Weak, Low-Oxygen Exchange Flow Drives Hypoxia in Puget Sound's Inlets

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Abstract

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Puget Sound is a highly productive estuary, and many of its inlets experience seasonal hypoxia (dissolved oxygen concentration < 2 mg/L), posing a significant threat to bottom-dwelling species. Models predict that hypoxia is most prevalent near the terminus of branching channels (i.e., terminal inlets) throughout the region. However, not all of Puget Sound's terminal inlets become hypoxic and many remain oxygenated throughout the summer and fall. Therefore, to fully describe the underlying processes driving Puget Sound hypoxia, it is crucial to identify the characteristics which differentiate oxygenated inlets from hypoxic ones. Leading hypotheses that explain hypoxia include high productivity, low initial oxygen concentrations, and long flushing times.

A realistic numerical model of the region and surrounding coastal waters is used to identify the dominant factors contributing to hypoxia. Two-layer dissolved oxygen budgets are calculated with the Total Exchange Flow method in twenty-one terminal inlets across Puget Sound for the year 2017.

Biological oxygen drawdown rates in hypoxic inlets are found to be no higher than those in oxygenated inlets. Additionally, the net rate of dissolved oxygen decrease is similar in both hypoxic and oxygenated inlets during the summer. Instead, hypoxia in terminal inlets is driven by low inflowing oxygen concentrations and long flushing times, both of which are attributed to the exchange flow of the inlet.

These findings imply that management strategies that treat Puget Sound as an interconnected system may be more effective than strategies that target isolated hotspots of hypoxia.

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Dedication

For Amy

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1. Introduction

Puget Sound is a very productive estuary, and consequently many of its inlets experience stress from seasonal low dissolved oxygen (DO) concentrations (Albertson et al., 2007; Ahmed et al., 2021a). In this thesis, DO refers to DO concentration [mg/L] unless otherwise specified. Hypoxia (DO < 2 mg/L) poses a significant risk to ecosystems, often leading to habitat compression, physiological stress, changes in food web dynamics, and sometimes mass mortality of fish and invertebrates (Breitburg et al., 2018; Diaz and Rosenberg, 2008; Vaquer-Sunyer and Duarte, 2008). In Hood Canal, Puget Sound's most problematic basin, upwelling of hypoxic water has led to several serious fish kill events since the 2000's (Newton et al., 2007; Newton et al., 2011). These events underscore the importance of understanding Puget Sound's oxygen dynamics.

Much of the research on Puget Sound's oxygen dynamics has been concerned with anthropogenic stressors. Puget Sound is surrounded by several urban centers, like the Seattle-metropolitan area, with the total regional population surpassing 4.3 million people in 2020 (Puget Sound Regional Council, 2020). Anthropogenic activity can result in *eutrophication*, in which excess nutrient loads fuel photosynthesis, generating phytoplankton blooms and eventually dead organic matter (detritus). The sinking organic matter is broken down by microbes in the water column and in the sediments, which consumes oxygen. Prior modeling studies suggest that anthropogenic nutrient loads decrease DO and increase hypoxic extent, particularly in *terminal inlets*– the ends of branching channels throughout Puget Sound (Khangaonkar et al., 2018; Ahmed et al., 2021b). These studies motivated the Puget Sound Nutrient General Permit, which mandates enhanced nutrient removal processes for high discharge wastewater treatment plants (WWTPs; State of Washington Department of Ecology, 2021).

However, anthropogenic discharges alone do not fully explain hypoxia in Puget Sound. Results from modeling studies show that hypoxia develops even when all anthropogenic nutrients loads are eliminated (Khangaonkar et al., 2018; Khangaonkar and Yun, 2023). Hence, naturally occurring physical and biogeochemical processes play an important role in seasonal hypoxia. In a Hood Canal modeling study, Kawase and Bahng (2011) determined that natural processes contribute more to hypoxic conditions compared to anthropogenic nutrient loads. Similarly, a mass balance study by Steinberg et al. (2011) concluded that 98% of nutrients in Hood Canal's surface waters are of oceanic origin. To further complicate this issue, upgrading regional WWTPs will increase sewer bills resulting in affordability concerns and hardship for households earning at, or below, the median household income (Burke et al., 2023). To understand the role that anthropogenic discharges play relative to natural processes, and to best inform management of regional hypoxia, it is imperative to identify the dominant mechanisms leading to hypoxia in Puget Sound. In this thesis, I identify the leading order mechanisms contributing to hypoxia in Puget Sound's terminal inlets and explain the main differences between inlets which develop hypoxia and inlets which remain oxygenated.

1.1. Puget Sound characteristics

Puget Sound is a fjord-like estuary with intricate physical dynamics and features, all of which can influence its oxygen dynamics. The estuary lies within the Salish Sea and receives most of its ocean input via the Strait of Juan de Fuca (Figure 1a).

As a system that was carved by glaciers, Puget Sound is an exceptionally irregular network of channels (Figure 1b). The estuary has deep basins (average depth 70 m; MacCready, 2017) and tidally energetic sills that modify circulation mechanics (Ebbesmeyer et al., 1988; Ebbesmeyer and Barnes, 1980; MacCready et al., 2021). Each of Puget Sound's sub-basins have distinct characteristics. For instance, Hood Canal has weak circulation, weak tidal currents, and a long *flushing time* compared to Puget Sound's Main Basin (Ebbesmeyer et al., 1988; Mofjeld and Larson, 1984; MacCready et al., 2021). Puget Sound also has many branching channels and terminal inlets, which tend to be the locations most susceptible to hypoxia (Khangaonkar et al., 2018).

Notably, Puget Sound has an intense estuarine *exchange flow* characterized by a deep, landward flowing layer and a near-surface, seaward flowing layer (Sutherland et al., 2011; MacCready et al., 2021). This persistent flow generates an advective flux of oxygen at depth that replaces bottom waters with the DO of new water masses (e.g., Scully, 2013; Silva and Vargas, 2014). The exchange flow also plays a major role in regulating the estuary's flushing time. Sutherland et al. (2011) and MacCready et al. (2021) estimate an average flushing time of 40- to 60- days in the whole of Puget Sound. Long flushing times contribute to hypoxia by increasing the duration over which microbes respire oxygen in isolated bottom waters (Fennel and Testa, 2019).

1.2. Hypoxia framework

This study adopts a simple, but generalizable, framework to describe why a system may become hypoxic. Fennel and Testa (2019) explain that a system is more susceptible to hypoxia if its oxygen drawdown rate is high, its initial DO concentration is low, or its flushing time is long. This study refers to these *factors* influencing DO, as the Drawdown-Factor, DO_0-Factor and T_{flush}-Factor, respectively (Figure 2) .

In a given system, one can identify which of these factors, or combination of factors, is the dominant reason why the system may be hypoxic. For example, persistent hypoxia in the Baltic Sea is attributed to a combination of eutrophication and increasing oxygen consumption rate as well as its 30-plus year flushing time (Drawdown- and T_{flush}-Factors; Carstensen et al., 2014). Along the Oregon Continental Shelf, severe hypoxia has been linked to upwelling of oxygen-depleted and nutrient-rich waters which cause high primary production rates (DO_0- and Drawdown-Factors; Grantham et al., 2004). This thesis identifies the dominant factors that differentiate hypoxic terminal inlets from oxygenated terminal inlets in Puget Sound.

In Puget Sound, researchers have hypothesized that Drawdown-, DO_0-, and T_{flush}-Factors could all have an influence on DO concentrations. For example, scientists are concerned about hypoxia in Hood Canal and inlets in South Sound because they have high surface chlorophyll and low surface nitrate during the growing season– symptoms of eutrophication often linked to greater oxygen drawdown (Drawdown-Factor; Harrison et al., 1994; Richardson and Jørgensen, 1996; Albertson et al., 2007). In Hood Canal, Newton et al. (2011) have suggested that dense water intrusions which bring low DO water into the system (Deppe et al., 2018) may establish a low initial DO concentration for the following hypoxic cycle (DO_0-Factor). Researchers are also concerned about hypoxia in Hood Canal and some South Sound inlets because of their weak mixing, poor circulation, and long flushing times (T_{flush}-Factor; Harrison et al., 1994; Mackas and Harrison, 1997; Newton et al., 2011). Despite these prior studies, the dominant factors are still an active area of research. The goal of this study is to determine which factor, or combination of factors, is most important in establishing hypoxia in Puget Sound's terminal inlets.

As mentioned earlier, anthropogenic nutrient loads are of particular concern in Puget Sound. Many other hypoxic systems attribute high oxygen drawdown to anthropogenic nutrient loads such as the Baltic Sea (Carstensen et al., 2014), the Chesapeake Bay (Hagy et al., 2004; Li et al., 2016), the Gulf of Mexico (Rabalais et al., 2002), and the East China Sea (Wang et al., 2016). However, the Salish Sea is distinct from these other systems because over 90% of its nutrients come from natural oceanic exchange (Mackas and Harrison, 1997; Xiong et al., in review). Thus, the role of anthropogenic nutrient loads to Puget Sound's oxygen is complex and requires further study. This thesis focuses on modeling circulation, fluxes, and biological sources and sinks of oxygen within terminal inlets, without tracing the sources of nutrients and organic matter that fuel the biological activity within the inlet. A follow-up study will explicitly evaluate the model-predicted influence of wastewater treatment plant discharges on oxygen in Puget Sound.

1.3. Study outline

This thesis analyzes six years of hindcast results from a realistic (i.e., inputs based on real data) regional model of the Salish Sea and its surrounding waters, and describes an in-depth analysis of oxygen dynamics in terminal inlets for the year 2017. Section 2 summarizes methods and modeling set-up. Section 3 describes the factors that explain why some terminal inlets are hypoxic while others are oxygenated. Section 4 discusses the importance of the exchange flow to oxygen dynamics as well as other mechanisms that may influence DO concentrations in terminal inlets.

2. Methods

A numerical model is used to simulate hydrodynamics and biogeochemical cycles in Puget Sound. All of the post-processing methods were conducted in Python.

2.1. Model set-up

The experiments described in this thesis use LiveOcean (MacCready et al., 2021), a realistic numerical model of the Salish Sea and Washington/Oregon coast developed with the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005). LiveOcean has a horizontal resolution of 500 m within the Salish Sea, expanding to 3 km at the open boundaries. There are 30 vertical sigma-layers. Sigma-layers are vertical layers of the model grid that stretch vertically over changing bathymetry. LiveOcean generates atmospheric forcing from a Weather Research and Forecasting model (Mass et al,. 2003), tidal forcing from the TPXO 9.0 tidal model (Egbert and Erofeeva, 2002), and ocean boundary conditions from the Hybrid Coordinate Ocean Model (HYCOM;

Metzger et al., 2014). Ninety-eight WWTPs and 131 rivers were added to the LiveOcean model for this study, as discussed in Appendix A.

LiveOcean is coupled to a nutrient, phytoplankton, zooplankton, detritus, plus oxygen (NPZD+O) biogeochemistry module (Banas et al., 2009; Davis et al., 2014; Siedlecki et al., 2015; Xiong et al., in review). The NPZD+O module tracks pools of nitrogen as they are transferred between different forms. Oxygen is produced during photosynthesis and consumed by water column bacterial respiration, zooplankton egestion, nitrification, and sediment oxygen demand.

This thesis uses the cas7_t0_x4b version of LiveOcean. Xiong et al. (in review) discusses this model configuration and its evaluation in detail. The simulation was initialized on model-day 7 October 2012 and ran through June 2024 for this thesis. Appendix B discusses the procedure taken to ensure the model is "bit-reproducible," allowing exact comparison of experiments with different nutrient loading. This study treats 2013 as a spin-up year and analyzes Puget Sound-wide spatial distributions of hypoxia from 2014 through 2019, inclusive.

Although LiveOcean is built from realistic forcing and bathymetry, it is important to acknowledge that models are not reality (Oreskes et al., 1994). The results presented in this thesis shed light on key mechanisms influencing oxygen, but do not represent objective truth. Appendix C presents a brief discussion of modeling philosophy, and Appendix C.1 discusses LiveOcean's performance compared to observations in terminal inlets. To summarize, LiveOcean has a bias of -1.08 mg/L and a root mean squared error of 1.60 mg/L compared to DO observations in terminal inlets (see Figure C2 and Table C1).

2.2. Terminal inlet two-layer budgets

To study the processes causing hypoxia in terminal inlets, I developed two-layer (surface and deep) DO budgets in twenty-one terminal inlets across Puget Sound (Figure 3). I use the same methods as Xiong et al. (in review) to calculate the budget terms. This budget analysis focuses only on 2017, which had Puget Sound-wide hypoxic volumes similar to the median hypoxic volume of all simulation years (see Figure 4). An additional benefit to 2017 is that it had several years of spin up.

Equations 1 and 2 show the surface and deep layer budget expressions, respectively.

$$\frac{\partial}{\partial t}\int_{V_{surf}} \mathrm{DO}\, dV_{surf} = Q_{out}DO_{out} + \text{airsea exchange} + \text{rivers} + \text{biology} + \text{vertical exchange} \qquad \text{(Eq. 1)}$$

$$\frac{\partial}{\partial t}\int_{V_{deep}} \mathrm{DO}\, dV_{deep} = Q_{in}DO_{in} + \text{WWTPs} + \text{biology} + \text{vertical exchange} \qquad \text{(Eq. 2)}$$

The left-hand side of both equations is the storage term, which represents the net change in volume-integrated oxygen within each layer. This term is calculated as the daily change in volume-integrated oxygen within each layer of the budget. The first term on the right-hand side of both equations is the transport of oxygen in and out of the inlet via the estuarine exchange flow. Q_{in} and Q_{out} are the volumetric inflow and outflow of the exchange flow, respectively. The sign convention is that Q_{in} is positive and Q_{out} is negative. DO_{in} and DO_{out} are the flux-weighted average DO concentrations of the inflowing and outflowing branches of the exchange flow, respectively. These exchange flow terms are calculated using the Total Exchange Flow (TEF; MacCready, 2011; Lorenz et al., 2019) method. These budgets assume that all inflow enters the terminal inlet through the deep layer and all outflow exits from the surface layer. The surface layer also includes an air-sea gas exchange term, which is calculated from wind speed and the Schmidt number (see Xiong et al., in review, for more details). Rivers provide a source of oxygen to the surface layer, and WWTPs provide a source of oxygen to the deep layer. These terms are calculated as the volumetric inflow rate of the river, or WWTP, times the DO concentration of the inflowing water (constant 5.9 mg/L concentration for WWTPs). The biology terms include a combination of all biological sources and sinks of oxygen, as parametrized in the NPZD+O module: photosynthesis, respiration, nitrification, and sediment oxygen demand. They are calculated following the method outlined in Xiong et al. (in review).

Lastly, I calculate the difference between the storage term and the sum of all terms on the right-hand sign of Equations 1 and 2, and I ascribe the residual to the vertical exchange term. The vertical exchange term represents the sum of advective transport and diffusive mixing of oxygen between the surface and deep layers. The sum of surface and deep layer vertical transport terms represents the error in the budget. In the inlet with the highest relative error (Lynch Cove), the annual average magnitude of error is 3.9% of the annual average magnitude of oxygen transport via the inflowing branch of the exchange flow (i.e., $Q_{in}DO_{in}$). These small errors suggest that the oxygen budgets are generally well-conserved.

A 71-hour lowpass Godin filter (Thomson and Emery, 2014) is applied to all budget terms to obtain a tidally-averaged, daily time series for every rate term. Although I calculated budgets for both a surface and a deep layer, my analysis focuses only on the less-oxygenated deep layer.

Note that in the results presented in Section 3.2, I combine the physical terms into a single term called "Exchange Flow & Vertical Transport." I also combine the biological processes into a single term called "Photosynthesis & Consumption." Because the "Photosynthesis & Consumption" term is the sum of all biological rate terms, it represents the *net biological drawdown* rate of the system (slope of lines in the hypoxia framework; Figure 2). Drawdown is not to be confused with the *net decrease* of oxygen within the system. In this context, *drawdown* refers only to the sum of biological processes, while the *net decrease* refers to the sum of all processes– both biological and physical in nature.

I applied a uniform criterion to select the interface depth of the terminal inlets based on typically-observed vertical density profiles. The interface between the layers is ⅓ the distance from the surface, relative to the deepest depth of the inlet. For inlets shallower than 13 m, the interface depth is ½ the distance from the surface.

2.3. Flushing time

Flushing times are calculated using the total volume of the inlet and the volumetric inflow rate of the exchange flow (Q_{in}):

$$T_{flush} = \frac{V_{inlet}}{Q_{in}} \quad \text{(Eq. 3)}$$

Recall that Q_{in} is calculated using the TEF method. This quantification of flushing time is based on the definition described in Monsen et al. (2002). Here, T_{flush} is a scale representation of the time it takes to fully replace the volume of fluid in the inlet. This definition assumes that tracers (i.e., oxygen) are homogeneously distributed in the volume, whereas in reality tracers are inhomogeneously distributed and thus some tracers may be retained in the volume for much longer than T_{flush}. Therefore, flushing time is an appropriate time scale for estimating retention, but it is not the exact retention time.

3. Results

Section 3.1 describes the temporal and spatial patterns of hypoxia across Puget Sound during the years 2014 through 2019. Section 3.2 compares the 2017 DO budgets of hypoxic and oxygenated terminal inlets. Section 3.3 investigates which other factors distinguish hypoxic inlets from oxygenated inlets.

