WASHINGTON STATE DEPARTMENT OF ECOLOGY

Estuarine Flow in the South Basin of Puget Sound and its Effects on Near-Bottom Dissolved Oxygen

Abstract

The south basin of Puget Sound is a complex and interconnected system of straits, open reaches, and fjord-like bays. South-basin waters exchange with main-basin Puget Sound waters over a sill (shallow area) and through the Tacoma Narrows.

Within the south basin, tidally-averaged net estuarine (residual) circulation can be normal (seaward at the surface, landward at depth), inverse (seaward at depth, landward at the surface), or sideways (seaward on one shore, landward on the other). This is due to the interaction of the basin's complex geometry with tidal forcing as well as processes such as seasonal variations in river flow, snowmelt, evaporation, and wind.

Low near-bottom dissolved oxygen is observed in some years at the north end of Case Inlet. Estuarine flow patterns around Harstine Island in the finger inlets could partially explain this variability in dissolved oxygen. Current meters were deployed in Dana and Pickering Passages for several months to test this idea. Results indicate that the estuarine flow alternates between (1) patterns of circulation splitting around Harstine Island, and (2) a surface clockwise (counterclockwise at depth) pattern with flow mostly out through Pickering Passage. We conclude that the estuarine flow pattern is controlled by variations in the wind.

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Waterbody numbers

Waterbody IDs and Water Resource Inventory Areas
for the South Basin of Puget Sound.

Station	WBID	WRIA
BUD005	WA-13-0020	13
CSE001	WA-PS-0090	15
CSE002	WA-PS-0090	14
DNA001	WA-PS-0090	13
ELD001	WA-14-0020	13
NSQ001	WA-PS-0290	15
OAK004	WA-14-0110	14
PCK001	WA-14-0010	14
TOT002	WA-14-0130	14

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Introduction

The South Puget Sound basin is a complex fjord-like estuary within Washington State (Figure 1) dominated by tidal currents. The open northern boundary of the south basin is defined by Tacoma Narrows and an entrance sill located just to the south of the Tacoma Narrows. The sill is a shallow reach left behind by retreating glaciers tens of thousands of years ago.

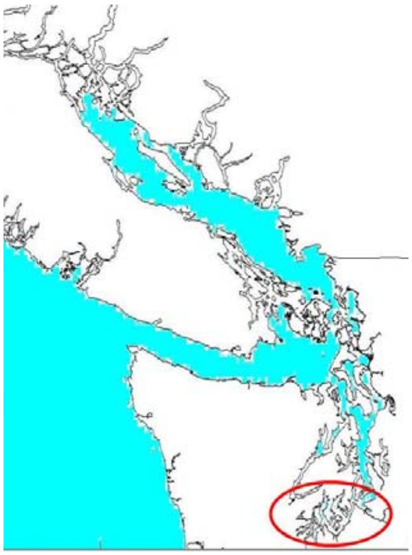

Figure 1. The South Sound basin.

These tidal currents are superimposed on a net estuarine (residual) circulation that is caused by outflow of buoyant fresh water at the surface and inflow of dense (salty) main Puget Sound basin water at depth that ultimately draws its source from the Pacific Ocean. Interactions caused by tidal mixing, turbulent flow through constrictions like the Tacoma Narrows, and meteorological forcing (e.g., the wind) regulate this estuarine flow.

The net motion of water in an estuary influences biological productivity because nutrients that enter a basin from one watershed can affect another area of the basin at some distance. These nutrients can accelerate plankton growth and ultimately reduce oxygen levels at depth.

Compared with the main basin, estuarine flow in South Puget Sound is more sluggish and stratified, resulting in lower annual productivity despite a spring plankton bloom that occurs earlier in the season (Strickland, 1983). Surface nutrients, typically nitrate, deplete in the summer (Newton et al., 2002), attenuating blooms despite plentiful sunlight. Such surface depletion suggests sensitivity to further nitrogen addition (eutrophication). In addition to eutrophication, the inlets' estuarine circulation may be important for causing marine population differences, as is the case on a larger spatial scale for Puget Sound versus the Strait of Juan de Fuca in diatoms (Rynearson and Armbrust, 2004).

As the human population grows along the eastern shore of Puget Sound, understanding these connections will become increasingly important. The purpose of this paper is to report a new understanding of how variation in the wind seems to explain where and when the deep areas of low oxygen (hypoxia) can be found.

Normal estuarine flow in an estuary goes from the landward side (head) to the seaward side (mouth). The estuarine circulation of South Puget Sound is complicated by its geometry, which branches into several finger inlets in its western extreme half (Figure 2). Estuarine flow patterns change in the dry season when snow melt is the only source for freshwater input via the Nisqually River.

Estuarine flow around Harstine (Hartstene) Island can also be influenced by the wind. Wind is certainly important elsewhere in Puget Sound as shown at Three Tree Point (Bretschneider et al. 1985), Point Monrow (Matsuura and Cannon, 1997), and summarized recently in Ebbesmeyer and Cannon (2001).

The Washington State Department of Ecology (Ecology) created a hydrodynamic and water quality model of South Puget Sound (Figure 2) for multiple purposes, but most importantly to determine vulnerability to eutrophication (Albertson et al., 2002a, b). Low-oxygen conditions have been observed in South Puget Sound from summer to fall (Bos et al., 2001). Low-oxygen levels often reach an annual minimum during September because of decreased photosynthesis due to fading sunlight, dying and sinking biological components acted upon by oxygen-consuming bacteria (decomposition), low winds, and lower tidal energy near the equinox. The most extreme high and low tides of the year occur around the solstices in June and December.

