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SUBJECT: **Technical Memorandum: Puget Sound Nutrient Source Reduction Project Phase II - Optimization Scenarios (Year 1)**

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Background

The Washington State Department of Ecology (Ecology) is conducting the Puget Sound Nutrient Source Reduction Project (PSNSRP) to address water quality concerns in Puget Sound. This is a collaborative process aimed at reducing anthropogenic nutrients from point and nonpoint sources to meet dissolved oxygen (DO) water quality standards in Puget Sound.

The Salish Sea Model (SSM) is a state-of-the-science computer modeling tool that simulates the complex physical, chemical, and biological patterns in the Salish Sea (Khangaonkar et al. 2018). This model is used to quantify the level of DO improvements resulting from different regional nutrient reduction scenarios. In collaboration with Ecology, the Pacific Northwest National Laboratory developed the SSM, with funding from the United States Environmental Protection Agency. The model includes flow and nutrient inputs from watersheds and point source outfalls that discharge to the Salish Sea.

This work aligns with the overall timeline of the PSNSRP. The next phase will include refinements to the Year 2 Optimization Scenarios as discussed later.

PSNSRP – Bounding Scenarios

Ahmed et al. (2019) published the results of the first phase of the PSNSRP, where SSM was used to run a series of Bounding Scenarios. These Bounding Scenarios included an evaluation of the impact of Washington State anthropogenic nutrient sources from watersheds and marine point sources. Additional model scenario results included improvements in DO levels from the hypothetical implementation of advanced biological nitrogen removal (BNR) at United States (U.S.) municipal wastewater treatment plants (WWTPs) that discharge to the Salish Sea.

The results of this first phase of modeling confirmed that human sources of nutrients are cumulatively influencing predicted DO noncompliances in multiple embayments and inlets; this excludes certain nearshore areas, which have been masked, as described in this memorandum in the section "Masked Areas." The Bounding Scenarios report described intra-basin transport that can influence predicted noncompliances. It also made it clear that a combination of nutrient reductions from both marine WWTPs, as a class of dischargers, *and* from watersheds, are most likely needed to attain water quality standards.

There was, therefore, a need to evaluate both watershed and marine point source nutrient reductions in more detail, and to answer questions such as:

1. What is the relative influence of watershed nutrient loads entering individual Puget Sound regions?
2. What is the relative influence of marine point source nutrient loads entering individual Puget Sound regions?
3. How do seasonal vs. annual nutrient load reductions at WWTPs influence potential water quality improvements?
4. What is the impact of increases in WWTP flows (and nutrient loads) due to projected future population growth on DO levels?
5. What combination of watershed and marine point source nutrient load reductions are needed to meet DO standards in Puget Sound?

On April 30, 2019, Ecology gathered feedback from the Nutrient Forum[1] on a draft list of 'Optimization Scenarios' that were developed to answer the above questions. The result of this process was a final list of 'Year 1' Optimization Scenarios, as well as a 'parking lot' for 'Year 2' scenarios. Figure 1 shows the different modeling phases of the Puget Sound Nutrient Source Reduction Project.

Puget Sound Nutrient Source Reduction Project		
Phase 1: Bounding Scenarios	Phase 2: Optimization Scenarios	
Volume 1: Model Updates and Bounding Scenarios Report (Ahmed et al., 2019)	Optimization Scenarios, Year 1 Technical Memorandum (2021)	Optimization Scenarios, Year 2 Volume 2 Report (expected 2022)
Model Scenarios (2006, 2008, 2014): 1. Impact of all anthropogenic sources 2. Impact of marine point sources 3. Improvement with BNR at all municipal WWTPs 4. Improvement with BNR at large WWTPs 5. Improvement with BNR at mid-size WWTPs	Year 1 Scenarios (2006, 2014): 1. Watershed reductions by region 2. WWTP reductions by region 3. Annual vs. seasonal WWTP reductions 4. Future growth scenarios 5. Watershed and WWTP reductions	Year 2 'Parking Lot' Scenarios: 1. Combination of watershed and WWTP reductions 2. Other scenarios to be determined

Figure 1. Puget Sound Nutrient Source Reduction Project phases and modeling scenarios.

Optimization Scenarios (Year 1)

The Optimization Scenarios (Year 1) for Phase 2 of the PSNSRP modeling work include distinct model scenarios determined from results of the Bounding Scenarios and guidance from the PSNSRP Nutrient Forums. This technical memorandum focuses on the results of the Year 1 Optimization Scenarios modeling effort (Table 1). In addition, both existing and reference conditions were re-run for 2006 and 2014 as updates were made (see Appendix A and C).

[1] All Nutrient Forum meeting documents can be found here: https://www.ezview.wa.gov/DesktopDefault.aspx?alias=1962&pageid=37106.

Table 1. List of Optimization Scenarios, including the year(s) modeled and model inputs for nutrient load estimates at watersheds and WWTPs.

Scenario Number	Scenario	Model Years	Watershed Loads	WWTP Loads
1	Watershed reductions	2006, 2014	Watersheds in focus region at reference; all others at existing	Existing Conditions
2	WWTP reductions	2006	Existing Conditions	WWTPs in focus region at reference; all others at existing
3	Annual BNR8 (DIN and CBOD at 8mg/L) at WWTP	2006, 2014	Existing Conditions	Annual reductions
4	Projected future growth	2040	Existing Conditions	Projected high and low WWTP flow estimates
5	Combined watershed and WWTP reductions	2006, 2014	15%, 40% or 65%* reductions in anthropogenic load	Annual or seasonal BNR with DIN of 8 mg/L or 3 mg/L
Existing	Baseline conditions of existing human sources	2006, 2014	Existing Conditions: Two slightly different versions used due to updates (see Appendix A)	Existing Conditions
Reference	Estimated natural conditions without regional human sources	2006. 2014	Reference Conditions**	Reference Conditions**

*65% watershed load was evaluated for only year 2006
** See definition of reference conditions in the modeling QAPP (McCarthy, 2018)

The first two sets of Year 1 Optimization Scenarios assess nutrient loading from watersheds (Scenario 1 simulations) and WWTPs (Scenario 2 simulations) by region. For Scenario 1 simulations, watershed nutrient inputs entering each region are individually set at estimated reference loads whilst the other regions remain at existing nutrient loads. Scenario 1 runs evaluate the impact of watershed nutrient loading from six different regions (discussed later) of the Salish Sea during years 2006 and 2014. Scenario 2 runs focused on reducing WWTP nutrient inputs entering each of the same six regions to reference conditions, but was only evaluated for year 2006, and therefore involved six model runs.

Scenario 3 evaluates the influence of BNR8 (DIN and $CBOD_5$ at 8 mg/L) applied at WWTPs annually during 2006 and 2014. These were then compared with the seasonally (April – October) applied BNR8 scenarios that were part of the Bounding Scenarios (BNR8 at all facilities, BNR8 at facilities discharging >1,000 kg/day of DIN, and BNR8 at facilities discharging > 8,000 kg/day of DIN). These seasonal BNR8 scenarios were rerun and reevaluated for this memorandum due to model updates described later.

Scenario 4 addresses the impact of future population growth on water quality conditions during the year 2040. Projected increases in population growth in the Puget Sound region will result in an increase in wastewater effluent flows. This scenario required two model runs, one using future effluent flows under a ‘low’ population alternative and one for a ‘high’ population alternative.

Scenario 5 simulations were designed to explore different combinations of watershed and WWTP nutrient reductions as shown in Table 2.

Table 2. Scenario 5 combined reductions in watersheds and WWTPs

Scenario 5	Anthropogenic Watershed reductions*	WWTP reductions
Scen5a	15%	Annual BNR8 at all WWTP (DIN = 8 mg/L, $CBOD_5$ = 8 mg/L)
Scen5b	40%	Annual BNR8 at all WWTP (DIN = 8 mg/L, $CBOD_5$= 8 mg/L)
Scen5c	40%	1. Seasonal BNR3 for WWTPs in South Sound, Main and Whidbey Basin: • Apr - Oct: DIN = 3 mg/L; CBOD = 8 mg/L) • Jan-Mar and Nov - Dec: DIN = 8 mg/L; CBOD = 8 mg/L 2. Annual BNR at all other WWTP: DIN=8 mg/L; CBOD = 8 mg/L
Scen5d	40%	Annual BNR3 at all WWTP (DIN = 3 mg/L, CBOD = 8 mg/L)
Scen5e	65%	Annual BNR3 at all WWTP (DIN = 3 mg/L, CBOD = 8 mg/L)

*These percent reductions are applied only to the anthropogenic portion of watershed nutrient loads i.e. the difference between existing and estimated reference loads. For example, 15% means a 15% reduction in existing anthropogenic loads (equivalent to 85% of existing anthropogenic loads). The percent reductions are also applied across all forms of nitrogen and organic carbon (ammonia, nitrate, dissolved and particulate organic nitrogen, and dissolved and particulate organic carbon).

Aggregating model results to regions

Both the Optimization and Bounding Scenarios involved aggregating model results into different areas of the Salish Sea to identify spatial patterns in water quality conditions. However, these groupings changed between the two phases of the project.

SSM Bounding Scenario results were grouped into the following eight ‘basins’: Strait of Juan de Fuca, Strait of Georgia, South Sound, Hood Canal, Main Basin, Admiralty Inlet, Whidbey Basin, and a single basin for Bellingham, Samish and Padilla Bays (also referred to as the ‘Northern Bays’).

Optimization Scenario results are grouped into six ‘regions’ for the present analysis (Figure 2). Admiralty Inlet is combined into a single region with the U.S. part of the Strait of Juan de Fuca. Bellingham, Samish, and Padilla Bays (also referred to as the *Northern Bays)* are combined into a single region with the U.S. part of the Strait of Georgia. The six regions used for Year 1 Optimization Scenario are, therefore, as follows:

1. Strait of Juan de Fuca/ Admiralty Inlet (aka SJF and Admiralty)
2. Strait of Georgia/ Bellingham, Samish, and Padilla Bays (aka SOG and N. Bays)
3. Whidbey Basin
4. Main Basin
5. South Sound
6. Hood Canal

These six regions are shown in Figure 2. Results are also aggregated to 'WA waters of the Salish Sea', which is equivalent to the area within all six of these regions. In this memo from here on, this area is referred to simply as 'WA waters', though it is limited only to Washington waters within the Salish Sea. There may be changes to the demarcations of these regions in Year 2 Optimization Scenarios or in future phases of the PSNSRP.

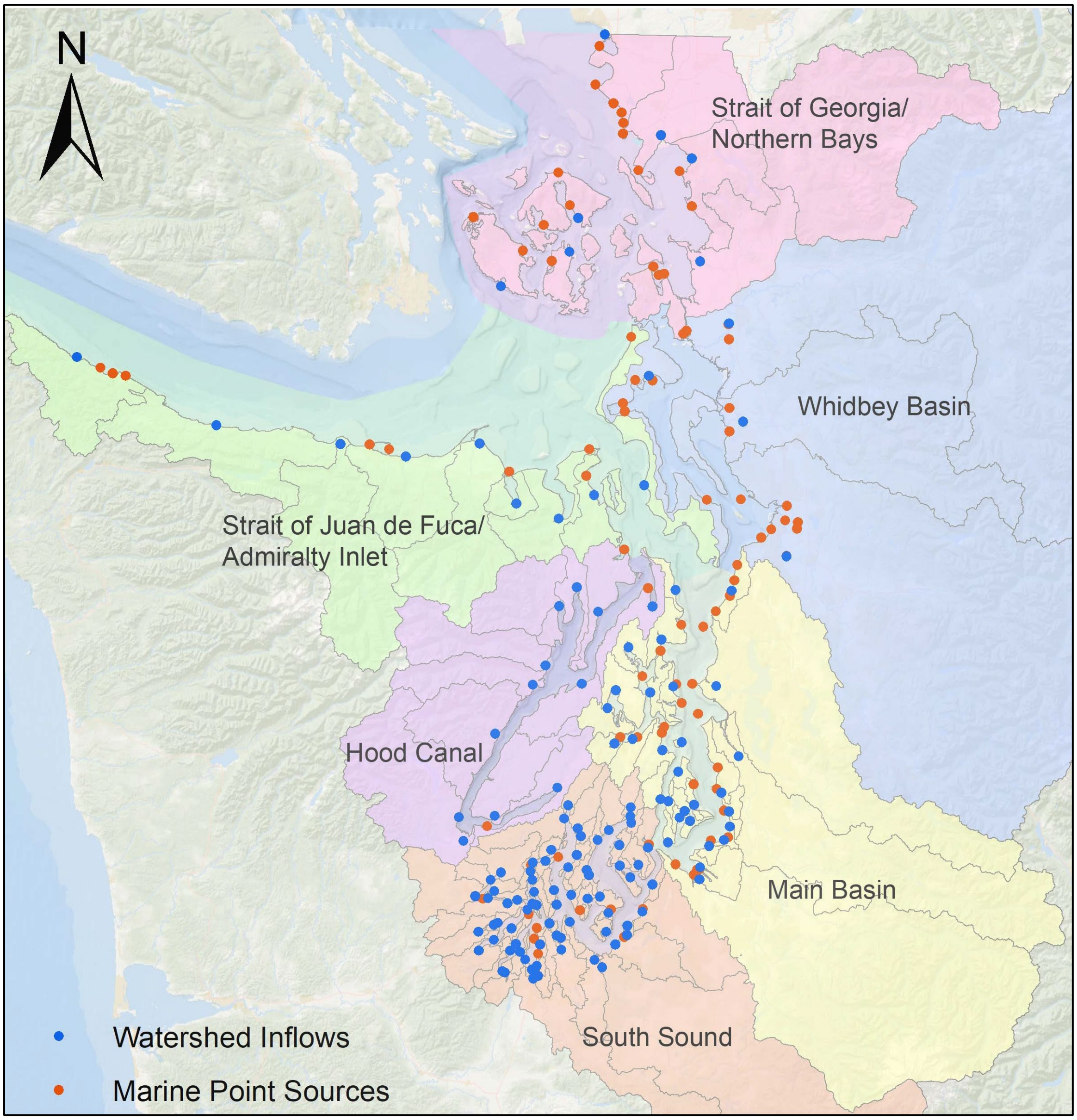


Figure 2. Salish Sea regions used to group results in the Optimization Scenarios.

Methods

Brief overview of modeling approach

Model inputs for SSM include 161 watershed inflows and 99 marine point sources (89 municipal WWTPs and 10 industrial sources, though not all of these are operating during all modeled years) that discharge directly to the Salish Sea in the U.S. and Canada, as identified by the blue and red circles in Figure 2. The freshwater inputs represent the nutrient load at the river mouth, which include all upstream sources in watershed. Previous reports (Ahmed et al., 2019; McCarthy et al., 2018; Mohamedali et al., 2011) provide further descriptions including load estimation methods for the SSM inputs.

Existing conditions refer to the hindcast model runs for the years 2006 and 2014 and includes the estimated human regional inputs of nutrients, and serve as baseline results for comparative purposes during scenario analysis. *Reference conditions* represent existing conditions excluding estimated human regional inputs of nutrients.

The difference between the model scenario and reference condition represent the changes due to anthropogenic nutrient inputs from Washington State in that particular scenario. When evaluating 2040 population growth with the SSM, 2014 hydrodynamics, meteorology, and watershed loads were used with WWTP flows representing 2040. Therefore, 2040 predicted noncompliant cumulative days and magnitudes are compared with the 2014 baseline.

Masked areas

Model output generated within intertidal and some shallow subtidal areas is not currently assessed for regulatory purposes. Due to SSM's bathymetric smoothing, areas with large intertidal flats are deeper in the model relative to their actual depth. As a result, steep changes in bathymetry at these nearshore locations are not realistically represented (Ahmed et al. 2019 Appendix J). Therefore, intertidal and shallow subtidal zones including brackish waters where river channels connect with marine waters are masked. Figure 3 shows the masked areas in WA waters. The following procedure was followed to mask these areas:

1. We used a coastal digital elevation model (DEM) from NOAA[2] to demarcate intertidal areas. The NOAA DEM files used include: Puget Sound, Strait of Juan de Fuca, and Port Townsend. For the area within Washington waters, between the US-Canada border and north of Bellingham Bay, we used a digital elevation map of this area that we obtained from Puget_Sound_DEM_2000 shape file (originally created by University of Washington) and was available in Ecology's database. This shape file has elevations in terms of NGVD29. The elevations for nodes in this area were extracted using GIS tools, and transformed to NAVD88 using Vertical Datum Transformation (VDatum).

[2] https://www.ngdc.noaa.gov/mgg/coastal/coastal.html

2. Intertidal areas are spatially defined as regions in which the mean lower low water (MLLW) is greater than or equal to zero. Average NOAA NAVD88 elevation was taken for each model grid cell within WA waters and transformed to MLLW with VDatum[3]. An offset of -0.77 represents the median difference between VDatum calculated MLLW elevations and NOAA NAVD88 elevations for WA waters. SSM grid cells with NAVD88 elevations of -0.77 or greater were used to define intertidal areas and were masked out.

