Relationships between the Composition of the Benthos and Sediment and Water Quality Parameters in Hood Canal

Task IV – Hood Canal Dissolved Oxygen Program

Washington State Department of Ecology

Western Washington University

Hood Canal Dissolved Oxygen Program

Puget Sound Assessment and Monitoring Program

December 2007

Department of Ecology Publication No. 07-03-040

Publication Information

This report is available on the Department of Ecology's website at
www.ecy.wa.gov/biblio/0703040.html

Sediment data for this project can be obtained from the following Environmental Information Management (EIM) studies (1989-2004): PSAMP_SP, PSAMP_LT, PSAMP_HP, and PSAMPNOA. The EIM website is www.ecy.wa.gov/eim/index.htm.

Ecology's Study Tracker Code for this study is AT-06-103.

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Cover photo: Hood Canal bridge and Olympic Mountains.

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Task IV – Hood Canal Dissolved Oxygen Program

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Waterbody Numbers:

WA-PS-0100, Hood Canal north
WA-PS-0250, Hood Canal south

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Glossary, Acronyms, and Abbreviations

Glossary

Anthropogenic	Human-caused
Assemblage	A group of organisms collected from the same location
Azoic	Devoid of animal life
Benthic	Bottom
Benthos	Organisms living at the bottom of, or in the sediments of, a waterbody
Epifauna	Animals that live attached to hard bottom substrates
Eutrophication	An increase in nutrients in an estuary that stimulates excessive plant growth
Hypoxia	Low oxygen
Indices	Metrics or methods
Infauna	Animals that live burrowing or buried in the soft sediments
Normoxic	Normal oxygen levels
Pielou's Evenness (J')	A measure of how equitably distributed the taxa are
Scatterplots	A plot of pairs of values of a set of bivariate (two-variable) data
Sill	A relatively shallow area of the seabed, typically found at the mouth of fjords, formed by accumulated rock at the glacier front
Taxa	Lowest level of identification for organisms
Taxa richness	Number of different taxa

Acronyms and Abbreviations

Following are acronyms and abbreviations used frequently in this report:

CNESS	Chord-normalized expected species shared
DO	Dissolved oxygen
Ecology	Washington State Department of Ecology
EMAP	Environmental Monitoring and Assessment Program (USEPA)
HC	Hood Canal
HCDOP	Hood Canal Dissolved Oxygen Program
m	meter
NOAA	National Oceanic and Atmospheric Administration
PAHs	Polycyclic aromatic hydrocarbons
PRISM	Puget Sound Regional Synthesis Model (University of Washington)
PSAMP	Puget Sound Assessment and Monitoring Program (Department of Ecology)
QA/QC	Quality assurance/quality control
SDI	Swartz' Dominance Index
SQS	Sediment quality standard
TOC	Total organic carbon
UPGMA	Unweighted pair-group mean average
USEPA	U.S. Environmental Protection Agency
UW	University of Washington

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Abstract

Sediment quality data and concentrations of water-column dissolved oxygen (DO) collected in Hood Canal from 1932 to 2005 were evaluated as part of the Hood Canal Dissolved Oxygen Program. The influence of these measures on the composition of sediment-dwelling invertebrate assemblages (benthos) was examined.

Sediment chemical contamination and toxicity was low, and confined to Port Gamble, Port Ludlow, and Dabob Bay. Coarse sands were found in northern Hood Canal and along shorelines. Fine-grained silts and clays were found in central and southern regions, at depth, and in shallow bays. Organic carbon concentrations increased in fine-grained sediments.

DO concentrations decreased from north to south and from shallow to deep water. Minimum DO levels measured from 1932 through 2005 decreased over time, periodically falling below critical values at most southern stations and at an increasing number of central and northern stations.

Benthic assemblages were identified for three regions and nine sub-regions of Hood Canal. The number of individuals and species decreased and stress-tolerant species became dominant southward as sediment grain size and near-bottom DO decreased, and organic carbon content and depth increased. These factors, in this order, acting together may have influenced the composition of the benthos.

Obvious changes in assemblage structure occurred within DO ranges of >3 to 6 mg/L and ≤ 1 mg/L. These two ranges may represent critical DO concentrations for Hood Canal benthos. Patterns of species succession over decreasing DO ranges were similar to responses by the benthos to stressors reported in fjords elsewhere.

Additional analyses indicated that there had been little change in northern Hood Canal benthos that could be attributed to declining oxygen levels. However, southern stations near the Great Bend have experienced changes consistent with declining DO concentrations since 1991.

Steps taken to develop initial critical DO values for the protection of the benthos, and a summary of data gaps and associated recommendations for future work on this topic, are presented.

Acknowledgements

The authors would like to thank the following persons for their contributions to this study:

- Jan Newton and Dan Hannafious, Hood Canal Dissolved Oxygen Program coordinators, for their funding support.
- Skip Albertson, Ecology Environmental Assessment Program, for providing the historical water column database.
- Joan LeTourneau, Gayla Lord, and Cindy Cook, Ecology Environmental Assessment Program, for formatting this report.

Executive Summary

The following work was conducted by scientists from the Washington State Department of Ecology (Ecology) and Western Washington University (WWU) to examine relationships between the composition of sediment-dwelling invertebrate assemblages (benthos), the quality of the sediments in which they live, and the concentrations of dissolved oxygen (DO) levels in overlying water in Hood Canal. Existing data were gathered and analyzed to evaluate the effects of low DO (hypoxia) on benthos as part of the Hood Canal Dissolved Oxygen Program (HCDOP). Some of the most significant outcomes of this evaluation are described below.

- **A data set was compiled that consisted of indices (metrics) of benthic infaunal community composition, measures of sediment quality, and dissolved oxygen concentrations**. This historical data set included measures of sediment grain size, total organic carbon (TOC), chemistry, toxicity, indices of benthic infauna composition, and water column DO levels. Sediment data were collected in Hood Canal from 1952 through 2005, whereas the water column DO data were collected from 1932 through 2005. All these data were compiled in an Access database. There were 30,943 sediment data records collected from 145 stations, and 165,649 DO data records collected from 128 stations.

- **Data summaries and analyses were completed**. The compiled data were summarized and evaluated to determine the spatial distribution and temporal variation for all parameters examined. Correlation, co-occurrence, and multivariate analyses were completed to examine the relationships between benthic indices, sediment variables, and DO values.

- **Direct comparisons of matching benthic, sediment quality and DO data were limited.** Most sediment and water column monitoring programs in Hood Canal were conducted independently to satisfy different goals and objectives. Simultaneous collection of benthic, sediment, and water column parameters occurred at only 30 stations: those sampled in 2004 for the Puget Sound Assessment and Monitoring Program (PSAMP) Spatial Sediment Monitoring Program. Efforts were made to use other existing water column data to estimate DO values at all sediment stations, but coverage was insufficient both spatially and temporally to produce reliable estimates. Analyses of relationships among various sediment parameters included data collected between 1989 through 2005 at 58 PSAMP sediment monitoring stations. However, our analyses of the relationships between benthic metrics, sediment parameters, and DO values were limited to data from the 30 PSAMP stations sampled in 2004.

The sediment, benthic, and water column DO data sets were summarized and evaluated separately to determine spatial patterns and temporal trends. These patterns and trends included the following:

- **Sediment grain size and measures of percent total organic carbon varied throughout Hood Canal.** Sediments were primarily composed of relatively coarse sands in northern Hood Canal near the entrance and on the sill, and in the shallows along the shorelines of both the main axis of the canal and the adjoining bays. Sediments collected south of the sill, down the central axis of the canal, at the greatest depths, and in portions of the terminal inlets were primarily finer-grained silts and clays. Concentrations of TOC usually were positively correlated with percent fines. Higher concentrations of TOC were found in finer-grained sediments. Both grain size and TOC were relatively constant at the long-term stations during the period 1989-2005. Both percent TOC and percent fines increased with increasing depth.

- **Sediment chemical contamination in Hood Canal was low.** Potentially toxic trace metals were detected more frequently (81% of samples tested) than organic pollutants (detected in 0-40% of the samples for most organics; 74-77% for polycyclic aromatic hydrocarbons (PAHs)). However, these chemicals rarely exceeded Washington State Sediment Quality Standards. Standards were exceeded for a suite of metals, PCBs, and benzenes at stations sampled in 2000 in Port Gamble; for naphthalene in a sample collected at one station in 1999 in Port Ludlow; and for butylbenzylphthalate in a sample collected at one station in 1990 in Dabob Bay.

- **Sediment toxicity in Hood Canal was low.** Like chemical contamination, toxicity exceeded critical values in a few locations in Port Ludlow, Port Gamble, Dabob Bay, near the mouth of Dabob Bay, and in southern Hood Canal near Lilliwaup. It is doubtful that chemically mediated toxicity caused any adverse effects to the resident benthos.

- **Benthic indices indicated a wide range of values and patterns throughout Hood Canal. Relatively distinct infaunal assemblages were distinguished for three large regions and nine smaller sub-regions of the canal.**

  - Detailed examination of the benthos and sediment data distinguished three large regions and nine smaller sub-regions with relatively well-defined infaunal assemblages. The three larger regions were northern Hood Canal, Dabob Bay and southern Hood Canal, and Lynch Cove. The nine smaller sub-regions were Port Ludlow, Port Gamble, northern Hood Canal, Dabob Bay (nearshore), Dabob Bay (deep), central Hood Canal (nearshore), central Hood Canal (deep), southern Hood Canal, and Lynch Cove. The dominant species, the benthic indices, and the measures of station depth, grain size, and TOC tended to be similar at stations within these nine sub-regions and differed among the sub-regions.

  - Infaunal indices suggested a pattern of decreasing total taxa abundance and taxa richness from north to south along the main axis of Hood Canal, with increasing percent fines and TOC, and with increasing depth.

  - There were a variety of spatial patterns in the abundance of the dominant taxa in the nine sub-regions of the canal. Some species were ubiquitous, living in varying abundance in most, or all, of the sediments sampled throughout the canal. Others appeared to be limited to one or two sub-regions. Some dominant taxa were found to overlap in several sub-regions, typically those that shared some common characteristics (e.g., percent fines, percent TOC) or were in geographic proximity to one another.

- The northern Hood Canal sub-region stations, with relatively low percent fines and TOC content, had the most diverse infaunal assemblages, with balanced mixtures of annelids, arthropods, and bivalves. Less stress-tolerant arthropods, echinoderms, and miscellaneous taxa became rare or absent from north to south, while more stress-tolerant polychaetes and bivalves became dominant southward. The ubiquitous bivalves, *Axinopsida serricata*, *Macoma carlottensis,* and *Macoma* sp., present throughout the canal in varying numbers, became more dominant in the southern Hood Canal and Lynch Cove sub-region stations where arthropods, echinoderms, and miscellaneous taxa were rare or absent.

- **No obvious increasing or decreasing trends in benthic indices were seen over time.** Although there was a pattern of decreasing total taxa abundance and taxa richness from north to south in the four PSAMP temporal trends stations, there were no obvious temporal trends within stations from 1989 through either 1994 or 2005. Also, there were no obvious differences between benthic indices measured at the PSAMP spatial stations in 1999 versus 2004.

- **The majority of Hood Canal benthic index values differed from the 1997-2003 Puget Sound baseline benthic index values.** Forty-two of the 58 stations (72%) sampled in Hood Canal from 1989 through 2005 had assemblages with index values lower than the median for the Puget Sound 1997-2003 baseline data set. In general, Hood Canal benthic assemblages were less abundant and diverse than elsewhere in Puget Sound. All stations with benthic index values equal to or greater than the median Puget Sound baseline data set were located in northern Hood Canal in shallow and nearshore stations with low percent fines and TOC. The percent of stations with less abundant and diverse (i.e., adversely affected) benthos was slightly higher, and appeared to extend further north, in 2004 (77%) than in 1999 (71%).

- **The concentrations of DO differ considerably throughout the Hood Canal region.** DO concentrations typically were highest in the entrance to the canal, over the shallow entrance sill, and along the shorelines of the canal and adjoining bays. The lowest concentrations typically were found in Lynch Cove at the southern end of the canal. The lowest concentrations each year have steadily decreased along the main axis of Hood Canal and Dabob Bay from north to south and from shallow to deep water. In recent years the southernmost and deepest stations typically had DO concentrations below the critical levels necessary to protect bottom-dwelling biota. In the 2004 survey, DO concentrations measured near the bottom ranged from >13 mg/L to <1 mg/L.

- **Annual minimum DO levels measured from 1932 through 2005 have decreased at most stations over time.** They continue to fall further below critical values in most southern stations and below critical values at an increasing number of central and northern stations. These patterns were especially noticeable in the measures made from the late 1990s through 2005.

Bivariate correlation analyses of benthic metrics, sediment quality, and DO parameters measured at 30 to 58 PSAMP sediment monitoring stations in Hood Canal were conducted to determine relationships between matching pairs of parameters.

- **Few correlations were significant. Biological indices were strongly correlated with each other and with percent fines, percent TOC, and depth; fewer correlated with sediment chemistry, toxicity, or near-bottom DO.** A relatively small percentage (58 of 527; 11%) of weak to strong significant linear relationships was calculated between benthic indices, sediment parameters, and measures of near-bottom DO. These correlations, and their associated scatterplots, verified some of the patterns seen in the geographic data displays. Some scatterplots suggested other types of non-linear relationships between these variables.

- **Percent fines, percent TOC, mean sediment quality standards (SQS) metals, station depth, and near-bottom DO appear to co-vary with each other and with some benthic indices.** Percent fines, percent TOC, mean SQS metals, station depth, and near-bottom DO were strongly positively correlated with one another, and negatively correlated with total abundance and taxa richness. Scatter plots of these data exhibited similar patterns, suggesting they co-vary with each other. It is possible that all of these variables jointly influenced the structure of benthic infaunal assemblages in Hood Canal.

Co-occurrence analyses were conducted, grouping the data for benthic indices and abundance of selected species within five ranges of near-bottom DO to determine similarities and differences between suites of values within these ranges. Several patterns were observed:

- **There were obvious changes in benthic assemblage structure as median DO levels decreased to ranges of >3 to 6 mg/L and ≤ 1 mg/L.** When grouped by specific DO ranges, the majority of the median index values were lower in the low-DO samples than in the high-DO samples. Noticeable changes in median index values, indicative of benthic assemblage structure, were seen within DO ranges of >3 to 6 mg/L and ≤1 mg/L, with values decreasing with decreasing levels of DO. These two ranges in DO concentrations may be important inflection points for many benthic species in Hood Canal.

- **Taxa abundance responded differently in differing DO ranges.** Examination of median abundance patterns for 17 selected taxa indicated four general patterns in abundance as DO concentrations decreased. Some species initially increased in abundance then decreased as DO concentrations decreased. Other species increased in abundance midway through the DO gradient, then decreased as DO decreased. Some species immediately decreased in abundance as DO began to decrease and eventually became rare or absent. Some species were relatively rare in all samples and therefore decreased in abundance only slightly as DO decreased. Median abundance for many taxa fell to 0 individuals/square meter within DO ranges of >3 to 6 mg/L or ≤1 mg/L.

Multivariate analyses of sediment quality, benthos, and matching DO parameters measured for the 30 2004 PSAMP spatial surveys in Hood Canal, and for the 58 PSAMP sediment monitoring stations, were conducted to further examine relationships among parameters. These analyses revealed information about the relationships among the benthic assemblage structures, sediment quality, and DO that were not identified with the bivariate correlation analyses or the co-occurrence analyses. The following were observed:

- **Strong spatial variation occurred in benthic communities.** Multivariate analyses indicated strong spatial variation in benthic communities in Hood Canal, and further evidence of three main regional assemblages in Northern Hood Canal (1), Central Hood Canal and Dabob Bay (2), and Lynch Cove (3). Several species – including *Axinopsida serricata*, *Euphilomedes producta*, *Heteromastus filobranchus*, *Macoma carlottensis*, and *Prionospio (Minuspio) lighti* – contributed strongly to these patterns. At lower similarity levels, the nine sub-regions could also be identified.

- **Together, grain size (percent fines), near-bottom DO, percent TOC, and depth may have influenced assemblage structure.** Of the environmental variables examined, grain size (percent fines) was best correlated with variation in benthic assemblage structure, followed by DO, percent TOC, and depth. DO was the most important of the measured environmental variables for several species.

- **The structure of the benthic assemblages at the Great Bend changed in a pattern consistent with declining DO concentrations since 1991.** Historic reconstruction of benthic assemblage response to DO by use of a multivariate index indicated that northern stations have experienced little change that can be attributed to changes in DO concentration over the past 15 years. However, stations in the Great Bend region have experienced changes consistent with declining DO concentrations since 1991.

In addition to the results of the data summaries and analyses generated for this report, a number of potential sources of uncertainty and gaps in the data are identified. Initial steps toward development of critical values/thresholds as indicators of adverse effects of lowered DO on the benthos are discussed. Recommendations for any future research to be conducted to evaluate the relationships between the benthos and sediment and water quality parameters in Hood Canal are presented.

Development of Initial Critical Values/Thresholds as Indicators of Adverse Effects of Hypoxia on Benthos

In this study, co-occurrence analyses were used to evaluate the matching benthos and DO data from the 30 stations sampled in the 2004 PSAMP Sediment survey. One of the objectives of these analyses was to determine if any critical DO thresholds affecting benthic assemblage structure could be identified. Co-occurrence tables and figures indicated that a range in DO values, rather than individual values, might be important in affecting the benthos. There appeared to be a wide range of DO concentrations that were critical to the many species living in the canal. Median benthic index data and median abundance of selected taxa, grouped into five DO ranges, indicated the following:

- **A DO range of >3 to 6 mg/L may be an initial critical DO threshold in Hood Canal.** Median benthic indices of total abundance, taxa richness, and dominance – along with the abundance of arthropods, molluscs, and miscellaneous taxa – exhibited a noticeable decline within the >3 to 6 mg/L DO range. The abundance of several species of clams, ostracods, and an amphipod decreased markedly or became zero in many samples in this DO range. An entire phylum (Echinodermata) disappeared in this range. This range coincides with the biological stress threshold of 5 mg/L previously identified by a panel of experts.

- **A DO range of ≤1 mg/L may be a second critical DO threshold in Hood Canal. T**here was a relatively severe decrease in most beneficial benthic metrics in samples with DO concentrations at or below 1 mg/L. Therefore, there is evidence that there may be a second critical value or threshold, ≤1 mg/L, below which adverse effects to the benthos in Hood Canal are much more severe. However, with a sample size in this range of only two, it is premature to declare that this value accurately represents a severe threshold.

The development of these initial critical values/thresholds as indicators of adverse effects of hypoxia on benthos is based on examination of only the data from the 30 2004 PSAMP Sediment survey stations. These stations were not evenly distributed along the Hood Canal DO gradient. More samples would be required to adequately conduct this analysis and accurately identify critical levels for protection of the benthos.

Data Gaps

A number of gaps in the information that currently is available became apparent during this effort to determine the relationships between benthic assemblage composition and sediment and water quality parameters in Hood Canal.

- **Little matching benthos, sediment quality, and water column DO data exist.** Among the many sediment and water column surveys conducted in Hood Canal since 1932, only the 2004 PSAMP Sediment survey simultaneously collected sediment quality, benthic assemblage, and water column DO data at each station. Our understanding of the adverse effects of hypoxia on the resident benthos in Hood Canal, therefore, currently is restricted primarily to what was learned from the 30 samples collected in 2004. Additional information was acquired indirectly from general trends in sediment and DO variables collected in other years. The results of the 2004 survey were of high quality, but indicated considerable variability in the relationships between DO concentrations and benthic properties. These relationships would become clearer if more matching data were collected.

- **Spatial coverage of benthos and sediment quality data is incomplete for the DO gradient.** Sediment survey designs did not target or adequately represent Hood Canal's DO gradient. The sediment surveys in Hood Canal either targeted specific small-scale sites of interest or employed a spatially random stratified sampling design to satisfy the differing goals and objectives of each survey. None of the sediment quality surveys conducted thus far specifically focused on sampling along the DO gradient in Hood Canal. As a result, existing sediment stations, including the 30 from the 2004 PSAMP Sediment survey, were not evenly distributed along the known DO gradient in Hood Canal. There were only two samples out of the 30 from 2004 in which the DO content was less than 1 mg/L. Consequently, there is a very small amount of data unequally distributed along the DO gradient with which to evaluate effects of hypoxia on the resident benthic assemblages.

- **Temporal sediment quality and benthos data are limited.** Sampling and analysis to determine changes over time in sediment quality and the composition of the benthic assemblages occurred sporadically since 1989 at seven stations. Analysis of temporal trends presently continues for only one station, sampled every April for PSAMP in northern Hood Canal. This record provided insufficient data to understand temporal shifts in community structure in the various Hood Canal sub-regions identified in this report.

- **Knowledge of water column DO values beyond the main north-south Hood Canal axis is incomplete.** Until the year 2000, all water column surveys targeted the north-south main axis of Hood Canal. No information was collected for Dabob Bay or shallow, nearshore stations until the year 2000 and beyond. Therefore, our knowledge of the spatial extent of hypoxia in Hood Canal is incomplete.

- **No DO measurements have been made at the sediment-water interface or in sediment pore water.** The DO measurements from all surveys examined were collected at least 1-2 meters above the bottom, and therefore may not accurately represent the conditions to which the benthos were exposed. In many surveys, DO was measured from the surface to mid-water column depths only. Data from studies conducted elsewhere (mostly in Europe) have shown that huge gradients in DO can occur over depths of one meter or less above the sediments. DO at or below the sediment surface may have been significantly lower than in mid-water column depths and near-bottom depths where most measurements were made.

- **"Snapshot" analyses conducted during the 2004 PSAMP Sediment survey do not account for seasonal changes in DO.** The 2004 PSAMP Sediment survey was conducted in June, whereas hypoxia in Hood Canal often is worst in late summer and early fall. The near-bottom DO measurements recorded simultaneously with the benthos and sediment quality measures in June 2004 probably do not reflect the lowest DO concentrations to which the benthos would have been exposed over the course of the year. Therefore, we have a poor understanding of the most influential and restrictive conditions to which the resident benthos are exposed each year.

- **Other environmental variables and further relational analyses may reveal more about relationships between and among sediment, benthos, and DO values.** Many environmental variables known to influence the composition of the benthic infauna were examined in this survey. These variables included sediment grain size, organic carbon content, station depth, chemistry, toxicity, and DO concentrations. While correlations between some of these variables and the metrics of benthic composition were statistically significant, many were not. Many were either weak or not linear. Undoubtedly, other variables such as nutrient concentrations, biological oxygen demand, and porewater salinity and temperature are important in influencing the composition of the benthos in Hood Canal. Distance from Admiralty Inlet may also affect benthic assemblage composition by influencing the availability of brood stock. Relational and multivariate analyses of additional matching data may contribute further insight into the relationships among these variables.

- **No field surveys or controlled laboratory experiments have been designed or conducted to specifically determine the effects of hypoxia on the benthos in Hood Canal.** Accurately establishing causality in a field survey in which many different factors can affect and influence the composition of the benthos is very difficult. In this study, the co-occurrence and multivariate analyses suggested that the DO concentrations near the bottom may have been limiting in areas in which they were lowest. The composition of the benthic assemblages often was different at stations with the lowest DO, with lower taxa abundance and richness, and a dominance of taxa known to be stress tolerant.

  The patterns in losses of numbers of organisms and species are similar to those reported in previous studies worldwide in which there was a gradient in eutrophication, organic enrichment, or hypoxia. However, without data collected in a study designed and conducted to specifically determine the effects of low DO on the benthos, it is not possible to conclude that hypoxia actually caused adverse effects to the benthos in Hood Canal. To adequately determine the effects of DO on benthos, an appropriate study design must be developed, funded, and implemented.

- **Critical DO values necessary to protect the benthos in Hood Canal are unknown.** The state standards for DO in marine waters were derived primarily to protect valuable fish, not the benthos. It cannot be assumed that DO levels necessary for maintenance of healthy fish stocks are identical to those needed to support the sediment-dwelling invertebrates that are a critical part of the food-chain in Hood Canal.

- **The spatial extent of the effects of hypoxia on the benthos in Hood Canal and changes in the size of the affected area over time is unknown.** The size and shape of the area in Hood Canal in which the benthos is affected by hypoxia are unknown. Therefore, it is not possible to determine and quantify if the problem is getting better, worse, or is remaining unchanged from year to year.

- **Nothing is known about benthic effects of hypoxia in other regions of Puget Sound.** Other regions of Puget Sound periodically become hypoxic during late summer/early fall. These are regions with limited exchange of bottom water and sources of organic matter, such as Dyes Inlet, Oakland Inlet (Shelton), Henderson Inlet, Possession Sound, Oak Harbor, and Penn Cove.

Recommendations

The following recommendations address the data gaps identified in this report and indicate the monitoring and analysis procedures necessary to better understand the relationships between the composition of the benthic assemblages and DO levels in Hood Canal. With a better understanding of these relationships, critical DO concentrations that must be attained and maintained to protect the benthos can be determined. Such effects-based criteria will support appropriate environmental action in Hood Canal to maintain this component of the ecosystem.

- **Collect additional matching sediment quality, benthos, and DO data in Hood Canal.** Sediment and water column properties exist and change on very different spatial and temporal scales in the environment. Methods and timeframes for sampling marine sediments and water differ greatly to optimize the information collected for each parameter and to address the specific questions posed by various studies. In data analyses such as those performed for this report, the data for the various parameters are matching, or collected at the same times and places. None of the surveys examined for this report were designed to collect matching sediment quality, benthos, and DO data to answer questions about the relationships between these variables. Therefore, we had a limited ability to compare these data for this report.

  Any future efforts to monitor or evaluate the relationships between these parameters in Hood Canal must include collection of matching sediment quality, benthos, and DO data that correspond both spatially and temporally.

- **Collect matching sediment quality and benthos data along the entire DO gradient.** Matching sediment quality and benthos data should be collected and analyzed along the well-known DO gradient in Hood Canal. Sediment stations should be sampled to provide more equitable representation of the ranges in DO concentrations. More stations should be sampled in areas in which near-bottom DO concentrations are expected to be 3-6 mg/L and <1 mg/L, the two ranges that appeared to be most significant to the benthos. To better understand the long-term history of benthic exposure to hypoxia, some stations should coincide with those for which there are long-term DO monitoring data.

- **Temporal sediment quality, benthos, and DO sampling must be adequately established and maintained in the nine Hood Canal sub-regions.** The composition of the infaunal assemblages differed among sub-regions of Hood Canal. Representative sediment, benthos, and DO samples from each sub-region must be monitored to determine changes over time and long-term relationships between parameters in these spatially defined assemblages. Such changes should continue to be monitored at the three sampling locations where a relatively long-term dataset already exists (PSAMP temporal stations 13R, 14, and 17) to assess future changes in benthic response to DO levels.

- **Evaluate the DO regimes in the terminal inlets, adjoining bays, and nearshore environments of Hood Canal.** Currently, no DO data are available for Port Ludlow and Port Gamble. There are very little data for Dabob Bay and Quilcene Bay. Data from the nearshore areas have only recently been collected. Benthic infaunal assemblages differ among these sub-regions of Hood Canal, and the relationships among sediment quality, benthos, and DO should be examined with matching data from each sub-region.

- **Measure DO at the sediment-water interface and in sediment pore water.** Historically, DO measurements in Hood Canal have been collected throughout the water column no closer than 1-2 meters from the bottom. Scientists elsewhere have shown that DO concentrations can decrease markedly in the bottom meter of the water column and in the pore waters below the sediment surface. Our current measures of DO probably over-estimate the concentrations to which the benthos are exposed. Ideally, DO should be measured at the sediment-water interface and in the interstitial water (i.e., pore water) of the surficial sediments. DO profiles could be measured from undisturbed sediment cores collected with a gravity-damped corer such as a multicorer or box corer. Additionally, a sampling apparatus with remotely operated probes that measure parameters such as DO, salinity, and pH in situ at the sediment-water interface could be deployed.

- **Evaluate seasonal variations in DO.** Benthic assemblages are influenced by both the duration and severity of low DO events, reacting to the cumulative effects of low DO over time. Past sediment surveys in Hood Canal were not designed to determine the effects of seasonally variable DO concentrations on benthos. Most sediment surveys were conducted in the late spring or early summer, not typically a time of low DO. Any new surveys conducted to determine relationships between DO and benthos must include collection of data describing the seasonal variation in DO near each target sediment station. Results of such surveys must report the lowest DO concentrations to which the benthos were exposed, because these conditions would be most influential and restrictive.

- **Sample other environmental variables and conduct further relational analyses.** Examination of additional environmental variables – including, but not limited to, nutrient concentrations, biological oxygen demand, porewater salinity and temperature, and distance from Admiralty Inlet – may yield further insight into relationships between sediment quality, benthos, and DO. Also, additional relational and multivariate analyses may contribute further insight to understanding the relationships between these variables.

- **Conduct field surveys or controlled laboratory or field experiments designed to determine the effects of hypoxia on the benthos in Hood Canal.** Field surveys and lab or field experiments which test benthic response to varying DO levels, while controlling other factors which influence the composition of the benthos, need to be designed and implemented.

- **Determine the DO concentrations that are most critical to the benthos of Hood Canal.** Future studies should focus on determining the minimum DO levels that are critical to maintaining healthy benthic assemblages in Hood Canal. There may be one or more levels that are critical to the benthic infauna. The spatial extent of DO concentrations below those critical values should then be determined to characterize the severity and extent of the hypoxia problem during different time periods. The co-occurrence analyses conducted in this report begin to fill this data gap. Targeted sampling and analysis are needed to produce more refined results.

- **Track changes in sediment quality, benthos, and DO conditions over time in Hood Canal by augmenting existing spatial and temporal monitoring programs. Use these programs to determine effectiveness of source controls in diminishing the hypoxia problem in Hood Canal.** Spatial monitoring should be continued and augmented to determine the size and shape of the area in Hood Canal in which the benthos is affected by hypoxia. Existing long-term monitoring programs should also be continued and augmented to record improvements if sources of organic matter that lead to eutrophication and hypoxia are reduced.

- **Conduct benthic surveys in other regions of Puget Sound that are at risk of hypoxia.** Although the conditions in Hood Canal may be unique, owing to the presence of the entrance sill, other inlets and bays in the Puget Sound basin may be at risk of the effects of hypoxia. They may include areas such as Henderson Inlet, Oak Harbor, Discovery Bay, Sequim Bay, and Penn Cove. There are no matching sediment quality, benthic, and DO data for these regions. Small-scale, exploratory surveys of at-risk areas should be conducted to ensure that hypoxia is not affecting resident benthos there.

Introduction

Historical Perspective

Hood Canal is a relatively narrow inlet of Puget Sound with many characteristics of a fjord. It was carved by the scouring of glaciers and subglacial meltwater to depths of up to 200 meters (m) and a length of about 100 kilometers (km). Hood Canal joins the greater Puget Sound basin in Admiralty Inlet seaward of the main basin of Puget Sound (Figure 1). There is a relatively shallow sill (depths of 25 to 50 m) near the entrance, inland of which water depths increase remarkably to 150 to 200 m. The canal takes a sharp turn to the east in the southern end at the Great Bend and terminates in Lynch Cove. Therefore, it is not a canal in the usual sense of the term because it does not connect two bodies of water.

The canal receives marine water from the Pacific Ocean via the Strait of Juan de Fuca and Admiralty Inlet and receives freshwater from many rivers and streams, primarily along its western shoreline on the Olympic Peninsula. Both shorelines of the canal are lightly populated with small communities, small businesses, vacation cabins, and resorts. There are no large urban centers or industrial harbors bordering the canal. Dabob Bay and Quilcene Bay join the canal inland of the sill, and Port Gamble Bay and Port Ludlow join it seaward of the sill.

Due to stratification and modest freshwater input, bottom water in southern Hood Canal has a long residence time, on the order of one to four months, and little exchange with overlying oxygenated water (Warner et al., 2001; Babson et al., 2006). As a result, the dissolved oxygen (DO) concentrations in parts of the canal can become very low, a condition commonly referred to as *hypoxia*.

Hypoxia was first reported in this region by the University of Washington (UW) during the 1950s and 1960s (Collias et al., 1974), with hypoxia restricted primarily to the southern reaches of the canal inland of the Great Bend and into Lynch Cove. Additional surveys conducted in the 1970s by Oregon State University (OSU) and the UW confirmed the occurrence of hypoxia in the canal and suggested that these conditions were worse than reported previously (Curl and Paulson, 1991). Data compiled from several ambient monitoring programs for the Hood Canal Dissolved Oxygen Program (HCDOP) also indicate a downward trend in mid-water column DO concentrations during the 1990s (Roberts et al., 2005). Data from the studies conducted in the 1990s for the Puget Sound Assessment and Monitoring Program (PSAMP) indicated many months of low DO concentrations in both southern and northern reaches of the canal, and again suggested the possibility that the severity and spatial extent of low DO concentrations were increasing (Newton et al., 1998).

Cumulatively, these observations led Newton et al. (2002) to conclude that "observations from the monitoring data indicate the possibility that DO conditions may be deteriorating in southern Hood Canal, that the spatial extent of low DO may be increasing northwards, and that eutrophication could be one of the processes contributing to this change." Much public attention was focused on this issue during 2002 to 2004, when fish kills during low DO conditions resulted in unprecedented closures to fishing in Hood Canal implemented by the Washington

Department of Fish and Wildlife. Mostly bottom-dwelling fishes (rockfish, flounders, sculpins, and gunnels) died in relatively large numbers where the DO concentrations were too low.

Additional descriptions of the hypoxia problem in Hood Canal can be found on a web site maintained by the Hood Canal Dissolved Oxygen Program (www.hoodcanal.washington.edu). It includes historical observations, diver observations of marine life, water column data, and a summary of efforts to improve the conditions in the canal region.

In a nationwide coastal eutrophication assessment conducted during the 1990s, 122 U.S. estuaries were classified as having either high, moderate, or low expressions of eutrophication (Bricker et al., 1999). Hood Canal was one of 44 estuaries and coastal bays listed as having high indications of eutrophication, one of only seven such sites along the U.S. Pacific coast given this classification. Most of the other areas with high expressions of eutrophication were located along the Gulf of Mexico or in the mid-Atlantic states. In addition, Hood Canal was one of two Pacific coastal ecosystems identified by the Pew Oceans Commission (2003) as sites of severe hypoxia associated with human activity. Symptoms of eutrophication, primarily the presence of high chlorophyll *a* concentrations, were described as occurring periodically and over extensive portions of Hood Canal.

The conditions in Hood Canal that contribute to eutrophication and hypoxia are similar to those that have been reported in northern Europe where eutrophication appears to be worsening in severity, spreading geographically, and causing mass mortalities among resident demersal fishes (Rosenberg, 1985). Adverse benthic effects, including mass mortalities, were reported worldwide for 44 marine systems in Europe, North America, Japan, Hong Kong, and Australia (Diaz and Rosenberg, 1995). The problems with hypoxia in these areas were considered to (1) be moderate to severe, (2) be periodic or persistent, (3) include some degree of annual recovery, and (4) involve mortality to fish and the benthos. More recently, symptoms of estuarine eutrophication have been repeated nationwide in the United States (USEPA, 2004).

Benthic Resources at Risk

In addition to demersal fishes, such as those killed in Hood Canal during 2002-04, the animals that live burrowing or buried in the soft sediments (infauna) and those that live attached to hard bottom substrates (epifauna) are exposed to the effects of hypoxia. The majority of these animals are invertebrates belonging to a wide array of phylogenetic groups. It has long been recognized that species diversity in soft-bottom benthic communities of Hood Canal, Puget Sound, and the San Juan Archipelago is high relative to other nearshore habitats (Lie, 1968; Sanders, 1969; Nichols, 1985). It is not unusual to find many hundreds of individuals and over 100 species in one 0.1 m^2 sample in unpolluted areas of Puget Sound (Long et al., 2003). These animals can be highly sensitive indicators of degraded conditions on the bottom of Puget Sound in addition to being important as a source of nutrition for predatory fish, octopus, seals, and marine birds. Fish nutrition biologists frequently find these kinds of invertebrates in the stomach contents of many Puget Sound fish (Simenstad et al., 1979).

Whereas fish are relatively mobile and can swim away to avoid hypoxic conditions, most benthic invertebrates have limited mobility to avoid such conditions. The members of the benthos differ in their sensitivity to stresses such as high toxicant concentrations and hypoxia. Some species, such as the amphipod crustaceans, are highly sensitive and are the first to die out when stresses occur. These sensitive animals are, therefore, often used in laboratory tests of the toxicity of sediments. Other species are more tolerant and can survive minor amounts of stress. In general, crustaceans tend to be more susceptible to low levels of DO than annelids, which tend to be more susceptible than bivalves (Diaz and Rosenberg, 1995). Under highly stressed conditions, only a few species of polychaete and/or oligochaete worms may be present, while under extremely stressful conditions, sediment may be azoic (i.e., devoid of animal life) (Bricker et al., 1999).

As part of a large scale assessment of sediment quality throughout Puget Sound conducted jointly by the Washington State Department of Ecology (Ecology) for the Puget Sound Assessment and Monitoring Program (PSAMP) and the National Oceanic and Atmospheric Administration (NOAA), sediments were sampled in 1999 at randomly selected locations along the length of the canal (Long et al., 2003). These samples were analyzed for concentrations of potentially toxic chemicals, tested for toxicity in laboratory tests, and examined for benthic infaunal composition.

Among the eight PSAMP monitoring regions for which these kinds of data were acquired, the quality of sediments was among the highest in Admiralty Inlet and Hood Canal. Only 5 of the 21 benthic samples in the Hood Canal region appeared to be adversely affected by chemical contamination, and all 5 were collected in the Port Ludlow and Port Gamble embayments, not in Hood Canal itself (Long et al., 2003). It was noted during a later analysis of the benthic samples from Hood Canal that some of the more abundant species were widely recognized as relatively tolerant of low DO and other stressful conditions. A total of 15 (71%) of the 21 stations appeared to have benthic assemblages with low abundance and diversity (Long et al., *in preparation(a)*). No measures of water column quality accompanied the benthic analyses as a part of the PSAMP/NOAA surveys, so the relationships between the health of the benthos and bottom-water DO concentrations could not be evaluated.

Also as a part of the PSAMP, Ecology surveyed sediment quality in Hood Canal a second time in 2004, using most of the same methods used in 1999 (Long et al., *in preparation (b)*). However, in the 2004 survey, the concentrations of DO were measured near the sediment-water interface. The benthic assemblages at 23 (77%) of the 30 locations that were sampled in Hood Canal and adjoining Dabob Bay were classified by Ecology biologists as adversely affected (low abundance and diversity). It was noted that many of the statistical and biological indicators used to measure the health of benthic communities were depressed in some samples that had the lowest near-bottom DO concentrations (1 mg/L or lower).

Classifying the Benthos as Adversely Affected

Benthic ecologists world-wide have been studying the ways that infaunal and epifaunal communities respond to increasing levels of stress, including decreases in DO concentrations, for decades (Pearson and Rosenberg, 1978; Boesch and Rosenberg, 1981; Dauer and Ranasinghe, 1992; Nilsson and Rosenberg, 2000). There are widely accepted methods for collecting samples, analyzing them, reporting and interpreting data, and classifying benthic assemblages as adversely affected (USEPA, 2000). Some kinds of adverse effects are sufficiently predictable to be modeled. Where hypoxic conditions are short-term (a tidal cycle or day), the adverse effects also can be relatively transient. In areas such as Hood Canal, where hypoxia is a longer term phenomenon, the adverse effects can be long-lasting.

The direct effects of hypoxia typically include relatively reduced numbers of animals, low numbers of species, low biomass (weight), avoidance by mobile epifauna, emergence by infauna, physical inactivity, and lethargy (Ritter and Montagna, 2001). Benthic ecologists studying the effects of pollution on benthic communities usually focus on indices of benthic community structure that are indicative of diversity, numbers of dominant species, presence of pollution-tolerant and absence of pollution-sensitive species, and biomass of all organisms. Worldwide, some benthic genera and species tend to be relatively resistant to severe hypoxia, others are sensitive to moderate hypoxia, while others are known to be sensitive to all levels of hypoxia (Diaz and Rosenberg, 1995). Many of these genera and some of these species are known to occur in Puget Sound, including Hood Canal; therefore, their presence or absence can be useful indicators of the effects of hypoxia there.

In Puget Sound, there are a number of amphipod species and other forms of sensitive crustaceans that can be abundant in unpolluted areas, but decrease in abundance markedly as pollution increases; and there are many pollution-tolerant polychaetes and molluscs that tend to proliferate in polluted areas (Long et al., 2003). Patterns of differential sensitivity among benthic infaunal species, and gradual losses in diversity as the levels of stress increase, have been reported elsewhere (Diaz and Rosenberg, 1995). This pattern forms the basis for the widely regarded model of benthic community response to either sediment contamination by toxicants or hypoxia observed and summarized in Scandinavian and other European fjords by Pearson and Rosenberg (1978).

As reported previously by Pearson and Rosenberg (1978), the abundance, diversity, and biomass of the benthos do not always take on a linear decline as stresses to the benthos increase. Such linear declines in the benthos have been reported in some regions – for example, in the lower Miami River, FL (Long et al., 2002a) – but in other regions the pattern often is curvilinear (Long et al., 2001).

Where the relationship is curvilinear, the supposition is that the benthos is depauperate in uncontaminated, coarse sands in which there is little food for deposit feeders. Abundance, diversity, and biomass gradually increase as the sediments increase in food content (a measure of which is total organic carbon [TOC]), then peak at some point that is most favorable for the benthos. As the measures of stress (hypoxia, high TOC, biological oxygen demand (BOD), percent fines, and chemical contamination) increase, the most sensitive species start to decline and eventually disappear. The declines in the benthos may be attributable to increases in toxic hydrogen sulfide, ammonia, contamination, or low oxygen content. As the measures of stress continue to increase, this gradual decline in the benthos eventually leads to losses in species, total numbers of organisms, entire phyla, and biomass – ultimately resulting in azoic conditions in sediments that are most stressed or polluted.

Data assembled from studies in Europe showed similar patterns in the gradual decreases in numbers of species, biomass, and total abundance as inputs of organic material increase either in time or space (Pearson and Rosenberg, 1978). In addition, there was a predictable succession in the species that were most abundant as organic enrichment occurred. As organic enrichment continued to increase, the most sensitive species were lost from the community, replaced by more tolerant species in a sequence of steps in which eventually total abundance, diversity, and biomass declined to near zero in anoxic conditions. The relationships between the organic enrichment of the sediments and the indices of benthic condition usually were not linear; instead, they often were curvilinear or bell-shaped, leading toward rather poor statistical correlations as determined with linear models.

We hypothesize that the exposure-response model reported by Pearson and Rosenberg (1978) would be observed in Hood Canal if the degree of hypoxia was sufficiently severe to adversely affect the benthos.

In surveys of the effects of sediment-bound toxicants in Puget Sound, benthic assemblages were classified as adversely affected by comparing both the species composition and the calculated indices of benthic structure at each station with comparable data from a compilation of locations throughout Puget Sound (Long et al., 2003; *in preparation (a)*). There is no widely accepted multi-parameter index of benthic health yet available for Puget Sound, and current state standards for marine benthos are limited and do not account for the complex composition of the communities. Thus, professional judgement and experience are required to classify the benthos as adversely affected.

Typically, samples have been classified by Ecology as adversely affected when (1) dominated by pollution-tolerant polychaetes, oligochaetes, and molluscs, (2) devoid of pollution-sensitive species, and (3) low in species diversity (or richness), evenness in species distribution, and numbers of dominant species (Long et al., 2003; *in preparation (a)*). Often, total abundance is high in these samples as a result of the proliferation of pollution-tolerant polychaetes. Often, relatively sensitive amphipods and echinoderms are rare or absent. For the purposes of this study, the assumption was made that the same set of indicators would be responsive to bottom-water hypoxia in Hood Canal as compared to normoxic stations. Therefore, we hypothesized that the exposure-response model reported by Pearson and Rosenberg (1978) would be observed in Hood Canal if the degree of hypoxia was sufficiently severe to adversely affect the benthos.

Worldwide, marine benthic ecologists have reported the benthos as adversely affected by hypoxia, using terms such as *degraded*, *impaired*, or *impacted* to describe the benthic assemblages (Diaz and Rosenberg, 1995). These terms often imply that the adverse effects were caused by human-induced (i.e., anthropogenic) conditions. In this report, we describe the benthos at some locations as "adversely affected" and define how they were affected, and we largely avoided using these judgmental terms. The conditions of eutrophication and hypoxia in Hood Canal may be, in part, a natural phenomenon in that region and only influenced by, but not entirely attributable to, anthropogenic conditions.

Determining Critical Dissolved Oxygen Levels in Hood Canal

Most animals require an adequate supply and concentration of oxygen to survive and function. At the onset of hypoxia, the benthic invertebrates that are mobile, for example crabs and shrimp, will attempt to move away from the affected area. However, many kinds of benthic species, for example clams and worms, are relatively immobile. They can reposition themselves only over very short distances. For these relatively immobile species, exposure to hypoxia triggers a number of complex physiological responses, the nature of which differs among the kinds of animals.

Most benthic invertebrates respond to hypoxia by first attempting to maintain an adequate oxygen supply by increasing their respiration rate and oxygen-binding capacities, or slowing their metabolic rates. These responses may lead to reduced reproductive ability, feeding rate, and growth, or other behavioral effects. Ultimately, as oxygen levels decrease, an animal must either resort to anaerobic respiration or move to avoid the hypoxic area, or it will perish. The sensitivity to hypoxia can differ considerably among species; therefore, the concentrations of DO that are critical to survival can differ among species. The concentrations of DO that are critical to the health of the benthos of Hood Canal are not well known.

The Washington State Water Quality Standards lowest 1-day minimum DO criteria for protection of marine life are 7.0 mg/L for *extraordinary* quality waters, 6.0 mg/L for *excellent* quality waters, 5.0 mg/L for *good* quality waters, and 4.0 mg/L for *fair* quality waters (Washington State Department of Ecology, 2003). Hood Canal is classified by Ecology as having extraordinary (AA marine) quality waters; therefore, the applicable criterion is 7 mg/L. Concentrations of DO are not to fall below these criteria at a probability frequency of more than once every ten years on average.

A panel of experts assembled by NOAA found that concentrations of 2 to 5 mg/L represent a "biological stress threshold" (Bricker et al., 1999). Concentrations of 3 mg/L are considered by Ecology as the upper limit of hypoxia (Newton et al., 2002; Roberts et al., 2005). In the Gulf of Mexico and other regions, DO concentrations below 2 mg/L are considered hypoxic, and concentrations of 0 mg/L are considered anoxic (Rabalais, 1998). Based on the European method of calculating DO concentrations, the critical limit for benthic invertebrates was reported as 2 ml/L (2.9 mg/L) or less, hypoxia was defined as DO concentrations of 2 to 0 ml/L, and anoxia was defined as 0 ml/L (Diaz and Rosenberg, 1995).

Hypoxia events have been recorded in southern Hood Canal for periods as long as 12 months, whereas biological stress levels or hypoxia occurred for periods up to 6 months in northern Hood Canal (Roberts et al., 2005). Historical and current data for central Hood Canal (Dabob Bay to the Great Bend) assembled for the past five decades by the UW indicate a gradual and downward trend in the mid-water column DO concentrations. DO concentrations were recorded on a monthly, quarterly, or periodic basis from the early 1950s to the present. Concentrations ranged from about 6 mg/L to about 7 mg/L during February through April in the 1950s, declining into the range of 4 to 5 mg/L during June through October, then increasing to 5 to 6 mg/L in November. In 2002-2005, in contrast, the range in concentrations was about 2.5 to 4 mg/L in all seasons except December of 2004 when it peaked at about 4.5 mg/L (Warner, 2007).

These observations in the water column may not accurately reflect the conditions on the bottom of Hood Canal near the sediment-water interface. Because organic matter that decomposes and strips the water of oxygen accumulates in greatest amounts in the surficial sediments and because flushing of water out of the canal may be slowest along the bottom, DO concentrations are generally lowest nearest the bottom. DO concentrations decrease steadily with depth in the sediments from the sediment-water interface, ultimately becoming anoxic within a few millimeters of the sediment-water interface. The slope of the DO gradient within the sediment is a function of the rate of organic-matter supply to the sediment, sediment porosity, temperature, oxygen content of overlying water, and the degree of burrowing and irrigation by the resident benthos (Diaz and Rosenberg, 1995).

Rates and processes of exchange of oxygen, nutrients, and other chemicals between the sediments and overlying water were described for the Washington continental margin and one location in Puget Sound in a series of papers (Devol and Christensen, 1993; Brandes and Devol, 1995; Hartnett and Devol, 2003). Among the various outcomes of these studies, the authors described the rates of oxygen consumption increasing with increasing water depth.

Single point measurements of DO may be misleading, and continuous monitoring over multiple tidal and diurnal cycles has been recommended to more accurately determine the level of hypoxia to which the resident benthos is exposed (Diaz and Rosenberg, 1995; Summers and Engle, 1993). The benthic effects of hypoxia appear to be functions not only of the oxygen concentrations at any point in time, but also the amplitude and temporal variations in the concentrations.

There is very little knowledge of the critical DO concentrations that adversely affect the benthos of Puget Sound, including Hood Canal, and the nature of the biological effects to the benthic communities. The Washington State criteria were established primarily for the protection of fish, not benthic organisms. However, the effects of low DO on benthos have been documented worldwide in many different studies (Diaz and Rosenberg, 1995).

One of the largest hypoxic zones in the world is in the Gulf of Mexico (Rabalais, 1998). Extensive studies there have recorded migrations of mobile species, large fish kills, losses of infaunal benthos, and the severely diminished catch of commercial fisheries. The severity and magnitude of the adverse effects there is dependent upon the sensitivity and mobility of the animals; however, most populations are affected when DO concentrations drop below 2 mg/L (Rabalais, 1998). In a study of short-term (daily or overnight) effects of hypoxia (DO <2.0 mg/L) in Corpus Christi Bay (Texas), it was observed that biomass, numbers of species, and diversity decreased slightly in hypoxic samples versus normoxic areas. Also, the species composition changed with some sensitive species not occurring where hypoxia occurred (Ritter and Montagna, 2001).

Thus far, the DO concentrations that are critical to the protection of benthic resources in Hood Canal have not been determined. The observations in recent years of benthic and demersal fish and invertebrate kills there suggest that some critical values, whatever they are, have been exceeded for some species of bottom organisms. The “biological stress threshold” of 5 mg/L and the upper limit of hypoxia of 3 mg/L reported for Puget Sound by Ecology, and the upper limit of hypoxia of 2 mg/L reported by others for other regions, suggest that the range of 2 to 5 mg/L is critical for many species, but based primarily on measures of effects to fish. Analyses of matching bottom water DO concentrations and benthic composition data from Hood Canal are necessary to establish the levels that are critical to the resident benthos of Hood Canal.

There is evidence that the benthos can recover following prolonged hypoxic conditions such as those in Hood Canal (Diaz and Rosenberg, 1995). The rate of recovery would be dependent on the severity and spatial extent of the hypoxia, the rate of abatement in inputs of organic matter, the rate of increase in DO concentrations, and the relative sensitivity of the local infauna to hypoxia. Recovery also can be a function of larval supply and the nature of the near-bottom currents that disperse invertebrate larvae. Because hypoxia and eutrophication are highly correlated, including in Hood Canal, recovery would be hindered by persistent inputs of organic matter.

It is most likely that recovery of the benthos in Hood Canal would follow the sequential steps in succession summarized by Pearson and Rosenberg (1978) in which opportunists, then transitional species, would colonize the sediments, ultimately leading to development of a mature community that included sensitive species. These species would be expected to colonize the sediments primarily as larvae from brood stocks in normoxic areas (e.g., Admiralty Inlet, eastern Strait of Juan de Fuca). More mobile epifaunal species, such as crabs and shrimp, may arrive by walking. Elsewhere, recovery of mature benthic communities following abatement of eutrophication has taken from two to eight years (Diaz and Rosenberg, 1995).

Goals and Objectives

This project was funded by the Hood Canal Dissolved Oxygen Program (HCDOP) to examine the relationships between DO levels and the structure of the benthic infaunal assemblages in Hood Canal. The overall goal of this project is to evaluate the nature and degree of adverse effects, if any, to the resident benthos of Hood Canal as affected by hypoxia.

This study will provide a database with which to assess the significance of low DO levels on the resident benthic resources of Hood Canal. The data compiled in this project will be analyzed to test the hypothesis that the resident benthic resources of Hood Canal are incrementally and increasingly affected by decreasing bottom water DO concentrations.

The overall goal was attained by satisfying the sequential series of technical objectives listed below. It is important to understand that because of the nature of this study that although the relationship between the degree of hypoxia and benthic effects can be evaluated, such a correlative approach cannot establish causality.

The technical objectives of this study are:

- Determine how the benthos of Hood Canal are distributed throughout the canal and how this distribution changes over time.
- Determine the patterns of bottom water DO levels throughout the canal and how this distribution has changed over time.

- Determine the relationship between indices of benthic community composition and the concentrations of bottom water DO.
- Determine which species, taxonomic groups, and benthic indices are most affected in Hood Canal and are, therefore, most important indicators of losses in benthic resources.
- Compare the benthos/DO relationships with those for other natural variables such as sediment texture, depth, and organic carbon content, and anthropogenic variables including chemical contamination and toxicity, to determine which relationships appear to be most important to the benthos.
- Identify the DO concentrations associated with the losses of important individual benthic species, sensitive taxonomic groups, and major phyla from the benthic communities.
- Develop an index for assessing the change in benthic community structure that can be attributed to variation in DO.

These objectives were satisfied by assembling and analyzing all available sediment quality, benthic, and near-bottom DO data. A variety of statistical and graphical analyses were performed to determine and illustrate the relationships between DO concentrations and changes, if any, to the benthos. Scientists from Ecology and WWU compared the composition of the benthos to nearby DO concentrations and other variables such as water depth, sediment grain size, organic carbon content, concentration of chemical contaminants, and sediment toxicity.

The analytical methods included the following:

- Univariate regional plots of key variables on base maps.
- Bivariate correlation analyses.
- Graphical scatterplots.
- Co-occurrence analyses.
- Multivariate analyses.

The concentrations of DO associated with minor shifts in composition, significant decreases in diversity, losses of sensitive species, and losses of major taxa groups were identified where possible. Gaps in the database were identified as an aid to recommending further field evaluations of the effects of DO on benthos in Hood Canal.

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Methods

The study area included the entire length of Hood Canal from its entrance to its terminus on the mudflats in Lynch Cove (Figure 1). Also included were the small bays of Port Ludlow and Port Gamble near the entrance, and both Dabob Bay and Quilcene Bay that adjoin the canal in the central reaches.

Acquisition, Compilation, and QA/QC of Sediment Quality Data

Data Sources

Hood Canal sediment data were acquired for this study from numerous sources, and compiled in an Access database. The majority of the data were collected from the database generated by Ecology's Marine Sediment Monitoring Team (MSMT) for the Spatial and Temporal Monitoring elements of the PSAMP Sediment Component. Additional data were found by searching Ecology's Sediment Quality Information System (SEDQUAL) database, which contains sediment quality data from over 15,000 sediment sampling stations in California, Idaho, Oregon, Washington, and Alaska. On-line and library literature searches for other data sets were also conducted.

Parameters Chosen

Sediment quality data compiled for the HCDOP database included over 250 physical, chemical, toxicological, and biological parameters measured in both large-scale and small-scale surveys in Hood Canal (Tables 1-3). For analysis in this report, these large suites of data were combined into a smaller matrix of directly measured and derived variables examined to determine their relationships with each other.

A list of all physical and chemical sediment parameters measured, along with an explanation of all derived parameters, is provided in Table 1. Directly measured physical and chemical parameters chosen for analysis included station depth, grain size, total organic carbon, and (in 2004) dissolved oxygen. The large classes of priority pollutant and ancillary metals, and classes of organic compounds including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), chlorinated pesticides, and others, were summarized into a series of mean Sediment Quality Standard (SQS) quotients.

Mean SQS quotients were calculated as the mean of the quotients derived by dividing the chemical concentrations in the samples by their respective SQS values. Mean SQS quotients are used to account for both the presence and concentrations of mixtures of these potential toxicants. The greater the mean SQS quotient, the greater the overall contamination of the sample as determined by the mixture of substances, and the greater risk of toxicity and/or benthic effects.

Mean SQS quotients were calculated for the following suites of chemicals:

Metals	the mean of the SQS quotients calculated for arsenic, cadmium, chromium, copper, lead, mercury, silver, and zinc
PAHs	the mean of the SQS quotients calculated for naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3,-c,d)pyrene, dibenzo(a, h)anthracene, and benzo(g, h, i)perylene
Misc. Organics	the mean of the SQS quotients calculated for 1,2-dichlorobenzene, 1,2,4-trichlorobenzene, 1,4-dichlorobenzene, benzoic acid, benzyl alcohol, dibenzofuran, hexachlorobenzene, hexachlorobutadiene, and n-nitrosodiphenylamine
Phenols	the mean of the SQS quotients calculated for 2,4-dimethylphenol, 2-methylphenol, 4-methylphenol, pentachlorophenol, and phenol
Phthalates	the mean of the SQS quotients calculated for bis-2-ethylhexylphthalate, butylbenzylphthalate, diethylphthalate, dimethylphthalate, di-n-butylphthalate, and di-n-octylphthalate

Sediment toxicity data from a suite of seven test procedures were available from past monitoring efforts in Hood Canal. These included toxicity tests conducted on a variety of sediment matrices (i.e., bulk sediment, sediment/water mixture, pore water, organic solvent extract) that were tested with different organisms (i.e., bacteria, amphipods, polychaetes, molluscs, echinoderms), cell cultures (i.e., human liver cells), and life history stages (i.e., adults, embryos, gametes). Table 2 provides information about each of these tests. Four kinds of sediment toxicity tests were performed in the Ecology/NOAA survey in 1999, and one of these tests was performed again in the 2004 survey. Other kinds of tests were performed by other programs and the results archived in the SEDQUAL database.

Benthic infauna collected from past sediment surveys in Hood Canal were identified to the lowest possible taxon (usually to species) and enumerated. Nine benthic infaunal indices of abundance, richness, evenness, and dominance were calculated from these data to represent assemblage structure. Pollution-sensitive and pollution-tolerant species were also identified, based on local experience of Ecology staff and observations made by others (Word, 1980; Tetra Tech, 1990; Diaz and Rosenberg, 1995). The definition of and calculation methods for all benthic indices used in these analyses are provided in Table 3.

Quality Assurance/Quality Control

Sediment data collected for the PSAMP Sediment Component have previously undergone quality assurance/quality control (QA/QC) review when originally generated, as per the program's original and current Quality Assurance Project Plans (Striplin, 1988; Dutch et al., 1998). Benthic infaunal data collected for PSAMP were also recently reviewed and standardized by Ecology staff for this study to ensure standardization of all taxonomic nomenclature between years. Any QA/QC review of data obtained from the SEDQUAL database was conducted during the original surveys. No additional QA/QC review was conducted for this study.

Acquisition, Compilation, and QA/QC of Water Column Dissolved Oxygen Data

Data Sources

Dissolved oxygen (DO) data collected via sampling of the water column in Hood Canal were compiled, along with the sediment data, into an Access database. Data were obtained from numerous sources, including a series of cruises conducted through the University of Washington (UW) commencing in the 1930s, water column monitoring conducted by Ecology over the past three decades, and recent citizen-volunteer sampling under the Hood Canal Dissolved Oxygen Program (HCDOP). Data were generated from conductivity/temperature/depth (CTD) casts, and from Winkler titrations of discrete water samples at varying depths.

Parameters Chosen

Water quality data compiled for the HCDOP database included depth, temperature, salinity, density, DO, pH, fluorometer, and par measurements from Hood Canal. Because the focus of this project was to examine the relationships between DO and benthos, only DO and depth data were extracted from the database for inclusion in the final sediment/DO data analysis matrix. As described below, however, simultaneously collected temperature, salinity, and density measurements were analyzed as auxiliary variables in one of the methods attempted for estimating DO concentrations at locations where DO was not measured directly.

Quality Assurance/Quality Control

Water column data collected for the PSAMP Marine Waters and Sediment Monitoring Components and for the Environmental Monitoring and Assessment Program (EMAP) had previously undergone QA/QC review when originally collected, per the original Quality Assurance Project Plans generated for each program (Janzen, 1992; Dutch et al., 1998; USEPA, 2001, respectively). No information was available concerning QA/QC review of the DO data from the 1932-1968 UW cruises, the UW Puget Sound Regional Synthesis Model (PRISM) Hydrographic Surveys, or the 1994-1999 Ecology Hood Canal cruises. Some of the HCDOP citizen-volunteer sampling data had undergone partial QA/QC; the remainder had not, until incorporation into the HCDOP database for this project.

After compilation into the database, all water column data were examined for completeness and accuracy, and graphed to determine reasonableness of values. Corrections were made to the database records when necessary to ensure standardization of station identifications, unique identification of replicates, and correct station locations and characteristics, and to remove any duplicate records.

Analysis of Sediment and Water Column Dissolved Oxygen Data

Geographic Distribution and Summary Statistics

Sediment Quality Data

All station locations, number and type of samples collected, and other survey information were summarized in tabular form, and summary statistics were generated for all measured and derived sediment values chosen for analysis. Station locations and values of all data analyzed were also mapped geographically to discern spatial distribution patterns and temporal changes in parameters, and any data gaps that might be evident in Hood Canal. Separate maps and statistical summaries were completed for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data acquired from the SEDQUAL database. Chemistry and toxicity data were also summarized and geographically displayed to indicate stations where values exceeded Washington State Sediment Quality Standards (Washington State Department of Ecology, 1995) and other existing critical values.

Two sets of numerical criteria have been developed to evaluate the condition of Puget Sound infaunal assemblages. The Washington State Sediment Quality Standards provide methods for comparing the relative abundance of higher taxonomic groups between study sites and reference areas (Washington State Department of Ecology, 1995), while ranges in a variety of benthic indices were calculated for Puget Sound reference areas (Striplin Environmental Associates and Weston, 1999). However, neither of these methods has been thoroughly evaluated for accuracy or adopted for standard use. Neither takes into account the presence and relative abundance of individual species that may be indicative of either stressed or pristine conditions. Additionally, since these values are based primarily on response to anthropogenic contamination, they do not take into account response to natural stressors such as low DO. A different method of evaluating the condition of the benthic assemblages in Hood Canal relative to assemblages from the broader Puget Sound region was developed for this study.

The Hood Canal benthic index values calculated for this study were compared to Puget Sound index values generated for 381 stations sampled from 1997-2003 for the PSAMP Sediment Component. These baseline stations were located throughout Puget Sound, from the Canadian border south to Budd Inlet, including the San Juan Islands, Eastern Strait of Juan de Fuca to Port Angeles, and Hood Canal. These 381 stations were assumed to represent a broad range of conditions within the Sound (e.g., both deep and shallow, polluted and uncontaminated, near and far from urban centers) and, thus, were viewed as representative of a broad variety of environmental conditions to which the resident benthos were exposed.

Median benthic indices for the baseline infauna data were calculated to provide a set of mid-range values. The 80% confidence limits around the medians were then calculated to provide a reference envelope, an approach previously used to classify sediment samples elsewhere (Fairey et al., 1998; Long and Wilson, 1997; Bergen et al., 2001; Smith et al., 2001). The 80% confidence limits were chosen as a widely used, reasonably protective set of ranges that would reflect the normal degree of biological variability around an estimate of central tendency.

The Hood Canal index values were then examined to determine whether they fell above, below, or within the 80% confidence limits around the median calculated for each baseline index value. Stations with the majority (five or more) of nine index values within or above the reference envelope were considered to have benthic assemblages similar to or more abundant and diverse than the Puget Sound baseline median. Stations with the majority of benthic indicators below the 80% confidence limits were considered to differ from the Puget Sound baseline median, possibly adversely affected by natural or anthropogenic stressors. Stations with index values above the reference envelope, but with large numbers of stress-tolerant taxa, were also considered to be possibly adversely affected by stressors. These chosen criteria, along with best professional judgment, were used to classify each Hood Canal station as similar or different from the Puget Sound baseline median, and as potentially "adversely affected" or "unaffected" by either natural or anthropogenic stressors.

Water Column Dissolved Oxygen Data

As with the sediment data, all water column station locations, number and type of samples collected, station depths, and other survey information were summarized in tabular form. Station locations and the lowest DO value collected per year at each station were also mapped geographically to discern spatial distribution patterns, data gaps, and any temporal changes that might be evident. These displays were generated for each decade. Data were also geographically displayed to indicate values that fell below Washington State Water Quality Standards (Washington State Department of Ecology, 2003) for DO in Hood Canal. Summary statistics generated included identification of the minimum and maximum DO values collected, total number of measurements made, and values that fell below Washington State Water Quality Standards for each station during each year sampled.

Estimation of Dissolved Oxygen Concentrations at Sediment Stations

Considerable effort was expended in attempts to find and/or estimate matching DO and benthic data from previous studies in the Hood Canal region. Matching data (i.e., synoptic, or collected at the same time and place) are necessary to evaluate the effects of hypoxia on the benthos.

The DO data collected for this study were examined along with the historical benthic community data collected from Hood Canal with the intent of finding reasonably good matches in both time and space. There are considerable amounts of both kinds of data for Hood Canal. However, the DO measurements were rarely taken near the bottom where the information would be relevant to the benthos. Often, these measurements were made from the surface to mid-water column depths. In addition, the benthic sampling stations were rarely located near any DO measurements or sampled at the same time. The majority of the DO measurements were made at stations located along the midline of the canal. Most of the benthic samples were collected from stations randomly selected throughout the canal, or were from focused studies targeting a small geographic site.

Nevertheless, statistical estimates of DO concentrations at benthic stations were generated with a variety of direct and indirect methods (Appendix A). These innovative methods included a nearest neighbor/depth slice method, kriging, cross-sectional profiles, long-term trends, and examination of statistical relationships between DO and oceanographic and geographical parameters. Ultimately, because of the limitations described above, these efforts did not provide any useful, reliable, matching DO data, and these estimates were not used in further analyses.

Relationships between Parameters

A variety of statistical and graphical analyses were performed to identify the relationships between and among the variables that were measured. Each kind of analysis has various strengths and weaknesses, and each provides different kinds of information. These analyses were not performed to declare that the DO concentrations were the cause of any effects observed to the benthos, or to dismiss other possible sources of benthic variability as possible causes. Rather, they were performed to determine the relative degree to which the variables measured in Hood Canal co-varied with one another.

Bivariate Analysis and Scatterplots

Pearson correlation analyses (Bonferroni-corrected significance level) were conducted to determine whether any pairwise linear relationships exist among benthic metrics, and between benthic metrics and DO concentrations and other variables in the data from the 1989-2005 PSAMP surveys. Scatterplots of the variables were examined as a visual check of the correlations.

The correlation analyses were performed with various pairs of matching data (i.e., data collected at the same place and same time). The database assembled for these correlation analyses consisted of matching DO measurements, sediment chemistry, other physical/chemical measures, toxicity, and benthic community measures of abundance and diversity made at 30 stations sampled by Ecology in June 2004. Matching data from the other benthic surveys in Hood Canal in which DO was not measured were also included in the database and subsequent analyses. With the addition of these data, the database was expanded to 58 stations that were sampled at various times and locations. Therefore, it should be understood that the underlying database analyzed in the correlation analyses differed among variables.

Co-occurrence Analysis

The data were also analyzed by co-occurrence analysis (Long et al., 1995; Long and MacDonald, 1998; Long et al., 2006). In this procedure, the data were assembled to contrast the median abundance of the calculated benthic indices and selected indicator species within five ranges of descending DO concentrations. The stations were sorted according to decreasing DO concentrations, then five ranges in concentrations were selected by visual examination of the data. Median benthic values were calculated for the stations within each range. These data were then examined to determine if there was an inflection point in the DO concentrations where the median values for the benthic metrics in multiple samples changed remarkably as DO concentrations decreased. Also, the ratios between the median benthic metrics in samples with the highest DO concentrations and those with the lowest concentrations were calculated to determine which benthic metrics changed the most and the relative degree of change.

Multivariate Analysis

A form of canonical analysis termed Redundancy Analysis (RDA) was performed on the 2004 data to (1) determine how overall patterns in benthic community structure varied with DO and other environmental variables in Hood Canal, and (2) develop a multivariate index of the response of benthic communities to DO. RDA is a method of comparing two data matrices, such as a station-by-environmental-variable matrix and a station-by-species matrix. It allows relationships between patterns in species abundances and environmental variables to be visualized and quantified. Because RDA preserves Euclidean distance among samples, which has been shown to be a poor distance metric for analyzing communities structured along environmental gradients (Legendre and Legendre, 1998), the benthic abundance data were transformed prior to RDA so that the distance metric CNESS (chord-normalized expected species shared) could be used (Trueblood et al., 1994; Legendre and Gallagher, 2001).

Data Transformations

The first transformation applied to the station-by-species matrix, Y, was the hypergeometric transformation,

$$y_i = 1 - \frac{\binom{N - N_i}{m}}{\binom{N}{m}}, \qquad (1)$$

where y_i represents the probability of sampling species i from a sample of N organisms with a random draw of m individuals. Grassle and Smith (1976) used the hypergeometric function in the calculation of the faunal similarity index NESS. Trueblood et al. (1994) used this transformation prior to a principle-components analysis. By varying the random sample size, m, the sampling probabilities contained in the matrix Y can be made sensitive to either the rare or the most common species. This property can be used to "tune" the analysis to find the maximum variance explained by the environmental variables.

