

## Technical Memorandum

# Nutrient Reduction Scenario Modeling: Whidbey Region

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### Objectives

The primary objective of this study is to assess the magnitude of change in dissolved oxygen concentrations in Puget Sound resulting from eliminating nitrogen loadings from specific locations and source types. This study specifically explores the impact of altering nitrogen loadings from rivers and wastewater treatment plants in the Whidbey region of Puget Sound. Potential impacts of each scenario are assessed throughout the Salish Sea Model domain and modeling results are presented for Puget Sound waters within Washington State for which dissolved oxygen criteria exist. This study is designed to better quantify the response of the system to altered loadings rather than to predict the performance of specific engineering controls or management actions.

The most widely applied version of the Salish Sea Model was used to explore the sensitivity of ambient dissolved oxygen conditions to altered nitrogen loadings in eleven scenarios, as described below. The Salish Sea Model used here, and post-processing scripts, have been demonstrated to produce results nearly identical to those previously applied by the State of Washington agencies (Appendix 1).

### Description of Scenarios

Eleven scenarios were evaluated in this report and compared with **2014 current conditions** and **reference conditions**, totaling thirteen model runs. In each scenario, nitrogen loads from specific wastewater treatment plants or rivers were altered by changing the nitrogen concentrations in the source while leaving the temperature and flow-rate unchanged, thus preserving the mixing, stratification, and dispersion characteristics among the scenarios. This allows the impact of altered loadings to be isolated from other potentially confounding factors.

**2014 Current Conditions and Reference Conditions:** the 2014 current conditions scenario represents a baseline for nutrient loading and hydrodynamics which are the best estimates of the “current conditions” for that year (also referred to as “existing conditions” by the State). The reference condition scenario uses the same physical conditions as the 2014 current conditions model run but replaces river and wastewater treatment plant (WWTP) loadings with estimates for nutrient loadings prior to modern land-use practices and population growth in Washington State. The difference between the 2014 current conditions and reference scenario reflects the modern-day human/anthropogenic influence. The results of both the reference and 2014 current conditions are virtually identical to those in the Washington State Department of Ecology’s optimization scenarios report (Ahmed et al, 2021), which updates the Ahmed et al. (2019) Bounding Scenarios report. Both 2014 current conditions and the Whidbey-specific loading scenarios described here are compared to this reference Condition in the calculations of “non-compliance” which is described further in Appendix 1.

For the following 11 scenarios addressed in this analysis:

- Whidbey region nitrogen source concentration ( $\text{NO}_2^-/\text{NO}_3^-$  and  $\text{NH}_4^+$ ) were manipulated specific to each scenario described below. See Table 1 for the wastewater treatment plant and river loading for each scenario.
- The physical environment and non-Whidbey sources of nitrogen are set to 2014 current conditions (i.e. hydrodynamics, meteorology, boundary conditions such as ocean exchange and river discharge, and resulting advection, diffusion, mixing, etc.).
- Wastewater treatment plant (WWTP) loading scenarios are grouped into small, medium, and dominant, using model input data on average TN kg/day for classification. This matches grouping in the [State’s permit documentation \(issued 12/1/2021\)](#), and are further detailed in Table 1. Medium plants are classified as moderate in the State’s documentation.
- All resulting plots and tables use the abbreviated labels (in bold) for each of the 11 scenarios.

**Wtp1. No Whidbey WWTPs:** the purpose of this scenario is to calculate the maximum change in dissolved oxygen possible by reducing nitrogen loadings from all wastewater treatment plants in the study region. In this scenario, the nitrogen concentrations were set to zero in 16 wastewater treatment plants that discharge in the Whidbey region.

**Wtp2. No Small WWTPs < 100 TN kg/day:** the purpose of this scenario is to explore the magnitude and spatial extent of nutrient loading from 10 smaller wastewater treatment plant effluent outfalls in the Whidbey region (classified here as <100 TN kg/day). In this scenario, the nitrogen concentrations were set to zero for the smaller treatment plants only.

**Wtp3. No Medium WWTPs 100 to 1000 TN/day:** the purpose of this scenario is to explore the magnitude and spatial extent of nutrient loading from 5 medium wastewater treatment plant effluent outfalls in the Whidbey region (classified as between 100 and 1000 TN kg/day). In this scenario, the nitrogen concentrations were set to zero for the medium treatment plants only.

**Wtp4. No Everett North (OF015) & South (OF100) WWTPs:** the purpose of this scenario is to explore the magnitude and spatial extent of nutrient loading from the two dominant wastewater treatment plant outfalls in the Whidbey region. In this scenario, the nitrogen concentrations were set to zero for Everett's northern outfall (OF015, which discharges into the shallow Snohomish River) and Everett's southern outfall (OF100, which discharges into deeper waters of Possession Sound). Both discharge to bottom layer of the model (layer 10).

**Wtp5. No Everett North (OF015) WWTP:** the purpose of this scenario is to explore the magnitude and spatial extent of nutrient loading from Everett's northern outfall. In this scenario, the nitrogen concentrations were set to zero for Everett's northern plant outfall (OF015), which discharges into the shallow Snohomish River.

**Wtp6. No Everett South (OF100) WWTP:** the purpose of this scenario is to explore the magnitude and spatial extent of nutrient loading from Everett's southern outfall. In this scenario, the nitrogen concentrations were set to zero for Everett's southern plant outfall (OF100), discharging into deeper waters of Possession Sound.

**Wtp7. Moving Everett OF015 to OF100 WWTP:** the purpose of this scenario is to explore the magnitude and spatial extent of moving all nutrient loading between Everett's two wastewater treatment plant outfalls. In this scenario, the nitrogen concentrations for Everett's shallow northern outfall (OF015) were set to zero, and those for Everett's deeper southern outfall (OF100) were increased to represent the total load across both outfalls for each month of 2014. Flows were not changed. Everett OF015 concentrations were scaled by the differences in discharge levels between the two plants before adding this concentration to OF100; effectively transferring loading without changing flow (Figure 1).

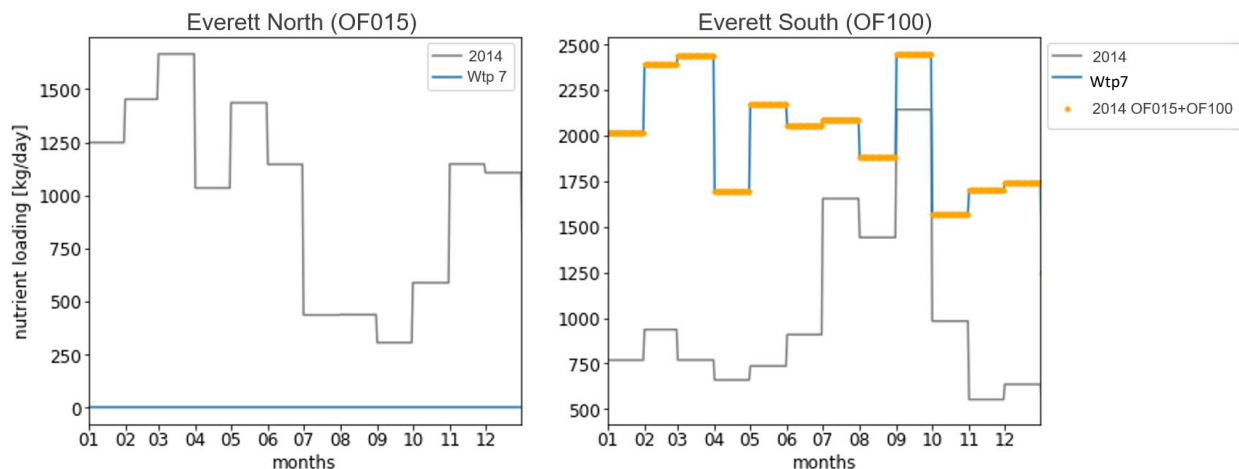


Figure 1. Manipulation of loadings applied in Wtp7 at Everett's northern outfall (OF015) discharging in the Snohomish River (left panel) and Everett's southern outfall (OF100) discharging into deeper waters in Possession Sound (right panel). Grey lines show levels for 2014 current conditions scenario, and blue lines show the levels used in this scenario (i.e. set to zero throughout the year for OF015 on the left panel, and including loads from both plants at the discharge of OF100 on the right panel). The orange overlapping blue lines for OF100 confirm that the concentrations were adjusted appropriately to match the desired transfer in loadings. Appendix 1 provides plots of all treatment plant inputs used in the 2014 current conditions scenario.

**Wtp8. Everett July-Nov OF015 to OF100 WWTP:** the purpose of this scenario is to explore the magnitude and spatial extent of moving the nutrient loading between Everett's two wastewater treatment plant outfalls for part of the year. In this scenario, the nitrogen concentrations for Everett's northern (OF015) and southern outfall (OF100) were manipulated using the same procedure as Wtp7, but only for the months of July to November.

**Wr1. No Whidbey River:** the purpose of this scenario is two-fold: first, to better understand the response in magnitude and spatial extent of dissolved oxygen from decreasing nitrogen loads from the rivers and their watersheds in the Whidbey region; second, to better understand the impact of WWTP loadings to the Whidbey region in the absence of river loadings. Nitrogen concentrations were set to zero in the four rivers that flow into the Whidbey region. Accordingly, nutrient input levels are below those of the estimated pre-industrial reference Conditions for Puget Sound, and are not physically attainable reductions for management actions.

**Wr2. 0.5x Pre-Industrial/Anthropogenic River Load:** similar to Wr1, the purpose of this scenario is to better understand the response in magnitude and spatial extent of dissolved oxygen from decreasing nitrogen loads from the rivers and their watersheds in the Whidbey region. In this scenario, concentrations at the four rivers in the Whidbey region were reduced by half from current conditions, taking the mid-point between the 2014 current condition and reference condition river monthly concentration inputs (Figure 2).

**Wr3. 2x 2014 River Load:** the purpose of this scenario is to better understand the response in magnitude and spatial extent of dissolved oxygen from increasing nitrogen loads from the rivers and their watersheds in the study area. In this scenario, the nitrogen concentrations in the rivers were set to twice the 2014 current conditions.

