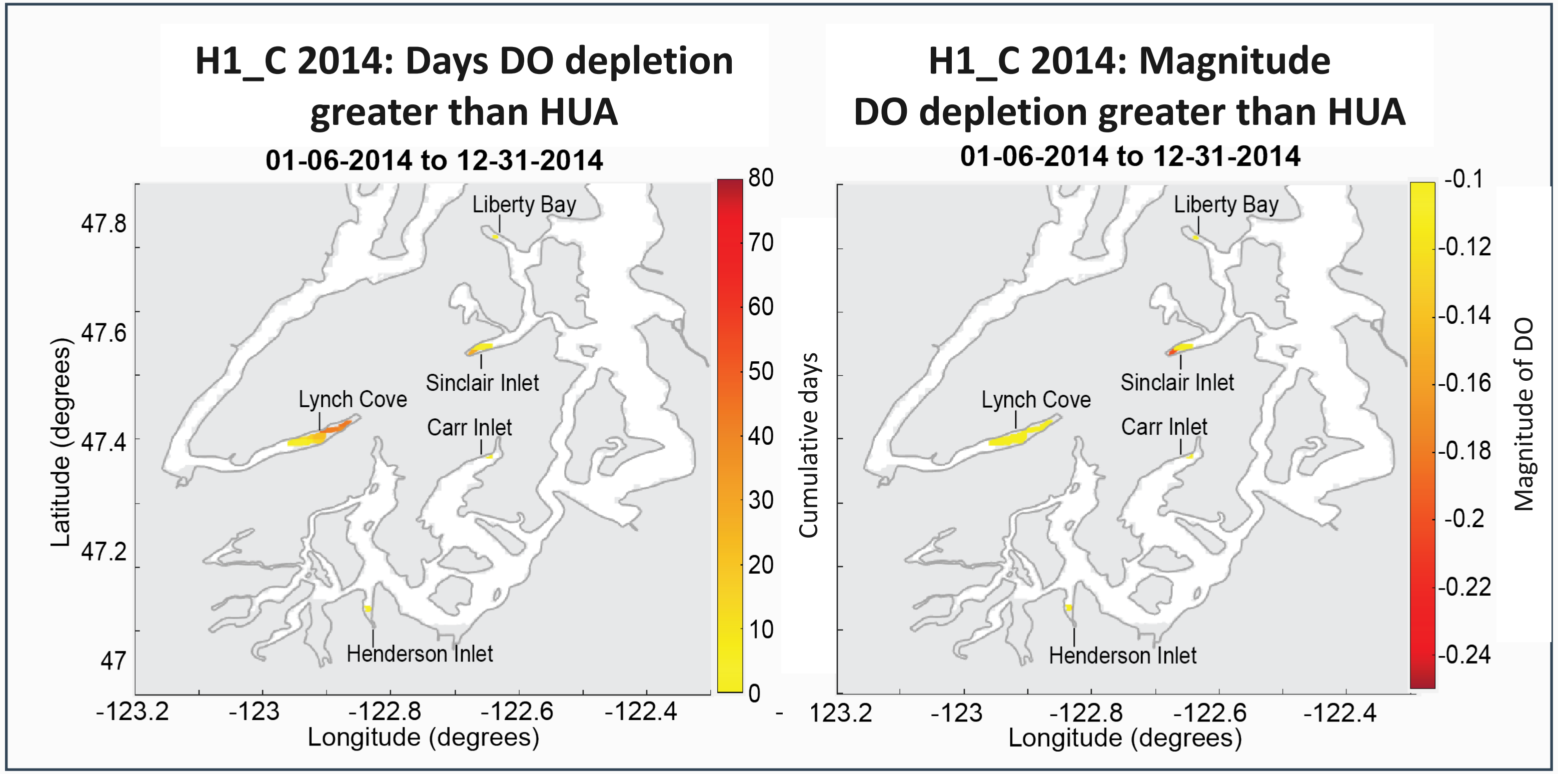
- **Scenario H1_C** identified the 'best' scenario to further refine
- H1_C resulted in similar improvement as H1_D, but with slightly less effort (capping WWTP loads in Hood Canal, Admiralty, SJF and SOG)

**Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)*



Best combo was Scenario H1_C

- Greater reductions in larger watersheds
- Greater reductions in watersheds entering N. Bays, Main Basin & S. Sound (relative to other basins)
- Capping loads in watersheds entering Straits
- All WWTPs at BNR 8/5/3

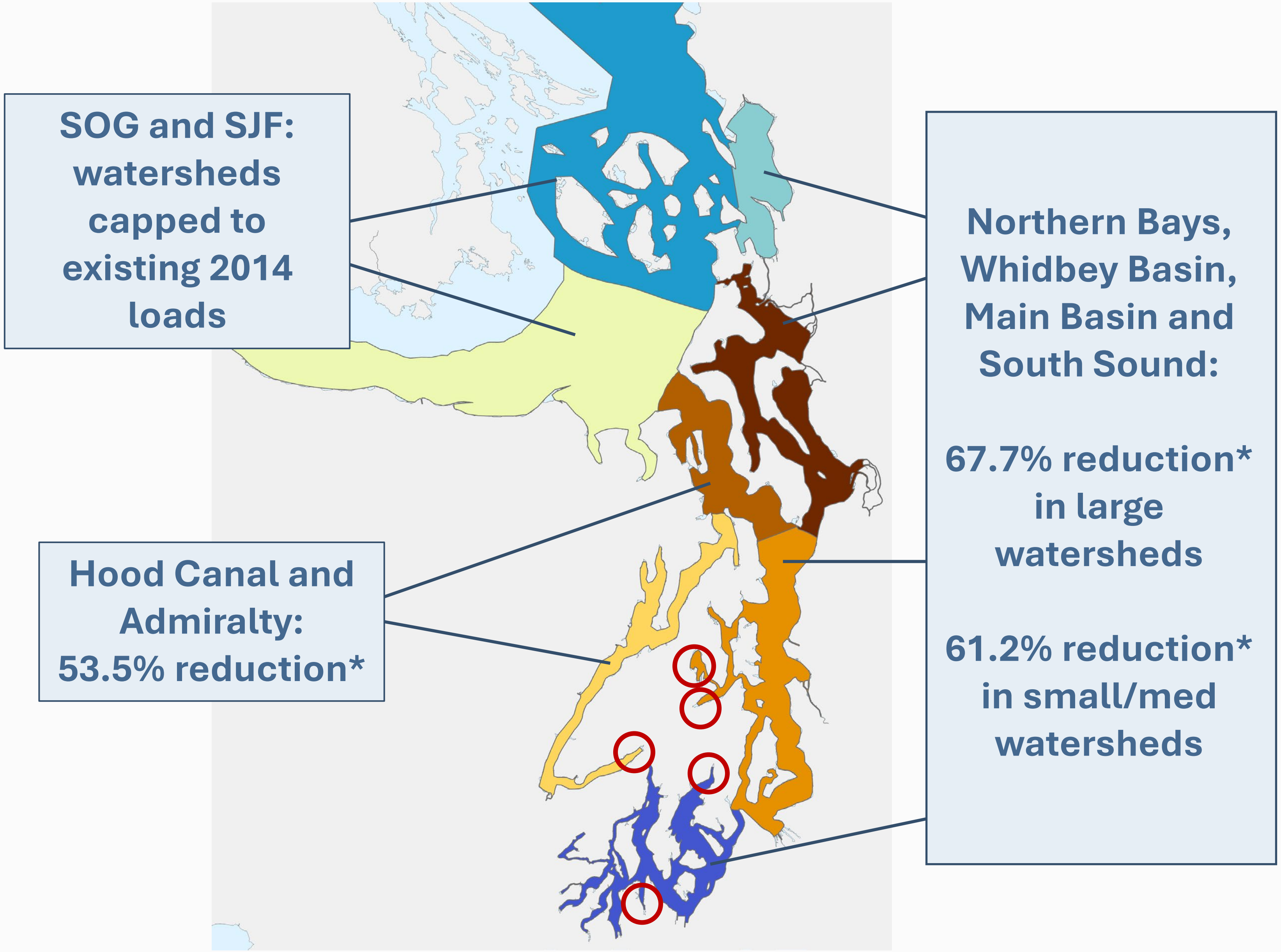


BNR 8 (cool) /5 (warm) /3 (hot)

Step 3: Refine Scenarios further

- "Best" watershed framework – a refinement of Watershed Framework H1
- Paired with **10 WWTP frameworks** – using WWTP Framework C as a starting point (BNR 8/5/3)
- Evaluating whether DO is meeting human use allowance (HUA) for all 10 scenarios
- Inform development of PSNSRP nutrient targets

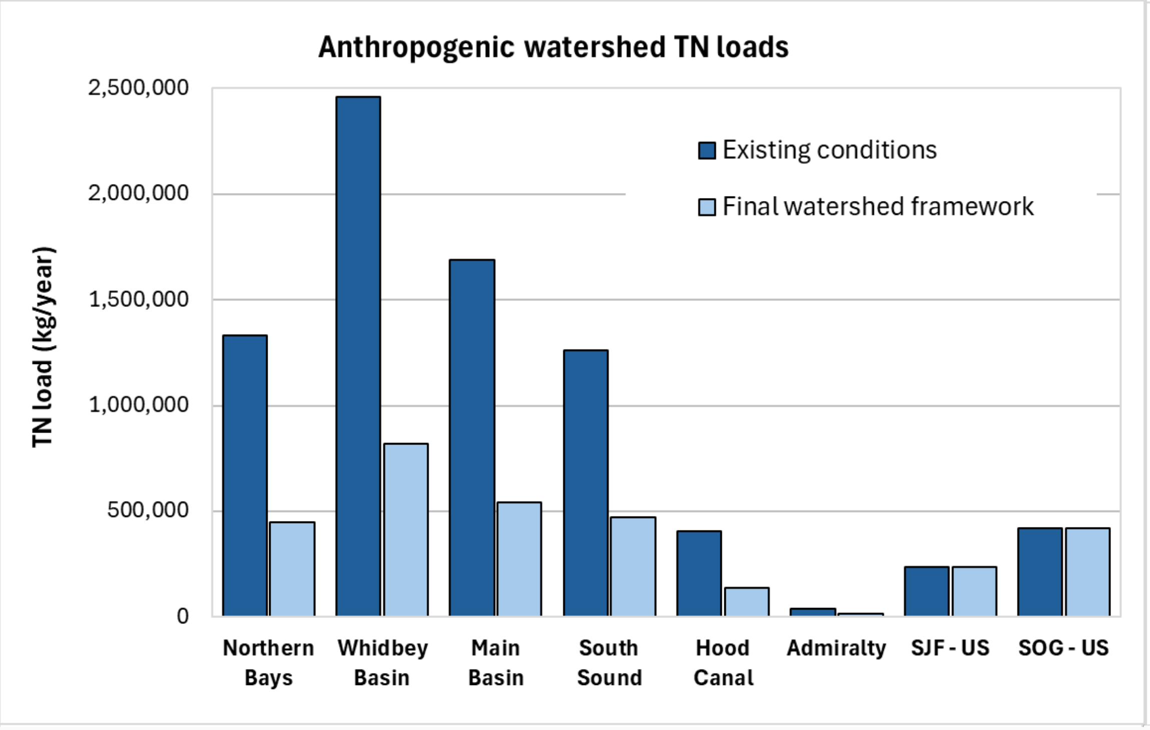
Step 3: "best" watershed framework with refinements

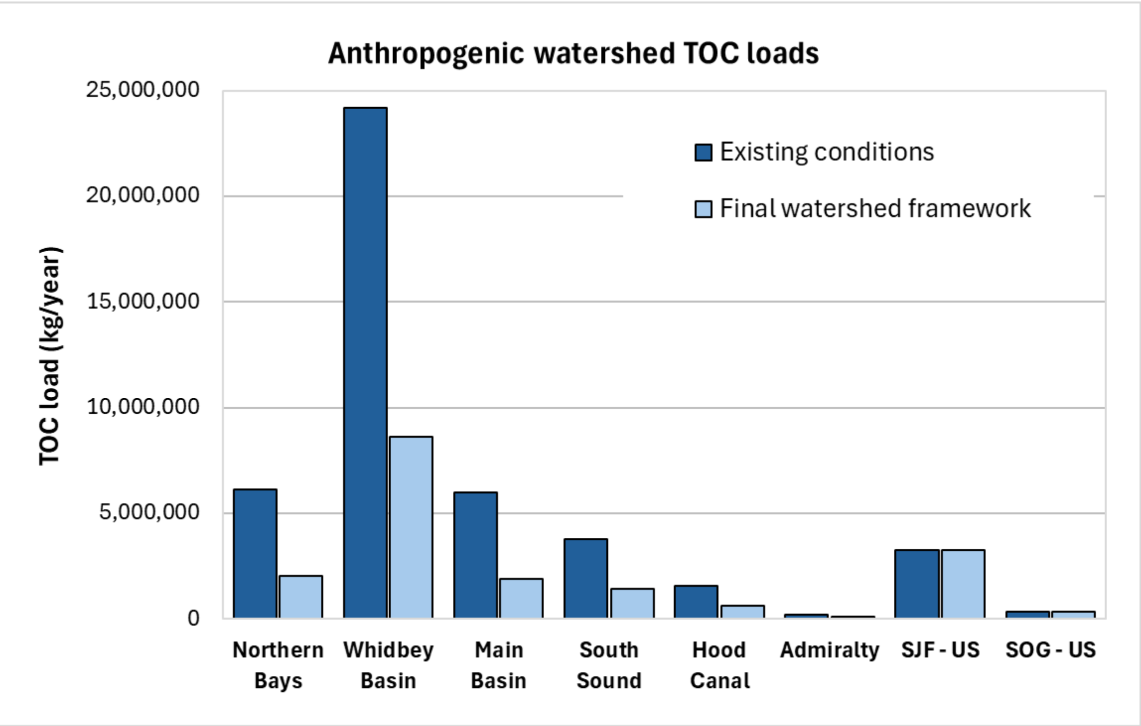


***Exceptions**

90% anthropogenic nutrient reductions in small streams entering **recalcitrant areas** where DO depletion is greater than the HUA: **Lynch Cove, Henderson, Carr and Sinclair Inlets, and Liberty Bay**

Nutrient Reductions for “best” watershed framework



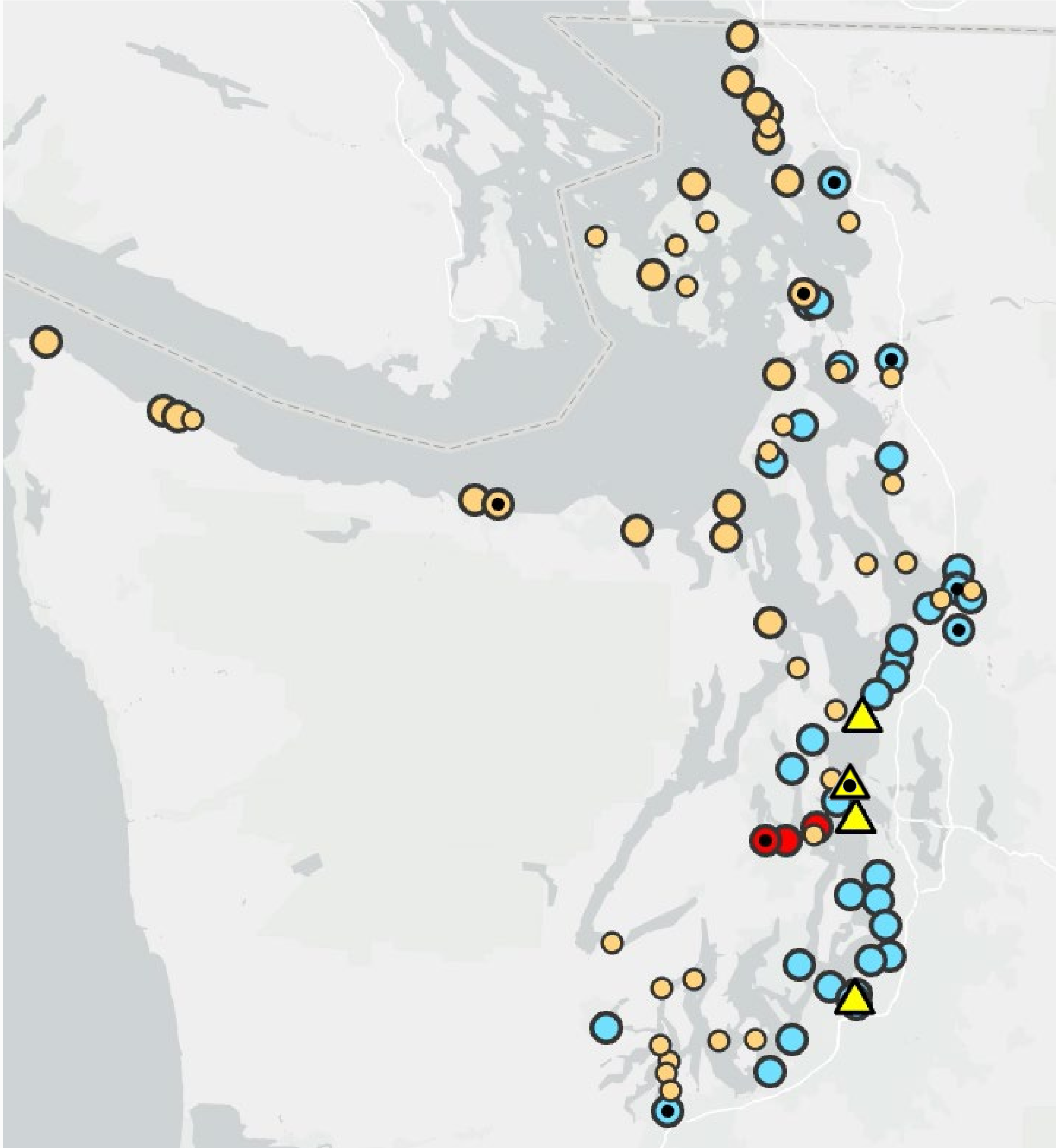


10 WWTP Variations

BNR levels were varied based on: season, discharge location, size and type of facility

