Appendix I.
Sediment Fluxes

This appendix summarizes independent observational and predicted Puget Sound sediment flux data sets and contains a comparative analysis of them. It describes drivers for sediment oxygen demand and nitrogen fluxes and contains graphics highlighting their temporal and spatial patterns. For definitions of terms, including statistical metrics, refer to the glossary in the main report.

ADA Accessibility

This appendix may contain tables, graphics, and images that may not meet accessibility standards. The Department of Ecology is committed to providing people with disabilities access to information and services by meeting or exceeding the requirements of the Americans with Disabilities Act (ADA), Sections 504 and 508 of the Rehabilitation Act, and Washington State Policy #188. To request an ADA accommodation, contact the Environmental Assessment Program Publications Coordinator at EAPPubs@ecy.wa.gov or call 564-669-3028. For Washington Relay Service or TTY call 711 or 877-833-6341. Visit Ecology's website for more information.[1]

[1]https://ecology.wa.gov/about-us/accessibility-equity/accessibility

Table of Contents

Organic Matter Deposited to the Sediments Drives Fluxes

Deposition of organic matter in the estuarine bed triggers multiple biogeochemical decompositional processes within the sedimentary layers. Deposited organic matter includes all forms of organic particulates, including phytoplankton and detritus. The processes that control sedimentary organic matter decomposition are complex and varied, including organic particulate deposition rate and composition, electron acceptor availability, and benthic community composition (Arndt et al. 2013). Belley et al. (2016), summarizing results from multiple studies, asserts that bottom water temperature, dissolved oxygen concentration, and particulate organic carbon flux to the bottom are the key drivers of benthic fluxes and organic matter remineralization. But Santana and Shull (2023) argued that water depth was more important than temperature in driving benthic fluxes and organic matter remineralization.

Sediment oxygen demand (SOD) refers to the flux of oxygen from the water column to the sediments that drives aerobic respiration in the organic matter remineralization process and oxidizes the reduced byproducts of anaerobic respiration. The rate of supply of organic matter to the sediments is a key driver for SOD as well as for nitrogen fluxes into and from the sediments.

The top layers of the sediment bed are highly porous and consist of mainly sediment pore water. Lavelle et al. (1985) measured porosities of around 85% in the top layers of cores extracted from Puget Sound. As particles become more closely packed, porosity decreases with depth. Eventually, particles become completely buried and no longer have interactions with the water column.

Resuspension and bioturbation influence the degree of mixing experienced in top layers. This effect is highly variable. Carpenter et al. (1985), using 210Pb cores, ascribed measured surface mixed layers of 2 – 22 cm in Puget Sound to bioturbation. Lavelle et al. (1986) reported that the bioturbated upper layers in Puget Sound ranged from about 5 to 40 cm.

Modeling sediment fluxes

Sediment flux modeling involves a representation of the chemical reactions that occur in the sediment pore water, or interstitial water, which fills the spaces between solid particles accumulated at the bottom of a water body (DiToro 2001). The Salish Sea Model (SSM) makes use of the sediment diagenesis model originally developed by DiToro (2001) and modified by Martin and Wool (2013). Pelletier et al. (2017) fully described the model theory and implementation of this sediment diagenesis module in SSM. In summary, the SSM sediment diagenesis module integrates the following:

1. Deposition of particulate organic carbon and nitrogen from the water column into the sediment. This includes all forms of particulate organic matter (POM) from phytoplankton and detritus.

2. Decomposition of particulate organic matter in the sediment, producing solutes in the sediment pore water.

3. The solutes resulting from these diagenetic reactions are transported between a thin aerobic layer at the surface of the sediment (H1) with a thickness that is dynamically calculated and a thicker anaerobic layer (H2) below the aerobic layer. Solutes can also be released in gaseous form.

4. Interactions with the overlying water occur. Dissolved oxygen from the overlying water is transferred into the sediment to supply the oxidation of solutes (dissolved organic carbon and ammonium) in the aerobic sediment layer. Mass transfer of dissolved forms of carbon and nitrogen between the sediment layers and the overlying water also occurs.

The anaerobic model layer, H2, is 10 cm thick and is an active layer driving the diagenetic reactions and the sediment fluxes (Di Toro 2001). The organic matter is represented as oxygen equivalents in three G classes, from labile to refractory attributes, as described in Appendix A.

Observed and predicted organic carbon in sediments

Carpenter et al. (1985) showed that the depth of the sediment mixed layer in Puget Sound can vary significantly via analysis of field replicate cores. Model layers with a dynamically shifting aerobic top layer and a fixed anaerobic layer can only aim to represent a generalized and broadly spatially averaged organic carbon deposition regime. As a result, due to the lack of stochasticity in the model and its constant thickness representation of the active mixed anaerobic layer, direct quantitative comparisons of discrete organic carbon observations in space and time within the sediment matrix are not feasible. However, a generalized and qualitative comparison using available organic carbon observations may be illustrative.

In most years since 1989, Ecology's sediment monitoring team measured the percent total organic carbon (TOC) in the upper 3 cm of the sediment column in the springtime, generally in April but as late as early June, at stations throughout the WA waters of the Salish Sea (Weakland et al. 2018). These data are downloadable from Ecology's Environmental

Information Management database, and a summary is shown in Table I-1. Station locations are shown in Figures I-1 and I-2. The locations shown in Figures I-1 and I-2 are a subset of the 50 long-term Ecology sediment stations referred to in Weakland et al. (2018) but correspond with locations where sediment flux observations are also available.

While not directly comparable to predicted concentrations of organic matter in H2, observations of dry gross (not differentiated by grain size) sediment TOC serve as a point of reference for the organic matter available in surface sediments. For instance, the mean 2014 predicted percent total carbon in the H2 layer in springtime, computed for stations where we also have SOD measurements, is 0.91%, whereas the mean percent total organic carbon measured at those stations over the years, as outlined above, is 1.54%.

Within the context of the sediment diagenesis model, sediment organic carbon composition is almost entirely due to the slow refractory organic matter (G3). The partly refractory fraction, with a half-life of about a year, G2, dominates the sediment flux reactions, whereas G1, the readily reactive and labile fraction with a half-life of about 20 days, decays most rapidly (Di Toro 2001).

Predicted labile particulate organic carbon (POC) concentrations in the sediments vary widely temporally. Figure I-3 shows the predicted temporal variation of labile (G1) POC in the anaerobic sediment model layer H2 at locations throughout the model domain where Rigby (2019), later published by Santana and Shull (2023), and Merritt (2017) measured sediment fluxes.

Predictions of labile organic carbon concentrations at a few locations, including Budd Inlet (blue line [6]) and Sinclair Inlet 2 (maroon line [25] in Figure I-3), peak in early July. These two stations also have the largest peak magnitude of predicted labile organics in the sediments (around 840 and 770 grams of carbon equivalents as O_2/m^3). The bulk of the stations show predicted peak organics in late summer, though there are stations that lag the rest with peak organics, though relatively lower in magnitude, in the fall (e.g., Hoodsport and Commencement Bay). Observations of TOC in surface sediments (Table I-1) show that stations with the highest organic carbon sediments are Lynch Cove, Sinclair Inlet 2, Budd Inlet, and Totten Inlet.

In addition to oxygen demand, the decomposition of particulate organic matter in the sediment produces dissolved forms of nitrogen in the sediment pore water. Well-known microbial processes, including ammonification, nitrification, anammox, dissimilatory nitrate reduction to ammonium, and denitrification, constitute key links in the mineralization of organic nitrogen. Nitrogen, in reduced and oxidized forms, is exchanged between the sediments and the overlying water.

Table I-1. Summary of gross surface sediment total organic carbon observations (1989 – 2023) at sites with available sediment flux observations.

Location	Station ID	Mean Percent Total Organic Carbon (dry weight)
BELLINGHAM BAY	4	2.02
N HOOD CANAL (S OF BRIDGE)	13	0.28
SARATOGA PASSAGE	19	1.82
PORT GARDNER (EVERETT)	21	1.28
SINCLAIR INLET 1	34	2.45
INNER BUDD INLET	49	2.77
CASE INLET (NISQUALLY R)	52	0.55
CENTRAL	191	1.67
SKAGIT BAY	209R	0.44
HOOD CANAL (N OF SEABECK)	222	1.56
CASE INLET	252	2.27
COMMENCEMENT BAY	281	1.35
LYNCH COVE	305R	3.66
SARATOGA PASSAGE (N of Camano I)	40007	0.27
CENTRAL BASIN, N of Shilshole	40011	1.53
READS BAY	40013	1.14
SARATOGA PASSAGE (South)	40015	1.92
BOUNDARY BAY	40017	0.37
HOOD CANAL (HOODSPORT)	40018	2.08
SHISHOLE BAY	40020	0.22
CRESCENT HARBOR	40021	1.57
WEST SOUND (SAN JUAN I)	40025	1.56
TOTTEN INLET	40028	2.72
N SAMISH BAY	40029	1.51
SINCLAIR INLET 2	40030	3.32
INNER CASE INLET (ROCKY BAY)	40032	0.59
N CENTRAL BASIN	40038	1.67
BELLINGHAM BAY, PORT FRANCES	BLL009	0.51

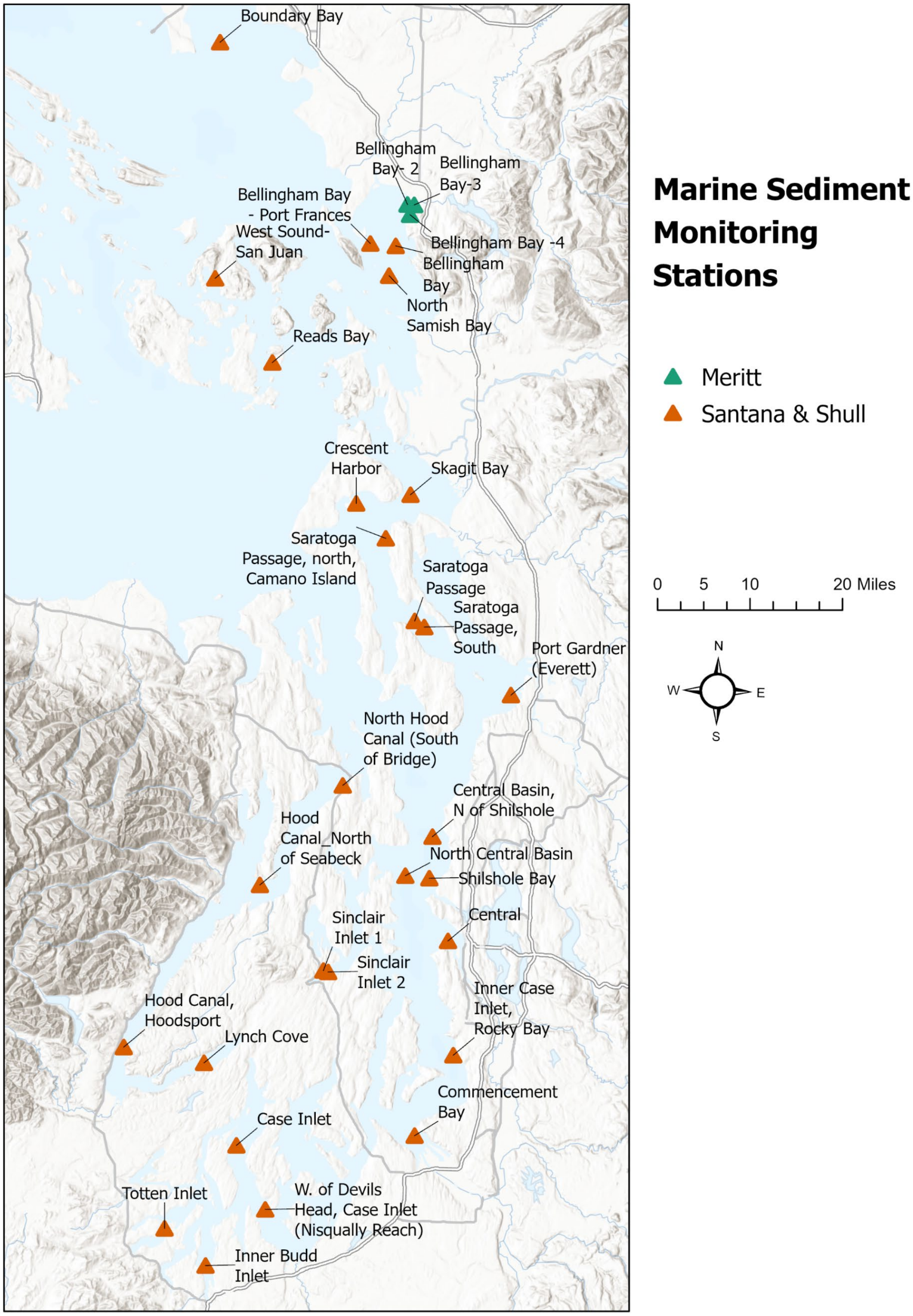

Figure I-1. **Overview map of sediment monitoring locations.**
Shown are Ecology/Santana and Shull stations (red) and Meritt stations (green).

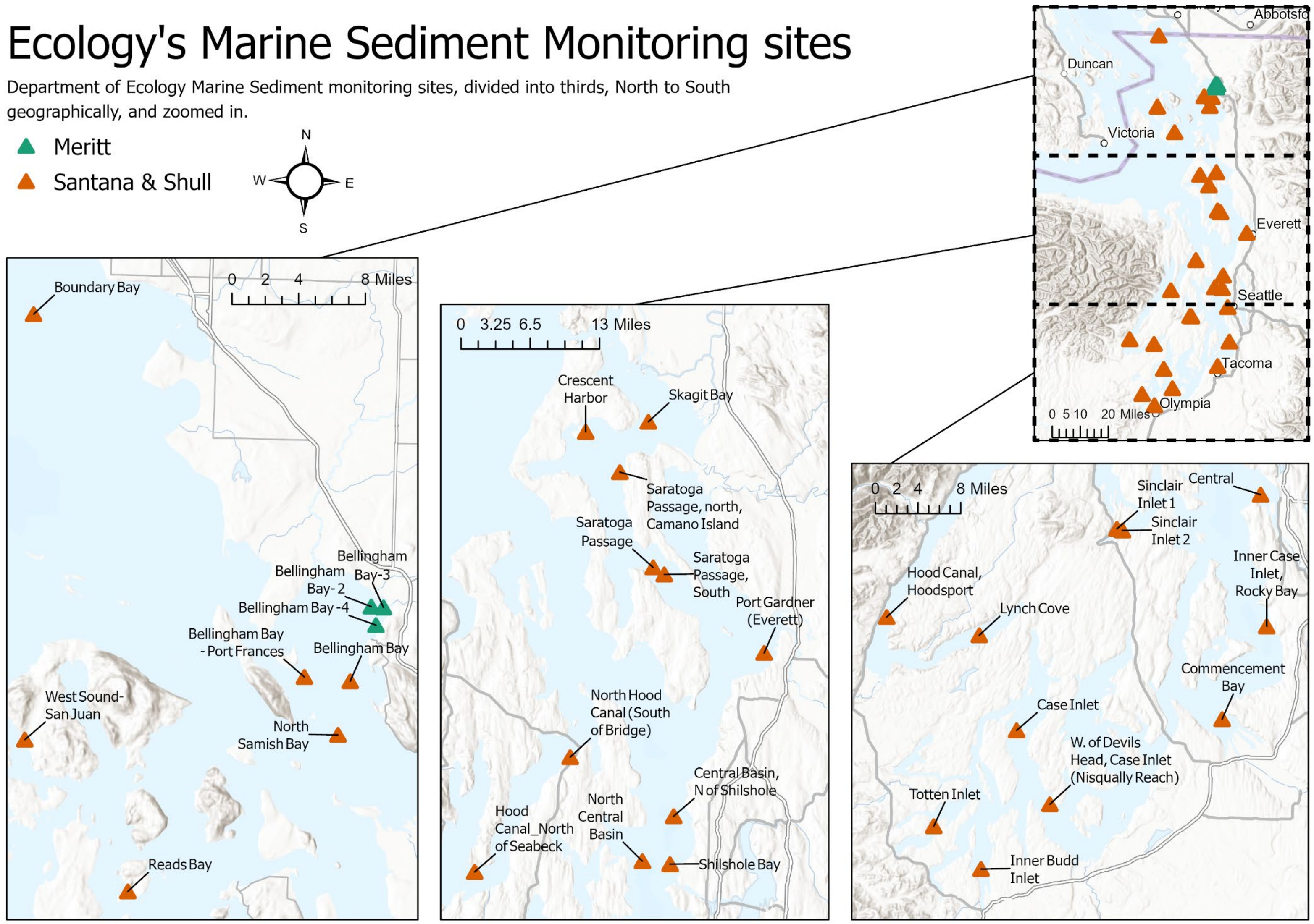

Figure I-2. Zoomed-in maps of sediment flux monitoring locations.
Meritt (green triangles) and Santana and Shull (red triangles) obtained benthic flux observations in June 2017 and April/ early May 2018, respectively.

Berner (1980) and DiToro (2001) describe the organic nitrogen degradation processes at play: Ammonium (NH_4^+) is produced during ammonification, whereas during nitrification, NH_4^+ is oxidized to nitrate (NO_3^-), and under low oxygen or anaerobic conditions, NO_3^- is eventually converted in a series of reactions to nitrogen gas (N_2) in the denitrification process, which requires energy fueled by organic carbon molecules. These processes are all represented in the sediment diagenesis module in SSM.

Another anaerobic process, more recently discovered to be active in coastal sediments, is the anaerobic conversion of NH_4^+ to N_2 with nitrite as the electron acceptor (Thamdrup and Dalsgaard 2002; Devol 2015). This latter reaction, also known as anammox and not represented in the diagenesis module, is of lower importance at shallower depths but of increasing importance at the continental shelf and beyond (Dalsgaard et al. 2005). However, data are not available to address the overall relative importance of anammox to total N_2 production in Puget Sound.