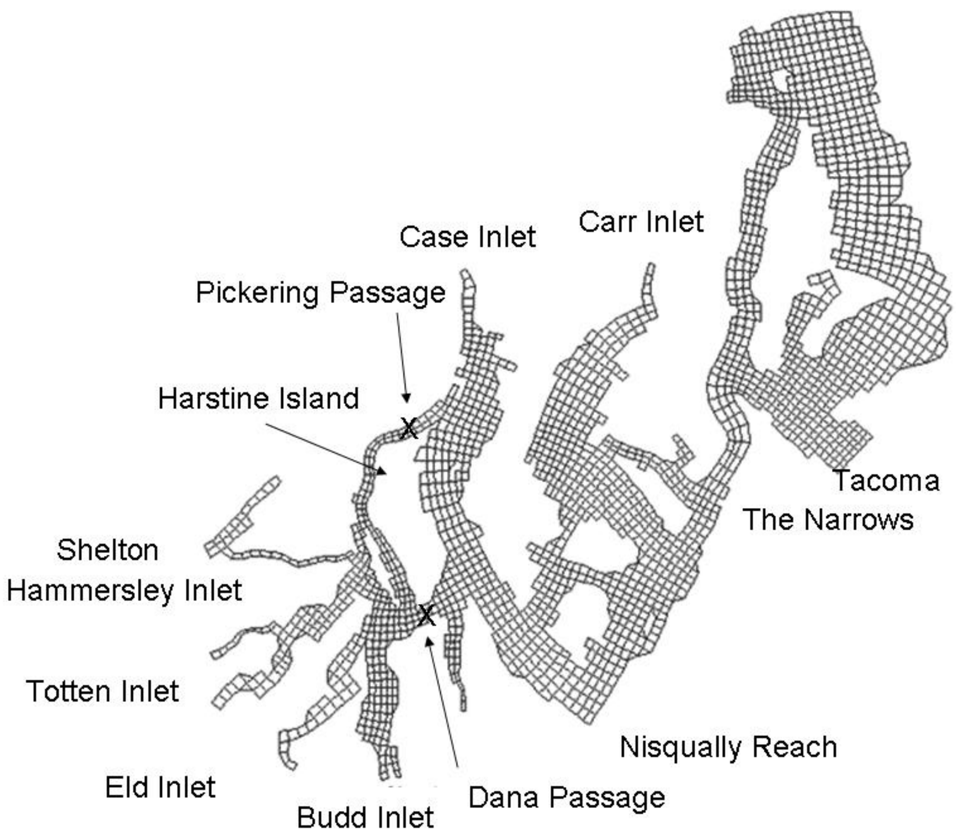

Figure 2. South Puget Sound model grid with current meter (ADCP) locations indicated by an **X**

In September 1997, Ecology first re-occupied the historic hydrographic stations (Collias et al., 1974) in conjunction with the Lacey-Olympia-Tumwater-Thurston County (LOTT) wastewater treatment plant study in 1996-7 (Aura Nova, 1998). In addition to finding low near-bottom dissolved oxygen (DO) in Budd Inlet, which was well-known and expected, there was also low DO in northern Carr and Case Inlets (Figure 3). This was a motivating factor for locating the prototype of a new vertical profiling mooring (ORCA, Oceanic Remote Chemical Analyzer) in Carr Inlet (Edwards et al., 2007). The low near-bottom DO in Case Inlet was particularly conspicuous in 1997, both in the data (Figure 3a) and Ecology's initial model (Figure 3b). The model run should not be considered with the same weight as data, particularly with regard to the low DO shown near Shelton in Oakland Bay.

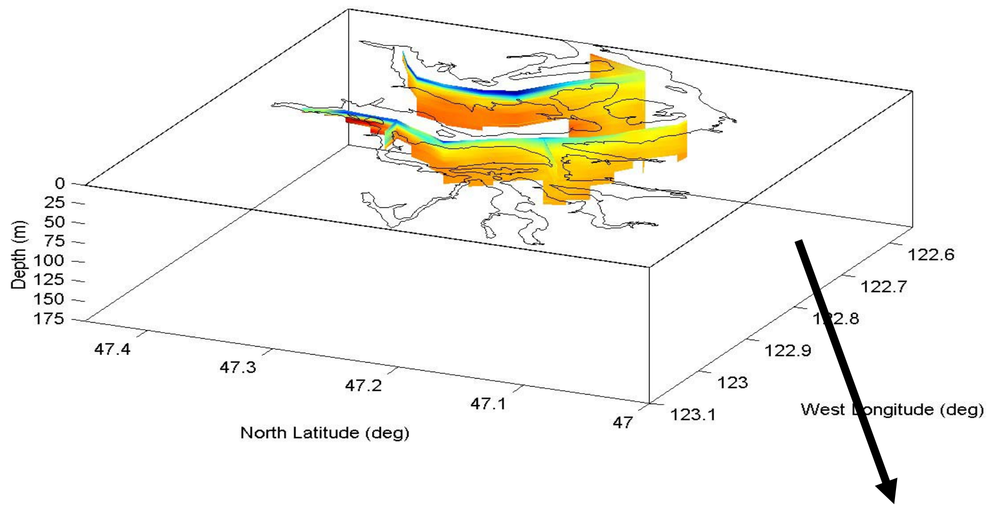

Figure 3a. Data-derived graph of dissolved oxygen within Case and Carr Inlets in September 1997.

