Near the mouth of the Elwha

Photo Courtesy: CMAP, SEA Program, Department of Ecology

Salish Sea Model
Modeling Team Members

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U.S. Environmental Protection Agency
Ben Cope

With past contributions from:
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Brandon Sackmann, Ph.D.
Taiping Wang, Ph.D.
Zhaoqing Yang, Ph.D.
Salish Sea Model: Significant Support from the Regional Scientific Community

- Observational records
- Shared insights
- Input data from other models
- Peer Review
- Opportunities for applications
- Numerous contributors

Photo Courtesy: CMAP, SEA Program, Department of Ecology
Contributors – thank you!

Data, Monitoring Tools, and Observations

Ecology’s Marine Monitoring Unit – data received from Mya Keyzers, Julia Bos, Skip Albertson, Carol Maloy, Christopher Krembs http://www.ecy.wa.gov/programs/eap/mar_wat/index.html


Fisheries and Oceans Canada http://www.dfo-mpo.gc.ca/index-eng.htm

Padilla Bay National Estuarine Research Reserve System – data downloaded online, with assistance from Nicole Burnett and Jude Apple http://cdmo.baruch.sc.edu/

King County – data from Stephanie Jaeger and Kim Stark http://green2.kingcounty.gov/marine/Monitoring/Offshore

University of Washington – UW PRISM cruise data in collaboration with NOAA, data from Simone Alin (NOAA) and Jan Newton (UW), Parker MacCready provided Matlab scripts http://www.prism.washington.edu/home


Many staff members of the wastewater treatment plants (WWTPs), particular in South and Central Puget Sound – provided data and assistance in collecting samples as part of the South Puget Sound Dissolved Oxygen Study for their facilities, which are the basis of some of the nutrient load estimates used in the model.

Ecology staff collected information under the separate South Puget Sound Dissolved Oxygen Study that was used as a basis for load analyses in the Salish Sea Model:

• Karen Burgess and Greg Zentner managed communications with the WWTPs through the permit writers (Mahbub Alam, Mike Dawda, Dave Dougherty, Alison Evans, Mark Henley, Tonya Lane), and Marc Heffner provided input regarding the Simpson industrial discharge.

• Chuck Hoffman analyzed and performed WWTP regressions.

• Ryan McEliece, Chris Moore, and Brandon Slone conducted all freshwater monitoring, including coordinating with WWTP staff for composite sample collection, in South and Central Puget Sound.

• Steve Golding helped develop the South and Central Puget Sound WWTP monitoring program.

• Dave Hallock and Bill Ward coordinated supplemental freshwater monitoring in South and Central Puget Sound.

Peer Reviewers

Simone Alin - Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration

Bob Ambrose, Ben Cope - U.S. Environmental Protection Agency

Stephanie Jaeger - Department of Natural Resources and Parks, Water and Land Resources Division, King County

Christopher Krembs, Tom Gries, Will Hobbs, Dustin Bilhimer - Washington Department of Ecology

Parker MacCready - University of Washington

Brian Rappoli - Ocean and Coastal Acidification and Coral Reef Protection Program, U.S. Environmental Protection Agency

Randy Shuman - King County

Samantha Siedlecki - Joint Institute for the Study of the Atmosphere and Ocean, University of Washington

Funding & In-kind Contributions

Framework Development

Pacific Northwest National Laboratory

Washington State Department of Ecology

United States Environmental Protection Agency

Individual Project Applications

National Estuarine Program

Nature Conservancy

National Oceanic and Atmospheric Administration

NW Straits Commission

Skagit River System Cooperative

Skagit Watershed Council

Tulalip Tribe

U.S. Army Corps of Engineers

Additional Support

Pacific Northwest National Laboratory (PIC) program: http://pic.pnl.gov/

NW Regional Modeling Consortium http://www.atmos.washington.edu/cliff/consortium.html

Contributors – thank you!
Salish Sea Model: What is it? Why is it needed?

• SSM is a 3-D biogeochemical diagnostic tool for predicting responses to key ecosystem parameters due to discrete changes.