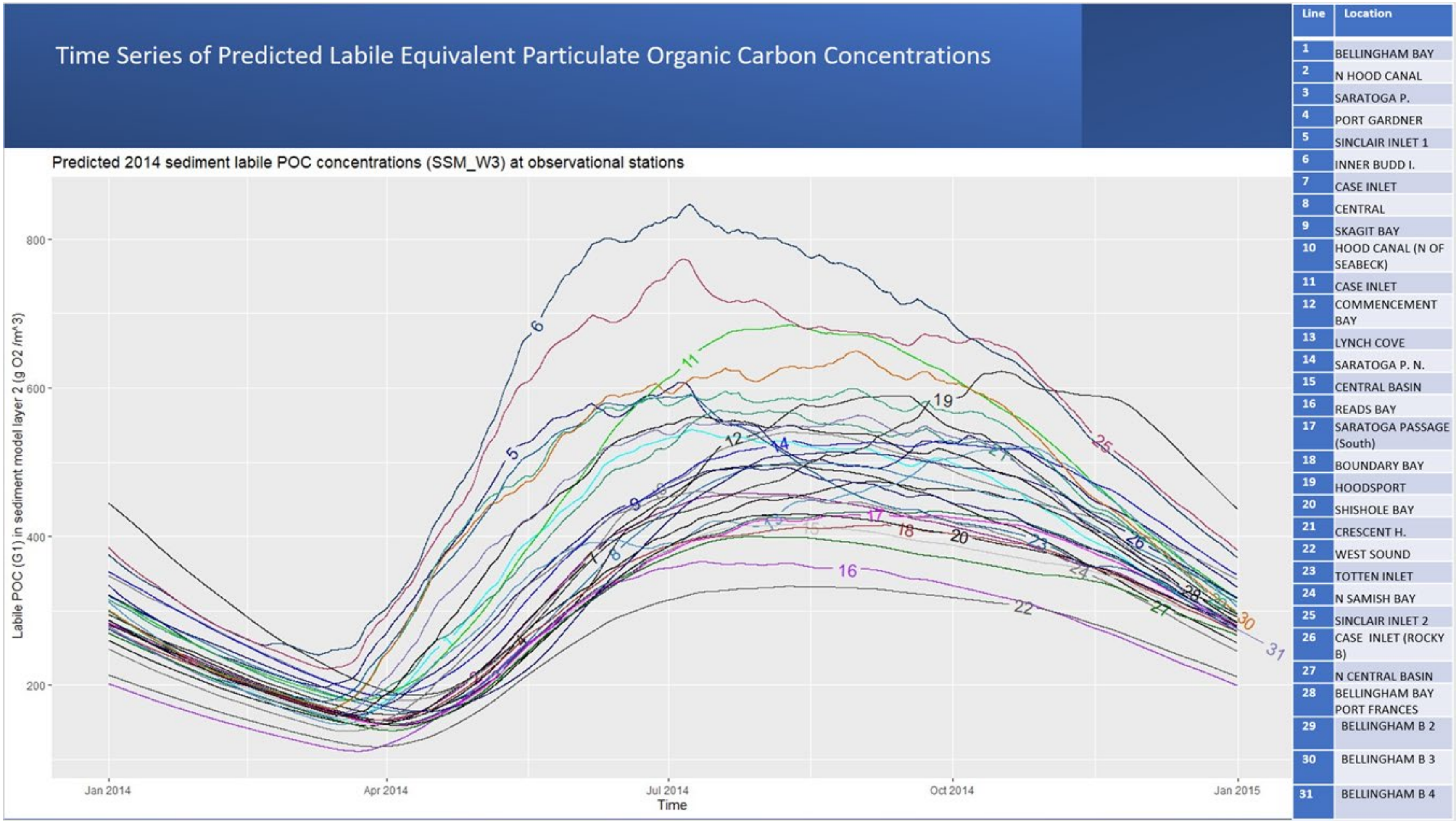

Figure I-3. Time series of predicted 2014 labile particulate organic carbon equivalent concentrations (g O_2/m^3) in anaerobic sediment layer H2 at locations in which Santana and Shull (2023) and Meritt (2017) conducted sediment oxygen demand measurements.

Sediment Fluxes

Sediment oxygen demand predictions

Recent model updates resulted in relatively lower peak predictions of sediment oxygen demand throughout the model domain than those Ahmed et al. (2019) reported. For instance, for the year 2006, the updated annual mean maximum SOD across all nodes of the model domain is 0.86 g O_2/m^2/day, compared to 1.4 g O_2/m^2/day reported previously by Ahmed et al. (2019).

We modeled 2006 and 2014 as reference and existing scenarios with different input loads. Reference scenario results, representative of pre-industrial loads from all local and regional sources, as expected, consist of lower SOD predictions compared to the existing scenarios, which represent the loads for each recent year. For example, the hourly median differences between existing and reference scenarios varied from close to zero to upwards of 0.6 g O_2/m^2/day in 2006. Differences are greatest in terminal inlets and bays. Most of the model domain is predicted to exhibit less than 0.1 O_2/m^2/day median difference in SOD between existing and reference scenarios, as shown in Figure I-4.

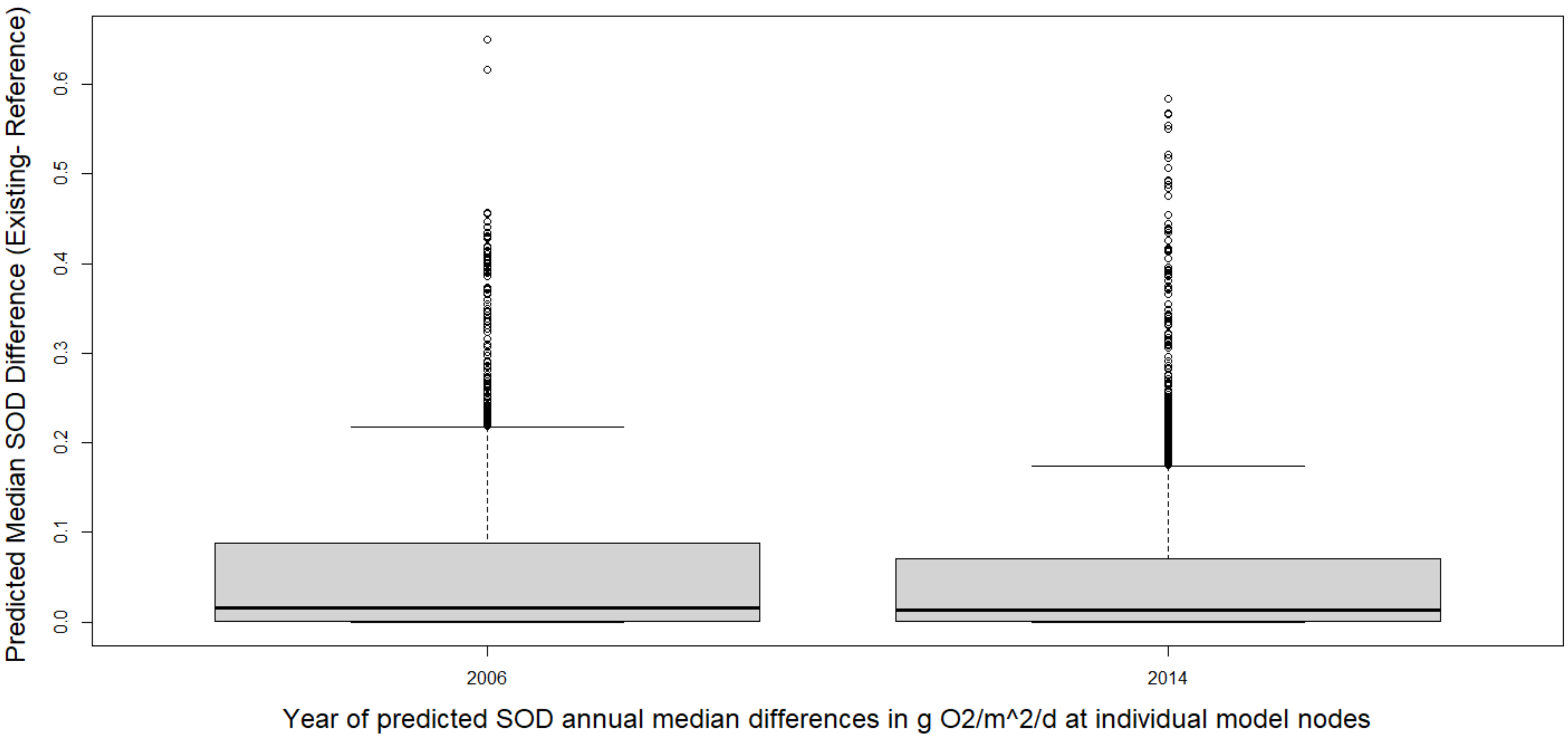

Figure I-4. Predicted median hourly SOD differences between existing and reference scenarios for each node in the model domain.

The spatial variability of predicted sediment oxygen demand (SOD) is similar between years. Figure I-5 shows SSM output for two years: 2006 consisted of relatively high residence times, whereas 2014 was an average year with respect to water column residence times in the main basin of Puget Sound. The plan view maps in this figure show the spatial annual median SOD variation for existing and reference scenarios. The far-right panels show the predicted change in annual average SOD between scenarios. Predicted SOD rates at shallow terminal inlets and bays are relatively higher in both scenarios compared to the rest of the domain. Higher rates at shallow locations are consistent with observed springtime benthic flux results reported by Santana and Shull (2023).

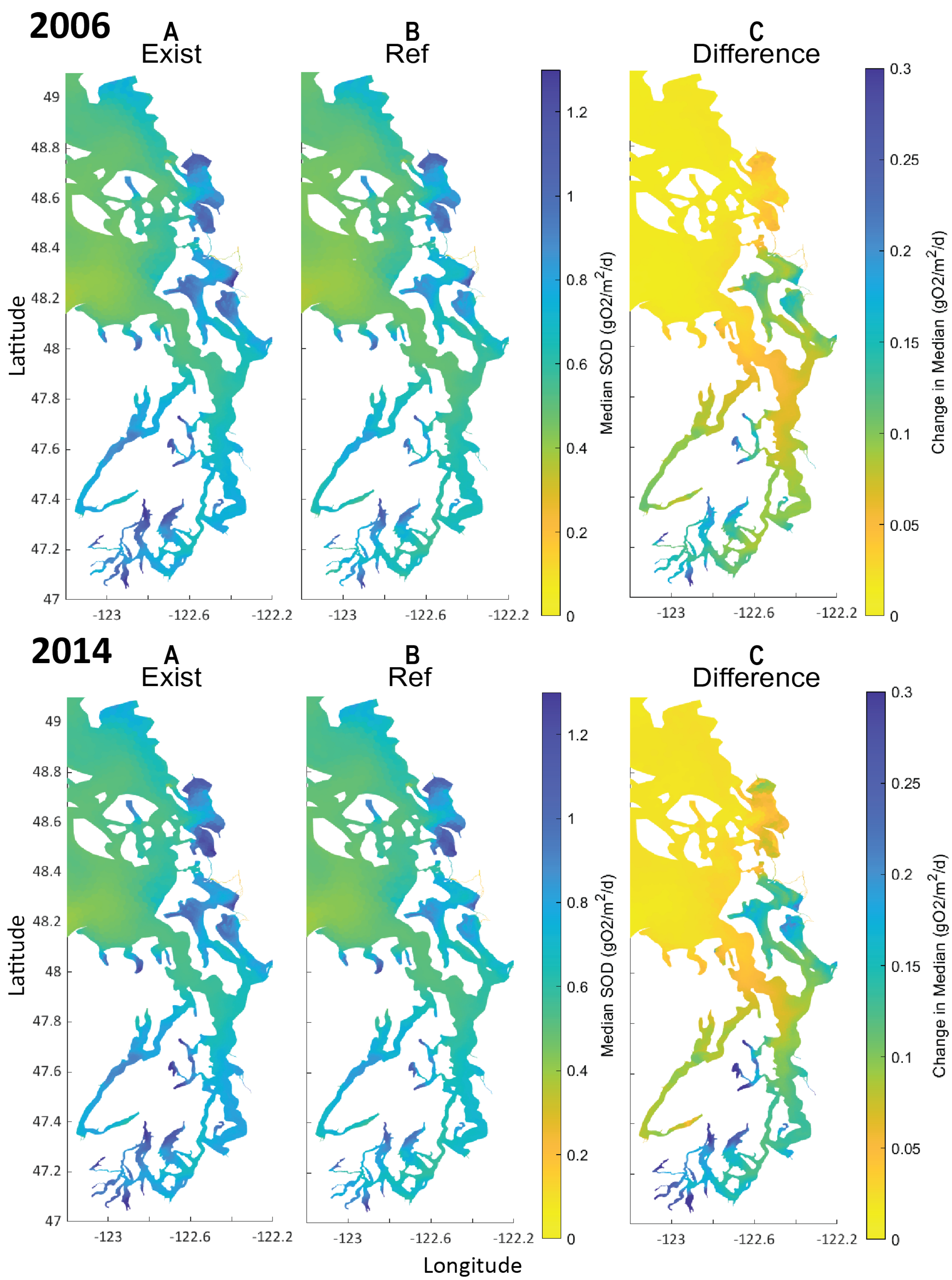

Figure I-5. Planview maps of predicted annual medians for 2006 and 2014 sediment oxygen demand.
Scenarios shown are existing (A), reference (B), and their difference (C). Units shown are in g O_2/m^2/day.

Nitrogen flux predictions

Fluxes are labeled positive in the direction of mass moving into the water column from the sediments and negative when mass is moving into the sediments from the water column. The NH_4^+ and NO_3^- predicted spatial flux patterns are very similar between years. Predictions for NH_4^+ fluxes, as shown in Figure I-6, are positive, so the sediments are anticipated to be releasing NH_4^+ into the water column. The opposite is true for NO_3^- fluxes. The sediments are predicted to generally uptake NO_3^- from the water column, as shown in Figure I-7.

The annual median hourly prediction of NH_4^+ release from the existing scenario sediments for the entire domain is about 0.016 and 0.014 g N/m^2/day for 2006 and 2014, respectively. The reference scenario median NH_4^+ flux predictions for the same years are close to those predicted for the existing scenario (0.014 and 0.013 g N/m^2/day for 2006 and 2014). SSM predicts that sediments in terminal inlets and bays release more ammonium to the water column than in other locations in the greater Puget Sound.

Conversely, SSM predicts that sediments uptake relatively less nitrate from the water column in terminal inlets and bays. At a few terminus points of inlets, the median values are relatively low but positive (in Figure I-7 these locations are shown in darkest blue), indicating a modest release of NO_3^- from the sediments to the water column. The annual median hourly prediction of NO_3^- flux consists of uptake from the existing scenario sediments for the entire domain with magnitudes of about -0.01 and -0.009 g N/m^2/day for 2006 and 2014, respectively. Predicted median reference NO_3^- fluxes for those years are about 10% lower than those predicted for existing conditions.

The spatial pattern of median releases of nitrogen gas from denitrification in the sediments is shown in Figure I-8. The annual median denitrification in existing scenario sediments for the entire domain is about 0.019 and 0.020 g N/m^2/day for 2006 and 2014, respectively. The median springtime denitrification rate that Santana and Shull (2023) estimated from the deviation of measured nitrogen to carbon ratios is in a similar range, around 0.015 g N/m^2/day. Reference scenario sediments are predicted to release about 3% less nitrogen gas from denitrification compared to the existing scenario.

SSM predicts relatively less denitrification occurring in several shallow locations within some terminal inlets and bays (e.g., portions of Bellingham Bay, Samish Bay, Skagit Bay, Dyes Inlet, Totten Inlet, tips of other South Sound inlets), which are shown in turquoise in Figure I-8 2014 (A). Some of these locations also correspond with relatively lower predicted uptake of NO_3^- into the sediments at those from the overlying water column. In contrast, at other deeper locations, the median predicted denitrification approaches 0.03 g N/m^2/day, shown in purple in Figure I-8 2014 (A), such as in large sections of Hood Canal and portions of South Sound.

Sulfide flux predictions

Sulfide fluxes occur via surface mass transfer from the sediments to the water column when insufficient oxygen is available in the surface sediment layer (Di Toro 2001). Sulfide fluxes in the model are expressed as oxygen equivalents. The annual median hourly prediction of sulfide release from the existing scenario sediments for the entire domain is about 0.0005 and 0.0004 g O_2/m^2/day for 2006 and 2014, respectively. Predicted median reference sulfide fluxes for those years are about 20% lower than for the existing condition. The spatial pattern of median sulfide releases is shown in Figure I-9. SSM predicts higher sulfide fluxes from Hood Canal.

