Project Overview
Transport and Fate of Nutrient and Pathogen Loadings into Nearshore Puget Sound (DW-13-92327601-01)

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Summary

The Puget Sound estuary provides one of the most valuable shellfish habitats in the Pacific Northwest. Shellfish are important economically, ecologically and socially to the Puget Sound basin (Dethier 2006). Ecologically, they are affected by the composition of freshwater entering the nearshore marine system and internal marine dynamics. Shellfish bed closures area-wide have decreased (PSP 2010), but in certain locations, persistent closures continue, affecting local growers and restricting commercial and recreational harvest opportunities. Shellfish growing area closures are considered to be a result of several factors that include growing areas exposed to excess nutrient and pathogen concentrations, with their effects complicated by non-point source nitrogen pollution (i.e., failing septic systems, agricultural wastewater, and stormwater) (Valiela et al. 1992, Vitousek et al. 1997). Declining water quality is associated with changes in the composition of watersheds and nearshore habitats from primarily forested to landscapes dominated by agricultural, rural residential and urban land uses (Glasoe et al. 2005). In addition, future climate changes will add another layer of complexity and increase potential threats to ecosystems that support shellfish through impacts on freshwater flows, marine circulation, and water temperature (Snover et al. 2005, CIG 2009). A Puget Sound Partnership priority is to reduce the risks of shellfish growing area closures and adverse effects on human health. Information that can predict pathogen concentrations and biotoxins along transport pathways where they pose a risk to shellfish and human health will help in achieving this goal.

For this project, we proposed to develop and apply an approach assessing how climate and restoration strategies affect variation in the levels of terrestrial and marine-derived water quality indicators (i.e., nutrients, biotoxins, fecal coliforms, and naturally occurring pathogens), and how changes in water quality in turn affect the magnitude of ecosystem service values provided by shellfish growing areas (i.e., filtration rates, food web support, and commercial and recreational harvest opportunity and socio-economic values). We used a field and quantitative modeling 'source-transport-fate' assessment approach to assess the vulnerability of shellfish growing areas to closures caused by watershed and marine-derived pathogens across alternative watershed land use/cover and climate futures.

This report presents an overview of the project. In the process of conducting the research, we encountered several unexpected challenges, which we describe below. Finally, we list the research products that correspond to the deliverables for EPA Grant DW-13-92327601-01.

Overview of Project

The core of the project plan (Figure 1) was to assess how watershed processes and conditions (Figure 1a) interact with nearshore and marine circulation and conditions (1b) in ways that affect shellfish growing areas (SGAs) (1c) and the delivery of ecosystem services from those areas (1d). This interlinked system is affected by both natural drivers such as climate (1e) and human drivers such as population growth (1f) and consequent changes in watershed features such as land use and land cover (1g). These drivers and changes affect freshwater flow and loadings of nutrients and pathogens from watersheds and so affect the conditions within SGAs. Investigating how this system works under various scenarios for the drivers and for management options could reveal strategies that are robust across the scenarios.

