Kickoff: The Science of Puget Sound Water Quality Summary

Last Updated: August 22, 2022

Overview

Thank you to everyone who contributed to an energizing discussion at our first workshop on *The Science of Puget Sound Water Quality* on July 26, 2022. Over 130 people joined us, including researchers at universities, scientists at local governments, tribes, and resource agencies, modelers from across the border, and leaders at environmental community-based organizations.

> *"It's really about the process for how you assemble your partners, how you assemble your tools, and how you can work together to have the conversations that can ultimately lead you towards cost-effective solutions for the problems that you're trying to identify."*
>
> *Dr. Martha Sutula, Southern California Coastal Water Research Project*

Some of the key insights Dr. Martha Sutula, with the Southern California Coastal Water Research Project, shared in the keynote included:

- Water quality managers in their region want to understand more than just the change in nutrients and chemistry, they also want to understand the biological effects of those changes
- Managers can be motivated to act if the science of biological effects is compelling, there is a strong linkage between impacts, and they believe it is within their jurisdiction
- Consensus on the problem you are trying to address allows more flexibility on solutions beyond nutrient management alone, including living solutions and watershed and estuarine restoration
- An honest characterization of model uncertainty should be done first, and then the water quality managers need to decide whether and how to use the models and outputs
- Deviation from natural conditions can be challenging to interpret because there is often insufficient temporal baseline data and climate change is shifting the baseline
- Existing water quality objectives are not "plug and play" for biological thresholds. To establish the biologically-relevant oxygen and pH targets that were presented, scientists and policymakers need to collaborate to consider the metrics, level of severity (e.g., acute, sublethal, healthy), targeted habitats and taxa, as well as variability in duration, frequency, extent, and exceedances

The breakouts jump-started conversations on the technical uncertainties that we will dig into further with the workshops later this year. *The breakouts were designed as a continuation of regional discussions from the Puget Sound Nutrient Reduction Project and the Marine Water Quality Implementation Strategy workshops where technical uncertainties were identified.*

- Interannual variability of the ocean and river influences may have an important impact on the availability of nutrients to the euphotic zone, particularly considering stratification
- Integrated terrestrial-marine models are needed to synthesize decades of terrestrial and marine data and identify comprehensive recovery solutions across habitats and scales
- Different watershed models can learn from one another, compare model techniques and outputs, and collaborate to address shared modeling uncertainties (e.g., data sources)
- The cause and extent of several observed changes at the bottom of the food web are unknown. Additional combined modeling, monitoring, and analyses at the basin scale can help to explore the hypotheses that have been proposed in regional monitoring forums
- There is an opportunity to analyze existing data sets, particularly in shallow embayments and terminal inlets, to explore hypotheses, biological impacts, and combined monitoring & modeling

Background

Our region is navigating complex and challenging decisions on how best to manage nitrogen, dissolved oxygen, and the potential impacts of eutrophication on the key habitats and species of the Salish Sea. Over the next year, the Puget Sound Institute is supporting a series of scientific workshops to help address technical uncertainties, advance modeling, and refine monitoring to improve our understanding of nutrients and broader water quality in the Salish Sea. Learn more.

Continue the discussion

- If you have not already, please join the listserv to receive periodic updates about Puget Sound Institute's program to foster regional water quality science, including information about upcoming workshops
- Join us for the workshops later this year to dig into these technical uncertainties further (dates in the table below)
- Reach out to Stefano Mazzilli (mazzilli@uw.edu) and Marielle Larson (marlars@uw.edu) if you:
    - Are interested in contributing or helping with one of the upcoming workshops or modeling and monitoring analyses
    - Want to recommend another expert, program, or study for us to connect with to help advance the research
    - Have additional ideas or questions