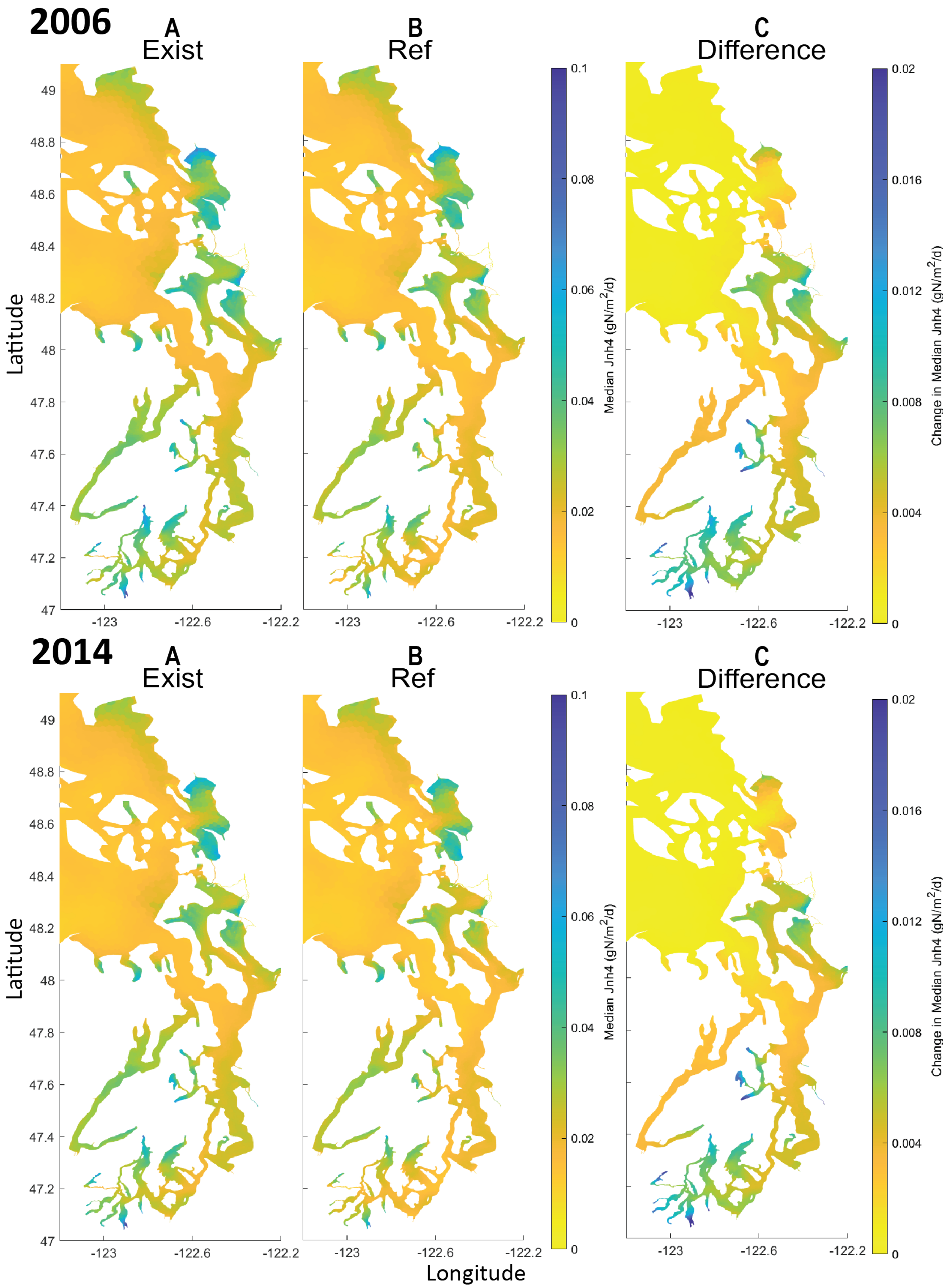

Figure I-6. Planview maps of predicted annual medians for 2006 and 2014 of ammonium fluxes.
Scenarios shown are existing (A), reference (B), and their difference (C). Units shown are in g N/m^2/day.

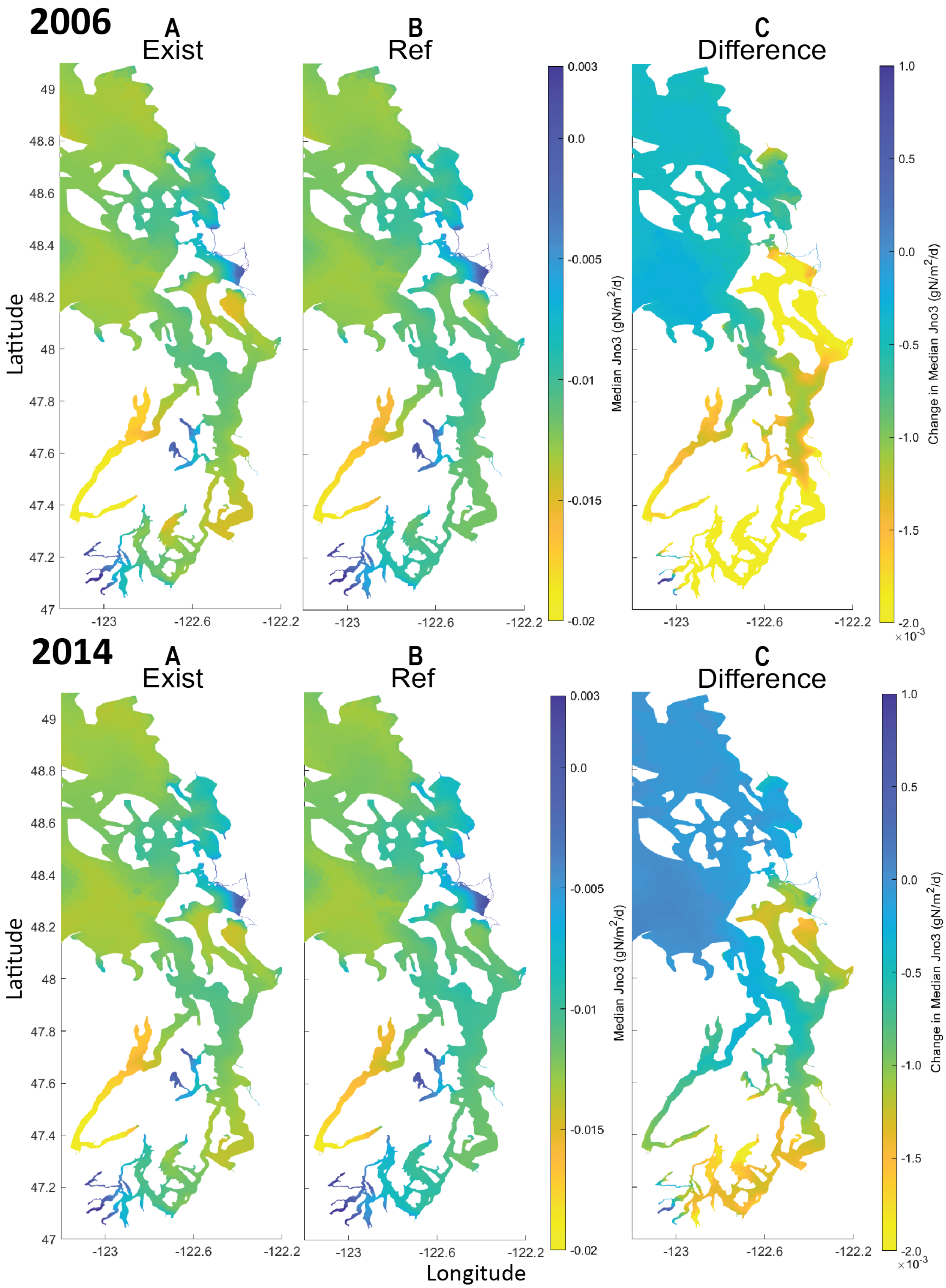

Figure I-7. Planview maps of predicted annual medians for 2006 and 2014 of nitrate fluxes.

Scenarios shown are existing (A), reference (B), and their difference (C). Units shown are in g N/m^2/day and the difference in same units X 10^{-3} (equivalent to mg N/m^2/day).

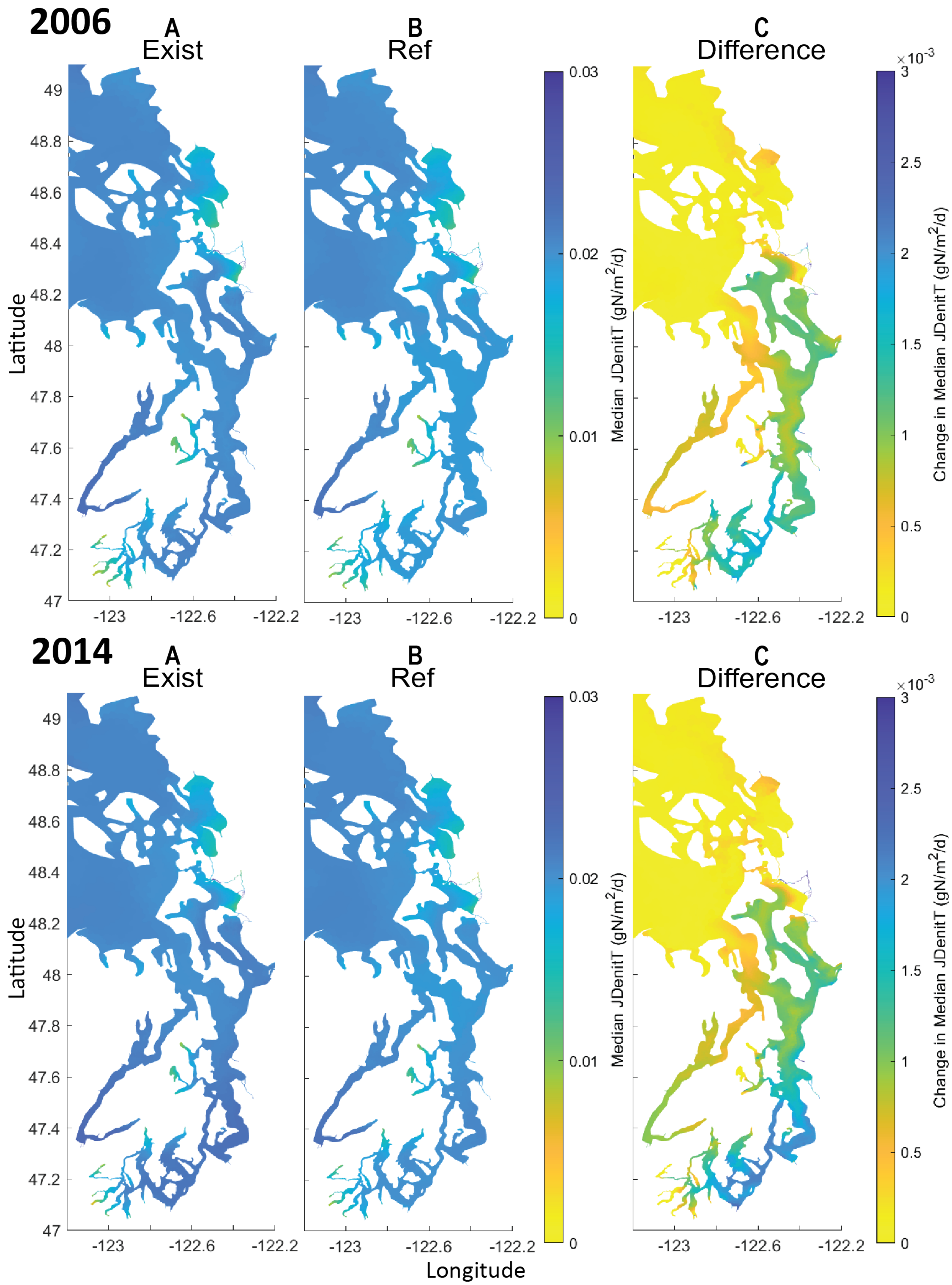

Figure I-8. Planview maps of predicted annual medians for 2006 and 2014 of nitrogen gas flux released from sediments.

Scenarios shown are existing (A), reference (B), and their difference (C). Units shown are in g N/m^2/day.

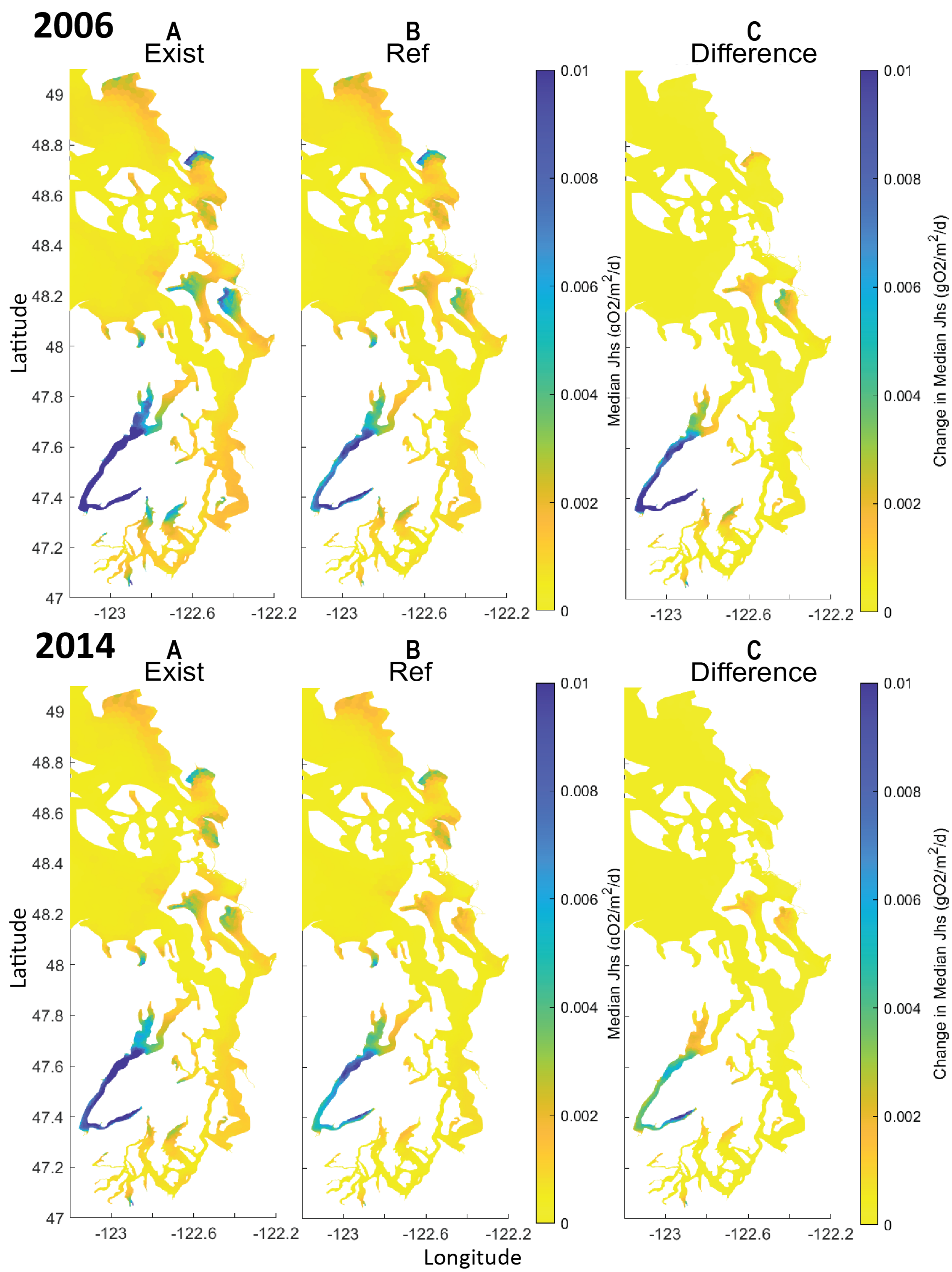

Figure I-9. Planview maps of predicted annual medians for 2006 and 2014 of hydrogen sulfide equivalents released from the sediments.
Scenarios shown are existing (A), reference (B), and their difference (C). Units shown are in g O_2/m^2/day.

Comparative analysis of observed and predicted sediment fluxes

While sediment fluxes are key biogeochemical drivers, their measurement presents difficulties and can vary widely due to inherent methodological limitations. Engel and Macko (1993) point out limitations and potential biases associated with measuring sediment fluxes.

Pamatmat and Banse (1969) conducted SOD measurements in Puget Sound and reported them in units of ml $O_2/m^2/hr$. The maximum rate they observed is roughly 1.2 g $O_2/m^2/d$ in South Sound, and the minimum is 0.2 $g/m^2/d$ in the central main basin. However, the exact coordinates of measurement locations are unknown.

Ahmed et al. (2019) and Pelletier et al. (2017) compared the limited, available at the time, Puget Sound SOD measurements with known locations to predictions. These measurements range from 1996 to 2017 and are often single, discrete measurements with no replicates. Ahmed et al. (2019) reported a percent difference of about 51% between overall means of observations and predictions computed from different model year outputs than those measured, but spatially corresponding to where measurements were taken. Mean predictions were higher, but data were not available from the older SOD measurements to compute confidence intervals for the observations. However, more data are now available, described below, to compute confidence intervals of the observed means and conduct a comparative analysis using them. We describe that analysis below, and the results are in the section titled: "Computation of observational flux confidence intervals of the means and comparison with predictions."

Since sediment flux data are sparse, we encouraged the acquisition of additional sediment flux data. As a result of collaborative work between Western Washington University (WWU) and Ecology's sediment monitoring team, a new observational sediment flux data set became available (Rigby 2019; Santana and Shull 2023). Henceforth, we refer to that data set as Santana and Shull (2023). They measured springtime (April – early May 2018) fluxes from stations using incubated cores sampled in the Washington waters of the Salish Sea. Cores were kept at 10°C during incubation, which is close to the in situ temperatures when the samples were obtained and close to the average predicted bottom water temperatures at these sites during the spring (around 9.3°C). Accordingly, we determined that temperature correction was not necessary for comparative purposes. The data are available for download via Ecology's Environmental Information database.

Merritt (2017), also working at WWU, produced another recent sediment flux observational data set that we are also able to compute confidence intervals for a subset of the observations and can use to compare with predictions. Merritt (20217) and Santana and Shull (2023) used cores, rather than in-situ chambers, to acquire fluxes. While both data sets were acquired in the spring, Merritt focused on sampling various locations within Bellingham Bay, while Santana and Shull measured multiple sites throughout the greater Puget Sound.

These data sets provide important information for model evaluation. For the analysis reported here, we are interested in the range of spatial variation within each site as well as variability between sites. Accordingly, we only used sites that have observations, including at least one spatial replicate. We calculated fluxes for dissolved oxygen (SOD), NH_4^+, and NO_3^- using the difference between the start of incubation and each valid measurement taken subsequently at each site.