3.1. Temporal and spatial distribution of hypoxia in Puget Sound (2014 - 2019)

Figure 4 shows the annual time series of hypoxic volume in Puget Sound from 2014 - 2019. In this analysis, data from the Strait of Juan de Fuca and Strait of Georgia are omitted because they may have different dynamics than Puget Sound. Figure 4a shows the region over which hypoxic volume is integrated.

There is a seasonal cycle in the hypoxia time series (Figure 4b). Hypoxia develops during the spring, peaks in late summer and early fall, then subsides during the fall and winter. Peak hypoxic volume varies from nearly 10 km^3 (~5% of Puget Sound volume) in 2014 to nearly 13 km^3 (~7% of Puget Sound volume) in 2018. Although there is interannual variability in the timing and magnitude of hypoxic volume in Puget Sound, hypoxic volume maxima consistently peak during the months of August and September. For the remaining analysis, the "hypoxic season" will be defined as August 1 through September 30.

To study the spatial patterns of hypoxia across Puget Sound, I examine DO concentrations in the bottom sigma-layer. My early analysis suggested that the lowest DO concentrations primarily occur in the bottom sigma-layer, validating this approach (see Appendix D). Figure 5a shows the average number of days per year that each LiveOcean grid cell experiences bottom hypoxia. The average number of days with bottom hypoxia is calculated by first determining the six-year mean bottom DO concentration on each yearday, then summing the days in which the mean bottom DO is less than 2 mg/L. Although the persistence of hypoxia varies between years, the locations which develop hypoxia are similar between years (Figures 5b through 5g) suggesting that there are recurring "hotspots" of low DO. These hotspots occur throughout Hood Canal, and in the terminal inlets of Penn Cove, Holmes Harbor, Port Susan, and Case Inlet, consistent with prior modeling studies that identified terminal inlets as problematic regions (Khangaonkar et al., 2018; Ahmed et al., 2021b; Khangaonkar and Yun, 2023).

A map of bottom oxygen provides another means of investigating the spatial patterns of Puget Sound's DO, without the limitation of a hypoxic threshold. Figure 6a shows the six-year mean bottom DO concentration during the hypoxic season. Figures 6b through 6g show the difference between an individual hypoxic season's average bottom DO and the six-year mean. Importantly, although some terminal inlets develop hypoxia during the hypoxic season, other terminal inlets remain oxygenated. The remaining analysis focuses on the factors and mechanisms that differentiate hypoxic terminal inlets from oxygenated terminal inlets.

3.2. Terminal inlet two-layer budgets (2017)

The final budget results discussed in this section focuses on *thirteen* terminal inlets throughout Puget Sound. Although the analysis began with twenty-one terminal inlets, I find that shallow inlets (mean depth < 10 m) never develop hypoxia because they are fully within the photic zone and hence produce oxygen throughout the water column. Thus, deep depth (mean depth > 10 m) is a necessary, but insufficient, criterion for developing hypoxia in terminal inlets. Remaining analyses focus on the thirteen deeper terminal inlets (mean depth > 10 m), which exhibit a combination of both oxygenated and hypoxic behavior. The shallow and deep inlets are denoted in Figure 3.

There are six hypoxic terminal inlets throughout Puget Sound, including two within Hood Canal (labeled in Figure 5a). During the 2017 hypoxic season, the mean percent hypoxic volume (compared to the inlet volume) within these inlets were 2.1% in Case Inlet, 10.3% in Penn Cove, 11.4% in Port Susan, 23.1% in Holmes Harbor, 48.0% in Dabob Bay, and 60.5% in Lynch Cove. All other terminal inlets had negligible (< 0.02%) hypoxic volume during the hypoxic season.

My budget analysis focuses on the terms influencing deep layer DO (DO_{deep}) concentrations, which is calculated from a larger volume than the bottom sigma-layer alone. To verify that the deep layer budget analysis method does not filter out the hypoxic signal, Figure 7a compares the monthly mean percent hypoxic volume of each inlet (relative to the inlet volume) to its monthly mean DO_{deep} concentration. For mean DO_{deep} concentrations less than 3 mg/L, percent hypoxic volume has a strong correlation to DO_{deep}. For mean DO_{deep} concentrations greater than 5.5 mg/L, the terminal inlets never experience hypoxia. Therefore, DO_{deep} is a useful proxy for differentiating between the most hypoxic and oxygenated terminal inlets. However, when mean DO_{deep} is between 3 and 5.5. mg/L, the relationship between DO_{deep} and percent hypoxic volume is muddled. The analysis in this thesis focuses on the dominant factors differentiating hypoxic and oxygenated inlets, and the more nuanced mechanisms are beyond the scope of this study.

Before analyzing the budgets, I first selected a time frame over which to compare the inlets' budget rate terms. Ideally, all thirteen terminal inlets should experience a net decrease of DO during this time frame. Figure 7b shows the 2017 time series of DO_{deep} in all thirteen terminal inlets. Note that all inlets experience a seasonal cycle in DO_{deep}, with DO_{deep} reaching a minimum during late summer to early fall. The timing of this seasonal cycle in DO_{deep} is consistent with observed patterns in Puget Sound's productivity (Newton and Van Voorhis, 2002). For the budget comparison, I selected the period from mid-July to mid-August because DO is decreasing in all thirteen terminal inlets during this time frame (denoted as the region between the vertical bars in Figure 7b).

Figure 8 shows an example budget for Lynch Cove. The time series in Figure 8a shows the time rate of change of all terms in Lynch Cove's deep layer oxygen budget in 2017. The period between the vertical bars denotes the drawdown period, in which DO is net decreasing in the deep layer of the inlet. Figure 8b shows the average value of each budget rate term in Lynch Cove during the drawdown period. Note that in Figure 8b, the budget terms have been normalized by the volume of Lynch Cove's deep layer. Following the same procedure for Lynch Cove, I calculated similar oxygen budgets for all thirteen inlets over the drawdown period.

Over the mid-July to mid-August drawdown period, I compare the deep layer budgets of all seven oxygenated inlets to all six hypoxic inlets (Figure 9). The budget rate terms are normalized by the volume of each inlet's deep layer. Figure 9a shows a breakdown of all individual budget rate terms, and Figure 9b shows a summarized budget with the rate terms consolidated into either a physical "Exchange Flow & Vertical Transport" term or a biological "Photosynthesis & Consumption" term.

The mean biological oxygen drawdown rate ("Photosynthesis & Consumption" term in Figure 9b) is -0.198 mg L^{-1} d^{-1} and -0.097 mg L^{-1} d^{-1} for oxygenated and hypoxic inlets, respectively. The mean net decrease rate ($\frac{d}{dt}DO$ term in Figure 9) is -0.044 mg L^{-1} d^{-1} and -0.036 mg L^{-1} d^{-1} for oxygenated and hypoxic inlets, respectively. These net decrease rates for Puget Sound terminal inlets are of the same order of magnitude as, but slightly smaller than, observed rates in Long Island Sound (2.4 mmol m^{-3} d^{-1} = -0.077 mg L^{-1} d^{-1}; O'Donnell et al., 2008) and Chesapeake Bay (1.88 - 3.19 mmol m^{-3} d^{-1} = 0.06 - 0.10 mg L^{-1} d^{-1}; Kemp et al., 1992; Testa and Kemp, 2014).

To quantitatively compare the terminal inlet budgets, I conduct a two-sided Welch's unequal variances *t*-test with a null hypothesis that hypoxic inlets and oxygenated inlets have the same mean drawdown rate (α=0.05; Welch, 1947). The *t*-test results in p = 0.133, indicating that hypoxic inlets and oxygenated inlets do not have different oxygen drawdown rates ("Photosynthesis & Consumption" term in Figure 9b). Therefore I conclude that hypoxia in terminal inlets is *not* driven by the local rate of oxygen drawdown (i.e. *not* the Drawdown-Factor).

Furthermore, the net effect of all physical and biological processes appears to result in a similar net decrease rate in all inlets ($\frac{d}{dt}DO$ term in Figure 9). Applying a two-sided Welch's *t*-test to these terms, I obtain p = 0.248, suggesting that the mean net decrease in DO_{deep} is also similar between both oxygenated and hypoxic inlets in Puget Sound.

Note that although WWTPs are included in the budget analysis, they are not shown in Figures 8 and 9. This is because the direct contribution of WWTPs to the terminal inlet oxygen budgets is insignificant relative to the other terms. However, this finding does not imply that WWTP impacts are entirely negligible. WWTPs could still indirectly influence hypoxia by changing the DO of inflowing water, or by altering the influx of nutrients and organic matter to terminal inlets. These analyses will be addressed in a follow-up study.

3.3. Dominant factors influencing terminal inlet DO (2017)

The prior budget analysis sheds light on processes influencing the rate of oxygen production and drawdown within the terminal inlets– which is useful for testing whether the Drawdown-Factor plays a dominant role in hypoxia development. What the budget analysis does not do is provide insight into the ambient DO concentrations of the inlets and the amount of time that water spends in the inlets– the DO_0- and T_{flush}-Factors, respectively. Because the exchange flow is the largest source of oxygen to the deep layer of terminal inlets (Figure 9a), the exchange flow likely establishes the initial DO concentration of the inlets' deep layers.

To test whether inflowing DO into the inlet is low (DO_0-Factor), or whether the flushing time of the inlet is long (T_{flush}-Factor), I plot monthly mean DO_{deep} versus monthly mean DO_{in}, colored by monthly mean T_{flush}, of each inlet (Figure 10a). There is a strong correlation between DO_{deep} and DO_{in}. Additionally, many oxygenated inlets have matching DO_{deep} and DO_{in} suggesting that DO_{in} plays a dominant role in establishing the deep DO concentrations of the terminal inlets. Low DO inlets that tend to have $DO_{deep} < DO_{in}$ also tend to have longer T_{flush}, implying that more oxygen can be drawn down from the inlet when the flushing time is long. Thus, for Puget Sound terminal inlets, both low initial DO (DO_0-Factor) *and* long flushing times (T_{flush}-Factor) are dominant factors in establishing DO concentrations.

I extend this analysis to examine whether DO_{in} and T_{flush} can also explain the percent hypoxic volume in terminal inlets. Figure 10b shows DO_{in} versus T_{flush} colored by monthly mean percent hypoxic volume of the inlet. While a combination of low DO_{in} and high T_{flush} distinguishes the most hypoxic inlets from the most oxygenated ones, there remains ambiguity in distinguishing hypoxic inlets with mid-level DO_{in} and T_{flush}. In other words, DO_{in} and T_{flush} coarsely explain hypoxia in terminal inlets.

4. Discussion

This section compares results to existing literature and contextualizes findings within the hypoxia framework introduced in Section 1.2. Additional discussion reflects on the importance of the exchange flow and introduces other mechanisms that may influence terminal inlet DO concentrations.

4.1. Model comparison of predicted hypoxia

Previous studies have used a different numerical model, the Salish Sea Model, to study the oxygen dynamics of Puget Sound (Khangaonkar et al., 2018; Ahmed et al., 2021b; Khangaonkar and Yun, 2023). Ahmed et al. (2019a) produced a time series of Puget Sound hypoxic volume for the year 2006 (see Figure 38 in their study). They found that under existing loading conditions, hypoxic volume peaks at 3 km^3. Although the LiveOcean simulation does not extend back to 2006, a 3 km^3 hypoxic volume is well below the range of peak hypoxic volumes shown in Figure 4b. Moreover, Khangaonkar et al. (2018) produced a map of the number of days in 2014 with bottom hypoxia (their Figure 19a) which I recreate in this study (Figure 5). In Hood Canal, they estimate roughly 100 fewer days of bottom hypoxia than LiveOcean estimates. LiveOcean also predicts hypoxia in Case Inlet and Holmes Harbor which Khangaonkar et al. (2018) does not predict.

There are many possible reasons for these differences. For instance, the Salish Sea Model has higher resolution in Puget Sound terminal inlets compared to LiveOcean (200 m vs. 500 m; Khangaonkar et al., 2017), which could result in a larger hypoxic volume estimate from LiveOcean. Different choices in the turbulence parameterizations and biogeochemistry modules could also contribute to differences in the resulting DO concentrations of the two models. Furthermore, LiveOcean tends to underestimate DO concentrations relative to observations (bias of -1.1 mg/L in terminal inlets; see Appendix C.1). When using a hard threshold, such as 2 mg/L, it takes only a small deviation in DO to push a grid cell’s oxygen concentration across the hypoxic threshold. Intermodel comparison is beyond the scope of this study, but these large discrepancies between the models warrant future investigation.

4.2. Seasonal cycle of DO_{deep}, DO_{in}, and T_{flush}

The relative influence of DO_{in} and T_{flush} on the seasonal cycle of DO_{deep} is inlet-dependent. To illustrate, I compare the seasonal cycle of DO_{deep} in Crescent Bay (Figure 11a) to that of Lynch Cove (Figure 11b). In Crescent Bay, T_{flush} is mostly constant throughout the year and monthly mean values of DO_{deep} and DO_{in} always fall on a line with a slope ≈ 1, suggesting that the seasonal cycle of DO_{deep} is primarily driven by a seasonal cycle in DO_{in}. In contrast, the monthly mean values of DO_{deep} and DO_{in} in Lynch Cove *sometimes* fall on a line with slope ≈ 1 (Figure 11b), but there is also a larger DO_{deep} deficit relative to DO_{in} at times when T_{flush} is long. These results suggest that seasonal cycles of both DO_{in} and T_{flush} are relevant to Lynch Cove's seasonal cycle of DO_{deep}. Because T_{flush} is inversely dependent on Q_{in} (Equation 3), the seasonal cycle in exchange flow strength thus contributes to the seasonal cycle of DO_{deep} in Lynch Cove. Thus, a combination of DO_{in} and the exchange flow strength explains a large portion of the seasonal and inter-inlet variability of DO_{deep}.

One lingering question is whether long flushing times fully explain the deficit in DO_{deep} relative to DO_{in}. Figure 11c investigates this question, showing the monthly mean DO deficit ($\Delta DO = DO_{in} - DO_{deep}$) plotted versus the monthly mean flushing time of each inlet. For hypoxic inlets, there is a reasonable correlation between ΔDO and T_{flush}, which supports the hypothesis that longer flushing times result in greater oxygen consumption (Fennel and Testa, 2019). Despite this correlation, variability in flushing time does not account for all of the variability in ΔDO. For example, Holmes Harbor has a relatively large DO_{deep} deficit, but a relatively short T_{flush}. Conversely, Dabob Bay experiences the longest flushing time of all inlets, but does not experience the largest DO_{deep} deficit. Therefore, other processes must also influence variability in oxygen consumption within the inlet.

4.3. Contextualizing results within the hypoxia framework

This thesis invoked a framework that simplifies the drivers of hypoxia to only three factors: high oxygen drawdown rates (Drawdown-Factor), low initial DO concentrations (DO_0-Factor), and long flushing times (T_{flush}-Factor). The results of this thesis suggest that the Drawdown-Factor does not differentiate between Puget Sound's hypoxic and oxygenated terminal inlets, and the DO_0- and T_{flush}-Factors are what drive hypoxia. Significantly, the exchange flow is a critical component to these factors. Figure 12 shows an updated hypoxia framework schematic to reflect my findings in Puget Sound terminal inlets and to emphasize the significance of the exchange flow.

The results in this study suggest that DO decreases at a similar rate in both hypoxic and oxygenated inlets (recall Section 3.2), which is represented by equivalent slopes in the updated hypoxia framework schematic (Figure 12). Notably, the slope is now labeled as $\frac{d}{dt}DO$ (i.e., the sum of physical and biological processes), rather than just biological drawdown. This is because biological drawdown does not accurately represent the rate of decrease of oxygen in Puget Sound's terminal inlets. Instead, the net decrease of oxygen is the result of physical sources of oxygen (positive) and biological sinks of oxygen (negative), which are nearly equal in magnitude (Figure 9b). The physical source of oxygen is, itself, a balance between large influxes of oxygen via the exchange flow, and large advective losses of oxygen via vertical transport. In fact, these two terms are the largest terms in the entire budget (Figure 9a). Despite being the difference between two large terms, the "Exchange Flow & Vertical Transport" term is always a net source of oxygen to the inlets. The reason this term is always positive is because the exchange flow has higher inflowing DO than the vertical advective losses, since biological processes consume oxygen in the inlets thus decreasing the outflowing DO concentration.

In Puget Sound inlets, the DO_0-Factor is driven by the inflowing DO concentrations of the exchange flow. Thus, Figure 12 describes inlets with low initial DO concentrations as having "Low-oxygen exchange flow." Because DO_{deep} is strongly correlated to DO_{in} (Figure 10a), sub-basin DO conditions are important in establishing conditions inside of the inlet. For example, the oxygenated conditions of the Main Basin inlets (Figures 5a and 6a) are likely related to high ambient DO concentrations of the Main Basin. The Main Basin is unlikely to develop hypoxia because it has strong circulation (MacCready et al., 2021; Ebbesmeyer et al., 1988). The dependence of inlet DO on inflowing water properties has been documented in other systems as well, such as micro-basins in the Chilean Patagonia Inland Sea where susceptibility to hypoxia is linked to the oxygen content of the inflowing water masses (Silva and Vargas, 2014).

