



Salish Sea Model (SSM_{HR}) - (shoreline resolving version) Quantification of residence and flushing times

^{1,2} Tarang Khangaonkar &
^{1,2} Lakshitha Premathilake

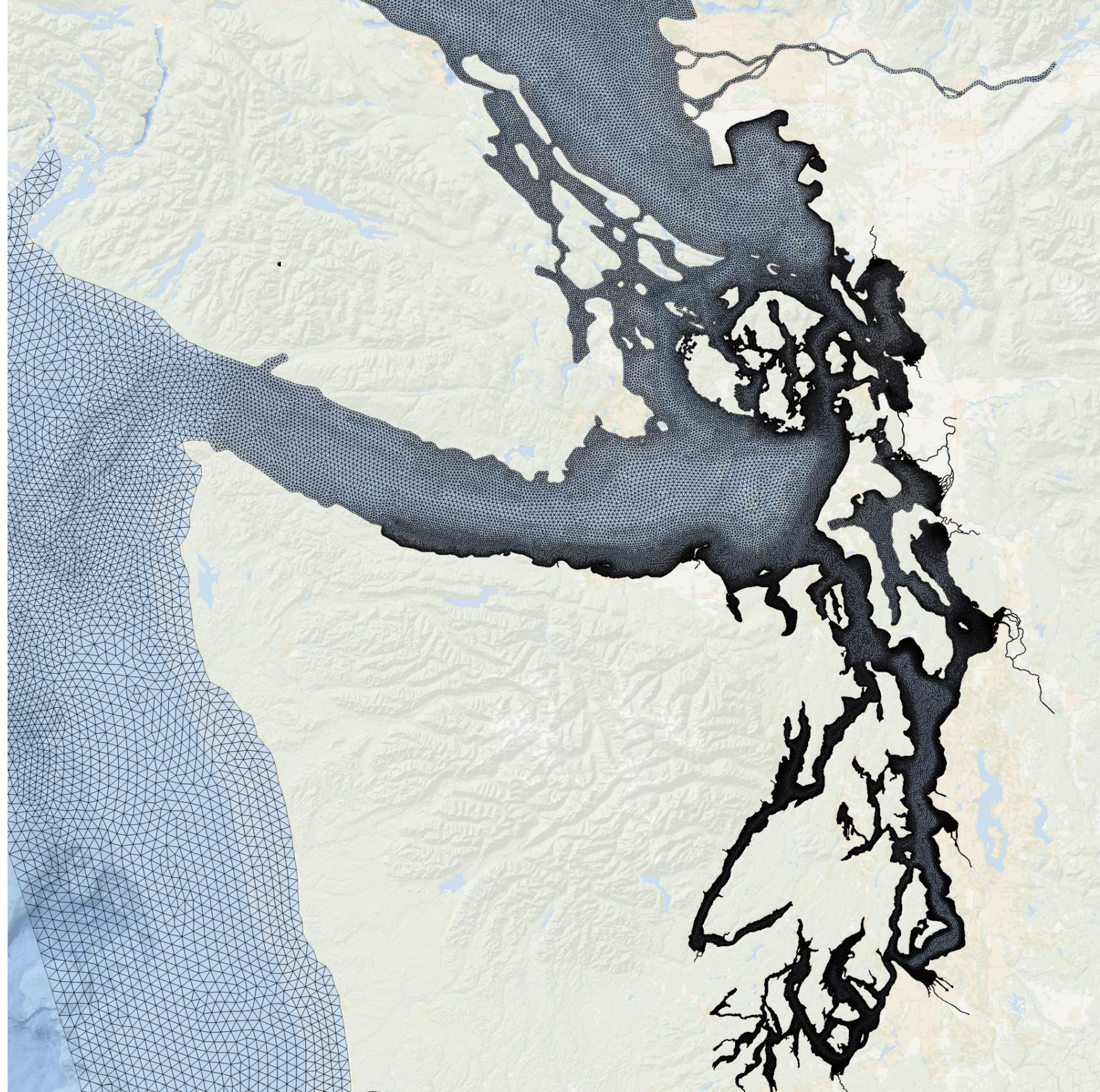
¹Coastal Sciences Division, Pacific Northwest
National Laboratory

²Salish Sea Modeling Center, University of
Washington

South Sound Science Symposium 2022
10/19/22



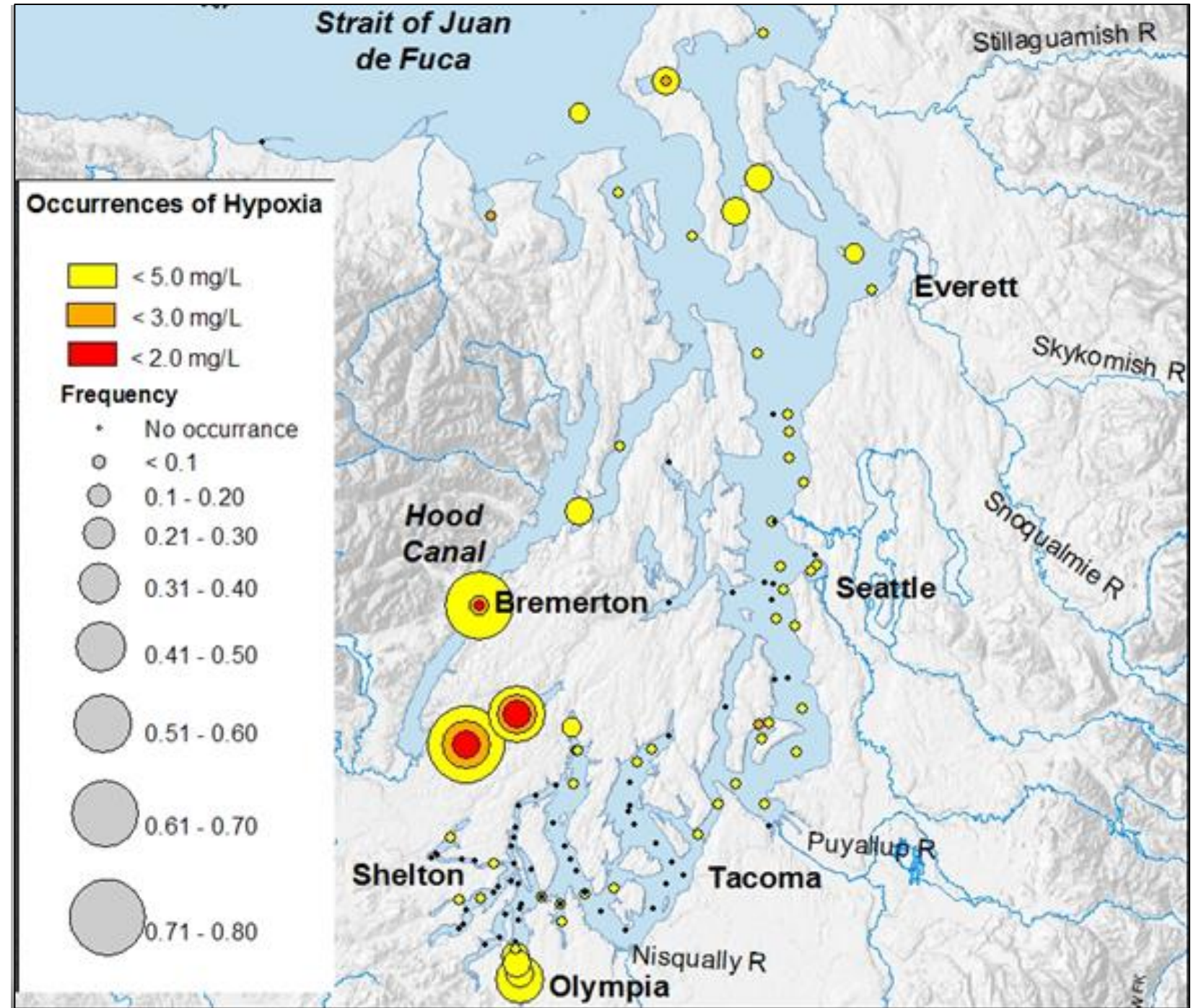
PNNL is operated by Battelle for the U.S. Department of Energy



Salish Sea Model development

Background and motivation

- Initial costal ocean model development work in Puget Sound
 - Effluent fate and transport
 - Nearshore tidal marsh and wetlands restoration
 - ✓ 1996 – to – present
- Hypoxia and nutrient pollution management
 - ✓ 2007 – to present



Source: Puget Sound Partnership 2009 State of the Sound

Salish Sea Model (SSM)

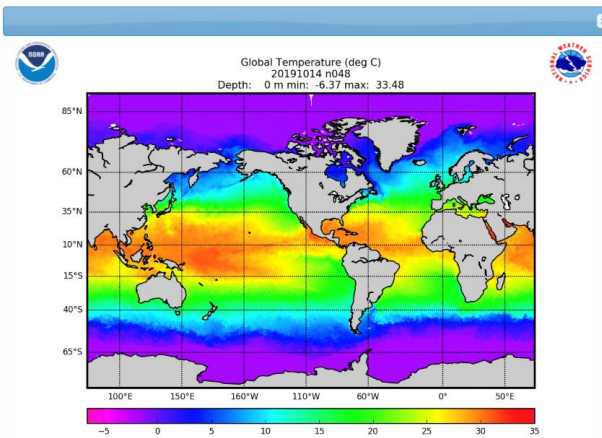
3D Unstructured Finite Volume Coastal Ocean Model

Hydrodynamic Model

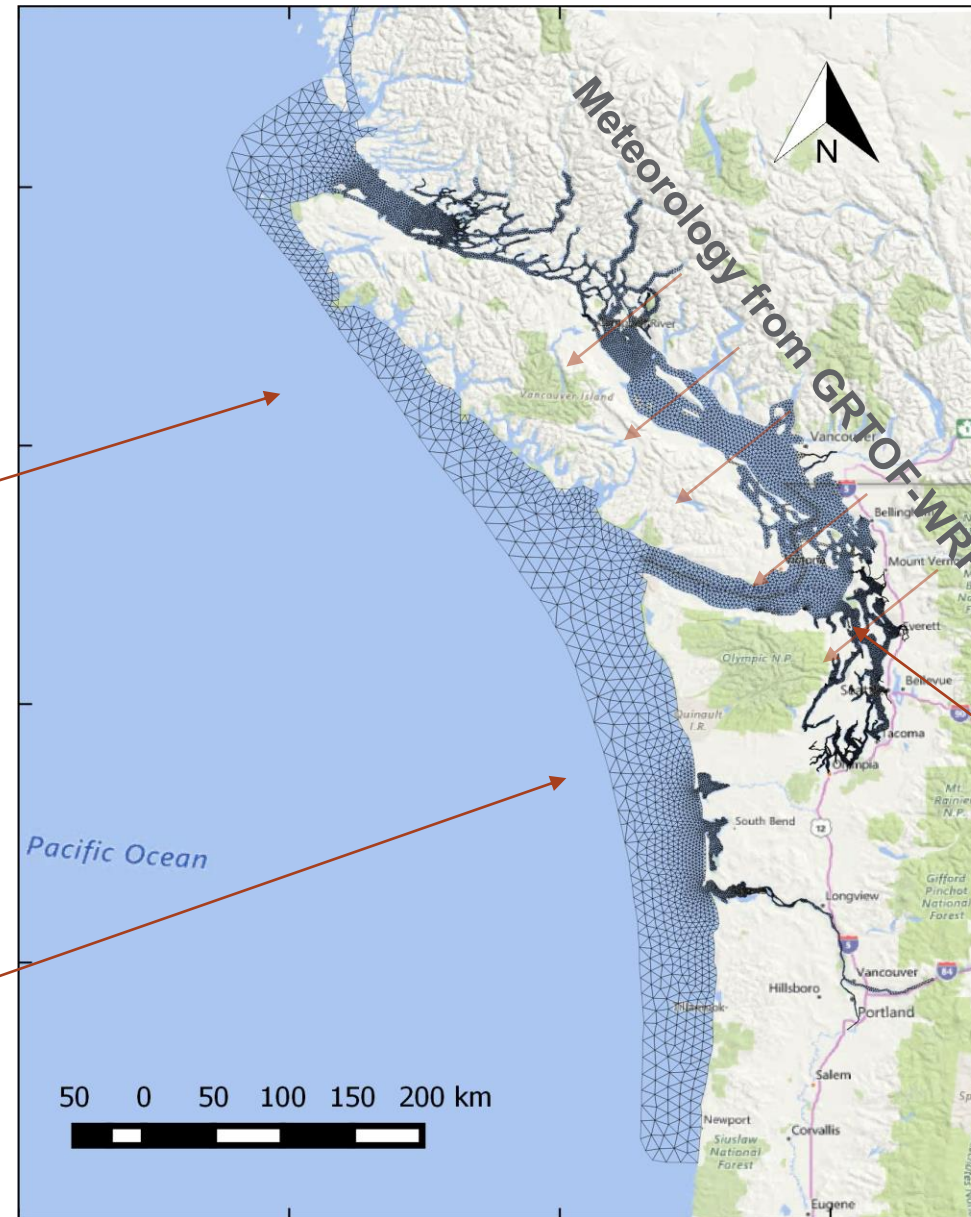
FVCOM (Chen et al 2003)

- Tides, Currents
- Salinity, Temperature

Ocean boundary T, S from HYCOM



Boundary Tides from NOAA & USACE / ENPAC



[Khangaonkar et al. (2018) – JGR Oceans]

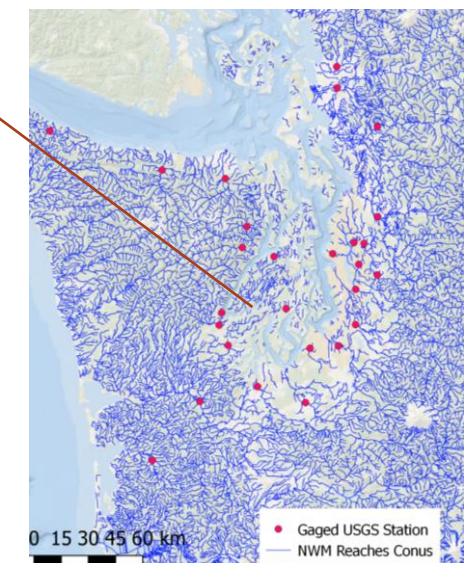
Salish Sea Model – <https://ssmc-uw.org/>

Water Quality Model

FVCOM-ICM (Kim & Khangaonkar 2011)

- Nutrients, carbon, algae
- Detritus, Zooplankton, larvae
- DO, pH, Toxics (PCBs),
- Sediments, Oil Spills, ...