• It is needed to support in the assessment of impacts to our estuarine system. It is the backbone tool that will be used in the Puget Sound Nutrient Reduction Strategy.

24 Peer reviewed papers and technical reports
**Spatial Scale:** Model has evolved--larger domain with finer horizontal grids focusing on Puget Sound. Ten vertical layers.

Intermediate scale model has a resolution varying from 250 meters in the inlets and bays to 800 meters in main basin, and up to 3000 meters in the strait of Juan de Fuca.

Finer scale grid has inlets and bays going down to approximately 40-50 m in South and Central Sound.
SSM: Approximating the biology, chemistry and physics of the Salish Sea

Combined Bathymetry and Topography of the Puget Lowland, Washington State

Finlayson 2005 Topobathy DEM


Water column

Algae growth

Particle flux

NH4

DO

Variable nutrient inputs

Sediment

Diffusion, resuspension, bioturbation, pore water processes

Deep burial

Sediment diagenesis
SSM simulations presented today will reference three separate years:

2006

“In September 2006, thousands of dead fish washed up on shore in Hood Canal.”


2008

High rates of shellfish larvae die-offs reported by Hood Canal commercial shellfish growers

Personal communication, Bill Dewey

2014

• Relative to previous years, Hood Canal DO conditions improved.
• Historic mean river flows exceeded in Spring.
• In September and October, the “Blob” moved in.

PSEMP 2014 Report
Comparable approach used to study Chesapeake Bay

**Mean Difference Between Model and Observations**

<table>
<thead>
<tr>
<th>Range of annual statistics</th>
<th>DO (mg/L)</th>
<th>Chlorophyll (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salish Sea</td>
<td>-1.56 to 0.35</td>
<td>-0.31 to 0.82</td>
</tr>
<tr>
<td>Chesapeake Bay</td>
<td>-0.522 to 0.775</td>
<td>0.32 to 1.55</td>
</tr>
</tbody>
</table>

Comparable model performance
An Overview of the *Salish Sea Model*: (A tool for Water Quality and Ecosystem Management)

*Hydrodynamics, Biogeochemistry, & Sediments* ...

Model Framework and Skill

Tarang Khangaonkar, Wen Long, Laura Bianucci, Wenwei Xu, Adi Nugraha
Pacific Northwest National Laboratory (PNNL)
Expanded Salish Sea Model
- The NW Straits
- Vancouver Island
- Continental shelf
- 18 Major Rivers and 145 fresh water & WWTP point sources
- Additional Rivers (Pacific Ocean)
  - Columbia / Willamette Rivers
  - Chehalis River
  - Willapa River
- Tidal forcing
- Meteorology
  - UW / WRF Model
- Ocean boundary conditions
  - Monitoring data or WOA
Model Calibration – Tides, S, & T

Year 2014

Tides – Greenbank, Whidbey Basin

Salinity – Bangor, Hood Canal
Calibration: Velocity
Dana Passage (example)

- Bottom Velocity
- Middle Velocity
- Surface Velocity

Date
10/1/06 10/6/06 10/11/06 10/16/06 10/21/06 10/26/06 10/31/06

Velocity (m/s)
-2
-1
0
1
2

Data
Model

Miles

Tides
Surface Currents

Fraser River Eddy

Juan De Fuca Eddy
Tidal Currents – San Juan Islands
High Resolution - Subdomain
Circulation in the Salish Sea
Puget Sound – Reflux flows

“Circulation in Embracing Sills”
- Ebbesmeyer et al. 1984

SJF = Strait of Juan De Fuca
ADM = Admiralty Inlet
HARO = Haro Strait
R = Reflux Flow at Admiralty Sill (estimated at 19 k, ~60% of surface outflow)

HNV/PSB = Hansville, Puget Sound
EP/CP = East Passage / Colvos Passage
TN = Tacoma Narrows
Simulated Surface Constituents (2006)

Algae

NO3+NO2

DO

Puget Sound Basin (PSB003)
Commencement Bay (CMB003)
Hood Canal Basin (HCB010)
Saratoga Passage (SAR003)

Alg C (mg/L)

NO3+NO2 (umol/L)

DO (mg/L)