The T_{flush}-Factor relates to the strength of the exchange flow in each terminal inlet. In Figure 12, inlets with long flushing times are thus described as having "Weak exchange flow." The TEF method used to calculate exchange flow strength is agnostic to the underlying mechanism driving the exchange flow. Hence, one major question that remains is: what drives the strength of the exchange flow in different terminal inlets? Some terminal inlets have rivers at their heads (e.g., Lynch Cove and Commencement Bay), and may thus develop classical gravitational circulation (Hansen and Rattray, 1965). In inlets without major rivers, the processes driving estuarine exchange might instead look like tidal pumping, an asymmetry in salt flux during flood and ebb tide (Chen et al., 2012). MacCready and Geyer (2024) found that the tidal pumping mechanism is necessary, but insufficient, to describe Puget Sound's exchange flow. It is also possible that inlets in Whidbey Basin, which receives roughly 30% of Puget Sound's river discharge, could also develop an inverse gravitational exchange flow when the basin salinity is lower than the inlet salinity. These distinct exchange flow mechanisms are still an active area of research, and Puget Sound offers a unique opportunity to study them in twenty-one inlets. It is important to understand the mechanisms of the exchange flow because it plays a key role in establishing terminal inlet hypoxia.

Figure 12 also shows a dashed line for "worst-case scenario" inlets that have both long flushing times (weak exchange flow) and low initial DO (low-oxygen exchange flow). Lynch Cove is an example of such an inlet. Lynch Cove receives inputs of low DO water from Hood Canal, which is well documented to be a hypoxic sub-basin with weak mixing and weak circulation (MacCready et al., 2021; Ebbesmeyer et al., 1988; Newton et al., 2007; Newton et al., 2011; Harrison et al., 1994). In addition to having low initial DO, Lynch Cove has a relatively long flushing time (~25 days; see Figures 11b and 11c), which provides time for biological processes to further draw down the inlet's oxygen.

4.4. Other mechanisms

Hypoxia is the result of a myriad of physical and biogeochemical processes and their interactions. This subsection discusses some other mechanisms that may play a role in Puget Sound oxygen dynamics and may potentially explain some of the variability in Figure 10b. These mechanisms include tracer retention, spring bloom timing, and stratification and wind effects.

Puget Sound has retentive properties. Given its strong exchange flow, Puget Sound is likely to retain sinking detritus since the deep layer of the exchange flow is usually directed up-estuary (Geyer and MacCready, 2014). The retention of organic matter could increase respiration towards the landward end of the system. Based on observations, Feely et al. (2010) concluded that inorganic nutrient concentrations within Hood Canal are higher than at its seaward entrance due to landward respiration during the summer. Furthermore, the sills at each end of Puget Sound's Main Basin create pathways for recirculation that can trap nutrients in the estuary for longer periods of time than if there were no sills at all (Ebbesmeyer and Barnes 1980; Ebbesmeyer et al., 1988). Perhaps the retentive nature of Puget Sound's terminal inlets differs from one another. Lynch Cove and inlets in South Sound, for instance, may accumulate more organic matter because of their locations at the landward end of Puget Sound's exchange flow. Future WWTP discharge experiments should pay attention to variability in how nutrients and organic matter are retained in the different inlets, and whether this variability contributes to the susceptibility of an inlet to develop hypoxia.

Another consideration is the onset and duration of oxygen decrease in each terminal inlet, which can vary considerably between the inlets (Figure 7b). Based on monitoring records, MacCready and Banas (2016) observed that the timing of spring blooms can vary between different inlets as well. Puget Sound regions that have spring blooms earlier in the year are likely to also experience oxygen consumption earlier in the year. This earlier net decrease can lead to lower DO bottom waters during the hypoxic season (Newton et al., 2011). Because terminal inlets are strongly influenced by DO_{in}, spring bloom dynamics outside of the inlet may also play a role in establishing hypoxia within the inlet.

Stratification also plays an important role in oxygen dynamics. Persistent stratification suppresses vertical mixing and limits ventilation of bottom waters, which can lead to periods of sustained oxygen depletion (e.g., Long Island Sound; Wilson et al., 2008). Stratification strength varies greatly across Puget Sound, with Hood Canal and Whidbey Basin being strongly stratified much of the year (Ebbesmeyer et al., 1988; Newton and Van Voorhis, 2002; Newton et al., 2011). Differences in stratification strength can result in different levels of reaeration in terminal inlet bottom waters. Therefore, vertical mixing is often a source of oxygen to deep layers. However, Figure 9a suggests that vertical transport is a sink, rather than a source, of oxygen between mid-July through mid-August. The reason for this is that vertical transport is the net result of both advective and diffusive fluxes of oxygen, and advective losses due to exchange flow convergence are greater than sources due to turbulent mixing of oxygen from the surface. Nonetheless, strong vertical mixing could still manifest as a reduction of the net DO decrease rate. Given the limitations of my analysis methods, I am unable to explicitly evaluate the role of stratification and vertical mixing. However, future research could explore spatial and temporal variability in stratification and mixing due to river discharge, due to tidal currents, or due to along-channel wind-stress, which also plays a role in setting up or breaking down stratification (Scully et al., 2005).

5. Conclusion and future work

In this study, I use a realistic numerical model of the Salish Sea and surrounding coastal waters to study the mechanisms leading to hypoxia in Puget Sound's terminal inlets. The model predicts that both the most extreme high DO and the most extreme low DO concentrations occur in terminal inlets across Puget Sound. To study these extremes in greater detail, I constructed two-layer oxygen budgets within twenty-one terminal inlets throughout Puget Sound. The model results suggest that biological drawdown rates are *not* higher in hypoxic inlets than in oxygenated inlets, meaning that local biological processes are not the main driver of hypoxia in terminal inlets. In fact, oxygen decreases at a similar rate during mid-July through mid-August in both hypoxic and oxygenated inlets. Instead, terminal inlet DO concentrations are largely determined by the DO concentration of the inflowing branch of the exchange flow. Inlets with long flushing times also tend to have a lower inlet DO relative to the inflowing DO concentration. Because inflowing DO concentrations and flushing times are both modulated by the exchange flow, the exchange flow plays a crucial role in establishing hypoxia in Puget Sound's terminal inlets. Thus, it will be valuable for future research to investigate the physical mechanisms driving the exchange flow in different inlets.

The major implication of this work is that hypoxia in Puget Sound terminal inlets is not driven by differences in local biological processes. Rather, it is mainly driven by external physical mechanisms– a combination of the source water properties and the exchange flow strength. This finding implies that nutrient inputs anywhere in Puget Sound have the potential to influence oxygen dynamics in inlets prone to hypoxia. In the context of nutrient management and oxygen monitoring decisions, I recommend strategies that consider Puget Sound holistically and treat hypoxic hotspots as the endmembers of a highly connected system.

5.1. Future work

This study is the first step in a larger effort to understand the dominant mechanisms that control oxygen in Puget Sound. Though this analysis uncovered key mechanisms which differentiate between oxygenated and hypoxic inlets, a detailed description of the processes and dynamics that lead to hypoxia is still unresolved. One important remaining question is the role of anthropogenic nutrient loads via WWTP discharges relative to the role of other hypoxic mechanisms.

In a future study, I will directly investigate the impact of WWTPs on Puget Sound oxygen based on a model comparison study. I will run LiveOcean with zero nutrient concentration in the WWTP effluent over the same simulation period as used in the present study. Then I will compare this "natural" simulation to the current simulation ("anthropogenic"), a condition which includes realistic nutrient concentrations and flows in the WWTP discharges.

As part of my comparison procedure, it will be instructive to repeat many of the same analysis steps taken in this study. For example, I will consider how the duration of hypoxia and spatial distribution of bottom DO concentrations differs between the natural and anthropogenic test cases. Quantifying differences in the DO budgets of the two test conditions may also help elucidate whether WWTPs impact inflowing DO concentrations to, or oxygen drawdown rates within, terminal inlets.

As an additional step, I will construct budgets of dissolved inorganic nitrogen ($NH4^+ + NO3^-$) to track how the flux of nutrients changes in the presence of WWTPs. These nutrient budgets will help identify which terminal inlets receive more WWTP loading compared to other inlets. This analysis is not the same as determining which terminal inlets are more strongly *impacted* by WWTP loading. The response of a system to nutrient inputs depends on its current trophic state, meaning that large nutrient inputs will have a smaller effect on locations with already high ambient nutrient concentrations (Harrison et al., 1994). Thus, my analysis will seek to quantify the difference in DO concentrations between the anthropogenic and natural runs as they relate to both WWTP loading and the background trophic level. The goal of this work is to inform the best nutrient management practices in Puget Sound.

Appendix A. Tiny river and point source (TRAPS) details

One recent improvement to LiveOcean was the addition of Tiny Rivers And Point Sources (TRAPS). The prior version of LiveOcean (described in MacCready et al., 2021) included only 45 major rivers using data from USGS gauged rivers and Environment Canada. I use the term “tiny rivers" to describe rivers that were not in the pre-existing versions of LiveOcean. Since MacCready et al. (2021), I have brought the total number of rivers to 176 (131 new tiny rivers). Additionally, the previous model did not include any WWTPs, so I have added 98 point sources, which includes both industrial facilities and WWTPs that discharge to Puget Sound. Figure A1 depicts the locations of rivers and WWTPs in the Salish Sea. I provide inputs of flow rate, temperature, DO, nitrate+nitrite (NO3+NO2), ammonium (NH4), total inorganic carbon (TIC), and total alkalinity (TA) to all TRAPS. TRAPS salinity is always zero.

A.1. TRAPS forcing

The forcing for TRAPS are based on Washington State Department of Ecology’s (hereafter referred to as Ecology) discharge and concentration time series (October 2020 version). Ecology generated these data using an observation-informed Multiple Linear Regression (MLR) model to estimate the daily nutrient loads of rivers and WWTPs discharging to Salish Sea waters between January 1999 through July 2017 (Mohamedali et al., 2011a, 2011b; Ahmed et al., 2019a, 2019b, 2021b). Originally, these data were developed for a numerical model known as the Salish Sea Model, which was used by Ahmed et al. (2021a), Khangaonkar et al. (2018), and Khangaonkar and Yun (2023). Rather than using Ecology’s raw time series data, LiveOcean’s TRAPS use climatology forcing inputs.

Climatologies are the average annual time series profile for each state variable, and they serve as a reasonable estimate of flow and nutrient concentrations for years outside of the Ecology dataset time period. Figure A2 shows example climatologies for Union River at the head of Hood Canal. There are a few nuances to these climatology calculations worth noting. First, for Fraser River NH4 concentration, LiveOcean does not use Ecology's data. Instead, LiveOcean's Fraser River uses a constant 4.43 uM concentration (S. Allen, personal communication, August 24, 2023), following the example of Olson et al. (2020). Second, outliers in streamflow timing were omitted prior to calculating climatologies (see Appendix A.3). Lastly, the average climatology of all other rivers is used as the forcing for several rivers discharging from British Columbia. This was done to fill in erroneous nutrient data such as negative TIC and near-zero DO, DIN, and alkalinity (see Appendix A.4).

One limitation to using climatologies is that they filter out high discharge events by averaging over several years. Because LiveOcean uses the same climatologies for both "wet" and "dry" years, TRAPS do not capture the effect of major weather events. Despite this limitation, the calculated climatologies provide a decent first estimate for discharge and nutrient concentration of TRAPS, enabling their addition to LiveOcean.

A.2. TRAPS implementation

Every TRAPS was implemented in ROMS as an individual river runoff point source (see WikiROMS, 2022). Latitude and longitude coordinates of TRAPS from Ecology's dataset were mapped to the nearest appropriate LiveOcean grid cell. The appropriate grid cell for rivers must be a coastal grid cell, as rivers discharge horizontally from a land cell into a water cell. The tiny river sources are enabled using the LuvSrc switch in the ROMS input file, and their direction is indicated in forcing files using either Dsrc = 0 or Dsrc = 1 for east-west or north-south flowing rivers, respectively. Unlike rivers, WWTPs are not bound to the coast, and they are mapped to the nearest water cell. WWTPs discharge vertically, which is implemented by enabling the LwSrc switch in the ROMS input file and ascribing a direction of Dsrc = 2 in the forcing file. Note that rivers discharge uniformly across the vertical sigma-layers, but WWTPs discharge solely to the bottom layer to mimic real WWTPs which discharge via a diffuser on the seafloor (Figure A3; King County, 2003). During the TRAPS mapping process, pairs of rivers and pairs of WWTPs occasionally mapped to the same LiveOcean grid cell. In these instances, I consolidated the overlapping TRAPS to a single source by summing their daily discharge values and using the flow-weighted average of their temperature and concentration climatologies. Lastly, I implemented a logical switch that sets WWTP discharge rate to zero for years in which a WWTP is inactive.

One key difference between pre-existing LiveOcean rivers and tiny rivers is that pre-existing LiveOcean rivers discharge upstream via a river track, whereas tiny rivers discharge from a single coastal grid cell. This implementation of tiny rivers is consistent with the intended use of the Ecology data. Ecology scaled upstream river gauge data by watershed area and rainfall rate to estimate streamflow at the mouth of the watershed (Mohamedali et al., 2011a). Thus, the difference in tiny river and pre-existing river placement is not cause for concern. If a river in Ecology's dataset was already pre-existing in LiveOcean (e.g., Fraser River or Skagit River), I replaced their nutrient profiles with the TRAPS climatologies described earlier, but maintained the same temperature and streamflow inputs used in prior versions of LiveOcean (see Appendix A.5).

During the TRAPS development, I encountered an issue in which WWTPs caused ROMS to blow up. My investigation led to a bug in the ROMS source code which ascribed v-velocity to vertical sources if both LuvSrc and LwSrc were enabled in the same grid and at least one horizontal LuvSrc discharged in the v-direction. I have communicated with the ROMS developers, and the bug is now resolved as of ROMS version 4.2 onwards (see https://www.myroms.org/projects/src/ticket/947).

I maintain detailed notes on TRAPS integration in the LiveOcean GitHub repository (https://github.com/parkermac/LO/tree/main/traps_notes).

A.3. Shifted rivers

Ecology used the Big Beef Creek USGS stream gauge as a streamflow reference for ungauged rivers throughout its watershed (located on the eastern boundary of Hood Canal; Ahmed et al., 2021b). These rivers, using Ecology's naming convention, include Kitsap NE, Kitsap Hood, Lynch Cove, NW Hood, Port Gamble, and Tahuya. In October 2012, the Big Beef Creek stream gauge was decommissioned (see https://waterdata.usgs.gov/nwis/inventory/?site_no=12069550), creating gaps in the streamflow data for all dependent rivers. To fill in these gaps, it appears that Ecology replaced missing streamflow data between 2012 to 2014 with duplicate data from 2009 to 2012. The replacement hydrograph was also shifted backwards by 3 months (presumably in error). Since these data do not add new information and they introduce abnormalities to streamflow timing, I omitted the duplicated discharge values before generating climatology profiles. Figure A4 shows the Union River ("Lynch Cove") hydrograph before and after I cropped out duplicate data.

A.4. Rivers that use average climatology

Many Canadian rivers in Ecology's data had unrealistic biogeochemistry values such as negative TIC or near-zero DO. Most of these rivers discharge into the northern Strait of Georgia, or from Vancouver Island into the British Columbia coast. In Ecology's naming convention, these rivers are: Neil Creek, Seymour Inlet, Holberg, Owikeno Lake, Salmon River, Brooks Peninsula, Clayoquot, Toba Inlet, Homathco River, Campbell River, Tsitika River, Nimpkish River, Tahsis, Alberni Inlet, Knight Inlet, Willamette R, Klinaklini River, North East Vancouver Island, Victoria SJdF, and Vancouver Isl C.

I replaced their biogeochemistry concentrations with the average climatology of all other rivers. For Vancouver Isl C, only DO and NH4 were replaced, and for Victoria SJdF, only DO was replaced. Note that the average river climatologies likely overestimate nutrient concentrations for these rivers as

Puget Sound watersheds are generally more urban than those in Vancouver Island and Northern Strait of Georgia (Mackas and Harrison, 1997).

A.5. Duplicate rivers

Several rivers in Ecology's dataset were already pre-existing in LiveOcean. Usually, both LiveOcean and Ecology refer to these rivers by the same name. Though on occasion, Ecology and LiveOcean used different names for the same rivers, such as "cedar" in LiveOcean and "Lake Washington" in Ecology's data. The latitude and longitude coordinates of the duplicates also differed between LiveOcean and Ecology's data. Special care was taken to ensure LiveOcean does not double-count any freshwater inflows. First, "potentially duplicate" rivers were identified based on proximity to each other. Then, the LiveOcean and Ecology hydrographs of the "potentially duplicate" rivers were compared to decisively rule out duplicates. At the end of this process, I identified 26 duplicate rivers.

In the cas7_t0_x4b version of LiveOcean used in this study, streamflow and temperature data for all 26 duplicate rivers maintain the same values as in the MacCready et al. (2021) version of the model. However, their biogeochemical fields were updated with the climatologies generated from Ecology's data. In the cases where a duplicate river in Ecology's dataset also had unrealistic biogeochemistry (see Appendix A.4), the biogeochemical fields also default to values used in the MacCready et al. (2021) version of the model. Although Ecology's data includes Willamette River, it is already implicitly accounted for in pre-existing versions of LiveOcean as a tributary to the Columbia River. Thus, Willamette River is also omitted from the updated forcing files.

Appendix B. Hydrodynamic bit-reproducibility

During comparative experiments (not discussed in this thesis), I discovered that different simulation conditions did not always replicate the same hydrodynamic behavior despite having identical hydrodynamic forcing and identical initial conditions. After just 24 hours of simulation time, surface velocities could differ by up to ~10 cm/s between runs (Figure B1a). In these experiments, the original simulation (R_0) was initialized using the "perfect restart" procedure on ten 40-cores nodes using a 20 x 20 tiling scheme. In contrast, the test condition (R_{test}) was initialized using the "continuation" procedure on five 40-core nodes using a 10 x 20 tiling scheme.