Materials

- Playlist with videos
- Chat from the workshop

Session	Slides	Recording	Attendees	Related Workshop this Year
Intro & Keynote from Dr. Martha Sutula Dr. Martha Sutula, *Southern California Coastal Water Research Project*	Slides	Video	~130	n/a
Breakout discussions				
Dissolved Oxygen Impacts on the Biological Integrity of Key Habitats and Species Dr. Martha Sutula, *Southern California Coastal Water Research Project*	Slides	Video	~23	Week of 9/26
Change in Interannual Variability of Rivers and Ocean Impact Dr. Parker MacCready, *Live Ocean, University of Washington* Dr. Tarang Khangaonkar, *Salish Sea Modeling Center, University of Washington*	Slides	Video	~22	Week of 10/17
Phytoplankton and Primary Production Julia Bos, *Primary Production Vital Sign Project Co-lead & King County Field Scientist*	Slides	Video	~26	Week of 10/24
Watershed Modeling Dr. Bob McKane, *Environmental Protection* Agency *Office of Research and Development*	Slides	Video	~30	Week of 12/12

Note: for full presentation slides and resulting discussion please see the link above. Below are some highlights from each presentation, followed by questions and key discussion points.

Keynote

Water quality managers on our coast share many of the same challenges in addressing water quality and potential eutrophication.

- Tremendous variability in pollution inputs, circulation, climate, and biological communities and the significant cost of the solutions, means it is important for us to have place-based conversations

Ingredients to a solution to increase coastal resilience to global and local stressors in Southern California:

- #1 Willing partners at federal, state, and regional level to invest in science and management conversations to explore solutions
- #2 Sustained investment in coastal numerical models to disentangle the contributions of climate change, natural variability, and local pollution
- #3 Identify solutions worth chasing
- #4 Modeling uncertainties are understood
    - Worked with Southern California Bight stakeholders (e.g., utilities, regulators, environmental NGOs) to compile anthropogenic inputs and on model validation to increase model credibility for pollution applications
    - Pulled together notable scientists, modelers, and managers globally to educate stakeholders on modeling uncertainty. Recommendations from the workshops included:
        - Assess the skill of the model, on an ongoing basis
        - Invest in and maintain an open dialogue
        - Invest in and maintain long-term chemical and biological monitoring
        - Managers should provide guidance on the interpretation framework
- #5 Scientific basis for thresholds of algal biomass, pH and DO impact marine biological resources, as the basis for new water quality goals
    - Southern California Bight has not made any management decisions yet, because our managers want to understand not just the chemical change information we have, but how they are manifesting in biological effects
    - Numeric pH and Dissolved oxygen (DO) water quality objectives are intended to be an "end of pipe" criteria, whereas nutrients are dispersed, and a "reference" to pristine conditions is not possible to measure directly
- #6 Flexibility on what a solution could look like
    - Not just a focus on nutrient management alone, but looking beyond this to living solutions that enhance coastal resiliency and considering how we manage water as a resource
    - Incentivize watershed and estuarine restoration, because factors other than nutrients (e.g. hydromodification, warming) can cause eutrophication!

Discussion with Martha Sutula, Keynote Speaker

- How do you square the very short time in which we need to act with the longer time that it takes to develop biologically relevant standards?
    - Southern California Bight's water quality managers do not always necessarily feel that they need revised standards to proceed with a management action in which the science

of biological effects is compelling and there is a strong linkage between those impacts and something they feel is in their jurisdiction
    - SCCWRP (Southern California Coastal Water Research Project) is in the middle of the process and has assembled scientists to help provide the evidence for those linkages
- Are you and your colleagues approaching uncertainty in terms of a) we understand the uncertainty and think it is good enough, so we are going to move forward or b) more probabilistic, we know there is uncertainty, all models have uncertainty, and we provide our best estimate of x, and we have probability y that we are wrong about that estimate?
    - Often a little bit of both: your model needs to be credible for certain applications and then describe the uncertainty as well as possible for a specific question
    - There is probably a difference of opinion amongst managers in terms of how far the Southern California Bight needs to go to characterize uncertainty relative to how quickly they would like to be able to decide on this problem
    - Honest characterization of uncertainty should be done first, and then the managers need to decide whether and how to use the models and outputs
- Additional questions and comments for the region to potentially consider moving forward:
    - Toxics in Marine Water Quality are also a critical data gap. For example, we need new technologies to be able to sample 20 liters or more through filtration for contaminants of emerging concern to address the method detection limit
    - What about the role of nutrients in secondary and tertiary production? To what extent are we enhancing fish/shellfish production, does anybody care? Has anyone tracked stable N isotopes across the food webs?
    - What about CAFOs of the sea - fish pens and shellfish farms that dump sewage into the marine system?

