Washington State Marine Water Quality in 1996 and 1997

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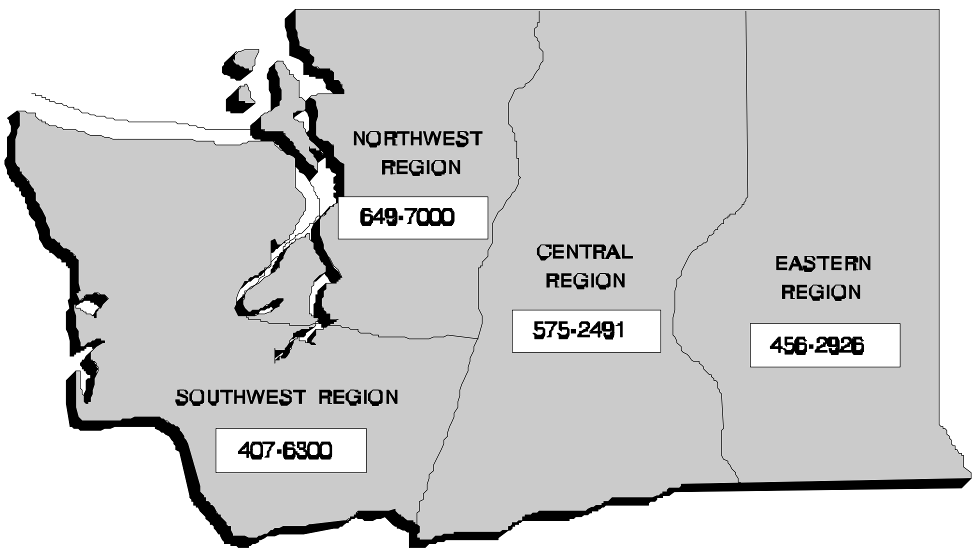

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Washington State Marine Water Quality in 1996 and 1997

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Abstract

The Washington State Department of Ecology initiated monitoring of marine waters in 1967 in order to assess water quality in Puget Sound, Grays Harbor, and Willapa Bay. Data are currently collected monthly for this ongoing, long-term monitoring effort by the Marine Waters Monitoring program. Monitoring of various water quality parameters during wateryears (WYs) 1996 and 1997 occurred at 29 and 25 stations, respectively, in Puget Sound each WY (WY 1996 = October 1995 through September 1996). For bot Wys, five stations in Grays Harbor and six in Willapa Bay were also monitored. In thi report, along with the WY 1996-97 data, five indicators of marine water column environmental condition are discussed.

Climatic conditions of WY 1996-97 were characterized by higher than norma precipitation in both years, particularly during fall and winter. Air temperatures averaged close to normal throughout the two-year period. Annual runoff of two major Washington rivers (Skykomish and Chehalis) was quite high, at approximatel 140-150 percent of the median flow in both years. These weather and flow conditions were evident in the sea-surface temperature and salinity of the monitoring stations. All stations showed predominately fresher sea salinity than the long-term average. Stations near rivers had a more extreme annual sea temperature range than those not near rivers.

The stratification characteristics of stations were classified into four groups: persistent, seasonal, episodic, and weak. The majority of the Puget Sound monitoring stations were either persistently (15 out of 38 stations) or seasonally (11 out of 38 stations) stratified. The degree of stratification has implications for water quality.

Dissolved oxygen (DO) concentrations <3 mg/L were measured at South Hood Canal, Penn Cove, and Discovery Bay; and <5 mg/L were found at 19 additional stations during WYs 1996-97. Observations of low DO primarily occurred in late summer to early fa but in South Hood Canal occurred year-round and reached anoxia at times. Persisten stratification co-occurred with low DO concentrations.

Very high ammonium-N concentrations (>0.14 mg/L) were seen in Budd Inlet and East Sound; high concentrations (>0.07 mg/L) were at 13 predominately South Puget Sound stations. Occurrence of consecutive months with <0.01 mg/L surface dissolved inorganic nitrogen (nitrate+nitrite plus ammonium) in combination with stratification and other indicators was used to indicate stations potentially sensitive to eutrophication.
Fecal coliform bacteria counts >14 organisms/100 mL were found at 12 Puget Sound stations and seven coastal estuary stations during WY 1996-97. Of these, contamination in Grays Harbor, Willapa Bay (near the Willapa River), Commencement Bay, and inner Budd Inlet appeared chronically persistent. Other stations (e.g., Elliott Bay and Bellingham Bay) showed wintertime highs in fecal counts.

Executive Summary

Water-quality sensitive areas are typically stations near urbanization and where persisten or seasonal density stratification of the water column exists. Well-mixed areas show less water quality impacts than persistently stratified areas. Rivers or other runoff maintain stratification and also deliver nutrients that support organic production, which may deplete oxygen concentrations at stations where physical mixing of the water column is low. Fecal coliform bacteria (fcb) enter marine waters through runoff. Thus, areas most sensitive to water quality problems are areas with high runoff, low mixing, and anthropogenic inputs of nutrients and sewage. The monitoring data and indicators presented here show this pattern for Washington State marine waters.

Climate also plays a large role in affecting water quality in Washington marine waters. Lower salinity was evident in WY 1996-97 and correlates with higher than normal runo recorded during 1995-97. This has implications on stratification and water quality. In view of interannual variation due to weather, we find it difficult to assess the impact o humans on water quality. This natural variability highlights the importance of lengthy, consistent time-series databases, and the need to acquire and use historical data.

The Marine Waters Monitoring program assesses conventional water quality as indicated by dissolved oxygen (DO), nutrients, and fcb, but due to funding limitations does not include assessment of chemical contamination, plankton species (e.g., toxic blooms), or changes in flushing characteristics. For the Puget Sound region in general, water quality appeared to be reasonably good; however, there are specific locations where water quality appeared reduced. For the coastal estuaries, the only water quality issue apparent was fcb contamination primarily in Grays Harbor and adjacent to the Willapa River. The representativeness of mid-bay monitoring stations can be questioned and definite undersampling of areas within Puget Sound is acknowledged.

Hypoxic DO concentrations (<3 mg/L) were found at relatively few (5 out of 38) stations. Conditions in South Hood Canal were especially severe, with low DO concentrations (<5 mg/L) evident year-round. Penn Cove and Discovery Bay also exhibited hypoxia. Whether anthropogenic processes are responsible for the severity of these conditions needs evaluation and must be done with an understanding of natural mechanisms for low DO such as oceanic and climatic influences. Low DO was found at 19 other stations, including Holmes Harbor, Bellingham Bay, Budd Inlet, Commencement Bay, and Elliott Bay. Low DO was not found in the coastal estuaries.

High fcb counts were found at 12 out of 38 Puget Sound stations; Commencement Bay and, to a less extent, inner Budd Inlet showed chronic contamination. For the stations assessed in WYs 1996-97, those showing the potential for sensitivity to impacts from eutrophication include: Hood Canal, Penn Cove, Holmes Harbor, Bellingham Bay, Budd Inlet, Elliott Bay, Commencement Bay, Possession Sound, Oakland Bay, East Sound, Saratoga Passage, Discovery Bay, and Drayton Harbor.

Introduction

This data report of the Washington State Department of Ecology (Ecology) Ambient Monitoring Section (AMS) represents water quality data for marine waters in Puget Sound, Willapa Bay, and Grays Harbor collected monthly during wateryears 1996 and 1997 (e.g., WY 1996 = October 1995 through September 1996). Collection of these dat comprises the long-term monitoring component of Ecology's Marine Waters Monitoring.

Since 1992, Ecology's Marine Waters Monitoring has taken two approaches: long-term monitoring and focused monitoring. Long-term monitoring consists of visiting numerous selected stations once per month, with the goal of establishing and maintaining consistent baseline environmental data. Results from this program have been reported either annually or biannually (Janzen, 1992a; Janzen and Eisner, 1993a; b; Newton, *et al.*, 1994; 1997). Focused monitoring entails sampling individua locations for a short period of time with increased spatial and temporal resolution than afforded with long-term monitoring. The focus is on specific hypotheses relevant to the environmental status of the location. Due to resource limitation, limited focused monitoring projects were conducted during WYs 1996 and 1997. Two surveys were conducted in the Snohomish estuary in August 1996 in support of Ecology's Snohomish Total Maximum Daily Load Study (Cusimano, 1997; Newton, 1995a). High-intensit spatial sampling of South Puget Sound was conducted during September 1997 (Albertson and Newton, 1997). Data from the focused projects are not described in this report bu are maintained in Ecology's AMS Marine Waters Monitoring database and are available upon request

Marine Waters Monitoring Program Statement of Purpose

The Marine Waters Monitoring program was designed to measure ambient water quality conditions in Puget Sound and the coastal estuaries of Washington State (Janzen, 1992b). Long-term ambient monitoring data is needed to establish baseline conditions with the goal of detecting effects from human activities leading to contamination and/or habita degradation. Ecology has maintained a database of marine water quality data since 1973. Access to the database is provided to the public, either through hard copy or electronic transmission. Access to the database is described at http://www.wa.gov/ecology/.

The long-term data collected by the Marine Waters Monitoring program are used to assess marine water quality throughout Puget Sound, Willapa Bay, and Grays Harbor, seasonal patterns, and the degree of non-seasonal variation at specific locations. The data are used for the maintenance of regulatory listings of various waterbodies throughout the state. Implementation of marine water quality management activities for Puget Sound and the outer coastal estuaries can be based, in part, on quantitative water quality data gathered b this monitoring program.

Program Objectives

Objectives of Ecology's Marine Waters Monitoring in Puget Sound, Willapa Bay, and Grays Harbor are to:

1) Characterize spatial and temporal patterns of basic water quality parameters (e.g., temperature, salinity, density, dissolved oxygen, pH, chlorophyll *a*, transmissometry, nutrients, etc.);

2) Identify significant changes in these parameters that may indicate environmenta changes and emerging problems;

3) Collect data that can be used to assess compliance with state and federal water quality regulations and to determine the effectiveness of regulatory actions designed to improve marine water quality

4) Provide water quality information to support specific programs within Ecology, at the U. S. Environmental Protection Agency and other agencies, and those programs identified in the Puget Sound Water Quality Management Plan (e.g., Puget Sound Ambient Monitoring Program);

5) Support environmental science research activities through the availability o consistent, scientifically and statistically valid data; and

6) Provide baseline water quality data as a service to the public and any other data requesters.

Program Background

Ecology initiated its statewide Marine Water Column Ambient Monitoring Program in 1967. The original purpose of the program was to determine the water quality of numerous areas on a regular basis and to identify spatial patterns and temporal trends from the results. Many of the original sampling sites were located near municipal and industria discharges in order to measure the effectiveness of agency regulatory programs. During the program's long history, changes have been made to the original program to meet growing information needs and to incorporate technological advancements in environmental sampling.
In 1986, the Puget Sound Water Quality Authority (PSWQA) appointed an interdisciplinary committee to design the Puget Sound Ambient Monitoring Program (PSAMP) with the objective of coordinating various monitoring efforts within

Puget Sound conducted by different government agencies into a comprehensive long-term monitoring program (PSWQA, 1988). Ecology's existing Marine Water Column Ambien Monitoring Program joined PSAMP in 1989. In accordance with PSAMP objectives, many of the near-shore marine water monitoring stations were discontinued in an attempt to focus on background rather than point-source affected conditions. Ecology's marine water column monitoring effort in Puget Sound and its coordination with PSAMP are described in the Marine Water Column Ambient Monitoring Plan (Janzen, 1992b), along with the design for Ecology's monitoring in the coastal estuaries of Willapa Bay and Grays Harbor. The present Marine Waters Monitoring program continues to follow the design presented in Janzen (1992b), as annually appended
(e.g., Newton, 1995b).

During 1995, PSAMP underwent external program review. A five-year summary o marine water column monitoring data from Puget Sound collected by Ecology since the implementation of PSAMP is presented in Newton (1995c). Discussion of marine water monitoring issues and recommendations and review panel comments can be found in Newton (1995c) and Shen (1995), respectively.

Methods

Wateryears 1996 & 1997 Long-Term Ambient Monitoring Approach

In an effort to preserve and extend long-term time-series records for marine waters, several monitoring stations have been established as “core” stations, meaning that these stations are monitored once per month every year. Many of the core stations have dat records of 20 years or more. As established in WYs 1996 & 1997, there were five core stations in Grays Harbor, six in Willapa Bay, and sixteen in Puget Sound (Figures 1 and 2). In Puget Sound, because of the large area and high diversity, additional non-core stations are sampled for one year. The strategy behind the additional stations is to monitor areas of specific interest or areas with no data. Results are used as a screening tool, highlighting the need for continued monitoring or study. We have retained the PSAMP three-year rotation of focus between North, Central and South Puget Sound, thus these additional Puget Sound stations are termed “rotational” stations.

In Puget Sound, 16 core stations and 13 rotational stations were monitored in WY 1996 and 19 core stations and 6 rotational stations were monitored in WY 1997. The rotational stations sampled during WYs 1996 and 1997 are shown in Figure 1. In WY 1996, PSAMP focus was on South Puget Sound, with 10 southern rotational stations, plus 3 stations, PNN001, EAS001, and SKG003, retained for water quality issues. In WY 1997, PSAMP focus was on North Puget Sound, with 6 northern rotational stations (Figure 1). Three core stations were added in WY 1997 to better characterize Puge Sound (ADM003, GOR001, and NSQ002). Station information and the parameters sampled are listed in Table 1.

The monitoring strategy outlined here is responsive to the PSAMP five-year review recommendations and agency scoping needs; however it does diverge from Janze (1992b). The rationale behind the change, adopted in WY 1997, is cited in the following excerpt (J. Newton memo to PSAMP, September 1996):

“The original idea of PSAMP “rotating” stations was to monitor a discrete set of stations on a three-year repeating cycle and assess whether these stations compared to the “core” stations in the vicinity. We have learned that the rotating stations do not mimic core stations and that the diversity of water-column conditions is exceptionally strong in Puget Sound. Although rotating stations do not usually resemble the nearest core station, rotating stations may or may not have water quality issues. We feel the best use of non-core stations is as screening tools to assess where water quality problems may exist. Thus, for a given year within a rotational cycle (North, Central,

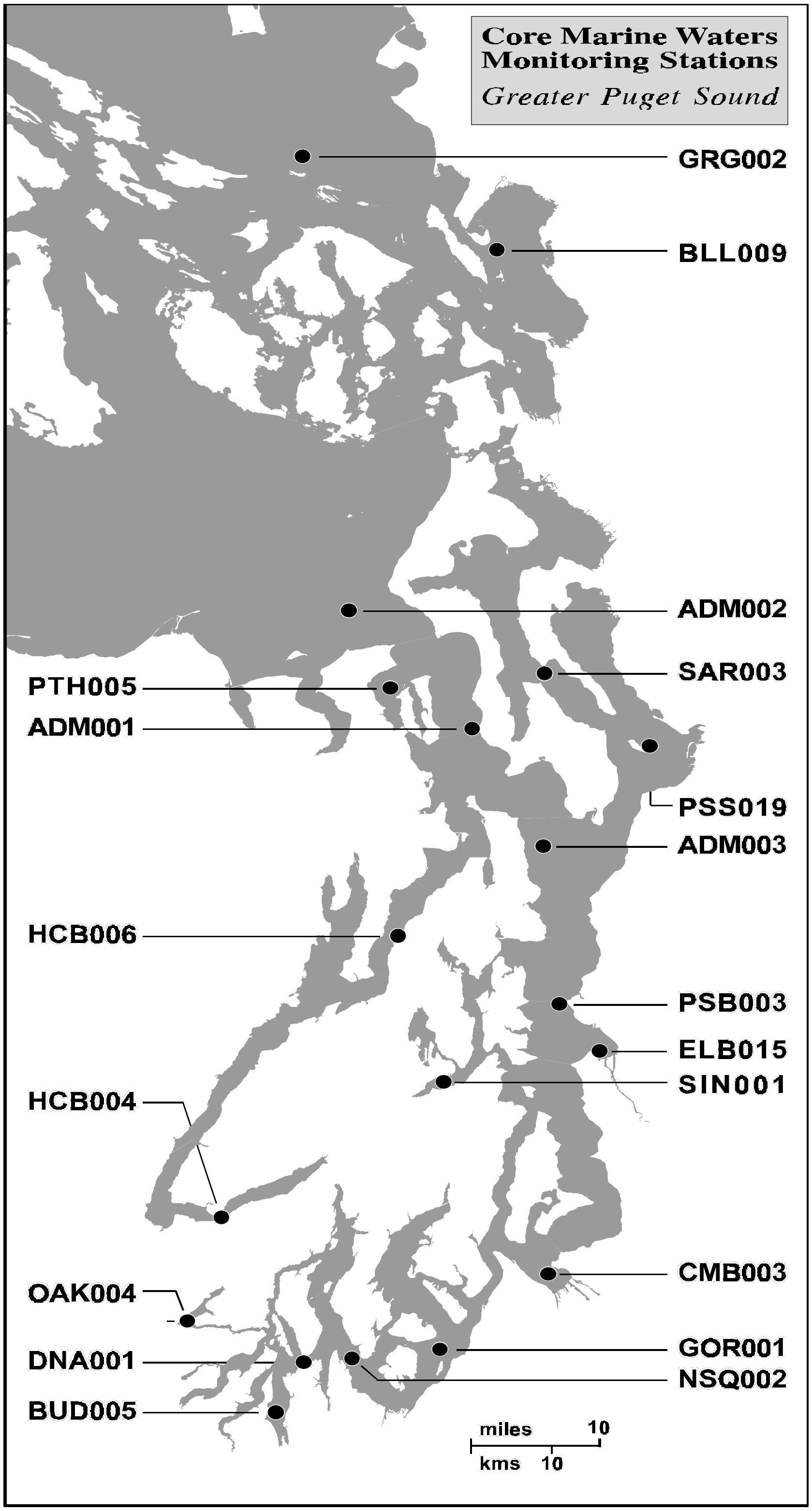

Figure 1A. Long-term Marine Waters Monitoring core stations in Puget Sound.

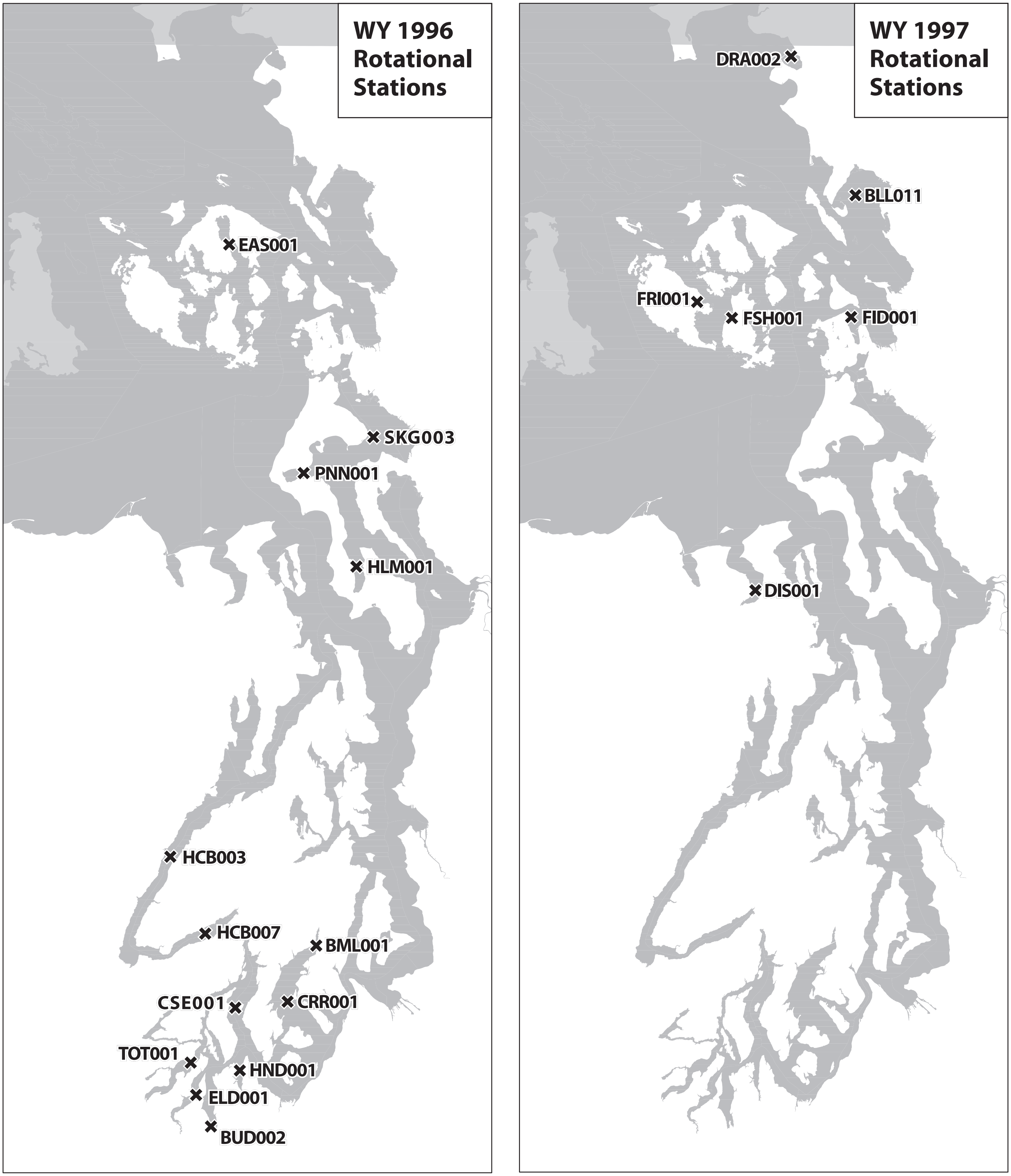

Figure 1B. Marine Waters Monitoring rotational stations for WY 1996-97 in Puget Sound.

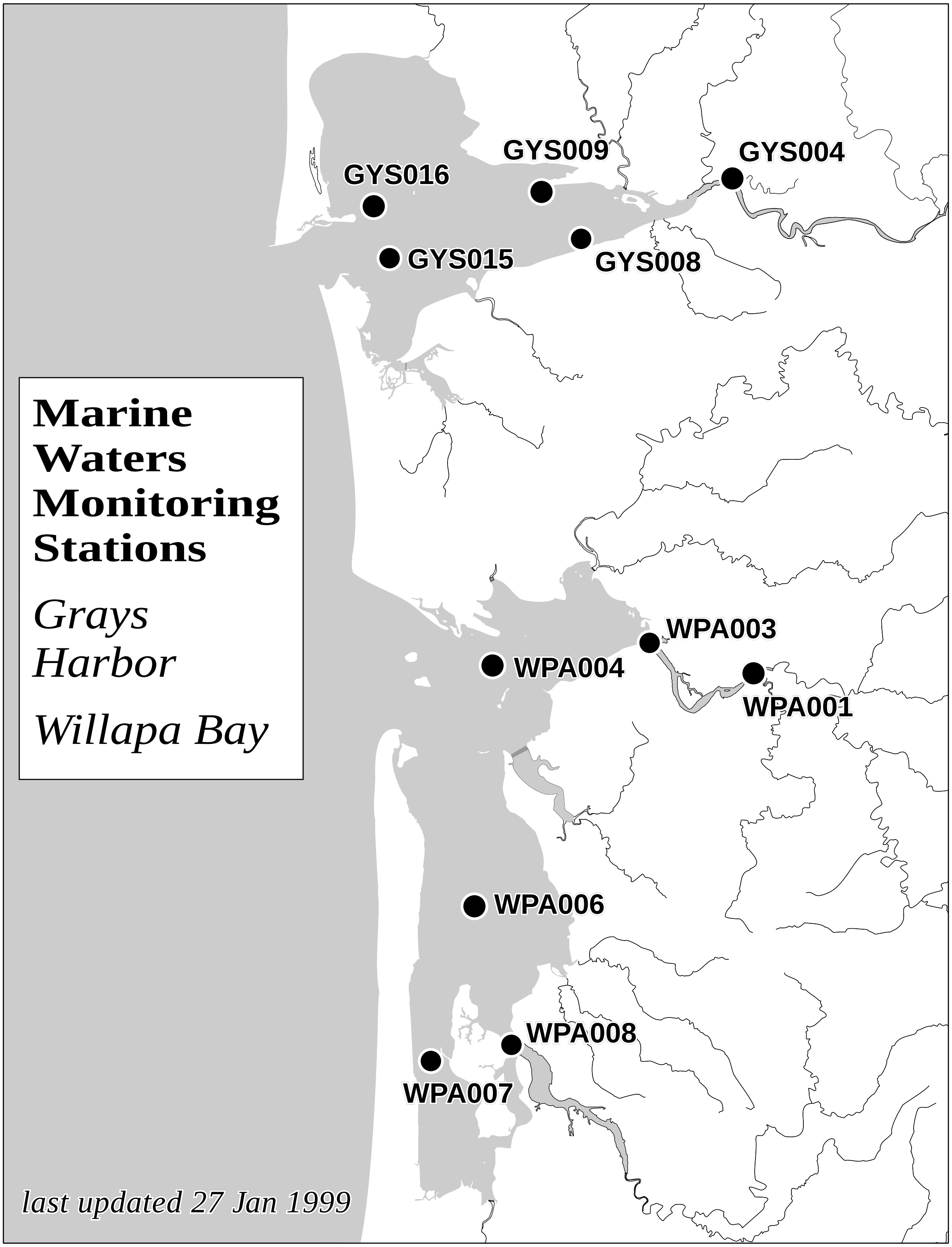

Figure 2. Long-term Marine Waters Monitoring stations for WY 1996-97 in Grays Harbor and Willapa Bay

Table 1. Marine Waters Monitoring stations sampled during WY 1996-97. Station type notation is C = core station and R - rotating station. Samples listed as 0 m were taken from 0.5 m, excep the fecal coliform bacteria sample which was from 0.1 m.

Station	Type	WY sampled	Lat. (N), Long. (W)	Basin	Parameters sampled*	Sample depths (m)
Puget Sound:						
ADM002	C	96, 97	48.188, 122.842	Northern Straits	All	0, 10, 30
BLL009	C	96, 97	48.686, 122.598	Northern Straits	All	0, 10
BLL011	R	97	48.733, 122.583	Northern Straits	All	0, 10
DIS001	R	97	48.018, 122.847	Northern Straits	All	0, 10, 30
DRA002	R	97	48.983, 122.762	Northern Straits	All	0, 10, 30
EAS001	R	96	48.643, 122.882	Northern Straits	All	0, 10, 30
FID001	R	97	48.513, 122.594	Northern Straits	All	0, 10
FRI001	R	97	48.538, 123.012	Northern Straits	All	0, 10, 30
FSH001	R	97	48.510, 122.917	Northern Straits	All	0, 10
GRG002	C	96, 97	48.808, 122.953	Northern Straits	All	0, 10, 30
PTH005	C	96, 97	48.083, 122.763	Northern Straits	All	0, 10
HLM001	R	96	48.064, 122.532	Whidbey Basin	All	0, 10, 30
PNN001	R	96	48.231, 122.674	Whidbey Basin	CTD/S	0, 10
PSS019	C	96, 97	48.017, 122.308	Whidbey Basin	All	0, 10, 30
SAR003	C	96, 97	48.108, 122.490	Whidbey Basin	All	0, 10, 30
SKG003	R	96	48.297, 122.488	Whidbey Basin	CTD/S	0, 10
ADM001	C	96, 97	48.030, 122.617	PS Main Basin	All	0, 10, 30
ADM003	C	97	47.879, 122.482	PS Main Basin	CTD/S	0, 10, 30
CMB003	C	96, 97	47.291, 122.449	PS Main Basin	All	0, 10, 30
ELB015	C	96, 97	47.591, 122.368	PS Main Basin	All	0, 10, 30
PSB003	C	96, 97	47.660, 122.442	PS Main Basin	All	0, 10, 30
SIN001	C	96, 97	47.549, 122.642	PS Main Basin	All	0, 10
HCB003	R	96	47.537, 123.022	Hood Cana	CTD/S	0, 10, 30
HCB004	C	96, 97	47.358, 123.024	Hood Cana	All	0, 10, 30
HCB006	C	96, 97	47.748, 122.730	Hood Cana	All	0, 10, 30
HCB007	R	96	47.398, 122.928	Hood Cana	CTD/S	0, 10
BML001	R	96	47.378, 122.632	Southern PS	All	0, 10
BUD002	R	96	47.050, 122.908	Southern PS	All	0, 10
BUD005	C	96, 97	47.092, 122.917	Southern PS	All	0, 10
CRR001	R	96	47.277, 122.708	Southern PS	All	0, 10, 30
CSE001	R	96	47.265, 122.847	Southern PS	All	0, 10, 30
DNA001	C	96, 97	47.160, 122.875	Southern PS	All	0, 10, 30
ELD001	R	96	47.105, 122.949	Southern PS	All	0, 10
GOR001	C	97	47.183, 122.633	Southern PS	All	0, 10, 30
HND001	R	96	47.151, 122.833	Southern PS	All	0, 10
NSQ001	R	Jul. 96	47.112, 122.697	Southern PS	CTD/S	0, 10, 30

NSQ002	C	97	47.168, 122.787	Southern PS	All	0, 10, 30
OAK004	C	96, 97	47.214, 123.076	Southern PS	All	0, 10
TOT001	R	96	47.164, 122.963	Southern PS	All	0, 10
Coastal Estuaries:						
GYS004	C	96, 97	46.978, 123.783	Grays Harbor	All, no pig.	0, 10
GYS008	C	96, 97	46.938, 123.912	Grays Harbor	All	0, 10
GYS009	C	96, 97	46.965, 123.948	Grays Harbor	CTD/S	0, 10
GYS015	C	96, 97	46.923, 124.075	Grays Harbor	CTD/S	0, 10
GYS016	C	96, 97	46.953, 124.092	Grays Harbor	All	0, 10
WPA001	C	96, 97	46.688, 123.748	Willapa Bay	All, no pig.	0, 10
WPA003	C	96, 97	46.705, 123.837	Willapa Bay	All	0, 10
WPA004	C	96, 97	46.687, 123.972	Willapa Bay	All	0, 10
WPA006	C	96, 97	46.545, 123.978	Willapa Bay	All	0, 10
WPA007	C	96, 97	46.453, 124.008	Willapa Bay	All	0, 10
WPA008	C	96 (2 mo.), 97	46.464, 123.939	Willapa Bay	All	0, 10

* "All" refers to: temperature, salinity, pH, light transmission, DO, Secchi depth, dissolved nutrients (see text), pigments (0.5 m and 10 m only), and fecal coliform bacteria (0.1 m only). "CTD/S" refers to all except nutrients, pigments and fecal coliform bacteria. At GYS004 and WPA001 there are no pigment samples taken.

or South Puget Sound) we will prioritize regional candidates for "rotating" stations based on: those with suspected problems but insufficient data; those where no data exist bu environmental and land-use features indicate potential for problems; those associated with specific requests to aid other environmental studies; and those with outdated data. We do not intend these to be re-visited on a strict cycle, but rather when need dictates."