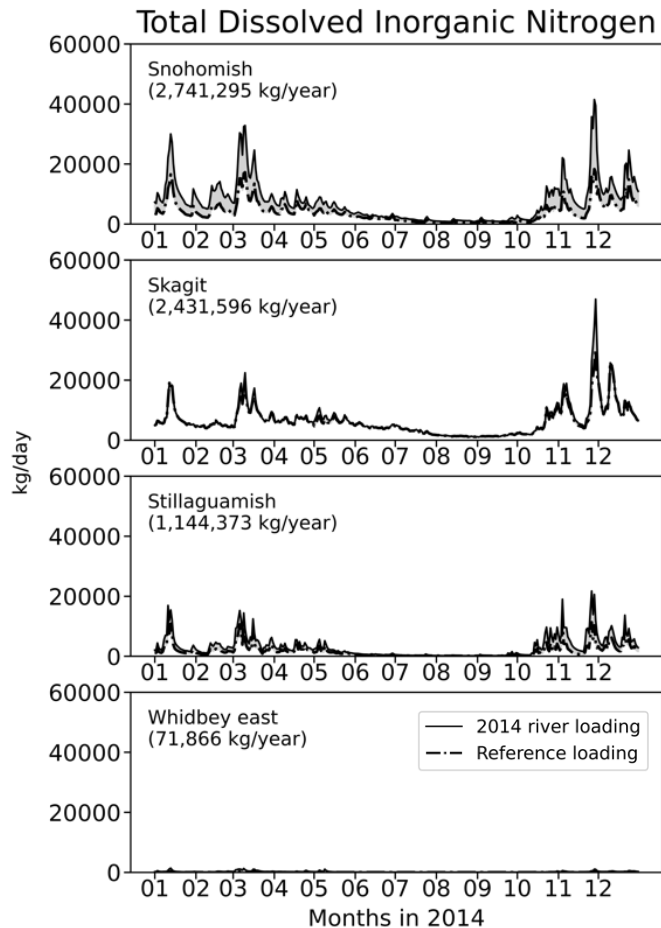


Figure 2. River/watershed loading of dissolved inorganic nitrogen (kg/day) for the current and reference conditions scenarios throughout the year 2014.

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Table 1. Whidbey Region Nutrient Loading Scenarios<sup>+</sup>. The 2014 total cumulative nitrogen load used as inputs to the model are shown for each WWTP or river input (rows) modeled for each scenario (columns).

WWTP	Annual Total Flow (Mgal/year)	Nitrogen Loading by Scenario (kg/year)												
		2014 current conditions	Reference	Wtp1 No WWTP	Wtp2 No Small	Wtp3 No Med.	Wtp4 No N&S	Wtp5 No North	Wtp6 No South	Wtp7 Move N>S	Wtp8 Move Seasonal N>S	Wr1 No Rivers	Wr2 0.5x Rivers (anthropogenic)	Wr3 2x Rivers
Everett South (OF100)	4,151	371,185	1,749	-	371,185	371,185	-	371,185	-	735,775	458,749	371,185	371,185	371,185
Everett North (OF015)	4,295	364,599	1,173	-	364,599	364,599	-	-	364,599	-	274,744	364,599	364,599	364,599
Mt Vernon	1,495	133,972	716	-	133,972	-	133,972	133,972	133,972	133,972	133,972	133,972	133,972	133,972
Marysville	1,144	132,781	280	-	132,781	-	132,781	132,781	132,781	132,781	132,781	132,781	132,781	132,781
Oak Harbor Lagoon	665	76,057	285	-	76,057	-	76,057	76,057	76,057	76,057	76,057	76,057	76,057	76,057
Lake Stevens 002	955	63,909	445	-	63,909	-	63,909	63,909	63,909	63,909	63,909	63,909	63,909	63,909
Snohomish	519	32,111	265	-	32,111	-	32,111	32,111	32,111	32,111	32,111	32,111	32,111	32,111
La Conner	110	11,414	51	-	-	11,414	11,414	11,414	11,414	11,414	11,414	11,414	11,414	11,414
Mukilteo	428	9,015	199	-	-	9,015	9,015	9,015	9,015	9,015	9,015	9,015	9,015	9,015
Stanwood	209	6,313	99	-	-	6,313	6,313	6,313	6,313	6,313	6,313	6,313	6,313	6,313
Coupeville	65	4,403	30	-	-	4,403	4,403	4,403	4,403	4,403	4,403	4,403	4,403	4,403
Tulalip	84	1,707	39	-	-	1,707	1,707	1,707	1,707	1,707	1,707	1,707	1,707	1,707
Langley	25	1,529	11	-	-	1,529	1,529	1,529	1,529	1,529	1,529	1,529	1,529	1,529
Swinomish	66	1,399	32	-	-	1,399	1,399	1,399	1,399	1,399	1,399	1,399	1,399	1,399
Skagit County 2 Big Lake	55	1,055	26	-	-	1,055	1,055	1,055	1,055	1,055	1,055	1,055	1,055	1,055
Penn Cove	12	883	6	-	-	883	883	883	883	883	883	883	883	883
Warm Beach		136	3	136	-	136	136	136	136	136	136	136	136	136
Campground	7													
<b>Total WWTPs (altered in this report)</b>		1,212,468	5,407	136	1,174,614	773,638	476,684	847,869	841,282	1,212,459	1,210,176	1,212,468	1,212,468	1,212,468
<b>Total WWTPs (all in model domain)</b>		26,237,734	14,183,138	25,025,402	26,199,880	25,798,903	25,501,950	25,873,135	25,866,548	26,237,725	26,235,442	26,237,734	26,237,734	26,237,734
<b>Rivers</b>														
Skagit	21,141	2,431,596	2,275,192	2,431,596	2,431,596	2,431,596	2,431,596	2,431,596	2,431,596	2,431,596	2,431,596	-	2,353,434	4,863,186
Snohomish	11,254	2,741,295	1,449,164	2,741,295	2,741,295	2,741,295	2,741,295	2,741,295	2,741,295	2,741,295	2,741,295	-	2,095,213	5,482,590
Stillaguamish	4,714	1,144,373	630,254	1,144,373	1,144,373	1,144,373	1,144,373	1,144,373	1,144,373	1,144,373	1,144,373	-	887,308	2,288,745
Whidbey east	105	71,866	14,618	71,866	71,866	71,866	71,866	71,866	71,866	71,866	71,866	-	43,242	143,732
<b>Total Rivers (altered in this report)</b>		6,389,129	4,369,229	6,389,129	6,389,129	6,389,129	6,389,129	6,389,129	6,389,129	6,389,129	6,389,129	-	5,379,198	12,778,253
<b>Total Rivers (all in model domain)</b>		25,511,237	19,999,812	25,511,237	25,511,237	25,511,237	25,511,237	25,511,237	25,511,237	25,511,237	25,511,237	19,122,109	24,501,306	31,900,362

<sup>\*</sup> For scenarios Wtp2-4, input data on the average TN kg/year was used to group WWTPs as small, medium, and large corresponding to each of these three scenarios. Each group includes the WWTPs in the Washington State Puget Sound Nutrient General Permit (PSNGP)<sup>1</sup> issued 1/12/2021, with a corresponding classification of smaller, moderate/medium, and dominant respectively with the following exceptions: a) the elimination of small WWTP loading scenario (Wtp2) also included removing the loading from Swinomish, Tulalip, and Warm Beach Campground outfalls, but these were not within the permit coverage, and b) Oak Harbor Lagoon outfall was included in the medium WWTPs scenario (Wtp3), but is classified as a small facility in permit document. Note also Snohomish is classified as medium/moderate outfall in the permit and these scenarios, but has <100 kg/day average for the 2014 model inputs.

<sup>+</sup> Kimberly Clark, Oak Harbor RBC, and Lake Stevens 001 are left on throughout all scenarios as they have modeled outfall in the Whidbey region, but are not covered in the Puget Sound Nutrient General Permit (PSNGP), or included in this table.

<sup>1</sup> <https://ecology.wa.gov/Regulations-Permits/Permits-certifications/Nutrient-Permit>

## **Assumptions and Limitations**

This set of scenarios are designed to explore the response of the modeled water quality parameters to large, systematic changes in nutrient loads. These scenarios are not designed to evaluate any specific engineering controls or management actions but rather provide insight into the sensitivity of dissolved oxygen levels to altered anthropogenic/human-influenced nutrient loadings.

As in earlier applications of the Salish Sea Model, the modeling results presented here represent hydrodynamic conditions of one fairly well-characterized calendar year (2014). Further work will be required to assess how the responses to nutrient loads reported here are influenced by interannual variability in oceanographic and meteorological conditions and to determine long-term responses to altered loadings.

Model parameters, including wastewater treatment plant and river nitrogen loading information, were adopted from earlier applications of the Salish Sea Model by the Washington State Department of Ecology without independent assessment of these source and run files.

Modification of nutrient loads in scenarios were done by changing nitrate/nitrite and ammonia concentrations. Where a treatment plant or river loading is removed (no Whidbey Rivers), the nitrogen concentration is set to zero for that input, which is below the pre-industrial reference condition. For most scenarios these percent changes in concentration were applied uniformly throughout the year, so that the same temporal cycle was used in each. The exception to this is for those scenarios focused specifically on varying seasonal nitrogen loading. Additional work would be required to further explore the impact of seasonal variations in nitrogen and carbon loading and speciation. Furthermore, to understand any potential impacts of changes to flow that may not be captured from manipulating concentration alone in these load reduction scenarios.

## **Methods to Assess Modeling Results**

The Salish Sea Model estimates values for water movement, mixing, and biogeochemical parameters (including dissolved oxygen) in 10 levels at each cell (or “node”) in the model, and hourly output is used throughout the model year. This model output was analyzed in several ways in order to provide complementary methods to evaluate the scenarios.

First, the minimum dissolved oxygen concentration at each location on each day was extracted and stored, reducing the file size used in analysis, and focusing on the lowest dissolved oxygen estimated for each day.

Second, the model results were grouped by region (i.e., each model cell was assigned to one of six regions in the U.S. waters of Puget Sound and adjoining areas outside of the Sound). These regions are identical to those used by the State of Washington in their water quality technical

reports (Figure 3). For the purpose of this analysis we refer to the total of the six regions as “Puget Sound,” noting that some of the US waters in the Strait of Juan de Fuca/Admiralty Inlet and in the Strait of Georgia/Northern Bays regions are outside of Puget Sound itself.

Third, within each region the daily minimum dissolved oxygen values at each cell/depth were evaluated for “non-compliance” using information about the relevant dissolved oxygen standard for that region and the corresponding modeled reference dissolved oxygen value. Following the State’s methodology, a cell was considered non-compliant if the minimum dissolved oxygen modeled in at least one layer of a cell:

- **Part A:** Was less than the numeric criteria for that location (e.g., extraordinary 7 mg/L)
- **Part B:** The minimum for the current condition was also at least 0.25 mg/L lower than the reference condition.