The second transformation was row normalization. Each row of the species data table, Y, was normalized so that the sum of the squared elements equaled one,

$$y'_i = \frac{y_{ij}}{\sqrt{\sum_{j=i}^{p} y_{ij}^2}}, \qquad (2)$$

where y'_i is the row-normalized sampling probability for species i. The purpose of row normalization is to convert Euclidean distance, which is preserved by RDA, to chord distance (Orloci, 1978). The Euclidean distance between two points, $D_{Euclidean}$, is

$$D_{Euclidean} = \sqrt{\sum_{j=1}^{p} \left(y_{1j} - y_{2j}\right)^2} \; . \qquad (3)$$

Chord distance between two points is given by the following formula:

$$D_{Chord} = \sqrt{\sum_{j=1}^{p}\left(\frac{y_{1j}}{\sum_{j=1}^{p} y_{1j}^2} - \frac{y_{2j}}{\sum_{j=1}^{p} y_{2j}^2}\right)^2} \quad . \tag{4}$$

Substituting y' (Equation 2) for y in Equation 3, gives the chord distance (Equation 4). Thus, the Euclidean distance among row-normalized sampling probabilities is equal to the CNESS distance among the untransformed data.

RDA

To perform the RDA, the transformed station-by-species matrix, Y, and the station-by-environmental-variable matrix, X, were first centered. Then a multiple regression was performed, $Ý = X\,[X'\,X]^{-1}\,X'\,Y$, where Ý is the matrix of transformed species abundances predicted by the regression, assuming these abundances are linear functions of the environmental variables. An eigenanalysis on the matrix Ý gives the canonical eigenvectors, U, which summarize the variance in Ý and are also linear functions of the environmental variables. The site scores, F, are calculated as follows: F=YU.

The stations, species, and environmental variables were displayed using biplots. The biplot scores, B, for the environmental variables, were found by calculating the correlations of X with the site scores, F. Since the variances of the site scores differ among the axes, the correlations are scaled by the eigenvalues of each axis,

$$B = r_k \sqrt{\frac{\lambda_k}{\sum \lambda}}, \tag{5}$$

where r_k is Pearson's correlation coefficient, calculated for each of the k canonical axes, and $\Sigma\lambda$ is the total variance in the matrix Y. This procedure was repeated with the residuals, Y-Ý, to calculate the non-canonical axes and the total variance of the Y matrix. The relative contribution of individual species to the overall variance in community structure is equal to the squared distances to the origin of the sites scores, F (Greenacre, 1984).

The RDA was first performed on data collected during the June 2004 PSAMP spatial sediment monitoring cruise. Four environmental variables measured at each station during the cruise were included in the RDA: (1) DO concentration, (2) water depth, (3) percent silt-clay (< 63-µm diameter), and (4) sediment organic carbon content (%). An appropriate statistic to test the null hypothesis of no effect of environmental variables on community structure is the pseudo-F statistic,

$$F = \frac{tr(Ý'Ý)/(q-1)}{tr(R'R)/(n-q)}, \tag{6}$$

where tr(Ý'Y) is the hypothesis sums of squares and tr(R'R) is the residual sums of squares (McArdle and Anderson, 2001). For one variable, Equation 6 reduces to Fisher's F statistic. To test if DO concentration contributed significantly to variation in community structure, a new predicted matrix, $\acute{Y}_{red}$, was recalculated from the set of environmental variables excluding DO. The F statistic for testing the significance of the added explanation due to the addition of DO is

$$F_{ex} = \frac{tr(\acute{Y}'\acute{Y}) - tr(\acute{Y}'_{red}\,\acute{Y}_{red})}{tr(R'R)}. \tag{7}$$

These statistics were tested by random permutations (of the rows of Y), alleviating the need to comply with the assumption of multivariate normality. The degrees of freedom were not included in Equation 7 because they are unnecessary for permutation tests, as they remain constant.

Benthic community classification

The distance metric CNESS was used to identify distinct benthic communities from the 2004 Hood Canal benthos data via cluster analysis. Unweighted pair-group mean average (UPGMA) sorting was performed for cluster analysis using the program COMPAH96 (originally described by Boesch, 1977), a program distributed by Eugene D. Gallagher and available at www.es.umb.edu/edgwebp.htm.

Multivariate index of benthic community response to dissolved oxygen

A multivariate index was developed to reconstruct the effects of DO concentration on benthic community structure at three locations where historical data on benthic communities were available since 1989. These longer-term data were collected from station 13R, in northern Hood Canal, from station 14, farther south, and from station 17 in the Great Bend region. These data were analyzed under the assumption that the same relationships between environmental variables and benthic community structure quantified for the June 2004 PSAMP spatial sediment monitoring data apply to the station-by-species matrix of the longer-term benthic data set, Z, for which DO concentration measurements were not available.

Site scores for the longer-term benthic data set, F', were calculated as F' = Z'U, where Z' is the transformed station-by species matrix for the long-term data set, and U is the set of canonical eigenvectors for the RDA analysis of the 2004 data set. Thus, F' represents the locations of the long-term monitoring stations along the canonical axes calculated for the 2004 data. The multivariate index of DO effects on benthic community structure, M, is calculated as follows,

$$M = \frac{F \bullet B_{DO}}{|B_{DO}|}, \tag{8}$$

where $\bullet$ represents the dot product, B_{DO} is the biplot score for dissolved oxygen, and $|B_{DO}|$ is the norm of B_{DO}. Geometrically, M is a matrix containing the orthogonal projections of each station onto the dissolved oxygen biplot vector.

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Results

Summary and Geographic Display of Hood Canal Data

Data from 13 sediment and six water column monitoring surveys conducted from 1932 through 2005 were located and examined for this report. Information describing these surveys is listed in Appendix B. All available sediment chemistry, toxicity, and benthic infauna data, as well as all water column DO and related measures, were compiled in the HCDOP Task IV Access database (Appendix C), with a subset of selected data placed in matrix format for analysis (Appendix D). Sediment chemistry, toxicity, and benthos measurements for each of the PSAMP sediment stations sampled from 1989-2005 were summarized to determine the relative sediment quality at each station (Appendix E).

Sediment Quality Data

Data from the 13 subtidal sediment monitoring surveys conducted from 1952 through 2005 were examined in detail. Station locations are shown in Figure 2. A list of all projects, with station numbers, locations, and geographic coordinates, is given in Table 4. The numbers of stations sampled for various parameters in each survey are summarized in Table 5 and Appendix F.

These surveys included:

- The 1989-2005 PSAMP long-term (temporal) monitoring program.
- The 1999 PSAMP/ NOAA spatial survey.
- A 2004 PSAMP spatial survey of sediment parameters and near-bottom DO.
- A number of sediment cleanup-related surveys conducted by a variety of investigators (i.e., data retrieved from Ecology's SEDQUAL database).

None of these locations was selected specifically to evaluate the effects of hypoxia on the benthos, and only the 2004 study included measures of DO. Many stations were sampled in relatively shallow depths along the shoreline of the region or in Port Gamble and Port Ludlow. Therefore, these stations could not be expected to represent the nature of benthic effects in the deepest reaches of the canal. However, collectively, these locations provided a very broad coverage of the entire length of the canal.

From these summaries, it can be seen that while sediment parameters have been measured over a wide geographic range in Hood Canal (Figure 2), repeated annual sampling has occurred at only six stations (up to five PSAMP Temporal stations from 1989-1994, and one PSAMP Temporal station from 1989-2005). Canal-wide spatial assessment has occurred in only two surveys (21 stations - PSAMP/NOAA 1999; 30 stations - PSAMP Spatial 2004). The remaining surveys were focused studies where a small number of samples was collected only once at small-scale, target locations (Table 5).

Ecology's PSAMP spatial survey of sediment quality performed in 2004 was the only survey conducted in which sediment parameters and near-bottom DO samples were collected simultaneously. Although all HCDOP Task IV data were examined in this report, data from the 2004 survey were a focal point for examination, providing direct information on the relationships between sediment quality, benthos, and DO. The details regarding the 2004 station locations, the methods used to collect and analyze the samples, and the interpretations of the data were compiled and summarized in a companion report (Long et al., *in preparation (b)*).

Station Depths

The depth of the overlying water can be an important and controlling factor in the composition of the benthos. The depths of the sampling stations in the 2004 PSAMP survey, the 1999 PSAMP/ NOAA survey, and the seven PSAMP long-term stations (1989-2005) are shown in Figure 3. Depth data procured from the SEDQUAL database appeared to be inaccurate, based on known bathymetry, and were excluded from this summary. Stations ranged in depth from 4 meters to 177 meters. Relatively shallow depths occurred near the canal entrance, on the entrance sill, in Port Ludlow and Port Gamble, in the upper reaches of Dabob and Quilcene Bays, in all nearshore areas, and in Lynch Cove. Four stations sampled along the central eastern shoreline of the canal were shallowest. The deepest stations were those in central and southern Dabob Bay and in the central, mid-canal reach of Hood Canal south to the Great Bend. Depths gradually decrease toward the mudflats at the terminus of the canal.

The depth contour of the region is shown in Figure 4. It is based on a Digital Elevation Model (DEM) published by the Washington State Geospatial Data Archive (http://wagda.lib.washington.edu/data/index.html), and based on U.S. estuarine bathymetric data sets generated by NOAA (http://estuarinebathymetry.noaa.gov/). The depths depicted in the figure range from 3 meters above to 293 meters below extremely lower-low water (ELLW).

The entrance to the canal from Admiralty Inlet includes a relatively deep trough down the central axis of the canal. Progressing southward, the water depths in the trough gradually decrease onto a relatively shallow, flat, and broad sill that begins in the vicinity of the Hood Canal Floating Bridge and Squamish Harbor. The sill extends southward to the vicinity of Thorndyke Bay and the town of Vinland. Farther south, another deeper trough forms down the axis of the canal progressing into the central canal. This trough becomes increasingly wider southward into the middle reaches of the canal. The depths are greatest at the confluence of Dabob Bay and Hood Canal, in the middle and southern reaches of Dabob Bay, and in the mid-section of Hood Canal. Water depths gradually decrease toward the Great Bend, around the Great Bend, and into the canal terminus in Lynch Cove. The canal terminates in broad mudflats in Lynch Cove.

Sediment Grain Size

The composition of soft-bottom sediments can range from coarse sand and gravel to very fine-grained materials often referred to as silts and clays or mud. Often sediments in Puget Sound are composed of mixtures of sands, silts, and clays in various proportions. The composition of sediments is an important determinant in the abundance, diversity, and species composition of benthic assemblages. Sediment texture can influence the concentrations of toxic chemicals sorbed to the sediments. The percentages of total particles in sediments that were silts and clays (i.e., <63 μm diameter, referred to as percent fines) are compared among stations sampled in the four data sets in Figure 5.

Generally, the sediments near the canal entrance, on the sill, and in the shallows along the canal shoreline were relatively coarse sands (i.e., low percent fines), probably because of the effects of scouring by high-energy waves and currents. The composition of the sediments changed remarkably south of the sill. Samples collected along the deep central axis of Hood Canal south of the sill, and in portions of Dabob and Quilcene Bays, were primarily silts and clays (i.e., high percent fines), as were some stations in the terminal inlets of Port Ludlow, Port Gamble, and Lynch Cove. The sediment composition at four long-term stations did not change very much from 1989 to 2005.

Percent Total Organic Carbon (TOC)

The amount of organic matter in sediments can be an important indicator of the amount of food available to the deposit feeders in the benthos and the concentrations of toxic chemicals sorbed to the sediments. Concentrations of percent TOC often co-vary with percent fine-grained particles in the sediments. Hood Canal sediment percent TOC concentrations measured in the 2004 PSAMP survey, the 1999 PSAMP/NOAA survey, the long-term monitoring stations, and found in Ecology's SEDQUAL database are plotted in Figure 6.

Percent TOC concentrations generally indicated a pattern similar to that for percent fines. That is, TOC content was relatively low within and near the canal entrance, on the sill, and along the shorelines of both Hood Canal and the adjoining bays. The TOC content invariably increased at the deeper locations inland of the sill and in the terminal inlets. High concentrations occurred at one station in Port Ludlow, in Dabob and Quilcene Bays, in Lynch Cove, and in the deep central and southern regions of the canal. The highest concentrations were found in Port Gamble, in samples collected in 2002 from the site of a historical pulp and lumber mill. The concentrations of percent TOC at seven long-term monitoring stations varied from year to year but did not indicate a consistent pattern of change from 1989 to 2005.

Sediment Contamination

Summary statistics for concentrations of trace metals and organic compounds are listed in Table 6. The percentages of samples with undetected concentrations are listed in Table 7. Major and trace elements, and ancillary and priority pollutant metals, were usually detected in samples (0-19% undetected), while the majority of organic compounds (excluding PAHs) were detected less frequently (60%-100% undetected for most, 23-26% undetected for PAHs).

Maps displaying the mean SQS-Q's for detected chemical compounds are displayed in Figures 7-9. Spatial patterns observed for the chemical concentrations of some substances in Hood Canal are described below. Relative to the ranges in chemical concentrations observed in the urban bays of Puget Sound (i.e., Elliott Bay, Commencement Bay, Everett Harbor, Sinclair Inlet), the ranges in concentrations within Hood Canal were very small (Long et al., 2003). Therefore, although the following text will describe chemical concentrations as relatively high in some places and low at other locations within the study area, all of them were relatively low on the larger scale of the greater Puget Sound basin.

Trace metals concentrations varied among the stations sampled in the PSAMP 2004 survey near the entrance and along the eastern shoreline versus the deep stations inland of the sill (Figure 7). The metals concentrations were relatively uniform among the deep stations down the length of the canal. A similar pattern was apparent in the PSAMP 1999 and Temporal surveys, with relatively low concentrations near the entrance and among shallow stations, and somewhat higher concentrations at deep stations inland of the sill. There was a small amount of year-to-year variability in metals concentrations at the seven long-term monitoring stations, and no obvious trend of increases or decreases in concentrations. A query of Ecology's SEDQUAL database revealed sediment chemistry data for Port Gamble and Dabob and Quilcene Bays. The concentrations of metals were highest in Port Gamble and lowest along the eastern shoreline of Dabob Bay. They were intermediate in a few locations along the southwestern shoreline of Dabob Bay.

Concentrations of PAHs were very low at all except a few stations (Figure 8). The concentrations of these compounds were slightly elevated in only a few of the samples analyzed during the PSAMP 1999 survey, all of them from stations in Port Gamble and Port Ludlow. Otherwise, these concentrations in all samples from the PSAMP 2004 survey, the seven PSAMP long-term monitoring stations, and the SEDQUAL database were very low.

Concentrations of phthalates were either undetected or very low at all except a few stations (Figure 9). One sample collected near the entrance to Hood Canal in 2004, two samples (one from Dabob Bay and one from the Great Bend area) collected in 1990, and one sample from Port Gamble reported in the SEDQUAL database, had slightly elevated concentrations. Otherwise, these concentrations were uniformly very low throughout the region.

State standards were exceeded for various chemicals in only four locations (Figure 10 and Table 8). One sample from Port Ludlow had elevated low molecular weight PAHs, including naphthalene. One sample from Dabob Bay had an elevated concentration of a phthalate. Two samples from Port Gamble had elevated chemical concentrations, one with chlorinated organic compounds and the other with five trace metals and PCBs. None of the samples from the central axis of Hood Canal had chemical concentrations above the State standards. A more detailed review of the chemistry of Hood Canal sediments sampled for PSAMP in 1999, 2004, and at the long-term stations can be found in the respective reports of these data (Llanso et al., 1998a; Long et al., 2003; Long et al., *in preparation (b)*; Partridge et al., 2005).

Sediment Toxicity

Summary statistics for sediment toxicity tests conducted in Hood Canal between 1984 and 2004 are provided in Table 9. The widest ranges in responses were observed with the bacteria, bivalve embryos, sea urchin gametes, and human liver cells. The crustaceans and polychaetes were the least sensitive, as indicated by the narrowest ranges in response.

The locations of sampling stations in the Hood Canal region in which sediments were tested for toxicity in the 1999 PSAMP/NOAA and 2004 PSAMP Spatial sediment surveys and the magnitude of the various test results are shown in Figure 11. For the amphipod survival, sea urchin fertilization, and Microtox results, the highest bars indicate the least toxic samples. For the Cytochrome P-450 HRGS tests, the highest bars indicate the most toxic response. In the

1999 survey, test results for amphipod survival were uniformly high (i.e., relatively less toxic) throughout the canal, while urchin fertilization results were lower (i.e., relatively more toxic) in Port Gamble and Dabob Bay. Microtox test results were highest (i.e., relatively less toxic) within and just outside of Dabob Bay, while Cytochrome P-450 HRGS test responses were uniformly low (i.e., relatively less toxic) throughout the canal, with the exception of some higher responses (i.e., relatively greater toxicity) in Port Gamble and Port Ludlow.

Only the urchin fertilization tests were conducted on samples collected for the 2004 PSAMP Spatial sediment survey. They were performed with the same methods used in the 1999 survey to ensure comparable results. As in 1999, percent urchin fertilization success was lowest in Dabob Bay, and also at one station near Lilliwaup. Results of the tests for the two surveys are summarized and compared in Table 10. The samples tested in 2004 were more toxic than those tested in 1999. The mean percent fertilization was lower in 2004 in all three porewater concentrations, and the minimum percent fertilization was lower. The number of samples classified as toxic and the percentage of the study area that they represented were larger in 2004. Some of the samples were toxic in the 50% and 25% porewater concentrations in 2004, whereas none were toxic in 1999. There was one sample with an outcome of 0% fertilization in the 2004 samples, whereas the lowest percent fertilization in 1999 was 41%. A complete summary of these toxicity test results is provided in Long et al., 2002, 2003, and *in preparation (b)*.

A summary of stations in which critical values for the various sediment toxicity tests were exceeded in the SEDQUAL database and in the Ecology surveys is given in Table 11 and geographically displayed in Figure 12. There were significant results in the amphipod survival, bivalve embryo, sea urchin fertilization, and Cytochrome P-450 HRGS tests. Samples with toxicity exceeding critical values occurred in clusters of stations located in Dabob Bay and Port Gamble. The majority of significant responses in Port Gamble were from SEDQUAL data obtained from a sediment monitoring program near the Pope and Talbot mill. Other areas where sediment toxicity samples exceeded critical values included Port Ludlow, central Hood Canal, and the southern reach of the canal near Lilliwaup (Sund Creek).

Overall, the samples from this region tested in previous surveys or by Ecology/NOAA in 1999 and Ecology in 2004 were not highly toxic. The majority of the significant responses were in the most sensitive assays and in samples from Port Gamble, Port Ludlow, and Dabob Bay. The majority of samples from Hood Canal were not toxic in any of the tests. However, the significant response in the Cytochrome P450 HRGS assay of organic solvent extracts suggests that potentially toxic organic compounds may occur in sediments but are not readily bioavailable to benthic invertebrates.

Benthic Indices and Assemblage Structure

Benthic infaunal invertebrate assemblages in Hood Canal were examined from sediment samples collected for the PSAMP Temporal (1989-present), PSAMP/NOAA 1999, and PSAMP Spatial 2004 monitoring surveys. Infaunal data were not found from any other surveys. In the PSAMP surveys, organisms were identified to the lowest taxonomic level possible (usually species) and enumerated, and benthic indices of assemblage structure were calculated and examined. Details of this work are summarized in Llansó et al., 1998b; Long et al., 2002b, 2003, *in preparation (b)*; and Partridge et al., 2005.

Spatial and Temporal Patterns of Individual Benthic Infaunal Indices

Benthic infaunal indices calculated for all Hood Canal stations sampled between 1989 and 2005 are displayed geographically in Figures 13-19 and presented in greater detail in Tables 12 and 13. Each index was examined for spatial differences among stations, and for any changes that may have occurred over time.

Total taxa abundance (Figure 13, Table 12) was highest in all northern Hood Canal stations; in shallow, nearshore samples collected in 1999 from Port Gamble, Port Ludlow, and Dabob and Quilcene Bay; and at four shallow, nearshore stations sampled in 2004 along the eastern shoreline of the central canal. A pattern of decreasing abundance was seen from north (highest values) to south (lowest values) along the canal for all three surveys, and from shallow to deep stations. Total taxa abundance was lowest in the deep, central channel in Dabob Bay. With the exception of a peak in 1997-98 at the PSAMP Temporal station near the floating bridge, no obvious temporal trends in abundance were seen throughout the time periods sampled.

Taxa richness spatial patterns were similar to total abundance (Figure 14, Table 12). Values were highest in the northern stations; in shallow nearshore samples collected in 1999 from Port Gamble, Port Ludlow, and Dabob and Quilcene Bay; and at four shallow nearshore stations sampled in 2004 along the eastern shoreline of the central canal. As with total taxa abundance, taxa richness gradually diminished from north to south and with increasing depth. Values were lowest in the deep central channel in Dabob Bay and in Lynch Cove. There was some variability in taxa richness among years at the temporal trends stations, but no discernible pattern of steady increases or declines.

Pielou's Evenness index did not vary as much as total taxa abundance and taxa richness among stations (Figure 15, Table 12), but did indicate lower levels in Port Gamble, Port Ludlow, PSAMP Temporal station 13R (near the Hood Canal bridge), and in the southern canal and Lynch Cove stations. Swartz's Dominance Index (SDI) generally indicated the same spatial patterns as Pielou's Evenness, but SDI was also low in the deep Dabob Bay and some of the southern stations where evenness was high (Figure 16, Table 12).

The total abundance of each major taxonomic group (i.e., annelids, arthropods, molluscs, echinoderms, and miscellaneous taxa) at each station is displayed in Figures 17-19 and summarized in Table 12.

The annelids, primarily the polychaete worms, were present at all stations and often the most abundant taxa. They were especially abundant and dominant in the 1999 PSAMP/NOAA samples from Port Gamble and Port Ludlow, the 1999 and 2004 deep Dabob Bay and central canal stations, and the 1999 southern stations. Annelid abundance appears to show some variation over time at the PSAMP Temporal station nearest the Hood Canal bridge, increasing from 1999 through 2001, then decreasing to lower levels from 2002 through 2005. Annelids were noticeably low in abundance in 2004.

Arthropods were most abundant at stations sampled in Port Ludlow, Port Gamble, and northern Hood Canal, and in the shallow nearshore stations in Quilcene Bay and along the eastern shoreline of the central canal. They decreased sharply in abundance in the deep Dabob Bay, deep central canal, and southern stations, and were rare or absent in Lynch Cove.

Molluscs were the most abundant taxa at the PSAMP Temporal station near the Hood Canal bridge, and similar in abundance to the annelids in the northern canal and the shallow nearshore stations and at some stations near the Great Bend. Total abundance of molluscs appeared to fluctuate widely over time at the northernmost PSAMP Temporal station nearest the Hood Canal bridge, and at the PSAMP Temporal station in the central channel of the Great Bend.

The echinoderms and miscellaneous taxa were always lowest in abundance. One or both taxa groups were most numerous in the northern main axis of Hood Canal, Port Gamble, and the nearshore stations, and decreased in numbers or were absent progressing toward the southern end of the canal and in Port Ludlow, Lynch Cove, and the deep Dabob Bay stations. Echinoderms were present in moderate numbers in the deep central Hood Canal stations. The primary echinoderm present was the heart urchin, *Brisaster latifrons*, a deposit feeder that inhabits fine sand and mud.

Spatial and Temporal Benthic Infaunal Assemblage Patterns in Nine Hood Canal Sub-regions

Benthic infaunal indices were also examined collectively, and in relation to station depth, grain size, and percent organic carbon in the sediments, for all stations sampled (Tables 12 and 13), to determine spatial and temporal patterns of infaunal assemblages throughout Hood Canal. Based on this review, infaunal assemblage patterns were distinguished for nine sub-regions of the canal:

1. Port Ludlow
2. Port Gamble
3. Northern Hood Canal
4. Dabob Bay – Nearshore
5. Dabob Bay – Deep
6. Central Hood Canal – Nearshore
7. Central Hood Canal – Deep
8. Southern Hood Canal
9. Lynch Cove

These nine assemblages are displayed in Figure 20 and described below. They appear to be sub-groups of three larger assemblages that were identified in the multivariate statistical analyses described later in the report.

For each geographic assemblage, there are descriptive notes about the relative sensitivity or tolerance of various species to stress. For decades benthic ecologists worldwide have observed that infaunal species have a wide range in sensitivity to various kinds of stresses such as chemical pollution, hypoxia, low salinity, temperature, and physical disturbance. Although there is little universal agreement among benthic ecologists about which genera and species are most sensitive and most tolerant of these stresses, there are a number of documents that include observations of the behavior of many species relative to these kinds of stresses. The documents that proved useful in these evaluations included Diaz and Rosenberg (1995), Striplin Environmental Associates, Inc. (1999), Word (1990), Word et al. (1977), and Word and Mearns

(1979). These notes about stress sensitivity are not meant to be definitive with regard to hypoxia because each species may be differentially sensitive to different kinds of stress or combinations of stressors.

1. Port Ludlow

Port Ludlow, a small bay located near the entrance to Hood Canal, was sampled at three locations for benthos in 1999 only. These samples were collected from shallow depths (6-17 m) and had a mixture of percent fines and TOC values. Total abundance in these three samples was relatively high (688-1574 individuals), taxa richness was low to mid-range (29-53 taxa), evenness was relatively low (J' ranged from 0.29-0.63), and dominance was the lowest in the canal (SDI ranged from 1-6). Assemblages were dominated by high numbers of a few species of stress tolerant cirratulid polychaetes (*Aphelochaeta* sp., *Aphelochaeta glandaria* and oligochaetes). We have observed these species to be most abundant in urbanized bays and harbors of Puget Sound (Long et al., 2003). Several species of crustaceans (*Aoroides spinosus*, *Aoroides* sp., *Leptochelia savignyi*, and *Euphilomedes carcharodonta*) and molluscs (*Nutricola lordi*, *Axinopsida serricata)* were also among the dominant taxa. Echinoderms, some of which are known to be stress sensitive (Diaz and Rosenberg, 1995; Word and Mearns, 1979; Word, 1977), and miscellaneous taxa were rare or absent.

2. Port Gamble

Port Gamble, another small bay located near the entrance to Hood Canal, also was sampled in three locations for benthos in 1999 only. Benthic assemblages in Port Gamble shared some similarities with those in Port Ludlow, but displayed some differences as well. These samples were also collected from shallow depths (5-14 m), and had a mixture of percent fines and TOC values. The benthos was relatively abundant, including some of the highest levels in the canal (941-3479 individuals). Taxa richness was mid-range (55-83 taxa). However, evenness was relatively low (J' ranged from 0.30-0.50), and dominance index values were among the lowest in the canal (SDI ranged from 1-5). Assemblages were primarily dominated by high numbers of a few species of cirratulid polychaetes (*Aphelochaeta glandaria*, Cirratulidae), maldanids, and other polychaetes that we have observed to be abundant in the urbanized bays and harbors of Puget Sound (Long et al., 2003). The crustacean, *Euphilomedes carcharodonta*, also was dominant, as was the mollusc, *Odostomia* sp. Unlike Port Ludlow, echinoderms were present, along with a number of miscellaneous taxa.

3. Northern Hood Canal

Stations sampled in northern Hood Canal, in an area extending from Admiralty Inlet to the juncture of Hood Canal with Dabob Bay, included PSAMP Temporal stations 13R and 14, sampled from 1989 to the present and 1989 through 1994, respectively. Four stations were sampled in 1999 for the PSAMP/NOAA sediment survey, while 10 were sampled in 2004 for the PSAMP Spatial monitoring survey.

Station 13R, located just south of the Hood Canal bridge, was sampled repeatedly on an annual basis at 20-23 meters depths. Samples had low percent fines (3.7-16.0 %) and TOC (0.2-0.6%). Total abundance at station 13R was among the highest in the canal (625-3723 individuals) along with taxa richness (110-194 taxa). However, both evenness (J' ranged from 0.31-0.74) and dominance (SDI from 2-25) varied widely between years. Molluscs were the dominant taxa group (high numbers of the bivalves *Nutricola lordi*, *Axinopsida serricata*, *Alvania compacta*), with a relatively equal mixture of crustaceans (mainly the ostracod *Euphilomedes carcharodonta*) and annelids. Echinoderms and miscellaneous taxa were present in some of the highest numbers in the canal (2-8 and 9-125 individuals, respectively).

Just south of station 13R, station 14, sampled in deeper water (114-116 m) had higher percent fines (25-48%) and TOC (0.4-1.1%) than station 13R. Benthos had much lower total abundance (314-534 individuals) and slightly lower taxa richness (103-163) than station 13R, but very high evenness (J' ranged from 0.80-0.92) and dominance values (SDI ranged from 39-59) over the years sampled, indicating a rich benthic assemblage. A variety of polychaetes (*Maldane sarsi*, *Galathowenia oculata*) were the most abundant taxa, followed by molluscs (*Axinopsida serricata, Macoma spp*), then arthropods (*Euphilomedes spp, Pinnixa occidentalis, Parvamussium alaskense*). Echinoderms and miscellaneous taxa were again present in some of the highest numbers (18-39 and 4-11 individuals, respectively).

Benthic data from both station 13R and station 14, sampled annually over a number of years, were visually examined for any temporal trends in abundance. At station 13R, annelid abundance increased steadily from 1999 through 2001, then fell in 2002 to 2005 to levels similar to those recorded from 1989 through 1999. Abundance of molluscs, primarily the dominant bivalve *Nutricola lordi*, also increased dramatically in 1997 and 1998, and again in 2002 and 2003 when annelid abundance decreased. Abundance of *N. lordi* then declined precipitously in 2004. Station 14 displayed no obvious increases or decreases in benthic indices over time.

The 14 other stations in northern Hood Canal were sampled in 1999 and 2004 and had a wide range of depths (19-120 m), grain size (4.8-76.5 % fines), and TOC (0.1-2.5 %). Benthic assemblages at these stations also had wide ranges in total abundance (166-1075 individuals) and taxa richness (34-136 taxa), and average to higher evenness (J', 0.64-0.81) and dominance (SDI from 8-28) values. They were composed primarily of relatively equal and diverse mixtures of annelids (*Myriochele olgae, Cossura bansei*, *Prionospio lighti, Heteromastus filobranchus, Spiophanes bombyx, Leitoscoloplos pugettensis, Pectinaria californiensis*), arthropods (*Photis* spp, *Euphilomedes producta*, *E. carcharodonta*, *Rhepoxynius boreovariatus*, *Pinnixa* sp., *Gammaropsis thompsoni*), and molluscs (*Macoma carlottensis*, *M. eliminate*, *Axinopsida serricata*, *Alvania compacta*, *Nutricola lordi*, *Parvilucina tenuisculpta*). Echinoderms were present in some samples (1-10 individuals), while absent in others, and miscellaneous taxa ranged from few (3) to abundant (70). No obvious differences in benthic assemblage structure were seen between samples collected in 1999 and 2004.

4. & 5. Dabob Bay – Nearshore and Deep

Stations sampled in Dabob Bay include PSAMP Temporal station 15, sampled from 1989-1994, six stations sampled in 1999 for the PSAMP/NOAA sediment survey, and eight stations sampled in 2004 for the PSAMP Spatial monitoring survey. Station 15 and three of the 1999 stations sampled in Quilcene Bay were shallow (less than 30 meters) and located near the shoreline. Grain size and TOC were low at station 15 (5.0-8.2 % fines and 0.2-0.3 % TOC, respectively), and higher in Quilcene Bay (30.9-71.1 % fines and 1.3-3.2 % TOC). The other samples in

Dabob Bay were collected from deeper stations (45-177 m depth), with primarily fine sediments (34.9 to 91.6 % fines) and high TOC values (1.4-2.7 %) (i.e., Dabob Bay – Deep).

Benthos from repeated annual sampling of station 15 had the highest total abundance (392-760 individuals) and taxa richness (115-142 taxa) levels in Dabob Bay. Evenness (J' from 0.57-0.90) and dominance values (SDI from 14-50) were also high. Polychaete annelids were dominant (*Exogone lourei*, *Phyllochaetopterus prolifica*), followed by slightly fewer molluscs (*Macoma* sp, *Delectopecten vancouverensis*, *Alvania compacta*, *Psephidia lordi*), and a reduced number of arthropods. Echinoderms were usually present, while miscellaneous taxa (including Phoronida) were present in high numbers. Some species at this station (e.g., *E. lourei* and Phoronida) are typically found in sandy sediments. No obvious between-year differences were seen for the benthic indices at this station.

The three other shallow, nearshore stations in Quilcene Bay had abundant, but slightly less diverse, assemblage structures than station 15. Total abundance (745-754 individuals) was among the highest in the canal, while richness varied (44-73 taxa). Evenness was high (J' from 0.76-0.81), while dominance was average (SDI from 12-16). Annelids (*Trochochaeta multisetosa*, *Heteromastus filobranchus*, *Pectinaria californiensis*) and molluscs (*Axinopsida serricata*, *Macoma carlottensis*, *Macoma* sp., *Parvilucina tenuisculpta*) were dominant, followed by a reduced number of arthropods. Echinoderms and miscellaneous taxa were present in average to high numbers. Some species at this station (e.g., *Heteromastus filobranchus* and *Macoma* spp.) are typically found in siltier, organically enriched sediments and can be relatively resistant to hypoxia (Diaz and Rosenberg, 1995) or chemical contamination (Long et al., 2003).

In the deeper stations in Dabob Bay (i.e., Dabob Bay – Deep), benthic assemblages were less diverse. The ten stations sampled at depths between 45 and 177 meters, with higher percent fines and percent TOC, had a lower range of total abundance (27-321 individuals), taxa richness (6-54 taxa), and dominance (SDI ranged from 4-14). Annelids were dominant (*Heteromastus filobranchus, Leitoscoloplos pugettensis, Prionospio lighti*, *Cossura bansei*, *Pectinaria californiensis*, *Levinsenia gracilis*, *Nepthys cornuta*, *Paraprionospio pinnata*, *Lumbrineris cruzensis*, *Lumbrineris luti*, *Aricidea lopezi*, *Mediomastus californiensis*, *Galathowenia oculata*, *Decamastus gracilis*). There were very low numbers of molluscs (*Macoma carlottensis, Axinopsida serricata*) and few arthropods (*Eudorella pacifica*, *Euphausiacea*). Echinoderms and miscellaneous taxa were rare or absent.

A number of dominant species in these deep Dabob Bay stations were shared with those in Quilcene Bay, including *Heteromastus filobranchus*, *Pectinaria californiensis*, *Macoma carlottensis,* and *Axinopsida serricata*. Both sets of stations had high percent fines and TOC values. The lowest abundance (26-47 individuals) and richness (6-19 taxa) values measured in the canal were from stations 219, 220, 112, and 48, the deepest stations in Hood Canal. All were deeper than 170 meters.

6. & 7. Central Hood Canal – Nearshore and Deep

In central Hood Canal (south of Dabob Bay to Lilliwaup), different benthic assemblages appeared to be present in shallow (<30 m), nearshore stations and deeper (>130 m) stations nearer the central axis of the canal.

The four nearshore stations sampled in 2004 ranged in depth from 14-25 m, and had low percent fines (0.4-8.4 %) and low percent TOC levels (0.1-0.2%). Total abundance (373-487 individuals) was similar to PSAMP Temporal station 14 in northern Hood Canal (deep, low percent fines and TOC) and station 15 in Dabob Bay - Nearshore (shallow, low percent fines and TOC). Taxa richness (57-82 taxa), however, was lower than these other stations, while evenness (J' from 0.68-0.79) and dominance (SDI from 11-18) values were near the average. A mixture of annelids (*Exogone lourei*, *Galathowenia oculata*) and molluscs (*Axinopsida serricata*, *Nutricola lordi*) dominated the assemblage, with lower numbers of arthropods (*Euphilomedes producta*, *E. carcharodonta*). Echinoderms ranged from a few to none, while numbers of miscellaneous taxa were above average. *Phoronis* sp. was dominant at one station. The dominant species at these stations were also found at stations 14 and 15.

The five deep stations sampled in 1992, 1999, and 2004 in central Hood Canal ranged in depths from 134-175 m, with very high percent fines (72.3-96.5%) and high percent TOC levels (1.9-2.7%). All displayed low total abundance (69-126 individuals) and richness (20-37 taxa) values, and moderate dominance (SDI from 8-18) values. Evenness values (J' from 0.85-0.92) were high. As in the deeper stations in Dabob Bay, annelids (*Prionospio lighti, Leitoscoloplos pugettensis*, *Phyllochaetopterus claparedii*, *Cossura bansei, Lumbrineris cruzensis*) again were the dominant organisms in deep central Hood Canal, followed by lower numbers of a mixture of molluscs (*Thyasira flexuosa*, *Axinopsida serricata*, *Macoma carlottensis*), and one arthropod (Euphausiacea). Echinoderms were present (primarily *Brisaster latifrons*) while miscellaneous taxa were rare or absent. A number of the dominant species (*P. lighti, L. pugettensis, C. bansei, L. cruzensis, A. serricata*, *M. carlottensis)* in these stations overlapped with those in the deeper, stations in Dabob Bay. No obvious trends in benthic index levels were observed between years.

8. Southern Hood Canal

Stations in the southern end of Hood Canal (south of Lilliwaup to the Great Bend) included two PSAMP Temporal stations (stations 16 and 17) at the Great Bend, two stations from the PSAMP/NOAA 1999 survey, and three from the 2004 PSAMP Spatial survey.

The benthic assemblages at station 17 (81 m depth, 88.0-98.0 percent fines, 1.3-1.9 percent TOC), sampled annually from 1989-1994, typically had low total abundance (145-273, and 414 individuals) and taxa richness (35-41 taxa), and variable evenness (J' from 0.36-0.74) and dominance (SDI from 1-12). Molluscs (*Axinopsida serricata, Cylichnidae, Macoma carlottensis*) were dominant, followed by annelids (*Spiophanes berkeleyorum*, *Cossura bansei*, *Aricidea lopezi, Sigambra nr bassi*), then arthropods (*Eudorella pacifica*). Echinoderms were absent, while miscellaneous taxa were rare. No obvious trends were seen between years at this station. Station 16 (20 m, grain size not recorded, 1.8% TOC) had higher benthic index values, but a similar suite of dominant species.

The five other stations sampled in southern Hood Canal were deeper (87-132 m) than station 17, with high percent fines (57.9-85.4%) and TOC (2.0-2.4%). Benthos ranged slightly lower in total abundance (51-286 individuals) and taxa richness (20-36 taxa), and had a narrower range of evenness (J' from 0.65-0.87) and dominance (SDI from 5-11) values.

The suite of dominant taxa at these five southern Hood Canal stations was similar to those found at stations 16 and 17. Annelids (*Spiophanes berkeleyorum*, *Heteromastus filobranchus*, *Mediomastus sp.*, *Aricidea lopezi*, *Cossura pygodactylata*, *Prionospio lighti*, *Leitioscoloplos pugettensis*) were slightly more abundant than molluscs (*Axinopsida serricata*, *Macoma carlottensis*), with arthropod abundance (*Eudorella pacifica*) the lowest of the three. Again, echinoderms were absent, while miscellaneous taxa were rare. A number of the dominant species at these stations overlapped with the species found in the shallow Quilcene Bay, deep Dabob Bay, and deep central Hood Canal stations, all with high percent fines and TOC. Overlapping annelid species included *Prionospio lighti*, *Cossura bansei*, *Aricidea lopezi*, *Leitoscoloplos pugettensis*, all typically found in fine-grained sediments. Overlapping bivalve molluscs, *Axinopsida serricata* and *Macoma carlottensis,* were abundant throughout Hood Canal.

9. Lynch Cove

Five shallow (19-38 m), silty (59.1-93.9% fines), organically rich (1.7-4.2% TOC) stations were sampled in Lynch Cove, at the southern terminus of Hood Canal beyond the Great Bend. These included one PSAMP Temporal station sampled in 1992, two 1999 PSAMP/NOAA stations, and two 2004 PSAMP Spatial stations. All of these stations had among the lowest total abundance (127-339 individuals) and taxa richness (15-29 taxa) values, low to moderate evenness values (J' from 0.54-0.71), and dominance values (SDI from 2-5). Many of these benthic indices were almost as low as those at the stations in Port Gamble and Port Ludlow, which were the lowest in the canal.

Annelids, which dominated these assemblages, included *Paraprionospio pinnata, Sigambra* nr *bassi, Heteromastus filobranchus, Sigambra* nr *bassi, Pectinaria californiensis, Glycinde polygnatha*, *Podarkeopsis glabrus, Capitella capitata* complex. Several of the dominant species (*Paraprionospio pinnata, Heteromastus filobranchus, Capitella capitata* complex) are documented as tolerant of severe hypoxia (Diaz and Rosenberg, 1995; Word and Mearns, 1979) or were found in abundance in the urbanized bays of Puget Sound (Long et al., 2003). Arthropods and echinoderms, many of which are sensitive to various stressors (Diaz and Rosenberg, 1995; Word and Mearns, 1979; Long et al., 2003), were rare or absent. Molluscs and miscellaneous taxa were present in extremely low numbers, with the exception of a spike in molluscs at stations 128 and 118. The bivalve mollusc, *Axinopsida serricata*, was very abundant there. This species is ubiquitous in both Hood Canal and Puget Sound, including in some of the urbanized bays (Long et al., 2003) and therefore may be relatively tolerant of various kinds of stressors.

Comparison with 1999-2003 Puget Sound Baseline Data

Comparisons of the Hood Canal benthic index values to the 1997-2003 Puget Sound baseline median index values are summarized for 58 stations in Table 14 and Figure 21. Stations were characterized as "adversely affected" or "unaffected" as described earlier in the Methods section.

Based on these methods, 15 (or 71%) of 21 stations from the 1999 PSAMP/NOAA monitoring survey appeared to have benthic assemblages that were adversely affected. Those six that were unaffected included three (40-112 m, 4.8-21.3% fines, 0.3-0.6% TOC) in northern Hood Canal, and the three shallow stations (15-17 m, 30.9-71.1% fines, 1.3-3.2% TOC) near the shoreline in Quilcene Bay.

In the 2004 PSAMP Spatial monitoring survey, benthos appeared to be adversely affected at 23 of 30 stations (77%). Those stations that were unaffected included four stations in northern Hood Canal (19-75 m, 11-49% fines, 0.1-1% TOC), and three shallow (14-19 m, 0.4-6.5% fines, 0.1-0.2% TOC), stations along the eastern shore of central Hood Canal.

Four of the seven stations (57%) located in central and southern Hood Canal had adversely affected benthic assemblages in all years sampled, while three of the seven PSAMP Temporal stations sampled in northern Hood Canal and Dabob Bay (22-116 m, 3.7-48% fines, 0.2-1.1% TOC) had unaffected benthos. No temporal trends were seen at these stations. That is, assemblages from the same station did not change from unaffected to adversely affected, or adversely affected to unaffected over time.

In all three sets of Hood Canal sediment surveys, the majority of stations (42 of 58, 72%) had adversely affected benthic assemblages as defined in this report. This observation suggests that, in general, benthic assemblage structure in Hood Canal tends to be less abundant and diverse than in the main Puget Sound basin or dominated by taxa that appear to be tolerant of various kinds of stressors.

Spatial patterns suggest a gradient of increasingly affected stations from north to south along the main axis of the canal. In some, but not all cases, differences also seem to exist between stations with differing depths, grain size, and percent TOC. Some stations with higher percent fines and TOC (including Port Ludlow, Port Gamble, Dabob Bay – deep, Central Hood Canal – deep, southern Hood Canal, and Lynch Cove) had affected benthos. In contrast, those with lower percent fines and TOC (including many in northern Hood Canal, and Dabob Bay and central Hood Canal-nearshore) were primarily unaffected. The number of affected PSAMP Temporal stations showed no changes over time; however, the number of affected PSAMP Spatial stations indicated that the percent of stations with affected benthos was slightly higher in 2004 than in 1999. Affected stations also extended further north along the axis of the canal in 2004 than in 1999.

Summary - Benthic Indices and Assemblage Structure

Wide ranges of index values were generated from the Hood Canal benthic assemblage data, and spatial patterns were apparent for each index. Total abundance and taxa richness varied along both geographic and depth gradients. Highest values were measured in northern Hood Canal, decreasing southward to Lynch Cove. Values were also higher in the shallow nearshore stations of Port Gamble, Port Ludlow, Dabob and Quilcene Bays, and along the eastern shoreline of the central canal. Values were lower in the deepest stations in central and southern Hood Canal, and in Dabob Bay. Pielou's evenness index was less variable, but was lower in the terminal inlets of Port Ludlow, Port Gamble, and Lynch Cove, and one of the northernmost stations. Spatial patterns in the Swartz's Dominance Index were similar to those for evenness, but were low in the deep Dabob Bay stations and some of the southern stations, where evenness was relatively high.

Major taxa abundance indicated that the polychaete annelids were very important components of the benthic assemblages in this region. They were present at all stations and dominant at many stations throughout the canal. They were dominant in Port Gamble and Port Ludlow, in the deep Dabob Bay and central canal stations, and in the 1999 southern stations. Molluscs were present at most stations, and occasionally dominant at a few. They were most abundant in the northern and shallow, nearshore stations, and at some stations near the Great Bend. Molluscan abundance sometimes fluctuated widely between years, due to large increases or decreases in a few species. Arthropods were most abundant in Port Ludlow, northern Hood Canal, and in the shallow, nearshore stations, but were rare or absent in the deep and southern stations. Echinoderms and miscellaneous taxa were always lowest in abundance. They were most numerous in the northern and shallower stations and, with a few exceptions, were rare or absent in the more southern and deeper stations.

All of the calculated benthic indices were examined together with the lists of dominant taxa and some of the physical-chemical measures to determine if there were spatial patterns in the species composition of the assemblages at each station. These evaluations revealed that there were similar benthic assemblages in nine sub-regions of Hood Canal. The nine sub-regions with similar benthic assemblages were Port Ludlow, Port Gamble, Northern Hood Canal, Dabob Bay – Nearshore, Dabob Bay – Deep, Central Hood Canal – Nearshore, Central Hood Canal – Deep, Southern Hood Canal, and Lynch Cove. There were several spatial patterns in species composition within and among these areas.

There was a pattern of decreasing total taxa abundance and richness along a north-south gradient. Stations in the northern main axis of Hood Canal generally had the highest total taxa abundance and richness. With a few exceptions, there was generally a balanced mix of stress-sensitive and stress-tolerant annelids, arthropods, and molluscs, all in high numbers. These numbers gradually diminished southward along the main axis, with Lynch Cove having some of the lowest benthic index values in the canal. Assemblages there were composed of low numbers of individuals, dominated by a few stress-tolerant annelids and molluscs.

The infaunal indices also suggested a pattern of decreasing total taxa abundance and richness along a gradient of increasing depth, percent fines, and percent TOC. In many instances, shallow stations with lower percent fines and TOC values had benthic assemblages with higher index values and more taxa abundant and rich communities than deeper stations with higher percent fines and TOC enrichment. Some northern Hood Canal stations, station 15 in Dabob Bay, and the central Hood Canal nearshore stations all had lower percent fines and TOC, and assemblages with higher taxa abundance and richness. In contrast, the deep Dabob Bay, deep central Hood Canal, southern Hood Canal, and Lynch Cove stations all had higher percent fines and TOC, and assemblages with lower taxa abundance and richness. However, there were some exceptions to this pattern. Some shallow stations in the terminal inlets (Port Ludlow, Port Gamble, Dabob and Quilcene Bays, and Lynch Cove) had high percent fines and TOC with less abundant and diverse infauna.

The spatial patterns of presence and relative abundance differed among the infaunal species. Some taxa were ubiquitous, living in most or all of the sediments sampled throughout the canal. The stress-tolerant bivalve (Diaz and Rosenberg, 1995), *Axinopsida serricata*, was one of the top four dominant species at all stations except Port Gamble and was the dominant species in most of the southern Hood Canal stations. *Macoma carlottensis* or *Macoma* sp., also bivalves, were among the top four dominant taxa in all stations except Port Ludlow, Port Gamble, and Lynch Cove.

Other dominant taxa appeared to be limited to one, or sometimes two, sub-regions. *Aphelochaeta glandaria* was dominant only in Port Ludlow and Port Gamble. *Nutricola lordi*, a bivalve, was dominant only at station 13R in northern Hood Canal and in the nearshore central Hood Canal stations. The ostracods *Euphilomedes producta* and *E. carcharodonta* were dominant in most of the northern Hood Canal stations, Port Gamble and Port Ludlow, and in the nearshore central Hood Canal stations. The polychaete *Sigambra* nr *bassi* was dominant only in Lynch Cove. *Brisaster latifrons*, a heart urchin, was dominant only in the deep central Hood Canal stations.

Some of the dominant taxa were found to overlap in several sub-regions, typically those that shared some common characteristics (e.g., depth, percent fines, percent TOC) or were in geographic proximity to one another. Sub-regions varied in their degree of dominant species overlap. The benthos in some sub-regions, including Port Ludlow and Port Gamble, were composed of distinct assemblages with unique dominant species. The assemblages in these terminal inlets often were dominated by annelids locally known or previously documented as stress tolerant.

Other sub-regions, including those with similar grain size and TOC values (i.e., high percent fines and TOC or low percent fines and TOC), and those adjacent to one another along the main axis of the canal, had some similarity in dominant taxa from one sub-region to the next.

The northern Hood Canal stations, with relatively low percent fines and TOC values, had the most diverse assemblages, with well balanced mixtures of annelids, arthropods, and bivalves. Less stress-tolerant arthropods, echinoderms, and miscellaneous taxa became rare or absent from north to south, while more stress-tolerant polychaetes and bivalves became dominant southward and into Dabob Bay. The ubiquitous bivalves, *Axinopsida serricata*, *Macoma carlottensis*, and *Macoma* sp., present throughout the canal in varying numbers, became more dominant in the southern Hood Canal and Lynch Cove stations where arthropods, echinoderms, and miscellaneous taxa were missing.

Temporally, few obvious increases or decreases in benthic indices were seen. The PSAMP Temporal stations, while decreasing in total abundance from north to south, did not have any large increasing or decreasing temporal trends from 1989 through 1994. PSAMP Temporal station 13R, the only long-term station sampled from 1989 through 2005, did have large fluctuations in abundance of annelids and the mollusc, *Nutricola lordi*, between 1997 and 2005, with a large decline in abundance of both in 2004. Comparisons between 1999 PSAMP/NOAA and 2004 PSAMP Spatial assemblages suggested a slightly greater proportion of molluscs (*Axinopsida serricata*) in samples from the Central – Nearshore, Southern, and Lynch Cove regions in 2004.

Overall, comparison of the Hood Canal benthic index values with 1997-2003 Puget Sound baseline index values indicated that 42 of the 58 stations (72%) sampled in Hood Canal from 1989 through 2005 could be classified as “adversely affected.” That is, assemblage structure was less abundant and diverse, or dominated by more stress-tolerant taxa, than in the main Puget Sound basin. Spatial patterns suggested a gradient of increasingly affected stations from north to south along the main axis of the canal and into Dabob Bay. Some differences in the benthos between stations were related to differing grain size and percent TOC (i.e., adversely affected stations had higher percent fines and TOC). Although the number of affected PSAMP Temporal stations showed no change over time, the number of affected PSAMP Spatial stations suggested that the percent of stations with adversely affected benthos was slightly higher in 2004 than in 1999. Adversely affected stations also extended further north in 2004 than in 1999.

Water Column Dissolved Oxygen Data

Dissolved oxygen data from six water quality monitoring surveys conducted from 1932 through 2005 were examined in detail. Station locations are shown in Figure 22. A list of all projects, with station numbers, locations, and geographic coordinates is given in Table 15. The number of stations, number of DO records collected, and sampling dates for each project and year are summarized in Table 16 and Appendix G. The maximum and minimum concentrations for each station and year, and their relation to various critical values, are listed in Appendix H.

These surveys included:

- A series of historical water column monitoring cruises conducted by University of Washington researchers from 1932-1968.
- A series of cruises and marine flights conducted by Department of Ecology oceanographers from 1975 through the present.
- A series of cruises conducted by University of Washington researchers from 1998 through the present for the Puget Sound Regional Synthesis Model (PRISM).
- Weekly sampling by volunteer monitors from 2003 through the present for the Hood Canal Dissolved Oxygen Program.
- 30 near-bottom DO samples collected in 2004 for the PSAMP Spatial sediment monitoring event.

Only the 30 near-bottom DO samples collected during the 2004 PSAMP Spatial sediment monitoring effort were collected simultaneously with sediment and benthic infaunal samples taken in Hood Canal.

The majority of samples in these surveys were collected from stations located along the central axis of Hood Canal. Only the more recent 2003-present HCDOP volunteer monitoring and the 2004 PSAMP Spatial sediment monitoring had water column monitoring efforts located in other areas of the canal. None of the locations were sampled consistently during the entire period of 1932 to 2005, although a few were sampled for 20 to 30 years. Many have been sampled only once and recently. Also, the number of samples collected each year tended to increase from year to year, but not consistently, until recent years (2003-2005) when the number of DO samples collected increased dramatically. Samples cover the entire length of the canal from the entrance to the mudflats near the terminus, including transects from shore to shore and the deepest mid-canal reaches.

Dissolved Oxygen Concentrations

The lowest DO concentrations recorded for stations sampled by various monitoring programs in Hood Canal were illustrated in a series of maps spanning eight decades (Figures 23-30). The lowest concentration was chosen for display at each station, as it could potentially be influential in structuring the composition of the benthos. The measurements were made at various water depths; however, the lowest DO value did not always occur at or near the bottom, and may or may not have had a direct influence on the benthos.

During the period of 1932 through 1939, DO measurements were made regularly at one station in the entrance to Hood Canal and sporadically at seven other locations (Figure 23). At most stations, the measurements were made in either 1932 or 1933 and again in 1939. Some of the lowest DO concentrations occurred in the central and southern reaches of the canal, especially in 1932 or 1933. Because of missing data in this time period, it is not possible to determine any temporal trends in DO at the stations within the canal.

During the war years of the 1940s, very little data were collected (Figure 24). Relatively high DO concentrations were noted at three stations in various years. However, one station in Lynch Cove sampled in 1949 had a relatively low concentration.

The database included DO information for considerably more locations (14 stations) during 1952-1959 (Figure 25). Most stations in the northern and central reaches of the canal had relatively high DO concentrations in most years. However, there was a clear difference in the southern reaches, around Great Bend and into Lynch Cove where the concentrations often were much lower. The station nearest the terminus of the canal had very low concentrations in most years.

This same pattern and trend continued into the 1960s (Figure 26). There were data collected for 17 locations along the length of the canal. With some exceptions, most of the northern stations had relatively high DO concentrations in most years, whereas most stations in the central and southern reaches had relatively low or very low concentrations. There appeared to be a transition from relatively high DO to relatively low DO in the vicinity of Hamma Hamma. Also, there appeared to be a peak in DO in 1962, followed by sharp decreases at most stations in the late 1960s.

There were considerably fewer data in the 1970s. Four stations were sampled from 1975 through 1979 (Figure 27). DO concentrations were relatively high at the northern Hood Canal and Dabob Bay stations, intermediate at the station in the central canal, and very low at the station in the southern canal. The same spatial pattern was evident at the same four stations in the 1980s (Figure 28).

The amount of information that was collected increased remarkably in the 1990s with data reported for 21 stations along the entire length of the canal (Figure 29). As observed in previous years, DO concentrations were highest in the northern canal stations and lowest in the central and southern reaches. However, during this period the transition from low to high concentrations shifted northward to the vicinity of the confluence of the canal with Dabob Bay and the southern shoulder of the sill. At most stations where measurements were made over the entire decade, there was a gradual trend of decreasing concentrations or a peak in 1995, followed by a gradual decline. This pattern of decreasing concentrations was also evident in some of the northern canal stations on the sill.

The most recent years of monitoring data (2000 through 2005) are illustrated in Figure 30. Over 80 stations were sampled in Hood Canal. Several patterns were evident in this graph. First were the very low DO concentrations in the southern and central reaches of the canal. In general, these concentrations appear to be lower than in previous decades. Additionally, samples collected beyond the main axis of the canal indicate that low DO levels extend into Dabob and Quilcene Bays. The high DO values seen in stations along the eastern shoreline of the central canal were those sampled in the PSAMP Spatial sediment quality survey of 2004 and were in shallow waters. In northern Hood Canal, stations had moderate to high DO concentrations. Samples were never collected in Port Ludlow. Samples were collected only once in 2000 in Port Gamble, with moderately high values.

Appendix H summarizes the minimum and maximum DO values measured at each station for each year, and compares them to the critical ranges for biota identified earlier in this report, including ≥7 mg/L, <7 to 5 mg/L, <5 to 3 mg/L, and <3 mg/L (Washington State Water Quality Standards, Washington State Department of Ecology, 2003; Newton et al., 2002). In the earlier decades, a few southern stations had minimum DO levels ranging from 3 to <5 mg/L, while most fell below 3 mg/L. The majority of stations in the central canal had minimum DO values ranging from 3 to <5 mg/L, while a few were above and below this range. In northern Hood Canal, almost all stations had minimum DO levels above 5 mg/L. One station in Dabob Bay, first sampled in the 1980s, had most minimum DO values ranging from 3 to <5 mg/L.

Over the decades, the minimum values at all stations decreased. From the 1990s through 2005, most stations in southern and central Hood Canal had minimum DO values below 3 mg/L, while a few maximum values ranged from 3 to <5 mg/L. Most samples in Dabob Bay had minimum and maximum values ranging either below 3 mg/L or from 3 to <5 mg/L. In northern Hood Canal, many stations had minimum DO values and a few maximum values ranging from 3 to <5 mg/L. A few minimum values also fell below 3 mg/L.

In general, several patterns in the range of DO concentrations were seen over the eight decades examined. First, there were wide ranges in DO concentrations both within stations in the same year, and among years. This variability may have been attributable to the DO measurements being made at different depths and in different seasons. Some maximum concentrations ranged up to 13-16 mg/L, while some minimum values of 0 mg/L were recorded. Next, in general, in every year sampled, minimum DO values tended to decrease from north to south along the main axis of Hood Canal, with southern stations typically having minimum DO levels below critical values for biota. Perhaps more important, minimum DO levels decreased at all stations over time, falling even further below critical values in most southern stations, and falling below critical values at an increasing number of central stations and in some northern stations in the 1990s through 2005.

Patterns in near-bottom DO levels were examined for the 30 samples collected simultaneously with sediment and benthic infaunal samples for PSAMP in 2004 (Figure 31, Table 17). This is the only data set in which DO was measured near the bottom and, therefore, may best reflect the

condition to which the benthos were exposed. It is also the only data set in which both DO and the benthos were sampled synoptically. Near-bottom water DO levels differed considerably among stations, ranging from 0.44 to 13.1 mg/L. Concentrations generally decreased from north to south, and with increasing station depth. Levels of DO were greatest in the central, nearshore stations
(9.8-13.1 mg/L), lower in the northern stations (5.9-7.5 mg/L), and again lower in six of the deeper Dabob Bay stations (2.9-4.5 mg/L). DO levels were lowest in deep, central Hood Canal, in the southern part of the canal and Lynch Cove, and in the two deepest stations in Dabob Bay (0.4-3.2 mg/L).

The near-bottom DO level at station 112 in central Dabob Bay was 0.44 mg/L, the lowest value recorded in the survey. The second lowest concentration (0.95 mg/L) was recorded in the sample from station 48 also in central Dabob Bay.

DO concentrations continued to be relatively low (1-3 mg/L) in the deeper 2004 survey stations down the middle of the remaining length of the canal. The DO concentrations at the two last stations in the canal (numbers 128, 118) ranged from 1.06 to 1.6 mg/L, indicating that low DO levels in the middle of the canal continued to the head of the canal. Conditions were considerably different at the shallow stations (124, 252, 288, 248) along the eastern shoreline of the canal, where the DO concentrations ranged from 9.8 to 13.1 mg/L. These were the highest concentrations recorded among the 30 stations.

Of the 30 samples tested for near-bottom DO concentrations in 2004, ten, located either in deep central Dabob Bay or in the central and southern reaches of Hood Canal, were below the upper limit of near-hypoxia (≤3 mg/L) cited in Newton, 2002. An additional six samples, located in both deep and shallow locations in Dabob Bay, had near-bottom DO concentrations below the biological stress threshold (≤5 mg/L). An additional four samples, all located in northern Hood Canal, had DO concentrations less than the Washington State Water Quality Standards criterion (≤7 mg/L) for extraordinary quality waters. The remaining 10 stations, with DO levels above 7 mg/L, were located in shallow stations in northern Hood Canal and shallow nearshore stations along the eastern shoreline of central Hood Canal (Figure 32).

To illustrate the seasonal variability in water column DO concentrations, select data were plotted against the day of the year for stations in southern Hood Canal sampled from 1952 through 2007 (Figure 33, Warner, 2007). The data showed a repeating pattern of highest concentrations in the winter and spring months, followed by a gradual decline in June and July, and lowest concentrations in August and September, followed by a gradual increase in the fall and winter months. Most of the highest concentrations were reported in the 1950s and 1960s, and most of the lowest concentrations were reported in the 1990s and 2000-2007.

Relationships between Parameters

Bivariate Analyses

Bivariate Pearson correlation coefficients were calculated for (1) 32 selected sediment parameters measured at 58 stations in the 1989-2005 PSAMP sediment surveys, and (2) near-bottom DO concentrations measured in the 30 2004 PSAMP sediment survey stations. Correlations with the DO values included matching sediment-DO data for only the 30 2004 stations, while the other comparisons included matching sediment data for up to all 58 PSAMP stations. All correlation coefficients and scatterplots for these relationships are summarized in Appendix I -Table 1 and Figure 1. All significant correlation results are summarized in Table 18, while selected relationships between pairs of parameters are displayed in Figures 34 through 43 and described in more detail, below. Correlation coefficients (r) and Bonferroni-corrected p-values are noted in these tables and figures, and the relationships between pairs of significantly correlated variables are referred to in the text below as strongly ($0.9 \leq |r| \leq 1.0$), moderately ($0.5 \leq |r| < 0.9$), or weakly correlated ($|r| < 0.5$).

Biological/Biological Relationships

Weak to strong correlations were recorded among 12 pairings of benthic indices, including total taxa abundance, taxa richness, Pielou's evenness, arthropod and mollusc abundance, and the abundance of the ostracod *Euphilomedes carcharodonta* and the bivalve *Nutricola lordi* (Table 18, Figure 34). The strongest correlation in Figure 34 was between the abundance of *N. lordi* and total mollusc abundance. This outcome is not unexpected, given that *N. lordi* was the dominant mollusc. *E. carcharodonta* and *N. lordi* were the dominant, co-occurring taxa at PSAMP Temporal station 13R, the most frequently sampled sediment monitoring station in Hood Canal. Sampled 12 times between 1989 and 2005, the abundance of these two dominant species at this station appears to be driving this set of biological correlations.

A number of weak to strong correlations were also recorded between 13 other pairings of benthic indices (Table 18, Figure 35). This was not unexpected, as many of these indices are derived from overlapping subsets of infaunal data (e.g., taxa richness is used in the calculation of Pielou's evenness, J'; each major taxa abundance measure is a subset of total taxa abundance, etc.). Total taxa abundance values were moderately correlated with taxa richness, as well as annelid, arthropod, and mollusc abundance values. These relationships reflect the large number of northern Hood Canal stations with abundant, taxa rich assemblages, with large numbers of annelids, arthropods, and molluscs. Taxa abundance values were not significantly correlated with Swartz's Dominance Index, echinoderm, or miscellaneous taxa abundance values.

Taxa richness values were weak to moderately correlated with Swartz's Dominance Index values, and with arthropod, mollusc, echinoderm, and miscellaneous taxa abundance values. An increase in the dominance index (i.e., greater number of taxa composing the bulk of the total abundance) could be expected at stations with greater taxa richness. Taxa richness could also increase if greater numbers of echinoderm and miscellaneous taxa increased the overall number of taxa at a station. Taxa richness values were not significantly correlated with annelid abundance values.

Evenness values were moderately correlated with Swartz's Dominance Index values. This would be expected, as evenness and dominance values are both related to the distribution of numbers of organisms among sample taxa. Evenness values were also moderately correlated with total taxa, annelid, and mollusca abundance values. This would be expected at stations which were dominated by large numbers of a few stress-tolerant species, including both annelids (e.g., *Aphelochaeta* sp.) and molluscs (e.g., *Axinopsida serricata, Macoma* spp.). Evenness values were not significantly correlated with taxa richness, or abundance of arthropods, echinoderms, or miscellaneous taxa values.

In general, a complex variety of relationships was seen between some Hood Canal taxa and benthic indices. Some of these relationships were associated with the repeated temporal sampling of the same assemblage at one of the PSAMP Temporal stations, where two species, the ostracod *Euphilomedes carcharodonta* and the bivalve *Nutricola lordi*, tended to drive community structure. Other relationships were a reflection of the relatedness of the indices derived from overlapping subsets of infaunal data. Total taxa abundance and taxa richness were positively correlated, along with measures of evenness, dominance, and the abundance of annelids, arthropods, molluscs, echinoderms, and miscellaneous taxa. All of the biological relationships identified in these analyses emphasize the complex variation in benthic assemblage structure at the different stations in Hood Canal.

Biological/Physical Relationships

A number of significant correlations were recorded between suites of benthic indices and the measures of grain size, as measured by percent fines, percent TOC, and station depth (Table 18, Figure 36).

Percent fines had weak to moderate negative correlations with total taxa abundance, taxa richness, and arthropod and miscellaneous taxa abundance values. This suggests that Hood Canal sediments with higher percentages of silts and clays had less abundant and taxa rich benthic assemblages, with fewer arthropods and fewer miscellaneous taxa than sediments with more sand and gravel.

Organic carbon content of the sediments, as measured by percent TOC values, was weakly to moderately negatively correlated with taxa richness and Swartz's Dominance Index. Data for other benthic indices were not significantly correlated with percent TOC values, but did show similar distribution patterns in the scatterplots, suggesting a similar response to organic carbon levels. Like percent fines, these data suggest that Hood Canal sediments with higher percentages of TOC had less abundant and diverse benthic assemblages than sediments with lower organic carbon content.

Station depth values had weak to moderate negative correlations with total taxa abundance and richness values and positively correlated with evenness values. These data suggest that, in general, benthic assemblage structure becomes less abundant and diverse, but more evenly distributed, as depth increases in Hood Canal.

In general, these data suggest that sediments with higher percentages of silts and clays, higher percent TOC, and at deeper depths have less abundant and diverse benthic assemblages than those that have coarser sediments, lower TOC, and are shallower. While many of the correlations between the benthic index values and the values of grain size, TOC, and depth were not significant, the scatterplots indicated similarities in the response of the benthos to these three variables, suggesting covariance among these parameters. In addition, the scatterplots suggest that some of the relationships are curvilinear, rather than linear, with sharp inflection points below which benthic indices remain low. These inflection points may represent critical values for grain size, TOC, and depth for the Hood Canal benthos.

Biological/Chemical Relationships

Weak to moderate correlations were seen between some benthic indices and the concentrations of metals and PAHs (Table 18, Figure 37). Mean SQS quotients for metals were weakly to moderately negatively correlated with total taxa abundance, taxa richness, and arthropod abundance. Scatterplots of these relationships, as well as those that were not significant, were similar to those of benthic indices versus percent fines and TOC (Figure 36), suggesting covariance among these physical, chemical, and biological parameters. Contaminant metals are known to sorb to organically enriched, fine-grained suspended sediment particles, which then settle and become incorporated in bottom sediments in low-energy areas. Total taxa abundance, taxa richness, and arthropod abundance all decreased as sediments became siltier, more organically enriched, and higher in metals concentrations. Metals concentrations, however, were well below levels thought to cause harm to biota.

Mean SQS PAH concentrations had moderate negative correlations with annelid abundance and Pielou's evenness. Scatterplots indicated that these relationships were driven by higher PAH levels in the six Port Gamble and Port Ludlow samples collected in 1999. Annelid abundance (i.e., abundance of *Aphelochaeta glandaria* and *Aphelochaeta* sp.) increased at a number of these stations, resulting in lowered evenness values. Significant correlation results were seen between the abundance of these worms and PAH concentrations in samples collected in south Puget Sound in 1999 (Long et al., 2002b) although, as with metals, PAH concentrations were well below levels thought to cause harm to biota.

Physical/Physical and Physical/Chemical Relationships

Relationships between percent fines, percent TOC, station depth, and some chemical contaminants are displayed in Table 18, Figure 38. One of the strongest correlation coefficients between all sets of variables was for percent fines and TOC. Percent fines and station depths were moderately correlated, as fine-grained sediments were found in both very deep locations in the main channel of Hood Canal and central Dabob Bay, and in the shallower terminal bays, including Port Gamble, Port Ludlow, and Lynch Cove. Similarly, the relationship between percent TOC and station depth was not significant. In addition, percent fines and percent TOC both were moderately positively correlated with mean SQS metals.