Materials and Procedures

Field Procedures

Long-term monitoring was conducted from aDeHavilland Beaver floatplane, which allows a large geographic area to be sampled in a short amount of time. Four surveys were scheduled in separate weeks each month to complete sampling throughout the Puge Sound and coastal station networks, as weather allowed. Approximately eight to ten stations were sampled per survey. Stations were identified by dead-reckoning and verified by a Global Positioning System (GPS) receiver. Sample collection methods were in compliance with the Recommended Guidelines for Measuring Conventional Marine Water Column Variables in Puget Sound (Puget Sound Estuary Program (PSEP), 1991a) and are detailed in Janzen (1992b). Major features are summarized below.

A Sea-Bird Electronics, Inc. Seacat® model SBE-19 conductivity-temperature-depth profiler (CTD) was used for collecting continuous water column profile data. The CTD was lowered through an internal opening on the seaplane using a capstan winch and brace outfitted especially for the plane. In addition to measuring conductivity (used to compute salinity and density), temperature, and pressure, the CTD was equipped with sensors to measure pH, dissolved oxygen (DO), and light transmission. Both the conductivity and DO sensors were flushed continuously with sample water by a pump attached to and powered by the CTD. Profiles at each station were conducted from the sea surface to ~100 m depth, or the sea bottom when shallower.

The Secchi disk depth was used to indicate water clarity and to derive the extinction coefficient of incident light penetration through the water column. Secchi depths (to the nearest 0.1 m) were taken at each station using a solid white, 30-cm disk. Surface water conditions (glare and waves) are the main source of inaccuracy in Secchi depth readings. To help reduce sources of error, all field crew were trained to conduc Secchi depth readings using the same procedure. If surface conditions were not optimal, the reading was not recorded or was recorded as an estimate.

A 1.2-L Niskin® bottle was used to collect seawater at 0.5, 10, and 30 m. For stations shallower than either 10 or 30 m, a sample at the near-bottom depth (0.5-1 m above the seabed) was taken. Ideally, discrete water-column sampling would be done above and below the pycnocline (the layer of rapidly changing density); however, lack of real-time CTD data display capability from the present sampling platform precluded this. Data for these fixed depths must be interpreted with knowledge of the CTD profile made at the time. Discrete water samples were taken from the Niskin bottle for dissolved nutrients (ammonium-N, nitrate+nitrite-N, and orthophosphate-P), and pigments (chlorophy *a* and phaeopigment). Discrete samples for DO and salinity were drawn periodically for comparison with the *in situ* sensor values. Samples for fecal coliform bacteria were collected just below the surface (0.1-m) using sterile glass sample bottles.

Laboratory Procedures

Analyses for dissolved nutrients, pigments, and fecal coliform bacteria were conducted a the Manchester Environmental Laboratory (MEL) using methods described in Ecology (1992).

All nutrient samples were maintained at 4°C and then filtered through Nalgene® 0.45 µm pore cellulose acetate filters at MEL within 24 hours of collection. Nutrient samples were analyzed for ammonium-N, nitrate+nitrite-N, and orthophosphate-P using an Alpkem® series 300 autoanalyzer at MEL. If immediate analysis was not possible, samples were frozen after being filtered.

Samples for chlorophy *a* (chl *a*) and phaeopigment (phaeo) were filtered through Whatman® GF/F glass fiber filters (0.70 µm nominal pore size) at the end of the sampling day by AMS staff. The filters were stored in 90% acetone (Eisner, 1994) and frozen in glass centrifuge tubes for transfer to MEL. Prior to WY 1994, filters had been stored in air, which was shown by AMS staff to result in loss of up to 22% of the chlorophyll *a* compared with filter storage in acetone. This difference should be noted in comparisons with pre-WY 1994 data. Determination o chl *a* and phaeopigment concentrations was made by MEL using fluorometric detection with a Sequoia-Turner model 112 fluorometer and the APHA *et al*. (1989) protocol.

Fecal coliform bacteria samples were stored refrigerated and transferred to MEL within 24 hours of collection. Upon arrival, samples were incubated and analyzed using the membrane filter method (APHA *et al*., 1989).

The discrete samples for DO analysis were analyzed by AMS staff using the azide-modified Winkler method (APHA *et al*., 1989). Since liquid fixing reagents were no allowed on the seaplane for safety reasons, powdered forms of the reagents were used. These powdered reagents have the capability to accurately bind oxygen for DO concentrations up to 10 mg/L (Hach, 1989). Results from the Winkler DO analyses were compared with the *in situ* DO results obtained with the CTD's Beckman oxygen sensor. The comparison allows for monitoring of sensor calibration drift or sensor failure; however insufficient samples were obtained for precise calibration of the *in situ* sensor each flight. Only discrete sample results <10 mg/L were used for comparison with the *in situ* sensor.

Discrete salinity samples were analyzed by University of Washington Marine Chemistr Laboratory using a Guildline Instruments, Inc. Autosal® salinometer, using standard seawater as a reference.

Data Management

The CTD data files were processed using Sea-Bird Electronics, Inc. SEASOFT© software (version 4.218). The CTD data, with the proper calibration coefficients applied, were bin-averaged into 0.5-meter bins (an interpolation process that averages sub-groups of data). Profiles of salinity and density with depth were derived from measured values o temperature, conductivity, and pressure. Further details on WY 1996-97 CTD processing procedures can be found in the CTD Data Acquisition Software Manual (Sea-Bird Electronics, Inc., 1996).

All data from the CTD were entered into Ecology's AMS Marine Waters Monitoring database (Microsoft Access®), following quality assurance checks. The CTD parameter values from 0.5, 10, and 30-m depths were linked with the results from the discrete water sample analyses at those depths and entered into a table in the database. Printouts fro the database of the 0.5, 10, and 30-m data tables are in Appendix A and printouts of the CTD profiles are in Appendix B for WYs 1996 and 1997.

Quality Assurance/Quality Control

Data Quality Objectives

Table 2 lists the data quality objectives for Ecology's Marine Waters Monitoring program. These objectives were different from PSAMP QA objectives (PSWQA, 1988) in the following cases:

1) Ecology's reporting limits for orthophosphate-P were 0.01 mg/L whereas PSAMP requests 0.002 mg/L, and
2) Ecology's target precision (relative standard deviation (RSD)) for chl *a* and phaeopigment was 20% whereas PSAMP requests precision within 10%.

All other target objectives met or exceeded those listed in the PSAMP document. The QA standards and procedures for MEL are described in Ecology (1988).

Additional quality assurance procedures for other laboratory analyses and equipmen calibration are in Ecology (1988) and Janzen (1992b). Data qualifiers for laborator results are given with the station data reports in Appendix A

In situ Sensor Quality Control Procedures

An annual calibration to monitor both accuracy and precision was performed by the Northwest Regional Calibration Center on the CTD's temperature, conductivity and DO sensors, and a biennial calibration was done for the CTD's pressure sensor. In-house calibrations were conducted monthly on the DO and pH sensors, and on the ligh transmissometer. Calibration procedures for the CTD followed Sea-Bird Electronics, Inc. (1990) and Janzen (1992b). The most recent calibration coefficients were used in processing data, thus maintaining accuracy by correcting for drift in sensor performance.

Results from the discrete DO and salinity analyses were used to verify that the *in situ* sensors were operational only. The discrete samples cannot be used to derive sensor calibrations/corrections since the samples were obtained following, not at the same time as, the CTD cast. Variation in field conditions between the two estimates is likely high but is unknown.

Table 2. Marine Waters Monitoring data quality objectives.

Analytica parameters	Ecology's reporting units*	Ecology's reporting limit	Relative standard deviation (RSD)
laboratory analysis parameters:			
ammonium-N	mg/L	0.01	10%

nitrite-N	mg/L	0.01	10%
nitrate+nitrite-N	mg/L	0.01	10%
orthophosphate-P	mg/L	0.01	10%
chlorophyll *a* and phaeopigmen	μg/L	0.05	20%
fecal coliform bacteria	#/100 mL	1	20%
salinity	PSU (~ppt)	0.01	8%
CTD parameters:			
salinity	PSU (~ppt)	0.01	8%
temperature	degrees C	0.1	5%
pH	pH units	0.1	0.1 pH unit
dissolved oxygen	mg/L	0.1	8%
light transmission	% light	0.1	5%

* Conversion t μg-at/L can be computed as follows:
((mg/L*1000)/16.00) for oxygen; ((mg/L*1000)/14.01) for nitrogen;
((mg/L*1000)/30.97) for phosphorus.

Discrete Analysis Quality Control Procedures

Parameters evaluated were: fecal coliform bacteria; pigments (chlorophyll *a* and phaeopigment); and nutrients (ammonium (NH_4^+-N), nitrate + nitrite (NO_3^-+NO_2^--N), and orthophosphate (oPO_4^{-3}-P). Quality control (QC) procedures included field replicate samples, laboratory split samples, field and laboratory method blanks (nutrients and pigments only), laboratory check standards (nutrients only), and matrix spike samples (nutrients only).

One station per flight survey was selected for field QC procedures. Replicate surface water samples were collected at these same stations each month. A station was selected from each survey where concentrations above reporting limits were expected. Field replicate results provide an estimate of the total variability (sampling and analytical) in the results for nutrients, pigments, and fecal coliform bacteria. The procedure entailed the collection of triplicate water samples using three separate surface (0.5-m) bottle casts a each selected QA station. The field replicates were sent to the laboratory as blind samples and analyzed for dissolved nutrients and for pigments. Replicate surface water samples (a 0.1 m) for fecal coliform bacteria analysis were also collected at these pre-selected stations.

At the laboratory, analysis of splits from the same QC sample provides an estimate of variability due to analytical procedures alone. Select field samples were split at the laboratory for analysis of nutrients and fecal coliform bacteria.

For pigments, field blanks of filtered distilled water were sent to the lab as blind samples. Analytical blanks of 90% acetone were read in the fluorometer before and after batch analysis of pigment samples.

Nutrient samples were analyzed in batches. Each batch run included analysis of two blanks, five known concentration check standards (analyzed once before the batch run, and once after), and one spiked sample. Check standards are samples with a known concentration that are analyzed along with the other samples. Check standards are prepared independently of the calibration standards and are used to estimate analytica precision and check for bias due to calibration errors. Matrix spikes for nutrients were prepared in the laboratory by adding a known quantity of analyte (a spike) to an aliquot. Matrix spike samples indicate the bias in laboratory procedures and instrumentation used in nutrient analysis. If the spike recovery is between 70% and 130%, no interference fro the sample matrix is judged to be present, since recoveries will be randomly distributed about a mean of 100%. The acceptance range for spike recovery is wide because the random error in the difference between two measurements is relatively large.

Results and Discussion

In WY 1996, 45 of the 48 scheduled weekly monitoring surveys were completed. O these, 34 of 36 were conducted in Puget Sound, and 11 of 12 in Grays Harbor and Willapa Bay. In WY 1997, 46 of the 48 scheduled weekly monitoring surveys were completed. Of these, 35 of 36 were conducted in Puget Sound, and 11 of 12 in Grays Harbor and Willapa Bay. High winds, fog, and low cloud cover were among the reasons for failure to conduct planned surveys.

Station data, presented in Appendix A, include the 0.5, 10, and 30 m values from the CTD profiles for temperature (°C), salinity (PSU = practica salinity unit; ~equivalent to part per thousand), pH (standard units), DO (both mg/L and percent saturation), and light transmission (percent transmission). Also shown are the Secchi disk depths (m), and laboratory results of discrete water sample analyses for fecal coliform bacteria at 0.1 (number per 100 mL), dissolved nutrients (mg/L) at 0.5, 10, and 30 m, and pigments (µg/L) at 0.5, and 10 m. The appendices in this report, are divided into two sections: 1) data for Puget Sound stations, and 2) data for the coastal estuary stations (Grays Harbor and Willapa Bay).

Climate

Local weather can influence the water column parameters of Washington inland marine waters noticeably (e.g., Newton, 1995d). Thus it is important to gain an understanding o forcing by weather in a given year. In order to detect how weather (air temperature and precipitation) data for WY 1996 and WY 1997 varied from the long-term mean (a.k.a. climatology), anomalies were calculated by subtracting 30-y monthly means (1961-1990) from WY 1996-97 monthly mean values. Data were for Sea-Tac Airport weather conditions, obtained from the National Climate Data Center (NOAA, 1995; 1996; 1997).

The long-term means (climatology) of air temperature and precipitation (Figure 3A) show normal Western Washington weather transitioning between relatively cold, wet winter conditions and warm, dry summer conditions. Precipitation anomalies for WY1996 (Figure 3B) and WY1997 (Figure 3C) show notably higher than normal precipitation occurred during wintertime months (October through April) of both years. Summertime months (May through September) in both years show nearly normal precipitation, wit conditions that were slightly wetter in WY 1997. The precipitation anomaly averaged for the entire year indicated both WY 1996 and 1997 were high precipitation years: 2.8 cm in WY 1996 and 3.1 cm in WY 1997. The annual mean temperatures for both years were close to normal; slightly higher than normal in WY 1996 (annual anomaly = 0.4 degrees C) and about normal in WY 1997 (annual anomaly = -0.1 degrees C). Despite the near-normal annual means, variation in the

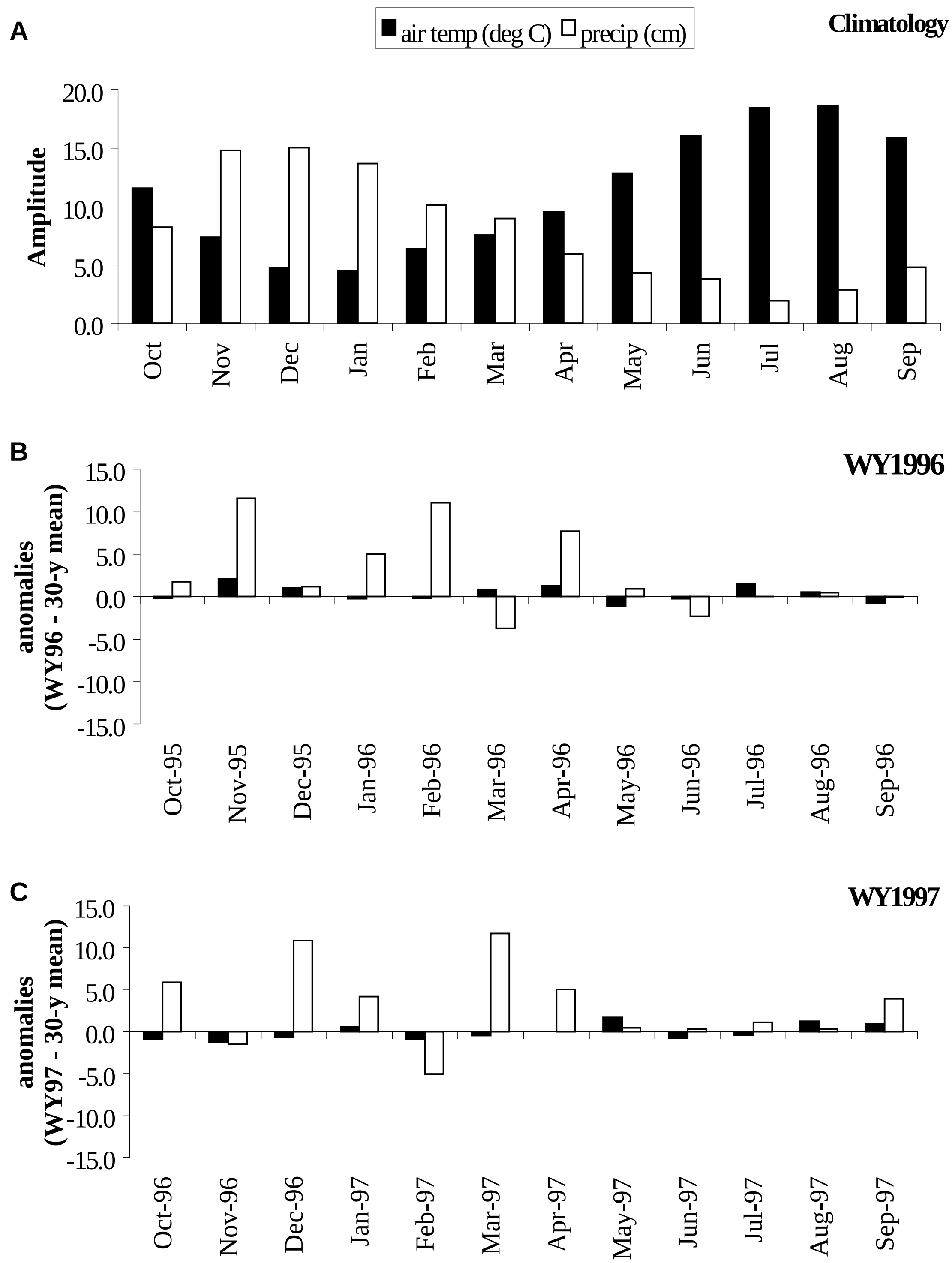

Figure 3. Climate data for WY1996-97. (A) Climatology (30 year-mean, 1961-90). (B) Anomalies for WY1996 air temperatures and precipitation compared to 30-year average. Data obtained from National Climate Data Center (NOAA, 1996; 1997) for Sea-Tac Airport.
(C) Anomalies for WY1997, as above.

temperature signal was substantial; however anomalies were seldom in one consistent direction for a seasonal timeperiod.

Consistent with the high precipitation anomalies in these years, fresh water flow was substantially above normal. The Skykomish and Chehalis Rivers are two river systems that are considered to be representative of western Washington. During WY 1996, the mean annual flow of the Skykomish and Chehalis Rivers was at 141% and 150%, respectively, of the median long-term flow, (USGS, 1996). During WY 1997, similarly high values, 148% and 146% respectively, were recorded (USGS, 1997). These sustained high flows represent a much stronger freshwater input to Puget Sound than normal

Temperature, Salinity, and Densit

Individual profiles of temperature (°C), salinity (PSU), and density (sigma- *t*) with depth (m) obtained from the CTD casts for the Puget Sound stations monitored during WY 1996-97 are in Appendix B.1; those for Grays Harbor and Willapa Bay are in Appendix B.2. Profiles were obtained from the sea surface to the seabed at most stations.

Temperature and Salinity Anomalies

A seasonal pattern in both weather variables and marine water temperature and salinity is strong in the Pacific Northwest region (Figure 3; Appendices A and B). In order to see the influence of weather on the physical character of Washington marine waters, monthly means and anomalies for both were calculated for seawater temperature and salinity (Figures 4 and 5). As with air temperature and precipitation, the marine water anomalies were calculated as the WY monthly value minus the long-term monthly mean value for both sea surface temperature and sea surface salinity.

Five stations from Puget Sound and one each from Willapa Bay and Grays Harbor were selected for this analysis. The selected stations in Puget Sound were: GRG002, in open waters of the Strait of Georgia, but potentially influenced by the plume of the Fraser River; ADM002, in open waters at the entrance to Admiralty Inlet, over the sill, in an often well-mixed regime that is not near riverine influence; PSB003, in open waters of the Puget Sound main basin off West Point where freshwater input from the Lake Washington ship canal and Elliott Bay (Duwamish River) would be evident; DNA001, in Dana Passage, a thoroughly mixed channel in southern Puget Sound where waters from several estuaries communicate with the main basin waters; and BUD005, a representative southern Puget Sound estuary with riverine input (Deschutes River), and relatively low mixing due to density stratification.

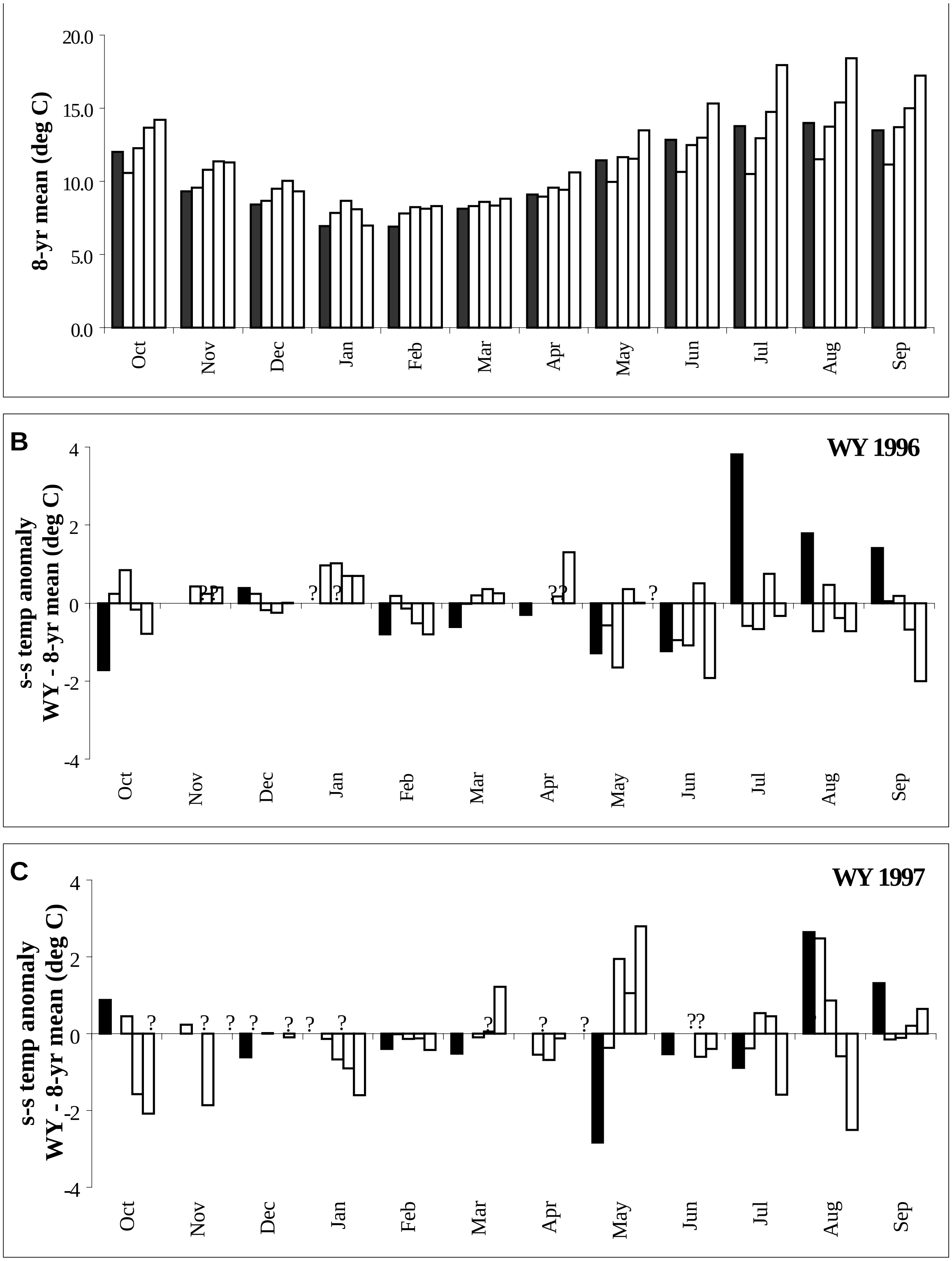

Figure 4. Sea-surface salinity and temperature means and anomalies for several stations in Puget Sound. (A) Eight-year sea-surface temperature means (WY 1990-97); (B) WY 1996 sea-surface temperature anomalies; (C) WY 1997 sea-surface temperature anomalies. A "?" denotes no data.

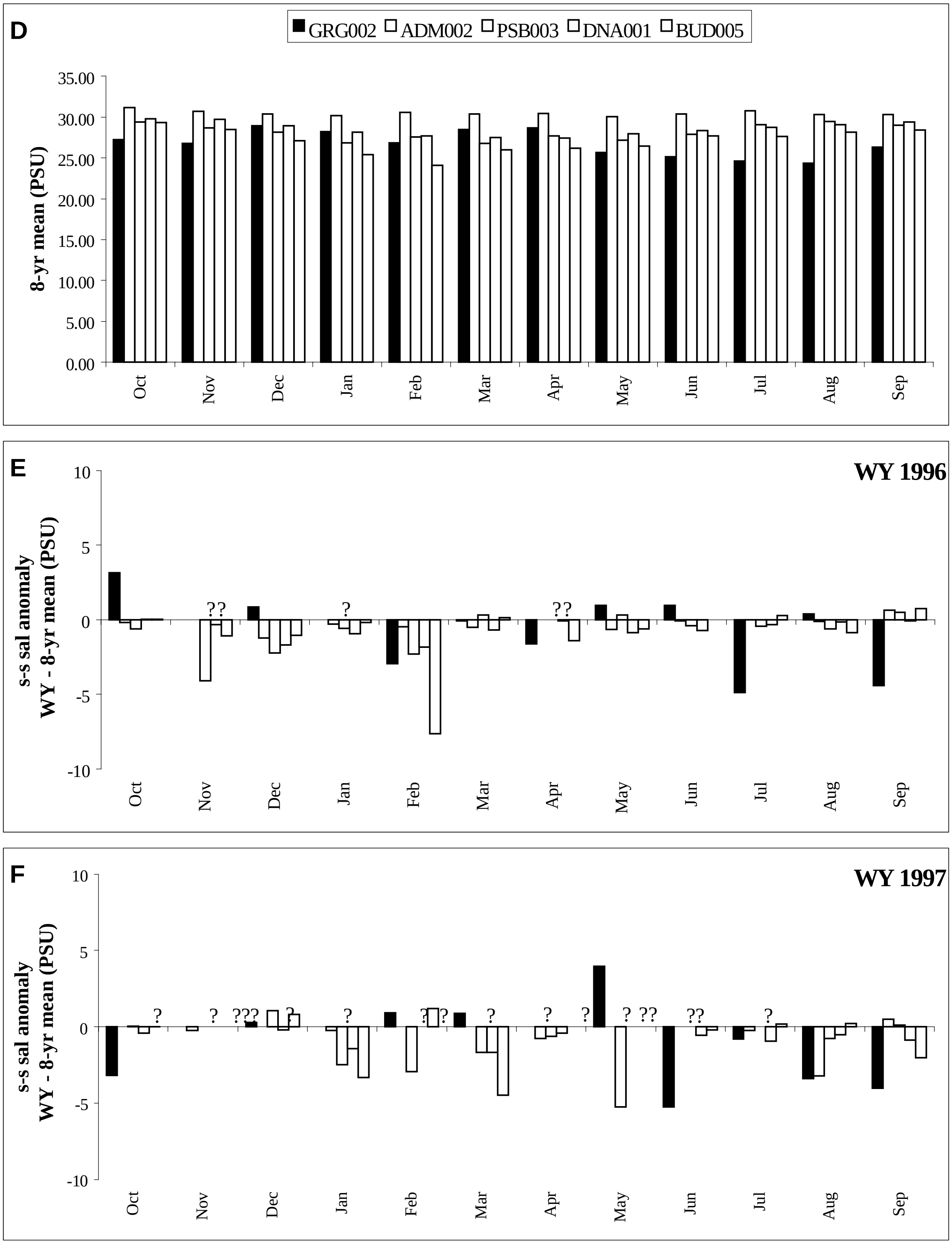

Figure 4. Continued. (D) Eight-year sea-surface salinity means (WY 1990-97); (E) WY 1996 sea-surface salinity anomalies; (F) WY 1997 sea-surface salinity anomalies. A "?" denotes no data.