River and wastewater inflows from Ecology and NOAA Hydrology Models



Need for a regional high resolution operational and forecasting model

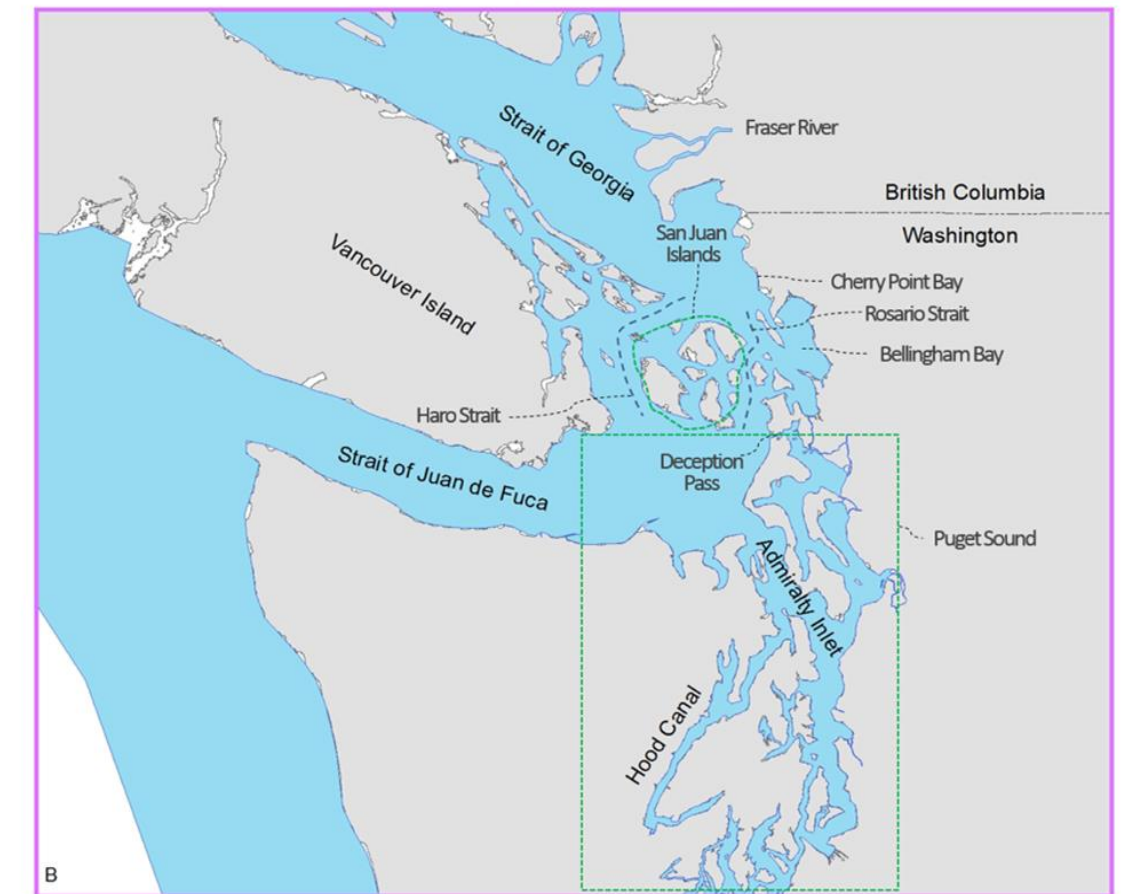
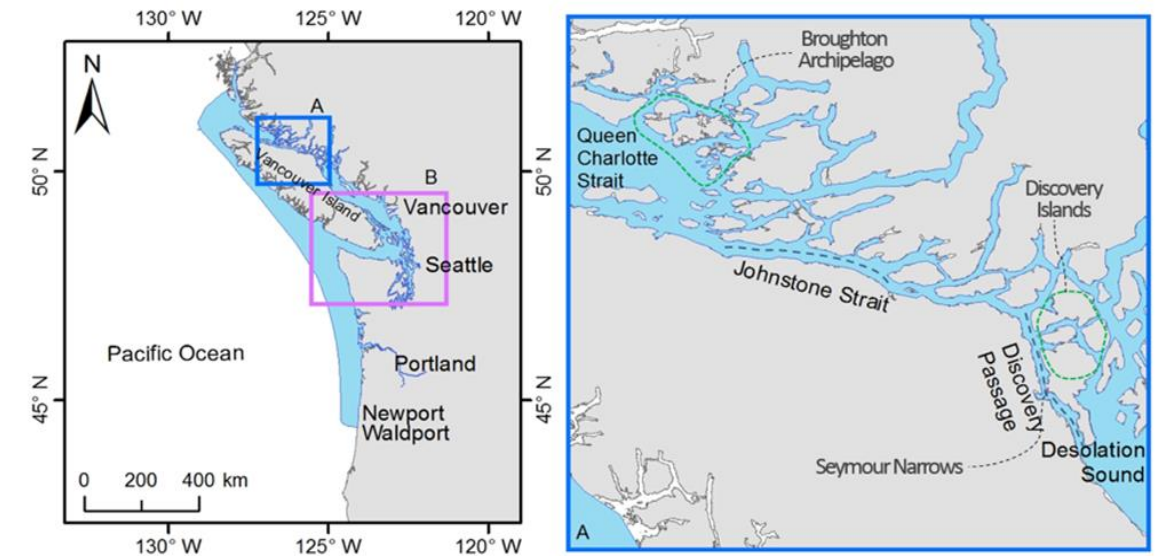
- Increased risk of maritime accidents
 - Projected 7-fold increase in tanker traffic in the region
 - ✓ Kinder Morgan Pipeline expansion
- Increased frequency of WWTP failures
 - King County West point WWTP (2/2017, 1/2021)

NOAA IOOS Grant (COMT Program) - 2018

Objective: Accurate real-time predictions for maritime emergency response (eg. Oil spills)

Harmful algal blooms

Source: <https://ecology.wa.gov/>



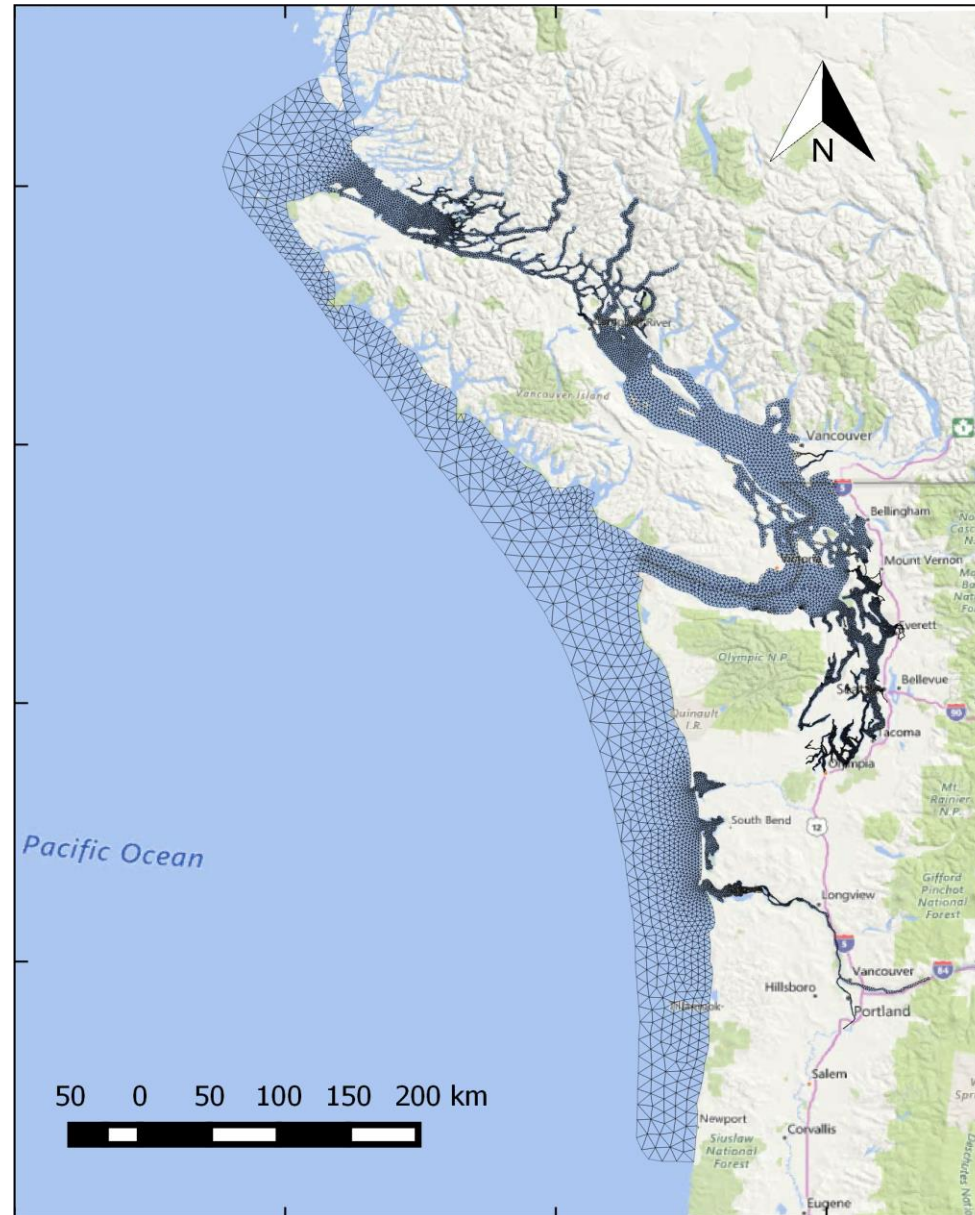
Oil spill Mitigation

Source: <https://ecology.wa.gov/>

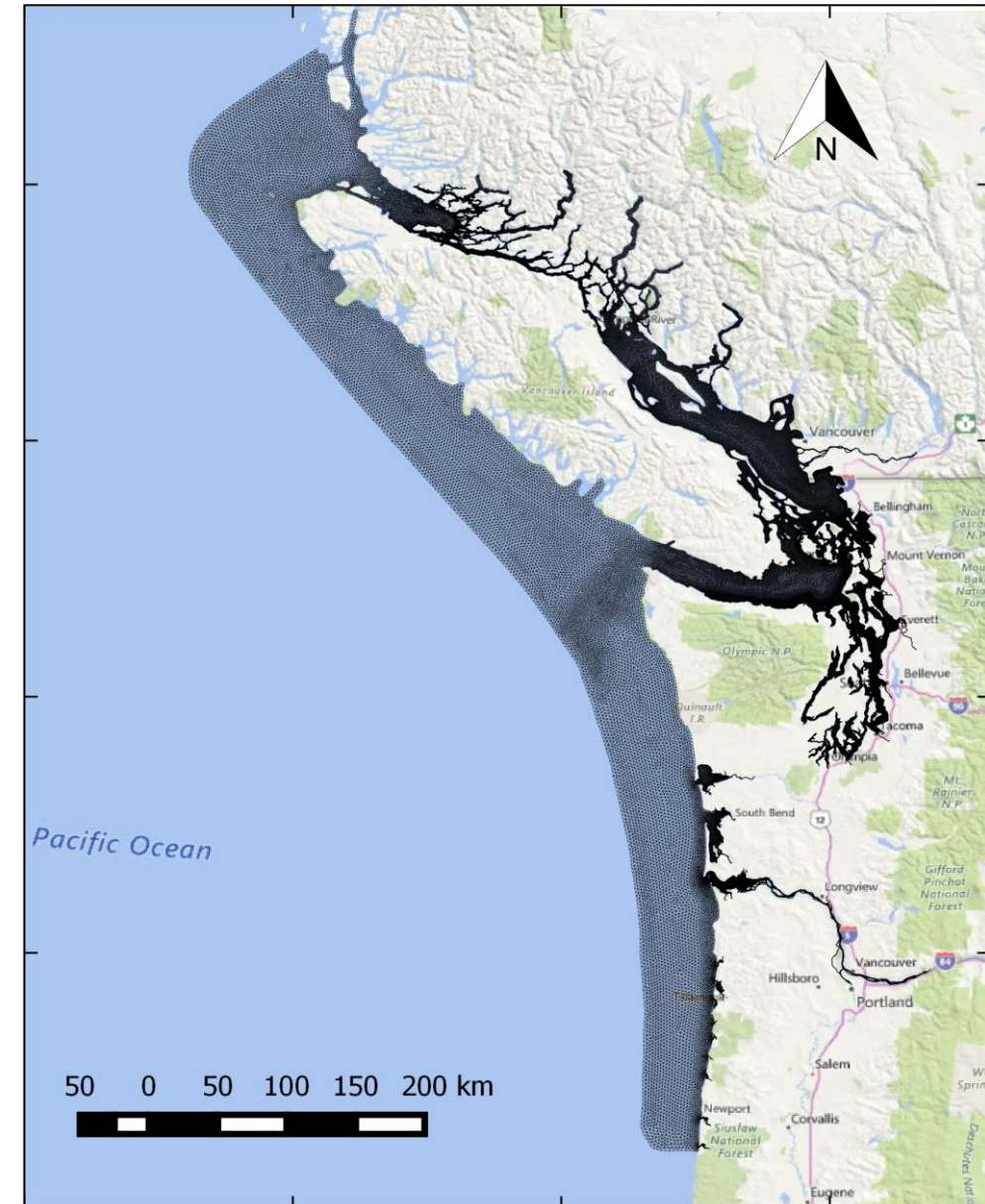
Salish Sea Model grid refinement (SSM_{HR})

Salish Sea and PNW Shelf

Original SSM Grid (16k Nodes)