The scatterplots emphasize the strong association between percent fines, percent TOC, and metals, indicating that the amounts of organic carbon and metals increased as the percentages of silts and clays in the sediments increased. Because silts and clays have larger surface areas per volume or mass than larger particles, they tend to attract and adsorb greater amounts of organic matter as well as some contaminants. Therefore, a positive association between percent fines, percent TOC, and metals is expected. These variables co-vary with one another, and to some degree with depth, in Hood Canal.

Station depth and total Aroclor concentrations were also weakly positively correlated (Table 18, Figure 38). This relationship may again be associated with the accumulation of toxicants in silt and clay particles, and some degree of co-variance between contaminants, grain size, and depth. Scatterplots of relationships between percent fines, percent TOC, and depth vs. other chemical contaminants (PAHs, miscellaneous organics, phenols, and phthalates) sometimes suggested positive relationships, although the correlations were not significant (Appendix I, Table 1 and Figure 1).

Chemical/Chemical Relationships

Very few of the chemical contaminants measured in Hood Canal were correlated with each other, reflecting the overall low level of sediment chemical contamination in Hood Canal. Total Aroclor values were weakly positively correlated with mean SQS values for miscellaneous organics and mean SQS values for phenols. Mean SQS phenols and mean SQS values for miscellaneous organics also displayed weak positive correlations with each other (Table 18; Appendix I - Figure 1).

Physical/Toxicological and Chemical/Toxicological Relationships

Both station depth and total Aroclor values displayed weak negative correlations with sea urchin fertilization results (Table 18), indicating toxicity in some deeper stations and some stations with measurable PCB Aroclors. Scatterplots of these relationships did not illuminate any strong patterns (Appendix I - Figure 1).

DO/Biological Relationships

Although none of the abundance values for the ten selected taxa were significantly correlated with near-bottom DO concentrations, examination of scatterplots suggested relationships among some of these variables (Figure 39). The scatterplots indicated three basic patterns in abundance as DO concentrations increased among stations.

Three species, the ostracods *Euphilomedes carcharodonta and E. producta*, and the bivalve *Nutricola lordi*, were most numerous in stations with DO values above 5 ppm, and were absent when DO values were lower, suggesting a sensitivity to low DO levels. However, the abundance of these species also declined to zero or near zero at stations with the highest DO concentrations ($\geq$10 mg/L).

The polychaete annelids *Cossura bansei*, *Prionospio lighti*, and *Heteromastus filobranchus*, along with the Euphausid crustaceans, were most abundant at the lowest DO levels, and decreased in abundance at higher DO levels. The peaks in abundance for these four species were in the range of about 2-6 mg/L DO, suggesting a tolerance to lower DO levels.

The bivalves *Axinopsida serricata* and *Macoma carlottensis*, and the polychaete *Leitoscoloplos pugettensis*, appear to be widespread throughout Hood Canal and numerous throughout the range of near-bottom DO concentrations. There were no obvious peaks in abundance over the range of DO concentrations, suggesting a tolerance for a wide variety of conditions, including lower DO.

These data suggest that there are assemblages of benthic invertebrates in Hood Canal with varying sensitivities to low DO levels.

Of the nine benthic indices, taxa richness and miscellaneous taxa abundance were moderately positively correlated with near-bottom DO values. DO level correlation with taxa richness and miscellaneous taxa abundance was moderately significant (Table 18). Scatterplots (Figure 40) indicated that total taxa abundance, species dominance, and annelid, arthropod, and mollusc abundance, while not significantly correlated, appeared to be somewhat positively associated with near-bottom DO values. Echinoderm abundance appeared to be somewhat negatively associated with near-bottom DO values. Evenness did not change very much among stations.

DO/Physical and DO/Chemical Relationships

Levels of near-bottom DO had moderate negative correlations with percent fines, percent TOC, and station depth; and strong negative correlations with mean SQS metals (Table 18). These correlation coefficients were among the highest of all parameters examined. Similarities in scatterplots indicated the strong relationship between DO and percent fines, percent TOC, depth, and mean SQS metals (Figures 41 and 42), and suggested a high degree of co-variance among these variables. Scatterplots for other measured sediment chemicals (total Aroclors, mean SQS quotients for miscellaneous organics and phenols) (Figure 42), while not significantly correlated, suggested a tendency toward a negative relationship with near-bottom DO values. Like metals, this relationship could be due to accumulation of chemical contaminants in fine sediments, and covariance among these parameters.

In summary, near-bottom DO levels decreased as sediments became deeper, siltier, and higher in organic carbon and metals (and possibly other contaminants) content. However, it is important to understand that the concentrations of these potentially toxic chemicals were very low, always well below levels thought to cause harm to biota.

Co-variance between Parameters

As indicated above, a number of the more strongly correlated sediment parameters appear to exhibit similar patterns in their relationships to one another. Figure 43 displays bivariate scatterplots of the relationships between percent TOC, depth, percent fines, total abundance, taxa richness, and near-bottom DO. Some of the strongest correlations were between these parameters, and the side-by-side scatterplot comparisons emphasize similarities in patterns, suggesting strong co-variance between these parameters.

Summary of Bivariate Analyses

Correlation analysis of sediment and DO parameters measured at 58 PSAMP sediment monitoring stations in Hood Canal indicated a number of weak to strong relationships between measures, supporting some of the patterns seen in the geographic data displays. These relationships included the following:

- Total taxa abundance and taxa richness were positively correlated, along with measures of evenness, dominance, and the abundance of annelids, arthropods, molluscs, echinoderms, and miscellaneous taxa. All of the biological relationships identified in these analyses emphasize the complex variation in benthic assemblage structure at the different stations in Hood Canal.

- Sediments with high percentages of silts and clays, high percent TOC, and from deep stations had less abundant and diverse benthic assemblages than those from shallower locations with coarser sediments and lower percent TOC values. Some of these relationships appeared to be curvilinear, rather than linear, with sharp inflection points below which benthic indices remain low. These inflection points may represent critical values in grain size, TOC, and depth for the Hood Canal benthos.

- Total taxa abundance, taxa richness, and arthropod abundance values decreased as sediment metals concentrations increased. Pielou's evenness values decreased, while annelid abundance (i.e., the polychaete *Aphelochaeta glandaria* and *Aphelochaeta* sp.) values increased with increasing PAH levels.

- Percent TOC and metals concentrations were positively correlated with percentages of silts and clays, and to some degree with depth, in Hood Canal.

- Very few of the chemical contaminants measured in Hood Canal were correlated with each other, reflecting the overall low level of sediment chemical contamination in Hood Canal. Correlations did occur in some locations where multiple contaminants were measured at higher levels (i.e., Port Gamble and Port Ludlow, Dabob Bay).

- Station depth and total Aroclor concentrations displayed weak negative correlations with some sea urchin fertilization results, indicating toxicity in some deeper stations and some stations with measurable PCB Aroclors.

- Total abundance of ten dominant taxa was not significantly correlated with DO levels, but suggested that different species of benthic invertebrates in Hood Canal have varying sensitivities to low DO levels.

- Taxa richness and miscellaneous taxa abundance were moderately positively correlated with near-bottom DO values.

- Total taxa abundance, species dominance, and annelid, arthropod, and mollusc abundance, while not significantly correlated, appeared to be somewhat positively associated with near-bottom DO values. Echinoderm abundance appeared to be somewhat negatively associated with near-bottom DO values.

- Near-bottom DO levels decreased as sediments became deeper, siltier, and higher in organic carbon and metals (and possibly other contaminants) content.

- A number of the more strongly correlated sediment parameters, including percent TOC, percent fines, mean SQS metals, depth, total abundance, taxa richness, and near-bottom DO, appear to exhibit similar patterns in their relationships with one another, suggesting strong co-variance between these parameters. These data suggest that a number of sediment parameters acting together, along with near-bottom DO levels, may influence the structure of benthic infaunal assemblages in Hood Canal.

Co-occurrence Analyses of Calculated Benthic Indices

The correlation coefficients and scatterplots of DO concentrations and various benthic indices indicated a general, but not always consistent, pattern of decreasing abundance and diversity as percent fines and TOC increased, and as DO concentrations decreased. The 2004 PSAMP data set, the only data set with simultaneously collected benthic infauna and near-bottom DO values, was examined to further investigate the relationship between near-bottom DO levels and benthic community structure.

Visual examination of the DO data indicated five relatively distinct ranges in DO concentrations among the 30 stations. There were three samples with DO concentrations greater than 10 ppm, 25 samples with intermediate concentrations, and two samples with the lowest DO concentrations (≤ 1 mg/L). The 25 samples with intermediate concentrations were divided into three ranges, including >6 to 10 mg/L, >3 to 6 mg/L, and >1 to 3 mg/L, with 10, 7, and 8 samples, respectively. The median (± mean absolute deviation) for each benthic index was calculated in each of the five ranges to determine the relative degree of differences between the stations with highest, intermediate, and lowest DO concentrations (Table 19, Figure 44). Past experience with these kinds of analyses has shown that the averages or medians calculated for adjacent ranges in physical/chemical concentrations tend to smooth over the variability in the relationships between an independent variable and a suite of dependent variables recorded in individual samples.

As the DO concentrations decreased among the five ranges, most of the calculated median values for the indices of abundance and diversity decreased (Figure 44). The patterns of decreases in the benthic attributes were rarely linear. Also, there often was considerable variability in the samples in the second ranges (>6 to 10 mg/L) as estimated with the mean absolute deviations. These characteristics of the data set probably accounted for many of the non-significant correlation coefficients. Most of the benthic metrics indicated inflection points from a flat or highly variable response to a precipitous decline as DO concentrations decreased below some level, but the inflection points differed among the metrics.

Most of the median benthic indices were similar in the first two ranges or decreased slightly between the first (> 10 mg/L) and second (>6 to 10 mg/L) ranges. For example, there were relatively small decreases in the total abundance, taxa richness, evenness (J'), species dominance, and the abundance of molluscs between the first and second ranges. However, the median abundance of miscellaneous taxa decreased by a factor of about 4 between the first and second ranges. The median abundance of annelids also changed considerably (by a factor of about 2) between the first and second ranges in DO concentrations. In contrast, the median abundance of arthropods increased between the first and second ranges. Collectively, these data generally showed relatively small (less than a factor of 2) differences between the benthos in samples with DO concentrations greater than 10 mg/L and those with >6 to 10 mg/L. The data, therefore, did not indicate large differences or an obvious inflection point in benthic properties between the first and second ranges.

The most obvious losses in taxa richness and abundance were apparent in the third range (DO concentrations of >3 to 6 mg/L) and again in the fifth range (DO concentrations ≤1 mg/L). Nearly all of the metrics in the third range indicated a loss of about one-half of their median values relative to the first and/or second ranges. Median total abundance dropped from 300-400 animals per sample in the first and second ranges to 136 in the third range. The median total numbers of taxa decreased from 59-80 to 32. Therefore, both median total abundance and median total taxa decreased by factors of roughly 3 between these ranges in DO.

In addition, the median counts of most of the major phyla (excluding the echinoderms) decreased by large factors. The median counts of annelids, arthropods, molluscs, and miscellaneous taxa decreased by factors of roughly 3, 7, 14, and 48, respectively, relative to the medians in the first or second ranges. There were no echinoderms and only one or two miscellaneous taxa at the stations in the third and fourth ranges. Therefore, there appeared to be an important inflection point in most benthic attributes as DO concentrations decreased to the range of >3 to 6 mg/L. The echinoderms were very rare in all of these samples.

There were no major changes or inflection points in the median benthic metrics between the third and fourth ranges in DO concentrations. The relatively low benthic values in the third range remained low in the fourth range. Likewise, there were no improvements or recoveries in benthic metrics as DO concentrations continued to decline into the range of >1 to 3 mg/L. An exception, the median count of molluscs increased a small amount in the fourth range relative to the third range, but decreased markedly again in the fifth range.

There were two stations, both in Dabob Bay, with DO concentrations less than 1.0 mg/L that constituted the fifth and lowest range in values. Both of the samples from these two stations were composed primarily of fine-grained particles (about 80% fines) and had relatively high TOC concentrations (2.4%). Most of the benthic metrics decreased again in the fifth range in DO concentrations, often by factors of about 3 or more relative to those in the fourth range. The median counts of molluscs decreased by a factor of nearly 10 between the fourth and fifth range. Exceptions included no echinoderms or miscellaneous taxa in the samples with the lowest DO concentrations, and median values for Pielou's evenness were slightly higher at >10 mg/L. These data suggest a second threshold or inflection point as DO concentrations decreased below values of about 1 mg/L. However, since there were only two samples in this range, the interpretations drawn from the benthic data in this range may be questionable.

The ratios between the median benthic values in the samples with the lowest DO concentrations and those with the highest concentrations ranged from 1.0 vs. 0 (echinoderm abundance) to 48 vs. 0 (abundance of miscellaneous taxa) (Table 19). On average there were 48 times more of the miscellaneous taxa, 41 times more molluscs, and 21 times more arthropods in the samples with the highest or second highest DO concentrations than in those with the lowest concentrations. The medians for total abundance and taxa richness were 13 and 10 times higher in the highest-DO samples than in the lowest-DO samples. With the one exception (evenness), every other median calculated metric was lower in the low-DO samples than in the high-DO samples. The loss in total abundance and total taxa between the first and fifth categories represented roughly 90% losses between the stations with highest and lowest DO concentrations.

The median absolute deviation (MAD) for each value in each range was calculated as a measure of variance within each range (Table 19). The degree of variance among samples in each range was relatively small (<10% of the median value) for some benthic indices (for example, Pielou's Evenness - J'). In other cases, the MAD was as much as 20 to 40% of the respective median (for example, total abundance). Therefore, the amount of variance within these ranges differed among both the indices and the various ranges in DO concentrations.

Co-occurrence Analyses of the Abundance of Indicator Species

The median abundance of 17 selected species or taxa also was compared among the five ranges in DO concentrations (Table 20**,** Figure 45). Some species were selected because they were relatively abundant in the normoxic samples and indicated a pattern of change in abundance among DO concentrations. Some were previously known to be pollution-sensitive, whereas others were known to be pollution-tolerant (Diaz and Rosenberg, 1995). Accordingly, a variety of patterns in the correspondence between the median abundance of the individual species and the DO concentrations were expected with these selected species and taxa. Consequently, the patterns in species abundance responses to decreasing DO concentrations were grouped according to the nature or pattern of the response (Figure 45). Some species decreased in abundance immediately as DO concentrations decreased in the second range, others initially increased in abundance then decreased, others remained similar in the first and second ranges then increased in a later range then decreased, and other species were relatively rare in all five ranges.

The abundance of 13 of these 17 species was zero in the lowest-DO samples. The abundance of some species decreased to zero in the higher DO ranges and remained so as DO continued to decline. There were 7 species out of these selected 17 in which abundance dropped to zero in samples with >3 to 6 mg/L DO. Therefore, the two inflection points (>3 to 6 mg/L and $\leq$1 mg/L) observed with the calculated benthic indices also seemed to be important for many of the individual species or taxa.

Figure 45a includes the median abundance of four species that decreased immediately from the first to the second DO range. The bivalve *Axinopsida serricata* was the most abundant species in the entire study. It has been observed to be slightly tolerant of polluted conditions in Puget Sound. Its abundance decreased slightly from the first to second range, decreased markedly in the third range, rebounded in the fourth range, then decreased to zero in the range with the lowest oxygen content. The bivalve *Nutricola lordi* was the most abundant species in the first range. They decreased sharply in samples with DO concentrations $\leq$10 mg/L, and declined to zero in all samples with DO <6 mg/L. The bivalve *Parvilucina tenuisculpta* is locally known to be moderately tolerant of polluted conditions. It was relatively abundant in the samples with the highest DO (>10 mg/L) but declined immediately in the second range and disappeared in subsequent ranges. Its abundance pattern was similar to that of *N. lordi*. The polychaete *Pectinaria granulata* was moderately abundant in the first range then decreased to zero.

Figure 45b shows the median abundance of two ostracods and a bivalve. Both of the ostracods, *Euphilomedes producta* and *E. carcharodonta*, known to be slightly tolerant of polluted conditions, occurred in relatively low numbers in the first range, increased sharply in the second range, then declined to zero in all subsequent ranges. The pattern in abundance of the tellinid clam *Macoma carlottensis* was similar, peaking in the second range with DO concentrations of >6 to 10 mg/L, then steadily decreasing as DO concentrations decreased. These clams were absent from the stations in the first range and present in all of the others. *Macoma carlottensis* has been reported as pollution-tolerant (Word, 1980; Tetra Tech, 1990).

Figure 45c shows the patterns of four species that were absent or rare in the first two ranges with the highest DO, peaked in abundance in the third range of DO concentrations, then decreased or were absent in the lowest (i.e., fourth and fifth) ranges. This group of species included the polychaete *Heteromastus filobranchus*, considered to be pollution tolerant (Word, 1980). It included the spionid polychaete *Prionospio lighti*, locally known to be a slightly tolerant species. This group also included the polychaetes *Cossura bansei* and *Aricidea lopezi*, both of which are subsurface deposit feeders that tend to tolerate a wide range of depths and sediment types (Blake et al., 1996). In any case, the patterns in abundance were similar for all four species.

Figure 45d illustrates the patterns in abundance for six species that were relatively rare in all samples and, therefore, showed relatively little correspondence with the gradient in DO concentrations. This group included five polychaetes (*Leitoscoloplos pugettensis*, *Mediomastus* sp., *Paraprionospio pinnata*, *Pectinaria californiensis, Magelona longicornis*), and the amphipod *Rhepoxynius boreovariatus*. The six species have a range in histories of pollution tolerance. Perhaps most unusual among them was the polychaete *L. pugettensis* which increased slightly in abundance as DO decreased, whereas the other five species tended to decrease slightly. However, all six species were relatively rare in all samples.

The counts of the phoxocephalid amphipod *Rhepoxynius boreovariatus* were relatively low in the first two ranges and declined to zero as DO concentrations decreased to >3 to 6 mg/L, thus indicating an important inflection point of 6 mg/L as observed with several other species. Another species of *Rhepoxynius*, *R. abronius*, is commonly used in the Pacific Northwest in laboratory tests of sediment toxicity, partially because of its high sensitivity to toxic chemicals.

Other patterns in relative abundance of benthos may have become apparent if other taxa had been selected for examination. Many other taxa and species (notably the echinoderms) were rare in all samples regardless of the DO concentrations. Some of the 17 species selected as indicators in these analyses were among the more abundant organisms in these samples. Therefore, the general pattern of decreasing abundance of these species with decreasing levels of DO may at least in part explain the overall pattern in decreasing total abundance of organisms and decreasing numbers of species (taxa richness) as DO concentrations decreased in these samples.

In summary, co-occurrence analysis conducted for benthic indices calculated with the 2004 PSAMP Spatial Hood Canal data indicated that, with a few exceptions, index values decrease with decreasing ranges of DO. The most significant changes occurred when DO values were within the range of >3 to 6 mg/L and when they were ≤1 mg/L. Examination of individual species indicated suites of species which increased and decreased in abundance in different DO ranges.

Multivariate Analyses

The Redundancy Analysis (RDA) was run with different values of the random sample size, m. A random sample size of 21 maximized the variance accounted for by the RDA (Figure 46). This random sample size was used in the subsequent analyses.

The 2004 PSAMP Spatial station site scores along the first two canonical axes are plotted in Figure 47, along with the results of the cluster analysis. At a higher similarity level, the canonical ordination of stations along with the cluster diagram indicates three benthic assemblages in Hood Canal. The ordination plot is displayed next to a chart of Hood Canal in Figure 48, showing the geographic locations of the stations. The relative positions of the stations in reduced space roughly correspond to their geographic locations in Hood Canal, indicating that the benthic community is spatially structured.

The geographic locations of the three major benthic assemblages are also evident. The first assemblage extends from the northern end of the canal to the mouth of Dabob Bay, encompassing the entrance sill. The second includes Dabob Bay and central and southern Hood Canal as far south as the Great Bend. The third assemblage occurs in Lynch Cove. These three benthic assemblages are also apparent in cluster analysis of the infaunal data from all 58 PSAMP stations at a high similarity level. At lower similarity levels, the nine sub-regions identified visually and indicated in Figure 20 are also distinguishable.

Species accounting for most of the variation along the first two axes, along with the measured environmental variables, are plotted as vectors in Figure 49. The relative sizes of the species vectors indicate the proportion of variance accounted for by each species. Only the largest vectors are labeled in this plot. The relative abundance of these species at each station can be determined by projecting each station onto these vectors.

Examination of the environmental variable biplot scores, plotted as vectors, indicates how they vary among the stations. Along the first two canonical axes, DO is strongly negatively correlated with sediment organic-carbon content and percent fines. This means that DO tended to decrease in concentration as TOC and depth increased. Stations in northern Hood Canal (benthic assemblage 1) tend to have higher DO concentrations compared to stations in southern Hood Canal and Dabob Bay. Differences between samples from Dabob Bay and the central Hood Canal (assemblage 2) and Lynch Cove (assemblage 3) are related to water depth.

The species vectors indicate that stations in northern Hood Canal, with relatively higher DO concentrations have relatively higher abundances of *Euphilomedes producta, Euphilomedes carcharodonta, Rhepoxynius boreovariatus,* and *Nutricola lordi*. Deeper stations in Dabob Bay and central Hood Canal tend to have higher abundances of *Leitoscoloplos pugettensis*. The bivalve *Axinopsida serricata* was relatively more abundant in southern Hood Canal stations and Lynch Cove, but not necessarily most abundant at stations exhibiting the lowest concentrations of DO.

The relative contributions to the overall variance in benthic community structure by the different species are listed in Table 21. Variation in the abundance of the top ten species contributes 33% to observed variation in community structure in Hood Canal. The top five species – *Axinopsida serricata, Euphilomedes producta, Heteromastus filobranchus, Macoma carlottensis,* and *Prionospio (Minuspio) lighti* – account for 20% of the variation.

To examine the relative importance of the environmental variables in controlling benthic community structure, differences in the value of these variables were plotted versus the CNESS distances among stations (Figure 50). Percent fines was the best predictor of variation in community structure, followed by DO concentration, percent organic carbon, and water depth. The relative importance of these variables on the distribution of the top 25 species is displayed in

Table 22, which lists the contribution statistic for each variable and its standardized beta coefficient.

The standardized beta coefficient is the slope of the linear relationship between transformed species abundance and the environmental parameters scaled by the standard deviations of those parameters. It indicates both the strength and direction of the relationship.

The contribution statistic is the product of the standardized beta coefficient and the simple linear correlation coefficient between the transformed species abundance and an environmental parameter. The contribution statistic represents the fraction of variation in species abundance accounted for by the environmental variable. See Bring (1994) for a discussion.

DO concentration appeared to be the most important measured environmental variable for four of the species in Table 22: *Parvilucina tenuisculpta, Exogone lourei, Phoronis* sp, and *Galathowenia oculata*. Percent fines was the most important measured environmental variable for most of the species in Table 22. The total variance in community structure explained by the environmental variables was 34.3%. This value is significantly higher than that expected by chance alone (Equation 7, $F = 0.52$, $p < 0.001$, 999 permutations). DO concentration alone was also statistically significant (Equation 8, $F_{ex}=0.36$, $p < 0.001$, 999 permutations) in relation to variation in benthic community structure.

To examine the historic changes in benthic communities relative to DO and the other environmental variables measured in the 2004 survey, the site scores for those stations included in the long-term data set were plotted along the canonical axes calculated for the 2004 data set (Figure 51).

The multivariate index of benthic response to oxygen was determined by projecting the site scores orthogonally onto the DO vector (Equation 8, Figure 52). In Figure 52, the index is plotted versus sampling date for stations in northern Hood Canal and at the Great Bend. Among the three stations, the index declines from north to south, consistent with the north-south spatial gradient in DO. Although there is no systematic change in the index value from year to year for the two northern stations, the value of the index for the Great Bend declines between 1990 and 1999. This pattern indicates that the observed changes in benthic community structure at the Great Bend are consistent with declining DO concentrations at this location. Changes in benthic communities in northern Hood Canal are not consistent with a decline in DO.

In summary, these multivariate analyses indicate strong spatial variation in benthic communities in Hood Canal, with three main assemblages in: Northern Hood Canal (1), Central Hood Canal and Dabob Bay (2), and Lynch Cove (3). By applying other methods and lower similarly levels, it is possible to identify nine sub-assemblages within these larger assemblages. Several species including *Axinopsida serricata, Euphilomedes producta, Heteromastus filobranchus, Macoma carlottensis* and *Prionospio (Minuspio) lighti* contributed strongly to this pattern. Of the environmental variables examined, grain size was best correlated with the CNESS distance among samples. DO was a statistically significant contributor to variation in benthic community structure and was the most important of the measured variables for several species.

Historic reconstruction of benthic community response to DO by use of a multivariate index indicated that northern stations have experienced little change that can be attributed to DO concentration over the past 15 years. However, stations in the Great Bend region have experienced changes consistent with declining DO concentrations there since 1991.

Discussion

Sources of Uncertainty

There are numerous potential sources of uncertainty in data analyses such as these. Any or all of them could have contributed to the variability in the DO/benthic relationships that were observed and to the uncertainty in the conclusions drawn from these data.

Aspects of the Study Design

The various surveys from which data were summarized for this report were not designed for the purpose of evaluating the adverse effects of hypoxia on the benthos of Hood Canal. They were designed for a variety of other goals and objectives. These included characterization of temporal trends in sediment quality at a few selected stations as well as regional spatial characterization of sediment quality at stations chosen with a random, stratified sampling design. Other stations were targeted for monitoring of sediment quality because of regulatory interests. DO and other parameters often were measured throughout the water column to provide a broad characterization of the region, primarily along the main north-south axis of the canal. Sampling locations, therefore, were not selected to represent a gradient in near-bottom DO concentrations that would be more representative of the conditions to which the benthos would be exposed.

It is important to also appreciate that as a result of the sampling designs, many factors other than just DO concentrations that could potentially influence the benthos varied widely from station to station in the study area. Interpretation of benthic data acquired in a field study conducted in two Norwegian fjords with a wide range in chemical pollution was similarly confounded by having such "nuisance" variables (Bayne et al., 1988).

Ideally, a study designed to evaluate effects of hypoxia on benthic infauna would have involved the selection of sampling stations with knowledge of the DO gradients in the study area and selection of stations to ensure representation of the DO gradients in Hood Canal. Equal numbers of stations would have been selected and sampled within each range in DO concentrations over the full range in concentrations. In addition, near-bottom or sediment porewater DO measures would have been collected simultaneously with every sediment sample. Simultaneously collected DO and sediment samples would have been collected seasonally, to reflect changes in DO levels throughout the year, and annually, to determine changes over time.

Fortuitously, however, the sampling stations selected for the PSAMP 2004 survey provided information from the canal entrance to its terminus, from shallow to deep locations, from coarse sands to muddy silts and clays, and, importantly, a sufficiently wide range in DO concentrations to warrant these analyses of the data. Nevertheless, different outcomes may have been observed if the study had been specifically designed to evaluate the benthic effects of hypoxia. The statistical relationships between DO concentrations and measures of benthic impacts may have been stronger if equal numbers of stations had been sampled within each range in DO concentrations.

A total sample size of 30 to 50 randomly-selected stations has proven to be sufficient to accurately characterize the spatial extent of sediment degradation in estuaries and marine bays of the U.S. (Heimbuch et al., 1995). However, the high variability in the relationships between the concentrations of DO at each station and most of the benthic metrics suggests that a larger sample size would have improved the accuracy of these relationships. There were only three and two stations in the first and fifth co-occurrence categories, respectively. A larger data set may make it possible to determine if hypoxia was (is) the actual cause of benthic impairment and to more accurately identify critical DO concentrations that are stressful to the benthos.

Applications of Statistical Models

There was a lack of universal agreement among all benthic indices (metrics) that they changed significantly as DO concentrations changed among stations sampled in 2004. The statistical relationships between the DO concentrations and many of the benthic metrics in this data set were not significant in bivariate analyses. Species richness and miscellaneous taxa abundance were significantly correlated with DO concentrations in bivariate analyses. Other benthic metrics were not. The counts of individual species were not significantly correlated with DO. However, in the multivariate analyses, DO was shown to be a significant contributor to variation in CNESS distances among stations.

Bivariate correlation models such as those applied to the 2004 data set tend to score the relationships between two variables as low or non-significant when there is considerable scatter in the data or the relationship is not linear. These relationships probably were not significant because of the distribution of the benthic data as the DO concentrations decreased among individual samples. That is, the patterns in decline of benthic metrics were inconsistent, highly variable, and/or curvilinear. There were several stations that were outliers in terms of the benthic metrics and the DO concentrations. As shown in Figure 45, the abundance of some species initially increased as DO concentrations decreased, but ultimately decreased or became zero at the stations with lowest DO.

The co-occurrence analyses, in which average conditions are calculated over ranges in DO concentrations with data from multiple samples, tended to smooth over the variability in the data for individual samples. Therefore, important relationships between DO concentrations and benthic metrics became apparent in the co-occurrence analyses, whereas relationships may have not been significant in the correlation analyses.

Co-occurrence analyses were conducted only on the 2004 PSAMP survey data because that was the only benthic data accompanied by measures of near-bottom DO. This kind of analysis has been conducted in many published reports, mainly to calibrate the biological response in either benthic community composition or in laboratory toxicity tests over ranges in chemical concentrations in sediments. The ranges in chemical contamination were selected with either a visual examination of the sorted data, or to obtain equally sized ranges, or to obtain equal numbers of samples in each category, or with logistic regression models (Long et al., 2000, 2006; Hyland et al., 2003; McCready et al., 2006; Field et al., 2002). Selection of the ranges in categories with the visual approach is vulnerable to some degree of subjectivity. The outcome of the analysis of the Hood Canal data could have been somewhat different if a different set of ranges had been selected. A different number of categories or different ranges could have been chosen.

However, after sorting the 2004 PSAMP benthic index data from highest to lowest DO concentrations, it became obvious that there were three stations with the highest DO concentrations (>10 mg/L), and there were two other stations with the lowest concentrations (< 1 mg/L). They were selected, therefore, as the first and fifth ranges, respectively. The remaining 25 samples were divided into three categories, more or less equal in numbers of samples.

An alternative approach would have been to combine the first and second ranges because many of the benthic endpoints either were similar in these two ranges or increased slightly from the first to the second category. Similarly, the third and fourth ranges could have been combined because the biological data were also relatively similar in those two adjacent ranges. However, it was possible to more clearly see where some species dropped out of the assemblages by having the five ranges instead of three. Also, the five ranges allowed us to see the curvilinear nature of some of the benthic impacts of decreasing DO (as shown in Figure 45), probably at least partially explaining the lack of statistical significance in some of the correlation analyses.

The strengths and limitations of the use of univariate and bivariate analytical methods in the interpretation of data, such as these for Hood Canal, were identified during an environmental effects workshop held in Norway (Bayne et al., 1988). The results of that workshop also led the scientists gathered for that event to conclude that various multivariate techniques could provide more powerful interpretations of the physical-chemical and benthic data. The multivariate analyses of the Hood Canal, indeed, provided evidence of the role of DO and the other variables in influencing the composition of three relatively distinct benthic assemblages. The results of the various kinds of data analyses tended to complement one another, giving us a reasonable level of confidence in our conclusions.

Patterns in Benthic Responses to Hypoxia

Multivariate analysis of the PSAMP benthic data indicated that assemblages in Hood Canal have a strong spatial structure, some of which can be attributed to DO concentrations. These analyses demonstrated that the benthos could be divided into three relatively distinct assemblages:

1. A northern assemblage in the entrance and sill dominated by a variety of taxa including many species of crustaceans, molluscs, and polychaetes.
2. A Dabob Bay and central Hood Canal assemblage dominated primarily by several species of polychaetes that favor deeper water.
3. A Lynch Cove assemblage dominated by the bivalve *Axinopsida serricata*, and a few species of stress-tolerant polychaetes.

Based on a finer scale of division, visual examination of the data suggested that there may have been as many as nine sub-assemblages. Therefore, the data indicated that the composition of the benthos differed from place to place in the canal, as a function of the influence of numerous environmental variables. The relative contributions to overall change in community structure, measured using the distance metric CNESS, indicated that sediment grain size, quantified as percent fines, was best correlated with change in community structure, followed by water-column DO, sediment organic carbon content, and water depth.

The apparent relationships observed in the co-occurrence analyses between bottom-water DO concentrations and virtually all attributes of the benthic community composition in this Hood Canal data set follow the basic pattern of stress-related benthic impairment reported in Scandinavian fjords that are bathymetrically similar to Hood Canal (Pearson and Rosenberg, 1978). The Scandinavian studies showed a repeating pattern either over time or space of species replacement, as sediment biological oxygen demand (BOD) concentrations increased, that ultimately led to a gradual loss of species, total abundance, and biomass. The most sensitive species were replaced by incrementally more pollution-tolerant species until no species could tolerate the high sulfur and ammonia content of sediments that were the most organically enriched. The species in Hood Canal that appeared to be most sensitive were mainly crustaceans, which are generally regarded worldwide as among the most sensitive (Diaz and Rosenberg, 1995).

The successional steps in the composition of the infauna over a range in sediment stressors, such as hypoxia, have been reported for some marine and estuarine regions of the U.S. as well. The primary succession of the infauna in previously stressed areas was defined as "a predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance" (Rhoads and Germano, 1982; 1986). They observed a set of sequential steps in the functional types of species that colonized soft-bottom sediments following a disturbance. The kinds of disturbances included scouring or erosion, changes in substrate type, changes in DO levels, or amounts of organic matter.

The species composition of these successional stages in colonization varies from place to place, but the stages have proven to be predictable on virtually a global scale (Rhoads and Germano, 1982; 1986). Pioneering species often are tubiculous, opportunistic worms that are able to tolerate highly stressed conditions that have improved only slightly. They may occur as dense aggregations of tube-dwelling worms. As conditions continue to improve, these worms gradually can be replaced by deposit-feeding infauna, often including deposit-feeding bivalves and tube-dwelling amphipods. An equilibrium assemblage is most persistent and dominant in deeply oxygenated sediments and may include a wide variety of species, including many that are so-called "head-down, conveyor belt" feeders. These species often are polychaetes along with some echinoderms and bivalves.

Therefore, it is likely that the same process of losses of the most sensitive species, followed by subsequent losses of incrementally more tolerant species as stress increases, is important in Hood Canal. However, our knowledge of the relative abilities of Puget Sound benthic species to tolerate stresses is incomplete. Some species are notoriously pollution-tolerant, and others are consistently sensitive (Diaz and Rosenberg, 1995). We often observe the same genera and species in the most polluted urbanized bays of Puget Sound as well as the absence of many other phyla, classes, genera, and species in these places (Long et al., 2003; Word, 1990). However, our collective knowledge of the majority of species found in the infauna is relatively poor. Therefore, the patterns in response to hypoxia may have been different if the abundance of other species had been tracked or other metrics of impairment had been calculated.

The multivariate index allowed reconstruction of the historical response of benthic communities to DO. The index determined for three stations in Hood Canal reproduced the north-south gradient in DO. When examined over the time period 1989 – 2004 for these stations, the index suggested that there has been little change in northern Hood Canal benthos that can be attributed to declining oxygen levels. However, changes in benthic community structure at the Great Bend were consistent with declining concentrations of DO between 1991 and 1999 in that area.

Dissolved Oxygen Concentrations and Proximity to the Bottom

The benthic infauna collected with the Ecology grab sampler lived within the upper 17 cm of surface sediments, the maximum penetration depth of the sampler. They are, therefore, exposed to environmental conditions at, and immediately above and below, the sediment-water interface (the benthic boundary layer).

Based on equilibrium partitioning theory (USEPA, 2005), the concentrations of acid-volatile sulfides and trace metals within the interstitial water, at the sediment-water interface, and immediately above the benthic boundary layer should be in dynamic equilibrium with each other. These principles should also apply to other dissolved chemicals, including hydrogen sulfide, ammonia, and oxygen. However, in a region such as Hood Canal with strong tidal currents, the effects of the transport of near-bottom water probably overpower this equilibrium, resulting in disequilibrium due to the shifting oxygen gradient.

There are some micro-scale analytical data to demonstrate this equilibrium and the presence of a diffusive boundary layer approximately 1 mm thick in which molecular diffusion between the sediments and overlying water occurs (Gunderson and Jorgensen, 1990). Oxygen micro-electrode profiles in Hood Canal sediments indicate oxygen penetration depths of approximately 3 mm (D. Shull, unpublished data).

Studies of benthic effects of hypoxia elsewhere (e.g., Long Island Sound, New York; Limfjord, Denmark) have shown that there can be large gradients in DO concentrations over small changes in depth immediately above the sediment-water interface (Diaz and Rosenberg, 1995; Rhoads and Germano, 1982, 1986; Jorgensen, 1980). In Denmark, there was a 15-fold difference (decrease) in DO concentrations between samples collected 0.5 m and 0.05 m off the bottom (Jorgensen, 1980). In the Lousianian Province of the USEPA's Environmental Monitoring and Assessment Program (EMAP) - Estuaries program, minimum DO concentrations throughout the province declined from 4.4 mg/L at the surface to 4 mg/L at 1 m depth to 3 mg/L at 2 m to 0.6 mg/L at 3 m and 0.0 mg/L 0.5 m off the bottom (Summers et al., 1993). Therefore, measures of DO one to a few meters above the sediment-water interface may not accurately represent the conditions to which the infauna are actually exposed. The measures likely would over-estimate the DO concentrations within the sediments.

The DO measurements made by Ecology for the 2004 PSAMP monitoring survey were about 2 m above the sediment-water interface when the grab sampler landed on the bottom; therefore, these measurements probably provided a relatively good representation of near-bottom conditions. However, the measurements cannot be assumed or construed to accurately represent the DO concentrations within the upper 17 mm of the sediments where the infauna resided.

Although some of the near-bottom DO concentrations in the Hood Canal survey were very low (1 mg/L or less), these concentrations probably underestimated the degree of hypoxia within the sediments themselves.

Representativeness of the Benthos

The 58 samples analyzed in this study were collected during March, April, or June from 1989 through 2005. The samples provide a snapshot of conditions in both the water column above the sediment-water interface (for the 2004 PSAMP samples) and the benthos at the time of collection. The benthic animals are year-round residents of the sampling locations and, therefore, can be reasonably good integrators of conditions over some extended, but unknown, period of recent history. However, benthic assemblages are not static in composition. Animals are continually producing progeny, migrating, colonizing, and departing or dying as a natural part of the biology of the infauna. Individual animals, species, taxonomic groups, and phyla come and go as a result of, or in response to, a wide variety of processes.

Both short-term and long-term temporal changes in benthic composition have been reported for multiple locations in Puget Sound over a period of three decades (1963 to 1992; Nichols, 2003) and more recently during 1989 through 1993 (Llansó et al, 1998b), and 1989 through 2000 (Partridge et al., 2005). There is no way of knowing what stages of succession the benthic assemblages sampled in this study were in at each station when the stations were sampled. Benthic assemblages at some locations could have been in a steep decline, whereas they could have been rebounding at other locations. Therefore, it cannot be assumed that the benthic assemblages at these stations were equivalent in terms of their stages in succession.

The sampling and analytical methods used to describe the benthic assemblages at each station followed commonly used, traditional protocols (PSEP, 1987), and all data have been taxonomically standardized by Ecology personnel. By following these protocols, the data in different regions of Puget Sound, including Hood Canal, can be assumed to be comparable, thus allowing comparison and ranking of the quality of sediments among regions. However, these traditional methods also can have some weaknesses (Rhoads and Germano, 1982, 1986). The information acquired from these kinds of methods cannot be used to describe secondary impacts on fisheries, pollution transfer within the food web, the ability of the benthos to metabolize organic matter, and recycling of nutrients from the seabed to primary producers in the water column. Therefore, with the data from these traditional protocols, it is difficult to describe the ecosystem level significance of losses in numbers of benthic species and organism abundance.

The 1-mm mesh sieves used to capture the organisms in the Hood Canal studies retain most of the macrofaunal (large) species and adult life forms (Word et al., 1980). However, the sieves allow the very small fauna, referred to as meiofauna, to pass through. The meiofauna can include the larvae and juvenile forms of some macrofaunal species and adult forms of very small taxa (e.g., protozoans) that may be highly important components of the benthos in some habitat types (Heip et al., 1988). Meiofauna were not accounted for with the PSAMP methods. The benthic grab sampler penetrates the sediments to a maximum depth of 17 cm. Some species of large clams, such as the geoducks, cannot be sampled with this equipment and, therefore, are not accounted for with such methods.

Years of previous experience in sampling Puget Sound sediments has demonstrated the high degree of small-scale variability in sediment types that can occur at a station. In most cases, the sediments appear to be similar in repeated deployments of the grab sampler at a station, but occasionally the sediments can be remarkably different over a horizontal distance of less than a meter. Benthic ecologists often collect multiple samples (i.e., “replicates”) at a station to assess within-station variability. Replicate samples were taken at only a few of the PSAMP Temporal monitoring stations in this survey, so there is no way to measure the degree of variability at most stations. Therefore, because of these and other sources of uncertainty, the representativeness of the benthic samples taken at each location may have varied considerably among the stations.

Classification of the Benthos as Adversely Affected

In many estuarine and marine regions of the U.S., indices of the relative health of the local benthos have been derived and used to classify sampling stations (Engle et al., 1994; Engle and Summers, 1999; Llansó et al., 2002a, b; Weisberg et al., 1997; van Dolah et al., 1999; Bergen et al., 2001; Smith et al., 2001; Janicki Environmental, 2003).

There are several kinds of benthic health indices, and each is derived with slightly different methods and information. Usually, these indices take into account the composition of the benthic samples by species that have had a history of being either pollution sensitive or pollution tolerant. These indices often account for the numbers of species or taxa in each sample. Some indices take into account the way that the species feed. In any case, they invariably provide a single numerical scale to be used in ranking and classifying each sample. In addition, the indices usually include ranges in values that are indicative of reference conditions: low, moderate, and high degrees of impairment. Therefore, the indices provide the advantage of compressing complex, technical information on species composition, abundance, and diversity into a single numerical scale.

These kinds of multi-variable indices have been derived for many nearshore and estuarine habitats in the U.S., including Chesapeake Bay, the mid-Atlantic coast, the Gulf of Mexico coast, Tampa Bay, Southern California, and San Francisco Bay, using local data from each region. No such index has been derived thus far and adopted for use in Puget Sound or the Pacific Northwest. Therefore, sediment quality analysts in the Puget Sound region must evaluate the benthic data on a species-by-species basis and with the various traditional, calculated indices listed in this report. Best professional judgment must be used to classify the benthos at each station as affected or not. Such judgments, although based on many year of experience, can be subjective and must ultimately rely upon opinions of the analysts. While these “traditional” methods and indices have been used for decades worldwide, a much clearer and more easily understood picture of the adverse benthic effects of hypoxia in Hood Canal may have been possible if a benthic health index had been available and applied to the raw data.

Representativeness of the Dissolved Oxygen Measurements

The DO measurements made by Ecology for the 2004 PSAMP survey were collected simultaneously with benthic samples over a two-week period. This was one small span in time during the natural long-term, successional changes in the benthos. While the benthic assemblages at each station reflect conditions integrated over some unknown, but extended, period of time, the DO measurements for each station were made from one instantaneous sample. Because of this method, there is no way to judge the water quality conditions each benthic assemblage was exposed to during the full span in time in which it was forming. Therefore, the DO snapshot may or may not accurately reflect the range or average DO concentrations to which each assemblage was exposed.

Some studies in relatively shallow, well-mixed estuaries have demonstrated the relatively large changes in DO concentrations over the period of a day and night (Summers and Engle, 1993). Huge diurnal (daily) cycles in DO concentrations can be affected by the tides, insolation, primary productivity, etc. Twenty-four hour profiles are recommended, therefore, for some shallow, southeastern U.S. estuaries (USEPA, 2000).

However, it is doubtful that such diurnal changes in DO concentrations occur in the relatively deep reaches of Hood Canal (Roberts et al., 2005; Newton et al., 1998). Probably the oceanographic processes with the greatest influence on DO concentrations in Hood Canal are the daily tides. Incoming tides carry highly oxygenated Pacific Ocean bottom water into the canal via the Strait of Juan de Fuca and Admiralty Inlet. Therefore, the concentrations of DO near the bottom of Hood Canal probably do not change a great amount during the course of a day. Ecology data, therefore, probably are representative of conditions on the day they were sampled. However, it is not possible to know how representative the snapshot DO measurements were of conditions during the long-term course of the development of the benthic assemblages at each station.

The Ecology samples were collected in 2004 to correspond with similar data collected in June elsewhere in Puget Sound during the annual PSAMP sediment monitoring surveys. Samples were not collected during the late summer or early fall months when DO concentrations are known to be the lowest in Hood Canal. Long-term ambient monitoring in the canal has shown that the worst hypoxia problems occur in the late summer and early fall. This is the season during which flushing of stagnant water is relatively slow, the fall phytoplankton blooms often occur, and organic matter tends to accumulate in the sediments. These conditions can lead to and cause eutrophication, which contributes to the hypoxia (Roberts et al., 2005; Newton et al., 1998). Therefore, these 2004 data may under-represent the actual degree, spatial extent, and nature of benthic effects of hypoxia in Hood Canal.

Inter-relationships among Sediment Grain Size, Total Organic Carbon, Depth, Dissolved Oxygen, and Biota

Sediment grain size, organic carbon content, depth, DO levels, and numerous other physical-chemical variables are known to influence infaunal community structure These observations have been made in Puget Sound (Lie, 1968; Nichols, 1985; Word, 1990) and in other regions with large ranges in these variables (Bayne et al., 1988; Pearson and Rosenberg, 1978; Diaz and Rosenberg, 1995; Rhoads and Germano, 1986; Hyland et al., 2003; Bergen et al., 2001; Smith et al., 2001; USEPA, 2000). Infaunal organisms preferentially inhabit sediments with grain sizes that are suitable for their specific physiological behaviors and needs, including feeding, locomotion, and tube building. Sediments rich in organic matter provide food for both macrophagous and deposit-feeding organisms.

Measures of percent fines and percent TOC in sediments typically are positively correlated with each other because fine-grained sediments tend to accumulate organic material. Coarse sediments often support relatively sparse infaunal assemblages because coarse sediments are typically low in organic carbon and provide very little silt and clay with which organisms can build tubes or burrow through. Although limited in scope, there is some anecdotal evidence that the abrasiveness of coarse sands can damage and kill some delicate species or their embryos (Long et al., 1990; Chapman and Morgan, 1983; Carr and Nipper, 2003).

Infaunal abundance and diversity typically increases as the food supply (our surrogate measure of which is percent TOC) increases (USEPA, 2000; Word, 1990). It is also well known that marine invertebrates are adapted to live in specific depth ranges (Sverdrup et al., 1963; Light, 1964). Some are capable of surviving in a wide range of depths, whereas some inhabit narrower depth ranges. Total abundance and taxa richness are typically greater in intertidal and shallow subtidal depths, and lower in deeper (i.e., abyssal) locations. Depth can be a controlling determinant of benthic community composition (Bayne et al., 1988). Sediments with high levels of DO typically support more aerobic organisms than sediments with low DO levels (Diaz and Rosenberg, 1995).

Given the wide ranges in grain size, TOC, depth, and DO in Hood Canal, infaunal abundance and diversity would be expected to vary throughout the canal. Highest values might be predicted to occur in sediments with higher percent fines and TOC in shallow to mid depths, and in stations with the highest DO values. The relationships among the various physical-chemical variables, among various benthic indices (metrics), and between the physical-chemical variables and the benthic metrics were explored with several methods. Both bivariate and multivariate analyses were performed on data compiled from 1989 to 2005 with emphasis focused on the matching DO and benthic data acquired during the 2004 survey. In addition, a co-occurrence analysis was performed on only the 2004 data set. Relationships between and among these variables were as expected for some and unexpected for others.

Benthic infaunal assemblages with the highest benthic abundance and diversity, as well as abundance of major taxa groups, were found in sediments collected in the north part of the canal, nearshore Dabob Bay, and near shore in the central canal. Most stations in these sub-regions had relatively low percent fines and TOC, were relatively shallow, and had relatively high near-bottom DO. Most metrics of abundance and diversity decreased strikingly at stations in deep Dabob Bay, deep central canal, south canal, and Lynch Cove sub-regions. These stations generally had relatively high percent fines and TOC, along with relatively low levels of DO. All of the benthic indices and DO decreased along a north-to-south geographic gradient. Sub-regions with low infaunal abundance and diversity levels varied in depth, from relatively shallow (e.g., 19 m in Lynch Cove) to very deep (e.g., >170 m in deep central Hood Canal and Dabob Bay).

The infaunal assemblages in the sub-regions of Port Gamble and Port Ludlow were composed of species generally not found in the other sub-regions. These assemblages had high total abundance, moderate taxa richness, and low evenness, and were dominated by only a few pollution-tolerant taxa. No DO measurements were made in these embayments, so the relationships between metrics of infaunal assemblage composition and DO are unknown. These sub-regions had high levels of potentially toxic contaminants at some stations, however, and were dominated by the polychaete annelids *Aphelochaeta glandaria* and *Aphelochaeta sp*., known locally in Puget Sound to be pollution tolerant. This genus of polychaete often is most prolific in chemically contaminated urban bays throughout Puget Sound (Long et al., 2003).

These observations about the inter-relationships among variables were generally, but not always, supported by the correlation analyses. Percent fines and TOC varied together as expected, but were unexpectedly negatively correlated with total abundance and taxa richness. Percent fines and TOC were also negatively correlated with DO. Correlations of all factors with depth were either weak or not significant. Percent fines and TOC tended to increase, and DO decreased, with increasing depth into central canal and Dabob Bay stations. However, percent fines and TOC showed the same pattern with decreasing depth into the shallows of Lynch Cove. Total abundance and taxa richness were positively correlated with each other as expected. However, taxa richness expectedly decreased significantly with decreasing DO, whereas total abundance unexpectedly did not.

Examination of all of the benthic indices and physical-chemical variables together indicate that these parameters co-varied with each other in complex relationships. While most varied either significantly or non-significantly as expected, it was unexpected to discover either non-significant or negative correlations between TOC content and various metrics of benthic composition. If organic carbon as a food source was a limiting factor in Hood Canal sediments, most beneficial measures of composition should increase with increasing amounts of food. This situation was not uniformly the case in these samples. The data suggest that the amount of near-bottom DO may be a stronger, limiting factor in these relationships. Decreasing DO levels may inhibit increases in abundance and taxa richness in the benthos, over-riding the benefits of an increased food supply as indicated by the measures of TOC.

While the data analyses suggest the various strengths of the relationships between the variables, it is important to consider that our collective understanding of the near-bottom oceanography and sediment geochemistry of Hood Canal is incomplete. Although the correlations among the physical-chemical variables, and between the physical-chemical variables and the various measures of benthic community composition, provide compelling evidence of the effects of hypoxia on the benthos, there are major gaps in our knowledge of other processes in this region that could affect the infaunal biota.

Other factors and processes that may be equally important determinants of benthic community composition include, but are not limited to, (1) the speed of currents at the sediment-water interface and rates of sediment deposition and resuspension, (2) the processes and rates of microbial degradation of organic matter in the sediments, (3) the processes and rates of bioturbation that may serve to oxygenate the surficial sediments, and (4) the type and number of broodstocks that may provide the larvae for colonization of these sediments. Until further work is done to fill in these gaps, conclusions drawn from the data compiled for this report must be interpreted with caution.

Are the Benthos of Hood Canal Being Affected by Hypoxia?

The question of whether the Hood Canal benthos are being affected by hypoxia can be examined in three parts: (1) Are the benthos of Hood Canal being affected? (2) Are the *effects* to the composition of the benthic assemblages that we can measure considered to be *adverse*? (3) Are these effects caused by hypoxia? Therefore, it is a complex issue and not easily resolved with the data available.

Clearly, there were large differences in the species composition, diversity, and abundance of the benthos among sampling stations and among three regions and nine sub-regions identified within Hood Canal. These spatial differences in the benthos could be an entirely natural phenomenon, and the benthos may have been structured this way for decades or centuries. However, the comparisons with equivalent baseline data for other regions of Puget Sound suggest that the benthos were different and unusual at most locations in Hood Canal.

The benthos in many samples were low in species richness and/or total abundance. Species known to be sensitive to various kinds of stresses were rare or absent, and some species known to tolerate such conditions were present or abundant. Some samples were populated by only a few species, all of which are known either locally or elsewhere as stress tolerant. These attributes are commonly viewed by benthic ecologists as indicative of adverse effects or impairments, although these are subjective terms. Therefore, based on our current knowledge, it appears that the benthos in some locations were affected and, as classified with our methods, the effects were adverse.

Taxa richness and the abundance of many species decreased significantly as near-bottom DO decreased. Although the relationships between the DO concentrations measured near the bottom and many indices of benthic condition are compelling suggestions that the near-bottom DO conditions were causative, these correlations do not constitute empirical or experimental evidence that the low DO concentrations actually caused the impairment to the benthos.

The coincidence between the occurrence of demersal fish kills in recent years and low DO concentrations provides additional evidence that the low DO levels may be causative. The concentrations of potentially toxic chemicals in the sediments were very low, and most of the sediment samples were not toxic in laboratory tests performed with highly sensitive organisms. Therefore, it is doubtful that alterations to the benthos were caused by toxicants. However, the composition, abundance, and diversity of estuarine benthic assemblages can be greatly affected by a large variety of natural factors, any or all of which could have been important in Hood Canal.

These factors can include differences among stations in water depth, sediment texture, scouring, smothering, salinity, predation by fish and whales, and proximity to brood stock, all of which are measurable variables in Hood Canal. The multivariate analysis indicated that station depth was an important determinant in benthic assemblage composition. The depths of these stations ranged from about 20 m to more than 170 m, the percentages of sediment particles that were silts and clays ranged from 4% to 90%, and sediment total organic carbon content ranged from 0.1% to 3%.

The stations ranged from those in the canal entrance nearest the source of larvae from the Pacific Ocean to those far inland nearest several river mouths. Other unmeasured, and perhaps, unknown, factors may also have had equal influence on assemblage composition. Therefore, although the co-occurrence of many measures of benthic impacts with decreasing near-bottom DO concentrations is compelling evidence that the low DO was causative, this evidence must be tempered with the reality that many other natural factors could have been equally or more important influences on benthic assemblage composition.

The science of ecology includes an extensive history of attempts to identify the causes of adverse biological impacts. Assessing the impacts of a single, acute event such as an oil spill is relatively easier than assessing impacts of a long-term, chronic set of circumstances such as in Hood Canal. A series of papers published in *Environmental Toxicology and Chemistry* (volume 21, number 6) summarizes recent work to infer cause-effect linkages in aquatic ecosystems (see, for example, Suter et al., 2002). The criteria for establishing the causes of marine fish kills were provided by Sindermann (1997) and provide a framework for determining causality in both acute events and with chronic conditions. Analyses of DO data, along with sediment chemistry, toxicity, and benthic data, in selected bays of the Gulf of Mexico included attempts to assign causality in each bay (Engle and Summers, 1998).

Perhaps the most important lesson learned in these previous studies is to not let the data mislead us to believe that we completely understand the causes of adverse biological impacts in nature (Norton et al., 2002). To be accurate, causal evaluations require more targeted studies and experimental analyses than are possible with this data set.

Conclusions

Hood Canal has had a history of hypoxia for many decades. The dissolved oxygen (DO) concentrations measured in the canal appear to be decreasing, and the area affected by hypoxia seems to be increasing. There have been high mortalities during summer months among demersal species of fish and invertebrates reported in the region in recent years. Data were compiled to track changes in DO concentrations in the canal over many decades. These data showed a steady decline in DO concentrations throughout the canal, especially in the southern reaches. They also showed that the area affected by hypoxia had expanded northward in the canal into the central reaches. Other data were assembled to track changes in the composition of benthic assemblages during the recent 10 to 20 years. These data showed some declines in metrics of abundance and diversity in some locations and no appreciable changes in other areas.

The relationships between DO concentrations near the bottom and the composition of the benthos were evaluated with a data set compiled from a survey of Hood Canal conducted in 2004 by Ecology. The metrics of abundance and diversity spanned very wide ranges among these samples. The majority of the samples collected in the 2004 survey supported benthic assemblages that were outside the range of typical, baseline conditions for Puget Sound. Some of the benthic assemblages were composed of a wide diversity of abundant arthropods, annelids, molluscs, and species in other groups. In contrast, some assemblages sampled where near-bottom oxygen was the lowest supported very few species, almost exclusively pollution-tolerant bivalve clams and polychaete worms.

Very few of these samples were chemically contaminated or toxic in highly sensitive laboratory tests. Measures of both chemical contamination and toxicity spanned relatively narrow ranges. Therefore, it does not appear that the composition of the benthos was affected by chemically induced toxicity. In contrast, there were wide ranges in station depth, sediment organic carbon content, sediment texture, and near-bottom DO concentrations, all of which could have affected the benthos.

The various statistical analyses of matching benthos and physical-chemical variables indicated a wide variety of relationships between metrics (or indices) of benthic abundance and diversity and the concentrations of DO near the bottom. The correlation coefficients and scatterplots of the data indicated that some of the relationships were neither consistent nor linear. The relationships between the abundance of some species and DO concentrations appeared to be curvilinear. There were some outlier stations that contributed to variability on a per-sample basis. These and other factors probably contributed to the lack of statistical significance.

However, there were other benthic metrics that were highly related to various physical-chemical variables, including decreases in DO concentrations. In some cases, the abundance of these animals was relatively high in samples with DO concentrations of 6 mg/L or greater, and declined to zero as concentrations dropped below 6 mg/L. There were numerous other species that followed this pattern, and, as a result, the metrics of total abundance and taxa richness decreased remarkably as DO concentrations dropped below values of about 6 mg/L.

The statistical analyses strongly indicated that many of the valued properties of the benthic assemblages (i.e., abundance and diversity) were, on average, considerably lower at stations with the lowest DO concentrations. With one exception (evenness, J'), every median, calculated metric was lower in the low-DO samples than in the high-DO samples. On average, there were 49 times more of the miscellaneous taxa, 47 times more molluscs, and 21 times more arthropods in the samples with the highest DO concentrations than in the samples with the lowest concentrations. The medians for total abundance and taxa richness were 14 and 10 times higher in the highest-DO samples than in the lowest-DO samples. The losses in total abundance and total taxa represented roughly 90% losses between the stations with highest and lowest DO concentrations.

There appeared to be two important inflection points in the DO concentrations (3-6 mg/L and 1 mg/L) whereupon the benthic metrics at the stations decreased precipitously relative to those with higher concentrations of DO. The abundance of some species dropped to zero in samples with less than 6 mg/L DO, other species dropped out at about 3 mg/L, and the abundance of additional species and one phylum (Echinodermata) dropped to zero in samples with DO concentrations of 1 mg/L or less. Scatterplots of the median abundance of selected species indicated a successional pattern in losses as DO concentrations decreased. The pattern in losses of valued benthic properties resembled the patterns described previously for other fjords, worldwide.

Results of a multivariate canonical analysis of the 2004 survey data indicated the presence of three relatively distinct spatial benthic assemblages. The assemblages in northern Hood Canal, in Dabob Bay and the other central reaches of Hood Canal, and in south canal/Lynch Cove were dominated by different species of infauna. There was evidence that these assemblages could be further sub-divided into nine assemblages. The composition of these assemblages appears to have been influenced by different environmental variables. Overall, however, the best predictor of variation in benthic composition was percent fines, followed by DO, organic carbon content, and station depth. A species of clam, *Axinopsida serricata*, had the greatest influence in defining the composition of the benthic assemblages throughout the region.

Application of canonical analyses results to the long-term, temporal trends data set allowed us to construct a multivariate index of benthic responses to DO. This index summarized the spatial variation in DO since 1991 and indicated that changes in benthic communities in the vicinity of the Great Bend were consistent with declining oxygen concentrations.

Although the data generated in this survey, along with the observations of fish kills by diverse and local residents, provided compelling evidence that hypoxia in Hood Canal caused or contributed to important losses in the living marine resources, there were a number of sources of uncertainty in these data. These sources included the study design which was intended to satisfy other objectives, the distance above the seabed where DO was measured, the questionable representativeness of the single "snapshot" in DO measurements, and the small number of simultaneously collected sediment and DO samples obtained from Hood Canal. Therefore, the actual cause(s) of effects to the benthos in these Hood Canal samples remain unverified. If hypoxia caused the observed benthic impacts, the critical DO concentrations below which these effects occurred were difficult to identify because of the small sample size.

It is probable that the DO concentrations were limiting and contributory but they may not have been the sole cause of the effects that were observed. Other important natural factors – including station depth, sediment grain size, and sediment organic carbon content – may have been important and contributory as well. Additional research is needed to confirm the effects of hypoxia on the resident benthos and to establish critical DO levels necessary to protect these living marine resources.

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Figures

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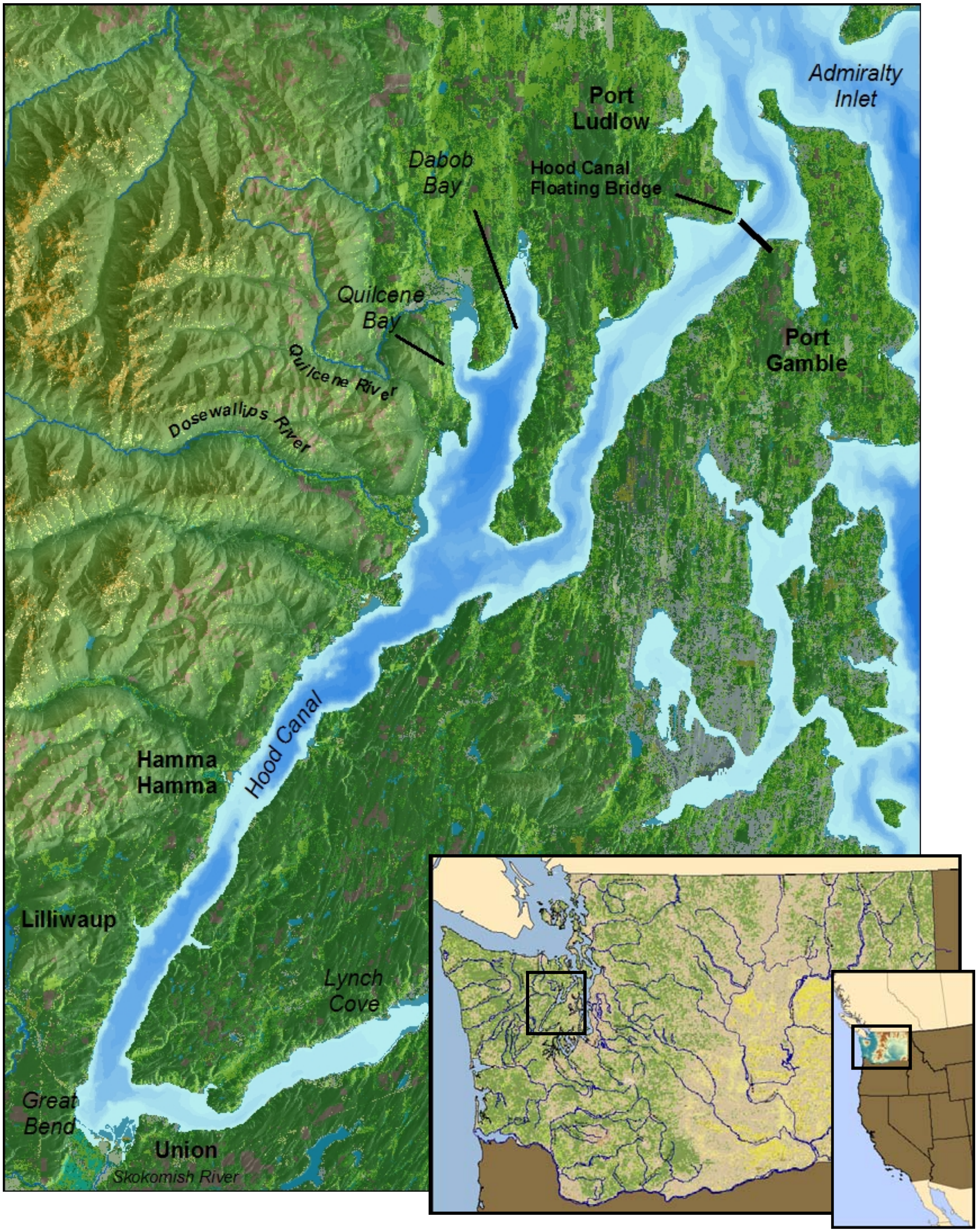


Figure 1. Hood Canal and vicinity.

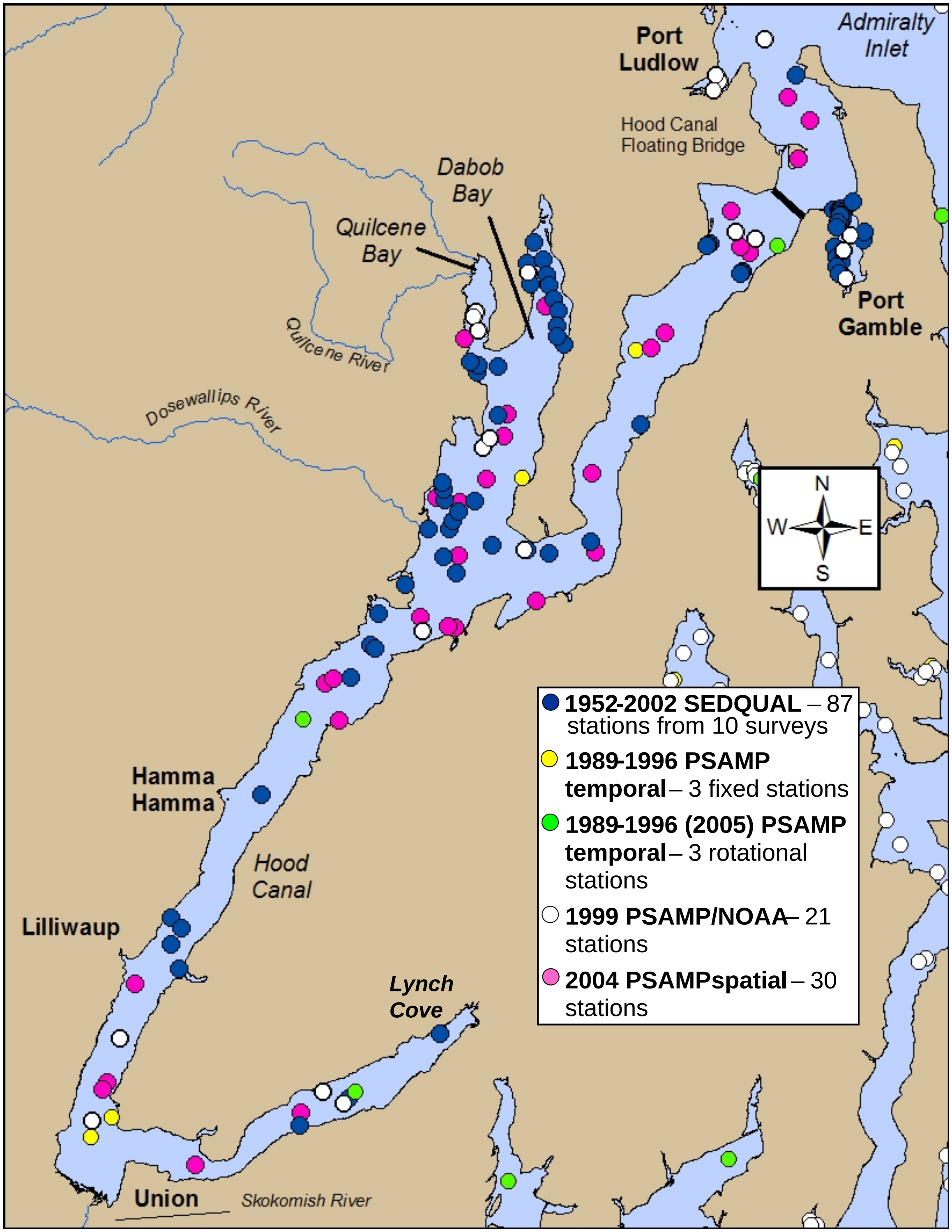
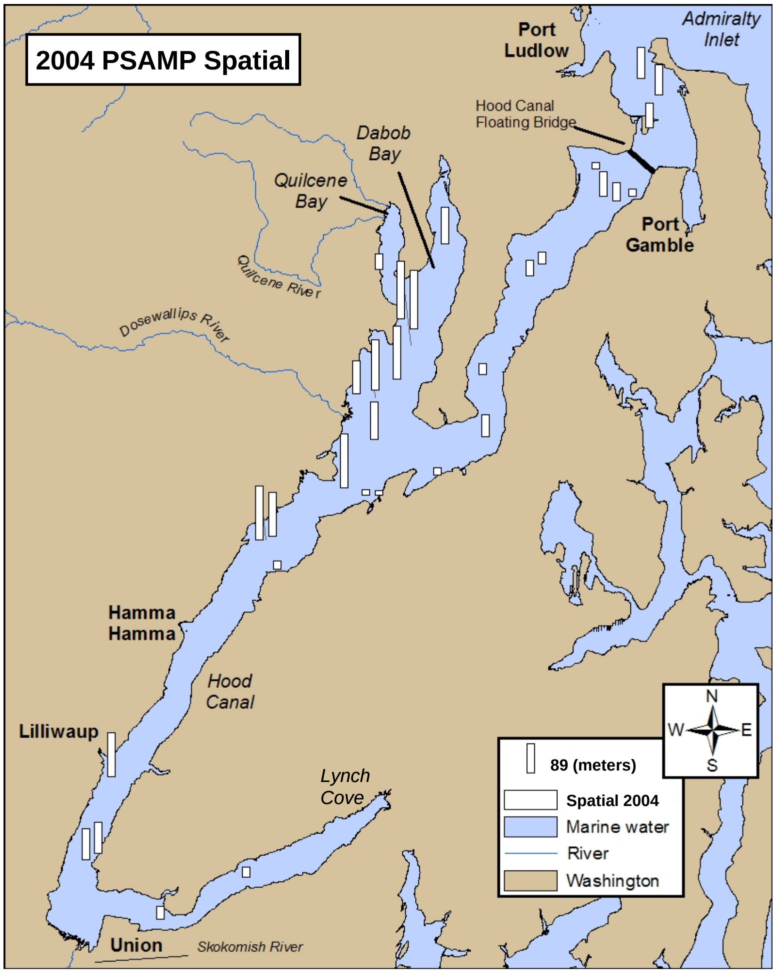
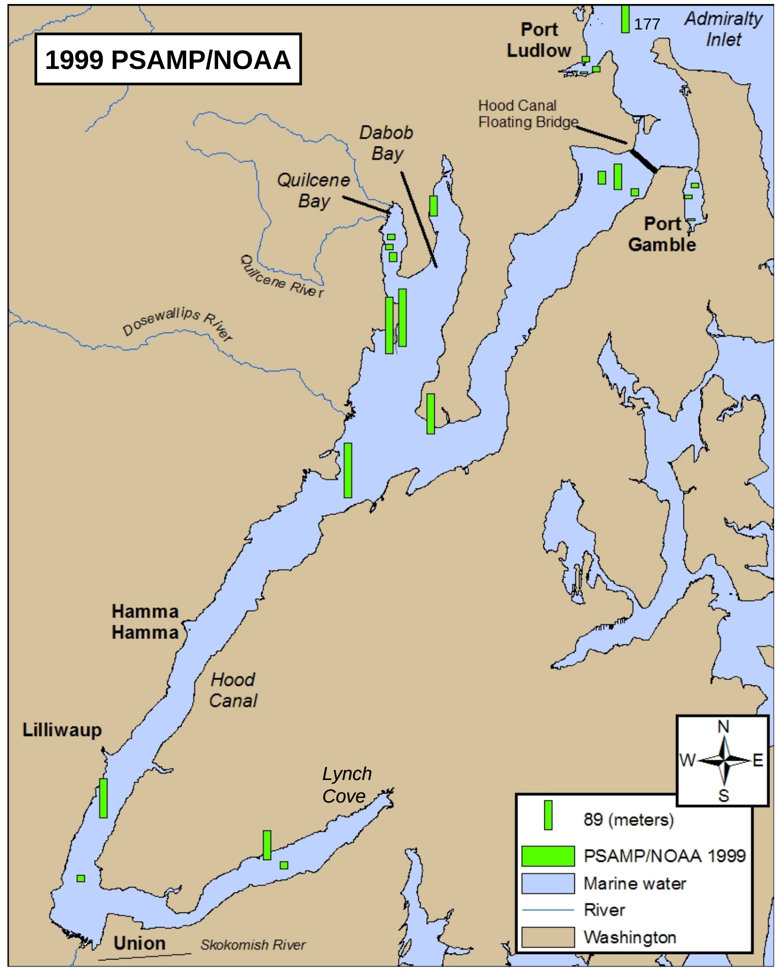


Figure 2. Sediment monitoring stations sampled in Hood Canal from 1952 through 2005.