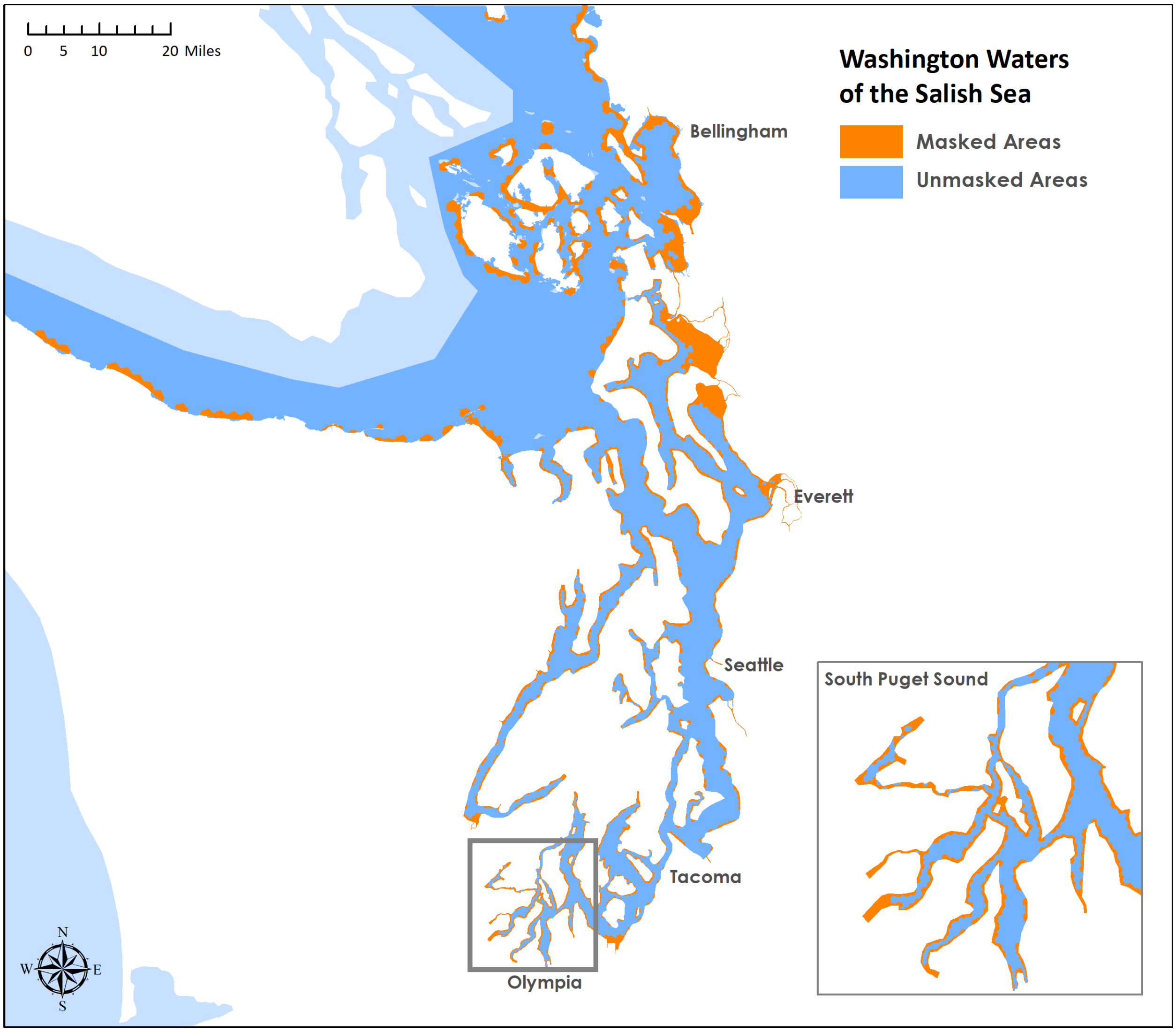


Figure 3. Areas masked from model output in Washington waters of the Salish Sea.

3. In addition to using the -0.77 offset mentioned above, all nearshore grid nodes with direct watershed inputs were masked, and a secondary offset was applied to each node where NOAA-NAVD88 elevations were greater than node-specific MLLW (obtained from VDatum).

[3] https://vdatum.noaa.gov/vdatumweb/

4. For nodes that had NOAA-NAVD88 elevations but no estimated VDatum offsets (areas not covered by VDatum), offsets of neighboring nodes were applied.

5. Waters within Washington State that do not have a marine dissolved oxygen (DO) standard (upstream reaches of rivers with freshwater DO standard and where model grid was present) were also masked.

We are not using model results from any masked area to evaluate compliance with DO standards.

Recent updates

Since the Bounding Scenarios report (Ahmed et al. 2019), several changes and updates were incorporated into the SSM, including changes in model inputs and further evaluation of model output. These updates are summarized in Table 3 and are described briefly in this section. Table 3 also provides the reference to appendices that provide additional details on each update or change.

Table 3. Updates to the Salish Sea Model (SSM) and DO standard comparison since Bounding Scenarios Report (Ahmed et al. 2019).

Update made to:	Optimization Scenario approach	Bounding Scenario approach	Appendix
Freshwater inflows – organic carbon	Freshwater organic carbon data (previously unavailable) were used to develop new regressions for DOC and POC for the following rivers: Skokomish, Snohomish, Stillaguamish, Samish, and Nooksack. As a result, these rivers also have new reference concentration estimates for these parameters.	DOC and POC for these rivers had been set to a constant year-round concentrations (which did not vary between existing and reference conditions)	Appendix A
Freshwater inflows – river concentrations for year 2014 model runs/scenarios	New regressions were developed for all rivers based on observed data from 2006 – 2018. These were used to create input files for rivers for all 2014 Optimization Scenarios. For 2006, the previous regressions (Ahmed et al. 2019) were used, except for organic carbon (as described above).	Original regressions documented in previous reports were used to estimate river concentrations for all model years.	Appendix A
Freshwater inflows – Hood Canal rivers	For several freshwater inflows entering Hood Canal, a few changes were made in terms of which regressions are used to estimate nutrient concentrations for these inflows.	All Hood Canal freshwater inflows followed our original approach and regressions.	Appendix A
Freshwater inflows- temperature timeseries	Temperature timeseries for several rivers were corrected for Scenario 5.	N/A	Appendix A
Freshwater inflows -review of limitations of estimates	Summarized known limitations and uncertainties for watershed inflows.	Freshwater inflow approaches were referenced to previous reports that discussed limitations.	Appendix A

Update made to:	Optimization Scenario approach	Bounding Scenario approach	Appendix
Freshwater inflows – watershed flows	No change to freshwater inflows (relative to Bounding Scenarios) except that additional analysis was conducted to assess and compare watershed flows entering different regions of the model domain, and more detailed documentation on the methods used to estimate Canadian freshwater inflows are included in Appendix B.	N/A – the approach is the same, but a detailed flow assessment for the Canadian inflows is now provided.	Appendix B
Organic carbon reference condition estimates	New regressions were developed with updated data, where available to generate time series for organic carbon which were previously a constant. Reference concentrations of labile POC are lower than reference concentrations of refractory POC	Organic carbon concentrations were a constant for some rivers. So, the reference condition was same as existing condition. Reference concentrations of labile POC were higher than reference concentrations of refractory POC	Appendix C
Ocean boundary for year 2014 model runs/scenarios	A global ocean model (HYCOM) was used to develop the ocean boundary condition for the SSM for all 2014-model runs. This boundary now has a higher spatial and temporal resolution.	Quarterly data from Department of Fish & Oceans (DFO, Canada) were used to develop the open boundary condition for all model runs/scenarios.	Appendix D
DO standards comparison – calculations and visualization	Comparison of model results with standards are done using an updated algorithm which includes rounding to 0.1 mg/L. Plan view maps show magnitude of *DO depletion from standards* rather than *total DO depletion* in those areas.	Plan view maps showed *the total magnitude of DO depletion* rather than the *magnitude of DO depletion below standards*. Utilized different algorithm for calculations (among other differences between algorithms, rounding method was not implemented).	Appendix F

DOC = Dissolved Organic Carbon
POC = Particulate Organic Carbon

Freshwater inputs

Computed estimates of water quality concentrations for rivers and streams using a multiple linear regression approach are described in previous reports (Ahmed et al., 2019; McCarthy et al., 2018; Mohamedali et al., 2011). We developed these original regressions using monthly data collected by Ecology primarily between 2006 and 2007, and in a few locations[4], historic USGS data collected between 1970s-1990s.

Since this original effort, Ecology's freshwater ambient monitoring unit collected additional data for major rivers. We used this larger observed dataset (2006–2018) to create a new set of regression equations for major rivers. We used new regressions, as well as other updates to freshwater inflows, for all year 2014 Optimization Scenario simulations. We also corrected the temperature boundary condition time series for a few rivers. Both regression and temperature updates are described in Appendix A. Additionally, Appendix A contains a section on limitations and uncertainties related to current freshwater estimates as well as plans for continued analysis and improvement. Appendix B describes the hydrologic analysis involved in the addition of watershed flows from Canada (which were included in the Bounding Scenarios report) and

[4] Historic organic carbon data were used in the regression for the Elwha, Skokomish and Skagit Rivers

provides comparisons of the relative magnitude of watershed flows entering different areas within the model domain. We also modified the reference condition to incorporate an improved estimate of the fraction of refractory particulate organic carbon flowing into marine waters from pristine river systems, and used new DOC data, where available, to update reference conditions. (Appendix C).

Marine water quality observations

We compared previously available observational data sets with datasets recently uploaded to the Environmental Information Management database (EIM) and added several observational sites formerly not included in our marine water quality observational database. We used this expanded observational set of marine observations to model output to evaluate model performance.

Data quality objectives are described in the QAPP (McCarthy et al., 2018), and observations that do not meet quality objectives are used qualitatively to assess overall patterns and trends (Ahmed et al., 2019). Further review of a sub-set of the data required updates that we incorporated and used to evaluate model performance, which is described in Appendix H1.

HYCOM ocean boundary condition (for 2014)

Previously, we developed the ocean boundary condition (OBC) for the SSM using data from the Department of Fisheries and Oceans Canada (DFO). However, DFO data are temporally limited because the data are collected only on a quarterly basis, and the data are spatially limited because they do not cover all of the SSM boundary nodes. Therefore, DFO data had to be interpolated in both time and space to establish the OBC for SSM.

We recognized the limitations of using DFO data to characterize the OBC when evaluating the SSM calibration for the year 2014. The warm “Blob” in the Pacific Ocean started to intrude into the Salish Sea in late 2014, and the quarterly DFO data did not adequately characterize this mass of warm water entering the Salish Sea. This, in turn, influenced SSM simulations of hydrodynamics and water quality.

To address this limitation, we applied a new method to characterize SSM’s OBC. This method involves using model-simulated output from the state of the science Hybrid Coordinate Ocean Model (HYCOM) to establish the OBC (instead of using DFO data). HYCOM covers the full ocean boundary of the SSM, and it includes daily or three hour predictions for water temperature, salinity, water surface elevation, and water velocity. Because HYCOM is a hydrodynamic model and does not predict water quality variables, we used regressions between observed salinity and select water quality variables to develop the full hydrodynamic and water quality open boundary conditions for SSM. More details about HYCOM and how it was used to establish the OBC for SSM are included in Appendix D.

Comparing model output with DO Water Quality Standard and related visualizations

SSM output includes a yearlong hourly time-series of DO predictions at all model grid cell-layers. To test whether Washington State water quality standards (WQS) for DO are met, an updated algorithm calculates the applicable DO concentration thresholds for each day at every model grid-cell-layer using the reference concentration and corresponding numeric criteria. Subsequently, the algorithm tests each grid-cell-layer for existing and other scenarios to check whether the standard is met. The largest predicted noncompliance magnitude for each grid cell is used to create plan view maps, tables and plots. Note that the term "noncompliance" used in this report is defined in the glossary. Appendix F contains a description of the testing algorithm used for this comparison and the changes are summarized below.

We implemented two significant changes as follows:

1. Updates to the testing algorithm, including rounding predicted noncompliances to 0.1 mg/L. This rounding approach was implemented to narrow the recovery area to locations that are predicted to not meet the standard by 0.05 mg/L or greater. Accordingly, this change reduced the computed predicted area not meeting the standard. The change in rounding scheme aligns with documented observational accuracy while allowing the last digit to be within observable precision[5].
2. For clarity, plan view maps and tables in this report refer to the *magnitude of predicted noncompliance* instead of magnitude of DO depletion, as was previously shown for the bounding scenarios in Ahmed et al. 2019.

Scenario loadings

Nutrient loads are calculated from nutrient concentrations multiplied by flows for each model input. Assumptions for concentrations of nutrients for watershed inputs, marine WWTPs, and reference conditions are described in McCarthy et al (2018). In general, when running Salish Sea Model scenarios, we are only varying the anthropogenic fraction of the load by changing the concentration only from each source input in Washington waters of the Salish Sea. For scenarios, we do not vary the natural load fraction, nor the ocean boundary condition, nor sources in British Columbia.

Anthropogenic loads comparisons

Table 4 shows anthropogenic nutrient loads into WA waters, and percent reduction in these loads relative to existing loads in 2006 and 2014 under the scenarios evaluated. We re-ran seasonal BNR scenarios included in Ahmed et al. (2019) due to the changes mentioned earlier.

In the Scenario 1 series, the greatest reduction in watershed anthropogenic nutrient loads occurs when watersheds in Whidbey Basin are set to reference conditions. A relatively large reduction in anthropogenic nutrient loads is expected when Whidbey Basin watersheds are set to reference since three major rivers (Skagit, Snohomish, and Stillaguamish) flow into this basin. Freshwater flows into Whidbey basin contribute about 53% and 58% of the total freshwater flow into WA

[5] *Standard Methods for the Examination of Water and Wastewater*, 22nd edition

waters of the Salish Sea in 2006 and 2014, respectively. This results in a total nitrogen (TN) load reduction of 10% and 12%, respectively in 2006 and 2014, to WA waters. Also, the total organic carbon (TOC) loads are reduced by 42% and 44%, respectively, in 2006 and 2014.

For Scenario 2 (which was only run for year 2006), the greatest reduction in municipal WWTP nutrient loads for both nitrogen and carbon occurs when WWTPs in the Main Basin are set to reference levels. While other marine point sources are included in SSM such as several industrial sources, reductions for industrial sources were not modeled in any of the Optimization Scenarios. The TN loads are reduced by 51%, and TOC loads are reduced by 5%.

Table 4. Annual average anthropogenic nutrient loads and percent load reductions to Washington waters of the Salish Sea in 2006 and 2014 calculated as input for each model scenario.

Scenario	2006 TN load (kg/d)	2006 TN % redctn	2014 TN load (kg/d)	2014 TN % redctn	2006 TOC load (kg/d)	2006 TOC % redctn	2014 TOC load (kg/d)	2014 TOC % redctn
Existing Conditions	56,323	n/a	54,126	n/a	198,341	0.0%	117,229	n/a
Scen1 Hood Wtshds @Ref	55,695	1.1%	53,686	0.8%	192,474	3.0%	111,706	4.7%
Scen1 Main Wtshds @Ref	52,920	6.0%	51,237	5.3%	182,340	8.1%	101,125	13.7%
Scen1 SJF & Admiralty Wtshds @Ref	55,917	0.7%	53,462	1.2%	146,018	26.4%	112,544	4.0%
Scen1 SOG & N. Bays Wtshds @Ref	51,696	8.2%	49,977	7.7%	186,668	5.9%	101,257	13.6%
Scen1 South Sound Wtshds @Ref	52,295	7.2%	50,719	6.3%	185,572	6.4%	107,080	8.7%
Scen1 Whidbey Wtshds @Ref	50,743	9.9%	47,768	11.7%	116,015	41.5%	65,647	44.0%
Scen2 Hood WWTPs @Ref	56,322	<0.01%	*	*	198,341	<0.01%	*	*
Scen2 Main WWTPs @Ref	27,437	51.3%	*	*	188,248	5.1%	*	*
Scen2 SJF & Admiralty WWTPs @Ref	55,973	0.6%	*	*	196,465	0.9%	*	*
Scen2 SOG & N. Bays WWTPs @Ref	54,718	2.8%	*	*	197,735	0.3%	*	*
Scen2 South Sound WWTPs @Ref	52,845	6.2%	*	*	197,853	0.2%	*	*
Scen2 Whidbey WWTPs @Ref	52,991	5.9%	*	*	194,023	2.2%	*	*
Scen3 BNR8-All (annual)	35,137	37.6%	31,524	41.8%	195,066	1.7%	115,124	1.8%
BNR8-All (seasonal)	44,289	21.4%	41,423	23.5%	196,683	0.8%	116,124	0.9%
BNR8-1000 (seasonal)	46,667	17.1%	43,804	19.1%	196,907	0.7%	116,382	0.7%
BNR8-8000 (seasonal)	48,747	13.5%	48,213	10.9%	198,090	0.1%	116,865	0.3%
Scen5a 15% watersheds, BNR8	32,654	42.0%	28,962	46.5%	167,378	15.6%	100,332	14.4%
Scen5b 40% watersheds, BNR8	27,893	50.5%	24,449	54.8%	122,299	38.3%	74,090	36.8%
Scen5c 40% watersheds, BNR balanced	24,845	55.9%	21,421	60.4%	122,299	38.3%	74,090	36.8%
Scen5d 40% watersheds, BNR3	20,846	63.0%	17,980	66.8%	122,299	38.3%	74,090	36.8%
Scen5e 65% watersheds, BNR3	16,085	71.4%	*	*	77,220	61.1%	*	*

*not run for year 2014;
TN = total nitrogen,
TOC = total organic carbon

Of the percentage of anthropogenic TN load in 2006, a total of about 67% (sum of all percentage reductions in Scenario 2 set) comes from WWTPs and 33% from watersheds (sum of all percentage reductions in Scenario 1 set). Conversely, of the percent of anthropogenic TOC load in 2006, about 9% comes from WWTPs and 91% comes from watersheds.

