Hypoxia in Hood Canal: An overview of status and contributing factors.

Jan Newton, Corinne Bassin, Al Devol, Mitsuhiro Kawase, Wendi Ruef, Mark Warner
University of Washington

Dan Hannafious, Renee Rose
Hood Canal Salmon Enhancement Group

Abstract—In its second year, the collective efforts of the Hood Canal Dissolved Oxygen Program's Integrated Assessment and Modeling study (HCDOP-IAM) have resulted in a better understanding of the extent and dynamics of hypoxia in Hood Canal as well as on-going evaluation into its contributing factors. In this presentation, we give an overview of the current status of Hood Canal, compared with historical data, and some insights on the major findings to date. We do find evidence to support the conclusion that oxygen concentrations during the 1990s and 2000s are lower in the southern reaches of Hood Canal than were found in the 1930s, 1950s, and 1960s. We differentiate the spatial scales on which chronic and episodic oxygen stress are found. We outline the environmental factors contributing to the occurrence of fish kills. Lastly, we summarize the contributing factors for the increasing hypoxia, which are still under study.

Introduction

The Hood Canal Dissolved Oxygen Program (HCDOP) was formed in response to observations that low dissolved oxygen conditions (hypoxia) in Hood Canal, especially its southern reaches, were getting worse (Curl and Paulson 1991; Newton et al 1995; Warner et al 2001; Newton et al 2002). This was based on the increasing presence, persistence, and distribution of hypoxia in Hood Canal during the 1990's and 2000's over that from the 1930's to 1960's and the repetitive fish kills during the early 2000's. Hood Canal has a long track record of low oxygen conditions (Collias, et al 1974; Curl and Paulson 1991; Newton, et al 2002; Paulson, et al 2006), with anoxia and fish kills noted (Fagergren, et al 2004). However, the recent data, collected using the same techniques (standard Carpenter (1965) oxygen titrations), show more severe and persistent conditions in the southern mainstem of Hood Canal (Figure 1) and at Sisters Point and Lynch Cove (Figure 2).

Understanding what is driving the low dissolved oxygen (DO) is difficult because of the complexity of the situation. Several factors are involved, including both natural factors such as climate and inputs of ocean and freshwater that affect the flushing of Hood Canal (Warner et al 2001, Paulson et al 2006), as well as human loadings of nutrients and carbon (Fagergren et al 2004) that affect the amount algal growth and the organic load that ultimately deteriorate and cause a drawdown in oxygen concentrations (Newton et al 1995).

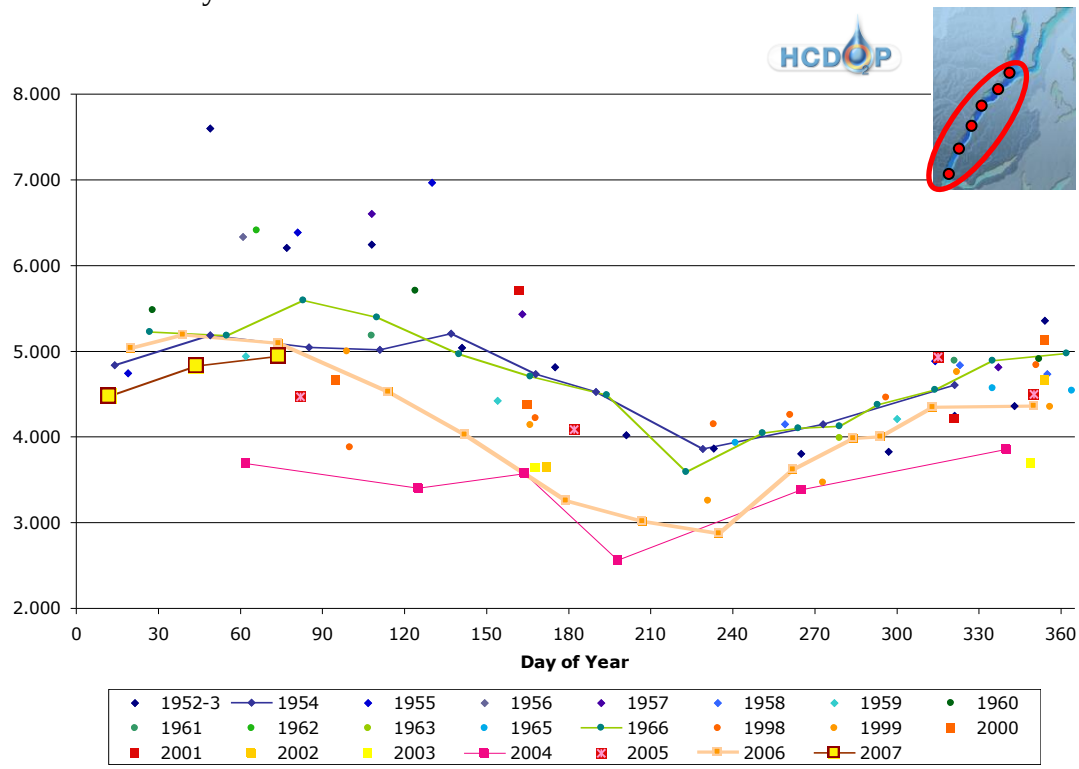
Because of this complex situation, the Hood Canal Dissolved Oxygen Program – Integrated Assessment and Modeling (HCDOP-IAM) science study was created. Details of the program can be found at http: www.hoodcanal.washington.edu. The multi-year study, begun in 2005, is primarily financed through federal funds secured by Congressman Norm Dicks. It also is leveraged by State of Washington and many other programs.