I ran additional 24-hour experiments to identify the cause of these deviations. Initializing two identical simulations using a "perfect restart" but a different number of nodes improved, but did not fully resolve, the issue (Figure B1b). Running two identical simulations using the same number of nodes but a different initialization procedure only slightly reduced hydrodynamic deviations (Figure B1c). It is only by matching the initialization procedure and the tiling scheme (i.e., same number of nodes) that LiveOcean preserves bit-reproducibility (Figure B1d).

Appendix C. Modeling as a tool to study hypoxia

There are limited locations in Puget Sound with consistent observational measurements. Mascarenas et al. (in prep.) compiled all available observational records in Puget Sound and found that due to the sparseness of data, long-term DO trends can only be identified at a few sites, and these sites are usually not the locations where hypoxia is of most concern. Additionally, the data that is available is typically only for DO concentrations, and not for other water quality variables. Thus, observations alone cannot elucidate a complete picture of the intricate dynamics that drive hypoxia in Puget Sound, necessitating the use of models.

Coupled hydrodynamic-biogeochemical models are important tools for studying oxygen dynamics in coastal systems with complex interactions (Breitburg et al., 2018; Fennel and Testa, 2019). Using models, scientists can assess an estuary's DO sensitivity to amplifications, reductions, or timing changes of physical and biogeochemical processes which cannot be replicated in the real world (e.g. Scully, 2013). Thus, models also serve as a key source of information for policy decisions since they can be used to explore reduced or enhanced nutrient discharges. For example, researchers have used them to study how nutrient management and wastewater recycling impact aerobic habitat in the Southern California Bight (Ho et al., 2023), and to evaluate the efficacy of nutrient reductions in Chesapeake Bay under future climate scenarios (Hinson et al., 2023).

Several model-based hypoxia studies have already been performed in Puget Sound. In a comparative modeling experiment, Ahmed et al. (2021a) discovered that the WWTPs discharging to the Main Basin of Puget Sound decrease DO throughout the estuary. Other work by Khangaonkar et al. (2018) predicted that land-based loads (WWTPs and rivers) are responsible for 39% of Puget Sound's hypoxic area. Khangaonkar and Yun (2023) concluded that Puget Sound hypoxic volume is minimally sensitive to whether WWTPs discharge entirely below the photic zone. Xiong et al. (in review) conducted a budget analysis using LiveOcean, the same model as the present study. They found that the Salish Sea loses oxygen during the summer primarily via estuarine exchange through the Strait of Juan de Fuca, and via DO consumption as a secondary loss term.

Although models are a powerful tool, scientists must interpret their results with caution. No model is an exact representation of reality. Models introduce assumptions, simplifications, and parameterizations for complex or unconstrained processes (Oreskes et al., 1994). For example, many pathways in the nitrogen cycle (Hutchins and Capone, 2022), and particle aggregation and sinking rates (Siedlecki et al., 2015), are undersampled or unknown, so they must be parameterized and estimated in model implementation. Different choices of parameter values impart different underlying assumptions about the nature of biogeochemical processes (Banas et al., 2009). Despite these uncertainties, Irby et al. (2016) and Arhonditsis and Brett (2004) found that models with different biogeochemical parameterizations and ecosystem complexity have similar model skill. Therefore, models remain useful tools for scientific discovery. However, modelers must be aware of the limitations and uncertainties in their findings, and it is imperative to conduct routine model comparisons to observations. Appendix C.1 details LiveOcean's performance in Puget Sound terminal inlets.

C.1. 2017 model evaluation in terminal inlets

Xiong et al. (in review) has already conducted an extensive model evaluation of the cas7_t0_x4b version of LiveOcean across the Salish Sea. I expand this evaluation to several terminal inlets in Puget Sound. Here, I compare modeled values to eight Ecology repeat CTD (conductivity, temperature, and depth) cast stations in terminal inlets, and six CTD stations in Puget Sound Main Basin (Washington Department of Ecology, 2024). See Figures C1 and C2 for locations of these stations. These CTD casts provide temperature, salinity, chlorophyll-α, and DO measurements throughout the water column at a monthly frequency. At each cast location for the year 2017, I calculate the mean bias (B) and root mean square error (RMSE) of LiveOcean using:

$$B = \frac{\sum_{i=1}^{N}(y_i - x_i)}{N} \tag{Eq. C1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}} \tag{Eq. C2}$$

where x_i are individual observations, y_i are the corresponding model values, and N is the number of observations.

Figure C1 shows model performance in shallow (mean inlet depth < 10 m) and deep (mean inlet depth > 10 m) terminal inlets. The shallow CTD monitoring stations are located in Hammersley Inlet and Budd Inlet, and the deep monitoring stations are located in Sinclair Inlet, Elliot Bay, Commencement Bay, Carr Inlet, and Lynch Cove. Note that there are two CTD stations within the Lynch Cove inlet. Bias and RMSE at each terminal inlet station are listed in Table C1. LiveOcean is more likely to overestimate salinity in shallow inlets (bias = 1.40 g/kg) compared to deep inlets (bias =

0.77 g/kg; Figure C1c). Additionally, LiveOcean has trouble reproducing observed chlorophyll concentrations in shallow inlets (bias = 4.92 mg/m^3, RMSE = 17.96 mg/m^3; Figure C1d); though the high bias and RMSE is mostly attributed to Hammersley Inlet (Table C1). For oxygen, the model is more likely to underestimate DO in deep inlets (bias = -1.15 mg/L) than in shallow inlets (bias = 0.22 mg/L; Figure C1e). In general, LiveOcean has moderate skill in reproducing observed temperature, salinity, chlorophyll, and DO in terminal inlets.

Figure C2 shows a comparison of LiveOcean performance in terminal inlets versus in Puget Sound Main Basin. Compared to Main Basin, the model has more variability for all state variables in terminal inlets (Figures C2b through C2e and bottom two rows in Table C1). However, the model's predictions are usually biased in the same direction in terminal inlets as they are in Main Basin. For example, LiveOcean tends to underestimate DO in terminal inlets (bias = -1.08 mg/L) to a slightly greater extent than in Puget Sound Main Basin (bias = -1.03 mg/L; Figure C2e).

Figure C3 shows LiveOcean performance over time in the surface and bottom 5 m of water in Elliot Bay, Lynch Cove, and Hammersley Inlet (see Appendix C.2 for calculation methods). These locations were selected to represent a range of model performance: Elliot Bay has model DO performance most similar to bulk performance across all terminal inlets, Lynch Cove has the largest model underestimate in DO, and Hammersley Inlet has the largest model overestimate in DO (Table C1). Note that because Hammersley Inlet is only 5 m deep, data were not split into separate surface and bottom groups. Generally, LiveOcean has reasonable skill in estimating observed temperature and salinity for all inlets (Figures C3a through C3f). Conversely, LiveOcean struggles to reproduce chlorophyll observations. The model has a tendency to predict a surface phytoplankton bloom that persists throughout the summer (Figures C3g through C3i). However, observations suggest that chlorophyll peaks have much more temporal variability. For example, observations in Lynch Cove (Figure C3h) show two chlorophyll peaks: one in April and one in November, a phenomenon which has been previously documented in Puget Sound (Newton and Van Voorhis, 2002). Across all terminal inlets, LiveOcean underestimates these short-term, high-chlorophyll events in favor of a sustained summer bloom, except in Hammersley Inlet where the model overpredicts phytoplankton blooms throughout the growing season (Figure C3i). LiveOcean also tends to underpredict DO concentrations in all terminal inlets. For example, observed bottom DO is higher than modeled bottom DO during the spring and summer in Elliot Bay (Figure C3j). Similarly, LiveOcean predicts anoxic bottom waters in Lynch Cove (Figure C1d) but observations only record hypoxic concentrations. The exception, again, is Hammersley Inlet where LiveOcean tends to overpredict oxygen concentrations (Figure C3l). One hypothesis for why LiveOcean behaves differently in Hammersley Inlet compared to all other terminal inlets is due to its extremely shallow depth and narrow channel width which may result in different dynamics than the other inlets.

These results highlight that it is challenging to represent the complexity of oxygen dynamics at the extreme edge cases of the model. Therefore, further improvement is recommended in future model iterations, particularly for the biogeochemistry module. Despite this, seasonal patterns of DO in LiveOcean generally agree well with observations (Figures C3j through C3l). Therefore, I continue with my analysis, but acknowledge the uncertainty in the model.

C.2. Averaging state variables over the surface and bottom 5 m

Special care was taken when calculating the average modeled state variable (e.g., DO) value over the surface and bottom 5 meters. This is because the sigma-layers do not have uniform thickness. First, I determined which sigma-layers fall within the surface and bottom 5 meters at each cast location. Then, I calculated a thickness-weighted average of the state variable. If the surface- or bottom-most sigma-layer was thicker than the 5 meter depth range of interest, then I simply used the state variable value at that surface- or bottom-most sigma-layer.

Appendix D. Depth of hypoxia

Early in my analysis, I investigated where in the water column the DO minima is likely to develop. Within every horizontal grid cell in Puget Sound (corresponding to the region in Figure 4a), I calculate the sigma-layer in which the DO minima occurs on every day of the year. I also extract the concentration of the DO minima. Figure D1 shows a 2D histogram of the sigma-layer of the DO minima vs. concentration of the DO minima, where the color bar indicates frequency in log scale. Note that the bottom of the water column corresponds to sigma-layer = 0. Across the entirety of Puget Sound for all time between 2014 - 2019, the DO minima predominantly occurs in the bottom sigma-layer.

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Figures

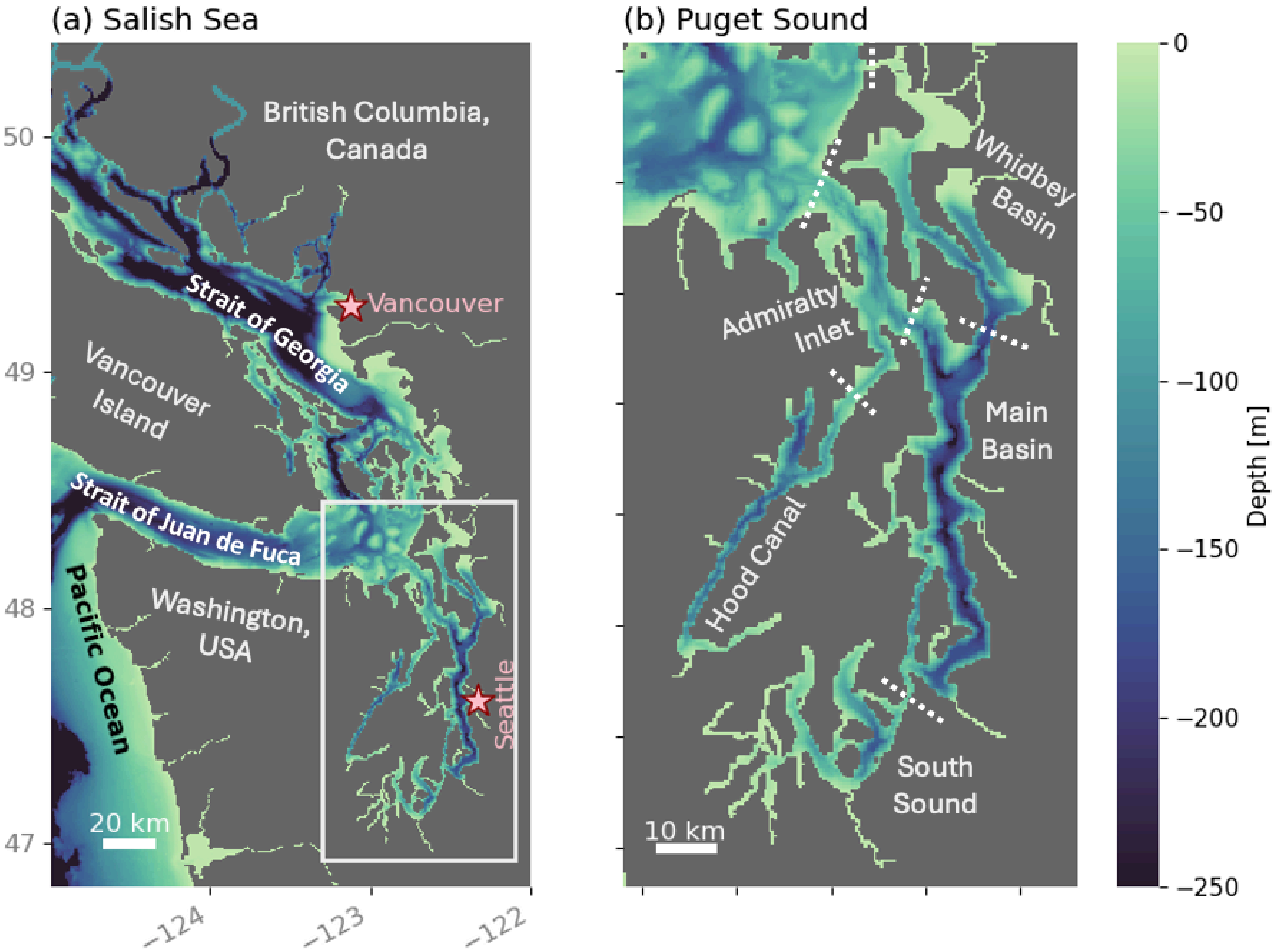


Figure 1. (a) Salish Sea map with major water bodies and cities labeled. (b) Puget Sound map with labeled sub-basins.

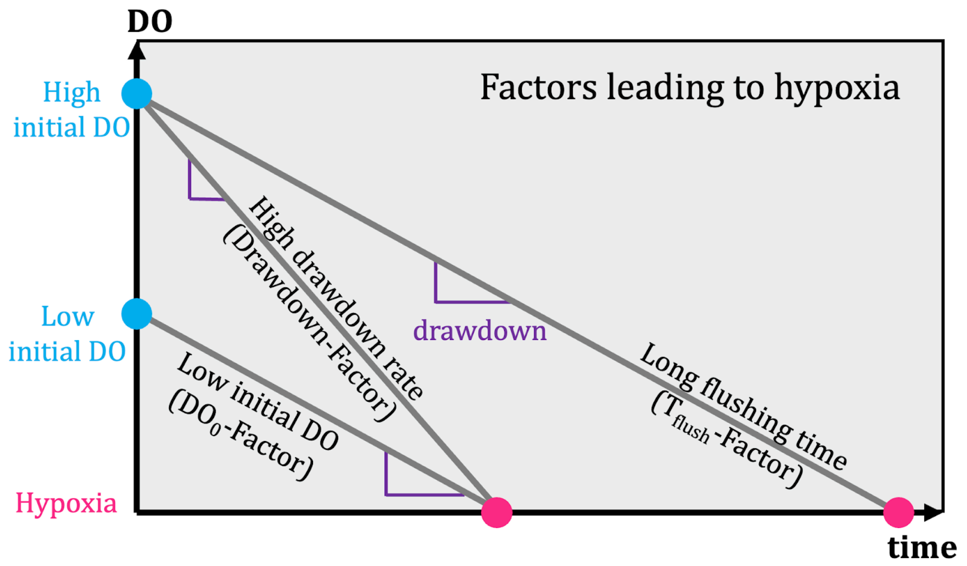


Figure 2. Depiction of factors influencing a system's susceptibility to hypoxia. A system with the Drawdown-Factor experiences high oxygen drawdown rates, and thus reaches hypoxia quickly. A system with the DO_0-Factor has low initial DO concentrations, and thus requires little oxygen drawdown before becoming hypoxic. A system with the T_{flush}-Factor has a long flushing time, and thus oxygen in its water can be consumed for long periods which can lead to hypoxia. Adapted from Fennel and Testa (2019).