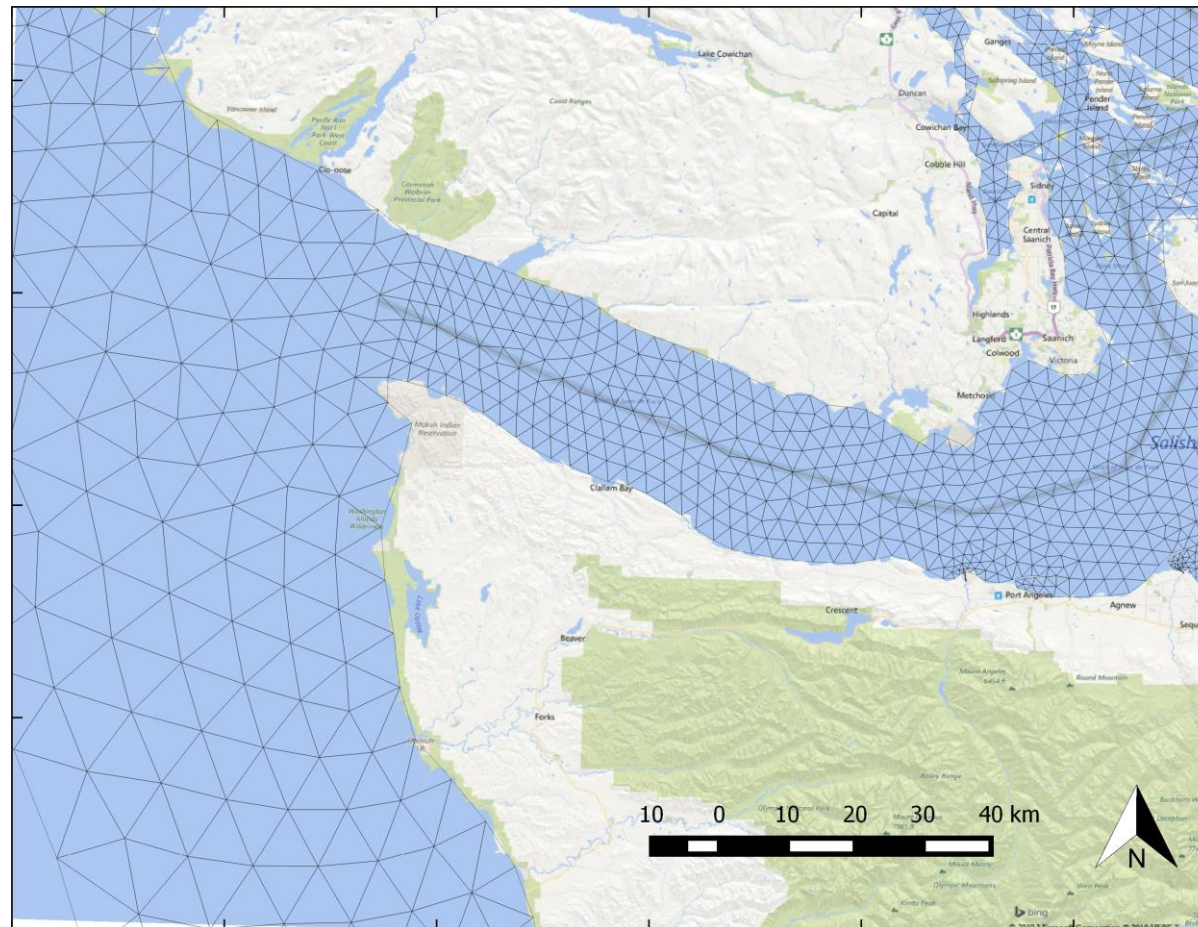


SSCOFS Grid (220k Nodes)