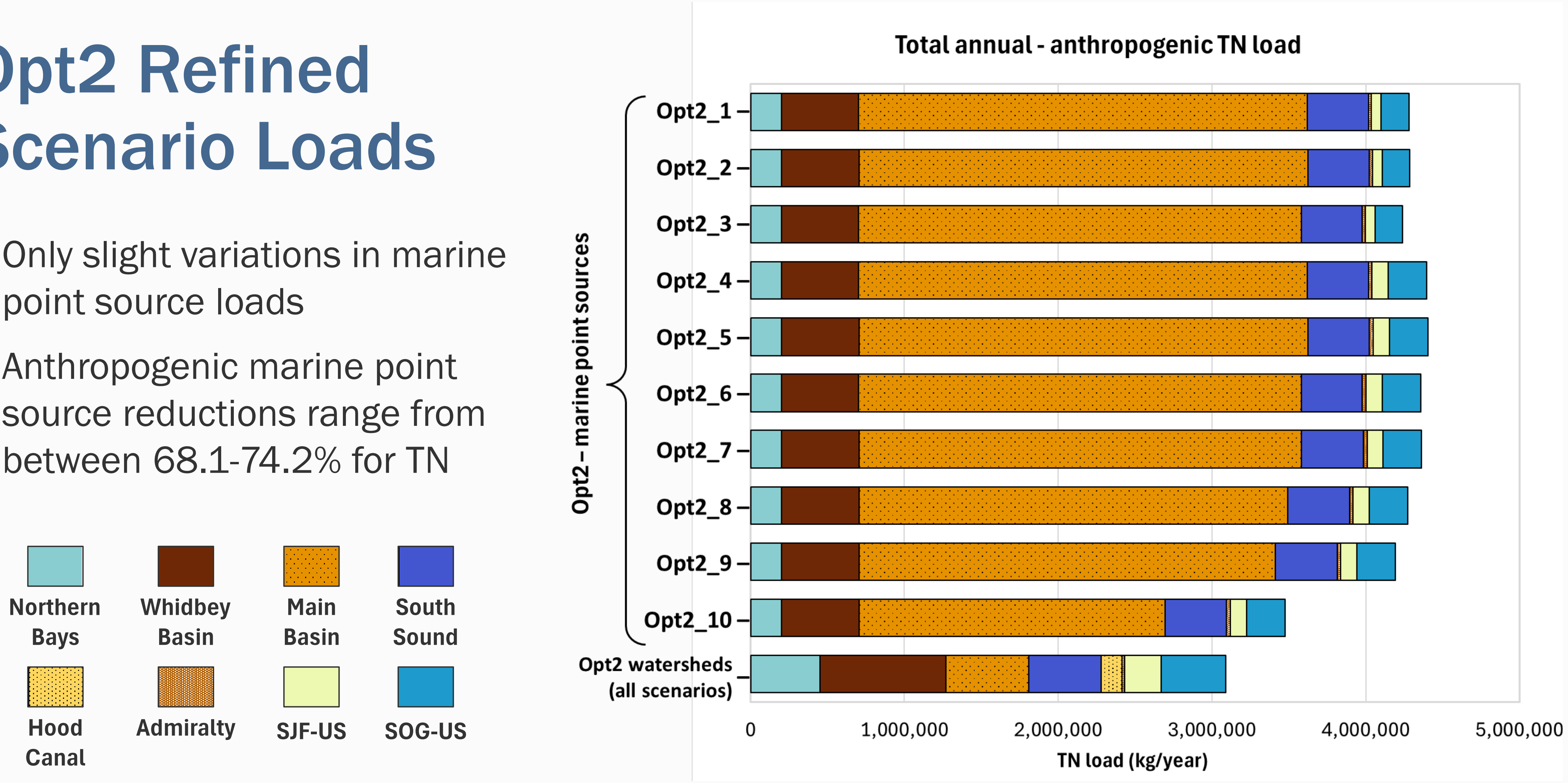
- Combined sewer facilities
- Very small WWTPs*
- WWTPs in Straits, Admiralty, Hood*
- Dominant Main Basin WWTPs
- WWTPs near Sinclair Inlet
- All other WWTPs - default BNR 8/5/3

*Capped to existing 2014 loads in several Opt2 Scenarios



Opt2 Refined Scenario Loads

- Only slight variations in marine point source loads
- Anthropogenic marine point source reductions range from between 68.1-74.2% for TN



Opt2 DO depletion greater than HUA

Opt2 Scenario	Anthropogenic TN load (thousands of kg/year)	Percent reduction in anthropogenic TN load relative to existing (%)	Total days DO depletion is greater than HUA	Total area where DO depletion is greater than HUA (km^2)	Max. magnitude of DO depletion is greater than HUA (mg/L)
Existing*	21,300		80,279	467	-1.1
Opt2_1	7,370	65.4%	57	2.50	-0.1
Opt2_2	7,380	65.4%	58	2.50	-0.1
Opt2_3	7,330	65.6%	36	0.93	-0.1
Opt2_4	7,490	64.8%	58	2.50	-0.1
Opt2_5	7,500	64.8%	58	2.50	-0.1
Opt2_6	7,450	65.0%	36	0.93	-0.1
Opt2_7	7,460	65.0%	36	0.93	-0.1
Opt2_8	7,370	65.4%	36	0.93	-0.1
Opt2_9	7,290	65.8%	35	0.93	-0.1
Opt2_10	6,570	69.2%	18	0.83	-0.1

**Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)*

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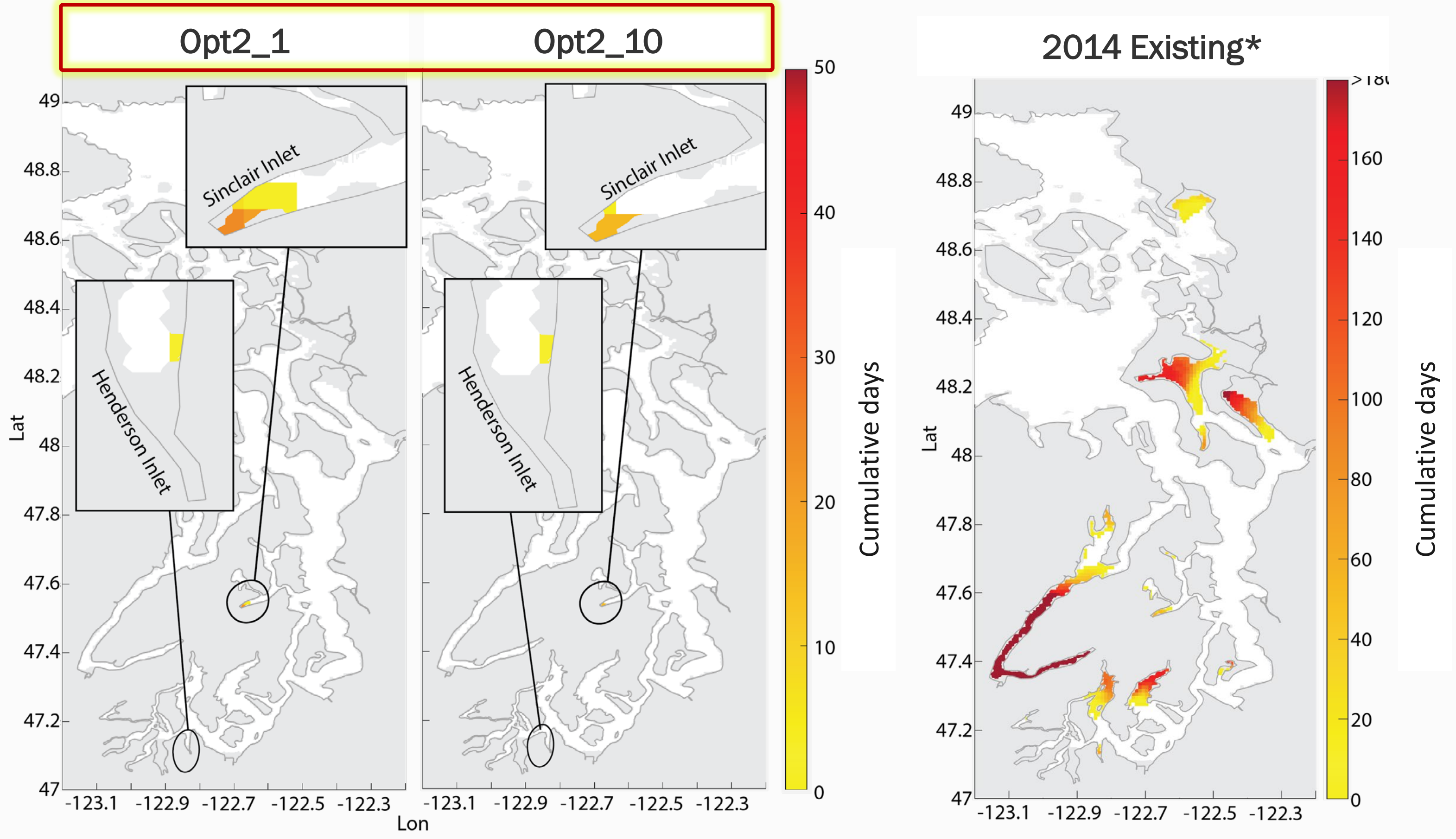
All these remaining areas where DO depletion is greater than the HUA are in a small portion of Sinclair and Henderson Inlets

Opt2 DO depletion greater than HUA

Opt2 Scenario	Total days DO depletion is greater than HUA
Existing*	80,279
Opt2_1	57
Opt2_2	58
Opt2_3	36
Opt2_4	58
Opt2_5	58
Opt2_6	36
Opt2_7	36
Opt2_8	36
Opt2_9	35
Opt2_10	18



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**Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)*

Capping* nutrient loads in Very Small WWTPs increases number of days DO depletion is greater than HUA by 0-1 days

*Capped to existing 2014 loads

Opt2 DO depletion greater than HUA

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Opt2_10	6,570	69.2%	18	0.83

**Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)*

Capping* nutrient loads from WWTPs discharging to Hood Canal, Admiralty, SJF and SOG increases number of days DO depletion is greater than HUA by 0-1 days

*Capped to existing 2014 loads

Opt2 DO depletion greater than HUA

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Increasing BNR treatment in WWTPs discharging to or near Sinclair Inlet reduces days DO depletion is greater than HUA locally by 22 days and area by 1.57 km^2

**Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)*

Opt2 DO depletion greater than HUA

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**Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)*

Increasing BNR treatment at dominant Main Basin WWTPs during warm months (8/3/3) reduces days DO depletion is greater than HUA by 0-1 day

BNR5 during warm months at all 4 dominant Main Basin WWTPs

BNR3 during warm months at 3 out of 4 dominant Main Basin WWTPs

BNR3 during warm months at all 4 dominant Main Basin WWTPs

Opt2 DO depletion greater than HUA

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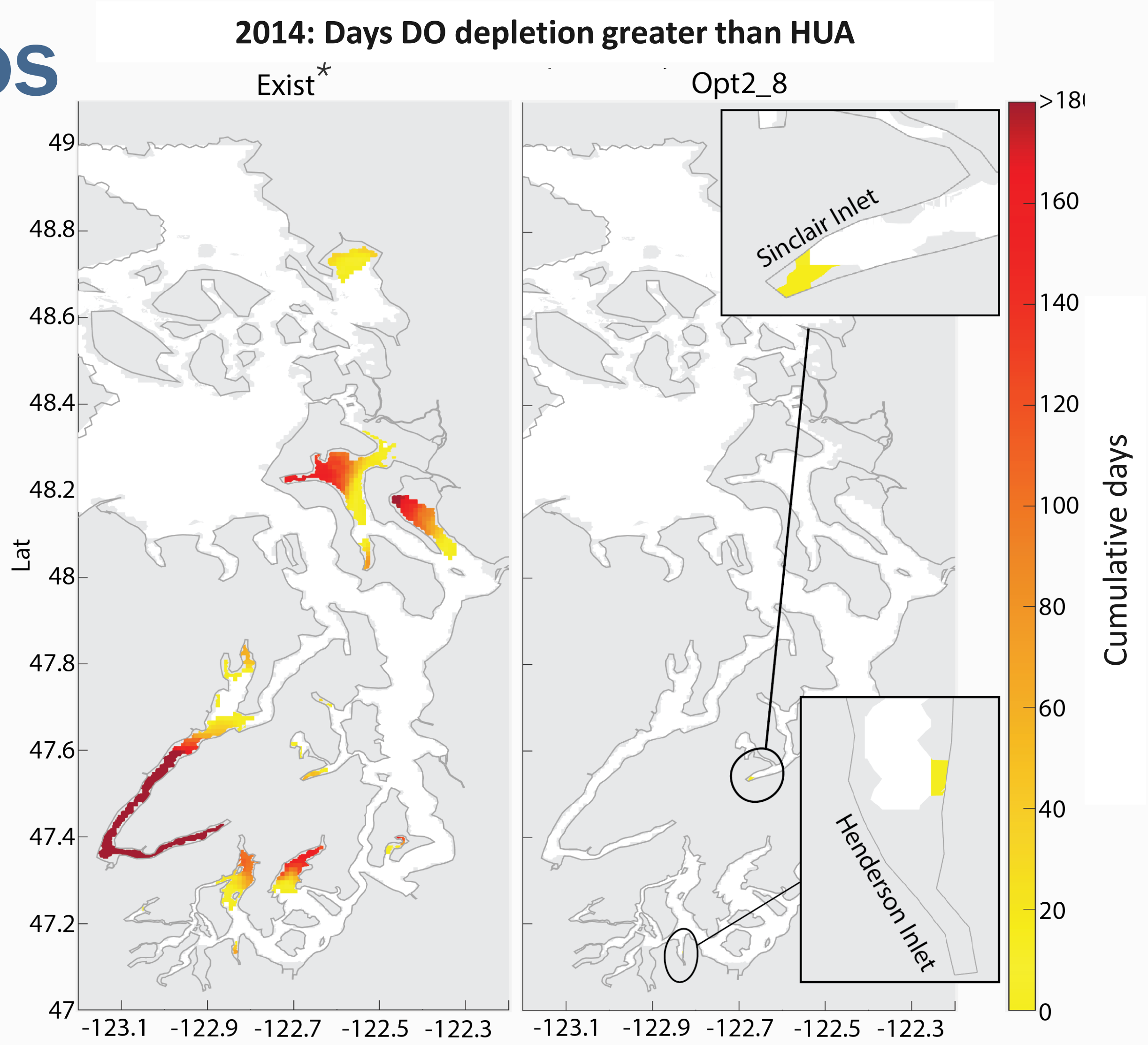
BNR 3 mg/L year-round at all WWTPs reduces days DO depletion is greater than HUA by 17 days and 0.1 km^2

Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)

Exist vs. 10 Opt2 Scenarios

- > 99% reduction in area where DO depletion is greater than HUA
- > 99% reduction days when DO depletion is greater than HUA
- > 90% reduction in the magnitude of DO depletion greater than HUA
- Up to 1.2 mg/L improvement in DO
- 20% reduction in SOD in terminal inlets
- Remaining areas where DO depletion is greater than HUA are localized in Sinclair and Henderson Inlets



*Daily minimum DO is less than BBC or depletion is greater than HUA (whichever is applicable)

Photo courtesy: Eyes over Puget Sound, MMU, ECY

Algal bloom in Dugualla Bay/ Skagit Bay. 7/28/2014

Pause for questions

Contact: c.figueroa@ecy.wa.gov

Model Updates & Performance

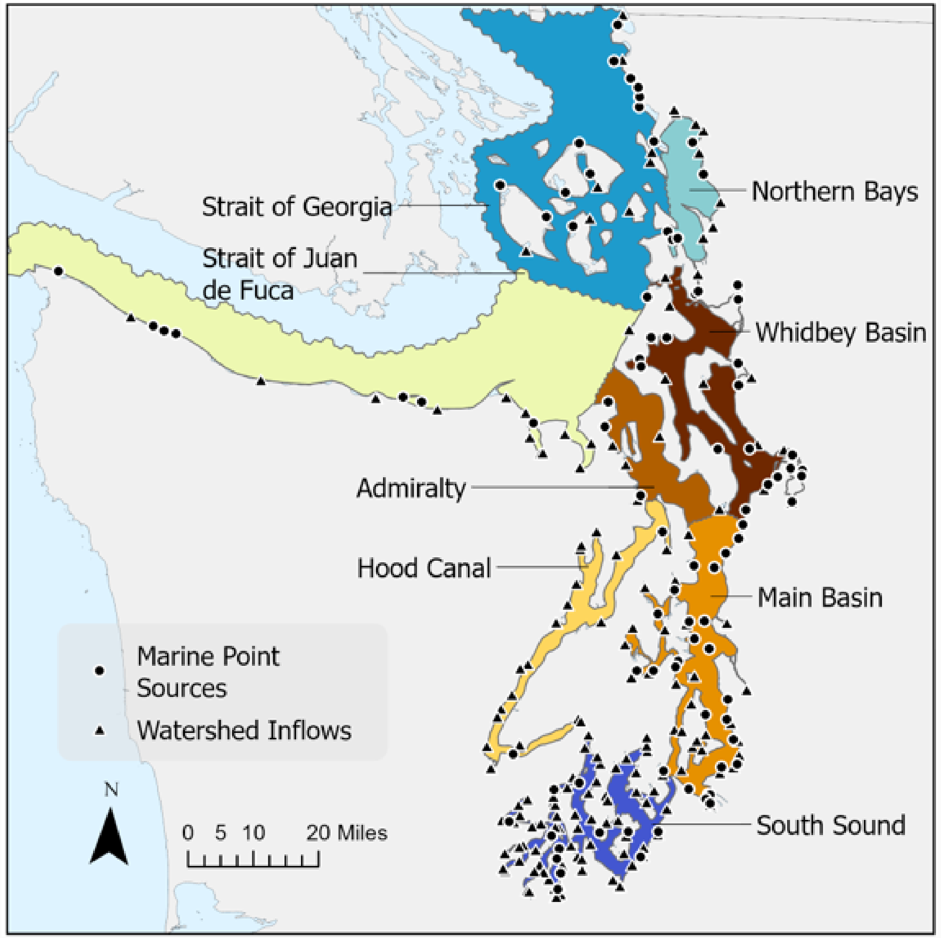
Photo courtesy: Eyes over Puget Sound, MMU, ECY