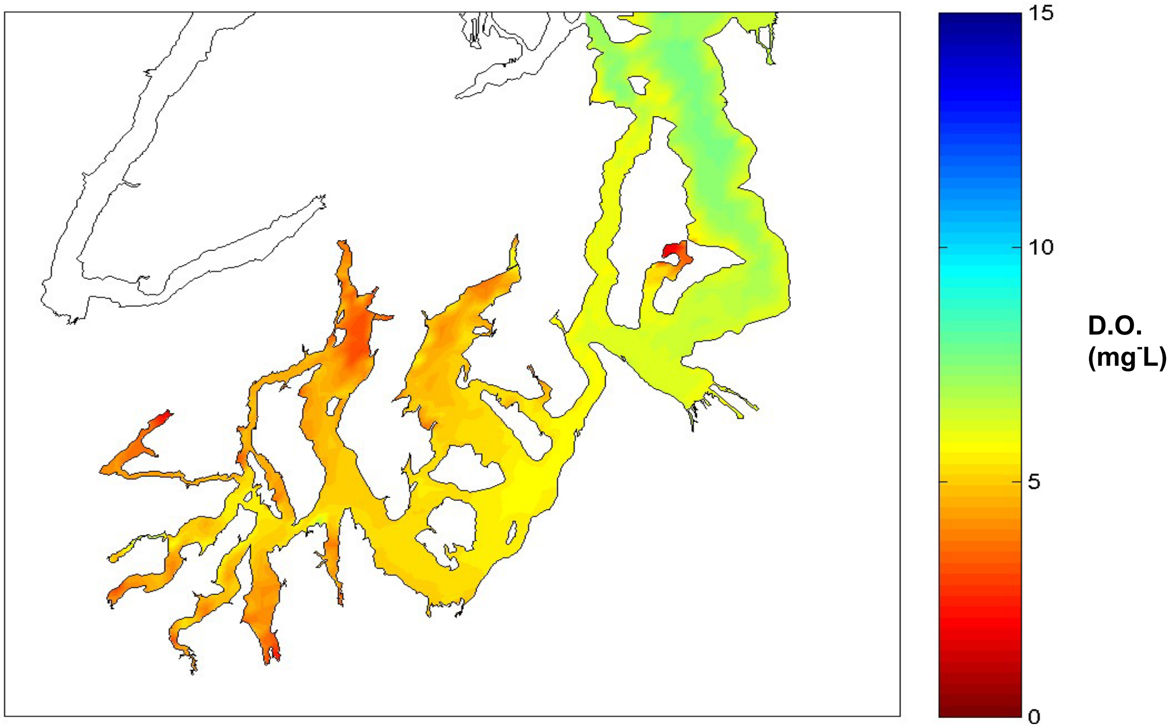

Figure 3b. Model-derived graph of near-bottom dissolved oxygen in September 1997.

Ecology, in partnership with the University of Washington, established annual September cruises to measure low oxygen for most years beginning in 1999. The measured near-bottom DO levels from 1999-2006 (excluding 2002) September cruises were averaged (Figure 4a) and subtracted from specific years to show anomalies. These anomalies exhibit different phases of interannual north-south variation. The most extreme phases observed of this variation occurred in 1999, a southern phase (Figure 4b) where Budd Inlet DO levels were lower than the mean; and in 2004, a northern phase (Figure 4c) when Carr and Case Inlet DO levels were lower than the mean. The pattern suggests biological oxygen demand moving south (1999) or north (2004) depending on the year, with Harstine Island in the middle.

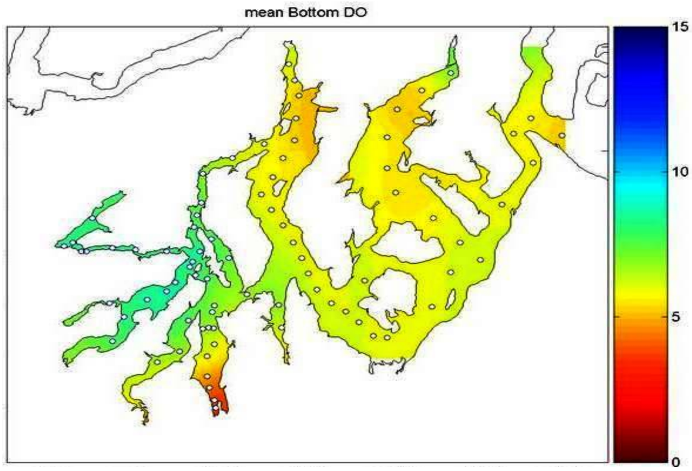

Figure 4a. Average near-bottom dissolved oxygen values for 1999-2006 (excluding 2002).

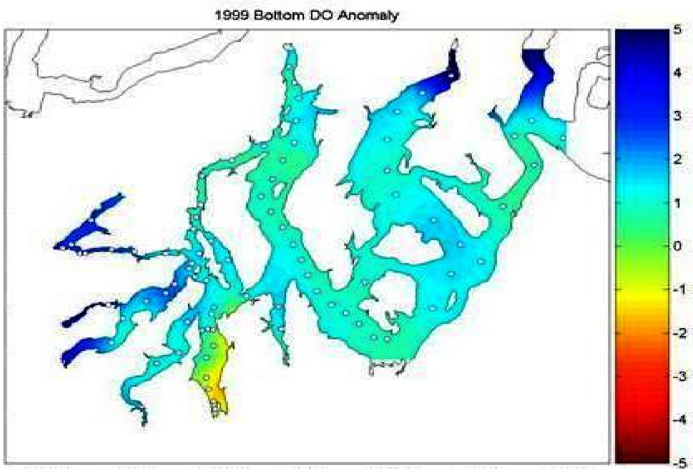

Figure 4b. Anomalies in near-bottom dissolved oxygen for 1999.

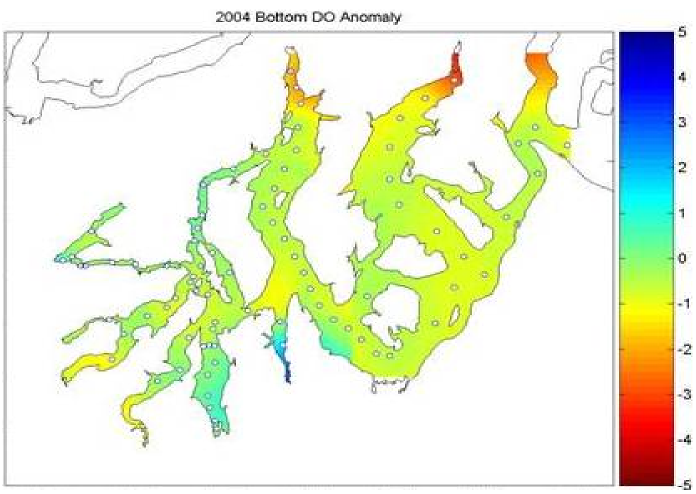

Figure 4c. Anomalies in near-bottom dissolved oxygen for 2004.