Further reading and papers mentioned during the discussion

- Kessouri, F., McWilliams, J. C., Bianchi, D., Sutula, M., Renault, L., Deutsch, C., Feely, R. A., McLaughlin, K., Ho, M., & Howard, E. M. (2021). Coastal eutrophication drives acidification, oxygen loss, and ecosystem change in a major oceanic upwelling system. *Proceedings of the National Academy of Sciences*, *118*(21). Available at: https://doi.org/https://doi.org/10.1073/pnas.2018856118.
- Deegan, L. A., Johnson, D. S., Warren, R. S., Peterson, B. J., Fleeger, J. W., Fagherazzi, S., & Wollheim, W. M. (2012). Coastal eutrophication as a driver of salt marsh loss. *NATURE*, *490*, 18. Available at: https://doi.org/10.1038/nature11533.
- Wasson, K., Jeppesen, R., Endris, C., Perry, D. C., Woolfolk, A., Beheshti, K., Rodriguez, M., Eby, R., Watson, E. B., & Rahman, F. (2017). Eutrophication decreases salt marsh resilience through proliferation of algal mats. *Biological Conservation*, *212*, 1–11. Available at: https://doi.org/10.1016/j.biocon.2017.05.019.
- Frieder, C., Yan, C., Chamecki, M., Dauhajre, D., McWilliams, J. C., Infante, J., McPherson, M., Kudela, R. M., Kessouri, F., & Sutula, M. (2022). A macroalgal cultivation modeling system (MACMODS): Evaluating the role of physical-biological coupling on nutrients and farm yield. *Frontiers in Marine Science*, 214. Available at: https://doi.org/10.3389/fmars.2022.752951.

Breakout: Dissolved oxygen impacts on the biological integrity of key habitats and species

Highlights

Martha Sutula with the *Southern California Coastal Water Research Project* shared:

- Criteria that are expressed as deviation from natural are problematic to interpret because we often have insufficient temporal baseline (e.g. pre-industrial) data, and climate change is shifting the baseline
- The Virginia Province Approach (EPA, 2000) is often used to develop site specific dissolved oxygen criteria based on the impacts to local biological integrity of sub-systems. There are also some further scientific challenges associated some of which are highlighted in Tomasetti and Gobler (2020).
    - Little data to define sublethal endpoints, particularly for Pacific West Coast species
    - Not considering multiple stressors (e.g., temperature, natural covariance of DO, etc.)
    - The Environmental Protection Agency experiments kept pH artificially high, while in nature they covary, adding an additional, unaccounted for stress
- Recommendations on applying methods that address biological integrity included:
    - Identify key data gaps through literature review first
    - Invest in coupled chemical and biological monitoring
    - Collect experimental datasets of physiological tolerances for most sensitive species that focus on sublethal endpoints (e.g. growth, reproduction)
    - Consider comparative approaches to setting DO criteria:
        - Compare the output from approaches like the Virginia Province Approach with other recently advanced approaches (e.g., metabolic index); to have a side-by-side comparison and constructive conversation about what is most protective and valuable to your purpose
        - The Metabolic Index combines pO_2 with temperature-dependent biological responses to oxygen to define "aerobically available habitat"
- It sounds like the science community in the Salish Sea can benefit from further defining, and reaching a consensus, on the problems you are trying to address (e.g., low dissolved oxygen, harmful algal blooms, ocean acidification, benthic impacts, etc.)