In 2006, BNR8-All (annual) reduces the anthropogenic TN load entering WA waters by 38% while BNR8-All (seasonal) reduces anthropogenic TN by 21% (i.e. a 17% additional reduction when BNR8 is applied year round). In 2014, BNR8-All (annual) reduces the anthropogenic TN load entering WA waters by 42% while BNR8-All (seasonal) reduces anthropogenic TN by 24% (i.e. a 18% additional reduction when BNR8 is applied year round).

Within WA waters, BNR8-All (annual) reduces the TOC loads by about 2% in both 2006 and 2014, while BNR8-All (seasonal) reduces TOC by about 1%. This low TOC reduction is because all WWTPs are already using secondary treatment processes, which reduces a majority of the influent TOC before the discharge.

Scenario 5 model runs incorporate combinations of watershed and WWTP reductions. Scenarios 5d and 5e resulted in the greatest reductions. In Scenario 5d, TN load to WA waters are reduced by 63% and 67% respectively in 2006 and 2014. TOC loads in Scenario 5d is reduced 38% and 37% respectively in 2006 and 2014. For Scenario 5e, TN and TOC load reductions are 71% and 61%, respectively, for 2006. We did not run Scenario 5e for 2014.

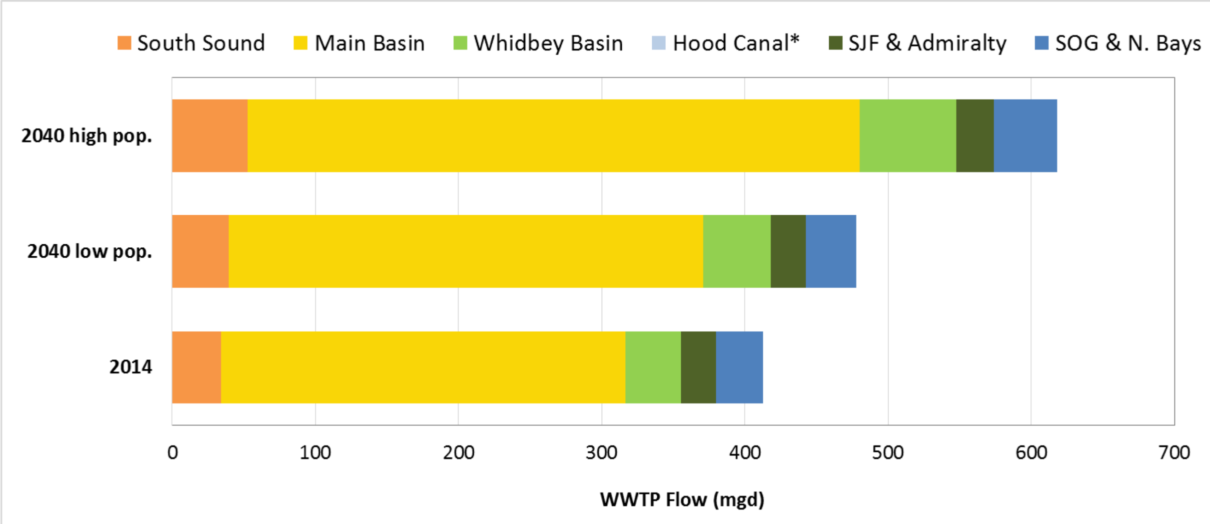
Future 2040 wastewater estimates

We developed Scenario 4 to evaluate the impact on DO compliance from increasing WWTP effluent flows resulting from projected regional population growth. We estimated future 2040 effluent flows by scaling existing 2014 flows, where the flow scalar is calculated as follows:

$$\boldsymbol{Flow\ Scalar} = \frac{2040\ projected\ population}{2014\ population}$$

We acquired 2040 projected population estimates from the Office of Financial Management's (OFM) forecasting division[6]. Future forecasts are available for both 'low' and 'high' population estimates. We used both population estimates in this scenario to represent a range in potential future effluent flows – therefore this scenario involved two model runs: "2040 high WWTPs flows" and "2040 low WWTP flows". Figure 4 shows the aggregate average annual flows into WA waters regions under these two scenarios compared with 2014 existing conditions. Detailed methods used to develop Scenario 4 can be found in Appendix E.

[6] https://www.ofm.wa.gov/washington-data-research/population-demographics



* Hood Canal flows are < .05 mgd and therefore are not visible in the plot above

Figure 4. Comparison of 2014 and future 2040 (high and low) annual average wastewater flows from facilities discharging into different regions of WA waters of the Salish Sea.

Results and Discussion

Since the completion of the Bounding Scenarios, we incorporated updates to the SSM and to the DO compliance calculations (as described in the *Methods* section). Additionally, we conducted Optimization Scenarios to test various potential nutrient reduction pathways towards achieving predicted compliance and evaluated a future growth scenario to assess the challenge associated with population growth. This section is broken into three sub-sections that cover:

1. Improved estimates of predicted DO noncompliance under existing conditions based on the incorporated updates.
2. Insights towards predicted DO compliance based on the various load reduction scenarios examined.
3. Challenges from future projected population growth.

As described under Methods, all model results presented here exclude masked, nearshore areas. The term *average magnitude of predicted noncompliance* refers to the arithmetic mean of the annual maxima predicted noncompliant magnitudes within grid-cells in WA waters (or within a region, if specified). The terms *maximum* or *minimum* magnitude of noncompliance correspond to the highest or lowest magnitude of predicted noncompliance from the regulatory standard within the WA waters (or within a region, if specified).

We assessed compliance with DO water quality standards under existing conditions, various Optimization Scenarios and future growth scenario. The water quality standards for marine DO are cited in the following parts of Washington Administrative Code:

- (Part A) 173-201A, Table 210(1) (this is the aquatic life criteria or biologically based numeric criteria).

- (Part B) 173-201A-210 – Marine Uses (1)(d)(i) (i) When a water body's D.O. is lower than the criteria in Table 210 (1)(d) (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the D.O. of that water body to decrease more than 0.2 mg/L.

Compliance with DO standards is tested for each model grid cell layer (Figure 5) and each model day. Appendix F contains details about how we test whether the DO standard is met.

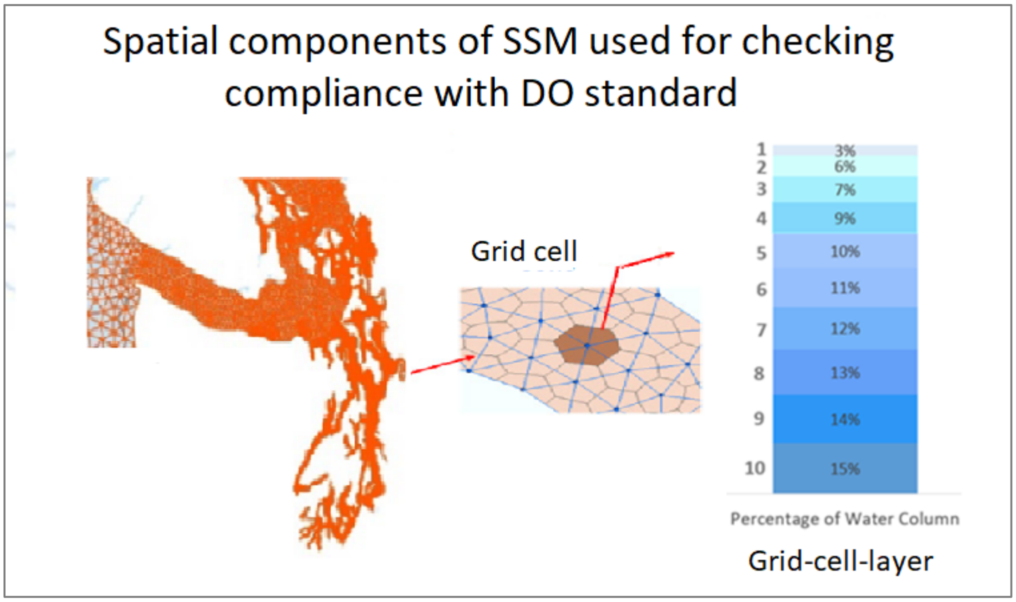


Figure 5. Grid cell and grid cell layers in SSM.

Figures 6 and 7 compare the predicted cumulative number of days and areas that do not meet standards during 2006 and 2014. Note that the *magnitude of not meeting DO standards*, referenced in this memorandum, is related, but different from the total magnitude of DO depletion, which is greater (and represents total depletion from reference conditions.) In the Bounding Scenarios report, plan view maps presented the predicted total DO depletion at all locations where depletion was predicted, whereas here, for clarity, plan view maps and tables present the predicted magnitude, area, or total days not meeting standards only.

Both Figures 6 and 7 show that, in general, the predicted extent of not meeting standards is greater for 2006 compared to 2014. The total area not meeting standards in WA waters was 480 km^2 and 341 km^2 for 2006 and 2014 respectively. The maximum number of days in any grid-cell within WA waters not meeting standards was 192 days and 163 days for 2006 and 2014 respectively. However, Hood Canal and Bellingham Bay have a greater extent of area not meeting standards in 2014 compared with 2006. This alludes to the fact that critical conditions can vary both temporally and spatially.

Figure 6 shows that the year 2006 also exhibited a higher number of predicted total days not meeting standards in certain regions compared to 2014 as shown by the extent of the darker blue shade. For example, while the area of not meeting standards in Hood Canal is greater in 2014 than in 2006, the number of total days not meeting standards in Hood Canal is greater in 2006 than in 2014. This is shown by the darker blue colors in Lynch Cove (at the end of Hood Canal) in Figure 6 which show a larger area with a greater number of total days not meeting standards in 2006 compared to 2014.

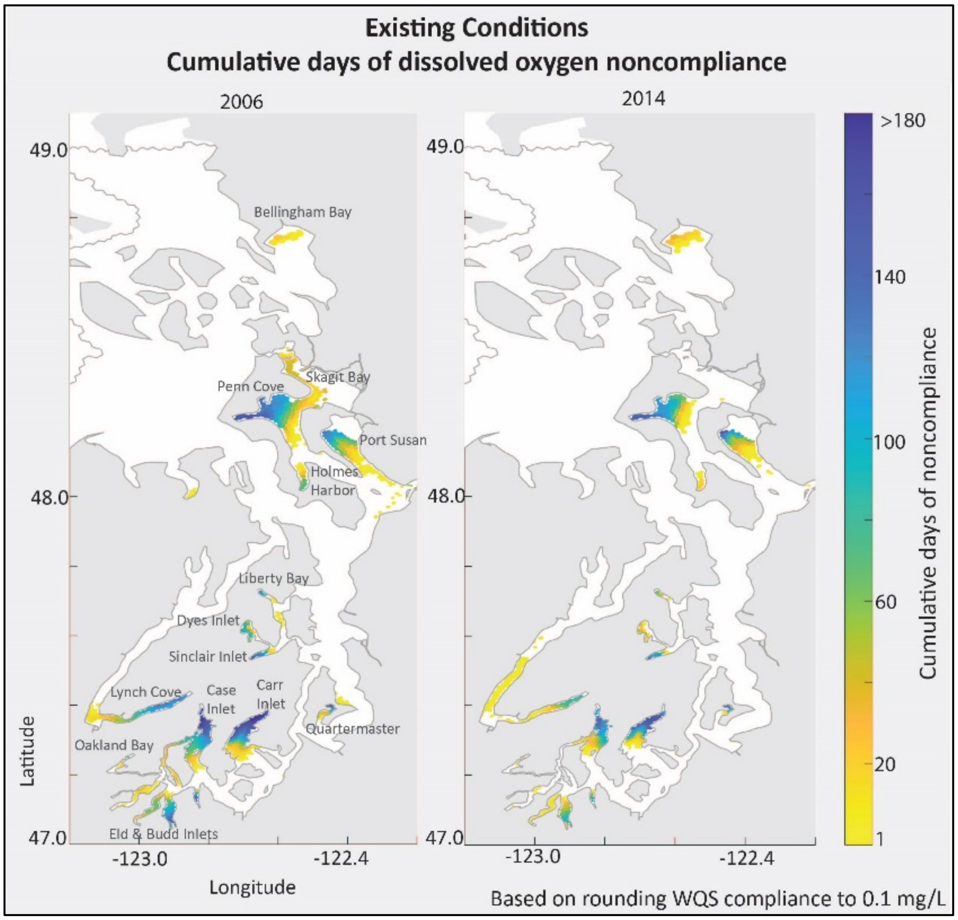


Figure 6. Predicted cumulative days of DO not meeting standards during 2006 and 2014 existing conditions.

Figure 7 shows the spatial distribution of predicted magnitudes of DO depletion below the standards under 2006 and 2014 existing conditions. The minimum predicted DO depletion below the standard is -0.1 mg/L, and the average predicted DO depletion below the standard in both years is -0.2 mg/L. The largest predicted magnitude of DO depletion below the standards in 2006 is -2.2 mg/L and -2.1 mg/L in 2014; both of these are in Budd Inlet.

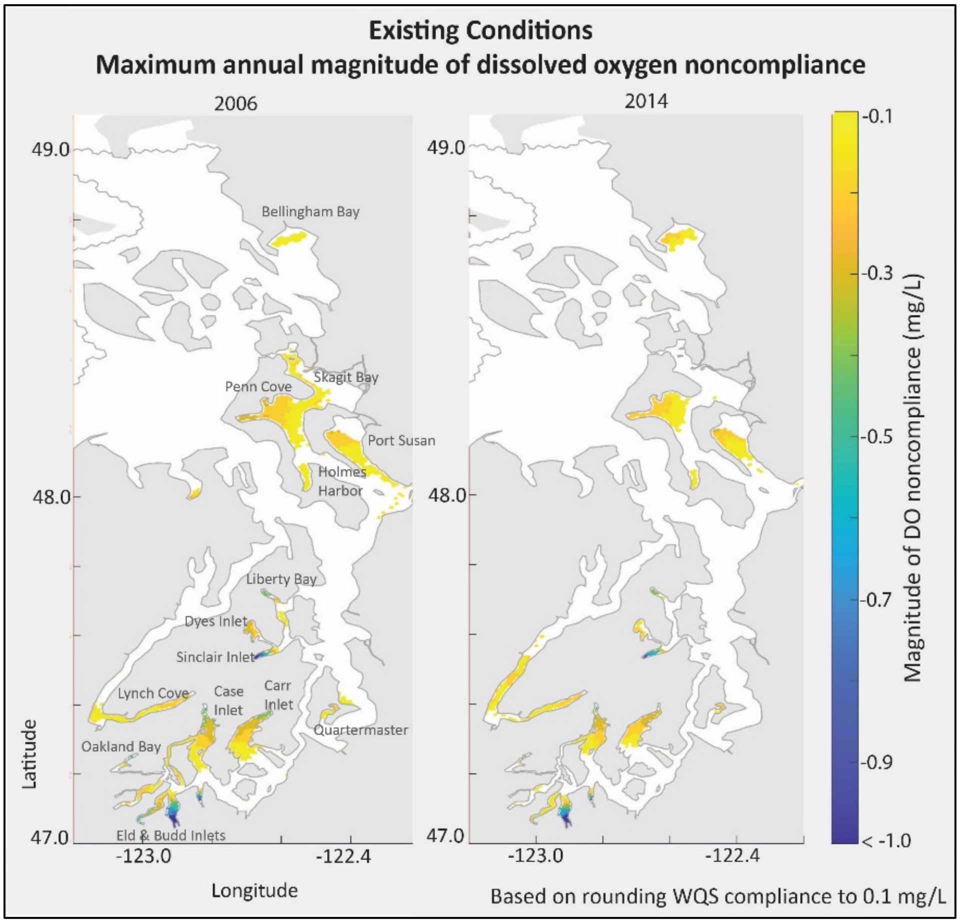


Figure 7. Annual maximum magnitude of predicted DO depletion below standards during 2006 and 2014 existing conditions.

Insights towards DO compliance

To gain insights on what different combinations of load reductions can achieve in terms of compliance, we begin with a comparison of results from all sets of scenarios, followed by more detailed analysis of results from each individual set of scenarios. Additionally, SSM results may be viewed in detail via the Optimization Scenarios web map[7]. Results showing the influence in WA waters of load reductions from watersheds located in specific regions (Scenario 1 runs), WWTPs in specific regions (Scenario 2 runs), and seasonal vs. annual application of BNR8 (Scenario 3 runs) are presented below. While those scenarios provide useful insights, SSM predicts that a combination of reductions from *both* watersheds and WWTPs (Scenario 5 runs) will result in the most DO compliance. This is congruent with previous work (Ahmed et. al. 2019).

We rely on four types of plots to illustrate the predicted DO compliance impact on WA waters from scenario runs:

1. Point graphs of predicted noncompliant area and days plotted against scenario loads that allow comparisons of noncompliance across all scenarios,
2. Bar charts of percent change in predicted noncompliant area and days (relative to baseline/existing conditions),
3. Bar charts displaying proportional areas of binned magnitudes of predicted noncompliance,
4. Plan view maps of predicted noncompliant area and cumulative days.

The point graphs (Figures 8-11) are x-y (Cartesian) plots where we represent each scenario by a point, and we represent each sets of scenarios with the same color. The reference conditions (green dots) serve as the origin with zero area or number of days of noncompliance and zero anthropogenic nutrient loads. Note that all scenarios appear to the right of the reference scenario point, as expected. The vertical location of each point relative to each other represents movement towards predicted compliance, where scenarios with points closer to the bottom are closer to predicted compliance relative to scenarios near the top. Data for Figures 8-11 are presented in Appendix G (Tables G-1 and G-2).

Figures 8 through 11 show the influence of the different scenarios on reducing the noncompliant area and days in WA waters in 2006 and 2014. We simultaneously reduced both TN and TOC. Since we did not separately evaluate the effect of anthropogenic TN and TOC reductions, Figures 8-11 show the impact of reducing *both* TN and TOC. Figures 8-9 show results for each scenario compared to corresponding anthropogenic TN load reductions, and Figures 10-11 show results compared to corresponding TOC load reductions.

