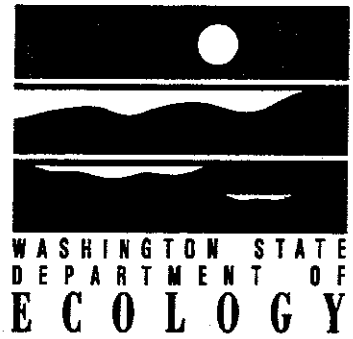


1992 Budd Inlet Seasonal Monitoring Report

by
Lisa B. Eisner, Carol D. Janzen,
Storrs L. Albertson, Sharon A. Bell, and Jan A. Newton

Environmental Investigations
and Laboratory Services Program
Ambient Monitoring Section
Washington State Department of Ecology
Post Office Box 47710
Olympia, Washington 98504-7710

July 1994
Publication #94-132

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

ACKNOWLEDGMENTS

A special thanks is due to all those involved with the Budd Inlet 1992 Seasonal Monitoring Project. This endeavor could not have succeeded without their help. A variety of seemingly endless tasks were performed by many individuals to bring this project from start to completion.

Many people assisted the authors of this report during data collection. These include: Bernard Strong, Larry Lake, Alberto Napuli, Russ Walker, Gerardo Chin-Leo, Kelly Carruth, Chris Prescott, Ken Dzinbal, Bob Cusimano and Julie Rector. Their efforts are greatly appreciated.

We would like to acknowledge Despina Strong, Dave Thomson, Michelle Elling, Debbie LaCroix, Will White, Pam Covey, Stuart Magoon and Cyma Tupas who were involved in the efficient delivery and analyses of our samples at Manchester Laboratory.

Bernard Strong provided invaluable support in the construction, maintenance and trouble shooting of our field equipment. Mark Golliet and Angie Thomson finalized many of the graphics, and Kati Brown processed CTD data for this report. Rita Horner conducted the phytoplankton taxonomy as well as providing helpful suggestions throughout the project. Kim Douglas conducted the final word processing and formatting for report preparation.

Peer review was done by Karl Banse, Rita Horner and Parker MacCready (University of Washington); Andrea Copping (Washington Sea Grant), Randolph Shuman (METRO), Gerardo Chin-Leo (The Evergreen State College), John Armstrong (Environmental Protection Agency); Chris Prescott (Puget Sound Water Quality Authority); Stewart Lombard (Quality Assurance Office, Manchester Laboratory); Ken Dzinbal, Mark Golliet, Dale Norton, Jim Cubbage, and Larry Goldstein (EILS program, Washington State Department of Ecology). All provided many useful suggestions and feedback.

ABSTRACT

Budd Inlet is a semi-enclosed partially mixed embayment located at the southernmost end of Puget Sound. Water quality problems in this embayment include eutrophication (nutrient enrichment and excessive phytoplankton growth) and low dissolved oxygen (D.O.) concentrations during summer and early fall. The low D.O. concentrations are partially due to persistent stratification and decay of organic matter. In order to better quantify the timing and extent of these problems, a seasonal monitoring project was conducted in Budd Inlet from March through October 1992. Additional impetus for the project was to provide baseline data prior to the implementation by the Lacey, Olympia, Tumwater, Thurston County Waste Water Treatment Plant (LOTT) of nitrogen removal from the effluent that is released into inner Budd Inlet. LOTT began removing approximately 90% of the effluent nitrogen during spring 1994. To investigate the impact of this change on water quality, monitoring was conducted in 1992 through 1994 (present). In 1992, surveys were conducted bi-weekly at up to 23 stations in Budd Inlet. One 52-h tidal cycle survey was conducted during mid-July. Measured parameters included temperature, salinity, depth, D.O., dissolved nutrients (nitrite+nitrate-N, ammonium-N, and orthophosphate-P), Secchi disk depth, chlorophyll *a* (*in situ* fluorometry and discrete laboratory analyses), phaeopigment, transmissometry, and phytoplankton taxonomy.

Results indicated that stratification was primarily salinity driven, being strongest in the inner bay, and decreasing from the head to the mouth of Budd Inlet. Low D.O. concentrations (D.O. <5.0 mg/L) occurred from July through October at near-bottom depths predominantly in the west inner bay, and to a lesser extent in the east inner bay and along the east side of the central bay. Near-hypoxic D.O. concentrations (D.O. <3.0 mg/L) were observed during late August and early October at inner bay stations at near-bottom depths. Surface nitrite+nitrate-N concentrations fell below reporting limits (0.01 mg/L) in the central and outer bay during mid-May and from mid-June to mid-September. The highest nutrient concentrations (particularly ammonium-N) were recorded in the west inner bay near the primary LOTT outfall. Phytoplankton blooms (chlorophyll *a* >10 μg/L) occurred throughout the bay during March through October, however, the highest chlorophyll *a* concentrations were consistently in the central bay, and were found during July through September. Although phytoplankton concentrations were higher in the central bay than in the inner bay, higher nutrient levels were found in the inner bay. The lowest D.O. concentrations were also in the inner bay, not in the central bay, where phytoplankton concentrations were highest. Blooms of dinoflagellate species known to migrate vertically occurred during July and August at central and inner bay stations. Phytoplankton vertical migration was indicated by the chlorophyll *a* profiles taken during the mid-July tidal cycle survey at the central bay stations but not at the inner bay station. This migration may be linked to nutrient availability. Potentially harmful (e.g. to vertebrates including fish or humans) phytoplankton species (*Pseudonitzschia pungens* and *Heterosigma carterae*) were present at both central and inner bay stations at various times throughout the sampling season, though no reports of toxicity or fish kills occurred during this time.

Tidal stage and diel variation affected many water quality parameters. Dissolved oxygen concentrations were lower during low tide than during high tide and lower at night than during the day. Phytoplankton blooms were located further out in the bay at low tide than at high tide. The freshwater lens from the Deschutes River/Capitol Lake outlet extended further out in the bay at low tide than at high tide. In order to deconvolute tidal (25-h period) from diel (24-h period) influences, sampling should occur over longer continuous time periods such as weeks. Continuation of water quality monitoring should be made following implementation of nitrogen removal from the LOTT effluent, to document the effect of nutrient input to an estuary of this type. The effect of the current input is difficult to assess without measurement of rates of nitrogen input and removal due to processes such as advection, primary production and benthic interactions.

INTRODUCTION

This report, prepared as part of the Washington State Department of Ecology's (Ecology) Marine Water Column Monitoring Program, contains results of the Budd Inlet Seasonal Monitoring Study conducted in the spring through fall months of 1992. Only specific examples of the data are presented here; although, the discussion of seasonal patterns in this report is based on all data collected. A complete data set can be obtained from Ecology's Ambient Monitoring Marine Water Column Unit.

Study Area

Budd Inlet, within the South Puget Sound Basin, is a semi-enclosed inlet with substantial urban development in its watershed (Figure 1). The inlet is a small (2.6 km x 11.1 km), shallow (average depth = 8.2 m at mean lower-low water) embayment without an entrance sill (Tetra Tech, 1988a), and has been classified as a stratified, partially mixed estuary (URS, 1986). Budd Inlet exhibits a two-layer flow pattern with saltier, generally colder water entering at depth from outer Puget Sound, and fresher, typically warmer water exiting at the surface (URS, 1986). This slow "conveyor belt" flow is superimposed on a much larger tidal exchange, with complex interactions resulting between the mixed semi-diurnal tidal forcing, salinity-induced stratification, bottom topography (friction) and wind stress. The tidal range in Budd Inlet is close to 4 m (Lavelle *et al.*, 1988).

Flushing rates are lowest near the head of the inlet where a variety of point and nonpoint sources of pollution are located. The Deschutes River, the major freshwater source into Budd Inlet (Tetra Tech, 1988a), discharges freshwater into Capitol Lake at the head of Budd Inlet. A control structure at the outlet of Capitol Lake allows the discharge into Budd Inlet (~1% of the total freshwater flow into Puget Sound; Tetra Tech, 1988b) to be adjusted to maintain water levels in the lake.

An assessment of spatial and temporal water quality trends in Puget Sound (Tetra Tech, 1988b) listed Budd Inlet as one of the most sensitive embayments to nutrient enrichment and subsequent eutrophication. Previous studies (URS, 1986; Tetra Tech, 1988a) have suggested that the inner portion of Budd Inlet is prone to periods of low dissolved oxygen (D.O.) in the near-bottom waters during late summer and early fall months. However, the area and timing of low D.O. events were not well defined in these previous studies. Low D.O. concentrations at different locations in the bay could be attributed to a variety of physical, biological, and chemical conditions, including:

- vertical stratification that inhibits vertical mixing of the water column;
- low flushing efficiencies;

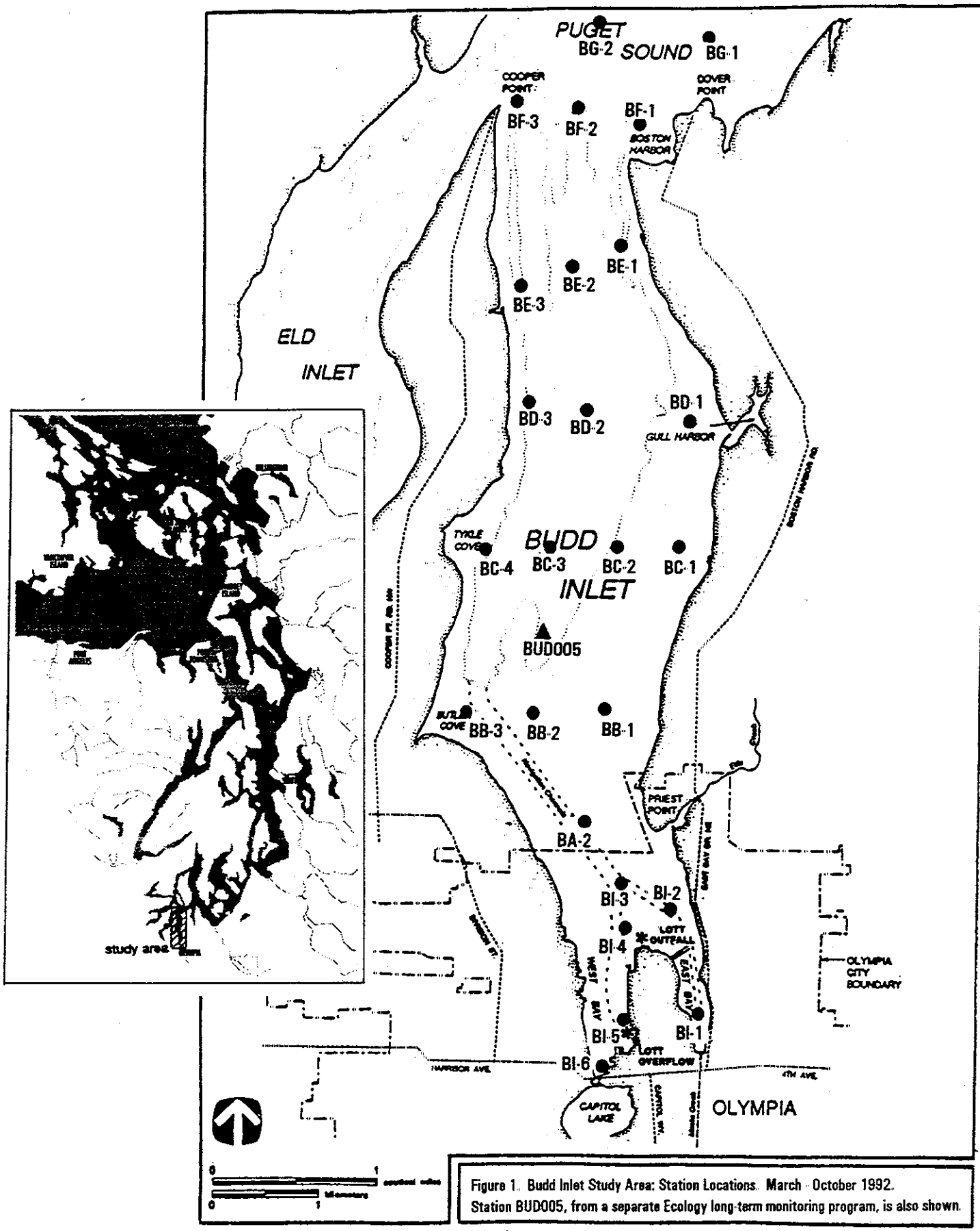


Figure 1. Budd Inlet Study Area: Station Locations. March - October 1992. Station BUD005, from a separate Ecology long-term monitoring program, is also shown.