Discussion

- Tessa Francis with Puget Sound Institute framed the discussion on the impacts on biology rather than the standards
- Accordingly, Marta Sutula noted it is interesting to flip the question to consider at what levels of oxygen and temperature are you sustaining healthy, thriving, reproducing populations? Particularly since some key species are already diminished so the goal is not just to sustain, but to help the population recover
- There is a difference between naturally low seasonal DO conditions, to which species can and have adapted, and anthropogenic driven low DO and what we can control (i.e., as a region we have less control over nitrogen loading from the ocean):
    - Paul McCollum shared that the Port Gamble S'Klallam Tribe has done research on:
        - Juvenile salmonids' respiration budget and found that < 50% saturation creates respiration stress at which point the salmon do not react to predation; so, it can quickly move from what could be considered chronic, to an acute impact

        - *A summary of hypoxia's impact on Chum salmon egg survival has also been shared and is available upon request to participants*
- Is a species-specific or an ecosystem approach better?
    - The approach to this with water quality managers is often driven by the regulatory framework (e.g., TMDL -Total Maximum Daily Load), individual permits, voluntary actions, etc.), trust, and stakeholders at the table
    - Even if we take an ecosystem approach, we still need species-specific data
    - The region has quite a number of endangered species that need consideration. It was noted however, that the language around engaged species legislation builds in consideration of the ecosystem supporting them
- There are challenges specifically in addressing nearshore species and habitats, in terms of: a) modeling gaps and monitoring gaps, b) their outsized importance as nursery areas for fish, and c) their significant daily DO swings
- There is a desire to consider multiple stressors, not just dissolved oxygen:
    - Some potential stressors to consider include toxins, contaminants, pH, temperature, etc.
    - Interest in taking an initial risk assessment approach to framing multi stressor considerations
    - It can be helpful to identify environmental drivers (e.g., nutrients) that are common across stressors
    - Martha noted this is challenging to address multi-stressors all at once, especially since there is a need to act quickly because our ecosystems are suffering. She suggested focusing on eutrophication as a subset, but looking at multiple lines of evidence including oxygen & temperature, harmful algal blooms, pH, and sediment organic matter accumulation to create a more holistic view of eutrophication in the system and to understand better the non-linear ecosystem feedbacks
- Additional questions and comments for the region to potentially consider moving forward:
    - Aside from modeling ocean sources nitrogen etc., knowledge from Tribal Oral History should be considered. Obviously, before contact and before industrialization, salmon and most other marine species were at fully functional levels of populations, so assuming that "natural" ocean sources are a main contributor to current problems is a huge mistake

Next steps

The Puget Sound Institute is planning to perform an initial literature review (i.e., desktop study) focusing on the sensitivity of the species of interest to low dissolved oxygen. We then have an opportunity to use model output data to produce spatially explicit exposure maps that identify areas of greatest species risk and includes a description of which species are at risk in each area. To help inform this literature review, we would appreciate input on:

1. Which **species and habitats should be prioritized** for consideration in the next year? *For example: shallow vs. deep water, benthic vs. pelagic, commercial importance, species, and lifecycle stage.*
2. How should we **consider sensitivity** of these species to stressors? *For example: severity (above sub lethal) vs. acute (some data available now) sensitivity.*
3. What **existing literature and monitoring data** can be included in an initial desktop study?