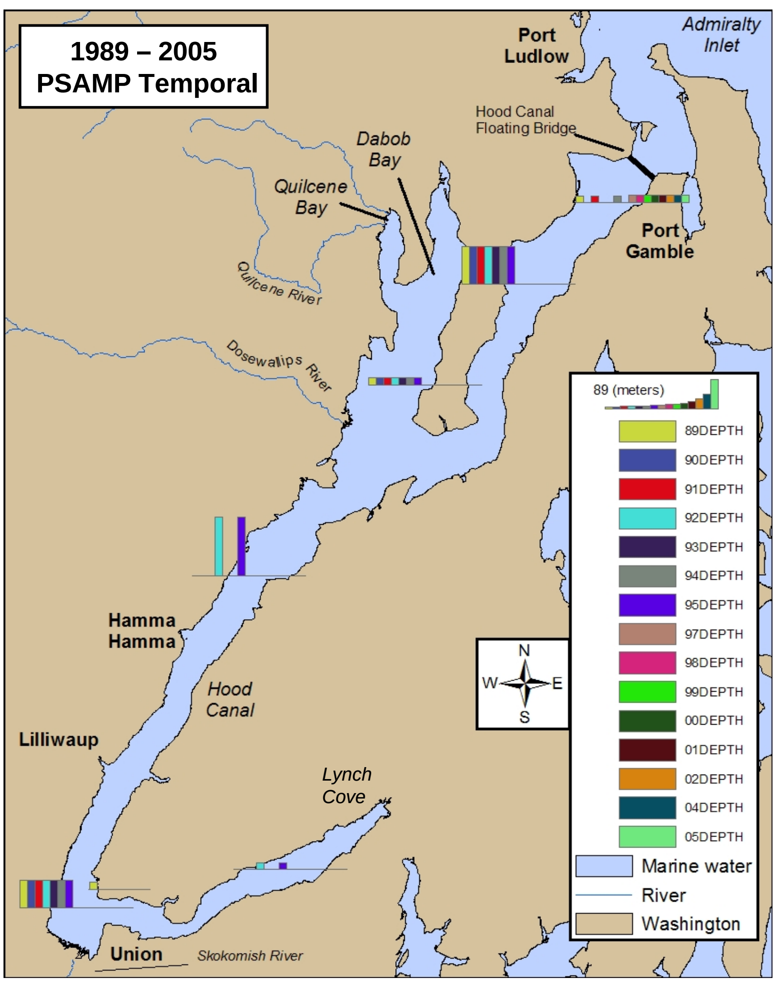


Figure 3. Depth (meters) measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program.

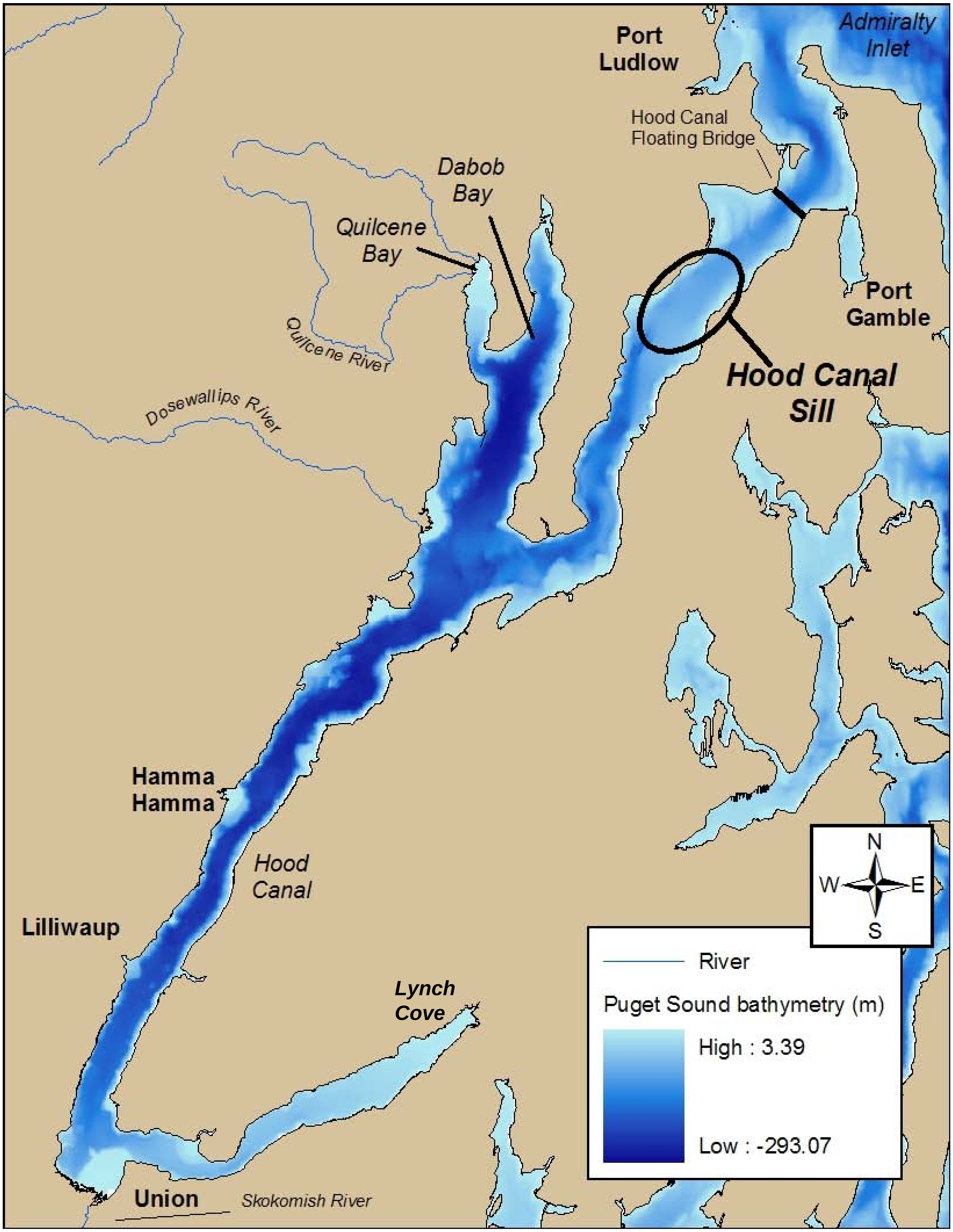


Figure 4. Depth contour of Hood Canal.
(Depth in meters relative to local extremely lower-low water (ELLW))

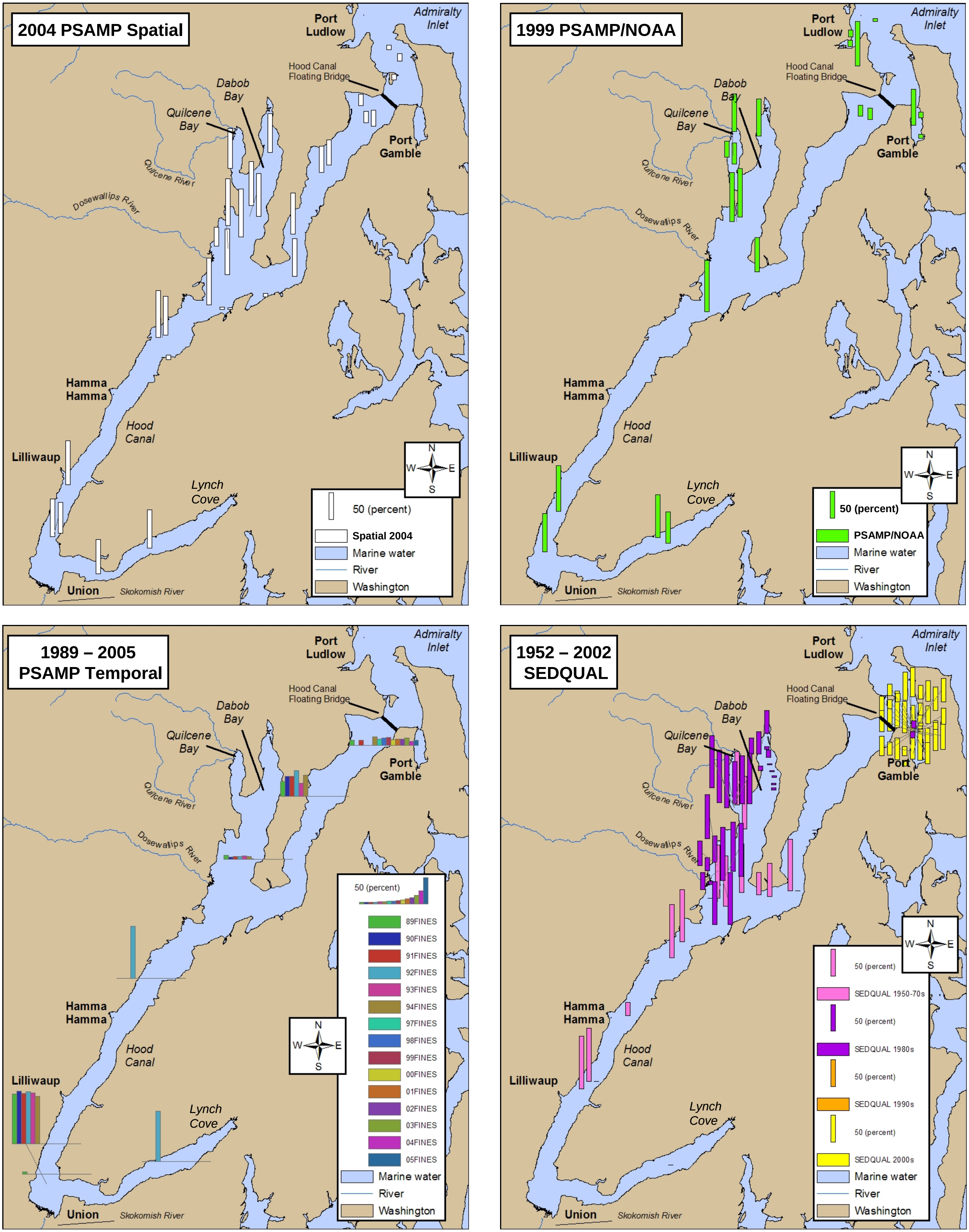


Figure 5. Percent fines measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.

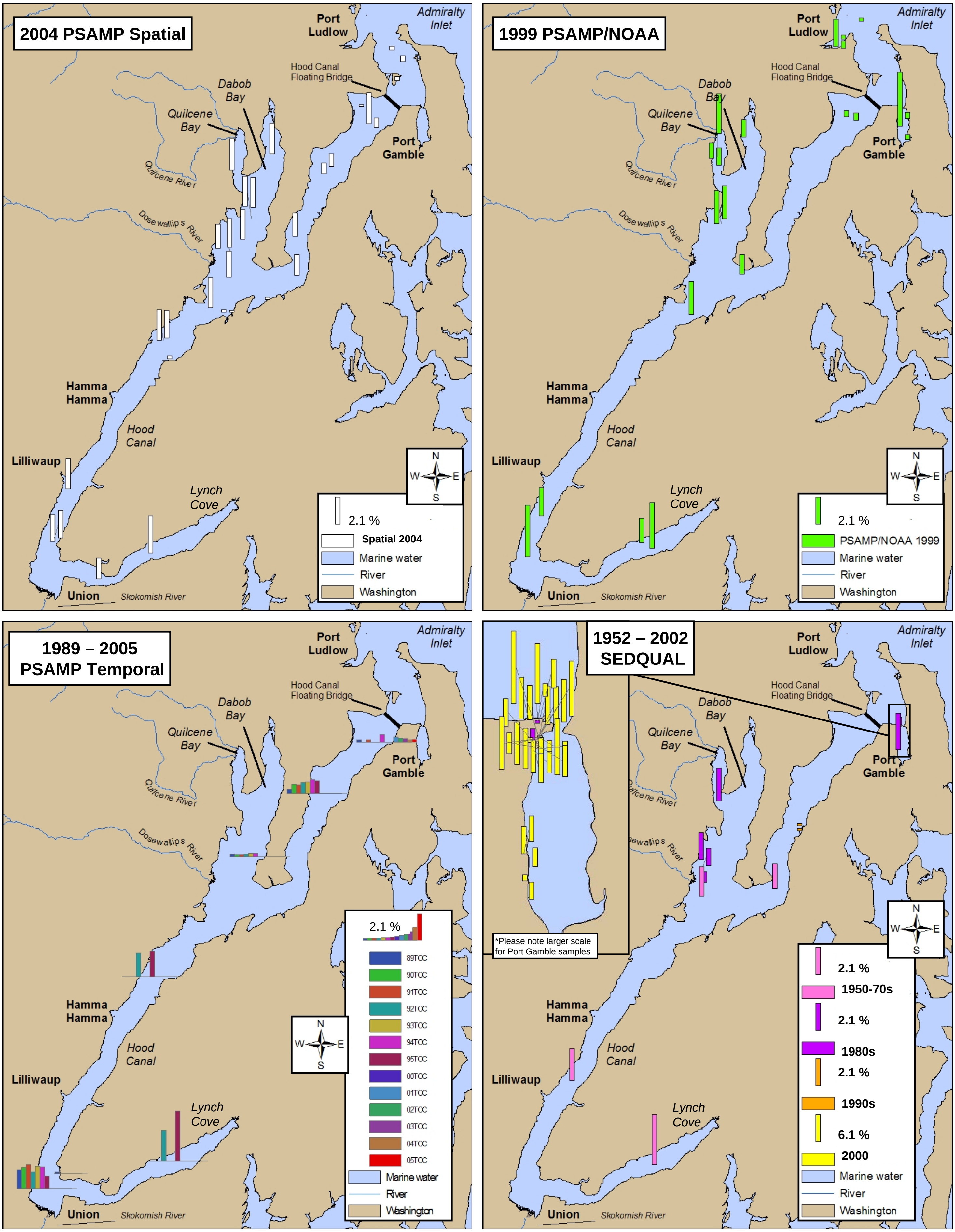


Figure 6. Total organic carbon (%) measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.

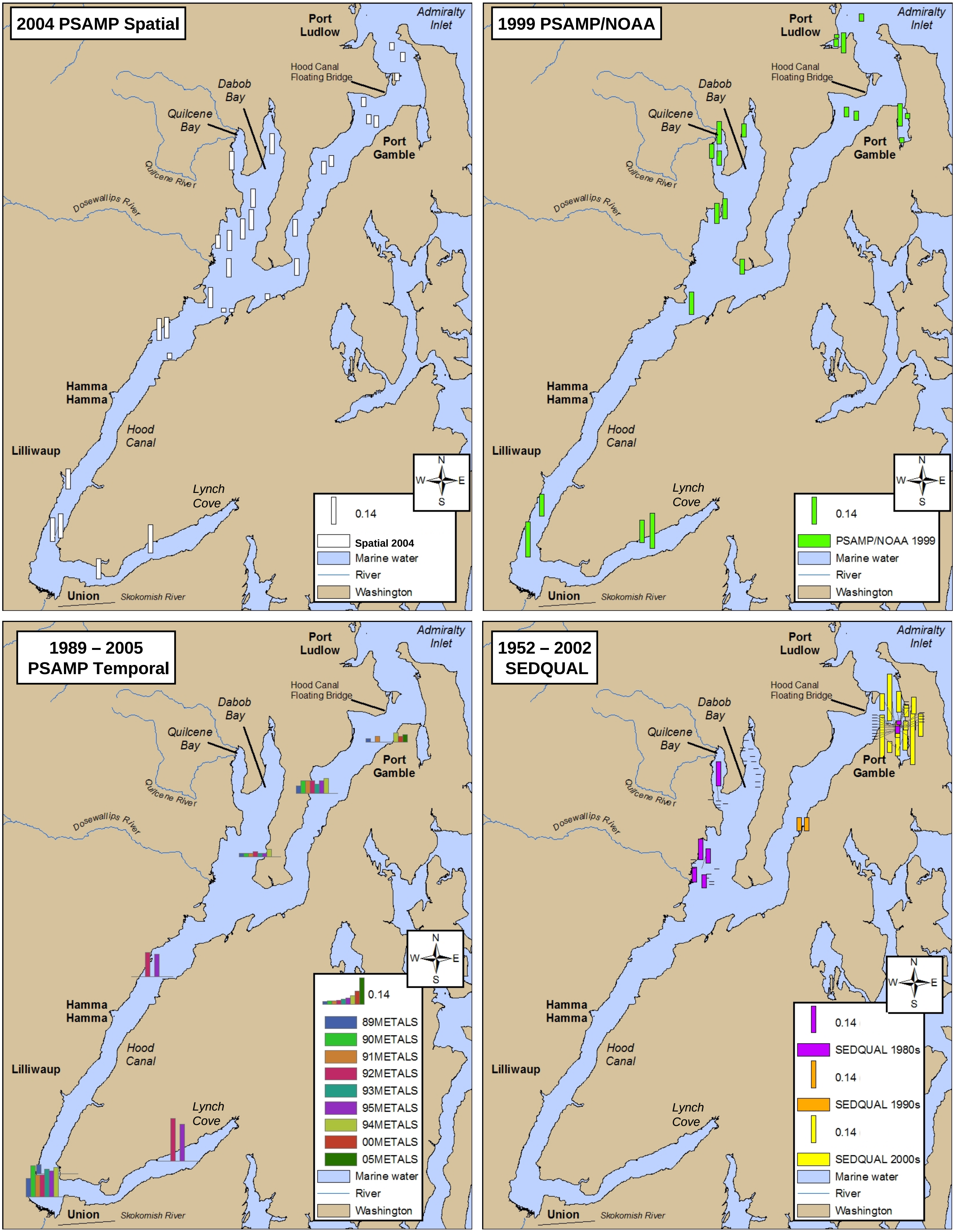


Figure 7. Mean SQS quotients for 8 metals measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.

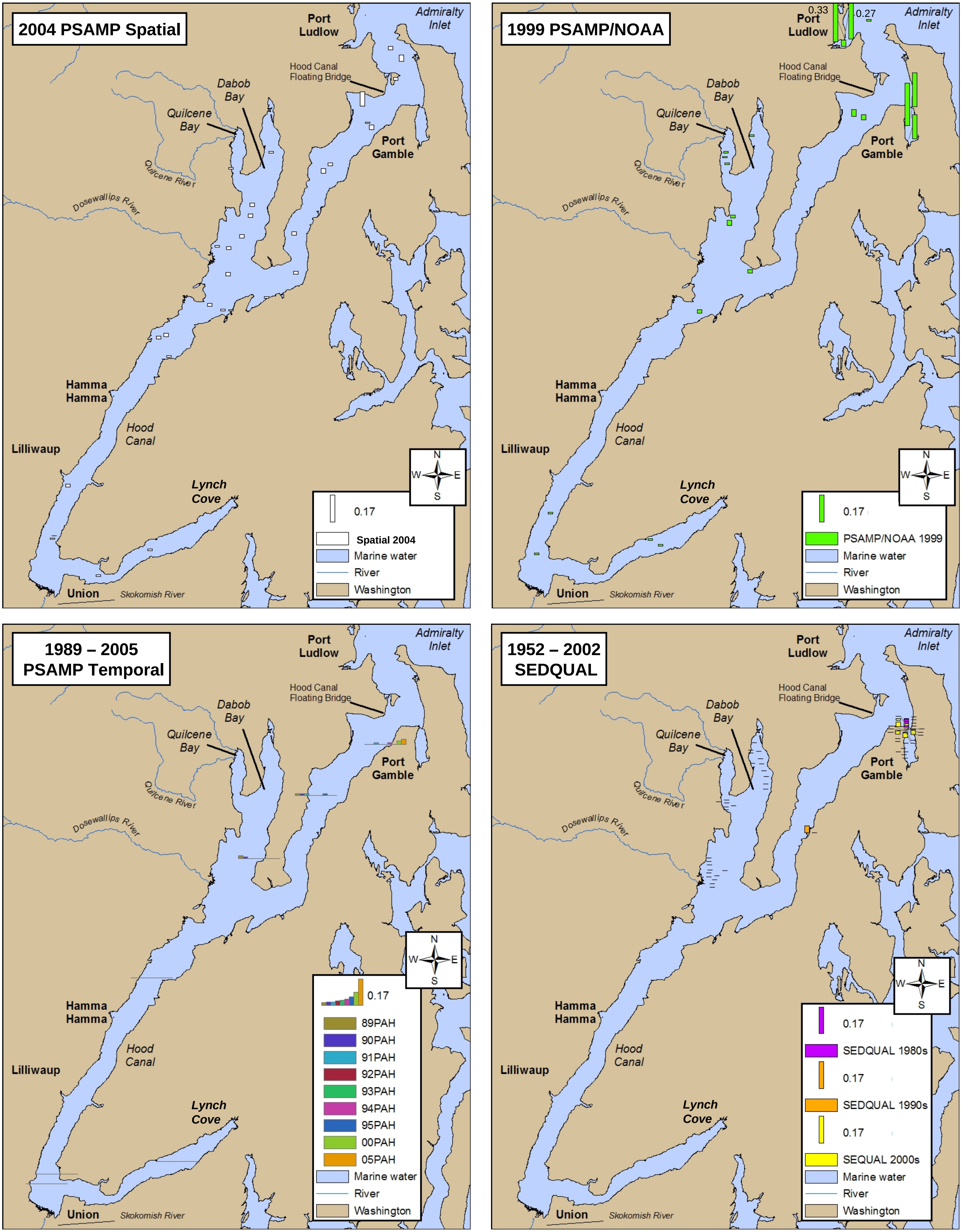


Figure 8. Mean SQS quotients for 15 PAHs measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.

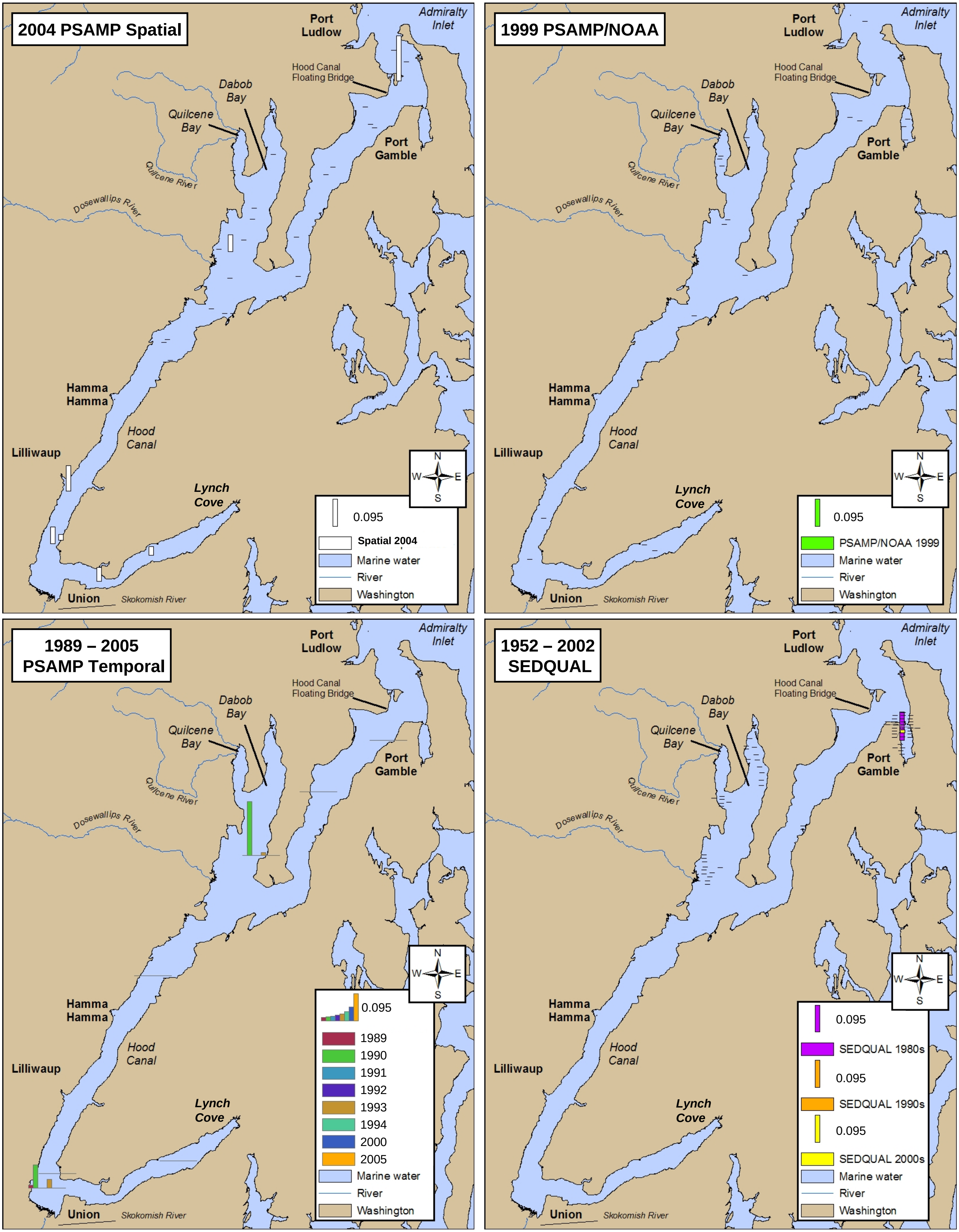


Figure 9. Mean SQS quotients for 6 phthalates measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.

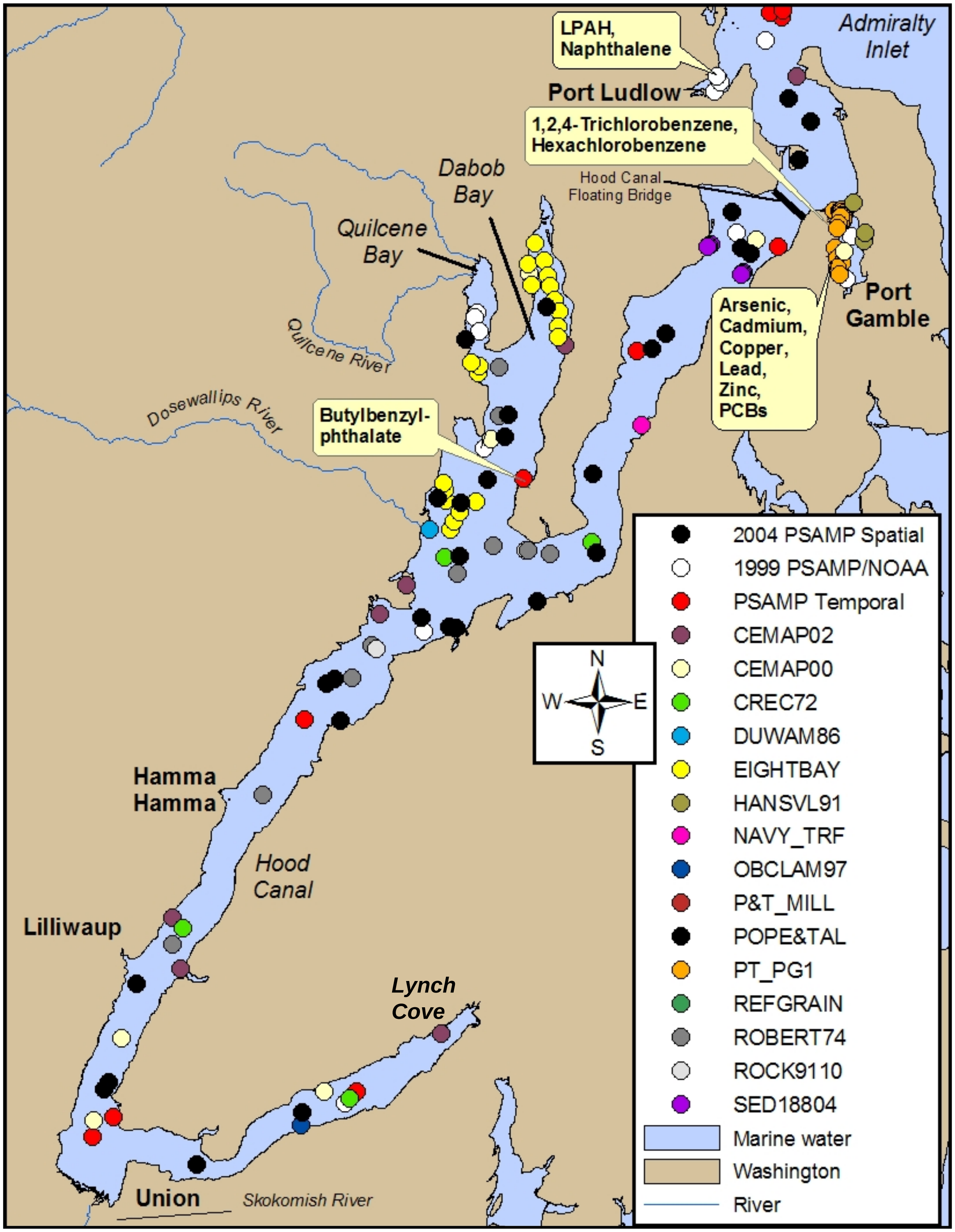


Figure 10. Sediment chemistry exceeding Washington State Sediment Quality Standards in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.

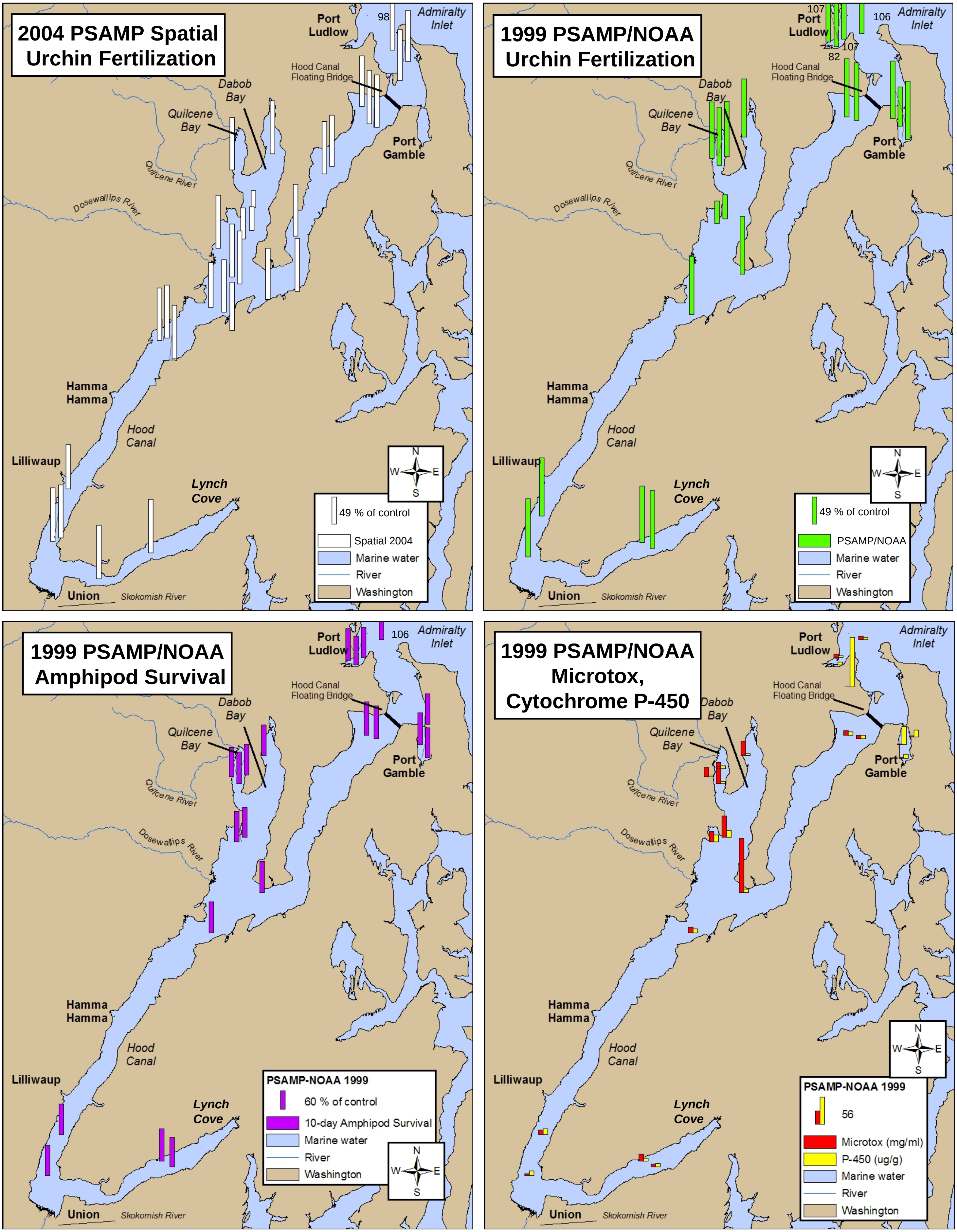


Figure 11. toxicity measured with sea urchin fertilization (% of control), amphipod survival (% of control), Microtox (mg/ml organic solvent extract), and Cytochrome P-450 HRGS (µg/g B[a]P equivalents) at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs. (Highest bars are most toxic results for Cytochrome P-450 HRGS, and least toxic results for amphipod survival, Microtox, and sea urchin fertilization tests.)

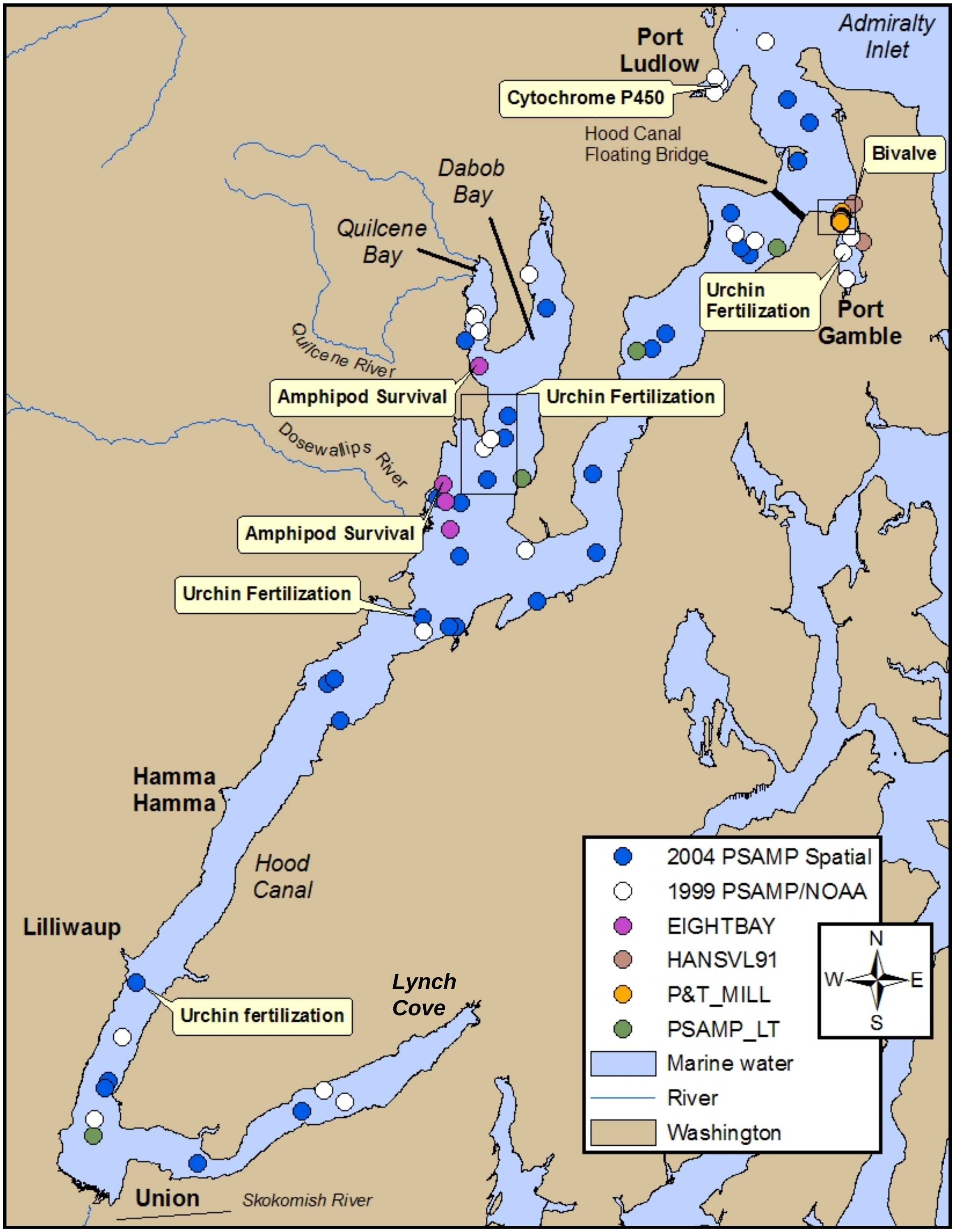
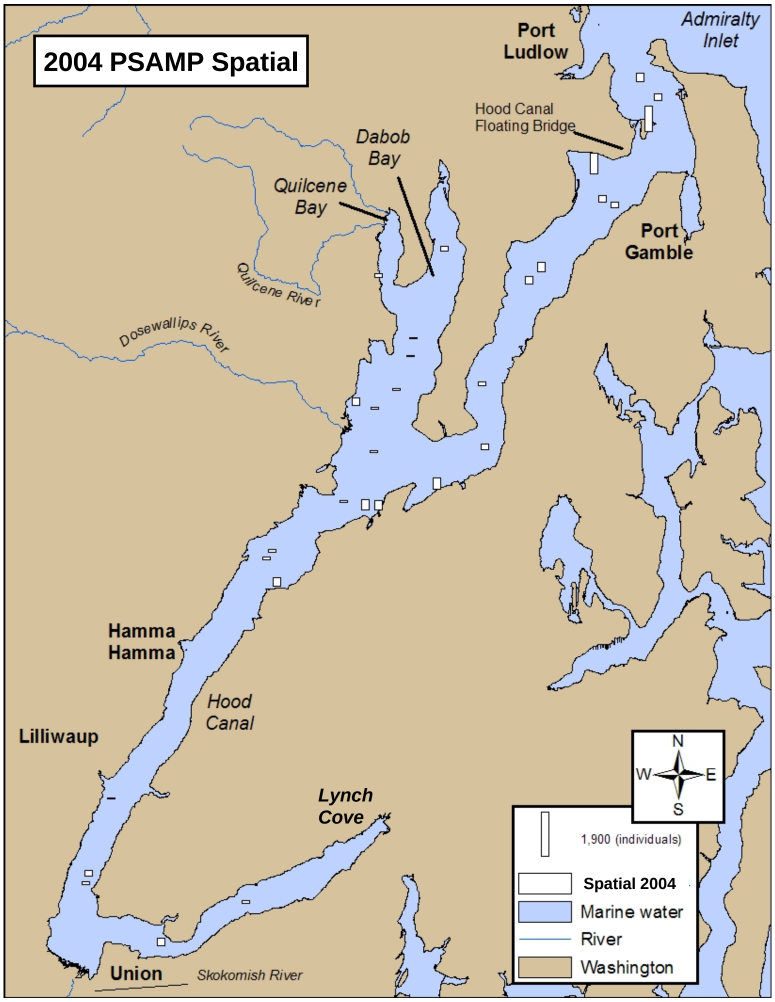
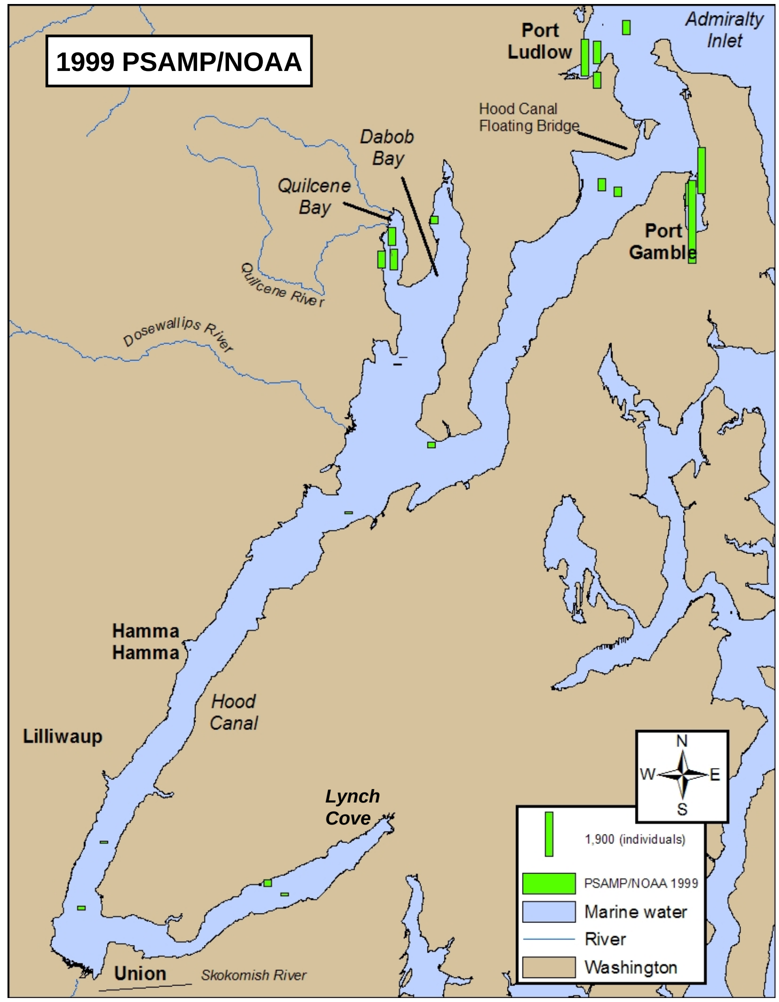


Figure 12. Sediment toxicity exceeding critical values in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data from the SEDQUAL database.





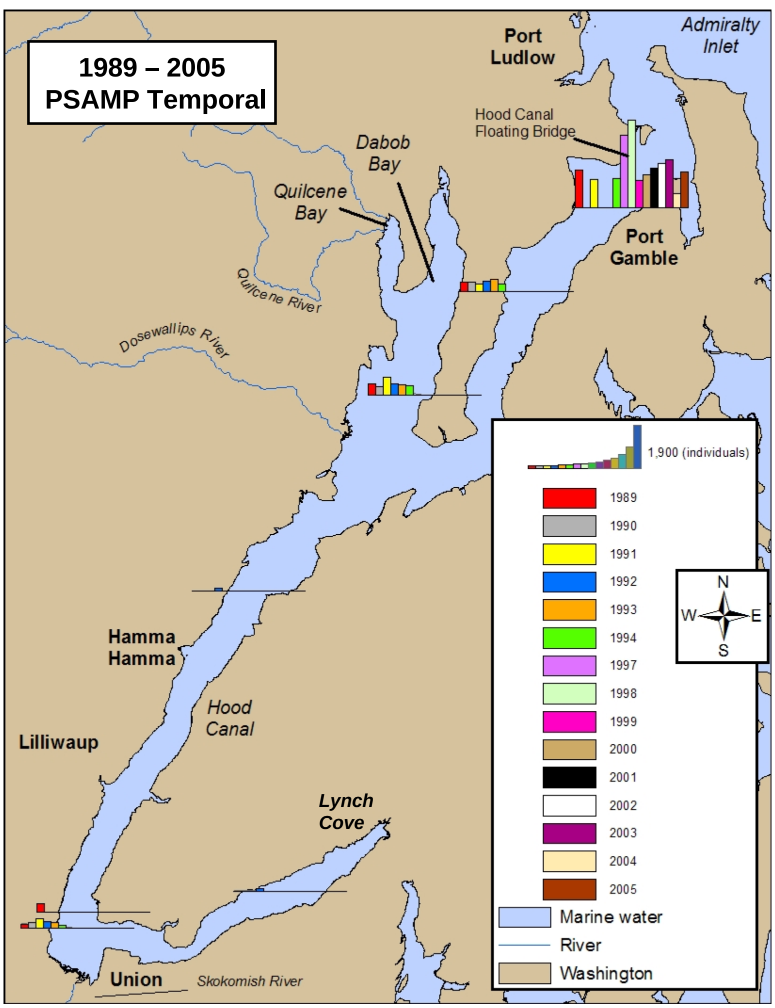


Figure 13. Total benthic abundance measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. No data were available from the SEDQUAL database.

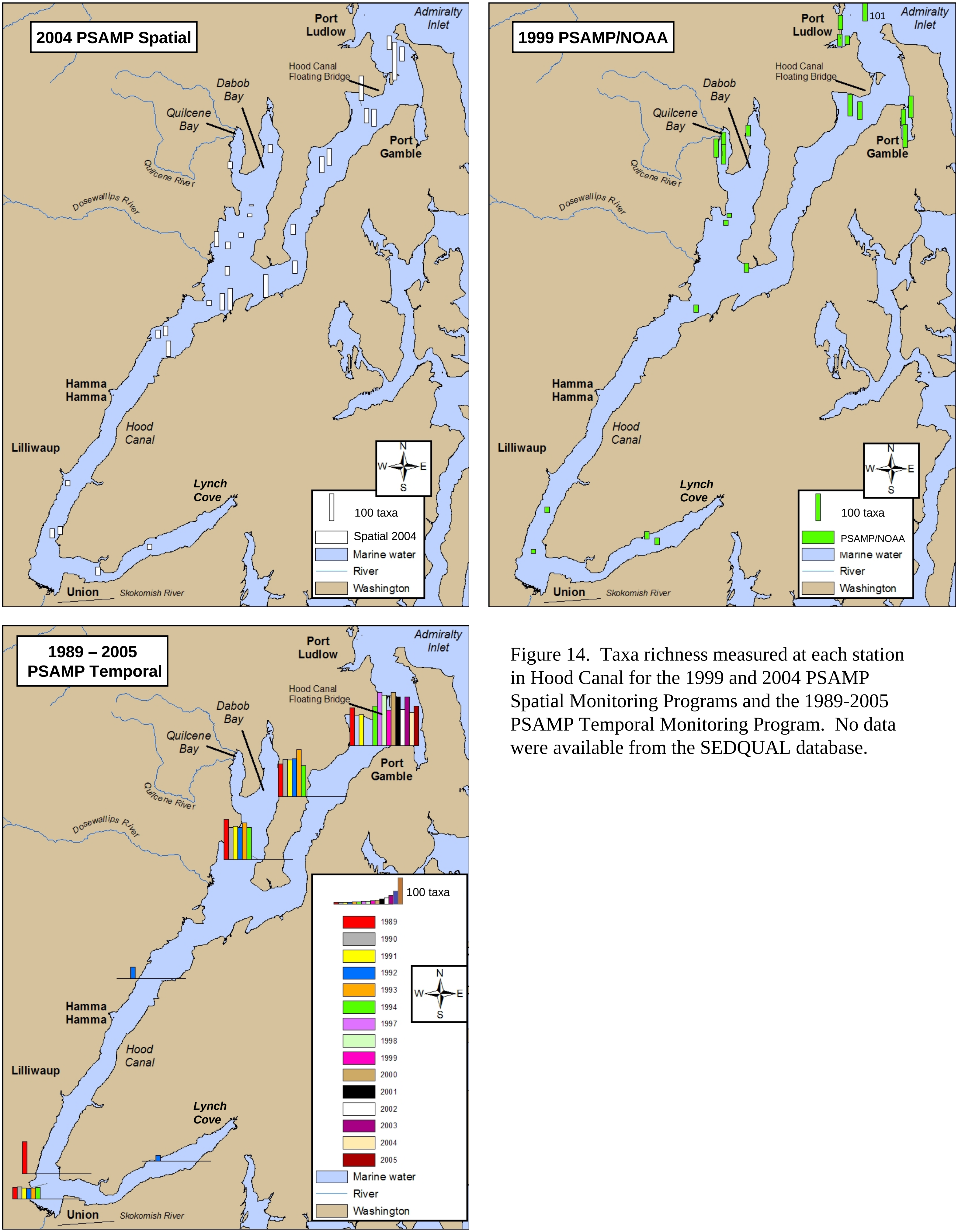


Figure 14. Taxa richness measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. No data were available from the SEDQUAL database.

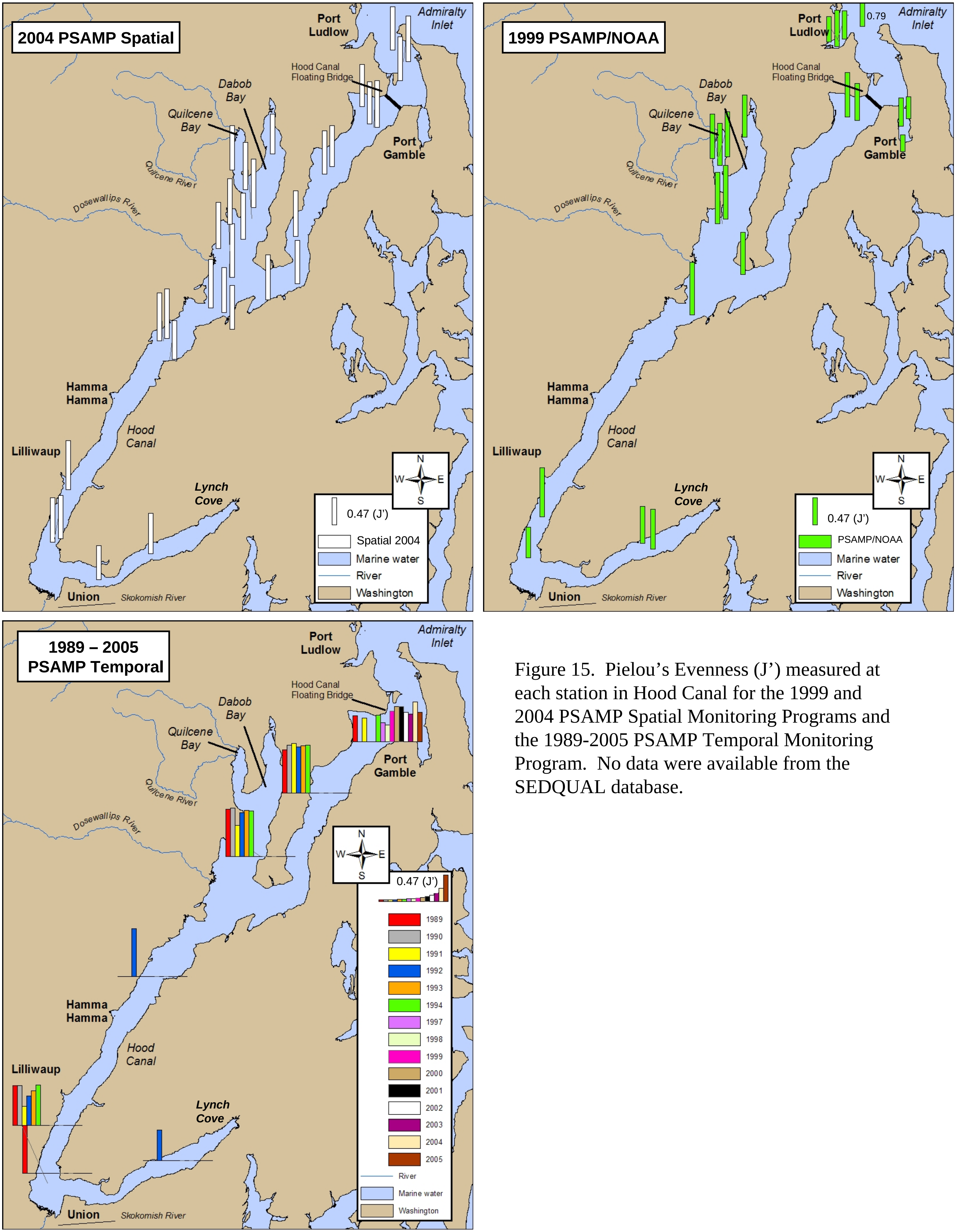
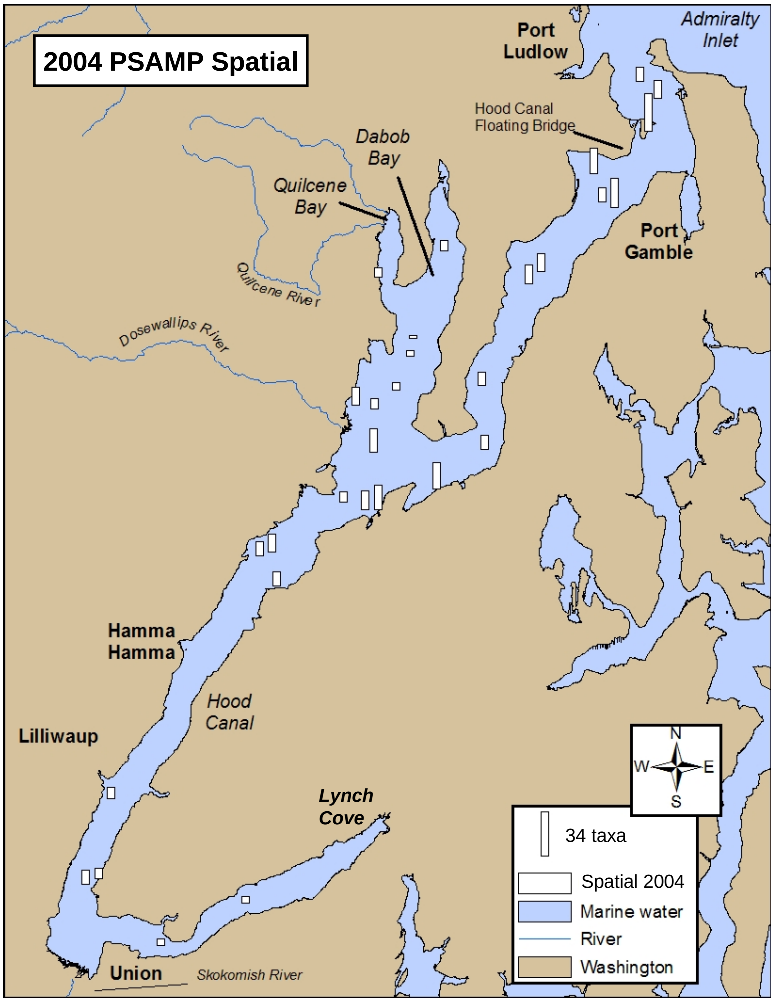
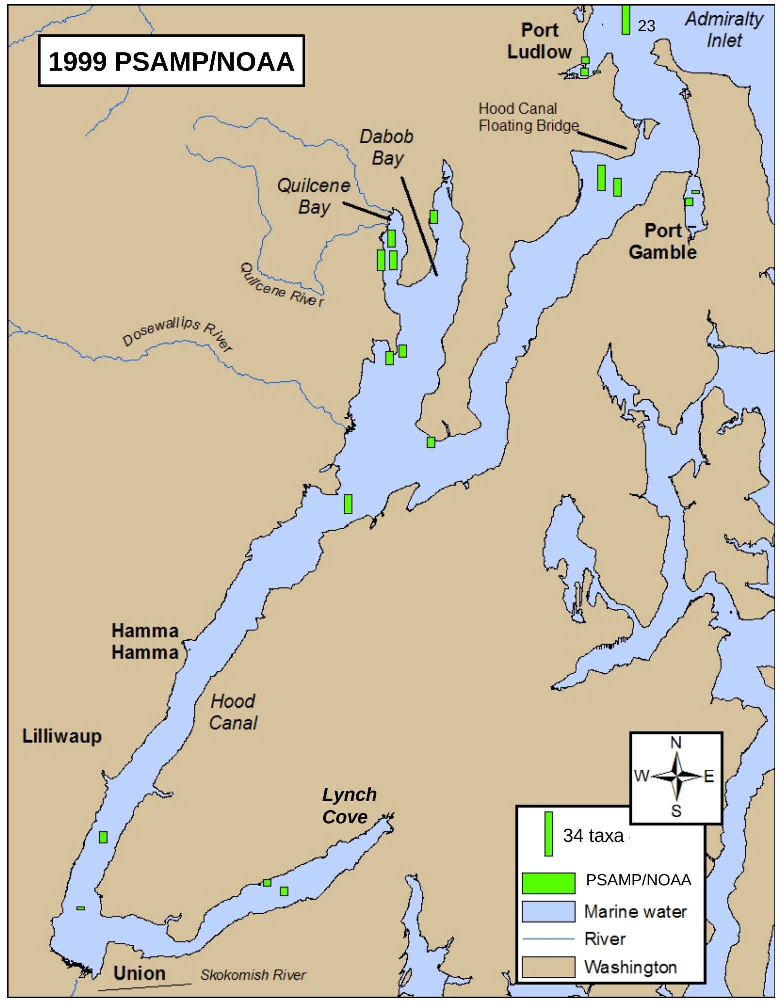


Figure 15. Pielou's Evenness (J') measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. No data were available from the SEDQUAL database.





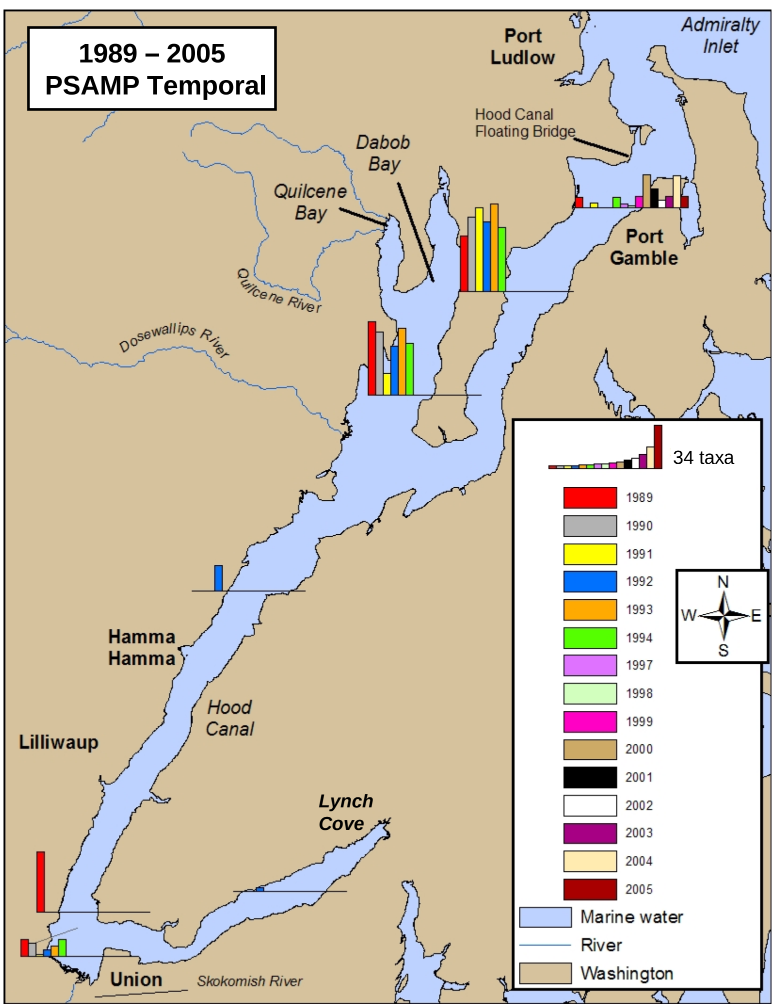


Figure 16. Swartz's Dominance Index measured at each station in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. No data were available from the SEDQUAL database.

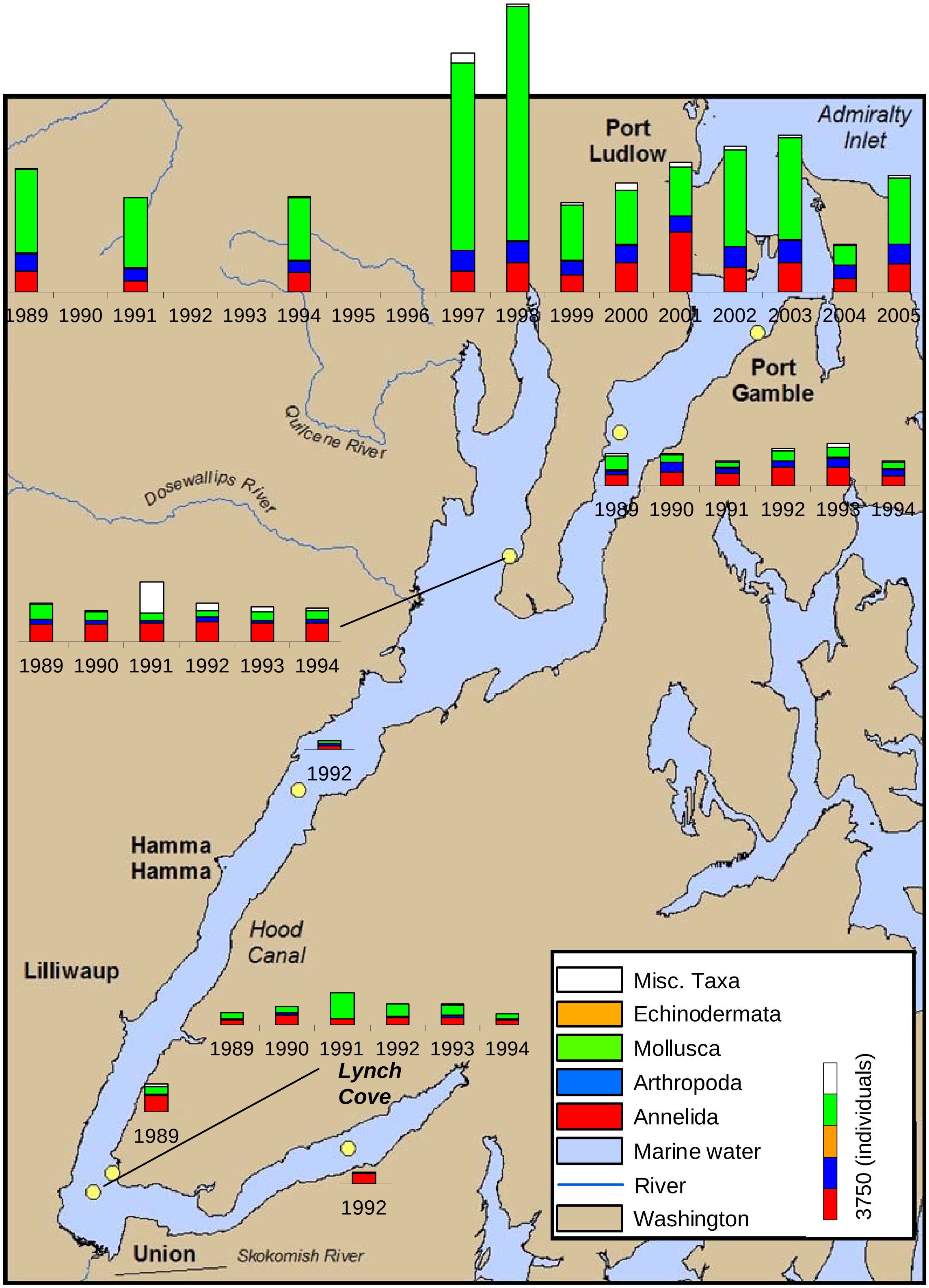


Figure 17. Major taxa abundance measured at each station in Hood Canal for the PSAMP Temporal sediment surveys.

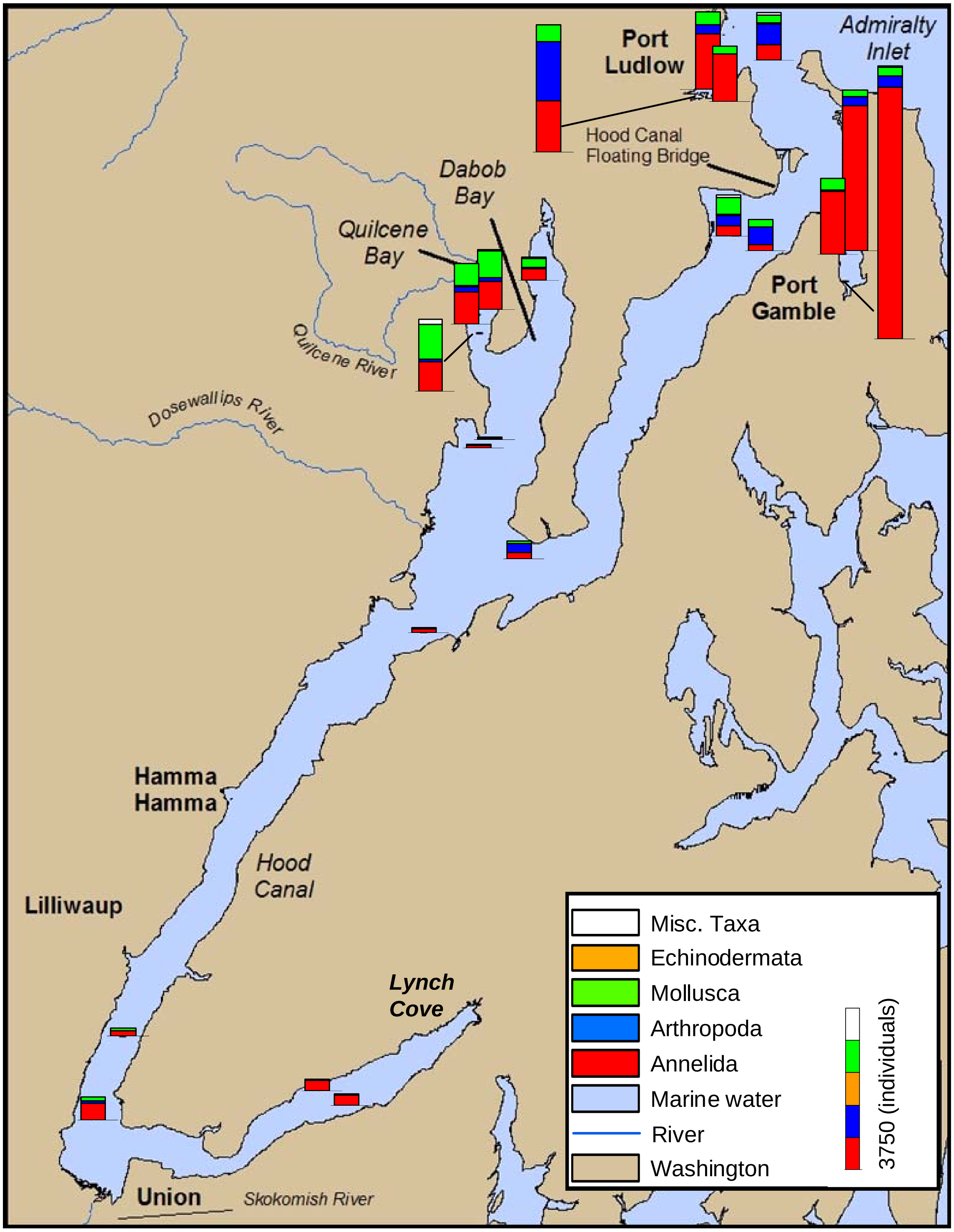


Figure 18. Major taxa abundance measured at each station in Hood Canal for the 1999 PSAMP/NOAA Monitoring Program.