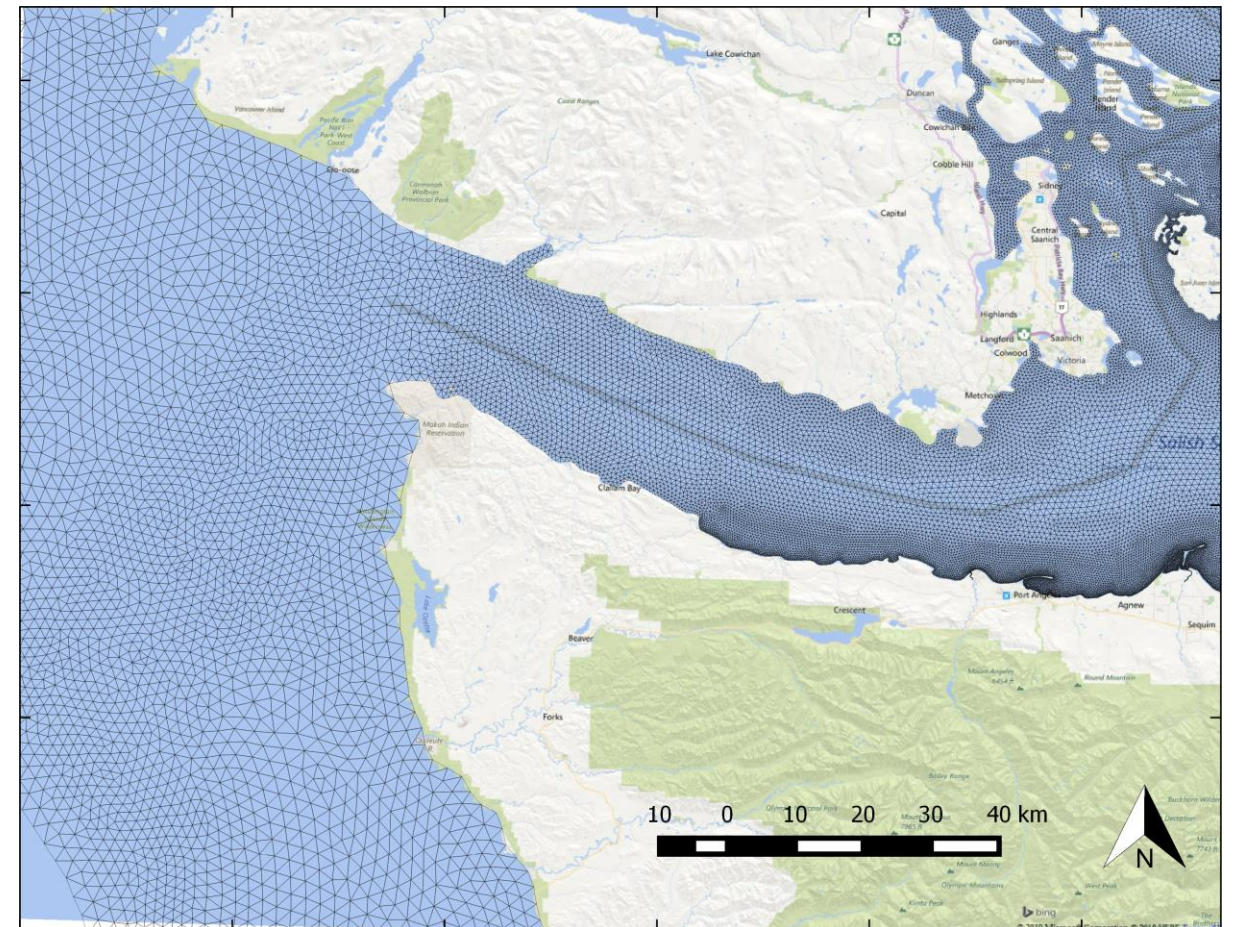


Salish Sea Model grid refinement (SSM_{HR}) Strait of Juan de Fuca

Original SSM Grid

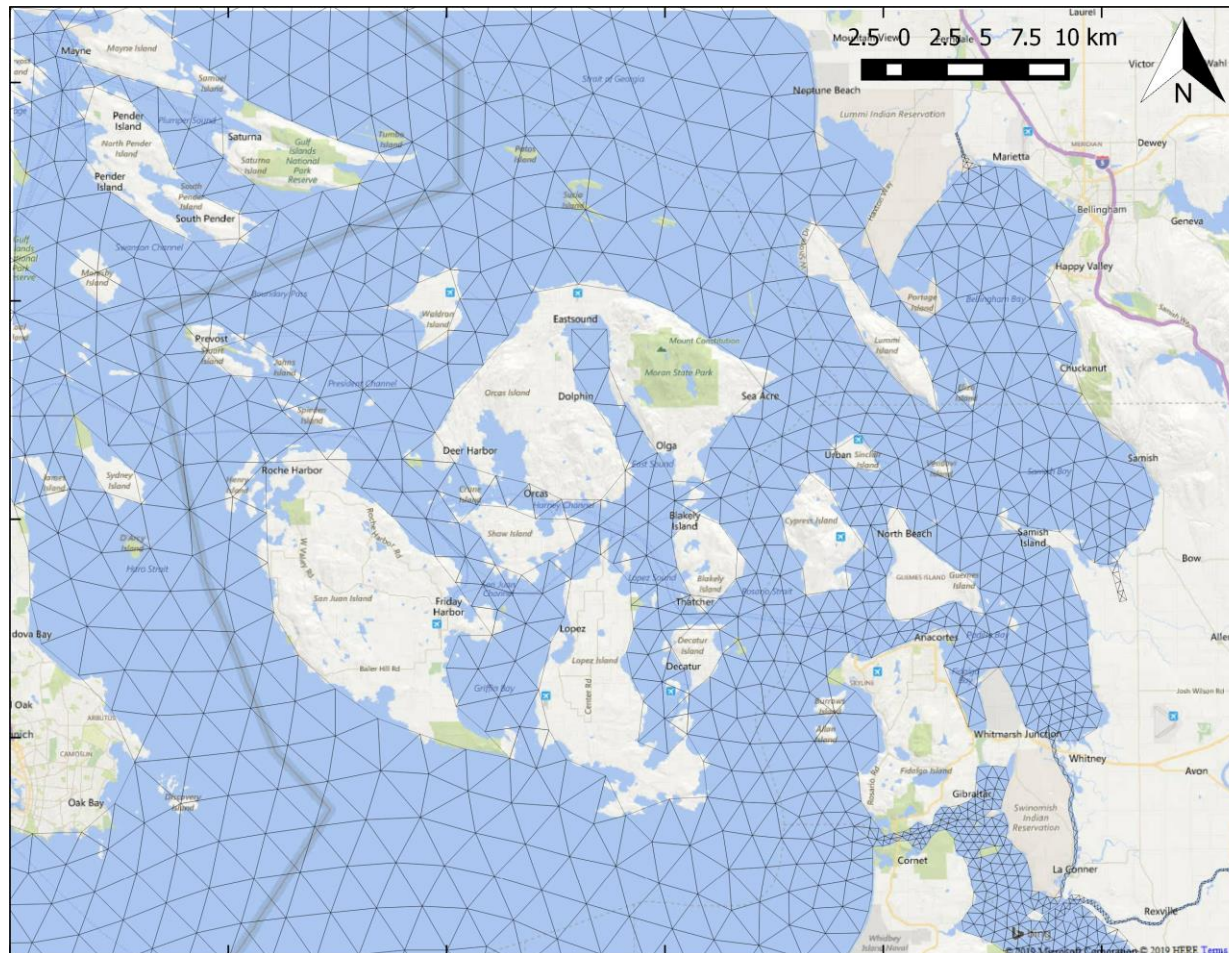


SSM-OFS Grid

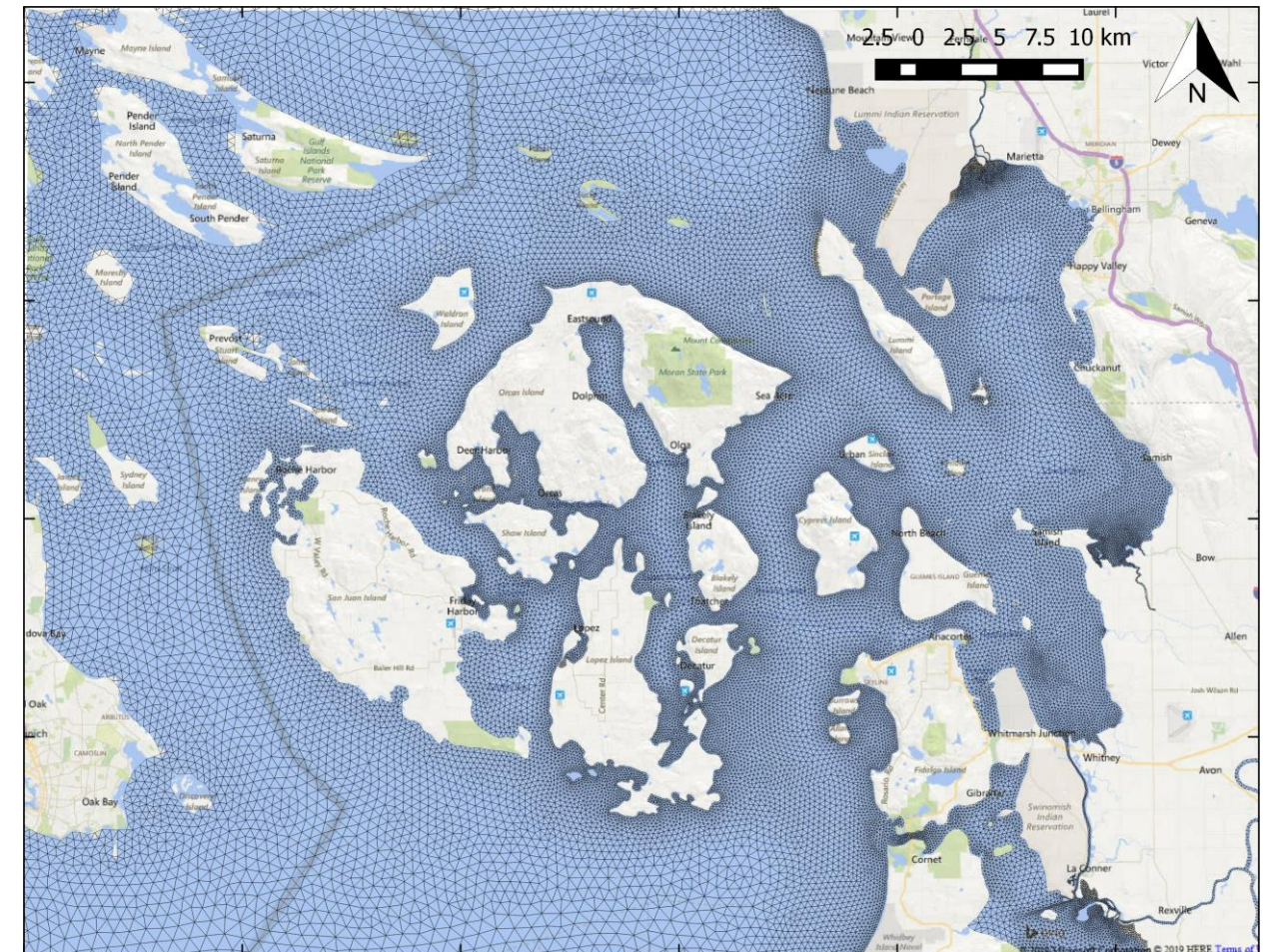


Salish Sea Model grid refinement (SSM_{HR}) Strait of Juan de Fuca

Original SSM Grid

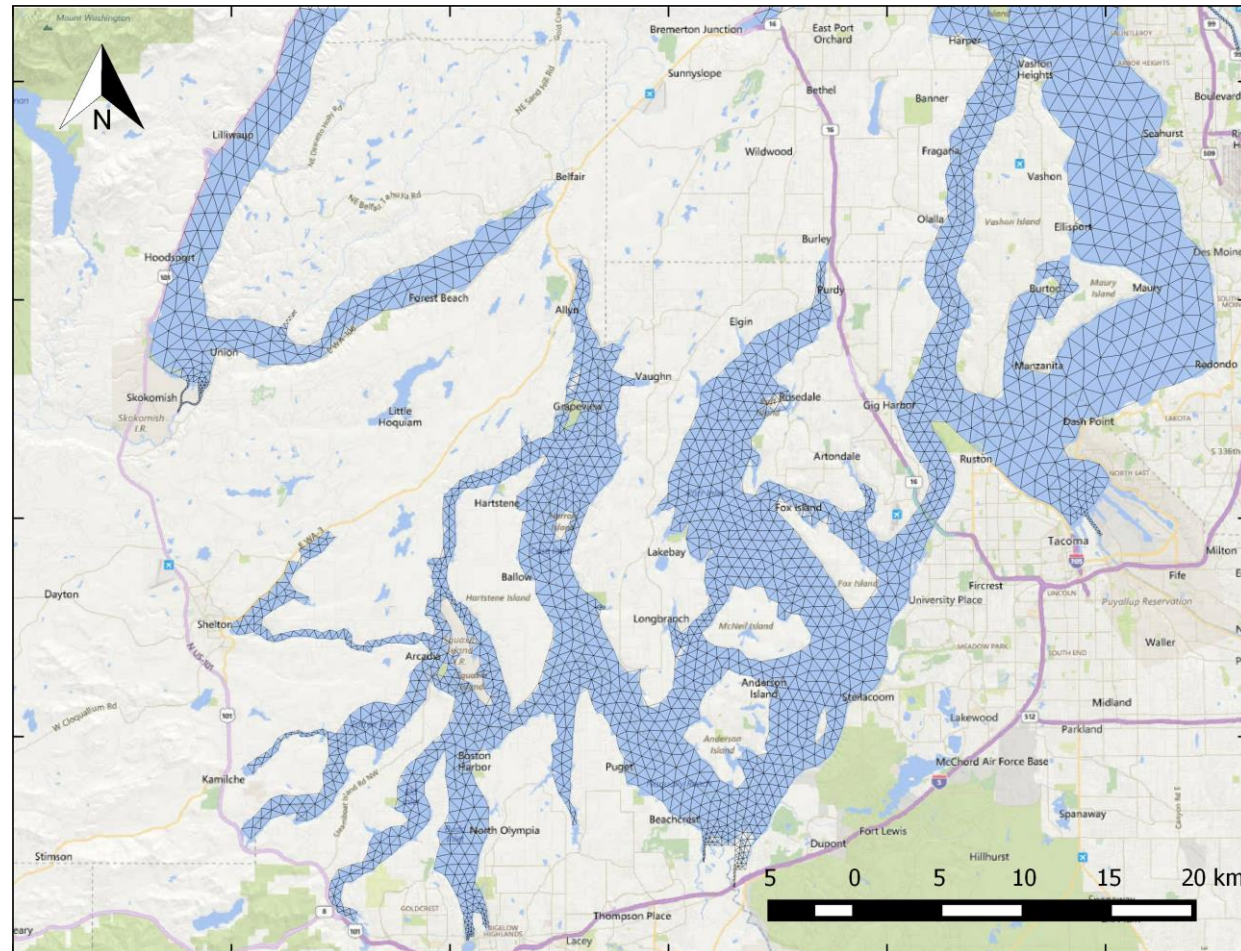


SSM_{HR} Grid

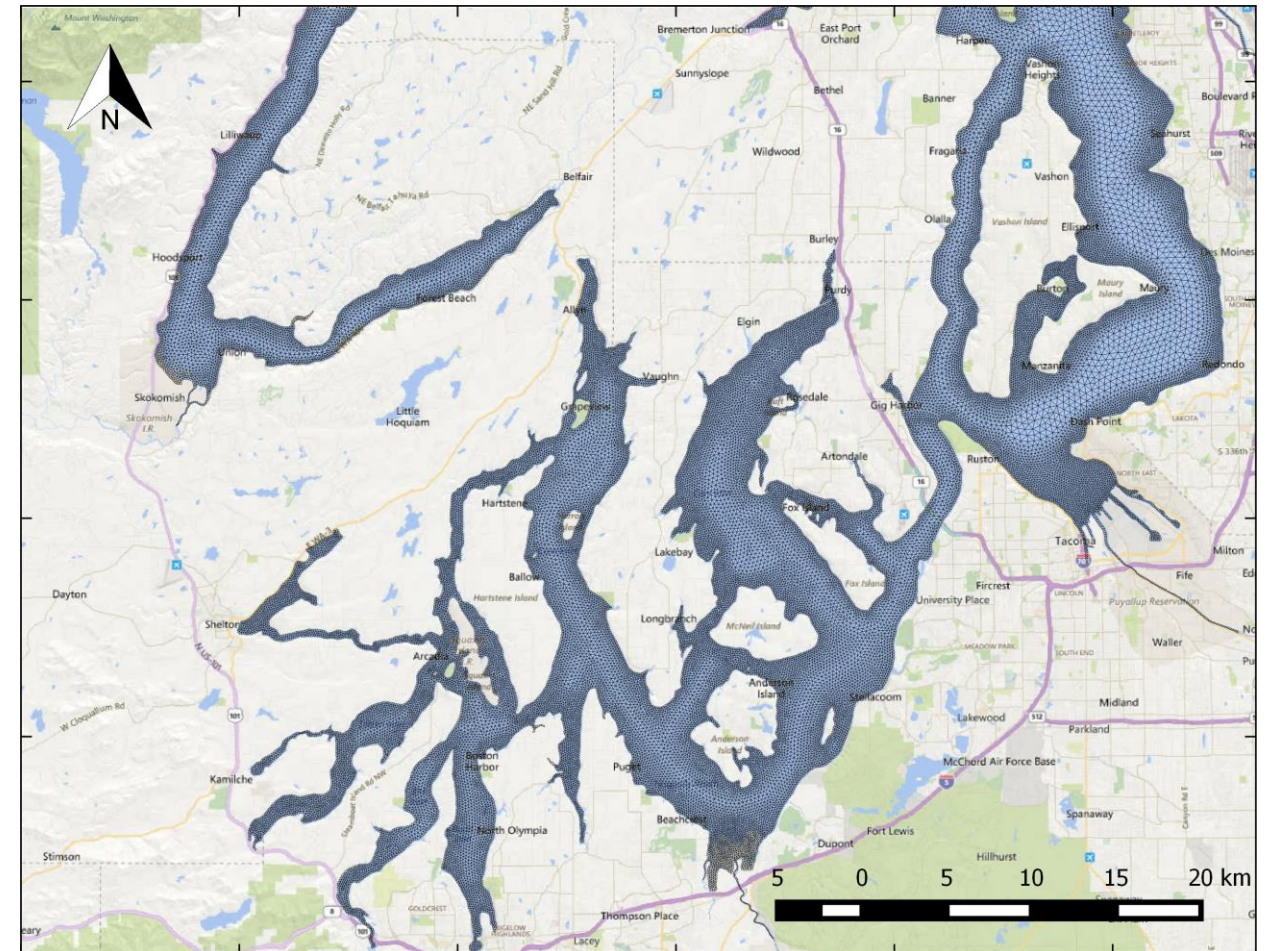


Salish Sea Model grid refinement (SSM_{HR}) South Puget Sound

Original SSM Grid



SSM_{HR} Grid

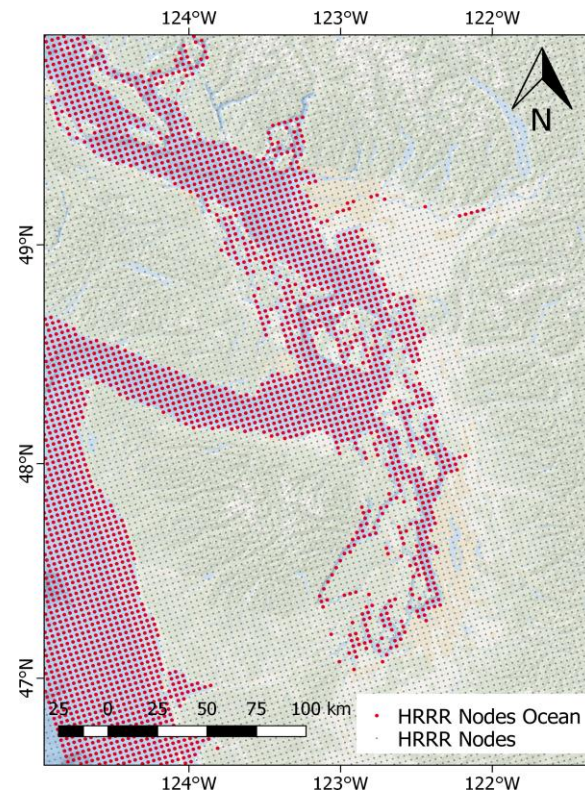


Salish Sea Model (SSM_{HR})

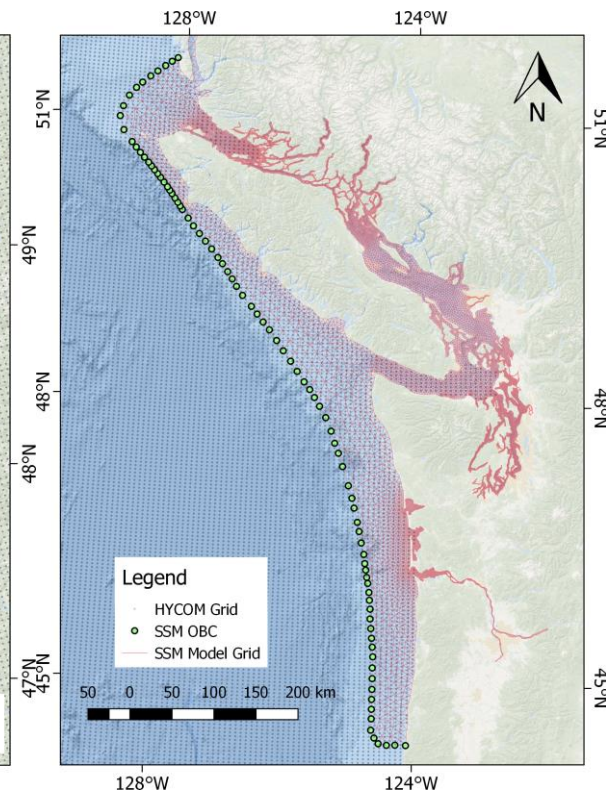
High resolution version

Premathilake and Khangaonkar (2022)– *Estuarine Coastal and Shelf Science*

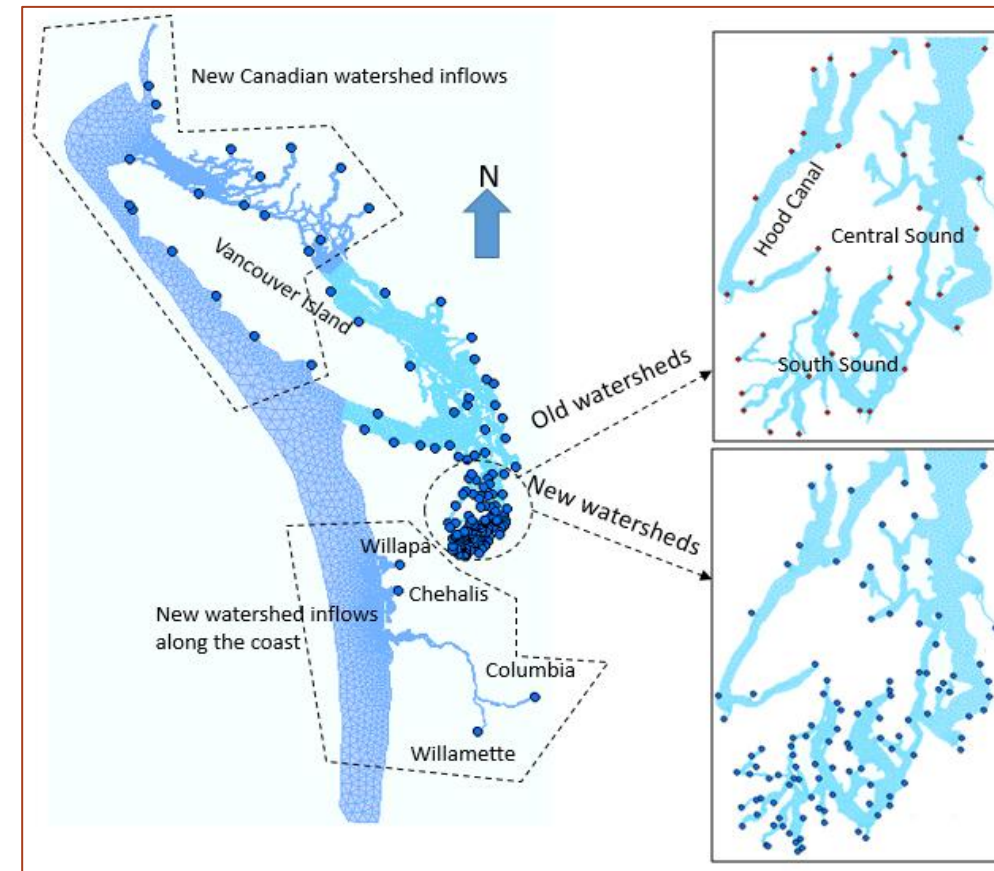
- Based on established Salish Sea Model
- Model is forced with operational products