Day of Year 2006

Gordon Point (GOR001)
Sinclair Inlet (SIN001)
Budd Inlet (BUD005)
Bellingham Bay (BLL009)
Simulation of Hypoxia - Hood Canal

Lynch Cove, Hood Canal – Ecology Station HCB004
The model can predict ocean acidification
### Representative Model Error Statistics

<table>
<thead>
<tr>
<th>Hydrodynamics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tides</strong></td>
<td></td>
</tr>
<tr>
<td>ME (m)</td>
<td>MAE (m)</td>
</tr>
<tr>
<td>-0.03</td>
<td>0.29</td>
</tr>
<tr>
<td><strong>Salinity</strong></td>
<td></td>
</tr>
<tr>
<td>ME (ppt)</td>
<td>RMSE (ppt)</td>
</tr>
<tr>
<td>0.35</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
</tr>
<tr>
<td>ME (°C)</td>
<td>RMSE (°C)</td>
</tr>
<tr>
<td>0.32</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water Quality</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DO</strong></td>
<td></td>
</tr>
<tr>
<td>ME (mg/L)</td>
<td>RMSE (mg/L)</td>
</tr>
<tr>
<td>0.35</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>Phosphate</strong></td>
<td></td>
</tr>
<tr>
<td>ME (mg/L)</td>
<td>RMSE (mg/L)</td>
</tr>
<tr>
<td>-0.69</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>Nitrate</strong></td>
<td></td>
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<tr>
<td>ME (ug/L)</td>
<td>RMSE (uM/L)</td>
</tr>
<tr>
<td>0.99</td>
<td>6.53</td>
</tr>
<tr>
<td><strong>Algae (Chl – a)</strong></td>
<td></td>
</tr>
<tr>
<td>ME (ug/L)</td>
<td>RMSE (ug/L)</td>
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<tr>
<td>0.82</td>
<td>4.37</td>
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<tr>
<td><strong>pH</strong></td>
<td></td>
</tr>
<tr>
<td>ME</td>
<td>RMSE</td>
</tr>
<tr>
<td>0.12</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Salish Sea Model summary

Hydrodynamic Model of Salish Sea


Expanded Domain Improvement

- Validation of the Circulation in Embracing Sills concepts proposed by Ebbesmeyer and Barnes (1980)
  - Nearly 2/3rd of surface outflow is refluxed back to Puget Sound near the Admiralty Inlet sill

Biogeochemical Model of Salish Sea

- Nutrients, phytoplankton (two algae groups) and carbon
- Sediment diagenesis
- Carbonate chemistry – alkalinity and pH

References:

- [Khangaonkar et al. (2011) – Estuary Coast and Shelf Science]
- [Khangaonkar et al. (2017) – Ocean Modelling]
- [Khangaonkar et al. (2016) - Northwest Science]
- [Khangaonkar et al. (2012) – Ocean Dynamics]
- [Bianucci et al. (2017 submitted)]
Residence Times in Salish Sea

How long a mass of water stays at a certain location?

Longer residence times promotes:

a. Buildup of pollutant concentrations
b. Increased productivity and depletion of nutrients
c. Oxidation of ammonia to nitrate which depletes oxygen
d. Decomposition of organic carbon (dead algae) by heterotrophic bacteria which deplete oxygen
e. Hot spots for biogeochemical stressors

Anise Ahmed

Residence Time index for Central Basin (Courtesy, Skip Albertson, 2015 PSEMP report)
“What is not known is the magnitude of the effect that the anthropogenic nitrogen inputs have on pH or aragonite saturation levels.

Resolving this issue is not trivial; it will require new knowledge of residence times, export production (the amount of particulate organic carbon that sinks out of the euphotic zone and is remineralized at depth), and oceanic boundary conditions (baseline pH and carbon species signals from the coast).”

“Basins with strong stratification and long residence times should be the most susceptible to land-based and human sourced inputs of nitrogen”.