- excessive algal blooms that die off, sink to the bottom, and consume oxygen as they decay; these blooms could be enhanced by large nutrient (especially nitrogen) inputs from Olympia and the surrounding developed areas, as well as from the Deschutes River/Capitol Lake outlet;

- blooms of vertically migrating dinoflagellates (a mobile phytoplankton) that have a net production of oxygen in the surface waters during the day, but consume oxygen at depth during the night; and

- high sediment oxygen demand.

In early 1994, the Lacey, Olympia, Tumwater, and Thurston County Wastewater Treatment Plant (LOTT) changed its treatment process to remove a substantial amount of the nitrogen from the treated effluent discharged into Budd Inlet. This nitrogen removal is intended to help reduce the human-influenced eutrophication conditions of the inner bay. This study, in addition to investigating occurrences of low D.O. in Budd Inlet, will provide baseline data for assessing the impact of the change in nutrient loading.

Project Objectives

The overall goal of the Budd Inlet 1992 Seasonal Monitoring Study was to gain an understanding of the nutrient/phytoplankton dynamics in the water column in order to detect and understand impacts of anthropogenic inputs of nutrients. Necessary for this is to have a working knowledge of physical and biological processes within the inlet and their dynamics. Specific objectives to meet this goal were to:

1. determine where and when stratification was most pronounced, since this will affect other parameters such as phytoplankton bloom occurrence and D.O. concentration;

2. determine the onset, duration and location of low D.O. concentrations;

3. determine nutrient concentrations during the period of maximum phytoplankton growth (growing season) and identify periods of nutrient depression;

4. determine concentrations of chlorophyll *a* found during the growing season and the timing and location of maximum phytoplankton blooms;

5. document the onset and duration of dinoflagellate blooms that may undergo vertical migration and subsequently aid in the depletion of near-bottom D.O.;

6. determine the occurrence of potentially harmful phytoplankton (species of phytoplankton that are known to be toxic or deleterious to humans, fish or other organisms);

7. determine how the tidal stage as well as time of day affect water quality parameters (particularly D.O. concentrations and depth of phytoplankton blooms); and

8. provide baseline data prior to implementation of nitrogen removal by LOTT in order compare pre and post removal conditions.

METHODS

Budd Inlet 1992 Seasonal Monitoring Study

Field surveys were planned every two weeks between 12 March and 21 October 1992, though logistical constraints occasionally prevented this regular sampling interval from being accomplished. Up to 25 stations were monitored in Budd Inlet and adjacent waters during the 1992 seasonal monitoring surveys (Figure 1).

Monitoring Approach and Design

The Budd Inlet Seasonal Monitoring Study consisted of multiple sampling strategies designed to document spatial and temporal patterns in physical, biological, and chemical conditions within the inlet. Table 1 lists each station, the latitude and longitude, sampling strategy, parameters sampled, and number of surveys conducted at that station.

Four strategies were employed:

1. Seasonal (bi-weekly) sampling that focused intensively on physical, biological, and chemical parameters at stations at the head of the inlet (*i.e.*, inner bay). These stations were nearest to the LOTT outfall and Deschutes River/Capitol Lake discharge;

2. Seasonal (bi-weekly) longitudinal transects from the inner to outer bay, conducted to detect gradients in many of these same parameters emanating outward from the head of the inlet;

3. Seasonal (bi-weekly) cross bay transects to characterize the distribution of these parameters over the entire inlet; and

4. Tidal cycle monitoring conducted to document a time series of water quality conditions over 52 hours, encompassing two complete 25-h tidal exchanges in Budd Inlet at inner and central bay stations. This was done to investigate both diel and tidal influences.

Inner Bay Sampling

Seasonal sampling concentrated on inner Budd Inlet, at stations adjacent to the LOTT outfall and Deschutes River/Capitol Lake discharge. Inner Budd Inlet encompasses the area south

Table 1. Budd Inlet station locations, sampling strategy, parameters sampled and number of surveys conducted during 1992. For type of sampling, I = inner bay, L = longitudinal transect, C= cross bay transect, T= tidal cycle survey. Where "CTD" is indicated, this includes a continuous depth profile of conductivity, temperature, dissolved oxygen, and transmissometer (and pH) or fluorometer readings "Chl a" indicates chlorophyll a and phaeopigment. "Phyto" indicates phytoplankton sample.

Station	Latitude (deg-min-hundreds)	Longitude (deg-min-hundreds)	Sampling Strategy	Parameters Sampled	# of Surveys Conducted
BI-1	47-03-08	122-53-69	I	CTD, Secchi	13
BI-2	47-03-74	122-53-85	I	CTD, Secchi, Nutrients, Chl a	16
BI-3	47-03-94	122-54-38	I	CTD, Secchi	16
BI-4	47-03-64	122-54-31	I	CTD, Secchi, Nutrients, Chl a, Phyto	16
BI-5	47-03-09	122-54-27	I, T	CTD, Secchi	16
BI-6	47-02-71	122-54-48	I	CTD, Secchi, Nutrients, Chl a	14
BA-2	47-04-32	122-54-65	L, C, T	CTD, Secchi, Nutrients, Chl a	14
BB-1	47-04-98	122-54-50	C	CTD, Secchi	14
BB-2	47-04-98	122-55-12	L, C	CTD, Secchi, Nutrients, Chl a	15
BB-3	47-04-98	122-55-73	C	CTD, Secchi	13
BC-1	47-06-03	122-53-88	C	CTD, Secchi	11
BC-2	47-06-03	122-54-44	C	CTD, Secchi	11
BC-3	47-06-03	122-55-00	L, C	CTD, Secchi, Nutrients, Chl a	13
BC-4	47-06-03	122-55-57	C	CTD, Secchi	11
BD-1	47-06-79	122-53-82	C	CTD, Secchi	12
BD-2	47-06-87	122-54-72	L, C, T	CTD, Secchi	14
BD-3	47-06-90	122-55-21	C	CTD, Secchi	11
BE-1	47-07-79	122-54-42	C	CTD, Secchi	9
BE-2	47-07-70	122-54-85	L, C	CTD, Secchi, Nutrients, Chl a	12
BE-3	47-07-61	122-55-28	C	CTD, Secchi	11
BF-1	47-08-65	122-54-28	C	CTD, Secchi	9
BF-2	47-08-75	122-54-80	C	CTD, Secchi	10
BF-3	47-08-82	122-55-31	C	CTD, Secchi	9
BG-1	47-09-15	122-53-68	C	CTD, Secchi	3
BG-2	47-09-25	122-54-75	C	CTD, Secchi	3

of Priest Point Park including both East Bay and West Bay (Figure 1). Six stations (BI-1 through BI-6) were sampled bi-weekly in the inner bay primarily during low slack tides. Low (and high) slack tide periods were considered to encompass the hour before and the hour after the peak low (or high) tide time. The slack tide was sampled in order to minimize the influence of dynamic conditions resulting from the tidal mixing and movement of water in and out of the bay. Twelve low slack periods and one high slack period were sampled in 1992 (Table 2). The low slack tide was sampled consistently in order to compare patterns in data throughout the season. Some inner bay stations were occasionally sampled during both low and high slack tides in order to compare data from different tidal stages. The first three surveys were conducted at times other than slack tide (Table 2).

Profiles of the conductivity-temperature-with-depth (CTD), with sensors measuring D.O. and either *in situ* fluorometry or light transmissometry, and Secchi disk measurements were conducted at all inner bay stations. Stations BI-2, BI-4, and BI-6 were sampled for dissolved nutrients (nitrite+nitrate-N, ammonium-N, and orthophosphorus) chlorophyll *a*, and phaeopigment. During each survey, a sample for phytoplankton species composition was collected at one station in (Station BI-3, BI-4, or BI-5) or bordering (Station BA-2) the inner bay.

Longitudinal Transect Sampling

To assess possible head-to-mouth gradients in the inlet, longitudinal transects were conducted every two weeks. These consisted of six stations (BA-2, BB-2, BC-3, BD-2, BE-2, BF-2) from the head of the inlet to the mouth along the central axis of the bay (Figure 1). The transect was sampled immediately following the inner bay sampling, thus during the same slack tidal period. CTD profiling casts and Secchi disk measurements were conducted at each station along the longitudinal transect. Stations BA-2, BB-2, BC-3, and BE-2 were also sampled for nutrients, chlorophyll *a*, and phaeopigment. This design allowed a view of the nutrient and chlorophyll *a* distribution from inner to outer bay with minimal dynamic influences from the tides.

Cross-Bay Transect Sampling

To better characterize the entire inlet, cross-bay sampling was conducted at five transects (BB, BC, BD, BE, BF), each with three or four stations spanning the width of the bay (Figure 1). This work was done in the direction of the tidal flow, and was thus accomplished consistently in one direction for each type of exchange, always moving in the direction of the tide. As a result, one-half of a complete tidal exchange was encompassed during the cross-bay transect sampling. Although ideal sampling conditions are during the least amount of dynamic change, as during slack tide periods or during small tidal exchanges, the majority of the sampling surveys occurred during large flood tide exchanges (Table 2). This was done in order to sample the low tide during daylight hours and to maintain consistent spring tide sampling. Thus, these data may show influences due to tidal

Table 2. Date and tidal stage of Budd Inlet seasonal surveys: March - October 1992. Slack tide (low or high) was considered to be within +/- 1 hour of the peak low or high tide time.

Date	Tidal Stage (Inner Bay and Longitudinal Transect)	Tidal Stage (Cross Bay Transects)	Tidal Range (m) (During Flood or Ebb Tide)
12-Mar	Ebb	Ebb and Low	3.9
25-Mar	Ebb	Ebb	3.4
7-Apr	Ebb	Ebb	4.5
30-Apr	Low	Flood	3.6
15-May	Low	Flood	4.8
28-May	Low	Flood	3.5
11-Jun	Low	Flood	4.2
2-Jul	Low	Ebb	5.0
17-Jul	Low		
29-Jul	Low	Flood	5.4
13-Aug	Low	Flood	4.3
26-Aug	Low	Flood	4.8
10-Sep	Low	Flood	3.8
23-Sep	Low		
7-Oct	Low	Flood	3.4
21-Oct	High		

advection as well as location. CTD profiling casts including *in situ* fluorometry or light transmissometry, and D.O., and Secchi disk measurements were conducted at each station in the cross bay transects. No additional water samples were collected during this portion of the monitoring, except during the first three surveys, when all stations were sampled for nutrients in order to determine early season nutrient distribution throughout the bay.

Tidal Cycle Monitoring

In an attempt to understand variability on shorter time scales, a tidal cycle survey was conducted in mid-July 1992. In order to encompass two complete 25-h tidal cycles, one 52-h survey was conducted from 1000 on 15 July through 1400 on 17 July. This survey was conducted at three stations: Station BI-5, located in the inner bay; Station BA-2, located at the border of the inner and central bays; and Station BD-2, located in the central bay, (Figure 1). Figure 2 shows the tide height and time of sampling for each station.

CTD profiling casts including *in situ* fluorometry and D.O., and Secchi disk measurements were conducted at each station every two hours. The CTD vertical profiles were plotted on a portable computer screen instantaneously (in "real-time") to identify the depth of the chlorophyll *a* maximum. At Station BA-2 and BD-2, nutrient samples were collected at 1-m and near-bottom (1 m from bottom) depths every four hours, and phytoplankton samples were taken from the chlorophyll *a* maximum every 10 to 12 hours (one during the day and one at night).