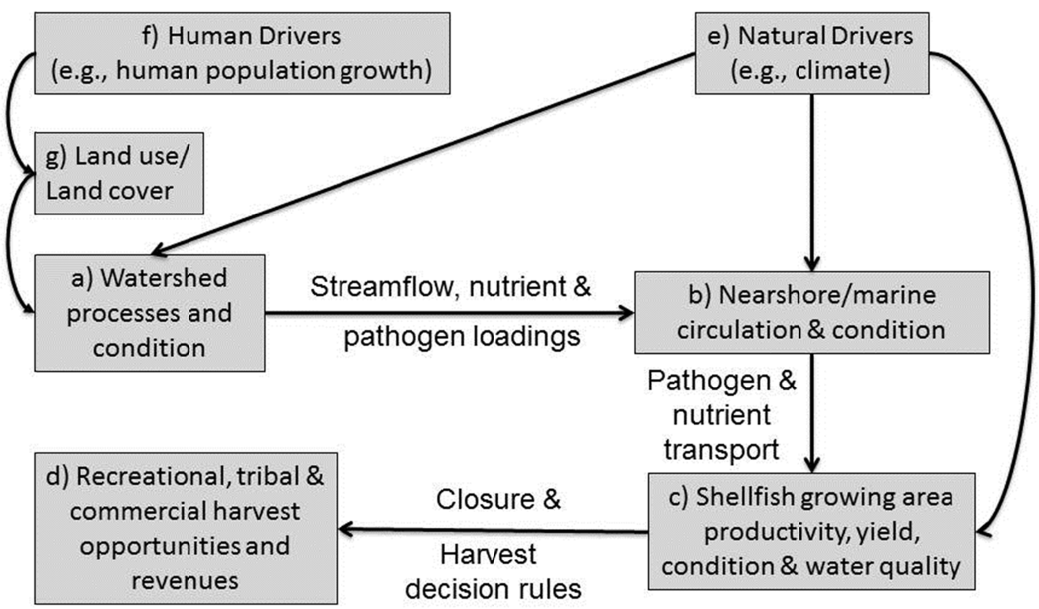

Figure 1: Conceptual plan for project "Transport and Fate of Nutrient and Pathogen Loadings into Nearshore Puget Sound" (EPA Grant DW-13-92327601-01).

Our plan for conducting this research had the following objectives and tasks:

Objective 1: Characterize the current spatial distribution, relative magnitude and *sources* of nutrients, pathogens, and marine biotoxins in shellfish growing areas.

a) *Compile existing data on water quality and shellfish tissue concentrations of nutrient, pathogen and marine biotoxins in the 3 study sites.*
b) *Characterize sources of nutrients by collecting water and shellfish tissue samples and analyzing them for stable isotopes ($\delta^{15}N$, $\delta^{13}C$, and $\delta^{18}O$).*
c) *Characterize sources of pathogens by using existing data for fecal coliforms and oceanographic/statistical modeling for the likelihood of Vibrio presence.*

Objective 2: Estimate *transport* of watershed-based nutrients and pathogens to shellfish growing areas and likely risk of exposure of shellfish

a) *Model marine transport of watershed-based loadings using a three-dimensional hydrodynamic model of Puget Sound and adjacent coastal waters (MoSSea, Modeling the Salish Sea, described in Sutherland et al. 2011) to calculate physical water properties (i.e. temperature) and the transport of river-derived nutrients and pathogens, under a range of land-use and future-climate scenarios.*
b) *Model marine pathogen occurrence using statistical analyses to examine relationships between physical water properties and pathogen data.*

Objective 3: Assess the *fate* of transported and in-situ nutrients and pathogens in terms of (i) vulnerability of shellfish growing areas to closure and (ii) consequences for ecosystem services provided by shellfish beds (i.e., filtration, food web support, value of recreational and commercial harvest) based on the scenarios generated by watershed and marine loading models.

a) *Estimate the relative contributions of pathogens to closures among growing areas using shellfish area management rules and classify growing area vulnerability to closures.*
b) *Evaluate consequences of shellfish growing area status for ecosystem service values (filtration rates, food web support, commercial and recreational harvest).*

Objective 4: Evaluate the individual and cumulative effectiveness of protection or restoration strategies to reduce risk of shellfish beds to closure and increase value of ecosystem services.

Associated with these objectives and tasks were a set of deliverables, listed in Table 1 below (following Project Objective, Tasks, Deliverables, and Research Products section).

Study Site Selection

Based on the historical prevalence of nutrient pollution, shellfish closures, and phytoplankton blooms in commercial and recreational shellfish growing area, we selected three nearshore sites--the Hamma Hamma (WRIA 16), Dosewallips (WRIA 16) and Samish (WRIA 3) (Figure 2). These nearshore areas are downstream from similarly-sized watersheds characterized by different land-use types (e.g., different cover of forested and agricultural lands), and they each have certified commercial and recreational shellfish beds. The Hamma Hamma (217 km^2) and Dosewallips watersheds (298 km^2) are mostly forested basins and are located in the western Hood Canal Basin. The Samish watershed (299 km^2) is predominantly rural with agricultural runoff as the dominant N-source inputs to the sound (WA DOH, Lawrence Sullivan personal communication). In the Samish Bay, several streams are listed as 'impaired' under 303(d), and the Washington Department of Ecology estimated that likely sources of fecal coliform bacteria (FC) contributing to violations of the water quality standard include stormwater, failing septic systems, agricultural manure and effluent from municipal wastewater plants. The Samish Bay site has experienced closures in recent years; the Hood Canal sites have not.

Challenges

The project encountered several challenges that changed the set of final outputs and products, which we describe below.

