WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Washington State Marine Water Quality, 1998 through 2000

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Washington State Marine Water Quality, 1998 through 2000

by
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Abstract

This is a report of the Washington State Department of Ecology long-term Marine Waters Monitoring Program for the period October 1997 through December 2000, summarizing water quality variables for stations in Puget Sound, Grays Harbor, and Willapa Bay. Five indicators of marine water column environmental condition are also evaluated. For the Puget Sound region in general, water quality appeared to be reasonably good; however, there are several specific locations where water quality was reduced, due to low dissolved oxygen concentrations, fecal coliform bacteria contamination, or an indication of sensitivity to eutrophication based on stratification or nutrient conditions. Areas of highest concern are Southern Hood Canal, Budd Inlet, Penn Cove, Commencement Bay, Elliott Bay, Possession Sound, Saratoga Passage, and Sinclair Inlet. For the coastal estuaries, the primary water quality issue apparent was chronic fecal coliform bacteria contamination in Grays Harbor and adjacent to the Willapa River. Climate is also an important driver of marine water conditions. Whether decreased water quality can be attributed to natural or anthropogenic causes is very difficult to assess and will likely vary at different locations throughout the region. The approach used in this report is intended to highlight sensitivity, in the goal of supporting wise management decisions.

Executive Summary

The Washington State Department of Ecology initiated monitoring of marine waters in 1967 in order to assess water quality in greater Puget Sound, Grays Harbor, and Willapa Bay. Data are currently collected monthly for this long-term monitoring effort by the Marine Waters Monitoring program. This is a report of the Washington State Department of Ecology long-term Marine Waters Monitoring Program for the period October 1997 through December 2000 summarizing water quality variables for stations in Puget Sound, Grays Harbor and Willapa Bay. The period of this report encompasses a shift from wateryears (WY) to calendar years (Y). Monitoring of water quality parameters during October 1997 – September 1998 (WY 1998), October 1998 – December 1999 (WYY 1999), and January 2000 – December 2000 (Y 2000) occurred at 29, 29, and 25 stations, respectively, in Puget Sound. Throughout the period, five stations in Grays Harbor and six in Willapa Bay were also monitored. In this report, along with the WY 1998 – Y 2000 data, five indicators of marine water column environmental condition are discussed.

The Marine Waters Monitoring program assesses conventional water quality as indicated by dissolved oxygen (DO), nutrients, and fecal coliform bacteria, but due to funding limitations does not include assessment of chemical contamination, plankton species (e.g., toxic blooms), or changes in flushing characteristics. The representativeness of monthly, mid-bay monitoring stations can be questioned and definite under-sampling of areas within Puget Sound is acknowledged.

Caveats aside, for the Puget Sound region in general, water quality appeared to be reasonably good; however, there are several specific locations where water quality appeared reduced due to low DO, fecal coliform bacteria contamination, or an indication of sensitivity to eutrophication based on stratification or nutrient conditions. Areas of highest concern are Southern Hood Canal, Budd Inlet, Penn Cove, Commencement Bay, Elliott Bay, Possession Sound, Saratoga Passage, and Sinclair Inlet. For the coastal estuaries, the primary water quality issue apparent was chronic fecal coliform bacteria contamination in Grays Harbor and in Willapa Bay adjacent to the Willapa River.

Water-quality sensitive areas are typically near urbanization and near rivers, where strong and persistent density stratification of the seawater exists such that zones of limited mixing occur. Well-mixed areas showed 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 enter marine waters through runoff. Thus, areas most sensitive to water quality problems are generally areas with high runoff, low mixing, and anthropogenic inputs of nutrients and sewage. The monitoring data and indicators presented here showed this pattern for Washington State marine waters.

Climate also plays a large role in affecting water quality in Washington marine waters. Differing climatic conditions, such as droughts, upwelling favorable winds, or cloud have implications on stratification, water properties, and resulting water quality. Thus, there is difficulty in assessing the impact of humans on water quality, in view of the high degree of interannual variation due to weather. This natural variability highlights the importance of lengthy, consistent time-series databases, and the need to acquire and use historical data.

Climatic conditions of the WY 1998 – Y 2000 period were characterized by higher than normal precipitation from Nov 1998 through Feb 1999 and in Nov 1999, and lower than normal precipitation in Nov-Dec 2000. Air temperatures averaged close to normal throughout the period, slightly higher in 1998 and slightly lower in 1999 and 2000. Annual runoff of two major Washington rivers (Skykomish and Chehalis) was near normal in 1998 and 2000, but relatively high, at 138-156% of the median flow in 1999. These weather and flow conditions were evident in the sea-surface temperature and salinity of the monitoring stations, which tended to correlate with the above patterns. Most notable were warmer than average sea surface temperatures in 1998, cooler sea surface temperatures in 1999 and 2000, correlating with air temperatures in those years, and lower salinities in 1999, and higher salinities in 2000, correlating with river runoff in those years. Stations near rivers had more extreme annual sea temperature range than those not near rivers.

The density stratification characteristics of the monitoring stations were classified into four groups based on intensity and frequency: Strong-Persistent, Strong-Intermittent, Moderate-Infrequent, and Weak-Infrequent. The majority of the stations (26 out of 56) had Moderate-Infrequent stratification, although strong stratification was just as common, with 13 each showing Strong-Persistent and Strong-Intermittent. The stronger the stratification the more likely reduced water quality can develop.

Hypoxic dissolved oxygen concentrations (<3 mg/L) were found at several (11 out of 54) stations. Dissolved oxygen (DO) concentrations less than 3 mg/L were measured in Hood Canal (4 stations, 51 observations), Penn Cove (6 observations), Saratoga Passage (2 observations), and one observation each in Bellingham Bay, Discovery Bay, Elliott Bay, Strait of Georgia, and West Point during WY 1998-Y 2000. Conditions in South Hood Canal were especially severe, with low DO concentrations (<5 mg/L) evident year-round. Penn Cove also exhibited re-occurring 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 from processes including upwelling, El Niño, and drought. Low DO was found at 18 other stations, including Saratoga Passage, Discovery Bay, Bellingham Bay, Elliott Bay, Budd Inlet, and Commencement Bay. Low DO was not found in the coastal estuaries except near the Willapa River.

During this period many stations showed more frequent, lower concentrations, or their first low DO concentration, compared with the record of comparable data which started in WY 1993. An exception was that DO concentrations appear to be increasing in inner

Budd Inlet. This would be consistent with the reduction in nutrient loading by LOTT since 1994. Observations of low DO primarily occurred in late summer to early fall, but in South Hood Canal occurred year-round and reached anoxia at times. Strong density stratification was well-correlated with low DO concentrations. Flushing time and proximity to recently upwelled ocean waters are also factors, as was a possible influence from the 1997-98 El Niño.

Very high ammonium-N concentrations (>10 µM) were seen in Budd Inlet, Bellingham Bay, Possession Sound, and Sinclair Inlet. All except Budd Inlet were unprecedented observations. High ammonium concentrations (>5 µM) were recorded at a total of 18 stations, eight of which were in South Puget Sound. Such observations in Willapa Bay (2 stations, 10 observations) and Grays Harbor (2 stations, 6 observations) were largely unprecedented.

Occurrence of consecutive months with <1 µM surface dissolved inorganic nitrogen (summed nitrate, nitrite, and ammonium) in combination with stratification and other indicators was used to indicate stations potentially sensitive to eutrophication. This condition was found in Budd, Case, and Carr Inlets, Southern Hood Canal, Sinclair Inlet, Possession Sound, Saratoga Passage, and Willapa Bay.

Fecal coliform bacteria counts >14 organisms/100 mL were found at 16 Puget Sound stations and seven coastal estuary stations during WY 1998-Y 2000. Of these, contamination in Grays Harbor, Willapa Bay (near the Willapa River), Commencement Bay, and inner Budd Inlet appeared chronically persistent. Rare but extremely high fecal counts (>100 org./100 mL) for marine waters were recorded at Elliott Bay (twice), Oakland Bay (twice), Port Orchard (3100 org./100 mL), Possession Sound, and Sinclair Inlet (890 org./100 mL).

Summing several water quality attributes using five indicators of marine water quality presented in this and previous reports (strong stratification, low DO, limiting nutrients, high fecal coliform bacteria concentrations and high ammonium concentrations) the highest water quality concern for the stations assessed during WY 1998 – Y 2000 is for Southern Hood Canal, Budd Inlet, Penn Cove, Commencement Bay, Elliott Bay, Possession Sound, Saratoga Passage, Sinclair Inlet, and inner Grays Harbor and to a lesser degree, Bellingham Bay, Case Inlet, Oakland Bay, inner Willapa, Discovery Bay, Strait of Georgia, Carr Inlet, Port Orchard, West Point, Skagit Bay, and Port Susan.

Introduction

This data report of the Washington State Department of Ecology (Ecology) Environmental Assessment Program (EAP) represents water quality data for marine waters in Puget Sound, Willapa Bay, and Grays Harbor collected monthly from October 1st (start of the 1998 wateryear) 1997 through December 31st, 2000. Collection of these data comprises the long-term component of Ecology's Marine Waters 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 regularly (Janzen, 1992a; Janzen and Eisner, 1993a; b; Newton, *et al.*, 1994; 1997; 1998a).

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 are needed to establish baseline conditions with the goal of detecting effects from human activities leading to contamination and/or habitat degradation. Ecology has maintained a database of marine water quality data since 1973. Access to the database is provided to the public, through hard copy or electronic transmission. On-line access to the database is at http://www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html.

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, with the intent of differentiating interannual and seasonal variation from variation due to human activities at specific locations. A major use of the data is for maintenance of the Federal Clean Water Act 303(d) list, a regulatory listing of impaired 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 by this monitoring program. The data are also used by interdisciplinary efforts aimed at assessing the health of marine ecosystem components, ranging from eelgrass to salmon, since these organisms live in and are affected by marine waters and its quality.

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*, light transmission, nutrients, etc.);

2) Identify significant changes in these parameters that may indicate environmental 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 of 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 industrial 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 Ambient 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.

During 1995, PSAMP underwent external program review. A five-year summary of marine water column monitoring data from Puget Sound collected by Ecology since the implementation of PSAMP is presented in Newton (1995a). Discussion of marine water monitoring issues and recommendations and review panel comments can be found in Newton (1995a) and Shen (1995), respectively. The sampling design used in 1998-2000 is responsive to the review conclusions.

Methods

Long-Term Ambient Monitoring Approach for 1998-2000

In an effort to preserve and extend long-term time-series records for marine waters (Shen, 1995), 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 data records of 20 years or more. During 1998-2000, Ecology occupied five core stations in Grays Harbor, six in Willapa Bay, and twenty 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 selection of these additional Puget Sound stations, termed “rotational” stations, follows the PSAMP three-year rotation of focus between northern, central and southern Puget Sound. Regional candidates for rotational stations are prioritized based on: those with suspected problems but insufficient data; those where no data exist but environmental and land-use features indicate potential for problems; those associated with specific requests to aid other environmental studies; and those with outdated data. Results are used as a screening tool, highlighting the need for continued monitoring or focused study.

The period covered in this report spans a shift from using wateryears to set the period of rotational station monitoring to using calendar years. Ecology’s water quality monitoring cycle had originally been aligned with the wateryear (1 Oct to 30 Sep of a given year), based on the freshwater hydrologic cycle. This wateryear rotation was used for marine waters monitoring as well as freshwater monitoring. However, water quality in marine systems are more strongly governed by the delivery of sunlight (solar cycle) rather than the delivery of rainfall (hydrologic cycle). In addition, physical mixing by wind and storms is often strongest in December-January. Thus, a calendar-year annual cycle is more appropriate for the marine waters monitoring cycle. Starting in 2000, Ecology adopted calendar years for setting the rotational stations for marine waters monitoring. To accomplish this shift, 1999 was a transitional year. Monitoring in 1998 was for the wateryear (1 Oct 1997 to 30 Sep 1998); monitoring in 1999 spanned 15 months (1 Oct 1998 to 31 Dec 1999); monitoring in 2000 was for the calendar year (1 Jan 2000 to 31 Dec 2000). In this report, these periods are designated as WY 1998, WYY 1999, and Y 2000, respectively.

The rotational stations monitored in 1998-2000 are shown in Figure 1; station information and the parameters sampled are listed in Table 1. During WY 1998, nine rotational stations were monitored primarily in central Puget Sound, at Penn Cove, Possession Sound, Skagit Bay (2), Port Susan, Eagle Harbor, Port Gamble, Port Orchard, and Quartermaster Harbor. During WYY 1999, eleven rotational stations were monitored primarily in southern Puget Sound, at Budd Inlet, Commencement Bay, Carr Inlet, Case Inlet (2), Eld Inlet (2), Totten Inlet (2), and Hood Canal (2). During Y 2000, seven rotational stations were monitored primarily in northern Puget Sound, at Drayton Harbor, Dungeness Bay, Discovery Bay, Sequim Bay, Bellingham Bay, and Hood Canal (2).

Materials and Procedures

Field Procedures

Long-term monitoring was conducted from a DeHavilland 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 Puget 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, all at 0.5 m interval "bins." 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 (top bin = 0.5 m) to ~100-m depth or the sea bottom when shallower. The CTD sensors are typically lowered to 0.5 - 1 m above the sea bottom, to avoid sensor damage.

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 conduct 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. Discrete water samples were taken from the Niskin bottle for dissolved nutrients (ammonium-N, nitrate+nitrite-N, and orthophosphate-P), and pigments (chlorophyll *a* and phaeopigment) and stored on ice. Discrete samples for DO and salinity were drawn periodically for comparison with the *in situ* sensor values. Samples for DO were fixed with powdered reagents for the azide-modified Winkler titration analysis (APHA *et al*., 1989), stored at ambient temperature. Samples for salinity were capped tightly and stored at ambient temperature. Samples for fecal coliform bacteria were collected just below the surface (0.1-m) using sterile glass sample bottles and stored on ice.

Laboratory Procedures

Analyses for dissolved nutrients were conducted by Manchester Environmental Laboratory (MEL) for ammonium, nitrate+nitrite, and orthophosphate for samples collected 1 October 1997 through 18 February 1999. All nutrient samples were filtered through Nalgene® 0.45 µm pore cellulose acetate filters in the field at the time of collection and maintained at 4ºC. Samples were frozen upon return to Ecology (roughly 2-7 hours after sampling). Nutrient samples were analyzed using an Alpkem® series 300 autoanalyzer at MEL (Ecology, 1992). Results are reported in mg/L units. For samples collected 19 February 1999 through 31 December 2000, sample collection, filtration, and storage procedures were the same but analyses for dissolved nutrients were conducted by the University of Washington Marine Chemistry Lab for nitrate, nitrite, ammonium, orthophosphate, and silicate. Nutrient samples were analyzed using Technicon AutoAnalyzer II at UW (UNESCO, 1994). Results are reported as micromolar (µM).

Samples for chlorophyll *a* (chl *a*) and phaeopigment (phaeo) from 0.5 and 10 m depths were filtered through Whatman® GF/F glass fiber filters (0.70 µm nominal pore size) at the end of the sampling day by Ecology staff. The filters were immersed in 90% acetone (Eisner, 1994) and stored frozen in glass centrifuge tubes. For samples collected 1 October 1997 through 30 June 1999, frozen samples were transferred to MEL for

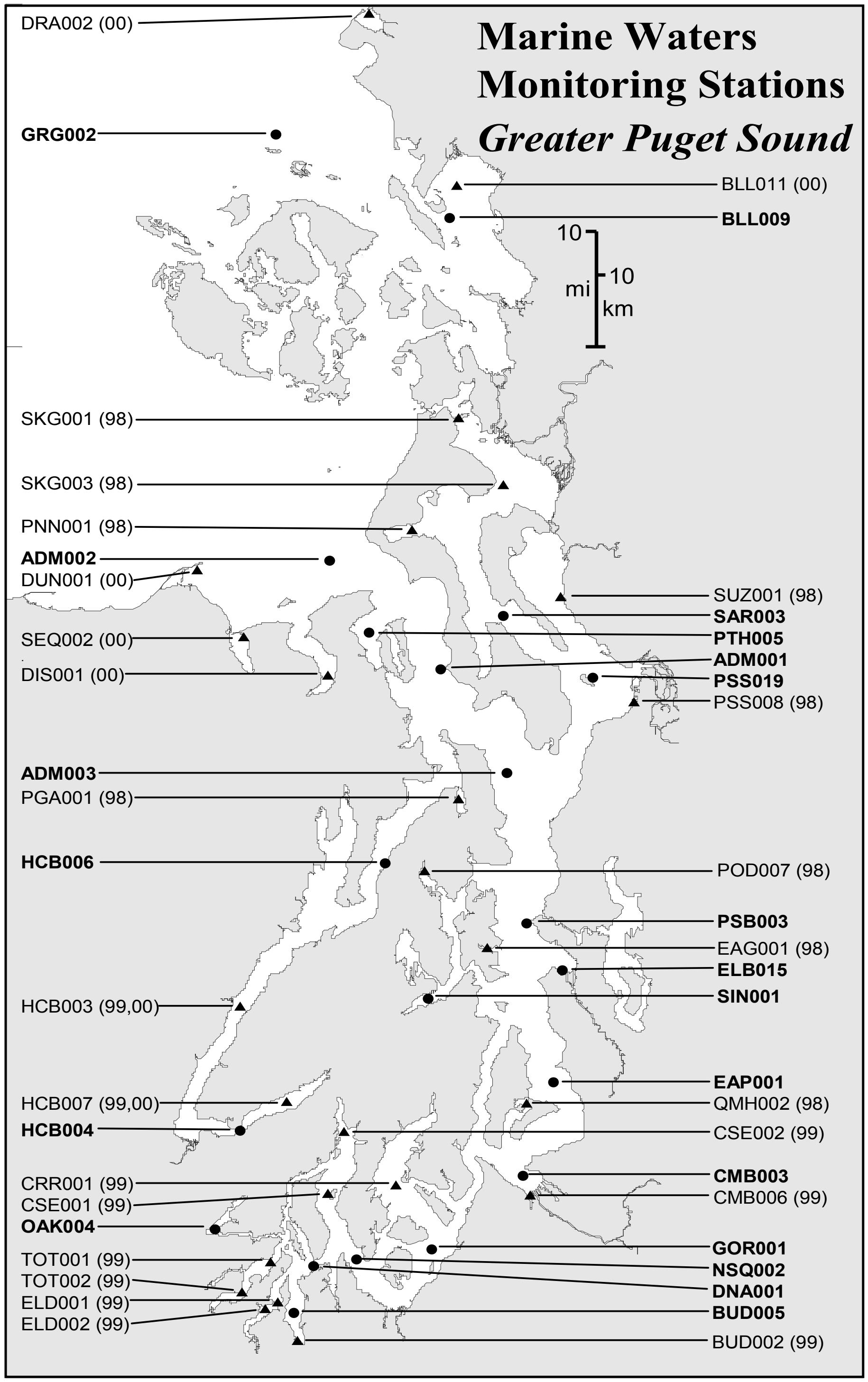


Figure 1. Marine Waters Monitoring stations in Puget Sound for WY 1998 – Y 2000. Rotational stations (triangles) are shown with the year sampled in parentheses. The core stations (circles) are sampled every year.

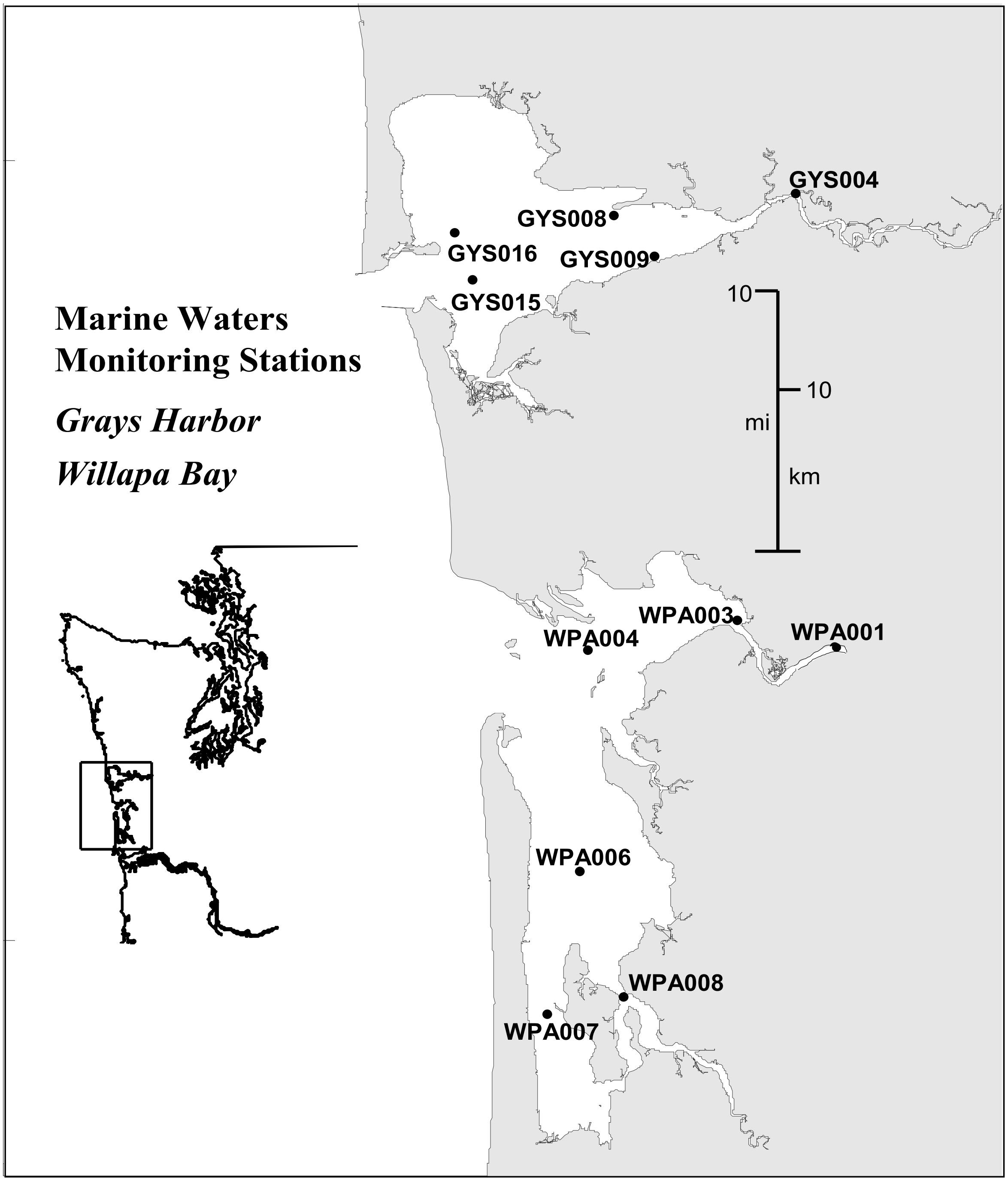


Figure 2. Marine Waters Monitoring stations for WY 1998 – Y 2000 in Grays Harbor and Willapa Bay. All stations are core stations.

Table 1. Marine Waters Monitoring stations sampled during WY 1998 – Y 2000. Station "Type" notation is "C" = core station and "R" = rotational station. Samples listed as 0 m were taken from 0.5 m, except for fecal coliform bacteria sample, which was from 0.1 m.

Station	Type	WY/Y sampled	Lat. (N),	Long. (W)	Basin	Parameters sampled*	Sample depths (m)
Greater Puget Sound:							
ADM002	C	98, 99, 00	48 11.25	122 50.50	E. Str. Juan de Fuca	All	0, 10, 30
DIS001	R	00	48 01.10	122 50.80	E. Str. Juan de Fuca	All	0, 10, 30
DUN001	R	00	48 10.40	123 06.80	E. Str. Juan de Fuca	All	0, 10
SEQ002	R	00	48 04.60	123 01.00	E. Str. Juan de Fuca	All	0, 10
GRG002	C	98, 99, 00	48 48.50	122 57.16	Strait of Georgia	All	0, 10, 30
BLL009	C	98, 99, 00	48 41.16	122 35.90	Strait of Georgia	All	0, 10
BLL011	R	00	48 44.00	122 35.00	Strait of Georgia	All	0, 10
DRA002	R	00	48 59.00	122 45.70	Strait of Georgia	All	0, 10
ADM001	C	98, 99, 00	48 01.80	122 37.00	Admiralty Inlet	All	0, 10, 30
PTH005	C	98, 99, 00	48 05.00	122 45.80	Admiralty Inlet	All	0, 10
PNN001	R	98	48 13.86	122 40.46	Whidbey Basin	All	0, 10, 30
PSS008	R	98	47 58.90	122 13.33	Whidbey Basin	All	0, 10
PSS019	C	98, 99, 00	48 01.00	122 18.45	Whidbey Basin	All	0, 10, 30
SAR003	C	98, 99, 00	48 06.47	122 29.41	Whidbey Basin	All	0, 10, 30
SKG001	R	98	48 23.69	122 34.80	Whidbey Basin	All	0, 10
SKG003	R	98	48 17.90	122 29.25	Whidbey Basin	All	0, 10
SUZ001	R	98	48 08.08	122 22.45	Whidbey Basin	All	0, 10, 30
ADM003	C	98, 99, 00	47 52.75	122 28.91	Central Puget Sound	All	0, 10, 30
CMB003	C	98, 99, 00	47 17.43	122 26.93	Central Puget Sound	All	0, 10, 30
CMB006	R	99	47 15.70	122 26.16	Central Puget Sound	All	0, 10
EAG001	R	98	47 37.30	122 31.30	Central Puget Sound	All	0, 10
EAP001	C	98, 99, 00	47 25.65	122 23.25	Central Puget Sound	All	0, 10, 30
ELB015	C	98, 99, 00	47 35.47	122 22.10	Central Puget Sound	All	0, 10, 30
POD007	R	98	47 44.00	122 39.00	Central Puget Sound	All	0, 10
PSB003	C	98, 99, 00	47 39.60	122 26.50	Central Puget Sound	All	0, 10, 30
QMH002	R	98	47 23.80	122 26.50	Central Puget Sound	All	0, 10
SIN001	C	98, 99, 00	47 32.96	122 38.53	Central Puget Sound	All	0, 10
HCB003	R	99, 00	47 32.22	123 01.35	Hood Canal	CTD/S	
HCB004	C	98, 99, 00	47 21.46	123 01.42	Hood Canal	All	0, 10, 30
HCB006	C	98, 99, 00	47 44.86	122 43.81	Hood Canal	All	0, 10, 30
HCB007	R	99, 00	47 23.90	122 55.70	Hood Canal	CTD/S	
PGA001	R	98	47 50.40	122 34.80	Hood Canal	All	0, 10
BUD002	R	99	47 03.02	122 54.47	South Puget Sound	All	0, 10
BUD005	C	98, 99, 00	47 05.53	122 55.01	South Puget Sound	All	0, 10
CRR001	R	99	47 16.60	122 42.50	South Puget Sound	All	0, 10, 30
CSE001	R	99	47 15.90	122 50.80	South Puget Sound	All	0, 10, 30
CSE002	R	99	47 21.20	122 48.80	South Puget Sound	All	0, 10
DNA001	C	98, 99, 00	47 09.61	122 52.50	South Puget Sound	All	0, 10, 30
ELD001	R	99	47 06.38	122 56.91	South Puget Sound	All	0, 10

ELD002	R	99	47 05.78	122 58.45	South Puget Sound	All	0, 10
GOR001	C	98, 99, 00	47 11.00	122 38.00	South Puget Sound	All	0, 10, 30
NSQ002	C	98, 99, 00	47 10.10	122 47.20	South Puget Sound	All	0, 10, 30
OAK004	C	98, 99, 00	47 12.81	123 04.58	South Puget Sound	All	0, 10
TOT001	R	99	47 09.87	122 57.80	South Puget Sound	All	0, 10
TOT002	R	99	47 07.30	123 01.20	South Puget Sound	All	0, 10
Coastal Estuaries:							
GYS004	C	98, 99, 00	46 58.48	123 46.80	Grays Harbor	All	0, 10
GYS008	C	98, 99, 00	46 56.25	123 54.71	Grays Harbor	All	0, 10
GYS009	C	98, 99, 00	46 57.88	123 56.90	Grays Harbor	CTD/S	
GYS015	C	98, 99, 00	46 55.38	124 04.53	Grays Harbor	CTD/S	
GYS016	C	98, 99, 00	46 57.21	124 05.50	Grays Harbor	All	0, 10
WPA001	C	98, 99, 00	46 41.14	123 44.97	Willapa Bay	All	0, 10
WPA003	C	98, 99, 00	46 42.10	123 50.06	Willapa Bay	All	0, 10
WPA004	C	98, 99, 00	46 41.82	123 58.50	Willapa Bay	All	0, 10
WPA006	C	98, 99, 00	46 32.73	123 58.73	Willapa Bay	All	0, 10
WPA007	C	98, 99, 00	46 27.13	124 00.55	Willapa Bay	All	0, 10
WPA008	C	98, 99, 00	46 27.82	123 56.35	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. No pigment samples are taken at GYS004 and WPA001.

analysis. Determination of 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. For samples collected 1 July 1999 through 31 December 2000, frozen samples were analyzed for chl *a* and phaeopigment by Ecology staff using a Turner 10 fluorometer according to the United States Joint Global Ocean Flux Study protocol (UNESCO, 1994). The two procedures do not differ substantially.