A key component of our evaluation is to compare the spatial sediment flux averages that the model predicts with data that account for the spatial variability inherent within a location and between locations. We combined the Santana and Shull (2023) data set with data from three locations in the Merritt (2017) study that included at least one replicate measurement within a single SSM node. In the Santana and Shull (2023) data set, there were eleven locations that did not have field/spatial replicates, so we dropped those. We eliminated all values that were flagged with a comment reflecting problems that occurred during the measurement process as they did not pass quality assurance procedures. Most benthic flux observational locations were within embayments. Bellingham Bay is the best represented location, with data from five different sites. The resulting data set used for our analysis from the Merritt plus Santana and Shull observations consists of data from 31 locations shown in Figure I-1 and Figure I-2.

We also reviewed the work and used the data reported in Sheibley and Paulson (2014) for inclusion in an analysis focused on ranges and means. They compiled in situ chamber and porewater nitrogen sediment flux observational data sets from Puget Sound. They noted the challenges and limitations associated with these measurements and found that all porewater diffusive flux measurements were considered underestimates of the true fluxes. Accordingly, for comparative purposes, we focus on the chamber measurements they compiled (138 observations), which represent year-round data primarily from inlets and bays in Puget Sound measured between 1982 and 2010.

Ranges and means of predicted and observed Puget Sound sediment flux data sets

Figures I-10 and I-11 show the inter-site maxima, minima, and mean for NH_4^+ and NO_3^- fluxes for each of the observational data sets described above. Additionally, the figures include 2014 predictions averaged over the entire model domain for the whole year and 2014 predictions corresponding to the Merritt and Santana/Shull locations in the spring.

Not surprisingly, the year-round data sets show the greatest range of flux values. For both NH_4^+ and NO_3^- fluxes, the observational Sheibley and Paulson data set (Obs_All_Seasons_Sheibley_P) shows the largest range between maxima and minima compared to all data sets.

The NH_4^+ flux range in the Sheibley and Paulson data set varies from about -0.013 to 0.19, with a mean of 0.05 g N/m^2/day. The predicted year-round range for 2014 (SSM_All_seasons_2014), which consists of all hourly data throughout the SSM domain, varies from -0.012 to 0.13 with a mean of 0.03 g N/m^2/day and falls within the Shibley-Paulson range. This points to reasonable SSM-predicted NH_4^+ fluxes.

The Merritt NH_4^+ flux observations (Obs_Spring-2017_Merritt) maximum, minimum, and mean values are higher than those for Santana and Shull observations (Obs_Spring-2018_S&S). Merrit measured only Bellingham Bay locations, whereas Santana and Shull measured sites throughout the greater Puget Sound. The 2014 predicted SSM springtime mean falls within the range of the Santana and Shull data set, and it is slightly higher than the mean of the Merritt data set. The predicted SSM inter-site ranges are slightly greater than the observed Santana and Shull and Merritt ranges in the springtime, but also within reasonable ranges.

The NO_3^- flux range in the Sheibley and Paulson data set varies from about -0.081 to 0.021, with a mean of -0.010 g N/m^2/day. The predicted year-round range for 2014 (SSM_All_seasons_2014), which consists of all hourly data throughout the SSM domain, varies from -0.023 to 0.011 and falls within the Sheibley-Paulson range. The predicted mean NO_3^- fluxes for all of 2014 is equal to the Sheibley and Paulson data set mean. These results also point to reasonable predicted SSM NO_3^- fluxes.

The Merritt NO_3^- flux observations (Obs_Spring-2017_Merritt) show the tightest range of all data sets with the highest mean. The SSM Spring 2014 NO_3^- flux ranges overlap both the Santana and Shull and Merritt ranges, but with slightly lower means.

Overall, SSM predicted NH_4^+ and NO_3^- fluxes fall within generally expected means and ranges. Predicted values not only agree with Puget Sound values but also are within ranges measured in the Strait of Georgia. Belley et al. (2016) conducted measurements within the Strait of Georgia and reported that sediment oxygen demand varied between about 0.06 and 0.55 g O_2/m^2/day. Belley et al. (2016) reported that sediments in the Strait of Georgia released rather than consumed ammonium, with fluxes ranging between about -0.001 g N/m^2/day and releases of up to 0.031 g N/m^2/day. The nitrate fluxes they reported ranged from -0.014 to 0.010 g N/m^2/day.

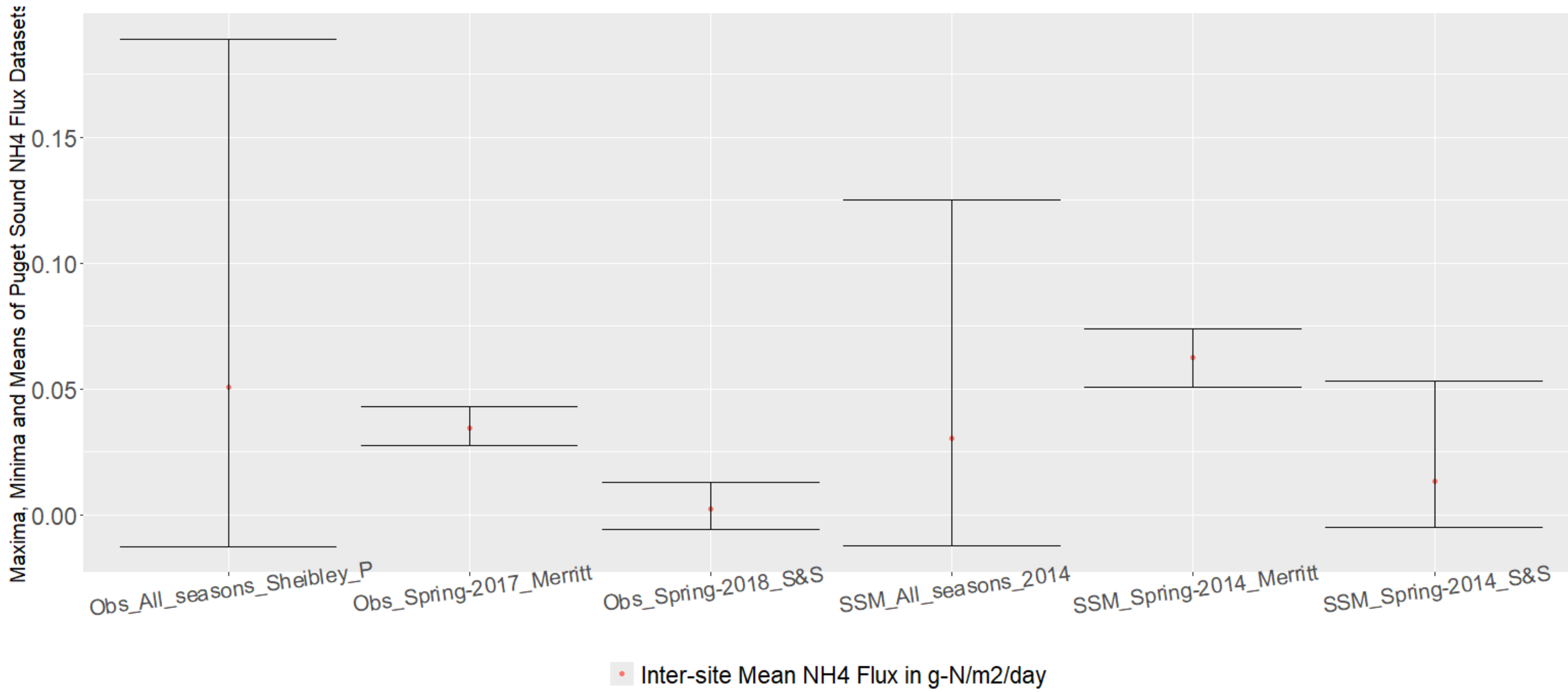

Figure I-10. Comparison of the maxima, minima and mean of NH_4^+ flux data sets observed in Puget Sound.

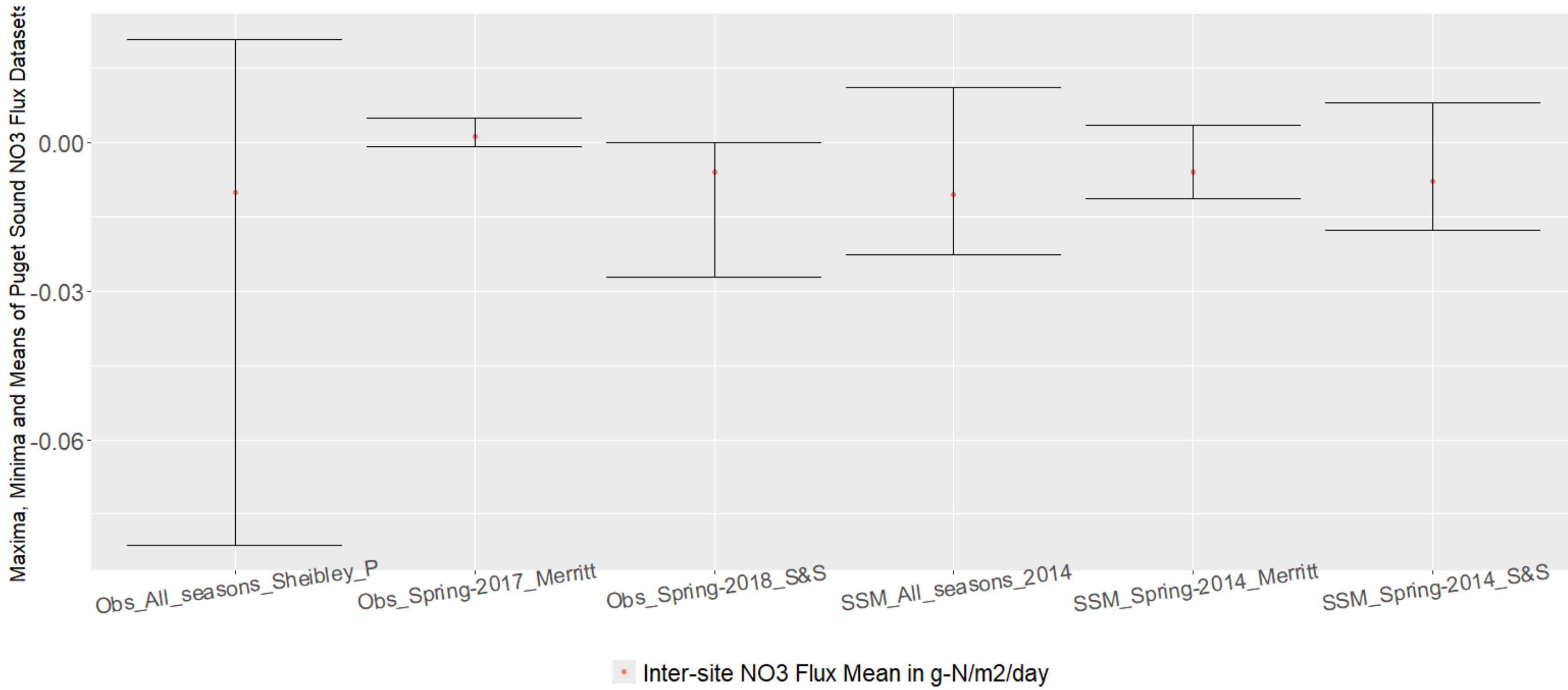

Figure I-11. Comparison of the maxima, minima, and mean of NO_3^- flux data sets observed in Puget Sound.

Computation of observational flux confidence intervals of the means and comparison with predictions

Comparing springtime only data with predictions for the same season with different modeled years presents limitations. Nonetheless, data that incorporates at least one field duplicate at multiple locations is available from the Santana and Shull and Merritt data sets to compute confidence intervals (alpha= 2.5%) of the means for the fluxes measured at each location based on the replicate cores obtained generally within 7.5 m from one another (Santana and Shull 2023) or, as detailed in Merritt (2017), within such proximity that more than one sample corresponds to the same space represented within an SSM computational node.

Computed 2018 SOD values match Santana and Shull (2023) for each station when there is only a single pair (a measurement at an incubation time paired with its corresponding initial time) of SOD observations for a site for each spatial replicate. However, when there were more possible pairs for each spatial replicate, we noted discrepancies with the mean SOD reported because Santana and Shull (2023) used only single pairs per replicate to calculate SOD.

In our re-analysis of the measurement data, when more than one pair per replicate of flux observations was available, the median percent absolute difference between the values using a single pair versus the values using all the possible valid pairs for each station is around 7%. But there are some cases when the difference is greater. The maximum percent difference is for Reads Bay, of around 230%. E. Santana (personal communication, July 28, 2023) confirmed that when more than two measurement pairs were available, their decision was to use only two measurements that encompassed the overnight period. They chose that approach because of the potential faunal inhibition of bio-irrigation and bioturbation, and for consistency with other analytes (DIC, pH, and nutrients) that only had two measurements.

Santana and Shull (2023) noted that some cores approached hypoxia towards the end of the observational period. Cores approaching hypoxia towards the end of the incubation period present potential limitations in terms of SOD estimation since SOD rates were expected to become lower as the oxygen level approaches hypoxic conditions. Nevertheless, we found inconsistencies in the data with respect to both lower DO and time-of-day measurement endpoints. For instance, for cores with lower DO endpoints (such as in Reads Bay, core 21 at site 40022 and cores 16 and 17 at site 40021), the estimated SOD rates from points closer to the start of incubation, when faunal inhibition may have been suspected due to sampling activities and ranging from elapsed time of about ~0.09 to 0.64 day, were higher than the second or third rates estimated (regardless of whether the final amount of oxygen was lower than 75 uM).

The above implies that inhibition of benthic organisms' activity shortly after sampling due to sound or vibrations was not occurring in all instances or, at least, was not generally a major driver for all samples and that low DO endpoints were not causing similar effects across the cores. There are only four instances in the data set we are using (which includes only sites that have at least one spatial replicate) where DO values dip below 45 uM. Two of those instances are for Reads Bay (station 40013), one instance for Sinclair Inlet-2 (station 40030), and one case for West Sound- San Juan (station 40025).

We compared both observed data sets with SSM predictions that correspond to the month of the year when the samples were collected. Santana and Shull (2023) samples were collected in April and the first week of May in 2018. Merritt (2017) samples were collected in June 2017. We spatially matched each observational site with its appropriate SSM node. While we matched each observation with the same time of the year, the years were not matched since our model runs were for simulations different than when the measurements were taken. Since sediment fluxes are expected to approach steady state at each location, comparing output from simulated years different from those when the observations were collected is a useful comparative illustration.

The 1.25th and the 98.75th percentiles were used to build T-distribution confidence intervals for the mean observations for each site. The confidence intervals for the prediction means used for comparative purposes were computed via resampling a block of 26 hours of output (Santana and Shull incubated samples generally for 26 hours or less)1000 times, with replacement, over the corresponding springtime window (albeit a different simulation year) in which sampling occurred. The SSM predictions are independent of all the observations used in this evaluation.

Sediment Oxygen Demand

Predicted and observed springtime SOD means, considering confidence intervals of the means, match each other well, as shown in Figure I-12. Most (63%) of the predicted SOD mean values fall within the 97.5% confidence intervals of the available observations. Five stations (Hoodsport, Sinclair Inlet 2, and three of the Bellingham Bay stations) have observed low-end confidence intervals that are negative but are shown in Figure I-12 with a low end of zero to confine the plot to an appropriate scale for most of the data. Nonetheless, the negative values are reported in Table I-2.

Of the 30 locations, at 10 locations, predicted means are, on average, 0.21 g O_2/m^2/day greater than the observed intervals for the means (Skagit Bay, Sinclair Inlet 2, Saratoga Passage, Port Gardner, Commencement Bay, Case Inlet west of Devil's Head in the Nisqually Reach, North Central Basin and Bellingham Bay 4). In one location, Central Basin N (Shilshole), the predictions are lower than the observed SOD intervals.

At locations that are predicted to experience a larger increase in SOD fluxes during the spring, the observed confidence interval of the mean may overlap predictions within the season, even if the computed *mean* predictions are not within the range. That is the case, for example, with Sinclair Inlet 1, where, as shown in Table I-2 and Figure I-17, the range of SOD predictions overlaps the 97.5th percentile confidence interval of the observations even though the mean of the predictions does not. In this case, the predicted springtime SOD is changing rapidly within the springtime window, and the predicted mean (0.74) is slightly higher than the observed confidence interval of the mean (0.23 to 0.72) for the samples which represent system conditions at an instant in time.

Ammonium Flux

Predicted and observed springtime NH_4^+ means, considering confidence intervals of the means, match each other well, as shown in Figure I-13. Most of the predicted NH_4^+ mean values fall within the 97.5% confidence intervals of the available observations.

Though both predicted and observed NH_4^+ fluxes are relatively small, hovering near zero in several cases, predicted fluxes are all positive, whereas the observation-based flux means are mainly positive, with a few that are slightly negative. If negative, the mean observed NH_4^+ fluxes going into the sediments measured were generally small or close to zero. Confidence intervals of the observed means straddle between positive and negative in most cases. Predictions at six stations (Saratoga Passage, Inner Budd Inlet, Central, Bellingham Bay Port Frances, Hood Canal at Hoodsport, and Port Gardner) of the 31 NH_4^+ mean flux predictions were outside the confidence intervals of the observed NH_4^+ mean fluxes.

Nitrate Flux

Predicted and observed springtime NO_3^- flux means, considering confidence intervals of the means, match each other well, as shown in Figure I-14. Most of the predicted NO_3^- mean values fall within the 97.5% confidence intervals of the available observations.

Most of the predicted NO_3^- fluxes are negative. Likewise, the observed fluxes, while exhibiting large confidence interval bands, have means that are mostly negative or very near zero. Only three stations (West Sound San Juan, Central, and Bellingham Bay 2) of the 31 NO_3^- mean flux predictions were outside the confidence intervals of the observed mean fluxes. Note that Figure I-14 does not show the confidence intervals for the observations for two stations (North Samish Bay and Crescent Harbor) because they were too large to fit in the plot at the scale shown; however, the confidence intervals are all reported in Table I-4.