Capitol Lake was drained into Budd Inlet from 0800 until lower low tide (~1230) on both 14 and 15 July. Capitol Lake was then backflushed with water from Budd Inlet during higher high tide (~2030) on 16 July. The volume of Capitol Lake is approximately 3.0 x $10^6 m^3$ (Bortleson *et al.*, 1976) and the volume of Budd Inlet at mean lower low water is approximately 2.4 x 10^8 m^3 (Tetra Tech, 1988a). The amount released and backflushed on 14-15 July is not known. However, the draining and subsequent backflushing of Capitol Lake likely affected the data collected in Budd Inlet during the tidal cycle monitoring. The coincidence of this event with the tidal cycle monitoring was not anticipated.

Materials and Procedures

Sampling was conducted from a 7-m (20-ft) Boston Whaler. A Magellan Global Positioning System (GPS) unit was used to navigate and locate stations. Landmarks and prepositioned Ecology or navigational buoys were used to facilitate station location.

A Sea-Bird Electronics Sealogger SBE-25 CTD profiler was used as the primary CTD for collecting continuous water column profile data. Real-time observation of the profiles was obtained with a data link to a lap-top computer. Parameters measured by the SBE-25 included conductivity (used to compute salinity), temperature, pressure (used to calculate depth), D.O., and fluorometry (to measure chlorophyll *a* concentration). Density was derived from salinity and *in situ* temperature. A Sea-Bird Electronics Seacat SBE-19 CTD profiler

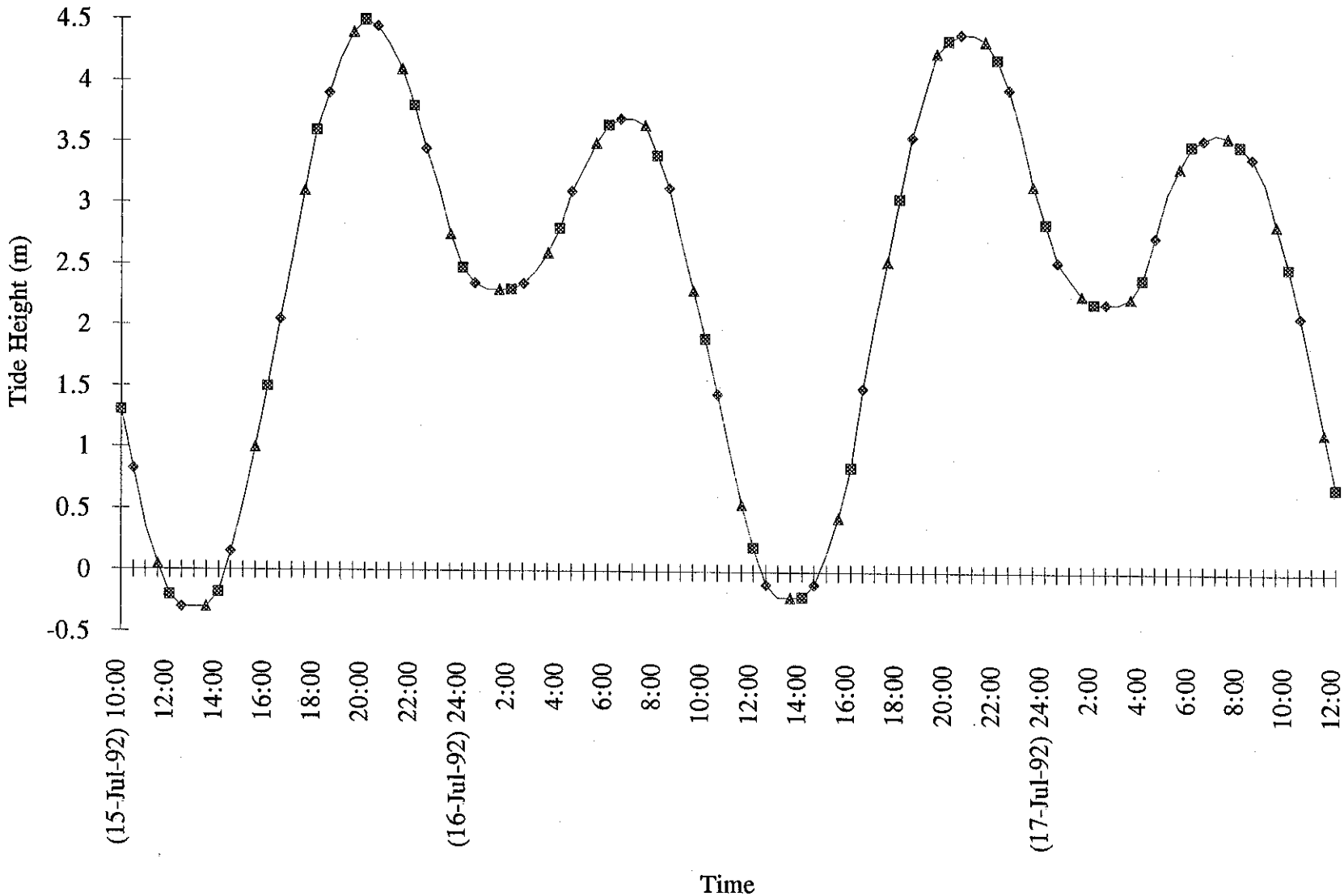


Figure 2. Tide height (above mean lower low water) and time of sampling for Stations BI-5, BA-2 and BD-2 during Budd Inlet tidal cycle survey 15-17 July 1992. Spring tide conditions occurred one day prior to the start of the survey. Sample collections are indicated by ■ for Station BI-5, ◆ for Station BA-2 and ▲ for Station BD-2.

was used for water column profile measurements in the early season surveys, and as a backup instrument when the SBE-25 was being calibrated. The SBE-19 CTD measured conductivity, temperature, pressure, D.O., light transmissometry, and pH. Most CTD casts were conducted to within 1.5 m of the bottom for the SBE-25 and to the bottom for the SBE-19. Sampling procedures followed the manufacturer's instructions (Sea-Bird Electronics, 1990 and 1992a), and are also described in the *Marine Water Column Ambient Monitoring Plan* (Janzen, 1992).

Secchi disk measurements were taken at each station using a solid white, 30-cm disk. Values were recorded to the nearest tenth of a meter. Secchi depth results indicate water clarity based on the extinction of light in the water column. Derivation of the extinction coefficient allows calculation of the euphotic zone depth.

A 1.2 liter (L) Niskin bottle was manually deployed to collect discrete water samples for dissolved nutrients (ammonium-N, nitrite+nitrate-N, and orthophosphate-P), chlorophyll *a*, phaeopigment, phytoplankton enumeration and taxonomy, D.O., and conductivity. Sample collection methods followed the *Recommended Protocols and Guidelines for Measuring Conventional Water Column Variables in Puget Sound* (PSEP, 1990). Specific details on Ecology's sampling methods are described in the *Marine Water Column Ambient Monitoring Plan* (Janzen, 1992).

Sampling Protocols

Dissolved Oxygen

Dissolved oxygen was measured using a polarographic D.O. probe attached to the CTD profiling unit. A Beckman sensor measured D.O. on the SBE-19 CTD, and a YSI sensor measured D.O. on the SBE-25 CTD. An integral pump kept a continual flush of sample water washing over the sensor membrane surface.

Dissolved oxygen samples collected for comparison to CTD values were analyzed at Ecology's field laboratory using the Winkler Method with the azide modification (APHA-AWWA-WPCF, 1989).

Nutrients

In order to obtain data within and below the mixed layer, nutrient samples were collected at both 1-m and near-bottom depths for bi-weekly and tidal cycle surveys. The near-bottom collection occurred at 10 m or at 1 m above the bottom in waters less than 10 m. Subsamples of approximately 50 mL were immediately filtered using a syringe and Nalgene cellulose acetate membrane filters (0.45 μm pore size). The samples were stored on ice until the end of the field survey, and then were frozen for preservation. Frozen samples were delivered to Ecology's Manchester Laboratory for analysis. Manchester Laboratory used an Alpkem series 300 autoanalyzer for analyses of dissolved nitrite+nitrate-N (NO_2+NO_3-N),

ammonium-N (NH_4-N) and orthophosphate-P (o-PO_4-P) following method numbers 353.2, 350.1 and 365.3, respectively, (EPA, 1984).

Chlorophyll *a* and Phaeopigment

Samples for pigment analysis were collected at the depth of the fluorescence maximum as determined from the real-time CTD observations. When this information was not available (generally prior to July), samples were collected at 1-m and near-bottom depths or at the Secchi disk depth (13 August survey only). Based on the transmissometer and D.O. profiles, the depths of maximum phytoplankton abundance for the early surveys (March through June) varied from 0.5 to 2.5 m. Therefore, 1-m chlorophyll *a* samples from these survey provide a reasonable estimate of peak chlorophyll *a* values.

Samples were filtered at the end of the survey day at the field laboratory. Fifty-mL subsamples were filtered onto Whatman GF/F glass fiber filters (0.70 μm pore size), previously moistened with aqueous magnesium carbonate solution. The filters were placed in centrifuge tubes, stored in the dark, and frozen for preservation. The tubes were delivered to Manchester Laboratory for fluorometric analysis. A Sequoia-Turner model 112 fluorometer was used for fluorometric detection of chlorophyll *a* and phaeopigment concentrations following method number SM17-10200 H-3 (APHA-AWWA-WPCF, 1989).

Phytoplankton

Inner bay phytoplankton samples were taken at 1 m from 12 March to 2 July and at the depth of the fluorescence maximum from 15 July to 7 October. These samples were always accompanied by a chlorophyll *a* sample. Near surface phytoplankton samples were also collected monthly in central Budd Inlet (Station BUD005, Figure 1) as part of a separate long-term monitoring program conducted by Ecology, and thus followed that program's sampling dates. The depth of sample collection at BUD005 was approximately 0.5 m except for the 10 August sample which was collected at 2.5 m (Secchi disk depth). Samples were collected in glass jars and preserved with a final concentration of approximately 0.4 percent formaldehyde buffered with sodium acetate (Throndsen, 1978). Taxonomic identification and enumeration using an inverted light microscope were conducted by Dr. Rita Horner, University of Washington.

Data Processing

CTD data were processed using SEASOFT Software, version 4.015. CTD data with the correct calibration coefficients applied were averaged over 0.250-m depth intervals for the SBE-25 Sealogger CTD and over 0.500-m depth intervals for the SBE-19 Seacat CTD. Profiles of salinity and density were derived using values of temperature, conductivity, and pressure. Further details on CTD data processing procedures can be found in Sea-Bird Electronics, (1992b).

Data Analysis

Contour Plots

Contour plots of hydrographic, D.O., and chlorophyll *a* values were made using Golden Software's SURFER package program. Data were first gridded by Kriging with the quadrant search method which allows data from a minimum of four different directions to be included in the interpolation process. The search radius was set to 10 km, which is much greater than the distance between stations. This forced the algorithm to search adjacent downcasts for intermediate interpolations at gridpoint locations. Gradient spacing was kept constant for all plots to facilitate comparison. The bottom depths for vertical contour plots vary slightly from one survey date to the next due to tide height variations, and because station locations were not exact due to fluctuations in the GPS signal.

Phytoplankton Biomass

A direct measurement of phytoplankton biomass was obtained from phytoplankton cell counts. However, since cell counts are labor-intensive, they were done only in the inner bay at one station per survey. Another measurement of phytoplankton biomass used was chlorophyll *a*. Fluorometric determination of chlorophyll *a* was conducted both *in situ* and by laboratory analysis of extracts from discrete water samples. Unfortunately, the *in situ* fluorometer was not available for all surveys and so transmissometry and D.O. readings were used as indirect indicators of phytoplankton biomass. Table 3 shows the methods used to evaluate phytoplankton/chlorophyll *a* distribution and concentration for each survey date. None of these indicators are unambiguously accurate for phytoplankton biomass.

Chlorophyll *a* is the most direct indicator of phytoplankton biomass since it is specific to all phytoplankton. However, this pigment can vary in content per cell in response to cell size, and light, nutrient and physiological conditions. Thus, chlorophyll *a* concentration is specific for phytoplankton biomass but the amount of phytoplankton (e.g., mg C) cannot be derived.