Algal bloom in Liberty Bay, 9/16/2014

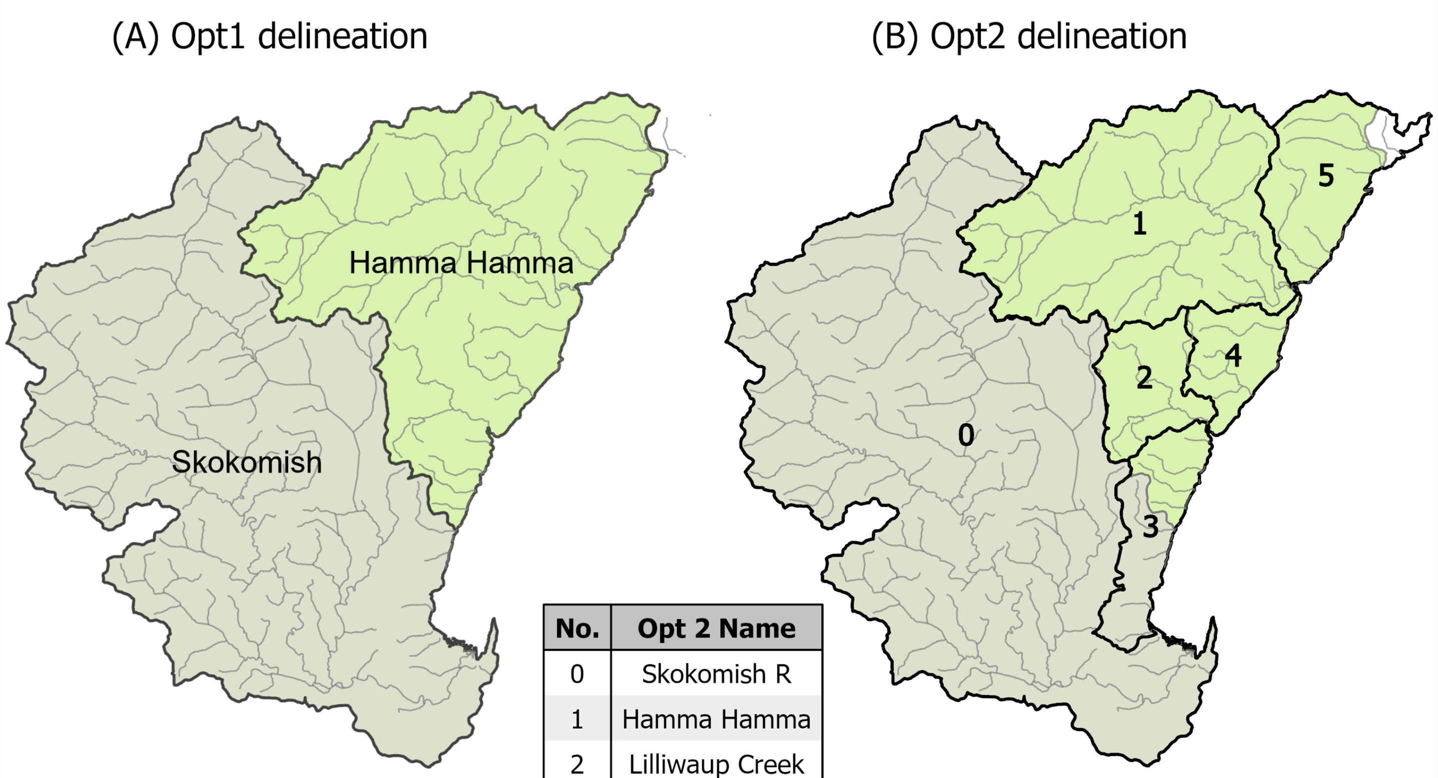
Watershed and Marine Point Source Updates

- Expanded previous 161 watersheds to 193 watershed inputs by disaggregating larger watersheds to sub-watersheds with observational data from various entities

- Updated water quality (WQ) for 99 WWTP point source discharges
  - Most regressions remained the same
  - Industrial WQ updated



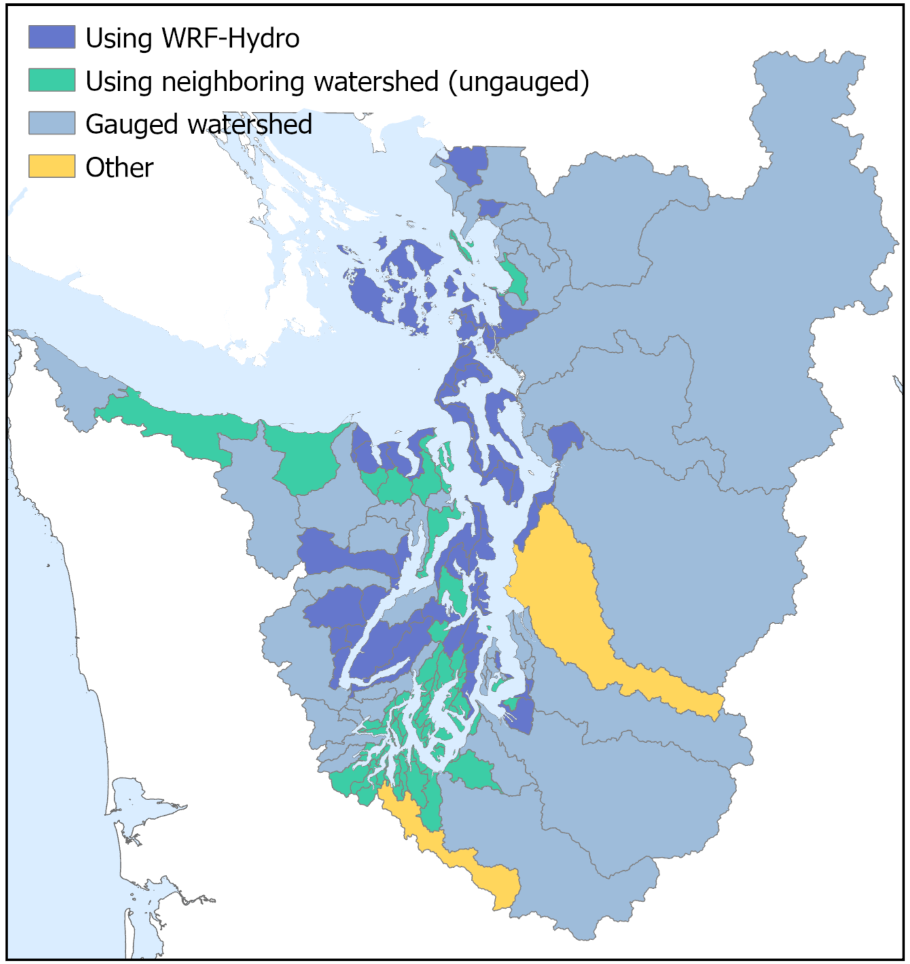
Delineation Update Example

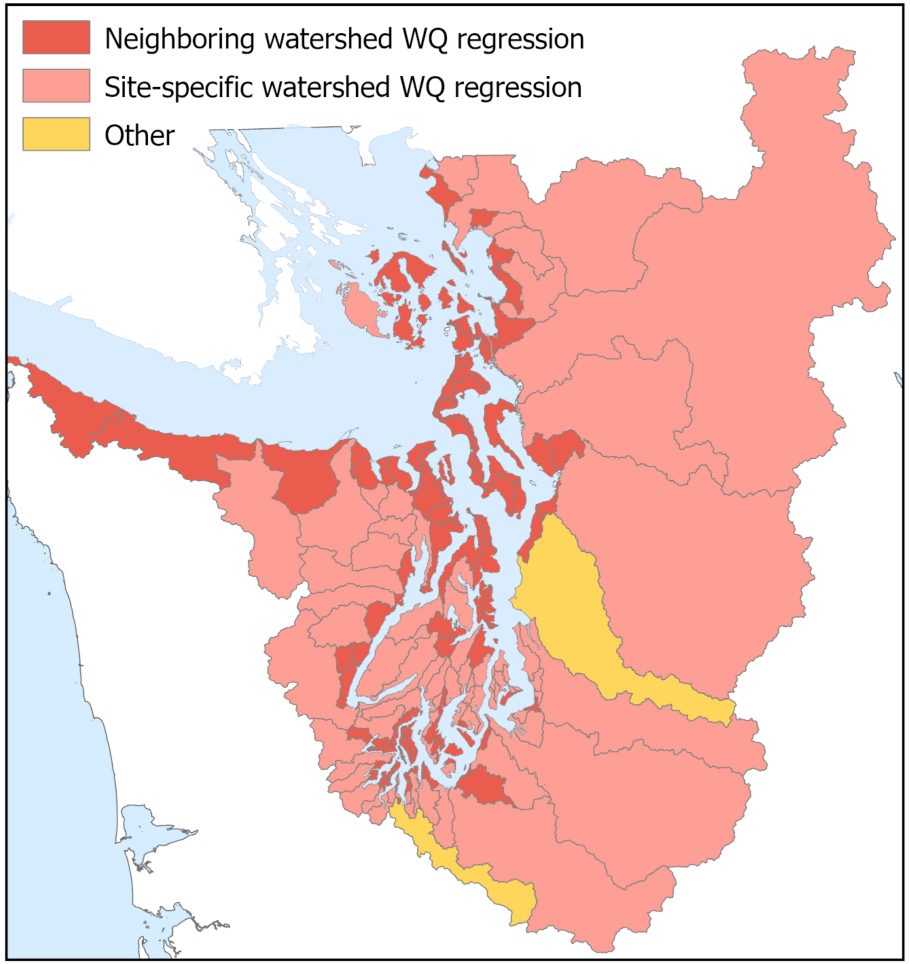


No.	Opt 2 Name
0	Skokomish R
1	Hamma Hamma
2	Lilliwaup Creek
3	Finch Creek
4	Eagle Creek
5	Fulton Creek

- Opt 2 Watershed resolution was revised from HUC 8 to HUC 12.
- Hamma Hamma for example, was divided into 5 watersheds in Opt2.

Watershed Flow and Water Quality Updates





Flow

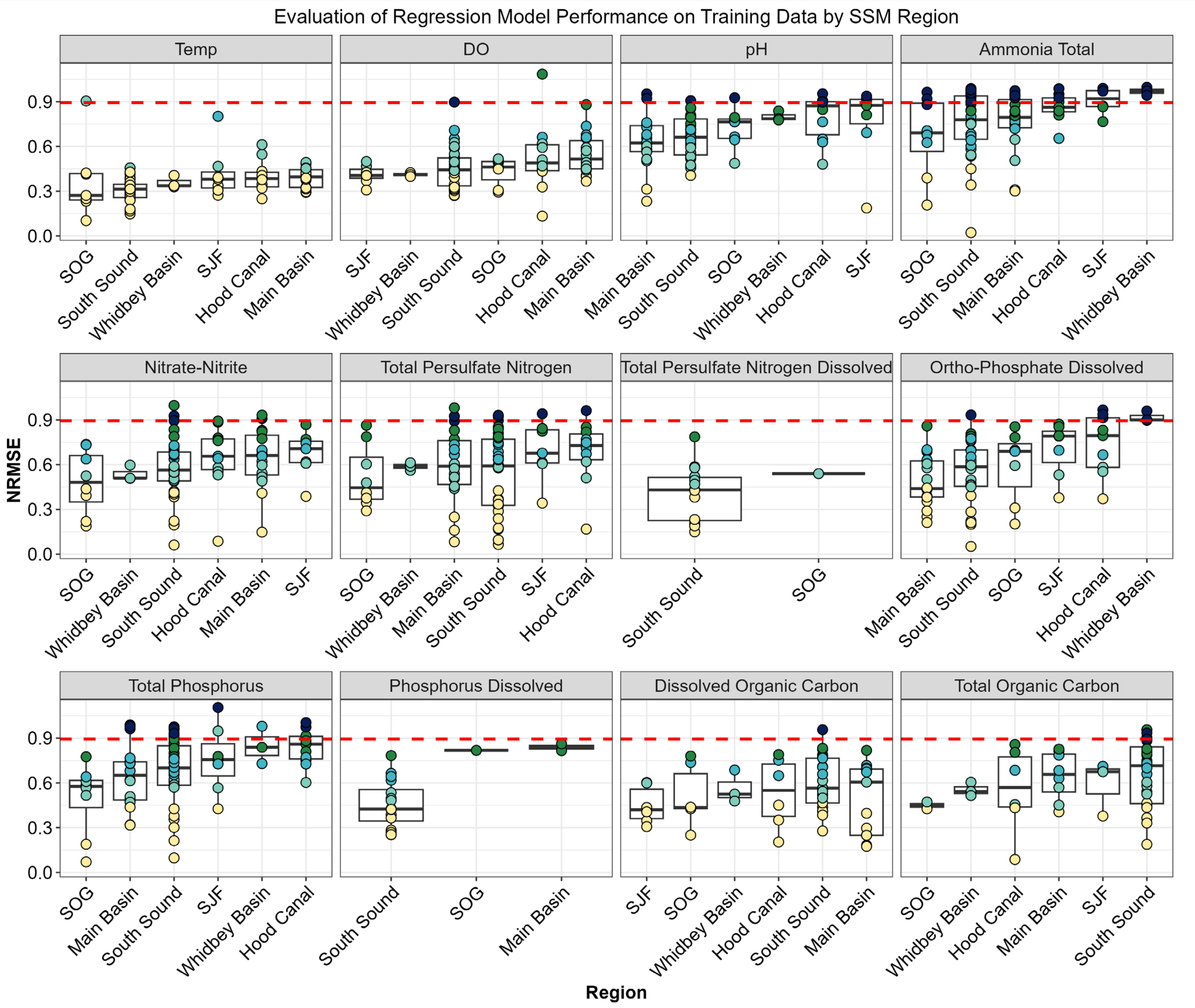
- 76% gauged (previously 72%)
- Only 8% of watersheds borrow flow (previously 22%)

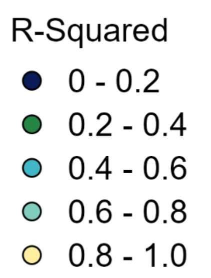
Water Quality

- 81% of watersheds had data for regressions (previously 72%)

Watershed regression evaluations

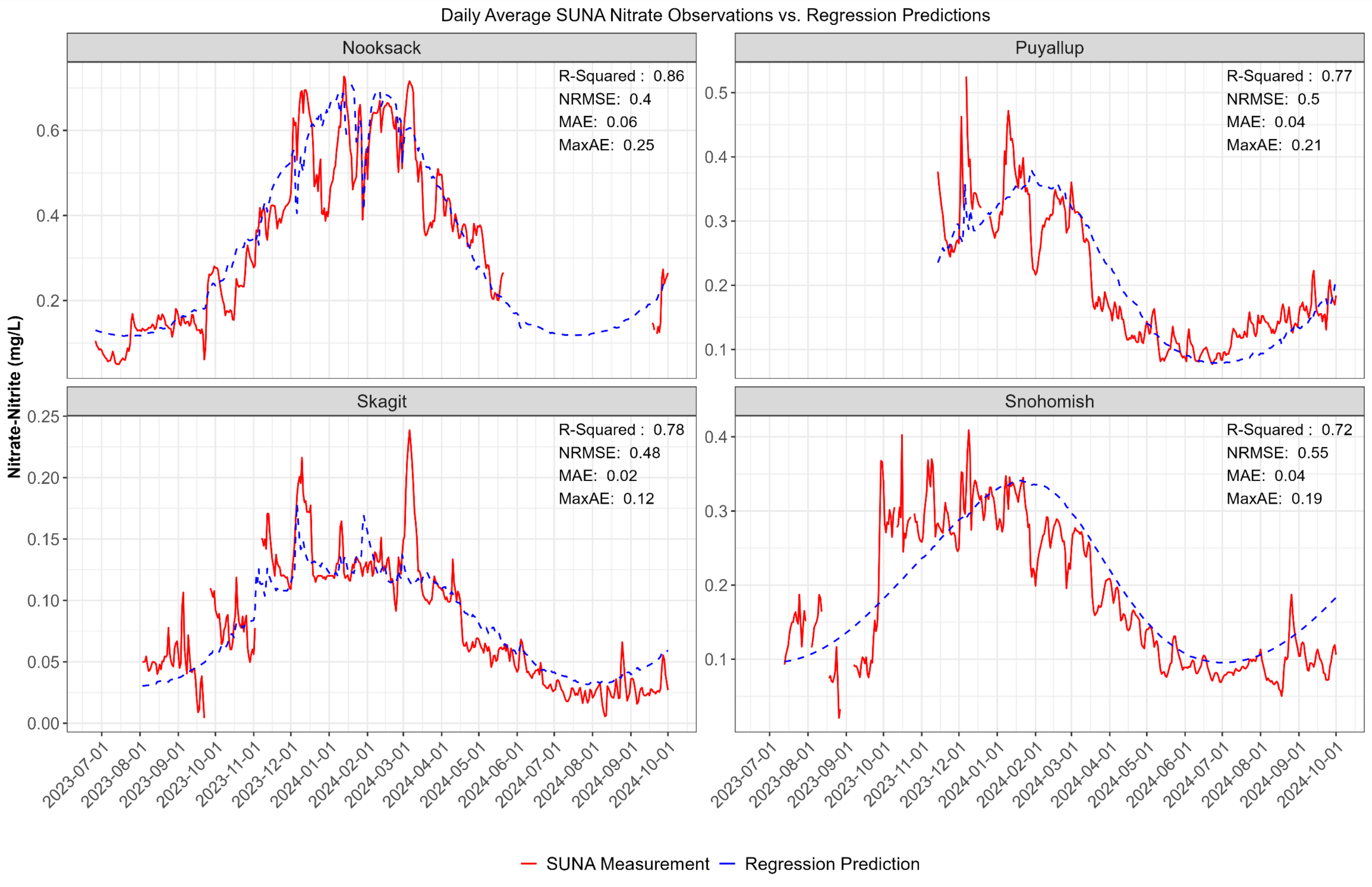
- Total of 750 regressions
- Discrete long-term monthly data used for training (1999-2022)
- Most met target stats (NRMSE and R^2)
- When targets not met, used observed data monthly averages (11%)