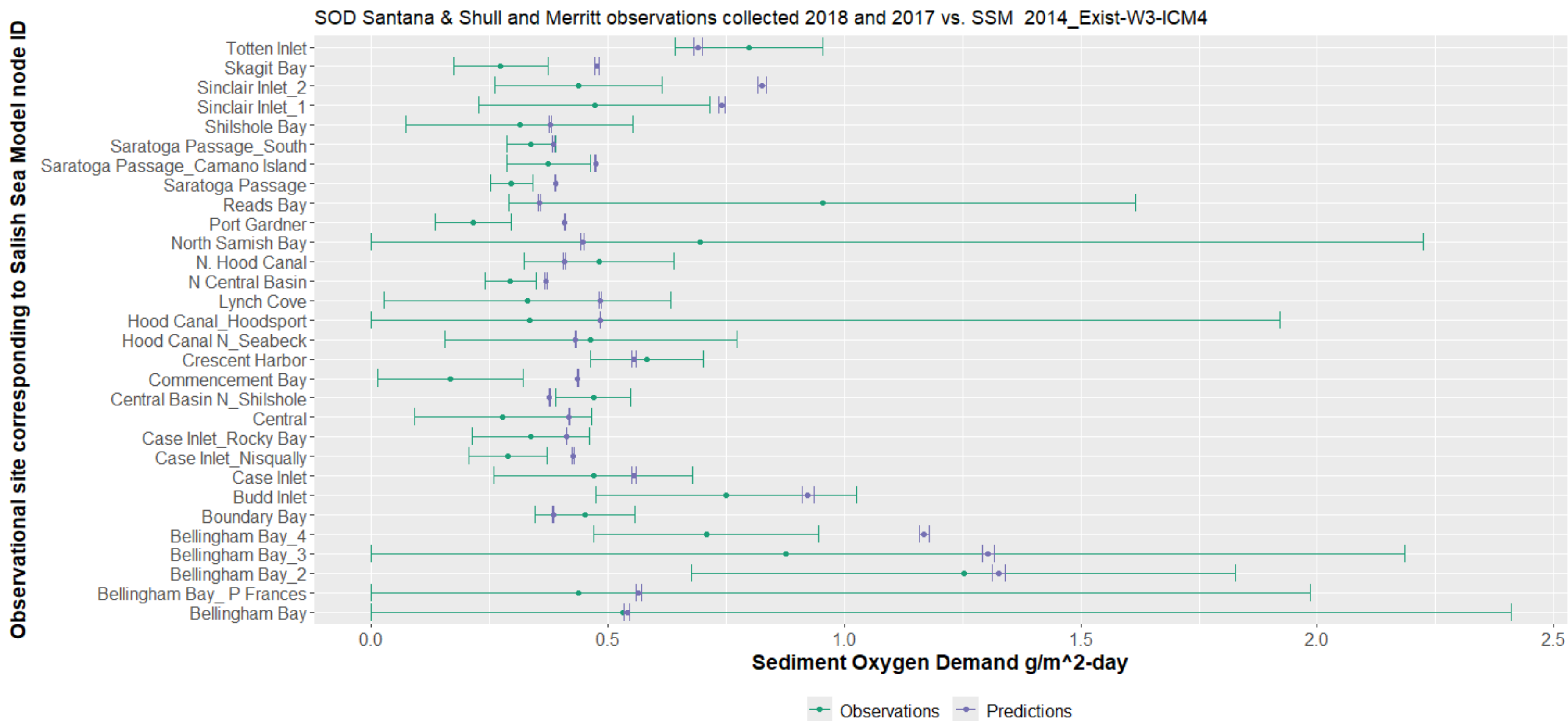

Figure I-12. Comparison of springtime observed (green) and predicted (purple) sediment oxygen demand at 30 stations including confidence intervals.
Predictions are based on the existing 2014 scenario. Observations are from Santana and Shull (2023) and Meritt (2017).

Table I-2. Springtime 2014 predicted sediment oxygen demand values compared to observed springtime values in 2017 and 2018.

Station ID	Location	Hourly Prediction Mean[a,b]	Minimum Hourly Prediction[a,b]	Maximum Hourly Prediction[a,b]	Number of Obs	Mean of Observations[b]	Standard Deviation of Observations[b]	1.25th Percentile of the Mean of Observations[b]	98.75th Percentile of the Mean of Observations[b]
4	Bellingham Bay	0.54	0.43	0.69	2	0.53	0.10	-1.35	2.41
13	N. Hood Canal	0.41	0.37	0.48	6	0.48	0.12	0.32	0.64
19	Saratoga Passage	0.39	0.37	0.43	4	0.30	0.02	0.25	0.34
21	Port Gardner	0.41	0.38	0.46	2	0.21	0.00	0.13	0.30
34	Sinclair Inlet_1	0.74	0.58	0.96	4	0.47	0.12	0.23	0.72
49	Budd Inlet	0.92	0.70	1.34	4	0.75	0.13	0.48	1.03
52	Case Inlet Nisqually	0.43	0.38	0.50	4	0.29	0.04	0.21	0.37
191	Central	0.42	0.40	0.46	4	0.28	0.09	0.09	0.46
209	Skagit Bay	0.48	0.41	0.58	4	0.27	0.05	0.17	0.37
222	Hood Canal N_Seabeck	0.43	0.42	0.46	6	0.46	0.24	0.16	0.77
252	Case Inlet	0.55	0.47	0.67	6	0.47	0.16	0.26	0.68
281	Commencement Bay	0.44	0.41	0.48	2	0.17	0.01	0.01	0.32
305	Lynch Cove	0.48	0.45	0.55	4	0.33	0.15	0.03	0.63
40007	Saratoga Passage Camano Island	0.47	0.45	0.53	4	0.37	0.04	0.29	0.46
40011	Central Basin N_Shilshole	0.38	0.35	0.43	4	0.47	0.04	0.39	0.55
40013	Reads Bay	0.36	0.31	0.42	4	0.95	0.32	0.29	1.62

[a] Corresponding to the seasonal interval in time observed.

[b] Units are in g $O_2/m^2/day$

Table I-2. Springtime 2014 predicted sediment oxygen demand values compared to observed springtime values in 2017 and 2018, continued.

Station ID	Location	Hourly Prediction Mean[a,b]	Minimum Hourly Prediction[a,b]	Maximum Hourly Prediction[a,b]	Number of Obs	Mean of Observations[b]	Standard Deviation of Observations[b]	1.25th Percentile of the Mean of Observations[b]	98.75th Percentile of the Mean of Observations[b]
40015	Saratoga Passage_South	0.38	0.36	0.43	2	0.34	0.00	0.29	0.39
40017	Boundary Bay	0.38	0.36	0.43	4	0.45	0.05	0.35	0.56
40018	Hood Canal_Hoodsport	0.48	0.48	0.50	2	0.33	0.09	-1.25	1.92
40020	Shilshole Bay	0.38	0.36	0.42	4	0.31	0.11	0.07	0.55
40021	Crescent Harbor	0.55	0.47	0.69	6	0.58	0.09	0.46	0.70
40028	Totten Inlet	0.69	0.51	0.93	6	0.80	0.12	0.64	0.95
40029	North Samish Bay	0.45	0.38	0.54	2	0.70	0.08	-0.83	2.22
40030	Sinclair Inlet_2	0.82	0.64	1.06	4	0.44	0.08	0.26	0.61
40032	Case Inlet_Rocky Bay	0.41	0.40	0.44	4	0.34	0.06	0.21	0.46
40038	N Central Basin	0.37	0.34	0.42	4	0.29	0.03	0.24	0.35
BLL009	Bellingham Bay P Frances	0.56	0.45	0.71	2	0.44	0.09	-1.11	1.98
WWU 23,24,25,29	Bellingham Bay_2	1.33	1.33	1.33	4	1.25	0.28	0.68	1.83
WWU 26,28	Bellingham Bay_3	1.30	1.30	1.30	2	0.88	0.07	-0.43	2.18
WWU 30,31,59,60	Bellingham Bay_4	1.17	1.17	1.17	7	0.71	0.21	0.47	0.95

[a] Corresponding to the seasonal interval in time observed.

[b] Units are in g O_2/m^2/day

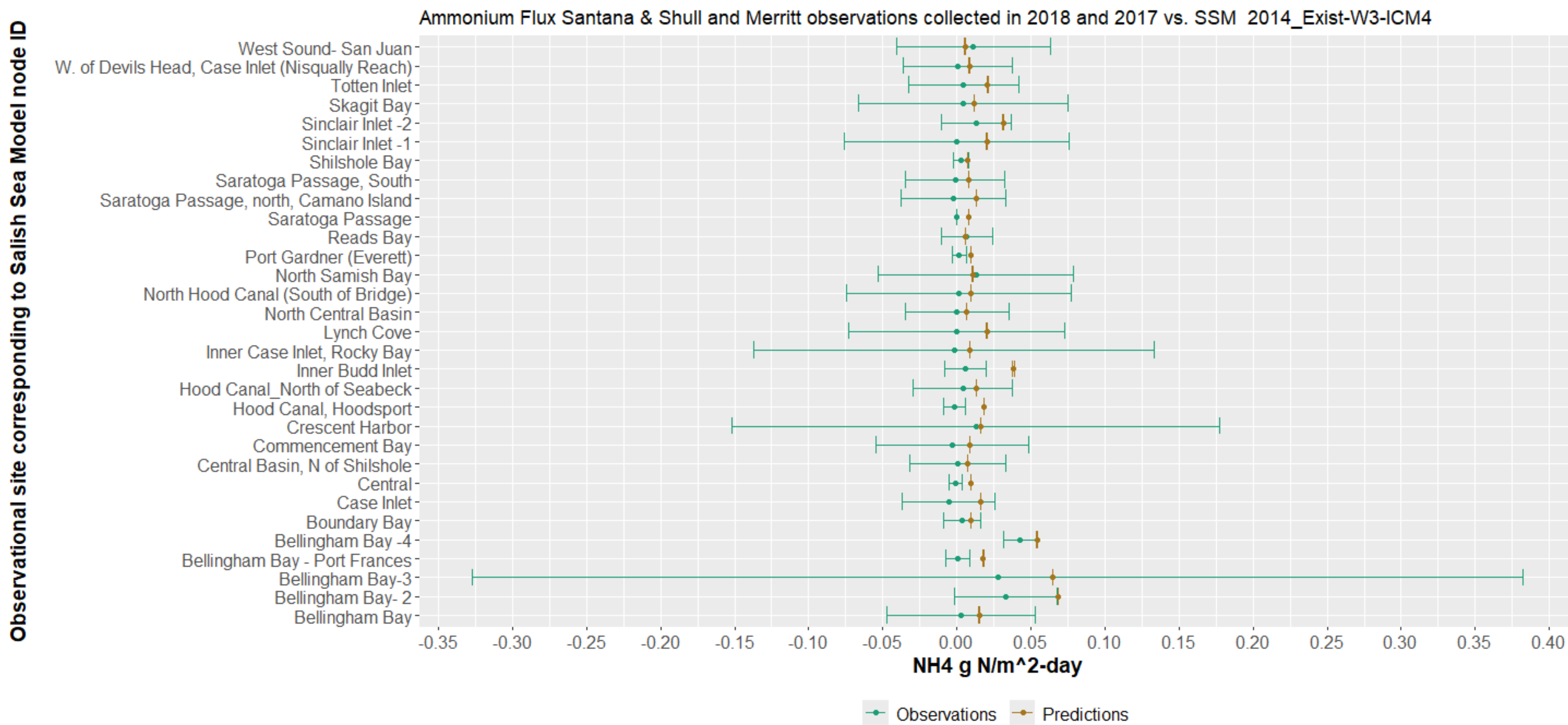

Figure I-13. Comparison of springtime observed (green) and predicted (brown) NH_4^+ ion fluxes at 31 stations, including confidence intervals.

Predictions are based on the existing 2014 scenario. Observations are from Santana and Shull (2023) and Meritt (2017).

Table I-3. Springtime 2014 predicted ammonium values compared to observed springtime values in 2017 and 2018.

Station ID	Location	Hourly Prediction Mean[a,b]	Minimum Hourly Prediction[a,b]	Maximum Hourly Prediction[a,b]	Number of Obs	Mean of Observations[b]	Standard Deviation of Observations[b]	1.25th Percentile of the Mean of Observations[b]	98.75th Percentile of the Mean of Observations[b]
4	Bellingham Bay	0.015	0.010	0.022	2	0.003	0.003	-0.047	0.053
13	North Hood Canal	0.010	0.008	0.012	2	0.001	0.004	-0.074	0.077
19	Saratoga Passage	0.008	0.007	0.010	2	0.000	0.000	0.000	0.000
21	Port Gardner	0.009	0.008	0.011	2	0.001	0.000	-0.003	0.006
34	Sinclair Inlet -1	0.020	-0.005	0.032	2	0.000	0.004	-0.076	0.076
49	Inner Budd Inlet	0.038	0.027	0.053	2	0.006	0.001	-0.008	0.020
52	Case Inlet (Nisqually Reach)	0.008	0.007	0.011	2	0.001	0.002	-0.036	0.038
191	Central	0.009	0.009	0.011	2	-0.001	0.000	-0.005	0.004
209	Skagit Bay	0.012	0.008	0.016	2	0.004	0.004	-0.067	0.075
222	Hood Canal N Seabeck	0.013	0.012	0.015	2	0.004	0.002	-0.030	0.038
252	Case Inlet	0.016	0.013	0.022	2	-0.006	0.002	-0.037	0.026
281	Commencement Bay	0.009	0.007	0.011	2	-0.003	0.003	-0.055	0.048
305	Lynch Cove	0.020	0.015	0.024	2	0.000	0.004	-0.073	0.072
40007	Saratoga Passage Camano Island	0.013	0.012	0.015	2	-0.002	0.002	-0.038	0.033
40011	Central Basin N_Shilshole	0.007	0.006	0.009	2	0.001	0.002	-0.031	0.033
40013	Reads Bay	0.005	0.004	0.008	2	0.007	0.001	-0.011	0.024

[a] Corresponding to the seasonal interval in time observed.

[b] Units are in g N/m^2/day.

Table I-3. Springtime 2014 predicted ammonium values compared to observed springtime values in 2017 and 2018, continued.

Station ID	Location	Hourly Prediction Mean[a,b]	Minimum Hourly Prediction[a,b]	Maximum Hourly Prediction[a,b]	Number of Obs	Mean of Observations[b]	Standard Deviation of Observations[b]	1.25th Percentile of the Mean of Observations[b]	98.75th Percentile of the Mean of Observations[b]
40015	Saratoga Passage South	0.008	0.007	0.010	2	-0.001	0.002	-0.035	0.033
40017	Boundary Bay	0.010	0.008	0.012	2	0.003	0.001	-0.009	0.016
40018	Hood Canal, Hoodsport	0.018	0.018	0.019	2	-0.002	0.000	-0.009	0.006
40020	Shilshole Bay	0.007	0.007	0.009	2	0.003	0.000	-0.002	0.008
40021	Crescent Harbor	0.016	0.011	0.022	2	0.013	0.009	-0.152	0.177
40025	West Sound- San Juan	0.005	0.005	0.007	2	0.011	0.003	-0.041	0.063
40028	Totten Inlet	0.021	0.011	0.032	2	0.004	0.002	-0.033	0.042
40029	North Samish Bay	0.011	0.007	0.016	2	0.013	0.004	-0.053	0.079
40030	Sinclair Inlet -2	0.031	0.020	0.044	2	0.013	0.001	-0.010	0.036
40032	Inner Case Inlet, Rocky Bay	0.009	0.009	0.010	2	-0.002	0.008	-0.137	0.133
40038	North Central Basin	0.007	0.006	0.008	2	0.000	0.002	-0.035	0.035
BLL009	Bellingham Bay - Port Frances	0.018	0.012	0.025	2	0.001	0.000	-0.008	0.009
WWU 23,24,25,29	Bellingham Bay- 2	0.068	0.064	0.074	4	0.033	0.017	-0.001	0.068
WWU 26,28	Bellingham Bay-3	0.065	0.061	0.071	2	0.028	0.020	-0.327	0.382
WWU 30,31,59,60	Bellingham Bay -4	0.054	0.061	0.060	7	0.043	0.010	0.032	0.054

[a] Corresponding to the seasonal interval in time observed.

[b] Units are in g $N/m^2/day$.