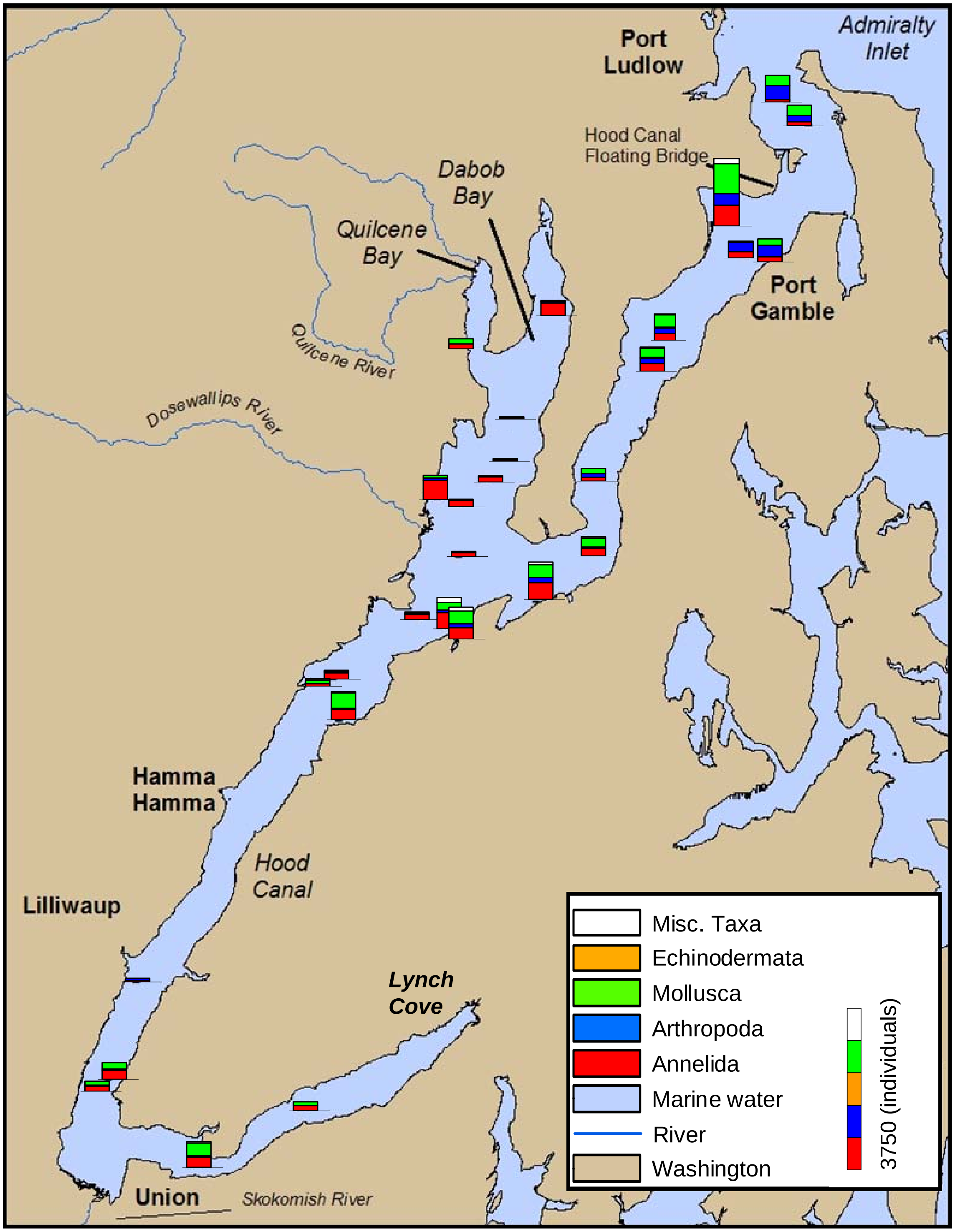


Figure 19. Major taxa abundance measured at each station in Hood Canal for the 2004 PSAMP Spatial Monitoring Program.

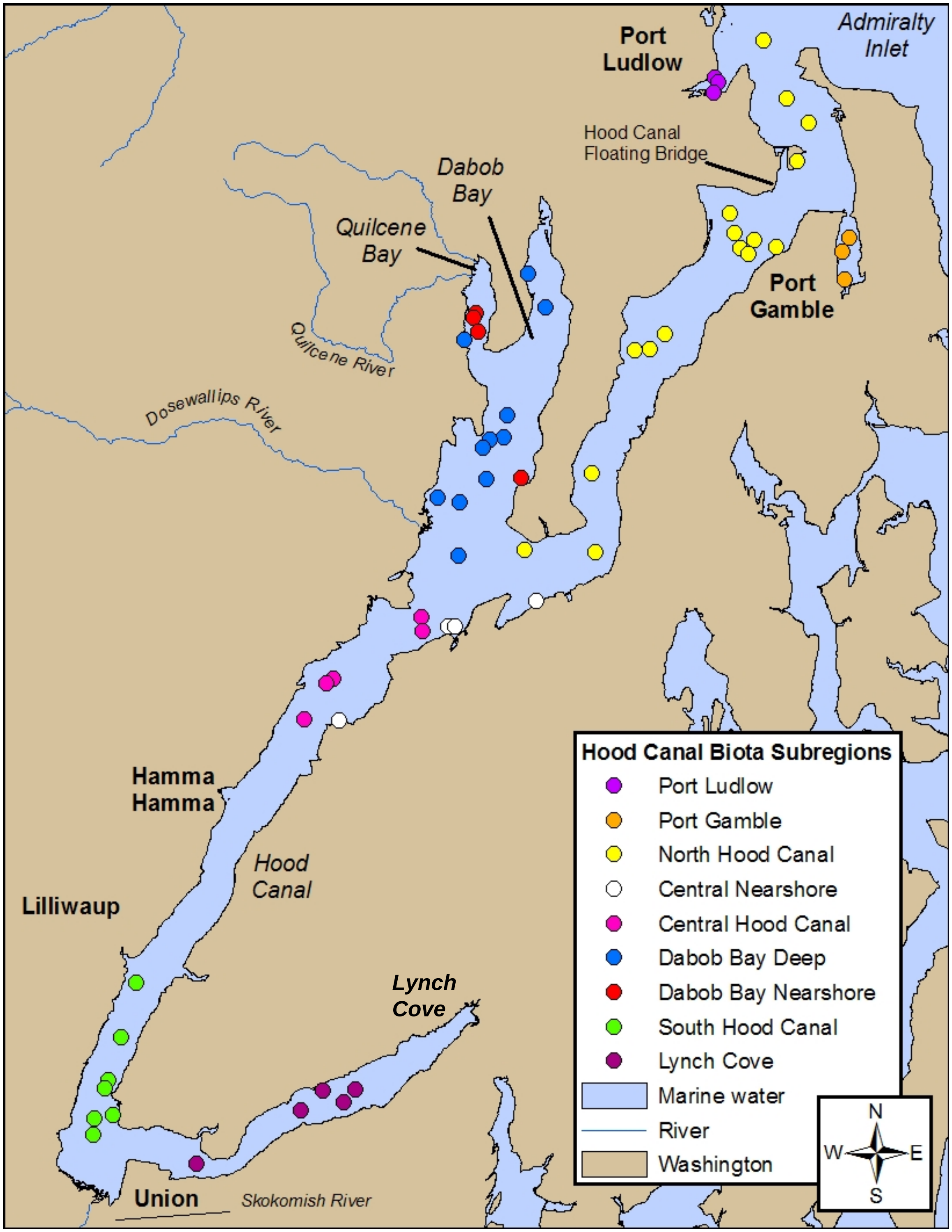
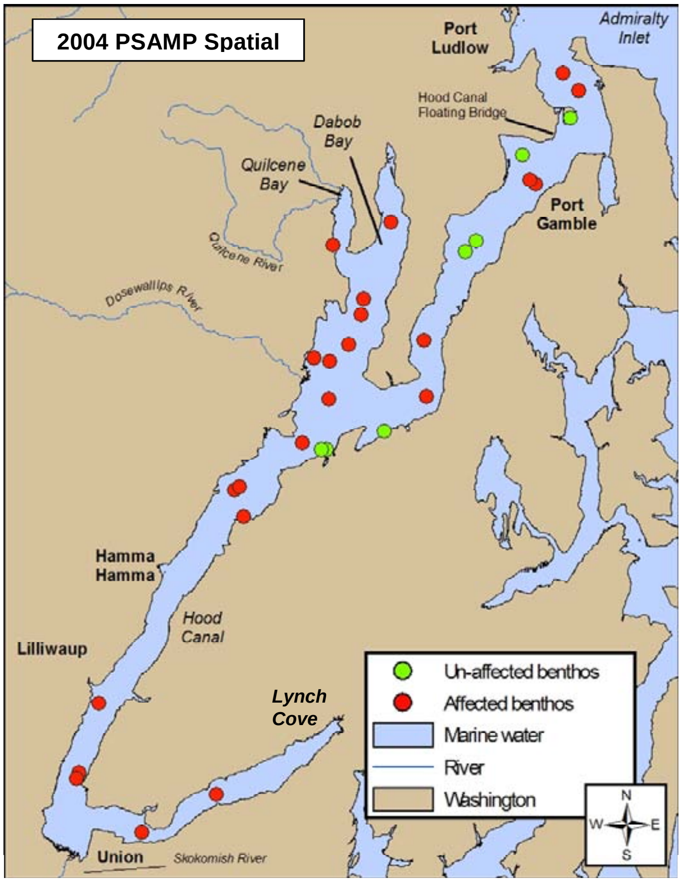
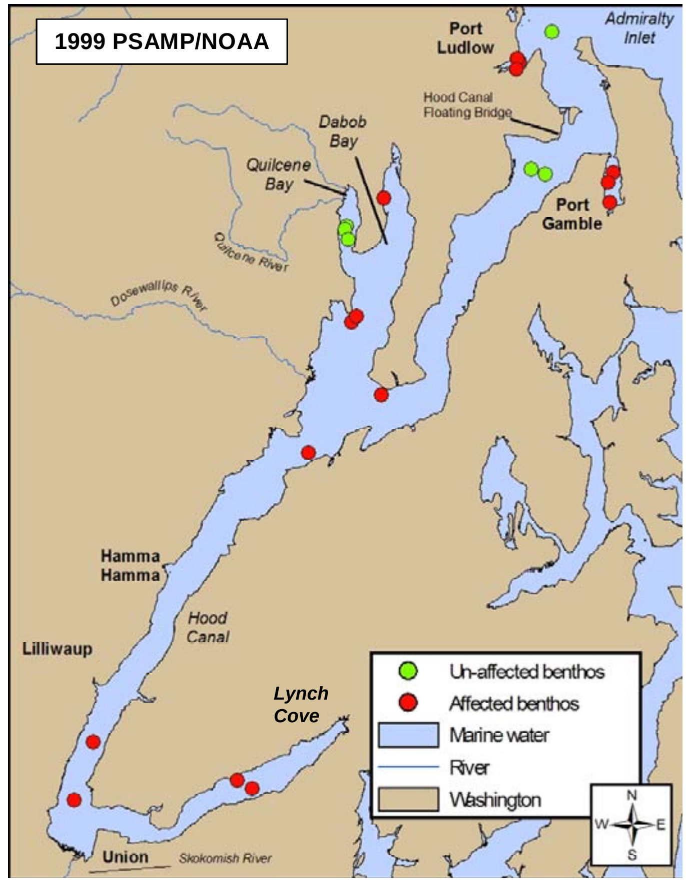


Figure 20. Nine sub-regions with similar benthic infaunal assemblages in samples collected from the 1989-2005 PSAMP Temporal, 1999 PSAMP/NOAA, and 2004 PSAMP Spatial sediment monitoring surveys.





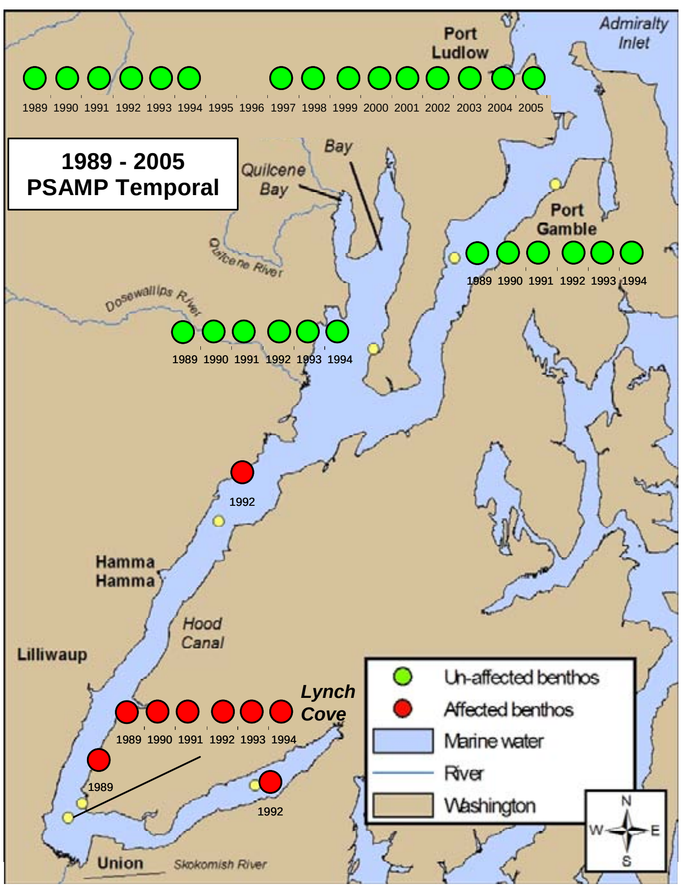


Figure 21. Hood Canal infaunal invertebrate assemblages with adversely affected* assemblage structure collected for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program.

*adversely affected = stations with the majority of benthic indicators being < 80% of the median 1997-2003 Puget Sound baseline benthic index values, or dominated by stress-tolerant taxa.

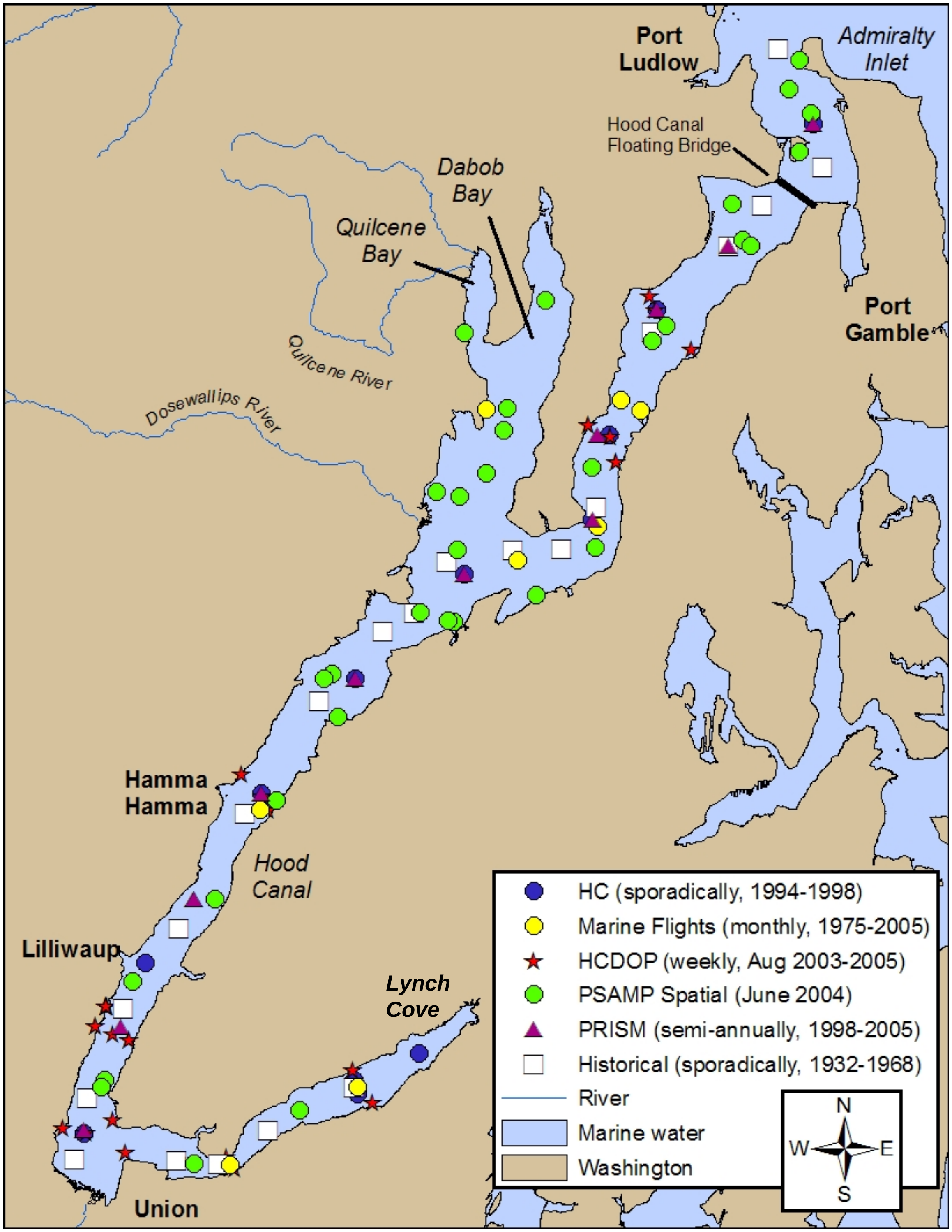


Figure 22. Water column monitoring stations sampled in Hood Canal from 1932 through 2005.

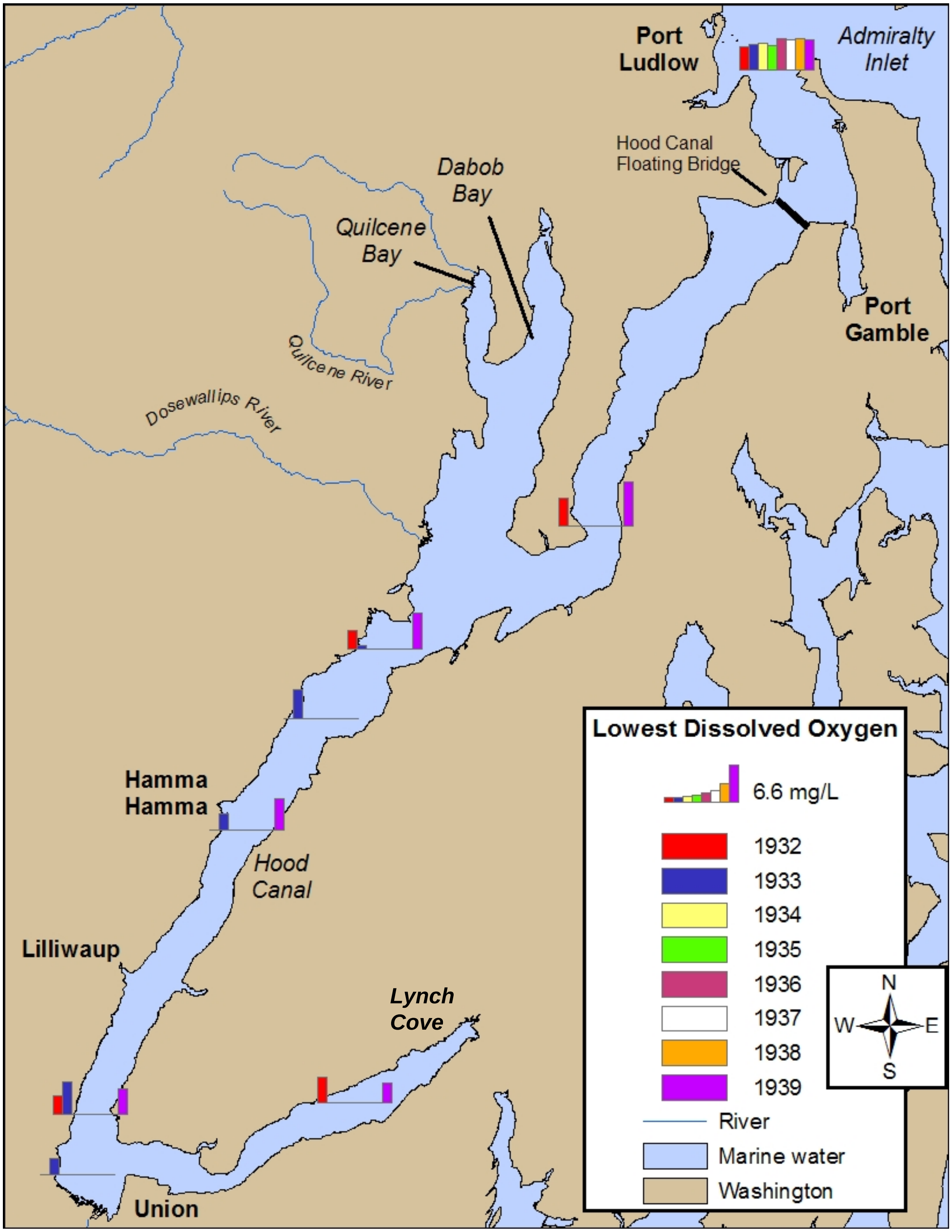


Figure 23. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1932 through 1939.

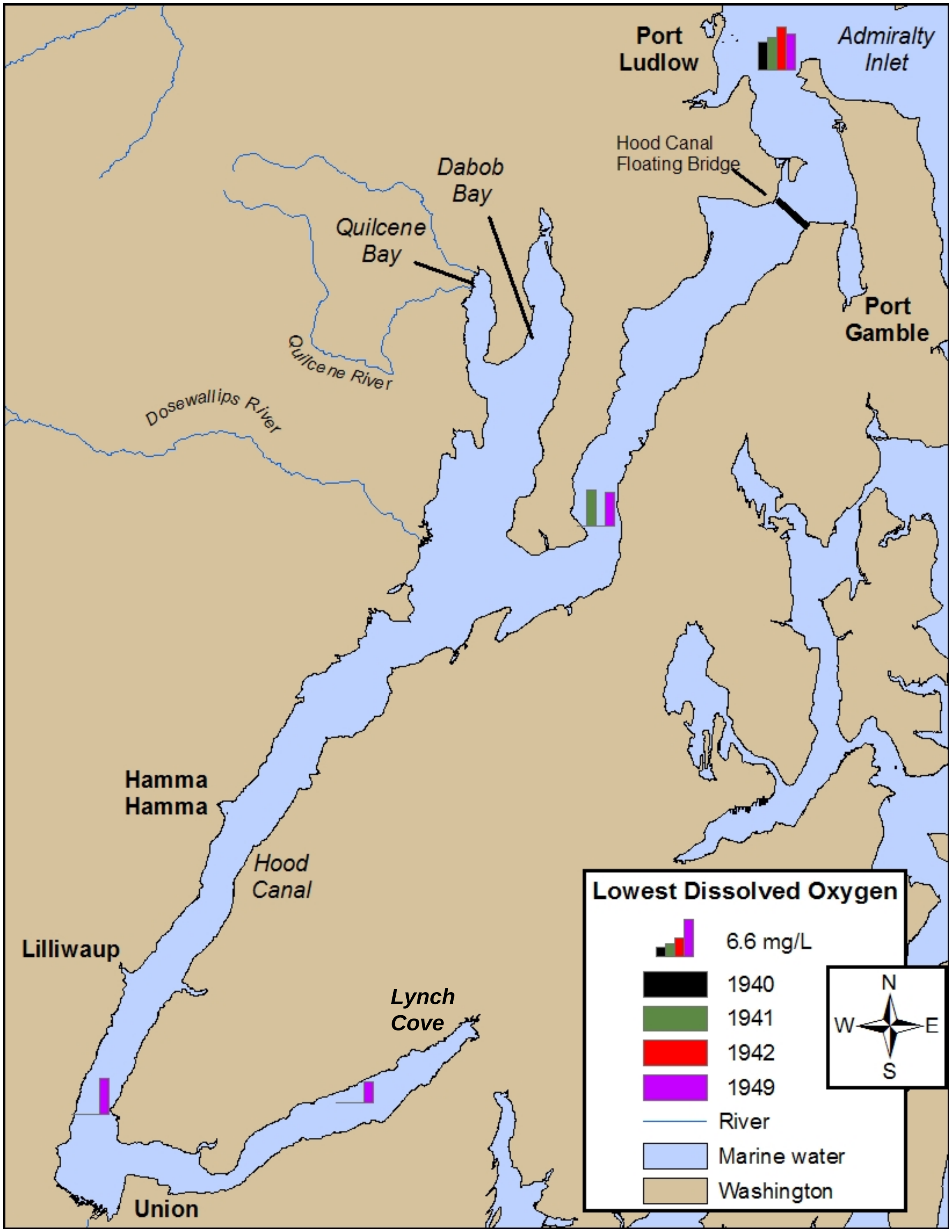


Figure 24. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1940 through 1949.

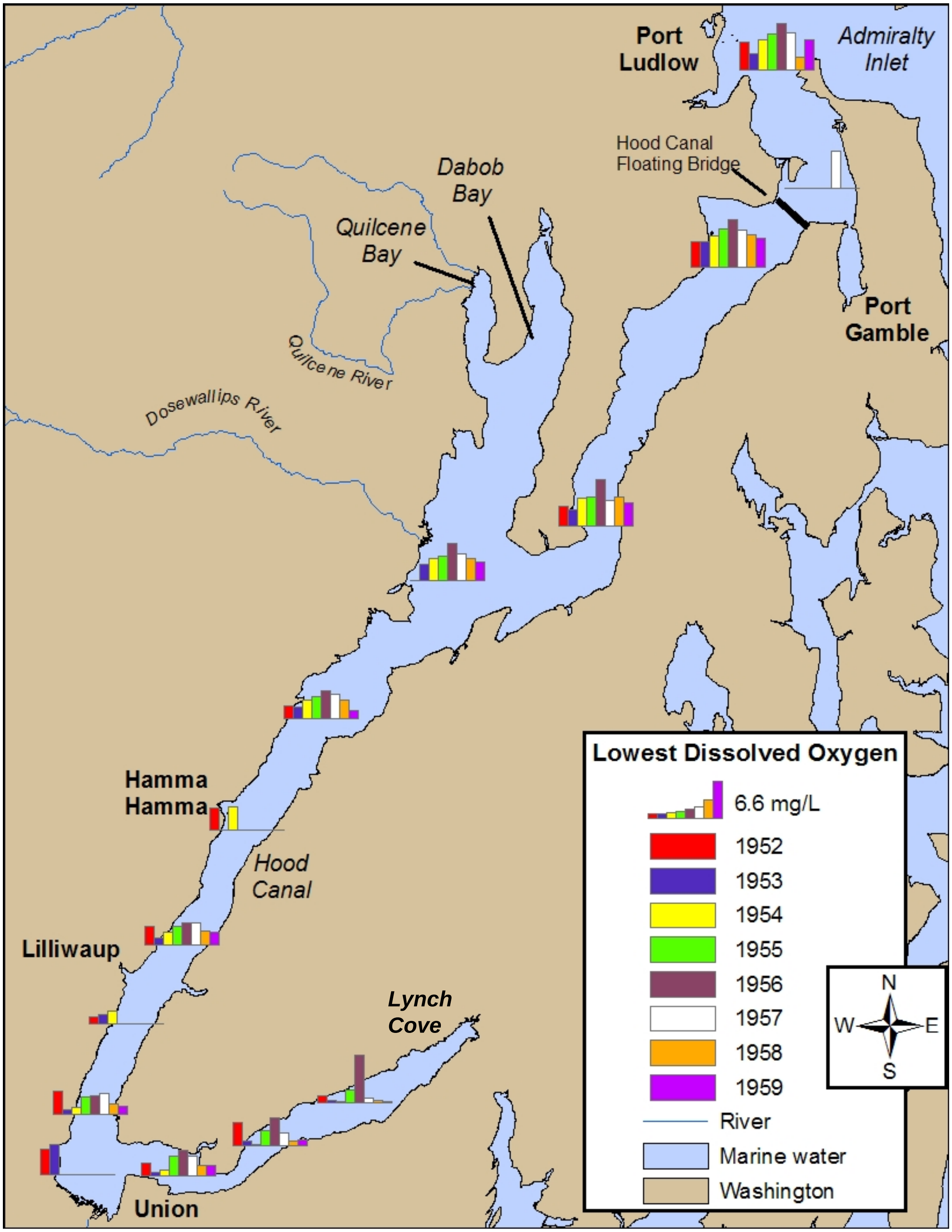


Figure 25. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1952 through 1959.

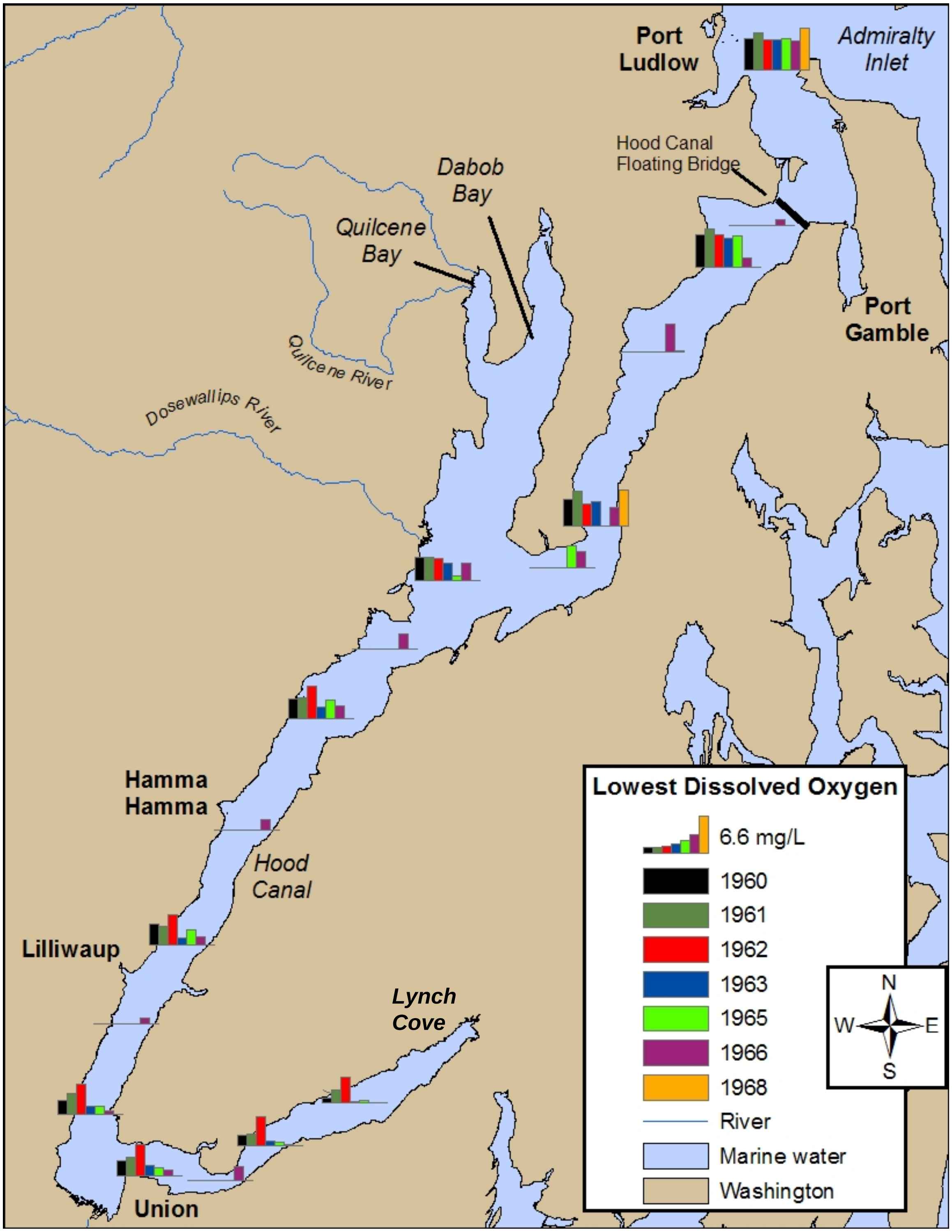


Figure 26. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1960 through 1968.

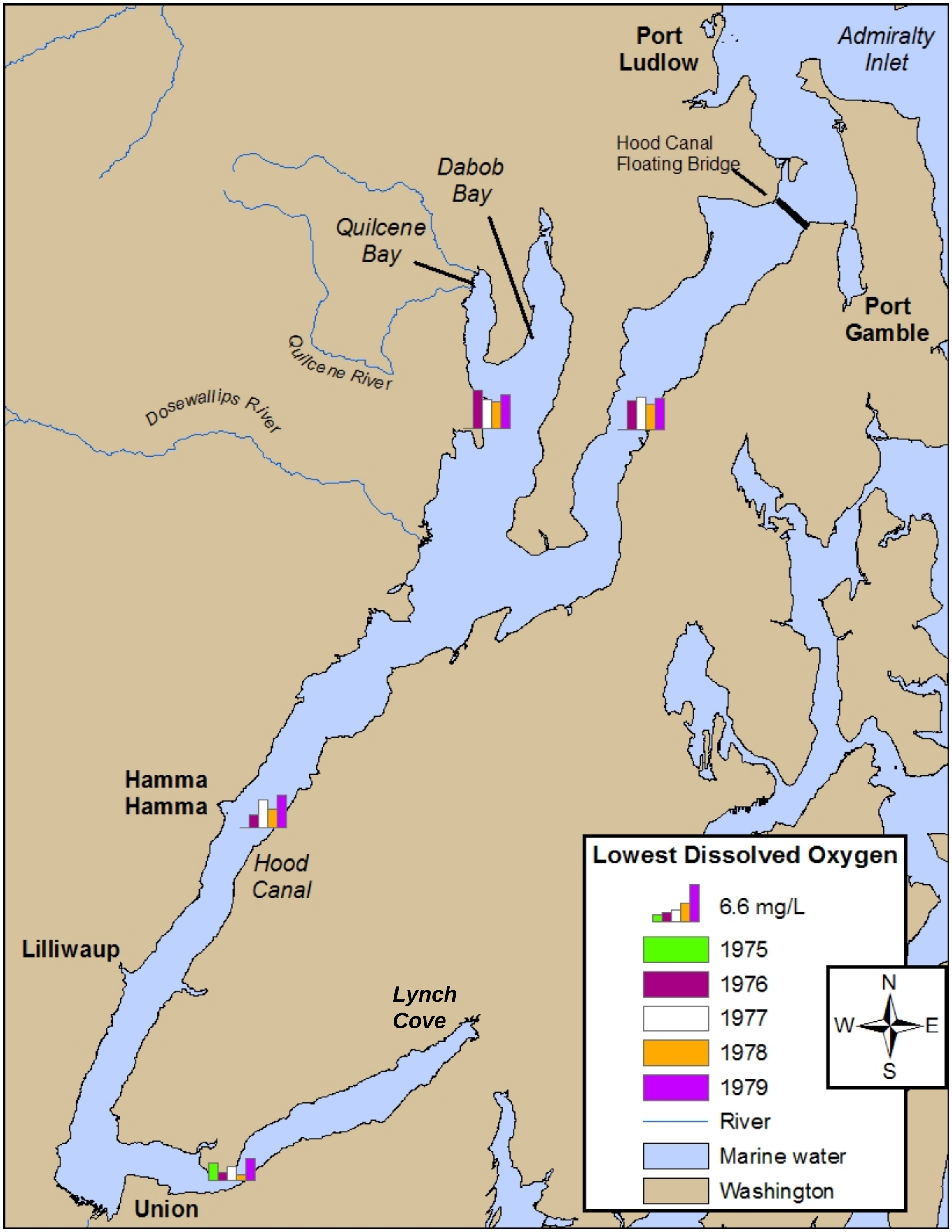


Figure 27. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1975 through 1979.

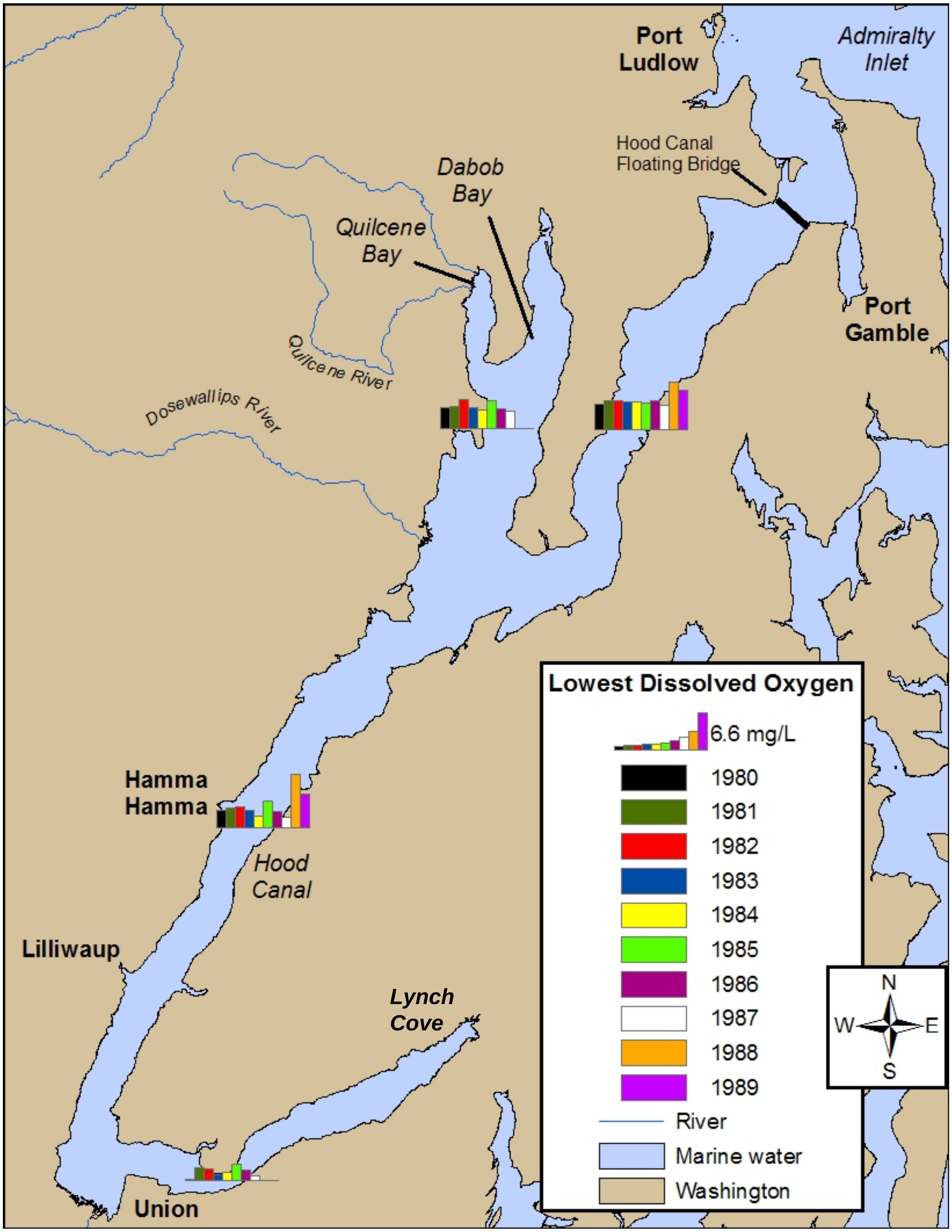


Figure 28. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1980 through 1989.

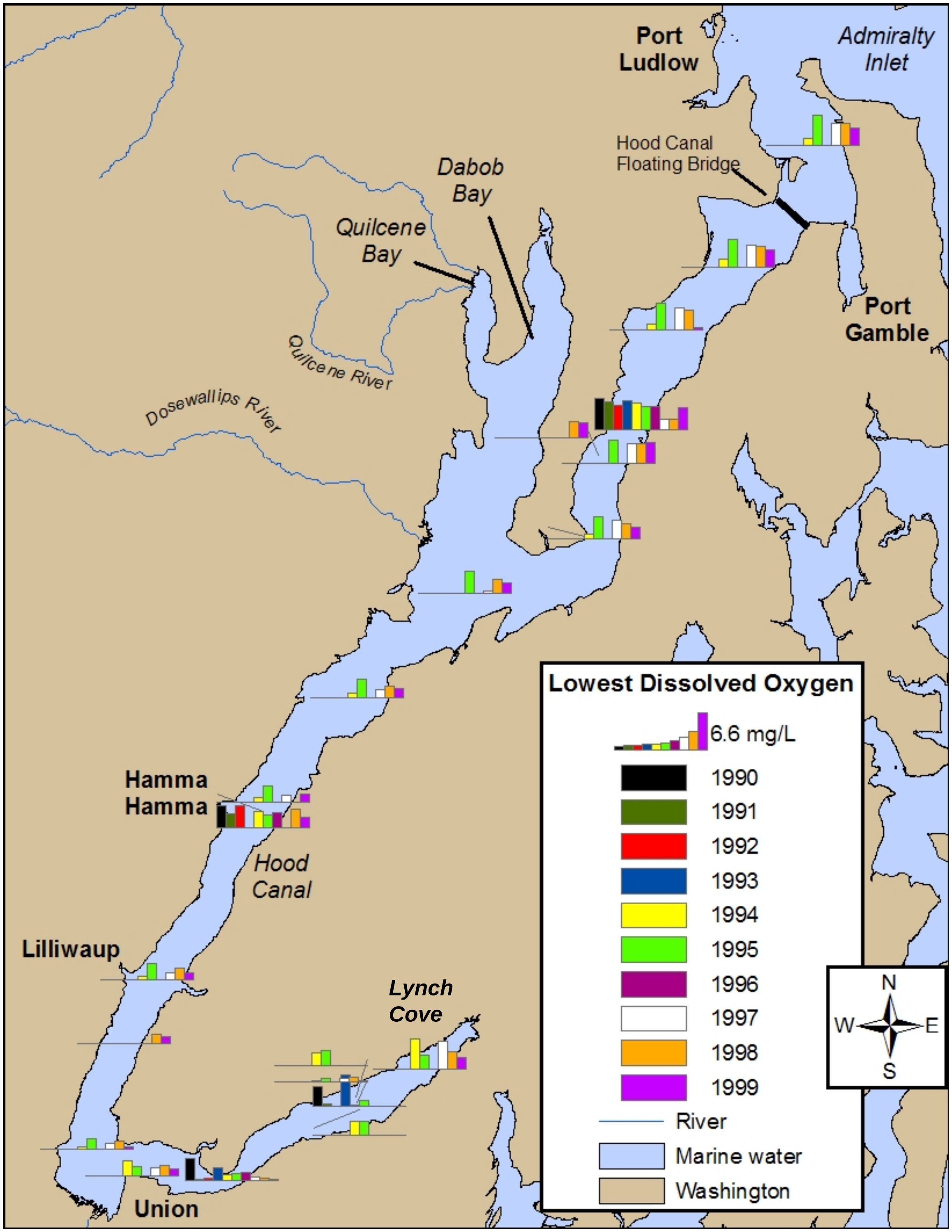


Figure 29. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 1990 through 1999.

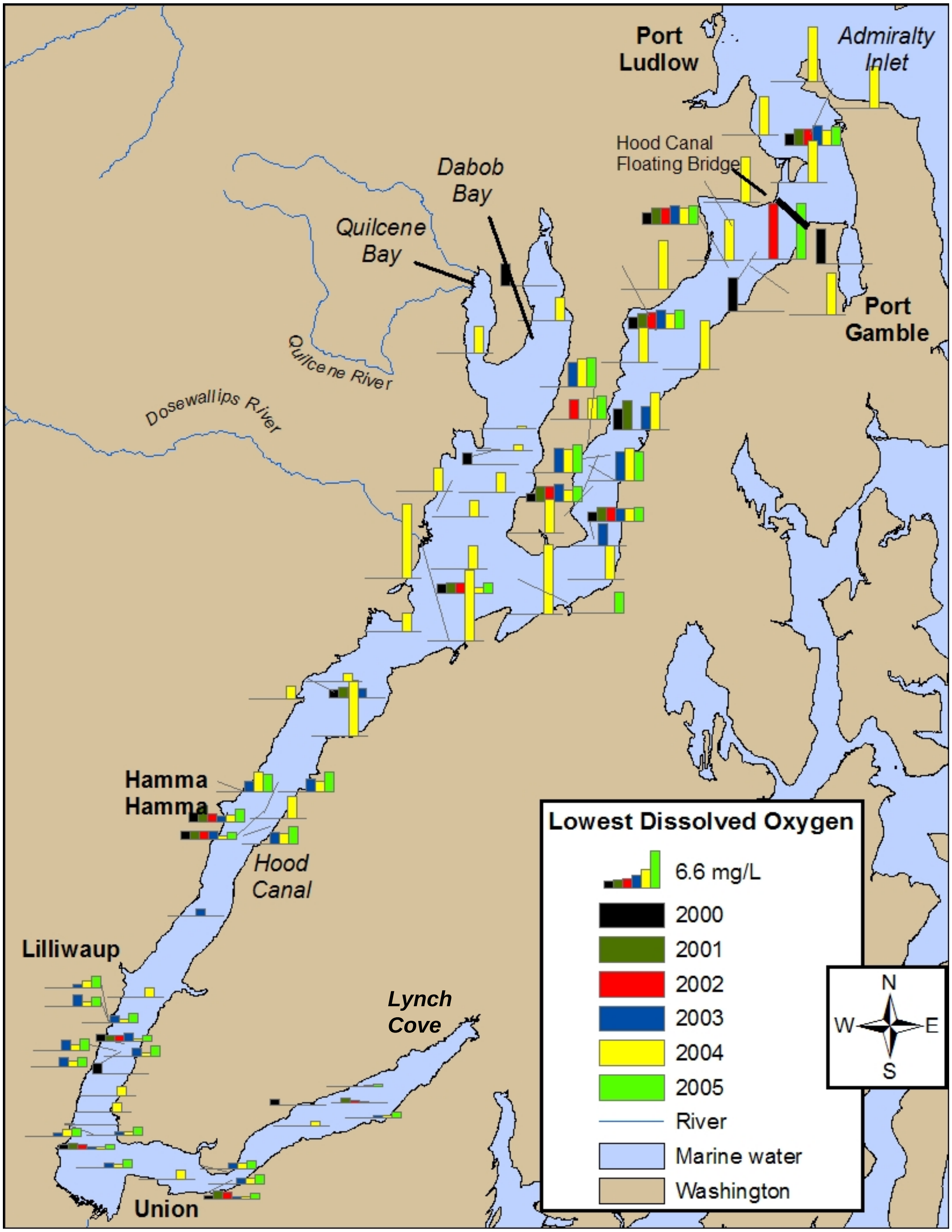


Figure 30. Lowest dissolved oxygen concentration measured annually at each station in Hood Canal for various monitoring programs from 2000 through 2005.

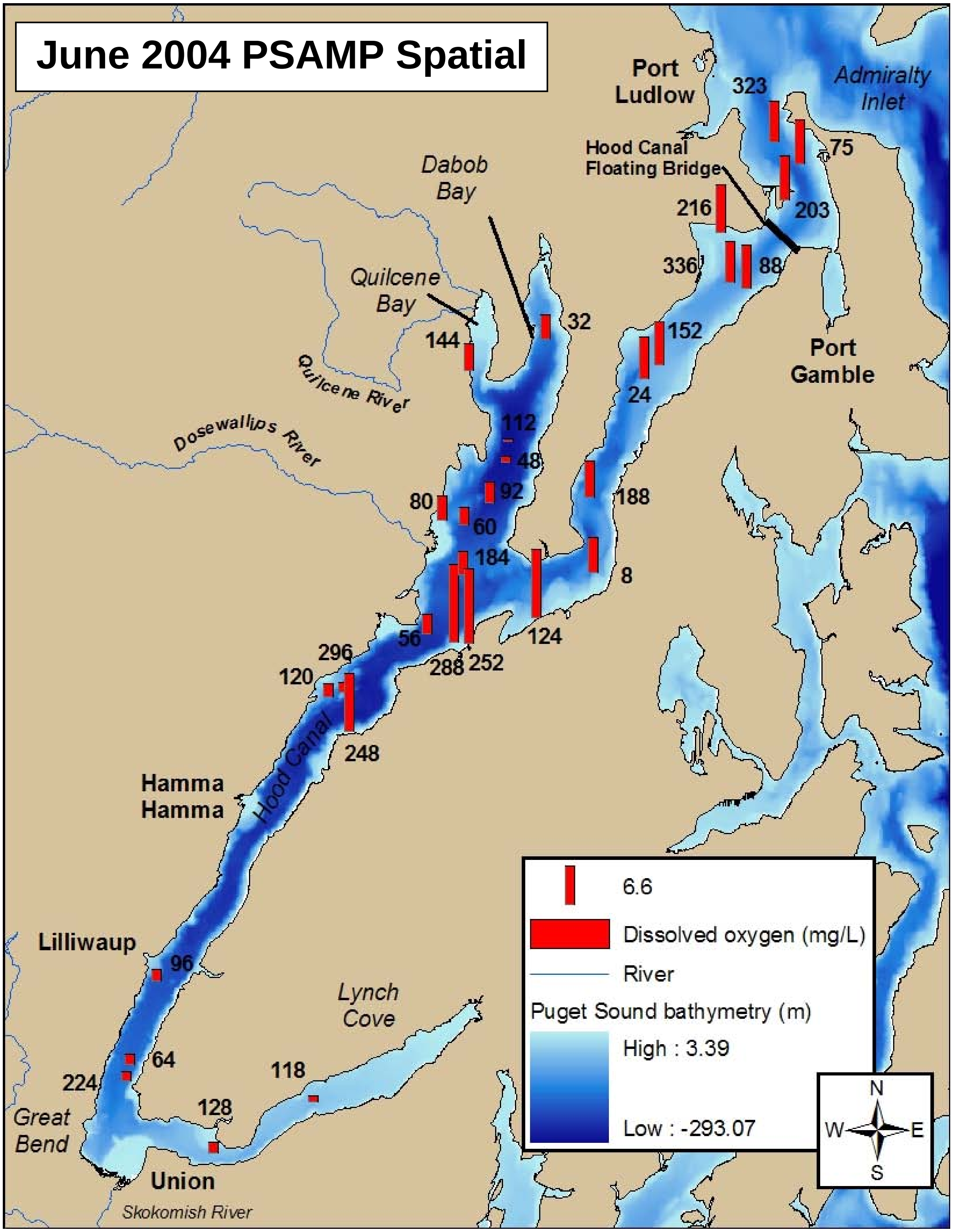


Figure 31. Dissolved oxygen concentrations measured during the June 2004 PSAMP Spatial Sediment Monitoring Program, and depth in meters relative to local extremely lower-low water (ELLW).

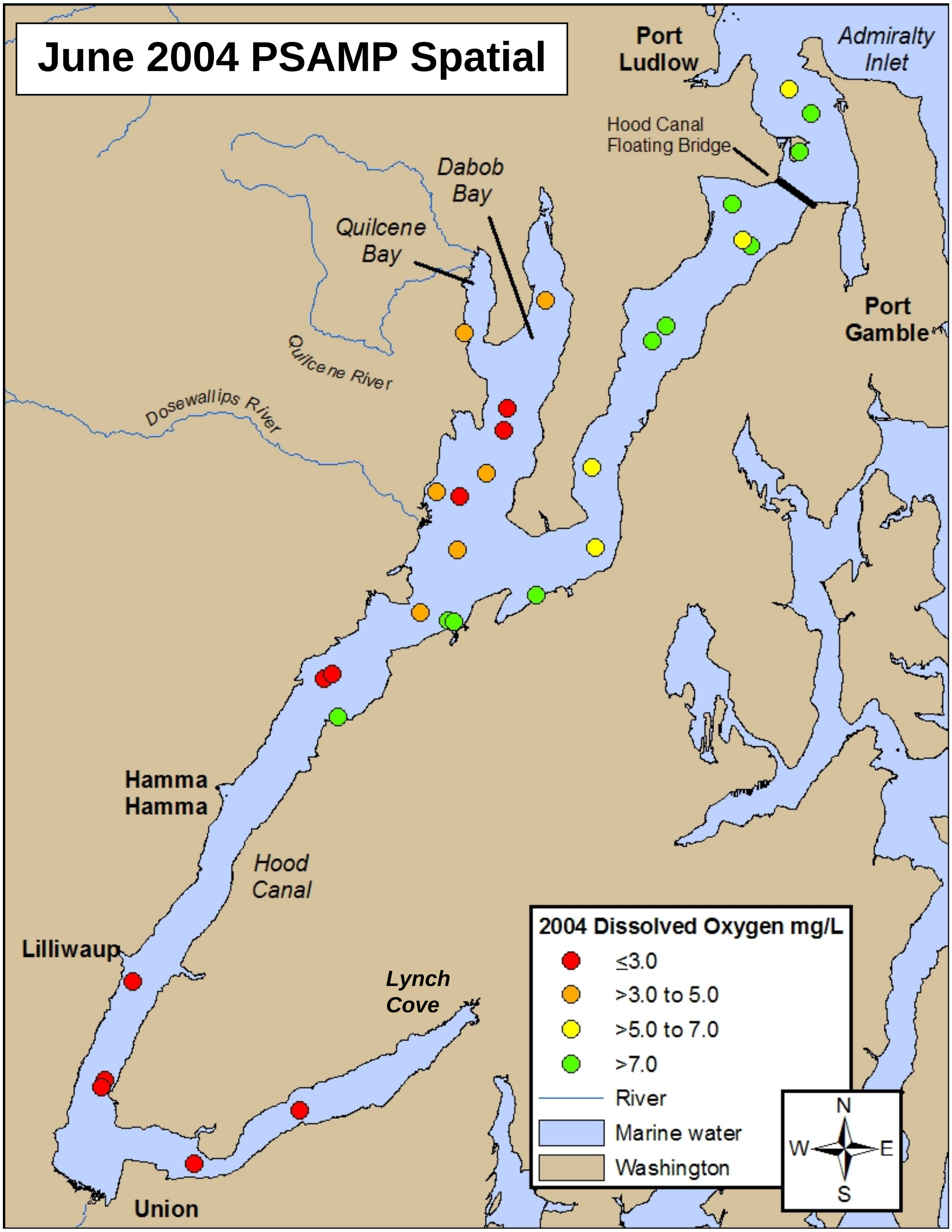


Figure 32. Dissolved oxygen concentrations measured during the June 2004 PSAMP Spatial Sediment Monitoring Program displayed relative to Washington State Water Quality Standards and threshold levels indicative of biological stress.

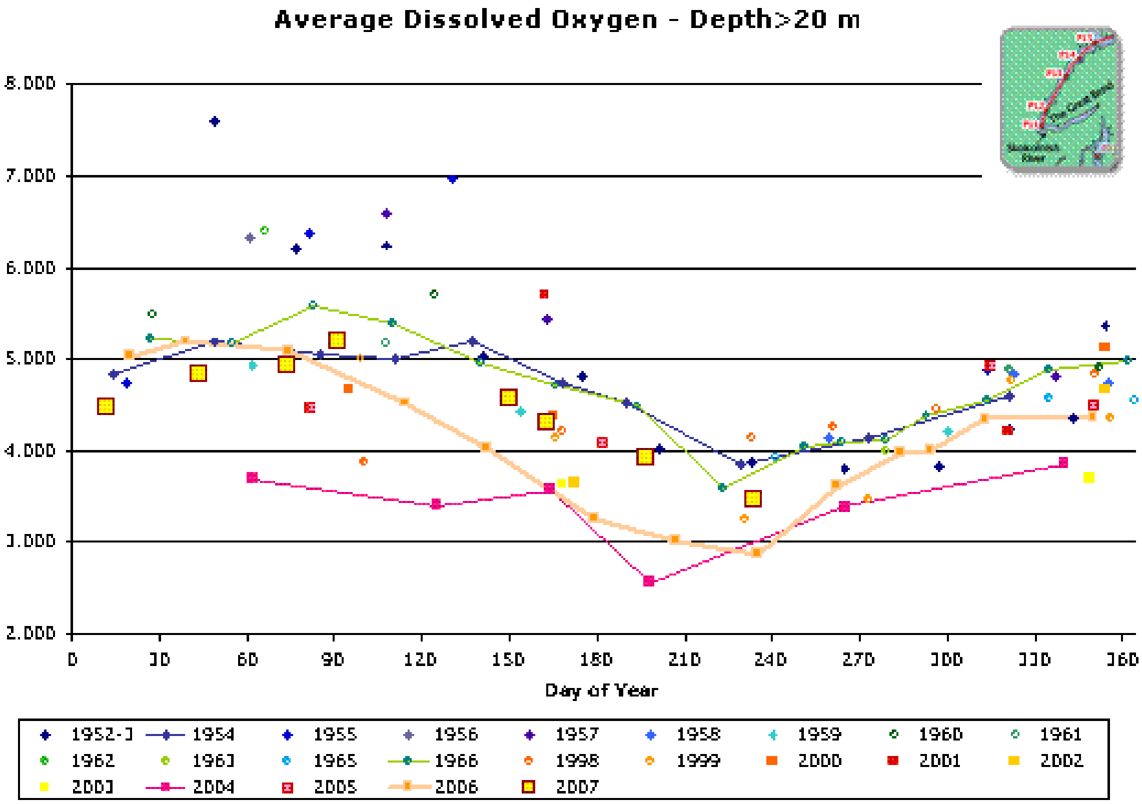


Figure 33. Average dissolved oxygen concentration in the water below 20 meters depth in the region between Dabob Bay and the Great Bend (PRISM Station 11) plotted versus the day of the year. Source: M. Warner (UW), HCDOP website: www.hoodcanal.washington.edu/observations/historicalcomparison.jsp *Viewed 14 August 2007*

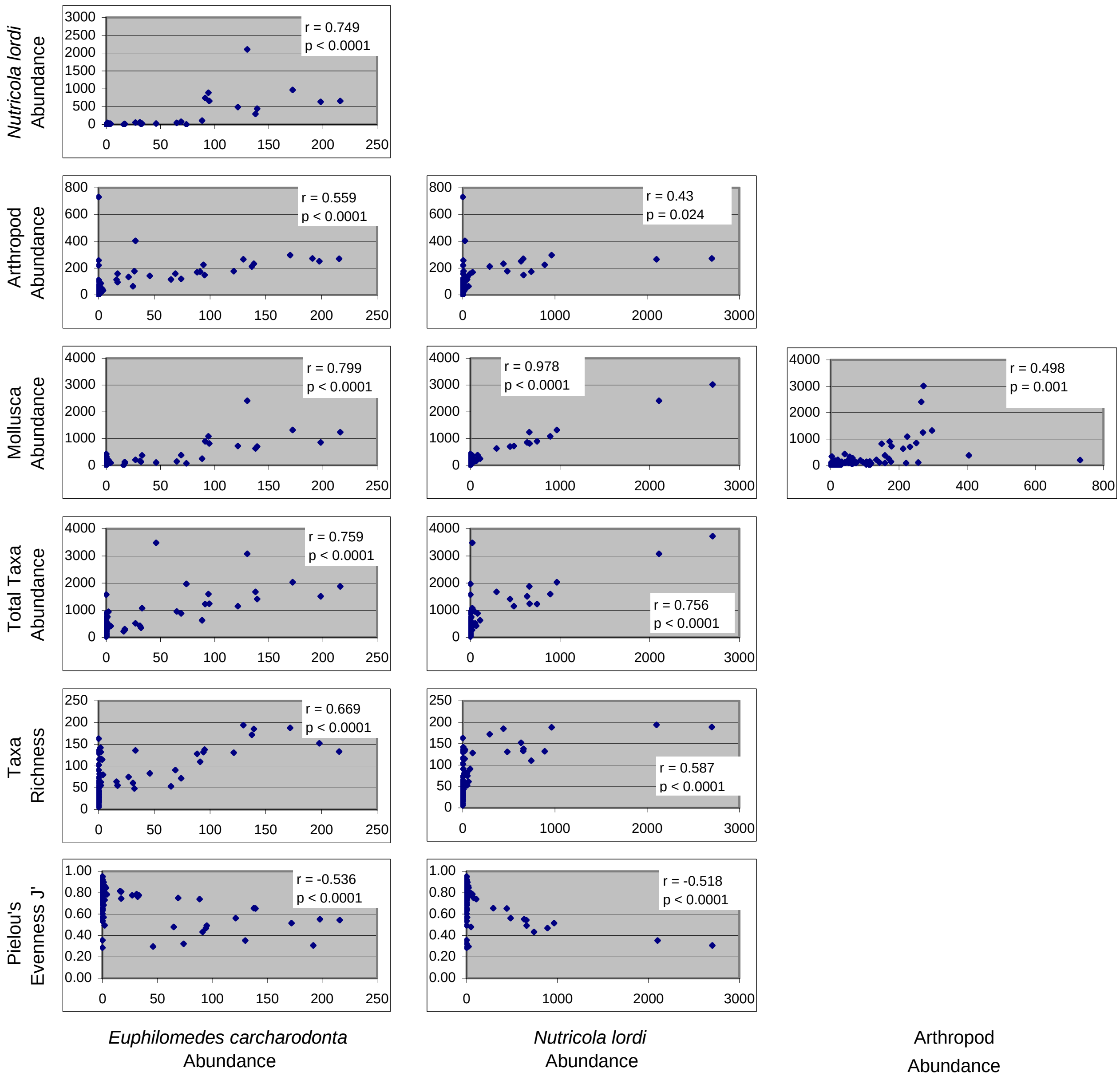


Figure 34. Bivariate scatterplots of selected biological measures from Hood Canal sediments for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value)

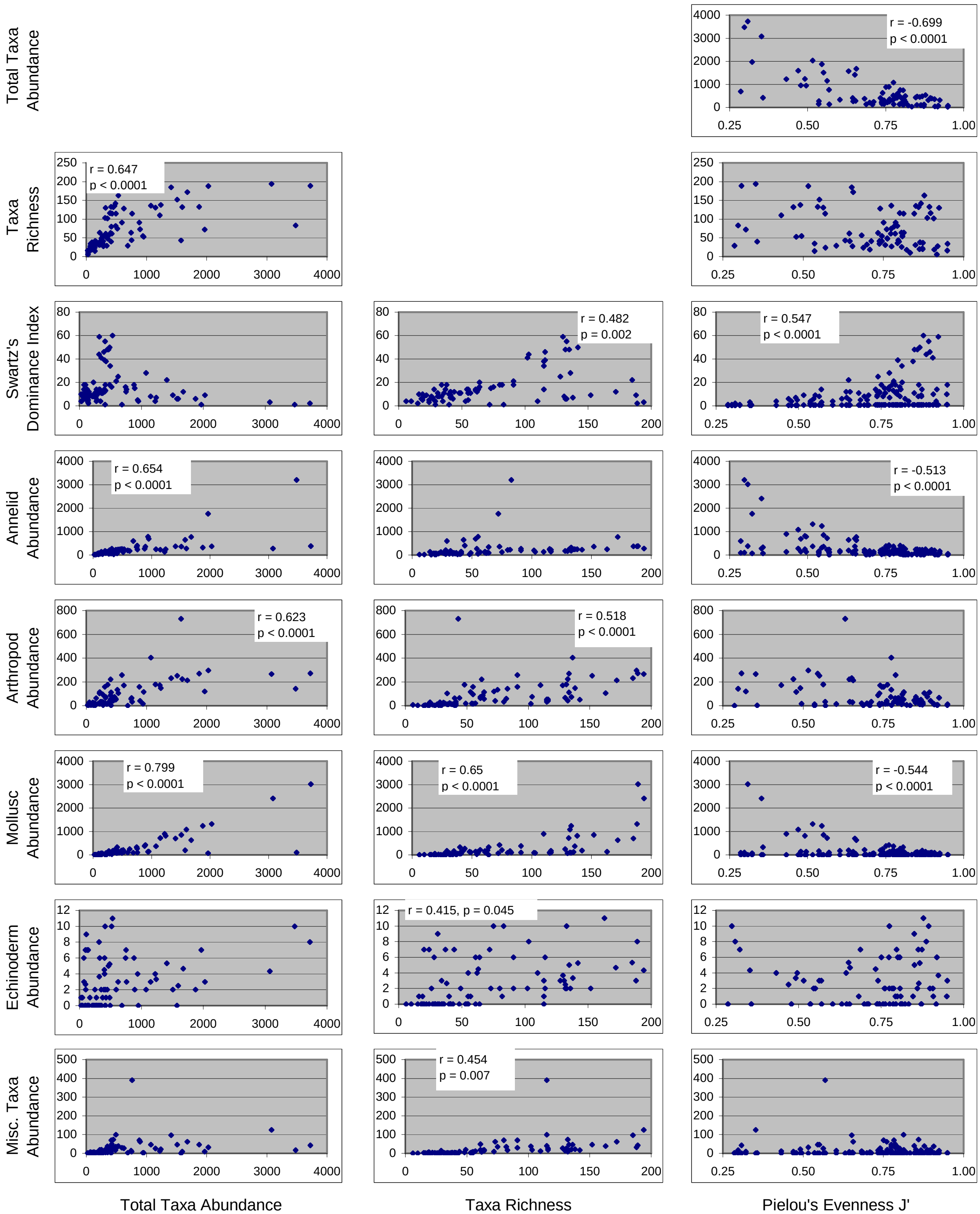


Figure 35. Bivariate scatterplots of selected biological measures from Hood Canal sediments for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation).

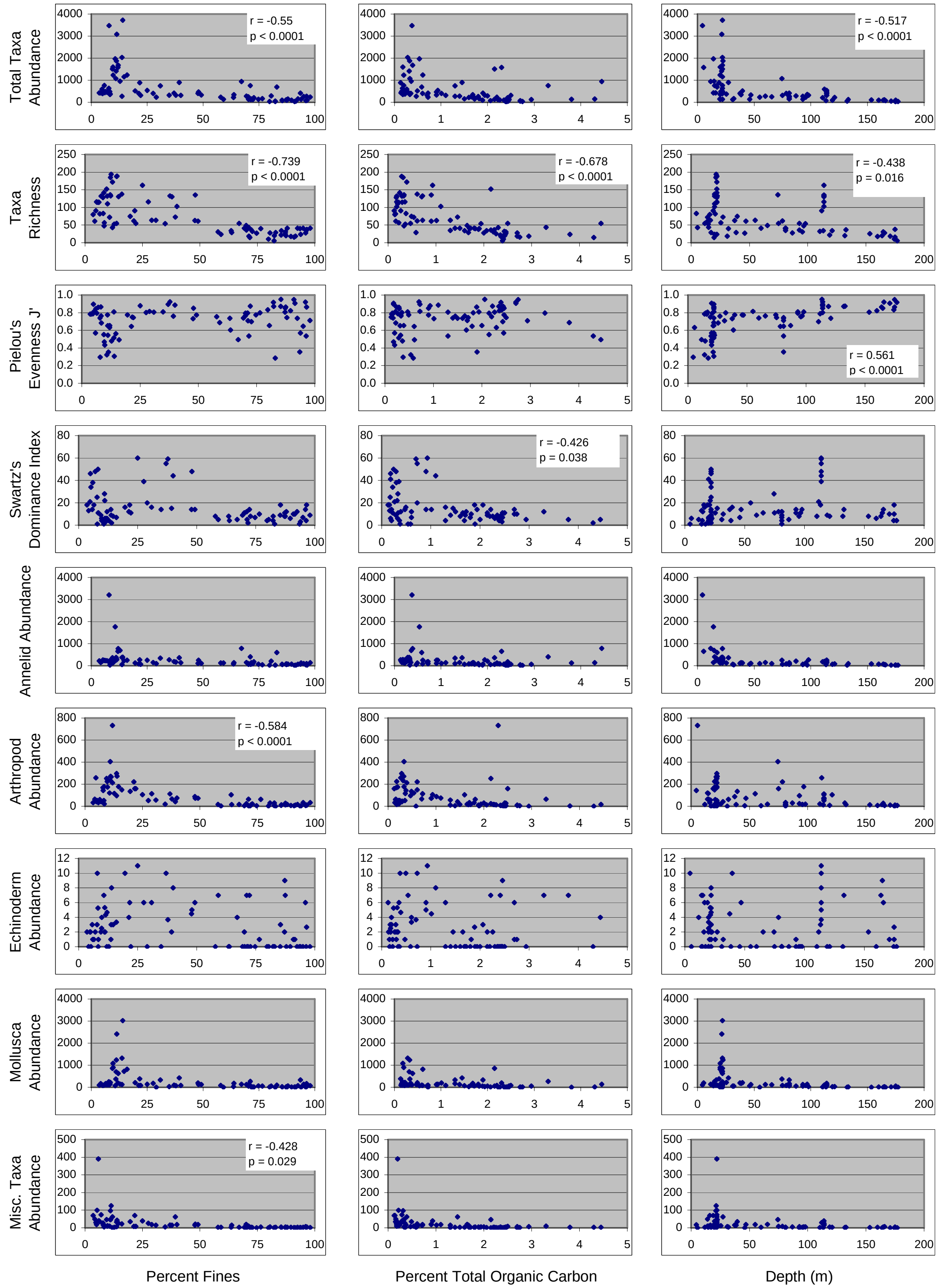


Figure 36. Bivariate scatterplots of selected biological and physical measures from Hood Canal sediments for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation).