Meteorological Forcing
NOAA CSDL Data –
HRRR/RAP



Open Ocean Boundary
Forcing NOAA CSDL
Data – G-RTOFS

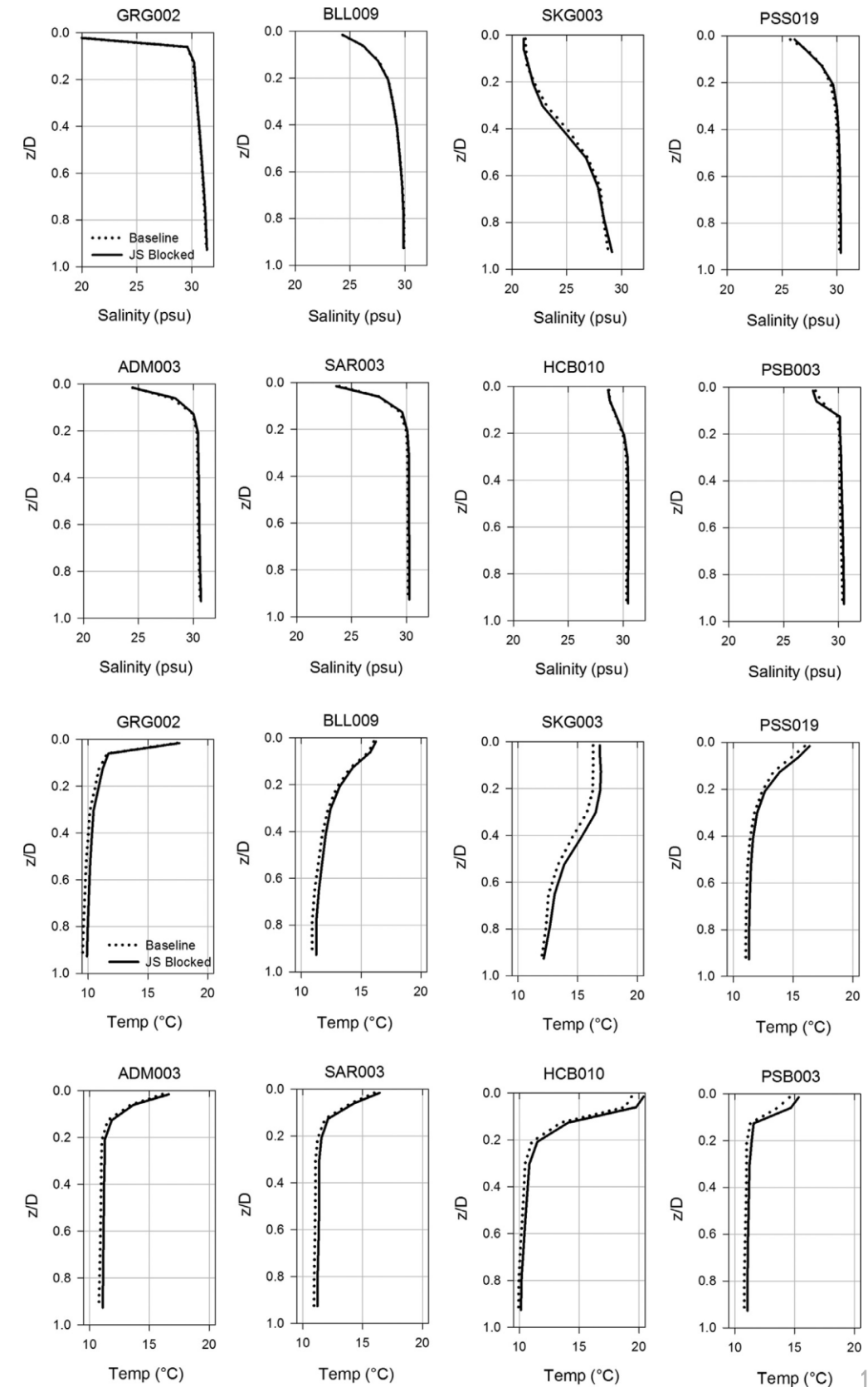
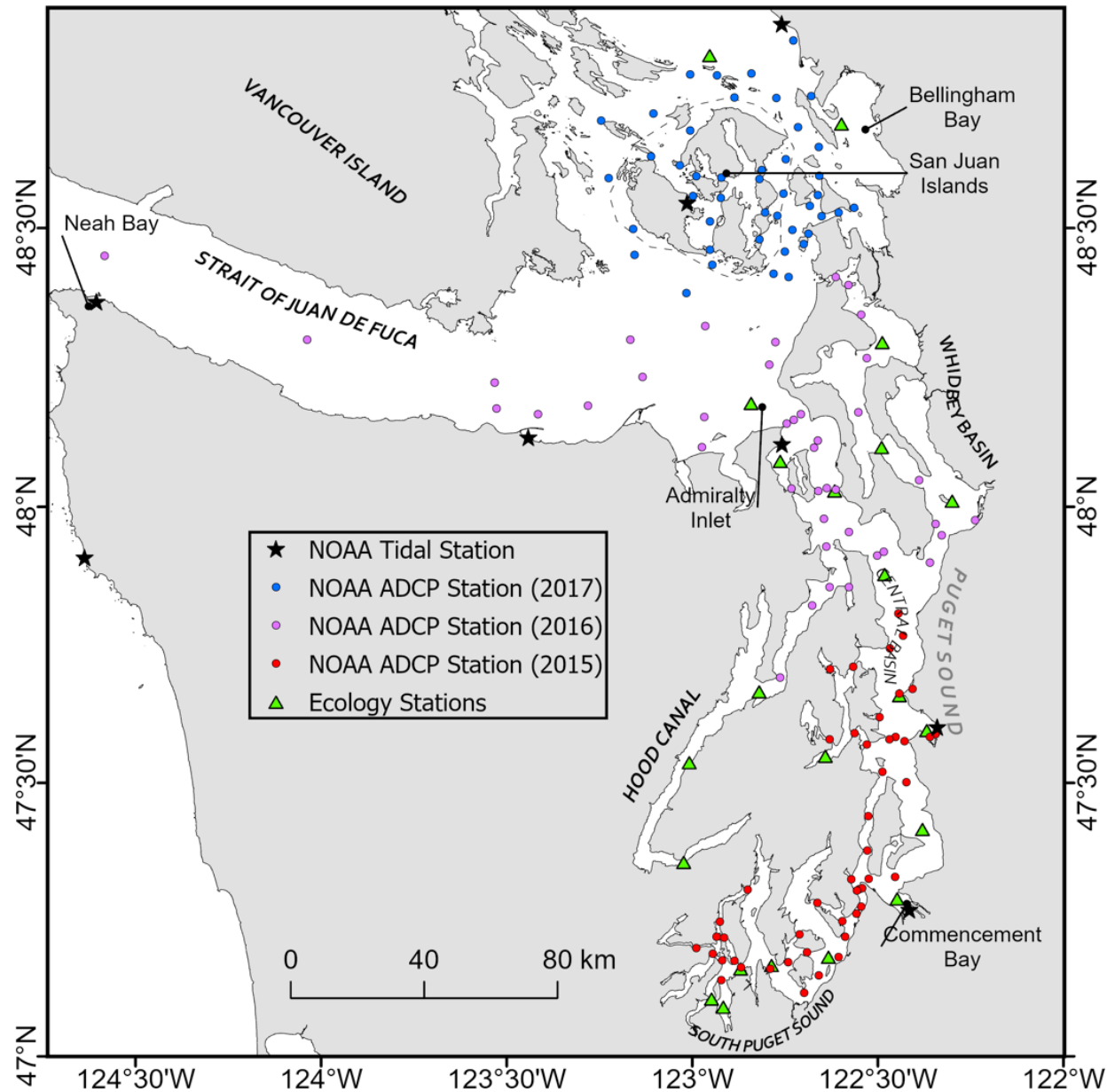


161 Freshwater
Inflows –
NWM

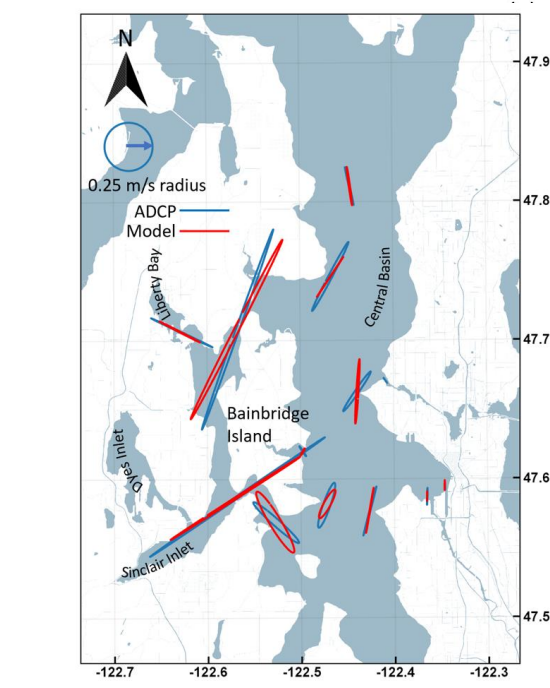
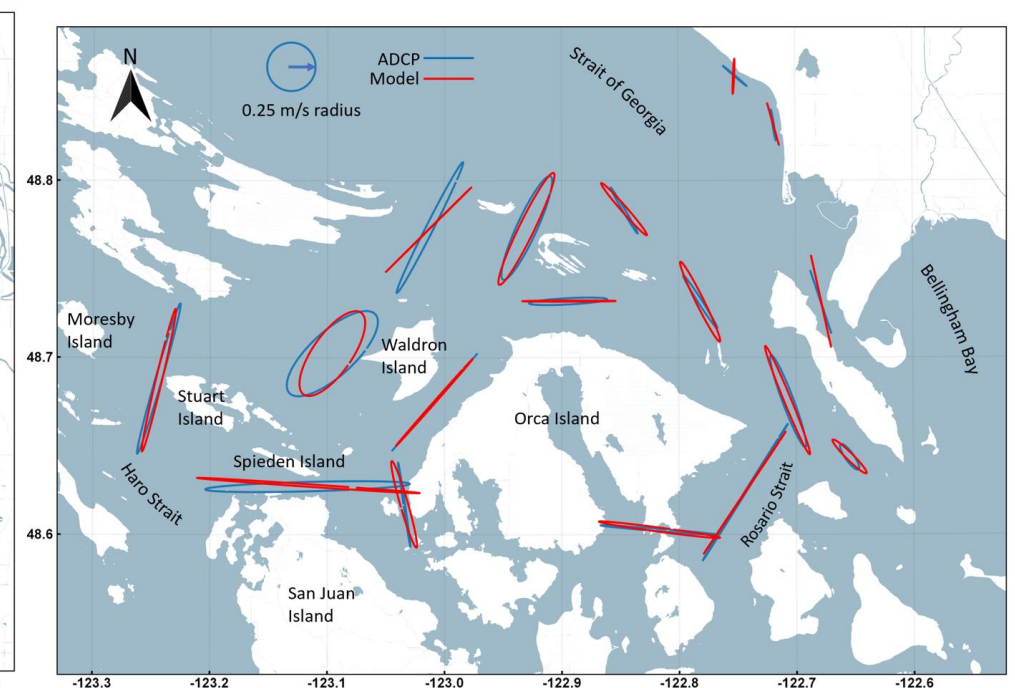
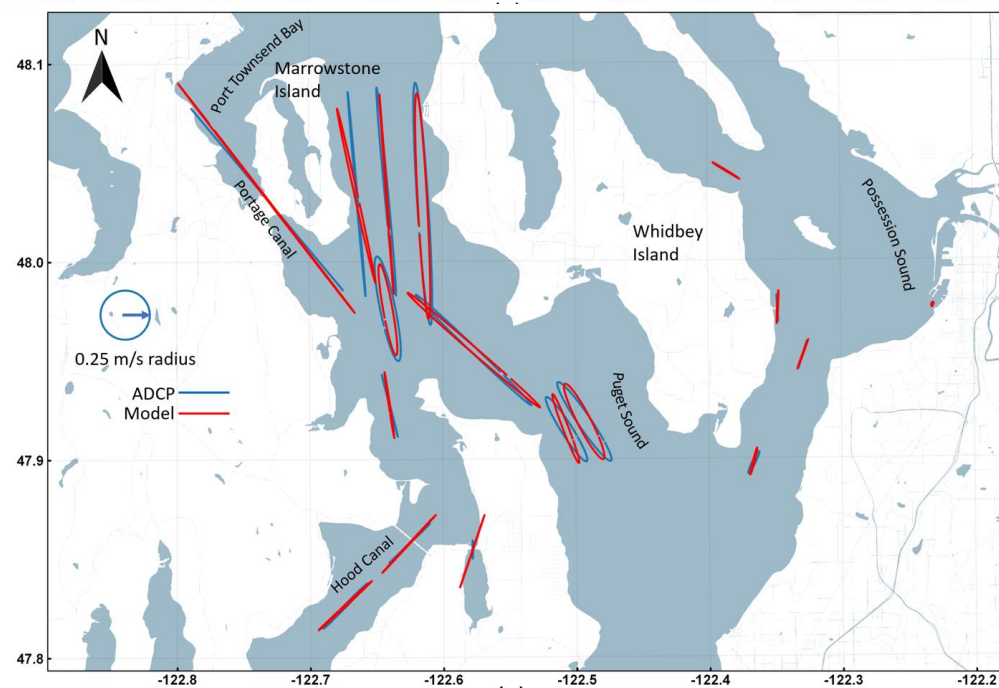
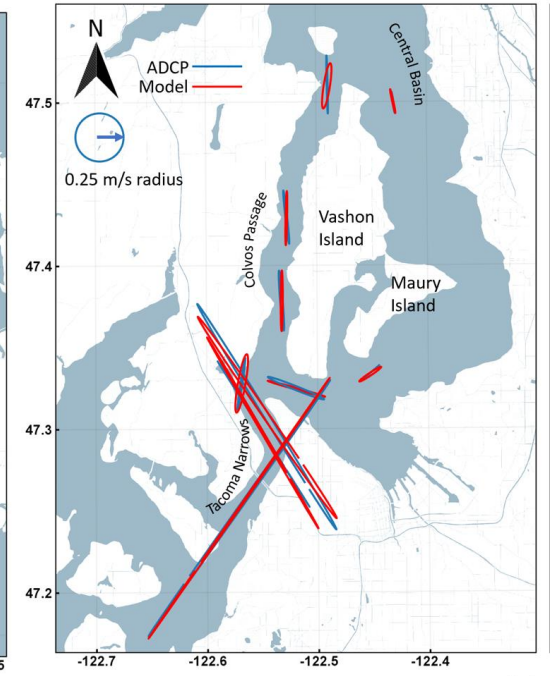
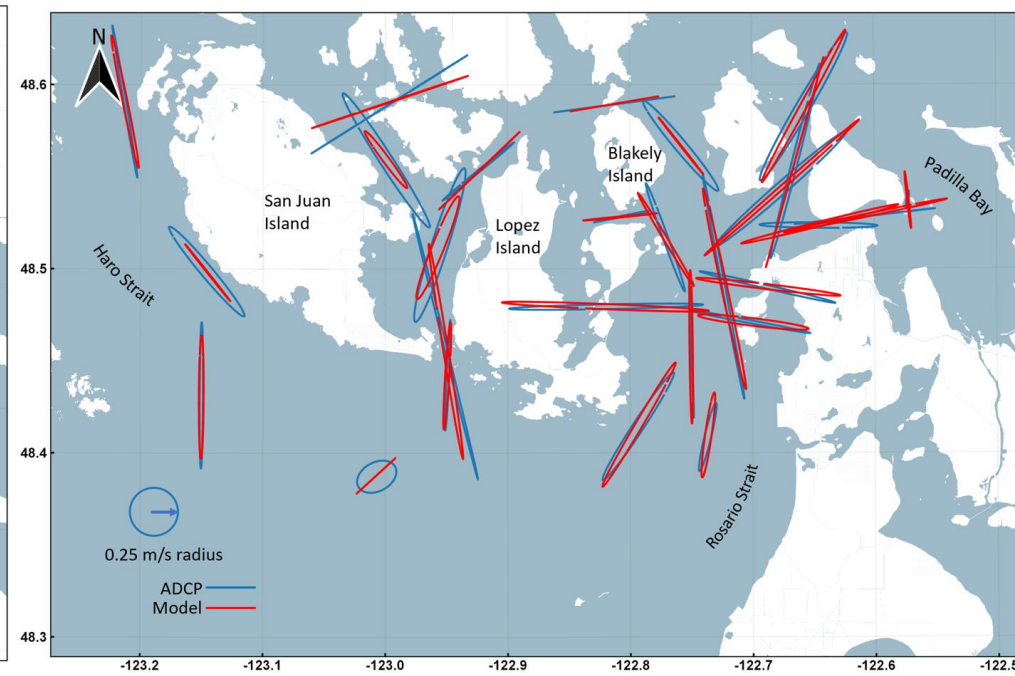
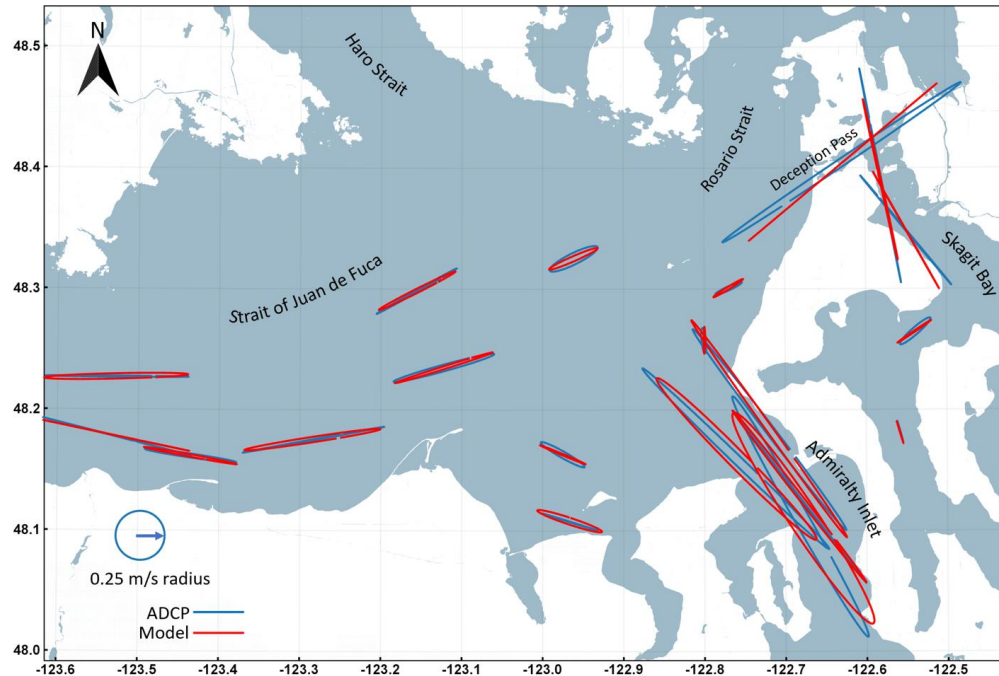
99 WWTPs -
Washington
State
Department of
Ecology