Further reading and papers mentioned during the discussion

- Tomasetti, S. J., & Gobler, C. J. (2020). Dissolved oxygen and pH criteria leave fisheries at risk. *Science*, *368*(6489), 372–373. Available at: https://doi.org/https://doi.org/10.1126/science.aba4896.
- Howard, E. M., Penn, J. L., Frenzel, H., Seibel, B. A., Bianchi, D., Renault, L., Kessouri, F., Sutula, M. A., McWilliams, J. C., & Deutsch, C. (2020). *Climate-driven aerobic habitat loss in the California Current System*. Available at: https://doi.org/doi/10.1126/sciadv.aay3188.
- Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H.-O., & Huey, R. B. (2015). Climate change tightens a metabolic constraint on marine habitats. *Science*, *348*(6239), 1132–1135. Available at: https://doi.org/10.1126/science.aaa1605.
- Keller, A. A., Ciannelli, L., Wakefield, W. W., Simon, V., Barth, J. A., & Pierce, S. D. (2015). Occurrence of demersal fishes in relation to near-bottom oxygen levels within the California Current large marine ecosystem. *Fisheries Oceanography*, *24*(2), 162–176. Available at: https://doi.org/https://doi.org/10.1111/fog.12100.
- Samhouri, J., Ramanujam, E., Bizzarro, J., Carter, H., Sayce, K., & Shen, S. (2019). An ecosystem-based risk assessment for California fisheries co-developed by scientists, managers, and stakeholders. *Biological Conservation*, *231*. Available at: https://doi.org/10.1016/j.biocon.2018.12.027.

Breakout: Change in interannual variability of rivers and ocean impact

Highlights

Parker MacCready, developer of the Live Ocean Model at the University of Washington, shared:

- An overview of nutrient loading in the Salish Sea, including how these sources change on monthly, annual, and longer time scales
- Because the vertical gradients are strong, any change in the depth of the ocean source of the exchange flow could also be very important
- When considering the importance of ocean source water, it is better to consider the import flux as opposed to the net import
- Biogeochemical Modeling would benefit from more observations of phytoplankton growth rates, zooplankton grazing rates, PAR (Photosynthetically active radiation), organic particle fluxes, and benthic fluxes

Tarang Khangaonkar, of the Salish Sea Modeling Center at the University of Washington, shared:

- An overview of the Salish Sea response to interannual variations during the marine heat wave years (2013-2017).
- That biological activity decreased a little during the heat wave, which may be because higher heat created stronger stratification which reduced the amount of diffusive flux into the euphotic zone
- That it is important to recognize that the strength of exchange flow into the Strait of Juan de Fuca is largely controlled by the Fraser River, which is dominated by snowmelt (which may also be impacted by the heat wave)
- Year-to-year changes in ocean conditions and freshwater loading from rivers can affect the biological response and therefore affect dissolved oxygen in the water column
- Running a multiyear investigation required an adjustment/relaxation of prior calibration parameter values
- The Salish Sea Model would benefit from improvements in some of the sub-basins of increased resolution and improve wind effects on mixing

Discussion

- When considering the deoxygenation in the northern Pacific:
  - The 20% declining trend at the Newport Line is a reasonable place to start to see if it makes a difference and as an estimate of the scale of variability
  - Downscaled projections of IPCC (Intergovernmental Panel on Climate Change) high emissions scenario estimated a drop of 1.6 mg/L of dissolved oxygen on the continental shelf by 2095 (Khangaonkar et al., 2020)
- How is climate change expected to change coastal upwelling intensity and upwelled nutrients?
  - Based on downscaled climate change projections, anticipate a " ≈ 16% increase in euphotic zone nitrate mass in future Y2095" (Khangaonkar et al., 2020).
  - It is hard to be confident in the climate model projections of wind intensity and upwelling
- Irrespective of the varying magnitude of nitrogen from the ocean, the euphotic zone still runs out of dissolved nitrogen because the algae seem capable of consuming all the nitrogen. In the summer, the euphotic zone is nutrient-limited, which is why we see a response to anthropogenic loads that may come directly to the surface
- There are parts of Puget Sound that are highly stratified and likely to react stronger to changes in nutrient loads like Hood Canal and Saratoga Passage, rather than other locations like Admiralty Inlet where there is heavy mixing