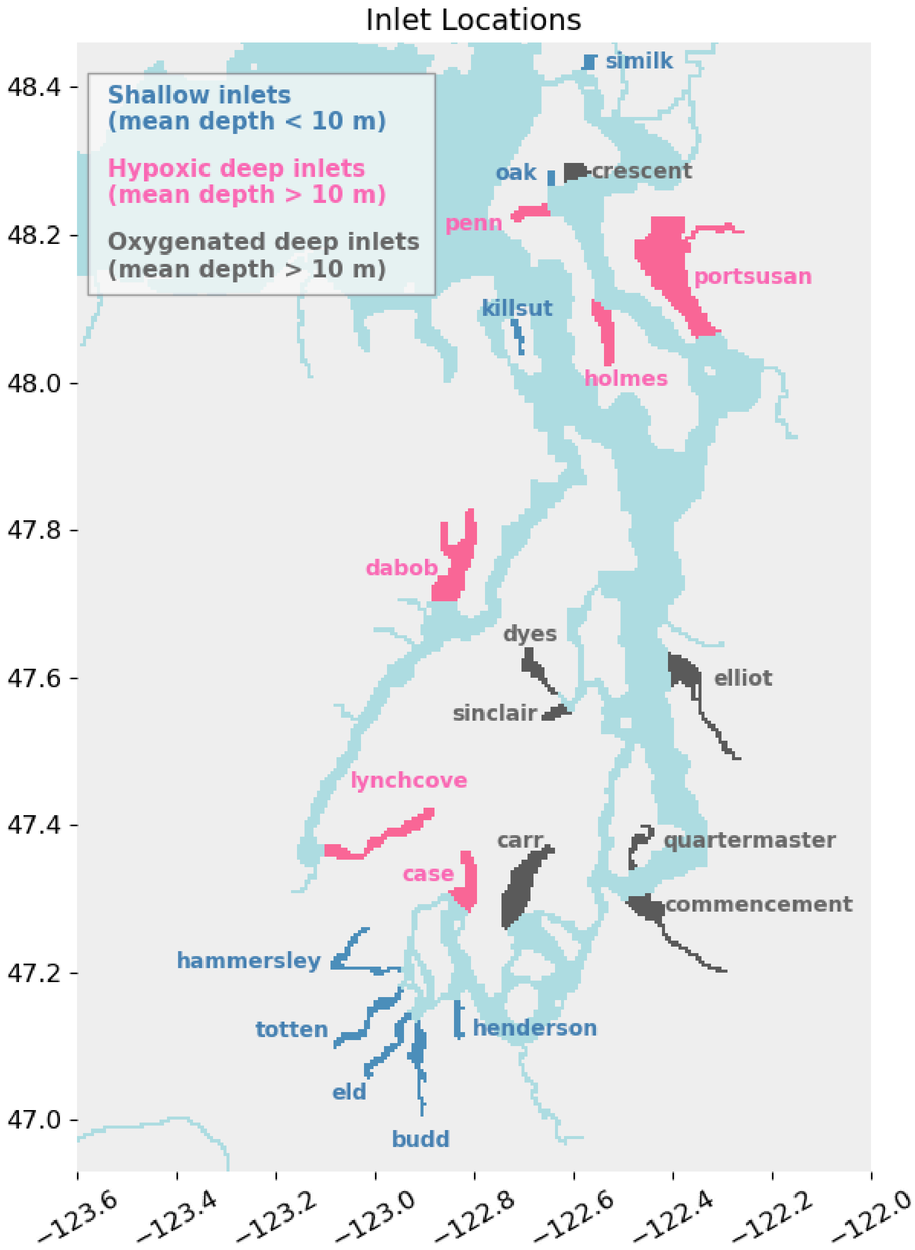


Figure 3. Map of the twenty-one terminal inlets in Puget Sound. Shallow inlets (mean depth < 10 m) are colored in blue. Hypoxic, deep (mean depth > 10 m) inlets are colored in pink. Oxygenated, deep (mean depth > 10 m) inlets are colored in gray.

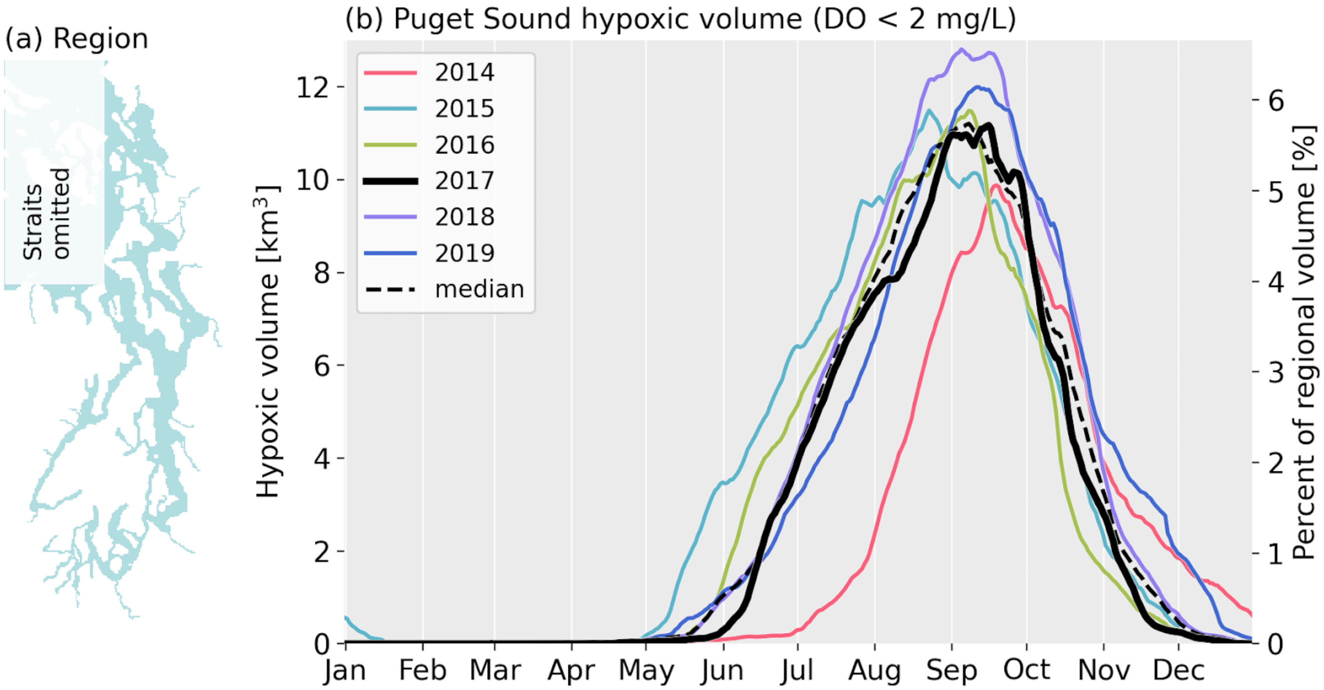


Figure 4. Hypoxic volume time series in Puget Sound. (a) Region over which I integrate hypoxic volume. (b) Annual time series of hypoxic volume and regional percent hypoxic volume for the years 2014 through 2019. The dashed line is the median hypoxic volume time series of all simulation years.

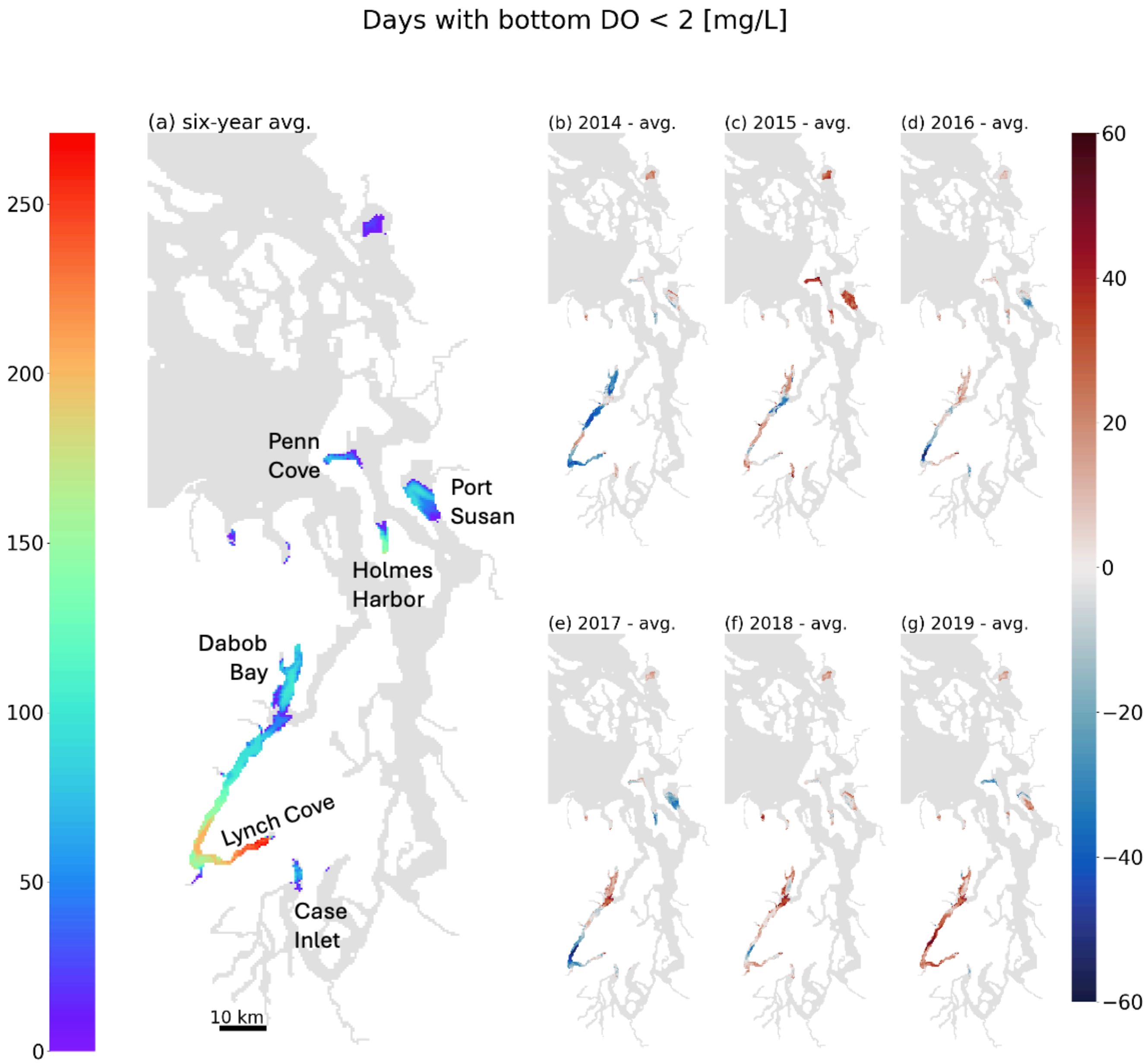


Figure 5. Number of days with bottom hypoxia in Puget Sound. (a) Average of years 2014 through 2019. (b) - (g) Difference between an individual year's number of hypoxic days and the six-year mean. Red indicates that the number of hypoxic days is higher than the six year mean, and blue indicates that the number of hypoxic days is lower than the six year mean. Any uncolored regions indicate that the bottom of the water column never experienced hypoxia.

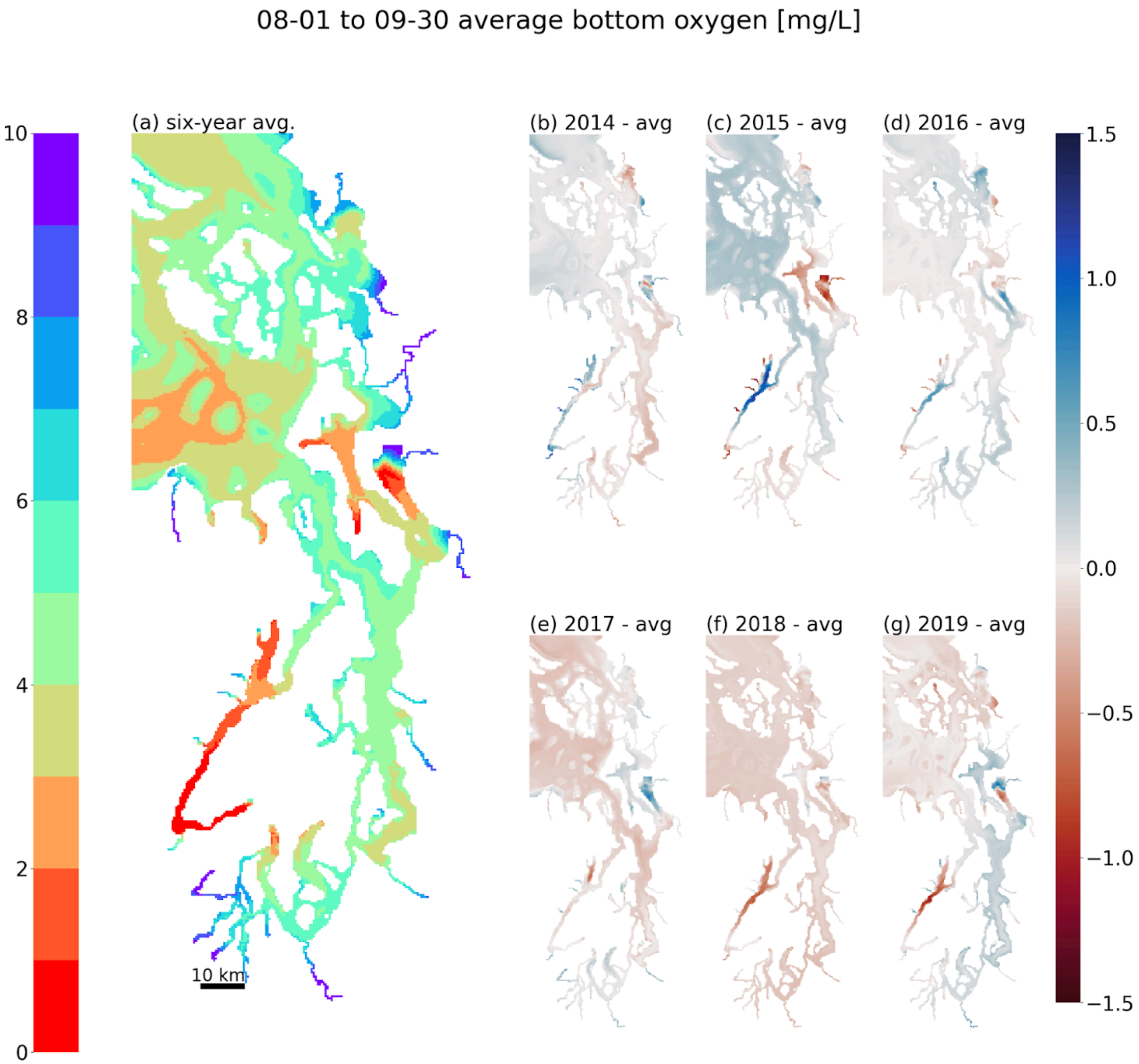


Figure 6. Average bottom DO in Puget Sound during the hypoxic season. (a) Average of years 2014 through 2019. (b) - (g) Difference between an individual year's average hypoxic season bottom DO and the six-year mean. Blue indicates that bottom DO is higher than the six year mean, and red indicates that bottom DO is lower than the six year mean

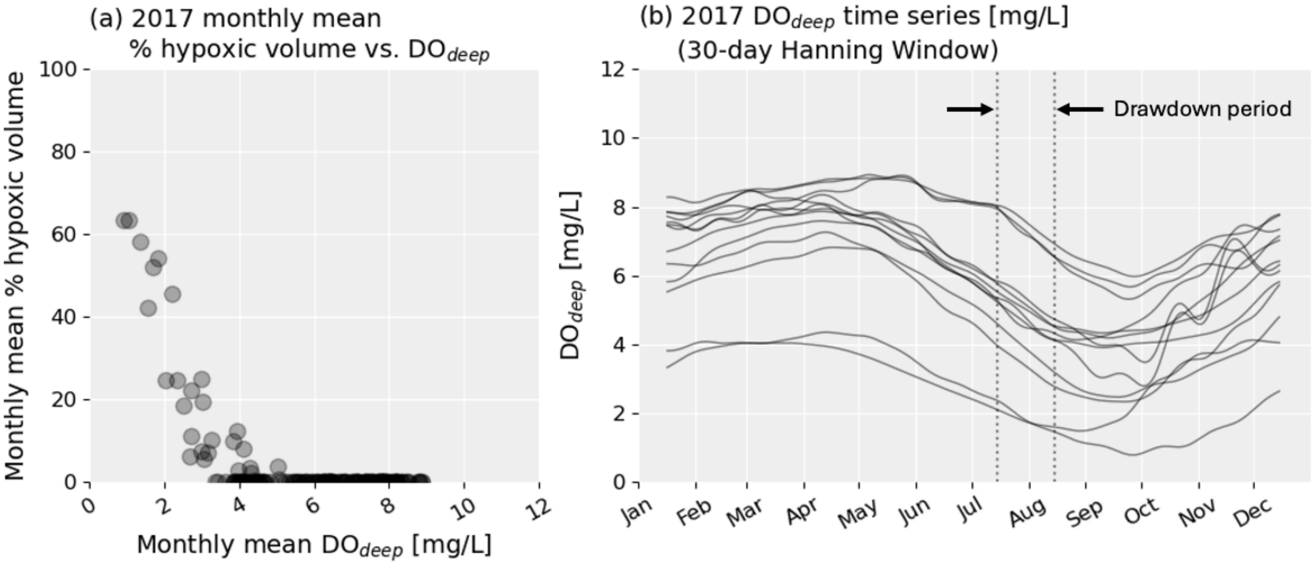


Figure 7. (a) 2017 monthly mean percent hypoxic volume vs. monthly mean deep layer DO (DO$_{deep}$) of all thirteen deep (> 10 m) terminal inlets. (b) 2017 daily time series of mean deep layer DO in all thirteen deep (> 10 m) terminal inlets, with a 30-day Hanning Window applied. The period between the two vertical bars indicates the mid-July through mid-August oxygen drawdown period in which DO$_{deep}$ is decreasing in all inlets.