The HCDOP-IAM study utilizes focused observations and modeling to address the quantitative balance of factors in driving observed hypoxia. The goal is to determine sources of low DO in Hood Canal and the effect on marine life, and then to work with local, state, federal, and tribal policymakers to evaluate potential corrective actions that could restore and maintain a level of DO that could reduce stress on marine life. The study integrates automated technology, observing networks, and numerical modeling to:

- Quantify marine processes
- Quantify watershed loadings
- Assess biota-oxygen interactions
- Model key processes to quantify driver(s) of oxygen
- Evaluate potential corrective actions

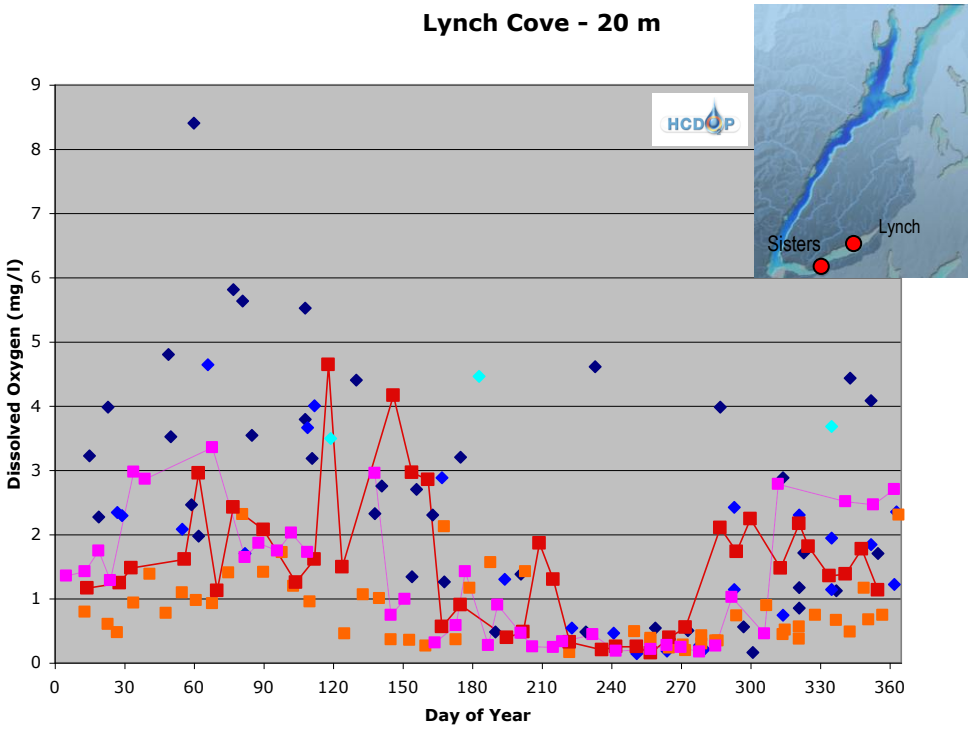
Co-managed by the University of Washington Applied Physics Laboratory and the Hood Canal Salmon Enhancement Group, there are over 25 groups involved directly with the HCDOP-IAM study, including scientists from tribes, counties, state, federal agencies, non-profit groups, and other universities (see http://www.hoodcanal.washington.edu/iam_study/studyparticipants.html).