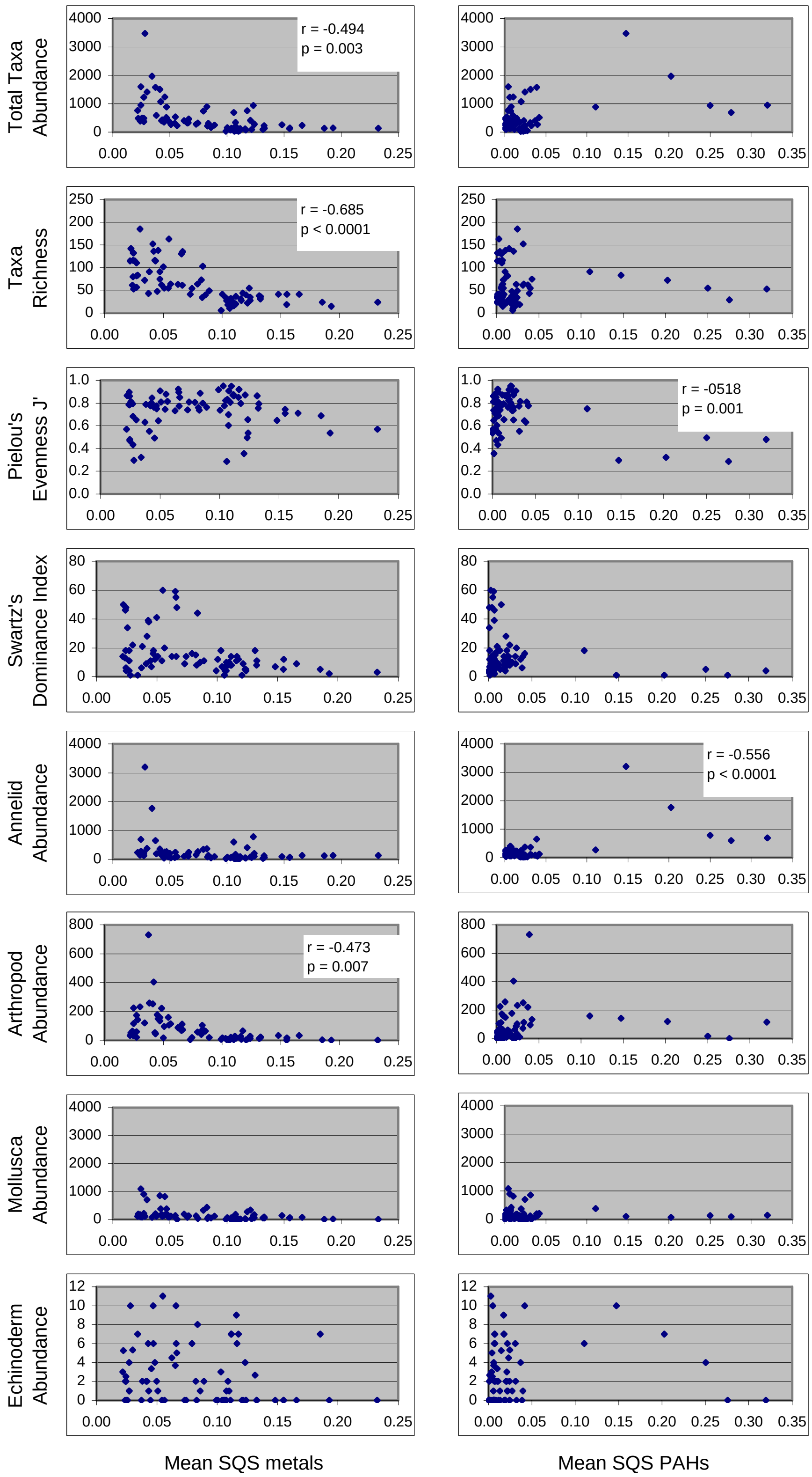


Figure 37. Bivariate scatterplots of selected biological and chemical measures from Hood Canal sediments for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation)

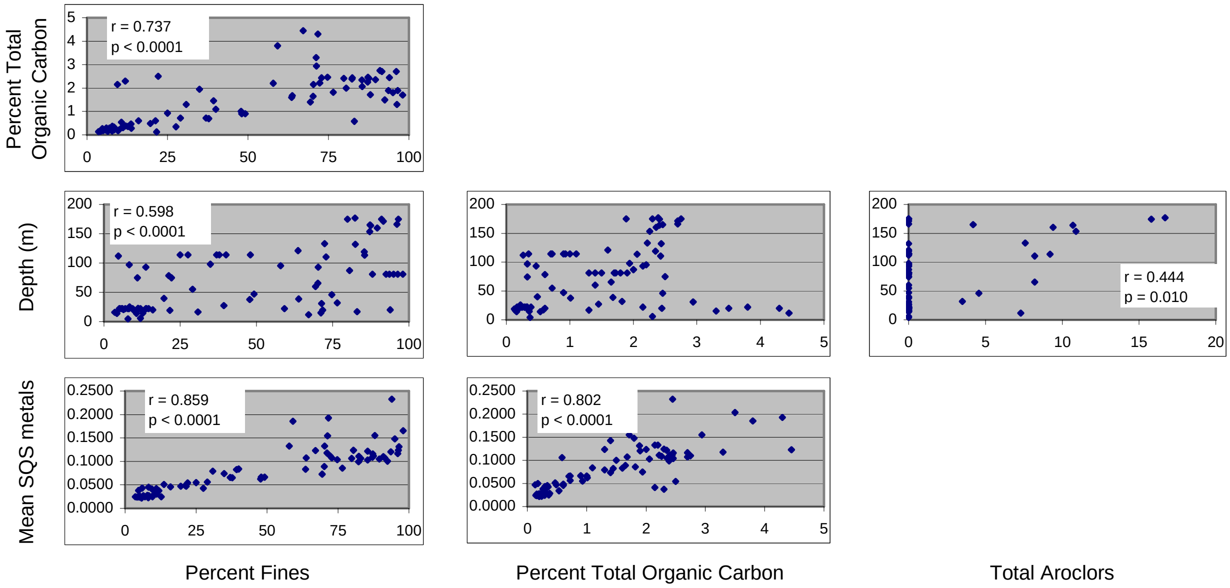


Figure 38. Bivariate scatterplots of selected physical and chemical measures from Hood Canal sediments for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation).

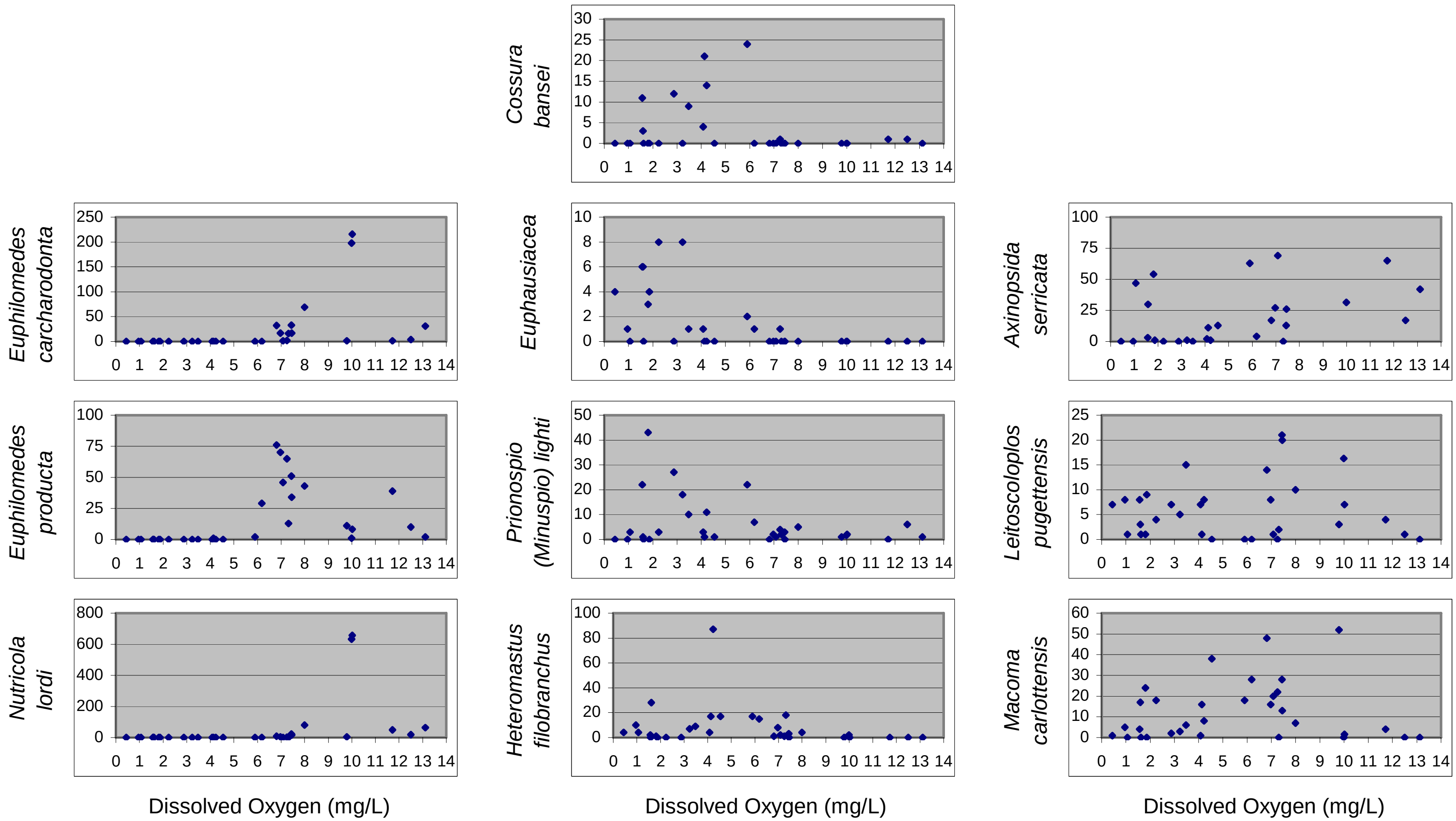


Figure 39. Bivariate scatterplots of selected biological vs. near-bottom dissolved oxygen measures from Hood Canal sediments for the 2004 PSAMP Spatial Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation)

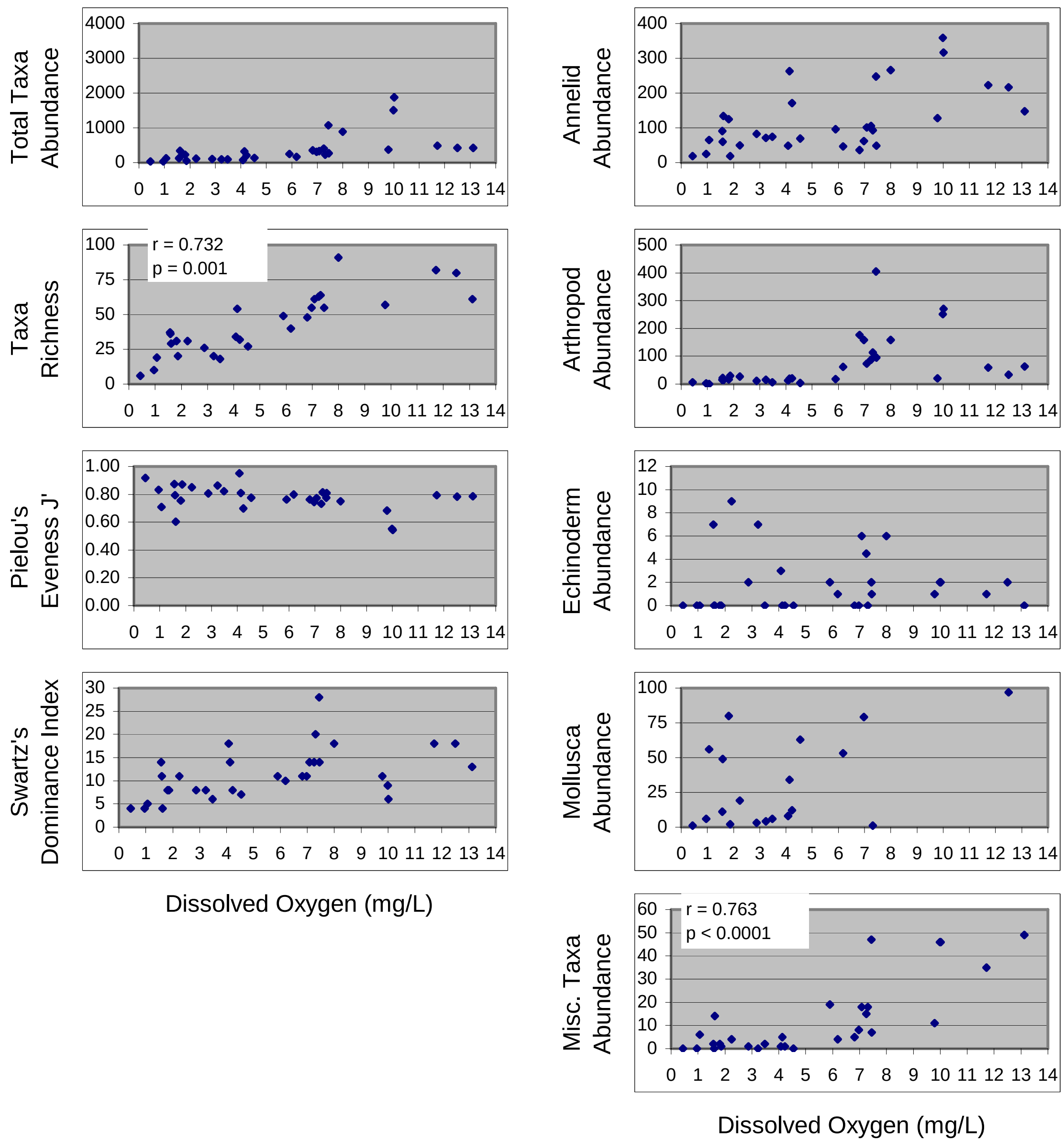


Figure 40. Bivariate scatterplots of selected biological vs. near-bottom dissolved oxygen measures from Hood Canal sediments for the 2004 PSAMP Spatial Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation)

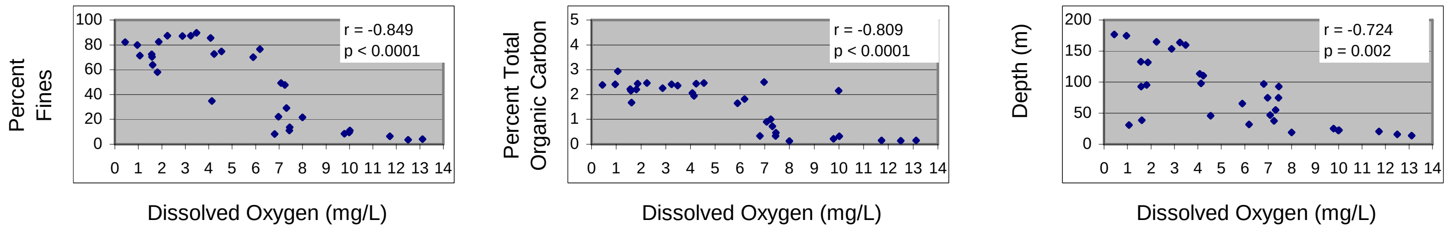


Figure 41. Bivariate scatterplots of selected physical vs. near-bottom dissolved oxygen measures from Hood Canal sediments for the 2004 PSAMP Spatial Monitoring Program. Plots without rho and p values have data that are not significantly correlated.

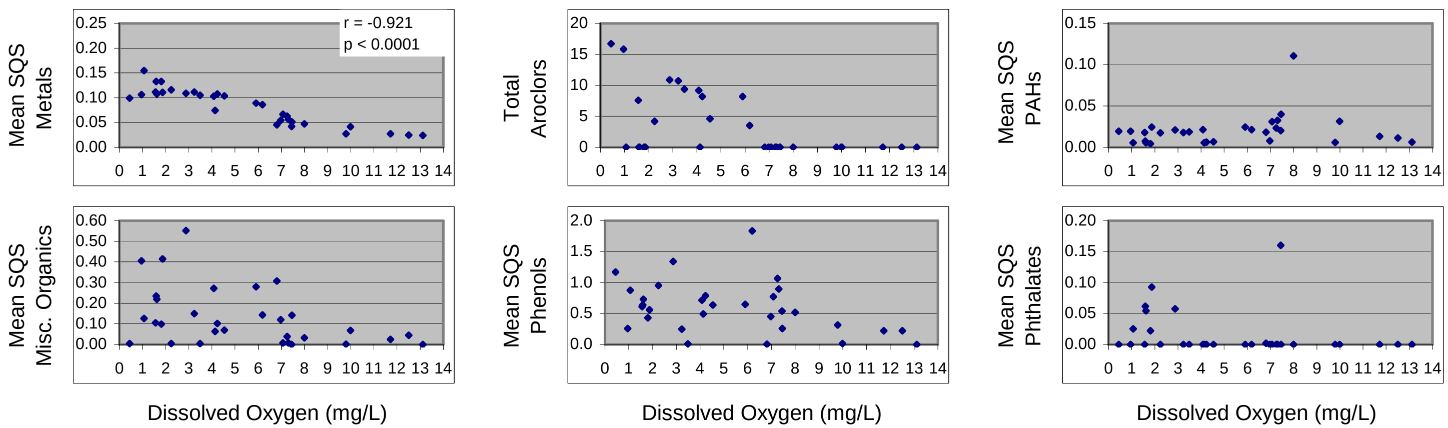


Figure 42. Bivariate scatterplots of selected chemical vs. near-bottom dissolved oxygen measures from Hood Canal sediments for the 2004 PSAMP Spatial Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation)

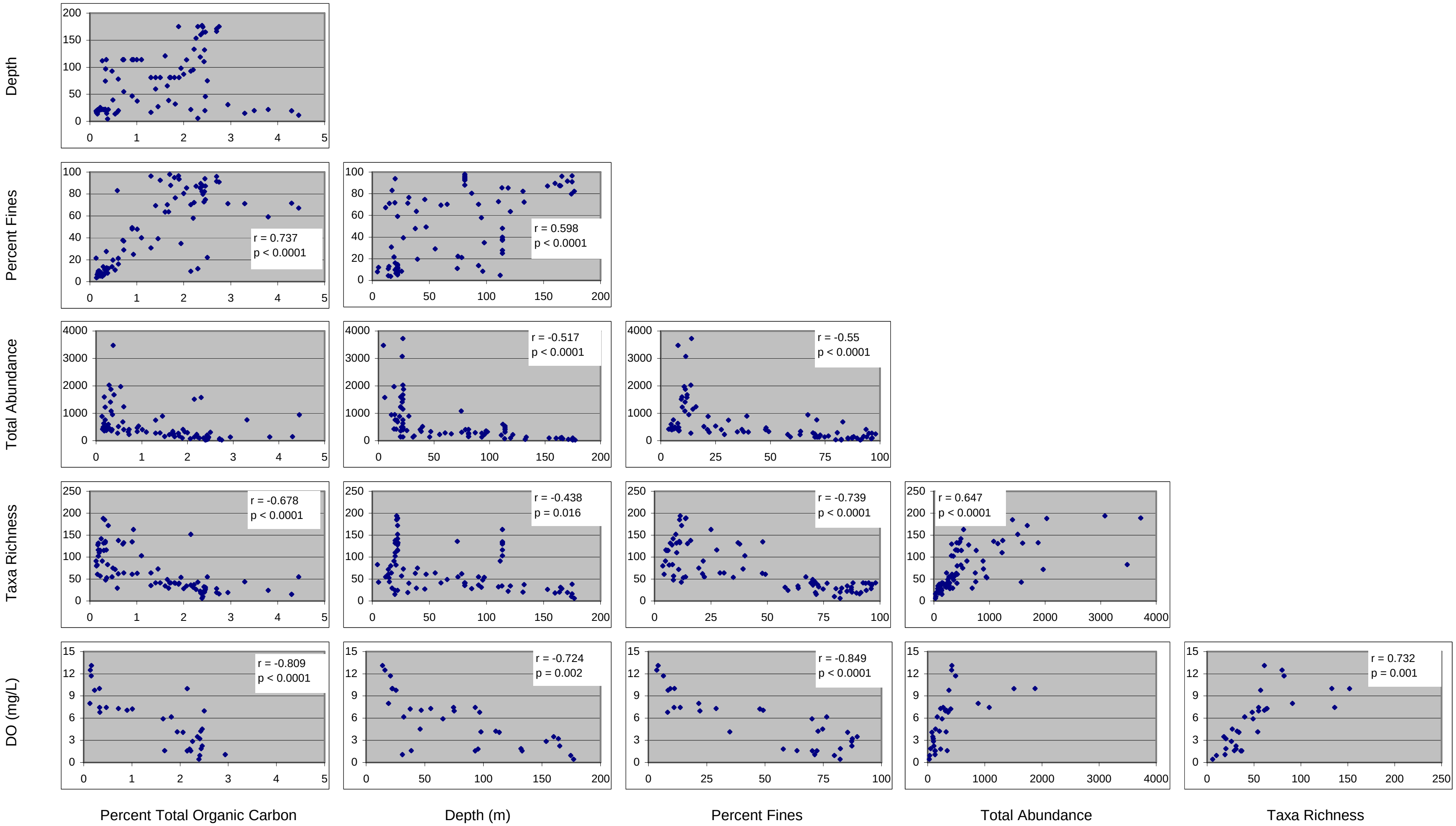


Figure 43. Bivariate scatterplots of selected biological and physical measures from Hood Canal sediments for the 1999 and 2004 PSAMP Spatial Monitoring Programs and the 1989-2005 PSAMP Temporal Monitoring Program. (r = correlation coefficient, p = Bonferroni-corrected probability value, plots without r and p values indicate non-significant correlation)

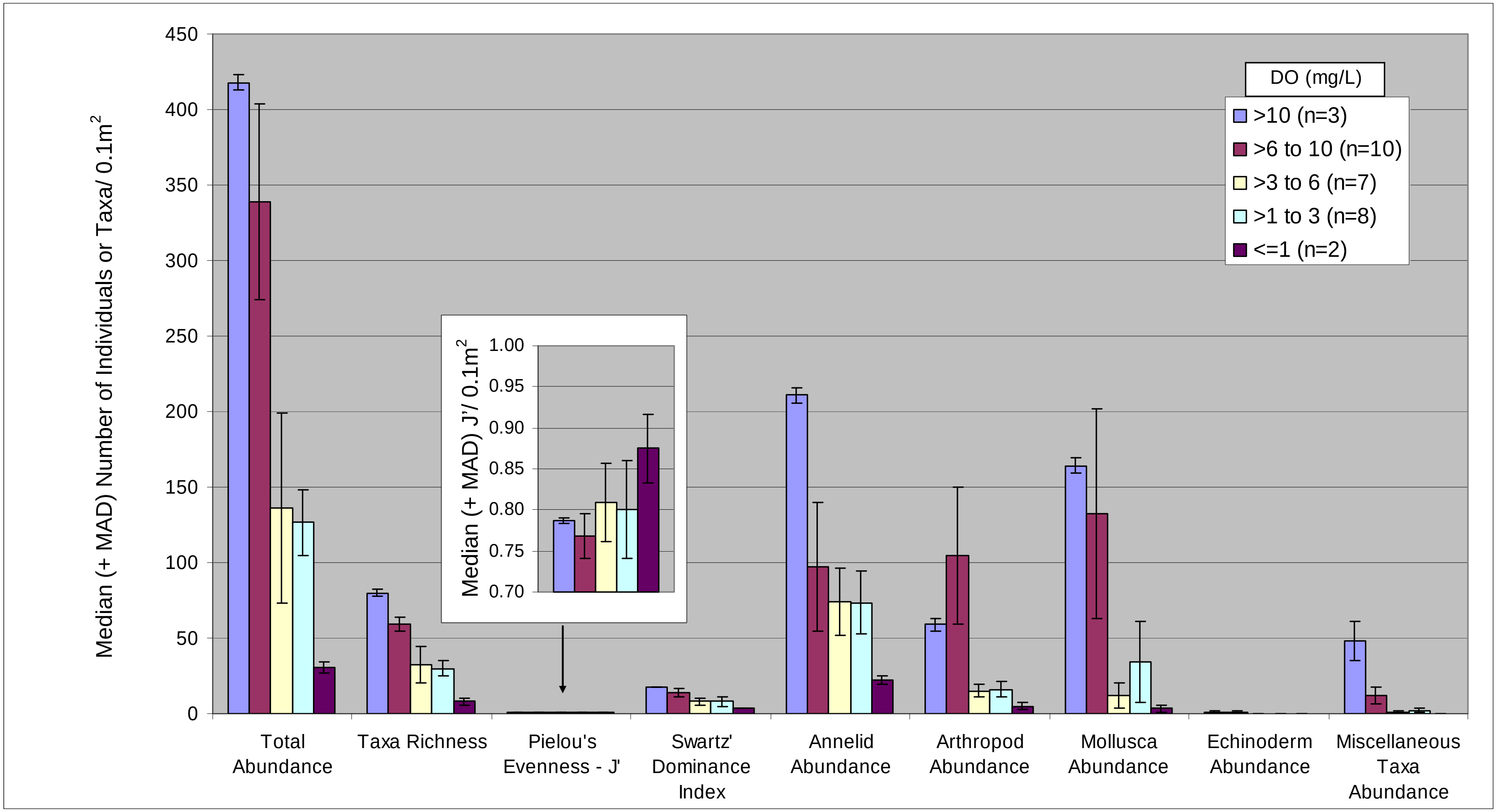


Figure 44. Median (+ MAD) benthic index values calculated for stations in five dissolved oxygen ranges measured during the June 2004 PSAMP Spatial Sediment Monitoring Program.

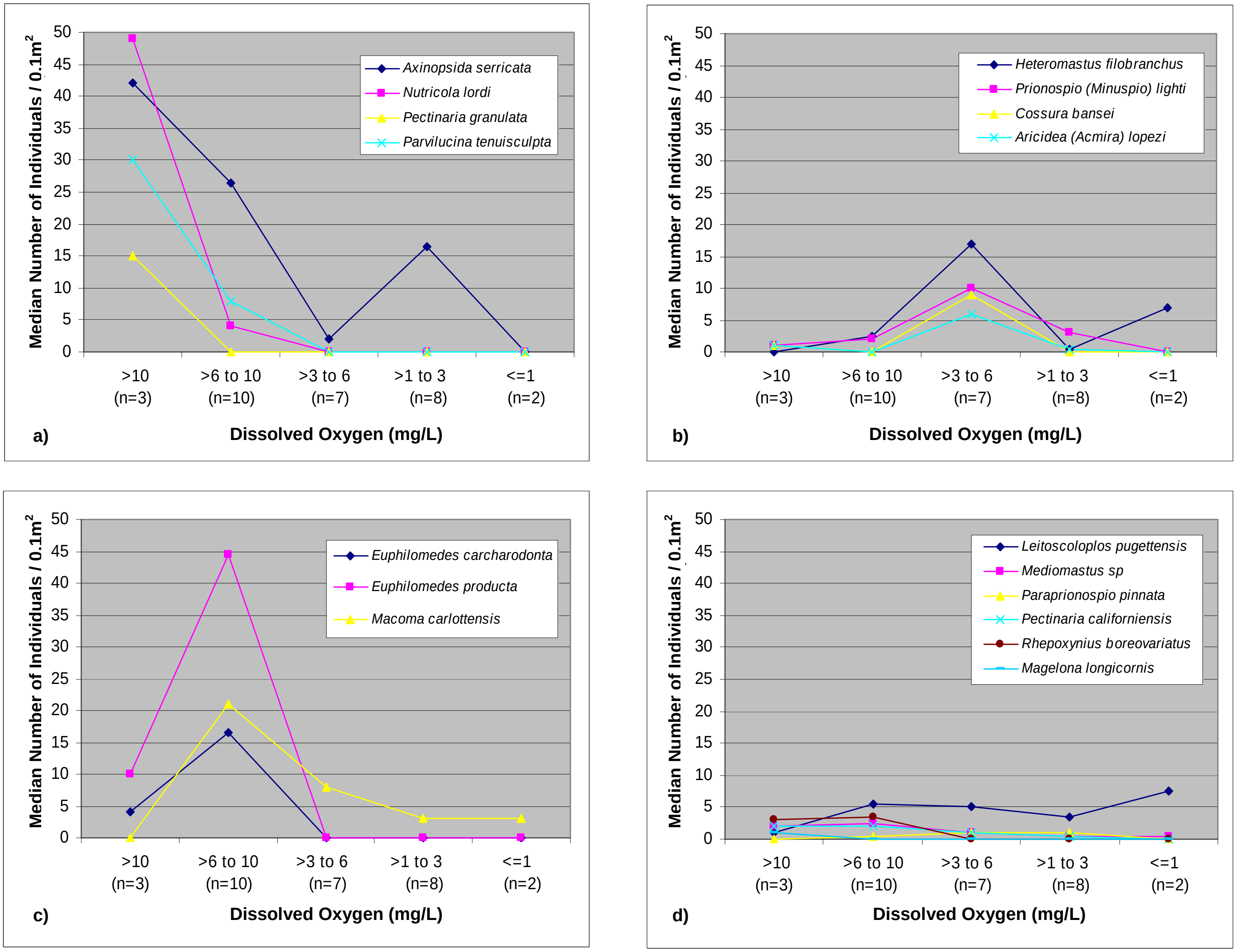


Figure 45. Median number of individuals for 17 indicator species, calculated for stations in five dissolved oxygen ranges measured during the June 2004 PSAMP Spatial Sediment Monitoring Program.

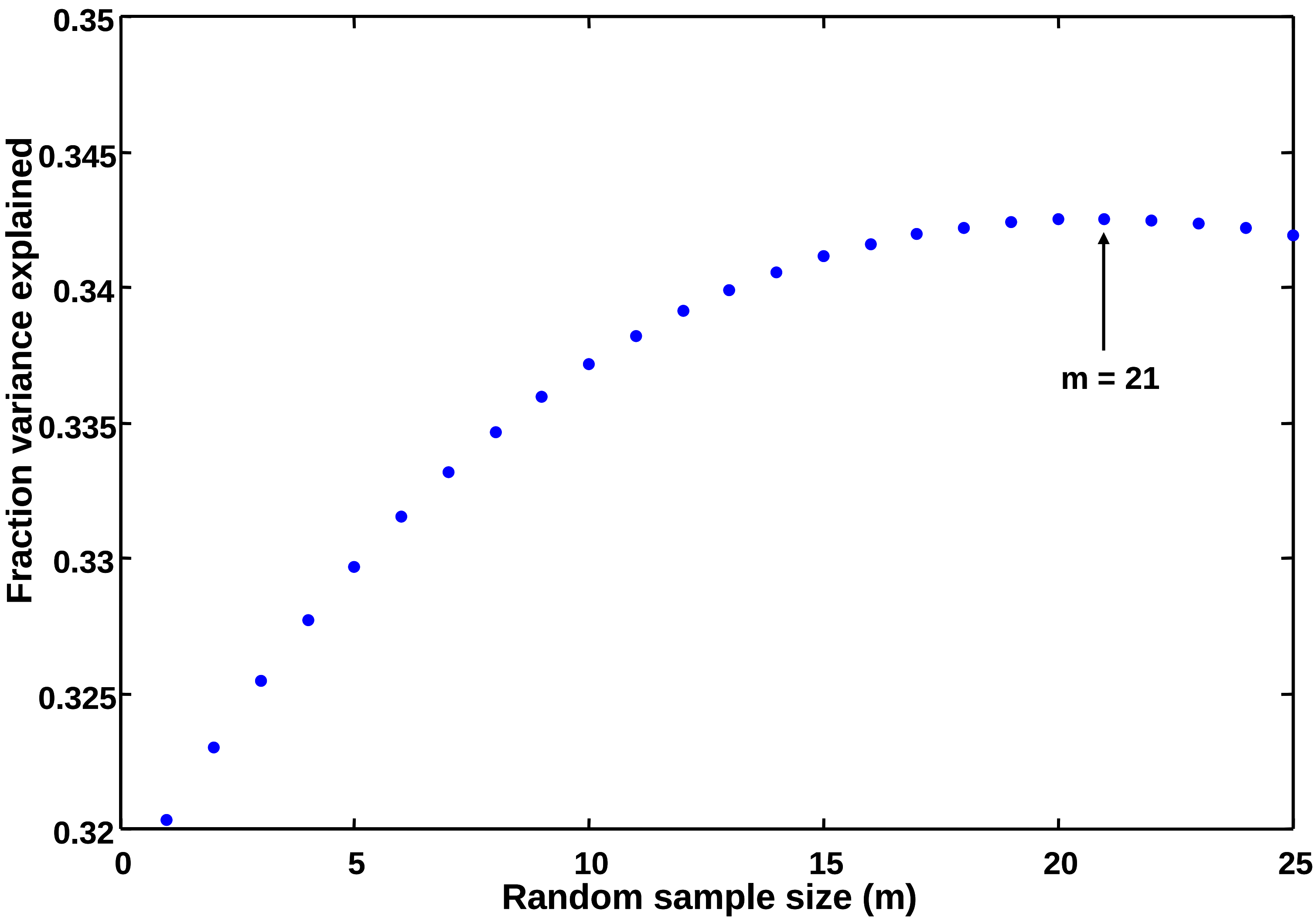


Figure 46. Determination of the optimal random sample size, m, for the hypergeometric transformation. The fraction of variance explained was calculated from the sum of the canonical eigenvalues.

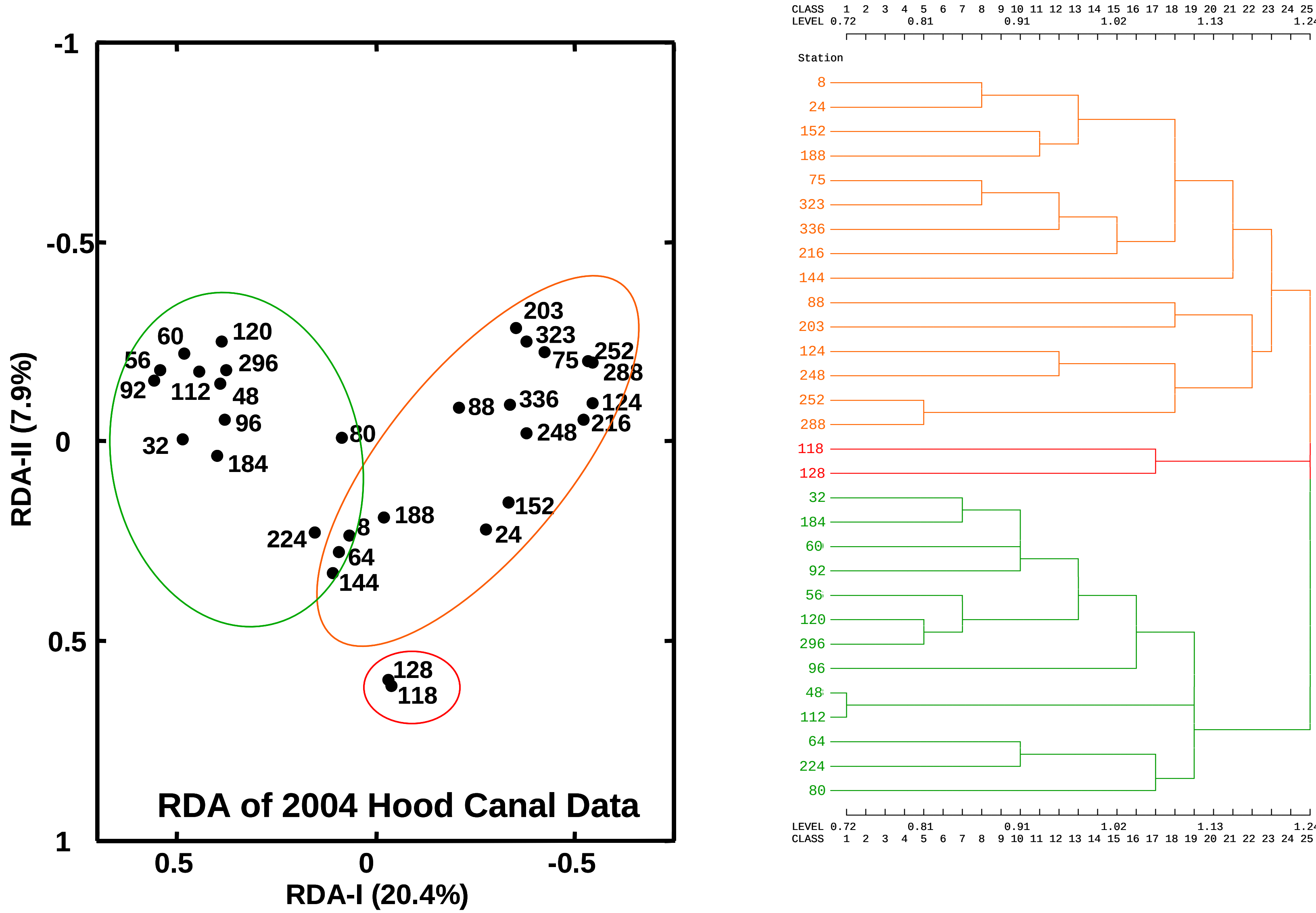


Figure 47. Plot of station sites from the 2004 survey along the first two canonical axes of the RDA (left). Circled stations correspond to the dendrogram (right), created from cluster analysis of the 2004 stations using UPGMA (unweighted pair-group method using arithmetic averages) clustering of the distance metric CNESS.

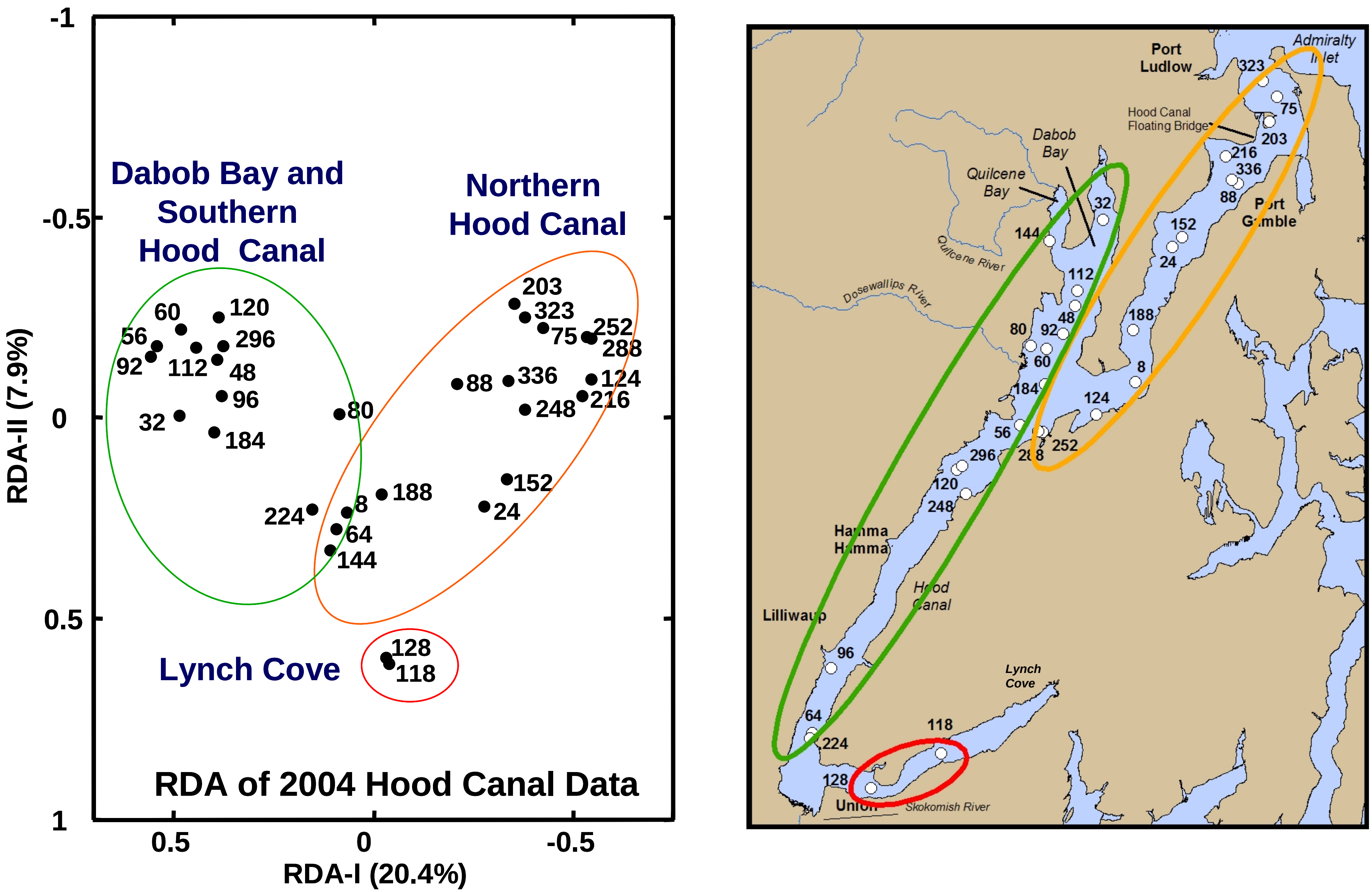


Figure 48. Station sites from the 2004 PSAMP Spatial Sediment survey (left), and map of Hood Canal showing the geographic locations of the sampling stations (right). Circled stations in plot correspond to the circled stations in map.

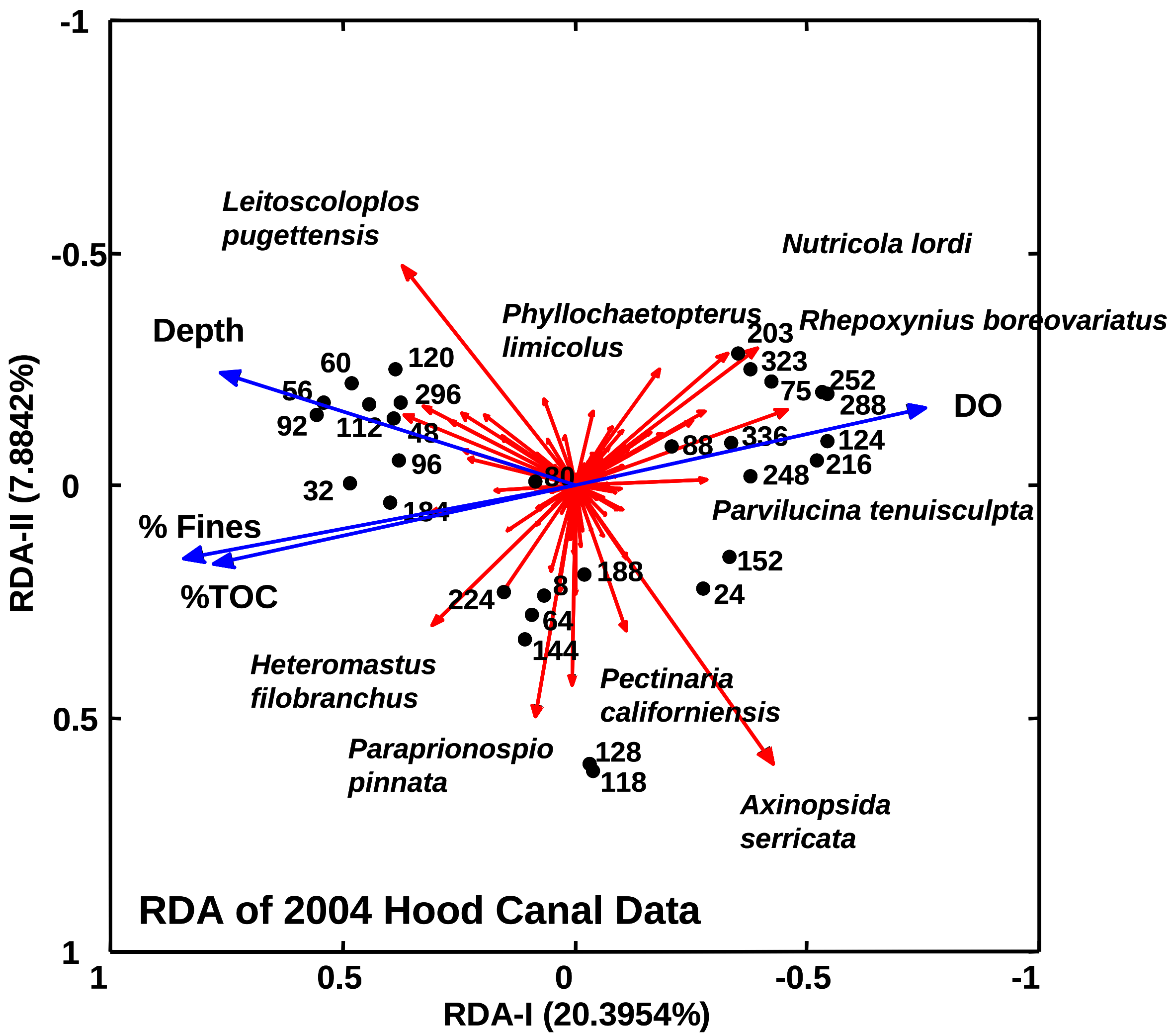


Figure 49. Plot of 2004 station sites along the first two canonical axes. Lengths of environmental vectors (blue) represent the correlation of the environmental variables with the first two axes. The arrangement of sites along the quantitative variable vectors approximates the rank order of stations corresponding to each variable. The arrangement of sites along the species vectors (red) approximates the rank order of abundance of that species at each site.

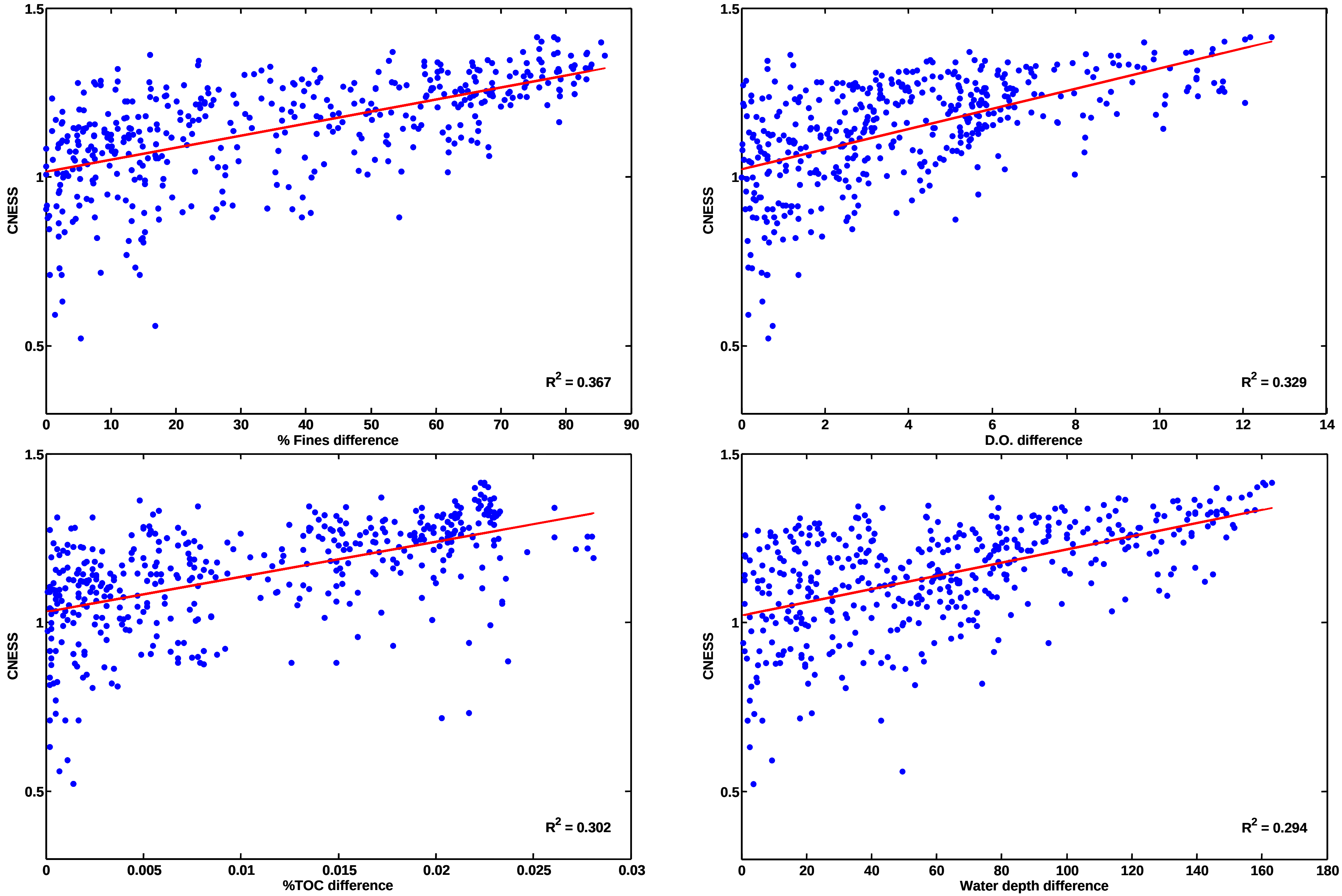
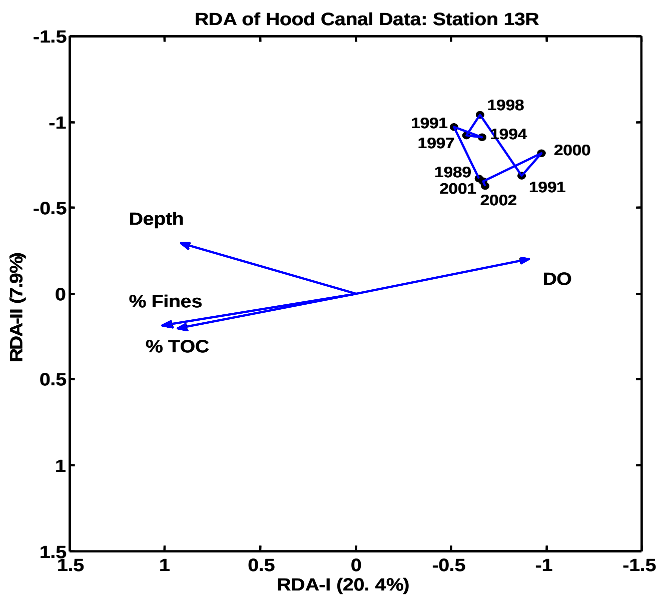
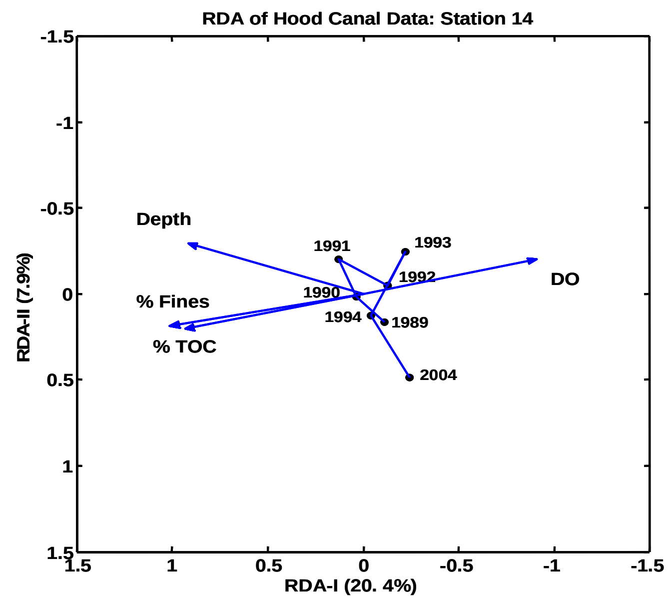


Figure 50. The CNESS distance among stations plotted versus the differences in % fines, dissolved oxygen, % total organic carbon, and water depth among stations.





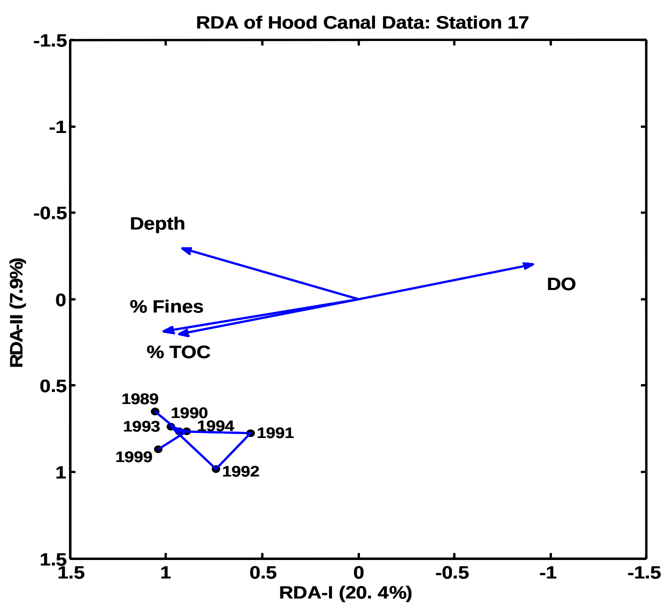


Figure 51. Plots of the station scores for the long-term data set for three locations along the first two canonical axes calculated using the 2004 data. Blue vectors represent the environmental variables. The contribution of dissolved oxygen to benthic community structure of each station can be estimated by the location of an orthogonal projection of the station onto the dissolved oxygen vector.

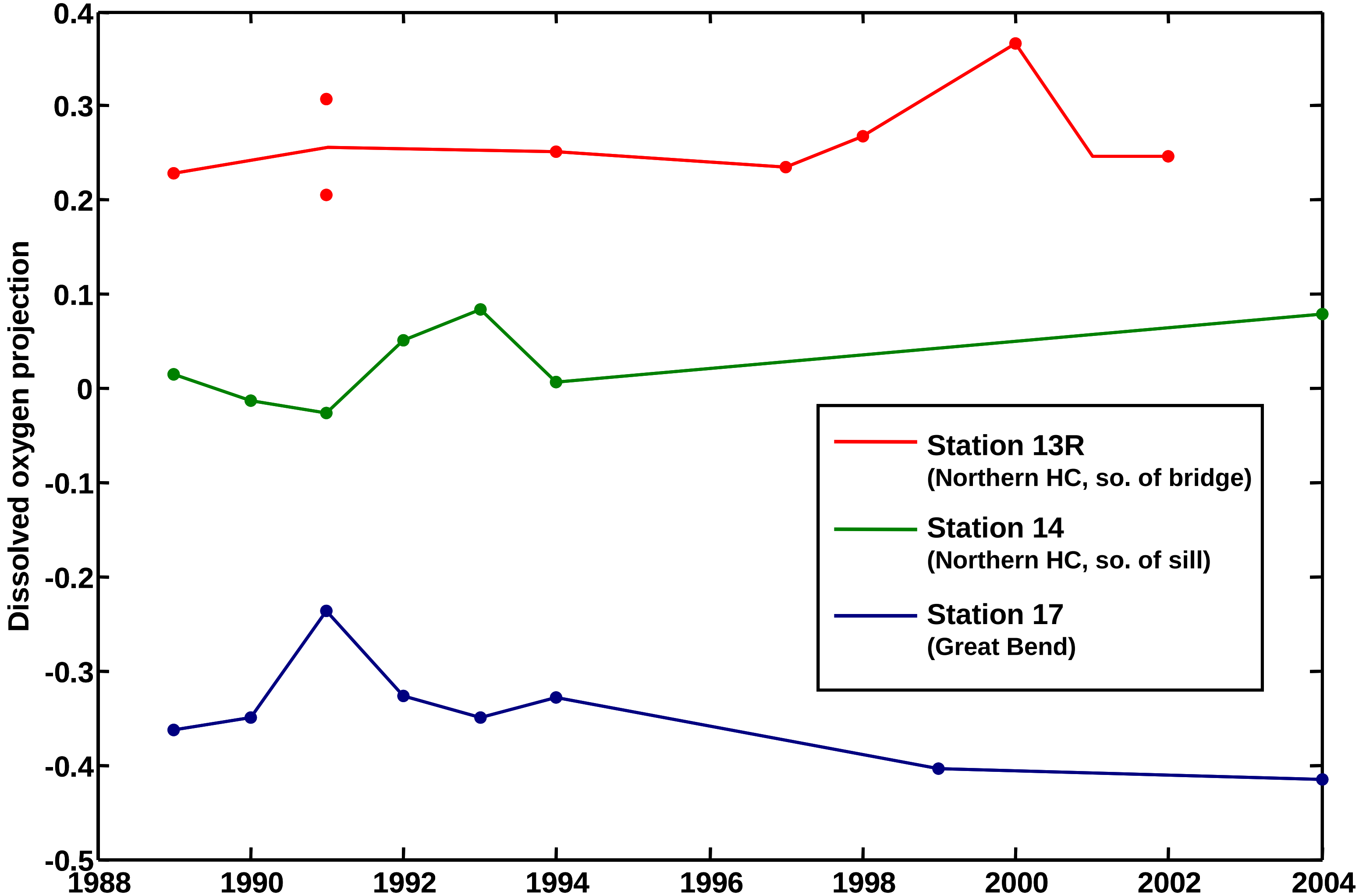


Figure 52. Index of the contribution of dissolved oxygen to overall variation in benthic community structure versus sampling year for the long-term benthic data set for three stations in Hood Canal. A positive value of the index indicates benthic community structure associated with relatively high dissolved oxygen concentration. A negative value indicates benthic community structure associated with relatively low dissolved oxygen concentration.

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Tables

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Table 1. Physical and chemical parameters measured and calculated for sediments collected from Hood Canal between 1952 and 2005.

<u>Related Parameters</u>
Depth
Grain Size
Overlying salinity
Total organic carbon
Sulfide
Carbon disulfide

<u>Inorganics</u>
Ancillary Metals
Aluminum
Barium
Calcium
Cobalt
Iron
Magnesium
Manganese
Potassium
Sodium
Vanadium

Priority Pollutant Metals
Antimony
Arsenic
Beryllium
Cadmium
Chromium
Copper
Lead
Mercury
Nickel
Selenium
Silver
Thallium
Zinc

Elements
Silicon
Tin

<u>Organics</u>
Aromatic and Chlorinated Aromatic
Benzene
Chlorobenzene
Ethylbenzene
Styrene
Toluene
Total xylenes

Chlorinated Alkanes
Hexachloroethane
Hexachlorobutadiene
Hexachlorocyclopentadiene

Chlorinated and Nitro-Substituted Phenols
2,4,5-trichlorophenol
2,4,6-trichlorophenol
2,4-dichlorophenol
2,4-dinitrophenol
2-chlorophenol
2-nitrophenol
4,6-dinitro-2-methylphenol
4-chloro-3-methylphenol
4-nitrophenol
Pentachlorophenol

Chlorinated Aromatic Compounds
1,2,4-trichlorobenzene
1,2-dichlorobenzene
1,3-dichlorobenzene
1,4-dichlorobenzene
2-chloronaphthalene
Hexachlorobenzene

Chlorinated Pesticides
2,4'-DDD
2,4'-DDE
2,4'-DDT
4,4'-DDD
4,4'-DDE
4,4'-DDT
Aldrin
Alpha-BHC
Alpha-chlordane
Beta-BHC
Cis-nonachlor
Delta-BHC
Dieldrin
Endosulfan I
Endosulfan II
Endosulfan sulfate
Endrin

Endrin aldehyde
Endrin ketone
Gamma-BHC (Lindane)
Heptachlor
Heptachlor epoxide
Methoxychlor
Mirex
Oxychlordane
Toxaphene
Gamma-chlordane
Trans-nonachlor

Ester
Vinyl acetate

Ether
2-chloroethyl vinyl ether
4-bromophenylphenyl ether
4-chlorophenylphenyl ether
Bis-2-chloroethoxymethane
Bis-2-chloroethylether
Bis-2-chloroisopropylether

Halogenated Alkane
1,1,1-trichloroethane
1,1,2,2-tetrachloroethane
1,1,2-trichloro-1,2,2-trifluoroethane
1,1,2-trichloroethane
1,1-dichloroethane
1,2-dichloroethane
1,2-dichloropropane
Bromodichloromethane
Bromoform
Bromomethane
Carbon tetrachloride
Chloroethane
Chloroform
Chloromethane
Dibromochloromethane
Dichloromethane
Fluorotrichloromethane
1,1-dichloroethene
Cis-1,2-dichloroethene
Cis-1,3-dichloropropene
Monochloroethylene
Tetrachloroethene
Trans1,2-dichloroethene
Trans-1,3-dichloropropene
Trichloroethene

High Molecular Weight
Polycyclic Aromatic Hydrocarbons
2-methylfluoranthene
Benzo(a)anthracene
Benzo(a)pyrene
Benzo(b)fluoranthene
Benzo(e)pyrene
Benzo(g,h,i)perylene
Benzo(k)fluoranthene
Chrysene
Dibenzo(a,h)anthracene
Fluoranthene
Indeno(1,2,3-c,d)pyrene
Perylene
Pyrene

Low Molecular Weight
Polycyclic Aromatic Hydrocarbons
1,6,7-trimethylnaphthalene
1-methylnaphthalene
1-methylphenanthrene
2,6-dimethyl-naphthalene
2-methylnaphthalene
2-methylphenanthrene
Acenaphthene
Acenaphthylene
Anthracene
Biphenyl
Dibenzothiophene
Fluorene
Naphthalene
Phenanthrene
Retene

Ketone
2-butanone
2-hexanone
4-methyl-2-pentanone
Acetone

Miscellaneous Extractable Compounds
1,2-diphenylhydrazine
Aniline
Benzidine
Benzoic acid
Benzyl alcohol
Betacoprostanol
Betasitosterol
Carbazole
Cholesterol
Cymene

P-isopropyltoluene
Dibenzofuran
Isophorone
N-nitrosodimethylamine
Pyridine

Organonitrogen Compounds
2,4-dinitrotoluene
2,6-Dinitrotoluene
2-nitroaniline
3,3'-dichlorobenzidine
3-nitroaniline
4-chloroaniline
4-nitroaniline
9(H)carbazole
Caffeine
Nitrobenzene
N-nitroso-di-n-propylamine
N-nitrosodiphenylamine

Phenols
2,4-dimethylphenol
2-methylphenol
4-methylphenol
Phenol
P-nonylphenol

Phthalate Esters
Bis-2-ethylhexylphthalate
Butylbenzylphthalate
Diethylphthalate
Dimethylphthalate
Di-n-butylphthalate
Di-n-octylphthalate

Organotin, Butyltin
Dibutyltin dichloride
Monobutyltin trichloride
Tetrabutyltin
Tributyltin chloride

Polybrominated Diphenylether

PBDE Congeners:
47
99
100
153
154

Polychlorinated Biphenyls

PCB Aroclors:
1016
1016/1242
1221
1232
1242
1248
1254
1260
1262
1268

PCB Congeners:
8
18
28
44
52
66
77
101
105
110
118
126
128
138
153
169
170
180
187
195
206
209

Table 2. Sediment toxicity tests conducted in Hood Canal between 1984 and 2004.

Toxicity Test	Sediment Matrix	Test Organism	Life History Stage	Endpoint
Amphipod 10-day	bulk sediment	*Ampelisca abdita*, *Eohaustorius estuarius*, or *Rhepoxynius abronius*	adult	survival as % of control
Neanthes 20-day	bulk sediment	*Neanthes arenaceodentata*	juvenile	growth, weight of individual organism
Bivalve larvae 48-hour	sediment/water elutriate	*Crassostrea gigas*	larval	% normal embryo development and survival
Sea urchin fertilization	sediment pore water	*Strongylocentrotus purpuratus*	gametes	mean egg fertilization in 100% pore water as % of control
Microtox	sediment pore water	*Vibrio fischerii*	cellular reaction	microbial bioluminescence activity
Microtox	organic solvent extract	*Vibrio fischerii*	cellular reaction	microbial bioluminescence activity
Cytochrome P450 Human Reporter Gene System (HRGS)	organic solvent extract	human liver cell culture	cellular reaction	cellular production of benzo[a]pyrene (µgB[a]p/gm) equivalence

Table 3. Infaunal indices calculated for benthic macrofaunal invertebrate assemblages collected from Hood Canal between 1989 and 2005.

Infaunal index	Definition	Calculation
Total Abundance	A measure of density equal to the total number of organisms per unit area (0.1 m^2, for this report).	Sum of all organisms counted in each replicate, divided by the number of 0.1 m^2 replicates.
Major Taxa Abundance (5 measures)	A measure of density equal to the total number of organisms in each major taxon group (Annelida, Arthropoda, Echinodermata, Mollusca, and Other Taxa) per unit area (0.1 m^2, for this report).	Sum of all organisms counted in each major taxon group in each replicate, divided by the number of 0.1 m^2 replicates.
Taxa Richness	Total number of taxa (lowest level of identification for each organism).	Count of all taxa identified at each station in each year.
Pielou's Evenness (J')	The observed diversity as a proportion of the maximum possible diversity; a measure of how equitably distributed the taxa are. Ranges from 0, for a single taxon comprising all individuals, to 1, when individuals are completely equally distributed among the taxa (Clarke and Warwick, 1994).	$J' = \frac{H'}{\log S}$, where *H'* is the Shannon-Wiener diversity index and *S* is the number of taxa (taxa richness).
Swartz' Dominance Index (SDI)	The minimum number of taxa composing the top 75% of the total abundance in a sample. The fewer the taxa composing the bulk of the total abundance, the smaller the value of Swartz's dominance index.	Count of the minimum number of taxa whose combined abundance accounts for 75 percent of the total abundance, *i.e.*, when the individual taxa are ordered from largest proportion of total abundance to smallest, the number of taxa corresponding to a cumulative proportion of at least 75%.

Table 4. Projects, station numbers, and station locations for sediment surveys conducted in Hood Canal between 1952 and 2005.