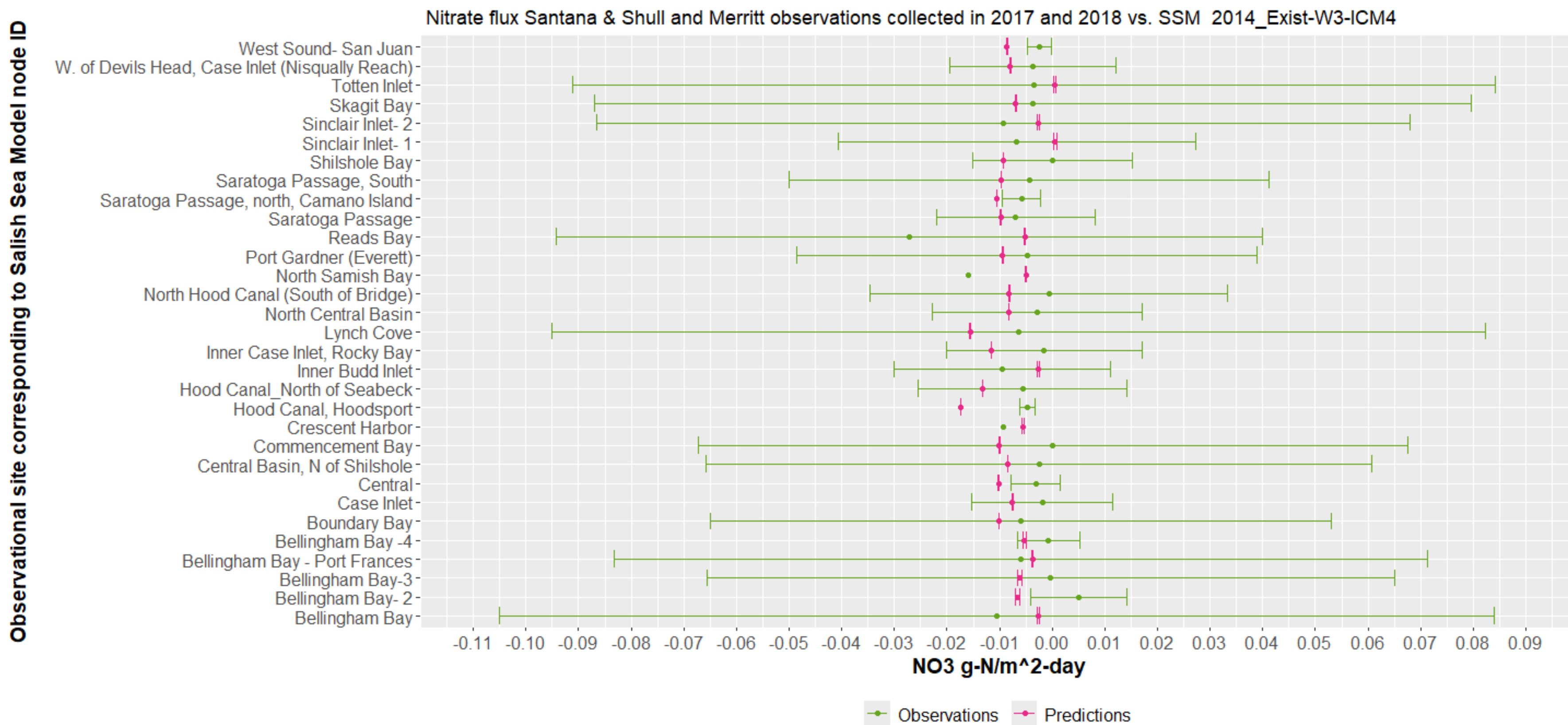

Figure I-14. Comparison of springtime observed (green) and predicted (pink) NO_3^- ion fluxes at 31 stations, including confidence intervals.

Predictions are based on the existing 2014 scenario.

Table I-4. Springtime 2014 predicted nitrate values compared to observed springtime values in 2017 and 2018

Station ID	Location	Hourly Prediction Mean[a,b]	Maximum Hourly Prediction[a,b]	Minimum Hourly Prediction[a,b]	Mean of Observations[b]	Standard Deviation of Observations[b]	Number of Obs	1.25th Percentile of the Mean of Observations[b]	98.75th Percentile of the Mean of Observations[b]
4	Bellingham Bay	-0.003	0.001	-0.006	-0.011	0.005	2	-0.105	0.084
13	North Hood Canal	-0.008	-0.006	-0.010	-0.001	0.002	2	-0.035	0.033
19	Saratoga Passage	-0.010	-0.008	-0.011	-0.007	0.001	2	-0.022	0.008
21	Port Gardner	-0.009	-0.008	-0.011	-0.005	0.002	2	-0.049	0.039
34	Sinclair Inlet- 1	0.001	0.008	-0.006	-0.007	0.002	2	-0.041	0.027
49	Inner Budd Inlet	-0.003	0.007	-0.006	-0.009	0.001	2	-0.030	0.011
52	Case Inlet (Nisqually Reach)	-0.008	-0.006	-0.010	-0.004	0.001	2	-0.020	0.012
191	Central	-0.010	-0.008	-0.012	-0.003	0.000	2	-0.008	0.001
209	Skagit Bay	-0.007	-0.002	-0.011	-0.004	0.005	2	-0.087	0.080
222	Hood Canal_North of Seabeck	-0.013	-0.012	-0.014	-0.006	0.001	2	-0.025	0.014
252	Case Inlet	-0.008	-0.005	-0.009	-0.002	0.001	2	-0.015	0.012
281	Commencement Bay	-0.010	-0.008	-0.012	0.000	0.004	2	-0.067	0.067
305	Lynch Cove	-0.016	-0.013	-0.017	-0.006	0.005	2	-0.095	0.082
40007	Saratoga Passage, Camano Island	-0.011	-0.009	-0.012	-0.006	0.000	2	-0.009	-0.002
40011	Central Basin, N of Shilshole	-0.008	-0.006	-0.011	-0.003	0.004	2	-0.066	0.061
40013	Reads Bay	-0.005	-0.004	-0.007	-0.027	0.004	2	-0.094	0.040

[a] Corresponding to the seasonal interval in time observed.

[b] Units are in g N/m^2/day.

Table I-4. Springtime 2014 predicted nitrate values compared to observed springtime values in 2017 and 2018, continued.

Station ID	Location	Hourly Prediction Mean[a,b]	Maximum Hourly Prediction[a,b]	Minimum Hourly Prediction[a,b]	Mean of Observations[b]	Standard Deviation of Observations[b]	Number of Obs	1.25th Percentile of the Mean of Observations[b]	98.75th Percentile of the Mean of Observations[b]
40015	Saratoga Passage, South	-0.010	-0.008	-0.011	-0.004	0.003	2	-0.050	0.041
40017	Boundary Bay	-0.010	-0.009	-0.011	-0.006	0.003	2	-0.065	0.053
40018	Hood Canal, Hoodsport	-0.017	-0.017	-0.018	-0.005	0.000	2	-0.006	-0.003
40020	Shilshole Bay	-0.009	-0.007	-0.011	0.000	0.001	2	-0.015	0.015
40021	Crescent Harbor	-0.005	0.001	-0.010	-0.009	0.007	2	-0.140	0.121
40025	West Sound- San Juan	-0.009	-0.007	-0.010	-0.002	0.000	2	-0.005	0.000
40028	Totten Inlet	0.000	0.007	-0.003	-0.004	0.005	2	-0.091	0.084
40029	North Samish Bay	-0.005	-0.003	-0.007	-0.016	0.008	2	-0.156	0.124
40030	Sinclair Inlet- 2	-0.003	0.006	-0.007	-0.009	0.004	2	-0.087	0.068
40032	Inner Case Inlet, Rocky Bay	-0.012	-0.011	-0.013	-0.002	0.001	2	-0.020	0.017
40038	North Central Basin	-0.008	-0.006	-0.011	-0.003	0.001	2	-0.023	0.017
BLL009	Bellingham Bay - Port Frances	-0.004	-0.001	-0.007	-0.006	0.004	2	-0.083	0.071
WWU 23,24,25,29	Bellingham Bay- 2	-0.007	0.002	-0.011	0.005	0.004	4	-0.004	0.014
WWU 26,28	Bellingham Bay-3	-0.006	0.004	-0.010	0.000	0.004	2	-0.066	0.065
WWU 30,31,59,60	Bellingham Bay -4	-0.005	0.003	-0.010	-0.001	0.005	7	-0.007	0.005

[a] Corresponding to the seasonal interval in time observed.

[b] Units are in g $N/m^2/day$.

Temporal Variability in Sediment Oxygen Demand and Nitrogen Fluxes at Selected Sites

To visualize the seasonal changes in predicted fluxes and the difference in scale among them, we plotted the predicted sediment flux time series at selected observational stations. The stations selected are four shallow sites (Bellingham Bay 3, N Hood Canal, Sinclair Inlet 1, and Lynch Cove), all less than 30 meters in depth, and two deeper sites, Case Inlet and Shilshole Bay, with depths of 52 and 82 m, respectively. Figures I-15 through I-20 show the selected sediment fluxes at these locations compared with the 2017/2018 springtime observations in context with the whole time series for 2014 and the concentrations of labile POC (G1 in H2) in the sediments. Note that each of the sediment flux scales in these plots is site-specific.

Pamatmat (1971) described the temporal variation of SOD based on seasonal measurements that he conducted at 23 locations in Puget Sound. Although the exact geographic coordinates of his sites are not known, these sites were in South Sound and the Main Basin. Pamatmat only measured once for each season (in January, April, July, and October). The seasonal SOD trends he reported increased from a minimum in January to April, peaking in July and decreasing again in October. The pattern he describes matches with the general temporal SOD trends that SSM predicts. The minima are often in late January or February. The maxima do occur in the summer, but some sites are predicted to experience large SOD fluctuations (e.g., Bellingham Bay, Lynch Cove, and to a lesser degree Sinclair Inlet). In the fall, SSM predicts SOD levels decrease.

Within this general pattern of seasonal flux variations, temporal patterns of predicted fluxes vary among stations. In this set of stations, shallow stations show a greater degree of flux fluctuations. Sites with notable SOD fluctuations include Bellingham Bay 3, Lynch Cove, and Sinclair Inlet 1.

Figure I-15 for Bellingham Bay 3, and Figure I-17, for Sinclair Inlet 1 show predicted SOD magnitudes reaching close to 1.7 g O_2/m^2/day in the summer, with a high degree of fluctuation in the summer and early fall, while LPOC values smoothly increase in the late spring, staying at relatively constant concentrations in the summer before slowly decreasing in the fall. Figure I-18 for Lynch Cove shows the predicted peak SOD slightly above 0.8 g O_2/m^2/day occurring in the Fall.

Figure I-21 shows that both Bellingham Bay and Sinclair Inlet 1 are predicted to experience swings in bottom water temperature and DO, which would explain the SOD flux pattern. SSM output shows Lynch Cove's bottom waters remaining relatively cool throughout 2014, with low DO in the winter, reaching hypoxic conditions in the summer, and fluctuating back slightly to more oxygenated conditions in the late Fall.

Figures I-16 for North Hood Canal, I-19 for Case Inlet, and I-20 for Shilshole Bay show SOD curves that more closely follow the LPOC curves. The temperature curves smoothly increase at these stations from spring to summer while the DO levels do the opposite, but without getting to low DO or hypoxic conditions (Figure 21).

Figures I-22 and I-23 show the temporal patterns for ammonium and nitrate fluxes predicted for 2014 at the selected sites. Bellingham Bay 3 and Sinclair Inlet 1 are predicted to release ammonium at greater rates throughout the spring and mid-summer and experience greater nitrate flux swings than the rest of the stations in this set. Case Inlet’s ammonium fluxes rise above Sinclair Inlet’s in the late summer. Lynch Cove shows a markedly different pattern in which the sediments release ammonium at a very gradually increasing rate from late spring through fall and uptake nitrate the whole year, but the rate of uptake is enhanced from late spring into the summer. This enhanced nitrate uptake is likely due to increasing denitrification in the sediments.

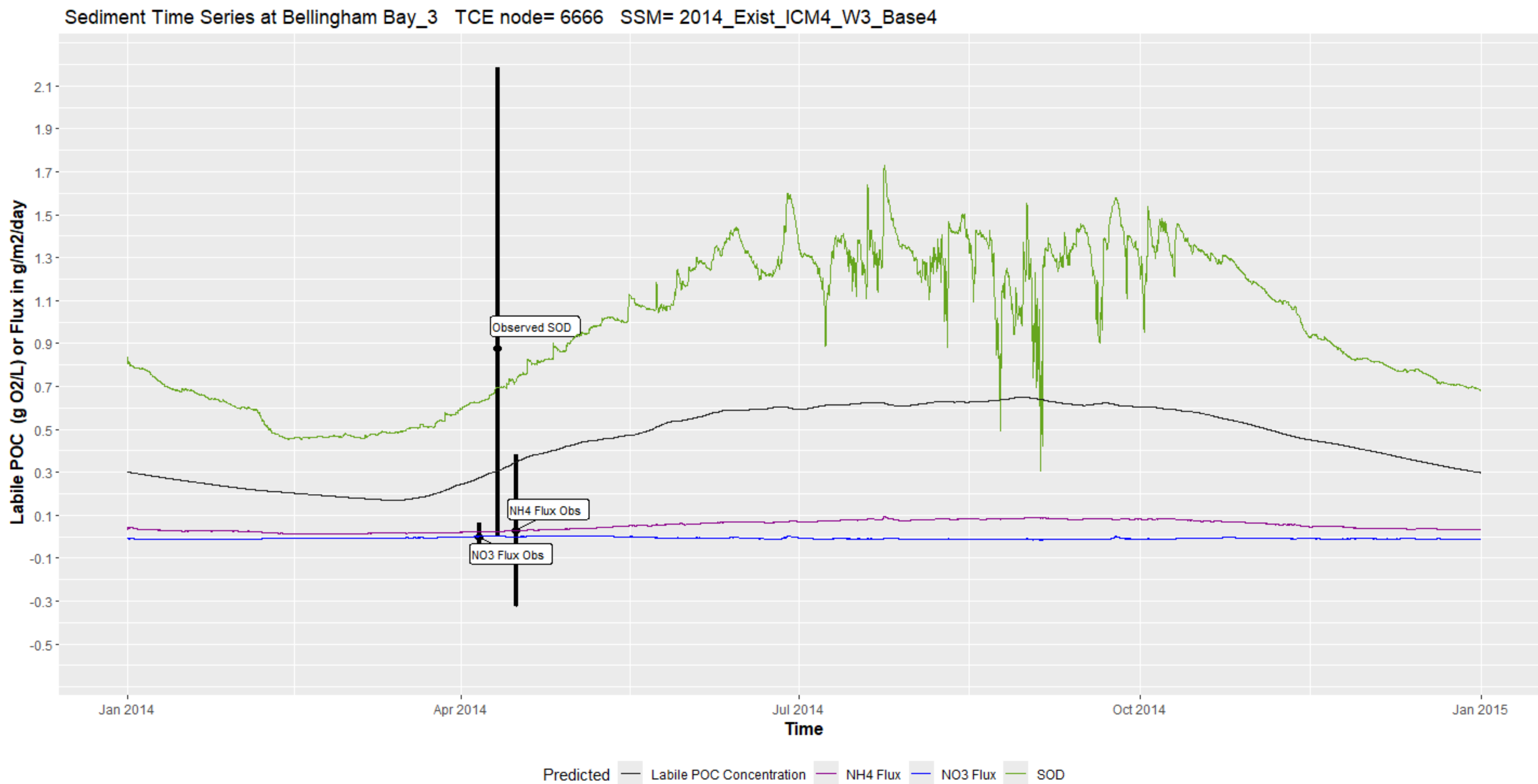

Figure I-15. Time Series for Sediment Oxygen Demand, Ammonium Flux, Nitrate Flux, and Labile Particulate Organic Carbon Concentration in the Sediments at Bellingham Bay 3.

The plot includes observational means and their respective 97.5th percentile confidence intervals. Units are for SOD g O_2/m^2/day, for N fluxes g N/m^2/day, and LPOC (G1 in sediment layer H2) is in g of equivalent (O_2/L).

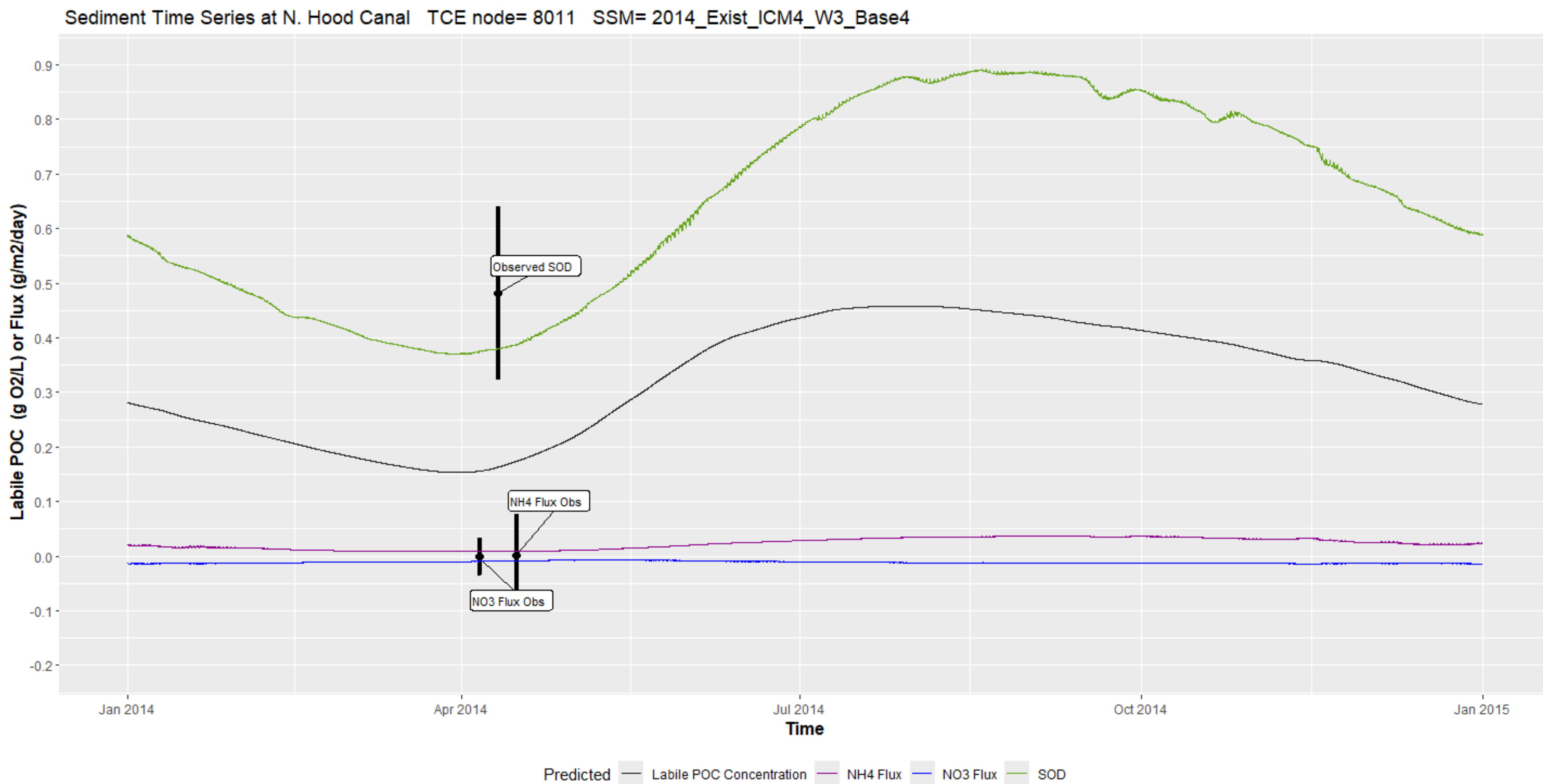

Figure I-16. Time Series for Sediment Oxygen Demand, Ammonium Flux, Nitrate Flux, and Labile Particulate Organic Carbon Concentration in the Sediments at N Hood Canal.