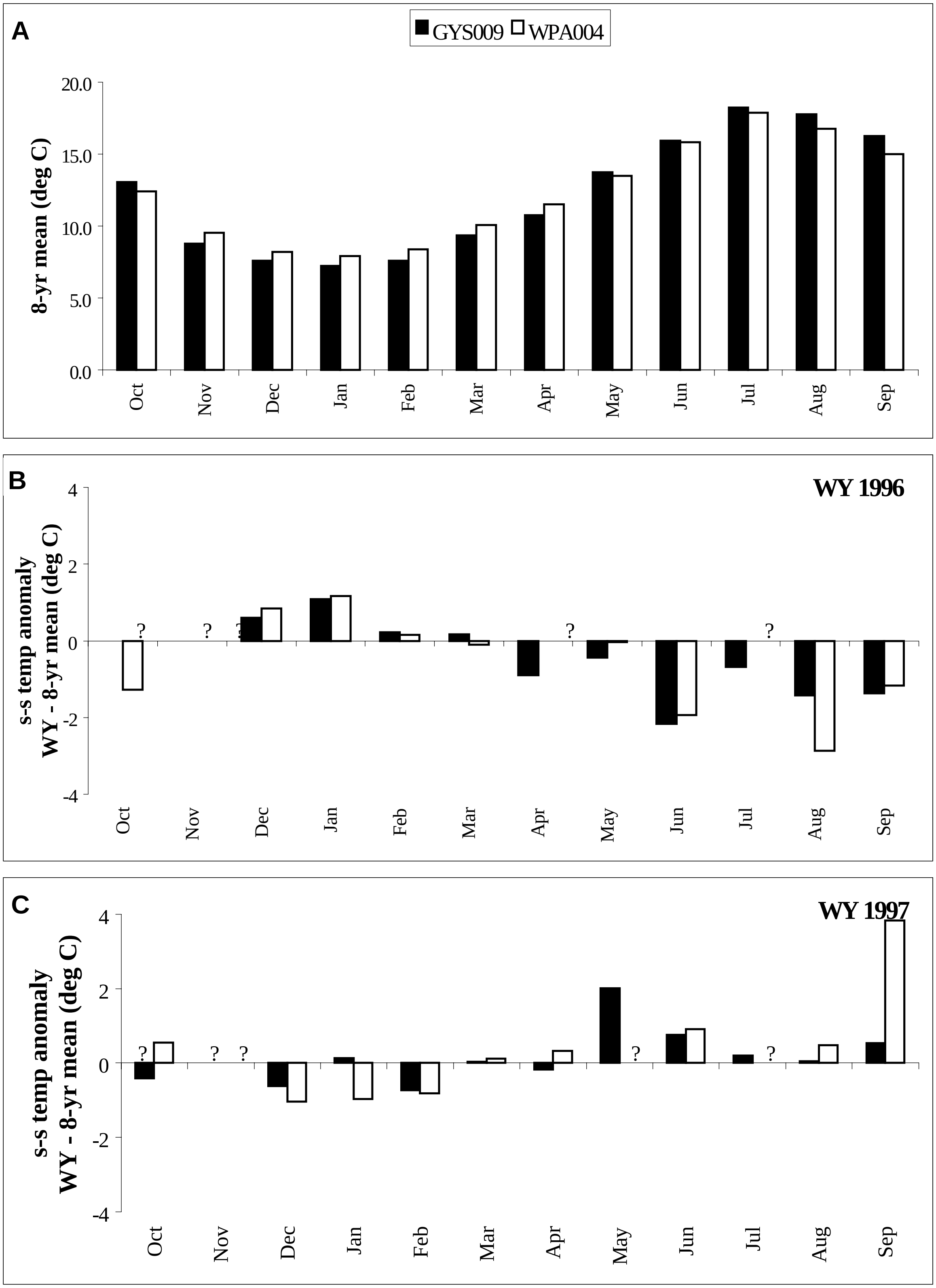

Figure 5. Sea-surface salinity and temperature means and anomalies for one station each of Willapa Bay and Grays Harbor. (A) Eight-year sea-surface temperature means (WY 1990-97); (B) WY 1996 sea-surface temperature anomalies; (C) WY 1997 sea-surface temperature anomalies. A "?" denotes no data.

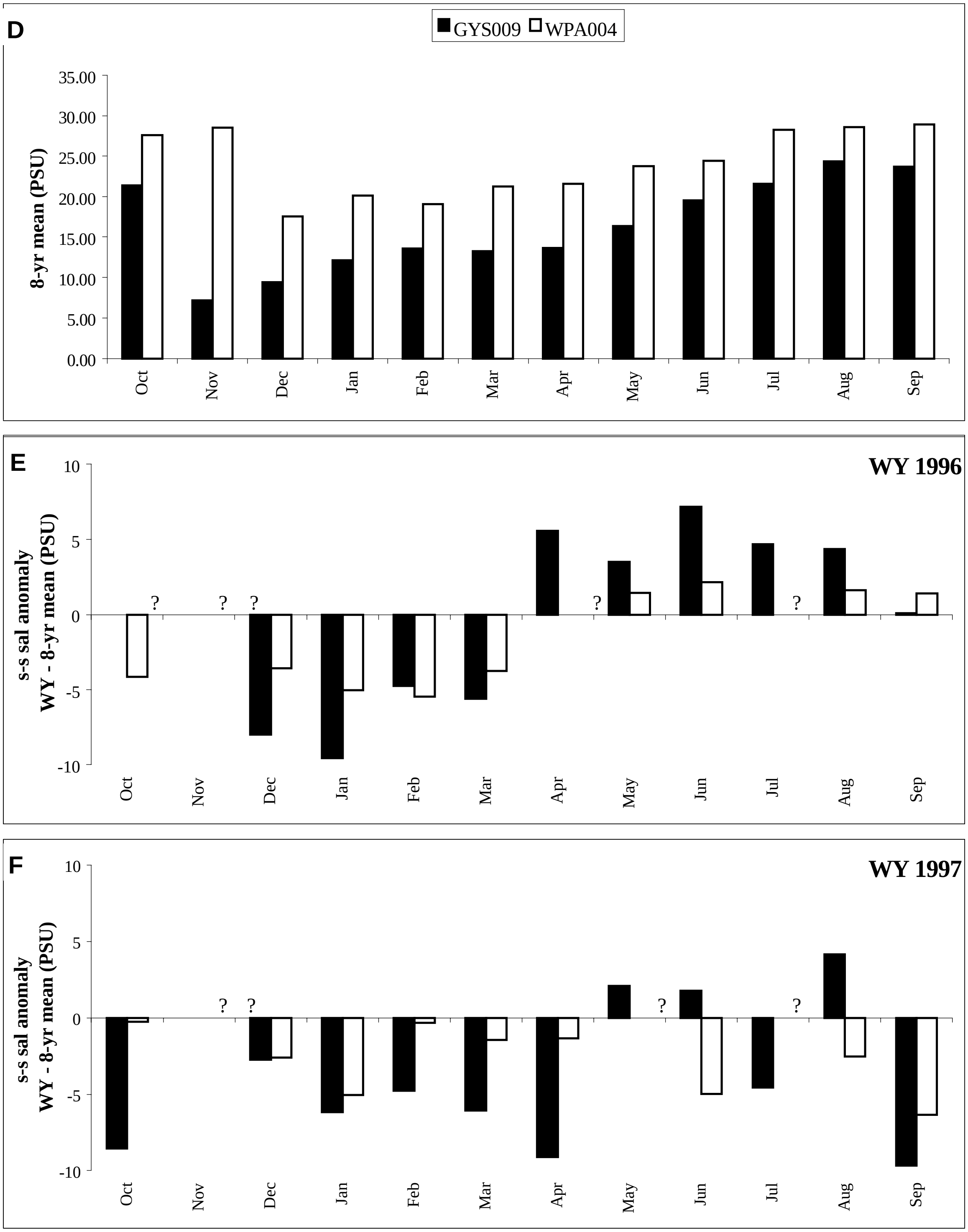

Figure 5. Continued. (D) Eight-year sea-surface salinity means (WY 1990-97); (E) WY 1996 sea-surface salinity anomalies; (F) WY 1997 sea-surface salinity anomalies. A "?" denotes no data.

The stations selected in Grays Harbor, GYS009, and Willapa Bay, WPA004, are located intermediate in these estuaries, and thus would be influenced by both riverine input and communication with Pacific Ocean waters. In these coastal estuaries, tidal stage is a strong determinant in the degree of marine versus riverine influence at a given sampling event in these coasta embayments. However, it was not logistically feasible to control for tidal stage in collecting these data.

The sea-surface temperature (SST) of inland Washington waters is influenced by Pacific Ocean conditions as well as by local air temperatures. In addition, stations proximal to rivers show an influence from freshwater input, which tends to be colder in winter and warmer in summer than seawater. In Puget Sound, SST and local air temperature have been observed to correlate fairly well (Newton, 1995d; Newton *et al.*, 1997). The SST anomalies for WY 1996-97 are consistent with this observation. The Puget Sound SST anomalies show a somewhat mixed signal (Figures 4B, C), which is similar to the air temperature anomalies (Figure 3B, C). The tendency toward positive SST anomalies in the latter months of WY 1997 is consistent with the onset of the 1997-98 El Niño and modest positive anomalies in air temperature in Aug-Sep 1997 (Figure 3C).

In the coastal estuaries (Figures 5B, C), the pattern shifts between warmer (Dec '95 – Feb '96), colder (Apr '96 – Feb '97) and warmer (May '97 – Sep '97) SST anomalies. The forcing for this pattern is unclear, except for a probable E Niño influence on the positive SSTs in latter WY 1997. Both Grays Harbor and Willapa Bay are more dynamic systems than Puget Sound due to the scale of their physical size relative to tidal forcing and river inputs. River flow and tidal stage strongly influence the monthly values obtained in these coastal estuary sites and neither is addressed in this analysis.

The 8-y means of Puget Sound SSTs (Figure 4A) illustrate that all five stations have relatively similar temperatures in Feb-Apr, but diverge profoundly in summer (especially Jul-Aug). As would be expected, the deep, well-mixed stations (e.g., ADM002) show less seasonal thermal variation than the shallow, stratified stations (e.g., BUD005). Of interes is the relation of the mean temperature at GRG002 relative to that at ADM002. The direction of their relative magnitudes changes in summer (GRG002>ADM002) versus winter (ADM002>GRG002). A similar pattern is observed between the SSTs of GYS009 and WPA004 (Figure 5A) and is likely due to river influence, which drives SSTs toward extreme values. Both GRG002 (Fraser River) and GYS009 (Chehalis River) have much more river influence than ADM002 and WPA004, respectively, as is evident in the sea-surface salinity (SSS) plots (Figure 4D and 5D, respectively).

The anomalies for sea-surface temperature and salinity must be interpreted with caution, since the long-term means used were based on only 8 years of monthly data from WY 1989 to WY 1997. Adequate data do not exist for calculating monthly means over a longer time period since prior to WY 1989 monitoring did not occur during winter months. Compounding this shortcoming is that these sea-surface anomalies are based on a single day's value obtained within the month, as opposed to the monthly means used for weather data. These factors could result in more noise in the long-term mean. However, the predominance of E Niño over La Niña events during the 1990's with its effect on the PNW tending towards warmer air temperatures and drier precipitation records (Mantua *et al.*, 1997; Ropelewski and Halpert, 1986; 1987) could bias the 8-y mean.

To assess variation in the long-term mean sea-surface temperatures, we compared the 8-y means from the Ecology monitoring stations to the only known source of continuously monitored sea-surface temperature data in the region. The location of the data is from the Pacific Ocean off the Washington coast at Cape Elizabeth (47.42N, 124.52W) at one o the NOAA/National Weather Service National Data Buoys. These data are valuable to show how our local estuaries compare with oceanic conditions as well as for their more comprehensive sampling (hourly data over 5.5 years, June 87-Dec 93). Despite the limited amount of data used for the Ecology long-term means, our sea-surface (0.5 m) means are very similar in magnitude and shape to the oceanic long-term sea-surface (0.6 m) (Figure 6). Some differences are also evident. The shallow and river-influenced stations (BUD005, WPA004, GYS009) are much warmer in summer and cooler in winter than the oceanic mean. This shows the effects from solar heating which is efficient a these stratified water-columns, as well as from river input which tends to be colder than seawater in winter and conversely in summer. Also of note is that the deep, well-mixed station ADM002 shows lower temperatures year-round, due to the strong mixing of surface waters with deep waters that occurs consistently at Admiralty Inlet.

Anomalies of sea-surface salinity (SSS) were predominantly negative at all Puget Sound stations during WY 1996-7 (Figure 4E, F). This might be expected given higher than normal precipitation at Sea-Tac (positive 3 cm) and higher than normal river flow (~150%) in both wateryears. Correlation of SSS anomalies with river flow and precipitation have been observed previously (Newton, 1995d; Newton *et al.*, 1997) in Puget Sound. The most variable station in terms of the SSS anomaly is GRG002. Fraser River plume waters sometimes flow past this station but sometimes go north bypassing this station. The 8-y long-term signature of SSS confirms an influence of the Fraser on this station (Figure 4D). Comparison of GRG002 with ADM002 not only shows reduced salinity but also that this difference increases in summer and decreases in winter.

Sea-surface salinity (SSS) anomalies for the coastal estuaries also show predominately negative values, with one notable period of exception Apr through Sep 1996 (Figures 5E, F). Watershed activities, tidal stage biasing of the monthly SSS data, and the

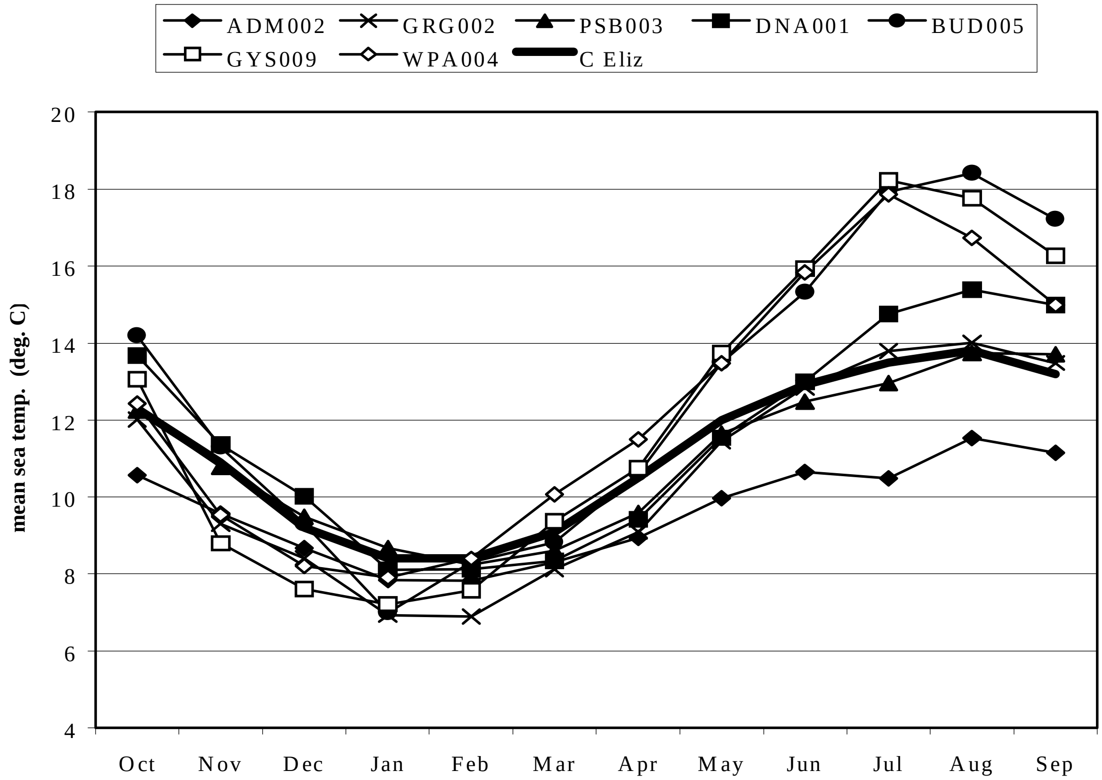

Figure 6. Sea-surface temperature long-term means for several Ecology monitoring stations and for the NOAA Cape Elizabeth National Data Buoy. Long-term means for Ecology data are monthly from WY 1990-97; for data buoy are hourly from June 1997 - Dec 93. Cape Elizabeth data source: NOAA National Buoy Center website.

monthly river flow anomalies for this period should be pursued for an explanation of this exception. The magnitude of the predominately negative SSS anomalies was quite large (up to 10 PSU). This large inter-annual as well as seasonal variation in salinity has implications for the biology in these coastal estuarine systems.

Density Stratification

Stratification refers to the horizontal layering of water masses within the water colum due to density differences. Water density is affected by both temperature and salinity, increasing with decreasing temperature or with increasing salinity. A change in density o 1 kg $^{-3}$ can be effected either by a 5°C change in temperature or 1 PSU change in salinity, or a combination of changes in both parameters (Pond and Pickard, 1983).

The vertical profiles of density in Appendix B are plotted in terms of "sigma-*t*", an oceanographic convention used to represent density. Millero and Poisson (1981) have most recently defined sigma-*t* as the density (kg m^{-3}) minus 1000 (kg m^{-3}). Therefore, a density of 1026.95 kg $^{-3}$ converts to a sigma-*t* of 26.95 (the units are typically left off). Temperature, salinity and pressure each contribute to water density. *In situ* temperature and salinity, and atmospheric pressure are used to derive sigma-*t*. The use of atmospheric pressure instead of pressure at depth does not have a significant affect on temperature or density for the shallow inland and coastal marine waters monitored here.

Density gradients within the water column indicate stratification. The layer where density increases rapidly with depth is known as the "pycnocline." Ambient air temperature, solar radiation, fresh water input from both precipitation and river flow, surface winds, internal waves, and tidal circulation are some of the factors that influence stratification in a water column. Any factor that mixes water masses
(e.g., winds, tidal circulation) will decrease stratification, and factors that increase density differences (e.g., fresh water input to the surface, high solar radiation) produce or maintain stratification. A typical model of estuarine stratification is of two layers: relatively warm, fresh water overlying colder, more saline water with separation marked by a distinct pycnocline.

In the coastal estuaries and many areas of Puget Sound (e.g., CMB003, ELB015, BUD002), differences in salinity have a stronger influence on density stratification than differences in temperature (Appendix B). The large variation in salinity is primarily due to the large amount of freshwater input from rivers in these areas. Salinity-driven stratification is typical of estuarine environments. Another general feature of the Puge Sound data is the lack of a classic "mixed layer" above the pycnocline. Instead, the pycnocline typically extends to the surface. Thus in this situation, the density change with depth is relatively constant from the water surface to the bottom of the pycnocline.
Most stations sampled in Puget Sound during WY 1996-97 exhibited distinc stratification, shown by a change in sigma-*t* (delta sigma-*t*) >2 over the pycnocline. However, the intensity and duration of the stratification varies greatly over time and between stations (Appendix B.1). Although much variation was evident, general stratification patterns can be identified for the Puget Sound stations visited in WY 1996-97 (Table 3).

Four patterns are differentiated and defined as indicators of stratification intensity : persistent, seasonal, episodic, and weak. "Persistent" stratification refers to stratification with a delta sigma-*t* of >2 evident within the water column that is observed throughout the wateryear. "Seasonal" stratification is when such stratification is observed primarily between April and September. "Episodic" stratification is when stratification occurs as isolated events or is seasonally random. "Weak" stratification refers to water columns tha were relatively well mixed during all observations (delta sigma-*t* ≤2).

Persistent and seasonal stratification patterns were most common and reflect the importance of freshwater input to the region's marine waters. The stratification patterns shown in Table 3 and Figure 7 were derived from analysis of data collected from WY 1990-97 (WY 1990 is when depth profiles were first obtained for Ecology monitoring stations). We have reported this analysis of stratification since WY 1993; due to interannual variation a few differences emerge from this more comprehensive analysis over previous years' classifications (PSB003, SIN001, TOT001 formerly seasonal, persistent, and weak, respectively).

Table 3. Classification of Puget Sound stations according to observed stratification pattern.

Persistent	Seasonal	Episodic	Weak
BLL009	ADM001	BML001	DNA001
BLL011	ADM002	FID001	FRI001
BUD002	ADM003	GOR001	PTH005
BUD005	CRR001	HND001	
CMB003	CSE001	NSQ002	
ELB015	DIS001	PSB003	
HCB003	DRA002	OAK004	
HCB004	EAS001	SIN001	
HCB006	ELD001	TOT001	
HCB007	FSH001		
HLM001	GRG002		
PNN001			
PSS019			
SAR003			
SKG003			

The patterns defined are general categorizations; for example, seasonal influences can be seen in data from stations exhibiting persistent stratification (Appendix B). Also, the gradient (magnitude of delta sigma-*t*) as well as the depth of the pycnocline varies from among stations. Station CMB003, which shows persistent stratification, has a very shallow (~5 m) pycnocline whereas station SAR003, also with persistent stratification, generally has a deeper (~10-20 m) pycnocline.

Annual stratification patterns in Grays Harbor and Willapa Bay are more difficult to assess. Both Grays Harbor and Willapa Bay have significant river inputs. USGS gauged rivers include the Chehalis River, which flows into the head of Grays Harbor, and the Willapa, North and Naselle Rivers, which flow into the northeastern, northern, and southern portions of Willapa Bay, respectively. Both estuaries are partially

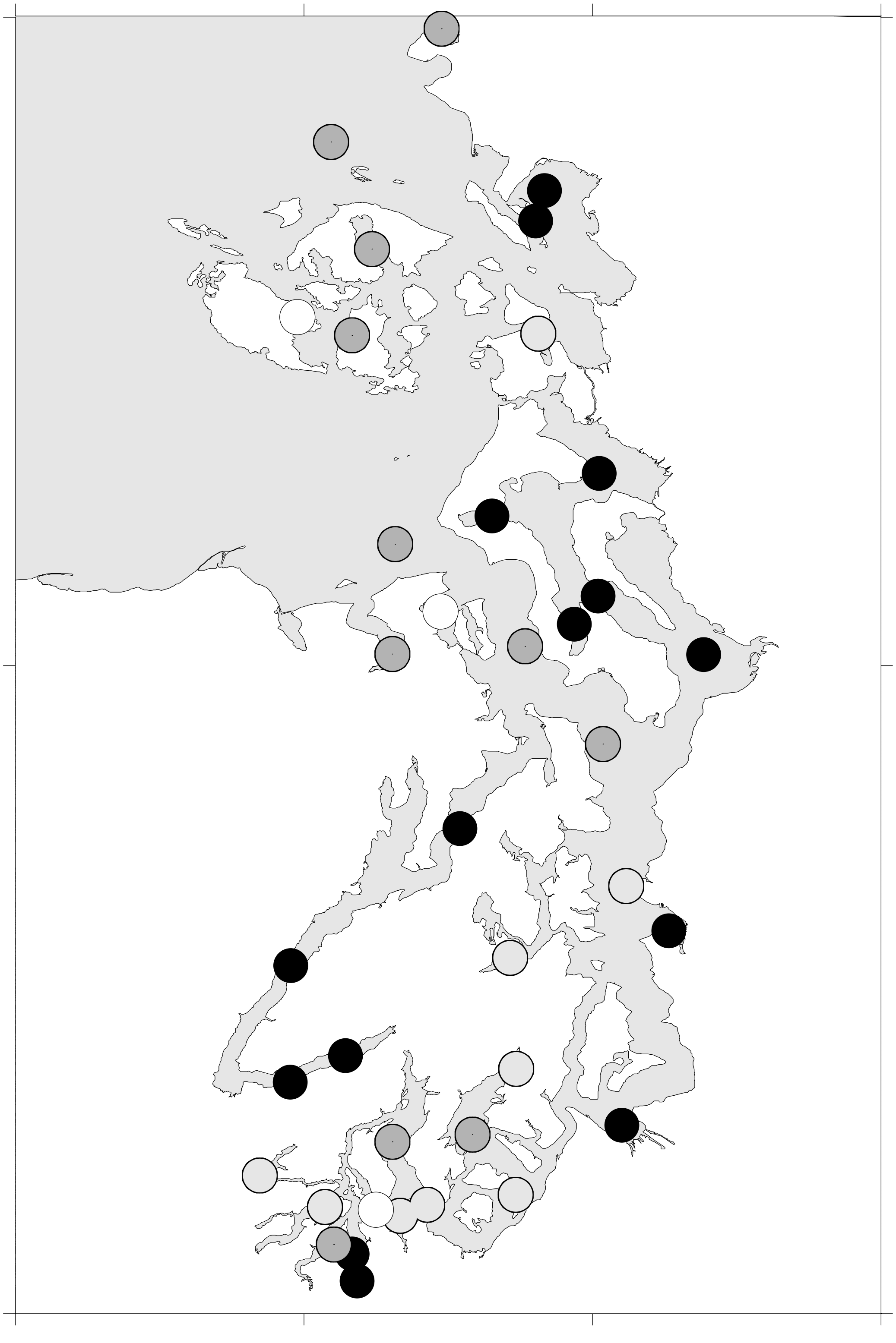

Figure 7. Stratification patterns for Puget Sound Marine Waters Monitoring stations based on data from WY 1990-97: persistent (black), seasonal (dark gray), episodic (light gray); weak (clear).

enclosed water bodies resulting in some restriction of water exchange with the Pacifi Ocean. Tidal stage plays a very strong role in whether a freshwater layer will be observed at a particular station at a given time and our sampling does not control for this source o variation. Stratification can be quite strong at all of the Grays Harbor stations sampled and at two of the stations in Willapa Bay (WPA001 and WPA003; Appendix B). The other Willapa stations (WPA004, WPA006, WPA007 and WPA008) appear to have a more episodic to weak pattern of stratification. Tidal mixing at these relatively shallow stations (10 m or less) plus mixing effected by wind stress may overcome stratification a these latter stations. Sampling with respect to tidal stage would be necessary to accurately determine annual or seasonal patterns and to further understand the dynamics o stratification in these estuaries.

Dissolved Oxygen and Light Transmission

Individual profiles of *in situ* dissolved oxygen concentration (mg/L) and light transmission (percent light transmission) with depth (m) obtained from the CTD casts for the Puge Sound stations monitored during WY 1996-97 are in Appendix C.1; those for Grays Harbor and Willapa Bay are in Appendix B. Profiles were obtained from the sea surface to the seabed at most stations.

Dissolved Oxygen

Low DO concentrations result when organic material is decomposed (oxidized) in waters that do not mix to the surface where aeration with atmospheric oxygen can occur. Upwelled deep waters and deep waters with overlying high organic production can have naturally low DO concentrations. Human input of nutrients that stimulate organic production can drive naturally low DO concentrations to even lower values. Depressed levels of DO available in the water column can have a serious impact on marine organisms. Effects of DO depletion are both organism- and habitat-specific (Harding *et al.*, 1992). The degree of impact is dependent upon the temporal and spatial stability of the depressed DO levels. The DO concentration where deleterious effects occur is not well explored for local waters. It also should be considered that DO concentrations in the water column may not reflect the DO concentrations experienced by benthic organisms. Jørgensen (1980) found that significant DO gradients can exist between 0.5 to 0.05 m above the sediment in a fjord.

Hypoxia, meaning low oxygen, is generally regarded as a DO concentration that i deleterious to many organisms. Although hypoxia has been commonly defined in the literature as occurring at concentrations between 0.5-3.0 mg/L (e.g., Harding *et al.*, 1992; PSEP, 1988) or between 0.2-2.0 mg/L (e.g., Pihl *et al.*, 1992; Llansó, 1992), there is evidence that the behavior of some organisms (e.g., fish, larvae) can be negatively affected at DO concentrations as high as 4-4.5 mg/L (Whitmore, *et al.*, 1960; Kramer, 1987; Breitburg *et al.*, 1994). Thus, the DO concentration of 5 mg/L is typically regarded as the upper limit for “biological stress” induced by low DO (NOAA, 1998). Anoxic waters, where no oxygen is available, are habitable only by anaerobic organisms, primarily bacteria.