1. Used the Salish Sea model developed by PNNL in collaboration with Ecology.

2. Used an initial virtual dye in Salish.

3. Estimated e-folding times from cell average concentrations.
## Residence times in different basins, days

### Basin Comparison

<table>
<thead>
<tr>
<th>Basin</th>
<th>2006</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salish Sea</td>
<td>160</td>
<td>54</td>
</tr>
<tr>
<td>South Sound</td>
<td>289</td>
<td>208</td>
</tr>
<tr>
<td>South &amp; Central *</td>
<td>249</td>
<td>165</td>
</tr>
<tr>
<td>Whidbey Basin</td>
<td>258</td>
<td>154</td>
</tr>
<tr>
<td>Hood Canal</td>
<td>261</td>
<td>181</td>
</tr>
<tr>
<td>South &amp; East Admiralty</td>
<td>249</td>
<td>158</td>
</tr>
</tbody>
</table>

* South of Edmonds

### Annual average flows, cms

<table>
<thead>
<tr>
<th>River</th>
<th>2006</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraser</td>
<td>2179</td>
<td>2940</td>
</tr>
<tr>
<td>Skagit</td>
<td>470</td>
<td>574</td>
</tr>
<tr>
<td>Stillaguamish</td>
<td>274</td>
<td>320</td>
</tr>
</tbody>
</table>
Thalweg animation:
Lynch Cove to Neah Bay
(residence times in bottom and surface layers)

Fresher, warmer water moves out at surface
Saltier, cooler water moves in at depth from the ocean

Neah Bay
Lynch Cove
Admiralty Inlet
Landward
Seaward
Lynch Cove – Neah Bay Thalweg dye animation

Dye simulation: 2006, 00-Jan
Conclusions

1. Longer residence times occur in remote inlets and “trapped” basins

2. In general, longer residence times occur for surface waters compared to bottom waters

3. Longer residence times occur with poor estuarine circulation from low freshwater flows

4. We can now use the Salish Sea model as tool to quantify residence times for any portion of the model domain or year.

5. Residence time maps show us areas that are susceptible to biogeochemical stressors, and can be made available to the scientific community
Nutrients entering the Salish Sea Model

The model needs inputs to simulate current, historic, and future conditions.

Sources of Loading?

Magnitude of loading?

Timing of loading?

What happens when these loads enter Puget Sound?

What proportion of modeled effects are caused by human activities?

What proportion of modeled effects are caused by human activities?
Nutrient parameters

- Model includes a full suite of water quality parameters, including:
  - nitrogen
  - phosphorus
  - carbon
- Both nitrogen and carbon parameters affect oxygen levels and acidification parameters and were both modified in the estimate of reference conditions
- Focus on this presentation is on inorganic nitrogen – limiting nutrient in growing season
- But, model results also show that organic carbon from human sources also plays a role

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Parameters</td>
<td></td>
</tr>
<tr>
<td>Nitrate + Nitrite</td>
<td>NO23N</td>
</tr>
<tr>
<td>Ammonium</td>
<td>NH4N</td>
</tr>
<tr>
<td>Total Persulfate Nitrogen</td>
<td>TPN</td>
</tr>
<tr>
<td>Dissolved Total Persulfate Nitrogen</td>
<td>DTPN</td>
</tr>
<tr>
<td>Ortho-Phosphate</td>
<td>OP</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>TP</td>
</tr>
<tr>
<td>Dissolved Total Phosphorus</td>
<td>DTP</td>
</tr>
<tr>
<td>Total Organic Carbon</td>
<td>TOC(^1)</td>
</tr>
<tr>
<td>Dissolved Organic Carbon</td>
<td>DOC(^4)</td>
</tr>
<tr>
<td>Calculated Parameters</td>
<td></td>
</tr>
<tr>
<td>Dissolved Inorganic Nitrogen</td>
<td>DIN</td>
</tr>
<tr>
<td>Particulate Organic Nitrogen</td>
<td>PON</td>
</tr>
<tr>
<td>Dissolved Organic Nitrogen</td>
<td>DON</td>
</tr>
<tr>
<td>Particulate Organic Phosphorus</td>
<td>POP</td>
</tr>
<tr>
<td>Dissolved Organic Phosphorus</td>
<td>DOP</td>
</tr>
<tr>
<td>Particulate Organic Carbon</td>
<td>POC</td>
</tr>
</tbody>
</table>
Excess nutrients are a problem