The plot includes observational means and their respective 97.5th percentile confidence intervals. Units are for SOD g O_2/m^2/day, for N fluxes g N/m^2/day, and LPOC (G1 in sediment layer H2) is in g of equivalent (O_2/L).

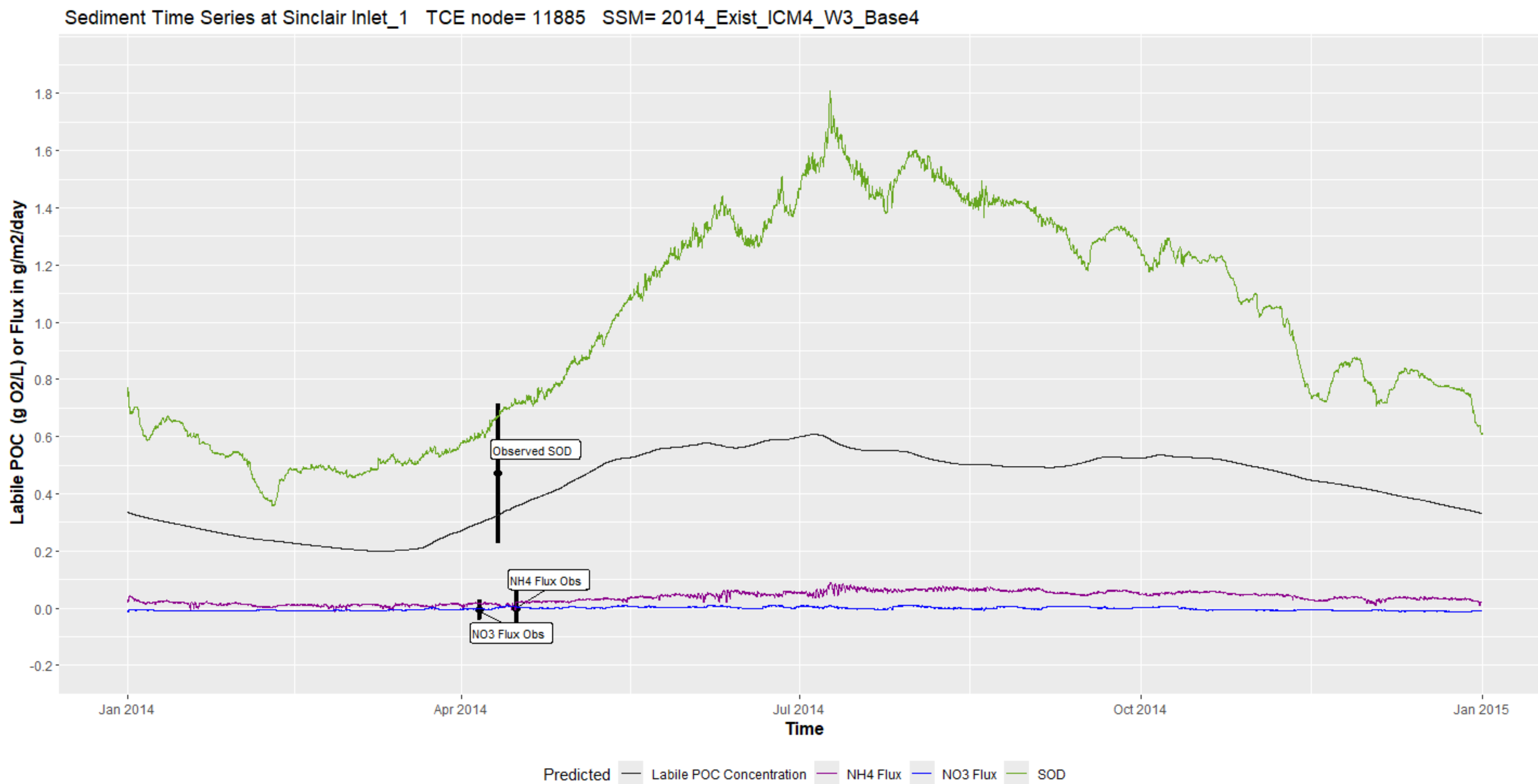

Figure I-17. Time Series for Sediment Oxygen Demand, Ammonium Flux, Nitrate Flux, and Labile Particulate Organic Carbon Concentration in the Sediments at Sinclair Inlet 1.

The plot includes observational means and their respective 97.5th percentile confidence intervals. Units are for SOD g O_2/m^2/day, for N fluxes g N/m^2/day, and LPOC (G1 in sediment layer H2) is in g of equivalent (O_2/L).

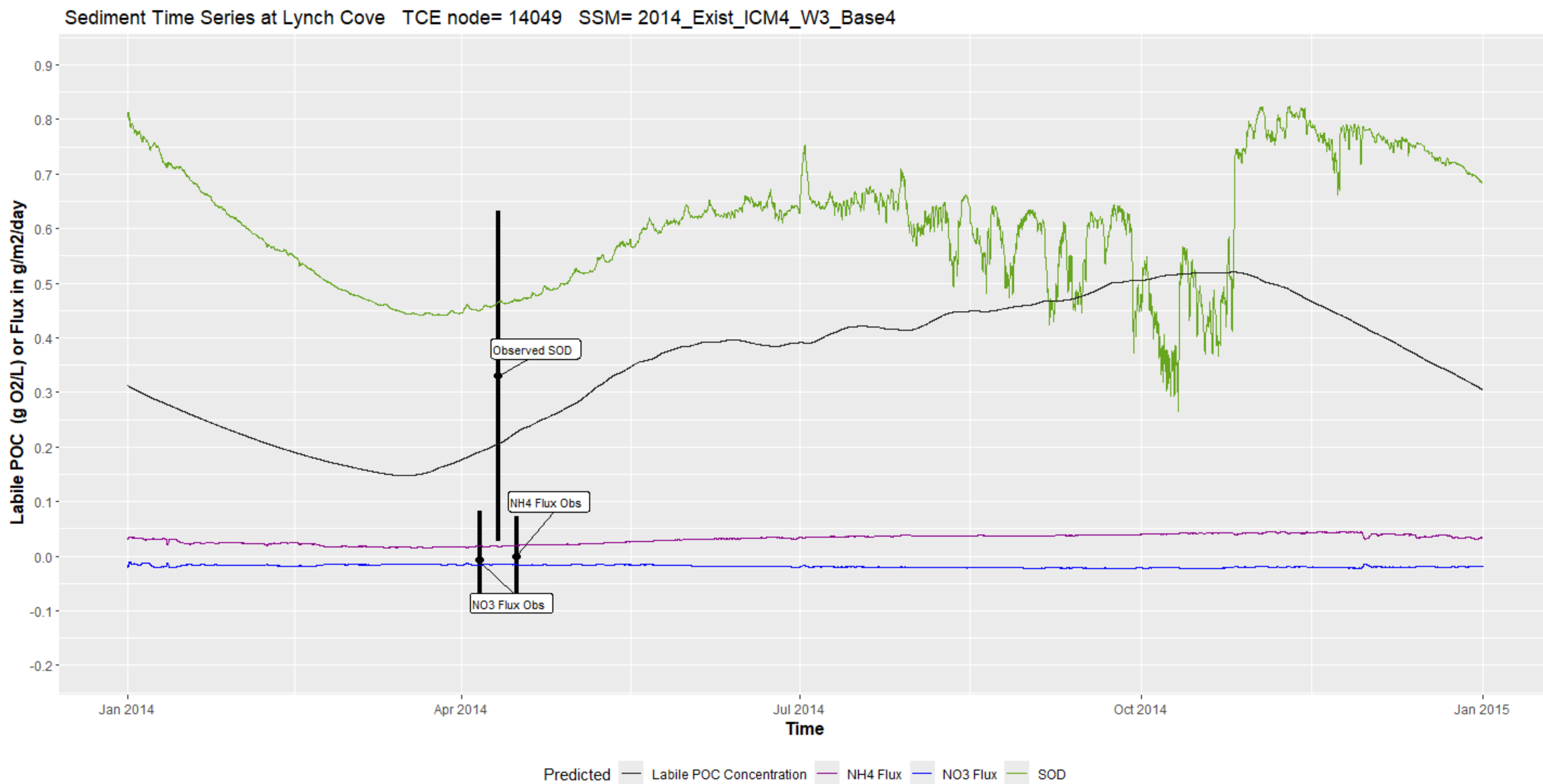

Figure I-18. Time Series for Sediment Oxygen Demand, Ammonium Flux, Nitrate Flux, and Labile Particulate Organic Carbon Concentration in the Sediments at Lynch Cove.

The plot includes observational means and their respective 97.5th percentile confidence intervals. Units are for SOD g O_2/m^2/day, for N fluxes g N/m^2/day, and LPOC (G1 in sediment layer H2) is in g of equivalent (O_2/L).

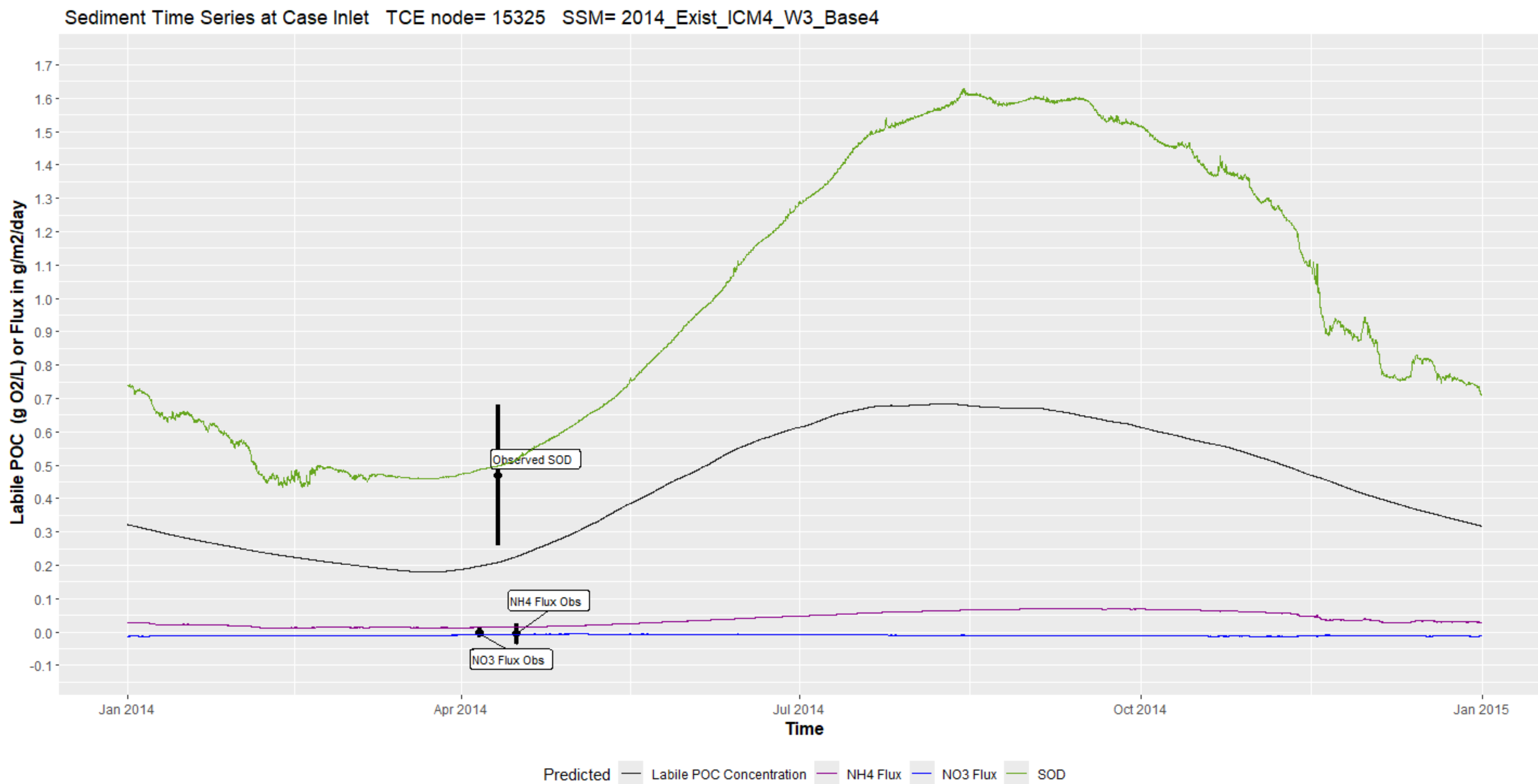

Figure I-19. Time Series for Sediment Oxygen Demand, Ammonium Flux, Nitrate Flux, and Labile Particulate Organic Carbon Concentration in the Sediments at Case Inlet.

The plot includes observational means and their respective 97.5th percentile confidence intervals. Units are for SOD g O_2/m^2/day, for N fluxes g N/m^2/day, and LPOC (G1 in sediment layer H2) is in g of equivalent (O_2/L).

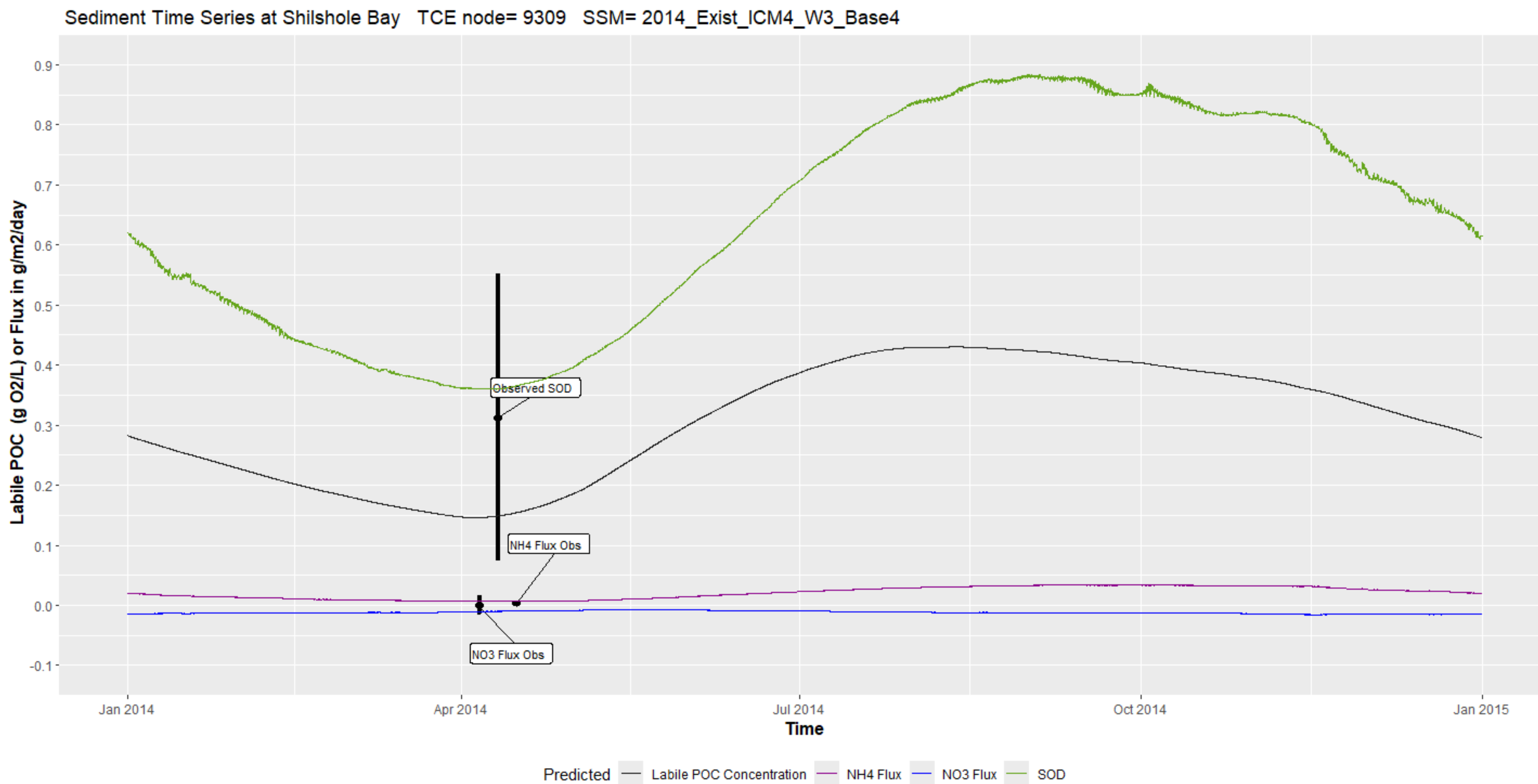

Figure I-20. Time Series for Sediment Oxygen Demand, Ammonium Flux, Nitrate Flux, and Labile Particulate Organic Carbon Concentration in the Sediments at Shilshole Bay.

The plot includes observational means and their respective 97.5th percentile confidence intervals. Units are for SOD g O_2/m^2/day, for N fluxes g N/m^2/day, and LPOC (G1 in sediment layer H2) is in g of equivalent (O_2/L).