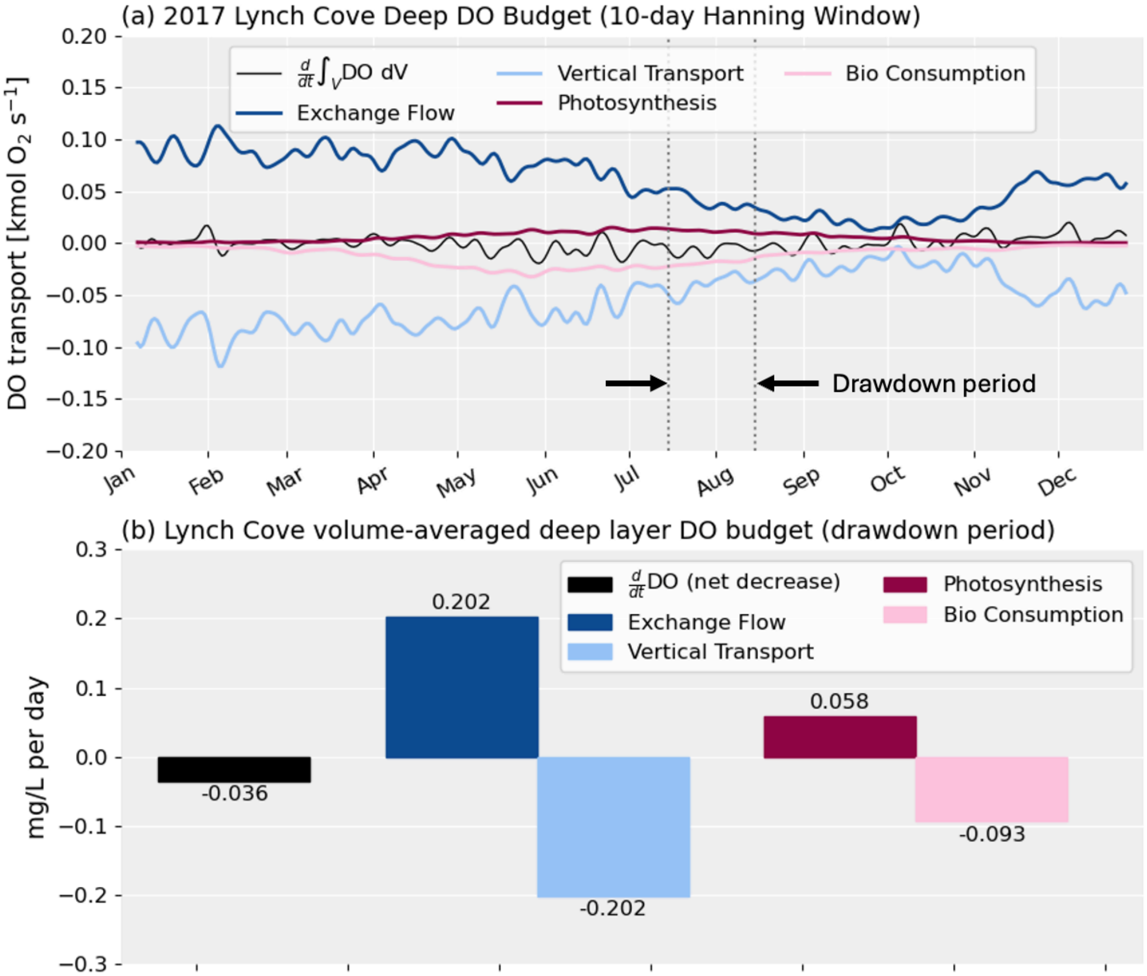
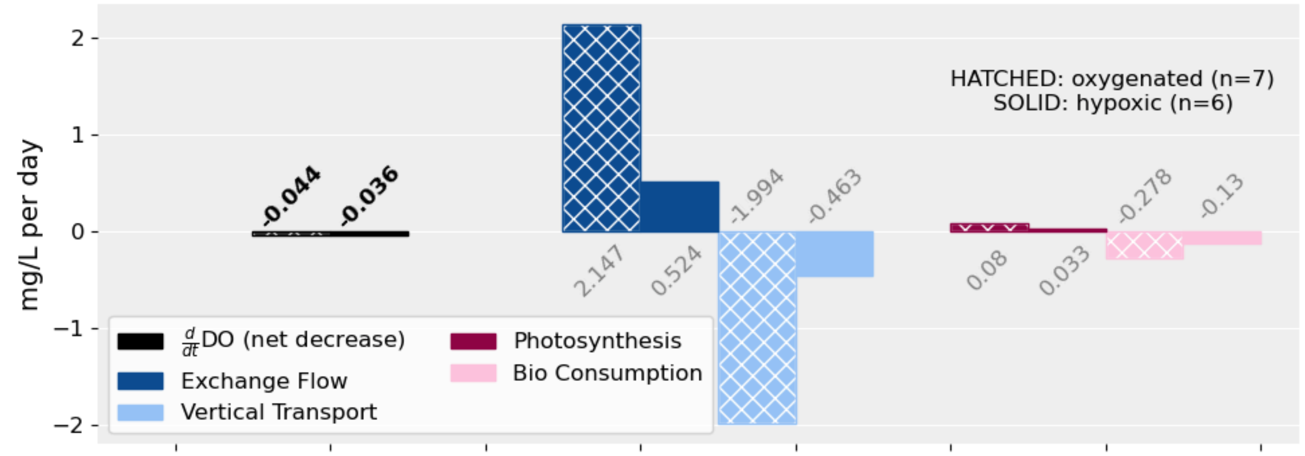


Figure 8. Example deep layer budget in Lynch Cove for the year 2017. (a) Daily time series of deep layer oxygen budget terms in Lynch Cove with a 10-day Hanning Window applied. The period between the two vertical bars indicates the mid-July through mid-August oxygen drawdown period in which DO$_{deep}$ is decreasing in all inlets. (b) Volume-averaged budget rate terms averaged from mid-July to mid-August in Lynch Cove's deep layer.

Volume-averaged deep layer budgets (mid-Jul to mid-Aug)

(a) All budget rate terms



(b) Combined physical and biological processes

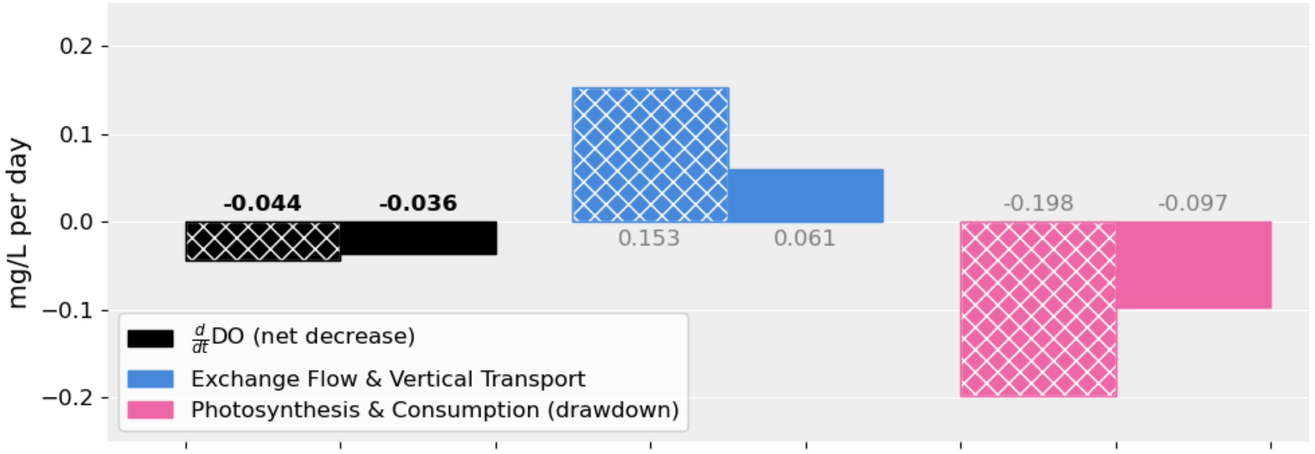


Figure 9. 2017 deep layer volume-averaged budget rate terms averaged from mid-July to mid-August in all thirteen deep (> 10 m) terminal inlets. Hatched bars show mean rate terms of all oxygenated inlets. Solid bars show mean rate terms of all hypoxic inlets. d/dt(DO) is the storage term, and it is the net sum of all other budget rate terms. (a) All individual budget rate terms shown separately. (b) Consolidated budget rate terms, with physical terms grouped into “Exchange Flow & Vertical Transport,” and biological terms grouped into “Photosynthesis & Consumption.” Note the change of y-axis scale between panels (a) and (b).

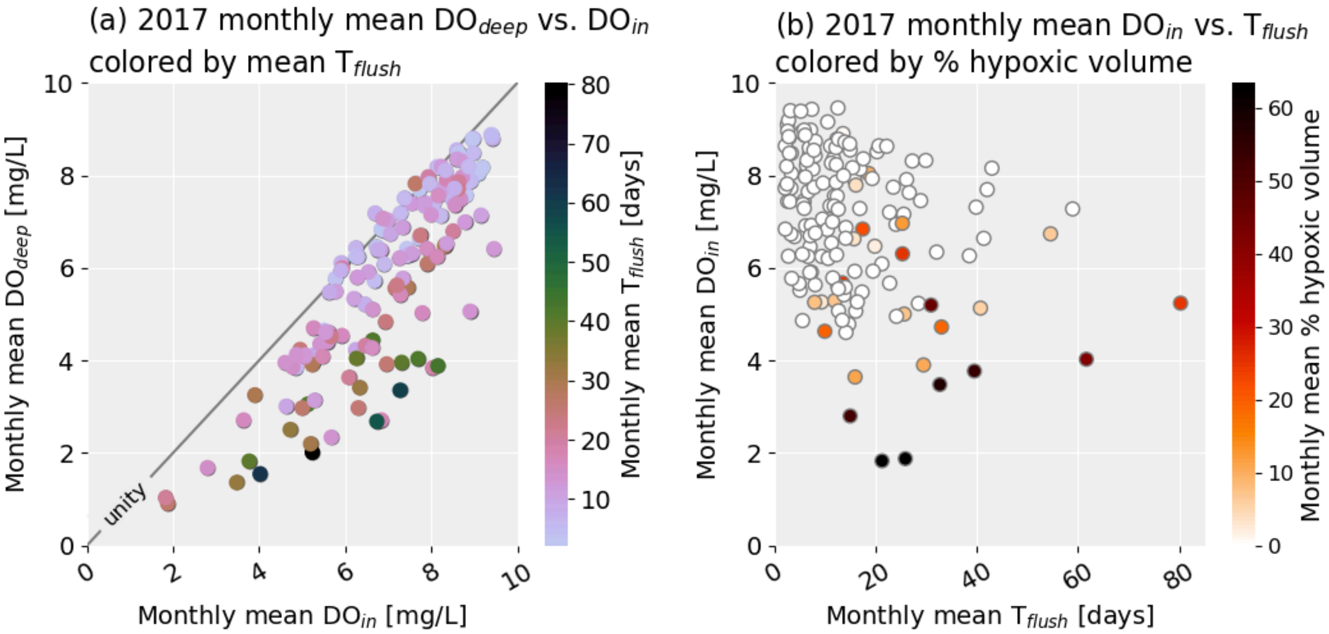


Figure 10. (a) 2017 monthly mean deep layer DO vs. monthly mean inflowing DO concentration colored by monthly mean flushing time for all thirteen deep (> 10 m) terminal inlets. The diagonal line is unity. (b) 2017 monthly mean inflowing DO concentration vs. monthly mean flushing time colored by monthly mean percent hypoxic volume of the inlet for all thirteen deep (> 10 m) terminal inlets.

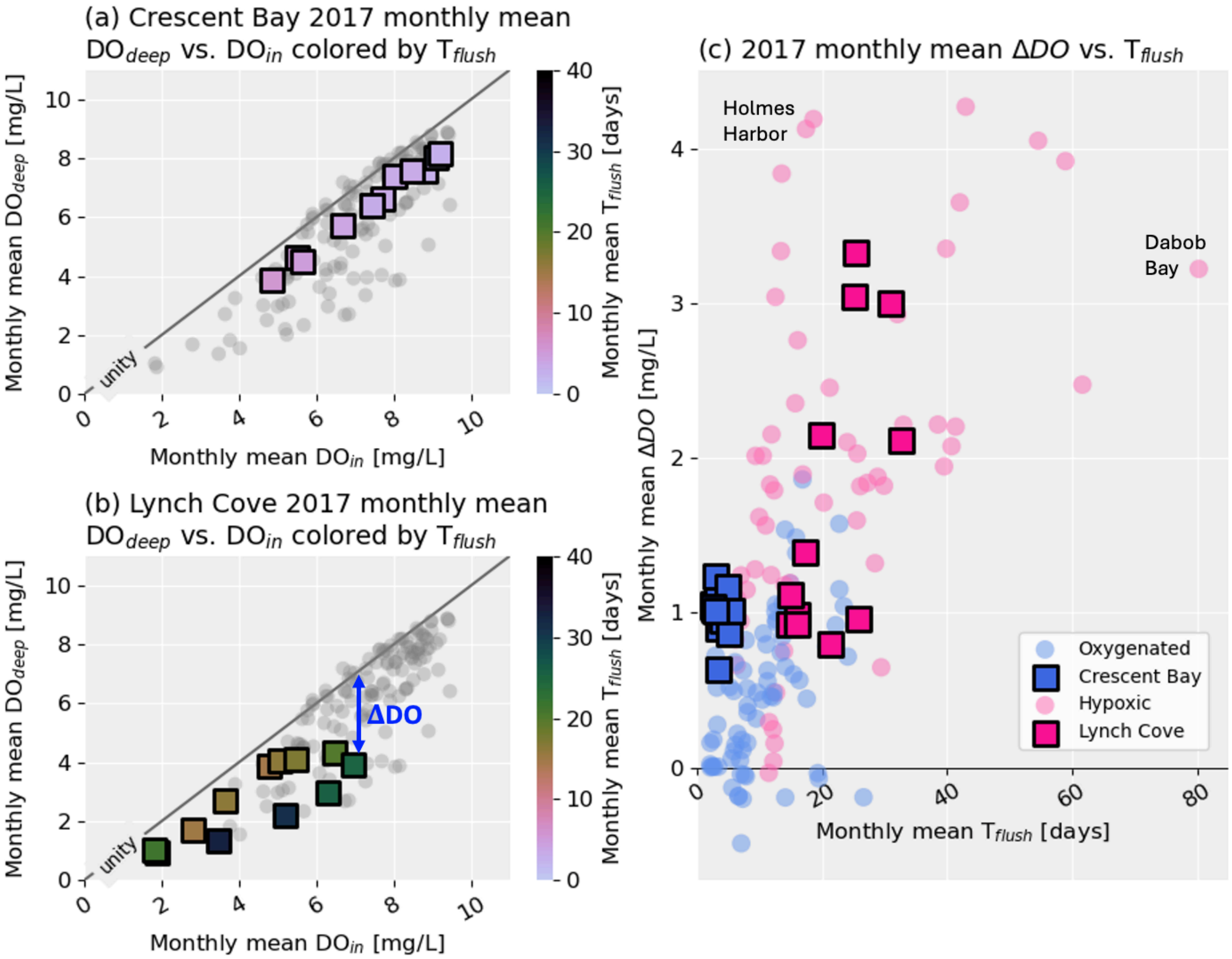


Figure 11. (a) Repeat of Figure 10a, except only highlighting points corresponding to Crescent Bay. The diagonal line is unity. (b) Repeat of Figure 10a, except only highlighting points corresponding to Lynch Cove. ΔDO, the deficit of DO$_{deep}$ compared to DO$_{in}$, is shown for emphasis. (c) 2017 monthly mean ΔDO vs. monthly mean flushing time. Hypoxic inlets are colored in pink, oxygenated inlets are colored in blue. Points corresponding to Crescent Bay and Lynch Cove are emphasized, as they directly map to the points highlighted in panels (a) and (b), respectively.

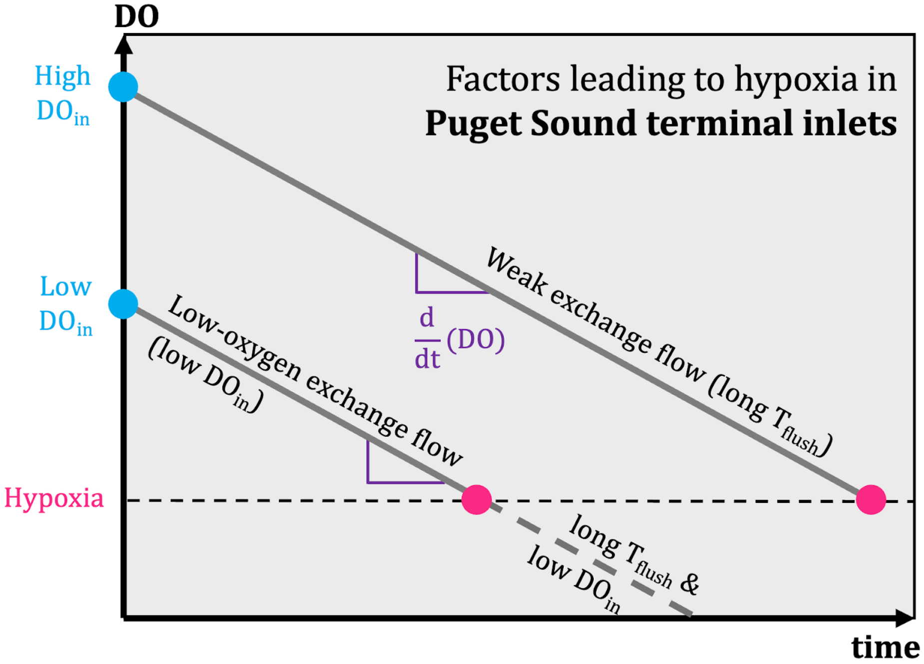


Figure 12. Depiction of factors influencing Puget Sound terminal inlets' susceptibility to hypoxia. The exchange flow plays a major role in modulating the flushing time (weak exchange flow means longer flushing times) and inflowing DO concentrations (low-oxygen exchange flow means low initial inlet DO). Note that both lines have the same slope, since DO decreases at a similar rate in all inlets. Adapted from Fennel and Testa (2019).