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 Ecology staff using the azide-modified Winkler method (APHA *et al*., 1989) and powdered reagents. The 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 because discrete samples were collected following the CTD cast, and could not obtained at the same time of sensor measurement, these results cannot be used for calibration of the *in situ* sensor.

Discrete salinity samples were analyzed by University of Washington Marine Chemistry Laboratory with 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 4.224 during WY 1998-WYY 1999; version 4.233 during Y 2000). 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 of temperature, conductivity, and pressure. Further details on CTD processing procedures can be found in the CTD Data Acquisition Software Manual (Sea-Bird Electronics, Inc., 2000).

All data from the CTD were entered into Ecology's 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 from the database for WY 1998-Y 2000 of 0.5, 10, and 30-m data are in Appendix A and CTD profiles are in Appendix B.

Quality Assurance/Quality Control

Data Quality Objectives

Table 2 lists the data quality objectives for Ecology's Marine Waters Monitoring program. All target objectives met or exceeded PSAMP QA objectives (PSWQA, 1988) with one exception. The reporting limit for orthophosphate-P was 0.01 mg/L for samples analyzed 1 October 1998 through 18 February 1999, whereas PSAMP requests 0.002 mg/L. After 18 February 1999 the reporting limit satisfies the PSAMP objective.

The QA procedures for MEL are described in Ecology (1988). The QA procedures for the UW lab were reviewed and maintained through its Washington State Accreditation status.

Additional quality assurance procedures for other laboratory analyses and equipment calibration are in Ecology (1988) and Janzen (1992b). Data qualifiers for laboratory 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, pressure, and DO sensors. In-house calibrations were conducted approximately bi-monthly on the

DO and pH sensors and on the light transmissometer. Calibration procedures for these sensors followed protocols in 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 the CTD cast, rather than at the same time. Variation in field conditions between the two estimates is likely high and is unknown.

Discrete Analysis Quality Control Procedures

One station per flight survey was selected for field QC procedures to assess variation associated with field replicates and laboratory analysis. Variables assessed were fecal coliform bacteria, pigments, and nutrients. At the QC station, triplicate water samples for pigment and nutrient analyses were collected using three separate surface (0.5-m) bottle casts each month. Also, replicate surface water samples (at 0.1 m) were collected for fecal coliform bacteria analysis. The field replicates were sent to the laboratory as blind samples. Field replicate results provide an estimate of the sampling and analytical variability. An estimate of analytical variability (due to laboratory analysis procedures) was assessed by analyzing splits of a single water sample. This was conducted in the lab for all three variables.

Table 2. Marine Waters Monitoring data quality objectives.

Analytical parameters	Reporting units*	Reporting limit	Relative standard deviation (RSD)
laboratory analysis parameters:			
ammonium-ME Lab	mg/L	0.01	10%
nitrite-ME Lab	mg/L	0.01	10%
nitrate+nitrite-ME Lab	mg/L	0.01	10%
orthophosphate-ME Lab	mg/L	0.01	10%
ammonium-UW Lab	μM	0.05	≤10%
nitrate-UW Lab	μM	0.1	≤10%
nitrite-UW Lab	μM	0.03	≤10%
orthophosphate-UW Lab	μM	0.03	≤10%
silicate-UW Lab	μM	0.1	≤10%
chlorophyll *a* and phaeopigment	μg/L	0.05	10%
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 to μM 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.
RSD = (std. dev./mean) * 100

Results and Discussion

In WY 1998, 47 of the 48 scheduled weekly monitoring surveys were completed. Of these, 36 of 36 were conducted in Puget Sound and 11 of 12 in Grays Harbor and Willapa Bay. In WYY 1999, 55 of the 60 scheduled weekly monitoring surveys were completed. Of these, 41 of 45 were conducted in Puget Sound and 14 of 15 in Grays Harbor and Willapa Bay. In Y 2000, 47 of the 48 scheduled weekly monitoring surveys were completed. Of these, 36 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 (ºC), salinity (PSU = practical 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 m (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.

Climate

Local weather can influence the water column parameters of Washington inland marine waters noticeably (e.g., Newton, 1995b). Thus it is important to gain an understanding of forcing by weather conditions in a given year. In order to detect how weather, specifically air temperature and precipitation, varied from the long-term mean during the period WY 1998 through Y 2000, anomalies were calculated by subtracting 30-y monthly means (1971-2000) from WY 1998-Y 2000 monthly mean values. Data were for Sea-Tac Airport weather conditions, obtained from the Western Regional Climate Center (http://www.wrcc.dri.edu/) and were split into WYY 1998, Y 1999, and Y 2000, for easier inter-annual comparison. The WYY 1998 period covers 15 months (Oct 1997-Dec 1998).

The long-term means (climatology) of air temperature and precipitation (Figure 3A) show typical Western Washington weather transitioning between relatively cold, wet winter conditions and warm, dry summer conditions. Precipitation anomalies for WYY 1998, Y 1999, and Y 2000 (Figure 3B, C, D) show higher than normal precipitation occurred during November 1998 through February 1999, and again but only in November 1999. Lower than normal precipitation was observed in November-December 2000, and was the indicative of the beginning of a drought period (November 2000-April 2001). Summertime months (May through October) in all years show nearly normal precipitation, with conditions that were slightly drier in Y 2000. For comparison, the precipitation anomaly averaged over a calendar year were 1.48 cm in Y 1998, 1.07 cm in

Y 1999, and -1.78 cm in Y 2000 indicating that 1998 was slightly wetter, 1999 was average, and 2000 was slightly drier than the mean.

The annual mean temperatures for all three years were close to normal; slightly higher than normal in Y 1998 (annual anomaly = 0.41 degrees C) and slightly lower in Y 1999 and Y 2000 (annual anomaly = -0.47 and -0.45 degrees C, respectively). These temperature patterns are consistent with the presence of El Niño conditions during 1997-1998 and La Niña in 1999 through 2000. Warmer (especially winter) air temperatures have been noted during El Niño in the Pacific Northwest (Ropelewski and Halpert, 1986; 1987).

Fresh water flows during this period were either average or above normal. The Skykomish and Chehalis Rivers are two river systems that are considered to be representative of western Washington. The Skykomish deposits into central Puget Sound near Everett while the Chehalis empties into Grays Harbor. During WY 1998, the mean annual flow of the Skykomish and Chehalis Rivers was about normal: 95% and 122%, respectively, of the median long-term flow, (USGS, 1998; http://waterdata.usgs.gov/nwis). During WY 1999, higher flows were recorded: 138% and 156% of the median flow, respectively, (USGS, 1999). During WY 2000, the mean annual flow of the two rivers returned to near normal values: 117% and 105% of the median flow, respectively (USGS, 2000). While nearly all flows were either at or above normal, most of these flows were at lower values than in the previous two WY 1997 and 1996 where flows were at 140-150% of the median long-term flow (Newton *et al.*, 1998a).

In summary, on average, 1998 was warm, wet, and with normal river flows, 1999 was cool, wet to average precipitation, and with higher than normal river flows, and 2000 was cool, dry, and with normal river flows. Note that the temperature and precipitation records from Sea-Tac are assumed to be representative of the same "Western Washington" region as the flow records from the Skykomish and Chehalis for this analysis.

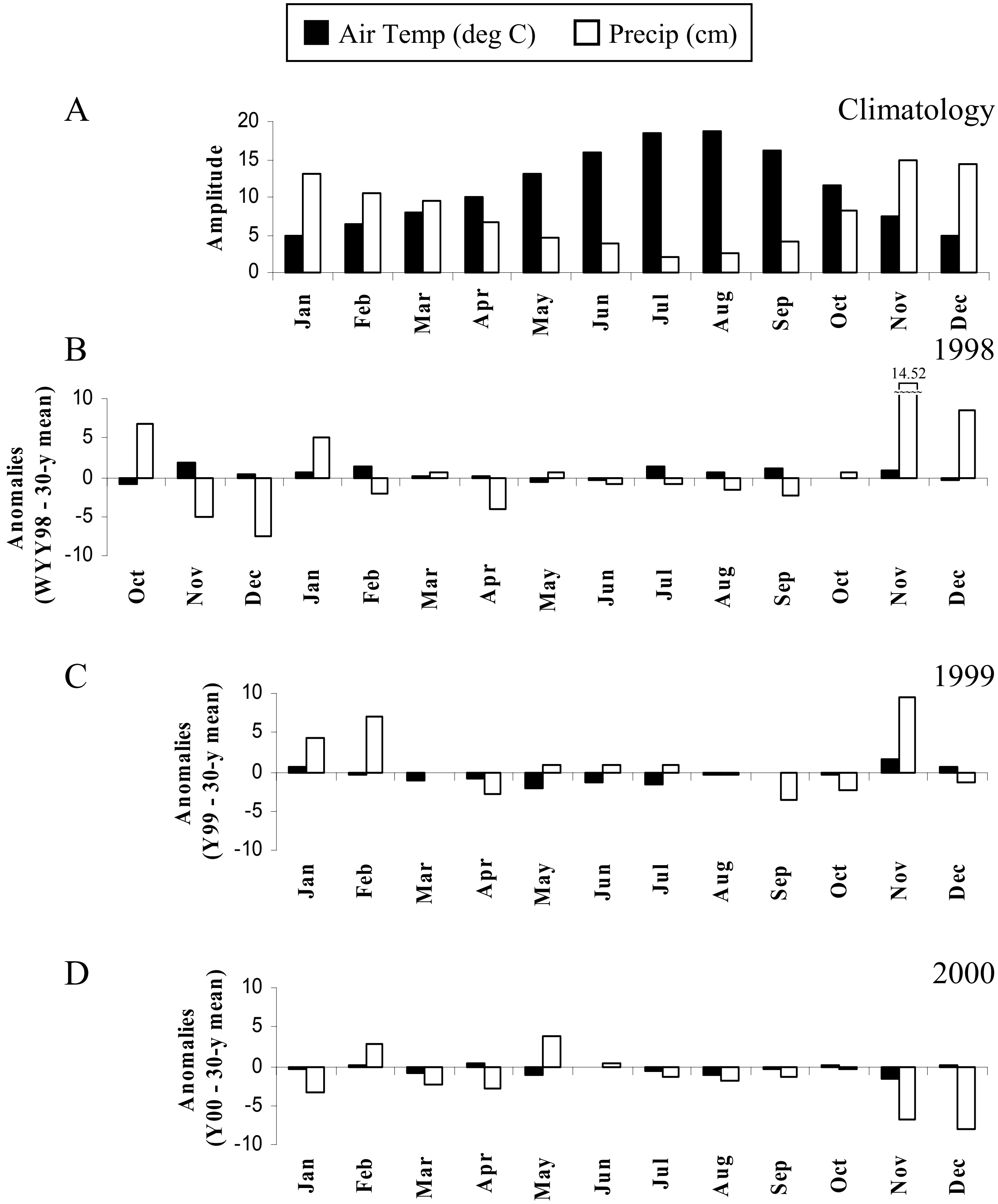


Figure 3. Climate data for WYY 1998, Y 1999, and Y 2000. (A) Climatology (30 year-mean, 1971-2000). (B, C, D) Anomalies for WYY 1998, Y 1999, and Y 2000 air temperatures and precipitation compared to 30-year average. Data obtained from the Western Regional Climate Center (http://www.wrcc.dri.edu/) for Sea-Tac Airport.

Temperature, Salinity, and Density

Individual profiles of temperature (ºC), salinity (PSU), and density (sigma-*t*) with depth (m) obtained from the CTD casts for the Puget Sound, Grays Harbor, and Willapa Bay stations monitored during WY 1998-Y 2000 are in Appendix B.

Temperature and Salinity Anomalies

A seasonal pattern in weather variables as well as marine water temperature and salinity is quite noticeable in the Pacific Northwest region (Figure 3; Appendices A and B). In order to see the influence of local climate on the physical character of Washington marine waters, monthly means and anomalies were calculated for seawater temperature and salinity (Figures 4 and 5). As with air temperature and precipitation, the marine water temperature and salinity anomalies were calculated as the monthly value minus a long-term monthly mean value. The long-term means were based on eleven-years of data, 1990-2000. Since the analysis is for core stations only, the data in Figures 4 and 5 are presented as WYY 1998, Y 1999 and Y 2000, in order to better facilitate inter-annual evaluations and comparisons with the climate records (Figure 3).

Five stations from Puget Sound and one each from Willapa Bay and Grays Harbor were selected for this analysis. The 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, in Budd Inlet, a representative southern Puget Sound estuary with riverine input (Deschutes River), and relatively low mixing due to density stratification.

The stations selected in Grays Harbor, GYS009, and Willapa Bay, WPA004, are located intermediate within these estuaries and thus show influence from both riverine and Pacific Ocean waters. 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. In these estuaries, tidal stage is a strong determinant in the degree of marine versus riverine influence at a given sampling event. River flow and tidal stage strongly influence the monthly values obtained in these coastal estuary sites and neither is addressed in this analysis. It is not logistically possible to control for tidal stage in collecting these monthly data.

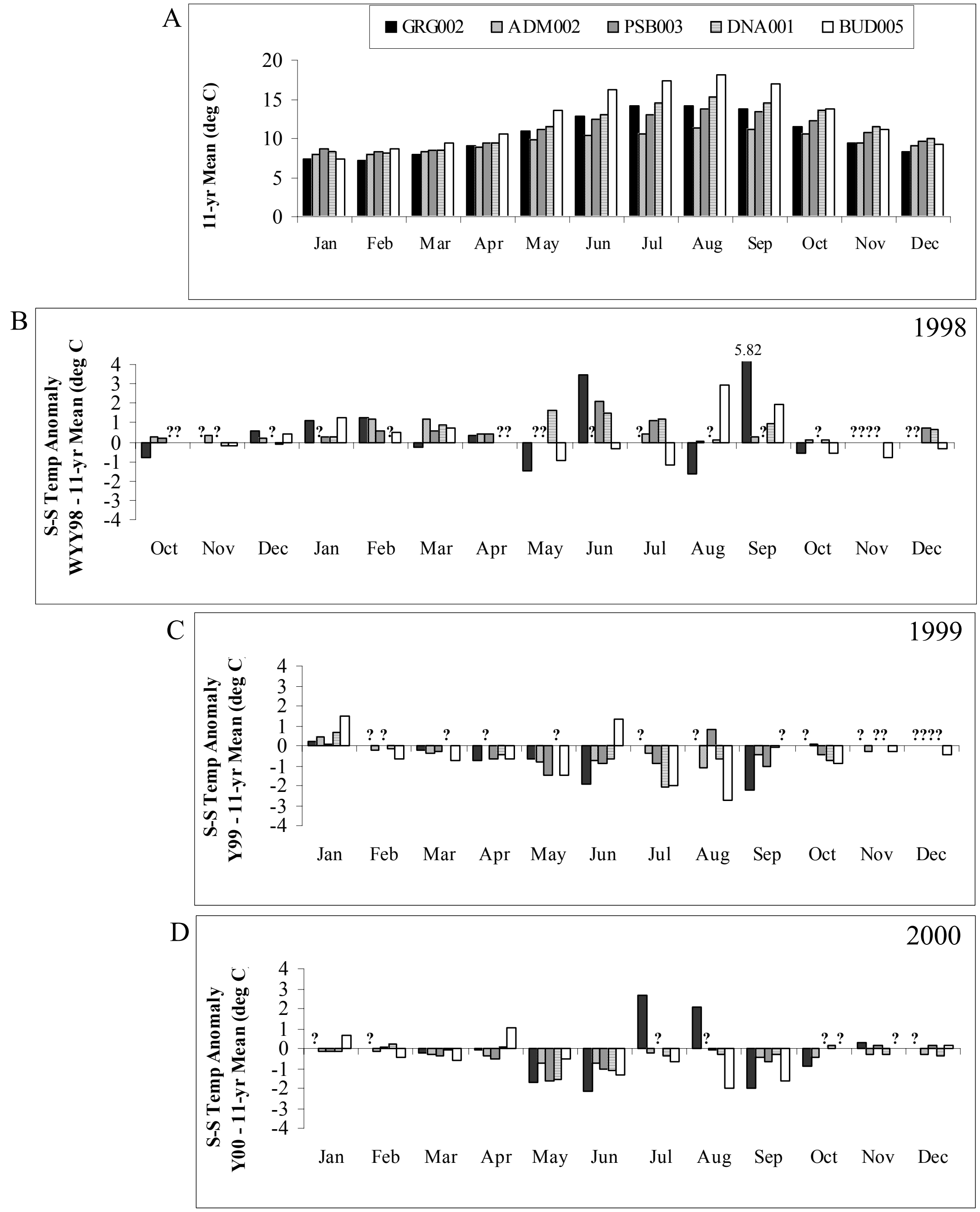


Figure 4. Sea-surface salinity and temperature means and anomalies for several stations in Puget Sound. (A) Eleven-year sea-surface temperature means (WY 1990–Y 2000); (B) WYY 1998 sea-surface temperature anomalies; (C) Y 1999 sea-surface temperature anomalies; (D) Y 2000 sea-surface temperature anomalies. A "?" denotes no data.

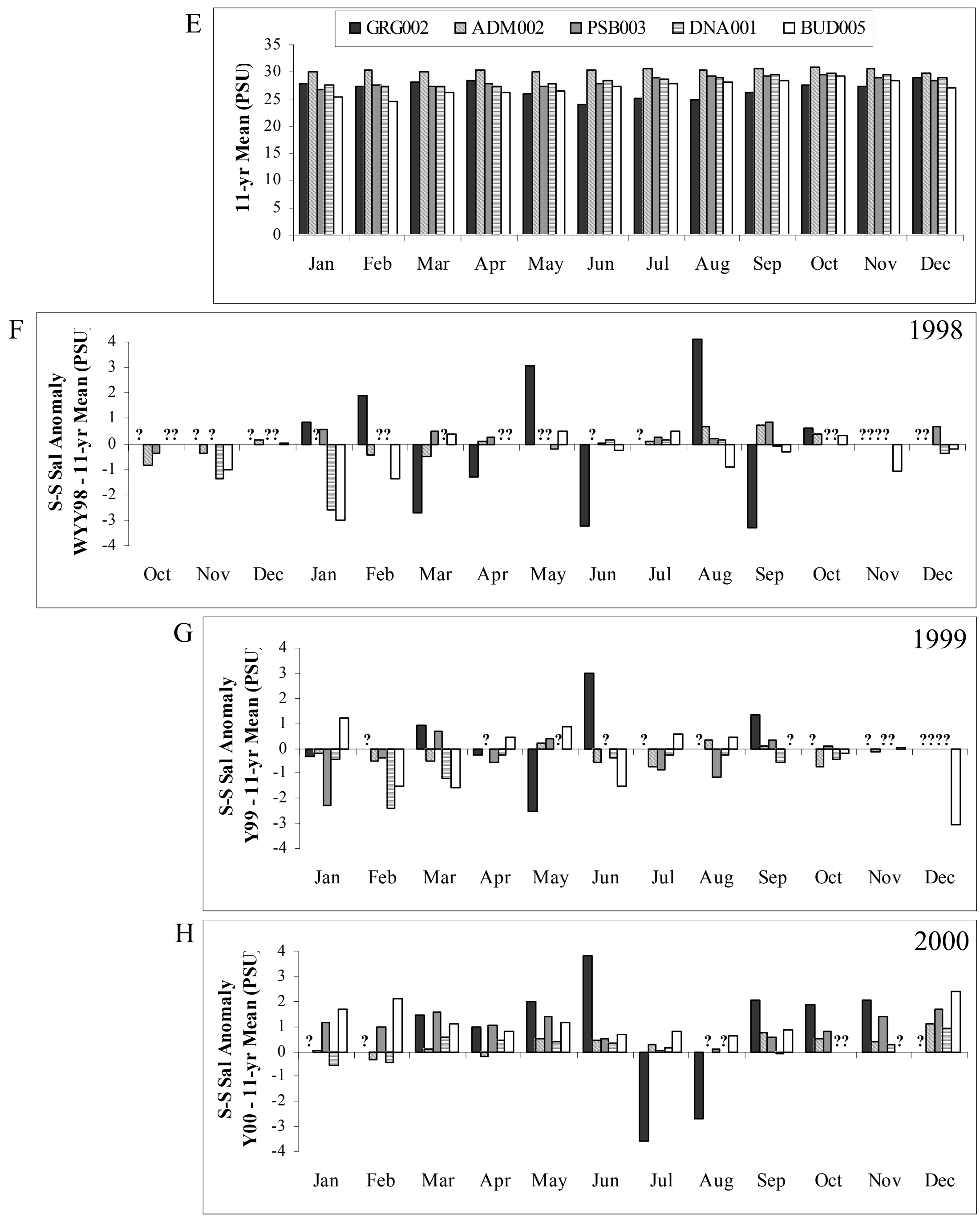


Figure 4. Continued. (E) Eleven-year sea-surface salinity means (WY 1990–Y 2000); (F) WYY 1998 sea-surface salinity anomalies; (G) Y 1999 sea-surface salinity anomalies; (H) Y 2000 sea-surface salinity anomalies. A “?” denotes no data.

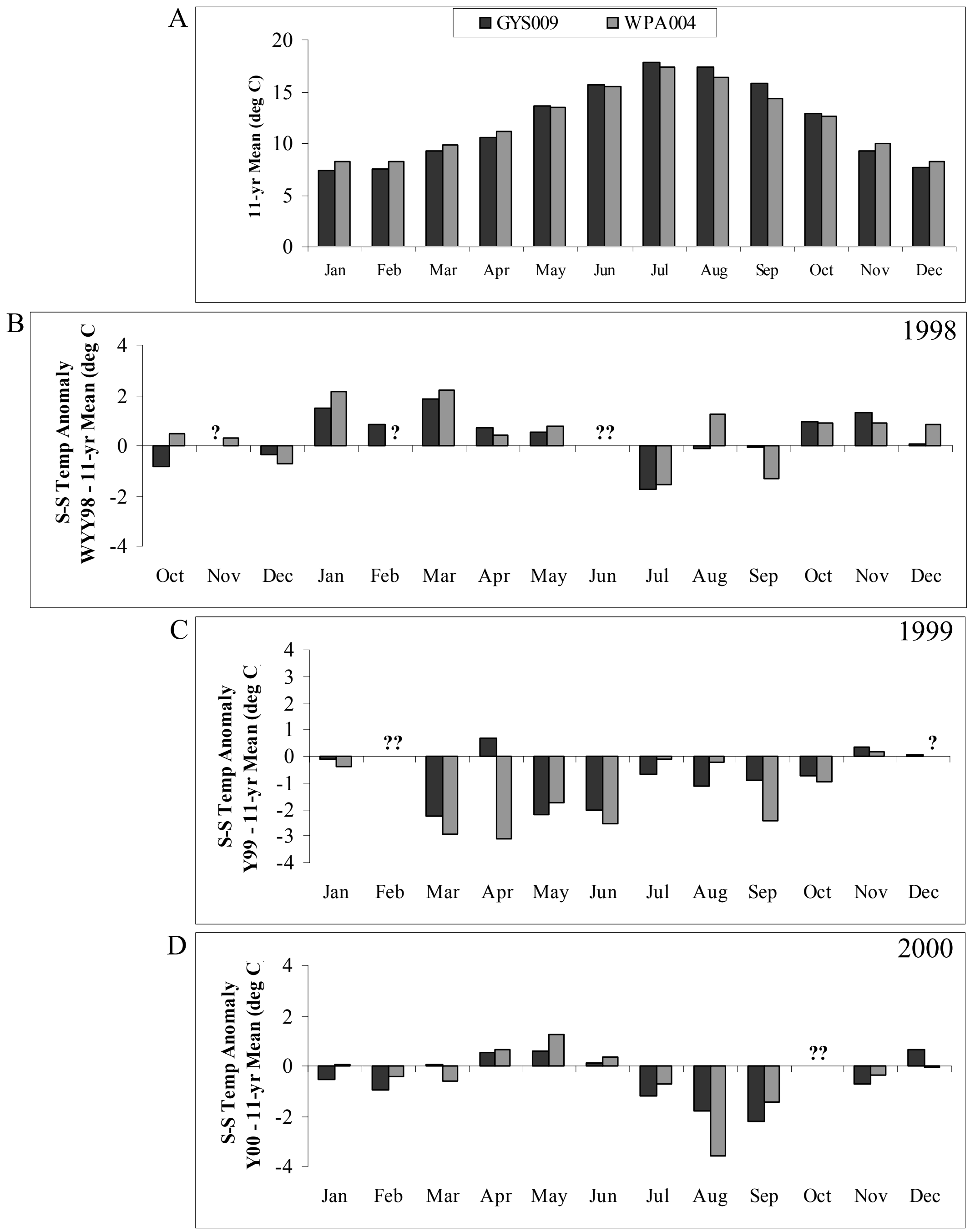


Figure 5. Sea-surface salinity and temperature means and anomalies for one station each of Willapa Bay and Grays Harbor. (A) Eleven-year sea-surface temperature means (WY 1990–Y 2000); (B) WYY 1998 sea-surface temperature anomalies; (C) Y 1999 sea-surface temperature anomalies; (D) Y 2000 sea-surface temperature anomalies. A "?" denotes no data.

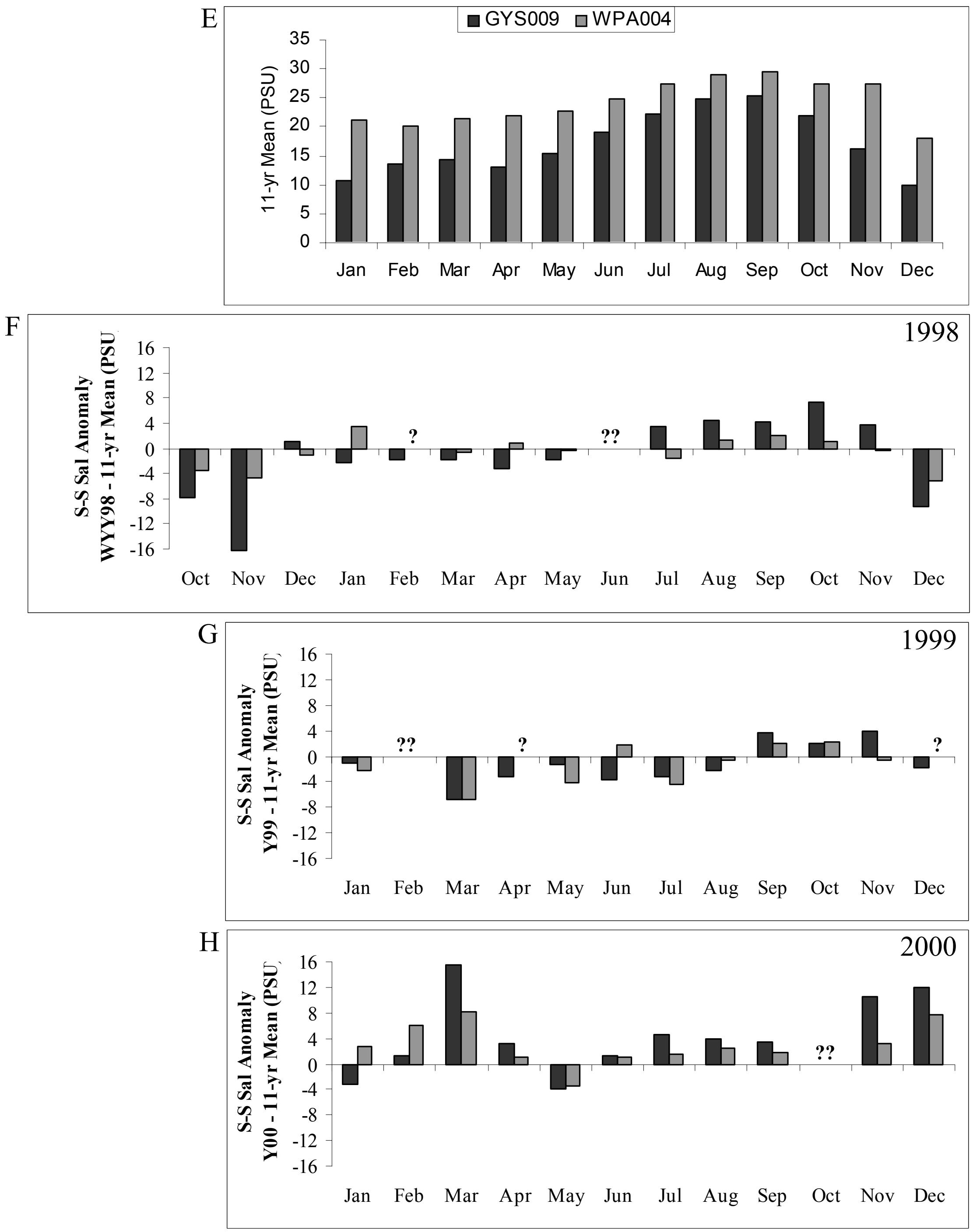


Figure 5. Continued. (E) Eleven-year sea-surface salinity means (WY 1990–Y 2000); (F) WYY 1998 sea-surface salinity anomalies; (G) Y 1999 sea-surface salinity anomalies; (H) Y 2000 sea-surface salinity anomalies. A “?” denotes no data.