In situ fluorometry yielded continuous vertical profiles; whereas, laboratory analysis of chlorophyll *a* fluorescence was conducted for one or two depths only. Both chlorophyll *a* and phaeopigment were determined in the laboratory analyses. Laboratory analysis is more sensitive than *in situ* measurements. This is because the measured fluorescence of chlorophyll *a* is stronger when extracted than *in situ*, since it is no longer masked by the cell wall and other particles (Lorenzen, 1966). Laboratory analyses also may be more accurate than *in situ* fluorometry if there is interference from dissolved organic material in the water column that may quench the *in situ* fluorescence signal. This may be prevalent in Budd Inlet due to its proximity to land. However, laboratory chlorophyll *a* results from July through October 1992 were qualified as estimates since the calibration coefficients used to calculate those results were from a calibration conducted several months later.

Table 3 Methods used to evaluate phytoplankton biomass in Budd Inlet during 1992

Date	Field Measurements with CTD Instruments: Fluorometer (Chlorophyll a)	Transmissometer	Dissolved Oxygen	Lab Analyses: Chlorophyll a
12-Mar		X	X	X
25-Mar		X	X	X
7-Apr		X	X	X
30-Apr			X	X
15-May			X	X
28-May			X	X
11-Jun		X	X	X
2-Jul	X		X	
17-Jul	X		X	
29-Jul	X		X	X*
13-Aug		X	X	X*
26-Aug	X		X	X*
10-Sep	X		X	X*
23-Sep	X		X	X*
7-Oct	X		X	X*
21-Oct		X	X	

* indicates result was qualified as an estimate

For surveys when fluorometry data were not available, transmissometer and D.O. data were used to indicate phytoplankton biomass, although both measurements are not specific for phytoplankton. Low transmissometer readings indicate high concentrations of suspended solids. However, what percent of the total suspended solids are phytoplankton cells is unknown. Low transmissometer readings that occurred away from areas of turbid runoff and disturbed bottom sediments are likely to be related to phytoplankton biomass, although detrital particles and zooplankton will also be detected.

High D.O. concentrations were generally assumed to be a result of phytoplankton photosynthesis, particularly when the high readings occurred at depths below the surface mixed layer. However, because D.O. is also affected by many other physiological and biological factors, such as, mixing with deep water and respiration, D.O. data can only be considered as very imprecise indicators of phytoplankton biomass.

QUALITY ASSURANCE

Data Quality Objectives

The data quality objectives for measurement units, reporting limits and precision for the Budd Inlet Seasonal Monitoring Study are listed in Table 4. These objectives meet or exceed those listed in the *Puget Sound Ambient Monitoring Program (PSAMP)* plan (PSWQA, 1988) except for two cases:

1. the reporting limits for orthophosphate-P (PSAMP requests 0.002 mg/L; Budd Inlet objective 0.01 mg/L); and

2. the precision (relative standard deviation) for chlorophyll *a* (PSAMP requests $\pm$ 10%; Budd Inlet objective $\pm$ 20%).

Laboratory Quality Control (QC) Procedures and Results

Laboratory QC Procedures

Manchester Laboratory QC procedures are described in the *Marine Water Column Ambient Monitoring Plan* (Janzen, 1992) and in the *Manchester Quality Assurance Manual* (Ecology, 1988). Manchester Laboratory maintains calibrations of the autoanalyzer and fluorometer to assure accuracy and consistency of nutrient, chlorophyll *a* and phaeopigment results.

Laboratory QC procedures included analyses of duplicate aliquots of selected samples. Two to four samples from each survey cruise were analyzed in duplicate for dissolved nutrients. A total of nine samples collected from March through October 1992 were analyzed in duplicate for chlorophyll *a*. However, QC evaluations were not conducted on chlorophyll *a* results of samples collected during July through October 1992, since these data were considered estimates due to a calibration error.

Table 4 Marine water column quality assurance/quality control objectives PSAMP units micrograms-atoms/L can be computed with the following equations: ((mg/L x 1000) /14.01) for nitrogen; ((mg/L x 1000)/30 97)) for phosphorus

Analytical Parameters	Ecology's Reporting Units	Ecology Reporting Limit	Relative Standard Deviation (RSD)
Laboratory Sample Parameters:			
Ammonium-N	mg/L	0.01	*10%
Nitrite+Nitrate-N	mg/L	0.01	*10%
Orthophosphate-P	mg/L	0.01	*10%
Chlorophyll a and Phaeopigment	mg/m3	0 05	20%
CTD Parameters:			
Salinity	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 Transmissivity	% light	0.1	5%
Fluorometry	mg/m3 (chl a)	Not Determined	Not Determined

* maximum RSD expected near the reporting limit

The precision of the nutrient and chlorophyll *a* data was estimated by calculating the Relative Standard Deviation (RSD; Coefficient of Variation) of laboratory duplicate results. The RSD was calculated as 100(standard deviation/mean). Results that fell below reporting limits were not included in the precision estimates. Reporting limits, the minimum concentration at which a pre-determined level of precision is attainable, are shown for all parameters in Table 4. Reporting limits were chosen by determining the minimum control standard concentration that yielded less than a 10% RSD during repeat analyses.

Laboratory QC Results

Table 5 shows the percent of data that fell within various RSD ranges for dissolved nutrients (nitrite+nitrate-N, ammonium-N, orthophosphate-P), chlorophyll *a* and phaeopigment. Based on the estimated precision, the variability of the orthophosphate-P and nitrite+nitrate-N data was quite small and that of the ammonium-N data was slightly greater (Table 5). Chlorophyll *a* and phaeopigment results showed fairly good estimated precision, although the low number of estimates prevents a thorough QC assessment.

CTD Calibration Procedures

CTD calibration procedures are described in detail in the *Marine Water Column Ambient Monitoring Plan* (Janzen, 1992), and in the Sealogger SBE-25 and Seacat SBE-19 CTD operator's manuals (Sea-Bird Electronics, 1990 and 1992a). Discrete water samples for conductivity and D.O. analyses were collected during the surveys as part of the quality assurance checks conducted on the CTD sensors. These values were used to verify that the sensor was performing to the needed resolution (RSDs within 8% for salinity and D.O., Table 4). Monthly laboratory calibrations conducted in a stable, aerated water bath were used to generate calibration coefficients for the D.O. sensor on the CTD. Calibration coefficients for temperature, conductivity and pressure sensors were determined at Seabird Electronics during routine annual factory calibrations. These coefficients were applied during data processing. The *in situ* fluorometer was factory calibrated annually by SeaTech.

RESULTS

Hydrography

Inner bay and longitudinal transect hydrographic data collected primarily during low tides are summarized in Table 6. Density data collected at central bay Station BB-2 during low tides and primarily during the subsequent flood tides are summarized in Table 7. Most of the data represent daytime and light wind (less than 10 km/h) conditions. Variations in the hydrographic parameters are evident spatially, primarily along the longitudinal axis of the inlet, and temporally, both with season and over tidal and diel cycles.

Table 5. Relative standard deviation (RSD) for nutrient, chlorophyll a and phaeopigment results in Budd Inlet during March - October 1992: lab duplicate results Below reporting limit data excluded RSD = 100 x standard deviation/mean. Shaded areas indicate the target RSD range (Janzen, 1992) for each parameter

RSD (%)	Nitrite+Nitrate-N (% total)	Ammonium-N (% total)	Orthophosphate-P (% total)
0-10	95.7%	83.3%	97.1%
10-20	4.3%	10.0%	2.9%
20-30	0.0%	6.7%	0.0%
30-40	0.0%	0.0%	0.0%
40-50	0.0%	0.0%	0.0%
50-60	0.0%	0.0%	0.0%
60-70	0.0%	0.0%	0.0%
70-80	0.0%	0.0%	0.0%
80-90	0.0%	0.0%	0.0%
90-100	0.0%	0.0%	0.0%
>100	0.0%	0.0%	0.0%
Total #	23	30	35

RSD (%)	Chlorophyll a (% total)	Phaeopigment (% total)
0-10	71.4%	60.0%
10-20	14.3%	20.0%
20-30	0.0%	20.0%
30-40	0.0%	0.0%
40-50	14.3%	0.0%
50-60	0.0%	0.0%
60-70	0.0%	0.0%
70-80	0.0%	0.0%
80-90	0.0%	0.0%
90-100	0.0%	0.0%
>100	0.0%	0.0%
Total #	7	5

Table 6. Summary of inner bay and longitudinal transect hydrographic data collected during 1992 in Budd Inlet. Minima and maxima for each survey are listed for inner bay and longitudinal transect data combined. Salinity and density data are also summarized separately for inner bay Station BI-5. Surface values were taken at a depth of 1 m to eliminate variability in initial CTD downcast depth. Near-bottom data were collected at 1 m from the bottom. The pycnocline is the depth at which the gradient of density is greatest. Larger values in the relative stratification column indicate greater relative stratification.

Date	Tide	Depth of Thermocline (m)	Maximum Surface Temperature (degrees C)	Minimum Near-Bottom Temperature (degrees C)	Maximum Near-Bottom Salinity (ppt)
12-Mar	Ebb	2.0	13.0	9.5	28.0
25-Mar	Ebb	3.0	12.5	10.0	28.0
7-Apr	Ebb	1.0	11.0	10.0	28.0
30-Apr	Low	1.0	12.0	11.0	28 to 28.5
15-May	Low	2.0	15.0	12.0	28.5
28-May	Low	2.5	15.0	12.5	28.5
11-Jun	Low	2.0	17.0	14.0	28.5
2-Jul	Low	1.0	18.0	14.5	29.0
17-Jul	Low	1.0	>19	15.0	29.0
29-Jul	Low	2.0	21.0	15.5	29.0
13-Aug	Low	2.0	23.0	15.5	29.0
26-Aug	Low	1.5	19.5	16.0	29.5
10-Sep	Low	2.5	18.0	15.5	29.5
23-Sep	Low	3.0	16.5	15.0	29.5
7-Oct	Low	4.0	15.5	15.0	29.5
21-Oct	High	*	14.0	14.0	30.0

Date	Tide	Minimum Surface Salinity at Station BI-5 (ppt)	Depth of Pycnocline at Station BI-5 (m)	Relative Stratification (change in sigma-t from 1 m to bottom) at Station BI-5
12-Mar	Ebb	23.7	1.5	3.5
25-Mar	Ebb	23.7	1.0	3.7
7-Apr	Ebb	20.8	1.0	5.9
30-Apr	Low	28.4	0.5	0.2
15-May	Low	27.3	0.5	1.3
28-May	Low	26.7	0.5	1.5
11-Jun	Low	27.5	0.5	1.8
2-Jul	Low	No Data	No Data	No Data
17-Jul	Low	19.1	1.5	9.1
29-Jul	Low	21.2	1.0	7.1
13-Aug	Low	26.6	0.5	2.7
26-Aug	Low	27.9	0.5	1.8
10-Sep	Low	28.0	0.5	1.8
23-Sep	Low	28.9	0.5	1.0
7-Oct	Low	28.0	1.0	1.7
21-Oct	High	No Data	No Data	No Data

* uniform temperature to bottom

Table 7. Summary of density data collected at central Budd Inlet Station BB-2 during 1992. The pycnocline is the depth at which the gradient of density is greatest. Larger relative stratification values indicate greater relative stratification.