To gain information on surface flow patterns, over 10,000 surface drift cards were released into Budd Inlet as part of the LOTT recertification project in 1996-7 (Aura Nova, 1998). Recoveries on beaches suggested a bifurcation (dividing into branches) of net surface flow around Harstine Island forming an "H" pattern where (1) water from Budd and Eld Inlets tends to head south around Harstine Island into Case Inlet via Dana Passage, and (2) water from Totten and Hammersley Inlets tends to head north around Harstine Island into Case Inlet via Pickering Passage (Figure 5). The flood tide meets itself somewhere between Hope Island and Hammersley Inlet. Going north or south from this location is against the current during flood tide and with the current during ebb tide. The phase delay of the lunar semidiurnal tide has been shown to be greatest back in Oakland Bay (Shelton; Lavelle, 1985).

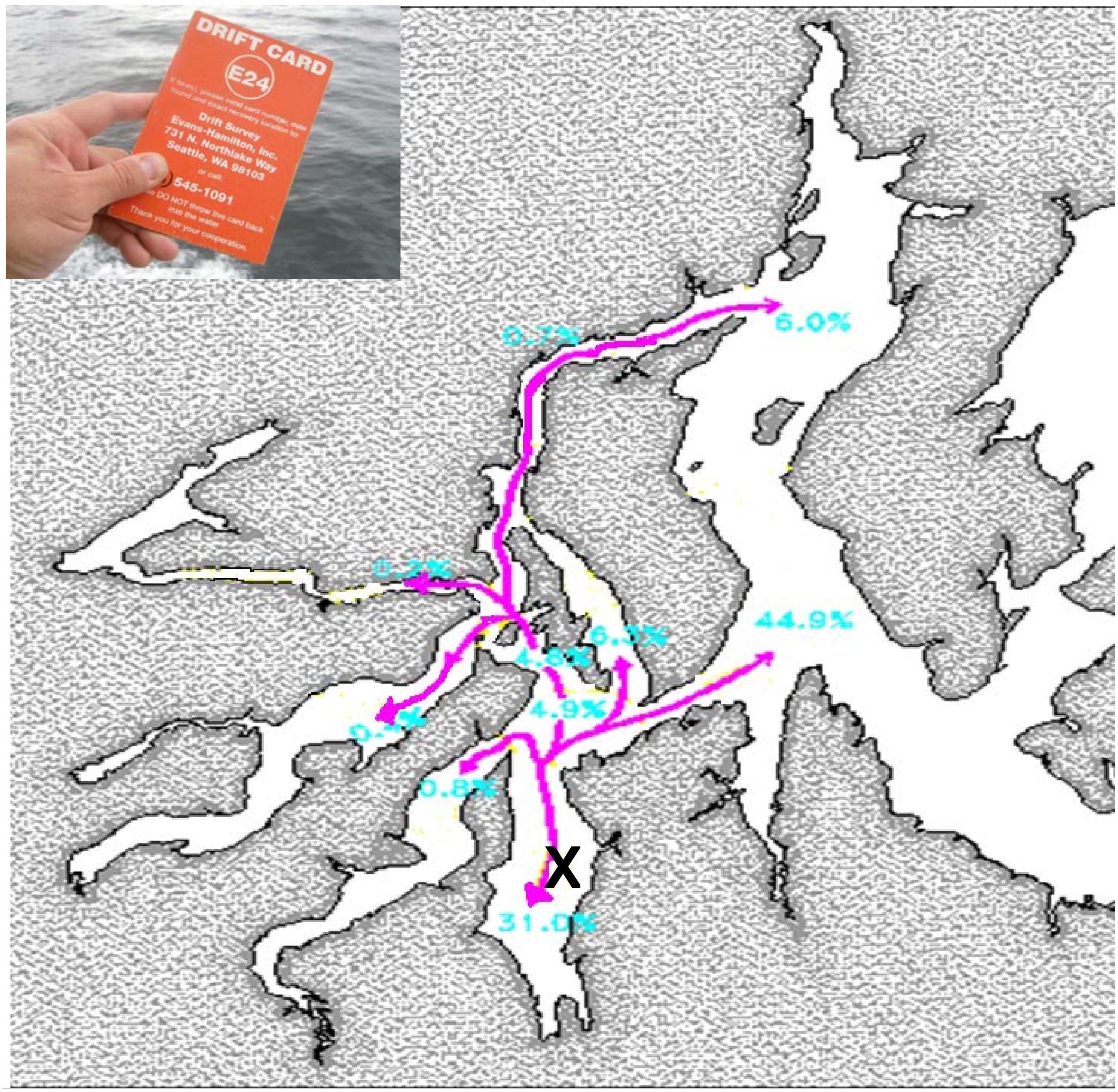

Figure 5. The surface flow pattern suggested by the LOTT drift card study. The X marks the location where drift cards were released.

Ecology's initial model (Albertson et al., 2002a), with minimal wind forcing, shows the net flow from a simulated dye release (neutrally buoyant tracer) travels south through Dana Passage (Figure 6). Details on this model's performance show that estuarine flow can be among the most difficult results to predict correctly (Albertson et al., 2003).

