Nutrient, Phytoplankton, and Dissolved Oxygen Dynamics: What can long-term monitoring tell us?

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Goals

• Understanding algal blooms in Central Puget Sound: What do we know about spatial and temporal trends, and what are the effects on water quality?

• How can we contribute to a better understanding of potential eutrophication processes in Puget Sound and the status of the Central Basin?
What is Eutrophication?

- Process which a waterbody becomes overly enriched with nutrients that causes excessive growth of algae and aquatic plants.
- Can lead to oxygen depletion.
Impairment pathways:
• Over-abundance of algae
• Shifts in phytoplankton dominance & size classes
• Increased harmful algal blooms
• Low dissolved oxygen related to blooms

(Source: Sutula and Senn 2017)
How Can We Monitor for Eutrophication in Marine Systems?

• **Status Indicators**
  1. **Nutrient concentrations and trends**
     • Water clarity

• **Biological Response Indicators**
  2. **Phytoplankton (chlorophyll-a) biomass**
     • Phytoplankton production rate (gross and net)
  3. **Phytoplankton species composition and abundance**
     • Zooplankton species composition and abundance
  4. **Dissolved oxygen levels**
     • Harmful algal blooms & toxin concentrations
     • Macroalgae and eelgrass abundance
Themes

• Place matters
• Variability is the backdrop to assessing change
• Consistent long-term monitoring is key
• Information gaps in understanding of a complex ecosystem
Puget Sound Basins

Source: Puget Sound Partnership
Juan de Fuca data from Ecology & WWU

Central Basin data from King County
Nutrients are one important fuel for primary production

Macronutrients

Dissolved Inorganic Nitrogen (DIN)
- Nitrate+Nitrite
- Ammonia

Phosphate (OP)
Silica (Si)

Dissolved organic matter

Micronutrients (such as iron, copper)
What are measurable variables of potential human nutrient enrichment in Puget Sound?

- Increased levels of nitrogen and phosphorus compounds
- And
- Decrease in Silica:Nitrogen ratio

Nutrient sources include:
- Freshwater inputs (N, P, Si, OC)
- Other human N, P sources
- Oceanic inputs (N, P, Si, Low O₂)

Nutrient fluxes:
- Nutrient uptake by algae
- Nutrient cycling

Nutrient compounds:
- Nitrogen (N)
- Silica (Si)
- Phosphate (P)
What do we observe in nutrients?

- Strong seasonal variability
- Differences in nutrient trends between basins over the last 2 decades and...
- Same trends across macronutrients in a particular basin
- Increase in both DIN and silica (Si) in the Central Basin in the winter and increasing Si:DIN ratio
- Similar ranges of nutrients compared to last century
- Suggests that hydrological cycle and circulation are important contributors
How does Puget Sound compare to other estuaries?

Source: Cloern & Jassby 2012, modified by B. Larson

Line in the box is median, boxes are 1st – 3rd quartiles, lines show all points within 1.5* interquartile distance (box height), points are outliers.
Seasonal Patterns Vary by Month & Location


Error bars are ± 1 std. dev.
Quartermaster Harbor: shallow, poorly flushed embayment in Central Sound

- Shorter data record (began 2006)
- Too variable for trends from once or twice monthly sampling
- Nitrogen management study completed 2007-2013
  - Sediment flux and groundwater nitrate likely play large roles
Daily & weekly variability can be high near the surface

Early April 2017 - Pt. Williams buoy at 1-m

Nitrate

Phytoplankton use nitrate

Low salinity can increase surface water stability

Winds can mix water

Wind vectors show relative speed and direction wind is coming from
How can we measure trends with high seasonal variability?

- One method = Non-parametric linear trend test by month (seasonal Mann-Kendall)

Slope = 0.0018 mg/L per year
Est. 6% increase per decade

Period of record is important to consider
### Dissolved Inorg. Nitrogen: Trends over 2 decades

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Legend: %Change over period of record

- **NS** = Not Significant (p>0.05)
Which season is driving this trend?