Survey Date	Depth (m) of Pycnocline Low Tide	Relative Stratification (Change in Sigma-T from 1m to Near-Bottom) Low Tide	Tidal Stage (Ebb, Flood or High)	Depth (m) of Pycnocline Ebb, Flood or High Tide	Relative Stratification (Change in Sigma-T from 1m to Near-Bottom) Ebb, Flood or High Tide
12-Mar	1.3	1.0	No Data	No Data	No Data
25-Mar	No Data	No Data	Ebb	1.3	1.6
7-Apr	No Data	No Data	Ebb	1.8	0.6
30-Apr	4.8	0.3	Flood	8.8	0.3
15-May	1.8	0.5	High	1.3	2.5
28-May	1.3	0.8	High	2.3	1.1
11-Jun	1.8	1.1	Flood	1.8	1.7
2-Jul	1.1	0.5	Ebb	1.1	0.5
17-Jul	1.1	1.1	No Data	No Data	No Data
29-Jul	1.1	1.1	Flood	1.1	1.3
13-Aug	1.3	1.7	Flood	No Data	No Data
26-Aug	0.9	0.6	Flood	0.9	1.2
10-Sep	0.9	0.4	Flood	0.9	0.9
23-Sep	1.1	0.4	No Data	No Data	No Data
7-Oct	1.4	0.6	High	1.3	0.6
21-Oct	No Data	No Data	High	6.8	0.2

Temperature

In April and late September through October, Budd Inlet was generally well mixed thermally, with a temperature difference from the surface to the bottom of only about 1°C (Figure 3a and c). A pronounced thermocline (temperature difference of ~3°C) was observed in March, weakened during April, and was noted again on 15 May (Table 6). By mid-summer, the temperature difference above and below the thermocline increased to approximately 5°C by mid-summer (Figure 3b). The thermocline was located high in the water column at about 2 m, and thermal stratification was greatest from 15 May until 10 September. From mid-September through October, the thermocline became deeper and weaker.

Overall, thermal stratification was greatest in West Bay out to Station BI-3 and along the eastern shore of the central bay (Figure 4c). In general, surface temperatures at stations on the east shore were warmer than those on the west shore (Figure 4a and b).

Pooling all data (low, flood, and high tide) measured on 26 August, the Temperature/Salinity (T/S) diagram (Figure 5) reveals a distinct endpoint (T=16°C, S=30 ppt). This endpoint indicates the temperature and salinity of the densest water in Budd Inlet. Waters with different T/S properties than this endpoint originate from input of heat or freshwater, primarily from solar radiation or mixing with riverine water, respectively. More salinity variation was seen in warmer than in colder waters (Figure 5). These warmer, less saline waters were typically located at the surface.

Salinity

Salinity varied substantially in Budd Inlet, both with season and with depth. The near-surface (1 m) salinity typically ranged between 27 to 29 ppt except for early spring (March through early April) and in July when salinities were reduced (Table 6). These reduced salinities reflect increased freshwater input, from precipitation, run-off, and river input (predominantly early spring) and/or Capitol Lake drainage (mid-July). Freshwater flow from the Deschutes River/Capitol Lake outlet was regulated by a controlled dam at the head of Budd Inlet. The flood gates on this dam open when the height of Capitol Lake exceeds a predetermined level (~4 m); typically this results in freshwater flow into Budd Inlet nearly every day (personal comm., Cliff Ikerd, Department of General Administration, Division of Capitol Facilities). This flow would be strongest in times of high river flow. The flood gates are closed during periods when the tide height is equal to or greater than the lake height, in order to reduce the amount of salt water intrusion into the lake. Once a year, during mid-summer, Capitol Lake is completely drained and then backflushed with salt water from Budd Inlet. This produced a period of intense freshwater input just prior to and during the mid-July tidal cycle survey.

The near-bottom (1 m from bottom) salinity increased throughout the year, from a low of about 28 ppt in March (Figure 6a) to a high near 30 ppt in September (Figure 6b) and

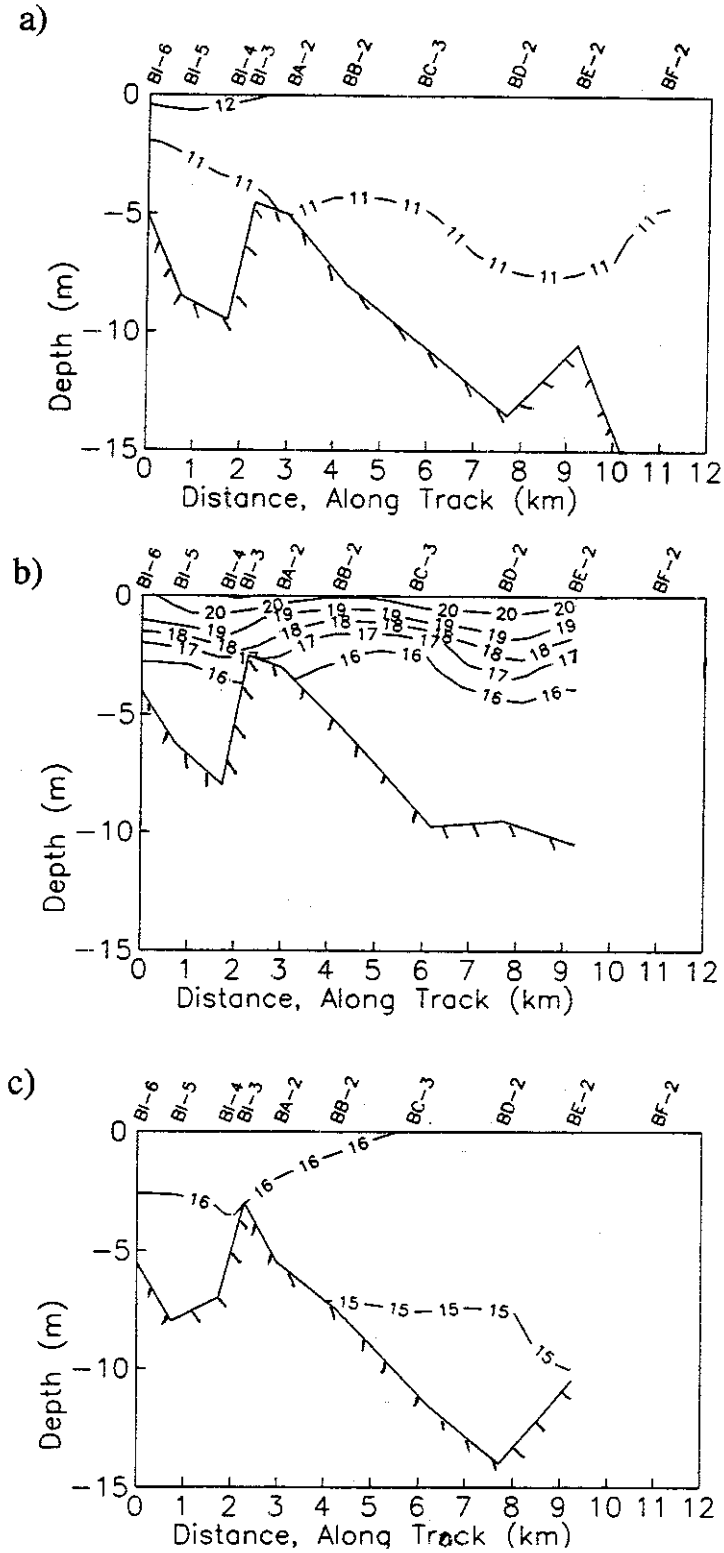


Figure 3. Temperature (°C) vertical contour plots for Station BI-6 out to Station BE-2 or BF-2 during low tide in Budd Inlet on a) 30 April 1992, b) 29 July 1992 and c) 23 September 1992. ⊤⊤⊤ indicates bottom contour.

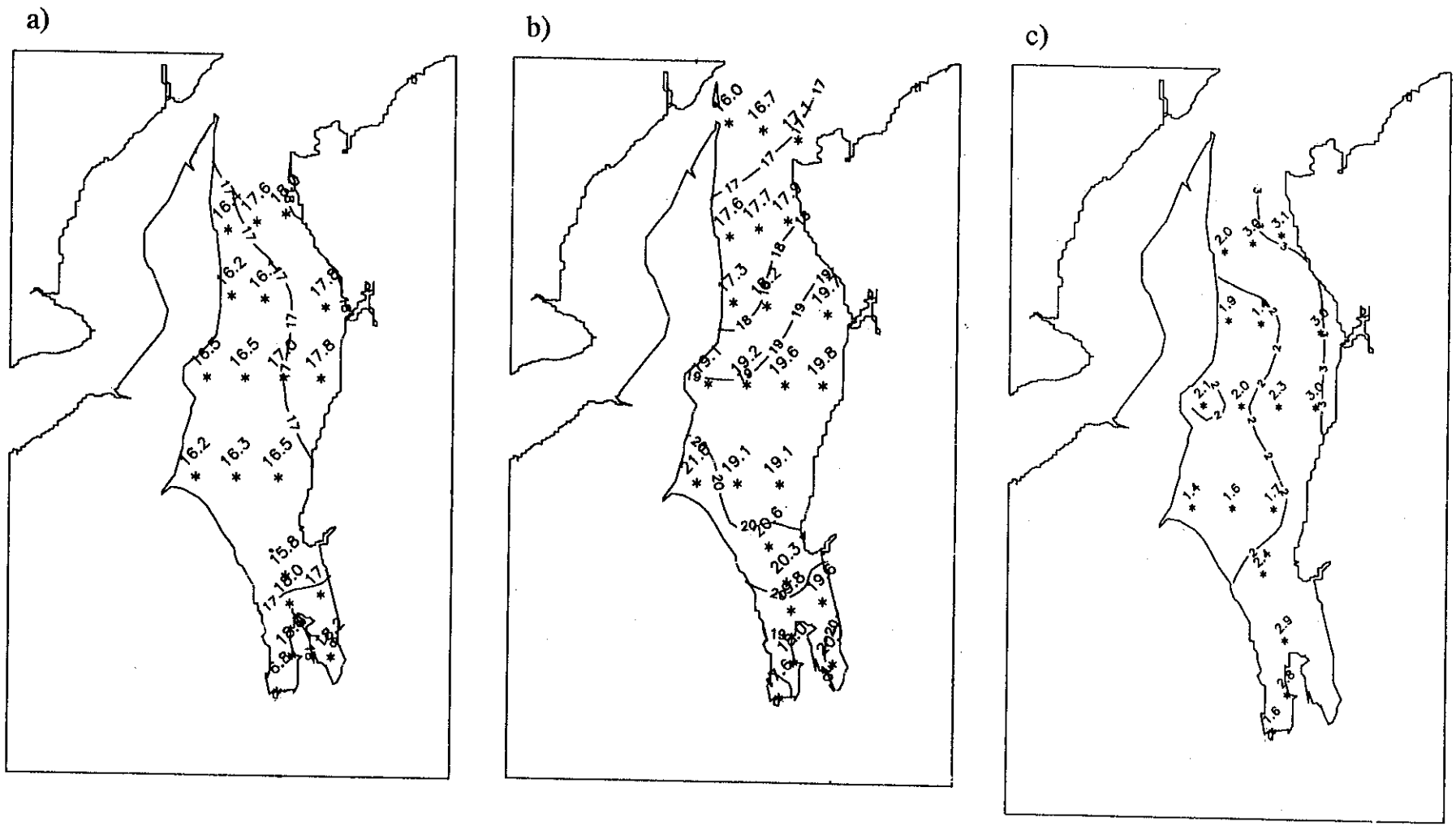


Figure 4. Temperature (°C) contour plots in Budd Inlet for a) 1-m temperatures on 02 July 1992 during ebb tide (central and outer bay) and low tide (inner bay), b) 1-m temperatures on 26 August 1992 during flood tide (central and outer bay) and high tide (inner bay) and c) temperature difference (ΔT) from 1 to 5 meters on 02 July 1992 during ebb tide (central and outer bay) and low tide (inner bay).