Eutrophication

nitrogen loading

nitrogen-rich surface water layers fuel algal blooms

algal bloom

algal cells die and decompose

decomposition lowers dissolved oxygen concentrations in bottom waters

low dissolved oxygen stresses marine organisms

Low dissolved oxygen (2014 water quality assessment)
Sources of nutrients

Atmospheric Deposition
Deposition of atmospheric nutrients (from natural sources plus emissions) onto watersheds and directly onto marine waters

Net Ocean Exchange
Nutrients from the Pacific Ocean and Puget Sound get exchanged at the Strait of Juan de Fuca and Admiralty Inlet

Rivers
Includes all upstream sources that drain into rivers, and are transformed by stream dynamics, before entering Puget Sound at their mouths

Sources included implicitly:
- near-shore septic systems
- direct marine discharge of groundwater

Sources not included:
- net pens
- vessel discharges
- Combined sewer outflows

WWTPs + other point sources
Human wastewater and industrial point sources with outfalls in marine waters
Nitrogen concentrations in ocean water are not the highest, but because of the amount of Pacific Ocean water entering Puget Sound, the Pacific Ocean contributes the largest nitrogen load to the sound.
Nitrogen from point sources

- All facilities that have outfalls in marine waters
- Model includes discharges from:
  - 78 US wastewater facilities
  - 10 US industrial facilities
  - 9 Canadian wastewater facilities
- Largest DIN loads coincide with the largest population centers
Nitrogen from nonpoint sources

- Model needs nutrients entering the model domain from all watersheds/river/nonpoint sources

- **Estimates shown are at the mouth of each river and stream and include all upstream sources:**
  - Stormwater runoff
  - Livestock manure
  - Agricultural and urban fertilizer application
  - Natural sources
  - Watershed septic systems
  - Point sources with outfalls in rivers/streams
  - Groundwater baseflow in streams

- Further source tracking studies may be necessary to identify upstream nutrient reduction strategies
Seasonality of river and WWTP nitrogen loading

Monthly DIN loads entering Puget Sound south of Admiralty Inlet

Annual DIN Load
- 60% Rivers
- 40% WWTPs

Summer DIN Load
- 80% WWTPs
- 20% Rivers

<table>
<thead>
<tr>
<th></th>
<th>Annual DIN Load</th>
<th>SUMMER DIN Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivers</td>
<td>22,630 kg/d</td>
<td>6,760 kg/d</td>
</tr>
<tr>
<td>WWTPs</td>
<td>32,210 kg/d</td>
<td>29,320 kg/d</td>
</tr>
</tbody>
</table>
Inter-annual variability of river loading

Stillaguamish River DIN Load

- 2006 DIN Load
- 2014 DIN Load

DIN Load (kg/d)

0 2,000 4,000 6,000 8,000 10,000 12,000 14,000 16,000 18,000

1-Jan 1-Feb 1-Mar 1-Apr 1-May 1-Jun 1-Jul 1-Aug 1-Sep 1-Oct 1-Nov 1-Dec
**Nutrient loading scenarios**

**Reference condition (no people)**
- Natural sources

**Current loading**
- **Point sources (WWTPs)**
- **Non-point sources (rivers)**

**Reference Condition** = nutrient loading in the absence of regional anthropogenic nutrient sources
- No change in ocean inputs
- No change in Canadian inputs

Published in Mohamedali et. al. (2011), updated in Pelletier et. al. (2017, Appendix B), estimates may be refined further in 2017-2018
Reference condition point and nonpoint source loading

Reference vs. human point and nonpoint source DIN loads to different regions in Puget Sound