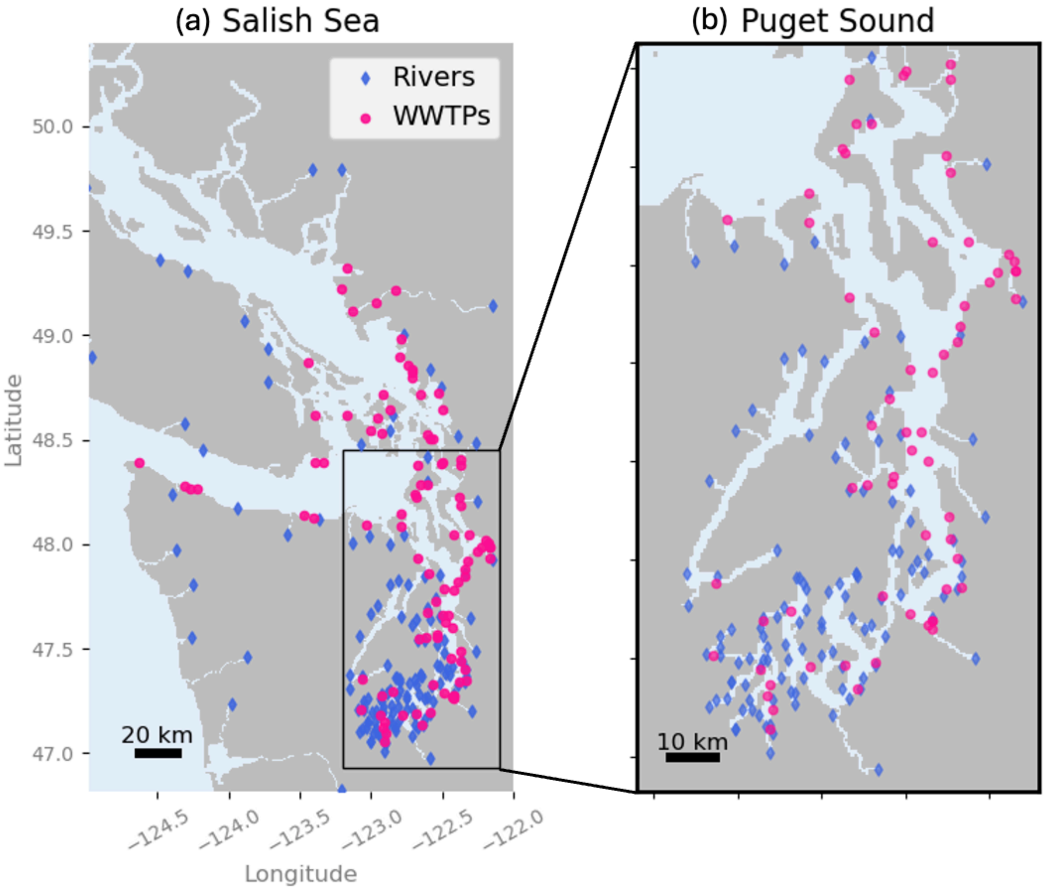


Figure A1. LiveOcean locations of rivers and WWTPs in (a) Salish Sea, and (b) Puget Sound.

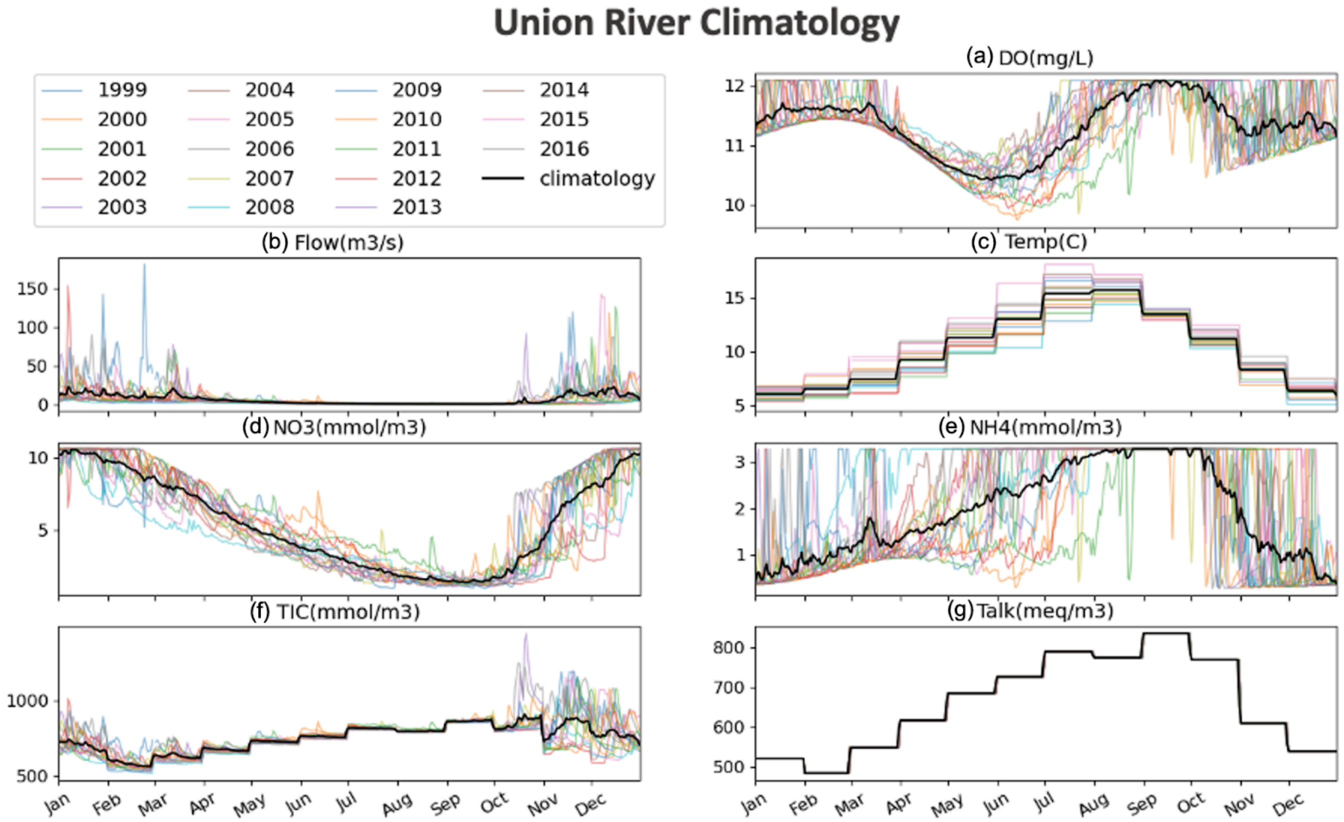


Figure A2. Example climatology profiles for the Union River, which discharges to the head of Hood Canal. Thin colored lines are raw Ecology time series data. Bold lines are the calculated climatologies (a) Dissolved oxygen profiles. (b) Hydrograph. (c) Temperature profiles. (d) Nitrate profiles. (e) Ammonium profiles. (f) Total inorganic carbon profiles. (g) Total alkalinity profiles.

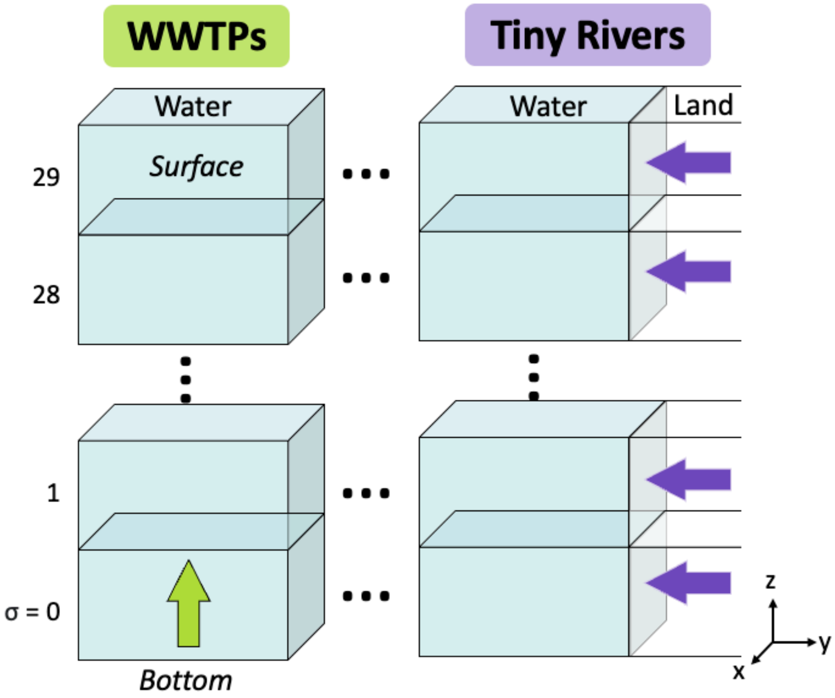


Figure A3. Schematic of TRAPS implementation. WWTPs (left) can discharge from open water grid cells, and they discharge solely to the bottom sigma-layer. Rivers (right) must discharge from land into water, and their discharge is distributed equally between all sigma-layers.

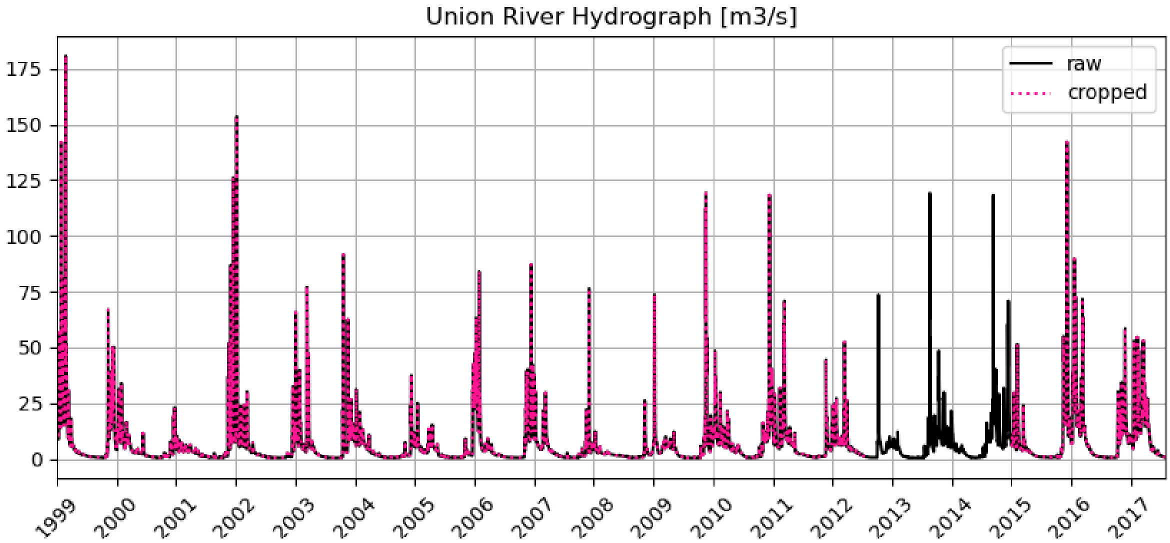


Figure A4. Comparison of the Union River ("Lynch Cove" in Ecology's naming convention) hydrograph before and after I omitted seemingly duplicate values between 2012 through 2014.

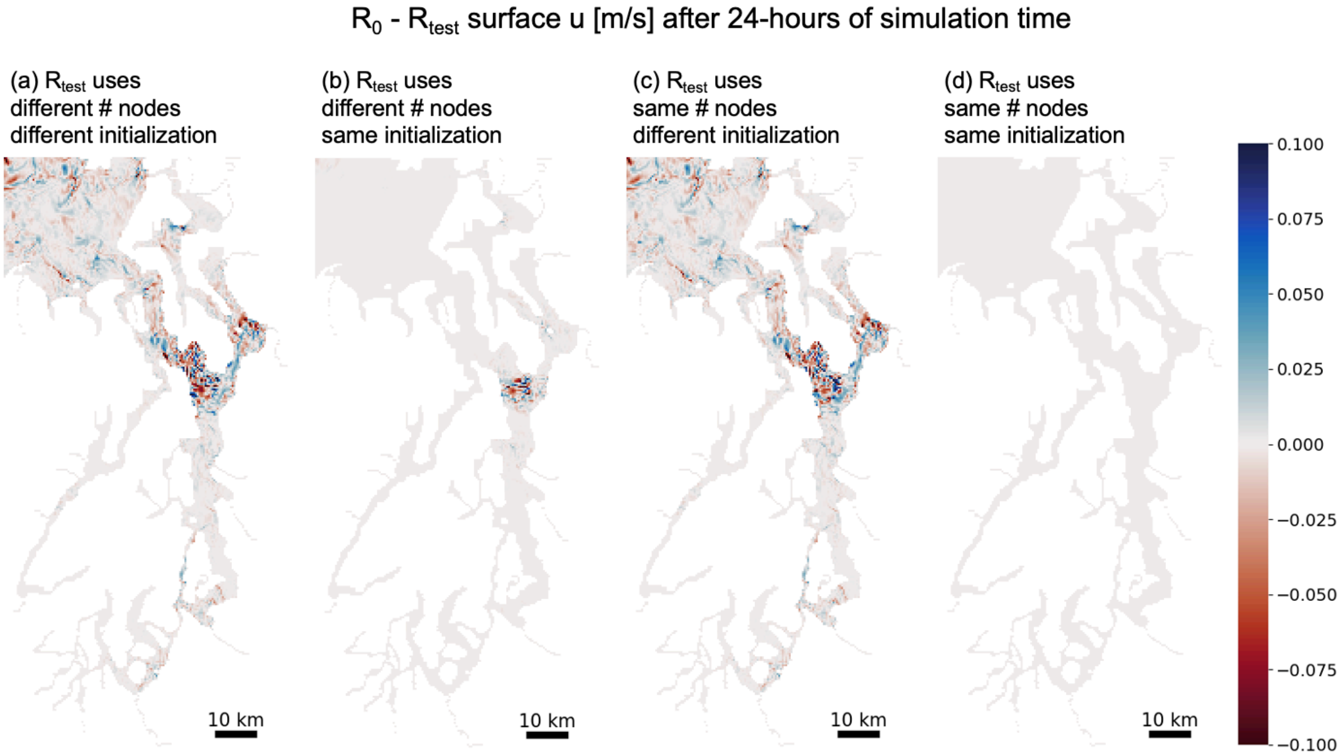


Figure B1. Hydrodynamic differencing results of surface u-velocity. Results are shown as a baseline simulation, R_0, minus a test simulation, R_{test}. Only u is shown because u and v have deviations of similar magnitude. (a) Result when R_{test} was run on a different number of nodes and initialized with a different procedure compared to R_0. (b) Result when R_{test} was run on a different number of nodes but initialized with the same procedure compared to R_0. (c) Result when R_{test} was run on the same number of nodes but initialized with a different procedure compared to R_0. (d) Result when R_{test} was run on the same number of nodes and initialized with the same procedure as R_0.

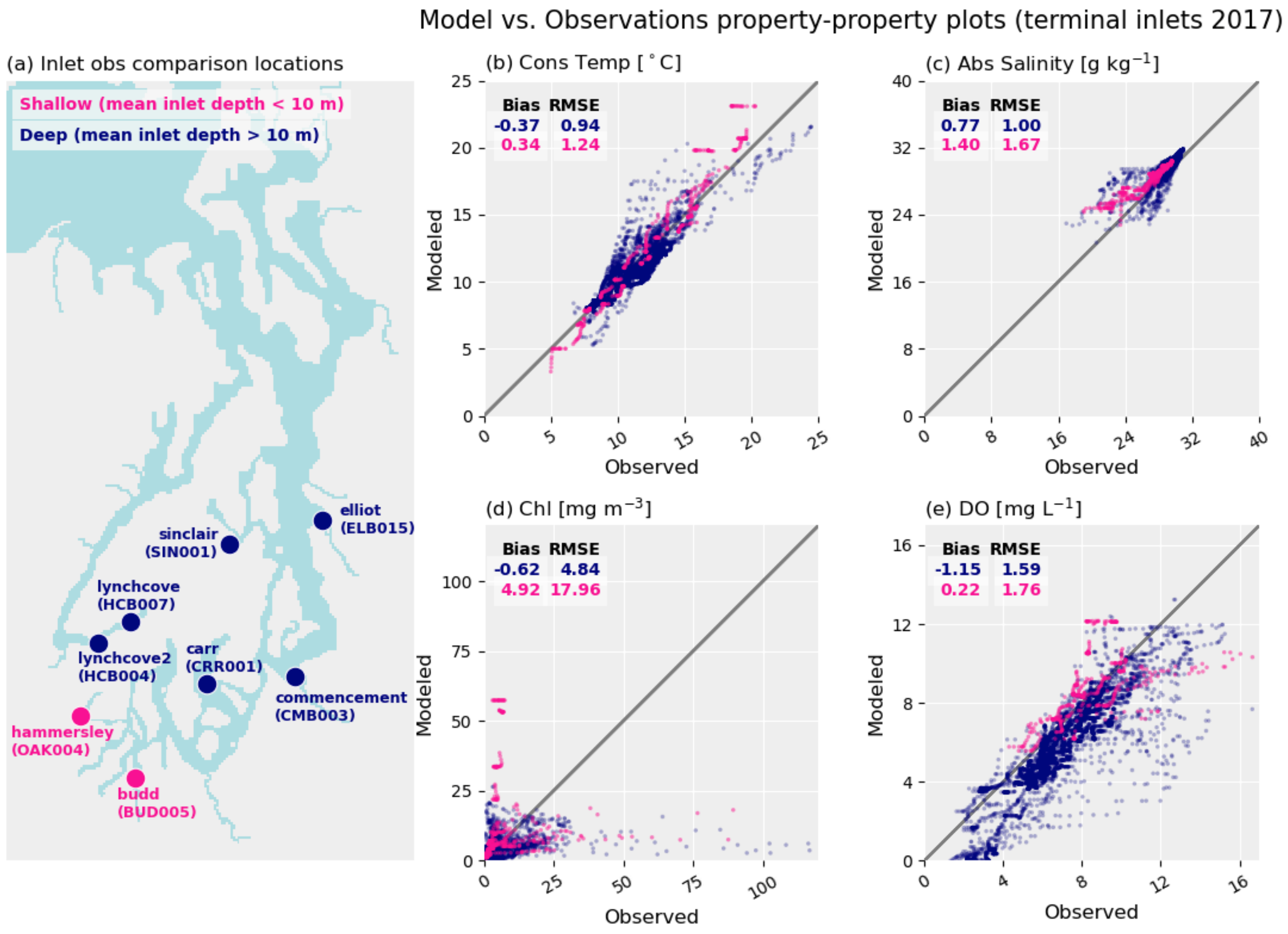


Figure C1. Model data property-property plots for 2017 in shallow terminal inlets (mean depth < 10 m; pink) and in deep terminal inlets (mean depth > 10 m; navy blue) (a) Locations of model data comparisons. The data come from Ecology CTD casts, and each cast is labeled with its Ecology station name in parentheses. The remaining panels show property-property plots at these locations for (b) conservative temperature, (c) absolute salinity, (d) chlorophyll, and (e) DO. Diagonal lines with slope = 1 are shown for reference. Bias and RMSE for all shallow and deep terminal inlet stations are listed in the top left corner of panels (b) though (e), with their colors corresponding to the location type defined in panel (a).