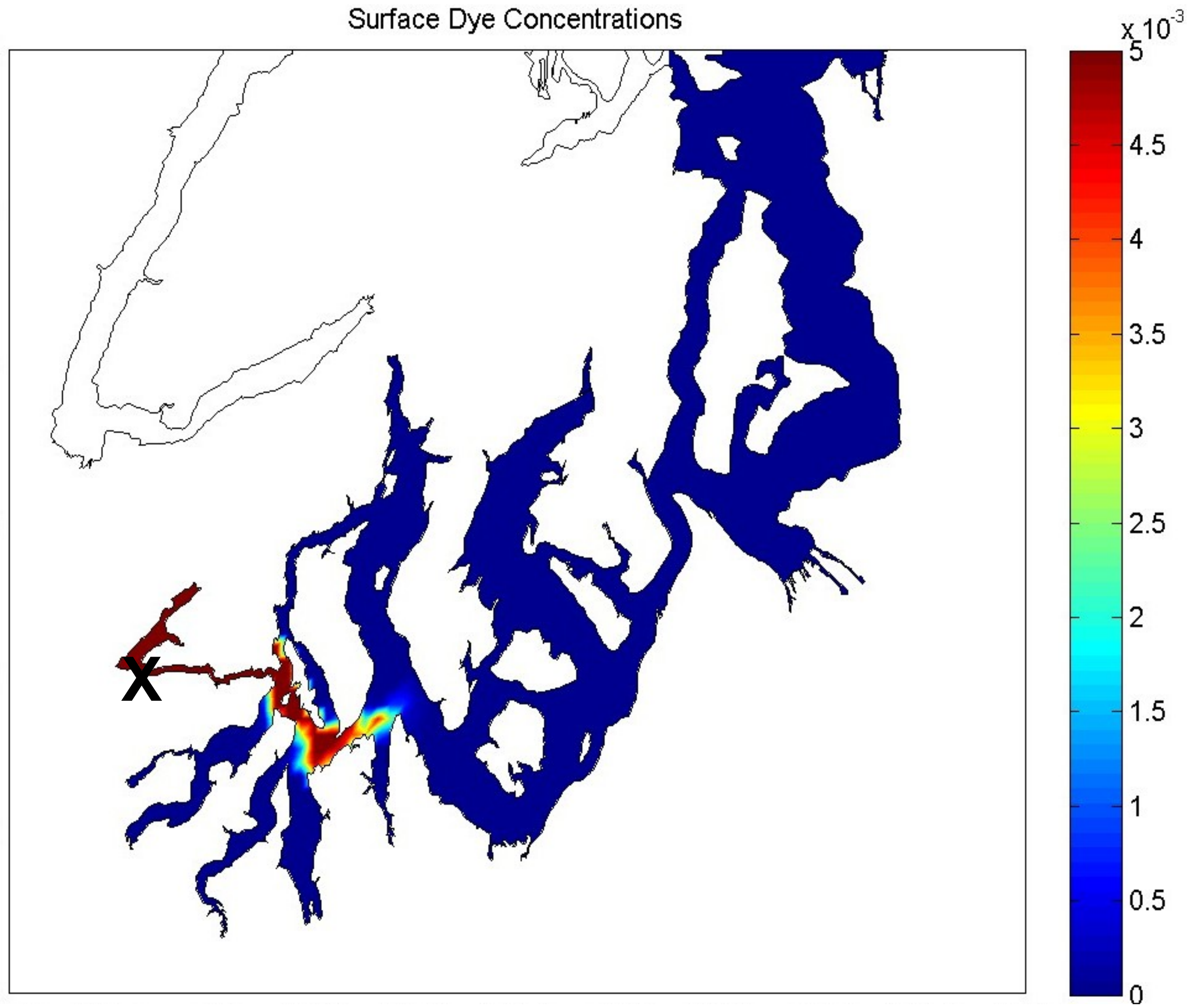

Figure 6. Dye release simulation from Ecology's initial South Puget Sound model. The X marks the location where the dye was released.

Evidence for estuarine flow coming out of Pickering Passage has been noted in most years during the September cruises (1997-2001). For example, in 1997 hyper-saline water that was denser than the seaward-end water was found sinking in Case Inlet at several stations closest to Pickering Passage (Figure 7). This surprising result indicates that, seasonally, evaporation can be important in the finger inlets in forming water masses and end members. A second patch of hypersaline water shown in the figure is to the north (right) of Pickering Passage. This might indicate that the estuarine flow is inverse – landward at the surface and seaward at depth.

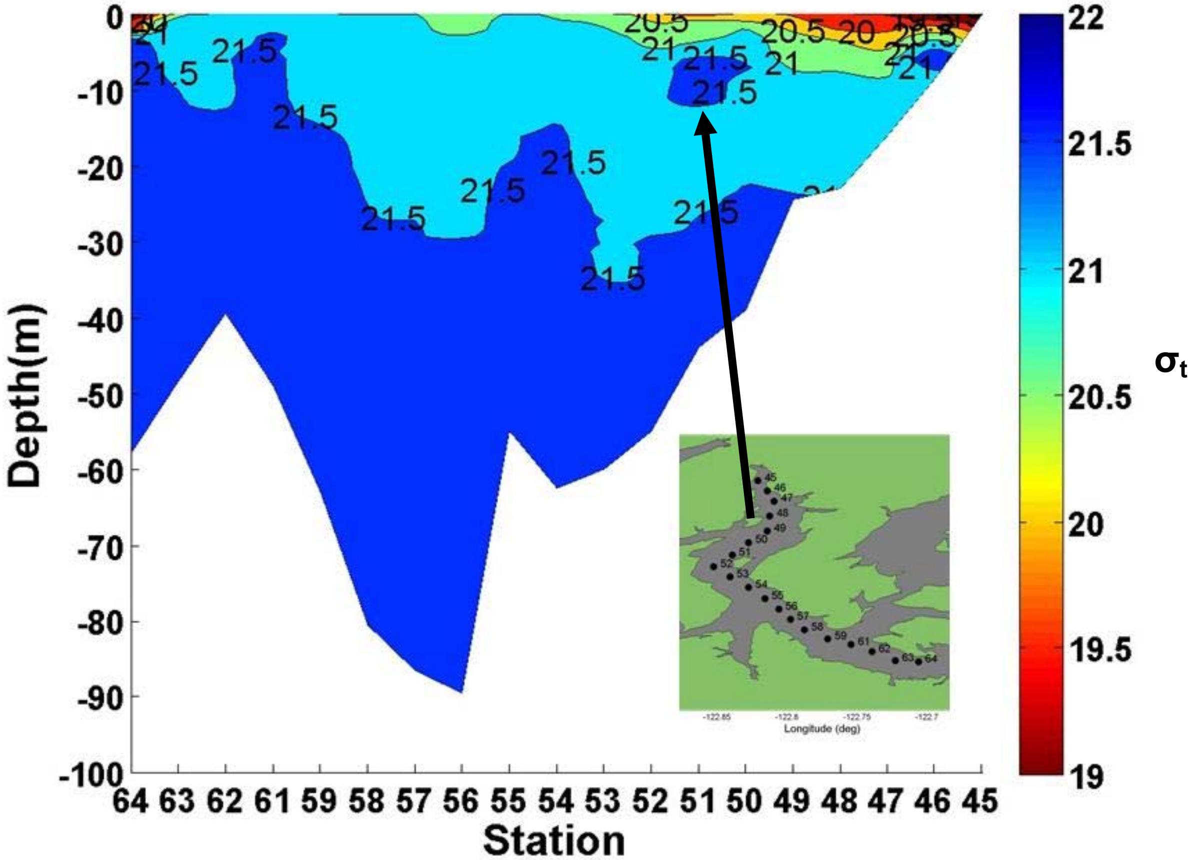

Figure 7. A density profile along the axis of Case Inlet in September 1997, indicating sinking masses of hyper-saline water emanating from Pickering Passage. Case Inlet station locations show in inset.