The sea-surface temperature (SST) of inland Washington waters is influenced by Pacific Ocean temperature conditions as well as by local air temperatures. In addition, stations proximal to rivers show a temperature influence from river water, 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, 1995b; Newton *et al.*, 1997; 1998a). The SST anomalies for WYY 1998-00 are consistent with this observation. The Puget Sound SST anomalies (Figure 4B, C, D) show a pattern similar to the air temperature anomalies (Figure 3B, C, D), with a preponderance of positive anomalies in 1998 and negative anomalies in 1999 and 2000. Especially marked is summer 1999, which shows negative anomalies in air temperature as well as water temperature.

In the coastal estuaries (Figure 5B, C, D), the SST anomaly pattern is variable except for consistent negative anomalies in summer 1999, coherent with negative air temperature and Puget Sound SST anomalies at the same time. The negative SST anomalies in the coastal estuaries during summer 1999 (2-3 degrees C) are even stronger than in Puget Sound (1-2 degrees C). This is consistent with strong coastal upwelling and a very shallow thermocline off the Pacific coast during 1999 seen at Newport, OR (Smith *et al.*, 2001) with resulting lower sea surface temperatures at the NOAA Cape Elizabeth National Data Buoy (Newton *et al.*, 2000).

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 interest 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 4E and 5E, respectively).

The anomalies for sea-surface temperature and salinity must be interpreted with caution, since the long-term means used were based on only eleven years of monthly data from 1990 to 2000. Adequate data do not exist for calculating monthly means over a longer time period since prior to 1990, monitoring did not occur during winter months. The predominance of El 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 11-y mean. Compounding this shortcoming is that these sea-surface anomalies are based on a single day's value obtained within the month, as opposed to means integrated over the month, as are used for weather data. These factors could result in more noise in the long-term mean.

To assess variation in the long-term mean sea-surface temperatures, we compared the 11-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 of 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 14.5 years, June 1987-Dec 2001). The estuarine SST (0.5 m) means are very similar in magnitude and shape as the oceanic SST (0.6 m) (Figure 6), though 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 at heating the upper layer of 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 than the oceanic station, due to the strong mixing of surface waters with deep waters that occurs consistently at Admiralty Inlet.

Anomalies of sea-surface salinity (SSS) were variable at all Puget Sound stations during WYY 1998 and Y 1999 (Figure 4F, G, H). Anomalies of SSS were consistently positive beginning in Y 2000, coincident with the beginning of the drought. This positive SSS anomaly might be expected given lower than normal precipitation at Sea-Tac (negative 3 cm) and average river flow (had been at 150% of median flow for three of the previous four years). Correlation of SSS anomalies with river flow and precipitation have been observed previously (Newton, 1995b; Newton *et al.*, 1997; 1998a) in Puget Sound. The most variable station in terms of the SSS anomaly is GRG002. Presumably, Fraser River plume waters flow past this station sometimes but other times flow north, bypassing this station. The 11-y long-term signature of SSS indicates an influence of river water on this station (Figure 4D), as compared with ADM002. GRG002 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 show positive and negative excursions (Figure 5 F, G, H). Positively anomalies were observed in late WYY 1998, negative anomalies in Y 1999, and positive anomalies in Y 2000. This pattern is coherent with the highest river flows being in 1999. The positive SSS anomalies in Y 2000 may reflect the 2000-2001 drought; SSS anomaly values range up to 16 PSU, four times stronger than any SSS anomaly observed in Puget Sound. The large inter-annual (SSS anomalies ranged from -16 to +16) as well as seasonal variation in salinity in these coastal estuarine systems as compared with a more muted variation in Puget Sound has implications for the biology and water quality of these systems.

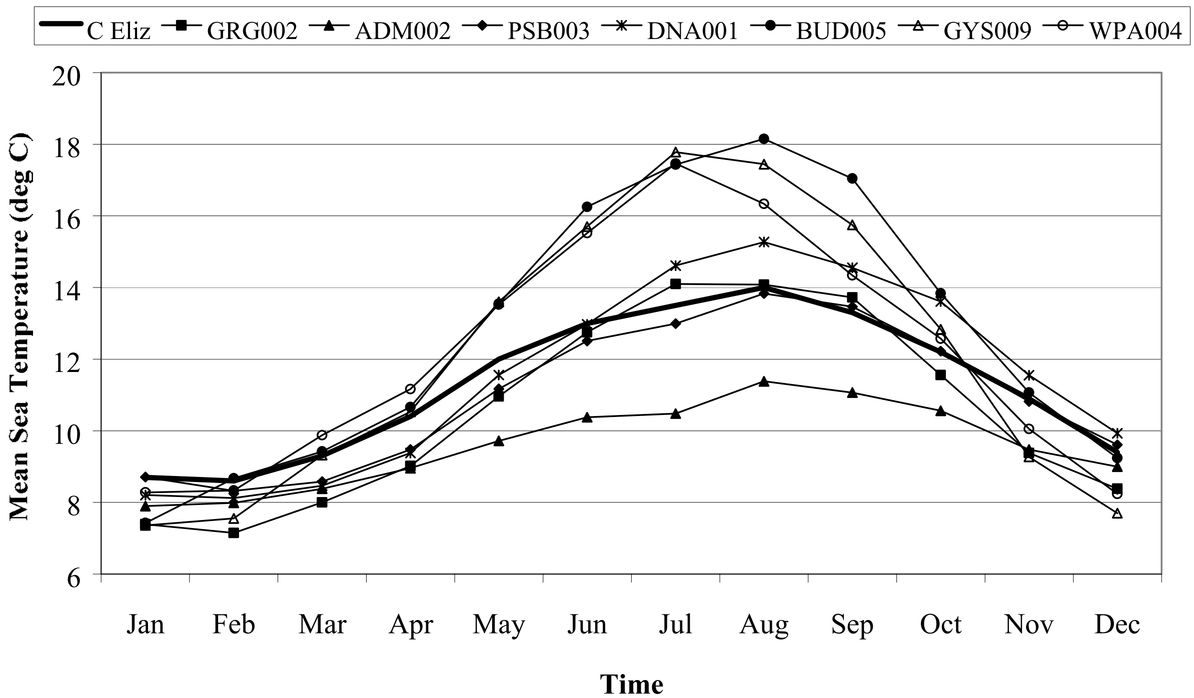


Figure 6. Sea-Surface temperature long-term means for several Ecology monitoring stations and for the NOAA Cape Elizabeth National Data Buoy. Long-term means for Ecology data are from monthly values from WY 1990 - Y 2000; long-term means for Cape Elizabeth data buoy are from hourly values from June 1987 - December 2001, as presented on the NOAA National Data Buoy Center website (www.ndbc.noaa.gov).

Density Stratification

Stratification refers to the horizontal layering of water masses due to density differences. A stratified water column will show distinct layers with less dense waters overlying more dense waters. Water density is affected by both temperature and salinity, increasing with decreasing temperature or with increasing salinity. A change in density of 1 kg m^{-3} can be effected either by a 5ºC 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 seawater density of 1026.95 kg m^{-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 Puget 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 of the Washington State marine waters monitoring stations sampled exhibited distinct 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).

Although much variation is evident, general stratification patterns can be identified based on intensity and duration (Table 3). Four patterns are differentiated: Strong-Persistent, Strong-Intermittent, Moderate-Infrequent, and Weak-Infrequent. To assign these patterns using station data, a matrix (Figure 7) was developed with three levels of stratification intensity on one axis. Weak, Moderate and Strong stratification were defined as delta sigma-*t* of 0-0.5, >0.5-2.0, and >2.0, respectively. The assessment was based on the change in sigma-*t* over the entire water column. The other axis of the matrix was stratification frequency, with three levels: Infrequent, Intermittent, and Persistent, defined as stratification of delta sigma-*t* occurring 0-33, >33-67, and >67-100 % of the times sampled. Delta sigma-*t* was measured over the entire water column.

The stratification patterns shown in Table 3 and Figure 8 were derived from analysis of data collected from WY 1990-Y 2000 (WY 1990 is when depth profiles were first obtained for Ecology monitoring stations). This categorization differs from previous analyses of these data (e.g., Newton *et al.*, 1997; 1998a), where the four categories used Persistent, Seasonal, Episodic, and Weak. The previous analysis did not address strength and duration consistently and was based on ‘eye-balling” annual profile data, rather than calculations over several years’ data.

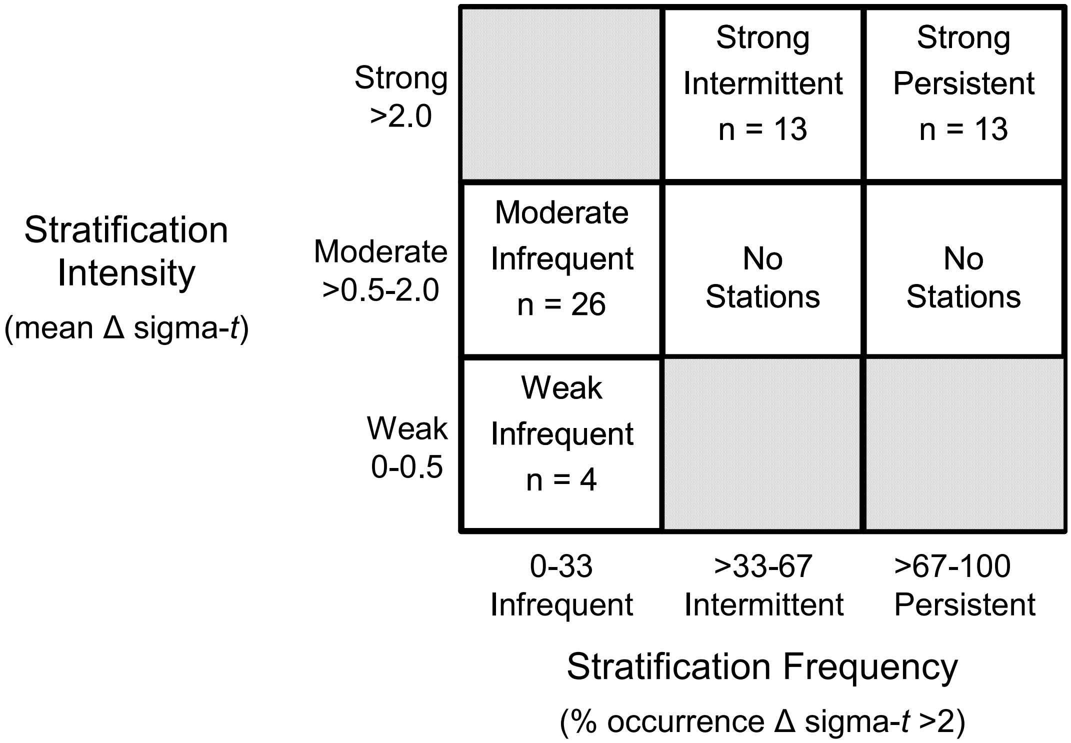


Figure 7. Matrix for classifying density stratification at Marine Waters Monitoring stations. Numbers of stations (n) in each category are noted; shaded cells are mathematically impossible to attain.

Of the 56 stations monitored during WY 1998-Y 2000, the stratification regime at nearly one-half of the stations sampled (n=26) were classified as Moderate-Infrequent. An equal portion was observed to have Strong stratification, with 13 being Persistent and 13 being Intermittent. The remaining 4 stations were categorized as having Weak-Infrequent stratification. Moderate and Strong stratification patterns were most common and reflect the importance of freshwater inputs to the region's marine waters. The stations with Weak-Infrequent stratification were generally areas of high mixing (i.e. large tidal currents) or low freshwater input.

The patterns defined are general categorizations; important features, such as the depth of the pycnocline, vary among stations. Station CMB003, which shows Strong-Persistent stratification, has a very shallow (~5 m) pycnocline whereas station SAR003, also with Strong-Persistent stratification, generally has a deeper (~10-20 m) pycnocline. This may have implications for water quality properties such as oxygen and fecal coliform concentrations.

Annual stratification patterns in Grays Harbor and Willapa Bay were classified the same way as the Puget Sound stations, but show more intra-annual variation (Appendix B).

Both Grays Harbor and Willapa Bay have significant river inputs. Tidal stage plays a very strong role in whether a freshwater layer will be observed at a particular station at a given time, which was not controlled for in this analysis. All but one of the five Grays Harbor stations show either Strong-Persistent or Strong-Intermittent stratification (Table 3). Willapa Bay exhibits more variation, with only two stations with Strong-Intermittent, three stations with Moderate-Infrequent, and one station with Weak-Infrequent stratification. Tidal mixing in this relatively shallow estuary (10 m or less), more variable river input, plus mixing affected by wind stress may overcome stratification. Sampling with respect to tidal stage would be necessary to accurately determine annual or seasonal patterns and to further understand the dynamics of stratification in these estuaries.

Table 3. Classification of WY 1998 – Y 2000 Marine Waters Monitoring stations according to observed stratification pattern. Former rankings from Newton *et al.*, 1998a are shown in parentheses (P=Persistent; S=Seasonal; E=Episodic; W=Weak).

Strong-Persistent	Strong-Intermittent	Moderate-Infrequent	Weak-Infrequent
BUD002 (P)	ADM003 (S)	ADM001 (S)	DNA001 (W)
CMB003 (P)	BLL009 (P)	ADM002 (S)	EAG001 (W)
HCB003 (P)	BLL011 (P)	BUD005 (P)	SEQ002
HCB004 (P)	CMB006 (P)	CRR001 (S)	WPA007 (E-W)
HCB007 (P)	ELB015 (P)	CSE001 (S)	
PNN001 (P)	GRG002 (S)	CSE002	
PSS008 (P)	HCB006 (P)	DIS001 (S)	
PSS019 (P)	OAK004 (E)	DRA002 (S)	
SAR003 (P)	SKG001 (P)	DUN001	
SKG003 (P)	GYS008 (P-E)	EAP001 (S)	
SUZ001 (P)	GYS015 (P-E)	ELD001 (S)	
GYS004 (P-E)	WPA001 (P-E)	ELD002	
GYS009 (P-E)	WPA003 (P-E)	GOR001 (E)	
		NSQ002 (E)	
		PGA001	
		POD007	
		PSB003 (E)	
		PTH005 (W)	
		QMH002	
		SIN001 (E)	
		TOT001 (E)	
		TOT002	
		GYS016 (P-E)	
		WPA004 (E-W)	
		WPA006 (E-W)	
		WPA008 (E-W)	

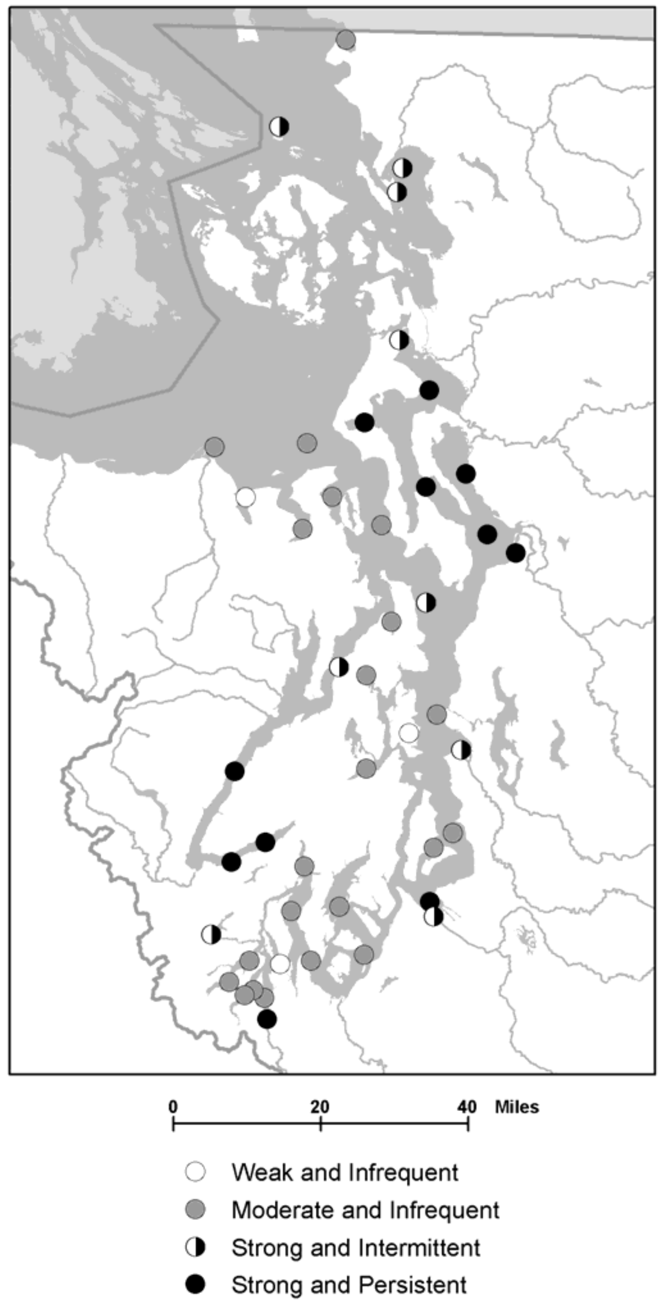


Figure 8. Stratification patterns for Puget Sound Marine Waters Monitoring stations based on data from WY 1990 – Y 2000.

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 Puget Sound, Grays Harbor, and Willapa Bay stations monitored during WY 1998-Y 2000 are in Appendix B.

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 for organisms is not well explored for Washington marine waters.

It should be considered that DO concentrations in the water column recorded with the CTD may overestimate 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, with lower values directly above the sediments.

Hypoxia, meaning low oxygen, is regarded as a DO concentration that is 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; Bricker *et al.*, 1999). 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 detected in the water column. The value of 5 mg/L was chosen as an indicator of low DO concentrations that may 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.

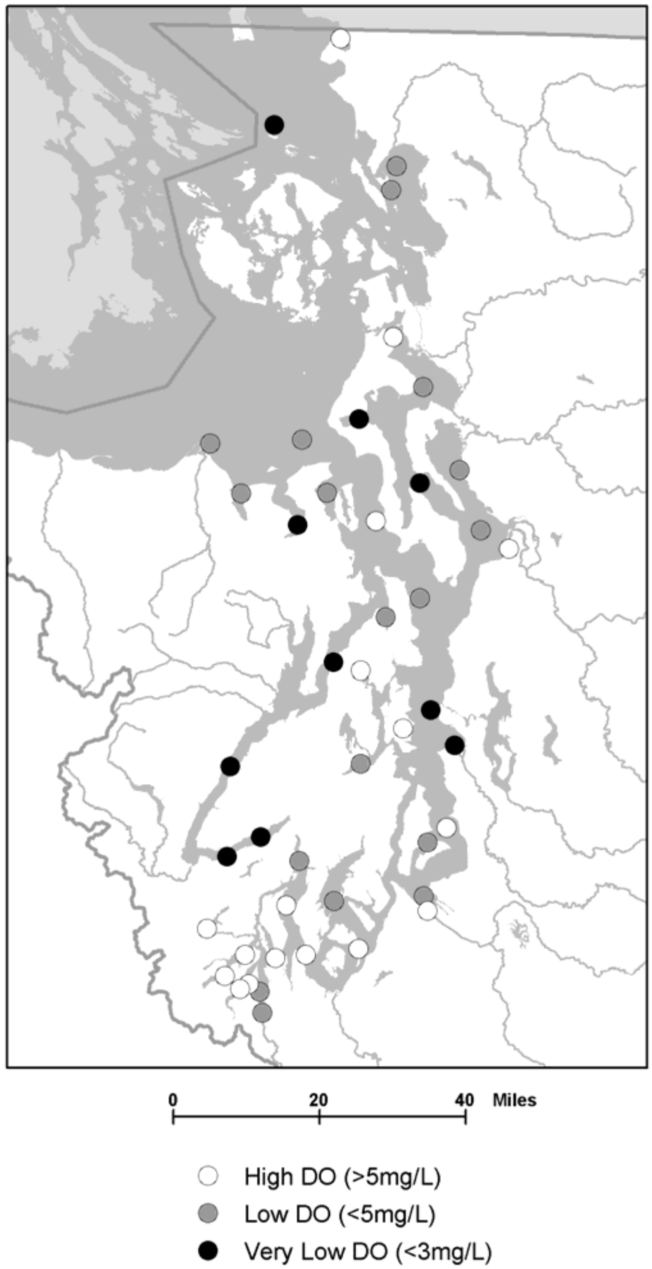


Figure 9. Puget Sound stations with minimum dissolved oxygen concentrations within the water column < 3mg/L, <5mg/L, and >= 5 mg/L detected at any time during WY 1998 – Y 2000.

Biologically stressful levels of DO were seen at several stations during WY 1998-Y 2000 (Table 4; Figure 9). Some of the low DO occurrences reflect natural conditions and some may indicate anthropogenic effects. It is difficult to establish whether the DO concentration in a given waterbody is being impacted by anthropogenic means. The natural productivity of the region is quite high, which produces seasonally low DO. Long time-series of reliable DO measurements to allow comparisons between current and historical data do not exist for many areas. Another compounding factor is the prevalence of coastal upwelling in our region. Upwelling, bringing deep waters with naturally low DO concentrations to the surface, occurs regularly off the Pacific coast as well as within basins like Puget Sound.

Strong oceanic input and flushing, as are evident in Puget Sound, have interesting implications for water quality and human impacts on DO concentrations. It can be both beneficial to water quality yet render the system even more sensitive to human activities that might lower DO concentrations. Seasonally, the Pacific Ocean waters entering Puget Sound through the Strait of Juan de Fuca are predominately upwelled deep oceanic waters that have naturally low DO concentrations. This low DO signal can be seen at ADM002 and other locations and is strongest in late summer when upwelling favorable winds are strongest. The flushing of the Puget Sound basin with oceanic waters can reduce potential water quality impacts from human activities by decreasing stagnation. 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 will have a more profound water quality impact, since the initial concentration is already about at the limit where some species encounter 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 very unique system in this respect. Human contributions to DO debt must be carefully evaluated.

Whether water quality at a particular DO concentration above or below a certain threshold is natural or is being impacted by human activities is very 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, in response to the Federal Clean Water Act. Waterbodies impaired due to human activity effects on DO are shown in the 303(d) list, appended to the 305(b) report (Ecology, 2000; http://www.ecy.wa.gov/programs/wq/303d/1998/wrias/1998_water_segs.pdf). 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 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 for stations where natural conditions, such as upwelling, cause DO to be depressed below the station's criteria, when DO is degraded by more than 0.2 mg/L over the natural level.

For the 50 Puget Sound stations monitored during WY 1998-Y 2000, 28 were recorded with DO concentrations below 5 mg/L. Of these, 19 had records showing these low concentrations in more than one month of a given year. Only 14 stations (shown in bold in Table 4) were judged as not meeting State water quality standards for DO, resulting in these being listed on the State of Washington 303(d) list for 1998 (Ecology, 2000). The State 303(d) listing process evaluates Marine Waters Monitoring data over the last 10 years as well as data from other sources. Of the eleven coastal estuary stations, only one station in Willapa Bay (WPA001) went below the DO threshold of 5 mg/L, but this was for only one month (Sept. 1999). No coastal estuary station was listed for DO on the 1998 State 303(d) list.

Understanding how much natural processes are affecting DO concentrations is important if human impacts on DO are to be identified. 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 affect ambient levels of DO and its distribution both vertically and horizontally. Other factors affecting DO include sediment oxygen demand and chemical oxidation processes.

Attribution of low DO concentrations to natural versus anthropogenic effects is very difficult to assess, especially from monthly monitoring data alone. Irrespective of source, DO of biologically significant low concentration was relatively prevalent in Puget Sound during WY 1998-Y 2000, with twenty-eight stations exhibiting DO concentrations <5 mg/L, and three locations, Hood Canal, Penn Cove, and Saratoga Passage, showing DO concentrations <3 mg/L for more than one month.

The monitoring program is designed to screen stations for low DO, as well as to monitor for trends. Trends can only be viewed for stations that are monitored consistently, both in time and methods. Only since 1993 have CTD casts been conducted all the way to the seabed. Even after then, the data can be misleading since not all stations are monitored every month due to bad weather or other reasons for missed sampling. For the 16 Puget Sound core stations monitored since January 1993[1], the percentage of stations showing an occurrence of concentrations of DO ≤ 5 mg/L in one or more months of a given year shows a similar pattern as the percentage of observations of low DO in a year (Figure 10). This variation shows strong inter-annual variation, but no clear trend. Further analysis against climate and ocean related drivers is recommended.

[1] ADM001, ADM002, BLL009, BUD005, CMB003, DNA001, ELB015, GRG002, HCB004, HCB006, OAK004, PSB015, PSS019, PTH005, SAR003, SIN001

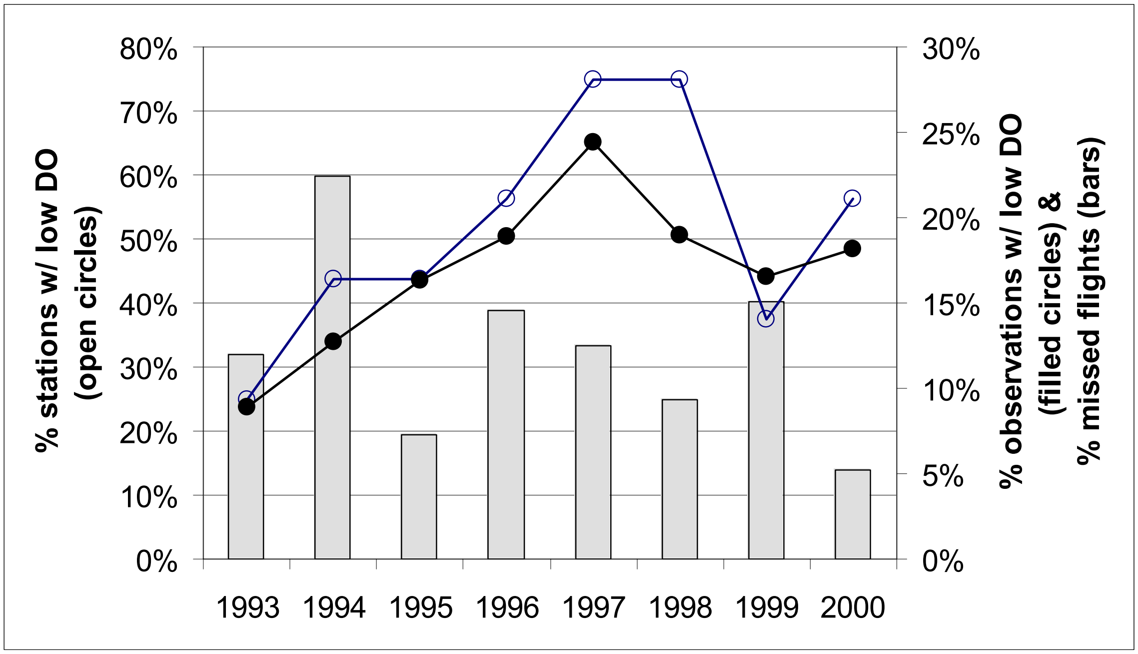


Figure 10. Occurrence of low dissolved oxygen (<5 mg/L) from WY 1993 – Y 2000. Shown is the percent of stations with low DO (open circles) as well as the % of the observations with low DO (filled circles). The percent of missed observations in a given year is shown by the bar.

Better assessment of the interannual variation in low DO would entail analysis of a variety of factors including flushing time, DO concentration of incoming ocean water (which may be related to upwelling intensity), river runoff (which may stimulate flushing but increase stratification), sunlight, and anthropogenic or natural increase in nutrient supply (stimulating organic production for nutrient-limited populations). A plot of the number of occurrences of low DO at core stations in a given month for the 1993 through 2000 period is shown in Figure 11, along with the Bakun upwelling index at 48° N, 125° W (http://www.pfeg.noaa.gov/). No strong correlation is evident, however reduced upwelling associated with the 1997-8 El Niño is seen in association with a high number of occurrences of low DO. The suppressed upwelling has been hypothesized to have affected how much flushing occurred in Puget Sound that period, since the incoming oceanic water was less dense it did not displace the Puget Sound water as effectively (Kawase, 2002). Clearly the natural processes regulating DO concentrations in Puget Sound are complex and require better assessment so that anthropogenic causes for reduced DO can be determined.