Scenario 5 outperforms all other scenario sets (purple dots in each of the Figures 8-11). Scenario 5 simulations achieved broad compliance throughout WA waters. For 2006, Scenario 5e resulted in 95% and over 97% improvement in noncompliant days and area respectively.

[7] https://waecy.maps.arcgis.com/apps/webappviewer/index.html?id=c7318e19bf3141aca62e980a7e5b53f2

Figure 8. Comparison of predicted noncompliant area in WA waters of the Salish Sea resulting from all Optimization Scenarios and BNR8 Scenarios, with each scenario's associated anthropogenic total nitrogen loading in 2006 (left) and 2014 (right).

*ratio of scenario annual cumulative noncompliant days to total number of existing noncompliant model grid cells

Figure 9. Comparison of normalized average predicted noncompliant days per model grid cell in WA waters of the Salish Sea resulting from all Optimization Scenarios and BNR8 Scenarios, with each scenario's associated anthropogenic total nitrogen loading in 2006 (left) and 2014 (right).

Figure 10. Comparison of predicted noncompliant area in WA waters of the Salish Sea resulting from all Optimization Scenarios and BNR8 Scenarios, with each scenario's associated anthropogenic total organic carbon loading in 2006 (left) and 2014 (right).

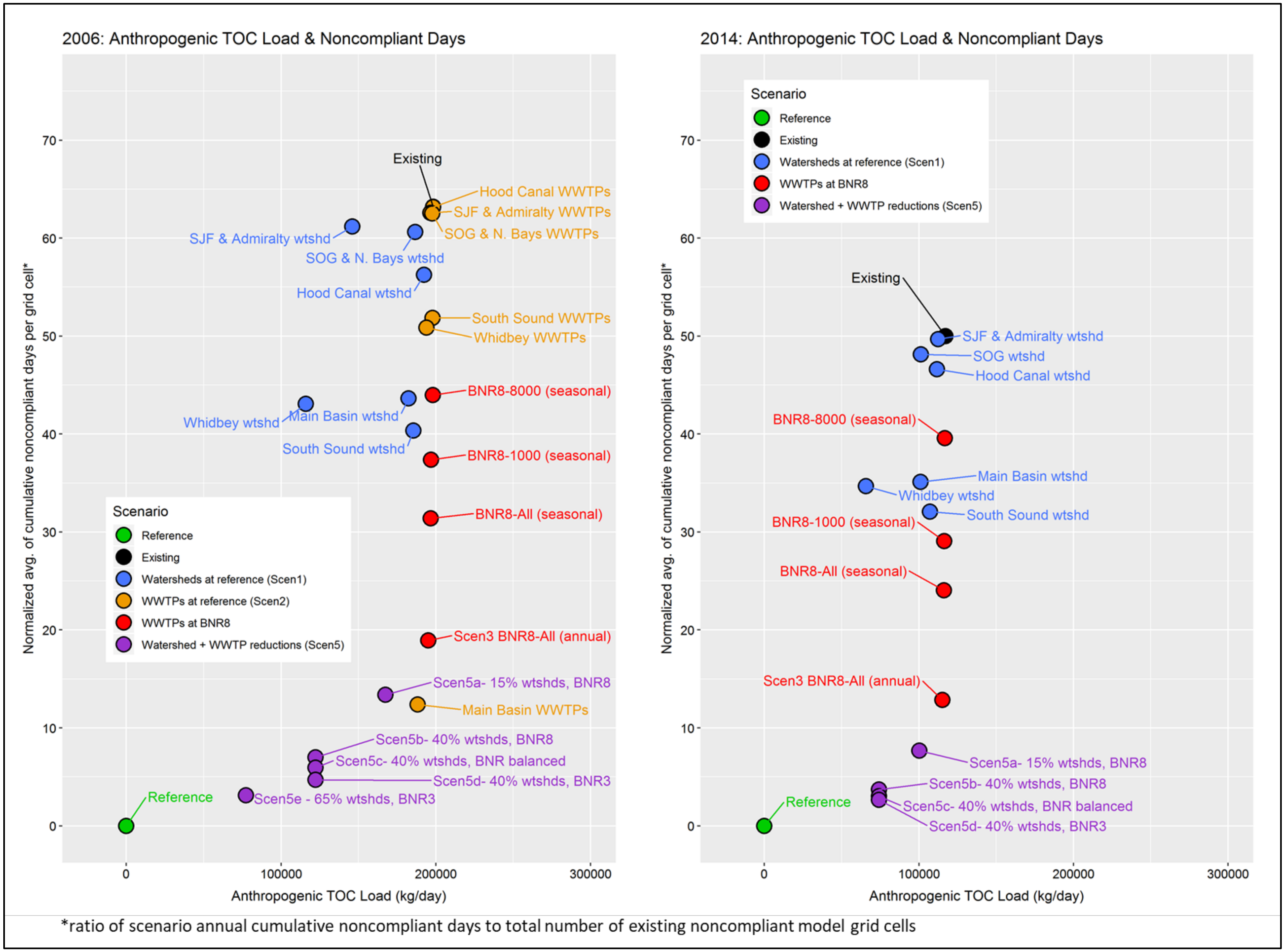


Figure 11. Comparison of normalized average predicted noncompliant days per model grid cell in WA waters of the Salish Sea resulting from all Optimization Scenarios and BNR8 Scenarios, with each scenario's associated anthropogenic total organic carbon loading in 2006 (left) and 2014 (right).

Within the Scenario 1 set (i.e. each region's watersheds at reference conditions, blue dots in the figures), the Whidbey Basin region has the greatest impact on reducing the extent of noncompliant area, and the South Sound region has the greatest impact on reducing the cumulative number of noncompliant days for both 2006 and 2014 (Figures 8 through 11). Among Scenario 2 runs (i.e. each region's WWTPs at reference conditions, gold dots in the figures, left panel), Main Basin region load reductions are predicted to have the greatest impact by far in terms of both area and days of noncompliance for 2006 (see left panel of Figures 8 through 11). We did not conduct Scenario 2 simulations for 2014.

Reductions based on applying BNR8 generally outperformed most Scenario 1 and 2 runs, and fell into middle positions relative to the vertical axes in Figures 8-11. Annual BNR8 scenarios at WWTPs (red dots in the plots) resulted in larger reductions compared to the seasonal BNR8 scenarios for both area and days of noncompliance in 2006 and 2014. For this set of scenarios, we re-ran the seasonal BNR8 scenarios included in the Bounding Scenarios Report (Ahmed et al. 2019) to include the updates discussed earlier in this memorandum.

Additionally, we compare results from the full sets of load reduction scenarios (1, 2, 3, and 5) conducted for 2006 using bar charts of percent change as shown in Figure 12. This plot complements Figures 8-11 by presenting model scenario results in terms of improvements represented as percentage decreases (expressed as a negative percentage) in predicted noncompliance.

For 2006, the top three Scenario 1 runs that resulted in the greatest decrease in noncompliant days and areas in WA waters are when South Sound, Main Basin, and Whidbey Basin watersheds are at reference (Figure 12A and Table 5). For 2014, model results for Scenario 1 also reveal similar results, and analogous bar charts are included in Appendix G (Figure G-1). The differences between load reductions associated with each of these three scenarios are shown in Table 4. In 2006, when watersheds in Whidbey Basin are set to reference condition, TN and TOC reductions are 10% and 42%, respectively. For the South Sound scenario, TN and TOC reductions are 7% and 6%, and for the Main Basin scenario, they are 6% and 8%, respectively.

Though relatively lower, load reductions from South Sound watersheds resulted in the greatest temporal improvement (-36% noncompliant days). Main Basin and Whidbey Basin watershed load reductions achieved similar improvements (about -31% noncompliant days). Whidbey Basin watersheds at reference resulted in the greatest improvement in the spatial extent of compliance (-34% noncompliant area). South Sound and Main Basin watersheds at reference conditions had very similar extents of spatial improvement (around -20% noncompliant area).

Regarding Scenario 2 runs (reduction in each region's WWTPs loads only), Figure 12B and Table 5 show that for 2006, the greatest improvement (-80% number of noncompliant days and over -63% in noncompliant area) occurs when Main Basin WWTPs are set to reference condition. These results are expected, as the level of load reduction (51%, and 5% for TN and TOC respectively) to WA waters from WWTPs in the Main Basin scenario is much higher than other Scenario 2 runs (6% TN each and 0.2% and 2% TOC, respectively, for South Sound and Whidbey basins).

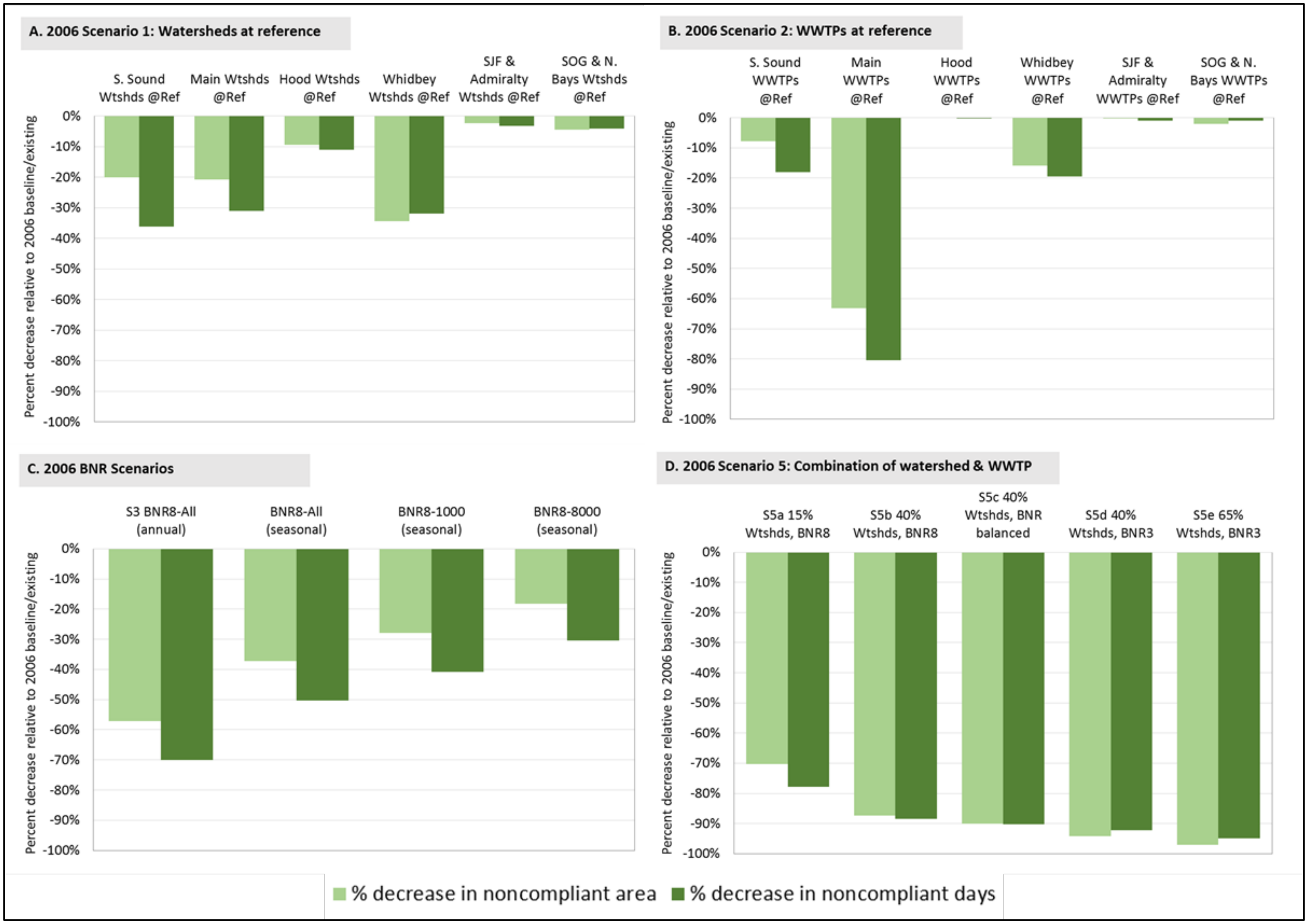


Figure 12. Percent change (decreases shown as negative values) in predicted noncompliant days and area in WA waters of the Salish Sea from all Optimization and BNR8 scenarios, relative to 2006 conditions.

Figure 12C and Table 5 show that for 2006 the greatest improvement in the number of days of noncompliance (-70%) and noncompliant areas (-57%) is when BNR8 is applied to all WWTP on an annual basis. This is a result of a 38% reduction (Table 4) in TN load and 2% in TOC load to WA waters. TN load reduction to WA waters from seasonal BNR8 at all WWTP is 21% and 1% for TOC. Seasonal BNR8 reduced the number of noncompliant days by approximately 50% and the noncompliant area by 37%. This set of model runs shows the predicted benefit of implementing BNR8 year round. Results for 2014 with simulated BNR scenarios presented in Appendix G (Figure G-1) show similar improvements in noncompliance.

Scenario 5 runs resulted in the largest improvements in WA waters. Figure 12D and Table 5 shows the progressive improvement in the 2006 results within the Scenario 5 set. This information for 2014 is included in Figure G-1 in Appendix G. The sub-section titled 'Potential pathways to compliance via combined watershed and WWTP reductions' contains a detailed discussion about the Scenario 5 set of simulations.

Table 5. Predicted percent changes in cumulative number of predicted noncompliant days and area in WA waters of the Salish Sea relative to existing baselines for 2006 scenarios.

2006 Scenario	Percent change in normalized noncompliant days* from baseline	Percent change in noncompliant area from baseline (km^2)
Scen1 South Sound Wtshds @Ref	-36.1%	-20.1%
Scen1 Main Wtshds @Ref	-31.0%	-20.7%
Scen1 Hood Wtshds @Ref	-11.0%	-9.4%
Scen1 Whidbey Wtshds @Ref	-31.8%	-34.4%
Scen1 SJF & Admiralty Wtshds @Ref	-3.2%	-2.3%
Scen1 SOG & N. Bays Wtshds @Ref	-4.0%	-4.4%
Scen2 South Sound @Ref	-18.0%	-7.8%
Scen2 Main WWTPs @Ref	-80.4%	-63.2%
Scen2 Hood WWTPs @Ref	0.0%	0.0%
Scen2 Whidbey WWTPs @Ref	-19.5%	-15.8%
Scen2 SJF & Admiralty WWTPs @Ref	-0.9%	-0.3%
Scen2 SOG & N. Bays WWTPs @Ref	-1.0%	-2.0%
Scen3 BNR-All (annual)	-70.0%	-57.1%
BNR-All (seasonal)	-50.3%	-37.2%
BNR-1000 (seasonal)	-40.9%	-27.9%
BNR-8000 (seasonal)	-30.4%	-18.1%
Scen5a 15% Wtshds, BNR8	-77.8%	-70.3%
Scen5b 40% Wtshds, BNR8	-88.4%	-87.3%
Scen5c 40% Wtshds, BNR balanced	-90.1%	-90.1%
Scen5d 40% Wtshds, BNR3	-92.2%	-94.2%
Scen5e 65% Wtshds, BNR3	-94.8%	-97.1%

*ratio of scenario annual cumulative noncompliant days to total number of existing noncompliant model grid cells

In terms of magnitudes of noncompliance, Figure 13 illustrates the areal proportion that falls into various ranges of predicted DO noncompliance magnitudes for single category (either WWTP or watershed) reduction scenarios evaluated. Under most scenarios, more than 50% of the predicted

DO noncompliant area and noncompliant magnitudes falls in the -0.1 to -0.2 mg/L noncompliant range for both 2006 and 2014.

Aside from reduction in overall noncompliant area, the proportion of low magnitude noncompliances generally increase with decreasing loads, and the proportion of the area with higher magnitudes of noncompliances generally decrease with decreasing loads. For instance, in 2006, when BNR8 is applied annually (Figure 13) the area of noncompliance in the -0.1 to -0.2 mg/L range increases from 57% to 72%, and the area of noncompliance in the > 0.2 mg/L range decreases from 57% to 28% relative to baseline conditions.

For regional scenarios (1 and 2), areas with the highest magnitudes of predicted noncompliance (>1.0 mg/L DO, black band in Figure 13) are most influenced when South Sound watersheds or Main Basin WWTPs are set to reference conditions. This is most likely due to near-field effects (i.e. local anthropogenic sources) around Budd Inlet in the South Sound case, and Sinclair Inlet in the Main Basin case.