Station ID	Project	Location	Longitude	Latitude
Port Ludlow				
207	PSAMP/NOAA	Port Ludlow	-122.679500	47.924465
206	PSAMP/NOAA	Port Ludlow	-122.676803	47.921772
208	PSAMP/NOAA	Port Ludlow, south shore	-122.680493	47.916665
Northern Hood Canal				
211	PSAMP/NOAA	Hood Canal, north	-122.642560	47.943890
323	PSAMP Spatial	Coon Bay	-122.624346	47.914229
75	PSAMP Spatial	Coon Bay	-122.606944	47.902461
203	PSAMP Spatial	Hood Head	-122.615079	47.882559
Port Gamble				
SG-1018	PT_PG1	Port Gamble	-122.580605	47.857597
SG-1016	PT_PG1	Port Gamble	-122.582947	47.857235
SG-1017	PT_PG1	Port Gamble	-122.581779	47.857155
B1	P&T_MILL	Port Gamble	-122.580025	47.857025
B2	P&T_MILL	Port Gamble	-122.580528	47.856804
POPE0502	POPE&TAL	Port Gamble	-122.580589	47.856560
B3	P&T_MILL	Port Gamble	-122.579666	47.854527
B4	P&T_MILL	Port Gamble	-122.580360	47.854359
B5	P&T_MILL	Port Gamble	-122.579857	47.854080
SG-1006	PT_PG1	Port Gamble	-122.579765	47.854027
B6	P&T_MILL	Port Gamble	-122.580307	47.854000
SG-1021	PT_PG1	Port Gamble	-122.580780	47.853951
B7	P&T_MILL	Port Gamble	-122.580444	47.853554
B13	P&T_MILL	Port Gamble	-122.581558	47.853500
B10	P&T_MILL	Port Gamble	-122.580887	47.853359
SG-1019	PT_PG1	Port Gamble	-122.581169	47.853096
POPE0101	POPE&TAL	Port Gamble	-122.581757	47.853065
LY-1020	P&T_MILL	Port Gamble	-122.580307	47.852943
SG-1003	PT_PG1	Port Gamble	-122.580147	47.852936
B8	P&T_MILL	Port Gamble	-122.580330	47.852917
B14	P&T_MILL	Port Gamble	-122.581413	47.852859
B11	P&T_MILL	Port Gamble	-122.580750	47.852608
B9	P&T_MILL	Port Gamble	-122.580223	47.852192
B15	P&T_MILL	Port Gamble	-122.581223	47.852165
B12	P&T_MILL	Port Gamble	-122.580666	47.851833
SG-1020	PT_PG1	Port Gamble	-122.580879	47.851753

Station ID	Project	Location	Longitude	Latitude
B17	P&T_MILL	Port Gamble	-122.581329	47.851471
SG-1002	PT_PG1	Port Gamble	-122.581490	47.851170
B16	P&T_MILL	Port Gamble	-122.580887	47.851109
212	PSAMP/NOAA	Port Gamble Bay	-122.572942	47.843908
214	PSAMP/NOAA	Port Gamble Bay	-122.578518	47.836292
LY-3001	P&T_MILL	Port Gamble	-122.583336	47.832664
SG-3001	PT_PG1	Port Gamble	-122.583374	47.832649
SG-3002	PT_PG1	Port Gamble	-122.580086	47.830410
SG-3003	PT_PG1	Port Gamble	-122.582840	47.827702
SG-3004	PT_PG1	Port Gamble	-122.580971	47.824360
213	PSAMP/NOAA	Port Gamble Bay, south	-122.575598	47.822298
North Central Hood Canal				
216	PSAMP Spatial	Sisters	-122.664954	47.854798
210	PSAMP/NOAA	Hood Canal	-122.661165	47.844500
209	PSAMP/NOAA	Hood Canal	-122.645938	47.841032
13R	PSAMP Temporal	North Hood Canal	-122.629005	47.837666
336	PSAMP Spatial	Bridgehaven	-122.656710	47.836925
88	PSAMP Spatial	N Four Corners	-122.650162	47.833882
152	PSAMP Spatial	Transit Station	-122.712473	47.791627
24	PSAMP Spatial	Vinland	-122.723201	47.783720
14	PSAMP Temporal	Central Hood Canal	-122.734665	47.782417
TRF_01MC	NAVY_TRF	Bangor	-122.729065	47.743855
TRF_01MC	NAVY_TRF	Bangor	-122.729065	47.743855
188	PSAMP Spatial	King Spit	-122.765510	47.718526
HC-01	CREC72	Hazel Pt.	-122.764603	47.683151
HC-012	ROBERT74	Central Hood Canal	-122.764603	47.683151
DB-H17	ROBERT74	Central Hood Canal	-122.839607	47.679817
222	PSAMP/NOAA	Hood Canal, Oak Head	-122.814677	47.678222
HC-011G	ROBERT74	Central Hood Canal	-122.812935	47.678150
8	PSAMP Spatial	Hazel Point	-122.761119	47.677800
HC-H09	ROBERT74	Central Hood Canal	-122.796265	47.676483
184	PSAMP Spatial	Misery Point	-122.865396	47.674132
HC-02	CREC72	Central Hood Canal	-122.876274	47.673153
HC-011M	ROBERT74	Central Hood Canal	-122.876274	47.673153
HC-H08	ROBERT74	Central Hood Canal	-122.866264	47.664818
124	PSAMP Spatial	Seabeck	-122.805128	47.652075
Dabob and Quilcene Bays				
DB19	EIGHTBAY	Dabob Bay	-122.815056	47.836174

Station ID	Project	Location	Longitude	Latitude
DB19	EIGHTBAY	Dabob Bay	-122.815056	47.836174
DB20	EIGHTBAY	Dabob Bay	-122.807358	47.826950
DB18	EIGHTBAY	Dabob Bay	-122.819191	47.824951
DB-18	REFGRAIN	Dabob Bay	-122.819191	47.824951
218	PSAMP/NOAA	Dabob Bay, north end	-122.818392	47.820575
DB21	EIGHTBAY	Dabob Bay	-122.804253	47.819256
DB17	EIGHTBAY	Dabob Bay	-122.816780	47.814369
DB22	EIGHTBAY	Dabob Bay	-122.802109	47.814007
DB23	EIGHTBAY	Dabob Bay	-122.798523	47.807175
32	PSAMP Spatial	Dabob Bay, Broad Spit	-122.804480	47.803197
DB24	EIGHTBAY	Dabob Bay	-122.794662	47.801338
DB25	EIGHTBAY	Dabob Bay	-122.795410	47.793369
DB26	EIGHTBAY	Dabob Bay	-122.794693	47.787952
215	PSAMP/NOAA	Quilcene Bay	-122.856973	47.799122
216	PSAMP/NOAA	Quilcene Bay	-122.858637	47.797132
217	PSAMP/NOAA	Quilcene Bay	-122.855327	47.790090
144	PSAMP Spatial	Fishermans Point	-122.865298	47.785367
DB16	EIGHTBAY	Dabob Bay	-122.860275	47.773563
DB15	EIGHTBAY	Dabob Bay	-122.854774	47.772312
DB-15	EIGHTBAY	Dabob Bay	-122.854774	47.772312
DB-15	REFGRAIN	Dabob Bay	-122.854774	47.772312
DB-H16	ROBERT74	Dabob Bay	-122.839607	47.771481
DB14	EIGHTBAY	Dabob Bay	-122.855469	47.768284
DB-14	REFGRAIN	Dabob Bay	-122.855469	47.768284
112	PSAMP Spatial	Dabob Bay, Tabook Pt	-122.831539	47.747203
DB-H18	ROBERT74	Dabob Bay	-122.837944	47.746479
48	PSAMP Spatial	Pulali Point	-122.833037	47.735933
220	PSAMP/NOAA	Dabob Bay, Pulali Point	-122.844077	47.734652
219	PSAMP/NOAA	Dabob Bay, Pulali Point	-122.849193	47.730050
15	PSAMP Temporal	Dabob Bay	-122.818665	47.714916
92	PSAMP Spatial	Dabob Bay, Zelatched Pt	-122.845906	47.713883
DB7	EIGHTBAY	Dabob Bay	-122.879166	47.711067
DB-07	EIGHTBAY	Dabob Bay	-122.879166	47.711067
DB6	EIGHTBAY	Dabob Bay	-122.877998	47.707485
80	PSAMP Spatial	Dabob Bay, Sylopash Pt	-122.882824	47.703727
DB5	EIGHTBAY	Dabob Bay	-122.876801	47.702152
DB-05	EIGHTBAY	Dabob Bay	-122.876801	47.702152
DB4	EIGHTBAY	Dabob Bay	-122.853737	47.702122

Station ID	Project	Location	Longitude	Latitude
60	PSAMP Spatial	Dabob bay, Seal Rock	-122.865150	47.701468
DB3	EIGHTBAY	Dabob Bay	-122.866516	47.696457
DB2	EIGHTBAY	Dabob Bay	-122.869858	47.691792
DB-02	REFGRAIN	Dabob Bay	-122.869858	47.691792
DB1	EIGHTBAY	Dabob Bay	-122.873138	47.687569
DB-01	EIGHTBAY	Dabob Bay	-122.873138	47.687569
DABOB	DUWAM86	Dabob Bay	-122.888206	47.687317
Central Hood Canal				
56	PSAMP Spatial	Stavis Bay	-122.892375	47.641708
288	PSAMP Spatial	Maple Beach, south	-122.871121	47.637771
252	PSAMP Spatial	Maple Beach, north	-122.866406	47.637306
223	PSAMP/NOAA	Hood Canal	-122.890847	47.634888
HC-H15	ROBERT74	Central Hood Canal	-122.929596	47.626476
HC-H07	ROBERT74	Central Hood Canal	-122.944603	47.609810
296	PSAMP Spatial	Fulton Creek, north	-122.957832	47.608867
120	PSAMP Spatial	Fulton Creek, south	-122.963286	47.606140
304R	PSAMP Temporal	Central Hood Canal	-122.979004	47.587666
248	PSAMP Spatial	Tekiu Point	-122.952192	47.587323
Southern Hood Canal				
HC-H06	ROBERT74	Southern Hood Canal	-123.009598	47.548145
HC-03	CREC72	Southern Hood Canal	-123.066269	47.478149
HC-034	ROBERT74	Southern Hood Canal	-123.066269	47.478149
HC-H05	ROBERT74	Southern Hood Canal	-123.074600	47.469818
96	PSAMP Spatial	Sund Creek	-123.100798	47.448840
221	PSAMP/NOAA	Hood Canal, Red Bluff	-123.110330	47.420633
64	PSAMP Spatial	Musquiti Point, north	-123.119413	47.397876
224	PSAMP Spatial	Musquiti Point	-123.122019	47.393927
16	PSAMP Temporal	Great Bend	-123.114502	47.380165
225	PSAMP/NOAA	Hood Canal, Lynch Cove	-123.129128	47.377977
17	PSAMP Temporal	Great Bend	-123.129585	47.369663
Lynch Cove				
128	PSAMP Spatial	Sisters Point	-123.050238	47.356713
118	PSAMP Spatial	Shoofly Creek	-122.971827	47.385640
226	PSAMP/NOAA	Hood Canal, Ayres Point	-122.956018	47.396542
224	PSAMP/NOAA	Hood Canal, Lynch Cove	-122.939750	47.390740
HC-04	CREC72	Lynch Cove	-122.936256	47.393150
305R	PSAMP Temporal	Lynch Cove	-122.931244	47.397167

Table 5. Numbers of stations sampled for various sediment parameters for sediment quality surveys conducted in Puget Sound between 1952 and 2005. Multiple numbers indicate that different parameters were sampled at different numbers of stations.

Parameter	**Year**																							
Project	**1952**	**1961**	**1972**	**1973**	**1983**	**1984**	**1986**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Grain Size																								
DUWAM86							1																	
EIGHTBAY					20	4																		
POPE&TAL								2																
PSAMP Spatial																							30	
PSAMP Temporal									4	3	4	5	3	4		1	1	1	1	1	1	1	1	1
PSAMP/NOAA																		21						
PT_PG1																			13					
REFGRAIN							4																	
ROBERT74	9	1		3																				
Total organic carbon																								
CREC72			4																					
EIGHTBAY						4																		
NAVY_TRF												2												
P&T_MILL																					19			
POPE&TAL								2																
PSAMP Spatial																							30	
PSAMP Temporal									5	3	4	5	3	4	5				1	1	1	1	1	1
PSAMP/NOAA																		21						
PT_PG1																			13					
Sulfide																								
DUWAM86							1																	
NAVY_TRF												2												
P&T_MILL																					19			
POPE&TAL								2																
PSAMP Temporal									5	3	4	5	3											
PT_PG1																			13					
Carbon disulfide																								
PSAMP Temporal									2	2	1	1	1											

Table 5 (continued).

Parameter	Year																							
Project	**1952**	**1961**	**1972**	**1973**	**1983**	**1984**	**1986**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Metals																								
CREC72			4																					
DUWAM86							1																	
EIGHTBAY						4																		
EIGHTBAY					20	4																		
NAVY_TRF												2												
P&T_MILL																					2			
POPE&TAL								2																
PSAMP Spatial																							30	
PSAMP Temporal									5	3	4	5	3	4	5				1					1
PSAMP/NOAA																		21						
PT_PG1																			13					
Silica, Tin																								
PSAMP Spatial																							30	
PSAMP/NOAA																		21						
Organics																								
DUWAM86							1	2	2	2	1	2	1											
EIGHTBAY						4		2																
NAVY_TRF								2				2												
P&T_MILL																					2			
POPE&TAL								2																
PSAMP Spatial																							30	
PSAMP Temporal								2	2,5	2,3	1,4	1,5	1,3	1	3				1,13					1
PSAMP/NOAA																		21						
PT_PG1																			13					
Toxicity																								
EIGHTBAY						4																		
P&T_MILL																					17			
PSAMP Spatial																								30
PSAMP/NOAA																		21						
Benthos																								
PSAMP Spatial																							30	
PSAMP Temporal									5	3	4	5	3	4	0	1	1	1	1	1	1	1	1	1
PSAMP/NOAA																		21						

Table 6. Summary statistics for physical and chemical parameters measured at sediment stations sampled in Hood Canal between 1952 and 2005.

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
Related Parameters (units)									
Station depths (meters)	68	53	47	4	177	173	89	0	0.0
Overlying salinity ($^{0}/_{00}$ – parts per thousand)	29	2	30	24	32	8	65	0	0.0
Percent fines (%)	49.06	35.07	46.3	2.2	99.6	97.4	152	0	0.0
Total organic carbon (%)	2.639	3.103	1.72	0.13	15.9	15.77	143	0	0.0
Sulfide (ppm – parts per million)	420.3	743.5	55.5	0	2700	2700	66	22	33.3
Carbon disulfide (ppb – parts per billion)	1.379	1.392	1.1	0	4.06	4.06	7	2	28.6
Inorganics									
Ancillary Metals (ppm – parts per million)									
Aluminum	14270	10197	11550	1	35400	35399	48	0	0.0
Barium	20.01	8.87	19.15	7.17	40.1	32.93	42	0	0.0
Calcium	7216	4114	5910	2180	15000	12820	42	0	0.0
Cobalt	10.94	6.79	8.6	1.4	25	23.6	46	0	0.0
Iron	24251	16364	20600	3	56600	56597	48	0	0.0
Magnesium	10375	5339	8815	2770	19600	16830	42	0	0.0
Manganese	442.5	506.7	268	29	2600	2571	44	0	0.0
Potassium	2288	1550	1900	560	8820	8260	34	0	0.0
Sodium	13500	10411	8840	3050	34300	31250	34	0	0.0
Vanadium	48.63	37.2	36.05	8.75	146	137.25	42	0	0.0
Priority Pollutant Metals									
Antimony	0.0592	0.2001	0	0	1.16	1.16	75	68	90.7
Arsenic	6.241	8.315	4.86	0	85	85	121	2	1.7
Beryllium	1.209	1.538	0.51	0	5.5	5.5	51	15	29.4
Cadmium	0.5173	0.9241	0.26	0	7.5	7.5	117	29	24.8
Chromium	35.36	17.82	31.1	9.22	108	98.78	113	0	0.0
Copper	33.01	31.86	22.8	0.75	116	115.25	117	0	0.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
Lead	7.811	5.503	6.32	0	29.8	29.8	137	3	2.2
Mercury	0.0375	0.03346	0.0294	0	0.12	0.12	138	30	21.7
Nickel	31.11	11.17	30.4	7.8	56	48.2	113	0	0.0
Selenium	0.4809	0.4727	0.415	0	1.5	1.5	68	28	41.2
Silver	0.1123	0.184	0.033	0	1.2	1.2	134	57	42.5
Thallium	0.0928	0.111	0	0	0.34	0.34	43	22	51.2
Zinc	57.69	25.84	57	15.3	117	101.7	117	0	0.0
Elements									
Major Elements									
Silicon	300191	65891	307000	207000	461000	254000	23	0	0.0
Trace Elements									
Tin	0.7716	0.3916	0.71	0.21	1.76	1.55	55	0	0.0
Organics (ppb – parts per billion)									
Aromatic and Chlorinated Aromatic									
Benzene	0.0238	0.0478	0	0	0.13	0.13	8	6	75.0
Chlorobenzene	0	0	0	0	0	0	8	8	100.0
Ethylbenzene	0	0	0	0	0	0	17	17	100.0
Styrene	0	0	0	0	0	0	8	8	100.0
Toluene	0.0263	0.0487	0	0	0.11	0.11	8	6	75.0
Total xylenes	0.0292	0.0562	0	0	0.15	0.15	13	10	76.9
Chlorinated Alkanes									
Hexachloroethane	0	0	0	0	0	0	44	44	100.0
Hexachlorobutadiene	0.0286	0.2928	0	0	3	3	105	105	100.0
Hexachlorocyclopentadiene	0	0	0	0	0	0	12	12	100.0
Chlorinated and Nitro-Substituted Phenols									
2,4,5-trichlorophenol	0	0	0	0	0	0	22	22	100.0
2,4,6-trichlorophenol	0	0	0	0	0	0	26	26	100.0
2,4-dichlorophenol	0	0	0	0	0	0	21	21	100.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
2,4-dinitrophenol	0	0	0	0	0	0	21	21	100.0
2-chlorophenol	0	0	0	0	0	0	21	21	100.0
2-nitrophenol	0	0	0	0	0	0	22	22	100.0
4,6-dinitro-2-methylphenol	0	0	0	0	0	0	21	21	100.0
4-chloro-3-methylphenol	0	0	0	0	0	0	22	22	100.0
4-nitrophenol	0	0	0	0	0	0	21	21	100.0
Pentachlorophenol	0	0	0	0	0	0	104	104	100.0
Chlorinated Aromatic Compounds									
1,2,4-trichlorobenzene	0	0	0	0	0	0	105	105	100.0
1,2-dichlorobenzene	0	0	0	0	0	0	88	88	100.0
1,3-dichlorobenzene	0	0	0	0	0	0	88	88	100.0
1,4-dichlorobenzene	0.0494	0.3249	0	0	2.3	2.3	87	85	97.7
2-chloronaphthalene	0	0	0	0	0	0	89	89	100.0
Hexachlorobenzene	0.0063	0.06508	0	0	0.67	0.67	106	105	99.1
Chlorinated Pesticides									
2,4'-DDD	0	0	0	0	0	0	64	64	100.0
2,4'-DDE	0	0	0	0	0	0	64	64	100.0
2,4'-DDT	0	0	0	0	0	0	64	64	100.0
4,4'-DDD	0.0292	0.075	0	0	0.31	0.31	90	77	85.6
4,4'-DDE	0.1339	0.2203	0	0	0.76	0.76	90	59	65.6
4,4'-DDT	0.0126	0.05575	0	0	0.33	0.33	93	88	94.6
Total of 6 isomers	3.725	0.797	3.65	3	4.6	1.6	4	0	0.0
Aldrin	0	0	0	0	0	0	89	89	100.0
Alpha-BHC	0	0	0	0	0	0	43	43	100.0
Alpha-chlordane	0	0	0	0	0	0	83	83	100.0
Beta-BHC	0	0	0	0	0	0	43	43	100.0
Chlordane	0	0	0	0	0	0	2	2	100.0
Cis-Nonachlor	0	0	0	0	0	0	22	22	100.0
Delta-BHC	0	0	0	0	0	0	43	43	100.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
Dieldrin	0	0	0	0	0	0	89	89	100.0
Endosulfan I	0	0	0	0	0	0	84	84	100.0
Endosulfan II	0	0	0	0	0	0	84	84	100.0
Endosulfan sulfate	0	0	0	0	0	0	84	84	100.0
Endrin	0	0	0	0	0	0	84	84	100.0
Endrin aldehyde	0	0	0	0	0	0	48	48	100.0
Endrin ketone	0	0	0	0	0	0	83	83	100.0
Gamma-BHC (Lindane)	0	0	0	0	0	0	64	64	100.0
Gamma-HCH	0	0	0	0	0	0	20	20	100.0
Heptachlor	0	0	0	0	0	0	87	87	100.0
Heptachlor epoxide	0	0	0	0	0	0	86	86	100.0
Methoxychlor	0	0	0	0	0	0	43	43	100.0
Mirex	0	0	0	0	0	0	59	59	100.0
Oxychlordane	0	0	0	0	0	0	58	58	100.0
Toxaphene	0	0	0	0	0	0	83	83	100.0
Gamma-chlordane	0.232	0.75	0	0	2.6	2.6	22	20	90.9
Trans-Chlordane (Gamma)	0	0	0	0	0	0	63	63	100.0
Trans-nonachlor	0	0	0	0	0	0	23	23	100.0
Ether									
2-chloroethyl vinyl ether	0	0	0	0	0	0	7	7	100.0
4-bromophenylphenyl ether	0	0	0	0	0	0	18	18	100.0
4-chlorophenylphenyl ether	0	0	0	0	0	0	18	18	100.0
Bis-2-chloroethoxymethane	0	0	0	0	0	0	18	18	100.0
Bis-2-chloroethylether	0	0	0	0	0	0	18	18	100.0
Bis-2-chloroisopropylether	0	0	0	0	0	0	17	17	100.0
Halogenated Alkane									
1,1,1-trichloroethane	0	0	0	0	0	0	8	8	100.0
1,1,2,2-tetrachloroethane	0	0	0	0	0	0	7	7	100.0
1,1,2-trichloro-1,2,2-trifluoroethane	0	0	0	0	0	0	7	7	100.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
1,1,2-tricloroethane	0	0	0	0	0	0	8	8	100.0
1,1-dichloroethane	0	0	0	0	0	0	8	8	100.0
1,2-dichloroethane	0	0	0	0	0	0	8	8	100.0
1,2-dichloropropane	0	0	0	0	0	0	8	8	100.0
Bromodichloromethane	0	0	0	0	0	0	8	8	100.0
Bromoform	0	0	0	0	0	0	7	7	100.0
Bromomethane	0	0	0	0	0	0	8	8	100.0
Carbon tetrachloride	0	0	0	0	0	0	7	7	100.0
Chloroethane	0	0	0	0	0	0	8	8	100.0
Chloroform	0.0033	0.01155	0	0	0.04	0.04	12	11	91.7
Chloromethane	0	0	0	0	0	0	7	7	100.0
Dibromochloromethane	0	0	0	0	0	0	7	7	100.0
Dichloromethane	0.214	0.567	0	0	1.5	1.5	7	6	85.7
Fluorotrichloromethane	0	0	0	0	0	0	5	5	100.0
1,1-dichloroethene	0	0	0	0	0	0	8	8	100.0
Cis-1,2-dichloroethene	0	0	0	0	0	0	5	5	100.0
Cis-1,3-dichloropropene	0	0	0	0	0	0	7	7	100.0
Monochloroethylene	0	0	0	0	0	0	7	7	100.0
Tetrachloroethene	0.0027	0.01033	0	0	0.04	0.04	15	14	93.3
Trans1,2-dichloroethene	0	0	0	0	0	0	7	7	100.0
Trans-1,3-dichloropropene	0	0	0	0	0	0	7	7	100.0
Trichloroethene	0	0	0	0	0	0	17	17	100.0
High Molecular Weight Polycyclic Aromatic Hydrocarbons									
2-Methylfluoranthene	13.29	20.48	5.4	1.2	86	84.8	23	0	0.0
Benzo(a)anthracene	23.19	55.03	6.6	0	334	334	111	27	24.3
Benzo(a)pyrene	25.53	68.89	7.4	0	496	496	111	30	27.0
Benzo(b)fluoranthene	25.72	39.82	14.5	0	228	228	68	3	4.4
Benzo(e)pyrene	25.93	50.06	14	0	284	284	60	1	1.7
Benzo(g,h,i)perylene	25.02	74.18	9.3	0	562	562	107	35	32.7

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
Benzo(k)fluoranthene	30.17	68.84	14	0	448	448	68	3	4.4
Chrysene	38.75	93.94	11	0	570	570	111	24	21.6
Dibenzo(a,h)anthracene	2.605	6.777	0	0	60	60	111	63	56.8
Fluoranthene	96	294.9	25	0	2210	2210	111	14	12.6
Indeno(1,2,3-c,d)pyrene	18.11	48.34	5.8	0	362	362	111	39	35.1
Perylene	46.19	46.65	31	0	208	208	86	10	11.6
Pyrene	86.4	297.1	23	0	2440	2440	111	13	11.7
calculated value									
Total Benzofluoranthenes	47.1	103.6	8	0	470	470	43	21	48.8
Low Molecular Weight Polycyclic Aromatic Hydrocarbons									
1,6,7-trimethylnaphthalene	10.06	8.54	7.2	0	31	31	59	2	3.4
1-methylnaphthalene	19.48	26.08	11	0	156	156	65	1	1.5
1-methylphenanthrene	13.04	13.95	7.2	0	66	66	60	4	6.7
2,6-dimethyl-naphthalene	40.96	34.49	33	0	131	131	61	1	1.6
2-methylnaphthalene	15.71	35.51	5.35	0	246	246	104	40	38.5
2-methylphenanthrene	14.24	20.47	8.8	0	114	114	60	3	5.0
Acenaphthene	7.06	36.89	0.52	0	286	286	111	50	45.0
Acenaphthylene	28.5	154.1	1.3	0	1190	1190	111	48	43.2
Anthracene	17.95	69.56	2.8	0	535	535	111	43	38.7
Biphenyl	64	305.1	5.4	0	1780	1780	60	7	11.7
Dibenzothiophene	4.291	6.796	2.5	0	41	41	59	1	1.7
Fluorene	8.73	30.01	1.6	0	228	228	111	50	45.0
Naphthalene	93.6	479.1	6.6	0	3980	3980	111	42	37.8
Phenanthrene	77	256.3	19	0	2030	2030	111	23	20.7
Retene	39.2	95.3	18.5	0	656	656	84	12	14.3
Ketone									
2-butanone	2.3	4.02	0	0	9.28	9.28	5	3	60.0
2-hexanone	0	0	0	0	0	0	7	7	100.0
4-methyl-2-pentanone	0	0	0	0	0	0	7	7	100.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
Acetone	2.44	4.18	0	0	9.1	9.1	7	5	71.4
Miscellaneous Extractable Compounds									
1,2-diphenylhydrazine	0	0	0	0	0	0	5	5	100.0
Aniline	0	*	0	0	0	0	1	1	100.0
Benzidine	0	*	0	0	0	0	1	1	100.0
Benzoic acid	Data Questionable								
Benzyl alcohol									
Betacoprostanol	343.8	503.1	83	0	2010	2010	61	23	37.7
Betasitosterol	1239	1373	680	0	4520	4520	53	53	100.0
Carbazole	1.397	2.09	0	0	6.9	6.9	41	24	58.5
Cholesterol	1078	848	888	0	3530	3530	57	6	10.5
Cymene	0	0	0	0	0	0	1	1	100.0
P-isopropyltoluene	0.0755	0.5494	0	0	4	4	53	52	98.1
Dibenzofuran	10.49	39.64	2.2	0	291	291	107	47	43.9
Isophorone	0	0	0	0	0	0	29	29	100.0
N-nitrosodimethylamine	0	0	0	0	0	0	4	4	100.0
Pyridine	0	0	0	0	0	0	1	1	100.0
Organonitrogen Compounds									
2,4-dinitrotoluene	0	0	0	0	0	0	18	18	100.0
2,6-Dinitrotoluene	0	0	0	0	0	0	22	22	100.0
2-nitroaniline	0	0	0	0	0	0	18	18	100.0
3,3'-dichlorobenzidine	0	0	0	0	0	0	6	6	100.0
3-nitroaniline	0	0	0	0	0	0	18	18	100.0
4-chloroaniline	0	0	0	0	0	0	9	9	100.0
4-nitroaniline	0	0	0	0	0	0	18	18	100.0
9(H)carbazole	2.632	6.217	0	0	30	30	48	25	52.1
Caffeine	0	0	0	0	0	0	54	54	100.0
Nitrobenzene	0	0	0	0	0	0	18	18	100.0
N-nitroso-di-n-propylamine	0	0	0	0	0	0	18	18	100.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
N-nitrosodiphenylamine	0	0	0	0	0	0	104	104	100.0
Phenols									
2,4-dimethylphenol	0	0	0	0	0	0	105	105	100.0
2-methylphenol	Data Questionable								
4-methylphenol									
Phenol									
P-nonylphenol	0.734	4.491	0	0	33	33	58	56	96.6
Phthalate Esters									
Bis-2-ethylhexylphthalate	7.1	39.23	0	0	380	380	105	94	89.5
Butylbenzylphthalate	1.015	8.132	0	0	82	82	105	101	96.2
Diethylphthalate	0.019	0.1952	0	0	2	2	105	104	99.0
Dimethylphthalate	0.02	0.2049	0	0	2.1	2.1	105	104	99.0
Di-n-butylphthalate	104.9	440	0	0	2990	2990	105	97	92.4
Di-n-octylphthalate	0.514	5.27	0	0	54	54	105	104	99.0
Organotin, Butyl tin									
Dibutyltin dichloride	0	0	0	0	0	0	22	22	100.0
Monobutyltin trichloride	0	0	0	0	0	0	22	22	100.0
Tetrabutyltin	0	0	0	0	0	0	22	22	100.0
Tributyltin chloride	0	0	0	0	0	0	22	22	100.0
Polybrominated Diphenylether									
PBDE Congeners:									
47	0.0945	0.1044	0.0305	0	0.32	0.32	40	20	50.0
49	0	0	0	0	0	0	4	4	100.0
66	0	0	0	0	0	0	4	4	100.0
71	0	0	0	0	0	0	4	4	100.0
99	0.0366	0.067	0	0	0.2	0.2	40	30	75.0
100	0.0033	0.02055	0	0	0.13	0.13	40	39	97.5
138	0	0	0	0	0	0	4	4	100.0

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
153	0.01	0.0632	0	0	0.4	0.4	40	39	97.5
154	0	0	0	0	0	0	40	40	100.0
183	0	0	0	0	0	0	4	4	100.0
184	0	0	0	0	0	0	4	4	100.0
209	0	0	0	0	0	0	4	4	100.0
Polycyclic Chlorinated Biphenyls									
PCB Aroclors:									
1016	0	0	0	0	0	0	70	70	100.0
1016/1242	0	0	0	0	0	0	17	17	100.0
1221	0	0	0	0	0	0	79	79	100.0
1232	0	0	0	0	0	0	79	79	100.0
1242	0.1186	0.708	0	0	4.9	4.9	70	68	97.1
1248	0.386	1.16	0	0	4.8	4.8	87	78	89.7
1254	0.824	1.953	0	0	7.3	7.3	87	73	83.9
1260	0.1356	0.8957	0	0	6.6	6.6	87	85	97.7
1262	0	0	0	0	0	0	20	20	100.0
1268	0	0	0	0	0	0	20	20	100.0
PCB Congeners:									
8	0	0	0	0	0	0	62	62	100.0
18	0	0	0	0	0	0	62	62	100.0
28	0.004	0.03175	0	0	0.25	0.25	62	61	98.4
44	0	0	0	0	0	0	62	62	100.0
52	0	0	0	0	0	0	62	62	100.0
66	0.0031	0.02413	0	0	0.19	0.19	62	61	98.4
77	0	0	0	0	0	0	62	62	100.0
101	0.0224	0.1084	0	0	0.6	0.6	62	59	95.2
105	0	0	0	0	0	0	62	62	100.0
110	0.0103	0.04638	0	0	0.25	0.25	40	38	95.0
118	0.0298	0.1059	0	0	0.65	0.65	62	56	90.3

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum	Range	N	No. of non-detects	% non-detects
126	0	0	0	0	0	0	62	62	100.0
128	0	0	0	0	0	0	62	62	100.0
138	0.0756	0.1956	0	0	0.79	0.79	62	51	82.3
153	0.0765	0.199	0	0	0.84	0.84	62	51	82.3
169	6.56	23.15	0	0	95	95	39	36	92.3
170	0.0029	0.02286	0	0	0.18	0.18	62	61	98.4
180	0.0103	0.0813	0	0	0.64	0.64	62	61	98.4
187	0.0045	0.03556	0	0	0.28	0.28	62	61	98.4
195	0	0	0	0	0	0	62	62	100.0
206	0	0	0	0	0	0	62	62	100.0
209	0	0	0	0	0	0	62	62	100.0

Table 7. Mean percent of samples in which metal and organic chemicals were detected (and undetected) in sediments collected from Hood Canal between 1952 and 2005.

Parameter	Average % Detected	Average % Undetected
Inorganics		
Ancillary Metals	100.0	0.0
Priority Pollutant Metals	81.1	18.9
Elements		
Major Elements	100.0	0.0
Trace Elements	100.0	0.0
Organics		
Aromatic and Chlorinated Aromatic	11.3	88.7
Chlorinated Alkanes	0.6	99.4
Chlorinated and Nitro-Substituted Phenols	0.0	100.0
Chlorinated Aromatic Compounds	0.5	99.5
Chlorinated Pesticides	2.6	97.4
Ether	0.0	100.0
Halogenated Alkane	1.5	98.5
High Molecular Weight PAHs	77.0	23.0
Low Molecular Weight PAHs	74.4	25.6
Ketone	15.4	84.6
Miscellaneous Extractable Compounds	40.3	59.7
Organonitrogen Compounds	6.6	93.4
Phthalate Esters	4.1	95.9
Organotin, Butyl tin	0.0	100.0
Polybrominated Diphenylether	14.0	86.0
Polychlorinated Biphenyls	3.5	96.5

PAHs = Polycyclic Aromatic Hydrocarbons

Table 8. Sediment chemistry exceeding Washington State Sediment Quality Standards in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data collected from the SEDQUAL database.

Station ID	Location	Project	Sampling year	Number of SQSs exceeded	Chemicals exceeding SQSs	Number of CSLs exceeded	Chemicals exceeding CSLs
15	Dabob Bay	PSAMP Temporal	1990	1	Other: Butylbenzylphthalate	0	
207	Port Ludlow	PSAMP/ NOAA	1999	1	LPAHs: Naphthalene	0	
SG-1001*	Port Gamble Bay	PT_PG1	2000	2	Other: 1,2,4-Trichlorobenzene, Hexachlorobenzene	2	Other: 1,2,4-Trichlorobenzene, Hexachlorobenzene
SG-1011*	Port Gamble Bay	PT_PG1	2000	4	Metals: Cadmium, Cooper, Lead, Zinc	3	Metals: Cadmium, Cooper, Lead
SG-1014*	Port Gamble Bay	PT_PG1	2000	1	Other: Total PCBs	0	
SG-1020	Port Gamble Bay	PT_PG1	2000	1	Metals: Arsenic	0	
SG-1027*	Port Gamble Bay	PT_PG1	2000	1	Metals: Cadmium	1	Metals: Cadmium
SG-2001*	Port Gamble Bay	PT_PG1	2000	3	Metals: Cadmium, Cooper, Lead	2	Metals: Cadmium, Cooper
SG-3001	Port Gamble Bay	PT_PG1	2000	1	Metals: Cadmium	1	Metals: Cadmium

SQSs – Sediment Quality Standards
CSLs – Cleanup Screening Levels
LPAH – Low Molecular Weight Polycyclic Aromatic Hydrocarbons
* – intertidal site

Table 9. Summary statistics for sediment toxicity tests conducted in Hood Canal between 1984 and 2004.

Test type	Test species	End point Measured (units)	Initial value	Final value					
				Mean	Median	Minimum	Maximum	Range	N
Amphipod 10-day	*Ampelisca abdita*	Survival*	20.0	17.3	17.3	16.6	19.0	2.4	21
	Eohaustorius estuarius	Emergence*	20.0	18.2	18.7	15.5	19.8	4.2	7
		Reburial*	12.0 (mean)	0.1	0.0	0.0	0.4	0.4	7
		Survival*	20.0	12.0	12.7	0.9	18.4	17.5	7
	Rhepoxynius abronius	Emergence*	20.0	15.8	14.9	12.6	20.0	7.4	17
		Reburial*	5.7 (mean)	0.6	0.5	0.0	1.2	1.2	10
		Survival*	20.0	11.5	14.1	0.0	19.0	19.0	21
Neanthes 20-day	*Neanthes arenaceodentata*	Biomass, total weight of all individuals (milligrams dry weight)	0.5	15.8	15.7	10.2	19.9	9.7	17
Bivalve larvae 48-hour	*Crassostrea gigas*	Abnormality*	105.1 (mean)	102.9	99.0	59.6	145.2	85.6	17
		Mortality*	193.0	105.1	102.2	62.4	147.6	85.2	17
		Normal Survival*	187.4	102.9	99.0	59.6	145.2	85.6	17
Sea urchin fertilization	*Strongylocentrotus purpuratus*	Percent Fertilization	100.0	87.5	97.0	2.8	99.4	96.6	51
Microtox (organic solvent extract)	*Vibrio fischerii*	Metabolic Activity (as luminosity)	Not applicable	17.2	7.4	1.0	111.7	110.7	21
Cytochrome P450 Reporter Gene System (HRGS)	Human liver cell culture	P450 Induction (B[a]P eq (µg/g)	Not applicable	13.8	7.4	3.6	102.9	99.3	21

* – number of individuals
N – number of samples

Table 10. Summary statistics for sea urchin fertilization tests performed on Hood Canal sediment pore waters collected in 1999 and 2004. Tests were performed with *Strongylocentrotus purpuratus*.

Summary statistic	Mean fertilization as percent of control		
	100% pore water	50% pore water	25% pore water
1999			
Minimum	40.9	84.1	97.8
Maximum	107.0	101.4	101.7
Range	66.1	17.3	3.9
Mean	96.8	98.8	100.5
N	21	21	21
% Hits	14.3	0.0	0.0
% Area	12.2	0	0
2004			
Minimum	0.0	7.2	46.9
Maximum	105.5	104.0	103.0
Range	105.5	96.8	56.1
Mean	88.9	90.9	96.7
N	30.0	30.0	30.0
% Hits	16.7	13.3	6.7
% Area	17.7	14.5	7.6

N – number of samples

Table 11. Sediment toxicity tests exceeding State critical values in Hood Canal for the 1999 and 2004 PSAMP Spatial Monitoring Programs, the 1989-2005 PSAMP Temporal Monitoring Program, and all data collected from the SEDQUAL database.

Station ID	Location	Project	Sampling year
Amphipod 10-day survival (mean survival <80% of control)			
DB-07	Dabob Bay	EIGHTBAY	1984
DB-15	Dabob Bay	EIGHTBAY	1984
B1	Port Gamble	P&T_MILL	2002
B11	Port Gamble	P&T_MILL	2002
B15	Port Gamble	P&T_MILL	2002
B5	Port Gamble	P&T_MILL	2002
B9	Port Gamble	P&T_MILL	2002
Bivalve larvae 48-hour (mean normal survival <85% of control)			
B1	Port Gamble	P&T_MILL	2002
B10	Port Gamble	P&T_MILL	2002
B11	Port Gamble	P&T_MILL	2002
B12	Port Gamble	P&T_MILL	2002
B13	Port Gamble	P&T_MILL	2002
B14	Port Gamble	P&T_MILL	2002
B15	Port Gamble	P&T_MILL	2002
B16	Port Gamble	P&T_MILL	2002
B17	Port Gamble	P&T_MILL	2002
B2	Port Gamble	P&T_MILL	2002
B4	Port Gamble	P&T_MILL	2002
B5	Port Gamble	P&T_MILL	2002
B6	Port Gamble	P&T_MILL	2002
B8	Port Gamble	P&T_MILL	2002
B9	Port Gamble	P&T_MILL	2002
Cytochrome P450 (>37.1 ug/g benzo[a]pyrene equivalents/g sediment determined as the 90% UPL (upper prediction limit) of the entire NOAA set (n=530))			
206	Port Ludlow	PSAMP/NOAA	1999
Urchin Fertilization (mean fertilization <80% of controls in 100% pore water)			
48	Dabob Bay	PSAMP Spatial	2004
92	Dabob Bay	PSAMP Spatial	2004
112	Dabob Bay	PSAMP Spatial	2004
219	Dabob Bay	PSAMP/NOAA	1999
220	Dabob Bay	PSAMP/NOAA	1999
214	Port Gamble	PSAMP/NOAA	1999
56	Stavis Bay	PSAMP Spatial	2004
96	Sund Creek	PSAMP Spatial	2004

Table 12. Benthic infaunal indices calculated for Hood Canal stations sampled between 1989 and 2005 (sampling area = 0.1 m^2). Station depth, percent fines, and total organic carbon measures are included. Stations are listed geographically from north to south, and in chronological order.

Station, Location	Project	Sampling Year	Depth (meters)	Percent Fines	Percent Total Organic Carbon	Total abundance	Taxa richness	Even-ness (J')	Swartz' Dominance Index	Annelid abundance	Arthropod abundance	Mollusca abundance	Echinoderm abundance	Misc. taxa abundance
1. Port Ludlow														
207, Port Ludlow	PSAMP/NOAA	1999	15	12.8	0.4	953	53	0.48	4	687	115	148	0	3
206, Port Ludlow	PSAMP/NOAA	1999	17	83.0	0.6	688	29	0.29	1	595	1	90	0	2
208, Port Ludlow, south shore	PSAMP/NOAA	1999	6	11.9	2.3	1574	43	0.63	6	645	731	198	0	0
2. Port Gamble														
212, Port Gamble Bay	PSAMP/NOAA	1999	14	10.7	0.5	1968	72	0.32	1	1764	119	69	7	9
214, Port Gamble Bay	PSAMP/NOAA	1999	12	67.1	4.4	941	55	0.50	5	781	16	138	4	2
213, Port Gamble Bay, south	PSAMP/NOAA	1999	5	7.9	0.4	3479	83	0.30	1	3202	143	107	10	17
3. Northern Hood Canal														
13R, North Hood Canal	PSAMP Temporal	1989	20	9.7	0.2	1596	132	0.47	6	273	224	1086	3	9
		1991	20	9.8	0.2	1224	110	0.43	4	136	173	901	4	11
		1994	20	16.0	0.6	1239	138	0.49	7	252	149	813	3	23
		1997	21	11.4	NR	3078	194	0.35	3	275	265	2408	4	125
		1998	22	14.0	NR	3723	189	0.31	2	382	272	3019	8	42
		1999	22	14.7	NR	1151	131	0.56	8	225	178	719	3	26
		2000	21	11.1	0.3	1412	185	0.65	22	376	232	702	5	97
		2001	22	12.0	0.4	1678	172	0.66	12	770	212	629	5	62
		2002	23	11.2	0.3	1877	133	0.55	6	316	271	1242	2	46
		2003	22	13.7	0.3	2028	188	0.52	9	375	297	1321	3	32
		2004	22	7.8	0.2	625	128	0.74	25	174	170	251	3	27
		2005	22	9.4	0.2	1510	152	0.55	9	359	251	852	2	46
14, Central Hood Canal	PSAMP Temporal	1989	114	27.6	0.4	404	116	0.80	39	142	53	178	6	26
		1990	114	37.0	0.7	412	133	0.89	55	182	112	92	10	16
		1991	114	37.8	0.7	319	130	0.92	59	160	66	75	4	14
		1992	114	48.0	0.9	467	135	0.85	48	243	73	125	5	21
		1993	114	25.0	0.9	534	163	0.88	60	245	105	133	11	39
		1994	116	40.0	1.1	314	103	0.89	44	131	75	83	8	18
211, Hood Canal, north	PSAMP/NOAA	1999	112	4.0	0.3	592	91	0.79	21	197	257	107	2	29
210, Hood Canal	PSAMP/NOAA	1999	40	19.0	0.5	517	75	0.77	16	127	134	211	10	35
209, Hood Canal	PSAMP/NOAA	1999	78	21.3	0.6	405	62	0.64	12	85	221	87	4	8
222, Hood Canal, Oak Head	PSAMP/NOAA	1999	120	63.6	1.6	219	34	0.74	8	82	104	30	0	3
323, Coon Bay	PSAMP Spatial	2004	103	8.3	0.3	355	48	0.76	11	36	177	137	0	5
75, Coon Bay	PSAMP Spatial	2004	95	13.7	0.5	271	55	0.81	14	48	95	120	1	7
203, Hood Head	PSAMP Spatial	2004	75	11.0	0.3	1075	136	0.77	28	247	405	374	2	47
216, Sisters	PSAMP Spatial	2004	19	21.6	0.1	883	91	0.75	18	266	159	382	6	70
336, Bridgehaven	PSAMP Spatial	2004	75	22.1	2.5	308	55	0.74	11	62	159	79	0	8
88, N Four Corners	PSAMP Spatial	2004	54	29.0	0.7	226	64	0.81	20	93	114	1	0	18
152, Transit Station	PSAMP Spatial	2004	37	47.8	1.0	404	63	0.73	14	105	87	192	5	15
24, Vinland	PSAMP Spatial	2004	47	49.2	0.9	327	61	0.77	14	102	73	128	6	18
188, King Spit	PSAMP Spatial	2004	109	76.5	1.8	166	40	0.80	10	46	62	53	1	4
8, Hazel Point	PSAMP Spatial	2004	66	70.2	1.7	251	49	0.76	11	96	18	116	2	19

Station, Location	Project	Sampling Year	Depth (meters)	Percent Fines	Percent Total Organic Carbon	Total abundance	Taxa richness	Even-ness (J')	Swartz' Dominance Index	Annelid abundance	Arthropod abundance	Mollusca abundance	Echinoderm abundance	Misc. taxa abundance
4. Dabob Bay - Nearshore (<30 m)														
15, Dabob Bay	PSAMP Temporal	1989	22	8.2	0.2	487	142	0.87	50	228	51	186	5	16
		1990	22	5.0	0.2	392	116	0.90	46	228	41	102	2	18
		1991	22	5.8	0.2	760	115	0.57	14	235	32	100	3	390
		1992	22	5.2	0.2	494	115	0.81	34	256	52	86	0	99
		1993	22	7.0	0.3	449	132	0.86	48	231	42	101	2	73
		1994	23	6.0	0.3	429	115	0.85	38	237	45	106	1	40
215, Quilcene Bay	PSAMP/NOAA	1999	15	71.1	3.2	754	44	0.80	12	405	64	269	7	9
216, Quilcene Bay	PSAMP/NOAA	1999	16	30.9	1.3	745	64	0.81	16	344	56	325	6	14
217, Quilcene Bay	PSAMP/NOAA	1999	27	39.3	1.4	893	73	0.76	15	361	41	427	2	62
5. Dabob Bay - Deep (>40 m)														
218, Dabob Bay, north end	PSAMP/NOAA	1999	61	69.4	1.4	282	41	0.74	9	148	4	127	0	3
220, Dabob Bay, Pulali Point	PSAMP/NOAA	1999	175	91.0	2.7	26	16	0.95	10	12	5	7	1	1
219, Dabob Bay, Pulali Point	PSAMP/NOAA	1999	171	91.6	2.7	47	19	0.91	10	25	10	11	1	0
32, Dabob Bay, Broad Spit	PSAMP Spatial	2004	110	72.8	2.4	205	32	0.70	8	171	21	12	0	1
144, Fishermans Point	PSAMP Spatial	2004	45	74.8	2.5	136	27	0.78	7	69	4	63	0	0
112, Dabob Bay, Tabook Point	PSAMP Spatial	2004	177	82.3	2.4	27	6	0.92	4	19	7	1	0	0
48, Pulali Point	PSAMP Spatial	2004	174	79.8	2.4	34	10	0.83	4	25	3	6	0	0
92, Dabob Bay, Zelatched Point	PSAMP Spatial	2004	159	89.6	2.4	88	18	0.82	6	74	6	6	0	2
80, Dabob Bay, Sylopash Point	PSAMP Spatial	2004	98	34.9	1.9	321	54	0.81	14	263	19	34	0	5
60, Dabob Bay, Seal Rock	PSAMP Spatial	2004	153	87.2	2.3	100	26	0.81	8	82	12	3	2	1
184, Misery Point	PSAMP Spatial	2004	113	85.5	2.1	73	34	0.95	18	48	13	8	3	1
6. Central Hood Canal - Nearshore (<30 m)														
124, Seabeck	PSAMP Spatial	2004	19	6.5	0.2	487	82	0.79	18	223	59	169	1	35
252, Maple Beach, north	PSAMP Spatial	2004	17	0.4	0.1	418	80	0.78	18	216	33	97	2	70
288, Maple Beach, south	PSAMP Spatial	2004	14	4.2	0.2	423	61	0.79	13	147	63	164	0	49
248, Tekiu Point	PSAMP Spatial	2004	25	8.4	0.2	373	57	0.68	11	128	21	212	1	11
7. Central Hood Canal - Deep (>130 m)														
304R, Central Hood Canal	PSAMP Temporal	1992	175	96.5	1.9	109	31	0.85	11	50	27	19	9	4
223, Hood Canal	PSAMP/NOAA	1999	166	96.2	2.7	69	28	0.92	14	45	6	5	6	7
56, Stavis Bay	PSAMP Spatial	2004	164	87.5	2.4	97	20	0.86	8	71	15	4	7	0
296, Fulton Creek, north	PSAMP Spatial	2004	134	72.3	2.2	96	38	0.86	18	28	11	50	3	4
120, Fulton Creek, south	PSAMP Spatial	2004	164	87.3	2.5	126	37	0.87	14	91	15	11	7	2
8. Southern Hood Canal														
16, Great Bend	PSAMP Temporal	1989	20	NR	1.8	352	102	0.91	41	201	17	95	2	37
17, Great Bend	PSAMP Temporal	1989	81	92.5	1.5	153	41	0.74	12	67	17	68	0	2
		1990	81	98.0	1.7	238	41	0.71	9	130	33	74	0	1
		1991	81	93.6	1.9	414	40	0.36	1	77	3	333	0	1
		1992	81	96.3	1.3	273	35	0.54	4	97	11	164	0	1
		1993	81	95.0	1.8	262	41	0.65	7	92	32	134	0	3
		1994	82	88.0	1.7	145	41	0.74	12	68	16	59	0	3
221, Hood Canal, Red Bluff	PSAMP/NOAA	1999	120	85.4	2.4	96	22	0.87	9	60	8	24	0	4
226, Hood Canal, Ayres Point	PSAMP/NOAA	1999	87	80.5	2.0	286	28	0.65	5	205	28	48	0	5
96, Sund Creek	PSAMP Spatial	2004	132	82.4	2.4	51	20	0.87	8	19	29	2	0	1
64, Musquiti Point, north	PSAMP Spatial	2004	95	57.9	2.2	224	31	0.76	8	125	17	80	0	2
224, Musquiti Point	PSAMP Spatial	2004	93	70.3	2.2	131	36	0.79	11	60	22	49	0	0

Station, Location	Project	Sampling Year	Depth (meters)	Percent Fines	Percent Total Organic Carbon	Total abundance	Taxa richness	Even-ness (J')	Swartz' Dominance Index	Annelid abundance	Arthropod abundance	Mollusca abundance	Echinoderm abundance	Misc. taxa abundance
9. Lynch Cove														
305R, Lynch Cove	PSAMP Temporal	1992	20	93.9	2.5	135	24	0.57	3	128	1	5	0	2
225, Hood Canal, Lynch Cove	PSAMP/NOAA	1999	19	71.7	4.2	144	15	0.54	2	134	0	7	0	3
224, Hood Canal, Lynch Cove	PSAMP/NOAA	1999	22	59.1	3.8	139	24	0.69	5	124	2	4	7	2
128, Sisters Point	PSAMP Spatial	2004	38	63.8	1.7	339	29	0.60	4	134	14	177	0	14
118, Shoofly Creek	PSAMP Spatial	2004	30	71.3	2.9	127	19	0.71	5	65	0	56	0	6
	Summary Statistics													
	Mean					615	73	0.72	15	244	88	256	3	24
	Standard Error					80	5	0.02	2	44	12	52	0	5
	Median					364	55	0.76	11	139	43	102	2	9
	Mode					N/A	41	N/A	8	82	1	107	0	1
	Standard Deviation					731	50	0.17	14	403	114	479	3	48
	Range					3697	188	0.66	59	3190	731	3018	11	390
	Minimum					26	6	0.29	1	12	0	1	0	0
	Maximum					3723	194	0.95	60	3202	731	3019	11	390

Table 13. Dominant taxa (i.e., top four most numerous taxa) at each sediment station sampled for benthos in Hood Canal between 1989 and 2005.

Station, Location	Sampling Year	Dominant taxa (abundance)
1. Port Ludlow		
207, Port Ludlow	1999	Aphelochaeta sp (321), Aphelochaeta glandaria (235), Axinopsida serricata (33), Acila castrensis (14)
206, Port Ludlow	1999	Aphelochaeta sp (293), Aphelochaeta glandaria (260), Euphilomedes carcharodonta (65), Nutricola lordi (47)
208, Port Ludlow, south shore	1999	Aoroides spinosus (411), Oligochaeta (350), Leptochelia savignyi (195), Aoroides sp (103)
2. Port Gamble		
212, Port Gamble Bay	1999	Aphelochaeta glandaria (1271), Cirratulidae (206), Euphilomedes carcharodonta (74), Scoletoma luti (55)
214, Port Gamble Bay	1999	Aphelochaeta glandaria (546), Dipolydora socialis (46), Odostomia sp (45), Paraprionospio pinnata (38)
213, Port Gamble Bay, south	1999	Aphelochaeta glandaria (2556), Cirratulidae (132), Maldanidae (96), Owenia fusiformis (74)
3. Northern Hood Canal		
13R, North Hood Canal	1989	Nutricola lordi (891), Euphilomedes carcharodonta (94), Mediomastus sp (55), Axinopsida serricata (52)
	1991	Nutricola lordi (742), Euphilomedes carcharodonta (91), Alvania compacta (58), Caprella mendax (40)
	1994	Nutricola lordi (660), Euphilomedes carcharodonta (95), Alvania compacta (67), Axinopsida serricata (34)
	1997	Nutricola lordi (2102), Alvania compacta (135), Euphilomedes carcharodonta (130), Phoronida (80)
	1998	Nutricola lordi (2702), Euphilomedes carcharodonta (192), Alvania compacta (123), Phyllochaetopterus prolifica (73)
	1999	Nutricola lordi (484), Euphilomedes carcharodonta (122), Alvania compacta (84), Axinopsida serricata (75)
	2000	Nutricola lordi (441), Euphilomedes carcharodonta (139), Axinopsida serricata (70), Alvania compacta (66)
	2001	Nutricola lordi (293), Boccardia pugettensis (255), Euphilomedes carcharodonta (138), Alvania compacta (131)
	2002	Nutricola lordi (658), Odostomia sp (265), Euphilomedes carcharodonta (216), Alvania compacta (127)
	2003	Nutricola lordi (963), Alvania compacta (179), Euphilomedes carcharodonta (172), Axinopsida serricata (62)
	2004	Nutricola lordi (106), Euphilomedes carcharodonta (88), Alvania compacta (79), Axinopsida serricata (23)
	2005	Nutricola lordi (633), Euphilomedes carcharodonta (198), Alvania compacta (102), Dipolydora socialis (67)
14, Central Hood Canal	1989	Axinopsida serricata (86), Macoma carlottensis (29), Echiurus echiurus alaskanus (16), Maldanidae (14)
	1990	Axinopsida serricata (26), Pinnixa occidentalis (22), Macoma sp (18), Maldanidae (15)
	1991	Parvamussium alaskense (21), Axinopsida serricata (13), Maldane sarsi (12), Sternaspis cf fossor (9)
	1992	Galathowenia oculata (55), Axinopsida serricata (35), Macoma calcarea (28), Maldane sarsi (23)
	1993	Axinopsida serricata (34), Maldane sarsi (28), Euphilomedes producta (24), Delectopecten vancouverensis (24)
	1994	Euphilomedes producta (31), Maldane sarsi (20), Axinopsida serricata (18), Macoma sp (15)
211, Hood Canal, north	1999	Photis parvidons (88), Photis sp (86), Spiophanes bombyx (36), Astyris gausapata (19)
210, Hood Canal	1999	Axinopsida serricata (68), Euphilomedes producta (68), Nutricola lordi (52), Leitoscoloplos pugettensis (36)
209, Hood Canal	1999	Euphilomedes producta (184), Macoma carlottensis (24), Pinnixa sp (16), Macoma elimata (13)

Station, Location	Sampling Year	Dominant taxa (abundance)
222, Hood Canal, Oak Head	1999	Eudorella pacifica (68), Pectinaria californiensis (35), Euphilomedes producta (18), Prionospio (Minuspio) lighti (13)
323, Coon Bay	2004	Euphilomedes producta (76), Macoma carlottensis (48), Euphilomedes carcharodonta (32), Rhepoxynius boreovariatus (29)
75, Coon Bay	2004	Euphilomedes producta (34), Axinopsida serricata (26), Parvilucina tenuisculpta (23), Rhepoxynius boreovariatus (23)
203, Hood Head	2004	Alvania compacta (202), Gammaropsis thompsoni (79), Euphilomedes producta (51), Metopa dawsoni (42)
216, Sisters	2004	Axinopsida serricata (193), Nutricola lordi (80), Euphilomedes carcharodonta (69), Euphilomedes producta (43)
336, Bridgehaven	2004	Euphilomedes producta (70), Pinnixa sp (47), Axinopsida serricata (27), Euphilomedes carcharodonta (17)
88, N Four Corners	2004	Pinnixa sp (47), Heteromastus filobranchus (18), Euphilomedes carcharodonta (16), Euphilomedes producta (13)
152, Transit Station	2004	Axinopsida serricata (105), Euphilomedes producta (65), Macoma carlottensis (22), Myriochele olgae (22)
24, Vinland	2004	Axinopsida serricata (69), Myriochele olgae (46), Euphilomedes producta (46), Macoma carlottensis (20)
188, King Spit	2004	Euphilomedes producta (29), Macoma carlottensis (28), Heteromastus filobranchus (15), Pinnixa sp (12)
8, Hazel Point	2004	Axinopsida serricata (63), Cossura bansei (24), Prionospio lighti (22), Macoma carlottensis (18)
4. Dabob Bay – Nearshore (<30 m)		
15, Dabob Bay	1989	Macoma sp (53), Exogone lourei (23), Delectopecten vancouverensis (17), Phyllochaetopterus prolifica (17)
	1990	Exogone lourei (34), Alvania compacta (19), Prionospio steenstrupi/jubata (15), Parvilucina tenuisculpta (15)
	1991	Phoronida (380), Exogone lourei (41), Alvania compacta (27), Decamastus cf gracilis (19)
	1992	Phoronida (86), Exogone lourei (48), Phyllochaetopterus prolifica (27), Delectopecten vancouverensis (17)
	1993	Phoronida (56), Exogone lourei (34), Psephidia lordi (19), Leptochelia savignyi (16)
	1994	Exogone lourei (65), Phoronida (26), Psephidia lordi (22), Decamastus cf gracilis (15)
215, Quilcene Bay	1999	Trochochaeta multisetosa (127), Parvilucina tenuisculpta (85), Heteromastus filobranchus (71), Axinopsida serricata (45)
216, Quilcene Bay	1999	Trochochaeta multisetosa (97), Macoma sp (89), Macoma carlottensis (60), Pectinaria californiensis (43)
217, Quilcene Bay	1999	Axinopsida serricata (123), Macoma sp (109), Trochochaeta multisetosa (102), Macoma carlottensis (65)
5. Dabob Bay – Deep (>40 m)		
218, Dabob Bay, north end	1999	Pectinaria californiensis (61), Axinopsida serricata (48), Macoma carlottensis (45), Levinsenia gracilis (21)
220, Dabob Bay, Pulali Point	1999	Macoma carlottensis (4), Pacifoculodes zernovi (3), Nephtys cornuta (3), Paraprionospio pinnata (2)
219, Dabob Bay, Pulali Point	1999	Macoma carlottensis (9), Leitoscoloplos pugettensis (5), Nephtys cornuta (5), Eudorella pacifica (4)
32, Dabob Bay, Broad Spit	2004	Heteromastus filobranchus (87), Cossura bansei (14), Prionospio lighti (11), Lumbrineris cruzensis (11)
144, Fishermans Point	2004	Macoma carlottensis (38), Heteromastus filobranchus (17), Axinopsida serricata (13), Paraprionospio pinnata (11)
112, Dabob Bay, Tabook Point	2004	Nephtys cornuta (8), Leitoscoloplos pugettensis (7), Heteromastus filobranchus (4), Euphausiacea (4)
48, Pulali Pt	2004	Heteromastus filobranchus (10), Leitoscoloplos pugettensis (8), Macoma carlottensis (5), Podarkeopsis perkinsi (4)
92, Dabob Bay, Zelatched Pt	2004	Aricidea lopezi (19), Leitoscoloplos pugettensis (15), Prionospio lighti (10), Cossura bansei (9)
80, Dabob Bay, Sylopash Pt	2004	Mediomastus californiensis (49), Galathowenia oculata (34), Decamastus gracilis (24), Cossura bansei (21)
60, Dabob Bay, Seal Rock	2004	Prionospio lighti (27), Cossura bansei (12), Aricidea lopezi (8), Lumbrineris cruzensis (8)
184, Misery Point	2004	Leitoscoloplos pugettensis (7), Eudorella pacifica (5), Lumbrineris luti (4), Heteromastus filobranchus (4)

Station, Location	Sampling Year	Dominant taxa (abundance)
6. Central Hood Canal – Nearshore (<30 m)		
124, Seabeck	2004	Axinopsida serricata (65), Nutricola lordi (49), Exogone lourei (39), Euphilomedes producta (39)
252, Maple Beach, north	2004	Exogone lourei (65), Phoronis sp (62), Parvilucina tenuisculpta (30), Galathowenia oculata (20)
288, Maple Beach, south	2004	Nutricola lordi (63), Axinopsida serricata (42), Parvilucina tenuisculpta (41), Euphilomedes carcharodonta (31)
248, Tekiu Point	2004	Axinopsida serricata (136), Macoma carlottensis (52), Galathowenia oculata (15), Exogone lourei (15)
7. Central Hood Canal – Deep (>130 m)		
304R, Central Hood Canal	1992	Thyasira flexuosa (19), Axinopsida serricata (10), Macoma carlottensis (5), Cylichnidae (3)
223, Hood Canal	1999	Leitoscoloplos pugettensis (11), Brisaster latifrons (5), Chaetoderma sp (5), Lumbrineris limicola (4)
56, Stavis Bay	2004	Prionospio lighti (18), Aricidea lopezi (16), Lumbrineris cruzensis (10), Euphausiacea (8)
296, Fulton Creek, north	2004	Prionospio lighti (22), Cossura bansei (11), Levinsenia gracilis (8), Leitoscoloplos pugettensis (8)
120, Fulton Creek, south	2004	Phyllochaetopterus claparedii (18), Macoma carlottensis (18), Brisaster latifrons (9), Euphausiacea (8)
8. Southern Hood Canal		
16, Great Bend	1989	Sipuncula (19), Spiophanes berkeleyorum (18), Macoma sp (15), Prionospio (Minuspio) lighti (12)
17, Great Bend	1989	Axinopsida serricata (57), Cossura bansei (13), Aricidea (Acmira) lopezi (8), Eudorella pacifica (7)
	1990	Axinopsida serricata (65), Spiophanes berkeleyorum (43), Cossura bansei (16), Sigambra nr bassi (12)
	1991	Axinopsida serricata (311), Spiophanes berkeleyorum (22), Cylichnidae (9), Macoma carlottensis (8)
	1992	Axinopsida serricata (149), Spiophanes berkeleyorum (36), Heteromastus filobranchus (11), Eudorella pacifica (7)
	1993	Axinopsida serricata (113), Spiophanes berkeleyorum (29), Eudorella pacifica (19), Cylichnidae (14)
	1994	Axinopsida serricata (48), Spiophanes berkeleyorum (20), Eudorella pacifica (8), Cossura bansei (5)
221, Hood Canal, Red Bluff	1999	Mediomastus sp (16), Macoma carlottensis (12), Axinopsida serricata (12), Heteromastus filobranchus (11)
226, Hood Canal, Ayres Point	1999	Spiophanes berkeleyorum (100), Heteromastus filobranchus (55), Macoma carlottensis (28), Eudorella pacifica (26)
96, Sund Creek	2004	Leitoscoloplos pugettensis (9), Eudorella pacifica (8), Aricidea lopezi (5), Calanoida (5)
64, Musquiti Point, north	2004	Axinopsida serricata (54), Prionospio lighti (43), Macoma carlottensis (24), Cossura pygodactylata (13)
224, Musquiti Point	2004	Axinopsida serricata (30), Spiophanes berkeleyorum (20), Macoma carlottensis (17), Euphausiacea (6)
9. Lynch Cove		
305R, Lynch Cove	1992	Paraprionosp (77), Podarkeopsis glabrus (14), Sigambra nr bassi (13), Capitella capitata complex (4)
225, Hood Canal, Lynch Cove	1999	Sigambra nr bassi (87), Paraprionospio pinnata (25), Axinopsida serricata (7), Glycinde polygnatha (6)
224, Hood Canal, Lynch Cove	1999	Sigambra nr bassi (54), Spiophanes berkeleyorum (19), Paraprionospio pinnata (10), Heteromastus filobranchus (10)
128, Sisters Point	2004	Axinopsida serricata (159), Pectinaria californiensis (55), Heteromastus filobranchus (28), Euphysa sp (12)
118, Shoofly Creek	2004	Axinopsida serricata (47), Paraprionospio pinnata (27), Sigambra nr bassi (16), Heteromastus filobranchus (4)

Table 14. Hood Canal stations with adversely affected* benthos sampled between 1989 and 2005. Stations are listed geographically from north to south, and in chronological order.

Station, Location	Project	Sampling Year
1. Port Ludlow		
207, Port Ludlow	PSAMP/NOAA	1999
206, Port Ludlow	PSAMP/NOAA	1999
208, Port Ludlow, south shore	PSAMP/NOAA	1999
2. Port Gamble		
212, Port Gamble Bay	PSAMP/NOAA	1999
214, Port Gamble Bay	PSAMP/NOAA	1999
213, Port Gamble Bay, south	PSAMP/NOAA	1999
3. Northern Hood Canal		
222, Hood Canal, Oak Head	PSAMP/NOAA	1999
323, Coon Bay	PSAMP Spatial	2004
75, Coon Bay	PSAMP Spatial	2004
336, Bridgehaven	PSAMP Spatial	2004
88, N Four Corners	PSAMP Spatial	2004
188, King Spit	PSAMP Spatial	2004
8, Hazel Point	PSAMP Spatial	2004
4. Dabob Bay - Nearshore (<30 m)		
none		
5. Dabob Bay - Deep (>40 m)		
218, Dabob Bay, north end	PSAMP/NOAA	1999
220, Dabob Bay, Pulali Point	PSAMP/NOAA	1999
219, Dabob Bay, Pulali Point	PSAMP/NOAA	1999
32, Dabob Bay, Broad Spit	PSAMP Spatial	2004
144, Fishermans Point	PSAMP Spatial	2004
112, Dabob Bay, Tabook Point	PSAMP Spatial	2004
48, Pulali Point	PSAMP Spatial	2004
92, Dabob Bay, Zelatched Point	PSAMP Spatial	2004
80, Dabob Bay, Sylopash Point	PSAMP Spatial	2004
60, Dabob Bay, Seal Rock	PSAMP Spatial	2004
184, Misery Point	PSAMP Spatial	2004
6. Central Hood Canal - Nearshore (<30 m)		
248, Tekiu Point	PSAMP Spatial	2004

Station, Location	Project	Sampling Year
7. Central Hood Canal – Deep (>130 m)		
304R, Central Hood Canal	PSAMP Temporal	1992
223, Hood Canal	PSAMP/NOAA	1999
56, Stavis Bay	PSAMP Spatial	2004
296, Fulton Creek, north	PSAMP Spatial	2004
120, Fulton Creek, south	PSAMP Spatial	2004
8. Southern Hood Canal		
16, Great Bend	PSAMP Temporal	1989
17, Great Bend	PSAMP Temporal	1989
		1990
		1991
		1992
		1993
		1994
221, Hood Canal, Red Bluff	PSAMP/NOAA	1999
226, Hood Canal, Ayres Point	PSAMP/NOAA	1999
96, Sund Creek	PSAMP Spatial	2004
64, Musquiti Point, north	PSAMP Spatial	2004
224, Musquiti Point	PSAMP Spatial	2004
9. Lynch Cove		
305R, Lynch Cove	PSAMP Temporal	1992
225, Hood Canal, Lynch Cove	PSAMP/NOAA	1999
224, Hood Canal, Lynch Cove	PSAMP/NOAA	1999
128, Sisters Point	PSAMP Spatial	2004
118, Shoofly Creek	PSAMP Spatial	2004

*adversely affected = stations with the majority of benthic indicators being < 80% of the median 1997-2003 Puget Sound baseline benthic index values, or dominated by stress-tolerant taxa.

Table 15. Projects, station numbers, and station locations for dissolved oxygen surveys conducted in Hood Canal between 1932 and 2005. Stations are listed geographically from north to south.