Climate impacts on circulation

In our proposal, we planned to explore how climate change alternatives could affect the interactions between watersheds and nearshore/marine conditions. Climate effects on precipitation and other conditions affect the amount and timing of freshwater received by watersheds. These in turn drive the freshwater inputs into Puget Sound which control the strength of the overturning circulation that flushes Puget Sound and controls the overall residence time of nutrients and pollutants. Ocean inputs also affect the strength of this circulation. (Note that these river and ocean effects on circulation strength are separate from the question of their contributions to biogeochemical budgets; we proposed to look at the former only in this project using the MoSSea model, since the model components required for the latter are only now under development.)

Our preliminary model experiments, however, demonstrated that these climate-timescale effects on circulation strength appear to be quite small compared with scenario uncertainty and natural variability in the system. Ensemble projections of future freshwater inputs, based on work by three groups at UW and University of Victoria, suggest ~20% changes in seasonal freshwater input by mid-century (and no significant trend in annual total freshwater input), which appears, based on MoSSea, to produce only subtle changes in circulation strength.

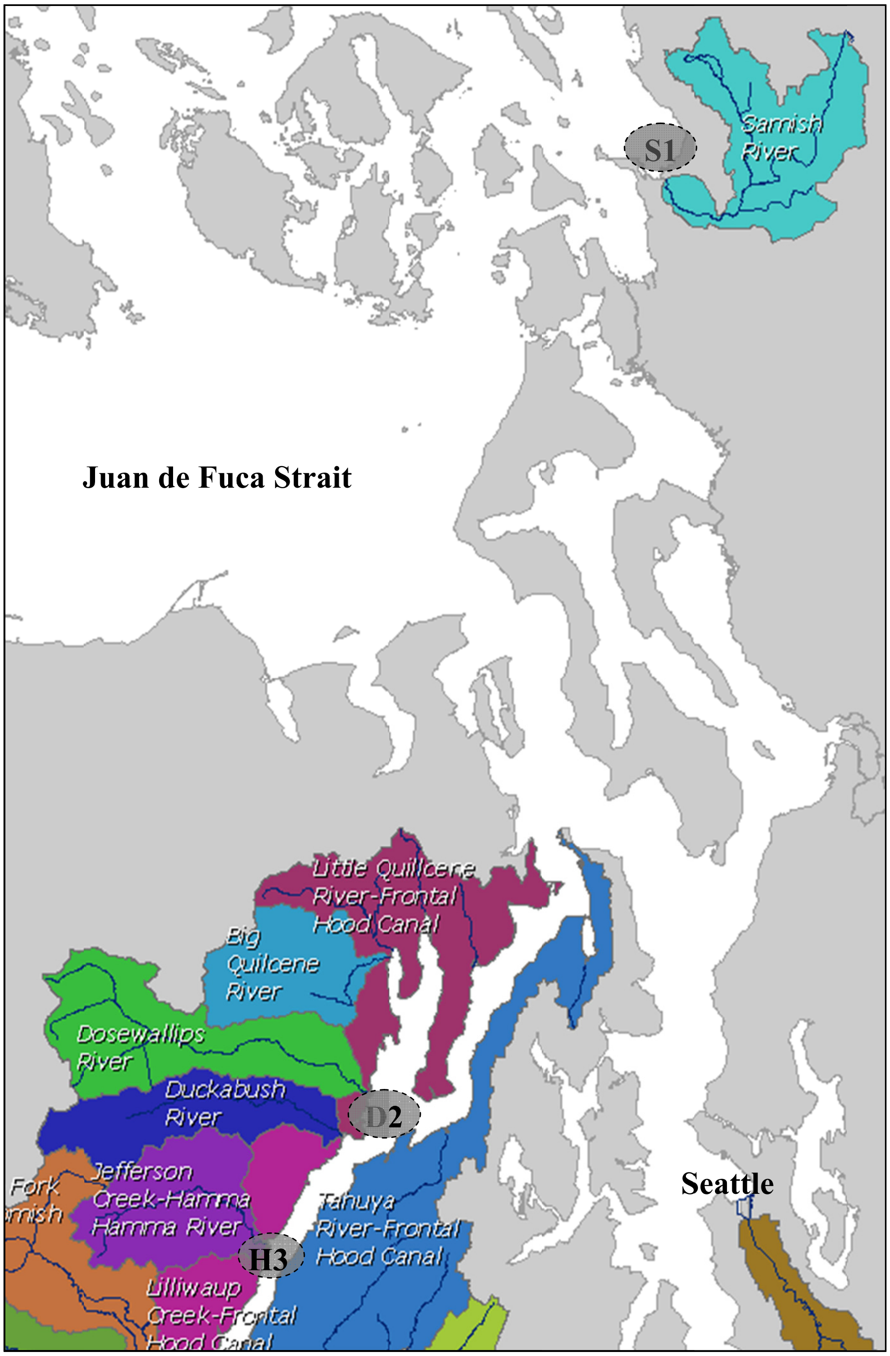

Figure 2: Map of project study sites, which are labeled S1 (Samish), D2 (Dosewallips) and H3 (Hamma Hamma).