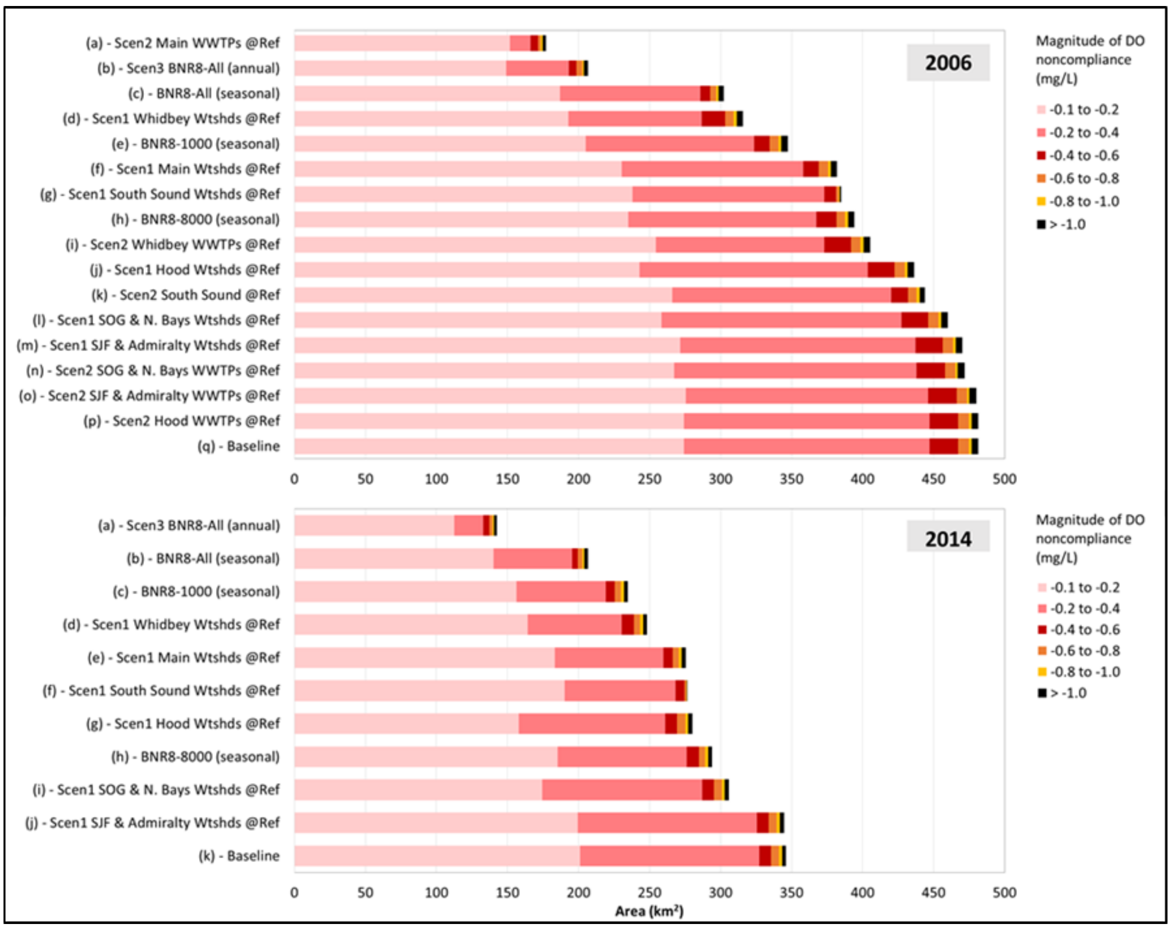


Figure 13. Distribution of magnitudes of predicted DO noncompliance within the total noncompliant area in WA waters of the Salish Sea resulting from Scenario 1 runs, Scenario 2 runs, and BNR8 Scenarios in 2006 (top) and 2014 (bottom).

Potential pathways to compliance via combined watershed and WWTP reductions

We focus this sub-section on describing details gleaned from Scenario 5 simulations, which explored the impact of combined reductions from both watersheds and WWTPs. We applied WWTP reductions as shown in Table 2. The Scenario 5 watershed reductions were applied equally everywhere, as prescribed for each scenario in Table 2, except in the case of the Deschutes watershed.

Modeling the interface of the Deschutes River with Budd Inlet presents specific challenges. Compared with the rest of the Puget Sound, Weakland et al. 2020 observed the highest concentrations of TOC in Budd Inlet sediments. Inlet-specific modeling studies (e.g. Roberts et al. 2015) have shown that a hydraulic modification (Capitol Lake, which is created by a dam) at the mouth of Deschutes River influences the relatively higher organic load and the speciation of the nitrogen load discharged to the inlet. Therefore, for the Deschutes River inflow estimates to SSM, we apply an additional TOC reduction and changed the ratios of inorganic and organic nitrogen when approximating the reference condition. The SSM is not set up to model the hydraulic modification in the Deschutes watershed. Consequently, a separate, refined modeling system specific to Budd Inlet is in use (Generalized Environmental Modeling System for Surface Water or GEMSS), instead of SSM, to determine compliance within Budd Inlet.

Figure 14 shows predicted noncompliant area that falls into various ranges of DO noncompliance magnitudes for Scenario 5 runs. As this set of scenarios progresses to larger reductions, a noticeable shift in the overall extent of noncompliant area can be visualized via plan view maps (Figure 16). Furthermore, the maximum magnitude of noncompliance shifts from -1.5 mg/L in Scenario 5a (black band in Figure 14) to -0.7 mg/L for Scenario 5e in 2006.

Figure 15 shows the shift in the maximum magnitudes of predicted noncompliance in each region under each of the Scenario 5 runs. In both 2006 and 2014, SSM predicts the largest magnitudes of noncompliance within the South Sound region, in Budd Inlet, under existing conditions. Results do show progressive improvement in terms of the maximum magnitude of predicted noncompliance particularly in South Sound, Main Basin and Whidbey Basin regions. Results also show that predicted noncompliance is eliminated in 2006 in the Hood Canal and SOG & N. Bays regions starting with Scenario 5b and 5a (respectively), but these regions have lower predicted noncompliance magnitudes under existing conditions to start with. In 2014, predicted noncompliance is eliminated in Hood Canal, Whidbey Basin, and SOG & Northern Bays regions starting at Scenario 5b, whereas predicted noncompliance is eliminated in SJF &Admiralty region starting with Scenario 5a.

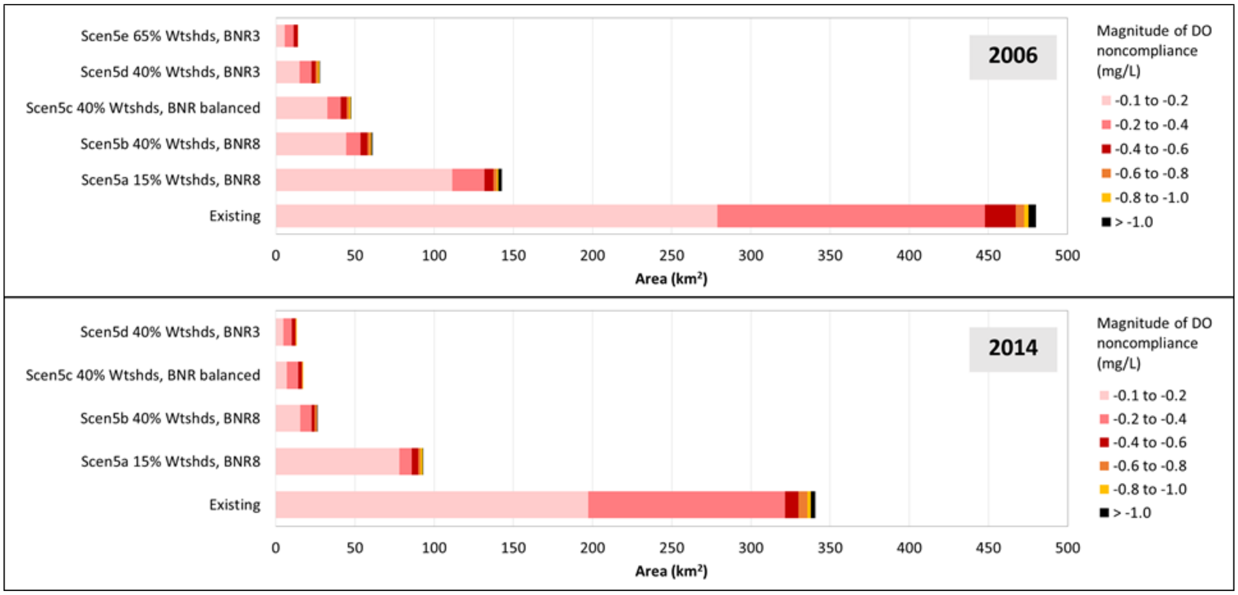


Figure 14. Distribution of magnitudes of predicted DO noncompliance within the total noncompliant area in WA waters of the Salish Sea across all Scenario 5 runs in 2006 (top) and 2014 (bottom).

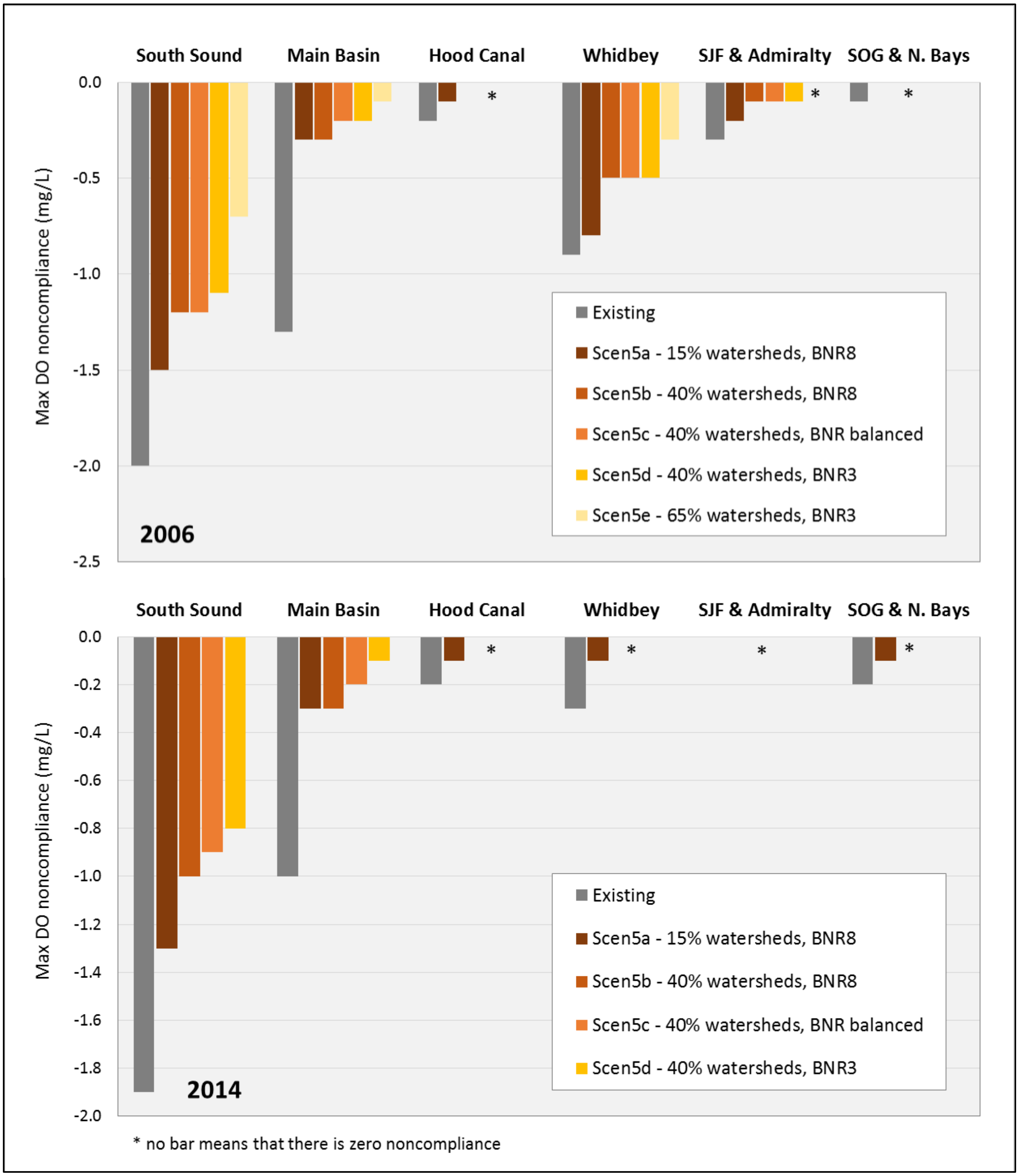


Figure 15. Maximum magnitude of predicted DO noncompliance in different regions of WA waters of the Salish Sea under existing and Scenario 5 alternatives in 2006 (top) and 2014 (bottom).

Figures 16 and 17 are plan view maps that compare existing conditions and the Scenario 5 model runs in terms of total predicted cumulative days and magnitudes of noncompliance for 2006 and 2014, respectively. These maps clearly show that the extent of days and area of predicted noncompliance are substantially reduced from existing conditions as a result of combined watershed and WWTP nutrient load reductions.

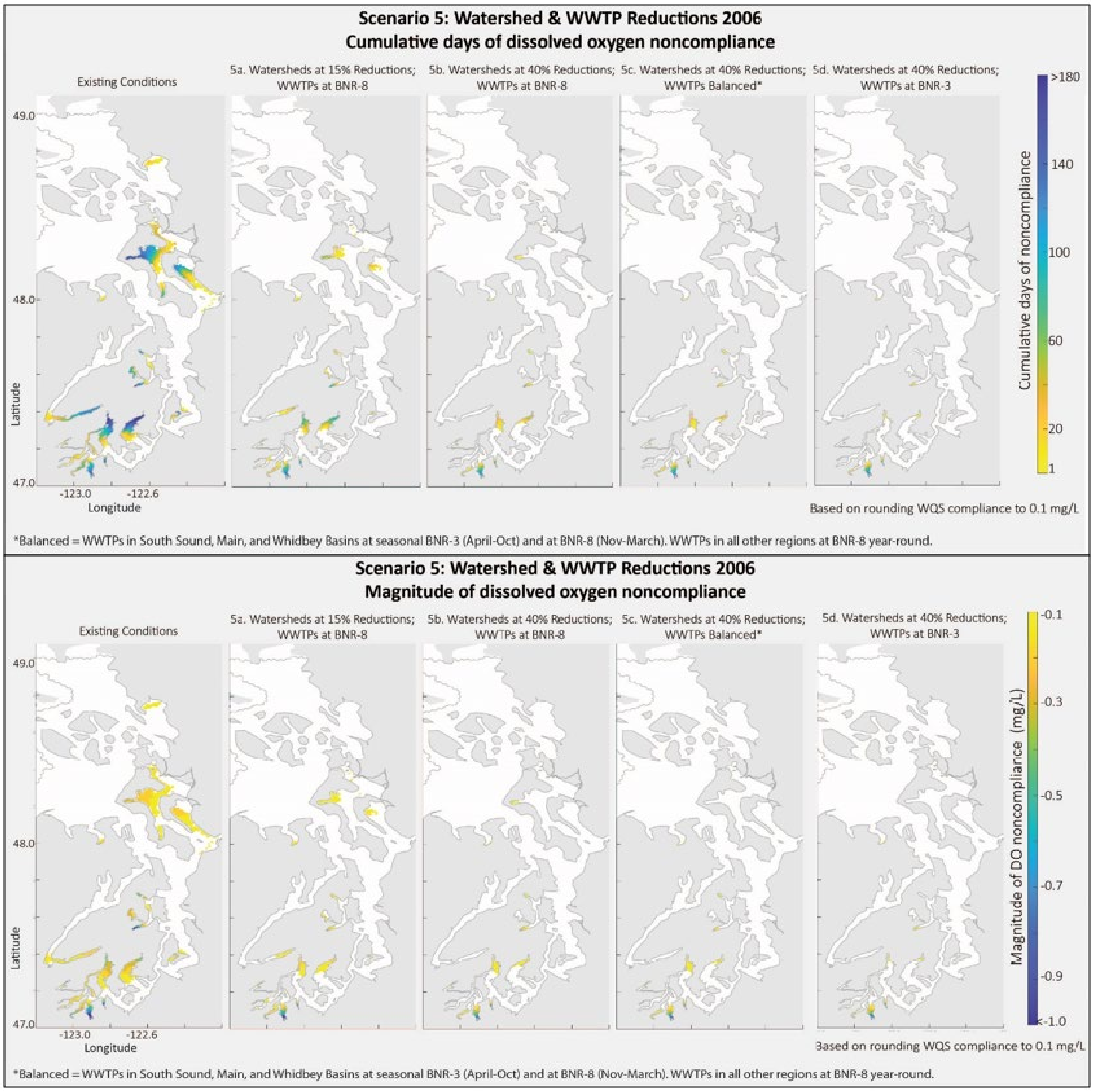


Figure 16. Plan view maps of Scenario 5a through 5d (2006) showing predicted cumulative days of DO noncompliance (top) and magnitude of DO noncompliance (bottom).