This paper is a synthesis of the current status of the understanding of oxygen dynamics from the HCDOP IAM study.



Data sources: Collias, 1974, PRISM, PSAMP, HCDOP

Figure 1. Average dissolved oxygen concentration in the water below 20 meters depth in the region between Dabob Bay and the Great Bend plotted versus the day of the year. See http://www.hoodcanal.washington.edu/observations/historicalcomparison.jsp.



Data sources: Collias, 1974, PRISM, PSAMP, HCDOP

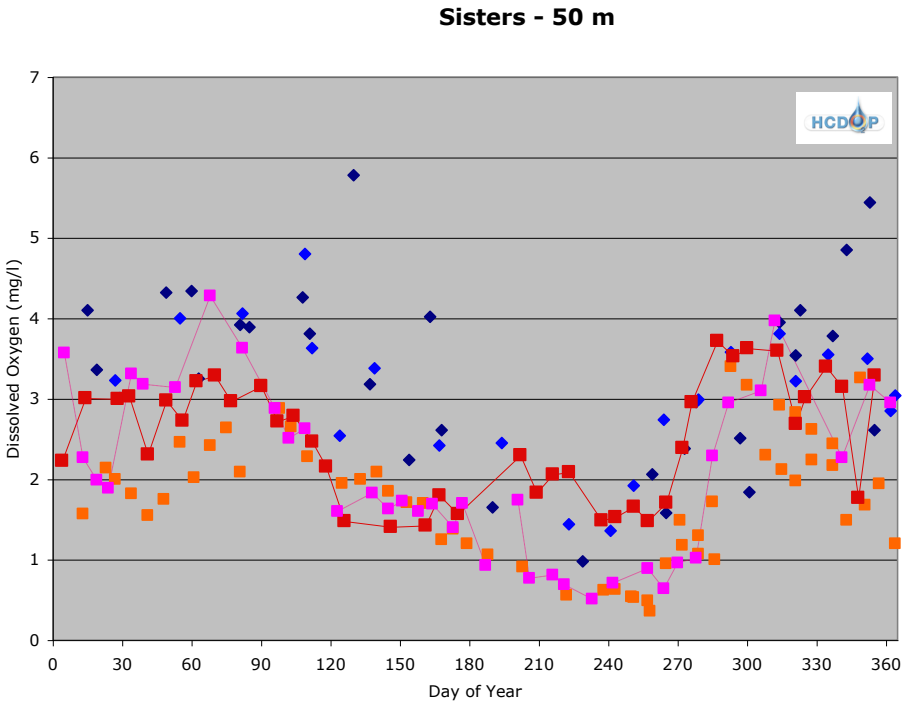


Figure 2. Dissolved oxygen concentration at the deepest depth measured (usually a few meters above the sea-bed) at Sisters Point plotted versus the day of the year. See http://www.hoodcanal.washington.edu/documents/document.jsp?id=2071.

Oxygen Stress

In Hood Canal, there are two different types of oxygen stress that a marine organism may encounter, episodic and chronic. These types of stress, which will be explained more fully below, are driven by different mechanisms. The two figures below reflect where in Hood Canal the potential is greatest for each type of stress, as revealed by HCDOP-IAM data and analyses.

Oxygen is needed for most all animal forms of life, including aquatic organisms such as fish and shellfish. When oxygen concentrations fall below 3-5 mg/L, many marine organisms experience stress and fish may exhibit avoidance behavior. Other organisms, especially benthic forms, are more resistant and do not incur stress until concentrations are lower. When concentrations of oxygen fall to 1-2 mg/L, some organisms will experience severe stress or die. Waters with anoxic conditions (no oxygen) can be inhabited only by some forms of bacteria.