Trends in coastal upwelling appear likely to produce significant changes in biogeochemical inputs (again, beyond the scope of our proposal) but negligible changes in mean circulation strength in the Strait of Juan de Fuca, according to initial model experiments using the CCSM3-A1B global scenario. Furthermore, we determined that current-generation global climate projections show so much uncertainty in future coastal winds that we cannot at this time project a trend in coastal upwelling significantly different from zero: some models predict noticeable (~20%) increases in upwelling wind intensity by mid-century at our latitude, and others predict decreases of the same magnitude.

This initial assessment of the climate-trend-to-uncertainty ratio led us to conclude that exhaustive examination of changes in Puget Sound circulation was not fruitful in an applied sense, and that we would better serve management needs by focusing primarily on spatial, rather than temporal, aspects of Puget Sound circulation using the MoSSea model.

Land use/cover scenarios

In our proposal, we planned to assess different scenarios involving alternate future land use/land cover and the associated streamflows and loadings of nutrients and pathogens. The needed outputs (streamflow and loadings) would come from the application of the University of Washington's DSEM[1] model through PRISM (Puget Sound Regional Synthesis Model). The development of the DSEM model was ongoing at the time of our proposal, but it unexpectedly did not continue to the point that could provide us with the needed information to build future watershed-based scenarios.

As an alternate approach for exploring future land use/cover scenarios, we utilized research being conducted by another group at the NW Fisheries Science Center, funded by the NOAA Comparative Analysis of Marine Ecosystem Organization (CAMEO) program ("Developing linked watershed-marine ecosystem service models to evaluate coastal management," http://cameo.noaa.gov/pres_mruckelshaus.html). This group used future land use/cover scenarios based on the spatially and temporally explicit multiple agent Envision modeling tool (Bolte and Vache 2010). These scenarios were used as inputs to watershed models developed by the CAMEO project to explore freshwater discharge and nitrogen loading to the marine system. (Appendix C of Conway-Cranos et al., Spatial and temporal variation in stable isotope ratios of primary producers and marine primary consumers in Puget Sound, provides some details on these models.)

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[1] DSEM is the DHSVM watershed model (Distributed Hydrology Soil Vegetation Model) linked to a solute export model (SEM).

As applied to our project, results from early CAMEO modeling work indicated that future land use/cover alternatives (based on Envision) did not produce substantial variation in broad land use/cover for our three study site watersheds. This lack of variation meant that the associated streamflows and loadings of nutrients and pathogens would also show little variation, and so we did not pursue this avenue analysis.

Modeling marine pathogen occurrence

Our plan for creating a predictive model of *vibrio* occurrence (specifically *Vibrio parahaemolyticus*) anticipated links between environmental variables such as water temperature and salinity and *vibrio* occurrence for Puget Sound. We based our plan on similar work that had built predictive models for *vibrio spp.* in Chesapeake Bay (de Magny et al. 2009, Jacobs et al. 2010) . Our attempts to build such a model for this project, however, did not prove to be fruitful. Investigation of historical observations of environmental conditions associated with vibrio occurrence in Hood Canal indicated that the high temperatures associated with high risk are a more local phenomenon than the subbasin-scale surface temperatures modeled by MoSSea. The implication of this for future research is that surface air temperature, rather than modeled water temperature, is likely to be a better basis for developing a statistical model of *vibrio* prediction, since the local heat balance on shallow mudflats appears to be of greater importance than basin-scale temperature variations. (This is the same methodology used by Moore et al (2009, 2011) for statistically modeling *Alexandrium catenella* risk in Puget Sound.) Limited time and resources did not allow us to pursue this approach.