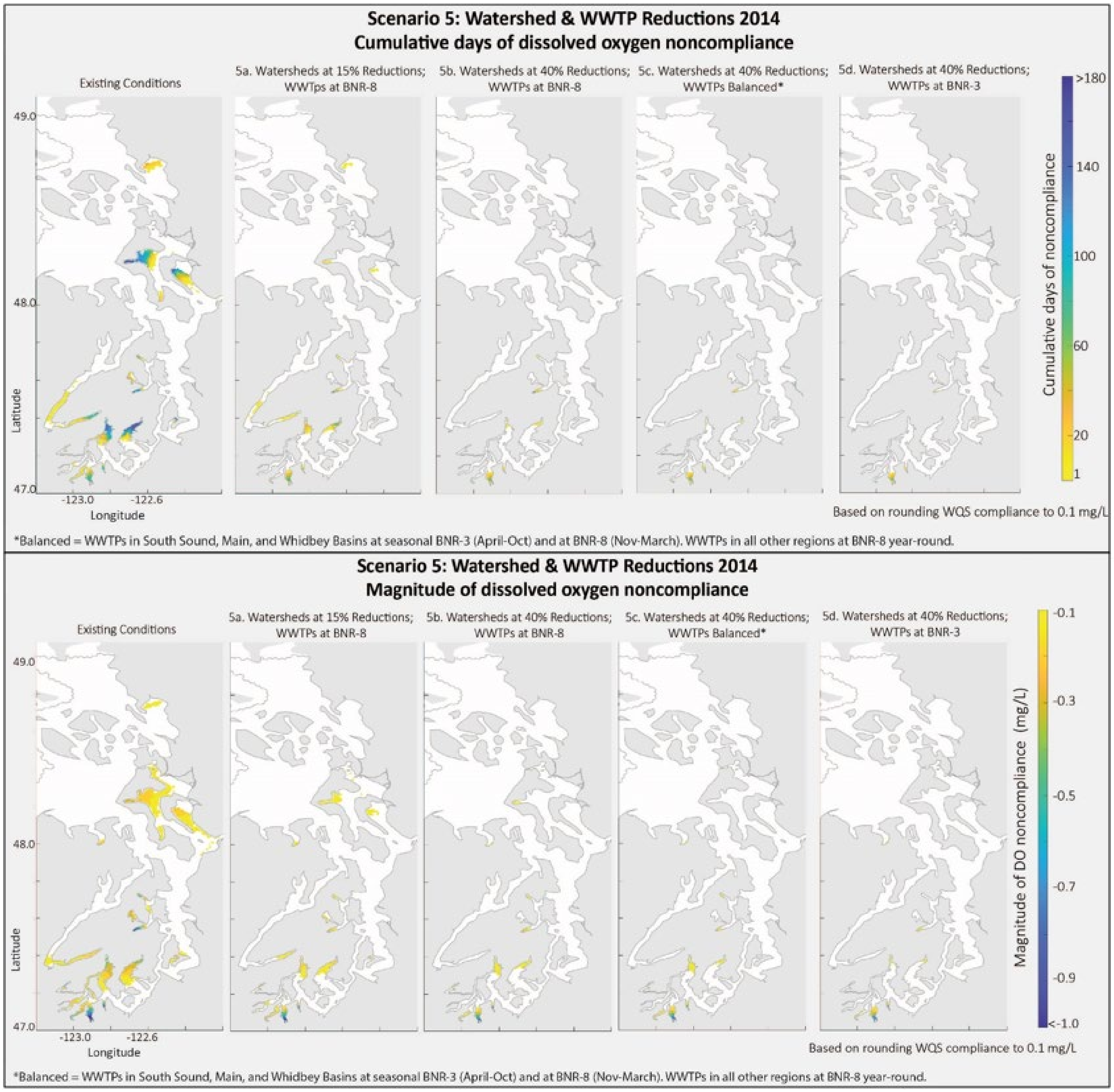


Figure 17. Plan view maps of Scenario 5a through 5d (2014) showing predicted cumulative days of DO noncompliance (top) and magnitude of DO noncompliance (bottom).

Although previous scenario reductions in some regions show impacts in others, Scenario 5 series suggests that *spatially comprehensive* reductions from *both* watersheds and WWTPs get closer to compliance than individual region reductions of either watersheds or WWTPs alone (i.e. single category scenarios). Additionally, the decrease in predicted noncompliance from Scenario 5 runs is achieved with a smaller reduction in overall nutrient loads. For example, for 2006, Scenario 5a achieved *more* compliance with *less* overall anthropogenic load reductions than the regional Scenarios 1 and 2 with more load reductions. Referring back to Table 4, in 2006, the Scenario 5a load reduction for TN (42%) is less than the largest regional TN reduction tested in Scenario 2 (53%). Likewise, Scenario 5a also includes a lower TOC reduction (16%) than the largest regional TOC reductions in the watersheds, Scenario 1 series (57%). Figures 8-12 also show that Scenario 5a outperforms all the single category reduction scenarios conducted in terms of improvements to predicted noncompliant area, and only one single category run (Scenario 2 Main Basin) outperforms it in terms of predicted improvements to normalized average noncompliant days per model grid cell.

Scenarios 5b through 5d (40% watershed load reductions and BNR targets of 8 to 3 mg/L DIN) incorporate further combinations of reductions than Scenario 5a. The predicted relative impacts of these are shown spatially in the plan view maps (Figures 16 and 17). Tables G1 and G2 in Appendix G also present the predicted noncompliant days, area, and magnitudes (and percent improvement) for each scenario in 2006 and 2014, respectively. Scenario 5e, the last in this series, comprises the highest watershed reductions in TN and TOC (65%) and includes all WWTPs applying annual BNR3 (target DIN of 3 mg/L). This was only run for year 2006. Scenario 5e resulted in a 97% and 95% reduction in noncompliant area and days, respectively.

In terms of annual differences, Figures 16 and 17 also show that the relative impact of Scenario 5 runs are similar in both 2006 and 2014. However, 2006 conditions exhibit more predicted resistance to improvement with local exceptions such as Bellingham Bay, which shows more resistance to improvement in 2014. For instance, Scenario 5d (40% TN and TOC reduction in watersheds and annual BNR reductions of DIN of 3 mg/L applied seasonally in select regions, and BNR of 8 mg/L elsewhere) in 2006 resulted in 28 km^2 of noncompliant area. This represents a 92% and 94% improvement over 2006 existing conditions in noncompliant days and areas, respectively. For 2014, Scenario 5d resulted in a total noncompliant area of 14 km^2. This represents a 95% and 96% reduction in noncompliant days and areas over 2014 existing conditions, respectively.

Figure 18 shows the plan view map of predicted cumulative noncompliant days and magnitude of noncompliance for Scenario 5e in 2006. The inserts in Figure 18 show four locations in which SSM predicts the 5% remaining noncompliant days. These areas are resistant as they are the only areas that do not achieve predicted compliance under Scenario 5e. These resistant locations are within Budd Inlet, Henderson Inlet, Oakland Bay, and Sinclair Inlet. As discussed earlier in this section, in the case of Budd Inlet, a separate modeling exercise to account for hydrodynamic differences between existing and reference conditions specific to that inlet is already underway. The remainder of the resistant areas are all nearshore, though not intertidal, and, in the case of Oakland Bay, are completely surrounded by masked cells. Sinclair Inlet and Oakland Bay are both fed by several small ungauged streams without site-specific nutrient measurements. Further model refinement and field observations would be necessary to study these resistant areas in more detail.

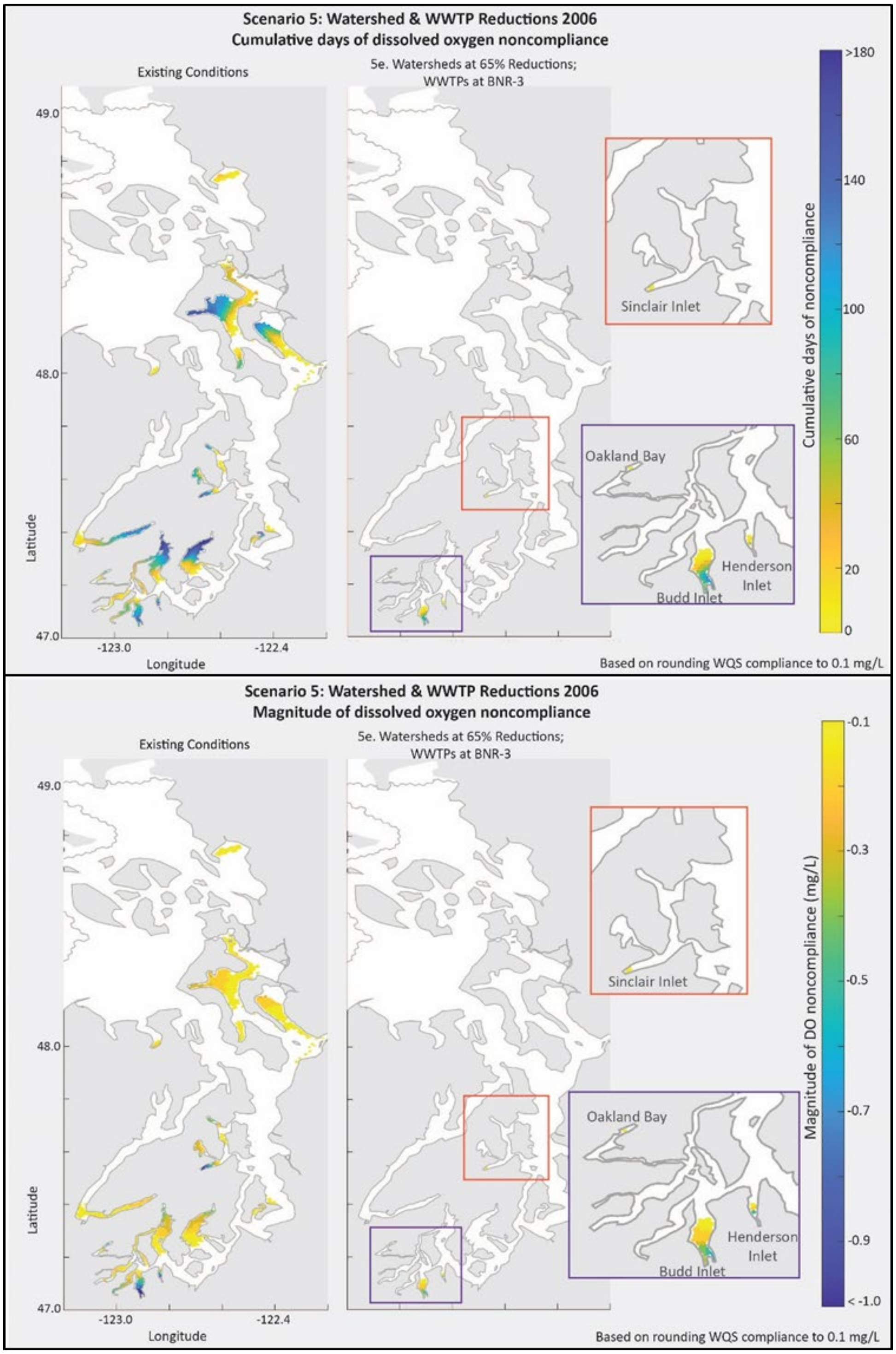


Figure 18. Scenario 5e plan view maps (2006) showing predicted cumulative days of DO noncompliance (top) and magnitude of DO noncompliance (bottom) in WA waters of the Salish Sea.

Spatial outcomes from single region/category load reductions

This sub-section contains a discussion of how hypothetical scenarios (Scenario 1 and 2) performed spatially for 2006 in terms of predicted compliance. These scenarios involved single category nutrient reductions in individual regions (i.e. reductions in either watersheds or WWTPs, but not both). These scenarios test the sensitivity of regional nutrient loads from watersheds *or* WWTPs by reducing them to estimated reference loads in specific regions, assuming *zero* anthropogenic nutrient loading in that region by that source category. These hypothetical scenarios are different from Scenario 5 runs, which reduce anthropogenic nutrient loads of *both* watersheds and WWTPs by *specific percentages, not complete removal*.

The plan view maps display predicted noncompliant days when either watersheds (Figure 19) or WWTPs (Figure 20) in each of the six regions were set to reference conditions in 2006. The area outlined by a thick grey line in each of the plots is the 'focus region' that was set to reference conditions in the corresponding scenario run. Plan view maps showing maximum magnitude of noncompliance for Scenario 1 for 2006 and 2014 are included in Appendix G (Figure G-2 and Figure G-3, respectively). Figure G-4 (Appendix G) includes the cumulative days of noncompliance for 2014 for Scenario 1. Additionally, a plan view map of maximum magnitude of noncompliance for Scenario 2 for 2006 is included in Figure G-5 (Appendix G).

All regions are responsive when watershed or WWTP loads are set to reference in the focus region. However, in half of the Scenario 1 simulations, noncompliances within the focus region disappear whereas in the other half of Scenario 1 runs, noncompliances still occur within the focus region due to out-of-region influences (Figure 19). For example, the regional days of noncompliance diminish to zero when watersheds in each of these regions are set to reference conditions: Strait of Georgia and Northern Bays, Strait of Juan de Fuca and Admiralty Inlet, and Hood Canal. However, this is not the case for Whidbey, South Sound, and Main Basin due to the influence of nutrient loading from other regions, which influence DO compliance in regions outside where these nutrients originate. For Scenario 1, the largest reduction in noncompliant days occurs when watersheds in South Sound were set to reference conditions.

Scenario 2 results (Figure 20) show that when WWTP loads are set to reference levels in the Main Basin, this causes spatially widespread reductions in DO noncompliance within the Main Basin and in *other* regions, particularly in South Sound, Hood Canal, and Whidbey Basin. Setting WWTPs in the SOG and Northern Bays region to reference levels reduced predicted noncompliant days within that region (specifically in Bellingham Bay), but these noncompliances did not disappear altogether as they did in Scenario 1, when the watersheds were set to reference, indicating the relative importance of watershed reductions in this region.

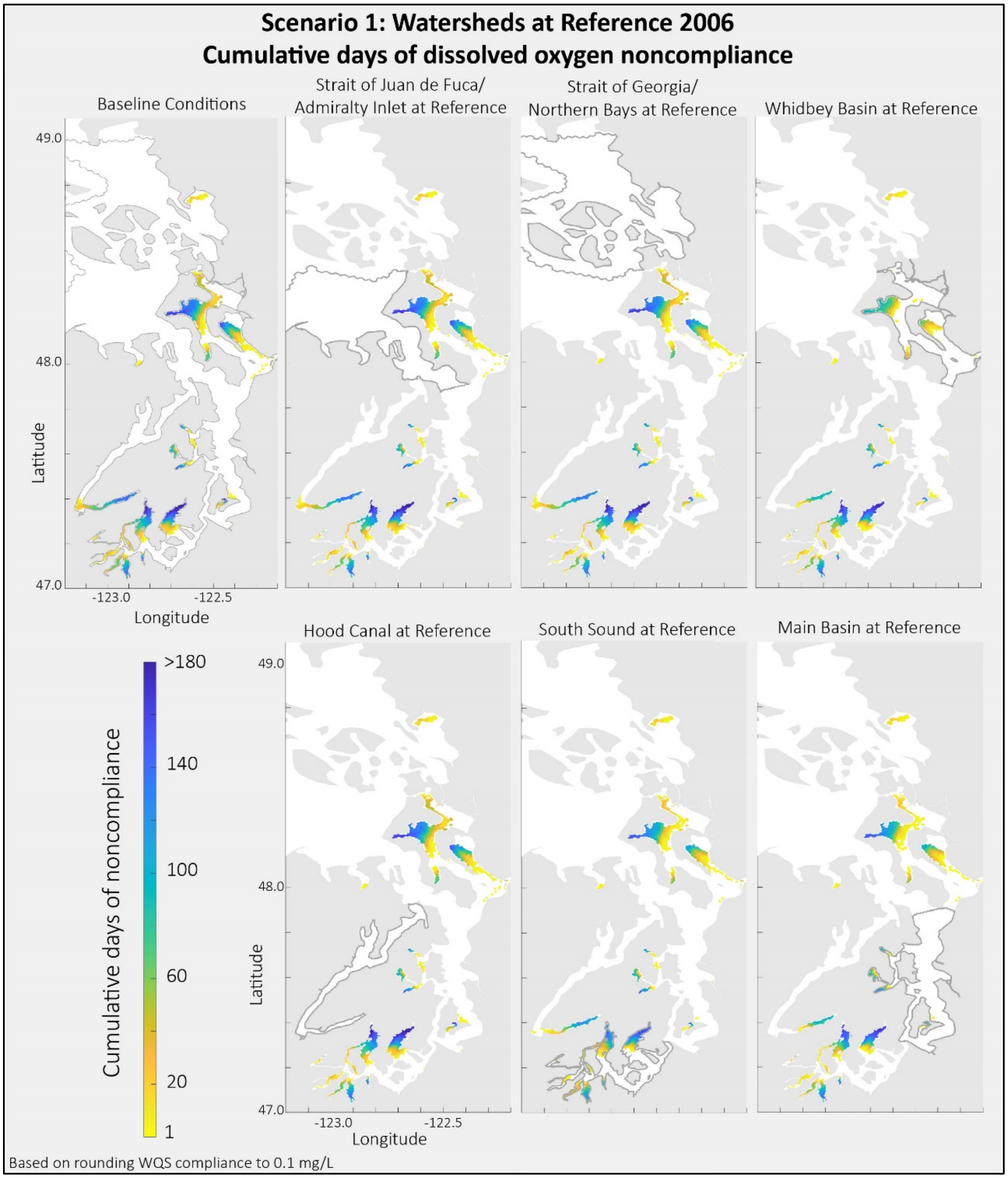


Figure 19. Plan view map of the predicted cumulative days of DO noncompliance when watersheds in each region are set to reference in Scenario 1 runs (2006).