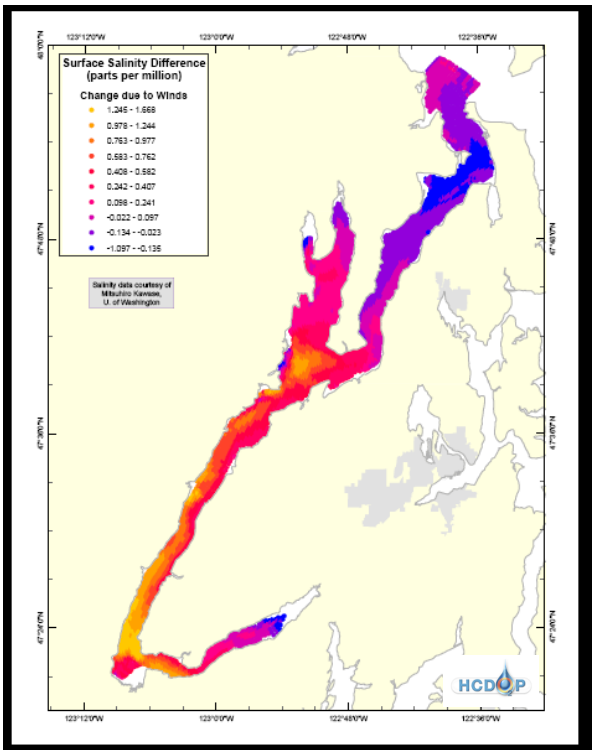
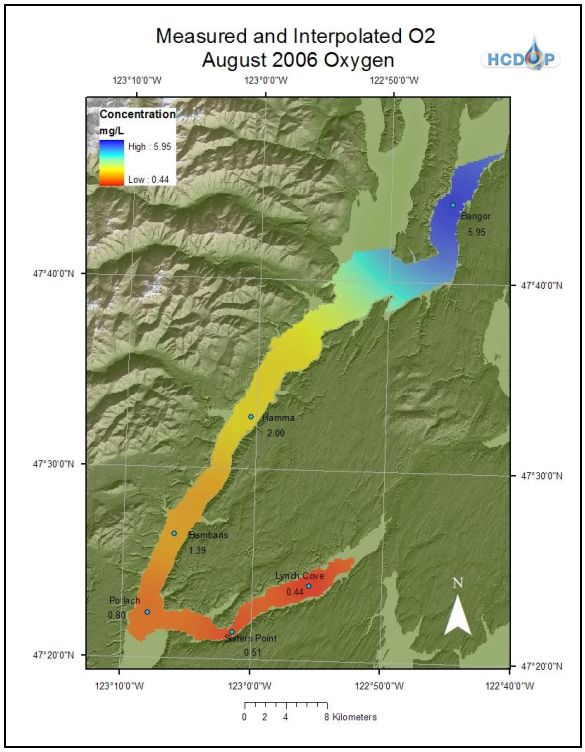


Figure 3. Map of Hood Canal showing areas where risk of exposure to episodic low oxygen conditions caused by wind-mediated upwelling is greatest. Intensity of yellow indicates where deep water rises to surface most effectively during southerly wind events. This indicates where highest risk of biota stress and mortality due to episodic wind-driven low oxygen events occurs.



Source: M. Kawase (UW) HCDOP model results and D. Gombert (WDFW) projection.

Figure 4. Map of Hood Canal showing areas where risk of exposure to chronically low oxygen is greatest. Intensity of red indicates where lowest oxygen concentrations are found, based on August 2006 measurements reflecting the typical

pattern. This indicates where highest risk of biota stress and mortality due to chronic exposure to low oxygen occurs.
Source: HCDOP Citizen Monitoring data and UW Spatial Analysis Lab projection.

Episodic: One type of oxygen stress observed in Hood Canal is the episodic fish kill event. Such events are often associated with the sudden appearance of dead fish and other marine life on beaches (Palsson, this volume). Fish kill events have been recently recorded in the falls of 2002, 2003, 2004 and 2006 and the spring of 2003. While the severity and dynamics of these events has varied, these typically occur in late summer to fall and are associated with processes that bring deep low-oxygen water to the surface. Upward movement of the oxygen minimum zone can be gradual, due to intrusion of newer, denser ocean water at depth or more rapid, due to southerly winds that push the surface layer in the mainstem of Hood Canal northwards, resulting in upwelling of deeper waters. Most of the fish kill events were documented with southerly winds.