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* = TP data thru 2010
Trends over 2 decades – stations combined

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<tr>
<th>Depth Bin</th>
<th>Dissolved Inorg. Nitrogen (DIN)</th>
<th>Silica</th>
<th>Total Phosphorus*</th>
<th>Silica:DIN Ratio</th>
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Similar trends for all nutrients within each basin suggests difference in watershed/ocean balance over this record

- Years of Data = 12 – 24 for Central Basin
  - = 19 yrs for Juan de Fuca
* = TP data thru 2010
Fraser River freshet meets saltwater
(Source: A. Perea)

El Niño

Potential Drivers

Marine Heat Wave

All other tropical storms must bow before El Niño.
(Source: SNL)
How does this compare to historical data collected from 1933 – 1975?

Eugene E. Collias (1926-2017) (Source: Eugene and Dorothy Collias Collection)
Deep Nitrate at Point Jefferson

Source:
- UW/Collias 1966-1975
- King County 1994-2017

Deep Silica

Source:
- UW/Collias 1933-1942 & 1966-1975
- King County 1994-2017
Information gaps:

- Variability on short time scales – can we link to drivers over time?
- No complete record of organic nutrient and carbon pools
- Possible that nutrient cycling and remineralization rate changes may play a role
Summary:

- Some increases in all nutrients over last 2 decades in Central Basin and decreases in Strait of Juan de Fuca; though limited to period of record
- Increase or no change in Si:DIN nutrient ratio across sites
- Similar deep nutrient ranges compared to historical observations, except for lower nutrients in summer in recent decades
- Suggest drivers related to circulation, climate, & hydrological cycle, rather than anthropogenic inputs → Needs exploration
Impairment pathways:

- Over-abundance of algae
- Shifts in phytoplankton dominance & size classes
- Increased harmful algal blooms
- Low dissolved oxygen related to blooms
Why Measure Chlorophyll-a?
Chlorophyll-a

- A lot of seasonal/interannual variation
- Concentrations and timing of spring bloom are generally similar over past 20 years
- Quartermaster Harbor different dynamics

Overall, long-term chlorophyll-a levels in the Central Basin (QMH excluded) do not indicate signs of eutrophication but do show climate anomaly effects.
Chlorophyll-a
Seasonal Dynamics
Spring bloom timing

- Feb
- Mar
- Apr
- May

- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 1966-67/1975

Winter et al. 1975
Campbell et al. 1977
Seasonal Dynamics
Point Jefferson last 20 years
Seasonal Dynamics
Point Jefferson: annual cycle in 2016
## Seasonal Dynamics

**By location**

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Annual Variability
Chlorophyll-a

2016 Station NSEX01 Chlorophyll fluorescence (\text{~mg/m}^3)
## Chlorophyll-a trends over time

### 0-3m Depth

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### Legend:
- % Change over record
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# Chlorophyll-a trends over time

Depth integrated average (1-35m)

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**Legend:**

- **NS** = Not Significant (p>0.05)

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<th>% Change over record</th>
<th>0-5%</th>
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King County
# Chlorophyll-a trends over time

June-August combined: 0-3m Depth

<table>
<thead>
<tr>
<th>Site</th>
<th>Years of data</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
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<th>Jul</th>
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<th>Sep</th>
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<th>Nov</th>
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</table>

NS = Not Significant (p>0.05)
# Chlorophyll-a trends over time

**April-September combined: 0-3m Depth**

<table>
<thead>
<tr>
<th>Site</th>
<th>Years of data</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
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<th>Jul</th>
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</tbody>
</table>

**NS** = Not Significant (p>0.05)
How Does Central Basin compare?
### Historical Data Comparison

**ug/L for surface layer**

<table>
<thead>
<tr>
<th></th>
<th>Station 1</th>
<th>Pt. Jefferson</th>
<th>West Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>April-June</td>
<td>8</td>
<td>15 0.3 - 46</td>
<td>9 0.7 - 40</td>
</tr>
<tr>
<td>May-June</td>
<td>28 - 82</td>
<td>14 0.3 - 38</td>
<td>9 0.7 - 33</td>
</tr>
<tr>
<td>August-September</td>
<td>1.4 - 18</td>
<td>10 0.6 - 58</td>
<td>14 0.5 - 32</td>
</tr>
</tbody>
</table>