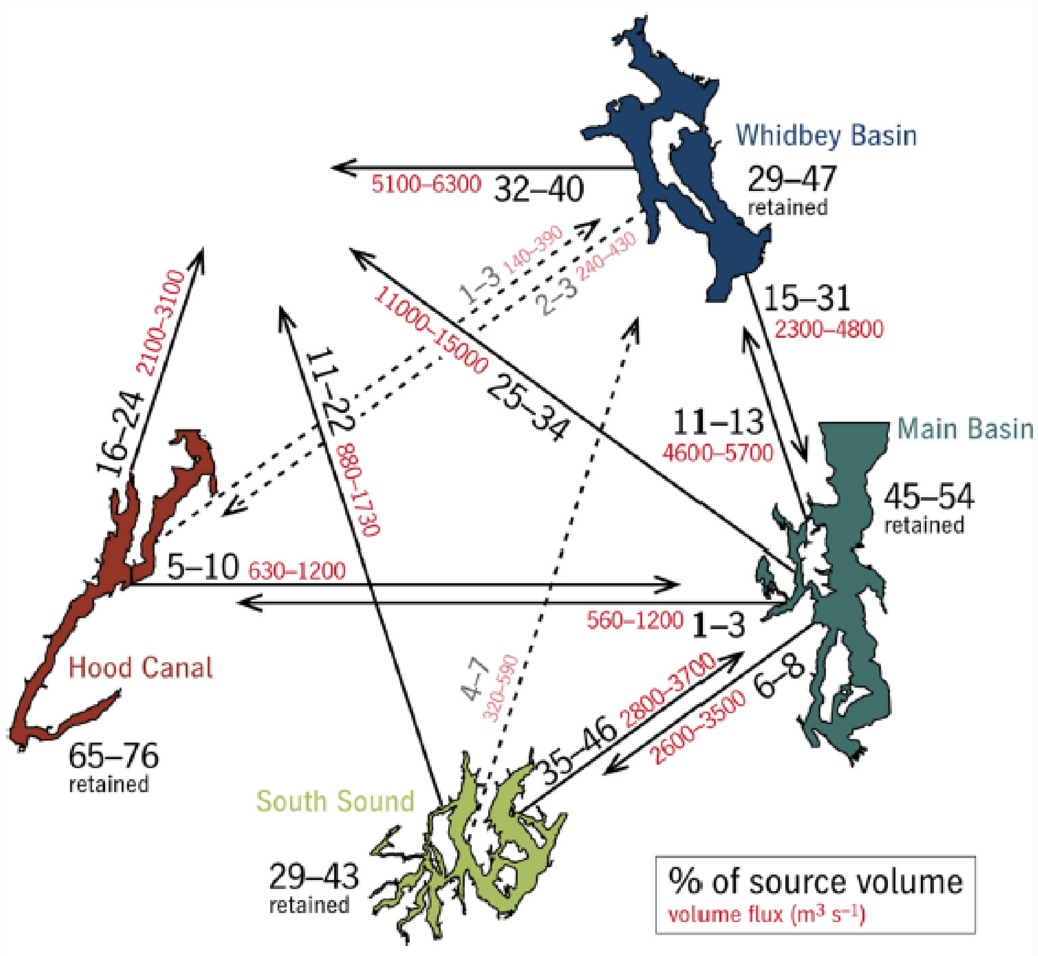


Watershed regression evaluations

- Compared with completely independent continuous data from four sites from recent years
- Met overall targets set previously
- Low flow predictions had greater discrepancy

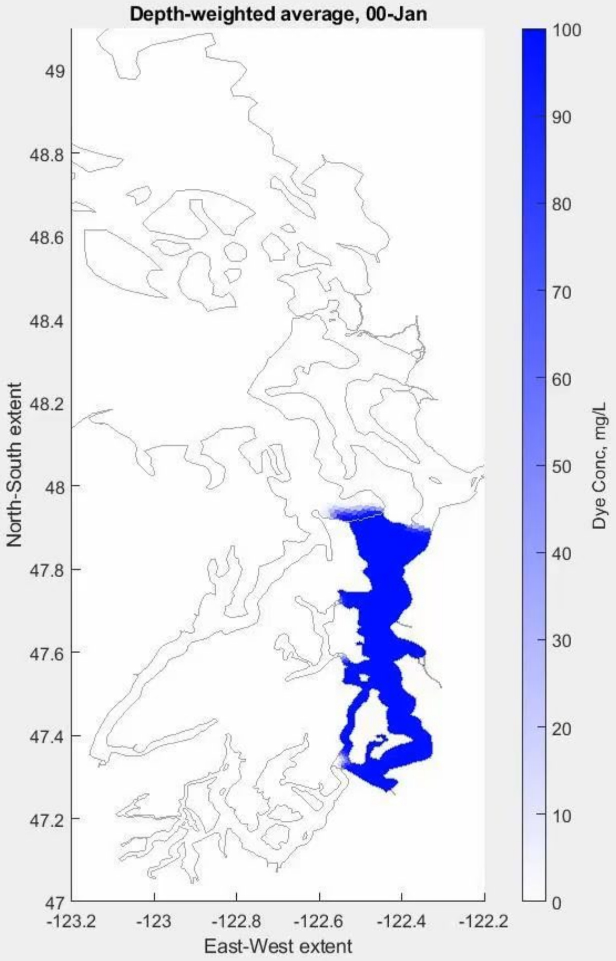


Inter-connectivity of basins

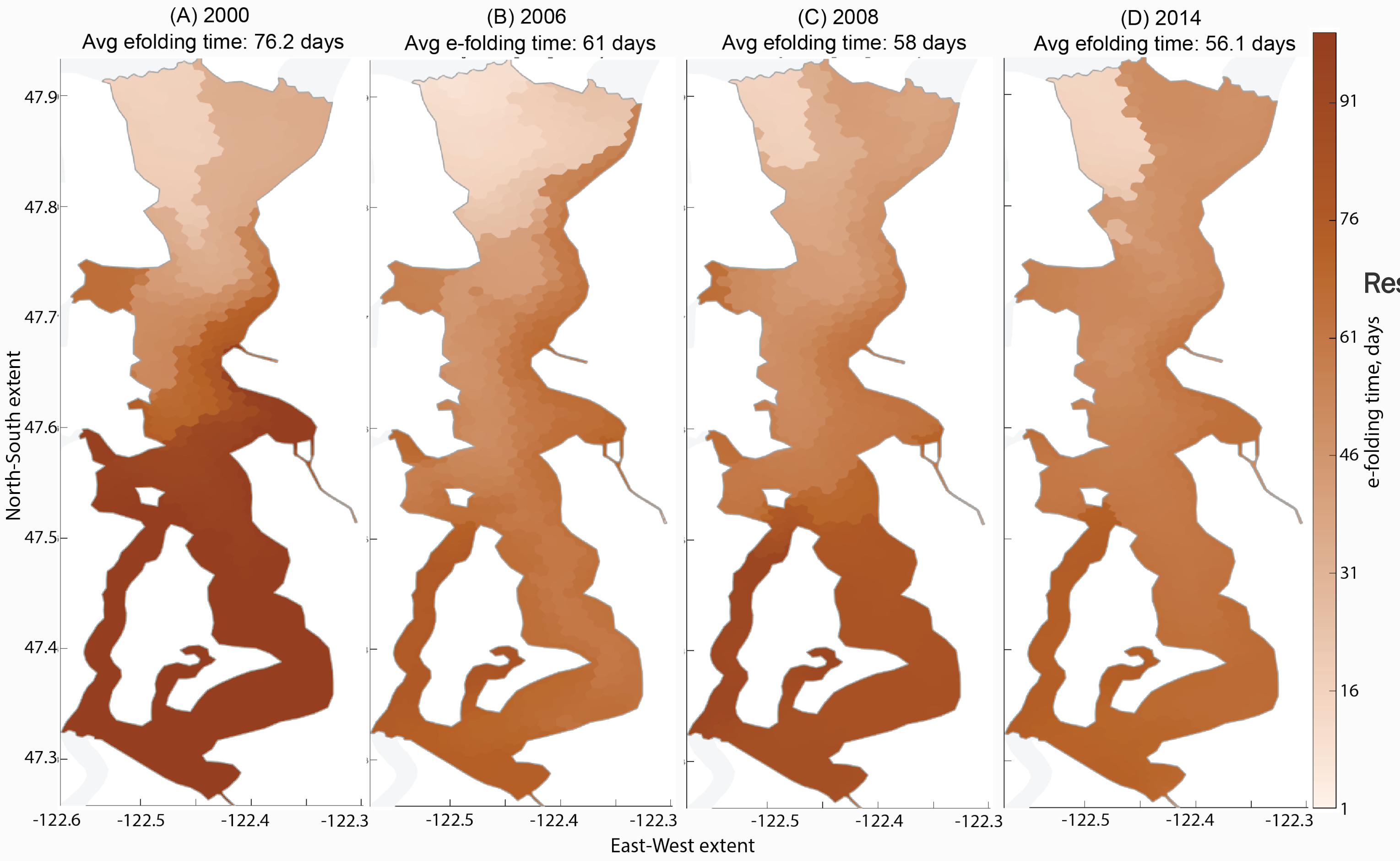


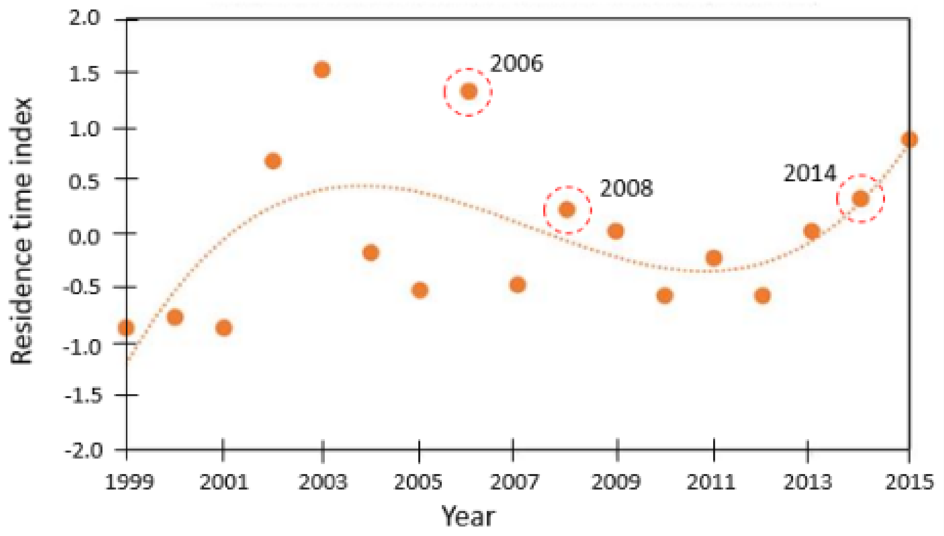
Banas et al. 2015. Estuaries and Coasts 38:735–753