To assess where risk for this type of oxygen stress is greatest in Hood Canal, output from the HCDOP IAM hydrodynamic model by Mitsuhiro Kawase (UW) is used to show where wind induced upwelling would be most effective in bringing deep water to the surface. This is seen in Figure 3 as where the change in surface salinity before and after the wind event is the greatest (yellow shading) indicating where wind-induced upwelling brings high salinity, low oxygen waters to the surface. See explanations of this dynamic by Kawase (this volume).

The major fish kill event in September 2006 was associated with southerly wind bursts after a long period of northerlies. The data from the ORCA (Oceanic Remote Chemical Analyzer) data show the water column changes associated with this event (Devol et al. this volume). The severity of the 2006 event was increased because offshore coastal ocean upwelling had contributed high density seawater to Hood Canal during the late summer. This intrusion displaced the deep water of the canal upwards, pushing low oxygen water to relatively shallow depths. WDFW divers led by Wayne Palsson noted more fish higher in the water column than usual prior to the fish kill event and the southerly wind bursts. Because the oxygen minimum zone was so shallow in 2006, the system was particularly poised for wind-induced upwelling to bring low oxygen water all the way to the surface. Fish essentially lost their shallow refuge as the entire upper water column became very low in oxygen. Underwater videography by WDFW captured this episodic condition.

Chronic: The other type of oxygen stress observed in Hood Canal is less obvious from the surface. It is the chronically low oxygen that worsens with distance from the mouth (north of Bangor) to the head of Hood Canal (in Lynch Cove). Risk for exposure to this type of oxygen stress is shown by the pattern in Figure 4, based on minimum oxygen concentrations measured during August 2006 at the sea-bed by the HCDOP-IAM Citizen Monitoring Program, led by the Hood Canal Salmon Enhancement Group and the Skokomish Tribe. This spatial pattern is consistent with that shown from previous historical and current data collected by UW (Collias et al., 1974; PRISM data at http://www.psmem.org) and Washington Department of Ecology PSAMP monitoring (e.g., Newton et al., 2002) and recent ORCA data (Ruef, this volume).

What has appeared to change is the persistence of how long oxygen remains below 3 mg/L in the southern Hood Canal and Lynch Cove areas. Because the oxygen concentration stays so low (annual range at Lynch Cove sea-bed can be as little as 0-3 mg/L; Figure 2), fish do not get caught suddenly in low oxygen waters, die and wash ashore, as they do in the episodic events.

Rather, the species existing in these areas have either adapted to low oxygen conditions or have found a stable refuge in the surface waters.

It is within these chronically low oxygen waters that the Skokomish Tribe observed dead organisms, such as crab, and widespread bacterial mats during the summer of 2006 (Elliott, this volume).

Comparison: At times, both episodic and chronic low-oxygen waters comprise large areas in Hood Canal. However, it is important to note that low-oxygen stress from the episodic events is confined to lasting days to several weeks, whereas stress from the chronic conditions persists mostly throughout the year.

While the mechanisms involved and the areas for risk from these two types of oxygen stress are somewhat different, there is a relation between the two. An increase in the persistence of chronically low oxygen or a decrease in minimum oxygen concentrations will increase the odds that episodic wind-driven events will result in biota death. While the natural factors of wind-driven upwelling and oceanic intrusions facilitate the episodic events, if oxygen concentrations were higher, biota mortality would be less or not occur at all.

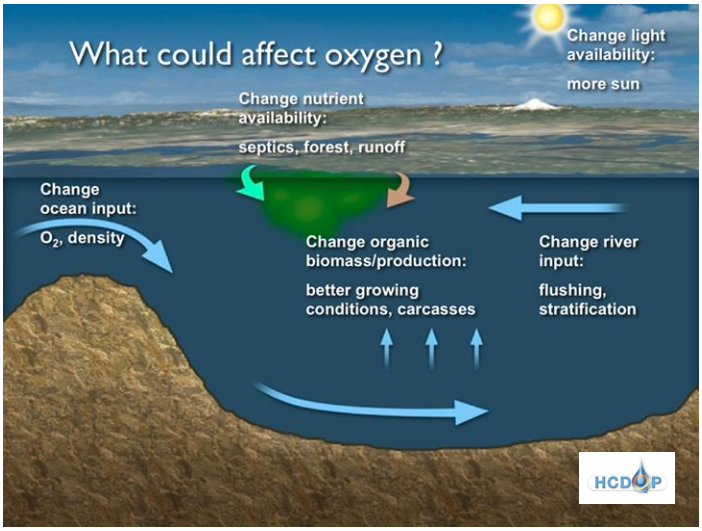
The September 2006 fish kill event occurred when our observing system was able to track it every 2 hours (Devol et al., this volume). This allowed us to see the necessary conditions for such an event and explain why these did not occur in other years with similarly low oxygen. The factors involved are low oxygen, compressed towards the surface by oceanic intrusion and not capped by strong stratification, that is suddenly uplifted by south winds. The association of those factors with conditions in recent years is shown in Table 1.