The entire region was counted as non-compliant on days when dissolved oxygen values were non-compliant at any depth within any cell. Figure 4 illustrates this method, where one bottom cell-layer in red for day 1 and three cell-layers for day 3 both trigger a day of non-compliance for the entire water-column, for that one cell. The total number of days in the year with at least one non-compliant cell within the region is reported here. A more detailed explanation of the application of the non-compliance calculation is provided in Appendix 1 along with all relevant code, sources, and methods of post-processing applied in the wider analysis.

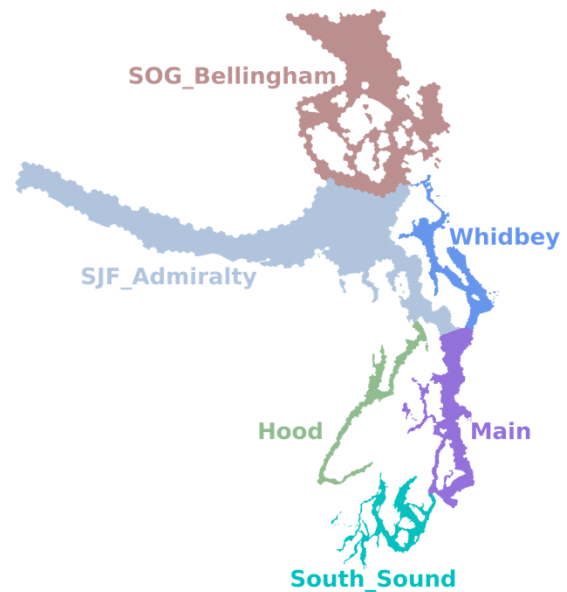


Figure 3. A map of the cells included in the regional analyses presented in this report. The cells in the six regions are given unique colors for identification, and these colors are used to represent these regions in the line graphics presented in this report.

Fourth, the non-compliance determination used above was adapted to estimate the volume of water that met the criteria within each region on each day of the year. Figure 4 illustrates the cell volumes in red in the water column that would count toward a non-compliant volume estimate each day. As described earlier, if any cell is red then that cell is considered non-compliant. The sum of these volumes across a region for each day is used to calculate a percent of total volume that is non-compliant and plotted as a time series for each region to demonstrate the seasonal nature of changing water quality conditions. These volumes are also summed over the year to create a single volume-day parameter that represents the time-integrated volume of water in each region that met the non-compliance determination.

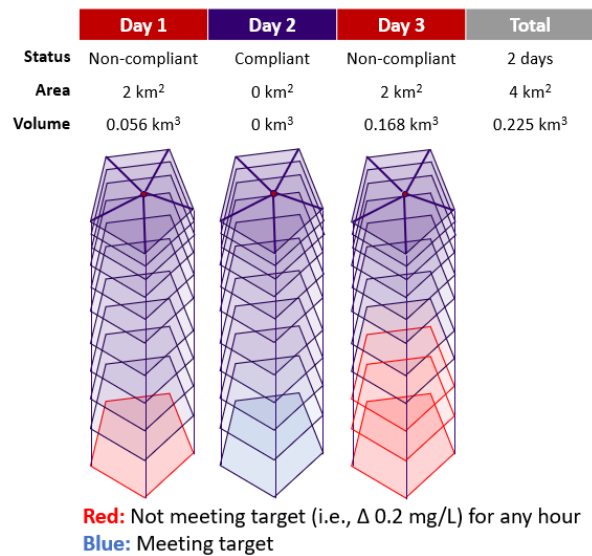


Figure 4: Schematic representation of the non-compliant days, area, and volume calculation.

Finally, the volume-day non-compliant calculation above was normalized to the 2014 current conditions, resulting in a “percent volume-days” value that can be compared to normalized loading.

## Results

Results are presented in three sections quantifying the predicted impacts on dissolved oxygen from changes to nutrient loadings in the Whidbey region. First, the impacts of nutrient loading scenarios are described by examining changes to days non-compliant following the methodology created by the State of Washington. Second, the impact of nutrient loading scenarios considering change by volume in days non-compliant are described. Third, the relationship between nitrogen loadings and dissolved oxygen levels across regions is explored.

### ***Number of Days Non-Compliant in Each Region***

The number of days non-compliant under 2014 current conditions range from 0 in the Straits of Juan de Fuca/Admiralty Inlet to 176 in the South Sound (Table 2 & Figure 5). As the Straits of Juan de Fuca/Admiralty Inlet has 0 days non-compliant for all scenarios, these results are not discussed further in this analysis.

Eliminating all wastewater nitrogen loads in the Whidbey region (Wtp1) results in a 35-day decrease in non-compliant days in the Whidbey region from 175 days to 139 days (Figure 6). Based on other scenario results, this may be attributed to the modeled load reductions of the two largest plants (Wtp4 = 25-day decrease) and the added influence of the 5 medium plants



(Wtp3 = 16-day decrease). Eliminating loads from the smaller plants (Wtp2) only had a 1-day reduction in non-compliant days. As expected, reductions in non-compliant days are, to some extent, proportional to the total load reductions applied for each scenario (Table 1).

Several scenarios examined the sensitivity to changes in river nitrogen loading. Reducing 50% of the estimated human contribution to river loading (Wr2) reduced the non-compliant days in the Whidbey region by 21 days from 174 to 153. Similarly, in this scenario days non-compliant were reduced for Hood Canal by 13 days, Main Basin by 9 days, and the Straits of Georgia/Northern Bay by 3 days. The days non-compliant in South Sound remained the same. Increasing loads to two times that of current 2014 current conditions (Wr3) resulted in a 35-day increase from 174 to 209 in non-compliant days in the Whidbey region, and a 61-day increase in Hood Canal from 146 to 207.

The three biggest contributors to river input of nutrient loading in this region are the Snohomish River (43%), followed by the Skagit (38%) in the north (and closer to the waters of the Straits of Georgia/Northern Bays), and Stillaguamish (18%) rivers (Table 1 & Figure 2). The natural sources of nitrogen, or “reference” loading for the Skagit is estimated to be very high, calculated at 94% of the Skagit’s total 2014 conditions. In comparison, the Snohomish and Stillaguamish rivers have natural sources of nitrogen that are also considerable (53% and 55% respectively), although this represents a much larger increase above estimated natural or pre-industrial levels for these two rivers (89% and 82% increase respectively). Although river loadings are roughly equal to WWTPs throughout Puget Sound, they are approximately 6 times the equivalent loading within the Whidbey region (Table 1).

*Table 2. Number of predicted non-compliant days for each scenario by region in 2014.*

	<b>2014 Cond.</b>	<b>Wtp1 No WWTP</b>	<b>Wtp2 No Small</b>	<b>Wtp3 No Med.</b>	<b>Wtp4 No N&amp;S</b>	<b>Wtp5 No North</b>	<b>Wtp6 No South</b>	<b>Wtp7 Move N&gt;S</b>	<b>Wtp8 Move Seasonal N&gt;S</b>	<b>Wr1 No Rivers</b>	<b>Wr2 0.5x Rivers (anthro- pogenic)</b>	<b>Wr3 2x Rivers</b>
<b>Hood</b>	146	130	145	137	134	135	142	138	145	41	133	207
<b>Main</b>	162	147	162	158	153	156	160	160	162	38	153	185
<b>SJF/Admiralty</b>	0	0	0	0	0	0	0	0	0	0	0	0
<b>SOG/Northern Bays</b>	39	36	39	37	37	37	37	37	39	0	36	45
<b>South Sound</b>	176	175	176	176	176	176	176	176	176	103	176	183
<b>Whidbey</b>	174	139	173	158	149	161	161	165	173	0	153	209
<b>ALL REGIONS</b>	229	215	228	223	221	223	224	223	229	115	222	270

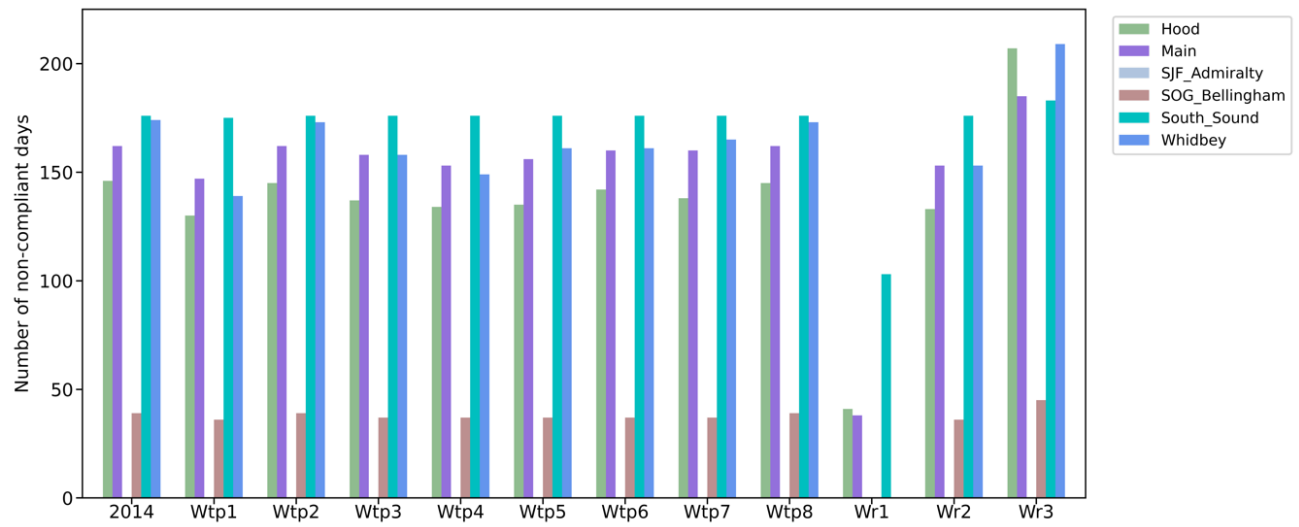


Figure 5: Number of predicted non-compliant days for each region shown in Table 2, grouped by scenario.