Skill assessment

NOAA procedures

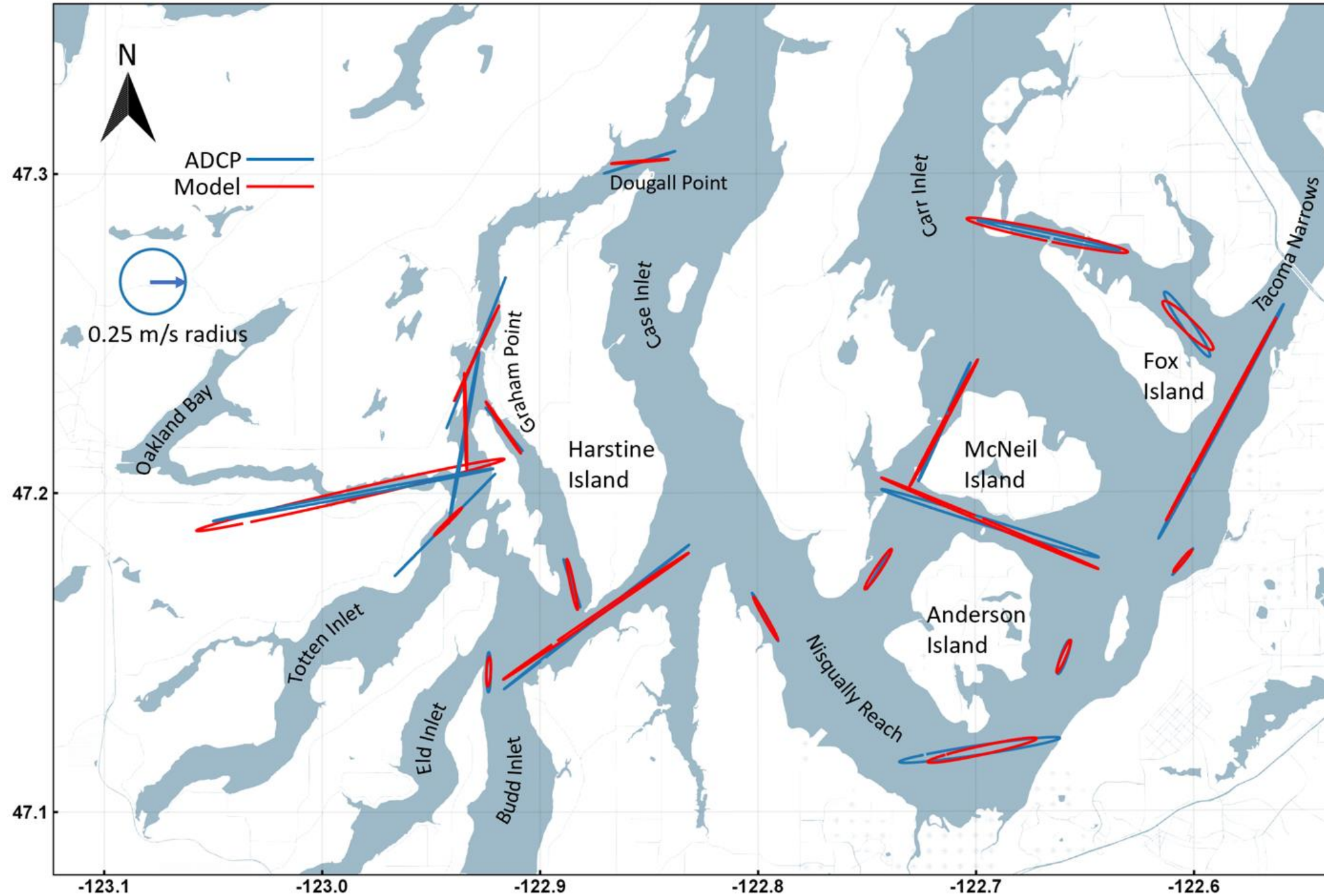


Model validation – tidal ellipses

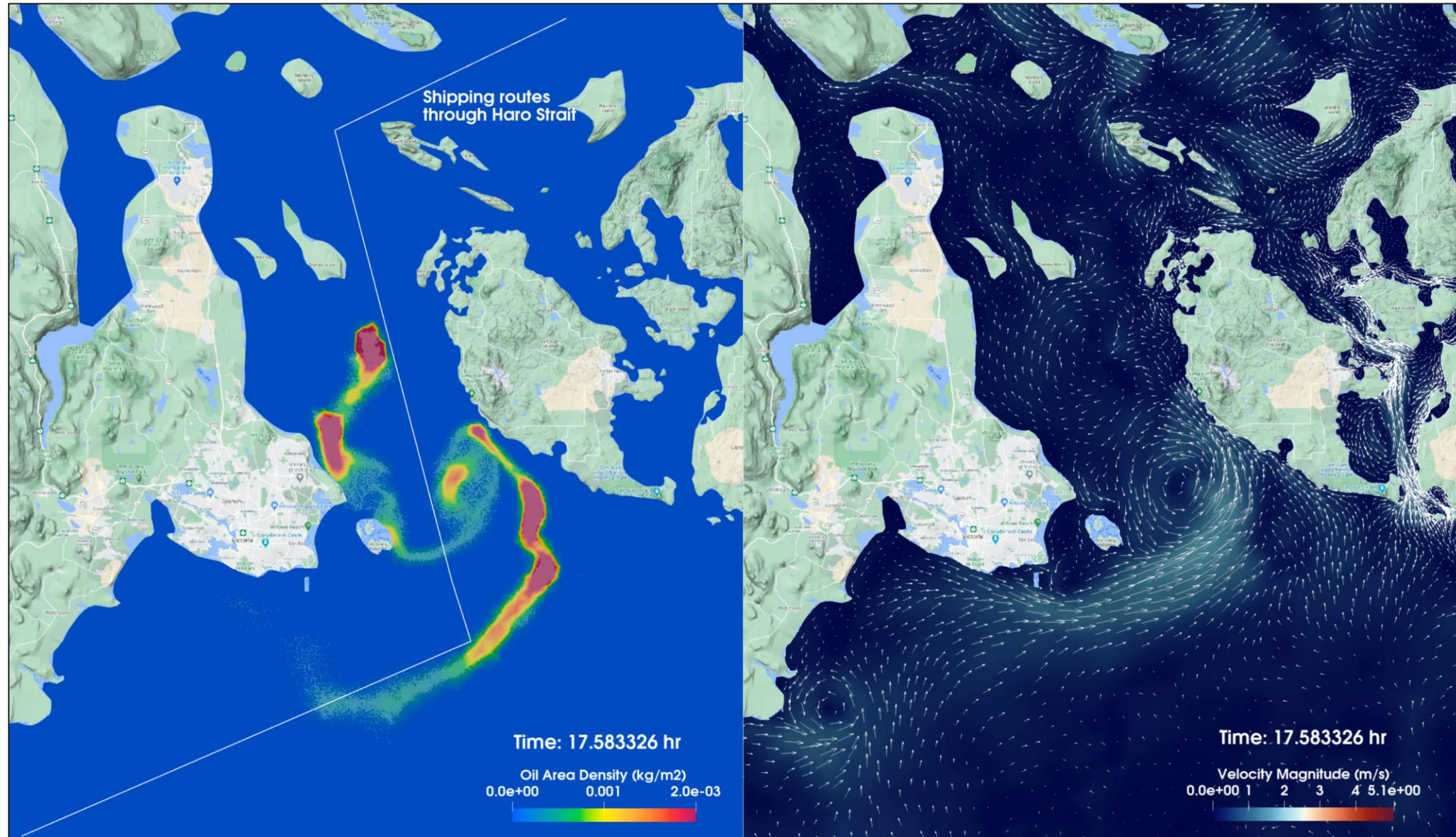


Model validation – tidal ellipses

South Puget Sound



Currents and plume transport Strait of Juan de Fuca



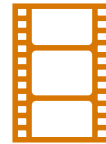
Surface currents behavior Haro Strait



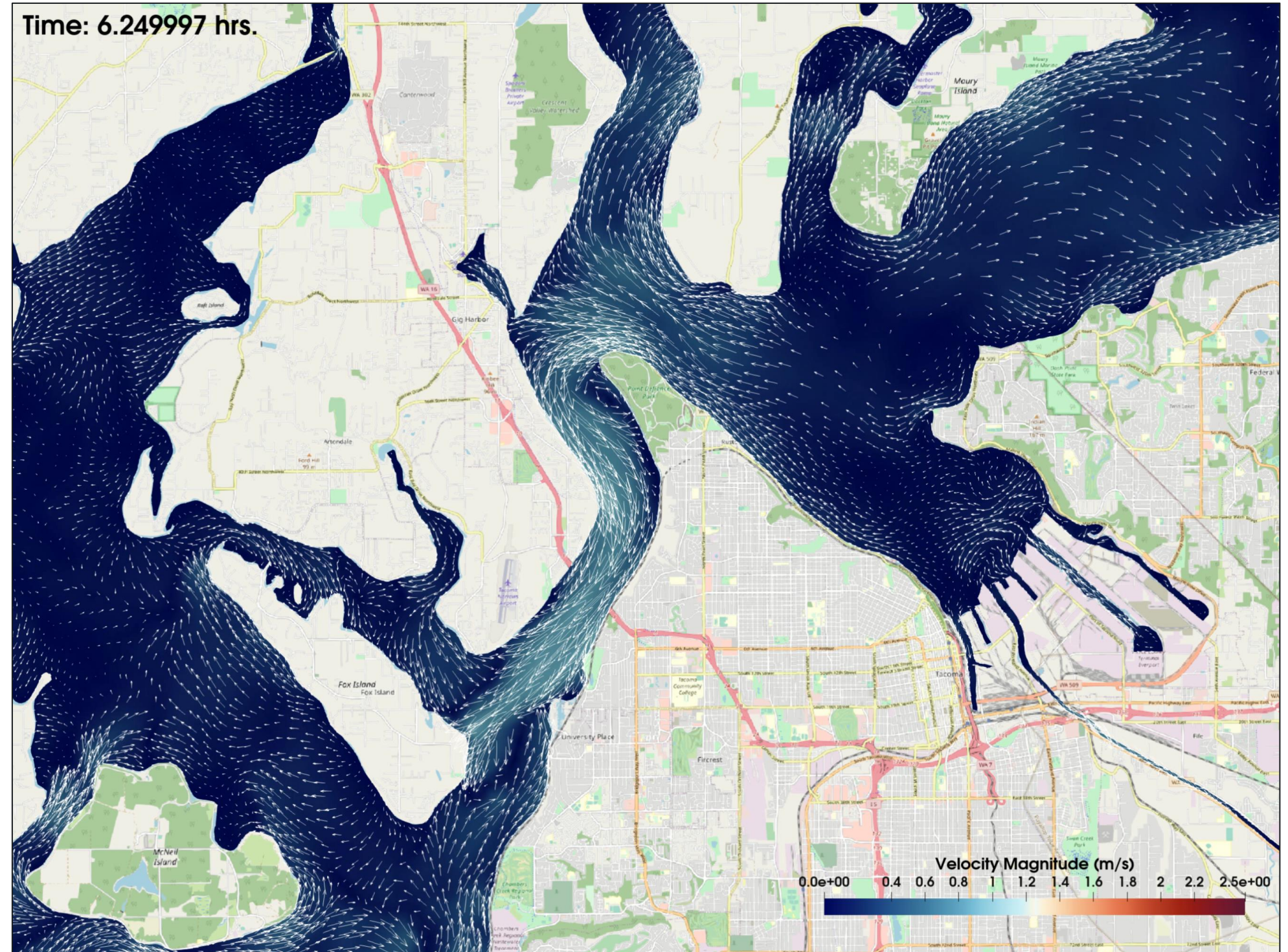


Pacific Northwest
NATIONAL LABORATORY

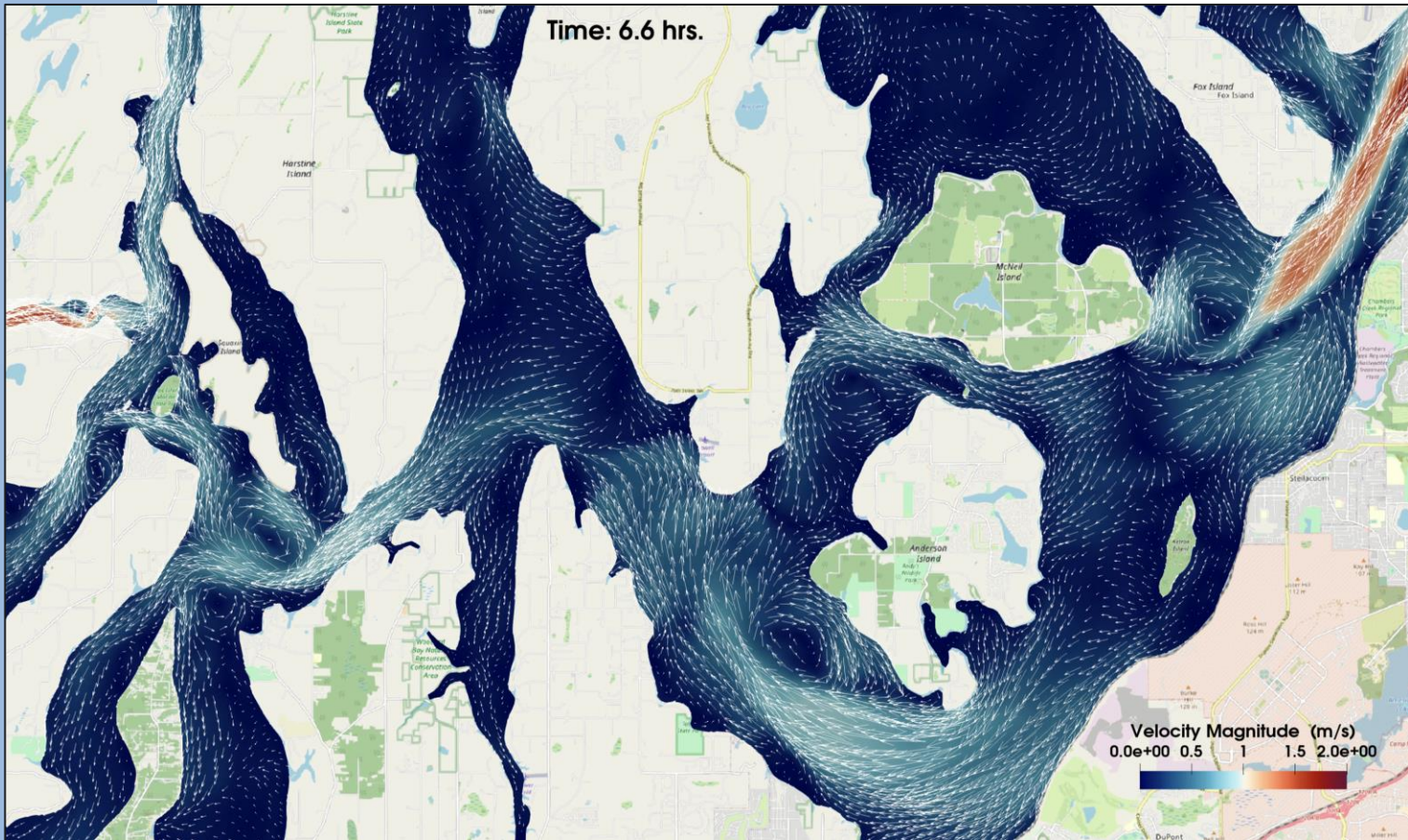
Surface Currents in Tacoma Narrows



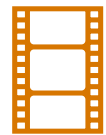
Currents – Tacoma Narrows



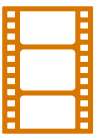
Surface Current Movement in South Puget Sound



Surface Currents in South Sound



Surface Currents in South Sound



Evaluating Transport Time Scales

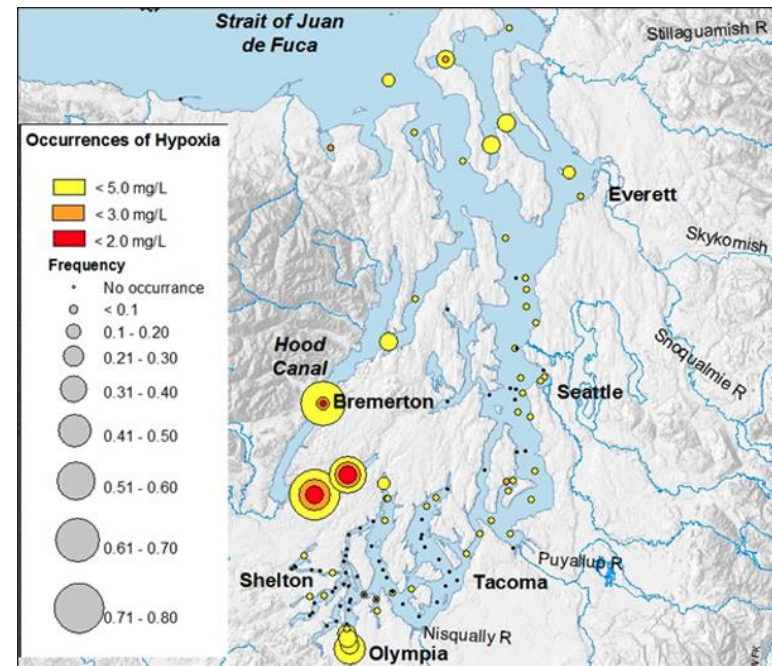
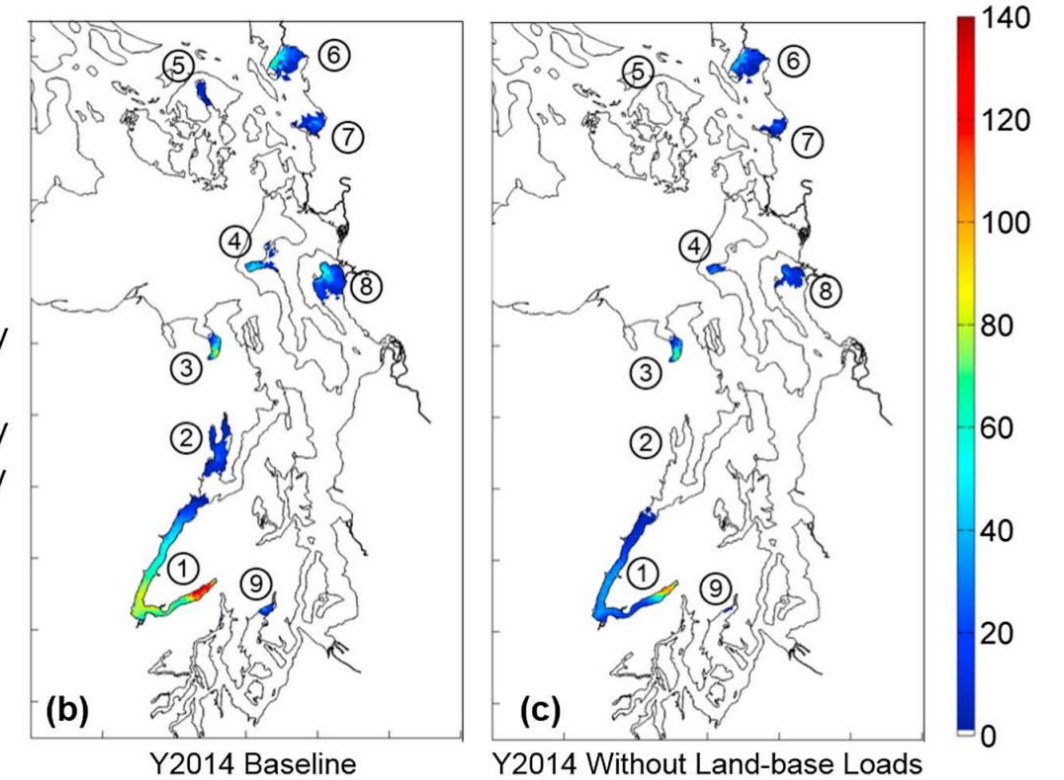
Residence and Flushing Times