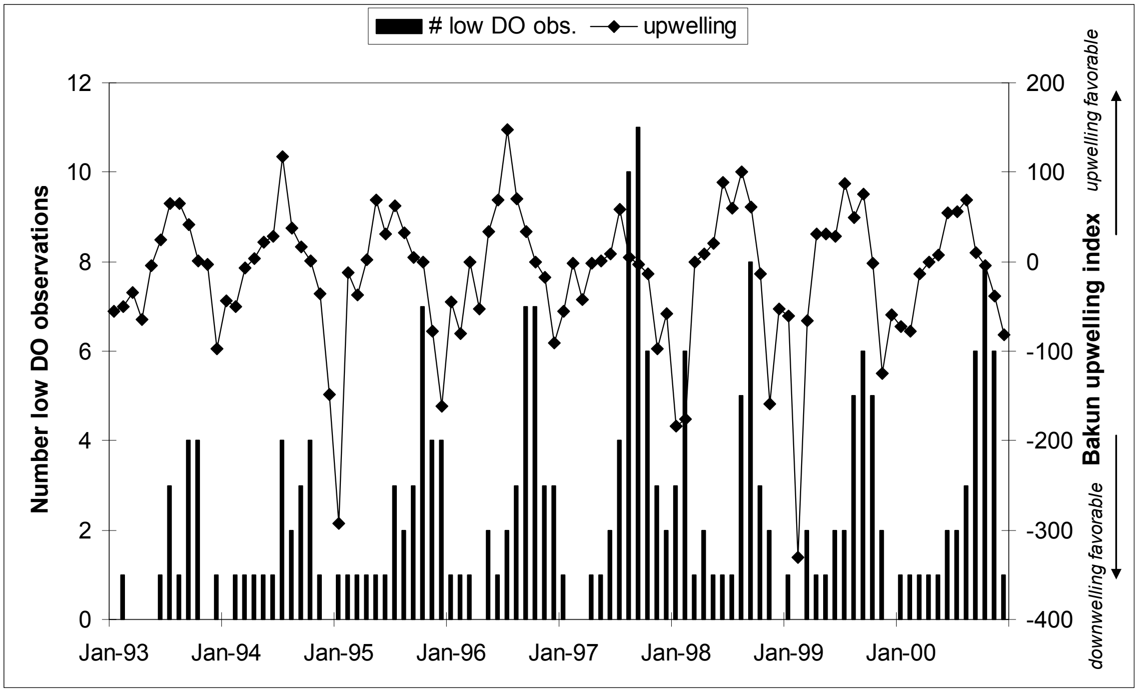


Figure 11. Number of observations of dissolved oxygen concentrations <5 mg/L at core stations and the Bakun upwelling index at 48° N, 125° W for 1993 through 2000. Note that the number of observations in a given month can be biased due to missing flights, see text.

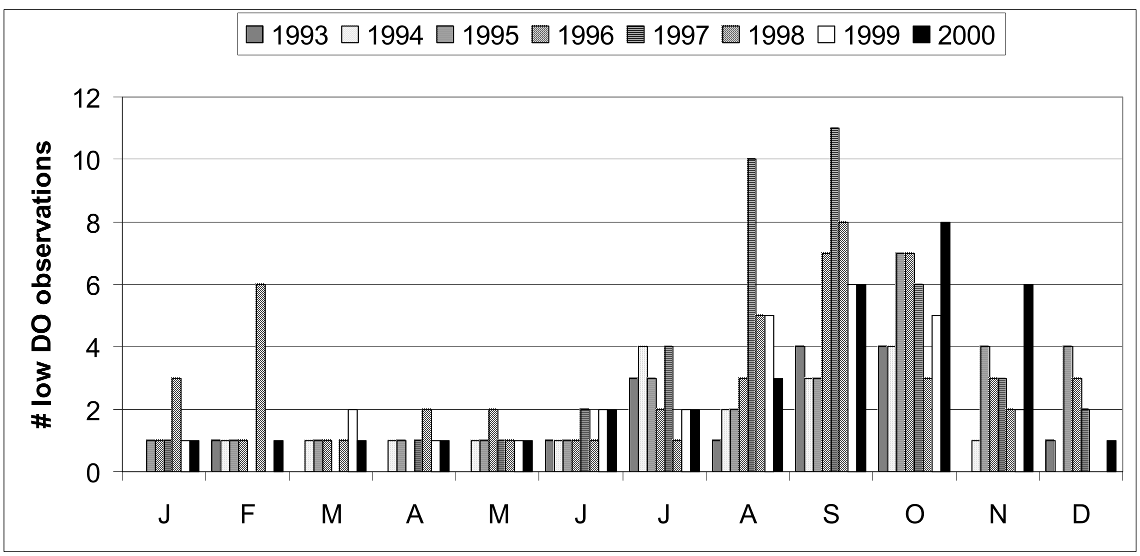


Figure 12. Number of observations in a given month of dissolved oxygen concentrations <5 mg/L for years 1993 through 2000. All data transformed to calendar year for this figure.

Analyzed over the course of a calendar year, the occurrences of low DO are most common in Sep and Oct. Viewing the data from such events at the core stations over WY 1993 through Y 2000 reveals a few periods with anomalously high records of low DO (Figure 12) in recent years. Late summer 1997 (Aug and Sep), early 1998 (Jan and Feb), and late 2000 (Oct and Nov) emerge as times when anomalously high observations of low DO occurred. Whether there was any effect on DO concentrations from the 1997-1998 El Niño or the 2000 drought should be further analyzed. Such analysis is outside the scope of this report.

While the number of stations with low DO was quite high in 1998 relative to 1999 and 2000, the number of occurrences of low DO at all 16 stations in a given year was relatively similar among 1998, 1999, and 2000, with 33, 27, and 33 observations, respectively, in a given year. This indicates low DO was found more widespread 1998 but more frequently at fewer stations in 1999 and 2000.

Strong density stratification appears to be well correlated with low DO concentrations. Thirty of the thirty-one stations where DO concentrations fell below 5 mg/L experienced strong or moderate stratification (Table 3). Excluding the coastal estuary stations, all eleven Puget Sound stations with Strong-Persistent stratification (Table 3) exhibited low DO (Table 4) except one (PSS008) and all nine stations with Strong-Intermittent stratification exhibited low DO except three (CMB006, OAK004, SKG001). The one coastal estuary station with low DO (WPA001) also had Strong-Intermittent stratification. 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. Further implications of density stratification on water quality are included in the General Discussion.

Notable exceptions to the utility of using strong stratification as an indicator for where low DO may occur are stations within Grays Harbor and Willapa Bay, the coastal estuaries. While stratification is important, the residence time of the deep waters also will influence if low DO conditions occur. The coastal estuaries, Willapa Bay and Grays Harbor, while having strong and moderate stratification in some portions, are relatively well flushed with ocean waters due to short residence times in the bay. The residence time is how long water remains a part of the bay before it is flushed out to sea. A long residence time allows more oxidation of organic material to occur before these waters exit the estuary. In Willapa Bay and Grays Harbor, relatively shallow depths, consistent river input, and strong tidal forcing all contribute to produce flushing times that are much less than in Puget Sound. Thus, it is less likely that low DO concentrations will be evident in these well-flushed estuaries.

Another factor influencing low DO is proximity to recently upwelled oceanic waters. Half of the twelve Puget Sound stations having only Moderate or Weak stratification are close to the Strait of Juan de Fuca, where upwelled oceanic waters are seasonally common (e.g., SEQ002, DUN001, PTH005, DIS001, PGA001, and ADM002). However, this factor may not be the only reason for the low DO observed at these locations.

Table 4. Stations with low DO concentrations during WY 1998 – Y 2000, their State waterbody class and stratification ranking (from Table 3). Also indicated, in italics, are stations reported on the 1998 303(d) listing as impaired waterbodies due to violation of State DO standards from anthropogenic sources. State water quality DO criteria for class AA, A and B waters are 7, 6 and 5 mg/L, respectively. The "-" indicates not monitored.

Station	State waterbody class	Stratif. rank	# observations DO < 5 mg/L			**# observations DO < 3 mg/L**		
			WY1998	WYY1999	Y2000	**WY1998**	**WYY1999**	**Y2000**
ADM002	AA	MI	7	1	3			
ADM003	AA	SI	1					
BLL009	A	SI	1					
BLL011	A	SI	-	-	2	**-**	**-**	**1**
BUD002	B	SP	-	1	-	**-**		**-**
BUD005	A	MI	1					
CMB003	A	SP			2			
CRR001	AA	MI	-		1	**-**		**-**
CSE002	AA	MI	-	1	-	**-**		**-**
DIS001	AA	MI	-	-	5	**-**	**-**	**1**
DUN001	AA	MI	-	-	2	**-**	**-**	
ELB015	A	SI	3	1	2	**1**		
GRG002	AA	SI	1	3	1		**1**	
HCB003	AA	SP	-	10	9	**-**	**3**	**3**
HCB004	AA	SP	12	12	12	**12**	**9**	**9**
HCB006	AA	SI	4	4	3	**2**		
HCB007	AA	SP	-	8	9	**-**	**7**	**6**
PGA001	A	MI	5	-	-		**-**	**-**
PNN001	A	SP	11	-	-	**6**	**-**	**-**
PSB003	AA	MI	1			**1**		
PSS019	A	SP	4	6	5			
PTH005	A	MI	1		1			
QMH002	AA	MI	1	-	-		**-**	**-**
SAR003	A	SP	4	3	4	**2**		
SEQ002	AA	WI	-	-	2	**-**	**-**	
SIN001	A	MI	2					
SKG003	A	SP	5	-	-		**-**	**-**
SUZ001	A	SP	6	-	-		**-**	**-**
WPA001	A	SI		1				

Of the remaining six Puget Sound stations with Moderate-Infrequent stratification but low DO, four are in Southern Puget Sound (CSE001, CRR001, BUD005, QMH002), an area that Ecology has identified as being susceptible to eutrophication (Albertson *et al.*, 2002). The other two are SIN001 and PSB003.

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 station of the same waterbody classification for reasons that are not due to 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 historical data; however Ecology DO data was collected down to 30 m with a CTD starting in WY 1990, to 50 m in WY 1992, and to the seabed starting in WY 1994. Historical Ecology data was not as well 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 1998-Y 2000 are Hood Canal, Penn Cove and, to a much less extent, Saratoga Passage, Bellingham Bay, Discovery Bay, Elliott Bay, Strait of Georgia, and West Point. Additional areas showing near-hypoxia from previous years are Budd Inlet and East Sound Orcas Island.

Hood Canal

HCB004: Sisters Point

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	0.56	2.5-3.5, 12, 16	4 -11, 12.5 -15.5, 16.5 -50.5	50.5
Nov-97	0.88	3.5-4.5	5 -52.5	52.5
Dec-97	0.93	3-4	4.5 -37.5	37.5
Jan-98	1.15	6-11.5	12 -48.5	48.5
Feb-98	0.88	5-10	10.5 -52.5	52.5
Mar-98	2.05	6-8.5	9 -44.5	44.5
Apr-98	2.02	7.5-9.5	10 -44.5	44.5

May-98	1.26	9.5-12	12.5 -43	43
Jun-98	1.60	7-10	10.5 -47.5	47.5
Jul-98	0.60	8.5-11	11.5 -50.5	50.5
Aug-98	0.47	10.5-12.5	13 -50.5	50.5
Sep-98	1.84	4.5-6	6.5 -44	44
Oct-98	2.45	2-3, 11-47	3.5 -10.5	47
Nov-98	2.57	5-20.5	21 -47	47
Jan-99	3.36	10-46.5	-	46.5
Mar-99	3.27	13-48.5	-	48.5
Apr-99	3.38	10.5-49	-	49
May-99	2.36	9.5-46, 51	46.5 -50.5	51
Jun-99	2.34	13-22.5	23 -43.5	43.5
Jul-99	1.61	10-12.5	13 -50.5	50.5
Aug-99	0.10	5.5-7.5	8 -43.5	43.5
Sep-99	0.26	6.5-9	9.5 -50.5	50.5
Oct-99	1.30	4-4.5	5-50	50
Nov-99	2.47	1.5-16.5	17 -48	48
Jan-00	3.50	17.5-48	-	48
Feb-00	3.87	10.5-42.5	-	42.5
Mar-00	2.70	9.5-21	21.5 -39.5	39.5
Apr-00	2.31	13-18, 19	18.5, 19.5 -47	47
May-00	2.19	10-21	21.5 -48	48
Jun-00	1.01	8-11.5	12 -46.5	46.5
Jul-00	0.95	9.5-12	12.5 -33.5	33.5
Aug-00	0.54	2.5-3.5	4-48	48
Sep-00	0.44	8.5-11	11.5 -32	32
Oct-00	1.06	1.5-2.5, 27-28, 29.5	3 -26.5, 28.5 -29, 30 -50	50
Nov-00	2.27	2-5.5	6 -38.5	38.5
Dec-00	3.04	1-47	-	47

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 sill located at Sister's Point, in approximately 50 m water depth. This station has Strong-Persistent stratification, with a pycnocline typically located in the upper 15 m. DO concentrations below 5 mg/L were recorded year-round: 12 out of 12 months monitored in WY 1998, 12 out of 12 months monitored in the 15-month WYY 1999, and 12 out of 12 months monitored in Y 2000. This recent pattern is reasonably consistent with data from previous years, from WY 1997 back through WY 1991. However, hypoxic conditions (<3 mg/L) were recorded more frequently during WY 1998 (12 months), WYY 1999 (9 months), and Y 2000 (9 months), as compared to 6, 4, 9, 4, 2, 5, and 4 months in WYs 1997 through 1991, respectively. Near anoxic conditions (>0.5 mg/L) were also seen during WY 1998-Y 2000 that were only seen before during WY 1991, 1992, and 1997, but were seen in each WY 1998, WYY 1999, and Y 2000.

HCB007: Lynch Cove

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-98	0.00	3-4	4.5 -11.5	11.5
Nov-98	2.48	6-17.5	18 -19	19
Mar-99	2.65	6.5-14.5	15 -16	16
Apr-99	2.22	9.5-12.5	13 -15.5	15.5
May-99	1.61	9.5-10.5	11-20	20
Aug-99	0.00	5-5.5	6 -10.5	10.5
Oct-99	0.00	5	5.5 -9.5	9.5
Nov-99	4.77	2.5	-	2.5
Jan-00	3.13	13-14.5	-	14.5
Feb-00	2.00	8-11	11.5 -14.5	14.5
Mar-00	5.00	10.5	-	10.5
Jun-00	0.35	8.5-10.5	11-15	15
Jul-00	4.62	9-10.5	-	10.5
Aug-00	0.00	3.5-4	4.5 -10	10
Sep-00	0.20	6-8	8.5 -14.5	14.5
Nov-00	0.17	2-3	3.5 -16	16
Dec-00	0.96	3	3.5 -9	9

Station HCB007 is a rotational station in South Hood Canal that was monitored in WYY 1999 and Y 2000. Located at the innermost portion of the canal in Lynch Cove, this station also has Strong-Persistent stratification. Though hypoxic conditions are not as frequent at HCB007 compared to HCB004, DO concentrations tend to be more severely low, reaching anoxia more frequently.

HCB003: Hamma Hamma

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-98	3.31	5-110.5	-	110.5
Nov-98	3.90	21.5-95	-	95
Mar-99	3.70	83.5-106.5	-	106.5
May-99	3.06	37-38.5, 39.5-45.5, 91-105.5		- 105.5
Jun-99	3.11	30.5, 31.5, 73, 88-88.5, 89.5, 92-92.5, 93.5-106		- 106
Jul-99	3.79	15-52.5, 53.5-89	-	89
Aug-99	2.82	11-18.5, 26, 27-43	19 -25.5, 26.5	43
Sep-99	2.18	7-10	10.5 -64	64
Oct-99	1.87	5-7, 34-53.5	7.5 -33.5	53.5
Nov-99	3.96	4-74	-	74
Apr-00	3.28	42-101.5	-	101.5
May-00	3.76	29-83	-	83
Jun-00	3.46	28.5-82.5	-	82.5
Jul-00	4.60	20.5-24.5	-	24.5
Aug-00	2.71	12.5-64.5, 65.5-67.5	65, 68 -103.5	103.5
Sep-00	1.99	5-11, 54, 55-106.5	11.5 -53.5, 54.5	106.5
Oct-00	1.61	4-6.5, 21-105.5	7 -20.5	105.5
Nov-00	3.04	4-102.5	-	102.5
Dec-00	3.77	1.5-100.5	-	100.5

Station HCB003, another rotational station, is located midway between the Great Bend and Dabob Bay. This station has Strong-Persistent stratification but is located closer to the Puget Sound Main Basin waters that flush the Canal. DO concentrations were not as low as those found in S. Hood Canal, but values were still near-hypoxic for three months each year monitored. Low DO was seen more frequently at HCB003 in the last few years: WYY 1999 (10 months), and Y 2000 (9 months), as compared to 6, 6, and 2 months in WYs 1996 through 1994, respectively.

HCB006: Bangor

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	1.94	8.5-21	21.5 -22	22
Feb-98	1.81	29-72	72.5 -108.5	108.5
Aug-98	4.23	11.5, 12.5-35	-	95.5
Sep-98	4.49	6-58, 60	-	99
Oct-98	4.90	12.5-22.5, 25.5-28.5, 29.5-30.5, 33	-	93.5
Aug-99	4.63	12.5-83, 86, 88.5, 101.5	-	104
Sep-99	4.36	11.5-67, 68-68.5	-	105
Oct-99	3.94	19-71.5	-	90
Sep-00	3.96	3-68.5, 69.5-70.5, 73.5	-	93
Oct-00	3.65	2.5-88, 89-89.5, 93-93.5	-	94.5
Nov-00	4.10	8-88	-	88

Station HCB006, a deep (~100 m) core station located near Bangor, is the farthest seaward of the stations monitored in the long, narrow Hood Canal. The station has Strong-Intermittent stratification, indicating that vertical mixing is more common here than in the southern Hood Canal stations. This station is showing differences in the last several years that are of concern. WY 1998 is the first year near-hypoxic values have been recorded at HCB006. In addition, there has been a higher frequency of <5 mg/L DO concentrations over the last several years; the frequency was 4 out of 12 months in WY 1998, 4 out of 13 in WYY 1999, and 3 out of 11 months in Y 2000. This pattern is similar to results from WY 1997 (5 out of 9 months) and WY 1996 (4 out of 11 months), but previously only 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 but not common in the north. Southern Hood Canal 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 of 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 are not severely low, the horizontal extent of the spread of low DO concentrations may be increasing since the 1950's when it rarely was observed past Hoodsport (Collias *et al.*, 1974).

Similar to our previous assessment (Newton *et al.*, 1998a), four observations from the monitoring data indicate the possibility that DO conditions may be deteriorating in southern Hood Canal, that the spatial extent of low DO may be increasing northwards, and that eutrophication could be one of the processes contributing to this change. Impacts of 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 northward increase in the horizontal extent of low DO values. Occurrences at both HCB003 and particularly HCB006 increased over the last several years.

3) Over the period of WY 1991 to Y 2000, high chl *a* concentrations have been observed in summer months in S. Hood Canal, when nutrient limitation of phytoplankton growth 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 primary 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. Effects from low DO on the biological community, such as fish or shellfish, should be assessed.

Penn Cove

PNN001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	2.30	12.5-20	20.5 -29	29
Nov-97	2.39	5-9.5, 15-21.5	10 -14.5, 22 -26	26
Dec-97	3.21	13.5-28	-	28
Jan-98	3.94	12.5-29.5	-	29.5
Feb-98	4.80	21.5	-	24
Apr-98	2.62	6-13, 27.5-28	13.5 -27	28
May-98	4.75	18.5-21.5	-	29.5
Jun-98	4.19	13-14, 16-28	-	28
Jul-98	2.75	8.5-22	22.5	22.5
Aug-98	0.83	7-8.5, 19-22, 24-27.5	9 -18.5, 22.5 -23.5	27.5

Sep-98	2.70	4.5-5.5, 6.5-7, 9.5-11, 12.5-29	3.5 -4, 6, 7.5 -9, 11.5 -12	29

Penn Cove exhibits Strong-Persistent stratification, an attribute associated with the natural development of low DO. The observations above indicate a definite level of concern for this area. During WY 1998 data show eleven months out of twelve months monitored with DO <5 mg/L, half of these with concentrations <3 mg/L, and one observation of near-anoxia. Penn Cove has been monitored by Ecology during WYs 1994, 1996, and 1998 only. During WY 1994 there were three months when DO <5 mg/L were observed, with one month (Oct '93) <3 mg/L when minimum concentrations were nearly anoxic. During WY 1996 low DO concentrations were not as extreme as in WY 1994 but low DO concentrations were observed more frequently; there were five months with DO <5 mg/L, two months <3 mg/L, and the minimum observed was 2.43 (Nov '95 and Sep '96).

Because DO concentrations can be very dynamic with time, these differences should not be over-interpreted. However, conditions do appear to be declining and DO concentrations are at biologically relevant low concentrations with alarming frequency in this area. Anthropogenic activities (both present and future) that add nutrients, stimulate plankton production, decrease circulation, or increase oxygen demand within the Cove should be carefully evaluated. Further monitoring and study is highly recommended.

Saratoga Passage

SAR003:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	3.93	50-105	-	105
Nov-97	2.73	32.5-40	40.5 -60.5	60.5
Jan-98	1.45	13-52	52.5 -96	96
Sep-98	4.92	48, 52-56	-	56
Aug-99	4.70	44.5, 46.5, 48-67.5	-	67.5
Sep-99	4.43	24-109.5	-	109.5
Oct-99	4.38	5-27, 28, 30, 32-33.5, 36-82.5	-	82.5
Aug-00	4.62	43-79.5	-	79.5
Sep-00	4.41	9-69.5	-	69.5
Oct-00	4.01	5.5-36.5	-	36.5
Nov-00	4.14	8-73	-	73

Station SAR003, a deep-water (~122 m) station located in Saratoga Passage between Whidbey and Camano Islands, has Strong-Persistent stratification (delta sigma-t ranged 3 to 9) with the pycnocline typically comprising the upper 10 - 20 m. This station is influenced by several rivers. This station has shown an increase in occurrence of low DO events and severity, though interannual variability is also strong. Since WY 1990, Saratoga Passage has consistently had one to two low DO occurrences per year with minimum concentrations ranging 4.4 to 5.0 mg/L. Depressed DO concentrations were typically observed during 1-3 months, most frequently in September/October. Then four occurrences recorded in WY 1996 and five in 1997 appeared as exceptions to this record, although the minimum values were not below 4.0 mg/L. Similar conditions now appear to be consistently observed, with four, three, and four observations of DO <5 mg/L during WY 1998, WYY 1999, and Y 2000, respectively. The very low concentrations <3 mg/L in late 1997 and early 1998, with a minimum concentration of 1.5 mg/L, are unprecedented at this station. The influence of the 1997-1998 El Niño on these anomalous conditions is not known.

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. The low DO concentrations observed may reflect a response to phytoplankton blooms, as chlorophyll *a* is occasionally quite high (approaching 40 µg/L), changes in circulation, or oceanic influences. Whether phytoplankton blooms are unnaturally high should be evaluated, as well as whether increasing influence from advection of low DO waters from PSS019 northward is occurring.

Bellingham Bay

BLL009:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Sep-98	3.16	12.5-13.5, 17-23	-	23

This station, on the outer boundary of Bellingham Bay has been monitored as a core station since Ecology's monitoring began. DO concentrations below 5 mg/L have not been found before at this station, despite its Strong-Intermittent stratification. Such a low concentration was not evident at other nearby locations.

BLL011:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Aug-00	1.84	7.5-10, 11.5-12,14-16	10.5 -11, 12.5 -13.5, 16.5 -18.5	
	18.5			
Sep-00	4.15	9-17	-	17

In inner Bellingham Bay, this station within the Nooksack River plume was monitored only once before in WY 1997. Stratification is Strong-Intermittent and the organic load from the Nooksack plume is high, so the presence of low DO is not surprising. Previous monitoring data showed low DO in Oct 96 and Jul-Sep 97, but the concentration was always 4 mg/L or above. The very low concentration in Aug 00 is unprecedented, though very limited data are available. The degree of human impact on this very low DO concentration is not known.

Discovery Bay

DIS001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Jul-00	4.64	23.5-26	-	26
Aug-00	3.46	29-39	-	39
Sep-00	3.51	16.5-38.5	-	38.5
Oct-00	2.94	14.5-38	38.5 -39	39
Nov-00	4.85	35.5-41	-	41

This is the second year that Discovery Bay has been monitored, having been first assessed in WY 1997. Results are similar to those seen before when DO was low in Oct 96 and Jul through Sep 97. The bay's seasonal stratification and high productivity make it a likely candidate for low DO concentrations. The apparent persistence of the low/hypoxic DO from July through November 2000 should be regarded with caution. The extent of any human impact on these DO concentrations is not known but could be important in consideration of the Bay's stratification and relative isolation. Its proximity to the Strait of Juan de Fuca would also result in a source of low-oxygenated oceanic water.

Elliott Bay

ELB015:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Nov-97	4.97	85.5	-	86.5
Feb-98	2.17	30.5-49, 61.5-62, 64.5, 65.5, 70.5-72.5	49.5 -61, 62.5 -64, 65	85
Sep-98	4.77	75.5-78, 79-87	-	87
Oct-98	4.72	74-75.5	-	75.5
Sep-00	4.61	52.5-79, 83-86	-	86
Oct-00	4.80	62.5-70.5	-	70.5

This station has shown an annual low DO that was first recorded in fall 1995. Since Ecology's monitoring began measuring depths below 30 m (June 1992), observations of DO <5 mg/L at this station were recorded in Aug and Oct 1995, Sep 1996, and Aug 1997 only. In each case the DO concentration was between 4-5 mg/L. These recent records show the continuation of this pattern, with the exception of 1999. The Feb 1998 DO concentration of 2 mg/L is unprecedented; similarly low DO in this month in Puget Sound was seen only at nearby West Point (PSB003). There is much anthropogenic impact on Elliott Bay and it has Strong-Intermittent stratification. Continued monitoring of this core station is warranted.

Strait of Georgia

GRG002:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	4.42	51.5, 53-54, 55-55.5, 56.5-61, 62-81.5, 106.5	-	108.5
Dec-97	1.59	65-90, 92, 93.5	90.5 -91.5, 93, 94 -98.5	98.5
Apr-98	3.47	87.5-104	-	104
Sep-99	4.43	63.5-105	-	105
Sep-00	4.74	82.5, 84-108	-	108

The Dec 1997 and Apr 1998 observations are the only records of DO concentrations below 4 mg/L at this station since Ecology's monitoring began. The influence of the 1997-1998 El Niño on these anomalous conditions is not known. Previous observations of DO <5 mg/L were recorded in autumns of WY 1994, WY 1996, and WY 1997 when the concentrations observed were just below 5 mg/L, similar to values recorded in autumn 1999 and 2000. These low DO observations likely reflect the signature of 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.

Puget Sound Main Basin - West Point

PSB003:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Feb-98	2.94	26-38.5	39	39

The only previous record of low DO at this core station was recorded during late summer (Aug-Sep) 1997 when DO measured just below 5 mg/L at depth and matched the concentration the deep waters at ADM001. This concentration measured in February 1998 is 2 mg/L lower than that and is not correlated with concentrations at ADM001. Low DO in February is unusual, but was also recorded to an even lower degree in Elliott Bay. The influence of the 1997-1998 El Niño on this anomalous condition is not known.

Stations with DO concentrations less than 5 mg/L

Admiralty Inlet

ADM002:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	4.01	17, 38-52.5	-	52.5
Aug-98	4.09	50.5-76.5	-	76.5
Sep-98	4.38	28-68	-	68
Jun-99	3.14	43.5-46	-	46
Jul-99	4.06	32.5-54	-	54
Aug-99	4.58	53.5-57	-	57
Sep-99	3.90	39-70.5	-	70.5
Oct-99	4.26	26-48.5	-	48.5
Jun-00	4.89	59-61.5	-	61.5
Oct-00	4.09	17, 19, 20-52.5	-	52.5

Nov-00	3.68	45-46, 47-74.5	-	74.5

ADM003:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	4.92	47	-	111.5

Low DO concentrations in Admiralty Inlet are typically natural, reflecting the influence of 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. The prevalence of low DO at ADM002 (outside entrance sill to Puget Sound) and its scarcity at ADM003 and ADM001 (inside the sill) reflects the mixing and aeration that water masses receive when flowing past the entrance sill at Admiralty Inlet.