Methods

To investigate for these estuarine flow patterns around Harstine Island, twin bottom-mounted RDI Broadband 300-kHz Acoustic Doppler Current Profilers (ADCPs) were deployed mid-channel on September 21, 2006 at the two areas constricting flow around the south end (Dana Passage) and north end (Pickering Passage) of the island (Figure 2).

Velocity profiles were collected every six minutes for several months by averaging 90-second ensembles of 1-second pings taken at a frequency of Workhorse Sentinel ADCPs, the generic model name for all non-phased array broadband ADCPs currently produced by Teledyne-RDI. A broadband ADCP uses coded pulses to make multiple measurements of phase with a single ping, and thereby greatly increases the precision of the measurement.

The deployment period included two snowstorms with strong north wind, a “pineapple express” with strong southwest wind on November 6, and a major wind event on December 14 (so-called Hanukkah Eve Windstorm of 2006) with hurricane-force southwest wind, as well as the mild late-summer conditions that also have a north-northeast wind pattern.

The bottom-mounted ADCP measured three components of water velocity in 1-meter depth bins with some error estimate from the fourth head; the two most important components of velocity for this study are east-west and north-south. Because of the mounting depth and blanking distance (distance closest to the ADCP where it cannot recover from sending a ping to measure reflected pulses), the data taken within 2.5 meters of the bottom cannot be recorded. Data within two meters of the surface are lost due to side lobe interference, where reflection of the side lobe signals off the surface interferes with the detection of the returning main acoustic signal.

Results

The depth of no-net-motion, which is the boundary between estuarine inflow and outflow, was around 20 meters in Pickering Passage and 22 meters in Dana Passage. These net surface and deep flows were found by averaging across all depth layers in each category (Figure 8).

Results for two periods show that surface layer estuarine flow alternates between two dominant modes. Positive net-flow velocities are *outbound* flows, whereas negative net-flow velocities are *inbound* flows (Figures 8a and 8b). Around October 18, 2006, the surface flow splits into the “H” pattern around Harstine Island with outbound flow (eastward) in both passages (Figure 8b and 8f). Around September 29-30, however, the surface flow direction is inbound at Dana Passage and outbound at Pickering Passage, indicating the clockwise surface “O” flow pattern around the island (Figure 8a and 8e). During this period, the compensatory flow at depth is counter-clockwise.

During the transition between these two modes, a third state exists. Around October 1-2, baroclinic estuarine flow in Dana Passage becomes negligible because all depths are moving in unison during ebb and flood tides (not shown). During this time the surface-out, bottom-in estuarine flow is most active in Pickering Passage.

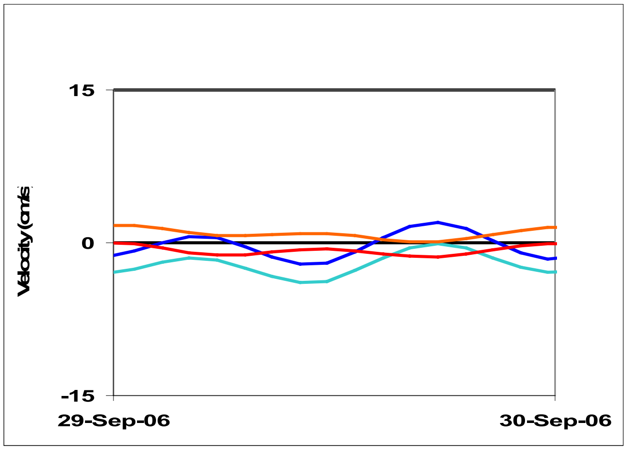

Figure 8a. Surface (teal and orange) and near-bottom (blue and red) flows in Dana (blue) and Pickering Passage (red) concurrent with northerly winds on September 29, 2006.

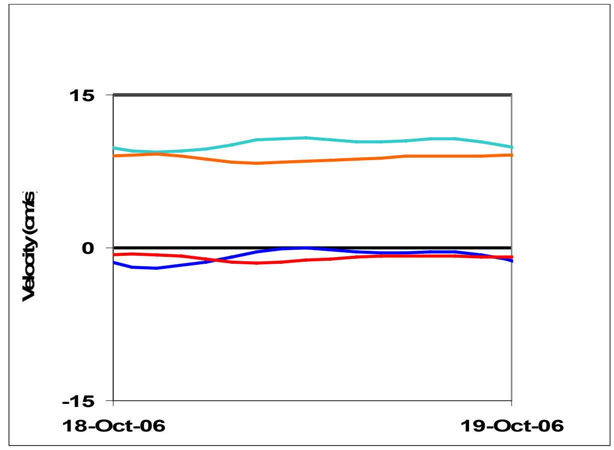

Figure 8b. Surface (teal and orange) and near-bottom (blue and red) flows in Dana (blue) and Pickering Passage (red) concurrent with southerly winds on October 18, 2006.