Dye concentration between Jan 1 – Feb 19, 2014

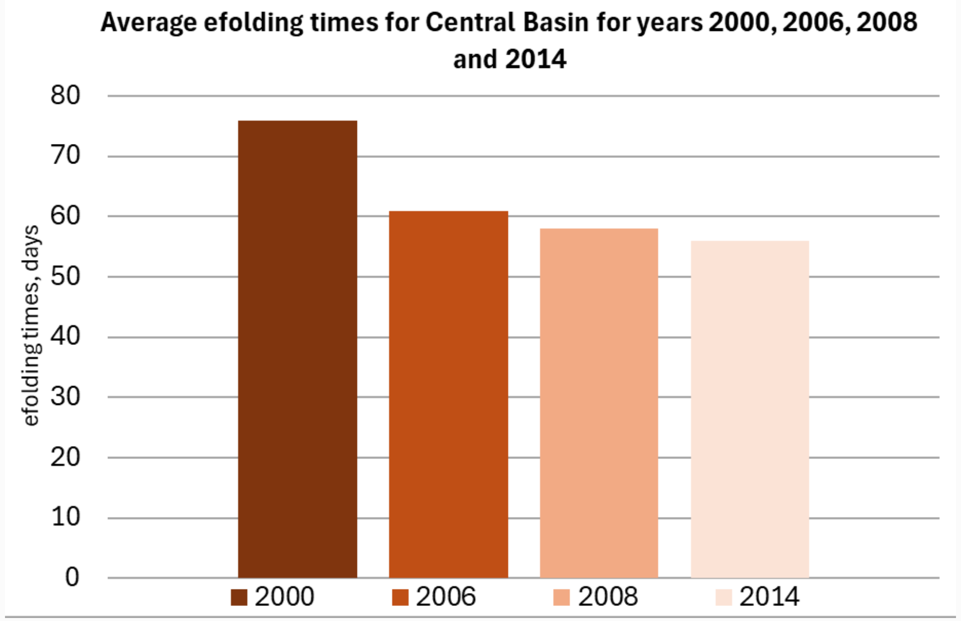


Flushing Times in central portion of Main Basin

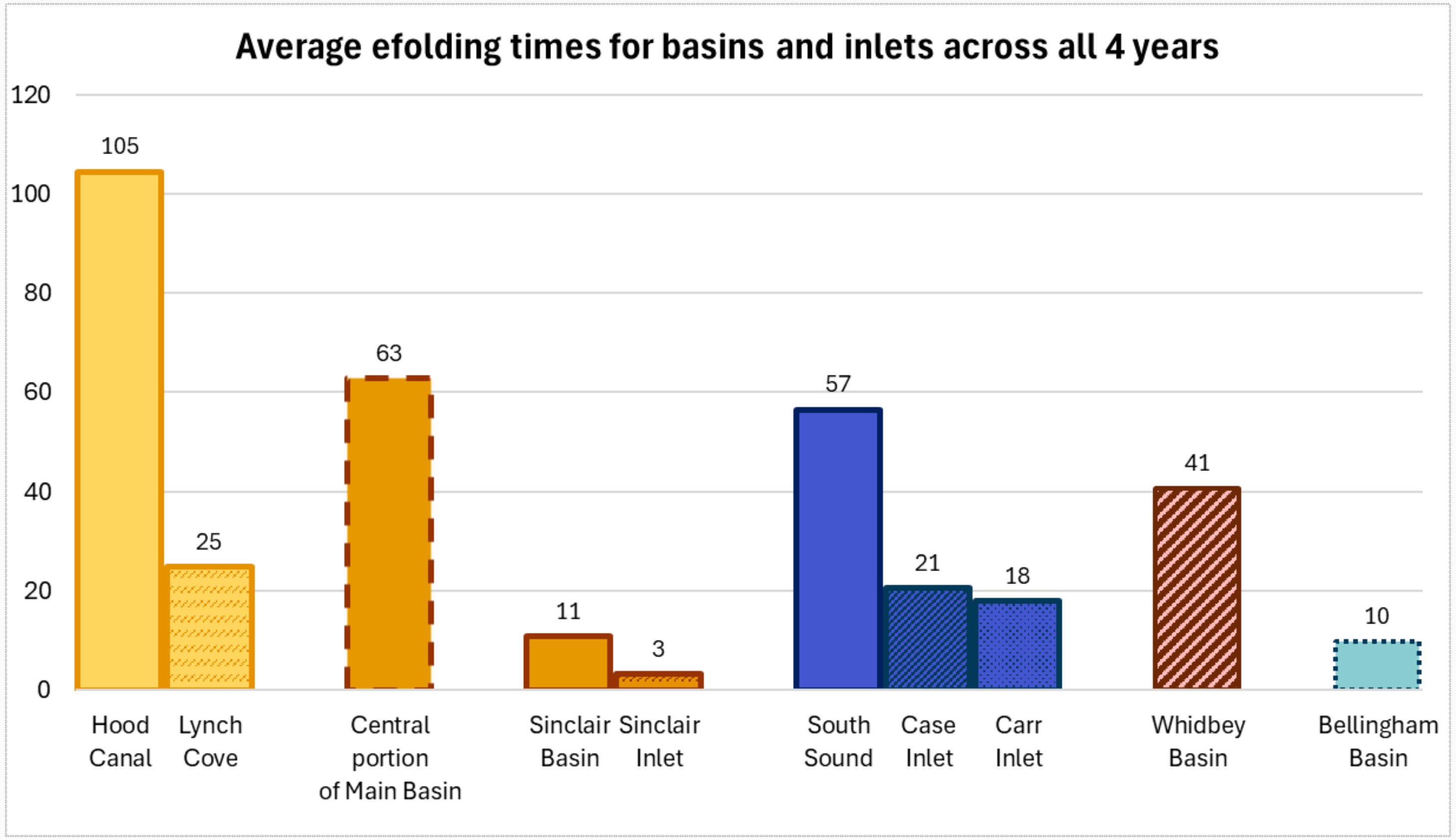


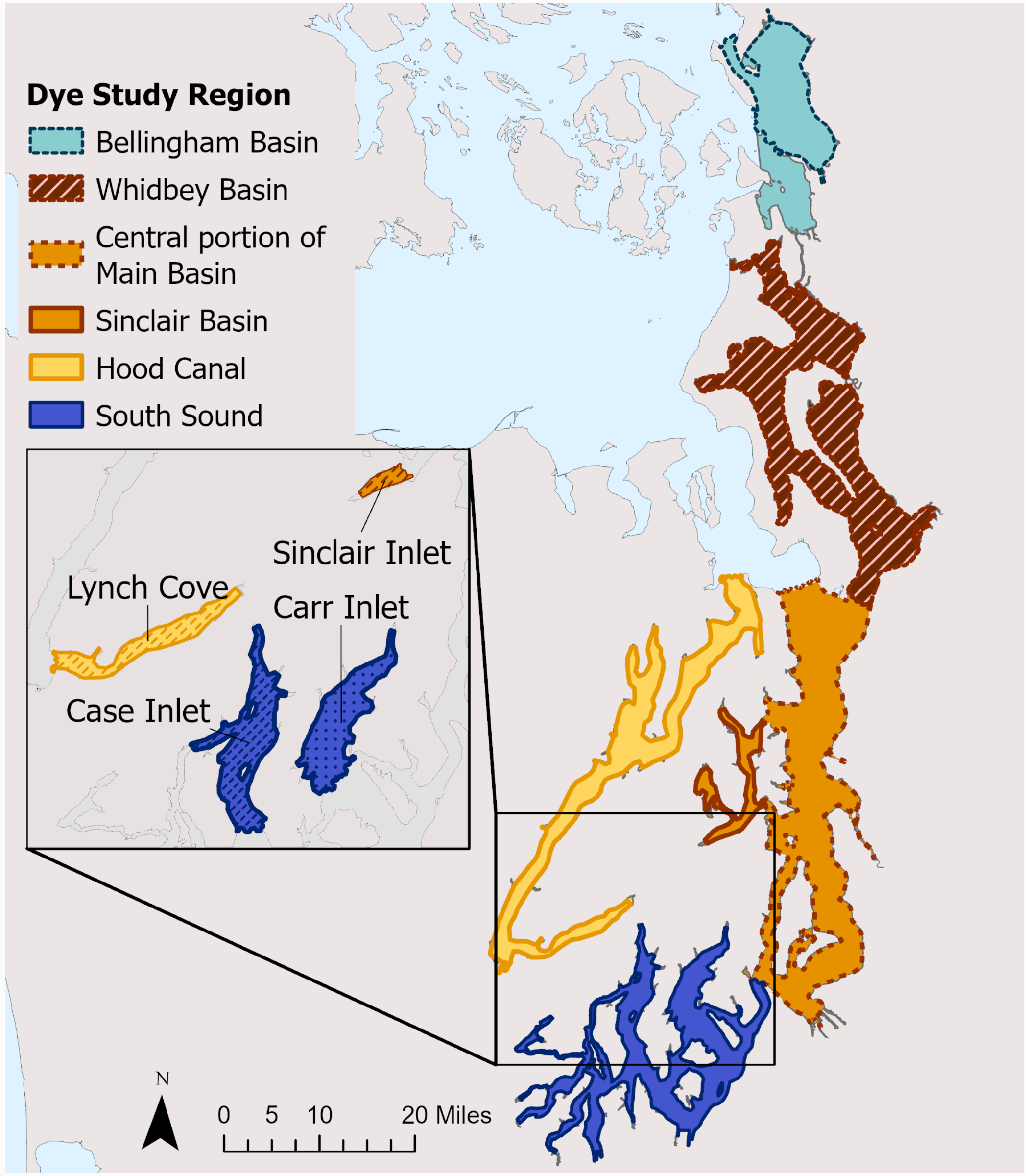


Residence time index in central portion of Main Basin (Albertson et al. 2016)



Flushing Times for basins

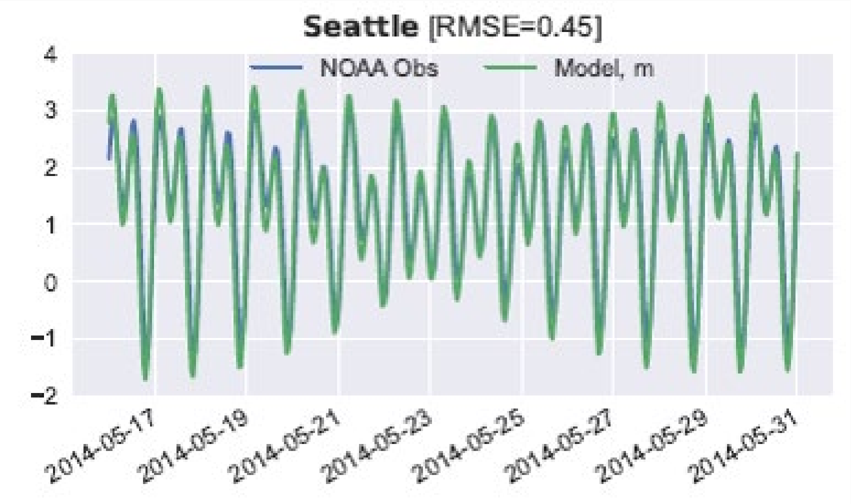




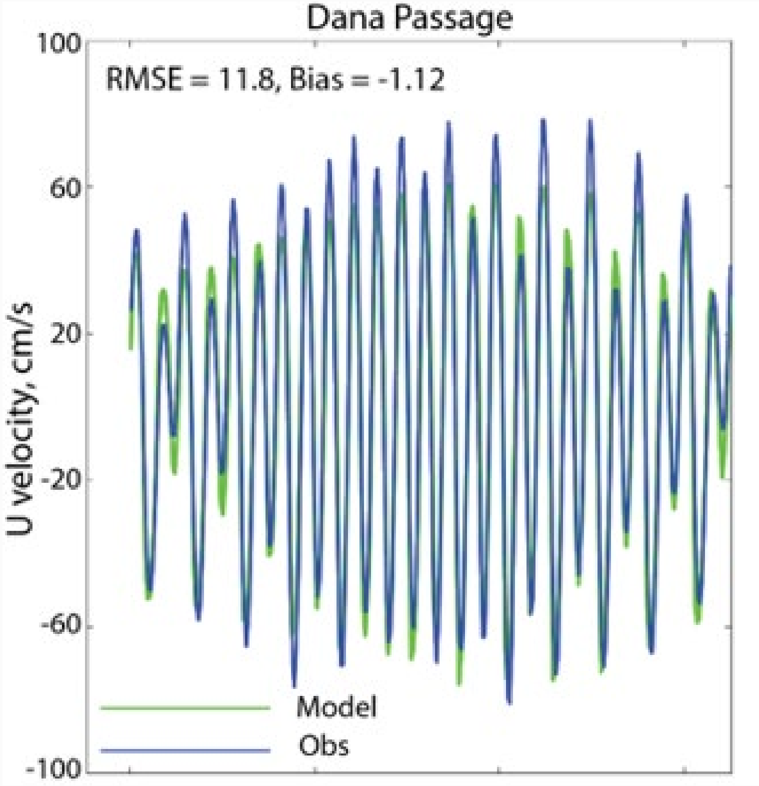
Hydrodynamic Model Performance Improved

- Prediction of observed surface water elevations improved by an average of 3 percent across all years
- Prediction of observed currents improved by 26%

Water surface elevations



Tidal currents



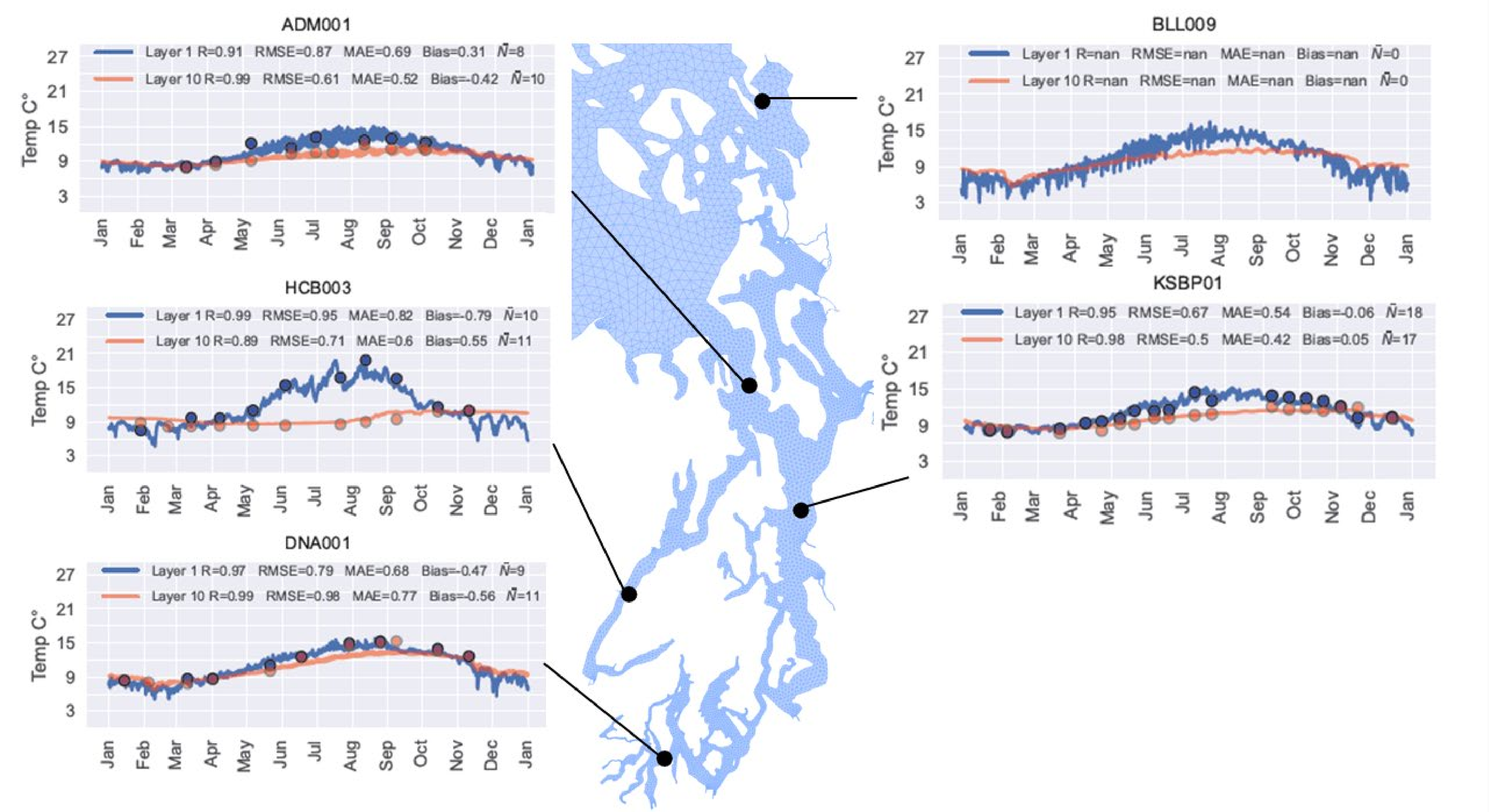
Water Quality Model Performance Improved

2014 model performance for water quality met the objectives in QAPP (McCarthy et. al., 2018)

Report	Variable	R	RMSE	Bias	N
BSR	Temperature (C)	0.95	0.87	-0.41	88,781
Opt1	Temperature (C)	0.95	0.78	-0.23	97,687
Opt2	Temperature (C)	0.95	**0.71**	**0.04**	99,074
BSR	Salinity (psu)	0.75	0.88	-0.37	88,585
Opt1	Salinity (psu)	0.82	0.84	-0.44	97,487
Opt2	Salinity (psu)	**0.83**	**0.72**	**-0.07**	98,884
BSR	DO (mg/L)	0.81	0.96	-0.34	87,284
Opt1	DO (mg/L)	0.83	0.98	-0.43	96,152
Opt2	DO (mg/L)	**0.86**	**0.82**	**-0.08**	97,566

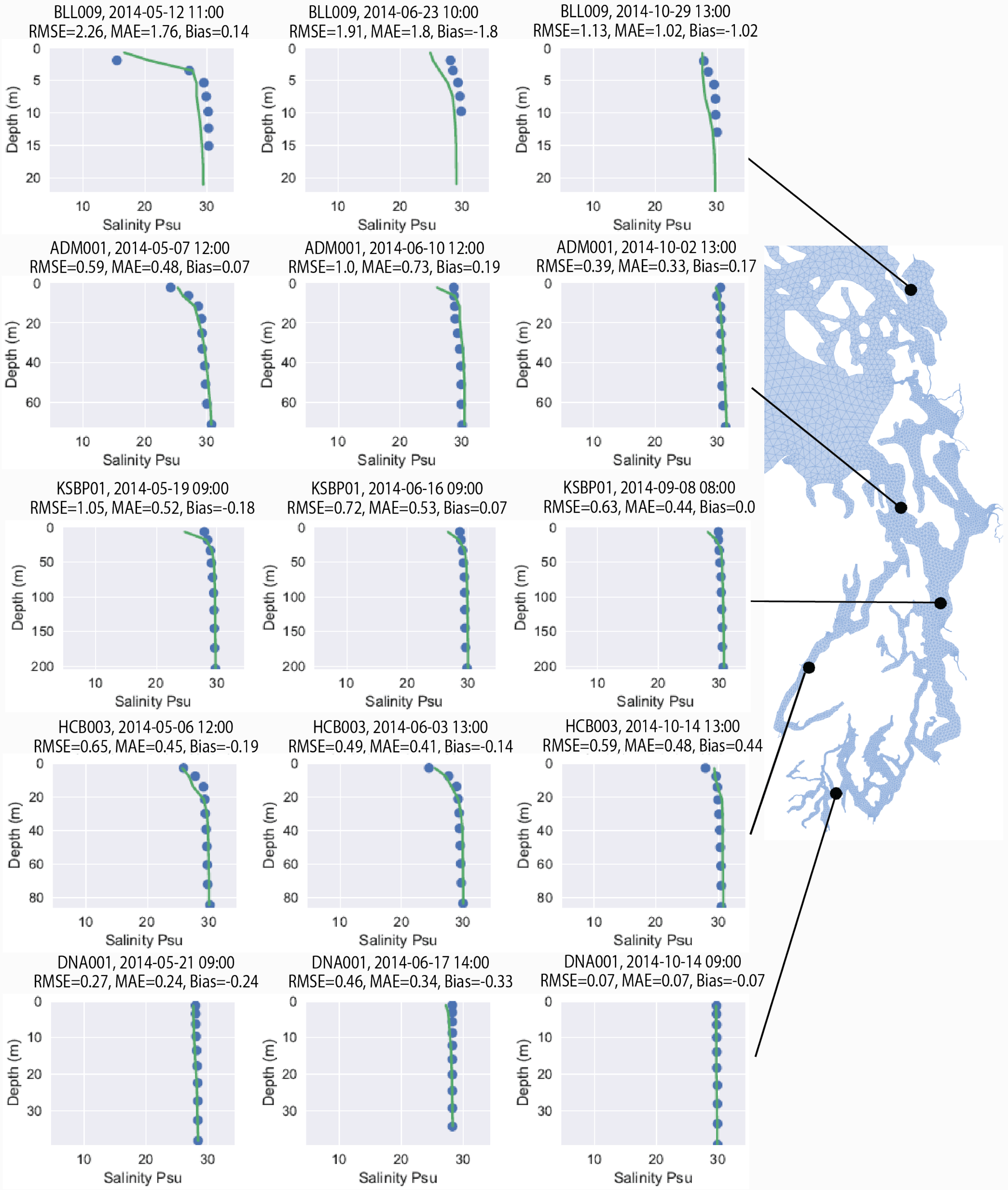
Water Quality Model Performance (continued)