Station ADM002 is a moderately deep station (~ 70 m) located in the Strait of Juan de Fuca off the Quimper Peninsula. Physically dynamic, stratification is Moderate-Infrequent, more likely to be evident from May through September but not always strongly developed. The pycnocline depth is quite variable. The minimum DO observed seasonally at ADM002 has varied between 3.3 and 5.3 mg/L from WY 1990 through 1997.

The result from Oct 1997 is the first record of DO concentrations <5 mg/L at ADM003.

Budd Inlet

BUD002:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Aug-99	4.47	1.5-2.5, 3.5-4, 5-8	-	8

BUD005:

depth month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast (m)
Aug-98	4.27	7-8, 9-9.5	-	13

Stratification is Strong-Persistent in inner Budd Inlet, due to freshwater input from the Deschutes River/Capitol Lake system, turning to Moderate-Infrequent stratification in the central inlet. The minimum concentrations recorded in Budd Inlet during WY 1998-Y 2000 are similar to those reported for WY 1996-97. These minimum concentrations, all above 4 mg/L, are higher than those seen in previous (WY 1994-95) years when values of 2 and 3 mg/L were recorded. The DO and other water column characteristics of Budd

Inlet have been well studied by Ecology and the Lacey-Olympia-Thurston-Tumwater partnership (LOTT) (e.g., URS, 1986; Eisner *et al.*, 1994; Eisner and Newton, 1997; Aura Nova, *et al.*, 1998). In these studies, water quality varied substantially on an interannual basis, influenced by local weather and location within the inlet, with lowest DO concentrations found towards the head of the inlet (e.g., near BUD002 and farther south). In contrast to other years monitored (see Newton *et al.*, 1997), DO concentrations in the inner inlet (BUD002) and the central inlet (BUD005) appeared similar. This was also the case in WY 1996-97. These data suggest that the minimum DO concentration in the inner Budd Inlet appears to be increasing. These observations are consistent with the implementation of nutrient removal from LOTT effluent, started in 1994, causing less eutrophication and oxygen demand.

Commencement Bay

CMB003:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-00	4.82	54, 59, 60-69.5	-	69.5
Nov-00	4.59	43-102.5	-	102.5

Since Ecology's monitoring began, CMB003, a core station, had not shown low DO concentrations until WY 1996-97 when seven occurrences were recorded in Oct-Nov 1995, Sep-Oct 1996, and Jul-Sep 1997. All values were above 5 mg/L during 1998 and 1999, but dipped below again in fall 2000. All of the low DO concentrations recorded were not much below 5 mg/L. Continued monitoring of this station with Strong-Persistent stratification and urban influence is recommended.

Carr Inlet

CRR001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Nov-00	4.82	43-44	-	44

Previously monitored in WY 1991, 1993, and 1996, this station with Moderate-Infrequent stratification had not shown low DO concentrations until Oct 95 and Sep 96, when values between 4.5 and 5.0 mg/L were recorded. The low DO concentration observed in 2000 is of a similar magnitude and duration, though later in the year. Further monitoring of this station is recommended to gain a better baseline for this productive inlet.

Case Inlet

CSE002:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Aug-99	4.79	10.5, 11.5-14.5	-	14.5

This is the first time the DO concentration has been recorded below 5 mg/L at this station; however, it was previously monitored only during WY 1991.

Dungeness Bay

DUN001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Sep-00	4.70	17-19.5	-	19.5
Nov-00	4.56	6.5-17	-	17

This is the first year this station has been monitored.

Possession Sound

PSS019:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	3.73	44.5-92	-	92
Jan-98	4.05	69.5-70, 76.5-104.5	-	104.5
Feb-98	4.77	96.5-99.5	-	99.5
Sep-98	4.96	42	-	42
Nov-98	3.81	64-104.5	-	104.5
Mar-99	4.24	98-100	-	100
Aug-99	4.26	44.5-68.5	-	68.5
Sep-99	4.35	32-52.5	-	52.5
Oct-99	4.32	13-70.5	-	70.5
Nov-99	4.95	49	-	49
Jul-00	4.96	93-93.5	-	104
Aug-00	4.39	56.5-91	-	91
Sep-00	3.83	19-76	-	76
Oct-00	4.12	8.5-33.5	-	33.5
Nov-00	3.91	6-67	-	67

Station PSS019, located off Gedney Island in the deep waters (~105 m) of Possession Sound, has Strong-Persistently stratification. A strong pycnocline (delta sigma-*t* ranged 3 to 14) is common in the upper 10 - 15 m, the result of a major freshwater source, the nearby Snohomish River. Ambient DO concentrations below 5 mg/L were observed in summer and fall, as were observed previously (Newton *et al.*, 1994; 1997; 1998a). Since WY 1994 the number of months observed with low DO per year has appeared to increase from a previous maximum of 3 to 5.

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 Gamble

PGA001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	3.63	12-20	-	20
Nov-97	4.05	19-19.5	-	19.5
May-98	3.99	18.5-20	-	20
Jul-98	3.85	12.5-15	-	15
Aug-98	3.99	12.5-18	-	18

This is the first year this station has been monitored.

Port Townsend Harbor

PTH005:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Feb-98	3.54	12.5-21.5	-	21.5
Oct-00	4.64	16-21	-	21

A core station with Moderate-Infrequent stratification, this area likely has strong influence from recently upwelled Pacific Ocean waters entering at Admiralty Inlet. Coincidence of low DO at PTH005 and ADM002 holds for the Oct 2000 observation, comparative data for ADM002 lacking in Feb 1998 but was seen, though at much lower concentrations, in Elliott Bay and West Point. Low DO concentrations were previously not observed at PTH005 since measurements began (WY 1990) until Oct 96 and Sep 97, when two values of 4.7 mg/L were recorded.

Quartermaster Harbor

QMH002:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Sep-98	3.35	4-7	-	7

This is the first year this station has been monitored.

Sequim Bay

SEQ002:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Aug-00	4.65	18.5-20	-	20
Sep-00	3.84	14.5-21.5	-	21.5

This is the first year this station has been monitored.

Sinclair Inlet

SIN001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Aug-98	4.25	11-13	-	13
Sep-98	5.00	12	-	12.5

This core station has Moderate-Infrequent stratification. These are the first records of low DO at SIN001 since comparable methods of monitoring began at this station. Portions of inner Sinclair Inlet were shown to have low DO concentrations infrequently, reaching as low as 2.9 mg/L (Albertson *et al.*, 1995). Continued monitoring of this core station is recommended.

Skagit Bay

SKG003:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	4.51	2-5	-	5
Nov-97	4.21	4-16	-	16
Dec-97	3.97	7-17.5	-	17.5
Jan-98	4.45	9-22.5	-	22.5
Sep-98	4.31	3-7	-	7

SKG003 is located in the Skagit River delta area with Strong-Persistent stratified waters and high particulate loads. Skagit Bay was monitored previously during WY 1991 without observed low DO concentrations, in WY 1995 with a single observation of low DO concentration in fall (4.15 mg/L in Oct 94) and in WY 1996 with two observations (4.42 in Nov 95 and 3.73 in Sep 96). The increased frequency in such observations during WY 1998 and its persistence for 4 months (Oct 97 through Jan 98) are unprecedented. Further monitoring of this rotational station is recommended.

Port Susan

SUZ001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Oct-97	3.97	28-76	-	76
Nov-97	3.77	39-98.5	-	98.5
Dec-97	3.10	12-12.5, 14, 20.5, 25-72.5, 82-107		- 107
Jan-98	4.56	41-73.5	-	99
Jul-98	4.57	49-77.5	-	99.5

Sep-98	3.75	12.5-75.5	-	75.5

Port Susan has Strong-Persistent stratification, with a pycnocline in the top 20 m and delta sigma-*t* ranging 3 to 20. Freshwater input from the Stillaguamish River maintains the strong stratification. This rotational station was previously monitored in WY 1995, when three occurrences of low DO were observed (Oct 94, Dec 94, Aug 95) with concentrations of 3.0, 4.7, and 3.4 mg/L, respectively. The persistent low DO in Oct 97 through Jan 98 is similar to that found at other stations including nearby Saratoga Passage. The influence of the 1997-1998 El Niño on these conditions is not known. Port Susan has naturally high production and stratification. This is a sensitive area with respect to organic or nutrient loading.

Previously, monitoring had occurred at this station continuously from 1973-1987 but with measurements only to 10 m depth. Low DO was observed in Oct 1973, Oct 1974, and Aug, Oct, Nov 1987.

Willapa Bay

WPA001:

month	Minimum DO conc. (mg/L)	DO < 5 mg/L depth range (m)	DO < 3 mg/L depth range (m)	Cast depth (m)
Sep-99	4.30	3-6.5	-	6.5

This core station has Strong-Intermittent stratification. These are the first records of low DO here since monitoring began at WPA001.

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 light 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 Jan 1998 or PSB003 in Aug 1999) is typically 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 or ADM002, exhibit few variations of this parameter with depth. Thin layers of reduced light transmission at the surface can indicate particle load from river water, and this conclusion can be confirmed by observation of the companion salinity profile (*e.g.*, PSS019 in Jun-Jul 1999). Stations GYS004 and WPA001, where light transmission rarely exceeds 30%, show the dramatic reduction in light transmission typical in river water. Low light transmission also can indicate high concentrations of phytoplankton, *i.e.*, blooms. For example, high phytoplankton concentration at HCB004 during Jun 1999 and May 2000 (~190 and 26 μg/L, appendix A), correlate with distinct minima in light transmission below the surface (~20 and 50%, 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. Yet chl *a* remains the best indicator of phytoplankton populations in common use. Phaeopigment (phaeo) refers to numerous degradation products of 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 phaeo concentrations indicate chl *a* that has been degraded, typically via zooplankton grazing. 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 that chl *a* concentrations (phytoplankton 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 fluorometric analyses of extracted chl *a* and phaeo concentrations (µg/L) are tabulated in Appendix A. Plots of the 0.5-m and 10-m chl *a* concentrations (µg/L) versus WY month sampled are shown in Appendix C. If comparing these data to historical Ecology data note that chl *a* concentrations from samples analyzed prior to WY 1994 are low by an unknown amount ranging up to 22 percent because of the filter storage procedure (in air versus acetone).

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* can 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 (0.5 and 10 m) 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 by 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 seasonal 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 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) most typically. Often the summertime chl *a* concentrations are of an intermediate to low value, likely reflecting nutrient limitation due to density stratification. Some stations exhibited this typical temperate phytoplankton pattern of spring and fall blooms, with moderate concentrations in summer, and lowest concentrations in winter (e.g., BLL009, and NSQ002).

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 nutrients (runoff, septic tanks, agricultural wastes) to the euphotic zone. Strong blooms

(>20 µg/L) in summer as well as in spring and fall were observed in BUD005, CMB003, HCB004, and OAK004, among others.

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 (likely due to being mixed out of the euphotic zone by strong tidal currents) than growth.

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 been 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 all stations monitored in WY 1998-Y 2000. 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:

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

Equation (1) was originally derived by Poole and Atkins (1929) for the English Channel 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 1998-Y 2000 are found in Appendix C. 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 necessary 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 by riverine inputs with high particle loads and resuspension of sediments due to tidal and wind-driven turbulence.

Some stations (e.g., BUD002, GYS016) show decreased 1% I_o depths during late fall through early spring. These stations are typically those located near rivers and the shallow euphotic zone depths are likely caused by large quantities of suspended sediment associated with increased river runoff, as is the case for BUD002 and GYS016. The presence of low salinity in the surface waters can be used to confirm this explanation for other stations.

Many stations (e.g., CRR001, 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 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 depth 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 ADM003, CSE002, DIS001, PSB003, and PTH005, areas distant from direct river input. Outliers with particularly high light extinction and low surface chl *a* were seen most frequently at stations where riverine input occurs, e.g., CMB003, GRG002, BLL009, and GYS016 (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 GOR001. 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., GYS008.

Many of the coastal estuary stations where chl *a* data were collected (GYS008, GYS016, WPA003-WPA008) show flat or negative slopes and with consistently high values of k (note variable scale for k), 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 of phytoplankton, the primary trophic level of the marine environment. In seawater, several 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. Marine diatoms, which are abundant in the Pacific Northwest, also require silicate. This nutrient had not been analyzed as part of the monitoring program, until 1999 when Ecology switched analytical labs (see Methods).

"Ammonium-N" is used here to refer to all ammonia-based nitrogen. The pH range of seawater drives the hydrolyzation reaction of ammonia such that less than 2% of the ammonia-based nitrogen is un-ionized ammonia NH_3, and 98% is ammonium, NH_4^+ (Grasshoff *et al.*, 1983). Since dissolved ammonia, but not ammonium, is toxic to fish and other organisms, this distinction is important. The amount of un-ionized ammonia can be calculated from the ammonium concentration and the pH, salinity, and temperature of a water sample.

The reporting of nitrate and nitrite varies in this report according to the laboratory conducting the nutrient analysis. Chemical analysis of 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". This is the notation used for samples analyzed prior to February 18, 1999. After that, values for both nitrate and nitrite are reported separately (Appendix A), but we have summed them for comparability in the following analysis.

Ammonium-N, nitrate+nitrite-N and orthophosphate-P concentration data for WY 1998-through February 18, 1999 and ammonium, nitrate, nitrite, orthophosphate, and silicate data for February 19, 1999 through Y 2000 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-m nitrate+nitrite concentration (mg/L) versus month are in Appendix C.

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 of nitrate+nitrite-N from 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). A 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 not adequate for statistical purposes to infer nutrient-chlorophyll relations.

Of the 802 samples collected at all stations for nitrate+nitrite-N analysis during WY 1998, 1.5% had below reporting limit (BRL) concentrations, as defined by Manchester Environmental Lab at 0.71 µM (0.01 mg/L), with 1.8% for Puget Sound samples and 0% from the coastal estuaries. In WYY 1999, 15% of the 819 samples were BRL, with 14%

for Puget Sound and 19% for the coastal estuaries. In Y 2000, 12% of the 797 samples were BRL, with 9% for Puget Sound and 20% for the coastal estuaries.

A strong difference is evident in the WY 1998 data compared with WYY 1999 and Y 2000 data, with far fewer stations showing low nitrate+nitrite-N concentrations. This could be linked with differences in precipitation, runoff or oceanic forcing, although no pattern is apparent. If anything, 1998 had reduced upwelling compared to 1999 and 2000, which would be expected to result in the opposite pattern (more BRL nitrate+nitrite-N during 1998). Changes in laboratory analysis, which switched in February 1999, cannot be ruled out. However, examination of BRL nitrate+nitrite-N concentrations since WY 1994 (Figure 13) shows a variable pattern with both WY 1997 and 1998 having the highest incidence of replete nutrients. Results from 1999-2000 are not different than those from 1994 through 1996.

The locations and months of occurrence for the samples with BRL concentrations (Table 5) show that nitrate+nitrite-N concentrations were low most commonly during May through August and at the 0.5 m depth. As has been found previously, low nitrate+nitrite-N concentrations throughout the water column (0.5 m to the station's deepest sampled depth) were primarily found in Southern Puget Sound (OAK004, ELD001, ELD002, TOT001, TOT002, CSE002, BUD005) and in Willapa Bay (all stations except WPA001).

Stations with $\geq$3 consecutive months of BRL surface nitrate+nitrite-N in Puget Sound are BUD005, CRR001, CSE002, DIS001, HCB004, HCB006, OAK004, PSS019, SAR003, SIN001, TOT001 and TOT002. All except OAK004, TOT001 and TOT002 are stations exhibiting low DO concentrations during the same years. Willapa Bay but not Grays Harbor shows several months of low 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 1994-97).

Samples with BRL nitrate+nitrite-N concentrations but detectable levels of ammonium-N are typically rare in marine systems. Such a pattern could be suggestive of possible eutrophication, since ammonium is a common nitrogen form added by anthropogenic sources like WWTPs, though it also is released naturally by zooplankton and bacteria. Only about 0.8% of the WY 1998-Y 2000 samples (20/2418) showed this pattern ("N" in Table 5). As with previous reports, the locations for these samples were in Budd Inlet (7 samples), Willapa Bay (2 samples), various South Puget Sound locations (ELD001, ELD002, OAK004, TOT002) and Saratoga Passage. More typically (6.5% of samples) both nitrogenous nutrients were low ("NA" in Table 5), and in some cases (2.0% of samples) all three nutrients ("NAP" in Table 5) were low.

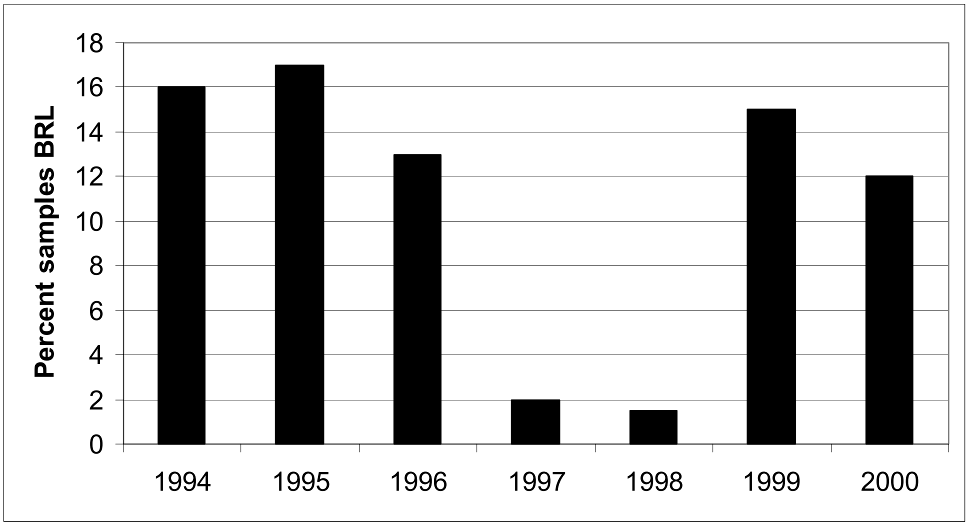


Figure 13. The percent nutrient samples collected with below-reporting-limit concentrations of nitrate+nitrite-N. Data for 1994 through 1998 represent wateryears; 1999 and 2000 follow the convention used in this report (WYY 1999 and Y 2000).

Nitrite-N

High concentrations of nitrite can be an indicator of eutrophication. If ammonium is abundant, nitrite, which is an intermediary product of bacterial nitrification, will be found at detectable levels. Due to a relatively high detection level and a low proportion of values over detection, analysis of nitrite had been discontinued from Oct 1991 to Sep 1994 at all but a few stations and then not at all from Oct 1994 to Feb 1999 (summarized in Newton *et al.*, 1998a). Nitrite analysis was re-instated in Feb 1999. During the period Feb 1999 through Dec 2000, nitrite concentrations above the previous cut-off for detectable values (0.71 µM or .01 mg/L) were found at 11 stations, primarily in South Puget Sound: BUD002, BUD005, CMB003, CRR001, CSE001, CSE002, DNA001, NSQ002, PSB003, and SIN001. Concentrations over 1.0 µM were found in Budd Inlet (4 observations), Dana Passage (2 observations), and at Nisqually (1 observation). The highest concentration was 1.29 µM in inner Budd Inlet.

Table 5. Stations with very low nutrient concentrations during WY 1998 – Y 2000. Nitrate+nitrite-N concentrations <0.71 µM indicated by "N" at a particular depth and month; ammonium-N concentrations <0.71 µM shown by "A"; ortho-phosphate-P concentrations <0.32 µM shown by "P".

Station		Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
North Puget Sound:																		
ADM001:	97				98		A	A	A		A	A	A	A	A			0 m
								A	A			A	A	A	A			10 m
		A						A			A	A	A	A	A			30 m
					99			A	A									0 m
								A	A									10 m
								A								A		30 m
					00		A	A				A	A	A		A	A	0 m
							A	A								A	A	10 m
						A	A	A								A		30 m
ADM002:	97		A		98		A	A	A			A	A	A	A			0 m
			A					A				A	A	A				10 m
			A					A	A			A	A	A	A			30 m
					99			A										0 m
								A										10 m
								A										30 m
					00		A	A								A	A	0 m
							A	A								A	A	10 m
							A	A								A		30 m
ADM003:	97				98			A	A		A	A	A	A				0 m
								A			A	A	A	A				10 m
								A				A	A	A				30 m
					99			A	A	A		NA	A	NA	A			0 m
								A	A	A					A			10 m
								A	A									30 m
					00		A	A	NAP		A	A	NA	A		A	A	0 m
							A	A	A			A	A			A	A	10 m
							A											30 m
BLL009:	97			A	98	A	A	A	A	A	A	NA	A	A	A			0 m
				A		A	A	A	A			A	A	A	A			10 m
					99				A	NAP	AP	A			A			0 m
									A									10 m
					00		A	A				A	NAP	NA				0 m
						A	A	A					NA			A	A	10 m
BLL011:					00				P			AP	NAP	A				0 m
																		10 m

Table 5. *continued*

Station	Yr	Oct	Nov	Dec	Yr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
DIS001:					00				NAP		NAP	NAP	NA	A	A			0 m
									NA									10 m
																		30 m
DRA002:					00				AP			NA	NAP					0 m
																		10 m
DUN001:					00		A									A		0 m
							A						A	A		A		10 m
GRG002:	97	A		A	98	A	A	A		A	NA		A	NA	A			0 m
		A		A		A	A	A	A	A	A		A	A	A			10 m
		A		A		A	A	A	A	A	A		A	A	A			30 m
					99			A	A	NAP	A			A				0 m
									A		A			A				10 m
									A					A				30 m
					00			A			A	A	NAP	A	A	A		0 m
								A			A	A	A	A		A		10 m
								A				A		A		A		30 m
PNN001:	97			A	98		A	A	A		NA	A	A	A				0 m
				A			A	A		A				A				10 m
				A			A		A									30 m
PSS008:	97				98				A		NA	NA		A				0 m
			A				A					A	A	A				10 m
PSS019:	97				98				A	A	NA	A	A	A				0 m
		A	A						A	A	A	A	A					10 m
		A							A	A	A	A	A	A				30 m
					99				AP	NAP	NAP	NAP	NA	NAP				0 m
									A			NAP	A	A		A		10 m
									A	A		NAP	A	A		A		30 m
					00				P	NAP	P	AP	NAP	NA	A	A		0 m
								A					A	A	A	A	A	10 m
								A	A		A	A	A	A	A	A		30 m
PTH005:	97				98	A	A	A	A	A	A	A	A	A	A			0 m
			A			A	A	A	A	A	A	A	A	A	A			10 m
					99			A	A	A	A	A				A		0 m
									A							A		10 m
					00							NA	A					0 m
								A										10 m
SAR003:	97				98		A	A	A	A	A	A		A				0 m
							A	A	A	A	A	A		A				10 m
		A	A				A		A	A		A		A				30 m

Table 5. *continued*

Station	Yr	Oct	Nov	Dec	Yr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
SAR003:					99			A	NA	NAP	NAP	NAP	N	A				0 m
									A			A	A	A				10 m
									A			NA	A	A		A		30 m
					00	A	A		NAP	NAP	NAP	NAP	NAP	NAP	NA	A		0 m
						A	A				A	A	A		A	A		10 m
							A		A	A	A	A	A	A		A		30 m
SEQ002:					00		A		A			A	NAP	A				0 m
							A			A								10 m
SKG001:	97		A	A	98	A	A	A		A	A	A	A	A				0 m
			A	A		A	A	A		A	A	A	A	A				10 m
SKG003:	97			A	98	A	A	A	A	A	A	A	A	A				0 m
			A	A		A	A	A	A	A	A	A	A	A				10 m
SUZ001:	97				98		A	A		A	A	A	A	A				0 m
		A	A				A			A	A	A	A	A				10 m
		A	A				A		A	A	A	A	A	A				30 m
Hood Canal:																		
HCB004:	97	NA	A	A	98		A	A	A	A	A	A	A	A				0 m
		A	A	A			A	A		A	A		A	A				10 m
		A	A	A			A	A	A	A	A	A	A	A				30 m
					99			NAP	NAP	A	NA	NA	NA	NA	NA	A		0 m
											A	A		A	A	A		10 m
											A	A	A	A	A	A		30 m
					00		NAP	NA	NA	NA	NAP	NA	NA	NA	NA			0 m
							A	A						A			A	10 m
						A		A		A	A		A	A	A			30 m
HCB006:	97	A	A	A	98		A	A	A	A	A	A	A	A	A			0 m
			A	A			A	A	A	A	A	A	A	A	A			10 m
			A	A			A			A	A		A	A	A			30 m
					99			A	NAP	A	A	A	NA	A		A		0 m
									A			NA	A	A				10 m
												NA				A		30 m
					00			NA	A	A	A	A	NA	A	A	A	A	0 m
									A		A		A	A	A		A	10 m
														A				30 m
PGA001:	97		A	A	98		A	A	A	A	A	A	A	A				0 m
			A	A					A		A		A	A				10 m
NSQ002:	97		A		98	A		A		A		A	A					0 m
			A			A		A		A		A	A				A	10 m
			A			A		A				A					A	30 m

Table 5. *continued*

		Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
NSQ002:																		
					99			A	A									0 m
								A	A									10 m
																		30 m
					00								A	A				0 m
									A									10 m
						A												30 m
Central Puget Sound:																		
CMB003:	97			A	98				A		A		A					0 m
				A			A		A				A	A	A			10 m
							A					A	A	A	A			30 m
					99													0 m
								A									A	10 m
								A	A				A				A	30 m
					00						A	A						0 m
						A	A					A						10 m
						A	A	A				A	A			A		30 m
EAG001:	97		A	A	98		A	A	A		A		A	A				0 m
			A	A			A	A	A				A	A				10 m
EAP001:	97				98	A		A	A		A	NA	A	A			A	0 m
						A		A		A		A	A	A			A	10 m
						A		A				A	A	A			A	30 m
					99			A	A									0 m
								A	A									10 m
								A	A									30 m
					00		A	A	A	NA		A	A	A		A		0 m
							A	A	A			A	A	A		A		10 m
							A	A				A	A					30 m
ELB015:	97	A			98			A	A		A	A	A	A	A			0 m
		A				A		A				A	A	A	A			10 m
		A				A		A				A	A	A				30 m
					99				A							A		0 m
								A	A							A		10 m
								A	A							A		30 m
					00	A	A						A			A		0 m
							A	A				A	A			A		10 m
						A	A	A				A	A			A		30 m
POD007:	97				98				A		A		NA	A				0 m
									A		A		A	A				10 m
PSB003:	97	A			98	A	A	A	A			A	A	A				0 m
		A				A	A					A	A	A				10 m
		A				A		A				A	A	A				30 m

Table 5. *continued*

Station		Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
PSB003:					99			A	A	A								0 m
								A	A					A				10 m
								A						A				30 m
					00		A		A			A	A			A		0 m
							A					A	A			A		10 m
												A				A		30 m
QMH002:	97				98			A	A		A	A	A	A				0 m
				A			A				A			A				10 m
SIN001:	97				98			A	A	A		A	A	A				0 m
			A	A			A	A					A	A				10 m
					99				A	A	NA	A		NA				0 m
																		10 m
					00				NAP	NAP	NA	A		NAP				0 m
																		10 m
South Puget Sound:																		
BUD002:					98													0 m
																		10 m
					99													0 m
											N		N	N				10 m
BUD005:	97			A	98		A		A	A	A	A	A	A				0 m
				A			A				A		A					10 m
					99				A	A	NA	NA	NA	N				0 m
									A		N		N	N				10 m
					00				AP	NAP	NA	NA	NA	NA				0 m
							A					NA						10 m
CRR001:					98										A			0 m
															A			10 m
															A			30 m
					99		A	A	A	NAP	NA	NA	NA	NA			A	0 m
								A	A								A	10 m
								A									A	30 m
CSE001:					98										A			0 m
															A			10 m
															A			30 m
					99		A	A	A	NA	NA		A					0 m
								A	A									10 m
								A										30 m
CSE002:					98										A			0 m
															A			10 m
					99				AP	NA	NA	A	NA					0 m
									A		NA	A						10 m

Table 5. *continued*

		Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
DNA001:	97		A		98	A		A		A		A	A					0 m
			A			A		A		A		A	A				A	10 m
			A			A		A		A		A	A				A	30 m
					99				A									0 m
																		10 m
								A										30 m
					00								A					0 m
													A					10 m
																		30 m
ELD001:					98													0 m
																		10 m
					99				A	NA	N		NA	NA				0 m
											N		NA	A				10 m
ELD002:					98													0 m
																		10 m
					99				A	NA	N		NA	NA				0 m
											N		N	N				10 m
GOR001:	97		A		98	A		A				A	A	A			A	0 m
			A			A		A									A	10 m
			A			A		A				A	A		A		A	30 m
					99			A	A									0 m
								A	A									10 m
								A	A									30 m
					00											A		0 m
													A			A		10 m
								A										30 m
OAK004:	97				98		A	A		A	NA		NA	A				0 m
							A	A		A	A		A	A				10 m
					99				A	NA	NA		NA	NA				0 m
									A	A	NA		NA	NA				10 m
					00				A	NA	N		NA	NA				0 m
									A	NA	NA		NA	NA				10 m
TOT001:					98													0 m
																		10 m
					99				A	NA	NA		NA	A				0 m
									A		NA		NA	A				10 m
TOT002:					98													0 m
																		10 m
					99				A	NA	N	N	NA	NA				0 m
									A	NA	N		NA	NA				10 m

Table 5. *continued*

		Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
Coastal Estuaries:																		
GYS004:	97		AP		98	AP	AP	AP	AP							A	P	0 m
			A			AP	AP		AP							A	P	10 m
					99			P	P	P	P				P		P	0 m
								P	P		P					P	P	10 m
					00	P		P		P	P	P						0 m
						P		P		P								10 m
GYS008:	97		A		98	A	A		A			A	A					0 m
						A	A					A						10 m
					99					AP	A							0 m
																		10 m
					00						AP							0 m
																		10 m
GYS016:	97				98	A	A	A					A	A	A			0 m
							A	A	A				A	A	A			10 m
					99				A	A		A		A				0 m
									A	NA		A		A				10 m
					00			A	A		A		A	A				0 m
						A	A	A										10 m
WPA001:	97				98	A		AP					A				P	0 m
						A		AP					A					10 m
					99				P	P	A	P	P					0 m
											P							10 m
					00	P	P		P	P	P	P	A					0 m
						P	P			P	P	P	A					10 m
WPA003:	97				98	A	A		A			A	A	A				0 m
						A	A		A			A	A	A				10 m
					99					P	A	P						0 m
									A	P	A	NA						10 m
					00		P		AP	AP	NAP	NAP						0 m
											NAP	NAP						10 m
WPA004:	97		A		98	A		A	A				A	A	A	A		0 m
			A			A		A	A				A	A	A	A		10 m
					99				A	NAP	A	NA	NA		A			0 m
									A	NAP	A	NA		A	A			10 m
					00	A	A	A	A		NA	NA	A	A				0 m
						A	A	A	A	N	NAP	NA	A	A				10 m

Table 5. *continued*

Station	Yr	Oct	Nov	Dec	Yr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Z
WPA006:	97		A		98	A	A	A	AP				A	A	A	A		0 m
			A			A	A	A	AP				A	A	A	A		10 m
					99				A	NA	A	NA	NA	A	A			0 m
									NA	NA	A	NA	NA	A	A			10 m
					00		A	A	NA	NA	NA	NA	NA					0 m
							A	A	NA	NA		NA	NA					10 m
WPA007:	97		A		98	A	A	A	AP			A	A	A		A		0 m
			A			A	A	A	AP			A	A	A		A		10 m
					99				NA	NA	NA	NA	NA	NA				0 m
							A		NA	NA	NA	NA	NA	N				10 m
					00		A		NA	NA	NA	NA	NA					0 m
									NA	NA	NA	NA	NA	A				10 m
WPA008:	97		A		98	A	A	A	A			A	A	A	A	A		0 m
			A			A	A	A	A				A	A		A		10 m
					99				NAP	AP	NA	NA	NA	NA				0 m
									NAP	NAP	NA	NA	NA	A				10 m
					00				A	NA	NA	NA	NA					0 m
									NA	NA	NA	NA	NA					10 m

Ammonium-N (NH_4^+-N)

Ammonium-N concentrations in Puget Sound and the coastal estuaries were generally lower than nitrate+nitrite-N concentrations (Appendix A). BRL concentrations (<0.71 µM; 0.01 mg/L) of ammonium-N were relatively frequent; 76%, 43% and 42% for WY 1998, WYY 1999, and Y 2000, respectively. The low ammonium 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 5 µM (0.07 mg/L) and 10 µM (0.14 mg/L) were arbitrarily selected (Newton, 1995a), based relative to the historical maximum Admiralty Inlet concentration of 2 µM (0.03 mg/L). Thus, ammonium-N concentrations >5 µM and >10 µM are used here as indicators of high and very high ammonium, respectively.