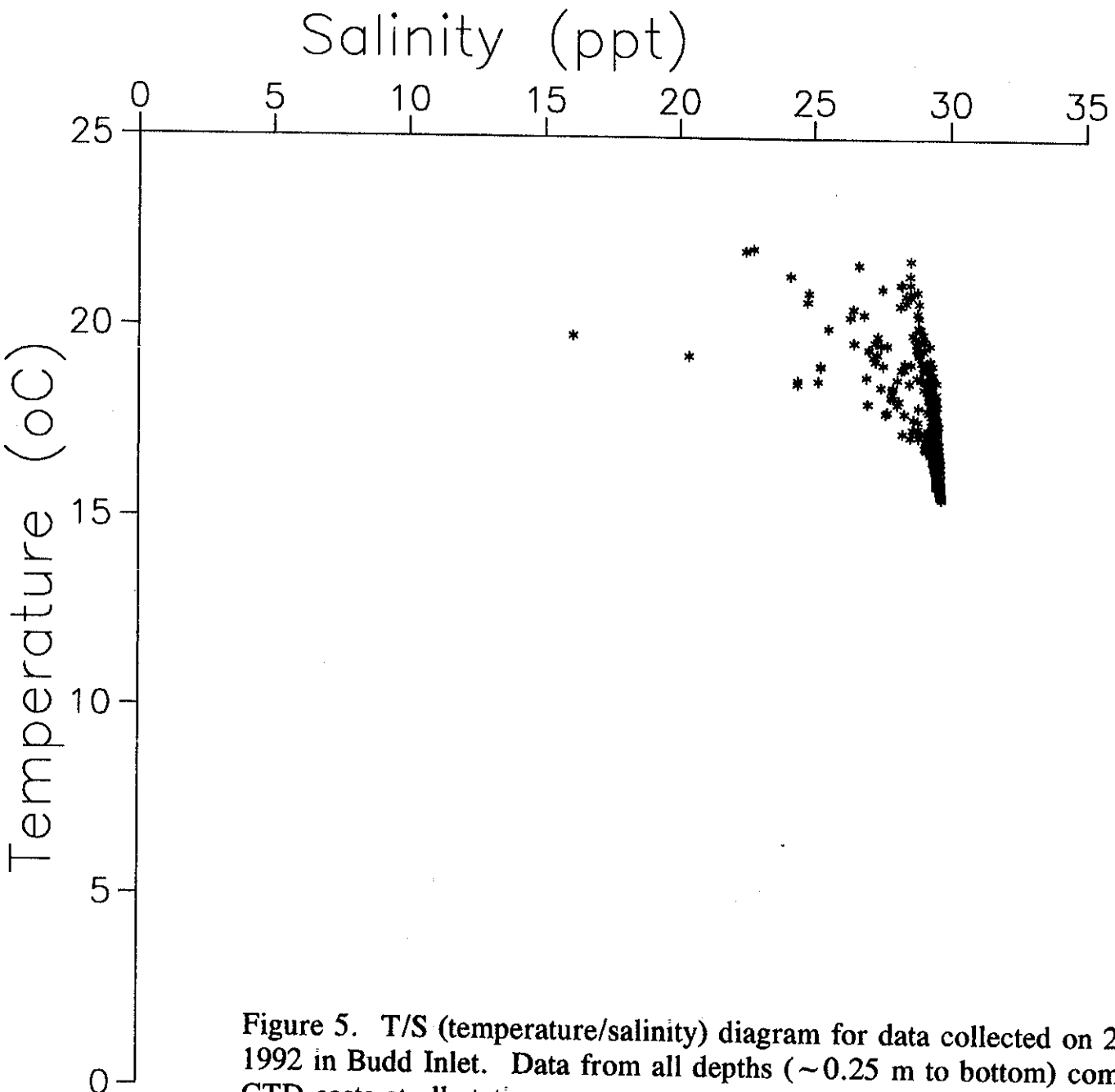


Figure 5. T/S (temperature/salinity) diagram for data collected on 26 August 1992 in Budd Inlet. Data from all depths (~0.25 m to bottom) combined from CTD casts at all stations.

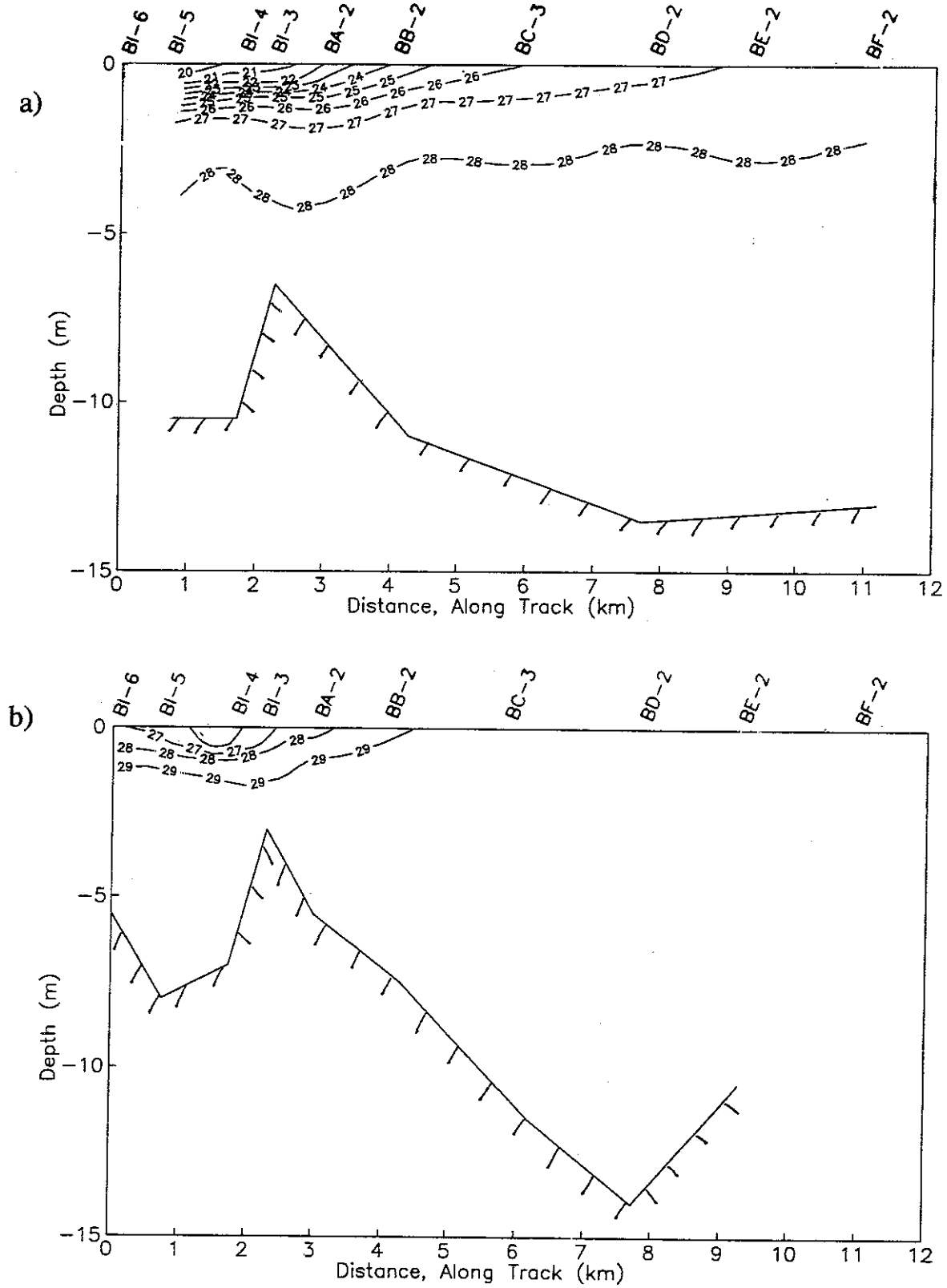


Figure 6. Salinity (ppt) vertical contour plots for Station BI-6 or BI-5 out to Station BE-2 or BF-2 in Budd Inlet on a) 25 March 1992 during ebb tide (no data included for Stations BI-6, BA-2, BC-3 and BE-2), and b) 23 September 1992 during low tide. ⟋⟋⟋ indicates bottom contour.

October (Table 6). This steady increase in salinity most likely reflects the reduced freshwater input to the inlet during the summer months, and the effect of saltier waters entering from Puget Sound.

Salinity variation was consistently greatest in the inner bay (Figure 7). The gradient in 1-m salinity in the inner bay was less pronounced during ebb and low tides, than during flood and high tides. This was likely a result of freshwater from the Deschutes River/Capitol Lake outlet, the major influence on salinity stratification in the inlet, spreading out during an ebb or low tide and remaining nearer the head of the inlet during a flood or high tide. LOTT was also a freshwater source in the inner bay. There are two minor sources of freshwater on the eastern shore located at Gull Harbor and Priest Point (Ellis Creek) and one on the southern end of East Bay (Moxlie Creek) (Figure 1); however, their impact on surface salinity may be low.

Density

A 1 ppt increase in salinity affects density as much as a 5°C decrease in temperature. In contrast to the ocean, where the salinity range is small and temperature becomes more important in controlling density stratification, an estuary derives most of its stratification (density layering) from variations in salinity. In Budd Inlet, salinity generally had a more significant effect than temperature on density. However, since both salinity and temperature affect density, the values of density provide the best overall understanding of stratification.

Although precipitation for 1992 was below normal (NOAA, 1993), Budd Inlet remained fairly density stratified throughout the summer (Figure 8a, b). Larger differences in density with depth mean stronger stratification. The stronger the stratification, the more energy is required by wind or tides to mix the water column. Vertical density data were used to calculate the relative stratification of the water column by subtracting the near-surface density (sigma-t) values from the near-bottom density (sigma-t) values (Tables 6 and 7). Density stratification generally decreased from the head to the mouth of the inlet (Figure 9). Within the central bay, stratification typically was stronger along the eastern shore (Figure 9). Stratification in the inner bay was strongest during March-April and July (Table 6). Inner bay Stations BI-1, BI-2, BI-4, BI-5, and BI-6 consistently showed stronger stratification than the central and outer bay Stations BB-2, BC-3, BD-2, and BE-2; the mean relative stratification for low tide data at Station BI-5 was 3.1, (s.d. = 2.6), whereas at Station BB-2 it was 1.5, (s.d. = 1.0). The depth of the major pycnocline was less than 1.5 m in the inner bay at Station BI-5 (Table 6) and typically less than 2 m in the central bay at Station BB-2 (Table 7).

In summary, Budd Inlet remained relatively stratified throughout the sampling season (March-October). Stratification occurred even though 1992 was a dry year, with below normal precipitation and hence a lower degree of salinity-induced stratification than may occur during a normal, or "wet" year. The salinity, temperature, and density data observed during these surveys were found to be consistent with a weak (partially mixed) two-layer estuarine circulation description (URS, 1986).