2014 Temperature timeseries



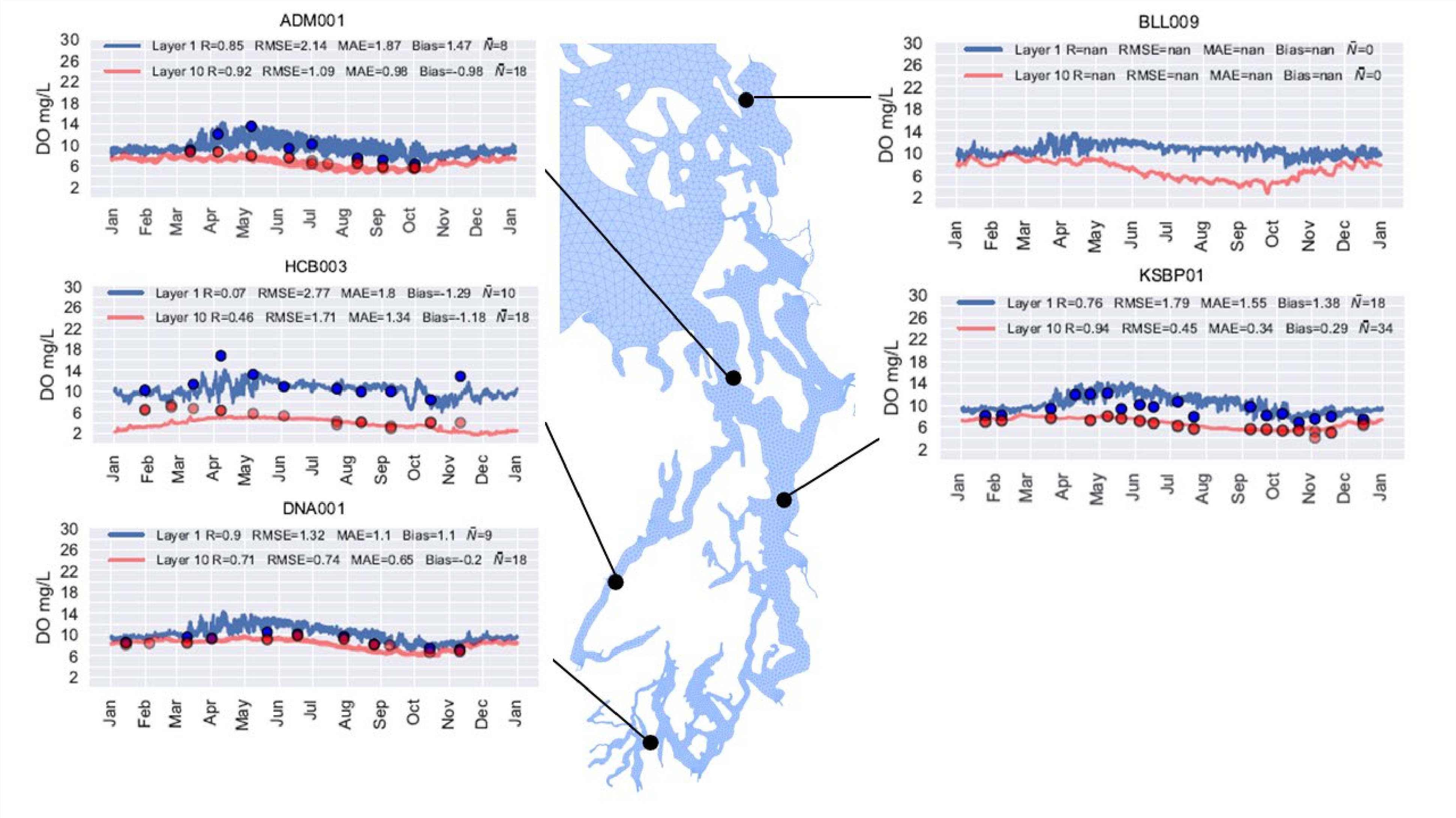
Water Quality Model Performance (continued)

2014 Salinity profiles



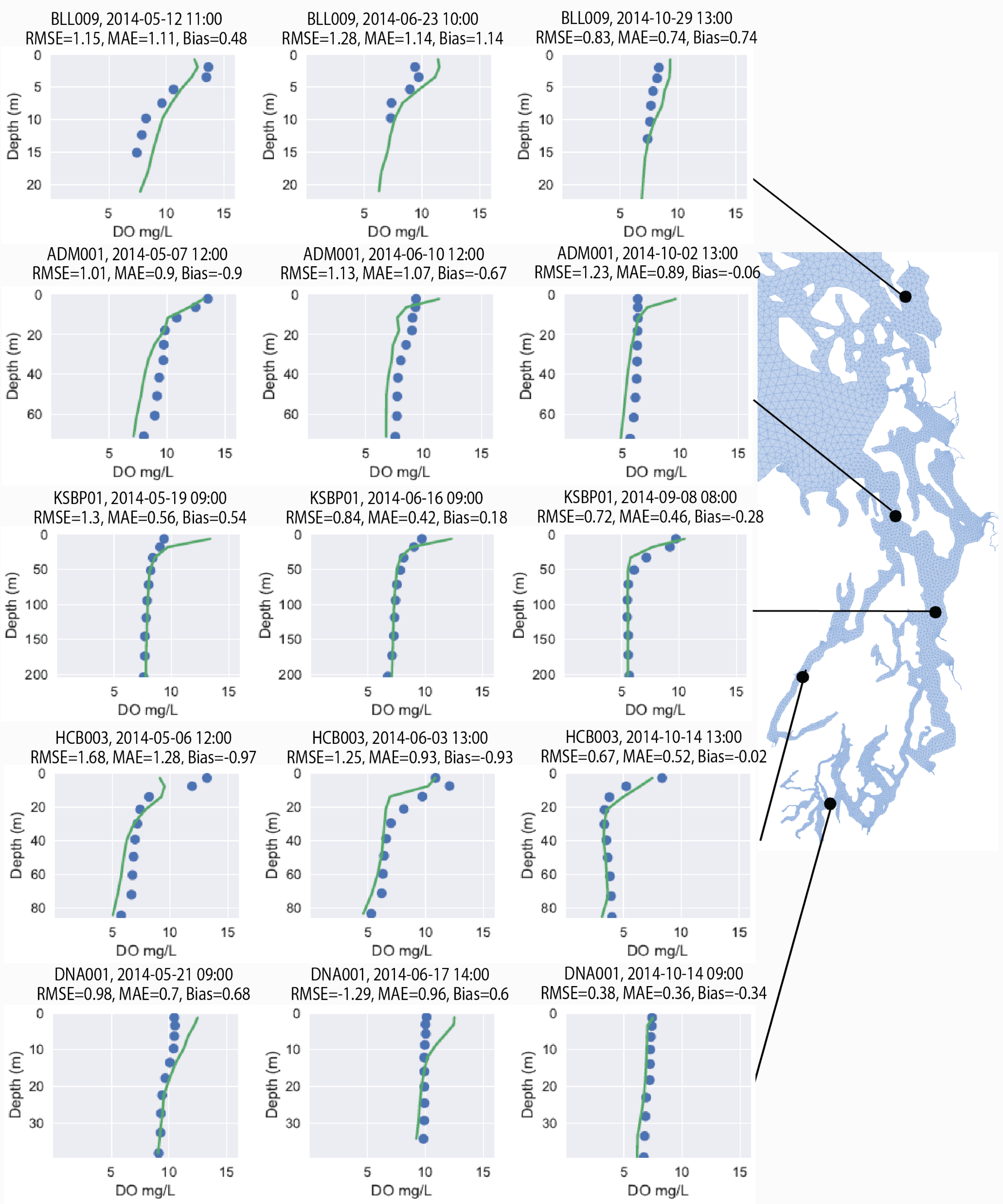
Water Quality Model Performance (continued)

2014 Dissolved oxygen timeseries

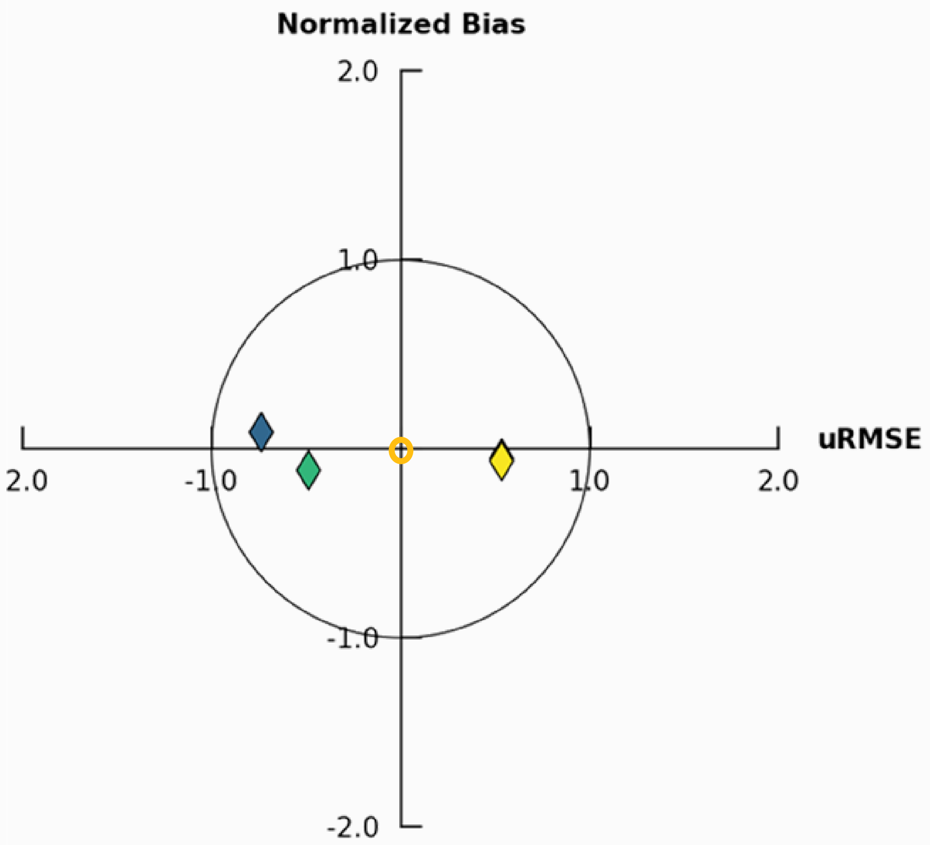


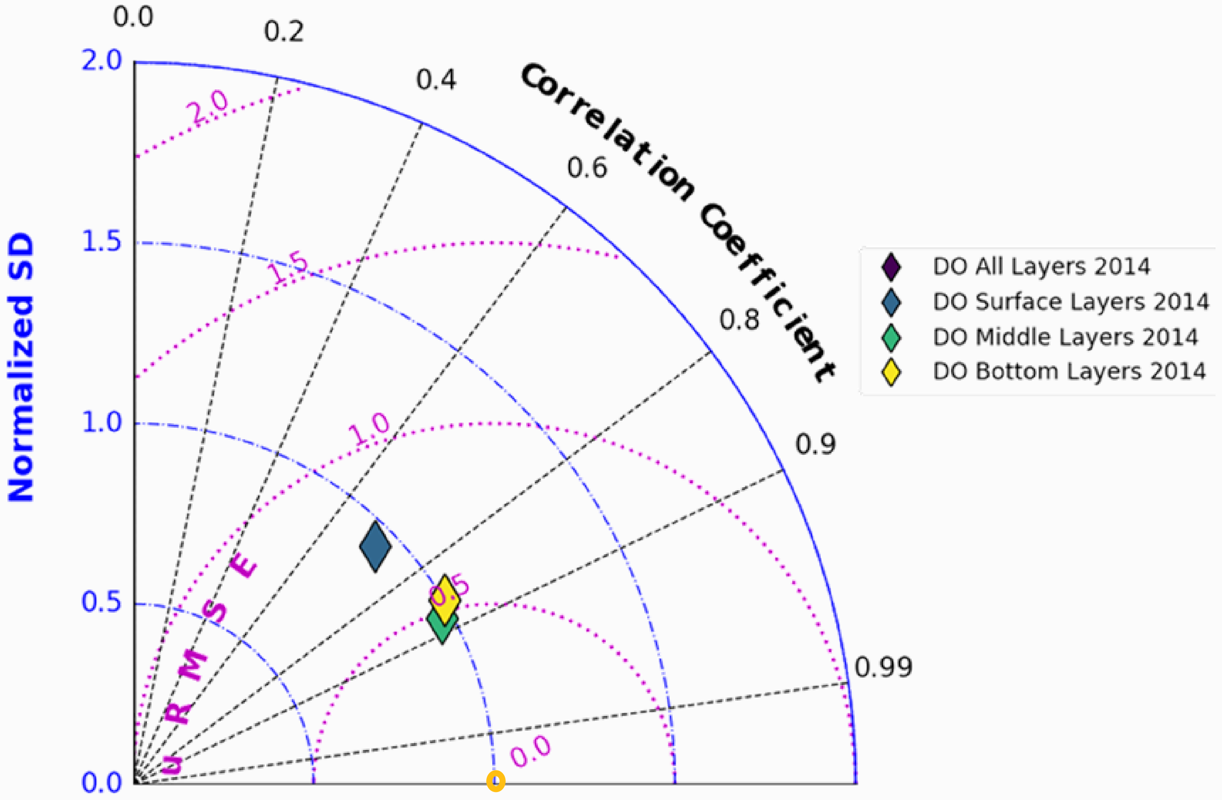
Water Quality Model Performance (continued)