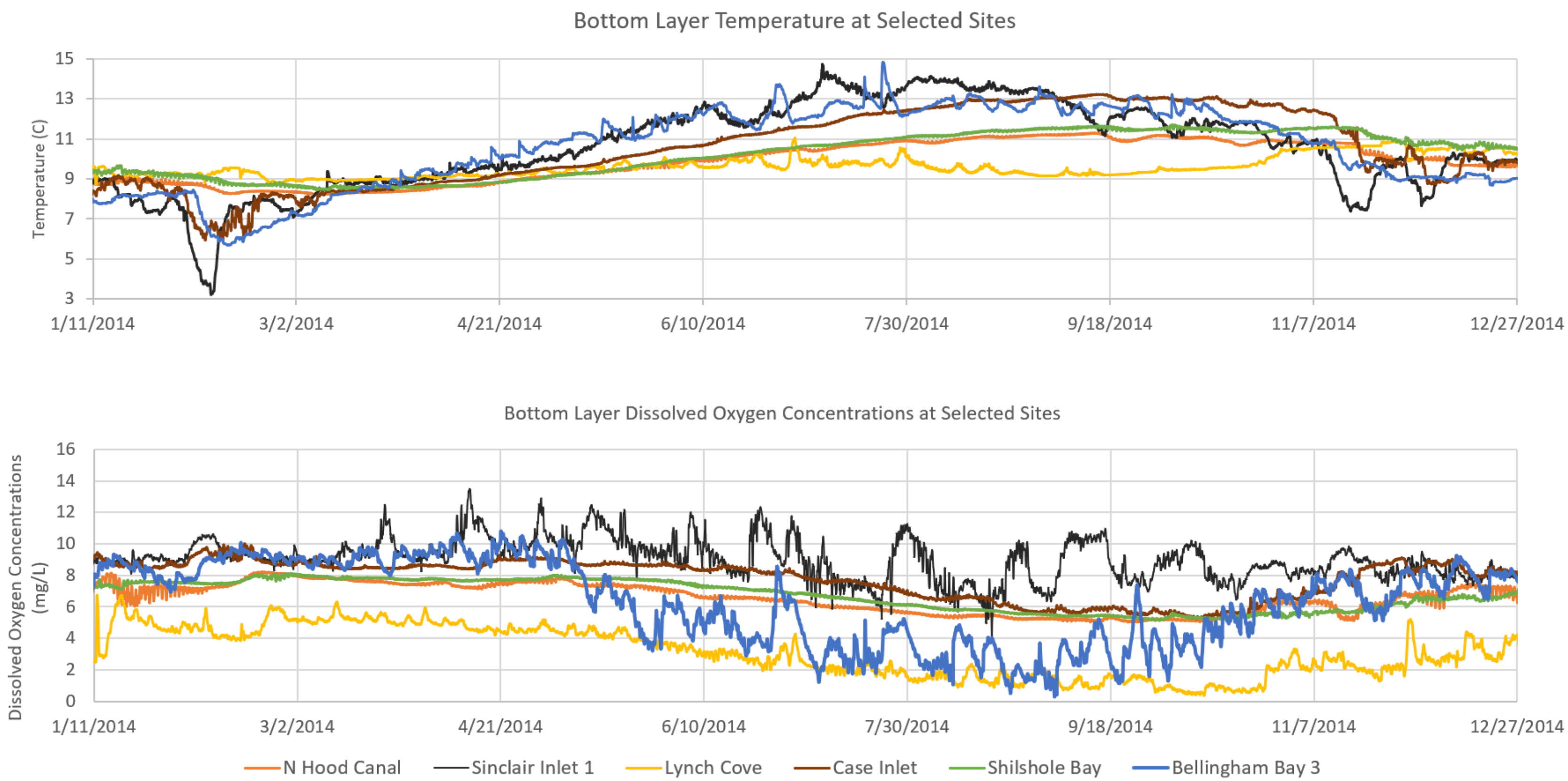

Figure I-21. Predicted Time Series for Temperature and Dissolved Oxygen in 2014 at Selected Sites.
Units for temperature are degrees Celsius, and for dissolved oxygen are mg/L.

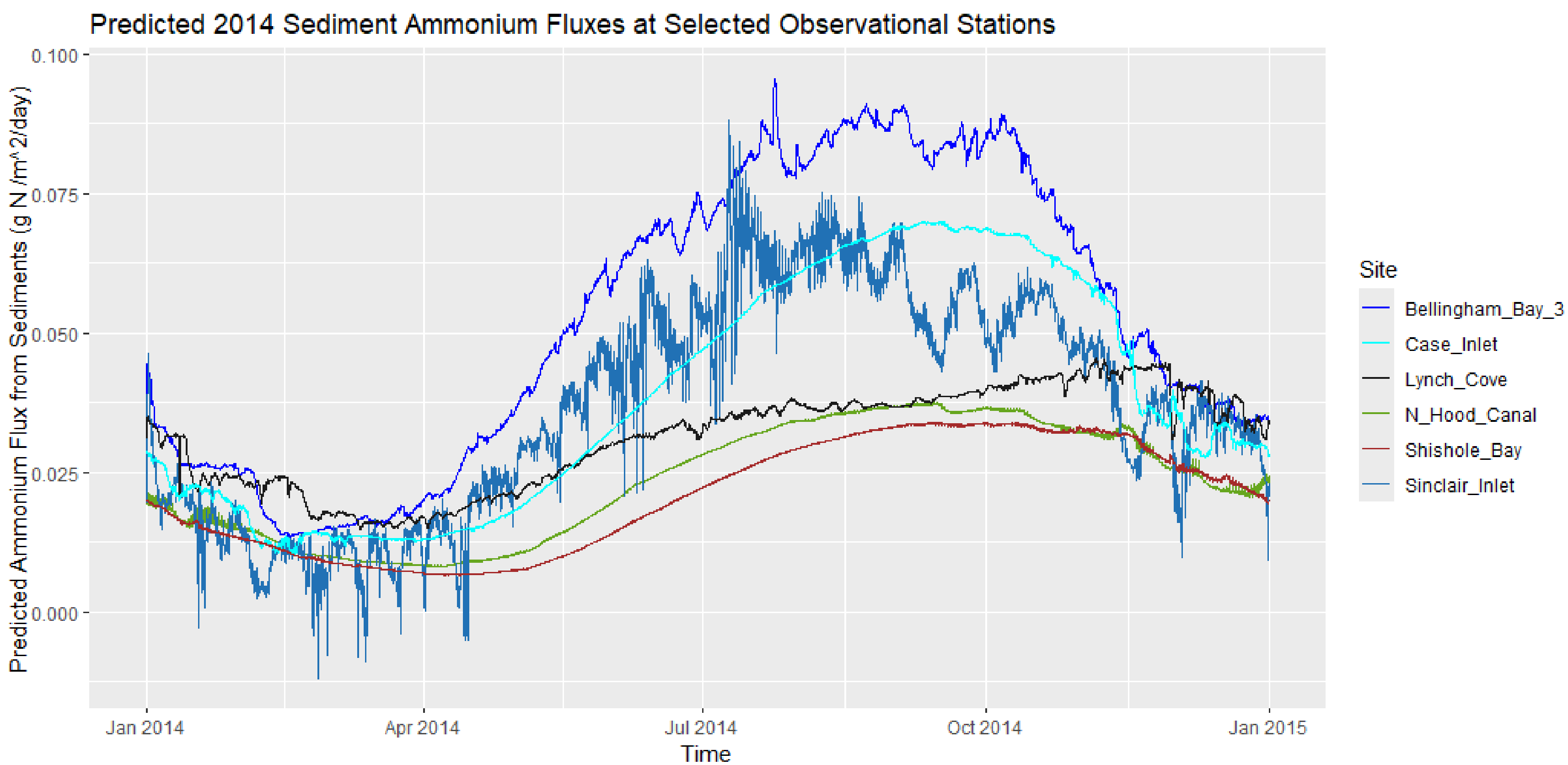

Figure I-22. Predicted Time Series for Ammonium Flux in 2014 at Selected Sites.
Units are g N/m^2/day.

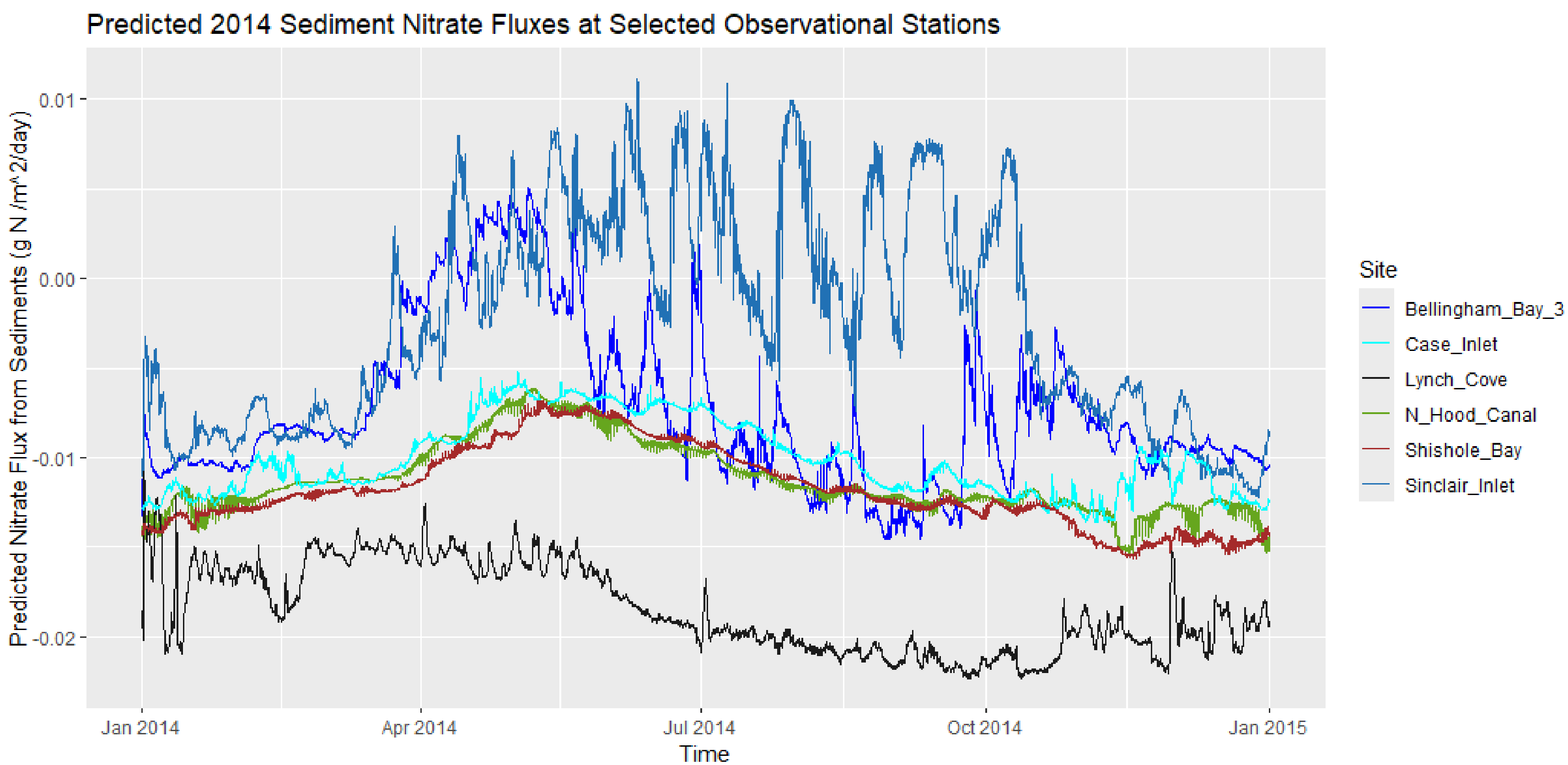

Figure I-23. Predicted Time Series for Nitrate Flux in 2014 at Selected Sites.
Units are g N/m^2/day.

Summary and Conclusions

We found good agreement between sediment oxygen demand and nitrogen flux SSM predictions and observations. Most predicted sediment oxygen demand, ammonium, and nitrate fluxes fall within 97.5 percentile confidence intervals of recently measured fluxes throughout Puget Sound (Merritt 2017; Santana and Shull 2023). The general magnitude and direction of nitrogen flux predictions fall within the range of values from an extensive compilation of nitrogen flux data for Puget Sound (Sheibley and Paulson 2014) and with other observations in the Salish Sea (Belley et al. 2016).

Predicted spatial flux patterns follow anticipated tendencies based on observational records. For example, shallower locations, such as those in South Sound, experience higher predicted SOD rates. The spatial variability of predicted sediment oxygen demand is similar between years. SSM predicts sediments to generally release NH_4^+ into the water column and to uptake NO_3^- from the water column. The annual median denitrification within sediments is close to the median springtime range that Santana and Shull (2023) calculated from the deviation of measured nitrogen-to-carbon ratios. SSM predicts that in terms of annual medians, sediments in terminal inlets and bays release more ammonium to the water column than other locations in the greater Puget Sound and uptake relatively less nitrate from the water column. In terms of nitrate uptake, Hood Canal is an exception—it is predicted to comparatively uptake more nitrate from the water column. Predicted reference conditions exhibit relatively lower fluxes.

Predicted SOD during the annual cycle shows a seasonal pattern consistent with that described in Pamatmat (1971). While predicted SOD curves generally follow labile POC curves, sharp SOD, ammonium, and nitrate flux swings may be ascribed to changes in temperature, variations in dissolved oxygen levels, and sudden shifts in the characteristics of the bottom water layer that could be due to variable mixing and flow regimes.

References

Ahmed A., C. Figueroa-Kaminsky, J. Gala, T. Mohamedali, G. Pelletier, and S. McCarthy. 2019. Puget Sound Nutrient Source Reduction Project, Volume 1: Model Updates and Bounding Scenarios. Publication 19-03-001. Washington State Department of Ecology, Olympia. https://apps.ecology.wa.gov/publications/SummaryPages/1903001.html.

Arndt, S., B. Jørgensen, D. LaRowe, J. Middelburg, R. Pancost, and P. Regnier. 2013. Quantifying the degradation of organic matter in marine sediments: A review and synthesis. Earth-Science Reviews 123: 53–86.

Belley R, Snelgrove PVR, Archambault P, Juniper SK. 2016. Environmental Drivers of Benthic Flux Variation and Ecosystem Functioning in Salish Sea and Northeast Pacific Sediments. PLoS ONE 11 (3): e0151110. doi:10.1371/journal.pone.0151110.

Berner, R. 1980. Early Diagenesis A Theoretical Approach, Princeton University Press, New Jersey.

Carpenter, R., M.L. Peterson, and J.T. Bennett. 1985. 210Pb-derived sediment accumulation and mixing rates for the greater Puget Sound region. Marine Geology. 64(1985)291–312.

Dalsgaard T, Thamdrup B, Canfield DE. 2005. Anaerobic ammonium oxidation (anammox) in the marine environment. *Res. Microbiol.* 156:457–64.

Devol, A. H. 2015. Denitrification, anammox, and N_2 production in marine sediments. Annual Review of Marine Science 7: 403–423.

Di Toro, D. 2001. Sediment Flux Modeling, John Wiley & Sons, Inc.

Engel, M., and S. Macko (editors). 1993. Organic Geochemistry: Principles and Applications. Plenum Press, New York.

Lavelle, J.W. G.J. Massoth, and E.A. Crecelius. 1985. Sedimentation Rates in Puget Sound from 210Pb Measurements, NOAA Technical Memorandum ERL PMEL-61.

Lavelle, J.W. G.J. Massoth, and E.A. Crecelius. 1986. Accumulation rates of recent sediment in Puget Sound, WA. Marine Geology. 72(1986)59–70

Martin, J.L. and T.A. Wool. 2013. Supplement to Water Analysis Simulation Program User Documentation. WASP Sediment diagenesis Routines: Model Theory and Users Guide. U.S. Environmental Protection Agency, Region 4, Atlanta GA.

Merritt, E. 2017. The influence of sedimentary biogeochemistry on oxygen consumption and nutrient cycling in Bellingham Bay, Washington. Thesis, Western Washington University, NSF REU at Shannon Point Marine Center, Anacortes.

Pamatmat, M., and K. Banse. 1969. Oxygen consumption by the Seabed II. In situ measurements to a depth of 180 m. Limnology and Oceanography 14(2): 250–259.

Pamatmat, M. 1971. Oxygen consumption by the Seabed Seasonal Cycle of Chemical Oxidation and Respiration in Puget Sound, Int. Review Hydrobiol. 56, 5, 769–793.

Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017. Salish Sea Model Sediment Diagenesis Module. Publication 17-03- 010. Washington State Department of Ecology, Olympia. https://apps.ecology.wa.gov/publications/SummaryPages/1703010.html

Rigby, E. 2019. Springtime benthic fluxes in the Salish Sea: Environmental parameters driving spatial variation in the exchange of dissolved oxygen, inorganic carbon, nutrients, and alkalinity between sediments and overlying water, Master of Science Thesis, Western Washington University.

Santana, E. and Shull D. 2023. Sedimentary Biogeochemistry of the Salish Sea: Springtime Fluxes of Dissolved Oxygen, Nutrients, Inorganic Carbon, and Alkalinity, Estuaries and Coasts 46:1208–1222. https://doi.org/10.1007/s12237-023-01197-8.

Sheibley, R.W., and Paulson, A.J. 2014. Quantifying benthic nitrogen fluxes in Puget Sound, Washington—A review of available data: U.S. Geological Survey Scientific Investigations Report 2014–5033, 44 p. http://dx.doi.org/10.3133/sir20145033.

Thamdrup, B., Dalsgaard, T. 2002. Production of N_2 through anaerobic ammonium oxidation coupled to nitrate reduction in marine sediments. Applied and Environmental Microbiology 68, 1312–1318.

Weakland, S., V. Partridge, M. Dutch. 2018. Sediment Quality in Puget Sound: Changes in Chemistry, Toxicity and Benthic Invertebrates at Multiple Geographic Scales, 1989–2015. Publication 18-03-004. Washington State Department of Ecology, Olympia. https://apps.ecology.wa.gov/publications/SummaryPages/1803004.html.