In this report, we review the water column data for areas with biologically significant low DO. The value of 5 mg/L was chosen as an indicator of low DO concentrations that ma induce biological stress. The value of 3 mg/L was chosen as an indicator of near- hypoxia. These two DO concentration thresholds are used in this report as indicators to help evaluate biological stress at a given monitoring station.

Biologically stressful levels of DO were seen at several Puget Sound stations during WY 1996-97 (Table 4; Figure 8) but not in the two coastal estuaries, Grays Harbor and Willapa Bay. Some of the low DO occurrences reflect natural conditions and some may indicate anthropogenic effects.

Whether water quality at a particular DO concentration above or below a certain threshold is natural or is being impacted by human activities is much more complex to assess, involving data and considerations that are outside the scope of this report. Washington State assesses human impacts on water quality every two years in the State's Section 305(b) report. Waterbodies impaired due to human activity effects on DO are shown in the 303(d) list, appended to the 305(b) report (Ecology, 1996). The listing process uses the data from this and other monitoring programs along with data on human activities (e.g., permitted uses, land-use changes, etc.) and evaluation of impaired uses in order to assess whether water quality criteria are being met or not due to human activities.

The Washington State marine water quality criteria for DO vary according to the classification of the waterbody (WAC 173-201, 1991), which is governed by the intended maximum beneficial use of those waters. The criteria and waterbody classifications are established to protect legal, political, social, and environmental concerns. The State's DO concentration criteria (Table 4) are intended to guide the identification of water quality deterioration from anthropogenic influence. A waterbody violates State water quality standards when DO is below the criteria for that waterbody, or when DO is degraded b more than 0.2 mg/L over the natural level for stations where natural conditions such as upwelling cause DO to be depressed below the station’s criteria.

For the 38 Puget Sound stations monitored in WY 1996-97, all but 2 (ELD001 and TOT001) violated the respective waterbody DO criteria at some time during the year. However, only eight stations (shown in bold in Table 4) were judged as not meeting Stat water quality standards for DO, resulting in these being listed on the State 303(d) list for 1996 (Ecology, 1996). No coastal estuary stations violated the State water quality standard for DO; Grays Harbor stations never exceeded the DO criteria and only during one month (August 1997) did four stations in Willapa Bay (WPA001, 003, 007, 008).

It is especially difficult to establish whether the DO concentration in a waterbody is being impacted b anthropogenic means within Puget Sound. This is because upwelling with naturally low DO concentrations occurs regularly off the Pacific coas as well as within basins like Puget Sound, because natural productivity is high seasonally and produces low DO, and because long time-series data of reliable DO measurements do not exist for man areas.

Table 4. Stations with low DO concentrations during WY 1996-97. Also shown, in bold, are stations reported on the 1996 303(d) listing as impaired waterbodies due to violation of State DO standards fro   anthropogenic sources. State water quality DO criteria for class AA, A and B waters are 7, 6 and 5 mg/L, respectively. The   nm" = not monitored.

Station	State waterbody class	# observations DO < 5 mg/L		# observations DO < 3 mg/L	
		WY1996	WY1997	WY1996	WY1997
ADM001	AA	-	2	-	-
ADM002	AA	4	4	-	-
BLL011	A	nm	4	nm	-
BUD002	B	1	nm	-	nm
BUD005	A	-	1	-	-
CMB003	A	3	4	-	-
CRR001	AA	2	nm	-	nm
CSE001	AA	0	0	0	0
DIS001	AA	nm	4	nm	1
DRA002	A	nm	2	nm	-
EAS001	AA	1	nm	-	nm
ELB015	A	2	1	-	-
FRI001	AA	nm	1	nm	-
GRG002	AA	1	3	-	-
HCB003	AA	6	nm	2	nm
HCB004	AA	12	9	4	6
HCB006	AA	4	5	-	-
HCB007	AA	8	nm	5	nm
HLM001	A	7	nm	-	nm
OAK	A	0	0	0	0
PNN001	A	5	nm	2	nm
PSB003	AA	-	2	-	-
PSS019	A	4	5	-	-
PTH005	A	-	2	-	-
SAR003	A	4	5	-	-
SKG003	A	2	nm	-	nm

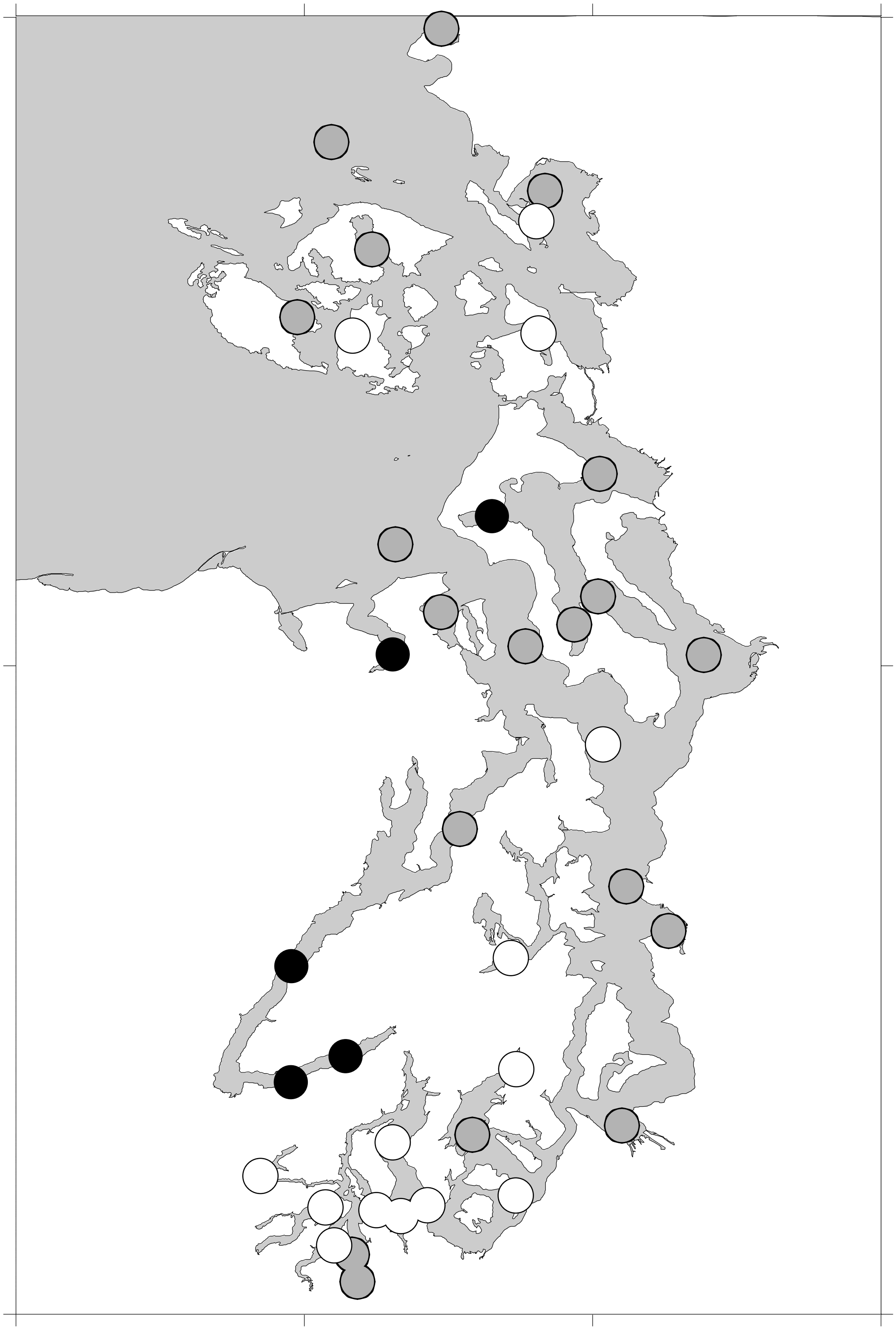

Figure 8. Puget Sound stations with DO < 3mg/L (black), < 5 mg/L (gray), and >= 5 mg/L (clear) during WY96-97.

In the context of human impacts on DO there is an interesting characteristic of Puge Sound that is both beneficial to water quality yet constraining on human activities that might lower DO concentrations. Pacific Ocean waters enter Puget Sound through the Strait of Juan de Fuca. Seasonally, these waters are predominately upwelled deep oceanic waters that have naturally low DO concentrations. This low DO signal can be seen a ADM002 and other locations. The strong flushing of the Puget Sound basin with oceanic waters to some extent reduces the potential water quality impacts from human activities, and thus could be advantageous. However, because the inflowing upwelled waters have a naturally low DO content that is minimum in late summer (at about 5 mg/L or less), any human activity that decreases the DO concentration w have a more profound water quality impact, since the initial concentration is already at the limit of where some species feel stress. This is especially important since the timing of the lowest DO concentrations from the oxidation of organic production is also in late summer. A small amount of anthropogenic nutrient input can have a larger effect at this time than it would if the oceanic waters' DO concentrations were higher. Puget Sound is a ver unique system in this respect. Human contributions to DO debt must be carefully evaluated.

Although anthropogenic effects are difficult to assess, biologically significant low DO was relatively prevalent in Puget Sound during WY 1996-97, with twenty-four stations exhibiting DO concentrations <5 mg/L, and three locations, Hood Canal, Penn Cove, and Discovery Bay, showing DO concentrations <3 mg/L during at least one month. Since DO profiling began (WY 1990), dissolved oxygen concentrations <5 mg/L have not been observed in either coastal estuary

A general observation relevant to DO in WY1996-97 is that the prevalence of low DO in these years is higher than typically observed for stations where comparisons can be made. A compilation of low DO occurrences at Puget Sound stations monitored throughout WY 1990-95 is shown in Table 8 in Newton (1995c). For the 15 Puget Sound core stations that have been monitored continuously since WY 1992, the prevalence of DO <5 mg/L a a station in a given year has been 27%, 33%, 40%, 33%, 60%, and 73% from WY 1992 through 1997. Differences in sampling technique do not appear to be the cause of these differences since the QC data has consistently corroborated the accuracy of the sensor (see QC results) and the same instrument and procedures have been used.

The dramatic increase in low DO prevalence the last two years may reflect an effect fro increased river runoff, lowering sea-surface salinity, that may have increased stratification intensity and thus prevalence of low DO. Freshwater runoff has been above normal fro 1995 through 1997. Also, changes in the DO concentration in waters from the Pacific Ocean may be the driving force. Climate-driven variations in upwelling off the Washington coast, which bring DO-poor waters to the surface, also may be operative. Low DO was found seaward of Admiralty Inlet (at ADM002) with higher frequency in both WY 1996 and 1997 than all years since WY 1992 and for the first time (in WY 1997) south of the entrance sill (at ADM001) since WY 1993.

Although many Puget Sound stations showed lower DO concentrations in WY 1996-97 than in previous years this was not true of all stations. Single observations of low DO concentrations were seen at BUD002, BUD005, and EAS001 during WY 1996-97. Low DO concentrations and prevalence have been worse in previous years (WY 1992-95) for both Budd Inlet and East Sound.

Density stratification was well correlated with low DO concentrations. All stations with persistent stratification (Table 3) exhibited low DO (Table 4) except one (BLL009). As is typical, low DO concentrations were largely constrained to near-bottom depths, where waters are not in contact with the sea-air interface. Density stratification of the water column favors the occurrence of low DO in bottom water, as it impedes mixing. Twenty-one of the twenty-four Puget Sound stations where DO concentrations fell below 5 mg/L experienced persistent or seasonal stratification (Table 3). Further implications of density stratification on water quality are included in the General Discussion.

Understanding the natural processes affecting DO is important if human impacts are to be detected. Local physical processes such as the input of low-oxygenated fresh or oceanic water, stratification intensity, circulation patterns and mixing regimes, in addition to biological activity (e.g., primary production, respiration, oxidative reactions), will affec ambient levels of DO and its distribution both vertically and horizontally. Other factors affecting DO include sediment oxygen demand and chemical oxidation processes.

A site-specific physical condition, such as sluggish circulation or proximity to oceanic deep water, may cause one station to have lower DO concentrations than another stati of the same waterbody classification for reasons that are not due t anthropogenic impact. Alternatively, the same anthropogenic impact, such as a certain amount of nutrient input, may have a much more profound impact on the DO concentration of one station than that of another within the same waterbody classification. Thus, each case must be evaluated in consideration of the natural characteristics of the location.

The following section contains information on the severity and persistence of the low DO concentrations for the stations listed in Table 4, as well as their physical characteristics (Appendix B) and potential causes. When possible, comparisons are made with historica data; however Ecology DO data was collected down to 30 m with a CTD starting in WY 1990 and to the seabed starting in WY 1992. Historical Ecology data was not as we calibrated as the post-1990 data.

Stations with DO concentrations less than 3 mg/L

Stations with DO concentrations less than 3 mg/L are treated separately here since this concentration has greater significance to biological organisms than does 5 mg/L and thus warrants a higher degree of concern. Even with DO concentrations <3 mg/L in a particular area, it is difficult to assess whether natural conditions or human activities are driving the concentrations lower. However, regardless of the cause of the observed low DO concentrations, land-use decisions in areas with near- hypoxic DO should be made with increased caution since these areas will have the highest sensitivity to human impacts.

Areas showing near-hypoxia during WY 1996-97 are Hood Canal, Penn Cove and (to a much less extent) Discovery Bay. Additional areas showing near- hypoxia from previous years are Budd Inlet and East Sound Orcas Island, both of which showed concentrations less than 5 but greater than 3 mg/L for the months monitored in WY 1996-97 (Table 4).

Hood Canal

HCB007: ***Lynch Cove***

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	DO <3 mg/L depth range (m)	Cast depth (m)
Oct 95	1.06	4.5 - 6.5	7 - 18.5	18.5
Nov 95	2.34	6 - 13.5	14 - 29	29
Dec 95	3.08	15.5 - 21	-	21
Jan 96	3.92	13 - 23	-	23
May 96	3.91	11.5 - 14	-	14
Jul 96	0.83	13.5 - 16	16.5 - 23	23
Aug 96	0.08	10 - 11.5	12 - 21	21
Sep 96	2.69	13.5 - 17	17.5 - 32.5	32.5

HCB004: ***Sisters Point***

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	DO <3 mg/L depth range (m)	Cast depth (m)
Oct 95	3.16	6.5 - 51	-	51
Nov 95	2.45	6 - 16.5	17 - 49.5	49.5
Dec 95	3.20	19.5 - 49	-	49
Jan 96	4.39	22.5 - 49	-	49
Feb 96	4.27	21.5 - 35.5	-	35.5
Mar 96	3.32	31.5 - 49.5	-	49.5
8 May 96	2.64	24 - 35	35.5 - 36.5	36.5
9 May 96	3.30	15.5 - 51.5	-	51.5
Jun 96	3.36	19 - 29	-	29
Jul 96	1.49	13.5 - 22	22.5 - 42	42
Aug 96	1.40	8 - 13.5	14 - 52.5	52.5

Sep 96	3.20	15 - 51.5	-	51.5
Oct 96	2.90	2.5 - 14 29 - 53.5	14.5 - 28.5	53.5
Dec 96	2.79	5.5 - 36	36.5 - 52	52
Jan 97	4.43	26 - 39.5	-	39.5
Apr 97	4.47	36 - 45.5	-	45.5
May 97	3.07	22.5 - 51	-	51
Jun 97	2.43	12 - 30	30.5 - 50	50.5
Jul 97	1.87	14 - 28.5	29 - 51	51
Aug 97	1.35	6 - 16	16.5 - 53	53
Sep 97	1.26	7.5 - 9.5	10 - 49	49

HCB003: ***Hamma Hamma***

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	DO <3 mg/L depth range (m)	Cast depth (m)
Oct 95	3.48	13 - 50	-	50
8 May 96	3.24	44.5 - 114	-	114
9 May 96	2.62	13 - 19.5 28.5 - 32.5	20 - 28	32.5
Jul 96	3.41	19.5 - 103	-	103
Aug 96	3.00	14.5 - 63.5	-	63.5
Sep 96	2.54	12.5 - 19 28.5 - 32.5	19.5 - 28	32.5

HCB006: ***Bangor***

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	DO <3 mg/L depth range (m)	Cast depth (m)
Oct 95	4.53	18 - 52	-	97
Dec 95	4.23	53 - 97	-	97
May 96	4.24	59.5 - 116	-	116
Sep 96	4.08	18.5 - 101.5	-	101.5
Oct 96	4.74	10.5 - 46.5	-	83
Jun 97	3.55	49 - 115.5	-	115.5
Jul 97	3.78	44 - 116.5	-	117
Aug 97	4.18	9.5 - 38	-	38
Sep 97	4.53	37.5 - 104.5	-	104.5

The DO conditions in South Hood Canal continue to be of concern (Newton *et al.*, 1995). Core station HCB004 is located east of the Great Bend of Hood Canal, just inside the s located at Sister's Point, in approximately 50 m water depth. This station is persistently stratified, with a strong pycnocline (delta sigma-*t* ranged 4 to 7) typically located in the upper 15 m. DO concentrations below 5 mg/L were recorded year-round: 12 out of 12 months in WY 1996 and 9 out of 10 months in WY 1997. This is consistent with other recent data: 11 out of 11 months in WY 1995, 10 out of 10 months in WY 1994, 7 out of 10 months in WY 1993, 9 out of 12 months in WY 1992 and 10 out of 10 months in WY 1991. Hypoxic conditions (≤3 mg/L), however, were recorded frequently during WY 1996 (4 months) and WY 1997 (6 months), as compared to 9, 4, 2, 5, and 4 months in WYs 1995 through 1991, respectively.

Station HCB007, a persistently stratified station located at the head of the canal in Lynch Cove and monitored in WY 1996 only, showed even more severe DO conditions than at HCB004 with concentrations approaching anoxia in the late summer. Near- hypoxia was observed in 8 out of 10 months monitored. Data from the two exceptions (Mar and June '96) were truncated shallower (15 and 10 m, respectively) than typical CTD casts at this station (20-30 m) and may not have reached the seabed.

Station HCB003, located midway between the Great Bend and Dabob Bay, exhibited less severely low DO concentrations than found in S. Hood Canal, but values were still near-hypoxic for 5 of 7 months monitored during WY 1996. This station is persistentl stratified but is located closer to the Puget Sound Main Basin waters that flush the Canal.

Strong temporal variability in DO concentrations at these stations may be seen from comparing the data from 8 May 1996 versus 9 May 1996 at HCB004 and HCB003. Variations in tidal currents, sunlight, and other physical and biological processes all w affect the DO signal at a given station at a given time. Heterogeneity in the DO concentration signal is evidently strong.

Station HCB006, a deep (~100 m) station located near Bangor, is the farthest seaward o the stations monitored in the long, narrow Hood Canal. The water column was persistently stratified with a typically weak pycnocline (delta sigma-*t* ≤2) in the upper 15 that became stronger seasonally. The high frequency of <5 mg/L DO concentrations observed at this station in WY 1996 (4 out of 11 months) and WY 1997 (5 out of months) are unprecedented in Ecology's database. Previously, single observations of low DO concentrations were recorded in WY 1995, 1994, 1993, and 1992.

Historical data from the 1950's and 60's (Collias *et al*., 1974) show that low DO was annually common in southern Hood Canal in late summer and fall. Southern Hood Cana has a naturally high primary production of organic material, due to the water-column stability and nutrient supply afforded by the riverine input (Skokomish and Tahuya Rivers) and the lack of disruptive mixing due to the sill's protection. Decomposition of this large amount of organic matter, strong and persistent stratification, and slow circulation due to the deep basin and an entrance sill are optimal conditions for a natural depletion of DO. However, the influence o anthropogenic input of nutrients (*e.g.*, via rivers, leaking septic tanks, terrestrial runoff) on the phytoplankton production cycle and DO content of these isolated waters is not established.

Also, the seasonally occurring low DO conditions recorded in Hood Canal in the 1950's appeared to originate at the head of the Canal, at Lynch Cove, and spread seaward along the canal (Collias *et al*., 1974; Curl and Paulson, 1991) along a density surface. Although the low DO concentrations observed at HCB006 during WY 1996 and 1997 are no severely low, the horizontal extent of the spread of low DO concentrations may be increasing since the 1950's when it rarely was observed pas Hoodsport (Collias *et al*., 1974).

Updated from our previous assessment (Newton *et al.*, 1997), four observations from the monitoring data indicate the possibility that DO conditions may be deteriorating in southern Hood Canal and that eutrophication could contribute to this change. Impacts o other human activities (e.g., freshwater diversions) as well as natural cycles must also be fully evaluated.

1) There is an alarmingly high frequency of hypoxic DO concentrations in recent data, including frequent occurrences even during winter months. Minimum DO values rarely exceed 5 mg/L year-round at HCB004 or HCB007 and have remained below 3 mg/L for substantial periods of time.

2) The frequency of low DO concentrations recorded along Hood Canal suggests a possible increase northward in the horizontal extent of low values.

3) Over the period of WY 1991 to 1997, high chl *a* concentrations have been observed i summer months in S. Hood Canal, when nutrient limitation of phytoplankton growt in stratified waters such as these would be expected.

4) Experiments conducted to test whether anthropogenic input of nutrients could influence the amount of phytoplankton in southern Hood Canal showed that primar productivity was increased as much as three-fold when nutrients were added to ambient water samples (Newton *et al.*, 1994).

In light of the severely low DO concentrations recorded in southern Hood Canal even in wintertime, further monitoring and study of southern Hood Canal are highly recommended. The severity and extent of low DO concentrations in Hood Canal are currently being assessed by Ecology from comparative historical data analysis. Additional field studies are also currently being conducted by Ecology and the University of Washington. Effects from low DO on the biological community, such as fish or shellfish, should be assessed.

Penn Cove

PNN001:

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	DO <3 mg/L depth range (m)	Cast depth (m)

Nov 95	2.43	7.5 - 18.5 24.5 - 26.5	19 - 24 27 - 30.5	30.5
Mar 96	4.80	31	-	31
Jun 96	3.07	17 - 27.5	-	27.5
Aug 96	3.43	19 - 30.5	-	30.5
Sep 96	2.43	8.5 - 15.5 20.5 - 23	16 - 20 23.5 - 30.5	30.5

Penn Cove exhibits persistent stratification with a strong pycnocline (delta sigma-*t* ranged 2 to 7), attributes associated with the natural development of low DO. Penn Cove has been monitored by Ecology during WYs 1994 and 1996 only. During WY 1994 there were three months when DO <5 mg/L were observed, with one month (Oct '93) where concentrations were nearly anoxic. The low DO concentrations recorded during WY 1996 were not as extreme as in WY 1994; however, low DO concentrations were observed more frequently in WY 1996 than in WY 1994. Because DO concentrations can be very dynamic with time, these differences are likely not significant. What can be concluded about Penn Cove is that DO concentrations are at biologically relevant low concentrations frequently in this area. Thus, anthropogenic activities (both present and future) that can stimulate plankton production, decrease circulation, or increase oxygen demand within the Cove should be carefully evaluated.

Discovery Bay

DIS001:

WY 1997 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	DO <3 mg/L depth range (m)	Cast depth (m)
Oct 96	3.18	27.5 - 40	-	40
Jul 97	4.26	41	-	41
Aug 97	3.05	19 - 19.5 20.5 - 39.5	-	39.5
Sep 97	2.94	18.5 - 39.5	40	40

This is the first year Discovery Bay has been monitored. The bay's seasonal stratification and high productivity make it a likely candidate for low DO concentrations. The apparen persistence of the low/hypoxic DO from July through September should be regarded with caution. The existence of any human impact on the DO concentration is not known.

Stations with DO concentrations less than 5 mg/L

Admiralty Inlet

ADM001:

WY 1996-97 Minimum DO conc. DO <5 mg/L Cast depth

month	(mg/L)	depth range (m)	(m)
Aug 97	4.87	71 - 104.5	105
Sep 97	4.51	10, 13.5, 16.5, 20, 22.5, 27.5, 29.5-30, 33, 77-82.5	82.5

ADM002:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.38	42 - 57.5	57.5
Jul 96	4.45	66.5 - 71	71
Aug 96	4.77	45.5 - 52.5	52.5
Sep 96	3.43	26 - 51	51
Nov 96	4.47	35 - 56	56
Jul 97	4.60	45.5 - 67	67.5
Aug 97	3.34	21 - 58	58
Sep 97	4.19	0.5 - 65.5	65.5

Low DO concentrations at these stations are typically natural, reflecting the influence o upwelled, naturally low-oxygenated Pacific Ocean waters that flow eastwards in through the Strait of Juan de Fuca beneath a less-saline surface layer flowing westwards. Deep oceanic waters have low DO content due to an extended isolation from the surface and direct consumption of oxygen through respiration. Deep Pacific Ocean waters off the Washington shelf at Copalis have DO concentrations as low as 3 mg/L (Landry *et al*., 1989). When upwelling-favorable winds are present (late summer-fall), deep waters flowing in through the Strait of Juan de Fuca will have low DO concentrations. This deep water will shoal when passing over the sill at Admiralty Inlet and mix with higher oxygenated waters as it enters Puget Sound.

Station ADM002 is a moderately deep station (~ 70 m) located in the Strait of Juan de Fuca off the Quimper Peninsula. Physically quite dynamic, stratification is more likely to be evident from May through September but is not always strongly developed and the pycnocline depth is quite variable. Station ADM001 is located south of the Admiralty Inlet sill in deep (80-100 m) waters. Like ADM002, this station is very dynamic physically. Note that low DO is found at ADM001 much less frequently than a ADM002. This likely reflects the mixing and aeration that water masses receive when flowing past the entrance sill at Admiralty Inlet. This is the first year ADM001 has recorded DO concentrations <5 mg/L though it has only been monitored since WY 1993. The lowest DO recorded previously was 6 mg/L. The minimum DO observed seasonally at ADM002 has varied between 4.6 and 5.3 mg/L from WY 1990 through 1995.

Bellingham Bay

BLL011:

WY 1997 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 96	4.00	12.5 - 16.5	16.5
Jul 97	4.01	13 - 15	15
Aug 97	4.00	12.5 - 22	22
Sep 97	4.05	10.5	10.5

WY 1997 was the first year that this station within the Nooksack River plume was monitored. Stratification is persistent and the organic is load high, so the presence of low DO is not surprising. The degree of human impact on the DO concentration cannot be assessed with these limited data. Low DO has not been found at the other Bellingham Ba station, BLL009, despite its persistent stratification.

Budd Inlet

BUD002:

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.93	6.5 - 10	10

BUD005:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Sep 97	4.72	7 - 14.5	14.5

Stratification is persistent in Budd Inlet, with freshwater input from the Deschutes River/Capitol Lake system. The minimum concentrations recorded in WY 1996-97 are higher than those seen in recent (WY 1994-95) years, but impact fro interannua variation and temporal variation within a month on these DO values are not known. The DO and other water column characteristics of Budd Inlet have been well studied b Ecology (e.g., Eisner *et al.*, 1994; Eisner and Newton, 1997). In these studies, water quality varied substantially on an interannual basis, influenced by local weather, and locationally within the inlet, with lowest DO concentrations found towards the head of the inlet (e.g., near BUD002 and farther south). DO concentrations at BUD002 and other inner inlet stations monitored by Ecology Eisner *et al.*, 1994) are often recorded below 5 mg/L, whereas DO at the mid-inlet BUD005 station seldom is, showing the danger o using mid-bay locations to assess low DO conditions throughout an inlet

Commencement Bay

CMB003:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.34	46 - 107.5	107.5

Nov 95	4.86	104 - 116.5	116.5
Sep 96	4.92	47.5 - 82.5	82.5
Oct 96	4.71	43 - 109.5	109.5
Jul 97	4.97	111.5	112
Aug 97	4.54	71.5 - 110.5	110.5
Sep 97	4.52	68.5 - 113.5	113.5

A core station, CMB003 has not shown low DO concentrations over the period since 1992 when >30-m profile data have been obtained until WY 1996 and 1997. The values recorded are not much below 5 mg/L and so may not implicate large changes. Continued monitoring is recommended.

Carr Inlet

CRR001:

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.56	53.5 - 99	99
Sep 96	4.97	31 - 35	106.5

Monitored in WY 1991 and 1993, this deep, seasonally stratified station has not shown low DO concentrations before. The concentrations observed in WY 1996 were barely below 5 mg/L. Further monitoring of this station is recommended to gain a better baseline for this productive inlet.

Drayton Harbor

DRA002:

WY 1997 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Aug 97	4.60	18 - 20.5	20.5
Sep 97	4.27	12 - 22	22

This seasonally stratified station has not been monitored previously. The low DO concentrations and seasonal range are not outside reasonable bounds for this environment. Because of the enclosed nature of this harbor, it would be sensitive to human activity tha could alter DO.