We note that our preliminary climate-projection experiments do indicate a significant trend in surface water temperature throughout Puget Sound, close to the trend in surface air temperature, and a parallel project (Puget Sound *Alexandrium* Harmful Algal Blooms (PS-AHAB), NOAA Ecohab program) is currently quantifying the implications of this trend for the seasonal window of opportunity for *Alexandrium* in Puget Sound. Vibrio, in contrast, appears likely to be sensitive to trends in *extreme events* in surface *air* temperature, as opposed to trends in *seasonal averages* in surface *water* temperature.

Connecting MoSSea modeling and SGA management

Our project plan envisioned linking the results of the MoSSEA transport modeling to the management of SGAs using management rules established by the Washington State Department of Health (WDoH) and the Washington State Department of Fish and Wildlife (WDFW). The management of these areas depends on water quality in two ways. First, the WDoH classifies SGAs according to methods outlined by the National Shellfish Sanitation Program (NSSP) (USFDA 2011). These methods use data on fecal coliform to classify shellfish beds according to degree of risk to human health from fecal pollution. DOH applies the following NSSP criteria:

- The concentration of fecal coliform bacteria cannot exceed a geometric mean of 14 organisms per 100 milliliters (ml) in water (applied in all cases).
- The estimated 90th percentile cannot exceed 43 organisms per 100 ml of water (applied to areas where only nonpoint sources are present).

In addition to fecal coliform data, the DOH also surveys the upland watershed and marine shoreline to find and assess pollution sources. DOH cannot approve an area if the shoreline survey reveals pollution sources that threaten public health, even if the water quality meets the NSSP criteria. The classification of a growing area then governs the harvest of both commercial and recreational shellfish harvest. A status of Approved has no limitations on harvest, while Conditionally Approved and Restricted have some conditions. A Prohibited status means that no harvest is allowed within the growing area.

A second way that water quality affects shellfish harvest is through the co-management of tribal and recreational harvests. Washington State Indian tribes have treaty rights to harvest fish and shellfish at all "usual and accustomed grounds and stations." This right translates into a 50-50 division between Washington State and the Indian tribes with treaty rights for public beach shellfish resources. The tribes and the Washington State Department of Fish and Wildlife (WDFW) work cooperatively to manage shellfish resources by developing joint management agreements and plans. These plans set harvest limits based in part on clam and oyster population surveys, conducted on a limited set of public beaches. To the extent that water quality affects the productivity of shellfish populations, changes in water quality may therefore be reflected in changes in the management of tribal and recreational harvests. Commercial harvests are also likely to be affected, but the determination of those harvests takes place through private actions, not public management.

Assessing the effects of changes in water quality on shellfish harvests, then, can in principle take place in two ways. First, the status of a given shellfish growing area can change depending on how the level of fecal coliform is predicted to change within the growing area. Using the NSSP rules, land use and other changes that are likely to change fecal coliform levels can be translated into a predicted change in the status of shellfish growing areas, and the levels of harvests that have historically taken place in those areas can be used as a first approximation of the loss or gain in shellfish harvest values. Second, changes in the productivity of shellfish populations can be translated into changes in the sustainable harvest of those populations, and again, historical harvests levels can be used as a baseline against which to assess the value of the changes.

Pursuing these links anticipated a relatively fine resolution for the MoSSEA transport modeling, which would allow us to track pathogen and nutrient particles into the SGA in a meaningful way. In developing the application of the MoSSea model to this project, the initial plan was to use tracers (specifically, dye tracers) that would produce relatively high-resolution results, which in turn would allow us to draw conclusions about potential changes in water quality within SGAs. Using this method to explore the connectivity among major Puget Sound rivers, however, proved to be untenable in terms of computational requirements. Instead, using particle tracers reduced the computational requirements more than 100-fold but also required a lower resolution (2 km grid) to ensure adequate sample sizes in tracking particles. The 2 km resolution yielded maps of connectivity among rivers and subbasins that are unprecedented in their detail, but was still too coarse to explore with any confidence the connectivity within individual SGAs. This limitation is expected to disappear with ongoing refinements to the core MoSSea model.

For this reason, the project was unable to explore the effects of transported nutrients and pathogens on the vulnerability of specific SGAs to possible closure or productivity changes and the consequences of either of those for ecosystem services provided by shellfish beds. In lieu of estimating the provision of ecosystem services across future scenarios, we have documented the current provision of ecosystem services related to harvest in the three study sites (Plummer, Ecosystem Services from Shellfish Harvest for Puget Sound).