2014 Dissolved oxygen profiles

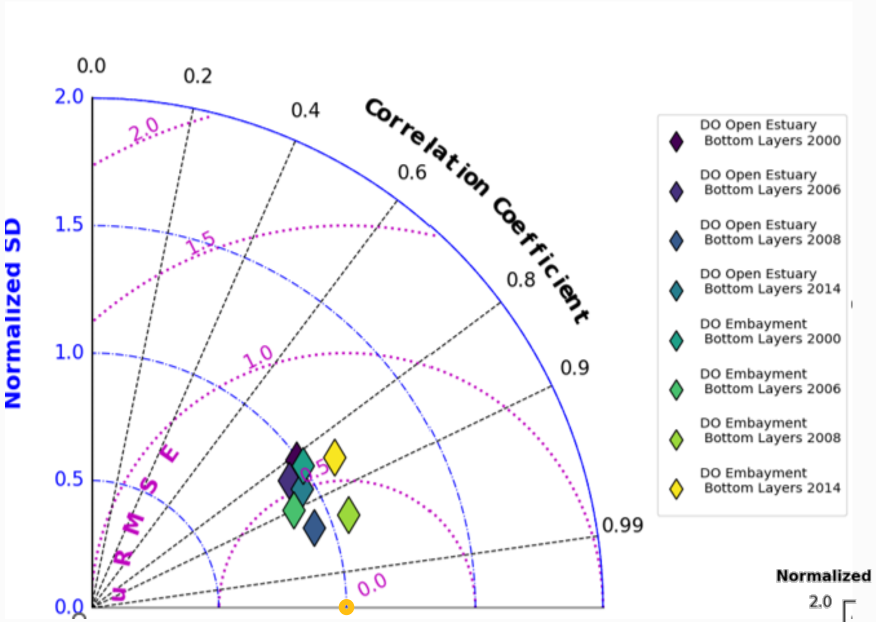


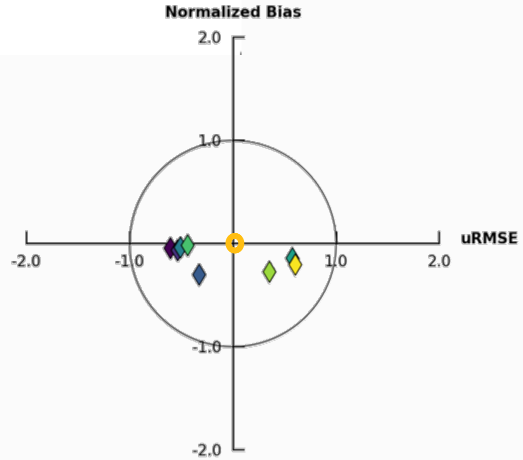
DO performance in water column

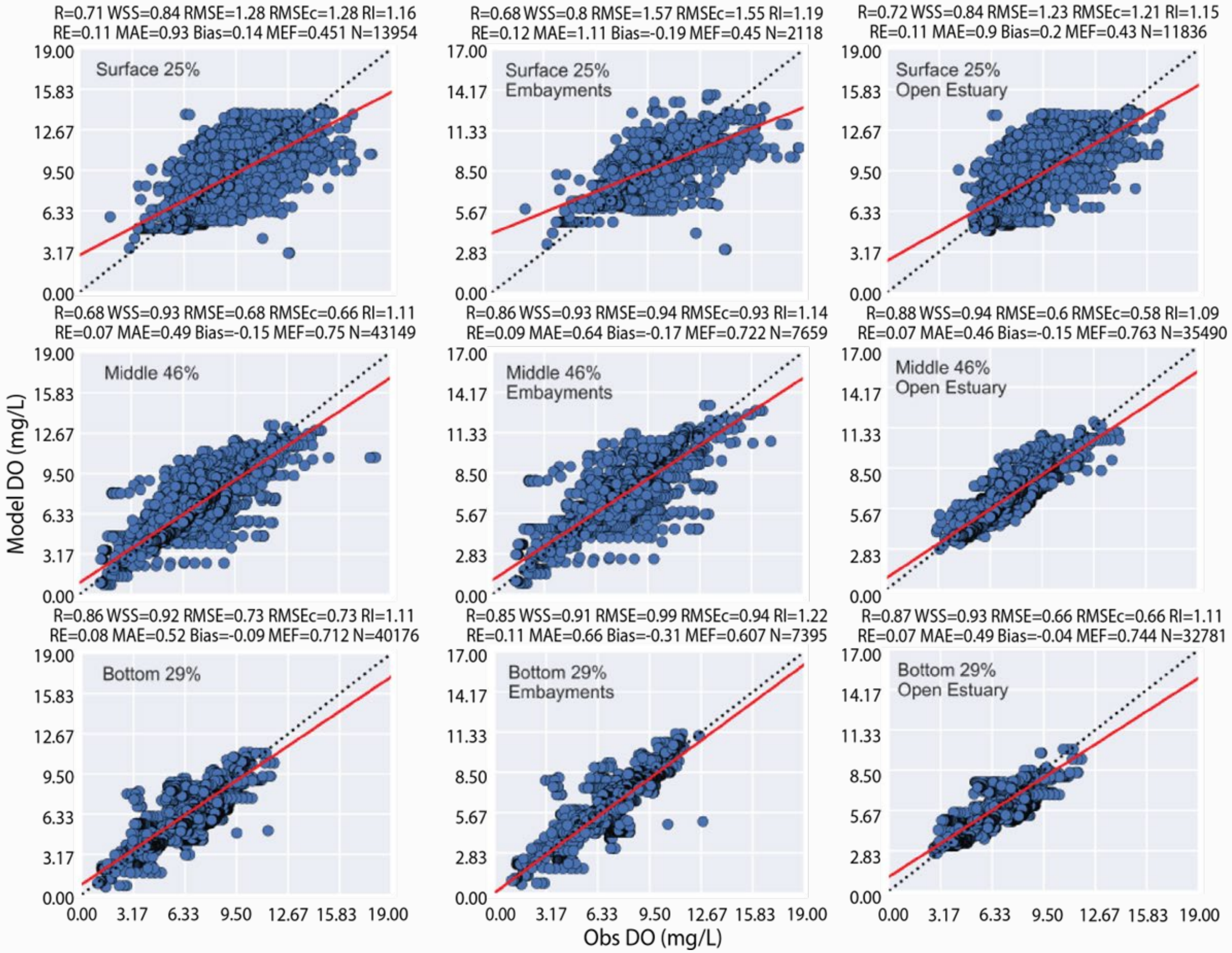




DO performance in embayments vs. open channel

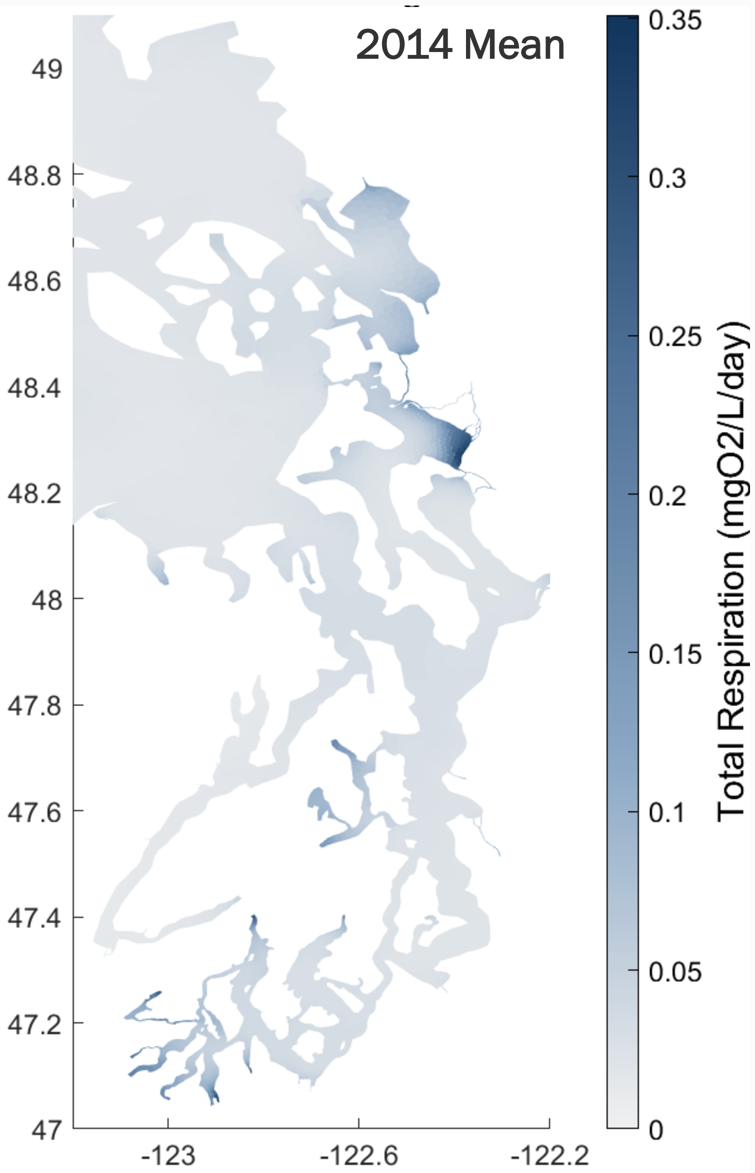






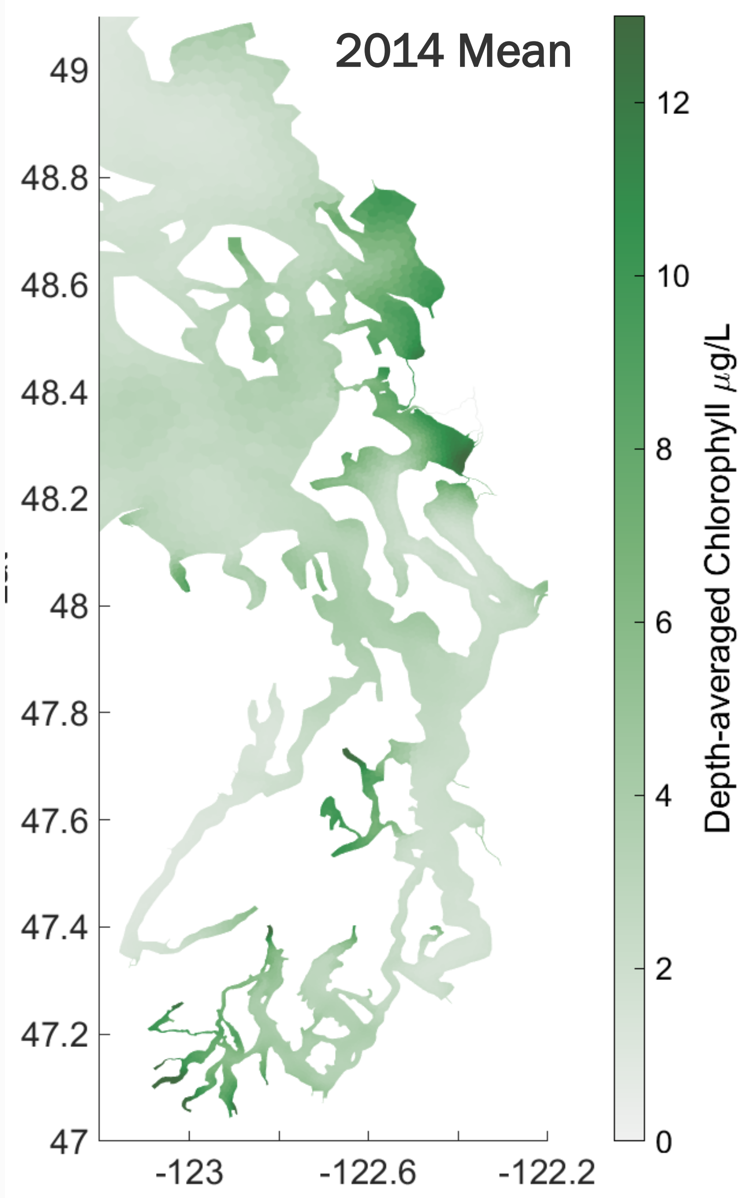
Bottom layer respiration

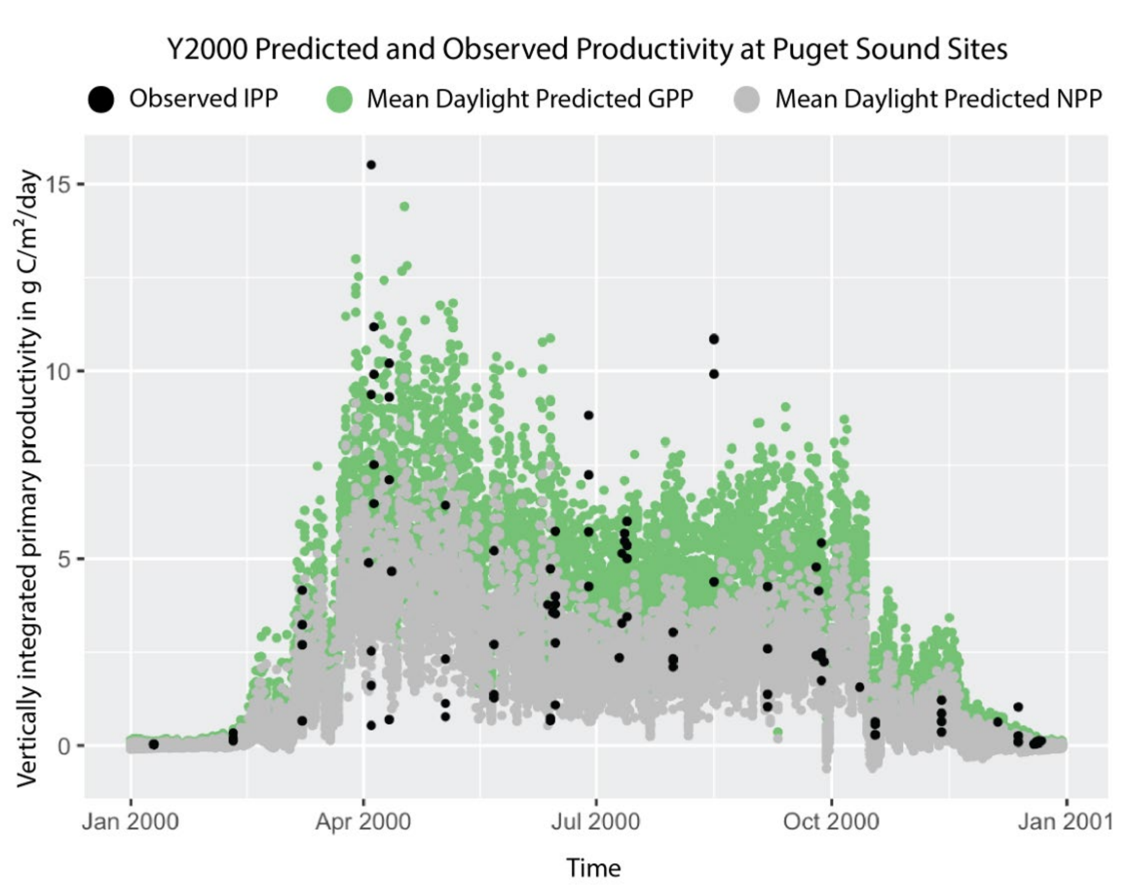
- In bottom waters, terminal inlets and bays are predicted to have higher respiration rates, with exceptions (Lynch Cove).
- Predicted respiration rates are within the expected observational ranges at the sites Apple and Bjornson (2019) sampled.



Primary production

- Largest depth-averaged Chl-a concentrations in inlets/ embayments.
- Generally good agreement between predicted and observed Chl-a and integrated primary productivity.

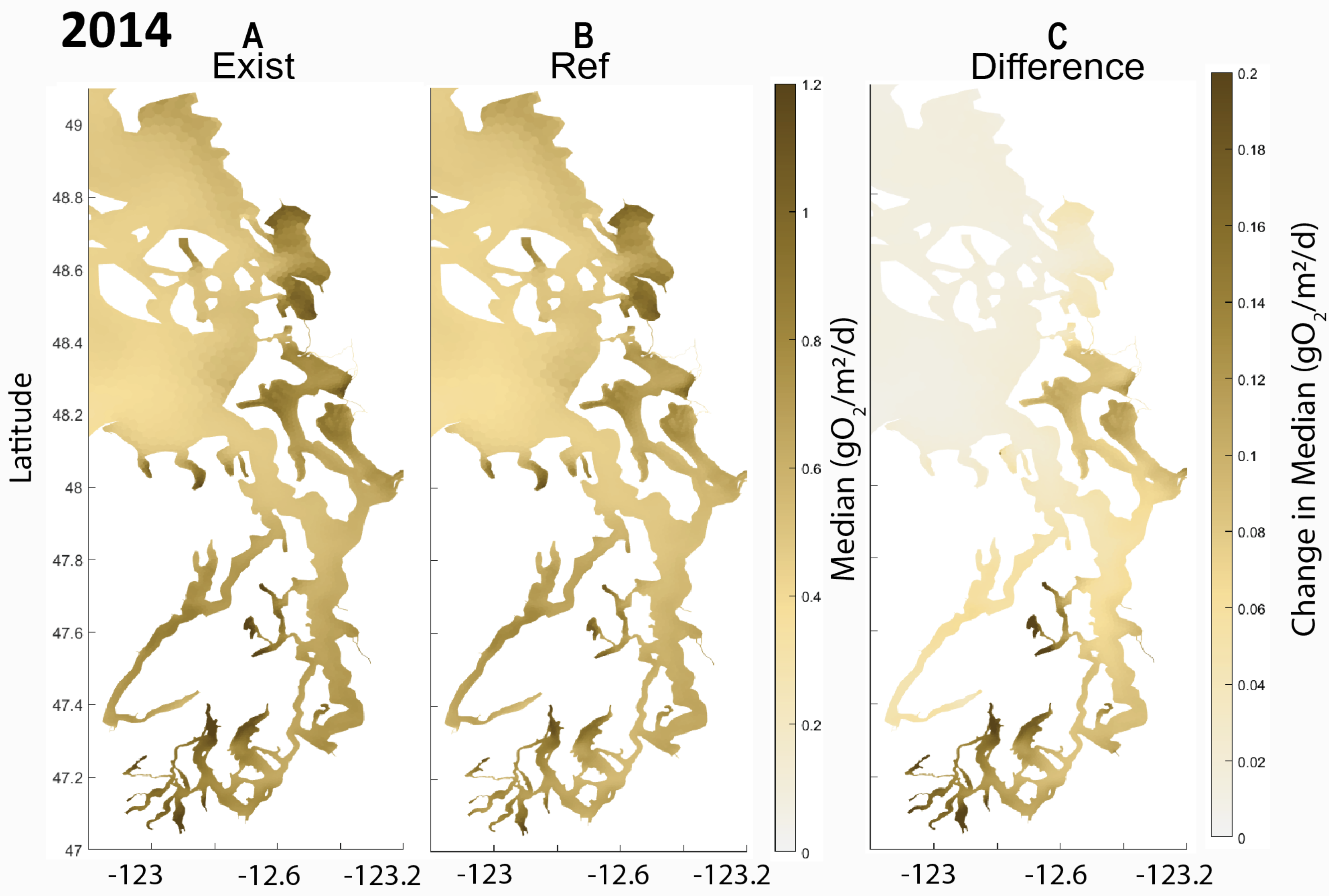




Year	Predicted Mean	Observed Mean	Range Observed	Mean Absolute Error (MAE)	MAE as Percent of Observed Range
2014	1.93	1.94	136.35	1.37	1.0%
2008	2.16	1.61	124.51	1.50	1.2%
2006	2.37	2.37	166.03	1.69	1.0%
2000	1.56	1.48	56.98	0.96	1.7%

Sediment oxygen demand (SOD)

- SOD responds to changes in nutrient loadings.
- SOD is greater in vulnerable inlets.
- Largest differences in terms of SOD response is in vulnerable inlets.