Table 1. Occurrence of environmental factors associated with fish kill events during recent years.

	2003	2004	2005	2006
	Fish kill	"Odd behavior"		Fish kill
South winds	X	X		X
Low DO	X	**X**	x	**X**
Shallow/ weak pycnocline	X			X

With respect to fish kill events, we can say we have learned the underlying physical mechanisms. However, the ultimate cause of why the oxygen is so low and more persistent is the content of ongoing and active research in the HCDOP-IAM study

Factors contributing to increasing hypoxia



Contributing factors for why oxygen concentrations are so persistently low in Hood Canal shown in Figure 5. The balance of these factors and how or if humans are contributing to this is the topic of ongoing and active research in the HCDOP-IAM study.

Figure 5. Conceptual model for factors contributing to the increasing hypoxia in Hood Canal.

Some of the preliminary HCDOP-IAM findings to date:

Nitrogen influence—We have confirmed that algae are limited by nitrogen and thus a major factor in understanding the oxygen dynamics (Figure 6). We are measuring nitrogen loads from a variety of sources, including streams, groundwater, vegetation (including alders), and on-site septics. A State-funded study is quantifying septic inputs.

Ocean influence—Although the ocean contributes the most nitrogen to Hood Canal (Paulson, et al 2006), preliminary results from the HCDOP IAM model indicate that much of the ocean input exits out Hood Canal without penetrating the zone where algae grow. In contrast, the human nitrogen inputs to the marine waters are at the surface. These nutrients will fuel production and ultimately result in an oxygen debt. In addition, the oxygen and density at the oceanic boundary are showing interannual differences.

Human nitrogen inputs—The scale of human inputs relative to the receiving basin may be important. Preliminary calculations show that an effect of human nitrogen inputs on oxygen in the greater Lynch Cover area is within the range of oxygen decline observed, and therefore cannot, as yet, be ruled out. We took the volume of greater Lynch Cove and calculated what

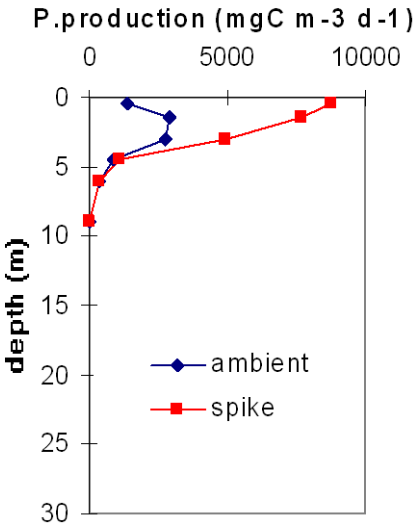


Figure 6. Results from C-14 incubation experiments to measure phytoplankton primary production (method in Newton and Van Voorhis, 2002). The carbon production in ambient seawater is shown in blue circles; that for seawater spiked with replete ammonium and phosphate is shown in red squares. Profiles are from southern Hood Canal at the Great Bend region.

oxygen debt a septic load of 5.88 MT per month for 6 months would produce. We used a total N loading value of (189 MT N/y) from Brett (pers. comm.) from a bootstrap method used by his UW Spring 2006 CEE 547 class (see http://www.hoodcanal.washington.edu/documents/document.jsp?id=1882). This is within the Puget Sound Action Team's Preliminary Assessment and Corrective Action estimate (35-219 MT/y) for Hood Canal (Fagergren et al 2004), but larger than the estimate of Paulson et al 2006 (28+/-15 MT/y). We used a six-month load only, to be conservative and to simulate the seasonal population dynamic of the lower Hood Canal region. The load of 5.88 MT N/mo could account for an oxygen debt of 2.7 mg/L. In southern Hood Canal, we have observed a drop in oxygen concentrations between the 1960s and 2000s on the order of about 1 mg/L (see Figures 1 and 2). Therefore, if the current load accounts for an oxygen debt of 2.7 mg/L, we could assume that the 1960's load would have accounted for an oxygen debt of 1.7 mg/L and thus the population would have needed to grow by 2.7/1.7 = 1.6. This appears to be on order with census data for Mason County, where population increased from 1980 to 2000 by a factor of 1.6.