East Sound, Orcas Island

EAS001:

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Jul 96	3.97	29.5 - 32	32

Station EAS001, located in Orcas Island's East Sound in roughly 30-35 m deep water, is seasonally stratified. A weak pycnocline (delta sigma-*t* ≤2) develops over the months of May through September, from the surface to typically 10 m or less. Low DO concentrations in WY 1996 were less prevalent than in recent years. Low DO concentrations were observed during most of the summer in WY 1994 and in early summer in WY 1995. Since monitoring at EAS001 began in WY 1991, the occurrence o low DO has been: 2 observations in WY 1992, 1 in WY 1993, 5 in WY 1994 and 2 in WY 1995 and now this 1 in WY 1996. The annual minimum DO consistently has been observed in July (except once in June), with concentrations below 3 mg/L observed in WYs 1992, 1993 and 1995.

The early timing of the minimum DO concentration (July) at EAS001 is unique compared to all other sites monitored. Minima in late summer/early fall are more typically found in Puget Sound and reflect the accumulated effect of stratification during summer and oxidation at depth of organic material produced during summer. Organic production is high at this station, as indicated by high levels of chlorophyll *a* (~30 µg/L) during April-July in WY 1995, but this is not unique to East Sound. The driving mechanism(s) behind the early timing of the low DO event at EAS001 cannot be determined from the data in this report.

Elliott Bay

ELB015:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.70	43 - 63	63
Sep 96	4.92	57 - 59.5	59.5
Aug 97	4.22	46.5 - 58.5	59

The only previous observation of DO <5 mg/L since Ecology's monitoring began measuring depths below 30 m (June 1992) at this station was in Aug 1995 and the concentration was barely below 5 mg/L. These observations are lower and more frequent; however, are consistent with the Sound-wide pattern during thesewateryears. There is much anthropogenic impact on Elliott Bay. Continued monitoring of this core station is warranted.

Friday Harbor - San Juan Island

FRI001:

WY 1997 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 96	4.89	14 - 18	18

This weakly stratified station has not been monitored previously. The DO concentration is barely below 5 mg/L and likely reflects an oceanic signal. Due to strong tides and little stratification, the waters within Friday Harbor apparently are well mixed with waters from the Straits.

Strait of Georgia

GRG002:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Sep 96	4.59	25.5 - 110.5	110.5
Oct 96	4.35	58.5 - 118.5	118.5
Aug 97	4.39	42.5 - 81.5	81.5
Sep 97	4.92	47.5 - 57	57

The only previous observation of DO <5 mg/L since Ecology's monitoring began measuring depths below 30 m (June 1992) at this station was recorded in WY 1994 and the concentration observed was just below 5 mg/L. These low DO observations likely reflect the signature o upwelled low DO waters from the Strait of Juan de Fuca, plus the influence from the Fraser River plume, which has a high organic load. Continued monitoring of this long-term core station is warranted though no problem is perceived.

Holmes Harbor - Whidbey Island

HLM001:

WY 1996 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	3.48	27 - 51.5	51.5
Nov 95	3.21	20 - 51	51
Dec 95	4.51	48 - 51	51
May 96	4.79	44 - 47	47
Jun 96	3.87	27.5 - 48	48
Jul 96	3.91	14.5 - 50.5	50.5
Aug 96	3.55	25.5 - 51	51

Monitored for the first time in WY 1996, this persistently stratified station shows strong sensitivity to low DO. Near-hypoxic concentrations lag into the winter and return fairl early in the summer, suggesting that circulation is not strong in this fairly enclosed harbor. This would be an important environment to closely monitor human activities that could exacerbate the low DO concentrations observed here.

Puget Sound Main Basin - West Point

PSB003:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Aug 97	4.78	47.5 - 61.5	62
Sep 97	4.22	58.5 - 68	68

The only record of low DO at this core station is during late summer 1997. DO is low a depth, probably reflecting upwelled Pacific Ocean waters that were low in DO. The concentrations match the deep waters at ADM001 during these same two months.

Possession Sound

PSS019:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.39	26 - 57	57
Nov 95	4.03	48 - 100	100
Dec 95	4.63	83 - 93.5	93.5
Aug 96	4.89	76 - 102	102
Oct 96	4.50	18.5 - 47.5	47.5
Nov 96	4.46	50 - 106.5	106.5
Dec 96	4.19	61 - 92	92

Aug 97	5.00	45 - 45.5	45.5
Sep 97	3.57	26.5 - 84	84

Station PSS019, located o Gedney Island in the deep waters (~105 m) o Possession Sound, is persistently stratified. A strong pycnocline (delta sigma-*t* ranged 3 to 10) is common in the upper 10 - 15 m, the result of a major freshwater source, the nearb Snohomish River. Ambient DO concentrations below 5 mg/L were observed in summer and fall, as were observed previously (Newton *et al.*, 1994; Newton *et al.*, 1997); however, the number of months observed per wateryear (4 and 5) is higher than in previous years DO (previous maximum was 3 in WY 1994).

The strong and persistent stratification observed in this area restricts mixing and therefore increases the potential for low DO conditions to develop. It is not known whether the high chlorophyll *a* concentrations observed occasionally (approaching 30 µg/L) are stimulated by anthropogenic input of nutrients, but this would be possible in these persistently stratified waters. Historical data from the area as well as organic material and nutrient input from the river and other sources in Everett Harbor should be assessed to evaluate this condition.

Port Townsend Harbor

PTH005:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 96	4.73	17.5 - 33	33
Sep 97	4.73	21 - 22.5	22.5

A core station, this weakly stratified station is likely reflecting the DO concentration from upwelled Pacific Ocean waters. Low DO concentrations have not been observed at this station since comparable measurements began (WY 1990).

Saratoga Passage

SAR003:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Oct 95	4.15	26.5 - 105	105
Nov 95	4.18	28.5 - 109.5	109.5
Dec 95	4.30	62 - 97	97
Sep 96	4.56	16 - 114.5	114.5
Oct 96	4.52	20.5 - 92.5	92.5
Nov 96	4.60	12.5 - 110	110
Dec 96	4.72	42 - 101.5	101.5
Aug 97	4.34	30.5 - 53.5	54

Sep 97	4.02	16.5 - 65	65

Station SAR003, a deep-water (~122 m) station located in Saratoga Passage, i persistently stratified (delta sigma-*t* ranged 3 to 10) with the pycnocline typically comprising the upper 10 - 20 m. This station is influenced by several rivers. Saratoga Passage has consistently had one to two low DO occurrences per year since WY 1990, with minimum concentrations ranging 4.4 to 5.0 mg/L. Depressed DO concentrations are typically observed during 1-3 months, most frequently in September/October. The four occurrences in WY1996 and five in 1997 are unprecedented; however, the values do not appear to be seriously low. For the time period from WY 1978 through 1990, when DO measurements only went to 30 maximum depth, values between 4.2 and 4.8 mg/L were observed in WYs 1979, 1980 and 1987.

The low DO concentrations observed may reflect a response to phytoplankton blooms, as chlorophyll *a* is occasionally quite high (approaching 40 µg/L). Waters with DO below 5 mg/L were occasionally measured in Possession Sound or in Skagit Bay in the 1950-1960's database of Collias *et al*. (1974) during fall, but were not seen in Saratoga Passage. Whether phytoplankton blooms are unnaturally high should be evaluated, as well as whether advection of low DO waters from PSS019 northward occurs.

Skagit Bay

SKG003:

WY 1996-97 month	Minimum DO conc. (mg/L)	DO <5 mg/L depth range (m)	Cast depth (m)
Nov 95	4.42	5 - 7	7
Sep 96	3.73	3 - 23	23

SKG003 is located in the Skagit River delta area in persistently stratified waters with high particulate loads. Skagit Bay was monitored previously in WY 1991 without observed low DO concentrations and in WY 1995 with a single observation of moderat concentration in fall (4.15 mg/L, Oct. ‘94). These annual fall lows are probably natural, o high-production-high-stratification origin, but its depth coverage can be substantial

Light Transmission

The profiles in Appendix C show % light transmission (transmissivity) with depth (m), as measured with an *in situ* transmissometer. The % light transmission at a certain depth indicates the particulate load suspended in that water. The ligh transmissometer measures the instantaneous light transmission over a 25-cm path of the ambient water column. The % light transmission decreases in response to increases in turbidity, since particles absorb and deflect light. Suspended sediments and phytoplankton cells are the most common causes of increased turbidity and are not differentiated by this measurement.

In areas known to have strong bottom currents, low % light transmission values near the bottom are caused by particles suspended from the seabed. However, a particularly severe decrease in the % light transmission at the bottom of a profile (*e.g.*, SIN001 in Sep 1996) is probably an artifact, caused by contact of the CTD with the bottom sediments.

Within the water column, low % light transmission values are hard to interpret, since both phytoplankton blooms and sediment plumes (*e.g.*, associated with river runoff) cause a decrease in light transmission. Profiles of % light transmission can be used as another indicator of stratification, since robust mixing will homogeneously distribute particles. Well-mixed stations, such as DNA001, exhibit few variations of this parameter with depth. Thin layers of reduced light transmission at the surface can indicate particle load fro river water, and this conclusion can be confirmed by observation of the companion salinity profile (*e.g.*, GRG002 in June-August 1997). Stations GYS004 and WPA001, where ligh transmission rarely exceeds 30%, show the dramatic reduction in light transmission typica in river water. Low light transmission also can indicate high concentrations o phytoplankton, *i.e.*, blooms. For example, high phytoplankton concentration at ELD001 during August and September 1996
(~50 µg/L, appendix A), correlate with distinc minima in light transmission below the surface (<40%, appendix B).

Light transmissometer data are best interpreted in concert with other measured parameters, to confirm observations regarding stratification, river input, bottom currents, and phytoplankton concentrations.

Pigments

Chlorophyll *a* and Phaeopigment

The pigment chlorophyll *a* (chl *a*) is common to all organisms capable of photosynthesis. In the marine water column, chl *a* indicates phytoplankton biomass. Note that since the amount of chl *a* per cell can vary widely with light adaptation or nutrient level, chl *a* cannot be directly converted to number of cells or phytoplankton carbon. Ye chl *a* remains the best indicator of phytoplankton populations in common use. Phaeopigmen (phaeo) refers to numerous degradation products o chl *a*, including phaeophorbides and phaeophytins. In marine systems, these pigments are primarily the product of zooplankton herbivory and less commonly from cellular processes. Thus, marine water column phae concentrations indicate chl *a* that has been degraded, typically via zooplankton grazing. Therefore, the cells have been eaten and are no longer photosynthesizing and producing oxygen.

Phytoplankton blooms (an accumulated high concentration of phytoplankton) require conditions conducive to high phytoplankton growth rates in order to occur. These conditions include sufficient light, nutrients, and stability as well as a relative lack of loss processes (e.g., sinking, mixing, grazing). Low incident radiation, nutrient limitation, lack of stratification (phytoplankton is mixed out of euphotic zone), high levels of turbidity (light limitation), and zooplankton grazing all prevent phytoplankton biomass accumulation and thus can lead to low chl *a* concentrations. It must be recognized tha chl *a* concentrations (phytoplankt biomass) are not a proxy for phytoplankton growth. The phytoplankton concentration is the net result of growth and loss processes. Thus, the same concentration could exist with high phytoplankton growth and high loss through grazing or mixing, as could exist with low growth and low losses. Blooms occur when high growth is sustained in the absence of substantial loss processes (e.g., before grazing zooplankton are numerous, before nutrients or light limit phytoplankton growth, before mixing washes cells out of the euphotic zone).

Results of the MEL fluorometric analyses of extracted chl *a* and phaeo concentrations (µg/L) are tabulated in Appendix A. Plots of the 0.5-m and 10- chl *a* concentrations (µg/L) versus WY month sampled are shown in the second panel of Appendix C. I comparing these data to historical Ecology data note that chl *a* concentrations from samples analyzed prior to WY 1994 may be low by up to 22 percent because of the filter storage procedure (see Methods).

The plots of chl *a* concentration with time show seasonal patterns (Appendix C) which can reflect the balance of growth and loss processes at each station. However, it must be noted that chl *a* can change on time-scales much faster than monthly (hours to days), thus adequate resolution of seasonal patterns from monthly data is not feasible. Perhaps more than any other variable, chl *a* is undersampled by our monitoring design because chl *a* ca vary an order of magnitude or more in both time and space (both horizontal and vertical). This severely limits what can be resolved from the data presented here. The occurrence and dynamics of phytoplankton blooms cannot be adequately resolved without higher temporal resolution sampling (hourly to daily), such as via moored sensors or remote sensing. Total phytoplankton biomass cannot be adequately assessed from our two-depth measurements but would require increased vertical resolution such as afforded by an *in situ* fluorescence detector; surface chlorophyll concentrations may or may not directly correlate with the phytoplankton population and these relations need to be established for our local waters. Regional comparisons of phytoplankton abundance cannot be adequately assessed without higher horizontal resolution data, as would be provided b remote sensing, since blooms can be very patchy and thus missed by a single point station. Thus, it is highly likely that the sometimes strong inter-annual variation in seen in seasona patterns of chlorophyll when comparing different years' monitoring data at a certain station are influenced by under-sampling (1x per month, two depths only) instead of reflecting true variation from nature.

Although interpretation must be made with caution for the reasons stated above, some general patterns are evident from the monthly data. For most Puget Sound stations, chl *a* concentrations were higher from late spring through early fall than in winter. In winter, light limitation and strong mixing (from winds or lack of thermal heating) prevent phytoplankton accumulation. Phytoplankton blooms require stable conditions and adequate levels of light and nutrients. High chl *a* concentrations, indicating blooms, tend to occur in spring (April- May) and fall (September-October). Often the summertime chl *a* concentrations are of an intermediate to low value, reflecting nutrient limitation due t stratification. Some stations exhibited the typical temperate phytoplankton pattern o spring and fall blooms, with moderate concentrations in summer, and lowes concentrations in winter (e.g., BLL009, and BML001).

Some stations showed elevated chl *a* concentrations (blooms) in summertime as well as in spring and fall, indicating that nutrients were not limiting. This nutrient supply can be natural, due to a lack of stratification allowing nutrients to be injected into the euphotic zone from depth, or it can be anthropogenic, due to an additional supply of nutrient (runoff, septic tanks, agricultural wastes) to the euphotic zone. Blooms in summer as we as spring and fall were observed in BUD005, EAS001, HCB004, and HLM001.

Stations with deep mixed layers (e.g., ADM002) showed chl *a* concentrations that were relatively low throughout the growing season, reflecting a phytoplankton population with higher loss (mixed out of the euphotic zone due to strong tidal or current dynamics) than growth.

The chl *a* data for the coastal estuaries have large gaps that make interpretations o seasonal pattern difficult. However, blooms in July-August are evident and this pattern appears somewhat different than that observed in most of Puget Sound.

Secchi Disk Depths

Light Extinction and the Euphotic Zone Depth

Secchi disk readings (depth of the disk's disappearance) can provide an indication of the penetration of incident radiation (sunlight striking the sea surface) into the water column. Secchi disk readings are used to calculate the light extinction coefficient, which can be used to derive an estimate of the euphotic zone depth. The euphotic zone is the portion of the water column where there is sufficient light for photosynthesis.
A shallow euphotic zone means less of the water column is available for growing phytoplankton. By convention, the depth of the euphotic zone has bee defined as the depth at which 1% of the incident radiation (I_o) is available (e.g., Steemann Nielsen, 1975). Some investigators have used the 0.1% light level as the lower limit; however, in temperate regions where incident radiation is not strong the 1% light level is an appropriate delimiter.

Individual Secchi readings, recorded to the nearest 0.1 m, are listed in Appendix A for a stations monitored in WY 1996-97. These readings were used to calculate estimates of k, the extinction coefficient of light, and of the euphotic zone depth.
The extinction coefficient, k, was first determined from the equation:

$$k\ (\ ^{-1}) = 1.6 / \text{Secchi disk reading (m)} \qquad (1)$$

Equation (1) was originally derived by Poole and Atkins (1929) for the English Channe with a value of 1.7, instead of 1.6. The value of 1.6 used here is based on empirical observations for local Puget Sound waters and the work of Holmes (1970) who found this constant to be lower in coastal waters.

The euphotic zone depth, or 1% I_o depth, is derived using the formula for light extinction in water:

$$I_z/I_o = e^{-kz} \qquad (2)$$

substituting 0.01 (*i.e.*, 1%) for I_z/I_o, and solving for z, the depth (m) at which 1% of I_o is found.

Plots of 1% I_o depths versus month for each station occupied during WY 1996-97 are found in the top panel of Appendix C.1 for Puget Sound and of C.2 for the coasta estuaries. Deep euphotic zones indicate the absence of particles. Shallower euphotic zones reflect suspended particulates, but this can be caused either from sedimentary load or high phytoplankton concentrations. Shown in the second panel of Appendix C are plots of chlorophyll *a* concentrations (chl *a*, µg/L) versus month. Comparisons of the euphotic zone depths with the chl *a* data and salinity profiles (Appendix B) are necessar to aid in the interpretation of shallow euphotic zones. Regardless of their cause, shallow euphotic zones restrict the distribution of phytoplankton production, since adequate light for photosynthesis is available only in the euphotic zone.

Euphotic zone depths were generally very shallow in both Grays Harbor and Willapa Bay. Many of these coastal estuary stations are located at river mouths or in shallow areas heavily influenced b riverine inputs with high particle loads and resuspension of sediments due to tidal and wind-driven turbulence.

Some of the Puget Sound stations (e.g., SKG003) show decreased 1% I_o depths during late fall through early spring. These shallow euphotic zone depths are likely caused by large quantities of suspended sediment associated with increased river runoff. The presence of low salinity in the surface waters can be used to confirm this explanation. Many Puget Sound stations (e.g., BUD005, PTH005) exhibit shallow euphotic zone depths during late spring to early fall. These shallow euphotic zones are likely caused by algal blooms, which are often observed during this time. The presence of high chl *a* concentrations can be used to confirm this explanation. Many Puget Sound stations exhibit increased chl *a* concentrations corresponding to periods of shallow euphotic zone depths (Appendix C).

Light Extinction Coefficient versus Surface Chlorophyll *a* Concentration

To identify the source of light extinction for a particular station, regressions of k versus surface (0.5 m) chl *a* concentration were made. The regression results are shown in the bottom panels of Appendix C. If light extinction was only due to phytoplankton and not suspended sedimentary particles, then the regression slope would be positive and the fit would be tight (r^2 approaching 1). An outlier above the regression line (a higher value of k than the regression) would indicate non-chlorophyll containing particles that extinguish light. Lack of a positive slope implies surface chl *a* concentration is not a determinant of the light extinction coefficient

A shortcoming of this approach is that the surface chl *a* concentration was used instead of the integrated value for the whole water-column. This can be a problem since chl *a* may not be homogeneously distributed. For instance, if surface chl *a* concentrations are low (e.g., due to nutrient limitation in the surface layer) yet a substantial concentration exists subsurface, then the wrong inference could be made about the cause of light extinction based on the regressions of k vs. surface chl *a*. Continuous profiles of chl *a* are not presently measured, therefore integrated values are not available. Chlorophyll *a* concentrations at 10 m can be checked for indication of a subsurface population; however without better vertical resolution, light extinction by a subsurface population at a dept other than 10 m can not be ruled out as the cause of poor fit.

In spite of this crude treatment, some patterns are found that are informative.
A positive slope with a good fit indicates that phytoplankton biomass was a strong determinant of the light extinction coefficient. This was observed, for instance, at EAS002, PTH005 and HCB006. Outliers with particularly high light extinction and low surface chl *a* were seen most frequently in the high runoff months of September through April at stations where riverine input occurs, e.g., GRG002, BLL009 (Appendix C).

Generally flat slopes can be observed for three main reasons. First, as mentioned, surface chl *a* may not represent the total phytoplankton population. Second, chl *a* concentrations may be consistently low throughout the year, e.g., ADM002 and FRI001 (1997). Third, non-chlorophyll containing particulates (sediments) are determining the light extinction, particularly when chl *a* is low, thus resulting in a consistently high value of k, e.g., NSQ002.

In the coastal estuaries at stations where chl *a* data were collected (GYS008, GYS016, WPA003-WPA008) the slopes are flat or negative and k is consistently high, demonstrating the profound influence of river water sedimentary load in these estuaries.

Nutrients

Dissolved inorganic nutrients, primarily forms of nitrogen and phosphorus, are an important component of marine ecosystems since nutrients are required for the growth o phytoplankton, the first trophic level of the marine environment. In seawater, severa forms of dissolved nutrients exist. Common dissolved inorganic forms of nitrogen in seawater include ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-). Dissolved organic forms of nitrogen (e.g., amino acids, urea), not measured here, also exist in seawater and the role of these forms in phytoplankton nutrition is gaining attention (Antia *et al.*, 1991; Paul, 1983). Phosphorus also is found in seawater in both organic and inorganic forms. The primary phosphorus form in seawater is orthophosphate (oPO_4^{-3}), which is the form that is most easily taken up by phytoplankton.

"Ammonium-N" is used here to refer to all ammonia-based nitrogen. The pH range of seawater drives the hydrolyzation reaction of ammonia so that less than 2% of the ammonia-based nitrogen i un-ionized ammonia NH_3, (Grasshoff *et al.*, 1983) and 98% is ammonium, NH_4^+. Since dissolved ammonia, but not ammonium, is toxic to fish and other organisms, this distinction is important. The amount o un-ionized ammonia can be calculated from the ammonium concentration and the pH, salinity, and temperature of a water sample.
The summed concentration of nitrate and nitrite is reported here. Chemical analysis o nitrate requires a step to separate nitrate-N from nitrite-N. Since nitrite-N concentrations are usually quite low, this step is often eliminated and both nutrients are recorded together as "nitrate+nitrite-N", with the assumption that this approximates the nitrate-N concentration.

High concentrations of nitrite-N can be an indicator of eutrophication. If ammonium is abundant, nitrite-N, which is an intermediary product of bacterial nitrification, will be a detectable levels. To adequately assess nitrite-N concentrations, a detection level of 0.005 mg/L should be achieved (PSWQA, 1988); however, MEL has a reporting limit of 0.01 mg/L. Historically, a very large percentage of the marine samples Ecology analyzed for nitrite-N showed below reporting limit (BRL, <0.01 mg/L) concentrations (Janzen and Eisner, 1993a; b). Thus, in 1992 Ecology discontinued nitrite-N analysis for all but a few urban bay stations until lower reporting limits were available. For the period WY 1992-1995, 93-100% of the samples from these urban bays had BRL nitrite-N. The few times nitrite-N was detected, the concentrations were only slightly above 0.01 mg/L. Analysis of nitrite-N was discontinued post-WY 1995 for cost-savings.

Ammonium-N, nitrate+nitrite-N and orthophosphate-P concentration data for WY 1996-97 are tabulated in Appendix A. Because nutrient samples are relatively expensive, sampling was not comprehensive (Table 1). Plots of the 0.5-m and 10-nitrate+nitrite-N concentration (mg/L) versus WY 1996 and WY 1997 month are in the third panel of Appendix C.

Low Nutrient Concentrations

Dissolved inorganic nitrogen, as opposed to phosphorus, is generally considered to be the limiting nutrient in marine systems (e.g., Valiela, 1984). The opposite is generally true for freshwater systems. While low ambient nitrogen concentrations may be associated with limited marine phytoplankton production, this is not exclusively true.
First, nutrients may not be the growth-limiting factor. Light, which is often in short supply in local waters due to high latitude and suspended particulates, may limit phytoplankton growth. Also, losses due to mixing or grazing may reduce phytoplankton biomass such that the population production is low even though growth is high. Thus, light limitation and/or biomass losses may be responsible for low primary production. Second, nutrient limitation cannot be assumed even when nutrient concentrations are below reporting limits. A nutrient concentration may be low or undetectable, yet its uptake rate b phytoplankton may be large but equivalent to its resupply rate. In such a case, significan growth can occur yet, because uptake and supply rates are balanced, no accumulation o nutrients occurs. Third, it is not possible to document nutrient “depletion” from nutrient concentration data because some phytoplankton have such high affinities for dissolved nutrients that uptake occurs at analytically undetectable concentrations (Hecky and Kilham, 1988). Bioassay experiments designed to determine phytoplankton production with and without added nutrients are necessary to determine whether nutrient limitation of phytoplankton growth is occurring at a given station. Fourth, compounding this complexity, some species of photosynthetic dinoflagellates found in Puget Sound can undergo diel vertical migrations across the nitricline, gaining nutrients at night and photosynthesizing in the day, thus producing high biomass during times of undetectable surface nutrients.

However, because low nutrient concentrations can be related to limited phytoplankton production, a measure of the “potential” for this nutrient-limited production is useful. Threshold concentrations for nutrient limitation of phytoplankton growth vary with species, light and temperature conditions (Parsons *et al*., 1984). Although the range for different species is quite wide, a common guideline for where nitrate concentrations *may* be limiting to the phytoplankton population is 0.014 mg/L (1.0 µmol/L) (see Goldman and Glibert, 1983), which is at the MEL reporting limit (0.01 mg/L). Using the range o minimum nitrogen to phosphorus (N:P) molar ratios necessary for algal growth in coastal waters, (between 5:1 and 15:1; Ryther and Dunstan, 1971; McCarthy, 1980), the similar cut-off concentration for orthophosphate can be calculated to be from 0.0028 to 0.0009 mg/L. These concentrations fall well below the MEL reporting limit of 0.01 mg/L for orthophosphate-P.

The threshold concentration used here (0.01 mg/L) is lower than that used by Ecology in reports prior to WY 1993. In those reports (Janzen, 1992a; Janzen and Eisner, 1993a; b), nitrate+nitrite-N "depletion" was defined as concentrations below 0.04 mg/L (2.86 µmol/L), based on a model derived in a study conducted by URS (1986) in Budd Inlet. However, several studies have shown significant uptake for coastal phytoplankton species at this concentration (Kokkinakis and Wheeler, 1987; Raymont, 1980; Parsons and Harrison, 1983).

A discussion of nutrient limitation in Puget Sound is found in PSEP (1991b), which concludes that the few nutrient-addition bioassay studies conducted in this region have failed to show nutrient limitation in the main basins and channels of Puget Sound. This result would be expected in these areas which are well-mixed and thus typically have adequate nutrients. However, some areas of Puget Sound have persistent stratification, restricted circulation and can show nutrient levels below reporting limit for extended periods (e.g., narrow, constricted estuaries). Nutrient limitation has not been investigated in most of these areas. Nutrient-addition experiments conducted as part of focused monitoring by Ecology showed a substantial increase in phytoplankton production with added nutrients in Hood Canal but not in the main basin o Puget Sound (Newton *et al.*, 1994). Nutrient limitation has not been thoroughly studied in Washington State waters, but stratified waters are the most likely to respond to nutrient addition.

In conclusion, while it is inappropriate to conclude either nutrient limitation or nutrient depletion from nutrient concentration data, low nutrient concentrations for extended periods of time *may* be indicative of nutrient limitation of the growth of the phytoplankton population. Other information (e.g., results from nutrient-addition experiments) would be required for confirmation. Nutrient concentrations at or below the reporting limit of MEL (0.01 mg/L for all nutrients) are referred to as "BRL." In this report, the occurrence o consecutive months of BRL surface DIN (dissolved inorganic nitrogen; equals nitrate+nitrite-N plus ammonium) is used as an indicator of potential nutrient-limitation.

Nitrate+Nitrite-N (NO_3^-+NO_2^--N)

Detectable nitrate+nitrite-N concentrations were generally observed at all stations from October through March (Appendix C). Processes that promote detectable nitrate+nitrite-N concentrations in surface waters are increased river runoff, low phytoplankton concentrations, and reduced water column stratification, which allows for greater mixing between nutrient-rich deep waters and surface waters. Removal o nitrate+nitrite-N fro surface waters is through uptake by phytoplankton.

Months with low nitrate+nitrite-N concentrations (late spring through early fall) often correspond with increased chl *a* concentrations (Appendix C), indicating nutrient uptake by phytoplankton. Other factors that may contribute to lower nitrate+nitrite-N levels during this time period are decreased river runoff and increased stratification. An inverse correlation of nitrate with chl *a* is typical of marine systems (e.g., PSEP, 1991b). correlation analysis of these two parameters would require integrated values over the euphotic zone; the two to three data points (0.5, 10 and 30 m) in this database are no adequate for statistical purposes to infer nutrient-chlorophyll relations.

Of the 854 samples collected for nitrate+nitrite-N analysis in WY 1996, 13% had BRL concentrations (<0.01 mg/L). For Puget Sound samples, 12% were BRL and for the coastal estuaries, 18% were BRL. In WY 1997, 2% of the 795 samples were BRL, with <0.5% for Puget Sound and 6% for the coastal estuaries. A strong difference is evident in the WY1997 data with far fewer stations showing BRL nitrate+nitrite-N concentrations. This could be linked with strong inputs for precipitation and runoff or from differences in oceanic forcing, which is the dominant input of nitrate-N.