Next steps

Several areas of research have been identified to improve our understanding of interannual variability related to future scenarios and nutrient management both short term and long term. These include natural variability, climate change, and population growth. Short-term, we have an opportunity to better constrain uncertainty related to the physical controls of natural interannual variability including the:

- Timing and magnitude of **ocean influences** on the Salish Sea
- Timing and magnitude of the **freshet and riverine influence**
- Accordingly,
  - The availability of nutrients to the **euphotic zone**, first considering the role of temperature and salinity on **stratification**
  - Influence on residence time and flushing time of shallow embayments where low DO is observed (**ocean exchange** and **riverine flushing**)

What questions can we address in the short-term using modeling, existing monitoring, and analysis to reduce key uncertainties about these physical controls?

Further reading and papers mentioned during the discussion

- MacCready, P., McCabe, R. M., Siedlecki, S. A., Lorenz, M., Giddings, S. N., Bos, J., Albertson, S., Banas, N. S., & Garnier, S. (2021). Estuarine Circulation, Mixing, and Residence Times in the Salish Sea. *Journal of Geophysical Research: Oceans*, *126*(2). Available at: https://doi.org/10.1029/2020JC016738.
- Khangaonkar, T., Nugraha, A., Yun, S. K., Premathilake, L., Keister, J. E., & Bos, J. (2021). Propagation of the 2014–2016 Northeast Pacific Marine Heatwave Through the Salish Sea. *Frontiers in Marine Science*, *8*, 787604. Available at: https://doi.org/10.3389/fmars.2021.787604.
- Khangaonkar, T., Nugraha, A., Premathilake, L., Keister, J., & Borde, A. (2021). Projections of algae, eelgrass, and zooplankton ecological interactions in the inner Salish Sea – for future

climate, and altered oceanic states. *Ecological Modelling*, *441*, 109420. Available at: https://doi.org/10.1016/j.ecolmodel.2020.109420.

- Khangaonkar, T., Nugraha, A., Xu, W., & Balaguru, K. (2019). Salish Sea Response to Global Climate Change, Sea Level Rise, and Future Nutrient Loads. *Journal of Geophysical Research: Oceans*, *124*. Available at: https://doi.org/10.1029/2018JC014670.

Breakout: Watershed modeling

Highlights

Bob McKane, with the Environmental Protection Agency Office of Research and Development shared:

- Strategies for reducing uncertainties in watershed modeling, using the Visualizing Ecosystem Land Management Assessments (VELMA) model work on urban stormwater runoff and contaminant loads (i.e., 6PPD-Q) in Puget Sound nearshore streams as an example. *See the sources of uncertainty below*
- It is beneficial for different models to learn from one another and compare model techniques and outputs
- That integrated terrestrial-marine models are needed to synthesize decades of terrestrial and marine data and identify comprehensive recovery solutions across habitats and scales

Sources of Uncertainty	Key Questions
1) Model equations and parameters	Does the model adequately represent the processes controlling the outputs of interest? *For example, runoff via natural (soil matrix) and engineered (stormwater infrastructure) flow paths.*
2) Data for model implementation	Do the data accurately represent the system at the scales required to model the outputs of interest?
3) Calibration methods	Has the problem of equifinality been minimized? *Can we systematically disqualify solutions for which calibrated parameters provide the right answers for the wrong reasons?*
4) Propagation of uncertainty among submodels	Has model calibration reduced model uncertainty and its propagation among submodel components? *What model performance tests can help address these questions?*

Discussion

- *There were several clarifying questions about VELMA's functionality and future refinements*
- The importance of identifying contaminant hot spots on the landscape and other targeting mechanisms to prioritize solutions where they can be most effective. For example, the current approach of rain gardens everywhere may not be as effective as targeted green stormwater infrastructure
- It is beneficial to use VELMA in collaboration with folks of different expertise (GIS (Geographic Information Systems), hydrology, landscape features, etc.)