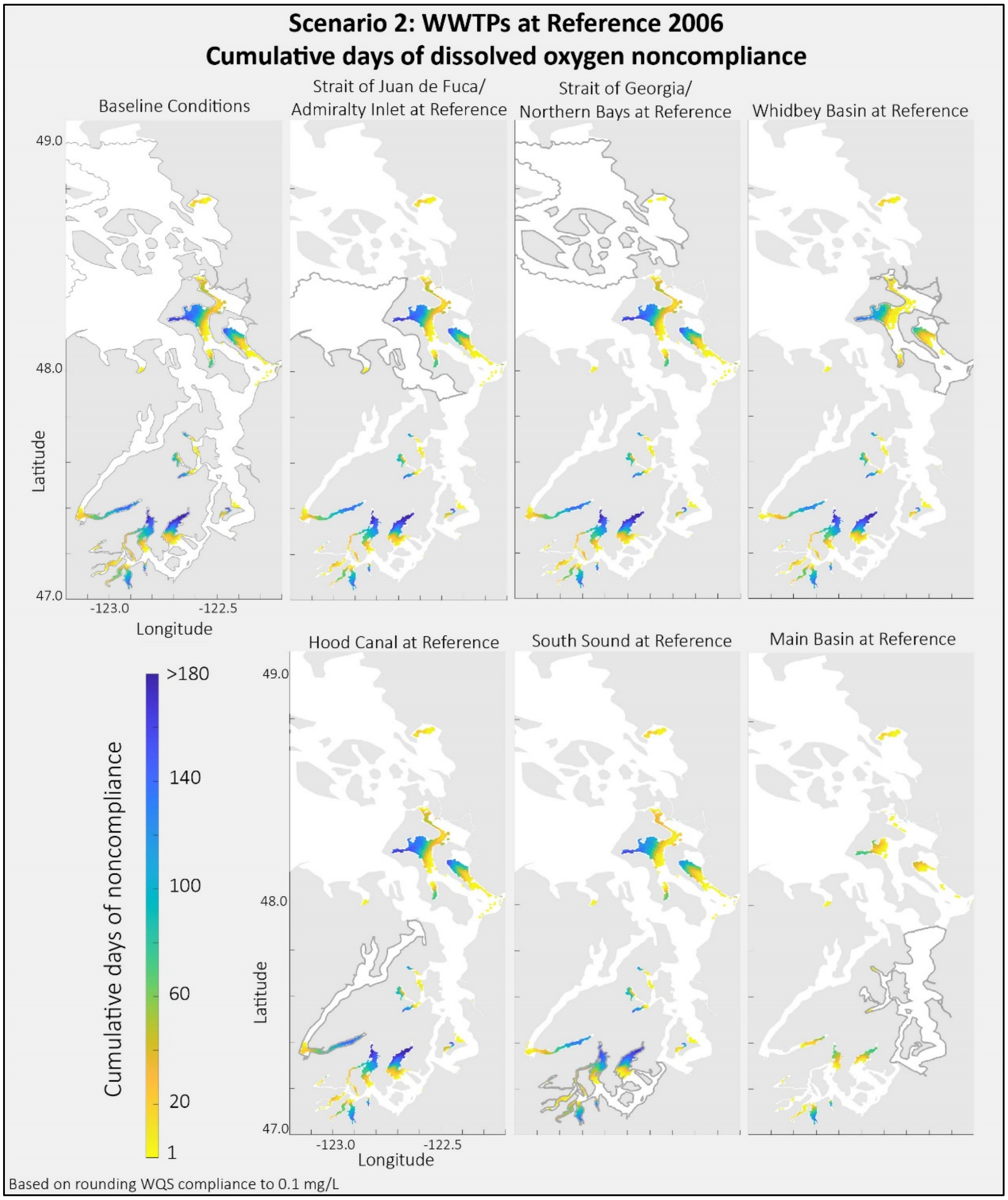


Figure 20. Plan view map of predicted cumulative days of DO noncompliance when WWTPs in each region are set to reference in Scenario 2 runs (2006).

Figures 21 and 22 show percentage decrease (relative to 2006 baseline levels) in predicted noncompliant days and area *within* each of the six regions for Scenario 1 and Scenario 2. Appendix G presents analogous figures for year 2014. The more negative the magnitude of the percent decrease in predicted noncompliance, the greater the improvement. Scenario 1 and 2 results show that single category nutrient reductions in Main Basin, South Sound and Whidbey Basin influence compliance *outside* of their respective regions, but single category reductions in Hood Canal, SJF & Admiralty, and SOG and N. Bays only influence compliance *within* the same region in which nutrients are reduced.

Figure 21 also shows that when Main Basin or Whidbey Basin watersheds are set to reference conditions, more improvement occurs in Hood Canal than when South Sound watersheds are at reference. South Sound and Main Basin almost equally influence each other and the Whidbey Basin region in terms of noncompliances, whereas the Whidbey Basin's greatest out-of-region influence is in Hood Canal.

Figure 22 shows that when WWTP loads are set to reference within Main Basin or Whidbey Basin in 2006, the largest decreases in predicted noncompliances occur *within* each of those regions. Additionally, as the plan view maps reflect, the influence can also be relatively large in other regions, particularly when the Main Basin is set to reference. There are noticeable decreases in predicted noncompliant area (-60% to -70%) and days (-70% to -90%) in other regions (South Sound, Whidbey Basin, and Hood Canal) when WWTPs in the Main Basin are set to reference conditions. In this scenario, the average magnitude of remaining predicted noncompliances in WA waters is around -0.2 mg/L (the range is -0.1 mg/L to -1.7 mg/L). These noncompliances of the DO regulatory standard include both portions of the standard, the aquatic life criteria (Part A) and the human allowance (Part B).

In contrast, when WWTP loads are set to reference in SOG and Northern Bays, the reduction in predicted noncompliance is primarily isolated to within this region. The other two regions (Hood Canal, and SJF & Admiralty) have very low WWTP loads to begin with, so reductions to these have minimal to no impacts in any region.

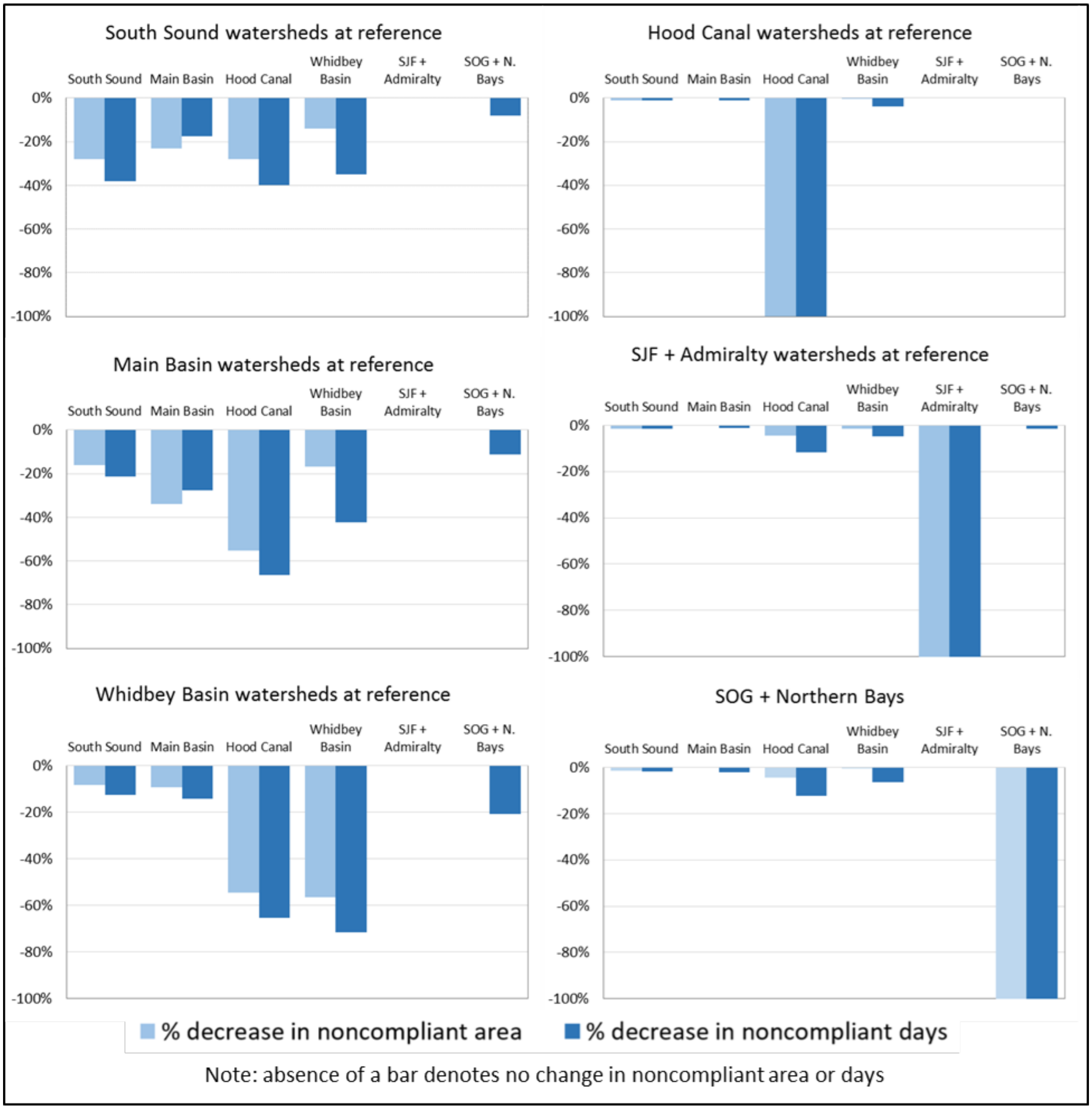


Figure 21. Percent change (decreases shown as negative values) in predicted noncompliant days and area within each region from Scenario 1 runs, when watersheds for each of the six regions are set to reference conditions in 2006.

Figure 22. Percent change (decreases shown as negative values) in predicted noncompliant days and area within each region when WWTPs in each of the six regions are set to reference conditions in 2006.

Seasonal and annual Biological Nitrogen Removal (BNR)

The Bounding Scenarios Report (Ahmed et al., 2019) contains a discussion about model results when seasonal BNR is implemented at U.S. WWTPs. In those model scenarios, WWTPs were set to levels of DIN and $CBOD_5$ equal to or less than 8 mg/L (BNR8) between the months of April through October. This phase of the study, Scenario 3 of the Year 1 Optimization Scenarios, evaluated annual BNR8, where these BNR levels were extended throughout the whole year. We compare results from that annual BNR8 scenario to seasonal BNR8 scenarios for both 2006 and 2014. We only discuss 2006 BNR simulations here, and present more plots of both 2006 and 2014 BNR scenarios in Appendix G.

Following is a list of the BNR scenarios conducted, in descending order of total improvement in terms of compliance:

1. Annual BNR8 at all U.S. WWTPs.
2. Seasonal BNR8 at all U.S. WWTPs.
3. Seasonal BNR8 at all U.S. WWTPs with DIN load of 1,000 kg/day or more (BNR8-1000).
4. Seasonal BNR8 at all U.S. WWTPs with DIN load of 8,000 kg/day or more (BNR8-8000).

The annual BNR8 scenario outperformed all seasonal BNR scenarios with respect to decreases in noncompliant area and cumulative number of noncompliant days. This is likely indicative of the influence of late fall and winter loads on sediment oxygen demand coupled with nutrients circulating in the system due to long residence times.

Figure 23 shows plan view maps of the cumulative number of days of noncompliance for each of the 2006 BNR8 scenarios. BNR scenarios are presented from left to right in order of largest to least improvement in noncompliant days, as listed above. Table 5 (above) shows the improvement in compliance (based on reductions in noncompliant days and areas in WA waters) for each of the BNR scenarios.

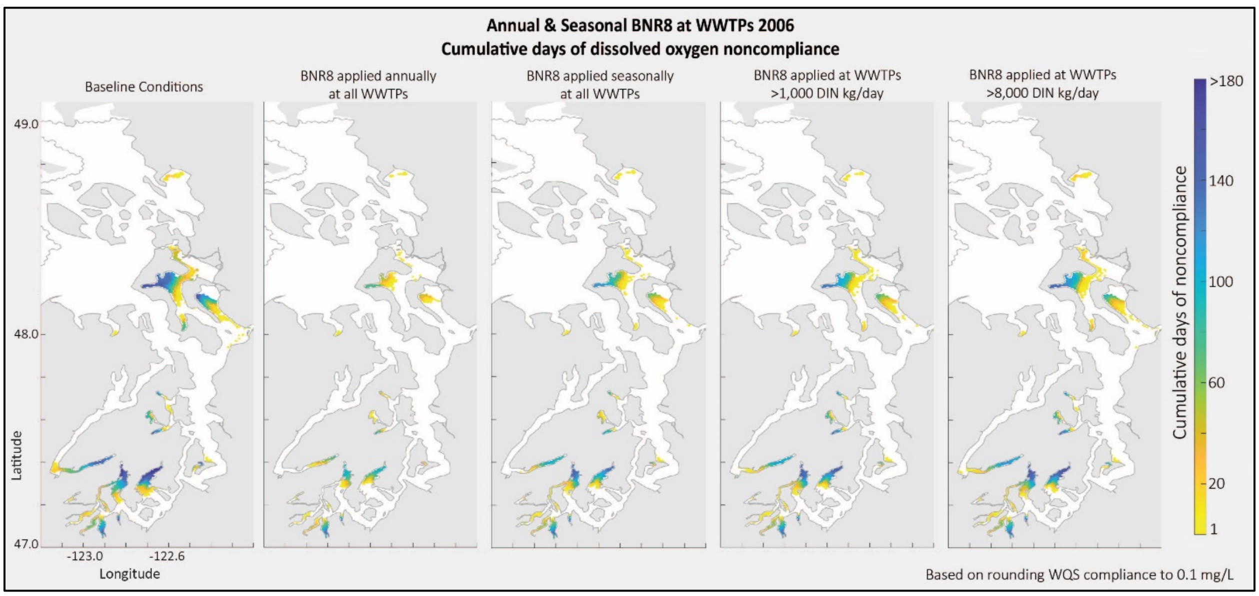


Figure 23. Cumulative days of noncompliance under existing baseline conditions and the different BNR scenarios

For 2006, the *magnitude* of average predicted noncompliance throughout WA waters remained around -0.2 mg/ L. Therefore, the progressively smaller predicted noncompliant areas for each scenario share, on average, the same noncompliance magnitude. Reduction in magnitude of maximum (peak) predicted noncompliance with the 2006 baseline was most pronounced (11%) with the annual BNR scenario. Seasonal 2006 scenarios resulted in about 5% reduction in peak predicted noncompliance, except for the seasonal BNR8-8000 scenario in which no reduction in maxima was observed. Reduction in maximum magnitudes seem to be most influenced by local sources (either watersheds or WWTPs located within the impacted embayment).

Projected WWTP flows in 2040

Both of the 2040 projected low and high WWTP flow scenarios resulted in increases in noncompliances compared to the 2014 baseline. The total predicted number of noncompliant days for 2040, relative to 2014 conditions, are shown in Figure 24 (A). Shown in Figure 24 (B) are the *additional* noncompliant days compared to the 2014 baseline. Appendix G contains additional plan view maps comparing 2014 noncompliant number of days and areas.

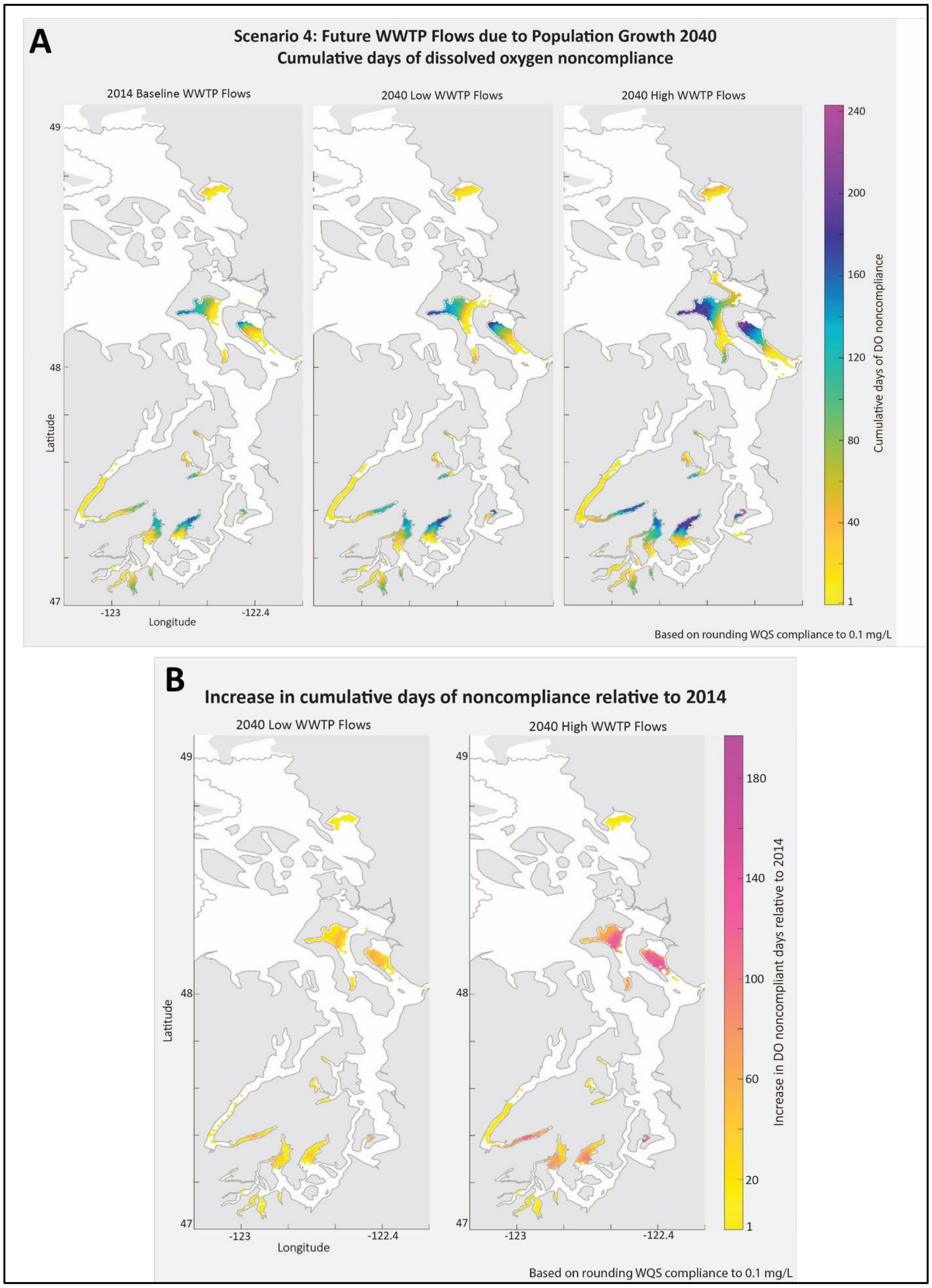


Figure 24. Predicted cumulative days of noncompliance (A) and change in noncompliant days (B) for 2040 WWTP projected low and high flows.