- Popular transport time scales
 - Residence Time
 - Flushing Time
- Site specific bathymetry and complex shoreline features
 - Poor mixing in certain basins
 - Hypoxia related issues
- Used SSM_{HR} to estimate Residence and Flushing Times

Legend

- ① Hood Canal
- ② Dabob Bay
- ③ Discovery Bay
- ④ Penn Cove
- ⑤ East Sound
- ⑥ Bellingham Bay
- ⑦ Samish Bay
- ⑧ Port Susan Bay
- ⑨ Henderson Bay

Bottom Hypoxia (DO < 2 mg/L) Occurrence [Days]

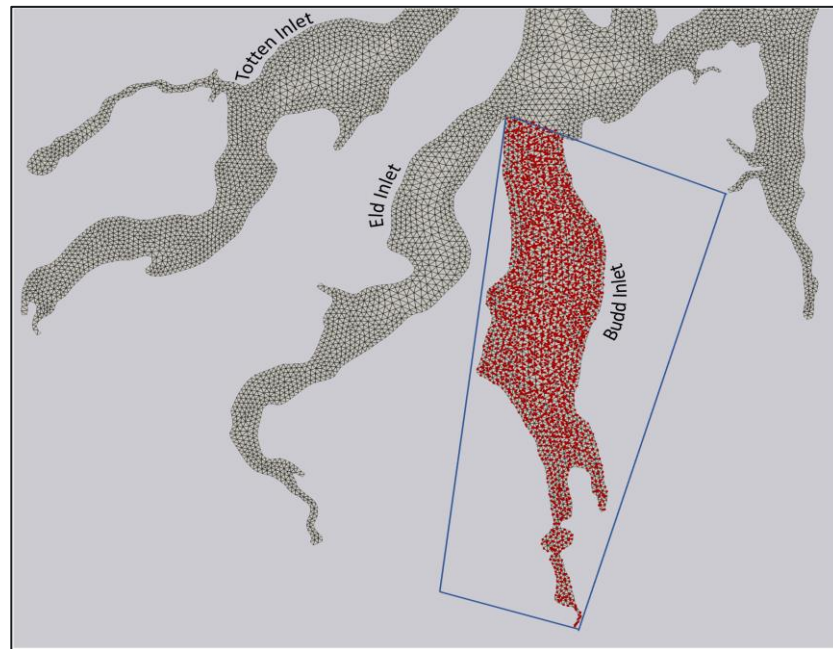


Source: Khangaonkar, T., Nugraha, A., Xu, W., Long, W., Bianucci, L., Ahmed, A., Mohamedali, T., & Pelletier, G. (2018). *Analysis of hypoxia and sensitivity to nutrient pollution in Salish Sea. Journal of Geophysical Research: Oceans*, 123, 4735–4761. <https://doi.org/10.1029/2017JC013650>

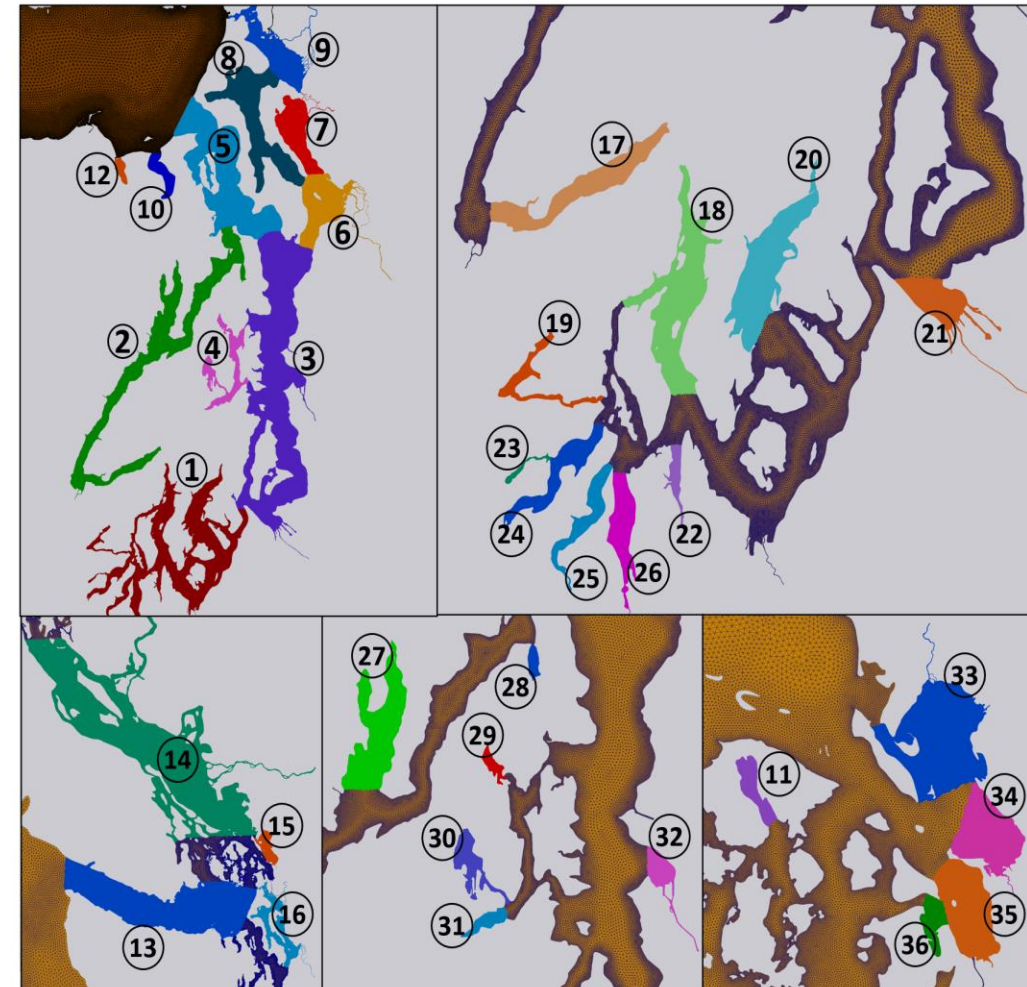
Source: Puget Sound Partnership 2009 State of the Sound