HCDOP site	Location	Projects that sampled this site	Station	Longitude	Latitude
Admiralty Inlet					
117	Admiralty Inlet	HC	1	-122.620000	47.983333
	Admiralty Inlet	PRISM	7	-122.620000	47.983333
Outer Hood Canal					
114	Twin Spits	historical	501	-122.633333	47.935000
118	Twin Spits	PSAMP Spatial	139	-122.616695	47.929259
116	South of Twin Spits	PSAMP Spatial	323	-122.624346	47.914229
120	North of Point Hannon	PSAMP Spatial	75	-122.606944	47.902461
121	North of Point Hannon	HC	2	-122.605000	47.896667
		PRISM	8		
119	Point Hannon	PSAMP Spatial	203	-122.615079	47.882559
122	North of Bridge	historical	502	-122.596667	47.875000
Port Gamble					
123	Port Gamble Bay	EMAP	WA00-0025	-122.578518	47.836292
Sill					
113	Squamish Harbor	historical	507	-122.641667	47.855000
107	Squamish Harbor	PSAMP Spatial	216	-122.664954	47.854798
111	South Point (just north of the sill)	EMAP	WA00-0024	-122.645938	47.841032
115	North Hood Canal (south of bridge)	PSAMP Temporal	13R	-122.629005	47.837666
109	South Point (just north of the sill)	PSAMP Spatial	336	-122.656710	47.836925
110	South Point (just north of the sill)	PSAMP Spatial	88	-122.650162	47.833882
106	Bridgehaven	HC	3	-122.666667	47.833333
		historical	508		
		PRISM	9		
98	Thorndyke Bay	HCDOP	P10 W	-122.725420	47.806680
101	Thorndyke Bay	HC	4	-122.720000	47.800000
		HCDOP	P10	-122.720600	47.800030
		PSAMP Spatial	152	-122.712473	47.791627
		PRISM	10	-122.720000	47.800000
99	South of Thorndyke Bay	historical	509	-122.723333	47.788333
102	Vinland	HCDOP	P10 E	-122.692710	47.780120
100	South of Thorndyke Bay	PSAMP Spatial	24	-122.723201	47.783720
Bangor					
95	King Spit, Bangor-post 9/11	Marine Flights	HCB008	-122.745000	47.753300
97	King Spit, Bangor	Marine Flights	HCB006	-122.730000	47.748330

HCDOP site	Location	Projects that sampled this site	Station	Longitude	Latitude
86	Keyport	HCDOP	HCDOP 2 BANGW	-122.769710	47.740030
92	Keyport	HC	5	-122.753333	47.735000
93	Keyport	HCDOP	HCDOP 1 BANGOR	-122.752778	47.734722
89	Keyport	historical	510	-122.761667	47.698333
		PRISM	17	-122.761667	47.735000
94	King Spit	HCDOP	HCDOP 3 BANGE	-122.747880	47.721750
87	Hood Canal North	PSAMP Spatial	188	-122.765510	47.718526
126	North of Hazel Point	historical	510	-122.7616667	47.69833333
88	Hazel Point	HC	6	-122.765000	47.691667
	Hazel Point	PRISM	16		
91	Hood Canal - Hazel Pt, Bangor	Marine Flights	HCB009	-122.760000	47.688330
90	Hood Canal	PSAMP Spatial	8	-122.761119	47.677800
85	Oak Head	historical	511	-122.786667	47.676667
79	Misery Point	Marine Flights	HCB010	-122.820000	47.670000
83	Hood Canal	PSAMP Spatial	124	-122.805128	47.652075
Dabob Bay					
68	Dabob Bay	PSAMP Spatial	60	-122.865150	47.701468
75	Dabob Bay	PSAMP Spatial	92	-122.845906	47.713883
62	Dabob Bay	PSAMP Spatial	80	-122.882824	47.703727
77	Dabob Bay	PSAMP Spatial	48	-122.833037	47.735933
76	Dabob Bay, Pulali Point	EMAP	WA00-0027	-122.844077	47.734652
78	Dabob Bay	PSAMP Spatial	112	-122.831539	47.747203
74	Dabob Bay	Marine Flights	HCB002	-122.846660	47.746670
67	Quilcene Bay	PSAMP Spatial	144	-122.865298	47.785367
84	Dabob Bay	PSAMP Spatial	32	-122.804480	47.803197
81	Dabob Bay, north end	EMAP	WA00-0026	-122.818392	47.820575
Dosewallips-Hama					
66	Brinnon	PSAMP Spatial	184	-122.865396	47.674132
63	Brinnon	historical	541	-122.873333	47.668333
69	Mouth of Dabob Bay	HC	7	-122.860000	47.661667
		PRISM	15	-122.860000	47.661667
65	Hood Canal	PSAMP Spatial	252	-122.866406	47.637306
64	Hood Canal	PSAMP Spatial	288	-122.871121	47.637771
59	Quatsap Point	PSAMP Spatial	56	-122.892375	47.641708
58	Quatsap Point	historical	542	-122.896667	47.641667
56	Hood Point	historical	543	-122.920000	47.631667
47	Hood Point	HC	8	-122.940000	47.606667
		PRISM	14		

HCDOP site	Location	Projects that sampled this site	Station	Longitude	Latitude
43	Triton	PSAMP Spatial	296	-122.957832	47.608867
42	Triton	PSAMP Spatial	120	-122.963286	47.606140
41	Tekiu Point	historical	544	-122.966667	47.595000
46	Tekiu Point	PSAMP Spatial	248	-122.952192	47.587323
31	Cummings Point	HCDOP	HCDOP 5 HAMAW	-123.023170	47.556280
37	Eldon, Hamma Hamma R.	PSAMP Spatial	272	-122.996256	47.543281
34	Eldon, Hamma Hamma R.	PRISM	13	-123.008333	47.546667
	Eldon, Hamma Hamma R.	HC	9		
	Eldon, Hamma Hamma R.	HC	10		
	Eldon, Hamma Hamma R.	HC	10a		
	Eldon, Hamma Hamma R.	HC	10b		
	Eldon, Hamma Hamma R.	Marine Flights	HCB003	-123.008300	47.538330
35	Eldon, Hamma Hamma R.	HCDOP	HCDOP 4 HAMA	-123.006944	47.545833
36	Eldon, Hamma Hamma R.	HCDOP	HCDOP 6 HAMAE	-123.002500	47.538780
32	Hamma Hamma, Chinom	historical	545	-123.020000	47.536667
Ayock-Potlatch					
25	North of Eagle Creek	PRISM	401	-123.056667	47.491667
23	Eagle Creek	historical	546	-123.066667	47.476667
22	Lilliwaup Bay	HC	11	-123.091667	47.458333
21	South of Lilliwaup Bay	PSAMP Spatial	96	-123.100798	47.448840
18	Red Bluff	historical	547	-123.106667	47.435000
12	Sund Creek	HCDOP	HCDOP 19 SDRK70	-123.119300	47.435440
9	Sund Creek	HCDOP	HCDOP 17 SDRK	-123.120110	47.435570
10	Sund Creek	HCDOP	HCDOP 18 SDRK40	-123.119750	47.435460
17	Red Bluff	PRISM	12	-123.108333	47.425000
19	Red Bluff	HCDOP	HCDOP 21 BAMBE	-123.101520	47.418600
16	Red Bluff	EMAP	WA00-0028	-123.110330	47.420633
14	Red Bluff	HCDOP	HCDOP 20 BAMBAN	-123.114060	47.421510
7	Miller Creek	HCDOP	HCDOP 22 BAMBW	-123.127260	47.425200
11	North of Musqueti Point	PSAMP Spatial	64	-123.119413	47.397876
8	Musqueti Point	PSAMP Spatial	224	-123.122019	47.393927
4	Musqueti Point	historical	548	-123.131667	47.388333
15	Ayres Point	HCDOP	HCDOP 9 POTE	-123.112430	47.377880
6	Ayres Point	EMAP	WA00-0029	-123.129128	47.377977
3	Great Bend	HCDOP	HCDOP 7 POTLCH	-123.131944	47.370833
		PRISM	11	-123.133333	47.370000
		HC	12		
		HC	12a		

HCDOP site	Location	Projects that sampled this site	Station	Longitude	Latitude
		HC	12b		
1	Potlatch	HCDOP	HCDOP 8 POTW	-123.149320	47.372680
2	Annas Bay	historical	549	-123.140000	47.356667
Union-Sisters					
20	Union	HCDOP	HCDOP 10 POTSO	-123.101380	47.361230
24	Tahuya River	HC	13	-123.063333	47.358333
		historical	550		
26	Tahuya River	PSAMP Spatial	128	-123.050238	47.356713
28	Sister's Point	historical	551	-123.031667	47.356667
29	Sister's Point	HCDOP	HCDOP 12 SSTRN	-123.025940	47.360620
30	Sister's Point	HC	14	-123.023333	47.356667
		HCDOP	HCDOP 11 SISTER	-123.023300	47.356700
		Marine Flights	HCB004		
33	Sister's Point	HCDOP	HCDOP 13 SSTRS	-123.019100	47.354890
Lynch Cove					
38	Shady Beach	historical	552	-122.995000	47.375000
40	Shoofly Creek	PSAMP Spatial	118	-122.971827	47.385640
44	Lynch Cove	EMAP	WA00-0030	-122.956018	47.396542
50	Center of Lynch Cove	historical	553	-122.931667	47.398333
51	New, north channel in Lynch Cove	HC	15	-122.931667	47.401667
49	Lynch Cove	HCDOP	HCDOP 16 LYNCHN	-122.932470	47.406850
53	Center of Lynch Cove	HC	16	-122.930000	47.398333
54	New, south channel in Lynch Cove	HC	17	-122.928333	47.395000
55	Center of Lynch Cove	HCDOP	HCDOP 14 LYNCH	-122.928300	47.398300
		Marine Flights	HCB007		
57	South Lynch Cove	HCDOP	HCDOP 15 LYNCHS	-122.917380	47.391010
61	New, head of Lynch Cove (light N, ramp S)	HC	18	-122.883333	47.416667

Table 16. Number of Hood Canal dissolved oxygen stations and data values for each project and year between 1932 and 2005. Number of stations (number of values).

Year	Project						Total for year
	HC (Hood Canal)	Marine Flights	HCDOP	Historical	PSAMP Spatial	PRISM	
1932				5 (6)			5 (6)
1933				7 (8)			7 (8)
1934				1 (12)			1 (12)
1935				1 (10)			1 (10)
1936				1 (13)			1 (13)
1937				1 (10)			1 (10)
1938				1 (12)			1 (12)
1939				6 (17)			6 (17)
1940				1 (12)			1 (12)
1941				2 (14)			2 (14)
1942				1 (2)			1 (2)
1949				4 (7)			4 (7)
1952				12 (42)			12 (42)
1953				12 (122)			12 (122)
1954				12 (103)			12 (103)
1955				10 (41)			10 (41)
1956				10 (11)			10 (11)
1957				11 (31)			11 (31)
1958				10 (30)			10 (30)
1959				10 (45)			10 (45)
1960				11 (48)			11 (48)
1961				10 (20)			10 (20)
1962				10 (32)			10 (32)
1963				10 (10)			10 (10)
1965				12 (90)			12 (90)
1966				22 (390)			22 (390)
1968				4 (4)			4 (4)
1975		1 (1)					1 (1)
1976		4 (14)					4 (14)
1977		4 (19)					4 (19)
1978		4 (23)					4 (23)
1979		4 (18)					4 (18)
1980		4 (31)					4 (31)

Year	Project						Total for year
	HC (Hood Canal)	Marine Flights	HCDOP	Historical	PSAMP Spatial	PRISM	
1981		4 (24)					4 (24)
1982		4 (32)					4 (32)
1983		4 (32)					4 (32)
1984		4 (30)					4 (30)
1985		4 (31)					4 (31)
1986		4 (22)					4 (22)
1987		4 (22)					4 (22)
1988		2 (3)					2 (3)
1989		2 (7)					2 (7)
1990		4 (18)					4 (18)
1991		4 (45)					4 (45)
1992		4 (33)					4 (33)
1993		3 (22)					3 (22)
1994	17 (84)	4 (33)					21 (117)
1995	17 (48)	4 (46)					21 (94)
1996		4 (33)					4 (33)
1997	15 (16)	2 (21)					17 (37)
1998	16 (71)	4 (27)				10 (20)	30 (118)
1999	19 (56)	4 (36)				10 (30)	33 (122)
2000		4 (45)				10 (20)	14 (65)
2001		4 (36)				10 (20)	14 (56)
2002		4 (31)				10 (10)	14 (41)
2003		5 (36)	22 (307)			11 (22)	38 (365)
2004		5 (32)	25 (701)		30 (30)	10 (20)	70 (783)
2005		5 (41)	27 (734)			10 (10)	42 (785)

Table 17. Near-bottom dissolved oxygen measurements in waters collected from Hood Canal for the 2004 PSAMP Sediment Component.

Station, Location	Depth (m)	Bottom DO (mg/L)
North Hood Canal		
323, Coon Bay	103.0	6.812
75, Coon Bay	95.0	7.452
203, Hood Head	75.0	7.441
216, Sisters	19.0	8.001
336, Bridgehaven	75.0	6.973
88, N Four Corners	54.0	7.307
152, Transit Station	37.0	7.250
24, Vinland	47.0	7.076
188, King Spit	109.0	6.186
8, Hazel Point	66.0	5.901
Dabob Bay - Deep (>40 m)		
32, Dabob Bay, Broad Spit	110.0	4.229
144, Fishermans Point	45.0	4.537
112, Dabob Bay, Tabook Point	177.0	0.443
48, Pulali Point	174.0	0.953
92, Dabob Bay, Zelatched Point	159.0	3.484
80, Dabob Bay, Sylopash Point	98.0	4.135
60, Dabob Bay, Seal Rock	153.0	2.873
184, Misery Point	113.0	4.080
Central Hood Canal - Nearshore (<30 m)		
124, Seabeck	19.0	11.719
252, Maple Beach N	17.0	12.499
288, Maple Beach S	14.0	13.118
248, Tekiu Point	25.0	9.788
Central Hood Canal - Deep (>130 m)		
56, Stavis Bay	164.0	3.234
296, Fulton Creek N	134.0	1.566
120, Fulton Creek S	164.0	2.242
Southern Hood Canal		
96, Sund Creek	132.0	1.864
64, Musquiti Point N	95.0	1.809
224, Musquiti Point	93.0	1.589
Lynch Cove		
128, Sisters Point	38.0	1.615
118, Shoofly Creek	30.0	1.063

Table 18. Significant Pearson correlation coefficients (r) for data from 32 sediment parameters measured from up to 57 PSAMP Sediment Component samples collected from 1989 through 2005, and near-bottom dissolved oxygen samples measured from 30 PSAMP Sediment Component samples collected in 2004.

0.9 ≤ |r| ≤ 1.0 - strong, 0.5 ≤ |r| < 0.9 - moderate, |r| < 0.5 - weak correlations; p values <0.05 - significant (light shading), <0.0001 - highly significant (dark shading). (Subset of all correlations presented in Appendix I, Table 1)

	PARAMETER	BIOLOGICAL									
		Euphausiacea	*Euphilomedes carcharodonta*	*Nutricola lordi*	Total Taxa Abundance	Taxa Richness	Pielou's Evenness - J'	Swartz's Dominance Index	Annelid Abundance	Arthropod Abundance	Miscellaneous Taxa Abundance
BIOLOGICAL	*Nutricola lordi*		0.749								
	Total Taxa Abundance		0.759	0.756			-0.699				
	Taxa Richness		0.669	0.587	0.647						
	Pielou's Evenness - J'		-0.536	-0.518							
	Swartz's Dominance Index					0.482	0.547				
	Annelid Abundance				0.654		-0.513				
	Arthropod Abundance		0.559	0.430	0.623	0.518					
	Echinoderm Abundance					0.415					
	Mollusca Abundance		0.799	0.978	0.799	0.650	-0.544			0.498	
	Misc. Taxa Abundance					0.454					
PHYS	Percent Fines		-0.491		-0.550	-0.739				-0.584	-0.428
	% Total Organic Carbon					-0.678		-0.426			
	Depth	0.427			-0.517	-0.438	0.561				
CHEM	Mean SQS Metals				-0.494	-0.685				-0.473	
	Total Aroclors	0.450									
	Mean SQS Misc. Organics										
	Mean SQS PAH						-0.518		0.556		
	Mean SQS phenols										
TOX	Sea Urchin Fertilization										
DO	Near-bottom DO					0.732					0.763

	PARAMETER	PHYSICAL			CHEMICAL				TOXICITY
		Percent Fines	% Total Organic Carbon	Depth	Mean SQS Metals	Mean SQS PAH	Total Aroclors	Mean SQS Misc. Organics	Sea Urchin Fertilization
PHYS	Percent Fines								
	% Total Organic Carbon	0.737							
	Depth	0.598					0.444		-0.531
CHEM	Mean SQS Metals	0.859	0.802						
	Total Aroclors								
	Mean SQS Misc. Organics						0.483		
	Mean SQS Phenols						0.448	0.458	
TOX	Sea Urchin Fertilization						-0.550		
DO	Near-bottom DO	-0.849	-0.809	-0.724	-0.921				

Table 19. Median (+ Mean Absolute Deviation) benthic metric values within five ranges of decreasing near-bottom DO concentrations in Hood Canal, and the ratios between the metrics in highest DO samples and lowest DO samples. Data are from the 2004 PSAMP Sediment Monitoring survey. Sampling area = 0.1 m^2.

DO (mg/L) (no. samples)	Total Abundance	Taxa Richness	Pielou's Evenness (J')	Swartz' Dominance Index (SDI)	Annelid Abundance	Arthropod Abundance	Mollusca Abundance	Echinoderm Abundance	Miscellaneous Taxa Abundance
>10 (n=3)	418 (5)	80 (2)	0.79 (0.00)	18 (0)	211 (5)	59 (4)	164 (5)	1 (1)	48 (13)
>6 to 10 (n=10)	339 (65)	59 (5)	0.77 (0.03)	14 (3)	97 (42)	105 (46)	133 (70)	1 (1)	12 (6)
>3 to 6 (n=7)	136 (63)	32 (12)	0.81 (0.05)	8 (2)	74 (22)	15 (4)	12 (8)	0 (0)	1 (1)
>1 to 3 (n=8)	127 (22)	30 (5)	0.80 (0.06)	8 (3)	74 (21)	16 (5)	34 (27)	0 (0)	2 (2)
≤1 (n=2)	31 (4)	8 (2)	0.88 (0.04)	4 (0)	22 (3)	5 (2)	4 (3)	0 (0)	0 (0)
ratio (high/low)	418/31	80/8	.88/.77	18/4	211/22	105/5	164/4	1/0	48/0

Table 20. Median (+ Mean Absolute Deviation) taxa abundance values for 17 species within five ranges of decreasing near-bottom DO concentrations in Hood Canal, and the ratios between the metrics in highest DO samples and lowest DO samples. Data are from the 2004 PSAMP Sediment Monitoring cruise. Sampling area = 0.1 m^2.

DO (mg/L) (no. samples)	*Aricidea (Acmira) lopezi*	*Axinopsida serricata*	*Cossura bansei*	*Euphilomedes carcharodonta*	*Euphilomedes producta*	*Heteromastus filobranchus*
>10 (n=3)	1 (0)	42 (23)	1 (0)	4 (3)	10 (8)	0 (0)
>6 to 10 (n=10)	0 (0)	27 (25)	0 (0)	17 (16)	45 (18)	3 (2)
>3 to 6 (n=7)	6 (3)	2 (2)	9 (9)	0 (0)	0 (0)	17 (8)
>1 to 3 (n=8)	1 (1)	17 (17)	0 (0)	0 (0)	0 (0)	1 (1)
<=1 (n=2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	7 (3)
ratio (high/low)	1/0	42/0	1/0	4/0	10/0	0/7
DO (mg/L) (no. samples)	*Leitoscoloplos pugettensis*	*Macoma carlottensis*	*Magelona longicornis*	*Mediomastus* sp.	*Nutricola lordi*	*Paraprionospio pinnata*
>10 (n=3)	1 (1)	0 (0)	1 (0)	2 (0)	49 (14)	0 (0)
>6 to 10 (n=10)	6 (5)	21 (8)	0 (0)	3 (3)	4 (4)	1 (1)
>3 to 6 (n=7)	5 (4)	8 (7)	0 (0)	1 (1)	0 (0)	1 (0)
>1 to 3 (n=8)	4 (3)	3 (3)	0 (0)	1 (1)	0 (0)	1 (1)
<=1 (n=2)	8 (1)	3 (2)	0 (0)	1 (1)	0 (0)	0 (0)
ratio (high/low)	1/8	0/3	1/0	2/1	49/0	0/0
DO (mg/L) (no. samples)	*Parvilucina tenuisculpta*	*Pectinaria californiensis*	*Pectinaria granulata*	*Prionospio (Minuspio) lighti*	*Rhepoxynius boreovariatus*	
>10 (n=3)	30 (11)	2 (1)	15 (1)	1 (1)	3 (3)	
>6 to 10 (n=10)	8 (3)	2 (2)	0 (0)	2 (2)	4 (4)	
>3 to 6 (n=7)	0 (0)	1 (1)	0 (0)	10 (8)	0 (0)	
>1 to 3 (n=8)	0 (0)	1 (1)	0 (0)	3 (3)	0 (0)	
<=1 (n=2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	
ratio (high/low)	30/0	2/0	15/0	1/0	3/0	

Table 21. Relative contribution (percent) of the top 48 species to overall variation in benthic community structure as measured by chord-normalized expected species shared (CNESS).

Species	Rank	Contribution	Cumulative contribution
Axinopsida serricata	1	5	5
Euphilomedes producta	2	4	9
Heteromastus filobranchus	3	4	13
Macoma carlottensis	4	3	17
Prionospio (Minuspio) lighti	5	3	20
Cossura bansei	6	3	23
Leitoscoloplos pugettensis	7	3	26
Euphilomedes carcharodonta	8	3	28
Euphausiacea	9	3	31
Nutricola lordi	10	2	33
Aricidea (Acmira) lopezi	11	2	36
Lumbrineris cruzensis	12	2	38
Parvilucina tenuisculpta	13	2	40
Pinnixa sp	14	2	42
Pectinaria californiensis	15	2	44
Nephtys cornuta	16	2	46
Eudorella pacifica	17	2	48
Hyperiidae	18	2	49
Paraprionospio pinnata	19	2	51
Exogone lourei	20	2	53
Mediomastus sp	21	2	54
Phyllochaetopterus limicolus	22	2	56
Phoronis sp	23	2	58
Galathowenia oculata	24	2	59
Rhepoxynius boreovariatus	25	1	61
Bathymedon pumilus	26	1	62
Scoletoma luti	27	1	63
Brisaster latifrons	28	1	65
Spiophanes berkeleyorum	29	1	66
Sigambra nr bassi	30	1	67
Levinsenia gracilis	31	1	68
Alvania compacta	32	1	70
Myriochele olgae	33	1	71
Decamastus gracilis	34	1	71
Pulsellum salishorum	35	1	72
Acila castrensis	36	1	73
Podarkeopsis perkinsi	37	1	74
Prionospio (Prionospio) jubata	38	1	75
Cossura pygodactylata	39	1	75
Calanoida	40	1	76
Chaetozone commonalis	41	1	77
Gammaropsis thompsoni	42	1	77
Rochefortia tumida	43	1	78
Compsomyax subdiaphana	44	1	79
Phyllochaetopterus prolifica	45	1	79
Astyris gausapata	46	1	80
Ennucula tenuis	47	1	81
Levinsenia oculata	48	1	81

Table 22. Environmental variable contribution statistics. Contributions and standardized beta coefficients for the 25 species that contributed most to CNESS variation in Hood Canal benthic community structure.

Environmental variable	***Axinopsida serricata***		***Euphilomedes producta***		***Heteromastus filobranchus***		***Macoma carlottensis***		***Prionospio (Minuspio) lighti***	
	contribution	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**
depth	**0.7165**	**-0.958**	0.0523	-0.1021	-0.0403	-0.1681	**0.0786**	**0.269**	0.0406	0.1173
D.O.	-0.1861	-0.5511	0.0724	0.1156	-0.0207	0.0486	0.0034	-0.015	-0.1907	0.5689
% fines	0.1373	-0.318	**0.1841**	**-0.2826**	**0.1583**	**0.3159**	-0.0155	-0.0795	**0.4017**	**0.7296**
%TOC	-0.0173	0.0497	0.1546	-0.2394	0.198	0.3857	0.022	0.103	0.1191	0.2529

Environmental variable	***Cossura bansei***		***Leitoscoloplos pugettensis***		***Euphilomedes carcharodonta***		**Euphausiacea**		***Nutricola lordi***	
	contribution	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**
depth	0.0967	0.2751	**0.8509**	**0.9948**	-0.066	0.2021	**0.3993**	**0.5531**	-0.0662	0.1297
D.O.	-0.1099	0.4299	0.0053	-0.0105	-0.0497	-0.0919	0.1109	-0.1817	0.2909	0.3698
% fines	**0.1702**	**0.4379**	-0.0409	-0.0946	**0.5893**	**-0.8325**	0.1692	0.2842	**0.2996**	**-0.3758**
%TOC	0.051	0.1523	-0.0562	-0.1386	0.0575	-0.0942	-0.1169	-0.2256	0.1795	-0.2278

Environmental variable	***Aricidea (Acmira) lopezi***		***Lumbrineris cruzensis***		***Parvilucina tenuisculpta***		***Pinnixa* sp**		***Pectinaria californiensis***	
	contribution	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**
depth	0.2707	0.5046	0.1033	0.2823	0.1317	-0.2402	0.0284	-0.1452	**0.2433**	**-0.6773**
D.O.	-0.2803	0.9007	-0.1619	0.6059	**0.3483**	**0.5744**	0.0287	0.1882	0.0043	-0.8476
% fines	**0.5178**	**0.8835**	0.1519	0.3616	0.0929	-0.1777	**0.0957**	**-0.5031**	0.0061	-0.0531
%TOC	0.0674	0.1478	**0.1812**	**0.4407**	-0.1529	0.3314	-0.023	0.6504	0.0482	-0.3833

Environmental variable	***Nephtys cornuta***		***Eudorella pacifica***		**Hyperiidae**		***Paraprionospio pinnata***		***Exogone lourei***	
	contribution	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**
depth	**0.0581**	**0.1647**	-0.0316	-0.3173	**0.3523**	**0.5377**	**0.1427**	**-0.8494**	0.0074	-0.0152
D.O.	0.0582	-0.1529	0.0162	-0.0531	0.0901	-0.17	0.1169	-0.3331	**0.4544**	**0.6594**
% fines	-0.0062	-0.0179	**0.4505**	**0.9572**	0.1271	0.2487	0.0732	0.193	0.0178	-0.0306
%TOC	0.055	0.1499	-0.1128	-0.3783	-0.1125	-0.2589	0.2365	0.5255	-0.0043	0.0073

Environmental variable	***Mediomastus* sp**		***Phyllochaetopterus limicolus***		***Phoronis* sp**		***Galathowenia oculata***		***Rhepoxynius boreovariatus***	
	contribution	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**	**contribution**	**stand. beta**
depth	0.0925	0.3346	**0.0858**	**0.4201**	-0.0023	0.0043	-0.0087	0.024	-0.0534	0.3742
D.O.	0.0244	-0.113	0.0323	0.6967	**0.5711**	**0.7377**	**0.2836**	**0.5463**	-0.0061	-0.0156
% fines	-0.0004	-1.1244	0.0208	0.2324	0.1218	-0.1794	0.162	-0.3366	**0.6808**	**-1.1316**
%TOC	**0.2595**	**0.9435**	0.0116	0.193	-0.0841	0.1287	-0.1369	0.3401	-0.1323	0.3202

Appendices

On the following pages

A. Dissolved oxygen estimation methods
   - Figure 1. Hood Canal segments based on bathymetry and geographic features.
   - Figure 2. "Nearest neighbor/depth slice" method of estimating dissolved oxygen.
   - Figure 3. Differentiation between areas with sediment-sampling stations and water - sampling stations.
   - Figure 4. Example of estimated dissolved oxygen concentrations at PSAMP sediment stations using kriging.
   - Figure 5. Relationship between bottom dissolved oxygen at center and sides of Hood Canal.
   - Figure 6. Demonstration of variability in maximum depth at which dissolved oxygen was measured at a given water-sampling station.

B. Sediment and water quality surveys conducted in Hood Canal from 1932 through 2005.

On the enclosed CD

C. HCDOP Task IV Access database, including all sediment and water column dissolved oxygen data collected from Hood Canal between 1932-2005.

D. Matrix of all Hood Canal sediment quality and dissolved oxygen data selected for analysis.

E. Selected results for chemistry, toxicity, and infaunal analyses for all PSAMP sediment stations sampled in Hood Canal between 1989 and 2005.

F. Parameters and number of sediment stations sampled for projects conducted in Hood Canal between 1952 and 2005.

G. Station numbers and sampling dates for all Hood Canal dissolved oxygen stations.
   - Table 1. Station numbers and sampling dates for all historical Hood Canal dissolved oxygen stations (1932-1968).
   - Table 2. Station numbers and sampling dates for all PSAMP Hood Canal marine water column flight stations (1975-2005).
   - Table 3. Station numbers and sampling dates for all water column stations sampled by Ecology in Hood Canal (1994-1999).
   - Table 4. Station numbers and sampling dates for all water column Hood Canal PRISM stations (1998-2005).
   - Table 5. Station numbers and sampling dates for all water column HCDOP stations (2003-2005).

H. Summary statistics for dissolved oxygen measured in Hood Canal between 1932 and 2005.

On the following pages and on the CD, in part

I. Relationships between benthic index values and sediment and water quality parameters.

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A. Dissolved oxygen estimation methods

DO concentrations for sediment stations

In most cases, DO concentrations were not measured when the sediment and benthos were sampled. In order to examine possible relationships between DO and benthos, it was necessary to estimate DO levels for the locations and times of the sediment sampling, if possible. Several direct and indirect methods were used in attempts to estimate DO both directly and indirectly from available DO data, including: (1) a nearest neighbor/depth slice method, (2) kriging, and (3) examination of statistical relationships between DO and oceanographic and geographical parameters, cross-sectional profiles, and long-term trends.

However, all of these methods fell victim to the same underlying problem: the paucity and scarcity of relevant DO data available for this study from studies which were designed for entirely different purposes. In some cases, DO estimates hinged on a single measured value. (Although CTD casts provide hundreds of measurements in a single sample, only the DO concentration at or near the seabed is relevant to the benthos.)

Attempts to estimate DO directly from data

Subsets of the DO data collected from 1989-2005 were chosen as bases for attempts at estimating values to pair with benthos, including:

- DO at maximum depth sampled for each water station
  - by month for the 12 months preceding the June 2004 PSAMP/PRISM cruise,
  - by month for the 12 months preceding the June 1999 PSAMP/NOAA cruise, and
  - by year for the 12-month period preceding each of the 1989-2005 PSAMP Sediment Temporal sampling events

and

- DO at the same depth levels as the sediment stations
  - by month for the 12 months preceding the June 2004 PSAMP/PRISM cruise,
  - by month for the 12 months preceding the June 1999 PSAMP/NOAA cruise, and
  - by year for the 12-month period preceding each of the 1989-2005 PSAMP Sediment Temporal sampling events.

The methods employed for estimating DO concentrations at the sediment-sampling stations are described below.

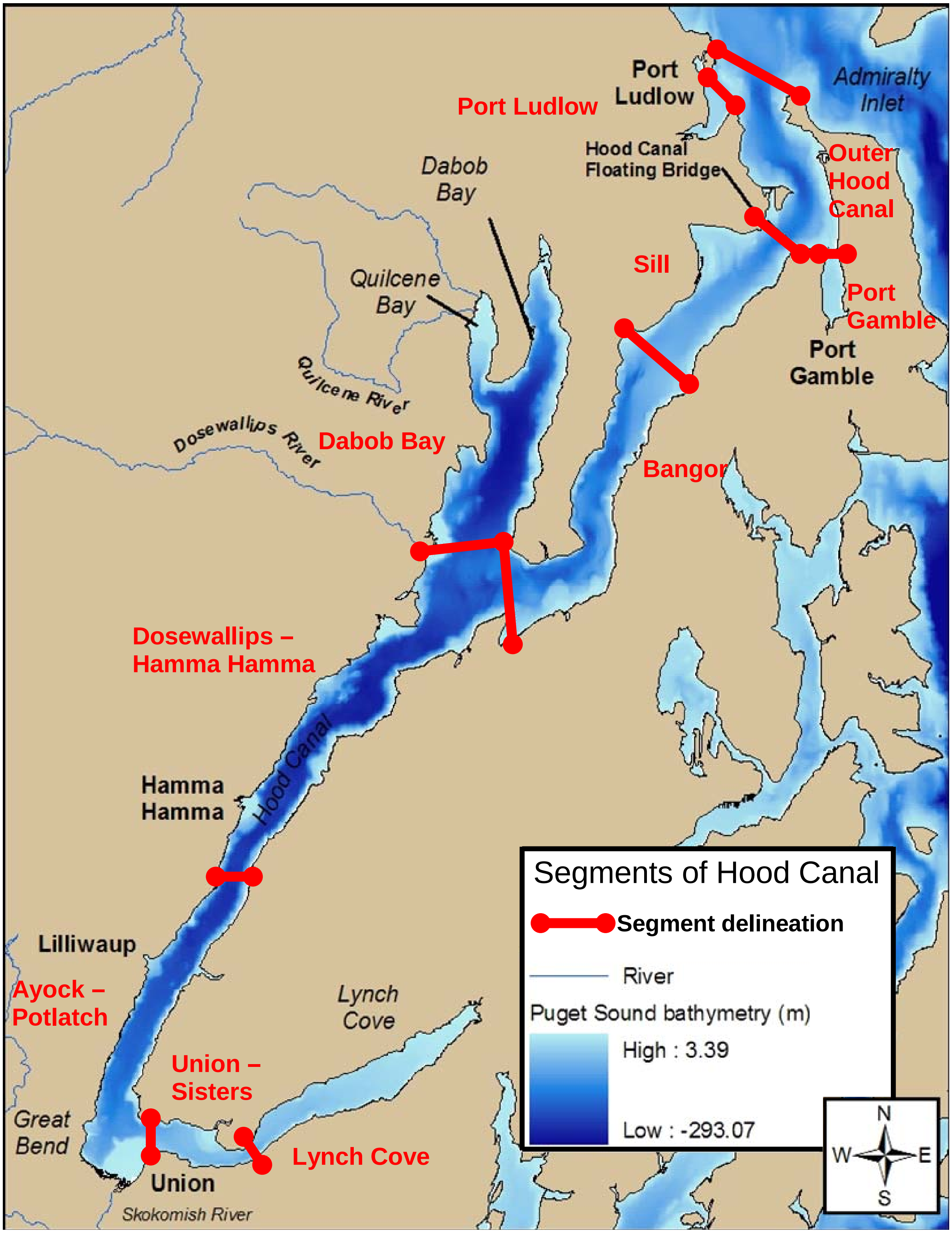
- **"Nearest neighbor/depth slice" method –** Estimated DO values were generated by matching sediment station locations to the nearest DO data available partitioned by depth and segment of Hood Canal. Hood Canal was divided into segments based on bathymetry and geographic features (Appendix A, Figure 1). All Winkler and CTD data available at the depth levels of the sediment-station depths were pulled from the database (Appendix A,

Figure 2). The lowest DO value during the time period of interest (described above) was selected for each water-sampling station. (The rationale for choosing the lowest DO measurement in the 12 months preceding the sampling of the infauna was that low DO would have affected the parental generation.) Of the lowest DO values for each water station, that for the closest station within the same segment of Hood Canal as the sediment station was chosen.

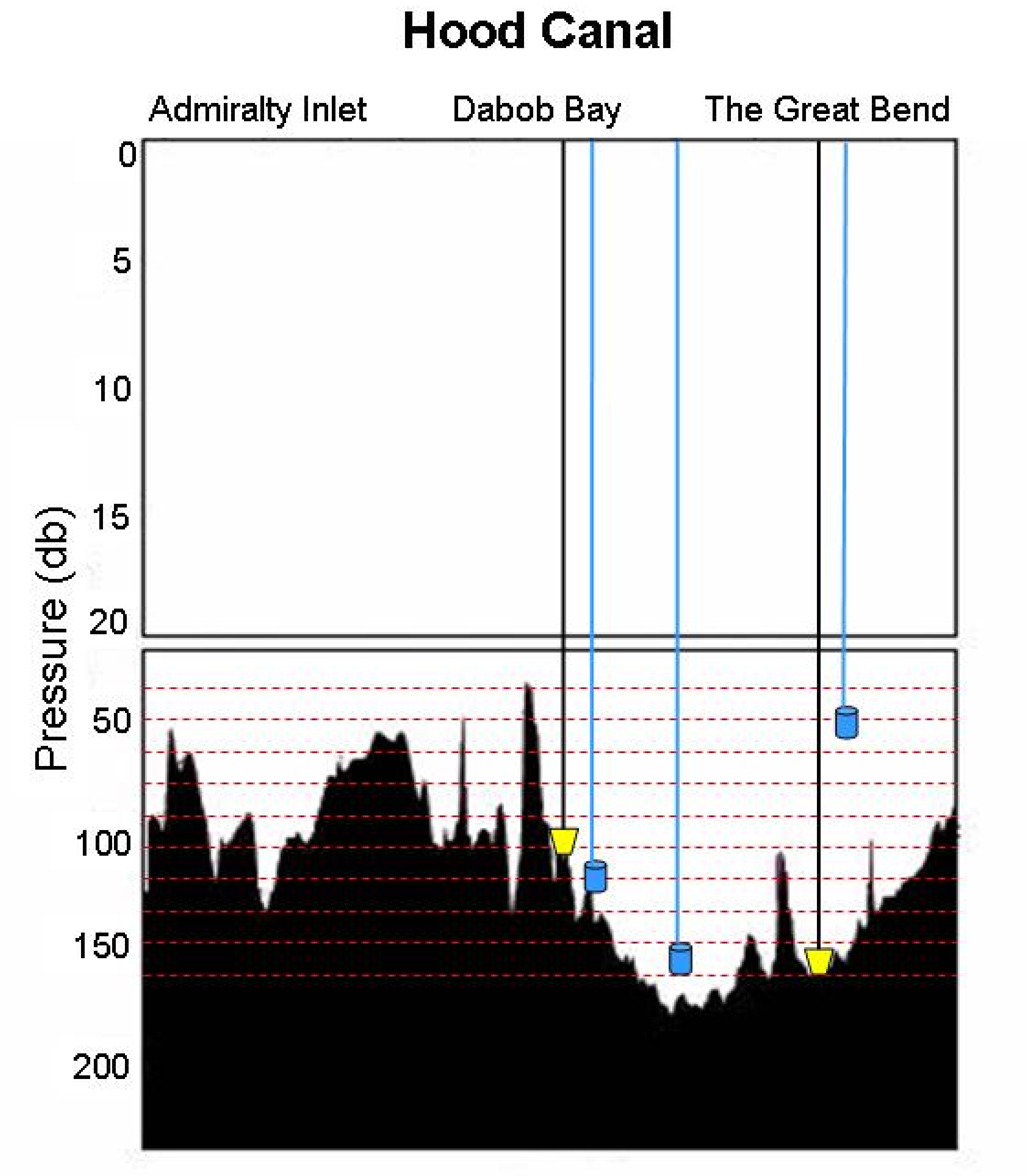
However, data for "nearest neighbor" stations were sparse and often non-existent (Appendix A, Figure 3). Although PRISM cruises provided a relatively consistent source of DO data for some stations, the timing (Junes and Decembers) was such that both peaks and, more importantly, valleys in DO were missed.

- **Kriging –** DO data at maximum depth sampled for each water station, as described above, were run through kriging algorithms in ArcMap Spatial Analyst to determine estimates of DO values for different segments of Hood Canal. Based on the shapes of the semi-variograms, the exponential model was selected for use. The areas of interpolation were restricted to ellipses with diameters approximately the sizes of segments of Hood Canal (e.g., the sill and the Bangor section, as described earlier), so that DO from water stations in Lynch Cove were not used to estimate DO at sediment stations in the central or northern portions of Hood Canal, and vice-versa. Color maps were produced indicating estimated DO levels in each segment for each of the time periods of interest (described above), based on the existing data (Appendix A, Figure 4).

  However, the lack of spatial and temporal coverage of Hood Canal by the water-sampling stations left large areas without DO interpolations. Furthermore, often there were too few sample points to run the kriging algorithm, let alone have any confidence in the answers. In addition, most of the stations for which DO data were available during the year preceding the 2004 PSAMP Spatial sediment sampling event were HCDOP volunteer stations. Two-thirds of these volunteer stations have a maximum depth of 9 meters (the edge stations), not representative of the depths at bottom of the sediment stations. DO estimates based on those HCDOP data were therefore biased high.

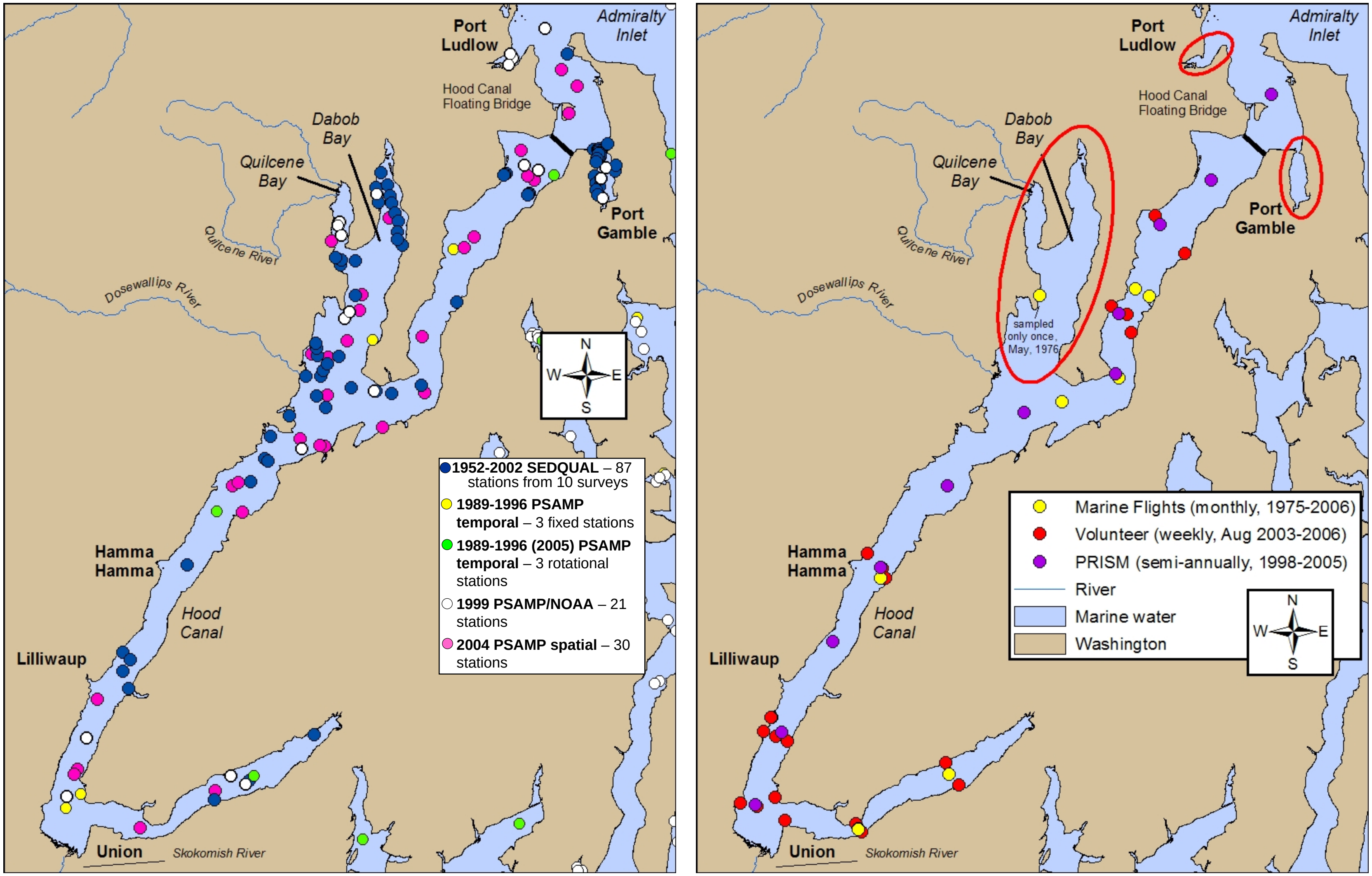


Appendix A, Figure 1. Hood Canal segments based on bathymetry and geographic features. (Depth in meters relative to extremely lower-low water.)

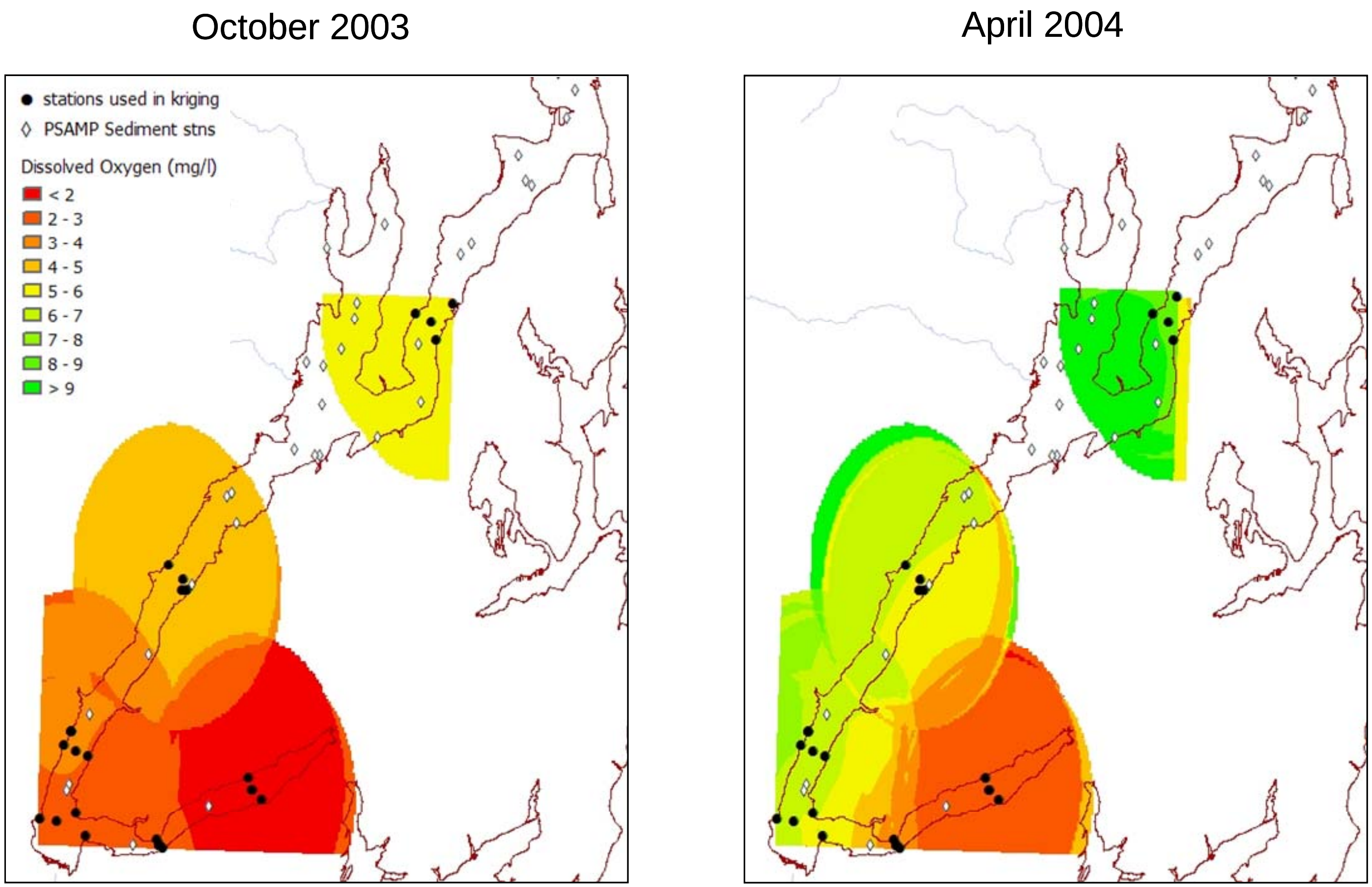


Appendix A, Figure 2. "Nearest neighbor/depth slice" method of estimating dissolved oxygen.

DO values from the nearest water-sampling station (within the same segment of Hood Canal) at the depth level of the sediment station, if available, were used. The diagram depicts the bathymetric profile of a longitudinal section down the center of Hood Canal from Admiralty Inlet to the Great Bend. The blue cylinders represent CTDs, yellow trapezoids represent van Veen grabs, and dashed lines represent the depth "slices." Note that the nearest water-sampling station in the same segment as a sediment-sampling station may be nowhere near as deep. Note also that the nearest water-sampling station at (or deeper than) the same depth as the sediment-sampling station may be in different segments of Hood Canal with different properties.



Appendix A, Figure 3. Differentiation between areas with sediment-sampling stations (left) and water-sampling stations (right). Circled areas (right) indicate data gaps.



Appendix A, Figure 4. Example of estimated dissolved oxygen concentrations at PSAMP sediment stations using kriging.

Attempts to estimate DO indirectly via statistical relationships

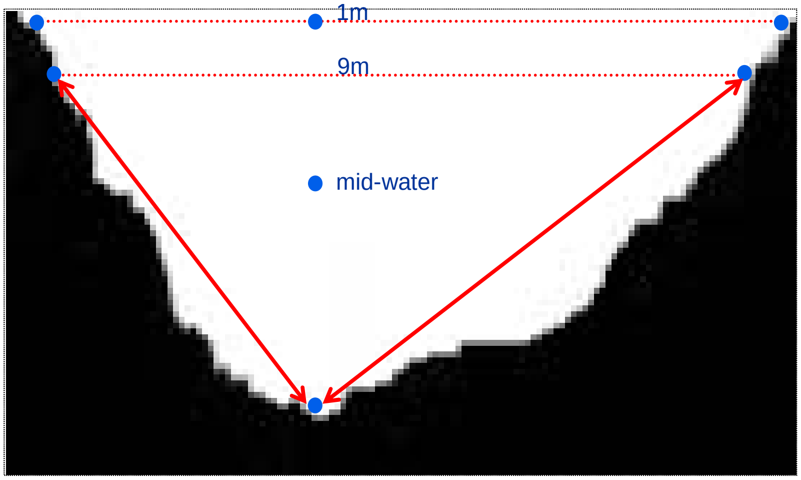
- **Oceanographic and geographical parameters –** Statistical relationships between DO and a number of oceanographic and geographical parameters were examined, using all data available from 2003 through 2005 for the DO at maximum depth and depth of minimum DO. The variables included water depth, temperature, salinity, density, latitude, longitude, distance from Admiralty Inlet, percent depth of station depth, and percent depth of maximum depth (for depth of minimum DO). No relationships useful to estimate DO values at the sediment stations could be determined.

- **Cross-sectional profiles –** DO data at the surface, middle, and bottom depths sampled for the HCDOP volunteer monitoring stations were examined to determine whether a relationship between the center and sides of Hood Canal at given points could be described (Appendix A, Figure 5). No such relationship was found.

- **Examination of long-term trends –** Linear trends in available DO data were estimated by segment of Hood Canal and for "nearest neighbor" stations over the period 1988-2005. The data used were CTD DO measurements from PRISM cruises, pre-PRISM Ecology cruises, and marine flights, for consistent depths defined by the mean, median, and minimum of the maximum depths at which measurements were taken at each station. In other words, for a given station, the maximum depths at which DO was measured were summarized, then DO values were selected from all sampling events at that station at the depth level of the minimum of the set of maximum depths (maxdepths) at that station, at the depth levels of the median and mean of the maxdepths at that station, and at all maxdepths (regardless of depth) at that station.

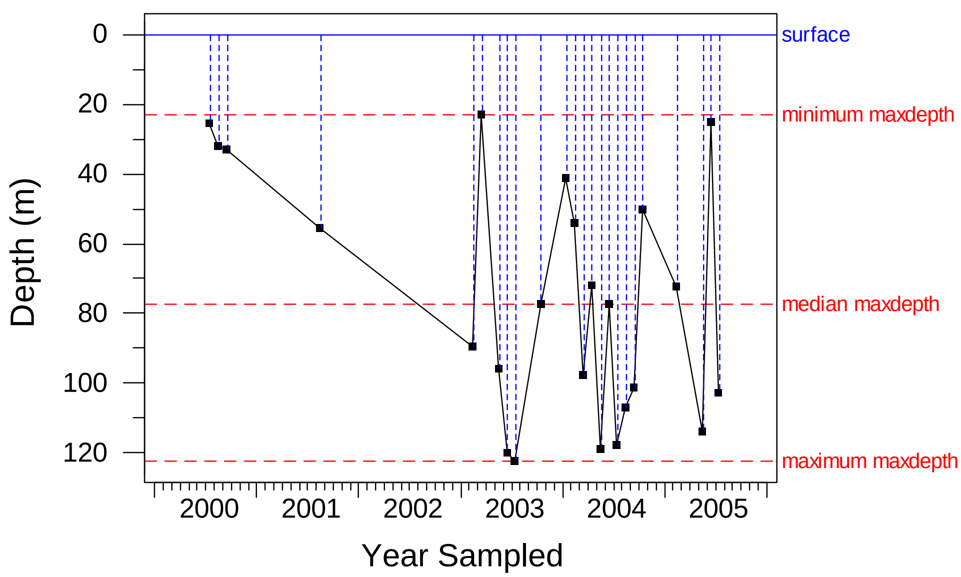
  Although using the minimum of the maxdepths resulted in the largest number of data points for a given station (Appendix A, Figure 6), in some cases, the minimum maxdepth was near the surface and nowhere near the bottom. In addition, for stations at the same location but in different studies (most often PRISM stations situated at the same locations as pre-PRISM Ecology stations), the minimum maxdepths were usually quite different for the different studies. The median maxdepths, however, were quite close for all but one pair of co-located stations of different studies, but there were fewer data points (generally only half as many). The mean maxdepths for overlapping stations were not as close as the medians, and had similarly fewer data points. To use the maximum of the maximum depths, though closest to the bottom, would have resulted in as few as one single data point for each station and hence was not practical for examining trends.

  In addition, DO data at minimum, median, and all maxdepths were combined (averaged when originating in the same months) for groups of stations located near sediment stations, and general linear trends were examined for those groups and/or for the entire segment of Hood Canal in which those groups of stations were located. Drawbacks to this approach include (1) the maximum depths differed for stations within a group, and (2) those maxdepths may not have been close to the depths of the sediment stations (i.e., the bottom).



Appendix A, Figure 5. Relationship between bottom dissolved oxygen at the center and sides of Hood Canal.

Figure 5 above depicts the bathymetric profile of a cross section of Hood Canal at a hypothetical location. The blue dots represent discrete water samples taken at surface, middle, and bottom depths at HCDOP volunteer monitoring stations, for analysis of DO concentrations by the Winkler method.



Appendix A, Figure 6. Demonstration of variability in maximum depth at which dissolved oxygen was measured at a given water-sampling station (i.e., the lowest depths of the conductivity/ temperature/depth (CTD) casts at that station over time).

Note that to select DO measurements taken at a consistent depth is to diminish the number of measurements available for examination of trends: the maximum number of measurements occurs at the minimum maxdepth, and the minimum number of measurements (1) occurs at the maximum maxdepth. To use the median maxdepth is to retain DO measurements from about half of the sampling events (CTD casts).

B. Sediment and water quality surveys conducted in Hood Canal from 1932 through 2005.

Appendix B, Table 1. Sediment and water quality surveys conducted in Hood Canal, 1932 - 2005.

Survey ID	Reference Title	Survey Description	Survey Begin Date	Survey End Date	Survey Chief Scientist	Survey Agency Name
Sediment Data						
*CEMAP02	National Coastal Assessment Quality Assurance Project Plan 2001-2004	Coastal EPA/EMAP 2002	6/1/2002	11/12/2002	Valerie Partridge	U.S. Environmental Protection Agency/ Washington State Department of Ecology
CREC72	Metals in Puget Sound Sediments 1970-1972	Metals in Puget Sound sediments 1970-72	1/1/1972	1/1/1972	Eric Crecelius	Dept of Oceanography, University of Washington
DUWAM86	National Benthic Surveillance Project: Pacific Coast. Part II. Technical Presentation of the Results for Cycles I to III (1984-1986). NOAA Technical Memorandum NMFS F/NWC-170.	NOAA's Duwamish River Study	5/1/1986	6/20/1986		NOAA
EIGHTBAY	Reconnaissance Survey of Eight Bays in Puget Sound. Volumes I and II.	1985 Puget Sound Eight-Bay survey	8/6/1983	5/29/1984		
NAVY_TRF	U.S. Navy Bangor TRF Drydock Dredge	U.S. Navy Bangor TRF Drydock dredge	2/7/1992	4/7/1992	Stephanie Stirling	U.S. Navy
P&T_MILL	Former Pope & Talbot, Inc. Mill Site - Port Gamble, WA	Pope and Talbot Mill Site Sediment	6/24/2002	9/5/2002	Phil Struck	Pope & Talbot
POPE&TAL	Log Raft/Chip Barge Area, Port Gamble	Log raft/chip barge area, Port Gamble	12/28/1988	12/29/1988	Dave Kendall	U.S. Army Corps of Engineers
PSAMP_LT (= PSAMP Temporal)	Puget Sound Ambient Monitoring Program 1989 Marine Sediment Monitoring Final Report	PSAMP Temporal Sediment Monitoring	1/1/1989	ongoing	Margaret Dutch	Washington State Department of Ecology

Survey ID	Reference Title	Survey Description	Survey Begin Date	Survey End Date	Survey Chief Scientist	Survey Agency Name
PSAMP/NOAA	Puget Sound Ambient Monitoring Program Marine Sediment Monitoring Component - Final Quality Assurance Project and Implementation Plan. Measures of bioeffects associated with toxicants in Puget Sound	PSAMP/NOAA Measures of Bioeffects	6/2/1997	6/30/1999	Edward Long	Washington State Department of Ecology/NOAA
PSAMP Spatial	PSAMP Spatial Sediment Monitoring	PSAMP Spatial Sediment Monitoring	6/1/2002	Ongoing	Margaret Dutch	Washington State Department of Ecology
PT_PG1	Pope and Talbot - Port Gamble 1	Pope and Talbot - Port Gamble 1	3/6/2000	3/8/2000	Jennifer Hawkins	Parametrix, Inc.
REFGRAIN	Misc. PS Reference Area Grain Size	Misc. Puget Sound Reference area grain size	11/23/1981	7/1/1987	Dewitt, Broad, Chapman	Western Washington University, NOAA, Oregon State University
ROBERT74	Puget Sound & Strait of Juan de Fuca Grain Size	Puget Sound & Strait of Juan de Fuca Grain Size	6/19/1950	3/1/1973	Richard Roberts	University of Washington Department of Oceanography
SED18804	Puget Sound Reconnaissance Survey-Spri	Puget Sound Reconnaissance Survey	4/19/1988	5/28/1988	Eric Crecelius	USEPA, Region X, Seattle
Water Quality Data						
HC	Hood Canal water column surveys	Hood Canal water column surveys	4/4/1994	12/9/1999	Jan Newton	Washington State Department of Ecology
HCDOP	Hood Canal Dissolved Oxygen Program - Water Column monitoring	HCDOP volunteer water column monitoring	9/7/2003	Ongoing	Jan Newton	HCDOP
Historical	RV Thompson cruises	Water column monitoring	7/1/1932	6/9/1968	Eugene Collias	University of Washington
Marine Flights	Puget Sound Ambient Monitoring Program Water Column monitoring	PSAMP Water Column monitoring	11/11/1975	Ongoing	Carol Janzen, Skip Albertson, Lisa Eisner, Jan Newton, Julia Bos, Brian Grantham, Carol Maloy	Washington State Department of Ecology

Survey ID	Reference Title	Survey Description	Survey Begin Date	Survey End Date	Survey Chief Scientist	Survey Agency Name
PRISM	Puget Sound Regional Synthesis Model	Water column monitoring	6/16/1998	Ongoing	Jan Newton, Mark Warner, Mitsuhiro Kawase	HCDOP
**PSAMP Spatial	PSAMP Spatial Sediment Monitoring	PSAMP Spatial Sediment Monitoring	6/1/2002	Ongoing	Margaret Dutch	Washington State Department of Ecology

*Coastal EPA/EMAP 2002: these intertidal samples were not included in the analyses in this report
**PSAMP Spatial: bottom water DO samples were collected during the 2004 sediment sampling survey in Hood Canal

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C. HCDOP Task IV Access database, including all sediment and water column dissolved oxygen data collected from Hood Canal between 1932-2005. *(on enclosed CD)*

D. Matrix of all Hood Canal sediment quality and dissolved oxygen data selected for analysis. *(on enclosed CD)*

E. Selected results for chemistry, toxicity, and infaunal analyses for all PSAMP sediment stations sampled in Hood Canal between 1989 and 2005. *(on enclosed CD)*

F. Parameters and number of sediment stations sampled for projects conducted in Hood Canal between 1952 and 2005. *(on enclosed CD)*

G. Station numbers and sampling dates for all Hood Canal dissolved oxygen stations. *(on enclosed CD)*

H. Summary statistics for dissolved oxygen measured in Hood Canal between 1932 and 2005. *(on enclosed CD)*

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I. Relationships between benthic index values and sediment and water quality parameters. *(on enclosed CD, in part)*

Appendix I, Figure 1. (See enclosed CD)

Appendix I. Table 1. Pearson correlation coefficients (r) for data from 32 sediment parameters measured from up to 57 PSAMP Sediment Component samples collected from 1989 through 2005, and near-bottom dissolved oxygen samples measured from 30 PSAMP Sediment Component samples collected in 2004. $0.9 \leq |r| \leq 1.0$ - strong, $0.5 \leq |r| < 0.9$ - moderate, $|r| < 0.5$ - weak correlations; p values <0.05 -significant (light shading), <0.0001 - highly significant (dark shading).

PARAMETER	*Axinopsida serricata*	*Cossura bansei*	*Euphausiacea*	*Euphilomedes carcharodonta*	*Euphilomedes producta*	*Heteromastus filobranchus*	*Leitoscoloplos pugettensis*	*Macoma carlottensis*	*Nutricola lordi*	*Prionospio (Minuspio) lighti*	Percent Fines	Total Aroclors	% Total Organic Carbon	Mean SQS metals	Mean SQS PAH	Mean SQS misc. organics	Mean SQS phenols
Axinopsida serricata	1.000																
Cossura bansei	0.035	1.000															
Euphausiacea	-0.162	0.084	1.000														
E. carcharodonta	0.161	-0.210	-0.164	1.000													
E. producta	0.051	-0.177	-0.127	-0.036	1.000												
H. filobranchus	-0.020	0.282	-0.061	-0.173	-0.085	1.000											
L. pugettensis	-0.053	-0.113	-0.039	0.388	0.226	-0.151	1.000										
Macoma carlottensis	0.184	-0.003	0.023	-0.188	0.292	0.218	-0.098	1.000									
Nutricola lordi	0.064	-0.138	-0.108	0.749	-0.068	-0.114	0.225	-0.119	1.000								
P. lighti	-0.057	0.347	0.374	-0.160	-0.051	0.049	-0.073	0.046	-0.122	1.000							
Percent Fines	0.023	0.372	0.324	-0.491	-0.287	0.253	-0.320	0.009	-0.322	0.198	1.000						
Total Aroclors	-0.234	0.292	0.450	-0.176	-0.168	0.191	0.029	-0.065	-0.140	0.337	0.392	1.000					
% Total Organic Carbon	-0.163	0.209	0.281	-0.342	-0.257	0.338	-0.268	-0.003	-0.288	0.155	0.737	0.359	1.000				
Mean SQS metals	0.034	0.254	0.231	-0.397	-0.294	0.223	-0.315	-0.053	-0.308	0.124	0.859	0.179	0.802	1.000			
Mean SQS PAH	-0.068	-0.139	-0.080	0.219	-0.020	-0.084	0.209	-0.168	-0.049	-0.048	-0.106	0.024	-0.078	-0.149	1.000		
Mean SQS misc. organics	-0.115	0.229	0.267	-0.053	-0.015	0.053	0.106	0.006	-0.107	0.319	0.211	0.483	0.183	0.113	0.102	1.000	
Mean SQS phenols	-0.031	0.177	0.378	-0.159	0.062	0.153	-0.113	0.104	-0.156	0.295	0.233	0.448	0.196	0.130	-0.097	0.458	1.000
Mean SQS Phthalates	-0.021	0.053	0.073	-0.062	-0.005	-0.084	0.128	-0.045	-0.076	0.026	-0.017	-0.071	-0.064	0.025	-0.104	0.195	0.137
Pielou's evenness - J'	-0.308	0.115	0.256	-0.536	0.063	0.023	-0.174	0.129	-0.518	0.151	0.225	0.228	0.108	0.019	-0.518	0.087	0.231
Total taxa abundance	0.089	-0.235	-0.229	0.759	-0.041	-0.127	0.343	-0.112	0.756	-0.177	-0.550	-0.261	-0.401	-0.494	0.423	-0.181	-0.284
Taxa richness	0.082	-0.261	-0.299	0.669	0.073	-0.265	0.246	-0.167	0.587	-0.212	-0.739	-0.371	-0.678	-0.685	-0.055	-0.333	-0.302
Swartz's Dominance Index	-0.150	-0.105	-0.131	-0.202	0.088	-0.175	-0.081	-0.083	-0.200	-0.051	-0.329	-0.211	-0.426	-0.400	-0.245	-0.252	-0.182
Annelid abundance	-0.073	-0.129	-0.152	0.244	-0.109	-0.033	0.230	-0.121	0.064	-0.093	-0.319	-0.129	-0.192	-0.267	0.556	-0.085	-0.208
Arthropod abundance	-0.009	-0.255	-0.199	0.559	0.248	-0.173	0.361	-0.075	0.430	-0.117	-0.584	-0.248	-0.326	-0.473	0.074	-0.123	-0.131
Echinoderm abundance	-0.049	-0.209	0.139	0.185	0.157	-0.099	0.226	-0.058	0.196	0.012	-0.246	-0.047	-0.153	-0.207	0.095	-0.198	-0.105
Mollusca abundance	0.198	-0.172	-0.160	0.799	-0.032	-0.110	0.237	-0.042	0.978	-0.151	-0.389	-0.235	-0.372	-0.403	-0.033	-0.191	-0.218
Misc. taxa abundance	0.019	-0.163	-0.151	0.205	0.019	-0.138	0.060	-0.092	0.199	-0.127	-0.428	-0.169	-0.375	-0.382	-0.080	-0.164	-0.139
Amphipod Mortality	0.033	0.693	.	-0.342	0.154	0.451	-0.085	0.042	-0.197	-0.015	0.509	0.202	0.351	0.460	-0.269	-0.204	0.191
Cytochrome P-450 RGS	0.011	-0.065	.	-0.095	-0.125	-0.136	-0.202	-0.231	-0.169	-0.221	0.301	0.243	-0.047	0.159	0.570	0.577	0.305
Sea Urchin Fertilization	0.209	-0.012	-0.182	0.198	0.178	0.097	0.010	0.227	0.134	0.074	-0.342	-0.550	-0.302	-0.130	0.086	-0.091	-0.105
Microtox	0.142	-0.024	.	-0.238	-0.028	-0.098	-0.223	0.186	-0.193	0.602	0.220	-0.146	-0.042	-0.004	-0.303	-0.350	-0.141
Depth	-0.225	0.282	0.427	-0.401	-0.059	0.008	-0.032	-0.009	-0.277	0.275	0.598	0.444	0.350	0.305	-0.275	0.231	0.163
Near-bottom DO	0.314	-0.190	-0.527	0.432	0.414	-0.173	0.042	0.105	0.396	-0.286	-0.849	-0.523	-0.809	-0.921	0.176	-0.428	-0.377

Appendix I. Table 1. (cont.)

PARAMETER	Mean SQS Phthalates	Pielou's evenness - J'	Total taxa abundance	Taxa richness	Swartz's dominance index	Annelid abundance	Arthropod abundance	Echinoderm abundance	Mollusc abundance	Miscellaneous taxa abundance	Amphipod mortality	Cytochrome P-450 RGS	Sea urchin fertilization	Microtox	Depth	Near-bottom DO
Axinopsida serricata																
Cossura bansei																
Euphausiacea																
E. carcharodonta																
E. producta																
H. filobranchus																
L. pugettensis																
Macoma carlottensis																
Nutricola lordi																
P. lighti																
Percent Fines																
Total Aroclors																
% Total Organic Carbon																
Mean SQS metals																
Mean SQS PAH																
Mean SQS misc. organics																
Mean SQS phenols																
Mean SQS Phthalates	1.000															
Pielou's evenness - J'	0.125	1.000														
Total taxa abundance	-0.046	-0.699	1.000													
Taxa richness	0.085	-0.236	0.647	1.000												
Swartz's dom. index	0.145	0.547	-0.182	0.482	1.000											
Annelid abundance	-0.067	-0.513	0.654	0.198	-0.134	1.000										
Arthropod abundance	0.090	-0.325	0.623	0.518	-0.023	0.239	1.000									
Echinoderm abundance	-0.161	-0.009	0.359	0.415	0.336	0.336	0.142	1.000								
Mollusca abundance	-0.020	-0.544	0.799	0.650	-0.176	0.091	0.498	0.213	1.000							
Misc. taxa abundance	-0.036	-0.138	0.269	0.454	0.149	0.056	0.131	0.118	0.232	1.000						
Amphipod mortality	.	0.253	-0.432	-0.362	0.013	-0.358	-0.329	-0.112	-0.266	-0.064	1.000					
Cytochrome P-450 RGS	.	-0.471	0.005	-0.201	-0.392	0.077	-0.202	-0.188	-0.137	-0.215	-0.031	1.000				
Sea urchin fertilization	0.014	-0.382	0.250	0.384	0.152	0.199	0.101	0.232	0.273	0.189	-0.039	-0.066	1.000			
Microtox	.	0.363	-0.291	-0.169	0.188	-0.285	-0.145	-0.317	-0.018	0.093	0.108	-0.181	-0.111	1.000		
Depth	0.012	0.561	-0.517	-0.438	0.066	-0.381	-0.332	-0.031	-0.359	-0.306	0.341	-0.146	-0.531	0.423	1.000	
Near-bottom DO	-0.203	-0.380	0.577	0.732	0.507	0.579	0.488	-0.008	0.491	0.763	.	.	0.334	.	-0.724	1.000