Winter et al. 1975
Campbell et al. 1977
Phytoplankton/Physical Relationships

Weather/climate anomaly

- Early stratification
- Cold and wet
- Strong spring stratification
- Marine heat wave
- Early southerly winds
- Persistent stratification

Early bloom: 2009
Delayed spring bloom: 2011
Late fall bloom: 2014
No fall bloom: 2016
Sustained bloom: 2017
Information Gaps

Past

Future

Data

Data

Data

Cause/effect
Chlorophyll-a Central Basin Summary

• No observed consistent shift in timing of spring bloom; observed variance corresponds to weather/climate anomalies.
• Interannual variability is observed but no large long-term increase.
• Do not see sustained levels throughout growing season (2017 weather anomaly exception) for all but QMH sites.
• Quartermaster Harbor has issues in the fall.
• Statistical analyses indicate no increasing trend in the surface layer in any month, but there was an increase in annual trend at West Point.
• Statistical analyses indicate no increasing trend during the summer months or throughout the entire growing season.

Overall, long-term chlorophyll-a levels in the Central Basin (QMH excluded) do not indicate signs of eutrophication but do show climate effects.
What do we observe in phytoplankton?
Impairment pathways:
- Over-abundance of algae
- Shifts in phytoplankton dominance & size classes
- Increased harmful algal blooms
- Low dissolved oxygen related to blooms
Plankton – drifting organisms

Phytoplankton
- plant-like
- autotrophic (photosynthetic)

Zooplankton
- animal-like
- heterotrophic
So...
what is phytoplankton?
Diatoms

- No active locomotion - drift
- Often in chains, large
- Glass case → need silica

Dinoflagellates

- Flagella – swim up and down
- Usually single, often small

Other

- Mostly small flagellates

Autotrophic

- Autotrophic
- Heterotrophic
- Mixotrophic
How do we quantify phytoplankton?

**Biomass**
In food webs, **carbon biomass** is considered a currency of energy transfer. But ... it’s difficult to measure.

So we use proxies:

**Chlorophyll a**
Universal photosynthetic pigment, extracted from cells
Most practical but not easily related to cell biomass

**Abundance**
Count cells or particles
Often the most practical but can be difficult to relate to carbon biomass

**Biovolume**
Can be related to carbon and biomass
Good proxy
What are the potential impacts of nitrogen enrichment on Puget Sound phytoplankton assemblages?

<table>
<thead>
<tr>
<th>Category</th>
<th>Impact Description</th>
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</thead>
<tbody>
<tr>
<td>Growth</td>
<td>Increased biomass production</td>
</tr>
<tr>
<td>Seasonality</td>
<td>Longer growth period, fewer dips, more persistent</td>
</tr>
<tr>
<td>Total biomass</td>
<td>Increased cumulative biomass</td>
</tr>
<tr>
<td>Species richness</td>
<td>May decrease if certain nutrients become limiting (e.g. silica)</td>
</tr>
<tr>
<td>Species composition</td>
<td></td>
</tr>
<tr>
<td>• Cell size</td>
<td>- nutrient-rich environments favor larger cells</td>
</tr>
<tr>
<td>• Diatoms vs. dinoflagellates</td>
<td>- diatoms may be Si-limited (lower Si:DIN)</td>
</tr>
<tr>
<td>• Autotrophic vs. heterotrophic</td>
<td>- heterotrophic dinos may do well if food source is more abundant</td>
</tr>
<tr>
<td>• Increase in HABs</td>
<td>(harmful species)</td>
</tr>
</tbody>
</table>
Puget Sound phytoplankton is dominated by diatoms.
Seasonal patterns in phytoplankton biomass vary year to year with environmental conditions.
Inter-annual variability in bloom timing, magnitude and species composition make it difficult to assess trends.
10-yr record of central basin taxa shows a large group of common taxa present every year, but some changes in 2017.
How does seasonal phytoplankton growth relate to nitrogen levels in the water?