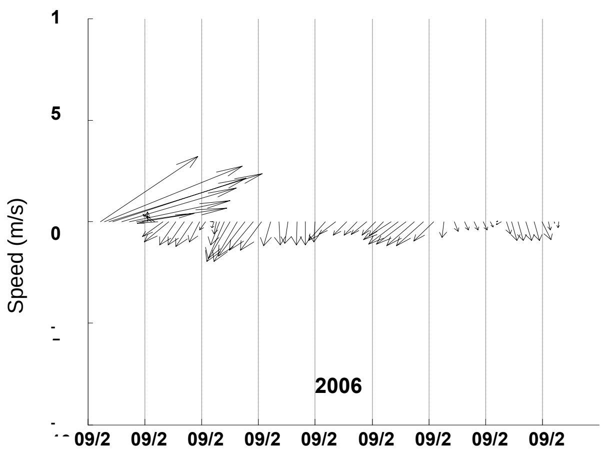

Figure 8c. Predominately northerly winds.

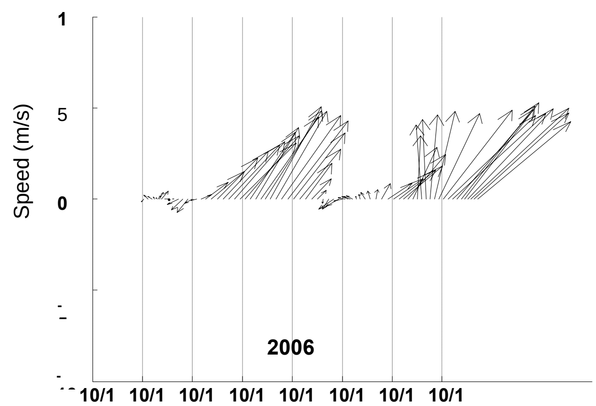

Figure 8d. Predominately southerly winds.

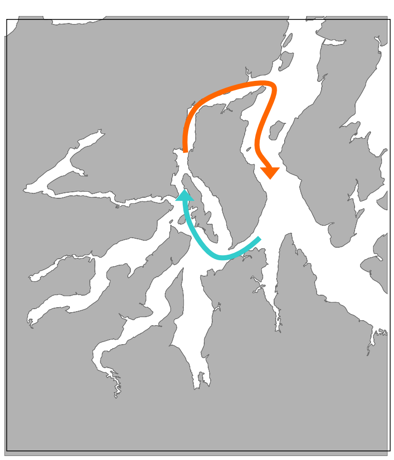

Figure 8e. "O" flow pattern during northerly winds.

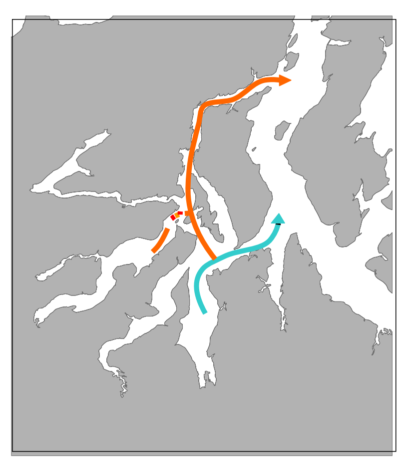

Figure 8f. "H" flow pattern during southerly winds.

During the “O” state, there is a greater possibility that more biological oxygen demand (e.g., dissolved organic matter) could be moving along with water masses into northern Case Inlet via Pickering Passage. If these states are being controlled by something that varies between years (e.g., the wind), then variability in that controlling force might explain why dissolved oxygen in northern Case Inlet is lower in some years than in others.

Dominant wind directions in the region are from the south-southwest and north-northeast (Figure 9).

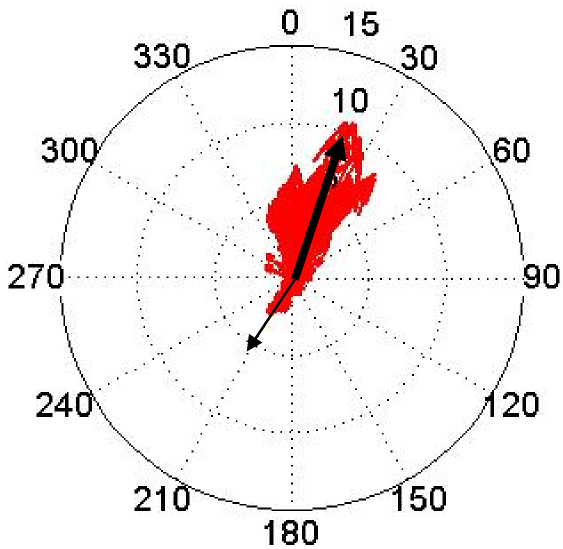

Figure 9. Compass wind rose depicting dominant Pacific Northwest wind directions from September 21 – December 15, 2006 taken at McChord Air Force Base in Tacoma, WA. A *southerly* wind from the SW points to the NE on this graph (larger arrow), and a *northerly* wind from the NE points to the SW (smaller arrow).

By averaging the flows at all depths forward and backward in time by 25 hours, and not splitting the flows into surface and bottom layers, a de-tided time series for both locations can be derived for the entire deployment period (Figure 10). The temporal patterns of these flow results align very well with the wind patterns, as the shifts in estuarine flow direction coincide with distinctive wind events. Depths, recorded by color, are actual distances measured above the instrument so that peak flows are just below the sea surface. The most responsive layers to the wind were near the surface, but slightly deeper in Pickering Passage (34 meters above the ADCP) than in Dana Passage (40 meters above the ADCP). The average depth at both locations was similar at about 44 meters; the tidal range in the area is about 4 meters so that depth bins greater than 40 meters are exposed to the air at low tide.

Estuarine circulation is forced by runoff and inflow from rivers and tributaries, but winds cause the major variations around Harstine Island. Updates to the initial South Puget Sound study will be needed to verify that buoyancy forcing, when the only source of freshwater is from snowmelt on the Nisqually River, is not controlling the estuarine flow around Harstine Island as much as wind does.