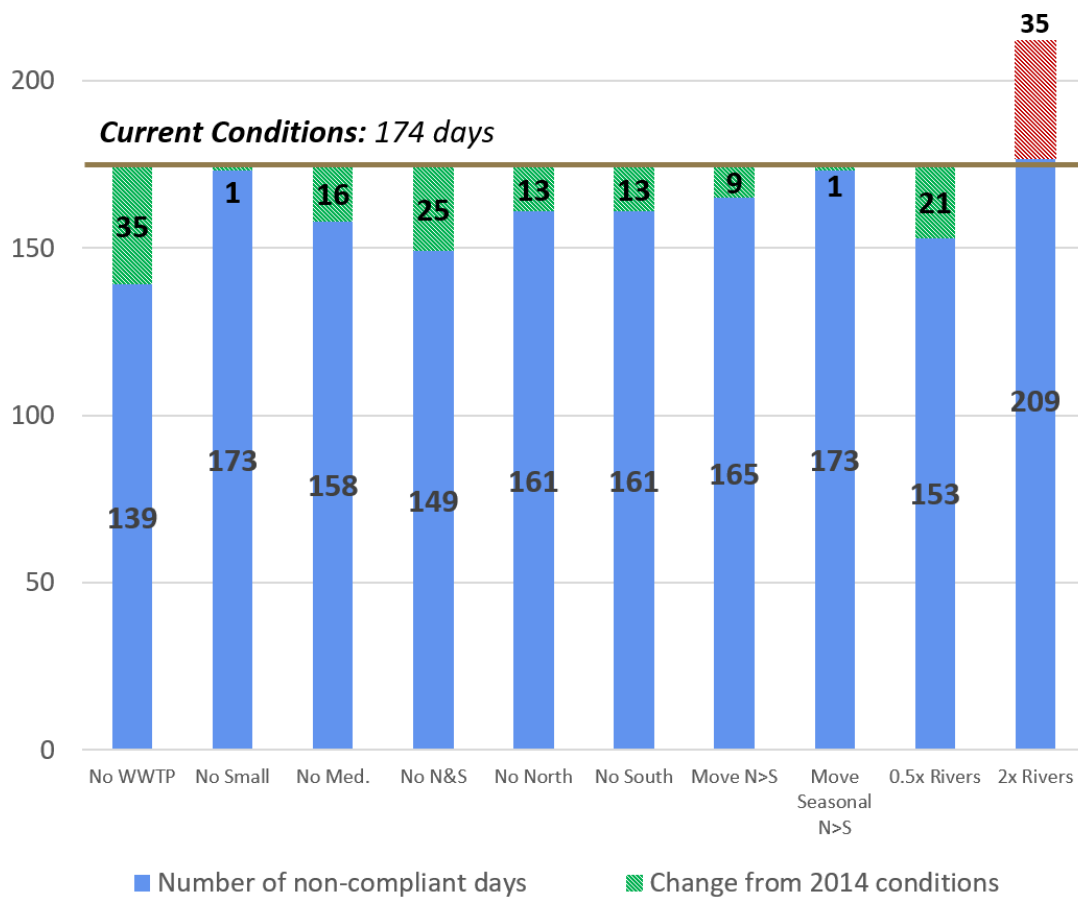


Figure 6. Summary of changes in non-compliant days from 2014 current conditions, for each scenario. Green highlights the number of non-compliant days that are reduced in the given scenario while red highlights the number of additional non-compliant days.

**Percent Volume Non-Compliant Within Each Region**

Model results for each of the scenarios were analyzed to calculate the fraction of the water in each region that is non-compliant during each day of the year. This provides an index of how much of the available water in each region is depleted in dissolved oxygen when applying the State of Washington non-compliance methodology. The total annualized result for each region is summarized in Table 3, tabulated for each scenario investigated in this report. Results for each day of the year for the Whidbey region are shown in Figure 7.

*Table 3. Percent volume-days non-compliant in each region\**

	<b>2014 Cond.</b>	<b>Wtp1 No WWTPs</b>	<b>Wtp2 No Small</b>	<b>Wtp3 No Medium</b>	<b>Wtp4 No N&amp;S</b>	<b>Wtp5 No North</b>	<b>Wtp6 No South</b>	<b>Wtp7 Move N&gt;S</b>	<b>Wtp8 Move Seasonal N&gt;S</b>	<b>Wr1 No Rivers</b>	<b>Wr2 0.5x Rivers (anthro- pogenic)</b>	<b>Wr3 2x Rivers</b>
<b>Hood</b>	0.052	0.039	0.052	0.047	0.044	0.046	0.049	0.047	0.051	0.007	0.042	0.247
<b>Main</b>	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.000	0.006	0.012
<b>SJF/Admiralty</b>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<b>SOG/Northern Bays</b>	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.001
<b>South Sound</b>	1.146	1.018	1.144	1.100	1.064	1.089	1.122	1.112	1.141	0.050	1.055	1.789
<b>Whidbey</b>	0.501	0.184	0.490	0.346	0.293	0.371	0.400	0.448	0.498	0.000	0.299	5.052
<b>All Regions</b>	0.051	0.034	0.050	0.043	0.040	0.044	0.046	0.048	0.051	0.001	0.040	0.262

For the 2014 current conditions (solid line in each panel in Figure 7), up to maximum of approximately 3% of the waters of the Whidbey region were estimated to be non-compliant, peaking in August and September, with sustained levels above 1% for four months over summer and autumn. Results outside of this period indicate that these waters are likely in compliance with respect to dissolved oxygen; with values close to zero for the majority of the first six months and last month of the year. Modeled removal of nitrogen loadings from all wastewater treatment plants in the region (dashed line in the first panel) reduced the maximum non-compliant volume in Whidbey from approximately 3% to just over 1%.

Temporal trends in the modeled 2014 current conditions were largely preserved throughout all scenarios. However, scenarios estimating the removal of all loadings from both of the largest two plants at the same time, or all WWTPs, shortened the extent of sustained non-compliance in late autumn to end in early October, and almost completely eliminated the last spike in non-compliance later in the year (Figure 7). The influence of removing the five medium plant loadings was similar but slightly greater than the removal of either Everett North or South outfall loadings and less than the removal of both of these plants combined (Figure 7). This similarity is to be expected as the loading for all medium plants combined is more than each of the two larger outfall loadings individually and less than the loading of the two larger outfalls combined (Table 1). This similarity is also reflected in the total percent volume reduction for the Whidbey region calculated for each of these three scenarios (Table 3). The influence of smaller plants was minimal on both the magnitude and timing of non-compliant volume, with model results virtually identical to the 2014 current conditions (Figure 7).

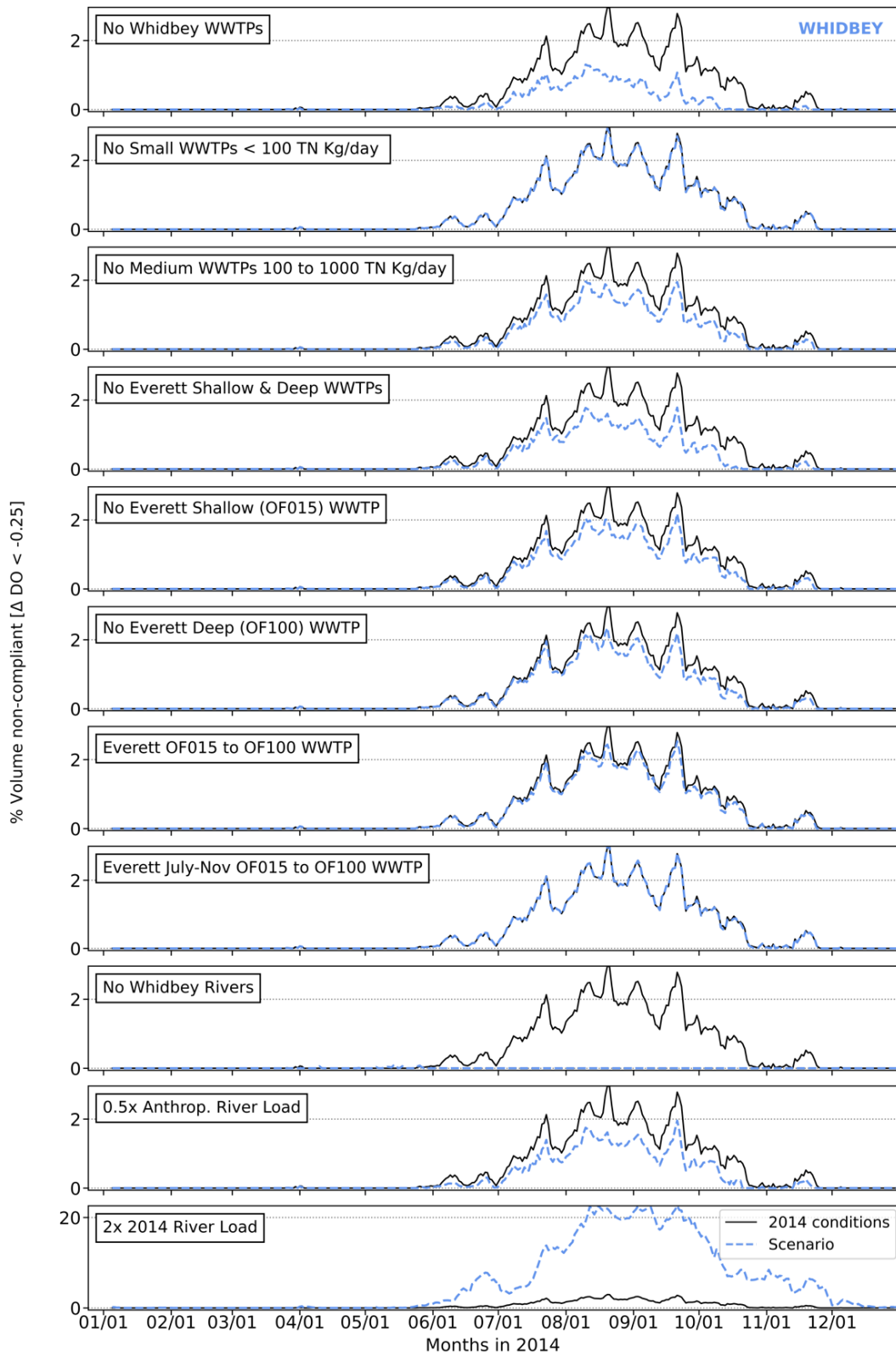


Figure 7. Percent volume non-compliant for nodes in the Whidbey region as a result of changes in nutrient loading to the Whidbey region (See Appendix 1 for results for other regions and details on methodology).

The waters in and around Penn Cove and Port Susan are the two areas of the Whidbey region with sustained periods of calculated hypoxia ( $< 2\text{mg/L}$ ) and days non-compliance. Results from September 22, 2014, are exemplary of the period where hypoxia is most widespread in 2014; present within at least one layer of the water column at each cell shown in red, and extending beyond the modeled “natural” hypoxic area calculated in the same way from the reference condition scenario (Figure 8). The maximum extent of the area of non-compliance for Penn Cove and Port Susan is around August 19 and 15 respectively (see Appendix 1 for further detail).