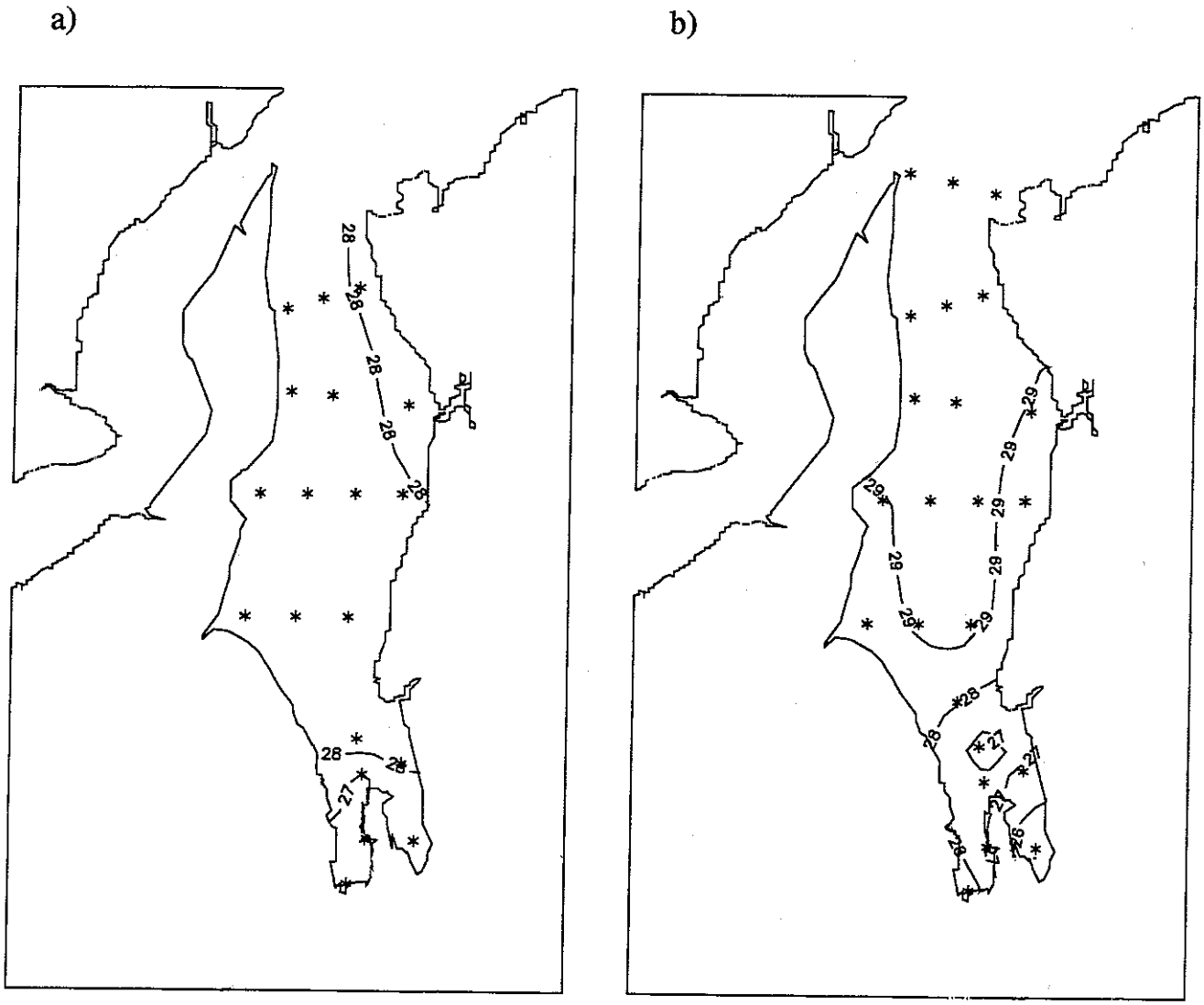


Figure 7. One-meter salinities (ppt) in Budd Inlet on a) 02 July 1992 during ebb tide (central and outer bay) and low tide (inner bay) and b) 26 August 1992 during flood tide (central and outer bay) and high tide (inner bay).

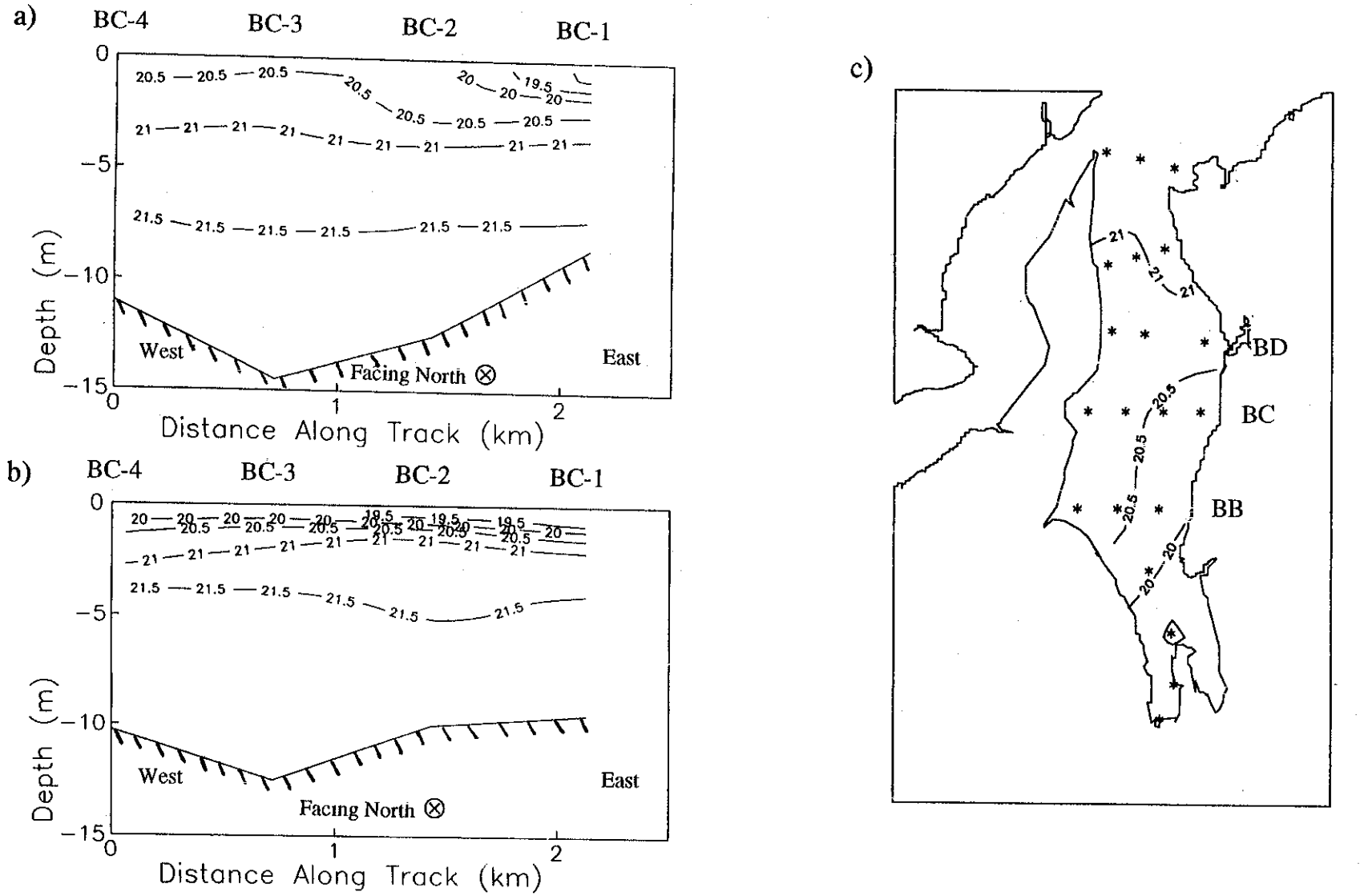


Figure 8. Density (sigma-t) contour plots for Budd Inlet during flood tide on a) 11 June 1992 at the BC cross bay transect, b) 26 August 1992 at the BC cross bay transect, and c) 11 June 1992 at 2 m. ⌒⌒⌒ indicates bottom contour.

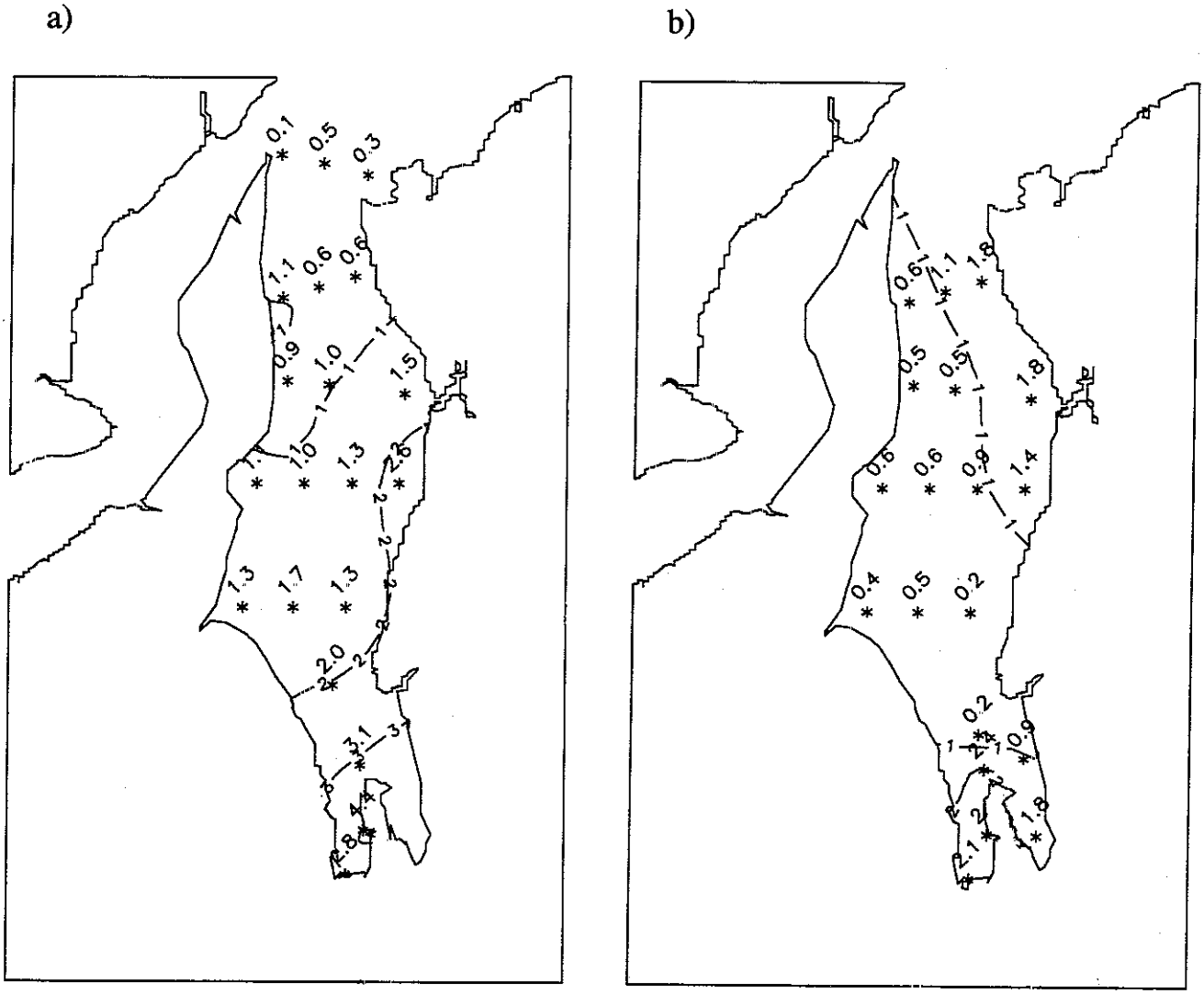


Figure 9. Relative stratification (surface to near-bottom density differences) in Budd Inlet on a) 11 June 1992 during flood tide (central and outer bay) and high tide (inner bay) and b) 02 July 1992 during ebb tide (central and outer bay) and low tide (inner bay). Density differences were obtained by subtracting the 1-m density (sigma-t) value from the near-bottom density (sigma-t) value. Higher numbers indicate greater relative stratification.

Baroclinic and Barotropic Flows

The data collected in Budd Inlet during the 1992 monitoring showed that isopycnals (surfaces of constant density) not only varied along the longitudinal transects at constant depth in Budd Inlet, but along the cross bay transects as well. Isopycnals were generally sloped relative to isobars (surfaces of constant pressure), indicating a baroclinic flow. Baroclinic flows are internal flows that exist in different vertical density layers, in response to density variations relative to a level of constant pressure. In contrast, the barotropic component of a flow is driven by pressure gradients such as tides. In a fluid of constant density, only barotropic flow is possible; in a fluid with two or more density layers, there may be barotropic flow, as well as a baroclinic flow across the density interfaces.

In Budd Inlet, during flood tides, fresher, lower-density water was generally observed along the eastern shore (Figures 8 and 10). URS (1986) also observed fresher water on the eastern side of Budd Inlet. Understanding the cause of this freshwater outflow along the eastern shore could help explain the distribution of phytoplankton and other parameters throughout the Inlet. This pattern of flow could be the result of several factors including: inertial flow (denser water moves to the outside of a bend), complex interactions between tidal forcing and stratification (Jay, 1991), friction along the sea bed, and wind. A westerly wind, for example, would cause a downward slope in the isopycnals from west to east, such as shown in Figures 8a and b, and 10. A baroclinic flow would show a northward surface flow relative to the southward barotropic flow of the flood tide.