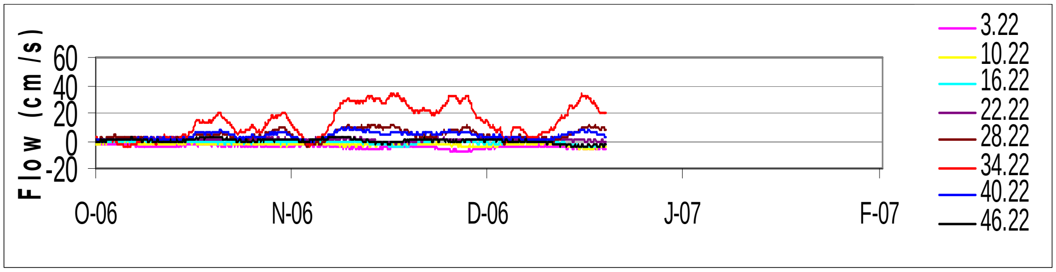

Figure 10a. The estuarine (tidally-averaged) east-west flow at Pickering Passage depth (m) off the bottom.

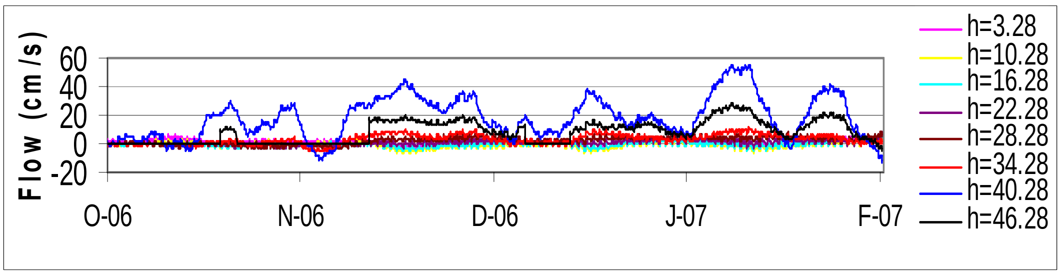

Figure 10b. The estuarine (tidally-averaged) east-west flow at Dana Passage depth (m) off the bottom.

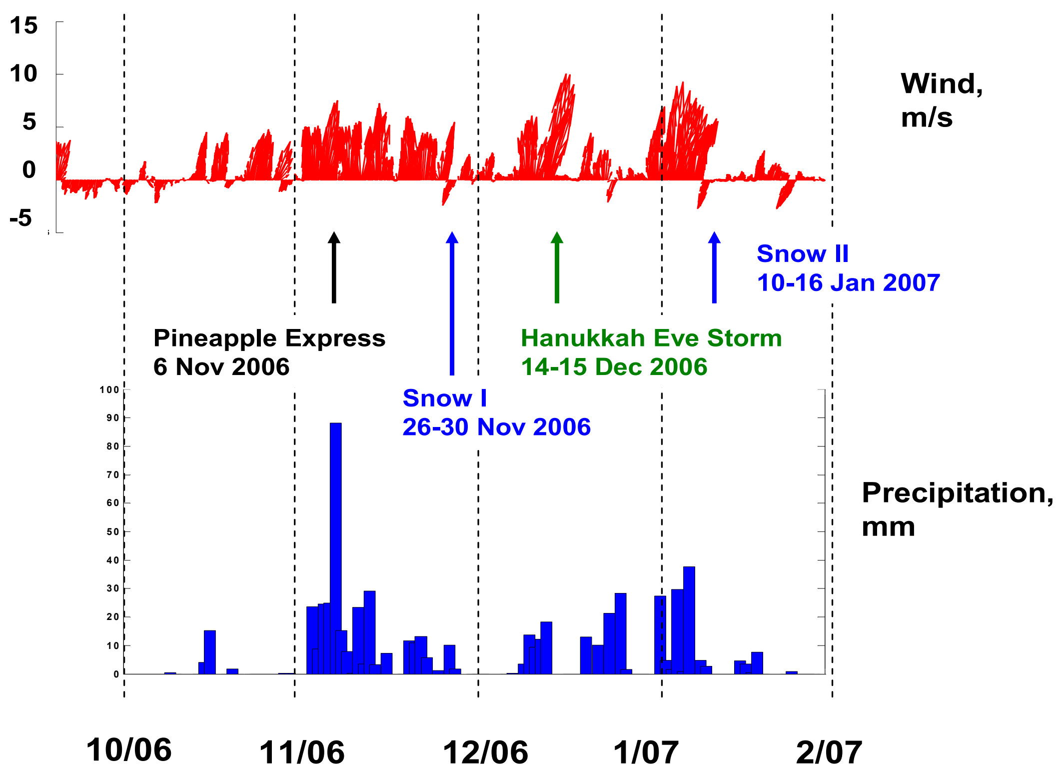

Figure 10c. Wind and precipitation data from McChord Air Force Base in Tacoma.

Conclusions and Recommendations

This report presents new findings to aid in the understanding of water quality and dissolved oxygen (DO) in South Puget Sound. Wind is affecting the estuarine flow around Harstine Island, and that flow can affect near-bottom DO levels in north Case Inlet and Budd Inlet to the south. Understanding this is important to making correct interpretations of annual near-bottom DO minima in South Puget Sound and perhaps ultimately setting discharge levels of nitrogen throughout the region.

All long-term trends in DO, if there are any, are superimposed on year-to-year variations in climate. During years with long, hot summers when wind is coming off the land (from the northeast), there is upwelling on the coast pumping low-DO, nutrient-rich, deep ocean water into Puget Sound. In addition to upwelling-related intrusions, these local effects of estuarine flow also occur around Harstine Island.

Major unknowns remain:

- How much more organic matter and biological oxygen demand enter north Case Inlet during periods of northerly winds?
- Is the less vigorous net flow pattern that occurs with northerly winds sufficient to explain these year-to-year variations?
- Does northern Case Inlet simply not flush as well without the robust estuarine flow of more moderate summers with marine influence driven by southwest winds?
- Does some altered pathway of organic matter and oxygen demand take place, perhaps also driven by wind patterns or even changes in the estuarine circulation of Case Inlet? There is some evidence that estuarine circulation in Case Inlet slows down by salinity inversion (fresher water at the mouth of the inlet), perhaps driven by summer snowmelt from the Nisqually River.
- How important are these local effects compared to intrusions of upwelled nutrient-rich water?

A more complete study of this phenomenon will be undertaken with Ecology's subsequent model development and DO study in the basin starting in 2007 (Albertson et al., 2007).

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