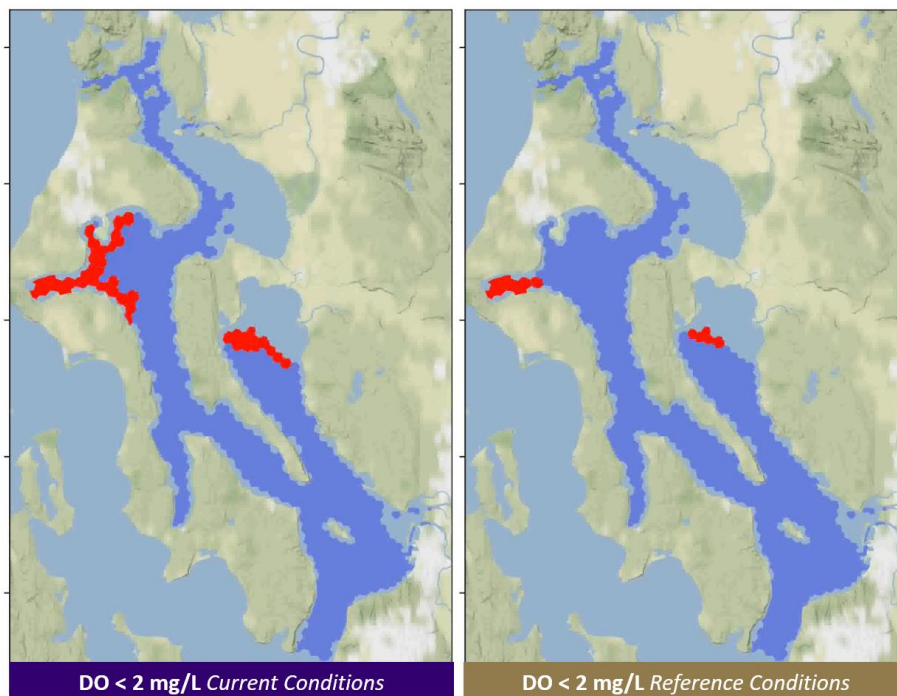


Figure 8. Maximum extent of hypoxia ( $< 2\text{mg/L}$ ) between current and reference conditions. Results from September 22, 2014 are shown which is an example from the period where hypoxia is most widespread. Modeled cell areas shown in red have at least one of the 10 underlying water-layers below exhibiting hypoxic conditions for at least one hour of the day presented.

### ***Relationship between Nitrogen Loadings and Dissolved Oxygen Levels Across Regions***

The modeled scenarios allow an initial assessment of the impact on dissolved oxygen across regions of Puget Sound from changes in nutrient loadings of wastewater treatment plants and rivers in the Whidbey region. Regional responses show differences based on the source type and location, total loading, and the metrics used to quantify impacts.

Hood Canal and Main Basin, followed by the Strait of Georgia/Northern Bays, have the greatest change in modeled days non-compliant across most wastewater treatment plant and river scenarios (Table 2 and Figure 5). In comparison, South Sound has the largest number of non-

compliant days under 2014 current conditions for all of Puget Sound (176), but the smallest reduction (1 day) with the removal of all local discharge loading in the Whidbey region. Conversely, South Sound showed a greater response across scenarios changing both treatment plants and river loadings, when considered through the lens of volume days non-compliant (Table 3 and Figure 9). Combined, these results highlight the potential impact of: (a) model architecture and scale on the representation of varying geometry between regions or sub-regions, and (b) the “roll-up” of calculated metrics of change, such as days non-compliant or volume days non-compliant.

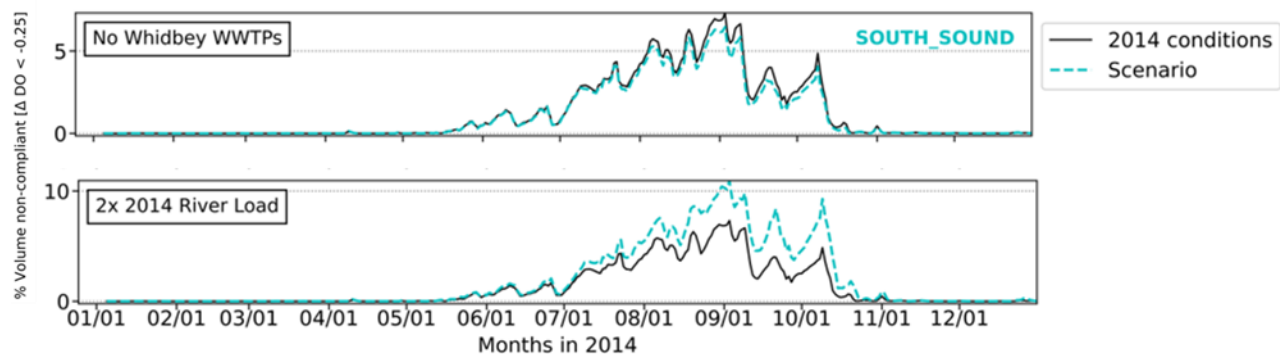


Figure 9. Percent volume non-compliant for cells in the South Sound region as a result of changes in nutrient loading to the Whidbey region (See Appendix 1 for details on methodology and plots for all scenarios across different basins).

The number of non-compliant days calculated across the southern regions of Puget Sound (Table 2 and Figure 5) decrease more when modeled loading is eliminated from the Everett Northern (OF015) outfall (Wtp5) rather than the Everett Southern (OF100) outfall (Wtp6); even though the total load for the southern outfall is slightly larger and is located closer to the southern regions (Table 1). These results suggest that the placement of the two outfalls may potentially influence loading impact. The northern outfall is relatively shallow and discharges directly into the Snohomish river, which may influence the “downstream” impacts of nutrient loading in the river plume on non-compliance in other regions. Conversely, Everett’s southern outfall is deeper, discharging off-shore at a depth of approximately 100m where nutrient loadings may be more directly entrained into currents exchanging with the open ocean. Moving just part of the load during the drier season appears to cause a smaller reduction in the number of days noncompliant (Wtp6).

Figure 10 shows the relationship in the Whidbey region between the total annual nitrogen loading (kg/year) and resulting change in annual average volume of non-compliant water for each scenario in this analysis. Not surprisingly, for both the treatment plant (left panel) and river (right panel) scenarios, the greatest reductions in normalized volume days non-compliant are the result of the greatest amount of nitrogen loading reduction. The change in response of volume days also differs between treatment plants and rivers, when comparing each scenario in sequence from the smallest to largest loading. Notable outliers amongst the treatment plant

cases (left panel) include the Wtp7 scenario, in which nitrogen loading is moved from Everett's northern (and shallower) outfall, to Everett's southern (and deeper) outfall. The volume days non-compliant is reduced by 10% in this scenario despite no change to Whidbey nitrogen loading (Table 3). Similarly, Wtp5 (No Everett North) exhibits a lower number of non-compliant volume days compared to Wtp6 (No Everett South), despite similar loadings (Figure 10). These results suggest that reducing loading from the northern plant discharging into the Snohomish river may have a bigger impact on resulting volume non-compliant than reductions at the southern and deeper outfall.

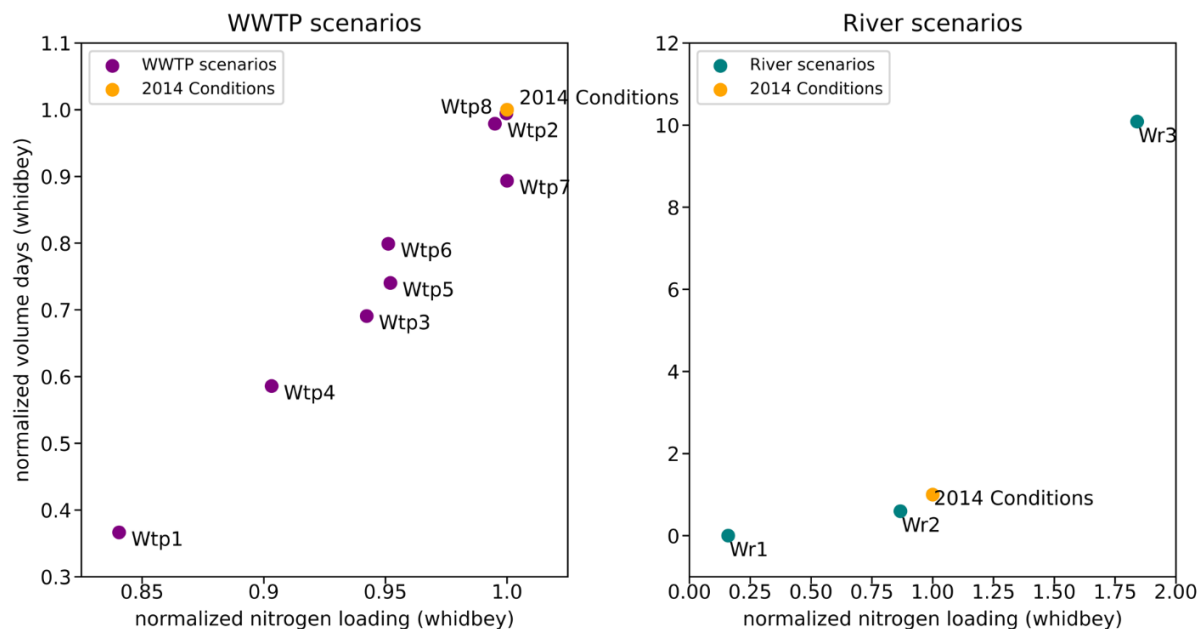


Figure 10. Volume days noncompliant as a function of nitrogen loading for scenarios changing wastewater treatment plants (left panel) and river (right panel) loadings in the Whidbey region, normalized to 2014 current conditions. Nitrogen loading data and resulting volume days noncompliant are sourced from Table 1 and Table 3 respectively for the Whidbey region.

Changes to loadings of rivers in the region appear to show a different response in volume days non-compliant compared to WWTPs (Figure 10). Although the model results presented here show a sensitivity to river loadings and potential influence of river hydrodynamics on WWTPs (e.g. moving modeled WWTP loads from the Snohomish river to deeper waters - Wtp7), additional runs are needed to assess the impact between different river sources, as well as possible impacts from the timing of loadings and discharges into, and from, these rivers.



## Summary

The sensitivity of dissolved oxygen levels throughout Puget Sound was assessed with changes in nitrogen loadings from wastewater outfalls and rivers in the Whidbey region. The Salish Sea Model was used to run various scenarios representing change in nitrogen loading sources, which were compared to the scenarios for 2014 current conditions and reference (naturally occurring, pre-industrial estimates of nitrogen) conditions, as established by the State of Washington. Model results were interpreted for non-compliance against Washington's dissolved oxygen standard both in terms of a) the number of non-compliant days following the State's methodology and b) the percentage of the region's water volume that was predicted to be non-compliant throughout the year. Results are specific to the scenarios completed and only strictly apply to the manipulation of source loadings in the Whidbey region. Further work is required to conduct similar analyses throughout other regions of interest.