Stations with ammonium-N concentrations >5 µM during WY 1998-Y 2000 (Figure 14) and the number of months (n) observed were: BLL011 (3), BUD002 (3), BUD005 (5), CSE002 (5), DNA001 (2), GYS004 (5), OAK004 (2), POD007 (4), PSS008 (2), SIN001 (5), TOT002 (2), WPA001 (8), WPA003 (2), and 1 each in CSE001, DIS001, ELD002, GYS008, and QMH002. Underlined stations are those with previously recorded high ammonium concentrations. Eight of these 18 stations are located in South Puget Sound.

Particularly notable is the number of high ammonium-N observations in Budd Inlet (8), which has much history of such observations, and in the coastal estuaries Willapa Bay (10) and Grays Harbor (6), which have no history of such observations , except for at WPA001. Also notable is that BLL011 (1), BUD002 (3), BUD005 (1), PSS008 (1) and SIN001 (1) all had ammonium concentrations exceeding 10 µM. Such high concentrations are typically rare. Except for the Budd Inlet stations, these represent unprecedented occurrences. These exceptionally high ammonium concentrations were recorded at BLL011 (May 2000), PSS008 (Aug 1998) QMH002 (Aug 2001) and SIN001 (Sep 2000) spanned nutrient analyses by both labs used in this period (MEL prior to 19 Feb 1999 and UW since), indicating that a laboratory-specific analytical difference does not appear to be the reason for these new observations.

While high ammonium concentrations (>5 µM) have been recorded at WPA001 before, values at WPA003, GYS004, and GYS008 have never been recorded above this threshold before 1998-2000. The high ammonium concentrations at GYS004 and GYS008 (Oct 1998, Oct-Nov 1999, Sep 2000, Oct 2001) also were found in analyses conducted by both labs. Since WY 1993, ammonium concentrations >5 µM previously recorded at WPA001 were in Jul, Sep 1995, Apr, Sep, Oct 1996, and in addition to the observations in Oct 1998, Oct, Nov 1999, Sep, Nov 2000, and Oct 2001.

High ammonium concentrations often have been observed in Budd Inlet. Data from WY 1993-Y 2000 show ammonium-N concentrations improved after 1994, but are showing a hint of an increasing pattern recently. Y 2000 ammonium concentrations are the highest seen since WY 1993 (~11 µM). Relative to other Puget Sound locations, ammonium-N concentrations remain high in Budd Inlet, particularly in the inner inlet (BUD002), although the concentrations have shown a reduction over pre-1994 levels. Suspected impacts from eutrophication led the Lacey-Olympia-Thurston-Tumwater (LOTT) 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 monitoring which spanned this change (Eisner and Newton, 1997).

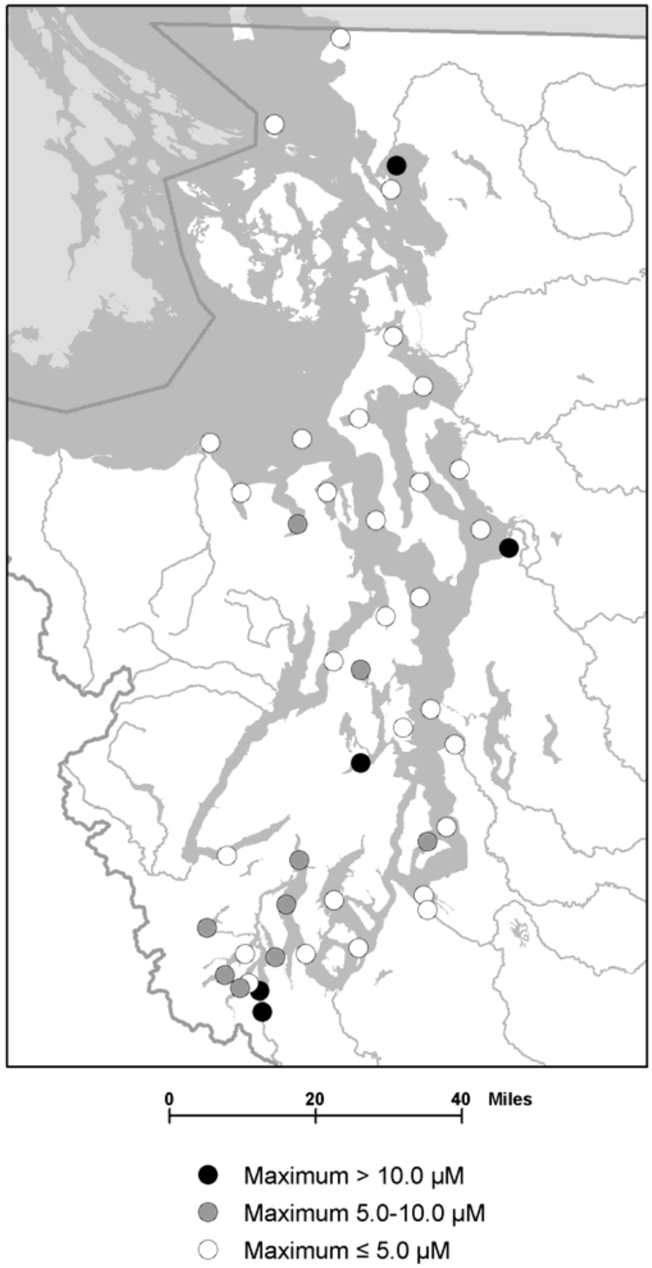


Figure 14. Maximum ammonium-N concentrations at Puget Sound stations during WY 1998 – Y 2000.

A post-1993 reduction in frequency of high ammonium concentrations in Budd Inlet is visible from the long-term monitoring data (Figure 15). Prior to 1994, station BUD005 in central Budd Inlet exhibited the most consistently high ammonium concentrations of all stations monitored. At its worst in WY 1992, concentrations >5µM (0.07 mg/L) were recorded in six out of twelve months and a maximum concentration of 13.6 µM reached twice, in Oct '91 and Jun '92. Similar conditions were observed in WY 1993 (Newton *et al.*, 1994). In contrast, following the N-removal implementation, the frequency of high ammonium concentrations at BUD005 for WYs 1994-97 was much lower, with only one occurrence of high ammonium per year during WY 1994 through 1996 and two in WY 1997. Maximum concentrations ranged 5.6 µM (May '94) to 8.1 µM (Aug '97). Similar patterns of the frequency of ammonium concentrations observations >5 µM were found in WY 1998 (once) and WYY 1999 (twice) but increased to three observations during Y 2000. One of the high ammonium-N concentrations recorded during Y 2000 was very high, at 10.9 µM in Jun '00. This increasing frequency of high ammonium-N concentrations may be of concern and may also indicate that inputs from other nutrient sources to Budd Inlet (e.g., Deschutes River, Moxlie Creek) should be further evaluated.

Ammonium-N concentrations were much higher and more frequent at BUD002, in the inner inlet, than at BUD005, in the central inlet, during WYY 1999 when this rotational station was monitored. This is consistent with results from WY 1996, when BUD002 was last monitored. Concentrations at BUD002 show similar results in both years. High concentrations (>5 µM) were observed three times at BUD002 (Jul '99, 2 depths, and Sep '99), compared to four observations during WY 1996. Very high (>10 µM) ammonium-N concentrations were recorded three times in Jun and Oct '99 (2 depths), compared to once in WY 1996.

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

Orthophosphate-P concentrations followed the same general pattern as nitrate-nitrite-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 (<0.32 µM, 0.01 mg/L) less frequently than the nitrogenous nutrients, in keeping with its generally non-limiting role in marine systems. BRL orthophosphate-P concentrations were observed in 1% of the nutrient samples during WY 1998, 6% during WYY 1999, and in 7% during Y 2000.

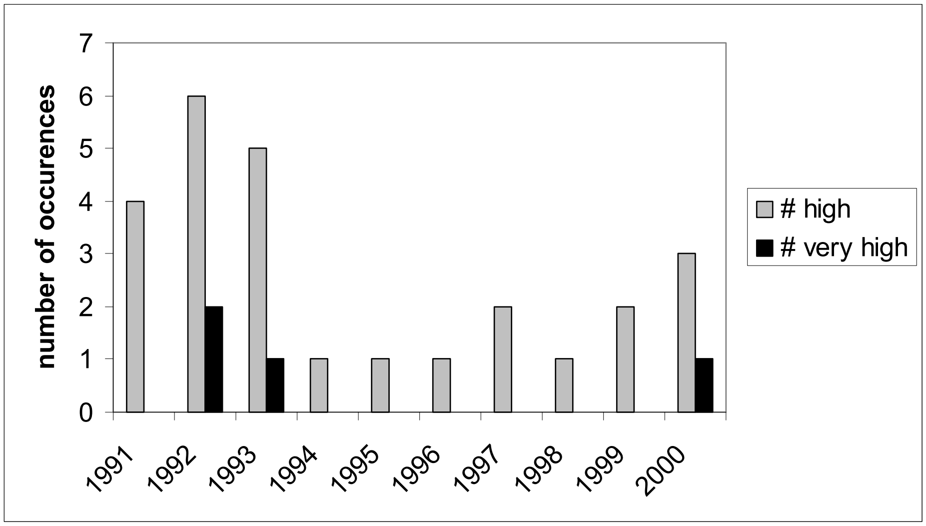


Figure 15. Number of observations of high (>5 µM) and very high (>10 µM) ammonium-N concentrations in central Budd Inlet at BUD005 since WY 1991. Nitrogen removal from LOTT effluent began in early 1994.

A notable difference is evident in the nutrient dynamics of Puget Sound stations versus the coastal estuary stations. BRL orthophosphate was observed in 0%, 3%, and 5% of the Puget Sound samples during WY 1998, WYY 1999, and Y 2000, respectively, but in 7%, 17%, and 15% of the coastal estuaries samples. Samples with BRL orthophosphate but detectable nitrate+nitrite-N or ammonium-N were exceedingly rare in Puget Sound (0.5%) yet were much more common (12%) in the coastal estuaries. Nutrient limitation due to nitrogen versus phosphorus is sometimes variable in estuaries with significant freshwater input. For the 71 samples with BRL orthophosphate but detectable nitrate+nitrite-N or ammonium-N, salinity was typically less than 20 PSU, with an average salinity in the samples of 10 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 indicated.

Silicate ($SiOH_4$)

Silicate was typically in high supply, which is characteristic of an estuary with significant riverine input. Silicate is an essential nutrient for diatoms, but not for other types of phytoplankton, such as dinoflagellates. Thus, its availability can sometimes influence phytoplankton species abundance.

Low silicate concentrations were only observed at stations outside of Puget Sound proper, at Sequim Bay and Discovery Bay and in the surface. Silicate concentrations below 3 µM were found in Jun-Jul 2000 in Discovery Bay and in Aug 2000 in Sequim Bay.

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 by phytoplankton may be large but equivalent to its resupply rate. In such a case, significant growth can occur yet, because uptake and supply rates are balanced, no accumulation of 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). While nutrient limitation can be seen at concentrations as high as 5 µM, several studies have shown significant uptake for coastal phytoplankton species at this concentration (Kokkinakis and Wheeler, 1987; Raymont, 1980; Parsons and Harrison, 1983). Although the range for different species is quite wide, a common guideline for where nitrate concentrations *may* be limiting to the phytoplankton population is 1.0 µM (0.014 mg/L) (see Goldman and Glibert, 1983).

Using the range of 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), a similar cut-off concentration for orthophosphate can be calculated to be from 0.07 to 0.2 μM.

Generally, areas of Puget Sound with strong, persistent stratification can show nutrient levels below detection for extended periods of time and nutrient-limited phytoplankton growth. While nutrient limitation has not been investigated in all of these areas, nutrient-addition experiments conducted as part of focused monitoring or other studies by Ecology showed a substantial increase in phytoplankton production with added nutrients in Hood Canal (Newton *et al.*, 1994), Budd Inlet (Newton *et al.*, 1998b), and Carr Inlet (Newton and Reynolds, 2002). Nutrient limitation has not been thoroughly studied in Washington State waters, but stratified waters are the most likely to respond to nutrient addition.

A discussion of nutrient limitation in Puget Sound found in PSEP (1991b) 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, recent and more extensive studies by Nakata and Newton (2000) using nutrient-addition assays show that this is not exclusively true.

In conclusion, while it is inappropriate to conclude either nutrient limitation or nutrient depletion from nutrient concentration data alone, low nutrient concentrations for extended periods of time *may* be indicative of nutrient limitation of the growth of the phytoplankton population. These would be areas where addition of nutrients could result in water quality effects. Other information (e.g., results from nutrient-addition experiments, modeling) would be required for confirmation and assessment of significance.

Below-threshold DIN

In this report, the occurrence of consecutive months with surface DIN (dissolved inorganic nitrogen; equals nitrate+nitrite-N plus ammonium-N) concentrations that are below 1 μM (0.014 mg/L) is used as an indicator of potential nutrient-limitation of marine phytoplankton. (This threshold is slightly different than that established in previous reports (Newton *et al.*, 1997; 1998a), which was based on the reporting limit for nitrate+nitrite-N at Manchester Environmental Laboratory of 0.1 mg/L.) To indicate nutrient-sensitive areas for marine phytoplankton, we have adopted the occurrence of 3 or 5 consecutive months of below-threshold surface dissolved inogranic nitrogen (DIN). Locations of stations with low DIN for $\geq$5 and $\geq$3 consecutive months are shown in Figure 16. Nutrient-limited populations are those that would be most sensitive to anthropogenic nutrient inputs. That is, adding nutrients to these locations could 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.

Stations showing the longest duration of below-threshold surface DIN in Puget Sound are, from north to south, Saratoga Passage, Possession Sound, Sinclair Inlet, Southern Hood Canal, and Carr, Case, and Budd Inlets. No stations in Grays Harbor exhibited this pattern, but four out of six stations in Willapa Bay did (WPA004, 006, 007, 008). These are similar patterns as were observed in WY 1996-1997, though with only a few locations (Saratoga Passage, Southern Hood Canal, Willapa Bay) showing $\geq$5 consecutive months (Newton *et al.*, 1998a).

The occurrence of consecutive months of below-threshold DIN can be from natural causes, when large spring blooms exhaust nutrients and stratified water-columns prevent re-injection of 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 with time. One generality is that in order to have brought nutrients to low levels, phytoplankton production must have been either high or prolonged without mixing . In summary, although it is not possible to interpret the cause of consecutive months of below-threshold DIN, this occurrence indicates that these areas would be the most sensitive to added nutrients.

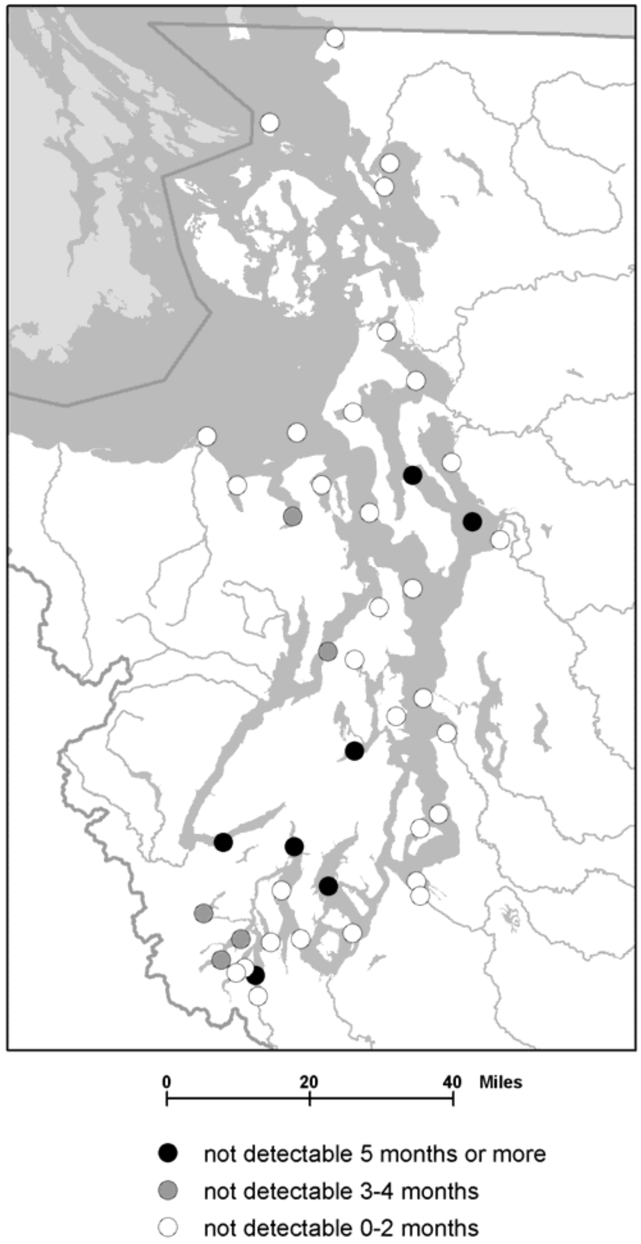


Figure 16. Puget Sound stations with below-threshold dissolved inorganic nitrogen during WY 1998 – Y 2000.

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 of fcb enter streams and rivers, and thus fresh water input is a major source of 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 org./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 Natural Resources and Parks does likewise for beaches in King County, as do many other municipalities in Washington State. A more thorough assessment of 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 org./100 mL (moderate count) as an indicator of where contamination may be of concern; and 43 org./100 mL (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 fcb concentrations.

During WY 1998-Y 2000, samples from 23 stations had moderate fcb counts during at least one month (Figure 17). Table 6 lists which stations were listed on the State of Washington Federal Clean Water Act Section 303(d) listing. Sixteen of these stations are in Puget Sound (Figure 18); three are in Grays Harbor and four in Willapa Bay. High counts were observed at 8 of the 16 Puget Sound stations, two of the three Grays Harbor stations and two of the four Willapa Bay stations.

Table 6. Stations with high fecal coliform bacteria concentrations during WY 1998 – Y 2000. Also shown, in italics, are stations reported on the 1998 303(d) (Ecology, 2000) listing as impaired waterbodies due to violation of State fecal coliform bacteria (fcb) standards from anthropogenic sources. The "-" indicates not monitored.

Station	State waterbody class	# observations fcb > 14 org./100mL			**# observations fcb > 43 org./mL**		
		WY 1998	WYY 1999	Y 2000	**WY 1998**	**WYY 1999**	**Y 2000**
BLL009	A	1					
BLL011	A	-	-	3	**-**	**-**	**1**
BUD002	B	-	4	-	**-**	**1**	**-**
BUD005	A	1	1		**1**		
CMB003	A	2	4	4		**1**	**2**
CMB006	B	-	5	-	**-**	**3**	**-**
CSE002	AA	-	1	-	**-**		**-**
DRA002	A	-	-	1	**-**	**-**	
EAG001	AA	1	-	-		**-**	**-**
ELB015	A	1	1	1	**1**		**1**
GYS004	B	4	10	4	**2**	**1**	**1**
GYS008	B	1	2	4	**1**	**1**	**1**
GYS016	A	1					
HCB004	AA			1			
OAK004	A	2	3		**1**	**1**	
POD007	AA	2	-	-	**1**	**-**	**-**
PSS008	B	3	-	-	**1**	**-**	**-**
PSB003	AA	1					
SIN001	A		2			**1**	
WPA001	A	3	5	5	**1**	**1**	**2**
WPA003	A	2	1	2	**1**	**1**	**1**
WPA004	A	1					
WPA008	A		1	2			

Observations of fcb concentrations in marine waters may be quite rare and erratic because of the very short lifetime of 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 concert with the other indicators presented in this report is discussed in the General Discussion.

In Puget Sound, the most consistently elevated fcb counts were observed in Commencement Bay. At core station CMB003, Browns Point, multiple occurrences of moderate counts were observed in all years. Another Commencement Bay station, CMB006, mouth of City Waterway, monitored in WYY 1999 showed even worse contamination (3 high, 5 moderate) than the data for CMB003 in the same time period (1 high, 4 moderate). These two stations were the only Puget Sound stations to show more than one occurrence of high counts in a given year. Previous Ecology monitoring data (Newton *et al.*, 1998a) also suggest that fcb contamination in Commencement Bay is chronically apparent. Possible sources and loading from the Puyallup River should be investigated.

Inner Budd Inlet (BUD002, South End Olympia Port) showed three moderate fcb counts and one high fcb count during WYY 1999 when this rotational station was monitored. Note that the core station in middle Budd Inlet (BUD005, Olympia Shoals) showed remarkably fewer instances (one moderate) during the same time period. This same decrease in probability was apparent in data for Bellingham Bay (BLL011 vs. BLL009) and Possession Sound (PSS008 vs. PSS019) and illustrates the short life-time and low probability of detecting fcb in mid-bay open-water sites.

Rare (once per year) but extreme (fcb counts over 100 org./100 mL) events were observed at Elliott Bay (two years), Oakland Bay (two years), Port Orchard, inner Possession Sound, and Sinclair Inlet. The events at Port Orchard (3100 org./100 mL) and Sinclair Inlet (890 org./100 mL) were exceptionally notable, while all others ranged 140-210 org./100 mL. While fcb counts over 100 org./100 mL are common in freshwater and rivers, counts of this magnitude are rare in marine waters for reasons mentioned previously.

Figure 19 shows the seasonal pattern of when fcb counts were moderate or high. For all Puget Sound stations, 80% of the elevated counts occurred during October through March. Wintertime high fcb counts have been common in Puget Sound and are associated with high runoff, which transports fcb to marine waters. Summertime high counts however, are not typically observed in Puget Sound but were observed during WYY 1998-Y 2000 at BLL011, BUD002, CMB003, ELB015, and OAK004. Summertime high fcb counts were especially rare during WYs 1990 through 1995 but were observed with a higher frequency during WY 1996 and 1997. Stations previously recorded (WY 1990 through 1997) with elevated fcb counts in summer are BUD002, CMB003, ELB015, OAK004, PSS019, and SIN001.

From analysis of WY 1998-Y 2000 data, it appears that fcb contamination in Puget Sound is worst at Commencement Bay, but problematic in Budd Inlet, Elliott Bay, Oakland Bay, Sinclair Inlet, Possession Sound, Bellingham Bay, and Port Orchard.

Grays Harbor and Willapa Bay continue to have consistently higher and more persistent fcb counts than are found at the Puget Sound stations (Figure 17). Both Grays Harbor and Willapa Bay appear to have strong fcb contamination in the inner portions of these estuaries. Chronic fcb contamination was evident in Grays Harbor and Willapa Bay at the stations closest to the Chehalis (GYS004 and GYS008) and Willapa rivers (WPA001).

High counts were observed at 4 of the 7 coastal estuary stations that had moderate counts. Unlike in Puget Sound, the moderate and high counts are recorded more consistently year-round with the seasonal pattern not as dominated by wintertime highs (Figure 19). Only 68% of the elevated counts occurred during October through March in these coastal estuaries as compared with 80% in Puget Sound.

Although still chronically elevated, the high fcb counts in Grays Harbor have been declining over the past several years. The maximum fcb count recorded in Grays Harbor during WY 1998-Y 2000 was 110 org./100 mL. Previously, in WY 1996-1997 maximum values were in excess of 300, and in WY 1995 counts greater than 1000 org./100 mL were recorded for 3 months.

Except for this difference in the maximum concentration, fcb counts in Grays Harbor and Willapa Bay appear to be at similar to higher levels as recorded in previous years. Previous to WY 1996, only the innermost coastal estuary stations showed elevated counts. Since then, elevated counts have shown up at stations that are farther seaward (e.g., GYS016, WPA004).

Most all of the stations with elevated fcb counts during WY 1998-Y 2000 have also shown elevated fcb counts in previous wateryears (Newton *et al.*, 1998a). Samples from Budd Inlet (BUD005), Commencement Bay (CMB003, CMB006), Oakland Bay (OAK004), Possession Sound (PSS008/PSS019), Grays Harbor (GYS004, GYS008), and Willapa Bay (WPA001) have all had counts over 14 org./100 mL during at least one month in each wateryear from 1990 through 2000.

In summary, based on review of Ecology's fcb data from 1990 through 2000, areas with chronically high fcb counts are Commencement Bay, Grays Harbor, and Willapa Bay. Areas with sporadic (within a year) but consistent (among years) high counts are Budd Inlet, Oakland Bay, and Possession Sound. Wintertime high counts in Elliott Bay and off West Point have been observed consistently only since WY 1993. Summertime high fcb counts in Puget Sound appear to be increasing in frequency; summertime high fcb were observed at five stations during WY 1998 through Y 2000 but only very rarely prior to WY 1996.