- **Puget Main**: 4% Reference, 96% Human Point Sources (WWTPs), 8% Human Nonpoint Sources (in rivers), 81% Total
- **Sinclair Dyes Inlet**: 11% Reference, 65% Human Point Sources (WWTPs), 11% Human Nonpoint Sources (in rivers), 81% Total
- **Admiralty**: 19% Reference, 54% Human Point Sources (WWTPs), 23% Human Nonpoint Sources (in rivers), 81% Total
- **Commencement Bay**: 19% Reference, 54% Human Point Sources (WWTPs), 23% Human Nonpoint Sources (in rivers), 81% Total
- **South Sound**: 27% Reference, 38% Human Point Sources (WWTPs), 22% Human Nonpoint Sources (in rivers), 70% Total
- **SOG**: 30% Reference, 48% Human Point Sources (WWTPs), 16% Human Nonpoint Sources (in rivers), 54% Total
- **SJF**: 45% Reference, 39% Human Point Sources (WWTPs), 16% Human Nonpoint Sources (in rivers), 48% Total
- **Elliott Bay**: 53% Reference, 47% Human Point Sources (WWTPs), 20% Human Nonpoint Sources (in rivers), 47% Total
- **Whidbey**: 47% Reference, 47% Human Point Sources (WWTPs), 20% Human Nonpoint Sources (in rivers), 47% Total
- **Hood Canal**: 59% Reference, 47% Human Point Sources (WWTPs), 20% Human Nonpoint Sources (in rivers), 47% Total

**Labels**: Human Point Sources (WWTPs) - Human Nonpoint Sources (in rivers) - Reference Condition
Nutrient loading scenarios

Reference condition (no people)

Current loading

Future loading: more people, different climate

Published in Mohamedali et al. (2011), updated in Pelletier et al. (2017, Appendix B), might be refined further in 2017-2018

Published in Mohamedali et al. (2011)

Published in Roberts et al. (2012), might be updated
Future nutrient loading

1. Climate Change
   - Changes in precipitation
   - Changes to river hydrology
   - Change in timing of freshwater flows and nitrogen loads to Puget Sound

2. Population Growth
Future nutrient loading

1. Climate Change
   - Changes in precipitation
   - Changes to river hydrology
   - Change in timing of freshwater flows and nitrogen loads to Puget Sound

2. Population Growth
   - Urbanization & development
   - Less forested/natural lands
   - Agriculture may or may not increase
   - More people = more wastewater
   - Possible technology changes to wastewater treatment

OSU Alternative Futures Project (Bolte and Vaché, 2010)

Puget Sound Toxics Assessment (Herrera, 2011)
Future point and nonpoint source loading

Annual average DIN loading estimates from point and nonpoint sources into Puget Sound (south of Admiralty Inlet)

Key assumptions:

- OFM 2012 ‘medium’ population projections
- No change in WWTP treatment processes/technologies or per capita wastewater flow, no new facilities
- Future hydrology from UW Climate Impacts Group VIC model based on downscaled A/B emissions scenarios
- Future nitrogen nonpoint source concentrations are only a function of empirical relationships to land use
- Future land use based on a ‘status quo’ of current land use trends in the region

Published in Roberts et. al. (2012), might be updated
‘Nitrogen in Puget Sound’ Story Map: (coming soon!)

Puget Sound: an overview

This story map, developed by scientists at the Washington Department of Ecology, shares the story of nitrogen in Puget Sound, related monitoring efforts, and analysis, as well as facts in our current understanding of the nitrogen cycle.

Nitrogen in Puget Sound

Excess nitrogen

Algal Blooms

Algal blooms are shown in this photo taken from an airplane just north of Elliott Bay. Algal blooms are a common feature in Puget Sound, where we typically see spring bloom and a summer bloom when phytoplankton in the water become productive. Excess nitrogen can result in a higher frequency and duration of algal blooms in Puget Sound.

Algal growth also depends on factors other than nitrogen which can either enhance or inhibit algal growth. The extent to which algal decomposition leads to dissolved oxygen.

Some algal blooms are harmful to human health because they can be toxic and affect human health either directly by causing illness in humans, or indirectly by consuming shellfish that are grown in water which has been exposed to harmful algae. While we know that nitrogen contributes to algal blooms, we do not know if nitrogen is also linked to harmful algal blooms in marine waters.