### Results\* from the 2014 current conditions scenario suggest:

1. The waters of the Whidbey region exhibit modeled dissolved oxygen levels that trigger continuously sustained levels of non-compliance for 4 months of the year, peaking in August and September. During these times, a maximum of approximately 3% of the water in Whidbey (by volume) is estimated to be non-compliant, compared to approximately 0.06% predicted in the Main Basin and 7% in the South Sound regions. Throughout the year, the modeled total days of non-compliance for the Whidbey region is 174 days\*.
2. Within the Whidbey region, the waters in and around Penn Cove and Port Susan have the greatest sustained periods of calculated hypoxia (<2 mg/L), reaching their maximum extent by area around 22 September. The maximum extent of days non-compliance in each of these embayments is around August 19 and 15 respectively.
3. Nitrogen loading to the Whidbey region is dominated by rivers to a greater extent than other regions, and the estimated naturally occurring loading of these rivers is high. The estimated total annual nitrogen loads is 6.4 million kg/year for the four rivers entering Whidbey region, of which 4.4 million kg/year are from human contributions and 2.0 million are naturally occurring. Of these rivers, the Skagit has the highest proportion of nitrogen load that is naturally occurring (94% of the Skagit's total load). In comparison to river loading, the load from the 16 wastewater outfalls total 1.2 million kg/year (approximately 1/6<sup>th</sup> of river loading) to the region, while Sound-wide these two loading sources are roughly equal.



**Results\* from the wastewater treatment plant and river nitrogen reduction scenarios suggest:**

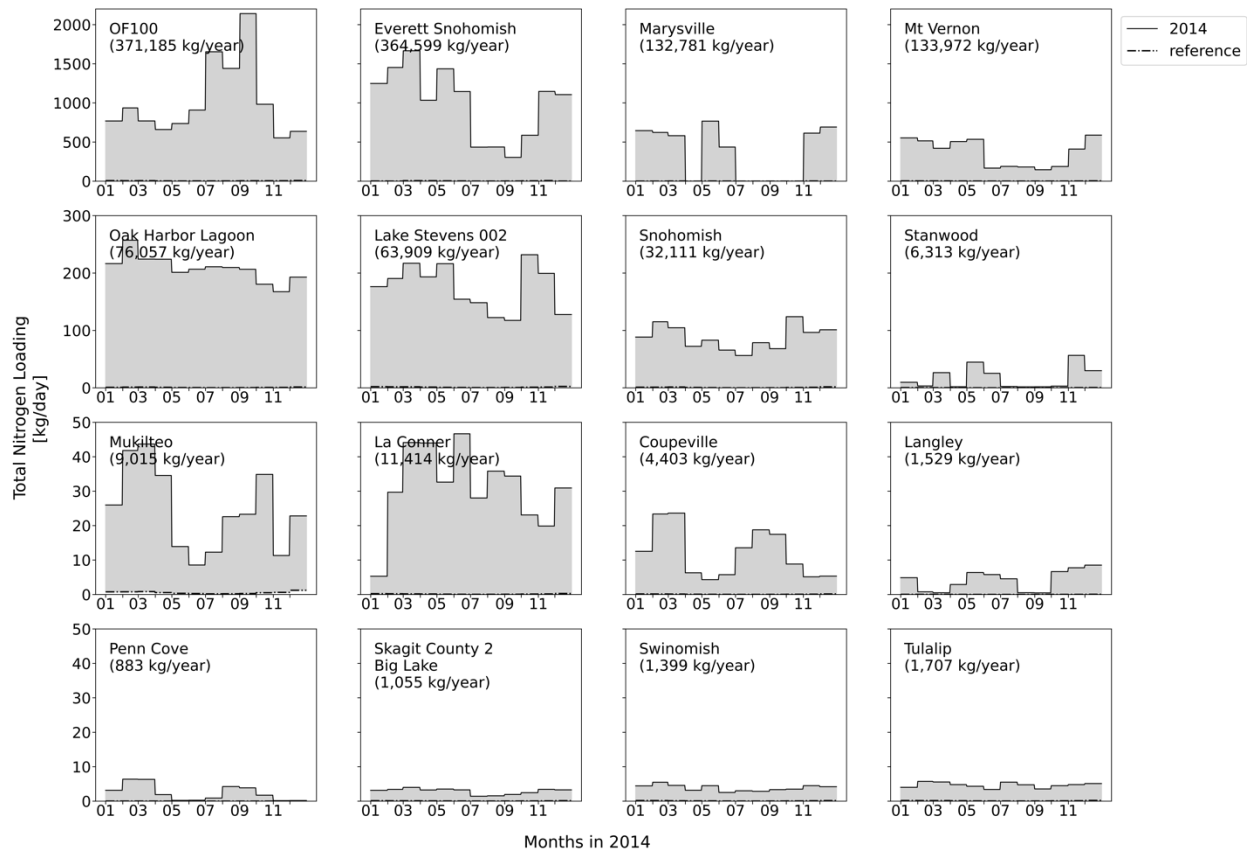
4. In the Whidbey region, eliminating the nitrogen loads from all 16 modeled wastewater treatment plants reduced non-compliance from 174 to 139 days and changed the corresponding magnitude and persistence of non-compliance throughout the year. The calculated maximum non-compliant volume for the waters of the region was reduced from approximately 3% to just over 1%. The period of sustained non-compliance was also shortened to end in early rather than late October, with the smaller spike of non-compliance in November reduced.
5. Reducing modeled nitrogen loading at treatment plant outfalls generally reduced the calculated non-compliance, proportional to the total load reduction applied across the Whidbey region. Within the Whidbey region, eliminating modeled nitrogen loading from:
  - the 10 smaller wastewater dischargers reduced the estimated days of non-compliance by only 1 day
  - the 5 medium discharges reduced non-compliance from 174 to 158 days
  - the two outfalls (combined) for the largest permitted wastewater discharger, reduced non-compliance to 149 days. When considered individually, each reduced non-compliance to 161 days.

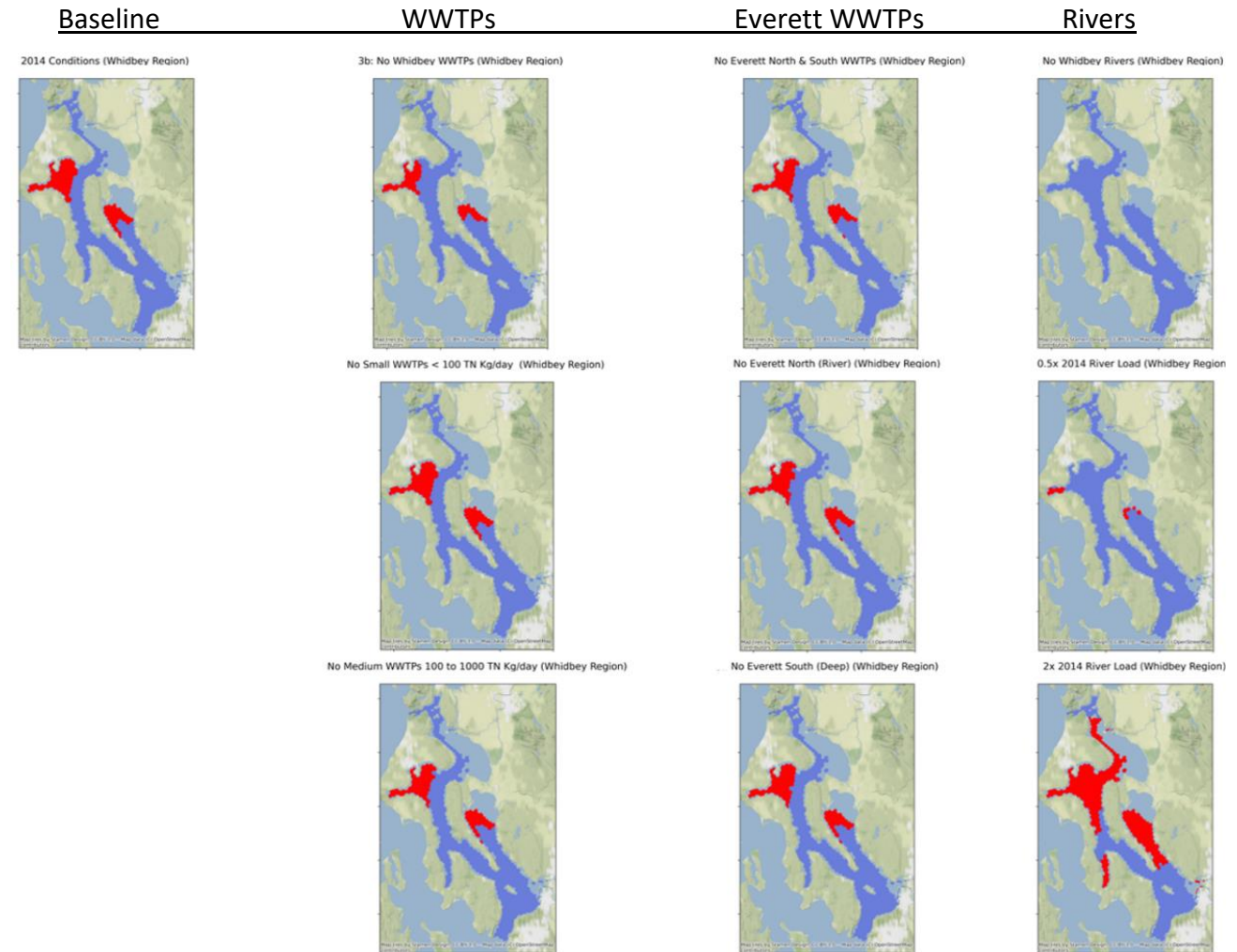
*\* The number of non-compliant days was calculated from model results following the State's methodology (Figure 4 and accompanying text). This method counts a day of non-compliance for a cell if the modeled minimum dissolved oxygen in at least one layer of the water column meets the criteria. If one or more cells are non-compliant, then that counts towards a day of non-compliance in regional calculations such as the Whidbey region.*