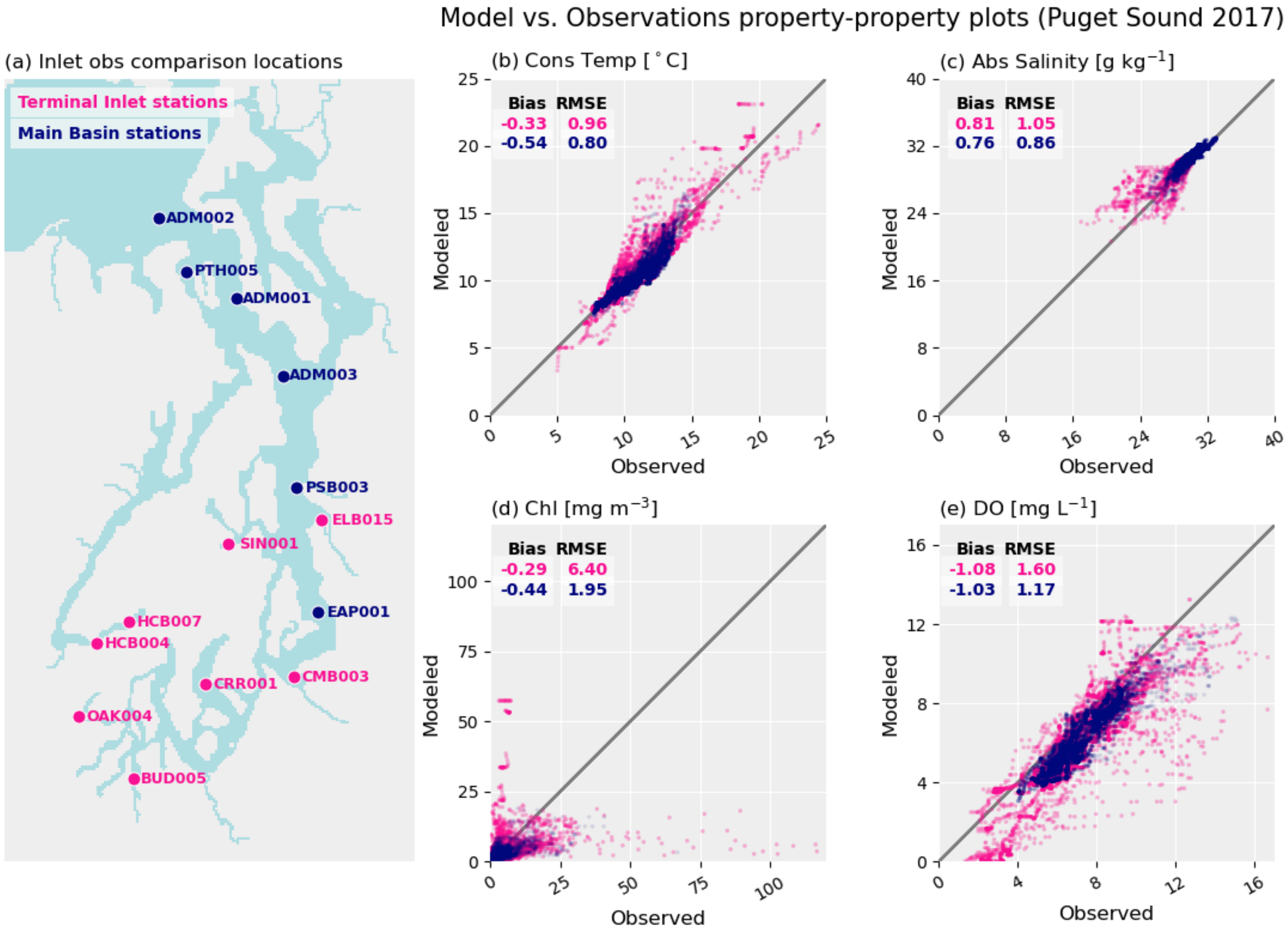


Figure C2. Model data property-property plots for 2017 in terminal inlets (pink) and in the Main Basin of Puget Sound (navy blue). (a) Locations of model data comparisons. The data come from Ecology CTD casts, and each cast is labeled with its Ecology station name. The remaining panels show property-property plots at these locations for (b) conservative temperature, (c) absolute salinity, (d) chlorophyll, and (e) DO. Diagonal lines with slope = 1 are shown for reference. Bias and RMSE for all terminal inlets and all Main Basin stations are listed in the top left corner of panels (b) though (e), with their colors corresponding to the location type defined in panel (a).

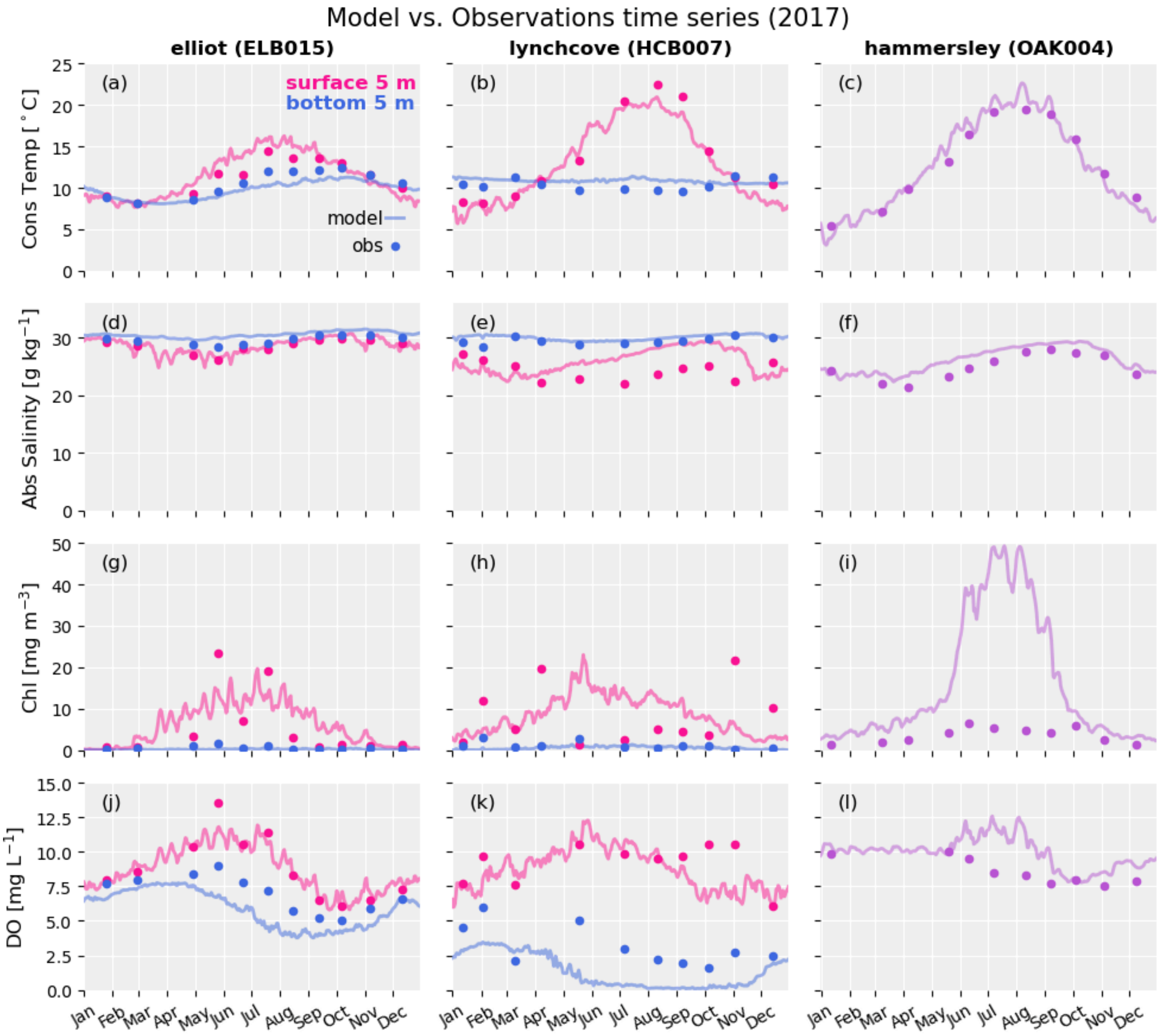


Figure C3. Model data time series for 2017. Comparisons in Elliot Bay (ELB015) are shown in the first column, Lynch Cove (HCB007) in the second column, and Hammersley Inlet (OAK004) in the third column. Panels (a) through (c) are conservative temperature, panels (d) through (f) are absolute salinity, panels (g) through (i) are chlorophyll, and panels (j) through (l) are DO. Modeled and observed values were averaged over the surface and bottom 5 m of the water column in Elliot Bay and Lynch Cove. In Hammersley Inlet, values were averaged over the entire water column because the inlet is so shallow (5 m at CTD cast location).

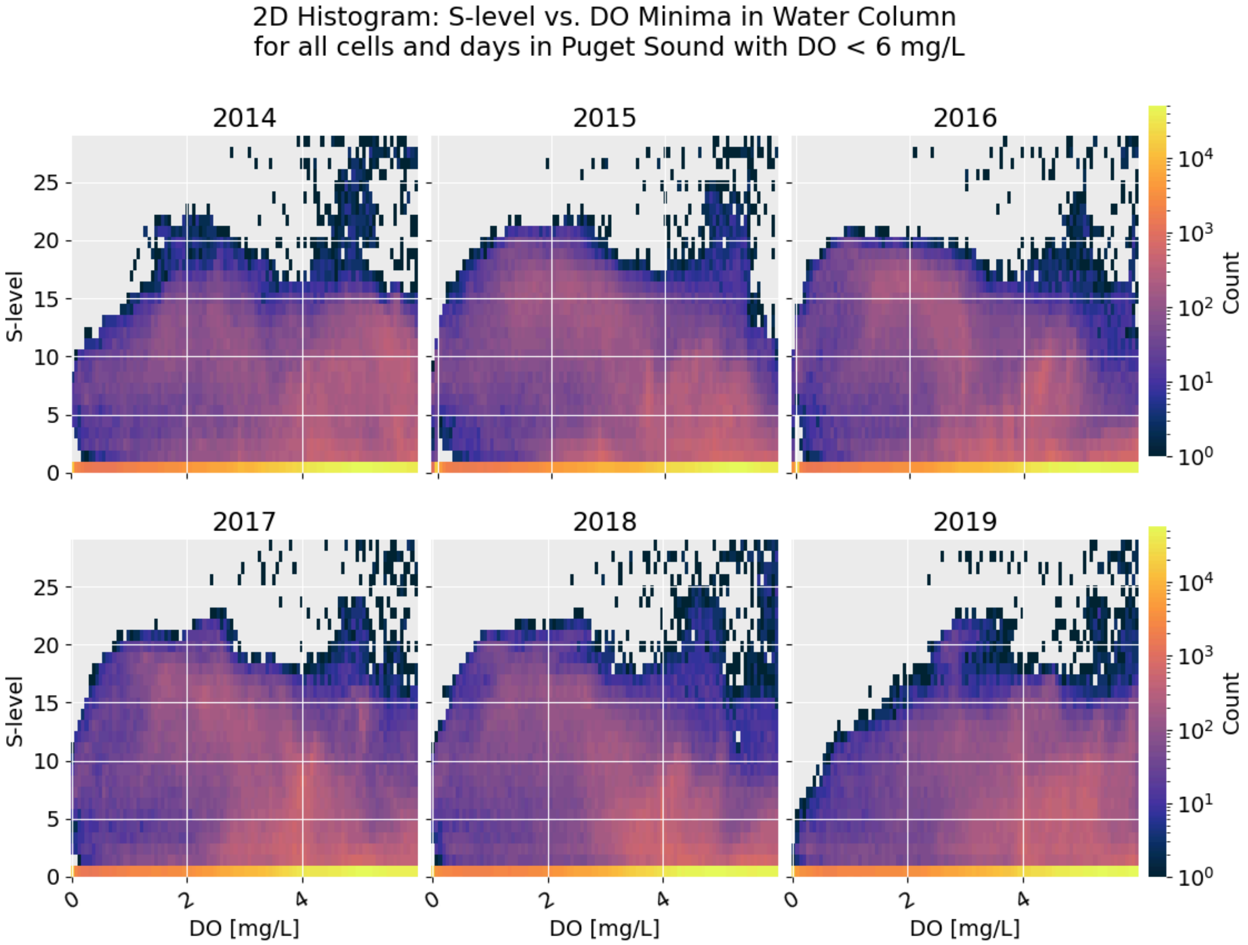


Figure D1. 2D histograms of the sigma-layer of the DO minima vs. DO minima concentration at every horizontal grid cell on every day of the year within the Puget Sound region (Figure 4a). A sigma-level of zero corresponds to the bottom of the water column. The histogram is plotted with 100x30 bins. Note that the colorbar is in log scale.

Tables

Table C1. Summary of LiveOcean mean bias and RMSE compared to 2017 Ecology CTD data in seven terminal inlets. Also included are LiveOcean's mean bias and RMSE compared to 2017 Ecology CTD data in Puget Sound Main Basin. Bias are shown in the first row, and RMSE are shown italicized and in parentheses in the second row.

Location	**Depth at station [m]**	**Ecology ID**	**Cons. Temp [°C]**	**Abs. Salinity [g/kg]**	**Chlorophyll [mg/m^3]**	**DO [mg/L]**
			Bias *(RMSE)*	Bias *(RMSE)*	Bias *(RMSE)*	Bias *(RMSE)*
Hammersley Inlet	5.0	OAK004	0.8 *(1.7)*	2.0 *(2.3)*	16.0 *(23.7)*	1.4 *(1.8)*
Budd Inlet	12.4	BUD005	-0.0 *(0.7)*	0.9 *(1.0)*	-3.5 *(11.8)*	-0.7 *(1.7)*
Sinclair Inlet	12.6	SIN001	0.1 *(0.8)*	0.5 *(0.6)*	-0.1 *(8.8)*	-1.3 *(2.1)*
Lynch Cove	20.1	HCB007	0.5 *(1.6)*	0.8 *(1.9)*	3.6 *(15.3)*	-1.9 *(2.9)*
Lynch Cove 2	31.6	HCB004	0.4 *(1.0)*	0.6 *(1.2)*	-1.0 *(6.2)*	-1.6 *(2.3)*
Elliot Bay	62.5	ELB015	-0.4 *(0.8)*	0.7 *(0.7)*	-0.6 *(3.2)*	-0.9 *(1.2)*
Carr Inlet	93.8	CRR001	-0.5 *(0.8)*	0.9 *(0.9)*	-0.1 *(2.2)*	-1.1 *(1.4)*
Commencement Bay	134.4	CMB003	-0.6 *(1.0)*	0.9 *(1.0)*	-0.4 *(1.9)*	-1.0 *(1.2)*
Shallow terminal inlets (mean depth < 10 m)	**N/A**	**N/A**	**-0.3** ***(1.2)***	**1.4** ***(1.7)***	**4.9** ***(18.0)***	**0.2** ***(1.8)***
Deep terminal inlets (mean depth > 10 m)	**N/A**	**N/A**	**-0.4** ***(0.9)***	**0.8** ***(1.0)***	**-0.6** ***(4.8)***	**-1.2** ***(1.6)***
All terminal inlets	**N/A**	**N/A**	**-0.3** ***(1.0)***	**0.8** ***(1.1)***	**-0.3** ***(6.4)***	**-1.1** ***(1.6)***
Puget Sound Main Basin	**N/A**	**N/A**	**-0.5** ***(0.8)***	**0.8** ***(0.9)***	**-0.4** ***(2.0)***	**-1.0** ***(1.2)***