Point Jefferson - surface

2016

2017
Phytoplankton Seasonal Succession: Is there a universal seasonal pattern?

East China Sea
Example of classical succession pattern

But Puget Sound is different:
There are abundant nutrients that favor large-celled diatoms year round, as long as silica is present (it is seldom limiting).

Puget Sound central basin:
Seasonality of major taxonomic groups

Biovolume means of 6 offshore stations (imaging technology)
• Year to year variations in seasonal pattern
• Diatoms always dominate – typical of many estuarine areas
Historical data for South Central Basin

Figure 4.24a. Total diatom numbers from 50% light depth in Seahurst Bight with smooth distribution.

Figure 4.25a. Total dinoflagellate numbers from 50% light depth in Seahurst Bight with smooth distribution.

Similar pattern to what we observe

Anderson et al. 1984
Puget Sound central basin: Seasonality of 6 top taxa for last 3 years

Biovolume means of 8 offshore stations

- Characteristic seasonal succession (mostly chain-forming diatoms)
  - *Thalassiosira* spp. → Other Diatoms → *Chaetoceros* spp

- Year to year variations are likely the norm
- Some taxa are abundant every year, others unpredictable
Puget Sound central basin: 12-Month Cumulative Biovolume

- Consistent spatial pattern in total biomass — the central basin is not homogenous
- Central Basin annual totals are similar year to year — no indication of changes in phytoplankton biomass (but short time series)
Has phytoplankton species composition changed in the last 10 years?

- 2008 – 2017 microscopic observations in central basin
- Presence / Absence at Pt Jefferson and/or East Passage
Number of taxa identified 2008-2017

Common Taxa (65)

- Diatoms
- Auto/Mixotrophic Dinos
- Heterotrophic Dinos

Most were present every year → no change

Less common Taxa (33)

Present 1-7 of 10 years → no trend

2017 General decline in # of taxa
Some “new” common taxa in 2017
Previously very uncommon or absent from our records

**DIATOMS**
- *Guinardia striata*
- *Asterionella formosa*

**DINOFLAGELLATES**
- *Ceratium lineatum*
- *Prorocentrum micans*
Mean Annual Biovolume (mm$^3$ L$^{-1}$)

* 4 HABs

10 Diatoms: 59%
8 Dinoflagellates: 30%
2 Other Phyto: 20%

Inter-annual variability as CV = SD/mean
Noctiluca
microscope counts
means of 10 stations
Noctiluca blooms

Three Tree Point

May 1975

June 1975

June 2018

Photo C. Krembs, Ecology
Phytoplankton Summary

- Puget Sound phytoplankton is dominated by diatoms, as is typical of nutrient-rich estuarine areas
- Phytoplankton draw down most of the ambient nitrogen during the peak growth season
- Seasonal patterns in phytoplankton biomass can vary year to year with environmental conditions (e.g. stratification)
- Inter-annual differences in bloom timing, magnitude and species composition make it difficult to assess trends (need longer time series!)
- 10-yr record of central basin taxa shows a large group of common taxa present every year, but some changes in 2017
- Noctiluca observations go back a long time, but there is no long-term data record
Impairment pathways:

- Over-abundance of algae
- Shifts in phytoplankton dominance & size classes
- Increased harmful algal blooms
- **Low dissolved oxygen (O₂)** related to blooms

Oceanic inputs

Freshwater

+O₂

algae

- O₂

respiration

algae bloom

+O₂

-- O₂

sediment oxygen demand

-- O₂

organic matter decay

++O₂

--O₂

King County
Low dissolved oceanic water can funnel into Juan de Fuca Strait and intrude in Puget Sound.

(Source: Alford & MacCready 2014)

Downwelling in winter reduces availability of lower DO over the Admiralty Sill while upwelling in summer increases availability of this lower DO bottom water.