The locations and months of occurrence for these BRL samples (Table 5) show that nitrate+nitrite-N concentrations were BRL most commonly during May through August and at the 0.5 m depth. As has been found previously, BRL nitrate+nitrite-N concentrations throughout the water column to the seabed (0.5 m through the station's deepest depth) were found in Southern Puget Sound (OAK004, BUD005) and in Willapa Bay. Locations of stations with BRL DIN for $\geq$5 and $\geq$3 consecutive months are shown in Figure 9.
Stations with >3 consecutive months of BRL surface nitrate+nitrite-N in Puget Sound are BUD005, CSE001, EAS001, ELD001, HCB004, HCB006, HLM001, OAK004, SAR003, and TOT001. All except CSE001, ELD001, and TOT001 are stations exhibiting low DO concentrations during the same years. Willapa Bay but not
Grays Harbor shows several months of BRL surface nitrate+nitrite-N. The reason for the difference in these two similar estuaries is not clear, but may have to do with the degree of river input to these systems. Both Grays and Willapa have shown this pattern in previous wateryears (e.g., WY 1994-95). This is the first year that Willapa Bay has shown any low DO concentrations since DO profile measurements commenced
(WY 1990). Low DO was observed at WPA001 for one month in WY 1997 only.

Samples with BRL nitrate+nitrite-N concentrations but detectable levels o ammonium-N are typically rare in marine systems. Such a pattern would be suggestive o eutrophication, since ammonium is the usual nitrogen form added fro anthropogenic sources. Only about 0.01% of the WY 1996-97 samples (12/1650) showed this pattern ("N" in Table 5). The locations for these samples were in Budd Inlet (5 samples), Willapa Bay (2 samples), various South Puget Sound locations (BML001, TOT001, OAK004, ELD001) and Saratoga Passage. More typically (7% of samples) both nitrogenous nutrients were BRL ("NA" in Table 5), and in some cases (2% of samples) all three nutrients ("NAP" in Table 5) were BRL.

To indicate nutrient sensitive areas, we have adopted the occurrence of >3 consecutive months of BRL surface dissolved inogranic nitrogen (DIN). DIN concentrations that are BRL for consecutive months are an indicator that phytoplankton populations may be nutrient limited. Nutrient-limited populations are those that would be most sensitive to anthropogenic nutrient inputs. That is, adding nutrients to these locations would result in increased organic production that could subsequently lead to lower DO concentrations. Thus it is useful to know where these locations are and how these nutrient patterns may change with time.

The occurrence of consecutive months of BRL DIN can be from natural causes, when large spring blooms exhaust nutrients and stratified water-columns prevent re-injection o nutrients from deep waters throughout the summer. Alternatively the same pattern can result when eutrophication produces a very large phytoplankton bloom, part of which survives and keeps DIN concentrations low (BRL) with time. One certainty is that in order to have brought nutrients to BRL levels, phytoplankton production must have been high. In summary, although it is not possible to definitively interpret the

Table 5. Stations with below reporting limit (< 0.01 mg/L) nitrate+nitrite-N concentrations during WY 1996-97. Occurences indicated by "N" at a particular depth and month. Also shown are the accompanying BRL observations for ammonium ("A") and ortho-phosphate ("P").

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Z
North Puget Sound:													
ADM001 - '96	A	A	A		A				A	A		A	0.5 m
			A		A					A		A	10 m
	A		A		A	A				A		A	30 m
ADM001 - '97	A	A		A	A	A	A		A	A	A		0.5 m
	A	A		A	A	A	A		A				10 m
	A	A		A	A	A	A		A				30 m
ADM002 - '96			A	A	A			A				A	0.5 m
	A		A	A	A					A		A	10 m
			A			A				A		A	30 m
ADM002 - '97		A		A	A	A	A	A			A		0.5 m
		A		A	A	A	A				A		10 m
		A		A	A	A	A				A		30 m
BLL009 - '96						A	AP	NAP	A	NA		A	0.5 m
		A	A		A	A		A				A	10 m
BLL009 - '97	A				A		A		A	A	A		0.5 m
					A		A				A		10 m
BLL011 - '97	A						A	A	A	A	NA	A	0.5 m
(only)		A	A				A						10 m
DIS001 - '97	A				A	A	A			A	A	A	0.5 m
(only)	A		A		A	A	A					A	10 m
			A		A	A	A						30 m
DRA001 - '97							A			A		A	0.5 m
(only)							A				A		10 m
EAS001 - '96			A			A	NAP	NAP	NAP	NA	A	A	0.5 m
(only)			A			A		NA					10 m
			A			A						A	30 m

Table 5. Continued

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Z
FID001 - '97							A				A	A	0.5 m
(only)					A	A	A				A	A	10 m
FRI001 - '97	A		A			A	A				A		0.5 m
(only)	A		A	A		A	A			A	A		10 m
	A				A	A	A			A			30 m
FSH001 - '97							A		A		A	A	0.5 m
(only)					A		A	A			A	A	10 m
GRG002 - '96			A		A	A		A	A	AP	A	A	0.5 m
			A		A	A		A	A	A		A	10 m
			A			A			A	A		A	30 m
GRG002 - '97	A				A	A			A	A	A	A	0.5 m
	A				A	A			A	A	A	A	10 m
	A					A				A	A	A	30 m
PSS019 - '96		A			P	AP	P	P	NAP	NAP			0.5 m
	A	A	A		A	A	A		A				10 m
	A	A	A		A	A	A		A		A		30 m
PSS019 - '97	A	A			A	A		A	A	A	A	A	0.5 m
	A	A		A	A	A		A			A		10 m
	A	A		A	A	A				A	A	A	30 m
PTH005 - '96		A	A		A	A		A	A	NA	A	A	0.5 m
			A		A	A						A	10 m
PTH005 - '97	A	A		A	A	A	A		A	A	A		0.5 m
	A	A		A	A	A	A		A	A	A		10 m
SAR003 - '96		A			A	NAP	NAP	NAP	NAP	NAP	N	NA	0.5 m
	A	A	A		A	A	A	A	A			A	10 m
	A	A	A		A	A	A		A	A		A	30 m
SAR003 - '97	A	A			A	A	A	A	NA	A	A		0.5 m
	A	A		A	A	A	A			A	A		10 m
	A	A		A	A	A	A			A	A	A	30 m

Table 5. Continued

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Z
Hood Canal:													
HCB004 - '96	NA	A	AP		A	A		NAP	NAP	NAP	NA	NA	0.5 m
	A		A	A	A	A		NA		A	A	A	10 m
	A		A	A	A	A				A	A	A	30 m
HCB004 - '97	A				A		A	A		A	NA		0.5 m
	A				A		A				A		10 m
	A		A		A		A				A		30 m
HCB006 - '96	A	A	A	A	A	A		NAP	NA	NAP	NA	A	0.5 m
	A		A	A	A	A		A		A	A	A	10 m
	A		A	A	A	A		A		A		A	30 m
HCB006 - '97	A						A	A		A	A		0.5 m
	A						A			A			10 m
	A						A						30 m
Central Puget Sound:													
CMB003 - '96							A	AP	A				0.5 m
		A	A				A	A				A	10 m
	A	A	A	A		A	A	A				A	30 m
CMB003 - '97					A								0.5 m
	A			A	A	A	A						10 m
	A			A	A	A	A				A		30 m
ELB015 - '96		A		A	A					A		A	0.5 m
	A		A	A	A	A				A		A	10 m
	A		A	A		A				A		A	30 m
ELB015 - '97	A				A	A	A		A				0.5 m
	A				A	A	A		A		A	A	10 m
	A				A	A	A		A		A	A	30 m
HLM001 - '96		NA			A	NAP	NAP	NAP	NAP	NAP			0.5 m
		A	A		A	A	A	AP	A	A			10 m
		A	A		A	A		A		A			30 m

Table 5. Continued.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Z

PSB003 - '96	A	A	A	A	A					A		A	0.5 m
	A		A	A	A					A		A	10 m
	A		A	A	A							A	30 m
PSB003 - '97	A			A	A	A	A		A	A	A	A	0.5 m
	A			A	A	A	A		A		A	A	10 m
	A			A	A	A			A		A		30 m
SIN001 - '96						A			NA	NA		A	0.5 m
												A	10 m
SIN001 - '97					A				A				0.5 m
					A				A				10 m
South Puget Sound:													
BML001 - '96			A		A		A	NA	N		NA		0.5 m
(only)			A	A		A	A	NA	NA				10 m
BUD002 - '96											N		0.5 m
(only)									N		N		10 m
BUD005 - '96					A			NA	NA	N	NA		0.5 m
			A		A			NA		N	NA		10 m
BUD005 - '97					A		A			A			0.5 m
				A	A								10 m
CRR001 - '96			A	A	A	A	NAP		NA		NA	A	0.5 m
(only)			A	A	A	A			A			A	10 m
		A	A	A	A	A						A	30 m
CSE001 - '96			A		A		NAP	NAP	NA	NA		A	0.5 m
(only)			A	A	A				NA			A	10 m
			A	A	A			A					30 m
DNA001 - '96			A	A	A				A	NA		A	0.5 m
			A	A	A				A			A	10 m
			A	A	A							A	30 m
DNA001 - '97					A	A	A						0.5 m
					A	A	A						10 m
					A	A							30 m

Table 5. Continued.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Z

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Z
ELD001 - '96 *(only)*							A	NAP A	NA NA	NA	NA N	A A	0.5 m 10 m
GOR001 - '97 *(only)*	A			A A A	A A A	A A	A A A						0.5 m 10 m 30 m
HND001 - '96 *(only)*							A	NAP	NA A				0.5 m 10 m
NSQ002 - '97 *(only)*				A A A	A A A	 A A	A A A		A				0.5 m 10 m 30 m
OAK004 - '96								NA NAP	NA NA	N NA	NA NA	A A	0.5 m 10 m
OAK004 - '97					A A		A A	A					0.5 m 10 m
TOT001 - '96 *(only)*						A A	A	NAP AP	NA NA	NA N			0.5 m 10 m
Coastal Estuaries:													
GYS004 - '96	P			P P	P P	P P	P P	P	A	AP P	 P		0.5 m 10 m
GYS004 - '97	AP P		P P	AP	AP AP	P P	P P	AP AP			 A	P	0.5 m 10 m
GYS008 - '96				P P	P	P P		A A		A A	P AP		0.5 m 10 m
GYS008 - '97				AP AP	AP AP	P P		A A	A A	A A			0.5 m 10 m
GYS016 - '96					 P	AP P	NAP NAP	A A					0.5 m 10 m
GYS016 - '97				AP A	AP AP	A A			A A	A A	A A		0.5 m 10 m

Table 5. Continued.

WPA001 - '96	P		P	P	P	P	AP	P		NAP			0.5 m
			P	P	P	P		P		NA			10 m
WPA001 - '97			P	AP	AP	P			A				0.5 m
	P			AP	AP	P			A				10 m
WPA003 - '96			P	P	P	P	AP	AP	NA	NA	NA		0.5 m
				P	P	P		P	NA	NA	NA		10 m
WPA003 - '97				AP	AP				A	A	A		0.5 m
				AP	AP			N	A		A		10 m
WPA004 - '96						P		A	A		A	A	0.5 m
				P	AP	AP	P	A	A		A		10 m
WPA004 - '97				AP	AP	A	A		A		A		0.5 m
				AP	AP	A	N		A		A		10 m
WPA006 - '96					P	AP	AP	NA	NA	NA	NA	A	0.5 m
				P	AP	AP	P	NA	A	NA	NA	A	10 m
WPA006 - '97				A	AP	A	NA		NA	A	A		0.5 m
				AP	AP	A	NA		NA	A	A		10 m
WPA007 - '96						AP		NA	NA	NA	NA		0.5 m
					AP	AP	AP	NA	NA	NA	NA		10 m
WPA007 - '97				A	AP	A	A		NA	A	A		0.5 m
				A	AP	A	NA		NA	A			10 m
WPA008 - '96									NA	NA	NA		0.5 m
									NA	NA	NA		10 m
WPA008 - '97				AP	AP		A		NA	A			0.5 m
				AP	AP		A		NA	A			10 m

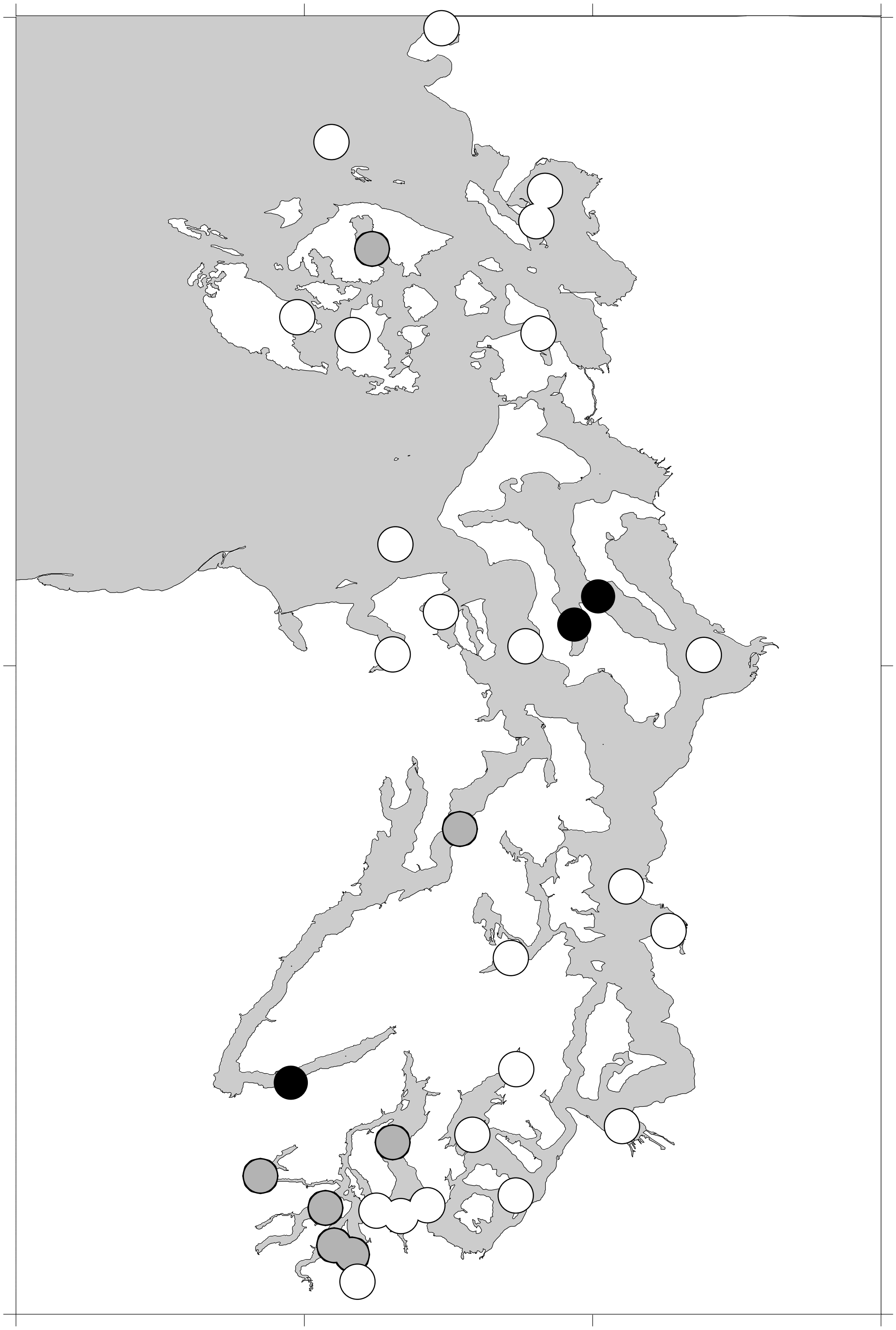

Figure 9. Puget Sound stations with BRL DIN for >= 5 (black), >= 3 (gray), and 0-3 (clear) consecutive months during WY96-97.

cause of consecutive months of BRL DIN, this occurrence indicates areas that would be sensitive to eutrophication.

Ammonium-N (NH_4^+-N)

Ammonium-N concentrations in Puget Sound and the coastal estuaries were generall lower than nitrate+nitrite-N concentrations (Appendix A). BRL concentrations o ammonium-N were relatively frequent 51% and 53%. These observations have been consistent in the Ecology data and are typical of marine waters. Ammonium-N is the regenerated form of N and is excreted by zooplankton (Dugdale and Goering, 1967; Valiela, 1984). Most phytoplankton assimilate ammonium-N much more rapidly than other sources of nitrogen since it is the reduced form (Parsons *et al*., 1984), and so it is rarely observed in substantial quantities in seawater. Its natural sources include the degradation of organic nitrogen and denitrification. Sometimes ammonium-N can be found in high concentrations in upwelled deep water but it does not usually persist due to rapid uptake by phytoplankton. Because ammonium-N is a by-product of degradation, it is found in high amounts in sewage or other anthropogenic inputs.

Stations with high ammonium-N concentrations could indicate the presence of an anthropogenic ammonia source (e.g., sewage input). To facilitate evaluation, ammonium-N concentrations of 0.07 mg/L (5 µmol/L) and 0.14 mg/L (10 µmol/L) were arbitrarily selected (Newton, 1995c), based relative to the historical maximum Admiralty Inlet concentration of 0.03 mg/L (2 µmol/L). Thus, ammonium-N concentrations >0.07 and >0.14 mg/L are used here as indicators of high and very high ammonium, respectively.

Stations with high ammonium-N concentrations (Figure 10) and the number of months (n) during WY 1996-97 were: BUD002 (5), BUD005 (3), OAK004 (3), WPA001 (3), BML001 (2), BLL011 (2), EAS001 (2), DIS001 (2), and 1 each in BLL009, CMB003, CRR001, CSE001, DRA001, ELD001, HCB004, and TOT001. Of these sixteen stations, nine are located in South Puget Sound. Only BUD002 (2) and EAS001 (1) had very high concentrations. In addition to these observations, two stations in Admiralty Inlet had ver high ammonium-N concentrations (ADM001 in Oct ’95 and ADM002 in Jul ’96). Such high concentrations have not previously been recorded at these stations since monitoring began.

High ammonium often has been observed in Budd Inlet. Data from the last two wateryears show ammonium-N concentrations remain high, particularly in the inner inle (BUD002). Suspected impacts from eutrophication led the Lacey-Olympia-Thurston-Tumwater wastewater treatment plant in early 1994 to implement N-removal for their effluent that is discharged into Budd Inlet during summer. Substantial differences in the water column nutrient concentrations were observed before versus after the change in N input by LOTT throughout Budd Inlet during Ecology’s focused

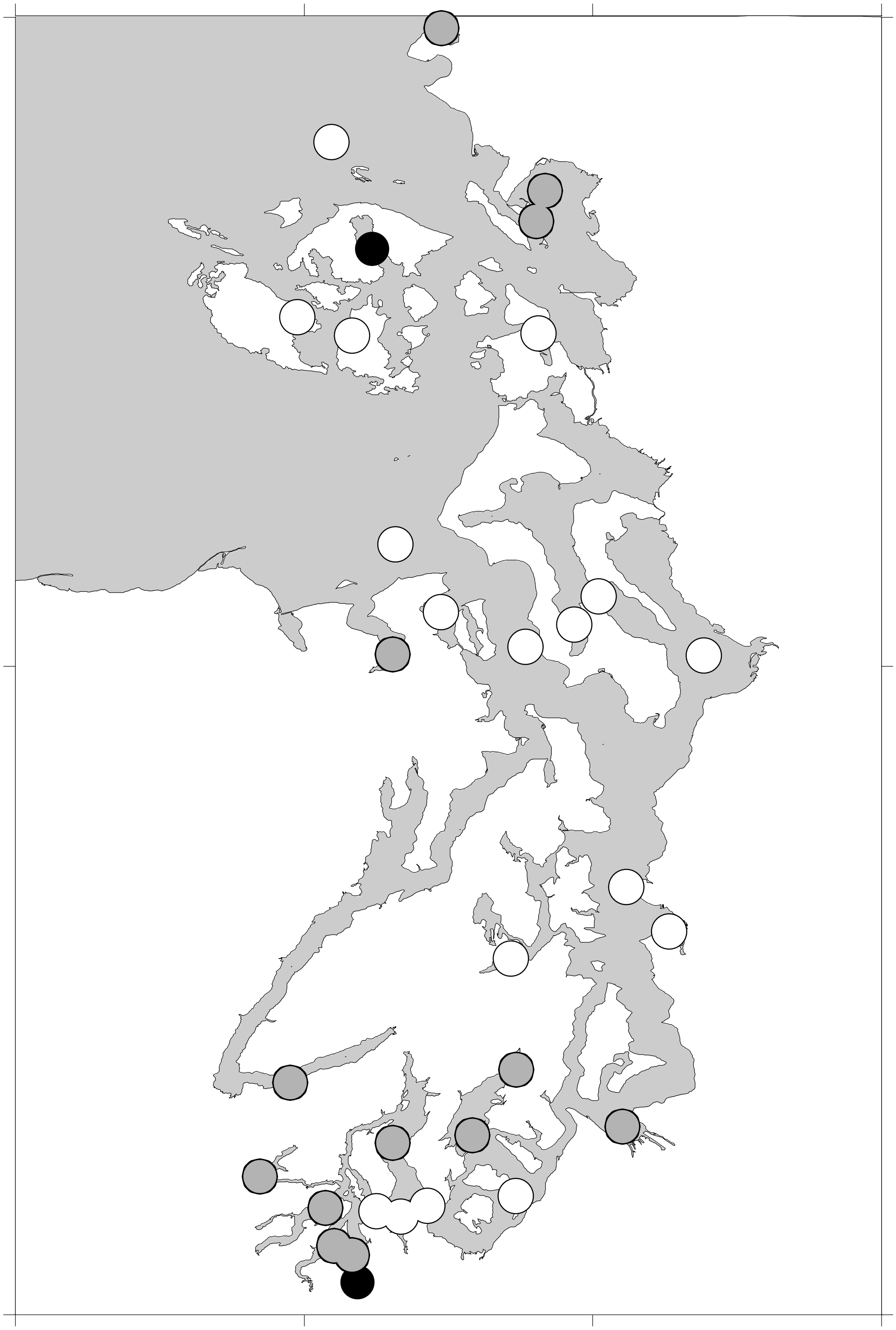

Figure 10. Puget Sound stations with >0.14 mg/L (black), >0.07 mg/L (gray), and <= 0.07 mg/L (clear) ammonium-N concentrations during WY96-97.

monitoring which spanned this change (Eisner and Newton, 1997). The reduction was visible from the long-term monitoring data as well. During WY 1993, station BUD005 in middle Budd Inlet exhibited the most consistently high concentrations of ammonium-N of all stations monitored that year. Concentrations >0.07 mg/L were recorded five out of twelve months, with a maximum of 0.148 mg/L in May '93 (Newton *et al.*, 1994). In contrast, water-column concentrations of ammonium-N at BUD005 for WYs 1994-95 were much lower than those from WY 1993, with only one occurrence per year of high ammonium-N (0.085 mg/L in May '94; 0.078 mg/L in May '95). The one high ammonium-N concentration observed at BUD005 during WY 1996 (0.078 mg/L in Oct '95) is consistent with this pattern, although two were observed in WY 1997 (0.086 mg/L in May '97 and 0.113 mg/L in Aug '97). Ammonium-N concentrations were much higher and more frequent at BUD002 in the inner inle during WY 1996 when this station was monitored. Very high ammonium-N concentrations were recorded in Oct '95 (0.157 mg/L) and high concentrations were observed four other times (Nov '95, Apr '96, May '96, and Jul '96). Inputs from other nutrient sources to Budd Inlet (e.g., Moxlie Creek, Priest Point) should be evaluated.

Station EAS001 in East Sound, Orcas Island, once again exhibited a very high ammonium-N concentration as it did in WY 1995 but not 1994 or 1993. A concentration of 0.211 (15 μmol/L) was observed in May '96, with a concentration of 0.074 (5 μmol/L) observed in Aug '96. The Orcas Watershed Education Alliance reported evidence of feca coliform bacteria contamination in 1995 in East Sound via Eastsound Village's stor water system (OWEA, 1995) that was apparently corrected. In light of the significantly low DO concentrations (as low as 2 mg/L in WY 1995) observed at EAS001, both natural and anthropogenic sources of ammonium-N to East Sound should be investigated. Although DO was not as low at this station during WY 1996, the system should be evaluated so that any future human impacts can be effectively planned in this sensitive environment.

Orthophosphate-P (oPO_4^{-3}-P)

Orthophosphate-P concentrations followed the same general pattern as nitrate-nitrit -N, with lower concentrations at 0.5 m than at either 10 or 30 m, and lowest concentrations from late spring to early fall (Appendix A). Orthophosphate-P was BRL less frequently than the nitrogenous nutrients, in keeping with its generally non-limiting role in marine systems. BRL orthophosphate-P concentrations were observed in 12% of the nutrient samples during WY 1996 and in 6% during WY 1997.

A notable difference is evident in the nutrient dynamics of Puget Sound stations versus the coastal estuary stations. BRL orthophosphate was observed in 6% and 0% of the Puge Sound samples during WY 1996 and WY 1997, respectively, but in 37% and 25% of the coastal estuaries samples. Samples with BRL orthophosphate but detectable nitrate+nitrite-N and ammonium-N were exceedingly rare in Puget Sound (0.02%) ye were relatively common (39%) in the coastal estuaries. Nutrient limitation due to N versus P is sometimes variable in estuaries with significant freshwater input. For the 150 samples with BRL P but detectable N salinity was always less than 20 PSU, with an average salinity of 7 PSU. Although this observation cannot be used to draw conclusions regarding nutrient limitation, a difference in the nutrient dynamics (linked with the significance of freshwater input) for Puget Sound phytoplankton versus that for Grays Harbor and Willapa Bay is clearly indicated.

Fecal Coliform Bacteria

Coliform bacteria are present in human and animal fecal wastes. Most coliform bacteria are not harmful to humans; however, some strains are pathogenic, causing severe complications and/or death. Even though most fecal coliform bacteria (fcb) are not harmful themselves, their presence can serve as an indicator for pathogenic bacteria and viruses that also are in feces. Both point (e.g., combined sewer overflows, direct marine effluent discharge) and non-point (e.g., surface water runoff from dairy farms) sources o fcb enter streams and rivers, and thus fresh water input is a major source o fcb to the marine environment. Increased river discharge and runoff caused by heavy rains often corresponds with elevated bacterial counts in marine waters.

The Washington State criterion for class A and AA marine waters states that the bacteria count shall not exceed a geometric mean value of 14 organisms/100 mL, with no more than 10 percent of samples exceeding 43 orgs./100 mL (WAC 173-201, 1991). This criterion is better applied to more intensive survey data within one system, where multiple samples are collected over a smaller area within one system, instead of the once per month point sample that is taken for a typically mid-bay open-water station, as monitored by Ecology. The Washington State Department of Health monitors shellfish areas and public beaches in a more intensive approach. The King County Department of Natura Resources does likewise for beaches in King County, as do many municipalities in Washington State. A more thorough assessment o fcb contamination may be obtained from these programs. However, the fcb data obtained from Ecology's Marine Waters Monitoring stations are useful to indicate where fcb contamination is likely chronic enough that it was detected at our open-water sites.

In this report we have taken a conservative approach to assessing fcb contamination at open water monitoring stations. We have adopted two thresholds: 14 orgs ./100 mL (high count) as an indicator of where contamination may be of concern; and 50 orgs,/100 mL (very high count) to indicate where contamination may be serious. We do not imply that this analysis should be used to enforce management practices (e.g., beach closures). The utility of this approach is as a crude estimate of environmental status at the Marine Waters Monitoring stations. We have taken a conservative approach because our sampling scheme is sub-optimal for observing high fcb. Observations of high fcb counts in marine waters may be quite rare and erratic because of the very short lifetime o fcb in seawater (1-2 d; Lessard and Sieburth, 1983). Further, the episodic nature of runoff events that can transport fcb to marine waters implies that sampling these events will be improbable. The proximity of sampling date to the runoff event will have a major impact on whether high fcb counts were recorded. Thus, the open-water Marine Waters Monitoring stations are particularly under-sampled with respect to the probability of identifying fcb contamination. Establishing accurate interannual trends is even more improbable. Use of this analysis as a screening tool to identify chronic contamination may be justified. Its utility in concer with the other indicators presented in this report is discussed in the General Discussion.

During WY 1996-97, samples from 19 stations had high fcb counts during at least one month (Figure 11). Twelve of these stations are in Puget Sound (Figure 12); three are in Grays Harbor and four in Willapa Bay Very high counts were observed at 6 of the 12 Puget Sound stations, all three Grays Harbor stations and two Willapa stations.