<u>Project Objectives, Tasks, Deliverables, and Research Products</u>

The project research products that correspond to the deliverables for each objective and set of tasks for EPA Grant DW-13-92327601-01 are listed in Table 1 and included as separate files. As noted above, in some cases the challenges faced in conducting the research altered the scope of the project in unexpected ways, and this is reflected in the research products listed in Table 1.

Table 1 Tasks, Deliverables, and Research Products for EPA Grant DW-13-92327601-01		
Task	**Deliverable**	**Research Products**
1a: Compile, validate and archive for access by stakeholders existing data on water quality and shellfish tissue concentrations of target indicators	Database from existing sources for nutrients and fecal coliform bacteria in the 3 shellfish growing areas included in the study	1) Description of Water Quality and Shellfish Tissue Sample Analyses Database 2) Database of Water Quality and Shellfish Tissue Sample Analyses Description and database are online at the Puget Sound Institute, Encyclopedia of Puget Sound (http://www.eopugetsound.org/articles/database-transport-and-fate-nutrient-and-pathogen-loadings-nearshore-puget-sound)

Table 1 Tasks, Deliverables, and Research Products for EPA Grant DW-13-92327601-01		
Task	**Deliverable**	**Research Products**
1b: Characterize sources of nutrients	Summary report of empirical data indicating the relative magnitude of watershed- v. marine-derived nutrients in 3 shellfish growing area, presented as current maps and associated databases	Summary reports 1) Conway-Cranos et al_Estuarine organic matter subsidizes shellfish beds_Summary and Key Findings 2) Conway-Cranos et al_Spatial and temporal variation in stable isotope ratios_Summary and Key Findings Manuscripts for publication 1) Conway-Cranos et al_Estuarine organic matter subsidizes shellfish beds_Manuscript (to be submitted to Marine Ecology Progress Series) 2) Conway-Cranos et al_Spatial and temporal variation in stable isotope ratios_Manuscript (to be submitted to Landscape Ecology)
1c: Characterize sources of pathogens	Summary report of empirical data indicating the relative magnitude of watershed- v. marine-derived pathogens in 3 shellfish growing area, presented as current maps and associated databases	See discussion above (Challenges, Modeling marine pathogen occurrence)

Table 1 Tasks, Deliverables, and Research Products for EPA Grant DW-13-92327601-01		
Task	**Deliverable**	**Research Products**
2a: Model marine transport of watershed-based loadings.	Maps and associated databases of transport pathways and relative intensity of watershed vs. marine sources of pollutants in study sites under alternative climate and management scenario conditions; documentation for circulation model of relevant chemical and physical parameters	<u>Summary Report</u> 1) Banas et al_Patterns of river influence and connectivity_Summary and Key Findings <u>Manuscripts for publication</u> 1) Banas et al_Patterns of river influence and connectivity_Manuscript (to be submitted to Estuaries and Coasts)
2b: Model occurrence of marine environmental variables related to pathogen occurrence	Report documenting the initial model runs using historical (1a) and collected (1b) data	See discussion above (Challenges, Modeling marine pathogen occurrence)
3a: Estimate the relative contributions of nutrients and pathogens to closures among growing areas and classify growing area vulnerability to closures.	Dataset covering the estimated relative levels (i.e., high, med, low change metrics) of indicator concentrations that trigger closures to nutrient and pathogen contamination	See discussion above (Challenges, Connecting MoSSea modeling and SGA management)

Table 1 Tasks, Deliverables, and Research Products for EPA Grant DW-13-92327601-01		
Task	**Deliverable**	**Research Products**
3b: Evaluate consequences of shellfish growing area status for ecosystem service values (filtration rates, food web support, commercial and recreational harvest).	Documentation and analyses of the spatial distribution and quantity (in biophysical units and dollars) of ecosystem services under different watershed, marine circulation, and climate scenarios, using user-defined scenarios of watershed and nearshore activities/actions agreed to by project leads and stakeholders	Plummer_Ecosystems Services from Shellfish Harvest for Puget Sound See also discussion above (Challenges, Climate impacts on circulation, Land use/cover scenarios, and Connecting MoSSea modeling and SGA management)
4: Evaluate the individual and cumulative effectiveness of protection or restoration strategies to reduce risk of shellfish beds to closure and increase value of ecosystem services.	Report that synthesizes results in terms of the relative contributions of watershed vs. marine vs. climate impacts on shellfish bed closures	See discussion above (Challenges, Climate impacts on circulation, Land use/cover scenarios, and Connecting MoSSea modeling and SGA management)

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