Low dissolved oxygen

Low dissolved oxygen levels have been observed in Puget Sound for a number of years, but were also present historically. Low dissolved oxygen conditions are

Nitrogen Monitoring

Ecology has several monitoring programs in and around Puget Sound that monitor for a variety of water quality parameters, including nitrogen. Ambient monitoring involves regular sampling at the same stations over a long period of time. The data from these efforts enable us to observe long-term trends in water quality conditions. Ecology has also focused nitrogen monitoring efforts designed to answer a specific question or explore data or water quality conditions in a specific location in more detail.

This map shows Ecology’s freshwater and marine monitoring stations within the Puget Sound.
Summary

• Dynamic variation in time and space is important
  o Inter-annual variability
  o Residence time matters: higher flows $\neq$ higher loads $\neq$ higher impact
  o Location matters: largest loads do not necessarily coincide with largest impact
  o Need to consider interaction between processes at different temporal and spatial scales

• Pacific Ocean:
  o Future conditions are highly uncertain and may change: incoming temperature, oxygen and nutrient levels, timing and duration of upwelling events
  o While highly influential, we are limited in our ability to manage these changes

• Extent of human influence:
  o Future nutrient loading will likely exacerbate local human impacts
  o Existing and reference condition model inputs can be used to run model scenarios in order to estimate the impact of human nutrients on Puget Sound, something we have not been able to do before – Greg’s presentation (next)
Salish Sea Model

Current model results and the response to regional anthropogenic nutrient sources

Greg Pelletier
Department of Ecology

Puget Sound Nutrient Dialogue, 19 Jul 2017
Fraction of May-Sep DIN, chlorophyll $a$, and non-algal organic C due to anthropogenic nutrient loads, surface 20 m
Cumulative days with DO less than 5 mg/l during 2006
Cumulative days with DO depletion > 0.2 mg/l during 2006
Change in Ω due to regional anthropogenic nutrient sources

Animation of April through September

Surface 20 meters

Bottom layer

Change in DO (mg/l)
### Changes in pH and $\Omega_{\text{arag}}$ due to anthropogenic sources

<table>
<thead>
<tr>
<th></th>
<th>Regional anthropogenic nutrient sources (this study)</th>
<th>Global anthropogenic sources (Feely et al. 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range of monthly average differences between historical (2008) and estimated pre-industrial</td>
<td>Difference between cruise observations (February and August, 2008) and estimated pre-industrial</td>
</tr>
<tr>
<td>pH (surface 20 m)</td>
<td>-0.07 to 0.06</td>
<td>-0.11 to 0.03</td>
</tr>
<tr>
<td>pH (bottom)</td>
<td>-0.10 to 0.05</td>
<td>-0.06 to 0.00</td>
</tr>
<tr>
<td>$\Omega_{\text{arag}}$ (surface 20 m)</td>
<td>-0.06 to 0.19</td>
<td>-0.33 to -0.09</td>
</tr>
<tr>
<td>$\Omega_{\text{arag}}$ (bottom)</td>
<td>-0.12 to 0.17</td>
<td>-0.16 to -0.02</td>
</tr>
</tbody>
</table>
Annual average change in pH due to regional anthropogenic nutrient sources

Surface 20 m

Bottom layer

Change in pH

Annual average change in pH due to regional anthropogenic nutrient sources
Change in pH due to regional atmospheric CO₂ increase from 400 to 450 ppm
Annual average change in $\Omega_{\text{arag}}$ due to regional anthropogenic nutrient sources
Change in $\Omega_{\text{arag}}$ due to regional atmospheric CO$_2$ increase from 400 to 450 ppm
Conclusions

- Regional anthropogenic nutrient sources significantly deplete DO
- Regional anthropogenic nutrient sources significantly decrease pH and $\Omega_{\text{arag}}$, especially in the deep layer
- pH and $\Omega_{\text{arag}}$ are sensitive to expected increases in local atmospheric CO$_2$, especially in the surface 20 m
Salish Sea Model
Next Steps:

Updated reference conditions
Organic N, carbon (before it was only DIN). May update again after further review/analysis

Refining nutrient loading inputs for refined model grid – finer delineations

Scenario Runs
Reference condition & future scenarios to be run on expanded, refined grid

Model Improvements
Salish Sea Model Journal Publications & Technical Reports