In Puget Sound, the most notably high fcb counts were observed in Commencement Bay (CMB003, Browns Point) which had multiple occurrences of very high counts in both years. Commencement Bay has shown a strong suggestion of fcb contamination based on previous Ecology monitoring data. In WY 1995, another Commencement Bay station (CMB006, mouth of City Waterway) was the only Puget Sound station to show pervasive or chronic high counts during WY 1994-95. During WY 1994-95, CMB003 had only one very high count and 1-2 high counts as compared with the 3-5 very high counts recorded in WY 1996-97. Precipitation was much stronger i
1996-97 than in 1994-95 and likely influences this pattern. Regardless of the strength o the precipitation that may transport fcb to marine waters, these data suggest tha fcb contamination in Commencement Bay is apparent and strong.

Inner Budd Inlet (BUD002, South End Olympia Port) showed chronically high fcb counts and occasionally very high fcb counts in the year it was monitored as a rotational stati (WY 1996). Note that the core station in middle Budd Inlet (BUD005, Olympia Shoals) showed remarkably fewer instances, which illustrates the short life-time and low probability of detecting fcb in mid-bay open-water sites.

Elliot Bay (ELB015) and Puget Sound Main Basin off West Point (PSB003) continue to show very high fcb counts occasionally during winter months as these stations have frequently shown since WY 1993.

Figure 11 also shows the seasonal pattern of when fcb counts were high. For all Puge Sound stations, high counts mostly occurred October through February, with the majorit in November through January. Wintertime high fcb counts have been common in Puget Sound and are associated with high runoff, which transports fcb to

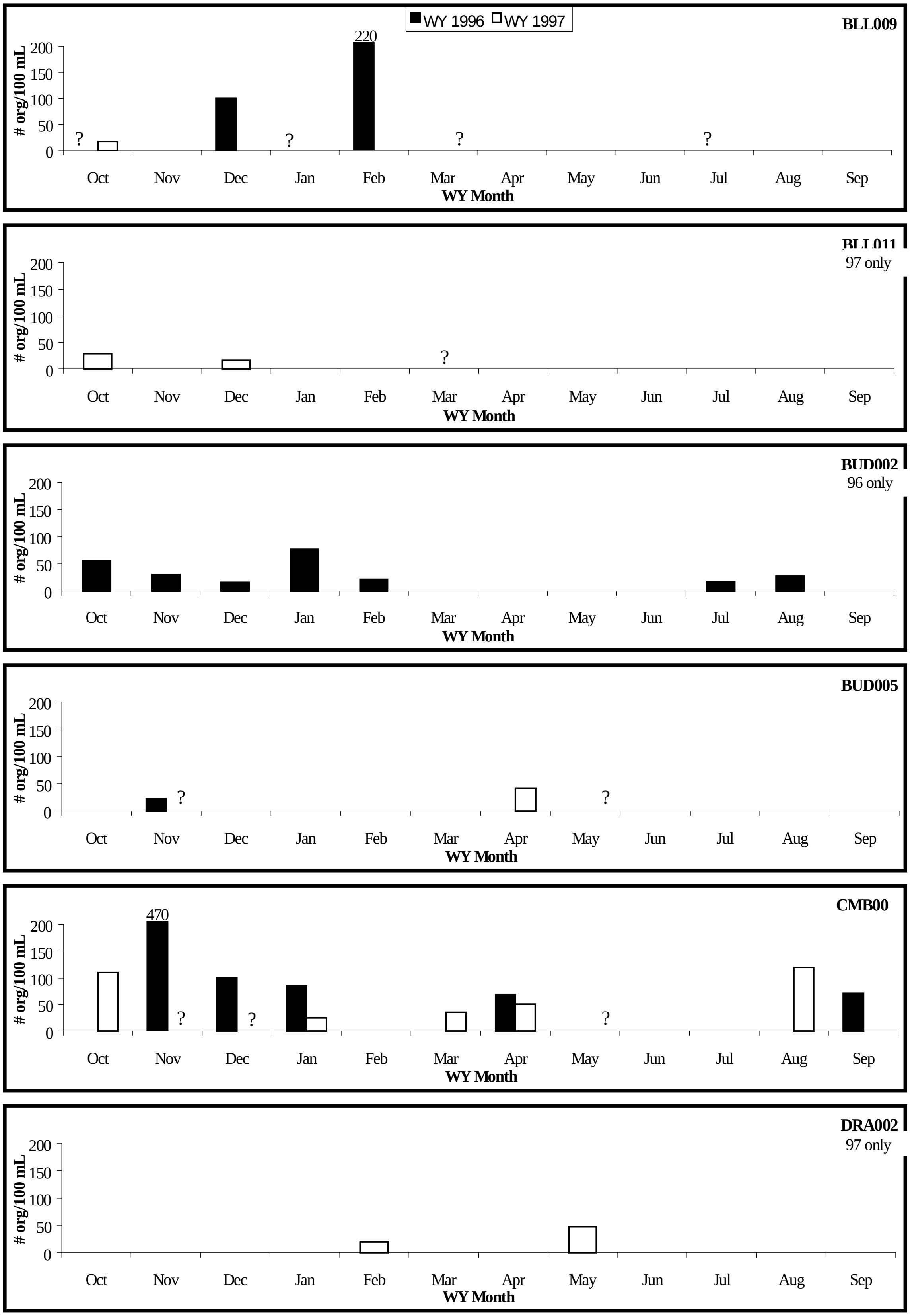

Figure 11. Fecal coliform bacteria counts versus Wateryear month for stations with high count (> 14 organisms/100mL) during WY 1999-97. The "?" indicates a sample was not obtained.

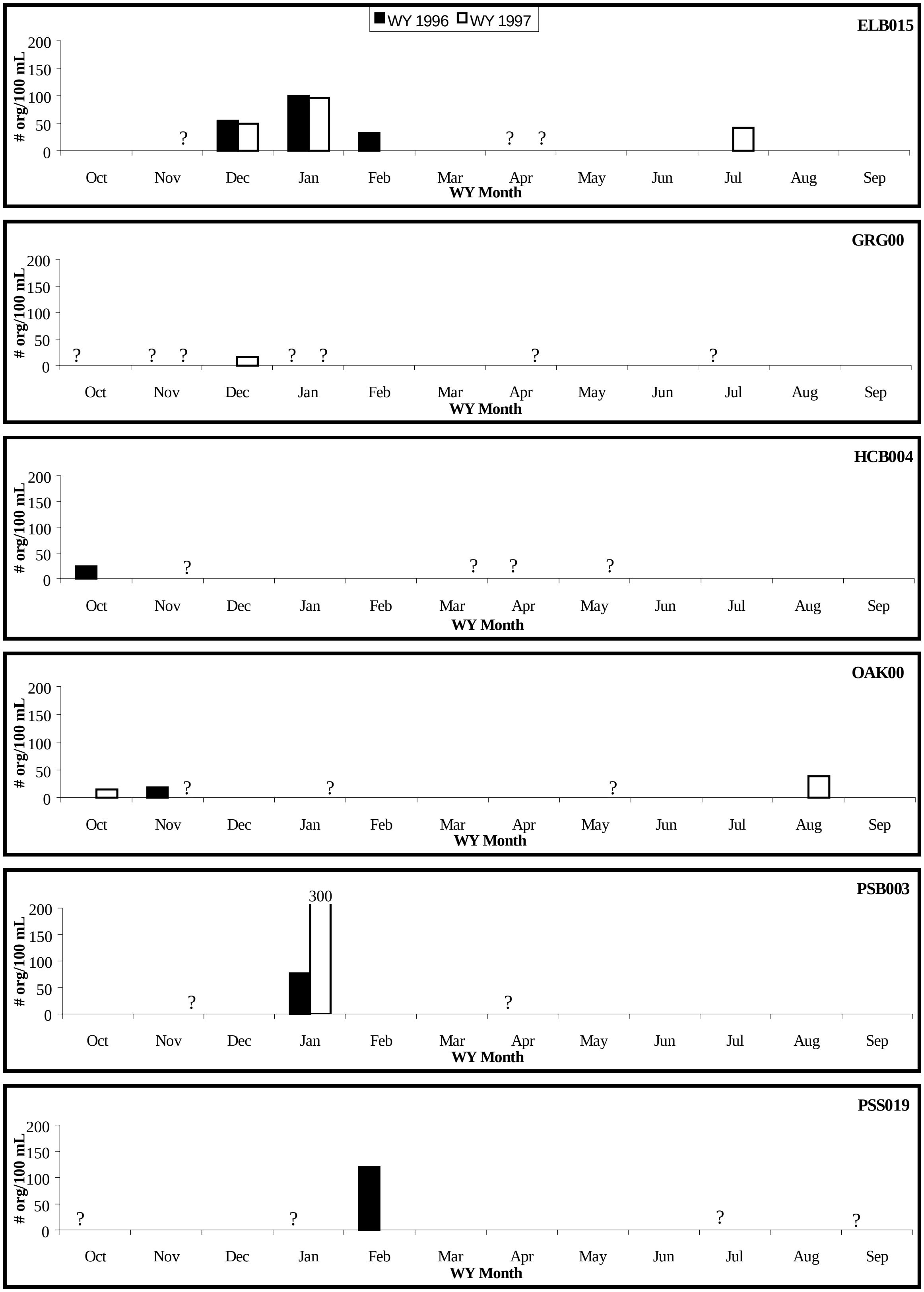

Figure 11. Continued.

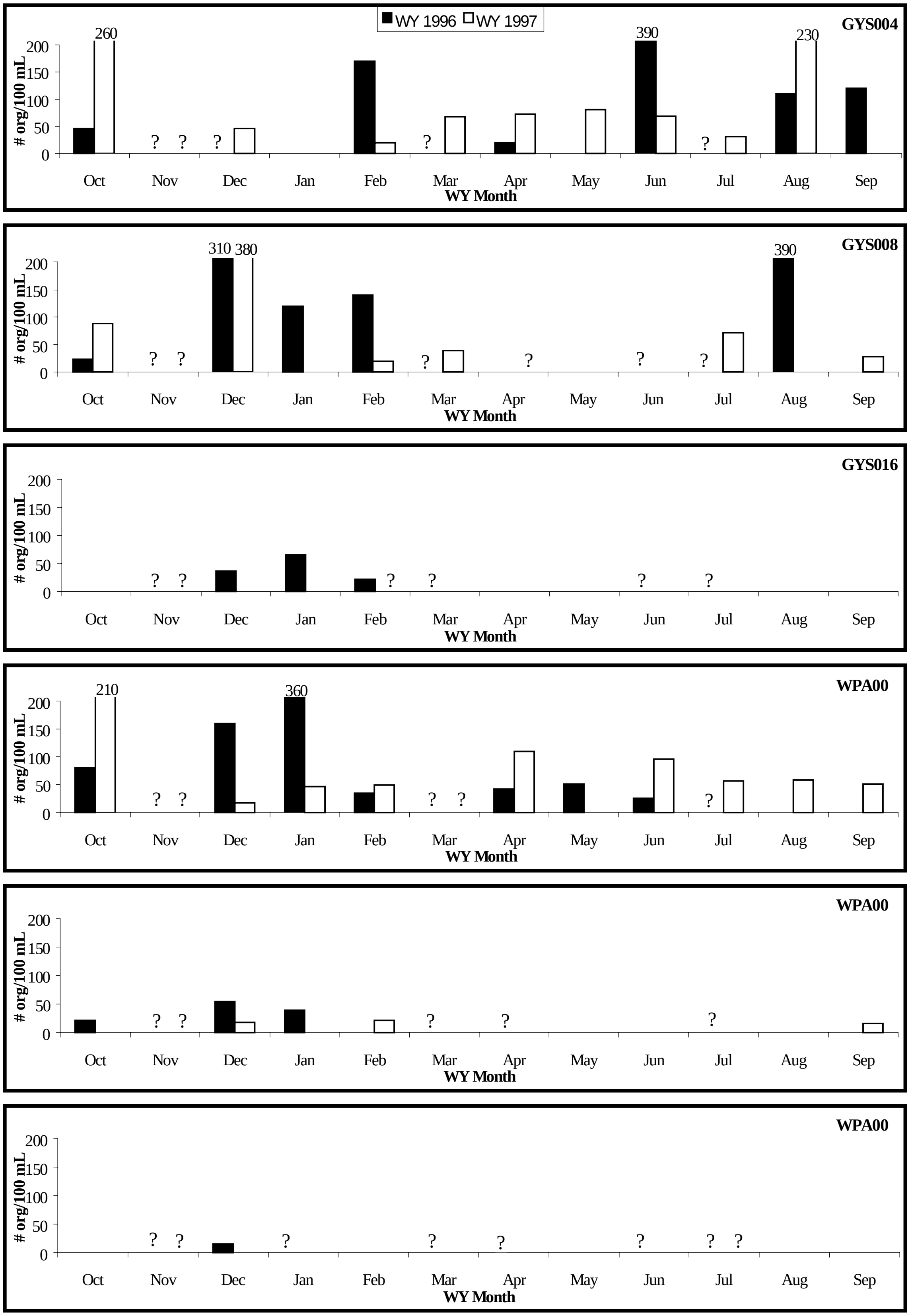

Figure 11. Continued.

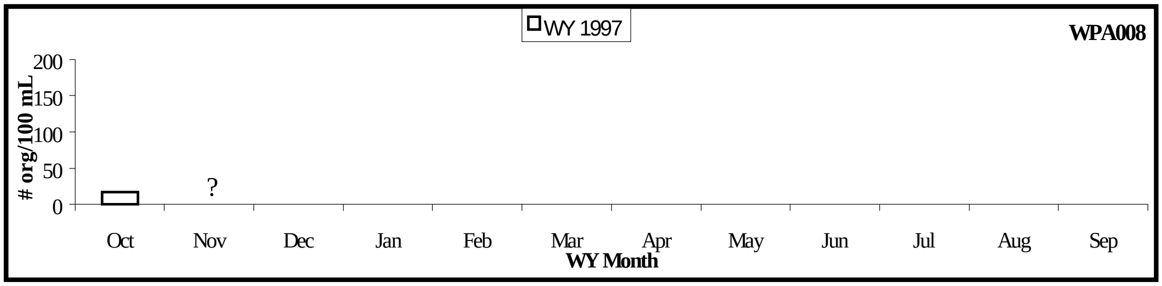

Figure 11. Continued

marine waters. Summertime high counts however, are not typically observed in Puget Sound but were observed at BUD002, CMB003, DRA002, ELB015, and OAK004 during WY 1996-97. Summertime high fcb counts were not observed at any of the stations monitored during WYs 1990 through 1995 with two exceptions. High counts observed at numerous stations during WY 1993 (PSS019, CMB003, ELB015, SIN001 in July; OAK004 in June) and may have been linked to freshwater runoff events that summer (Newton *et al.*, 1994). Very high and high counts were observed in CMB006 during March, May, June, and August of WY 1995, which does not appear to be related to precipitation but rather to localized conditions in Commencement Bay. The sporadic occurrence of high fcb counts in WY 1996 and 1997 are of interest because precipitation anomalies were not high in either summer (Figure 3). However, individual events may be driving these values.

Many of the coastal estuary stations have consistently higher and more persistent fcb counts than are found at the Puget Sound stations (Figure 11). Both Grays Harbor and Willapa Bay appear to have strong fcb contamination in portions of these estuaries. Unlike in Puget Sound, the high and very high counts are recorded year-round and the seasonal pattern is not dominated by wintertime highs. Very high counts were observed at 5 of the 7 coastal estuary stations with high counts. Chronic fcb contamination was evident in Grays Harbor (GYS004 and GYS008) and Willapa Bay (WPA001) at the stations closest to the Chehalis and Willapa rivers, respectively. Although the fcb counts in Grays Harbor were relatively high (in excess of 300), the counts are lower that the counts in excess of 1000 recorded for 3 months in summer of WY 1995. Except for this difference, fcb counts in Grays Harbor and Willapa Bay appear to be at similar to higher levels during WY 1996-97 than previous years. More coasta stations (7) recorded high counts than in previous years (3-4). The degree of influence of precipitation on this observation not known.

Most all of the stations with high fcb counts in WY 1996-97 have also shown high fcb counts in previous wateryears (Newton, 1995c). Samples from Budd Inlet (BUD005), Commencement Bay (CMB003, CMB006), Oakland Bay (OAK004), Possession Sound (PSS008/PSS019), Grays Harbor (GYS004, GYS008), and Willapa Bay (WPA001)

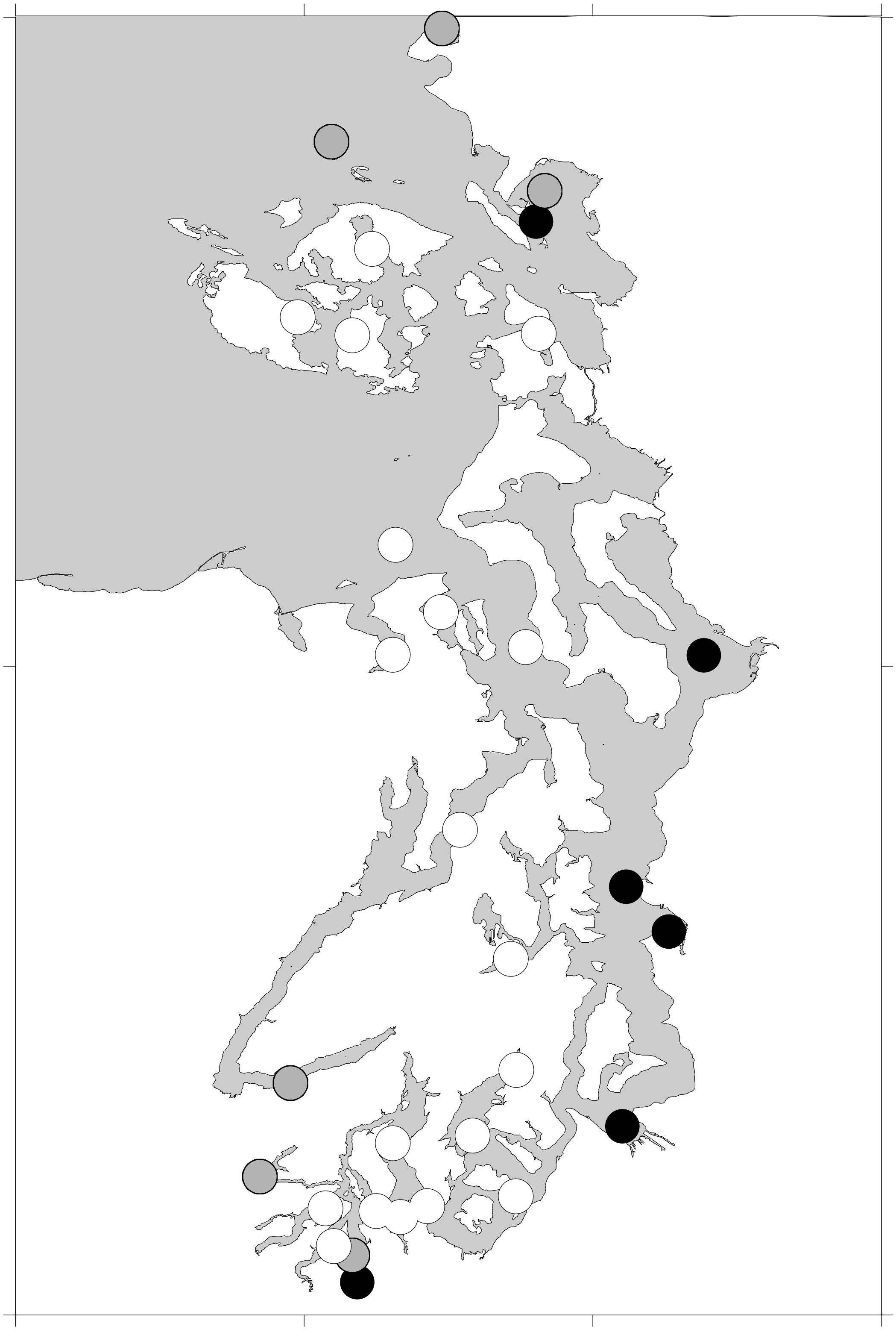

Figure 12. Puget Sound stations with fecal coliform counts >50 org/100 mL (black), >14 orgs/100 mL (gray) and <= 14 orgs/100 mL (clear) during WY96-97.

have all had counts over 14 orgs./100 mL during at least one month in each wateryear from 1990 through 1997.

Based on review of Ecology's fcb data from WYs 1990 through 1997, areas with chronically high fcb counts are Grays Harbor, Willapa Bay, and Commencement Bay. Areas with sporadic (within a year) but consistent (among years) high counts are Budd Inlet, Oakland Bay, and Possession Sound. The wintertime high counts in Elliott Bay and off West Point have been consistent only since WY 1993.

Quality Control

Quality control results for WY 1996-97 are summarized in Tables 6 through 8. In general, data quality was within target ranges. Data quality for nutrients was markedly improved over pre-1995 data (see Newton *et al.*, 1997). This improved accuracy and precision must be taken into account when assessing long-term trends in these parameters.

Precision

The precision of both replicate laboratory analyses (lab variation) and replicate field sample analyses (field + lab variation) was estimated by the relative standard deviation o these replicates (%RSD = (sample standard deviation / sample mean) * 100), as shown in Table 6. Below reporting limit (BRL) results were not included in the RSD calculations. In all cases field+lab variation exceeded lab variation, as would be expected. The target RSD ranges of 10% for nutrients and 20% for fecal coliform bacteria, chl *a*, and phaeo are those established in the Ambient Marine Water Column Monitoring Plan (Janzen, 1992b).

To assess variation due to laboratory procedures alone, an objective was established of 75% of lab replicate data within the target RSD range. This objective was not met for ammonium fcb, or phaeo, but was met for all other analyses (Table 6). The results for nutrients show a substantial improvement over previous years (Newt *et al.*, 1997). Although ammonium (67% o RSDs in target range) did not meet the 75% objective, this result is significantly better than the WY 1994-1995 assessment (27% o RSDs in target range). Corrective actions taken in 1995 for nutrient analyses were apparently successful. Both fcb and phaeo are inherently variable analytes, although both analyses have met the 75% RSDs in target range objective in previous years. High laboratory RSD values can be expected for fecal coliform bacteria data due to the frequency of samples with low numbers of organisms. A difference in one organism count has greater impact when tota organism counts are low. These results will continue to be monitored and corrective actions taken if consistent results are obtained. No procedural corrections are obvious at this time. In all cases where laborator RSDs did not meet the 75% target objective, the percentage in the target range was substantially higher than tha

Table 6. Relative standard deviations (RSD%) for various parameters. Shown in parentheses is how field+lab and lab only variation was estimated. Shading indicates target range for RSD%. Data below reporting limits were excluded.

	$NO^3 + NO^2$		NH^4		***o*PO**^{4}	
	FIELD+LAB (3 reps.)	LAB (2 splits)	FIELD+LAB (3 reps.)	LAB (2 splits)	FIELD+LAB (3 reps.)	LAB (2 splits)
n:	75	273	44	161	76	255
RSD%[1]						
0-10	63%	95%	50%	67%	50%	89%
>10-20	23%	4%	23%	20%	28%	9%
>20-30	5%	<1%	9%	11%	16%	2%
>30-40	5%	-	11%	<1%	5%	-
>40-50	3%	<1%	5%	<1%	-	-
>50-60	-	-	-	<1%	-	-
>60-70	-	-	2%	-	1%	-
>70-80	-	-	-	-	-	-
>80-90	-	-	-	-	-	-
>90-100	-	-	-	-	-	-
>100	1%	-	-	-	-	<1%
mean RSD:	13%	3%	16%	10%	13%	5%

	FCB		**CHL *a***		**PHAEO**	
	FIELD+LAB (2 reps.)	LAB (2 splits)	FIELD+LAB (3 reps.)	LAB (2 splits)	FIELD+LAB (3 reps.)	LAB (2 splits)
n:	38	40	77	42	72	38
RSD%[1]						
0-10	24%	40%	30%	62%	26%	47%
>10-20	16%	15%	31%	21%	26%	18%
>20-30	11%	15%	14%	7%	28%	8%
>30-40	3%	5%	10%	2%	6%	13%
>40-50	18%	10%	9%	2%	3%	3%
>50-60	5%	-	3%	2%	3%	3%
>60-70	5%	3%	1%	-	4%	-
>70-80	8%	8%	1%	-	-	-
>80-90	5%	5%	-	-	3%	-
>90-100	3%	-	-	-	-	3%
>100	3%	-	-	2%	1%	5%
mean RSD:	37%	25%	21%	13%	23%	23%

[1]RSD% was calculated as: = (sample standard deviation / sample mean) * 100

for field + lab variation (67% versus 50% for ammonium; 55% versus 40% for fcb; 65% versus 52% for phaeo). This implies that laboratory precision, although not optimal, i better than random field variation.

Accuracy

The accuracy of the laboratory nutrient analyses was indicated by the results of the check standards of high (0.5 mg/L) and low (0.075 mg/L) known concentrations analyzed wit each batch of nutrient samples processed (Table 7). Considering mean values of the % error, check standard results indicate reasonable accuracy ($\leq$10% error). This shows a decrease over 1994-95 mean values which were $\leq$5% (Newton *et al.*, 1997). The range in the % error for most of the nutrients is fairly broad with some errors over 20%. In general, 1997 results look better than 1996 results. No actions are indicated at this time.

Note that check standards were not in the concentration range of the bulk of the marine data presented in this report. The range of the percent error was larger for the low check standard than for the high check standard. The bulk of the marine water ammonium-N and orthophosphate-P concentrations are below 0.075 mg/L, and it is not uncommon for nitrate+nitrite-N concentrations to be below this level. The accuracy of samples with concentrations lower than 0.075 mg/L is impossible to determine from these data.

Perhaps a better indication of analytical accuracy within the range of the sample concentrations measured is obtained from spiked sample recoveries. The mean, RSD, and range of the percent recovery of nutrient spiked samples also indicate poor accurac (Table 8). None of the spiked sample percent recoveries fell within the acceptable range of 70% - 130% (S. Lombard, Ecology, pers. comm.) during WY 1996, but all did in WY 1997. The reason for this difference is not known.

Blanks

Blank values consistently fell below the reporting limits for nutrients and pigments, as anticipated.

Sensor verification samples

Comparison of the verification samples for DO analyzed by modified Winkler titration with the *in situ* DO sensor (n=70) shows good agreement for most samples (Figure 13). Both the r^2 (> 90%) and the slope (close to 1.0) are similar to other years. The only substantial disagreement was observed for DO >10 mg/L, which is greater than the range that powder chemical reagents are recommended. For DO concentrations less than 10 mg/L, accuracy was within 0.5 mg/L. For DO concentrations greater than 10 mg/L, accuracy increased to within 1.0 mg/L.

Table 7. Nutrien analysis check standard results for WY 1996 and WY 1997.

Parameter	n	Standard conc. (mg/L)	Determined conc. (mg/L)			% error[1]	
			mea	RSD	range	mea	range
1996:							
NH_4^+-N	26	0.500	0.509	4%	0.484 -- 0.551	2%	-3% -- 10%
	16	0.075	0.082	14%	0.054 -- 0.102	9%	-28% -- 36%
NO_3^-+NO_2^--N	22	0.500	0.517	2%	0.500 -- 0.537	3%	0% -- 7%
	13	0.075	0.082	9%	0.071 -- 0.094	9%	-5% -- 25%
oPO_4^{-3}-P	24	0.500	0.495	3%	0.465 -- 0.518	-1%	-7% -- 4%
	15	0.075	0.074	5%	0.068 -- 0.081	-2%	-11% -- 8%
1997:							
NH_4^+-N	31	0.500	0.516	5%	0.440 -- 0.572	3%	-12% -- 14%
	21	0.075	0.080	11%	0.063 -- 0.090	6%	-16% -- 20%
NO_3^-+NO_2^--N	31	0.500	0.512	3%	0.489 -- 0.556	2%	-2% -- 11%
	31	0.075	0.076	10%	0.064 -- 0.091	1%	-15% -- 21%
oPO_4^{-3}-P	32	0.500	0.504	5%	0.465 -- 0.571	1%	-7% -- 14%
	29	0.075	0.072	12%	0.061 -- 0.088	-4%	-19% -- 17%

[1]Percent error was calculated as: = [(mean determined conc. - standard conc.) / standard conc.] * 100

Table 8. Nutrient spiked sample recovery results for WY 1996 and 1997. The range o acceptable recovery is 70% - 130%.