Transport Time Scales for Salish Sea Basins/Sub-basins – Residence Times

- **Residence time – Many definitions and interpretations**
 - **Lagrangian perspective** (Zimmerman 1976; Takeoka 1984; Tartinville et al. 1997)
 - **Depends on initial positions**
 - **Re-entry or no re-entry** (Van et al., 2020)
 - **Spatially and temporally averaged estimate**



Basins/sub-basins/embayments of interest

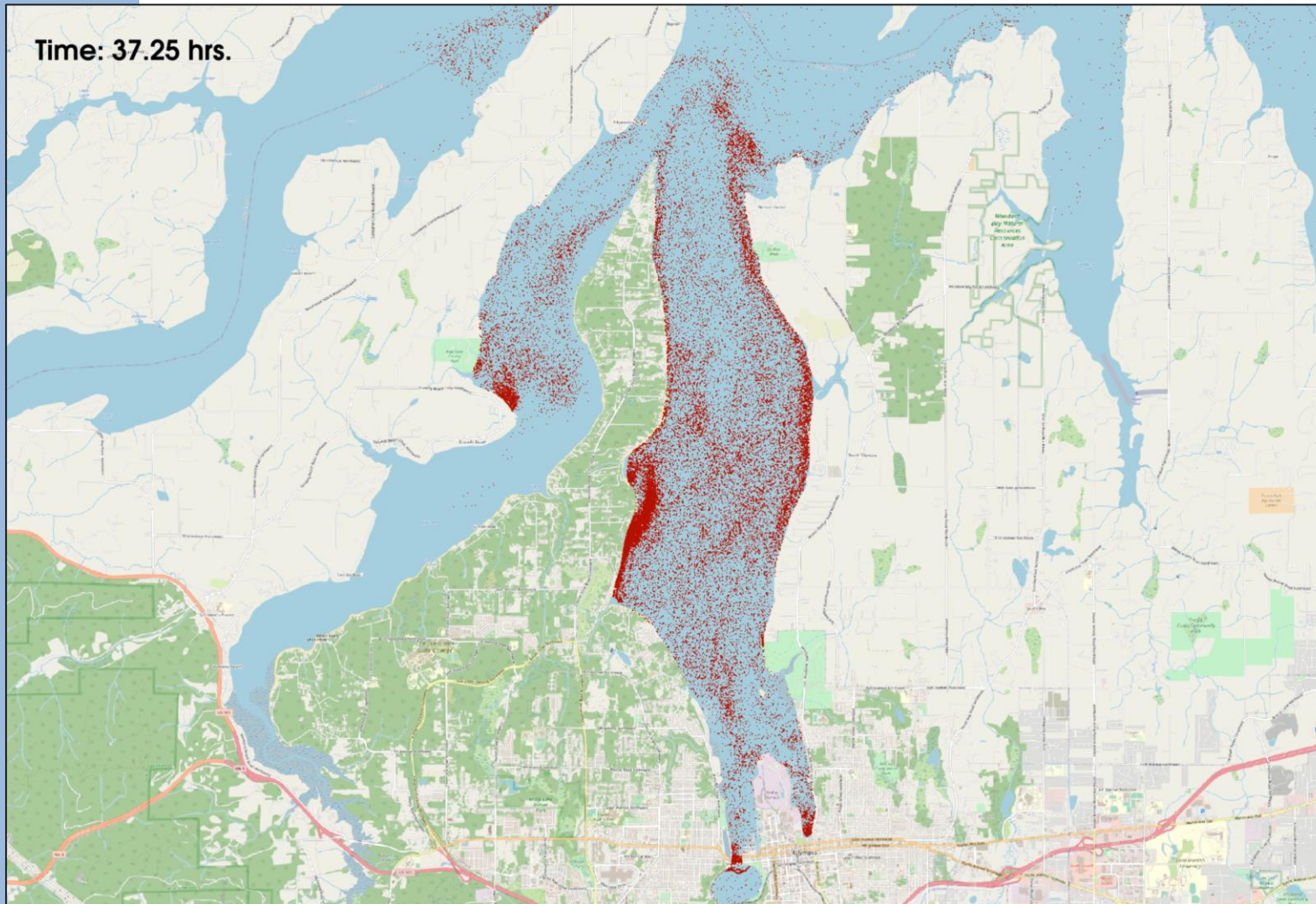


- | | |
|--------------------------|--------------------|
| ① South Sound | ②② Henderson Inlet |
| ② Hood Canal Basin | ②③ Skookum Inlet |
| ③ Central Basin | ②④ Totten Inlet |
| ④ Sinclair Basin | ②⑤ Eld Inlet |
| ⑤ Admiralty Inlet | ②⑥ Budd Inlet |
| ⑥ Possession Sound | ②⑦ Dabob Bay |
| ⑦ Port Susan | ②⑧ Port Gamble |
| ⑧ Saratoga Passage | ②⑨ Liberty Bay |
| ⑨ Skagit Bay | ③⑩ Dyes Inlet |
| ⑩ Discovery Bay | ③⑪ Sinclair Inlet |
| ⑪ East Sound | ③⑫ Elliot Bay |
| ⑫ Sequim Bay | ③⑬ Bellingham Bay |
| ⑬ Strait of Juan de Fuca | ③⑭ Samish Bay |
| ⑭ Strait of Georgia | ③⑮ Padilla Bay |
| ⑮ Bellingham Bay | ③⑯ Fidalgo Bay |
| ⑯ Whidbey Bay | |
| ⑰ Lynch Cove | |
| ⑱ Case Inlet | |
| ⑲ Hammersley Inlet | |
| ⑳ Carr Inlet | |
| ㉑ Commencement Bay | |

Initialization of particles in the domain of basin of interest

Transport Time Scales for Salish Sea Basins/Sub-basins – Residence Times

- Estimated Residence Times

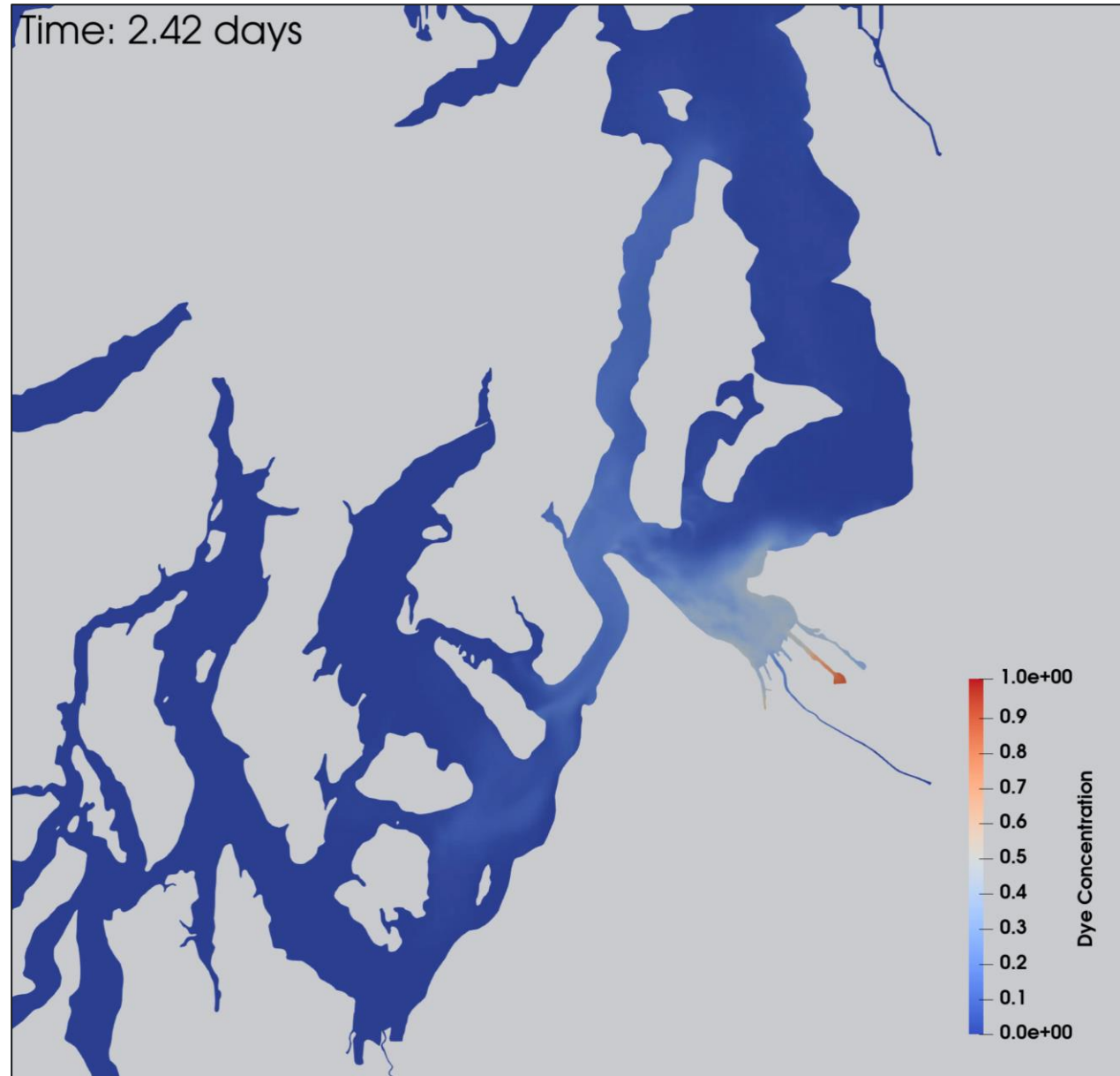


Premathilake and Khangaonkar (2022)– *Estuarine Coastal Shelf Science*

| Basins | Mean Residence time (days) | 90th Percentile Residence time (days) |
|------------------------|----------------------------|---------------------------------------|
| Admiralty Inlet | 1 | 3 |
| Bellingham Basin | 6 | 9 |
| Bellingham Bay | 2 | 4 |
| Budd Inlet | 2 | 6 |
| Carr Inlet | 11 | 24 |
| Case Inlet | 5 | 13 |
| Central Basin | 7 | 16 |
| Commencement Bay | 2 | 4 |
| Dabob Bay | 15 | 33 |
| Discovery Bay | 4 | 7 |
| Dyes Inlet | 4 | 9 |
| East Sound | 1 | 3 |
| Eld Inlet | 2 | 6 |
| Elliot Bay | 1 | 2 |
| Fidalgo Bay | 1 | 1 |
| Georgia Basin | 17 | 43 |
| Hammersley Inlet | 1 | 2 |
| Henderson Inlet | 2 | 7 |
| Hood Canal Basin | 15 | 43 |
| Liberty Bay | 4 | 7 |
| Lynch Cove | 9 | 20 |
| Padilla Bay | 1 | 4 |
| Port Gamble | 2 | 4 |
| Port Susan | 10 | 23 |
| Possession Sound | 3 | 8 |
| Samish Bay | 6 | 20 |
| Saratoga Passage | 7 | 15 |
| Sequim Bay | 3 | 6 |
| Sinclair Basin | 7 | 18 |
| Sinclair Inlet | 1 | 4 |
| Strait of Juan de Fuca | 6 | 18 |
| Skagit Bay | 2 | 3 |
| Skookum Bay | 6 | 21 |
| South Puget Sound | 11 | 20 |
| Totten Inlet | 2 | 5 |
| Whidbey Basin | 10 | 28 |

Transport Time Scales for Salish Sea Basins/Sub-basins – *Flushing Times*

- Estimated Flushing Times



| Basins | Eulerian Flushing Time (dye study) (days.) |
|------------------------|--|
| Admiralty Inlet | 2 |
| Bellingham Basin | 9 |
| Bellingham Bay | 8 |
| Budd Inlet | 5 |
| Carr Inlet | 12 |
| Case Inlet | 18 |
| Central Basin | 41 |
| Commencement Bay | 2 |
| Dabob Bay | 30 |
| Discovery Bay | 7 |
| Dyes Inlet | 6 |
| East Sound | 17 |
| Eld Inlet | 8 |
| Elliot Bay | 2 |
| Fidalgo Bay | 1 |
| Georgia Basin | 240 |
| Hammersley Inlet | 7 |
| Henderson Inlet | 4 |
| Hood Canal Basin | 138 |
| Liberty Bay | 8 |
| Lynch Cove | 18 |
| Padilla Bay | 6 |
| Port Gamble | 4 |
| Port Susan | 11 |
| Possession Sound | 5 |
| Samish Bay | 6 |
| Saratoga Passage | 20 |
| Sequim Bay | 7 |
| Sinclair Basin | 13 |
| Sinclair Inlet | 6 |
| Strait of Juan de Fuca | 13 |
| Skagit Bay | 2 |
| Skookum Bay | 2 |
| South Puget Sound | 40 |
| Totten Inlet | 9 |
| Whidbey Basin | 24 |

Questions and Discussion