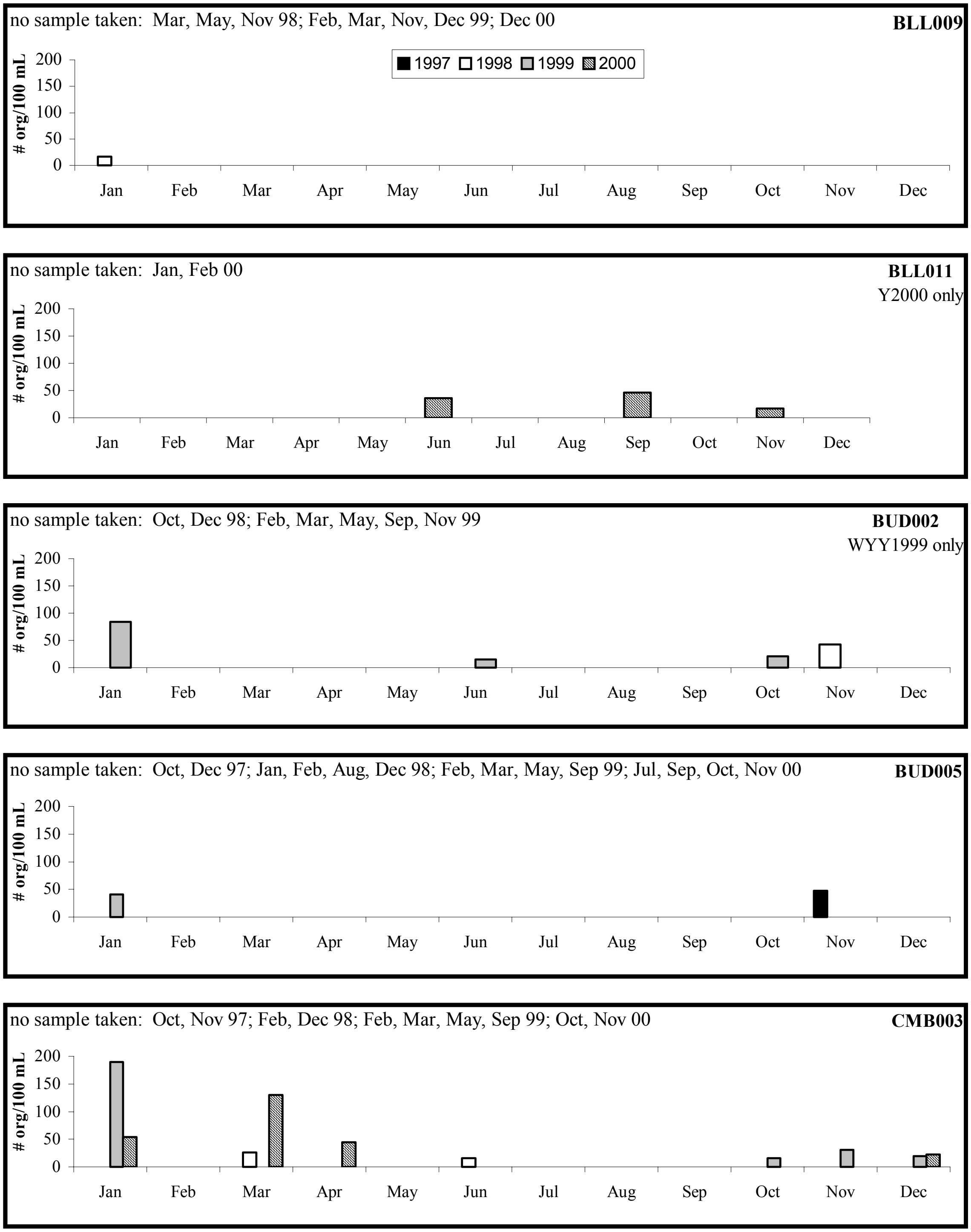
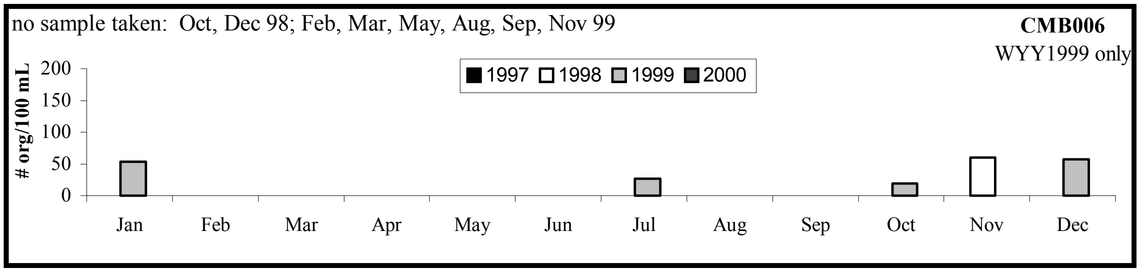
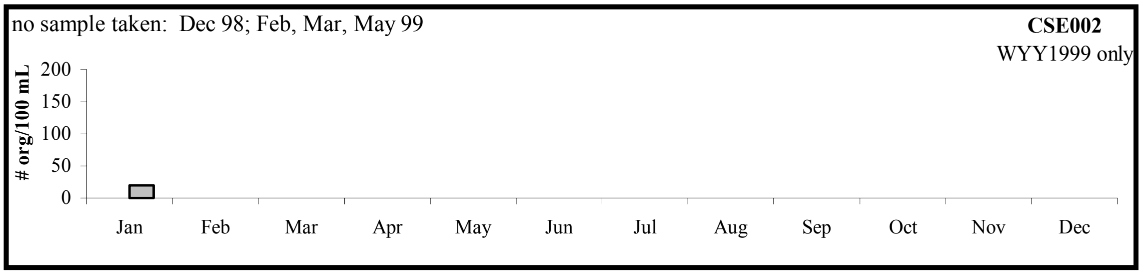
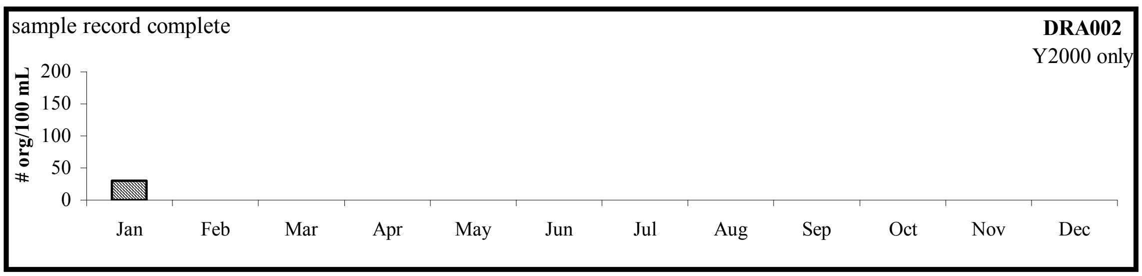
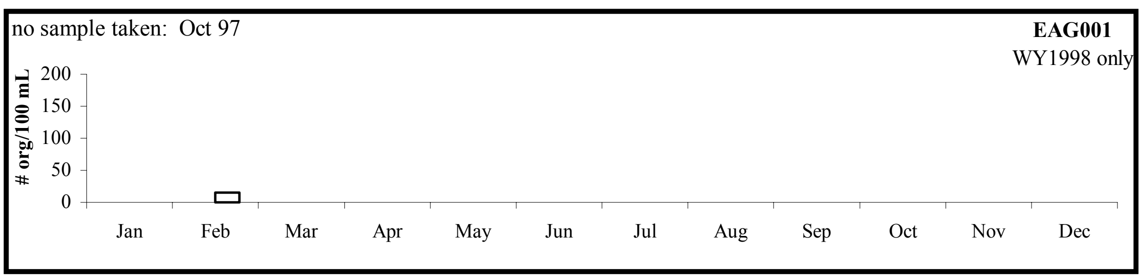


Figure 17. Fecal coliform bacteria concentrations versus calendar month for stations with high counts (> 14 organisms/100mL) during WY 1998 – Y 2000.









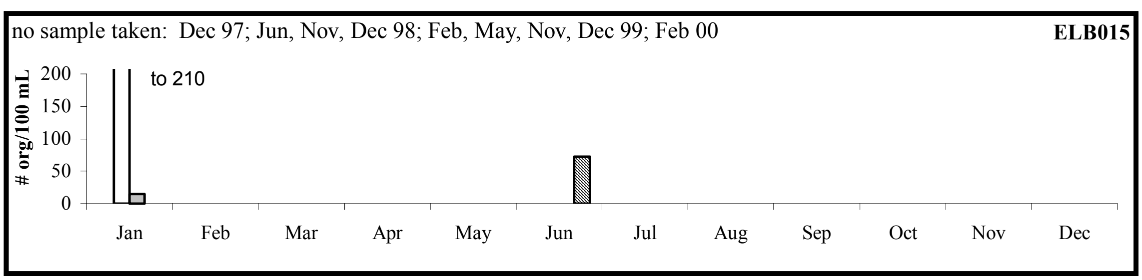


Figure 17. *Continued*.

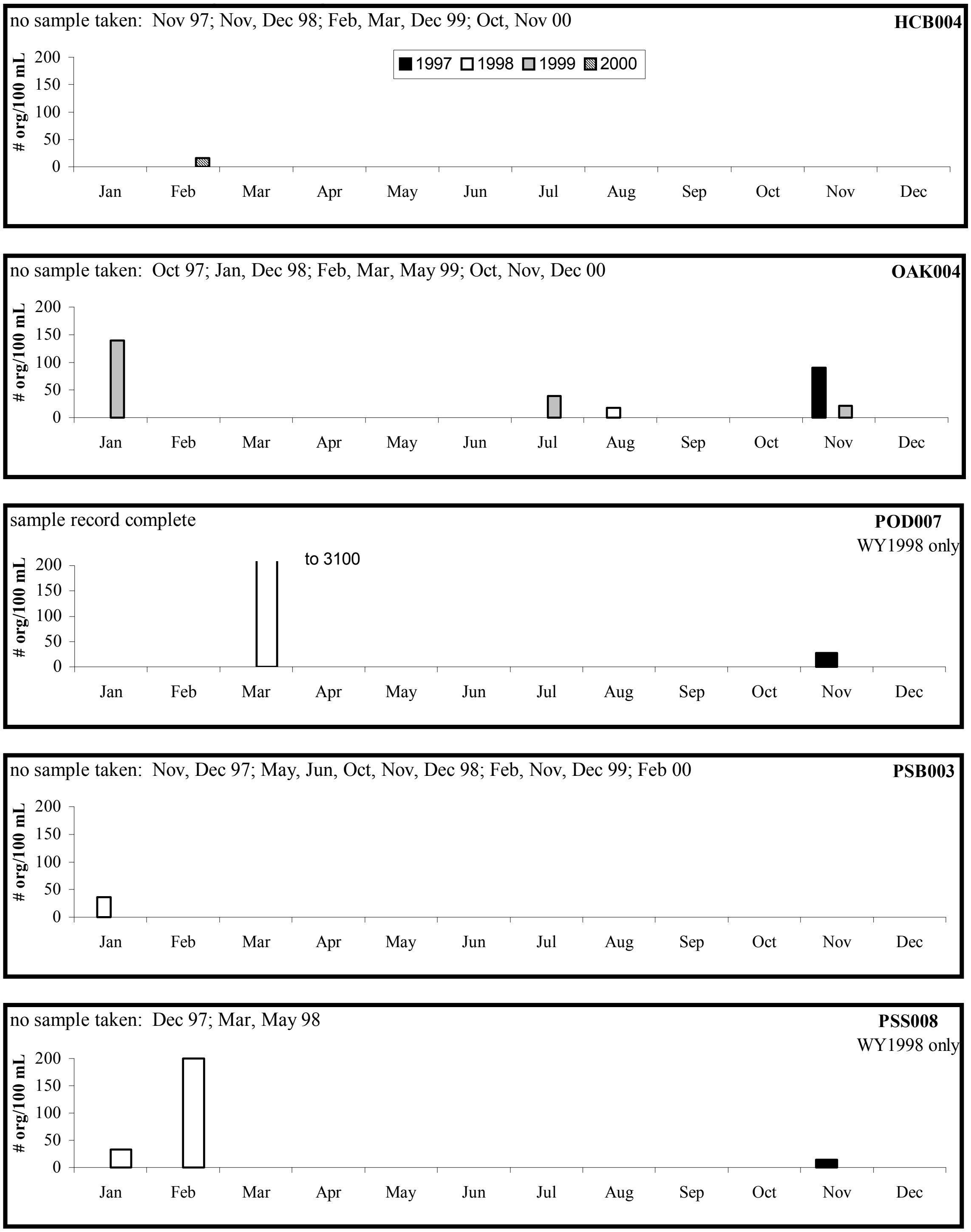


Figure 17. *Continued.*

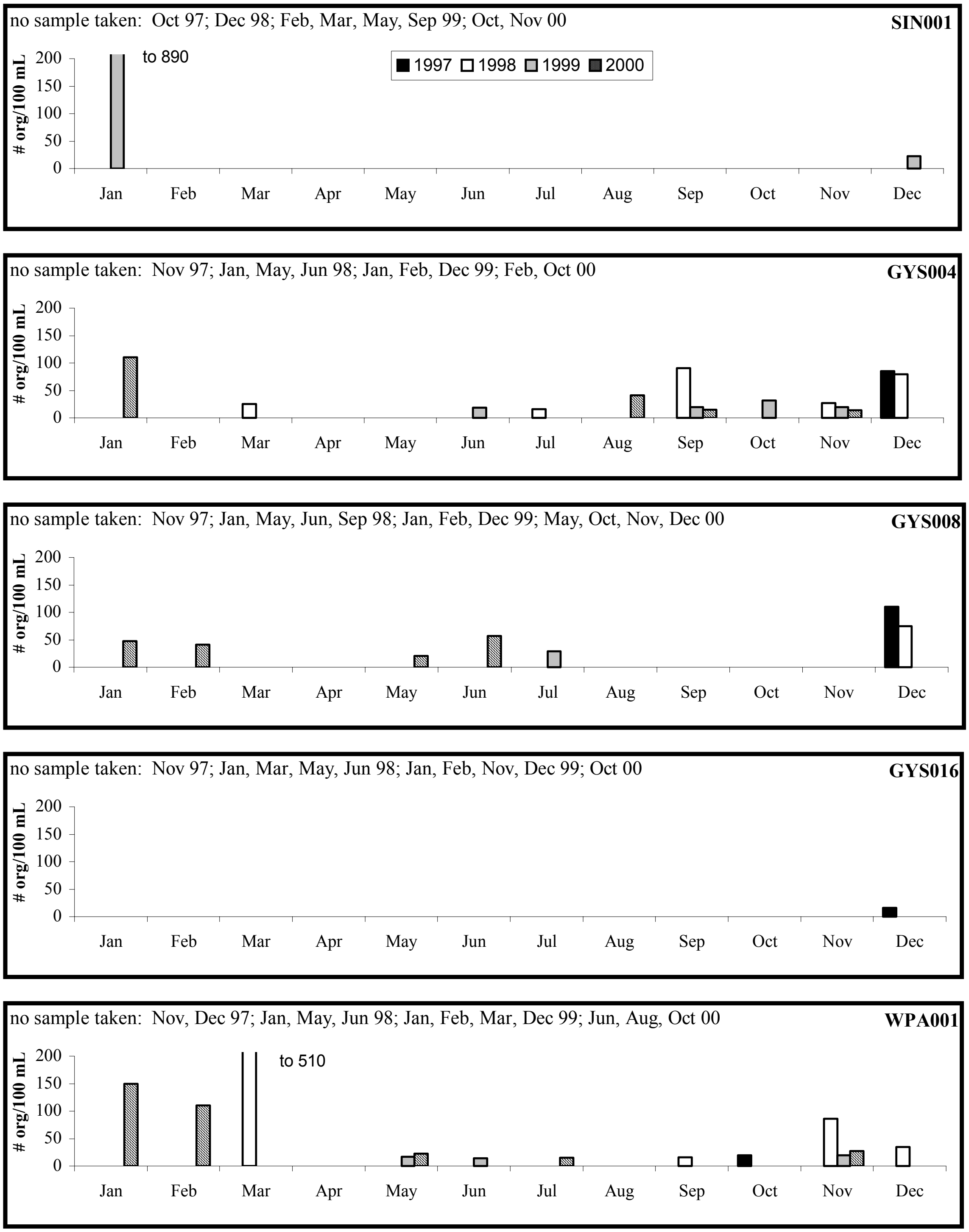


Figure 17. *Continued.*

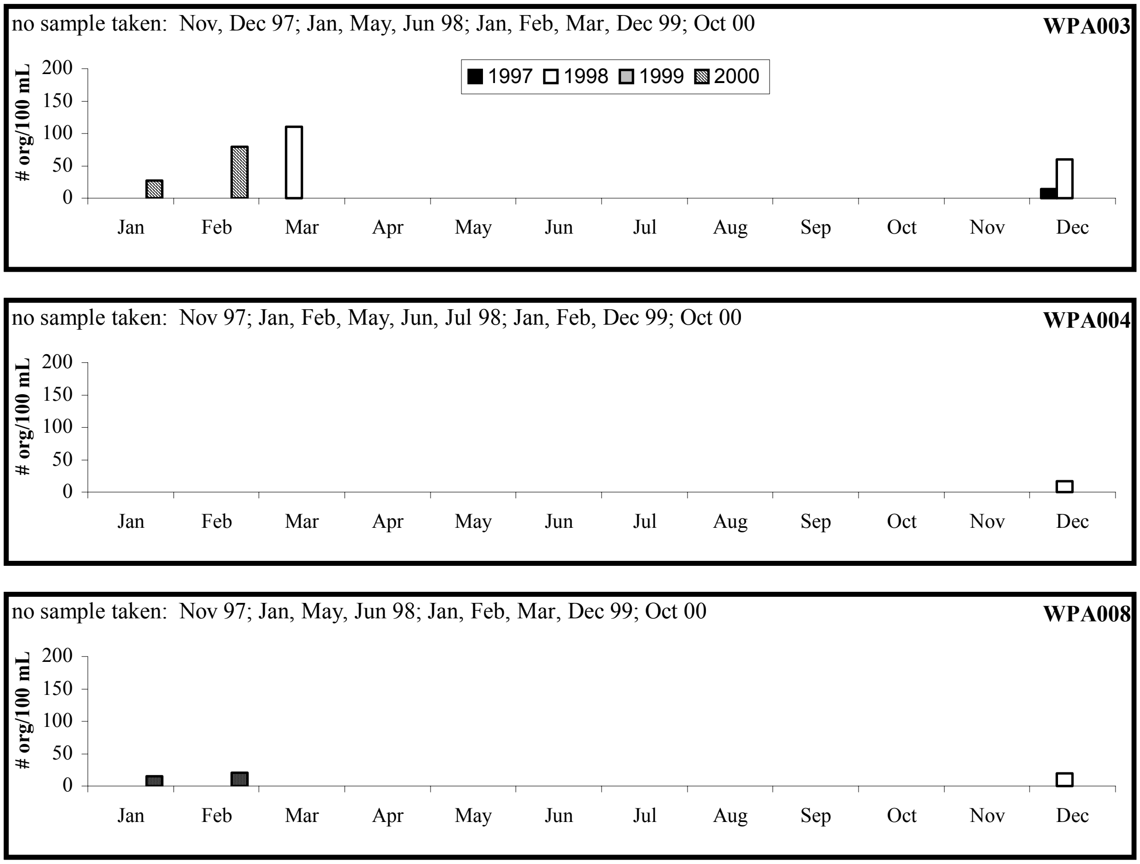


Figure 17. *Continued*.

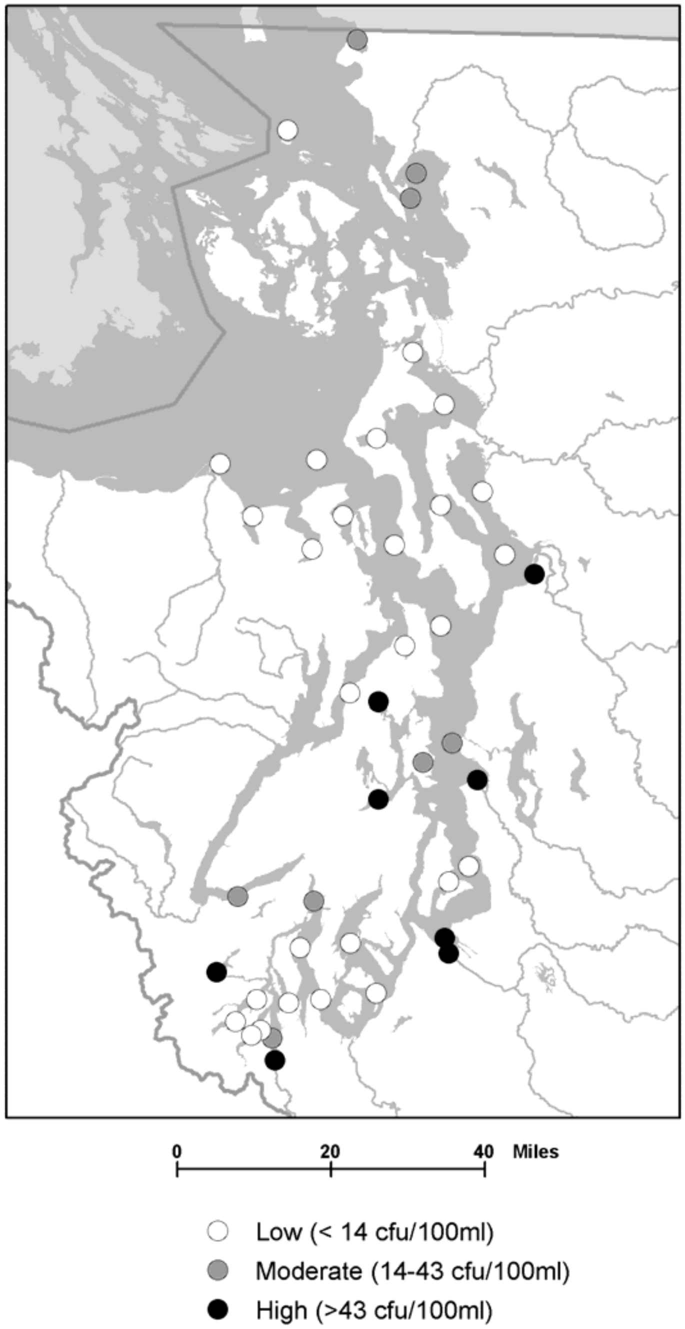
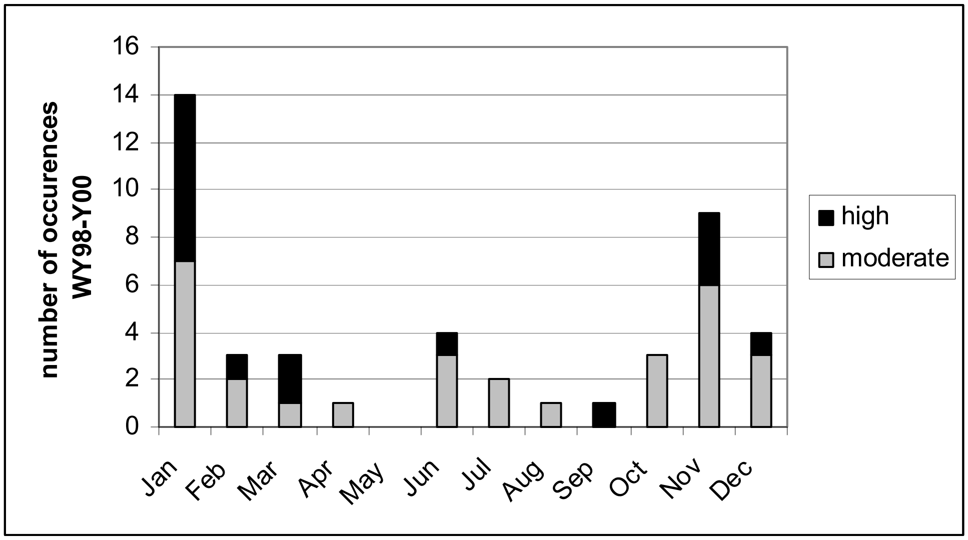


Figure 18. Puget Sound stations with fecal coliform counts >43 org./100 mL, >14 org./100 mL, and ≤ 14 org./100 mL observed during WY 1998 – Y 2000.

a)



b)

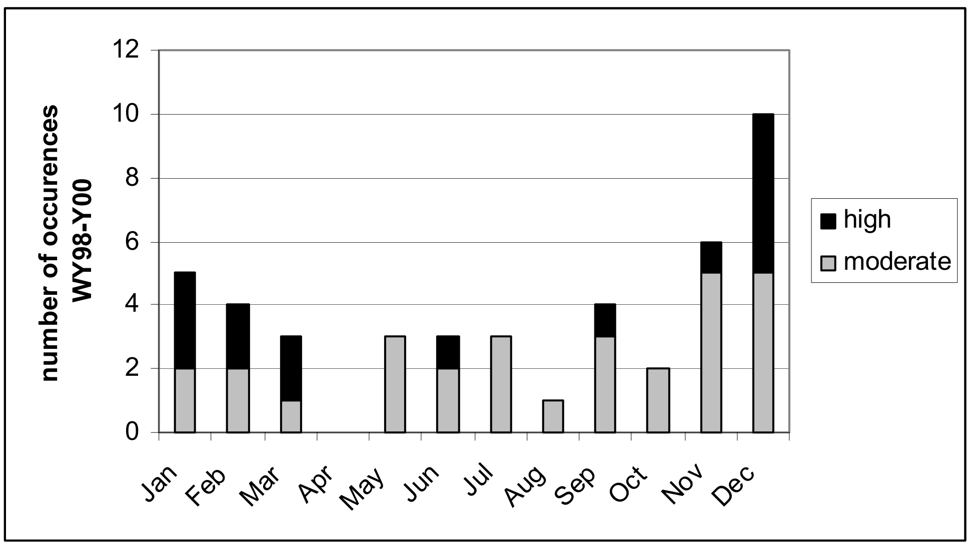


Figure 19. Annual distribution of the occurrences of high or moderate fecal coliform bacteria counts recorded during WY 1998 through Y 2000 for a) Puget Sound and b) Grays Harbor and Willapa Bay.

Quality Control

Quality control results, showing relative standard deviations for laboratory analyses conducted during WY 1998-Y 2000, are summarized in Table 7. In general, data quality was within target ranges for most laboratory analyses. Despite changes in laboratories, data quality objectives were consistently met.

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 of these replicates (%RSD = (sample standard deviation / sample mean) * 100). Table 7 shows the percent of the samples that fell into various RSD% ranges. Target RSD ranges (shared in Table 7) were 0-10%, except for fecal coliform bacteria which was 0-20%, reflecting inherent low and variable numbers obtained. In all cases determined, the mean RSD for field+lab variation exceeded that for lab variation, as would be expected.

Target mean RSD values of 10% for nutrients and 20% for fecal coliform bacteria and chl *a* were established in the Ambient Marine Water Column Monitoring Plan (Janzen, 1992b). All of these meet Puget Sound Ambient Monitoring Program (PSAMP) quality assurance (QA) objectives except chl *a*, which is requested at 10% (PSWQA, 1988). Both labs met the nutrient target RSD's of 10% or less, with results typically at 5% or less. Chlorophyll *a* RSD's were 9% for the Ecology EAP Lab analyses and 12% for Manchester Laboratory analyses, straddling the PSAMP QA objective but well within previously established objectives for this program. The fecal coliform bacteria RSD of 17% also was within the objective.

To assess variation due to laboratory procedures alone, an objective was established to have 75% of lab replicate data within the target RSD range. This objective was met for most all variables (Table 7), with a few exceptions (fcb, chl *a* at MEL). Samples for lab variation alone were not conducted at the University of Washington Lab, but their field+lab replicates met and even exceeded (>85%) this target objective. The objective was not met for fcb, as was also the case in WY 1996-1997, but not previous to that. Fecal coliform bacteria concentrations are an inherently variable analyte. 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 total organism counts are low. These results will continue to be monitored and corrective actions taken if results deteriorate. The 67% of samples within target RSD% <20% is an improvement over the 55% attained in WY 1996-97. No procedural corrections are obvious at this time. The chl *a* results for the Manchester Lab analyses met their target of 75% of samples within RSD% <20%, but did not meet the more stringent PSAMP target of RSD% <10.

Table 7. Relative standard deviations (RSD%) for laboratory analyses. RSD% was calculated as equal to (sample standard deviation / sample mean) * 100. Shading indicates target ranges for RSD%.