## Appendix 1

- 1.1 Wastewater Treatment Plant Dissolved Inorganic Nitrogen Loading (Kg/Day) for the 2014 Current Conditions Scenario Throughout the Year
- 1.2 Maximum Non-Compliant extent – shown on August 19, 2014
- 1.3 Time Series of Non-Compliance by Volume for Regions of Puget Sound
- 1.4 Review of Outfall Representation in the 2014 Current Conditions Scenario of the Salish Sea Model
- 1.5 Code Documentation, References and Further Reading

### Appendix 1.1: Wastewater Treatment Plant Dissolved Inorganic Nitrogen Loading (Kg/Day) for the 2014 Current Conditions Scenario Throughout the Year



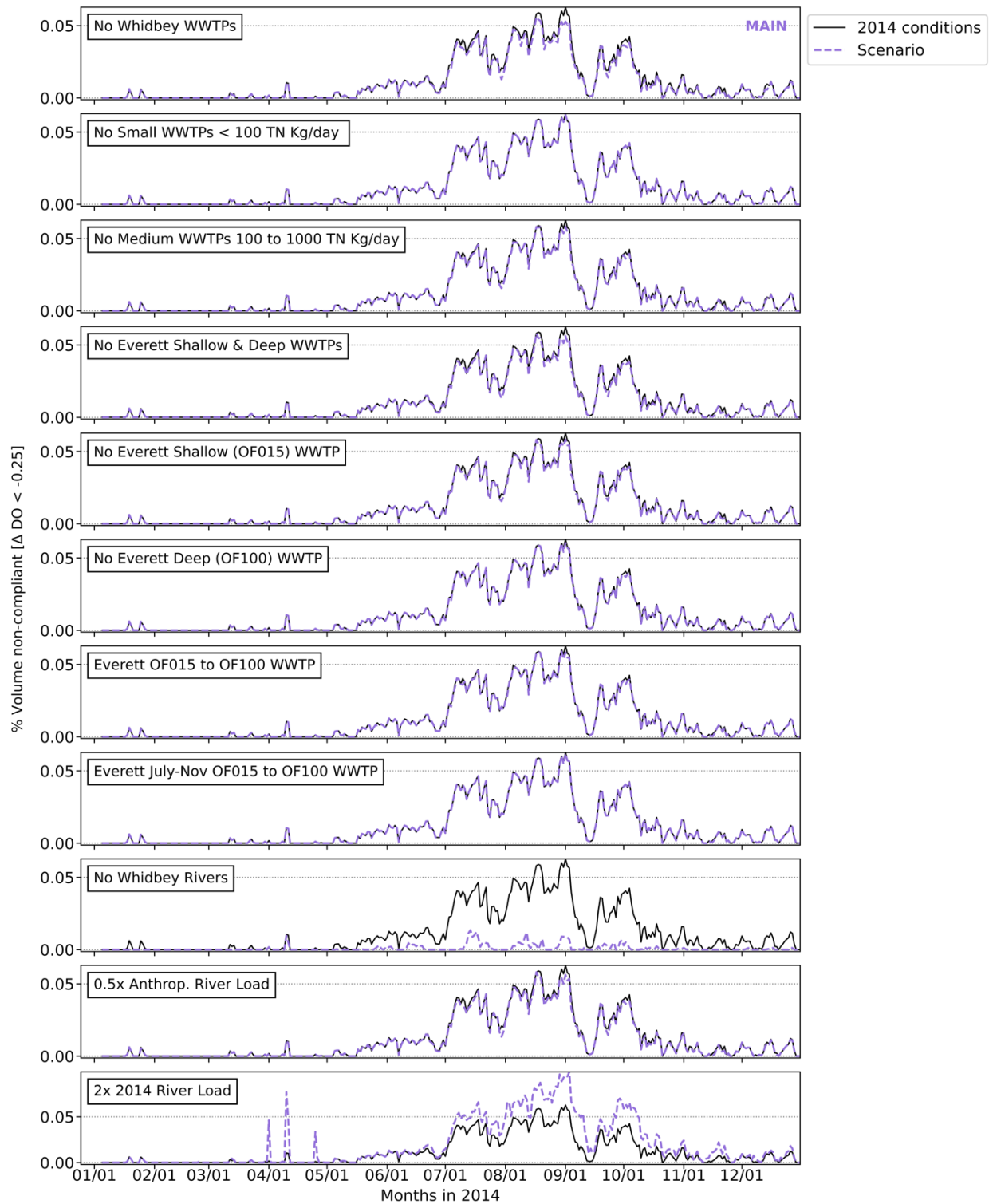
**Appendix 1.2: Maximum Non-Compliant extent – shown on August 19, 2014**

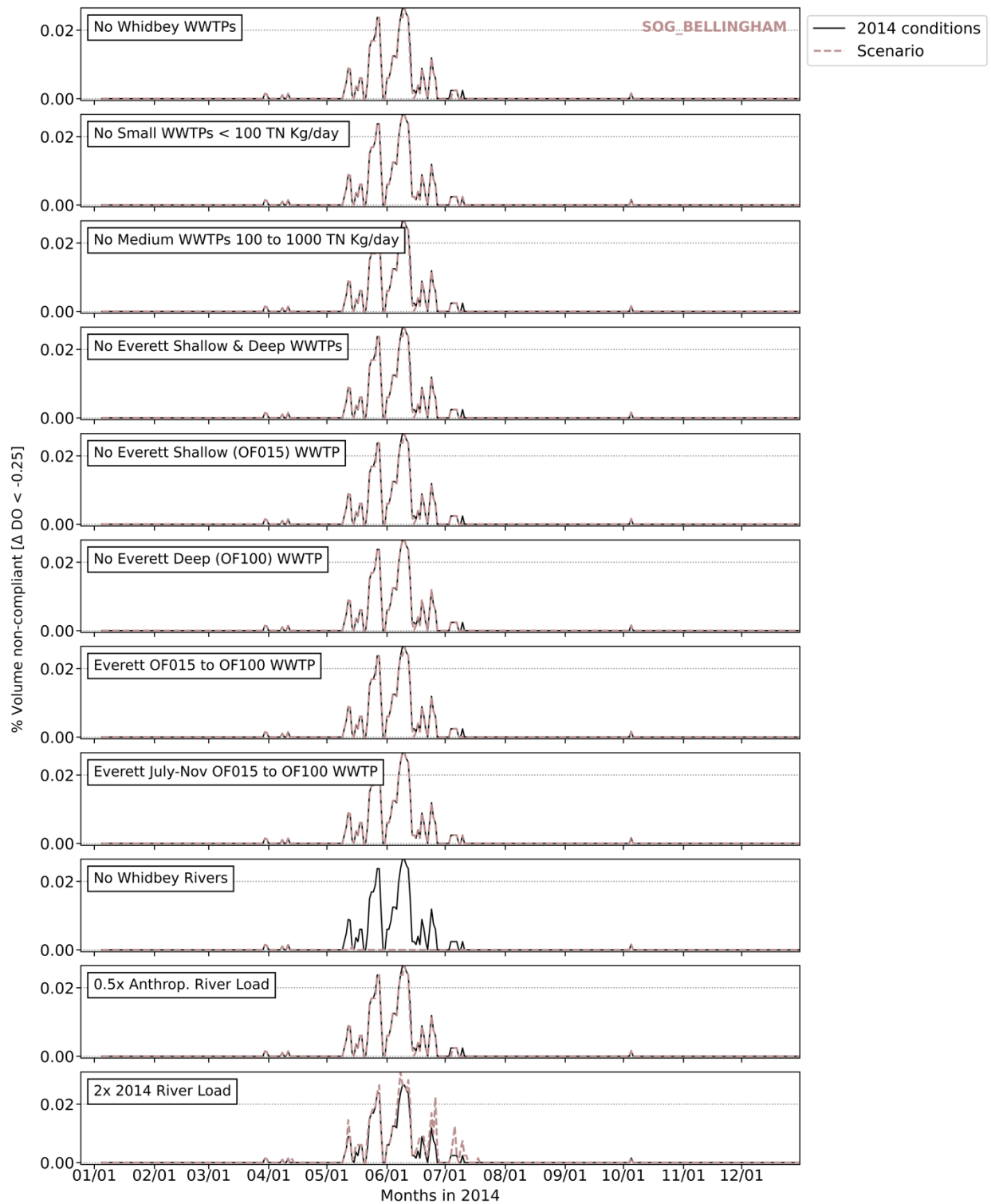
Model results from August 19, 2014, are exemplary of the estimated extent of maximum, region-wide, non-compliance for the Whidbey Region. However, the days of maximum non-compliance may vary for areas within this region. Take, for example, these two map results below showing non-compliant cells for August 15, 2014 and August 19, 2014. Non-compliance here covers a greater area around Port Susan on August 15, 2014, while showing a greater area around Penn Cove/Oak harbor on August 19, 2014. Node (cell) areas shown in red that are estimated to be non-compliant have at least 1 of the 10 layers below the node exhibiting non-compliance for at least one hour for the day shown, following the State's methodology described in section 1.5 of this appendix.