Next steps

- Building on Bob's insights about data for model implementation as a source of uncertainty, what watershed uncertainties are shared across different modeling efforts (e.g., land use, agriculture data, future climate scenarios, septic data, etc.)?
- What are the most important shared datasets for inputs and parameterization of watershed models in the region and how can their shared access be improved to support model development?

Further reading and papers mentioned during the discussion

- McKane, R., Halama, J., Pettus, P. B., Barnhart, B., Brookes, A., Djang, K., Khangaonkar, T., Kaplan, I., Harvey, C. J., Howe, E., Levin, P. S., Schmidt, M. W., & Giradin, R. (2018). 'An integrated environmental and human systems modeling framework for Puget Sound restoration planning,' *Salish Sea Ecosystem Conference, Seattle, United States, 4 May, 2018.* Available at: https://cedar.wwu.edu/ssec/2018ssec/allsessions/369/.

Breakout: Phytoplankton & Primary Production

Highlights

Julia Bos, the Phytoplankton and Primary Production Vital Sign Project Co-lead/King County Field Scientist, shared*:*

- In 2013 and 2016 the Puget Sound Ecosystem Monitoring Program, (PSEMP) work groups completed a monitoring gap analysis. The Marine Waters work group identified and prioritized eight monitoring gaps, including:
    - Spatial and temporal resolution of phytoplankton species and abundance
    - Phytoplankton rates (i.e., primary production, respiration, and sinking)
- From PSEMP Marine Waters work group meetings and other meetings, observed long-term changes at 27 of Ecology's core stations have been discussed. (*This data was not presented in this workshop. Please see presentations at the PSEMP phytoplankton group, May 18, 2022 for analyses.)* These changes include the following trends from 1999 – 2018 monitoring results:
    - Silicate to DIN (Dissolved Inorganic Nitrogen) ratios are declining
    - The near bottom to surface chlorophyll fluorescence amounts are declining
    - Seasonal changes have been observed in stratification and chlorophyll fluorescence
    - Seasonal changes in dissolved oxygen, DIN, salinity and temperature
- The cause and extent of these observed changes are unknown. Regional monitoring forums are discussing a number of hypotheses for these changes. These were the focus of discussion in this session, derived from the following:
    - Climate change has the effect of magnifying human nutrient contribution to Puget Sound and shifts the food web in the summer months
    - Changes in the nutrient balance can affect the growth conditions of the lower levels of the marine food web
    - In summer, the microbial food web has gained importance relative to the productive, diatom-based food chain
    - The organic particle export to deeper water has changed in response to shifts in the lower-trophic levels of the food web
    - *Source: See presentations by Christopher Krembs at Puget Sound General Nutrient Forum, July 19, 2017*