This crude calculation is far from definitive, but does show the need to quantitatively assess the anthropogenic inputs, their pathways into and within Hood Canal, and their spatial domain of influence. We are also documenting the presence of optical whiteners (man-made compounds) in Hood Canal, to gain a better understanding of human inputs.

Climate—Climate effects on Hood Canal dynamics also are likely contributing. This is likely from a variety of vectors, including sunlight, winds, precipitation, and temperature. Air temperature was significantly higher during the period 1997-2006 versus 1950-1959. This change may stimulate more algal growth because of associated higher water temperature and a possible connection to increased sunlight. These and other factors will be studied further.

In summary, our understanding of the various factors is still evolving. Their effects may differ when considering all of Hood Canal versus only Lynch Cove. Table 2 lists our current understanding of the relative impacts and some uncertainties that HCDOP IAM will address in the third year. For example, the human impact may be greatest on Lynch Cove, whereas variation in ocean boundary may be impacting Hood Canal mainstem but not reaching Lynch Cove. Our current uncertainties include the effect of oceanic input on greater Lynch Cove and the trajectory of the Skokomish River plume.

Table 2. Current understanding of the relative impact of factors contributing to increased hypoxia in both Hood Canal mainstem and greater Lynch Cove.

source	*factor*		Hood Canal mainstem	Greater Lynch Cove
Ocean	Low density Low DO		big effect	???
Watershed	Land-use Alders		? effect	? effect
Humans	Loading N		less effect	more effect
River	High flows Timing of flow		medium effect	???
Climate	Sunny, warm		effect	effect

References

Carpenter, J.H., 1965, The accuracy of the Winkler method for dissolved oxygen analysis, Limnol. Oceanogr., 10: 135-143.

Collias, E.E., N. McGary, and C.A. Barnes, 1974, Atlas of Physical and Chemical Properties of Puget Sound and Approaches, Washington Sea Grant 74-1, Seattle, WA.

Curl, H.C., Jr. and A.J. Paulson, 1991, The biochemistry of oxygen and nutrients in Hood Canal, In: Puget Sound Research '91 Proceedings, Volume 1, T.W. Ransom (Ed.), Puget Sound Water Quality Authority, Olympia, WA, pp, 109-115.

Fagergren, D., Criss, A. and Christensen, D., 2004, Hood Canal low dissolved oxygen: Preliminary assessment and corrective action plan: Olympia, WA, Puget Sound Action Team, Publication #PSAT04-06, 43 p.

Newton, J.A., A.L. Thomson, L.B. Eisner, G.A. Hannach, and S.L. Albertson, 1995, Dissolved oxygen concentrations in Hood Canal: Are conditions different than forty years ago? In Puget Sound Research '95 Proceedings, Puget Sound Water Quality Authority, Olympia, WA, pp. 1002-1008.

Newton, J. and Van Voorhis, K., 2002, Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound, Washington State Department of Ecology, Environmental Assessment Program, Publication #02-03-059, Olympia, WA.

Newton, J.A., S.L. Albertson, K. Van Voorhis, C. Maloy, and E. Siegel, 2002, Washington State Marine Water Quality in 1998 through 2000, Washington State Department of Ecology, Environmental Assessment Program, Publication #02-03-056, Olympia, WA.

Paulson, A.J., Konrad, D.P., Frans, L.M., Noble, M., Kendall, C., Joshberger, E.G., Juffman, R.L., and Olsen, T.D., 2006, Freshwater and saline loads of dissolved inorganic nutrients to Hood Canal and Lynch Cove, western Washington, U.S. Geological Survey Scientific Investigations Report, 2006-5106, 92 p.

Warner M.J., M. Kawase, and J.A. Newton, 2001, Recent studies of the overturning circulation in Hood Canal, In Puget Sound Research '01 Proceedings, Puget Sound Action Team, Olympia WA.