			% spike recovery[1]		
Parameter	Year	n	mea	RSD	range
NH_4^+-N	1996	45	91.3%	13.2%	48.2% - 115.4%
	1997	63	88.8%	9.4%	75.1% - 110.0%
NO_3^-+NO_2^--N	1996	46	100.4%	21.9%	22.9% - 161.4%
	1997	63	93.2%	13.5%	75.3% - 122.7%
oPO_4^{-3}-P	1996	45	91.9%	16.0%	28.0% - 112.6%
	1997	63	85.2%	11.6%	73.9% - 107.6%

[1]Percent spike recovery was calculated as: = [(measured spike + sample conc.) - measured sample conc.] / known spike conc.

Verification samples for the *in situ* salinity sensor ran using a salinometer (n=57) showed excellent agreement, with the percent difference for all paired samples at about 1%. The mean difference was 0.24 PSU and there was no directional variation. Thus, the accurac of the *in situ* salinity data is extremely high.

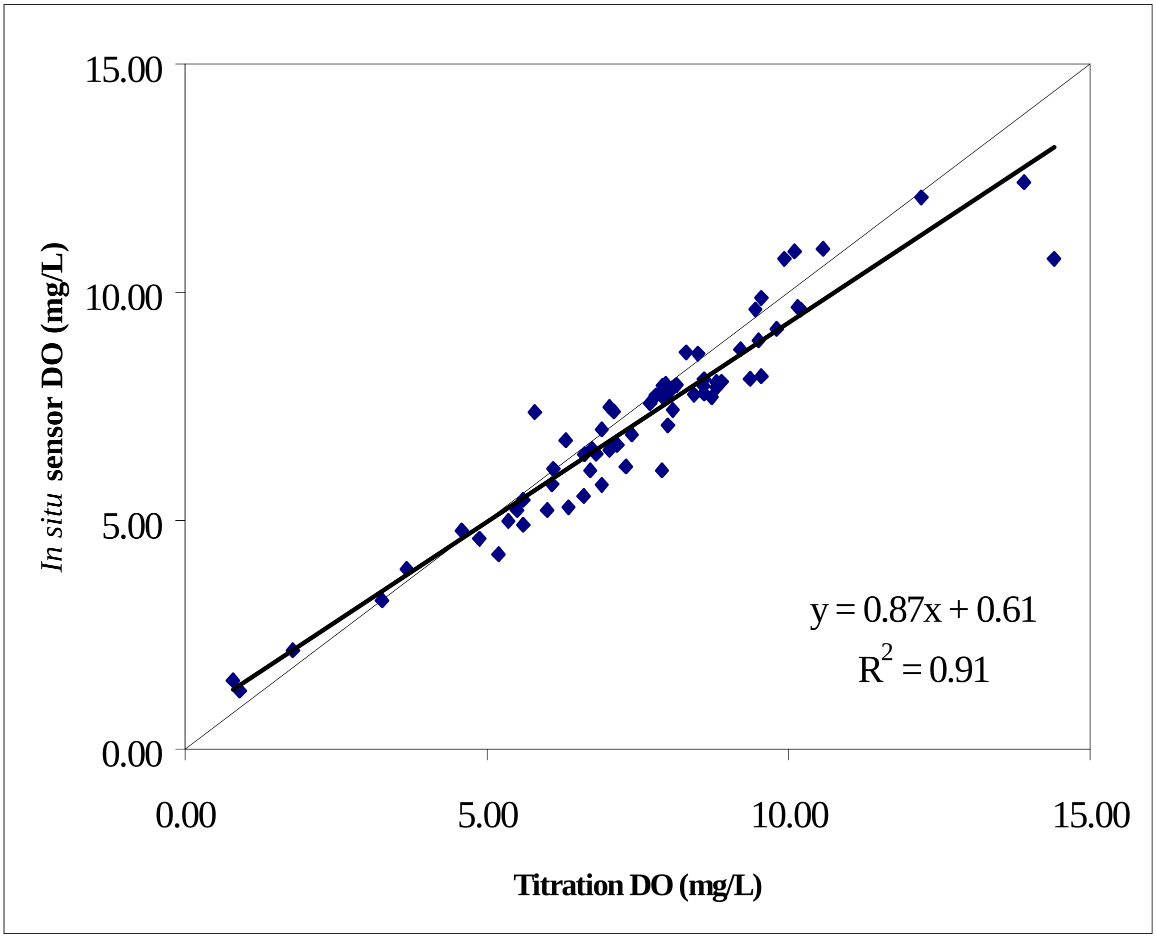

Figure 13. Regression of sensor versus titration results for DO sensor verification samples during WY 1996-97.

General Discussion

One impression that the user of this report will hopefully obtain is the complexity and interconnectedness of the data as well as the high degree of variation within Washington's marine waters. Stratification, chlorophyll, nutrients, light penetration, and dissolved oxygen data are interrelated variables and these vary markedly among different stations as well as through time. The resolution of the monitoring data is coarse in both spatial and temporal scales. Thus, only general patterns can be concluded from the data presented here. However, given the complexity of these data and the limitations o undersampling in time and space, the monitoring data can be used as screening tools and rough indicators o water quality. We have designated specific indicators of water quality that indicate either poor status or high susceptibility (Newton *et al.* 1997). An analysis of the indicators for WY 1996 and 1997 data follows initial discussion of stratification. Understanding stratification is important to those who want to assess water quality. Stratification, which is typically less ephemeral than nutrients or chlorophyll, has strong implications for water quality. Much of this discussion is focused on water quality effects from eutrophication since much of the monitoring program supports assessment of this stressor. However, stratification will influence the distribution of toxics and many other stressors.

Implications of Stratification for Water Qualit

The development of stratification within the water column is significant because of the physical barrier it presents with respect to vertical water movement. Turbulent eddies, driven by winds and tides, cause vertical mixing of phytoplankton, DO, nutrients, etc. If, however, the water is stratified, that is, its density increases significantly with depth, then the ability of turbulent eddies to accomplish vertical mixing will be greatly decreased. This is particularly true at the pycnocline, the region of greatest density change, which is often observed in the top several meters of the water column. Thus, stratification effectively isolates the surface water from the deep water. When stratification is intense, two environmental conditions can be affected: surface waters can become depleted o nutrients (dissolved nitrogen and phosphorus) and bottom waters can become depleted o oxygen. This is due to phytoplankton growth in the surface water that will deplete ambient nutrients, with no resupply from nutrient-rich deep waters, and to the decomposition of the organic material in the bottom water that will consume oxygen, with no resupply from oxygen-rich surface water.

Understanding the impact of human processes (e.g., sewage input) on water quality is complex because the concentrations of important variables (e.g., DO and nutrients) in the water column are the net result of many dynamic input and uptake processes. It is the relative magnitude of the transfer rates from sources and sinks that must be considered; yet we typically only measure a concentration. Also, sources and sinks of these compounds can be from either natural or anthropogenic processes. Examples of oxygen sources are photosynthetic production, diffusion of oxygen from the atmosphere through the water column, and advection or mixing of highly oxygenated waters into lower saturated waters (e.g., downward mixing of surface waters). Examples of oxygen sinks are respiration (especially by bacteria which decay organic matter), chemical oxidation-reduction reactions such as the oxidation of metals (e.g., rusting of iron) or sulfides, and advection/mixing of lower oxygenated waters into higher saturated waters (e.g., upwelling of deep waters). Nutrient inputs into marine waters include dissolved and particulate matter carried by rivers, effluent from sewage treatment plants, agricultural runoff, failing septic tanks, bacterial nutrient processing (e.g., nitrification), and upwelled deep waters. Nutrient uptake processes include consumption by phytoplankton, bacterial uptake, and possibly the adsorption of nutrients to particulates that eventually settle out.

Although stratification is necessary for phytoplankton growth it also optimizes the chances for low DO concentrations. Conditions favorable for phytoplankton growth are sufficient light and nutrients and some degree of stratification (i.e. to prevent mixing out of the euphotic zone. Under such conditions, phytoplankton biomass increases in the upper layer of the water column and nutrients are consumed as growth continues. Without a replenishing source, surface nutrient concentrations decrease and can limit phytoplankton growth, causing a decrease in their biomass. When a nutrient source is available to surface waters, however, phytoplankton production will never reach a nutrient-limited state. Nutrient input can occur naturally through mixing, but the mixing also causes ligh limitation thus preventing significant population increase. Eutrophication (externa increase in nutrient supply to system) of nutrient-limited stratified waters can result in ver large algal blooms and, after these sink, a correspondingly large DO debt in botto waters. However, the physical stratification of the water receiving the nutrient input are important, as inputs to well-mixed water columns have no immediate effect.

Depletion of DO in the water column can have a serious impact on marine ecosystems. The degree of impact upon any given ecosystem may be dependent upon the intensity of the DO depletion as well as the temporal and spatial stability/persistence of the depressed DO levels (Llansó, 1992). In addition, the effects of DO depletion are both organism- and habitat-specific (Harding *et al.*, 1992). Certain species of fish are stressed b environmental conditions of DO concentrations just under 5 mg/L (Kramer, 1987; Whitmore *et al.*, 1960). Other species may not exhibit stress at 2.0 mg/L (Pihl *et al.*, 1992). Benthic infauna and, particularly, molluscs are more resistant to hypoxia (Theede *et al.*, 1969).

Continuous or even intermittent hypoxic events may result in a shift in species composition. Fish may move away from the depleted area, or have higher susceptibility to disease (Smith *et al.*, 1992). Motile species that are affected will attempt to leave the hypoxic area. Sedentary species may be killed outright, or exhibit significant changes in reproductive rates and larval recruitment (Llansó, 1992). The species composition of a given area may also shift in response to changes in predator-prey relationships. Hypoxic conditions can initiate behavioral changes and physiological stresses (Roman *et al.*, 1993). The diel pattern of vertical migration exhibited by some zooplankton to avoid predation can be interrupted. Copepods have been found to remain in the pycnocline in an attemp to avoid a bottom layer of low-oxygenated water (Olson, 1989). Hypoxia may also inhibit the hatching of zooplankton eggs, thereby reducing larval recruitment, and suppress metabolic rates (Roman *et al.*, 1993).

Thus, the net effect of oxygen depletion in marine waters may be a shift in species composition, a decrease in population numbers and species diversity with a resulting decrease in amount and type o biomass, a disruption of the usual predator-pre interaction, and a shift in the expected trophic pathways. These combined effects can result in reduced availability and subsequent harvest of marine resources. Because the consequences of eutrophication are large, understanding its potential in local waters is important. The stratification index and other indicators presented in this report are usefu in increasing that understanding.

Indicators of Puget Sound and Coastal Estuary Water Qualit

Five indicators of environmental condition were introduced in the Results and Discussion section: 1) degree of stratification (persistent, seasonal, episodic, weak);
2) low DO concentrations (<3 mg/L, <5 mg/L); 3) consecutive months of BRL surface nitrate+nitrite-N concentrations (3 months, 6 months); 4) high ammonium-N concentrations (>0.07 mg/L, >0.14 mg/L); and 5) high fecal coliform bacteria concentrations (>14 orgs./100 mL, >50 orgs./100 mL). A summary of the indicators is in Table 9; their co-occurrence at stations is discussed in this section.

Table 9. Indicators of environmental condition at Marine Waters Monitoring stations during WY 1996-97. See text for details. No data collected is indicated by a "-".

Station	stratification[1]	low DO[2]	consecutive BRL DIN[3]	hi NH_4[4]	hi FCB[5]
Puget Sound Stations:					
BLL009	P			x	X
BLL011	P	x		x	x
BUD002	P	x		X	X
BUD005	P	x	x	x	x
CMB003	P	x		x	X
ELB015	P	x			X
HCB003	P	X	-	-	-
HCB004	P	X	X	x	x
HCB006	P	x	x		
HCB007	P	X	-	-	-
HLM001	P	x	X		
PNN001	P	X	-	-	-
PSS019	P	x			X
SAR003	P	x	X		
SKG003	P	x	-	-	-
CRR001	S	x		x	
CSE001	S		x	x	
DIS001	S	X		x	
DRA002	S	x		x	x
EAS001	S	x	x	X	
ELD001	S		x	x	
GRG002	S	x			x
BML001	E			x	
PSB003	E	x			X
OAK004	E		x	x	x
TOT001	E		x	x	
FRI001	W	x			
PTH005	W	x			

Table 9 Continued.

Station	stratification[1]	low DO[2]	consecutive BRL DIN[3]	hi NH_4[4]	hi FCB[5]
Coastal Estuary stations:					
Grays Harbor:					
GYS004	P-E				X
GYS008	P-E				X
GYS016	P-E				X
Willapa Bay:					
WPA001	P-E			x	X
WPA003	P-E		x		X
WPA004	E-W				x
WPA006	E-W		x		
WPA007	E-W		x		
WPA008	E-W		x		x

[1]Stratification: P = persistent; S = seasonal; E = episodic; W = weak
[2]Low DO: X = <3 mg/L; x = <5 mg/L
[3]BRL DIN: X = $\geq$5 consecutive months; x = $\geq$3 consecutive months
[4]High NH_4^+: X = >0.14 mg/L; x = >0.07 mg/L
[5]High FCB: X = >50 orgs/100 mL; x = >14 orgs/100 mL

With regard to eutrophication, the indicators presented here can be classified into indication of the status of eutrophication and indication of susceptibility to effects fro eutrophication. Status is given by the prevalence of low DO (with caveats for naturally low DO areas) whereas susceptibility to eutrophication is indicated by persisten stratification, consecutive months with BRL DIN, and the presence of high fecal colifor bacteria or ammonium, these latter two implying possible human organic loadings. summary map of these indicators is presented in Figure 14. Areas of concern include Hood Canal, Penn Cove, Discovery Bay, Bellingham Bay, Budd Inlet, Commencement Bay, Elliott Bay, Holmes Harbor, Possession Sound, Carr Inlet, Oakland Bay, East Sound, Saratoga Passage, and Drayton Harbor.

Stratification patterns appear to be a good indicator of areas that may be sensitive to developing low DO conditions. Several Puget Sound stations exhibited hypoxic (<3 mg/L) DO concentrations (DIS001, HCB007, HCB004, HCB003, and PNN001;

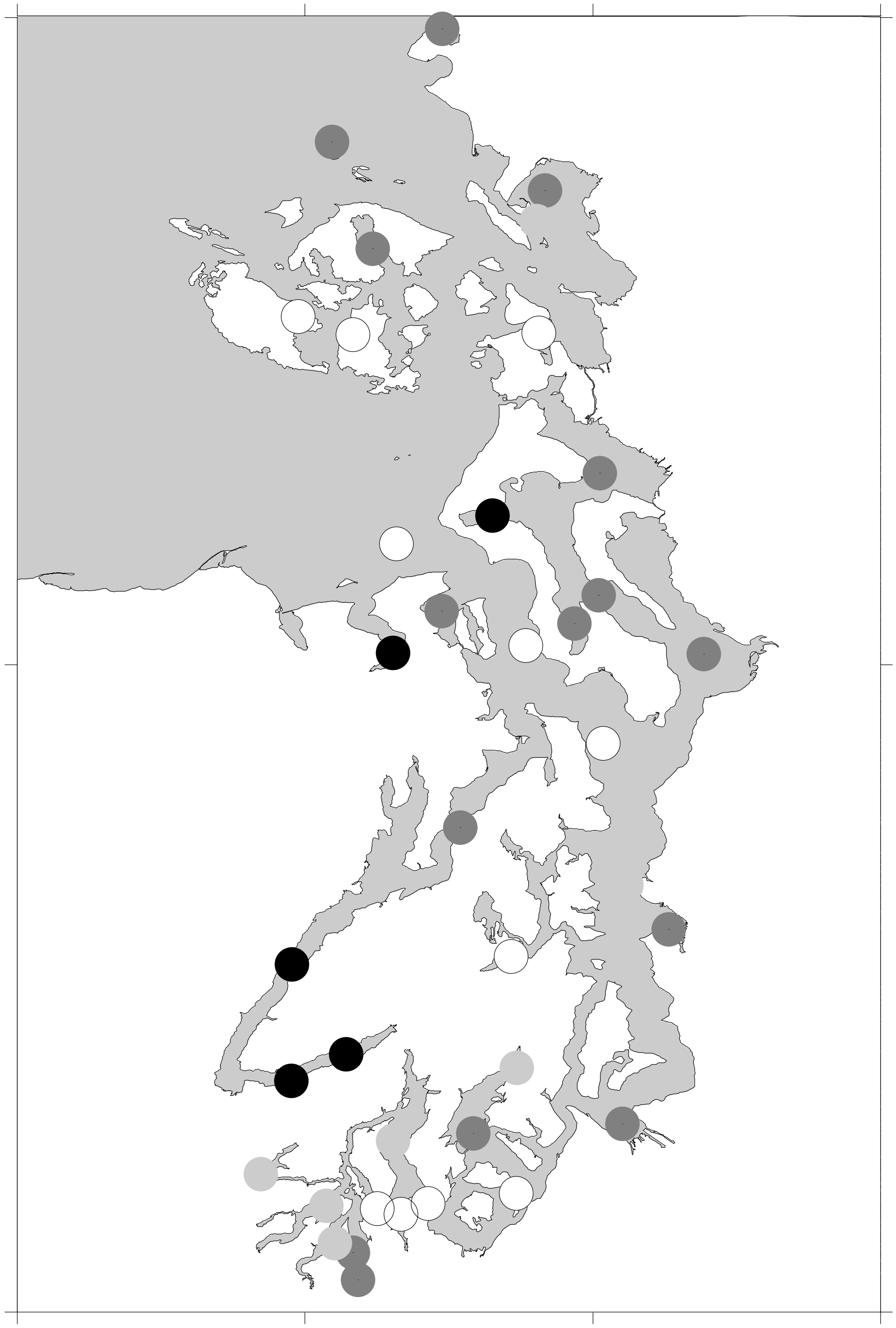

Figure 14. Prevalence of hypoxia (black) and low DO (dark gray) along with stations showing physical/chemical attributes of susceptibility to eutrophication (light gray).

Table 9). All of these stations except DIS001 showed persistent stratification, with DIS001 exhibiting seasonal stratification. Stations with two or more observations of low (<5 mg/L) DO concentrations were ADM002/1, BLL011, CMB003, CRR001, DRA002, ELB015, GRG002, HCB006, HLM001, PSB003, PSS019, PTH005, SAR003, and SKG003. All of these stations show persistent (8) or seasonal (6) stratification except PSB003 and PTH005.

Natural conditions were prime for development of low DO in Puget Sound during 1996 and especially 1997. Freshwater input has been higher than normal from 1995 through 1997 and sea temperatures were slightly above average for the latter part of 1997, both of which intensify stratification and may also select for high productivity.

Stratification and oxidation of production are not the only mechanisms for low DO to develop in Puget Sound. The influx of low DO waters from oceanic sources is also ver important in this region. In late summer 1997 we saw a strong signal of low DO water widespread in greater Puget Sound in 1997. It is possible this was associated with anomalous El Niño forcings off the coast but no DO data are available from oceanic sites for that time. Stations with low DO occurrences from the late summer 1997 event alone were ADM001, DRA002, PSB003 and PTH005. We typically observe a natural seasona influx of low DO water at ADM002 but the low DO signal typically disappears south o the sill (at ADM001) due to mixing with other water masses over the sill. The signal o low DO waters entering Puget Sound in late 1997 was stronger than in other years (lower concentration, longer duration), making assessments of basins and bays with anthropogenically mediated low DO more difficult. More needs to be understood abou the natural cycles of DO in Puget Sound, its linkage with the Pacific Ocean and the effects of climatic forcings.

Using stratification as an indicator of sensitive environments, other stations where persistent stratification was observed (Table 3) should be regarded as areas where significant nutrient loading could lower DO concentrations. Most of these stations are bays near urban areas where development could increase.

Regarding low DO, it must be stressed Ecology monitoring stations represent a single typically mid-bay location in most bays. Conditions within the bay can be quite variable. Typically, DO concentrations are lower at the heads of bays than in the middle or outer portions.

Further information on nutrient sensitivity (i.e. where nutrient loading could lead to low DO) may be obtained from the patterns of consecutive months with BRL DIN concentrations. In Puget Sound, the stations with 3 or more consecutive months of BRL DIN nearly all had persistent or seasonal stratification (Table 9). Puget Sound stations exhibiting 5-6 consecutive months of BRL DIN all had persistent stratification and low or hypoxic DO. In Willapa Bay BRL DIN was observed consecutively but it was no associated with low DO. In Grays Harbor there are fewer stations with nutrient data bu surface DIN was never BRL for consecutive months and low DO did not occur.

High ammonium-N concentrations were primarily observed in South Puget Sound, with a few exceptions (Bellingham Bay, Hood Canal, Discovery Bay Drayton Harbor, and East Sound). High ammonium-N concentrations and high fcb counts were often observed at the same stations (BLL009, BLL011, BUD002, BUD005, CMB003, HCB004, DRA002, and OAK004). Many of these stations are in areas with significant freshwater runoff. Freshwater runoff can be a source of both ammonium-N and fcb contamination.

The prevalence of fecal coliform bacteria in Puget Sound was highest at stations close to urban centers and with major freshwater inputs (BLL009-Bellingham-Nooksack, BUD002-Olympia-Deschutes, CMB003-Tacoma-Puyallup, ELB015-Seattle-Duwamish, PSS019-Everett-Snohomish, and PSB003-Seattle-Duwamish/Chittendon Locks/West Point). On the coast, Grays Harbor continues to show chronically high fcb counts throughout the estuary, whereas in Willapa Bay contamination appears constrained to the Willapa River.

In Puget Sound, physical forcing of biological response in a given area is strong, as was evident from the correlation of stratification index with low DO occurrence. Similarly, climate forcing of interannual variation is also evident. Freshwater input is a strong determinant of estuarine processes and its effects can be seen in the Puget Sound data. Freshwater runoff was higher than normal in both WY 1996 and WY 1997 and this impact was shown by the lower SSS recorded throughou Puget Sound (Figure 4). Many instances of high fcb counts were evident and often correlated with precipitation events (Figures 3, 11; note Nov '95, Feb '96 and Dec '96/Jan '97).

The increased stratification afforded from the increase in freshwater input can be hypothesized to affect the severity of the low DO conditions. Runoff of the Skykomish River for 1994 through 1996 was at 77%, 110%, and 141% of normal. The number o months with low DO recorded at the four monitoring stations in Hood Canal, a location with substantial freshwater input, for this timeperiod was 20, 29, and 30. In contrast, Eas Sound, which has no major freshwater input, does not fit this pattern, with 5, 2, and 1 observations of low DO for the same years. Other climatic variables (e.g., inciden radiation, wind stress) not addressed in this report also contribute to the inter-annua patterns observed.

The coastal estuary stations show different dynamics than the Puget Sound stations (Tabl 9). The lack of low DO concentrations in the coastal estuaries is significant, especially since the river input maintains intense stratification at times. Tidal action in these estuaries is strong and likely keeps DO concentrations well-mixed. Also, episodic wind mixing would be more effective in these relatively shallow estuaries. Interestingly, the very high fcb counts (>300 orgs./100 mL) in these estuaries (GYS004/008, WPA001) suggest tha

flushing is not completely effective or that the input o fcb in the coastal estuaries is exceptionally large. High ammonium-N concentrations were seen at only one of these stations (WPA001). Consecutive months of BRL nitrate+nitrite-N were observed primarily in Willapa Bay and not i
Grays Harbor. Understanding the dynamics of the coastal estuary stations will likely be difficult to resolve without conducting sampling according to tidal stage.

Conclusions

- Water quality in the Puget Sound region is highly diverse. In the open basins water quality—as indicated by DO, nutrients, and fecal coliform bacteria—appears to be reasonably good. However, there are individual locations within the Puget Sound region where water quality appears reduced (see below). For the coastal estuaries, the only water quality issue apparent is chronic fcb contamination. Counts were very high and chronic in the inner half of Grays Harbor and in Willapa Bay near the Willapa River. Note that this assessment of water quality does not include chemica contamination, plankton species assemblages, or changes in flushing characteristics. Also, the representativeness of mid-bay stations can be questioned and definite undersampling of locations within Puget Sound is acknowledged.

- Climate an important driver of marine water column conditions. The effect of three years (1995-97) with higher than normal runoff (110-150 percen), and precipitation appears to be evident as reduced sea-surface salinity at the monitoring stations.

- DO concentrations <3 mg/L were found at 5 of 38 Puget Sound stations. Hypoxic conditions in S. Hood Canal were especially severe, reaching anoxia. Hypoxia observed in Penn Cove and Discovery Bay was moderate but encompassed summer as well as fall months. Whether anthropogenic impacts are responsible for the severity of these conditions needs evaluation. DO concentrations <5 mg/L were found at additional stations, but is probably of most concern in Holmes Harbor, Bellingham Bay, Budd Inlet and possibly at Commencement and Elliott bays. The high prevalence of low DO throughout Puget Sound in late 1997, likely associated with oceanic or climatic conditions, makes evaluation difficult.

- Very high fcb counts (>50 org/100 mL) were observed at 6 of 38 Puget Sound stations, most often during winter. Very high fcb counts were recorded with chronic frequency at Commencement Bay and, with lower counts, in inner Budd Inlet. Ver high counts were observed in winter at Bellingham and Elliott Bays.

- Based on the various types of data collected, stations showing particular sensitivity to impacts from eutrophication include: Hood Canal, Penn Cove, Holmes Harbor, Bellingham Bay, Budd Inlet, Elliott Bay, Commencement Bay, Possession Sound, Oakland Bay, East Sound, Saratoga Passage, Discovery Bay, and Drayton Harbor.

- Both physical stratification and climate forcing play large roles in affecting water quality. Well-mixed areas show less water quality impacts than persistently stratified areas. In view o interannual variation due to weather, the impact of humans on water quality is difficult to assess. This highlights the importance of lengthy, consistent time-series databases and the need to incorporate historical data.

Recommendations

- *Re low DO in Hood Canal:* In light of the severely low DO concentrations recorded in S. Hood Canal even in wintertime, further monitoring and investigative study o water circulation and DO dynamics in Hood Canal should continue to be a priority Effects on other trophic levels, such as fish and shellfish, also should be assessed.

- *Re low DO entering Puget Sound:* Very little is quantitatively known about the dynamics of DO in water masses entering Puget Sound, how these are affected b oceanic and climatic conditions, and how the journey throughout Puget Sound changes the DO in water exiting Puget Sound. Implementation of a comprehensive and synoptic monitoring for the Strait of Juan de Fuca should be pursued.

- *Re low DO in Penn Cove:* This station was monitored first in WY 1994 when hypoxic low DO concentrations were observed, and was recommended for further monitoring. The re-observation of hypoxia and its persistent stratification mean tha anthropogenic impacts on the Cove should be carefully considered.

- *Re fcb contamination in Grays Harbor, Willapa Bay, and Commencement Bay:* Eight years of monitoring data show chronically high fcb counts in Grays Harbor, the Willapa River estuary, and Commencement Bay. High counts have not been reduced in either location, except for a reduction in Grays Harbor counts from numbers in the 1000's seen for several months in WY 1995 to numbers in the 100's in WYs 1996-97. There is no indication that current actions to curtail fcb contamination are effective.

- *Re sensitive bays:* Persistently stratified, urbanized bays are particularly sensitive to degraded water quality and should continue to be monitored. These include Bellingham Bay, Budd Inlet, Commencement Bay, Elliott Bay, Possession Sound, and Oakland Bay. Conditions elsewhere in these bays and inlets are recommended for study, since the monitoring stations often miss the more severe conditions. Other non-urbanized areas with incidence of poor water quality indicators include Saratoga Passage, Discovery Bay Drayton Harbor, Holmes Harbor, Carr Inlet, and East Sound.

- *Re Marine Waters Monitoring program:* Monitoring of water column variables that allow assessment of the influence of climate patterns on marine waters and their stratification should be continued. Moored sensors are needed to record event-scale variation. These data should be promoted for use in system models to explore dynamics and causative factors of the observed complex patterns.

  Priority should continue to be placed on entering high-quality historical data int Ecology's database in order to facilitate evaluation of changing conditions.

  To help identify eutrophication and food-web issues, assessment o chl *a* needs improvement. Avenues for obtaining and analyzing remotely sensed chl *a* data (via aircraft or satellites) should be pursued. Increased depth resolution measurements should be obtained by use of an *in situ* fluorometer to determine integrated values over the euphotic zone.

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APPENDIX A

Water quality data for WY 1996-97 at:

1) Puget Sound stations
2) Grays Harbor and Willapa Bay stations

APPENDIX B

Depth profiles of temperature, salinity, density, dissolved oxygen and light transmission for WY 1996-97 at:

1) Puget Sound stations
2) Grays Harbor and Willapa Bay stations

APPENDIX C

Seasonal plots of euphotic zone depth, chlorophyll *a*, nitrate+nitrite-N, and regressions of light extinction coefficient versus surface chlorophyll *a* concentration for WY 1996-97 data at:

1) Puget Sound stations

2) Grays Harbor and Willapa Bay stations