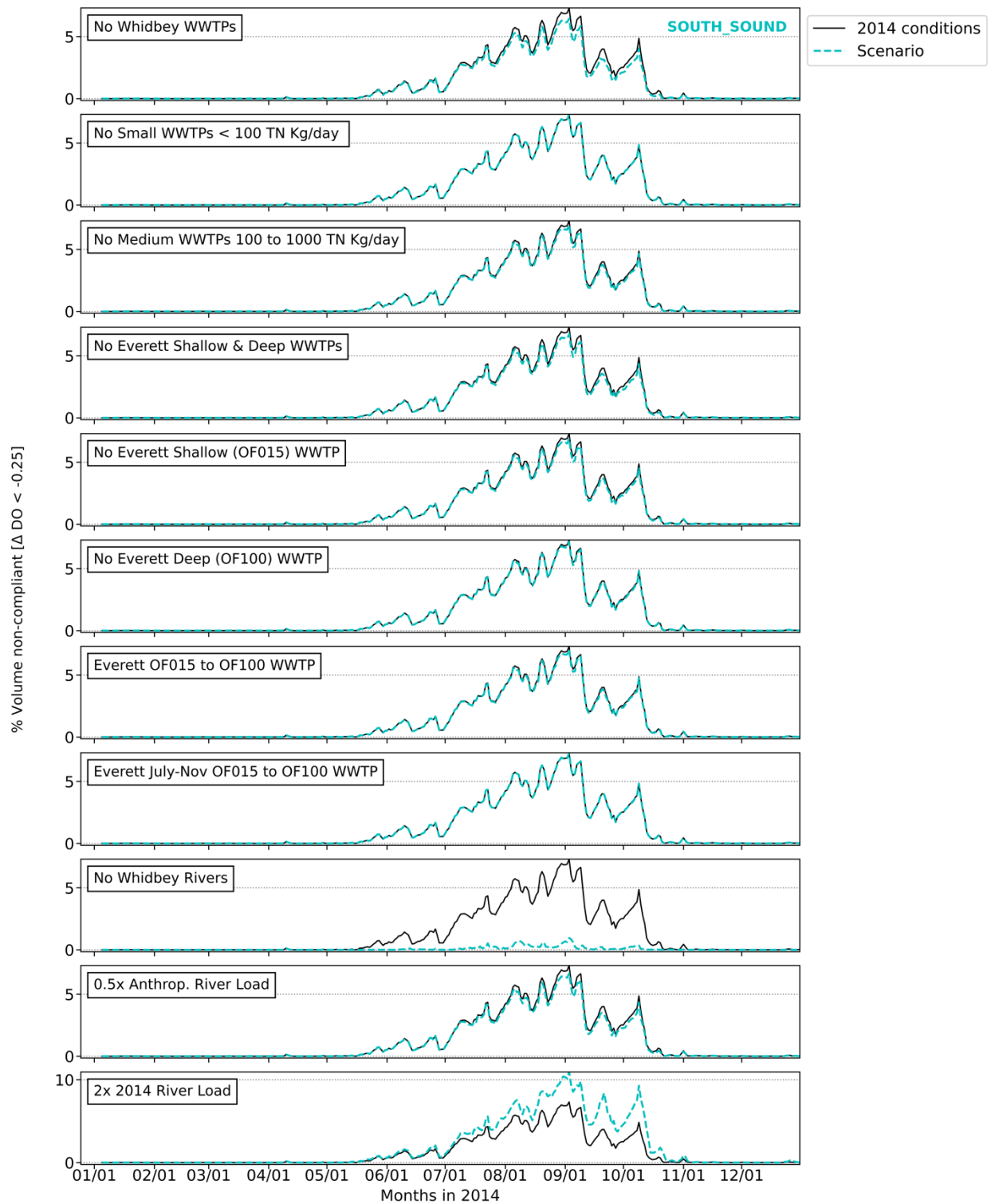
August 15, 2014

August 19, 2014



**Appendix 1.3 Time Series of Non-Compliance by Volume for Regions of Puget Sound**





#### Appendix 1.4: Review of Outfall Representation in the 2014 Current Conditions Scenario of the Salish Sea Model

Outfall and information in the model	Outfall information provided by utility	Review
<b>Everett Snohomish (Everett North - OF015)</b> Lat:48.0047471 Long: -122.1769 Node (& depth): 12179 (5.92m) Layer: 10 (bottom)	Lat: 48.004167 Long:-122.177222     OF015 was off-line (zero load) for 8/23 -9/15, 2014	Utility provided coordinates of outfall fall within the same cell (Node_id/tce=12179) as coordinates extracted from model input files  Flow entering Layer 10 of a modeled water column depth totaling 5.92m  OF015 discharge was modeled as online for the entire year (see figures in Appendix 1.1)
<b>OF100 (Everett South)</b> Lat:47.9683426 Long: -122.24931 Node (& depth): 9143 (76.07m) Layer: 10 (bottom)	Lat:47.969444 Long: -122.246667  Diffuser depth 103.6m to 106.1m below MLWL for a length of 424.37m	Utility provided coordinates of outfall fall within the same cell (Node Id/tce=9143) as coordinates extracted from model input files  Flow entering Layer 10 of a modeled total water column = 76.07m
<b>Marysville</b>	Everett South (OF100) receives Marysville effluent during the low flow season from 7/1 – 10/31.	Marysville discharge was modeled with zero load during this low flow season period (see figures in Appendix 1.1)
<b>All other outfalls in Whidbey</b>		All other outfalls in the region have the same location from model input files as provided in the Department of Ecology GIS files <sup>2</sup>

#### Appendix 1.5: Code Documentation, References and Further Reading - Including Code and Sources for Non-Compliant and Other Calculations, as well as Model Run Inputs.

The non-compliance values reported were calculated using “Part B” non-compliance as determined by the Washington State Department of Ecology<sup>3</sup>. In the Washington State Department of Ecology Optimization Report [Appendix F](#) (page 48), Part B noncompliance is calculated where:

1. Min DO for the reference case < DO standard + human allowance
2. Min DO (scenario) – Min DO (reference) < human allowance

A human allowance of -0.2 mg/L was used for all non-compliance estimates presented in this report. In addition, our calculations follow the department of Ecology’s “rounding method,” which effectively adds -0.05 mg/L to the human allowance for the second part of the assessment, with the result of flagging non-compliance where Min DO (existing or scenario) – Min DO (reference) < -0.25 mg/L.

The method used in this report to calculate non-compliance provided similar results to that of the States, presented in the Bounding Scenarios Update (Ahmed et al, 2021), and shown below in Table 1.5a. Furthermore, scenarios presented here used the same initialization files for

<sup>2</sup> <https://fortress.wa.gov/ecy/ezshare/EAP/SalishSea/SalishSeaModelBoundingScenarios.html#output>

<sup>3</sup> The Environmental Protection Agency disallowed Part B, the natural conditions allowance. Ecology plans to propose updated rule language for comment in early 2024.



reference and current condition runs for the year 2014 [11]. Total non-compliant area over all regions was 2.1% different, while maximum number of non-compliant days was 3.1% different, likely attributed to the simplified methodology applied here only to Part B of the standard. At the time of writing, the scripts used by Ecology were not available for direct review of the code, however the methodology are described in Appendix F of the Bounding Scenarios Update report [12].

The Ecology input files used in this analysis are from January 1, 2014 – to January 1, 2015. Therefore, our calculated loading inputs at WWTPs and rivers use a total of 366 days. The first 5 days of result outputs are considered as “spin-up time”, as implemented by the Salish Sea Modeling Center and applied by the Department of Ecology. Accordingly, calculations of model results in this analysis are based on 361 days of output data.

*Table 1.5a. A comparison of “Area non-compliant” and “Max days non-compliant” between those presented by the Department of Ecology Optimization Scenario Report (DOE values) and those calculated according to the method described here.*

	DOE values	PSI methodology	Relative Difference
<b>Area</b>	341	348	2.1%
<b>Max Days</b>	163	158	3.1%

### Overview of computing process

The following code was used in the analysis presented in this report. Please contact [mazzilli@uw.edu](mailto:mazzilli@uw.edu) or [rdmseas@uw.edu](mailto:rdmseas@uw.edu) regarding access and collaboration on further development:

1. Configuration file used to collate information for this set of runs [1].
2. Shapefile used in this report to define regions, region names, cell area, etc.[2], developed with inputs and analysis from Su Kyong ([sukyong.yun@pnnl.gov](mailto:sukyong.yun@pnnl.gov)) and Kevin Bogue ([kbogue13@uw.edu](mailto:kbogue13@uw.edu))
3. Notebook to create maps of the regions described in this report [3]
4. Notebook used for QAQC of non-compliance calculation by comparing PSI non-compliance values of area non-compliant and max number of days non-compliant with Department of Ecology values [4].
5. Python script used to create of spreadsheets that provide the following information for each scenario (and within each region defined by the shapefile listed above): Non-compliant days, area non-compliant, volume days non-compliant, percent volume days non-compliant [5]. Spreadsheet outputs are tabled in main report and available on request (e.g. whidbey\_wc\_noncompliant\_m0p25.xlsx)
6. Python script used to create the spreadsheet with percent non-compliant values for every scenario with columns representing regions and rows for every days in 2014 (starting with day 6 to avoid “spin-up” days) [6].
7. Python script used to create the multi-panel time-series graphic showing non-compliance for each day in 2014, for all regions with a sub-plot for each scenario [7].
8. Python script used to create graphics showing non-compliant cells (which were combined using “ffmpeg” to create a movie) [8].



9. Jupyter Notebook used to create graphics of nutrient loading shown in this report [9].
10. Jupyter Notebook used to create the graphics of normalized nitrogen loading to percent volume days [10].

## References

- [1] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/etc/SSM\\_config\\_whidbey.ipynb](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/etc/SSM_config_whidbey.ipynb)
- [2] File available on request from PSI
- [3] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot\\_region\\_maps.ipynb](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot_region_maps.ipynb)
- [4] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/QAQC/QAQC\\_days\\_noncompliant.ipynb](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/QAQC/QAQC_days_noncompliant.ipynb)
- [5] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/py\\_scripts/calc\\_noncompliance.py](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/py_scripts/calc_noncompliance.py)
- [6] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/py\\_scripts/calc\\_noncompliance\\_timeseries.py](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/py_scripts/calc_noncompliance_timeseries.py)
- [7] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot\\_noncompliance\\_timeseries.ipynb](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot_noncompliance_timeseries.ipynb)
- [8] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/py\\_scripts/plot\\_noncompliant\\_graphics4movie.py](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/py_scripts/plot_noncompliant_graphics4movie.py)
- [9] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot\\_nutrient\\_loading\\_whidbey.ipynb](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot_nutrient_loading_whidbey.ipynb)
- [10] [https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot\\_whidbey\\_loading\\_vs\\_noncompliance.ipynb](https://github.com/UW-PSI/SalishSeaModel-analysis/blob/main/notebooks/reports/plot_whidbey_loading_vs_noncompliance.ipynb)
- [11] Department of Ecology website providing initialization files for current and reference condition scenario runs for 2014:  
<https://fortress.wa.gov/ecy/ezshare/EAP/SalishSea/SalishSeaModelBoundingScenarios.html#OptimizationScenariosY1>
- [12] Appendix F of Department of Ecology's Optimization Scenario report describing the State's non-compliant methodology:  
[https://www.ezview.wa.gov/Portals/\\_1962/Documents/PSNSRP/Appendices%20A-G%20for%20Tech%20Memo.pdf](https://www.ezview.wa.gov/Portals/_1962/Documents/PSNSRP/Appendices%20A-G%20for%20Tech%20Memo.pdf)

## Contributors

The following people contributed to this report:

- Rachael Mueller ran simulations Wtp7,8 and Wr2, and wrote all code to produce results presented, unless otherwise noted
- Su Kyong Yun created the initialization files and ran all simulations used in this report except Wtp7, Wtp8, and Wr2.
- Kevin Bogue created the shapefile used by Rachael Mueller to create the post-processing framework and Stefano Mazzilli modified the shapefile.
- Ben Roberts provided code for post-processing the 1TB worth of raw SSM .out files for each scenario and also shared the code he uses for getting information from the input files, which Rachael Mueller used to upgrade her code for quantifying scenario nutrient loadings.