Discussion

- Monitoring gaps (and potential focus for monitoring/modeling analysis):
  - Benthic diatoms, especially in nearshore and shallow areas, and their effect on the reflux, and biochemical cycling. It is thought that these are potentially increasing which requires further data for investigation
  - Sustained program for submerged aquatic macrophyte monitoring (e.g. seagrass, kelp and other seaweeds), which are particularly important to the carbon and nitrogen cycling. Participants noted there are existing data and programs to leverage:
    - Washington Department of Natural Resources has a Nearshore Habitat Eelgrass Monitoring program
    - Washington Department of Natural Resources, Puget Sound Restoration Fund, Reef Check, and other groups are monitoring canopy and/or understory kelp in Puget Sound if data is needed for future efforts/modeling
    - Washington Department of Natural Resources, Department of Health, and King County have shallow area (near-shore) temperature and salinity data too
    - With an increase in kelp farms (some currently in permitting), it would be great to have funding for NANOOS (Northwest Association of Networked Ocean Observing Systems) to install moored sensors near farms to obtain observational data for nutrients/high-res pH that could help refine model parameterizations for macroalgae
- Focus on models with question-driven hypotheses (e.g., difference in remineralization rates)
- Need to utilize existing data sets to analyze hypotheses across regions where there are modeling gaps:
  - While the Salish Sea Model masks shallow areas, the region has a lot of data (e.g., King County, Washington Department of Natural Resources, etc.) that could be analyzed first to address hypotheses posed, and inform the discussion for monitoring/modeling co-development
  - Jan Newton noted earlier work on primary productivity rates and has relevant data from the 1990s and 2000s that has not yet been utilized
- Determine how well the Salish Sea (or other) models represent actual phytoplankton dynamics in Puget Sound, including benthic algal production
  - Limited, particularly in shallow water, and complex locations like Quartermaster Harbor
  - The Salish Sea Model and LiveOcean both have modules for phytoplankton (such as diatoms) and zooplankton (such as the dinoflagellate *Noctiluca scintillans* blooms). However, for the Salish Sea Model this is true only for the most recent version and not the current version used by Ecology.
- Identify other biogeochemical models that include benthic algae, macroalgae, or seagrasses
  - Jamaica Bay (New York state) modeling included benthic algae, macroalgae and potentially bivalves. The Long Island Sound modeling that is currently being updated will feed into living resource models in a subsequent phase that includes benthic/macro algae and submerged aquatic vegetation
  - The most recent version of the Salish Sea Model has modules for submerged aquatic vegetation.
  - Plans are underway in the region to link higher trophic level models such as Atlantis to biogeochemical models such as the Salish Sea Model, among others. This was briefly

mentioned in the watershed modeling breakout and was discussed in more detail at the Salish Sea Ecosystem Conference in McKane, 2018.

- Other researchers have incorporated both bottom up and top down processes into their modeling, which did a better job replicating the observed data. It may not be a question of either or, but rather when and where (Lynam et al., 2017)
- Susan Allen's presentation at the Salish Sea Ecosystem conference discussed modeling production in the Strait of Georgia and the impact of stratification in river influenced systems (Allen et al., 2018)
- Further questions and comments for consideration by the region moving forward:
    - When and how are phytoplankton light limited, grazing limited, or nutrient-limited?
    - There is more seaweed aquaculture in Puget Sound than many estuaries. What is the role of this and submerged aquatic vegetation more generally on nutrient cycling?
    - To what extent are shallow bay processes driving deeper waters?

Next steps

- An opportunity and need were recognized to first utilize existing data sets to analyze the proposed hypotheses where there are modeling gaps, and inform combined monitoring/modeling analysis and reduce model uncertainty
- It was proposed that an inventory of monitoring data would be a useful first collaboration for this workshop series and that of the PSEMP monitoring group. Specifically, considering data that can address the presented hypotheses, and parameters that further validate and improve associated model analysis
- It was proposed to prioritize analysis of different parts of the physics of the system on the availability of nutrients of the euphotic zone, to address some of these hypotheses with both monitoring and modeling data

Further reading and papers mentioned during the discussion

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Appendix – Questions and follow up

We are following up directly with individuals who had questions that were not addressed in time during the meeting discussion, including:

- Paul McCollum: "Toxics in Marine Water Quality is also a critical data gap. We need new technologies to be able to sample 20 liters or more through filtration for COC's to address MDLs."
- Alan Mearns: "What about the role of nutrients in secondary and tertiary production? To what extent are we enhancing fish/shellfish production, does anybody care? Has anyone tracked stable N isotopes across the food webs?"
- Richard Feeley: "Is there a change in the wind intensity under a future climate scenario?"
- Darlene Schanfald: "What about CAFOs of the sea - fish pens and shellfish farms that dump sewage into the marine system?"
- Michael Connor:
    - What are the hypotheses for having more gelatinous dominance?
    - There is more seaweed aquaculture in PS than many estuaries. Can we see its impact on phytoplankton?
    - To what extent are shallow bay processes driving deeper waters?

The complete list of discussion points and questions contributed in the chat during plenary and the breakout sessions is available here.