(Source: Deppe et. al 2018)
Dissolved Oxygen (DO) – Key Points

• Different processes dominate variability in DO in different areas
  • Low DO oceanic intrusions in the straits
  • Biological production/respiration in Quartermaster Harbor
  • Combination in Central Basin
• Consider DO levels with climate forcing and climate change
• No clear trends or changes in DO
  → Needs further exploration in other areas of Puget Sound
Dissolved oxygen varies seasonally with salinity.

2017 East Passage - Dissolved Oxygen (mg/L)

2017 East Passage - Salinity (PSU)

King County
Minimum monthly dissolved oxygen: 2006 - 2017

- Central Basin
- Biological stress for some spp.
- Hypoxia

Month

Puget Sound
Edmonds
Vashon Island
Federal Way
Minimum monthly dissolved oxygen: 2006 - 2017

- **Biological stress for some spp.**
- **Quartermaster Harbor**
- **Hypoxia**

Map showing Puget Sound, Vashon Island, and Federal Way.
Biological stress for some spp.

Minimum monthly dissolved oxygen: 2006 - 2017

Strait of Juan de Fuca

Puget Sound

Hypoxia

Minimum DO (mg/L)

Month

1  2  3  4  5  6  7  8  9  10  11  12
Inner Quartermaster Harbor – mooring at 1-m

Dissolved oxygen (mg/L)

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

King County
Zooming in to 3 days – huge daily swings in DO
How have dissolved oxygen levels changed over time?
Dissolved Oxygen Trends

<table>
<thead>
<tr>
<th>Site</th>
<th>Years</th>
<th>Deep Target Depth</th>
<th>Deep 80-100-m</th>
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<tr>
<td>Brightwater TP</td>
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Legend: %Change over record
NS = Not Significant (p>0.05)
Dissolved Oxygen Trends

Strait of Juan de Fuca

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Months</th>
<th>Deep Target Depth</th>
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<th>80-100-m</th>
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<td>19</td>
<td>All</td>
<td>140-m</td>
<td>NS</td>
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</table>

Quartermaster Harbor

- Short-term variability too high to accurately assess trends
- From 15-min mooring data: inter-annual variability but no indication of increase in duration or intensity of low DO events (caveat: short data record).
How does this compare to historical data collected from 1933 – 1975?

**Salinity at 200-m –**
Similar pattern

**Temperature at 200-m –**
↑Increase of ~ 0.5 – 1 °C

![Graph showing salinity and temperature changes](image-url)

- Δ UW/Collias 1933 - 1975
- ○ King County 2002 - 2017

Error bars are 95% CI of the mean

Dissolved oxygen at 200-m – Similar seasonal pattern, variable by month

Δ UW/Collias 1933 - 1975   ○ King County 1998 - 2017

Error bars are 95% CI of the mean
No clear shift in DO observed during late summer/fall Aug. – Nov. DO time series for Point Jefferson at 200-m
Overall Summary

- Large amounts of spatial and temporal variability
- Important to understand drivers of nutrient changes and evaluate potential impairment indicators beyond concentrations
- Chlorophyll-a observations do not indicate signs of eutrophication in Central Basin. Due to lack of historical data, Quartermaster Harbor story isn’t clear.
- No clear trends or changes in DO.
- Inter-annual differences in phytoplankton bloom timing, magnitude and species composition make it difficult to assess trends (need longer time series)
- Hydrological cycle and circulation are important for assessing trends
- Need to understand variability within and between basins
  → Could lead to different approaches and priorities for science and management.
Thank you!

Contributors:

- King County Environmental Lab staff for field sampling and lab analysis
- Bruce Nairn: Dissolved oxygen explorations
- Lyndsey Swanson: Phytoplankton analyses
Appendix

• Extra slides
Nitrate + Nitrite Anomalies: Central Basin vs. Strait

Pt. Jefferson – 200-m

N. Juan de Fuca – 140-m
Similar pattern but different magnitude between years

2015 East Passage - Dissolved Oxygen (mg/L)

2016 East Passage - Dissolved Oxygen (mg/L)

2017 East Passage - Dissolved Oxygen (mg/L)