Manchester Environmental Laboratory analyses:

Nutrients (Oct 97-Feb 99); Pigments (Oct 97-Jun 99); FCB (Oct 97-Dec 00)

	$NO_3 + NO_2$		**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:	36	134	37	133	37	133
RSD%						
0-10	31%	87%	73%	84%	43%	93%
>10-20	14%	10%	11%	11%	35%	7%
>20-30	25%	3%	11%	3%	14%	-
>30-40	14%	-	-	2%	3%	-
>40-50	3%	-	-	1%	3%	-
>50-60	8%	-	3%	-	-	-
>60-70	6%	-	3%	-	-	-
>70-80	-	-	-	-	-	-
>80-90	-	-	-	-	-	-
>90-100	-	-	-	-	-	-
>100	-	-	-	-	3%	-
mean RSD:	24%	4%	8%	4%	16%	4%

	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:	102	117	49	51	49	51
RSD%						
0-10	63%	65%	31%	57%	14%	47%
>10-20	6%	2%	37%	25%	35%	24%
>20-30	-	8%	6%	12%	10%	10%
>30-40	5%	3%	4%	2%	10%	8%
>40-50	9%	12%	8%	2%	4%	2%
>50-60	-	-	-	-	8%	6%
>60-70	1%	4%	4%	2%	8%	2%
>70-80	4%	3%	4%	-	4%	-
>80-90	5%	3%	2%	-	2%	-
>90-100	3%	-	4%	-	4%	-
>100	5%	-	-	-		2%
mean RSD:	23%	17%	25%	12%	33%	19%

Table 7. Continued

University of Washington Marine Chemistry Lab analyses: (Feb 99 – Dec 00)

	NO_3	NO_2	NH_4	*o*PO_4	$SiOH_4$
	FIELD+LAB (3 reps.)	FIELD+LAB (3 reps.)	FIELD+LAB (3 reps.)	FIELD+LAB (3 reps.)	FIELD+LAB (3 reps.)
n:	77	78	78	78	78
RSD%					
0-10	91%	99%	86%	96%	90%
>10-20	3%	1%	8%	3%	6%
>20-30	4%	-	1%	1%	4%
>30-40	-	-	3%	-	-
>40-50	1%	-	1%	-	-
>50-60	-	-	-	-	-
>60-70	-	-	-	-	-
>70-80	1%	-	-	-	-
>80-90	-	-	1%	-	-
>90-100	-	-	-	-	-
>100	-	-	-	-	-
mean RSD:	4%	0.2%	5%	3%	4%

Ecology EAP Lab analyses: (June 99 – Dec 00)

	CHL *a*		**PHAEO**	
	FIELD+LAB (3 reps.)	LAB (2 splits)	FIELD+LAB (3 reps.)	LAB (2 splits)
n:	65	66	65	66
RSD%				
0-10	49%	76%	43%	56%
>10-20	34%	14%	29%	27%
>20-30	5%	5%	9%	3%
>30-40	5%	2%	-	3%
>40-50	3%	2%	2%	2%
>50-60	-	2%	2%	2%
>60-70	-	2%	6%	2%
>70-80	2%	-	8%	2%
>80-90	2%	-	2%	-
>90-100	-	-	-	5%
>100	2%	-	-	-
mean RSD:	15%	9%	21%	16%

Accuracy

The accuracy of the laboratory analyses is assured through the laboratory procedures of the various accredited labs. These include standard recoveries, instrument calibrations, and other standard procedures. Accuracy has been demonstrated and assured in the State Accreditation process and those data are not repeated here.

Blanks

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

Sensor verification samples

Sensor verification samples are taken 5-10 minutes after the cast was taken with the sensor, so only provide rough information on sensor performance.

Despite this caveat, verification samples for salinity run using a salinometer (n=112) showed strong agreement with the *in situ* sensor values (Figure 20A). The mean of the absolute values of the difference between sensor and verification samples was 0.16 PSU; expressed as a percent difference, this is 0.6%. The range was 1.14 PSU and the standard deviation was 0.22 PSU. There was no evidence of directional variation or bias, as the mean percent difference was 0.06%. The accuracy of the *in situ* salinity data appears to be quite high.

Comparison of the verification samples for DO analyzed by modified Winkler titration with the *in situ* DO sensor (n=224) shows reasonably good agreement for most samples (Figure 20B). Both the r^2 values (~ 0.90, except for WY 1998 = 0.80) and the slope (close to 1.0) are similar to those found in previous years. The average accuracy of the DO sensor, compared to the titration, was 0.5 mg/L. For DO concentrations less than 3 mg/L, average accuracy was 0.32 mg/L or 27%. For DO concentrations greater than or equal to 3 and less than 10 mg/L, average accuracy was also 0.59 mg/L or 8%. For DO concentrations greater than or equal to 10 mg/L, average accuracy was 0.58 mg/L or 5%.

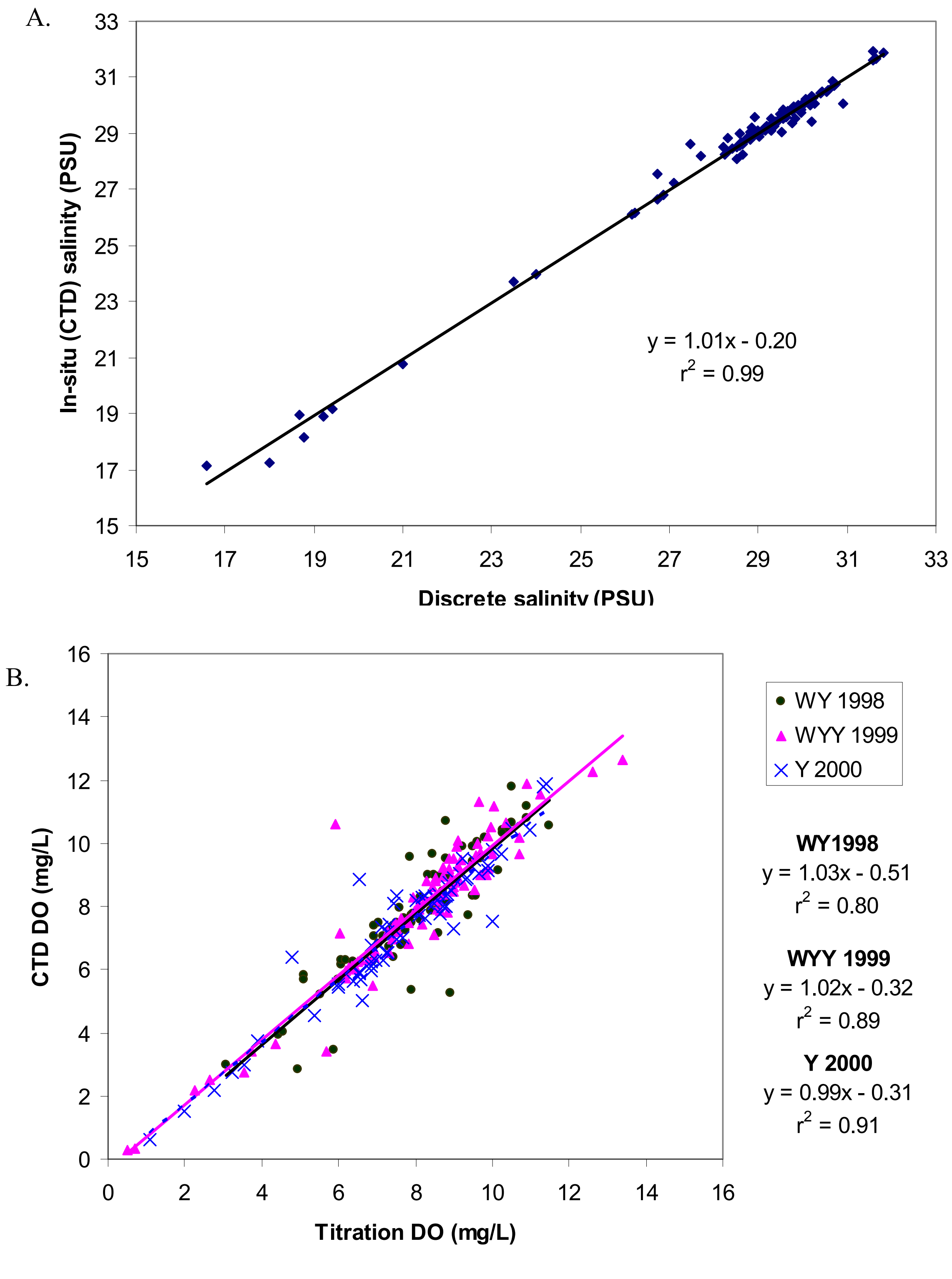


Figure 20. Comparisons of sensor versus discrete sample measurements. A. Regression of CTD sensor-derived salinity versus that from discrete samples. Data shown are composited samples for WY 1998-Y 2000. B. Regression of CTD sensor versus titration results for DO sensor verification samples collected in WY 1998, WYY 1999 and Y 2000.

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, even with the complexity of these data and the limitations of under-sampling in time and space, the monitoring data still can be used as screening tools and rough indicators of water quality. We have designated specific indicators of water quality that indicate either poor status or high susceptibility (Newton *et al.* 1998a). An analysis of the indicators for WY 1998 through Y 2000 data follows initial discussion of stratification. 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 Quality

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 of nutrients (dissolved nitrogen and phosphorus) and bottom waters can become depleted of 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, agricultural and domestic fertilizers, freshwater diversion, impervious surfaces) 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 light limitation thus preventing significant population increase. Eutrophication (external increase in nutrient supply to system) of nutrient-limited stratified waters can result in very large algal blooms and, after these sink, a correspondingly large DO debt in bottom waters. However, the physical stratification of the water receiving the nutrient input is 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 by 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 attempt 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 of biomass, a disruption of the usual predator-prey 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 useful in increasing that understanding.

Indicators of Puget Sound and Coastal Estuary Water Quality

Five indicators of environmental condition were introduced in the Results and Discussion section: 1) presence of strong density stratification (Strong-Persistent, Strong-Intermittent); 2) occurrence of low DO concentrations (<3 mg/L, <5 mg/L); 3) consecutive months with very low surface DIN concentrations (3 months, 5 months); 4) high ammonium-N concentrations (>5 µM or 0.07 mg/L, >10 µM or 0.14 mg/L); and 5) high fecal coliform bacteria concentrations (>14 org./100 mL, >43 org./100 mL). A summary of the indicators is in Table 8; their co-occurrence at stations is discussed in this section.

If numerical values are attached to the two threshold indicator levels, then rankings of relative water quality concern can be derived. A value of 5 was assigned to the "X" threshold in all categories, and a value of 1 was assigned to the "x". Stations with rankings above 10 are shown in bold in Table 8.

Table 8. Indicators of environmental conditions at Marine Waters Monitoring stations during WY 1998 – Y 2000. No data collected indicated by a "-". Stations indicated in bold show highest water quality concern, based on indicator values; see text for details.

Station	strong stratification[1]	low DO[2]	consecutive low DIN[3]	hi NH_4[4]	hi FCB[5]
Puget Sound Stations:					
ADM002		x			
ADM003	x	x			
BLL009	x	x			x
BLL011	x	x		X	x
BUD002	**X**	**x**		**X**	**X**
BUD005		**x**	**X**	**X**	**x**
CMB003	**X**	**x**			**X**
CMB006	x				X
CRR001		x	X		
CSE001				x	
CSE002		x	X	x	x
DIS001		X	x	x	
DNA001				x	
DRA002					x
DUN001		x			
EAG001					x
ELB015	**x**	**X**			**X**
ELD002				x	
GRG002	x	X			
HCB003	**X**	**X**	**-**	**-**	**-**
HCB004	**X**	**X**	**X**		**x**
HCB006	x	X	x		
HCB007	**X**	**X**	**-**	**-**	**-**
OAK004	x		x	x	X
PGA001		x			
PNN001	**X**	**X**			
POD007				x	X
PSB003		X			x
PSS008	**X**			**X**	**X**
PSS019	**X**	**x**	**X**		
PTH005		x			
QMH002		x		x	
SAR003	**X**	**X**	**X**		
SEQ002		x			
SIN001		**x**	**X**	**X**	**X**
SKG003	X	x			
SUZ001	X	x			
TOT001			x		
TOT002			x	x	

Table 8 *Continued.*

Station	stratification[1]	low DO[2]	consecutive low DIN[3]	hi NH_4[4]	hi FCB[5]
Coastal Estuary stations:					
Grays Harbor:					
GYS004	**X**			**x**	**X**
GYS008	x			x	X
GYS015	x	-	-	-	-
GYS016					x
Willapa Bay:					
WPA001	x	x		x	X
WPA003	x			x	X
WPA004			x		x
WPA006			X		
WPA007			X		
WPA008			X		x

[1]Stratification: X = Strong-Persistent; x = Strong-Intermittent
[2]Low DO: X = <3 mg/L; x = <5 mg/L
[3]Low DIN: X = <1 µM >5 consecutive months; x = <1 µM >3 consecutive months
[4]High NH_4^+: X = >10 µM (0.14 mg/L); x = >5 µM (0.07 mg/L)
[5]High FCB: X = >43 org./100 mL; x = >14 org./100 mL

This analysis of the five water quality indicators for WY 1998-Y 2000 resulted in rankings above 10 at thirteen stations in nine areas: Hood Canal (HCB004, HCB003, HCB007), Budd Inlet (BUD002, BUD005), Commencement Bay (CMB003), Sinclair Inlet (SIN001), Possession Sound (PSS008, PSS019), Saratoga Passage (SAR003), Elliott Bay (ELB015), Penn Cove (PNN001), and inner Grays Harbor (GYS004). Rankings above 5 were found in Bellingham Bay, Case Inlet, Oakland Bay, inner Willapa Bay, Discovery Bay, Strait of Georgia, Carr Inlet, Port Orchard, West Point, Skagit Bay, and Port Susan.

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, ELB015, GRG002, HCB003, HCB004, HCB006, HCB007, PNN001 PSB003, SAR003; Table 8). All of these stations except DIS001 and PSB003 exhibit strong stratification. Stations with two or more observations of low (<5 mg/L) DO concentrations in a given year were ADM002, BLL011, CMB003, DUN001, PGA001, PSS019, SEQ002, SIN001, SKG003, and SUZ001. All of these stations show strong (n=5) or moderate (n=4) stratification, except SEQ002.

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 very important in this region. Low DO was fairly widespread in greater Puget Sound (Figure 10) in 1998, as was previously observed in late summer 1997 (Newton *et al.*, 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. Unknown variability in the signal of low DO waters entering Puget Sound makes assessments of basins and bays with anthropogenically mediated low DO more difficult. More needs to be understood about 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 strong or persistent stratification is 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.

Information on nutrient sensitivity (i.e. where nutrient loading could lead to low DO) may be obtained from the patterns of consecutive months with very low DIN concentrations. For Puget Sound, the stations with 5 or more consecutive months of BRL DIN (BUD005, CRR001, CSE002, HCB004, PSS019, SAR003, SIN001) all had strong (n=3) or moderate (n=4) stratification and all exhibited hypoxic (n=2) or low (n=5) DO. In Willapa Bay BRL DIN was observed for 5 or more consecutive months at four stations but was not associated with strong stratification or low DO. Flushing in this bay is stronger than in most of Puget Sound, but nutrient deficits (due to biological nutrient uptake) can be established despite this relatively rapid exchange. Also, adjacent surface oceanic and river waters are evidently nutrient-poor (coastal ocean except during upwelling) or not significant inputs (rivers in summer) (Newton *et al.*, 2000). In Grays Harbor there are fewer stations where nutrient data are collected (n=3) but surface DIN was never BRL for consecutive months and low DO was not observed.

High ammonium-N concentrations were primarily observed in South Puget Sound (BUD002, BUD005, CSE001, CSE002, DNA001, ELD002, OAK004, QMH002, TOT002), other Puget Sound bays (BLL011, DIS001, POD007, PSS008, SIN001), and near the river mouths in both Grays Harbor and Willapa Bay (GYS004, GYS008, WPA001, WPA003). Whenever high ammonium-N concentrations were found, high fcb counts were observed at the same station in twelve out of eighteen stations (Table 8). Many of these stations are in areas with significant freshwater runoff. Freshwater runoff can be a source of both ammonium-N and fcb contamination. Exceptions were CSE001, DIS001, DNA001, ELD002, QMH002, and TOT002, all of which are not as proximal to direct freshwater input.

The prevalence of high concentrations of fecal coliform bacteria in Puget Sound was found at stations close to urban centers and with major freshwater inputs: BUD002-Olympia-Deschutes, CMB003/CMB006-Tacoma-Puyallup, ELB015-Seattle-Duwamish, PSS008-Everett-Snohomish. Exceptions are SIN001 near Bremerton, OAK004 near Shelton, and POD007 near Port Orchard but no major freshwater sources. On the coast, Grays Harbor (GYS004, GYS008) continues to show chronically high fcb counts throughout the estuary, whereas in Willapa Bay contamination appears more constrained to the Willapa River (WPA001, WPA003), although in both estuaries moderate fcb counts were found with a wider distribution.

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 marine water quality data. Freshwater runoff was higher than normal in 1999 and this impact was shown by the lower SSS recorded throughout Puget Sound and the coastal estuaries (Figures 4 and 5). Instances of high fcb counts were often correlated with precipitation events (Figures 3 and 17; note Nov '98 through Jan '99, Nov '99).

The coastal estuary stations show different dynamics than the Puget Sound stations (Table 8). 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. However, the very high fcb counts (>100 org./100 mL) in these estuaries (GYS004, GYS008, WPA001, WPA003) suggest that flushing is not completely effective or that the input of 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 throughout Willapa Bay but not in Grays Harbor. Understanding the dynamics of the coastal estuary stations will likely be difficult to resolve without conducting sampling according to tidal stage or more intensive studies.

With regard to eutrophication and the region's sensitivity to nutrient loading, the indicators presented here can be classified into indication of the status of eutrophication and indication of susceptibility to effects from eutrophication. Status is given by the prevalence of low DO (with caveats for naturally low DO areas), whereas susceptibility to eutrophication is indicated by persistent stratification, consecutive months with very low DIN, and the presence of high fecal coliform bacteria or ammonium, these latter two implying possible human organic loadings. Figure 21 shows this information for Puget Sound.

For WY 1998-Y 2000, the distribution of hypoxic concentrations of DO (<3 mg/L) is found in Hood Canal, Penn Cove, Saratoga Passage, Elliott Bay, West Point Discovery Bay, and in the Strait of Georgia. A level of DO that may begin to induce biological stress are found in Bellingham Bay, Budd Inlet, Commencement Bay, Carr and Case Inlets, Dungeness Bay, Port Gamble, Possession Sound, Port Townsend, Quartermaster Harbor, Sequim Bay, Sinclair Inlet, and Port Susan, as well as seasonally in Admiralty Inlet correlated with deep ocean water input. Whether any of these low DO concentrations are being influenced by anthropogenic sources is a separate issue (303(d) List, Ecology, 2000), but this map does show that all of these areas have concentrations of DO, natural or impacted, that are on the sensitive edge of being impacted if further eutrophication occurred.

Further illustrating sensitivity to eutrophication are the stations that do not show low DO concentrations but do show attributes (e.g., nutrient limitation and strong stratification) that nutrient loading could cause increased production and the development of low DO. Many of these stations are found in South Puget Sound (Case, Eld, Totten Inlets, Oakland Bay) as well as Drayton Harbor, Eagle Harbor, and Port Orchard.

Other attributes not discussed as indicators but contributing to an emerging view of South Sound as an area sensitive to eutrophication include: Strong phytoplankton blooms (>20 µg/L chl *a*) in summer as well as in spring and fall (BUD005, CMB003, and OAK004); detectable levels of ammonium-N but BRL nitrate+nitrite-N concentrations (BUD002, BUD005, ELD001, ELD002, OAK004, and TOT002), nitrite-N concentrations over 1.0 µM (BUD002, BUD005, DNA001, and NSQ002); and high fcb during summer (BUD002, CMB003, CMB006, and OAK004).

A summary map of the five water quality indicators described in this section for Ecology data from 1994 through 2000 (Figure 22) shows a similar evaluation of water quality to the three-year snap-shot presented in Table 8. Areas of highest concern include Hood Canal, Penn Cove, and Budd Inlet. Concern is also high at Discovery Bay, Bellingham Bay, Commencement Bay, Elliott Bay, Sinclair Inlet, Possession Sound, Oakland Bay, and Drayton Harbor. Whether decreased water quality can be attributed to natural or anthropogenic causes alone, or what the relative roles of these processes may be is very difficult to asses for this time period; it will likely vary at different locations throughout the region. However, the approach used in this report is intended to highlight "sensitivity", in the goal of supporting wise management decisions.

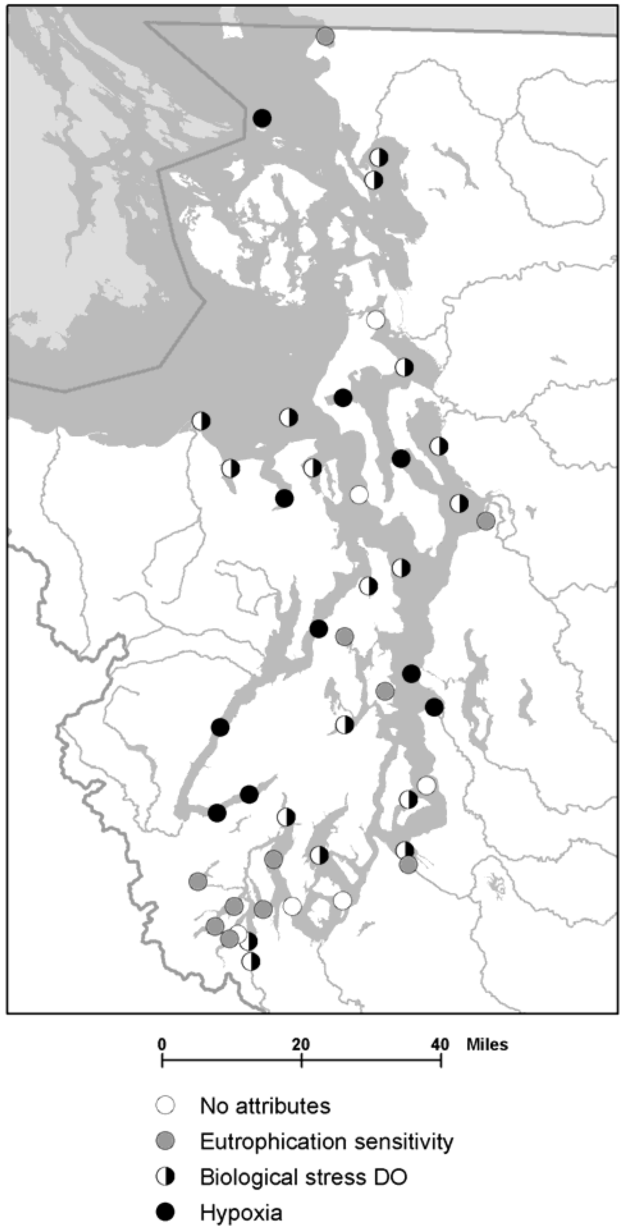


Figure 21. Occurrence of stations showing hypoxia and low dissolved oxygen as well as stations with physical/chemical attributes of susceptibility to eutrophication for Puget Sound stations during WY 1998 – Y 2000.

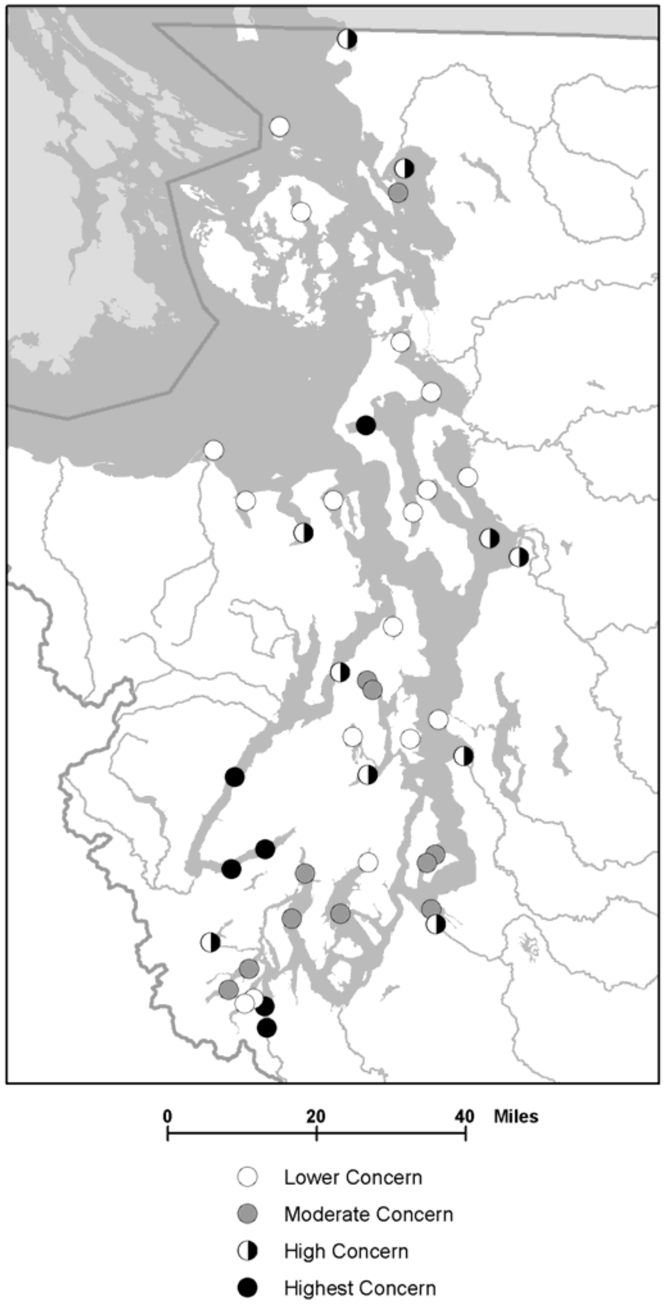


Figure 22. Relative water quality concern in Puget Sound based on summed indicators of water quality from 1994 through 2000. See text for further explanation.

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 for several attributes (see below for specifics). In contrast, in the coastal estuaries, the primary water quality issue apparent continues to be chronic fcb contamination in Grays Harbor and near the Willapa River. It should be noted that this assessment of water quality does not include chemical 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 is an important driver of marine water column conditions. The variation in air temperatures and runoff can be seen in the sea-surface temperature and salinity at the monitoring stations. Most notable were warmer sea surface temperatures in 1998 and cooler sea surface temperatures in 1999 and 2000 correlating with air temperatures, as well as lower salinities in 1999 and higher salinities in 2000 correlating with runoff.

- Low DO concentrations in 1998 through 2000 were found more widespread and frequent than other years. DO concentrations <3 mg/L were found at 11 of 54 Puget Sound stations. Hypoxic conditions in S. Hood Canal were especially severe, reaching anoxia. Hypoxia was also frequently observed in Penn Cove encompassing 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 18 additional stations. Many stations showed more frequent, lower concentrations, or their first low DO concentration, compared with the record of comparable data which started in WY 1993. An exception was that DO concentrations appear to be increasing in inner Budd Inlet.

- Fecal contamination was similar to or in excess of that reported in other years. Fecal coliform bacteria counts >14 organisms/100 mL were found at 16 Puget Sound stations and 7 coastal estuary stations during WY 1998-Y 2000. Of these, contamination in Grays Harbor, Willapa Bay (near the Willapa River), Commencement Bay, and inner Budd Inlet appeared chronically persistent. Rare but extremely high fecal counts (>100 org./100 mL) for marine waters were recorded at Elliott Bay (twice), Oakland Bay (twice), Port Orchard (3100 org./100 mL), Possession Sound, and Sinclair Inlet (890 org./100 mL).

- Based on the five indicators of marine water quality developed in previous reports (strong stratification, low DO, limiting nutrients, high fecal coliform, and high ammonium), the highest water quality concern for the WY 1998 – Y 2000 period is for Southern Hood Canal, Budd Inlet, Penn Cove, Commencement Bay, Elliott Bay, Possession Sound, Saratoga Passage, Sinclair Inlet, and Grays Harbor.

- Both physical stratification and climate forcing play large roles in affecting water quality. In view of 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 of water circulation and DO dynamics in Hood Canal should continue to be a priority. Effects on other trophic levels, e.g. fish and shellfish, 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 by 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 addressed.

- *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 that anthropogenic impacts on the Cove should be carefully considered.

- *Re fcb contamination in Grays Harbor, Willapa Bay, and Commencement Bay:* A decade of monitoring data show chronically high fcb counts in Grays Harbor, the Willapa River estuary, and Commencement Bay. High counts have only been reduced in Grays Harbor from numbers in the 1000's seen for several months in WY 1995 to numbers in the 100's seen in WY 1998-Y 2000. This indicates that current actions are substantially helping but are still not effective enough to curtail fcb contamination below State water quality criteria.

- *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 monitoring strategy:* 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. To help identify eutrophication and food-web issues, assessment of chl *a* needs improvement. Avenues for obtaining and analyzing remotely sensed chl *a* data (via aircraft or satellites) should be pursued.

- *Re analyses:* Statistical and trend analyses are recommended. Data comparability issues within the Ecology database must be first addressed. Priority should be placed on entering high-quality historical data (pre-1972) into an electronic database in order to facilitate statistical analysis and evaluation of changing conditions.

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