Comparing with SOD observations

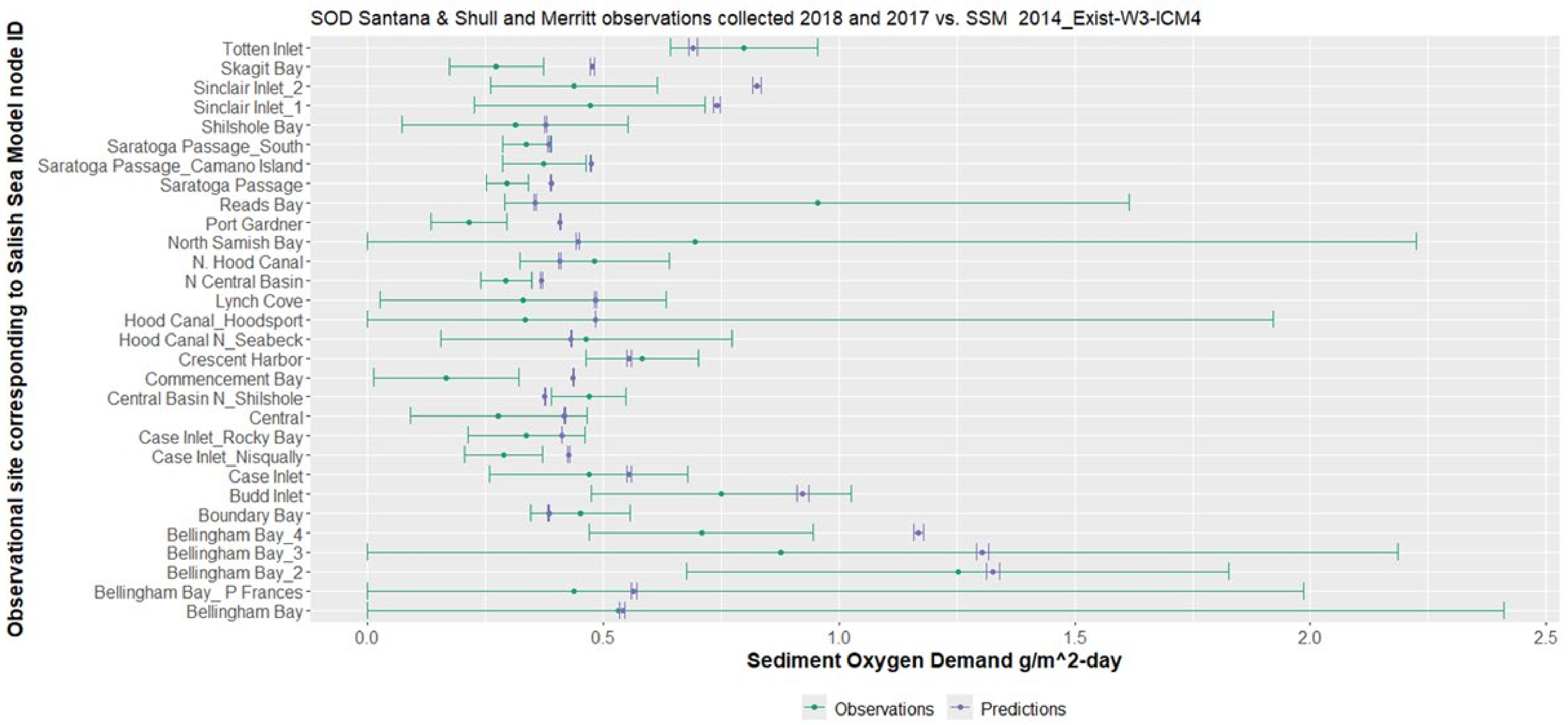
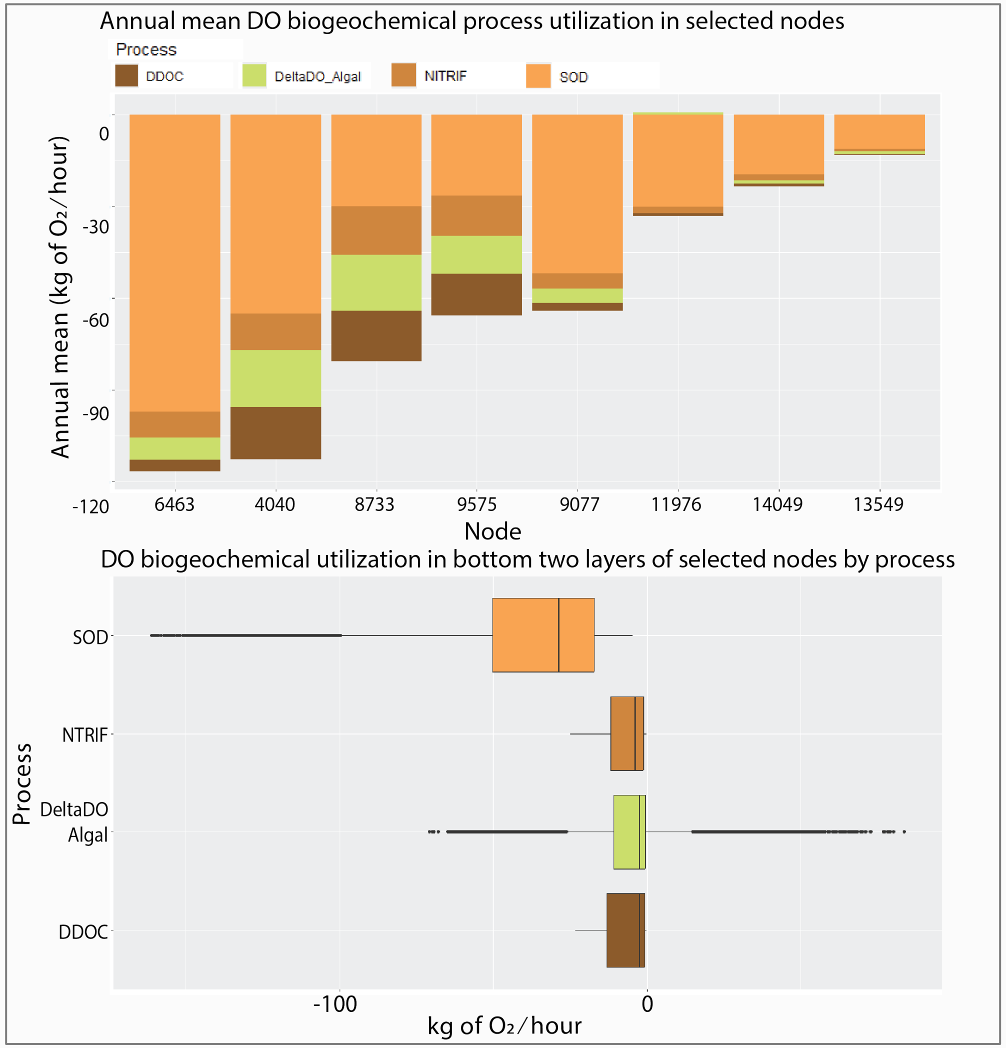


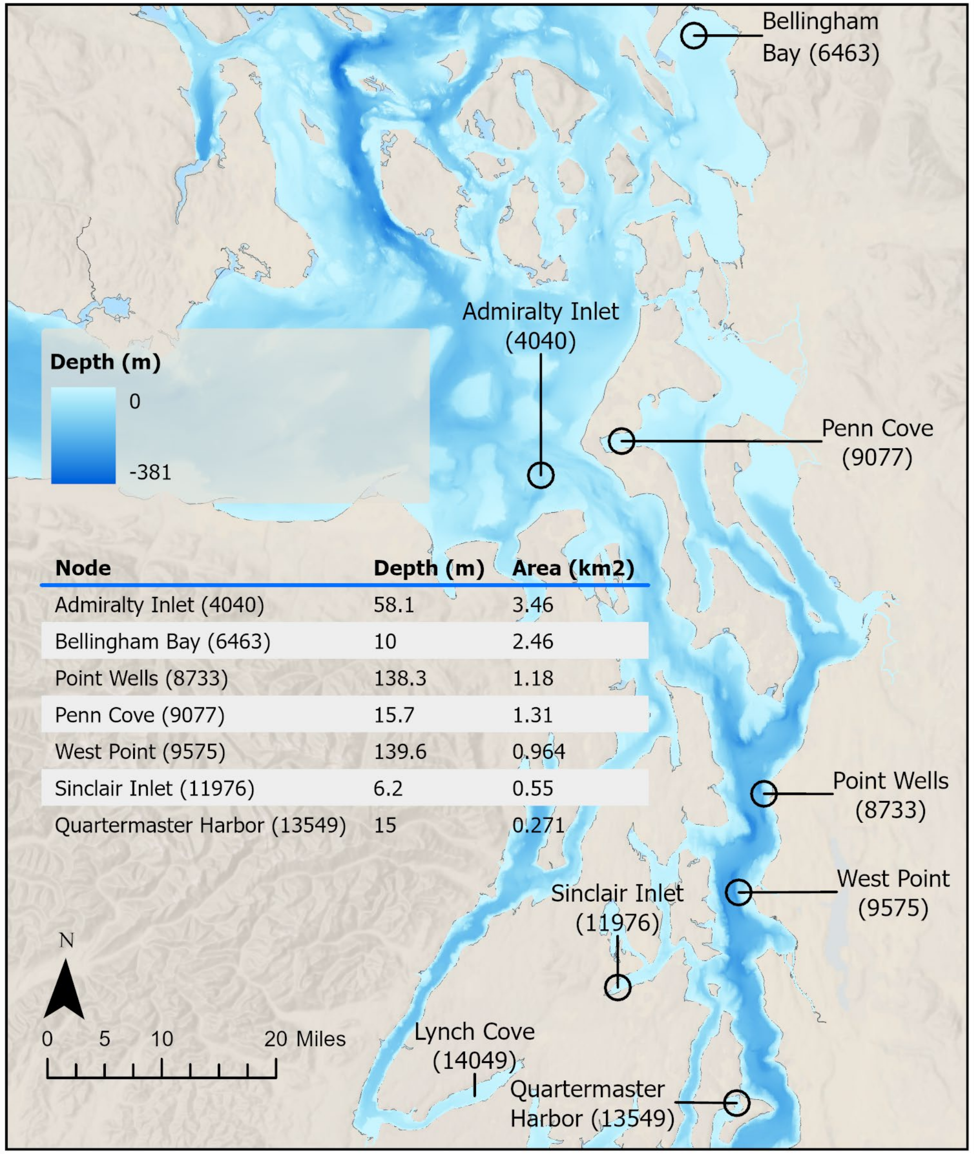
Figure I-12. Comparison of springtime observed (green) and predicted (purple) sediment oxygen demand at 30 stations including confidence intervals. Predictions are based on the existing 2014 scenario. Observations are from Santana and Shull (2023) and Meritt (2017).

SOD predictions match observations well.

DO consumption in bottom waters

Compared to other biogeochemical processes, SOD consumes the highest proportion of DO in bottom waters

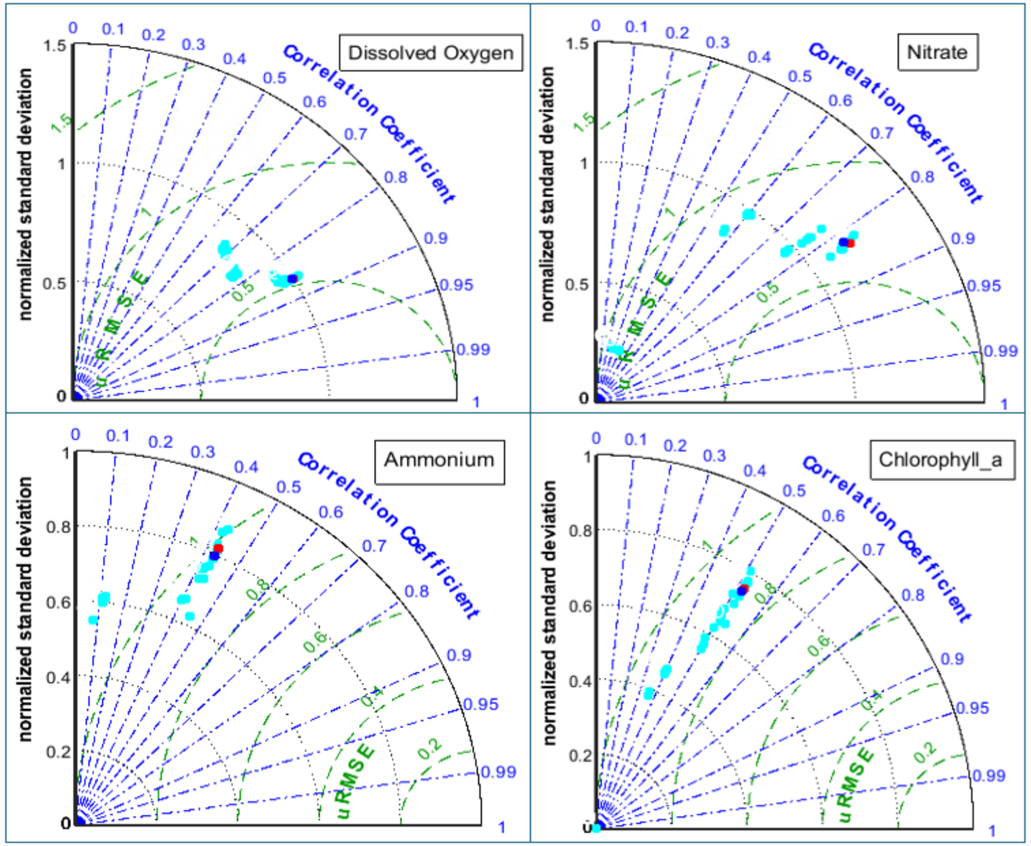




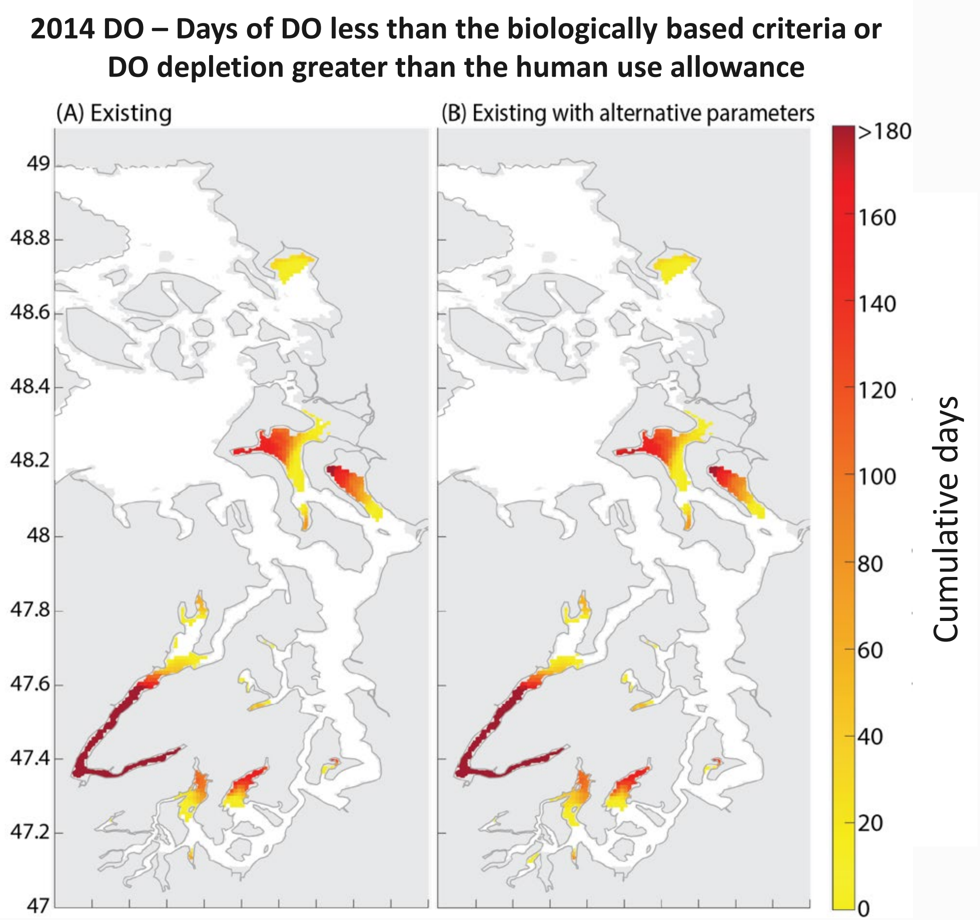
Node	Depth (m)	Area (km2)
Admiralty Inlet (4040)	58.1	3.46
Bellingham Bay (6463)	10	2.46
Point Wells (8733)	138.3	1.18
Penn Cove (9077)	15.7	1.31
West Point (9575)	139.6	0.964
Sinclair Inlet (11976)	6.2	0.55
Quartermaster Harbor (13549)	15	0.271

Sensitivity: modified Monte-Carlo analysis

60 runs: no runs with better skill stats
one run with essentially the same skill stats

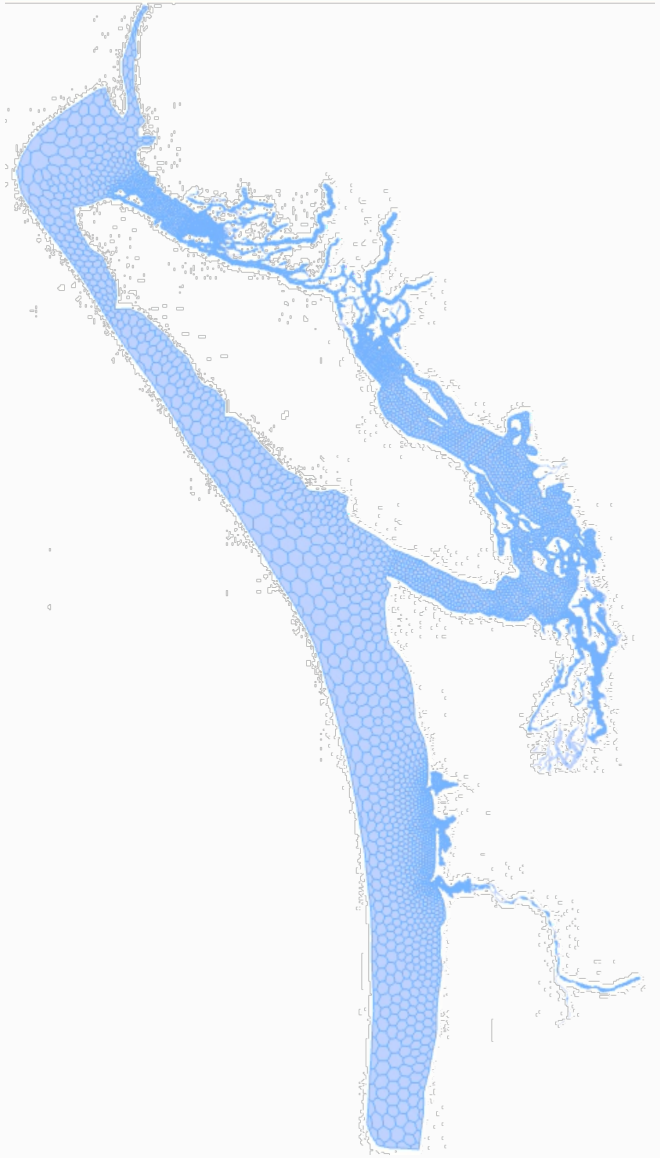


Very similar results



High level closing points

- Model performance improved due to updates.
- Fundamental key physical and biogeochemical processes are well represented in the model.
- Detailed report will be released in June 2025.
- Phase 2 scenarios will be used to inform Puget Sound Nutrient Reduction Plan.



Questions

Contact: c.figueroa@ecy.wa.gov

Photo courtesy: Eyes over Puget Sound, MMU, ECY
Large tidal eddy with organic surface debris. Brown-green bloom mixing around it.
Point White, Bainbridge Island, Sinclair Inlet, 7-28-2014.