Figure 25 shows the increase in noncompliance represented spatially in Figure 24, but expressed as percentages. The increase in noncompliant area in 2040 is projected to be 22% to 62% for low and high projected flows, respectively. The projected 2040 increase in noncompliant days varies from 35% to 126% for low and high projected flows, respectively.

Figure 26 shows that this increase in noncompliant area will result in shifts in terms of increased magnitude of noncompliance in some areas (larger deep pink, orange, yellow and black bands) compared to the 2014 baseline. However, the worst-case (maximum) magnitude of noncompliance anywhere in WA waters is projected to remain about the same (around -2 mg/L DO).

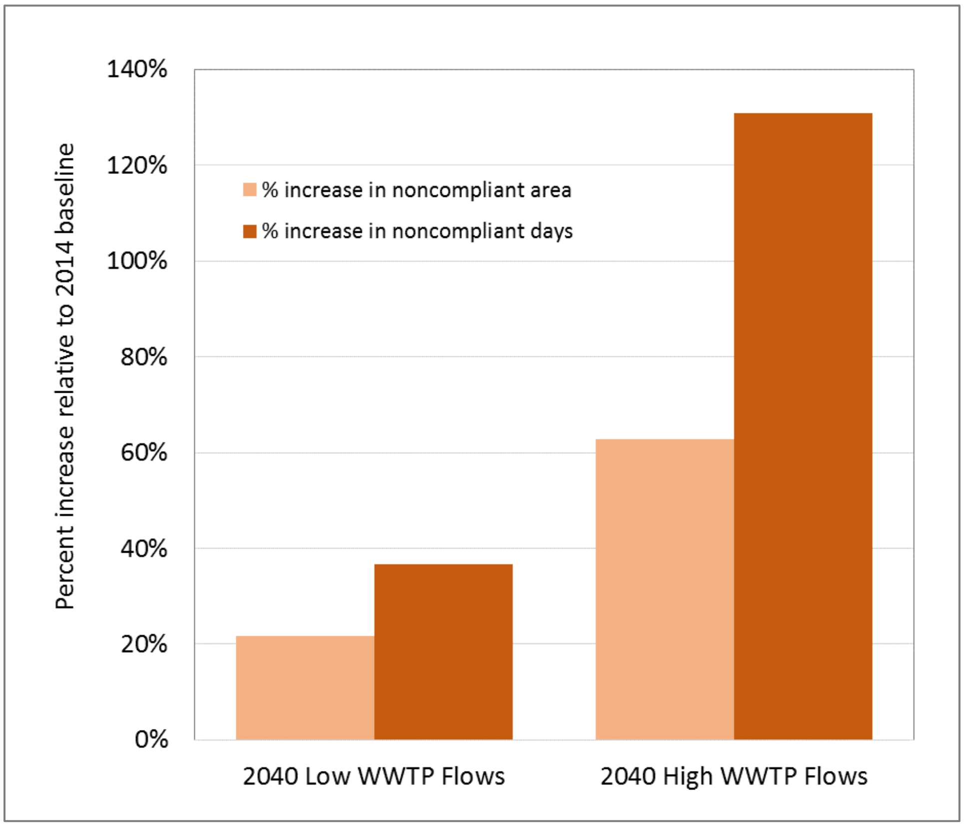


Figure 25. Increase (relative to 2014) in predicted DO noncompliant areas and days in WA waters of the Salish Sea as a result of projected 2040 low and high WWTP flows.

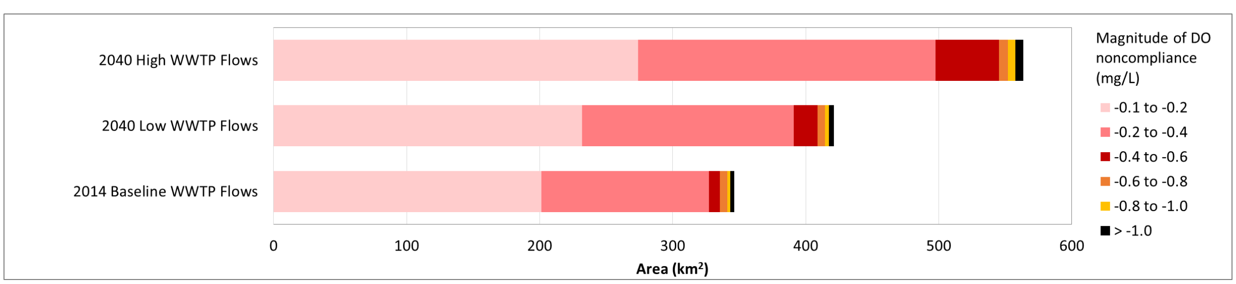


Figure 26. Predicted noncompliant area in 2040 under high and low WWTP flow scenarios in WA waters of the Salish Sea, partitioned into different DO noncompliance magnitude ranges.

Conclusions

The results from the Year 1 Optimization Scenarios support the following conclusions (note that the specific percent improvements in this section are for the year 2006, but are similar for year 2014):

1. The clearest pathway to predicted DO compliance includes comprehensive spatially and temporally distributed reductions from both WWTPs and watersheds. Scenarios with comprehensive, spatially distributed reductions outperformed scenarios with individual region and/or single category reductions, or scenarios with reductions isolated to the specific seasons (e.g. seasonal BNR8).

    - Within each series of spatially distributed scenarios tested (scenarios 3 and 5, where reductions were made throughout WA waters rather than in specific regions), greater predicted DO compliance improvements were achieved with progressively larger load reductions. However, scenarios including both comprehensive spatial distribution and reductions from both watersheds and WWTPs (Scenario 5 series) achieved the highest improvements towards predicted compliance. Scenario 5a demonstrated that a *lower* level of overall TN and TOC reductions WA waters could achieve *greater* improvement in predicted compliance than regional approaches associated with higher load reductions (scenarios 1 and 2).
    - SSM predicts compliance could be almost achieved in WA waters with Scenario 5e (95% and 97% reduction in total cumulative noncompliant days and areas, respectively, for 2006). This scenario is based on 65% anthropogenic nitrogen and organic carbon load reductions in the watersheds and annual BNR3 (DIN at 3 mg/L and $CBOD_5$ at 8 mg/L) applied to all WWTPs. Small nearshore areas within Budd Inlet, Henderson Inlet, Oakland Bay and Sinclair Inlet are predicted to remain resistant to compliance in Scenario 5e. Nearshore locations that remain resistant to predicted compliance within Henderson Inlet, Oakland Bay and Sinclair Inlet require further study and would benefit from refined observational and modeling analyses, as has been done for Budd Inlet.
    - Assessment of BNR at WWTPs suggests that annual BNR results in greater improvement in predicted total cumulative noncompliant days and areas than seasonal BNR. Annual BNR at all WWTPs resulted in 70% and 57% reduction in noncompliant days and areas, respectively, for 2006. With seasonal BNR at all WWTPs, these reductions are 50% and 37%, respectively. Annual BNR is associated with a higher anthropogenic TN load reduction (38%) than seasonal BNR (21%). Therefore, we conclude that this higher overall load reduction as well as fall and winter WWTP discharges are likely influential on DO compliance.

2. Based on simulations of the single region influence of WWTPs (Scenario 2), Main Basin WWTPs play a relatively larger role in attaining compliance in WA waters.

    Compared to all of the other regional/single category scenarios (scenarios 1 and 2) considered, setting WWTPs to reference conditions in the Main Basin had the greatest impact in reducing predicted noncompliant total cumulative days and areas (around 80%, and 63% respectively) in WA waters. Results from this scenario showed spatially widespread improvement in predicted compliance.

3. In terms of single region watershed influence (Scenario 1), Whidbey, South Sound, and Main Basin watersheds improve compliance outside of their respective regions.

   Setting watersheds in Whidbey Basin, South Sound, and Main Basin to reference conditions resulted in reductions from 31-36% and 20-34% in noncompliant total cumulative days and area, respectively, in WA waters. These three regional watershed reductions had a relatively larger overall predicted impact compared to the rest of the watershed reductions (Scenario 1) series.

4. Future year (2040) growth projections will present further DO compliance challenges.

   Increases in both predicted total cumulative number of days and noncompliant area are expected from population growth, which produces larger WWTP flows, and therefore, nutrient loads. The increase in predicted noncompliant days in WA waters in 2040 is calculated to be 37% to 131% for low and high projected flows, respectively. Increase in predicted noncompliant area in WA waters in 2040 is calculated to be 22% to 63% for low and high projected flows, respectively. This emphasizes the need for reductions in projected WWTP nitrogen discharges in future years as well as reductions under existing conditions in order to achieve predicted DO compliance.

5. Other general conclusions regarding predicted noncompliance in WA waters of the Salish Sea include:

   - We conducted various model updates and received additional guidance on application of the DO standard that resulted in changes to predicted noncompliance computations. As reported in Ahmed et al. 2019, the areas of predicted noncompliance are primarily located in terminal inlets and bays. However, the total area of predicted noncompliance reported here is less than previous computations primarily due to the Ecology decision to round the magnitude of noncompliance to -0.1 mg/L of DO depletion.
   - In terms of magnitude of noncompliance in 2006, 58% of the predicted DO noncompliant area in WA waters is due to DO noncompliance of -0.1 to -0.2 mg/L. The DO noncompliance of -0.1 to -0.2 mg/L is analogous to total DO depletions between -0.3 and -0.4 mg/L, under 2006 existing conditions as presented in the Bounding Scenario Report. Both predicted DO total cumulative days and noncompliant area are predominantly due to Part B (limit on cumulative human actions) of the DO standards.

Recommendations

The results from these Year 1 Optimization Scenarios provide insights for designing future modeling scenarios for the PSNSRP that will inform load allocations. SSM predicts that large reductions are needed to meet DO standards in WA waters. The predicted impact of future growth projections further support planning for widespread reductions.

The range of load reductions associated with the Scenario 5 series (a-d) can serve as a starting point, or, as a base level of nutrient reductions to help define the next set of model runs. The concept of a base level of nutrient reduction here refers to, for example, a specified level of spatially comprehensive nutrient reductions that need to be applied everywhere. These would be followed by additional reductions that may vary in time or space based on localized and seasonal impacts towards achieving DO compliance.

While Scenario 5 reductions do not result in predicted compliance everywhere, they are the scenarios in this phase of work that included spatially comprehensive load reductions, and resulted in the most widespread improvements in predicted compliance relative to the other scenarios evaluated. In the next phase, we recommend the following approach:

1. Develop additional scenarios that involve spatially comprehensive reductions and a combination of watershed and WWTP reductions, such as:
    - Spatially comprehensive watershed and WWTP reductions that are scaled to be commensurate with the size of their load.
    - Main Basin, Whidbey Basin, and South Sound are three regions that are predicted to have relatively larger influence on other regions. If intra-regional solutions are sought that can translate into out-of-region benefits, prioritizing those three regions for investigating further potential reduction opportunities beyond a base level would make sense.
    - Develop other combinations of spatial and temporal base level reductions that are technologically feasible, align with climate change mitigation strategies, and are developed with stakeholder input.
2. Consider localized reductions that may be needed beyond base level reductions to fully attain DO standards everywhere. Results from embayments fed largely by ungauged streams without site-specific nutrient measurements are expected to be more uncertain. Additionally, nearshore portions of model domain are currently masked. Consequently, spatially refined modeling analyses including additional field observations would need to be conducted for specific locations within embayments resistant to DO compliance or containing a large portion of masked areas, as described further below:
    - The Northern Bays part of the SOG & N.Bay region (including Bellingham, Samish, and Padilla Bays) contains a large portion of masked areas due to the intertidal shallow waters. More refined analyses are needed to determine whether further load reductions besides a base level are warranted in this region.
    - Conduct more refined analyses of locations that are predicted to be resistant to attainment of compliance and occur at the tip of several embayments. These specific locations are nearshore and very shallow, and will require further monitoring and modeling. For instance, compliance with DO standards for Budd Inlet is being assessed using the Budd Inlet DO GEMSS model. This effort is underway using an extensive inlet-specific field study. Other areas may require refined-scale analyses including compiling past data or conducting future location-specific, transect-based field monitoring efforts and modeling studies. These areas include, but are not limited to, the following: Henderson Inlet, Sinclair Inlet and Oakland Bay.
    - Refined analyses described in the previous bullets will require significant effort and therefore separate project scoping.
3. Additional work to continue to improve watershed estimates as well as sensitivity analyses with respect to uncertainties of these estimates will enhance understanding of current conditions and impact of future potential actions. Continuous nitrogen monitoring at the mouths of seven major watersheds was funded by the legislature but has been delayed in starting until 2022 due to COVID-19 related actions. Given that timeline, we may not be able to incorporate any of that new continuous watershed data into the final PSNSRP report.

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List of Figures and Tables

Glossary, Acronyms, and Abbreviations

Glossary

Anthropogenic: Human-caused.

Basin: Term used in the Bounding Scenarios report to describe distinct areas, generally separated by shallow sills, such as South Sound, Main Basin, Whidbey Basin, and Hood Canal.

Biologically-based numeric criteria: See 173-201A, Table 210(1).

Biological nitrogen removal (BNR): General term for a wastewater treatment process that removes nitrogen through the manipulation of oxygen within the treatment train to drive nitrification and denitrification. Nitrogen removal efficiency depends on site-specific conditions, such as treatment processes, climate, and the overall strength of the raw wastewater.

BNR3: BNR treatment process resulting in no more than 3 mg/L DIN in WWTP effluent.

BNR8: BNR treatment process resulting in no more than 8 mg/L DIN in WWTP effluent.

Compliance: For the purposes of this technical memorandum, compliance refers to model predictions that meet the location specific DO water quality criteria (WAC 173-201A-210(1)(d)), as discussed in Appendix F.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Grid-cell-layer: For the purposes of this technical memorandum, refers to each individual longitudinal and vertical spatial representation of marine waters used in the SSM.

Hindcast: Historical model run.

Marine point source: Point sources (see “point source” definition below) represented in the SSM that discharge directly to the Salish Sea or to a major river down gradient of the freshwater monitoring station used to represent watersheds. In most cases, these river discharges are to estuarine waters that are considered marine by definition in WAC 173-201A-260(3)(e).

Noncompliance: For the purposes of this technical memorandum, noncompliance refers to a modeled excursion from the location specific DO water quality criteria (WAC 173-201A-210(1)(d)), as discussed in Appendix F.

Nonpoint source: Pollution that enters waters of the state from any unpermitted dispersed land-based or water-based activities, including but not limited to atmospheric deposition; unregulated stormwater runoff from agricultural lands, urban areas, or forest lands; groundwater and unregulated interflow; and discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of “point source” in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Point source: The term "point source" means any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture. Examples of point source discharges include domestic wastewater treatment plants, regulated stormwater, and industrial wastewater.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Puget Sound: Includes South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal.

Region: Groupings of geographic areas for the purposes of this analysis, includes: South Sound Basin, Main Basin, Whidbey Basin, Hood Canal, the combined Strait of Juan de Fuca and Admiralty Inlet (aka SJF and Admiralty), and the combined Strait of Georgia, Bellingham, Samish, and Padilla Bays (aka SOG/Northern Bays).

Rivers/streams: A freshwater pathway that delivers nutrients and drains watershed areas. In the context of this report, "river inputs" and "river inflows" are used interchangeably with "watersheds," "watershed inputs," and "watershed inflows" to represent the delivery of flow and nutrient inputs into the Salish Sea Model. In the model, these estimates are applied to the mouth of each major river to represent loading to the Salish Sea. Data used to represent watershed loads is collected at sampling stations generally located upstream of marine water influences in the major river estuaries. These estimates include, but do not distinguish, between various upstream point and nonpoint sources in the watersheds that contribute to the loading at the mouth.

Total nitrogen (TN): Total nitrogen; includes the organic and inorganic fractions.

Washington Waters of the Salish Sea: Puget Sound, Strait of Georgia, and Strait of Juan de Fuca, the Northern Bays (Bellingham Bay, Samish Bay, and Padilla Bay) including their connecting channels and adjoining waters (Figure 1).

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

Watershed inflows: See definition of "rivers" above.

Watershed load: Nutrient inputs originating in a watershed and primarily discharged into the Salish Sea via rivers and streams. Watershed loads can be composed of both point and nonpoint sources.

Acronyms and Abbreviations

BNR	biological nitrogen removal
DFO	Department of Fisheries and Oceans Canada
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon

Ecology	Washington State Department of Ecology
et al.	and others
HYCOM	Hybrid Coordinate Ocean Model
MLLW	mean lower low water
NOAA	National Oceanic and Atmospheric Administration
OBC	ocean boundary condition
OFM	Office of Financial Management
POC	particulate organic carbon
PSNSRP	Puget Sound Nutrient Source Reduction Project
SJF	Strait of Juan de Fuca
SOG	Strait of Georgia
SSM	Salish Sea Model
TN	total nitrogen
TOC	total organic carbon
WA	Washington State
WQS	water quality standard
WWTP	wastewater treatment plant

List of Appendices

Appendices A through H are in a separate file