To evaluate the effect of the earth's rotation on both baroclinic and barotropic flows, calculation of the Rossby radius is used (Pond and Picard, 1983). The Rossby radius for barotropic flow is around 100 km, indicating rotational effects on barotropic flow in an estuary of this size are negligible. Calculation of the baroclinic Rossby radius (a ratio of buoyancy to rotational terms between density layers), yields a length scale over which rotation is important internally. The baroclinic Rossby radius was calculated with our density data during surveys when freshwater on the eastern shore was observed (e.g., 28 May and 10 September), using the equation from Pond and Pickard (1983):

$$RossbyRadius = ((g(\Delta\rho/\rho)((h_1 * h_2)/(h_1 + h_2)))^{1/2})/f$$

where:

- g = force of gravity (9.8 m/s^2)
- ρ = density (1.021 kg/m^3)
- $\Delta\rho$ = density change between layers (0.02 kg/m^3 on 28 May; 0.01 kg/m^3 on 10 September)
- h_1 = height of upper layer (2 m)
- h_2 = depth of lower layer (8 m)
- f = Coriolis force (1.07E-04 at this latitude)

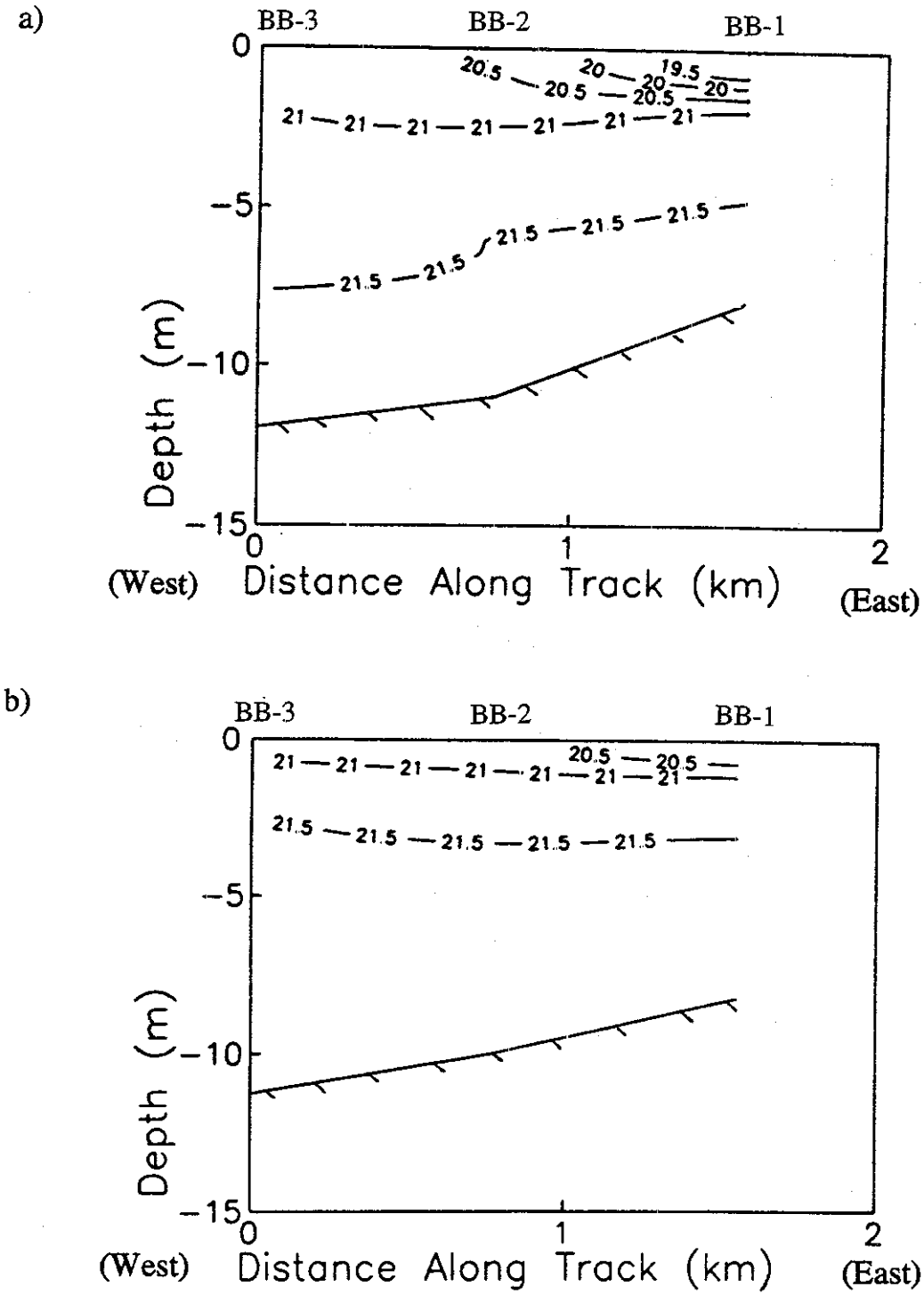


Figure 10. Density (sigma-t) values at cross bay transect BB in central Budd Inlet during flood tides on a) 28 May 1992 and b) 10 September 1992. ~~~~ indicates bottom contour.

This calculation yields an internal Rossby Radius of 5.2 km on 28 May, and 3.7 km on 10 September. These values are close to the dimensions of Budd Inlet (11.1 km x 2.6 km), indicating that rotational effects on baroclinic flow exist. The significance of this effect depends on the strength of other forces such as stratification, and inertial, buoyancy or wind forcing. The actual flow is likely the result of a combination of these effects. Winds were from the southeast to southwest with a daily average of 9.2 km/h (5.7 mph) on 28 May and from the north with a daily average of 7.1 km/h (4.4 mph) on 10 September according to data collected at the Olympia Airport by the National Weather Service. More extensive analysis of wind data as well as current meter data would be necessary in order to evaluate the effect of wind stress on these flows.

Tidal Cycle Survey Results

During the 52-h tidal cycle sampling period, temperature, salinity and density all showed substantial variation on the scale of a few hours (Figures 11-13). Release of freshwater from Deschutes River/Capitol Lake outlet is evident in data taken before 1230, on 15 July, from the inner bay salinity time series (Figure 12a). Other noticeable drops in salinity may be due to re-opening of Deschutes River/Capitol Lake flood gates for back-flushing, or the return of the freshwater previously released through tidal action. The weather over the three day period was clear and warm with light winds.

Temperature

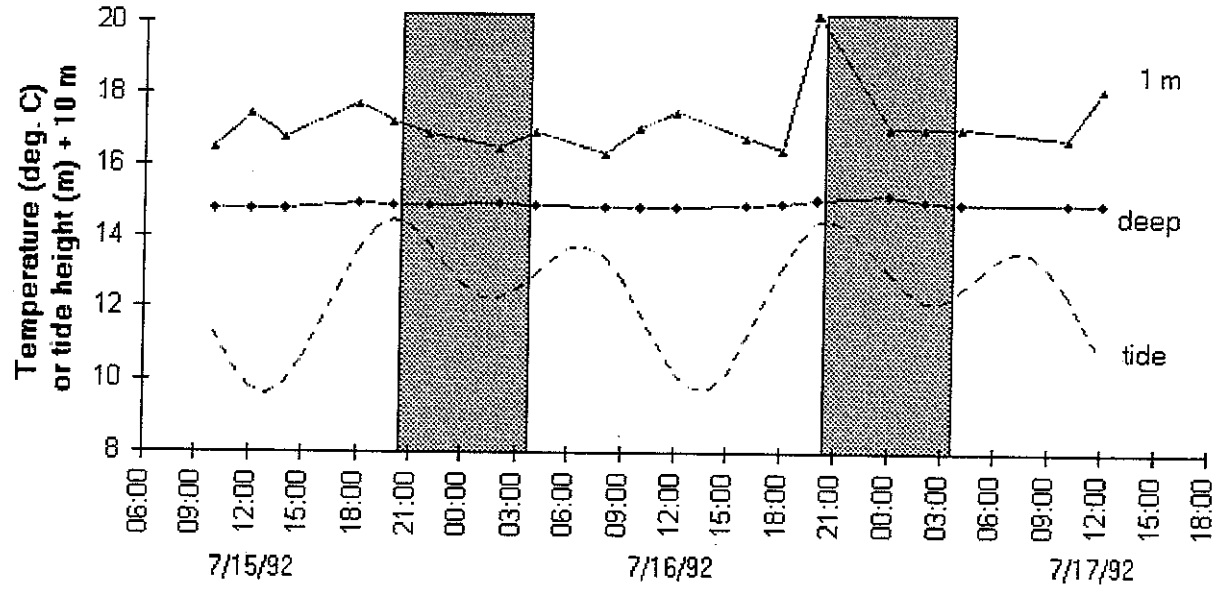
As expected, the near-bottom temperatures at all stations were much more stable than near-surface values (Figure 11). Near-bottom temperatures averaged 14.5°C. There was a slight increase in the near-bottom temperature observed over the sampling interval at both Stations BI-5 and BD-2. This temperature increase was 0.20°C at Station BI-5 and 0.15°C at Station BD-2 (instrument precision = $\pm$ 0.001°C; Seabird Electronics, 1992a). The tidal and diel variability make it difficult to determine if this increase represents an overall warming effect due to the warm weather.

The near-surface temperature in the inner bay, Station BI-5, varied inversely with the near-surface salinity (Figures 11a and 12a). A high temperature spike was recorded on 16 July around sunset near high tide at Station BI-5. This spike coincided with a salinity minimum and may reflect the return of the freshwater lens that had heated, or discharge from the LOTT overflow outfall during high tide. LOTT discharged from the overflow outfall located near Station BI-5 (Figure 1) during tide heights of 12 feet (~3.7 m) or more (URS, 1986).

Salinity

During the tidal survey, surface salinities in the inner bay were severely affected by drainage releases from the Deschutes River/Capitol Lake outlet and by tidal influences. The drainage of Capitol Lake occurred during ebb tide from 0800 until low tide on both 14 July (one day

a)



b)

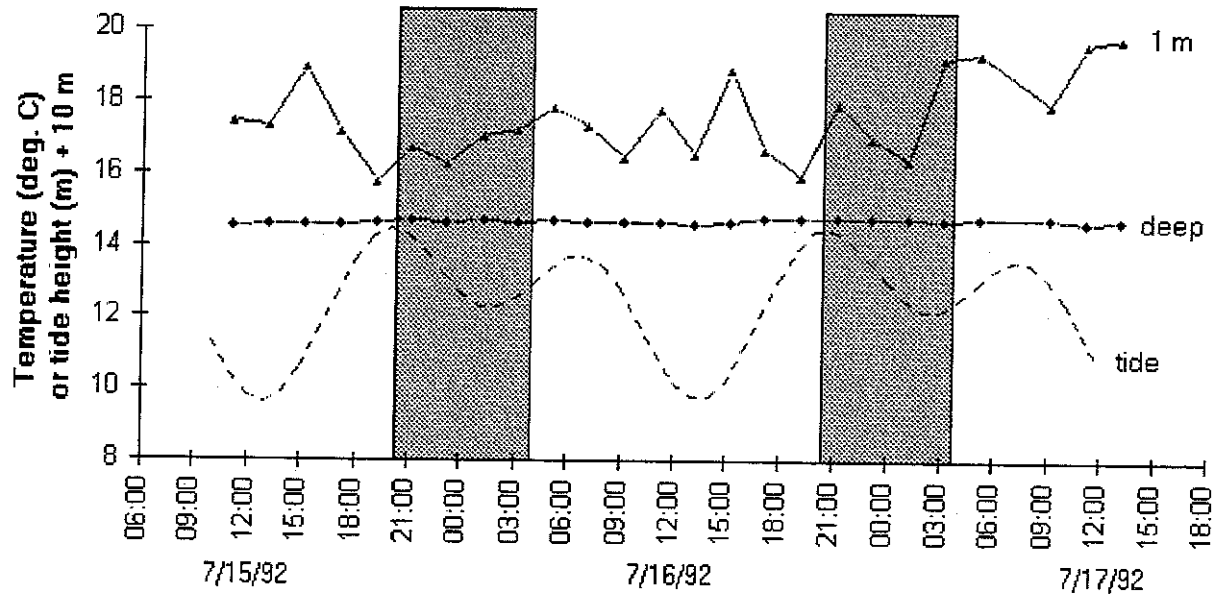
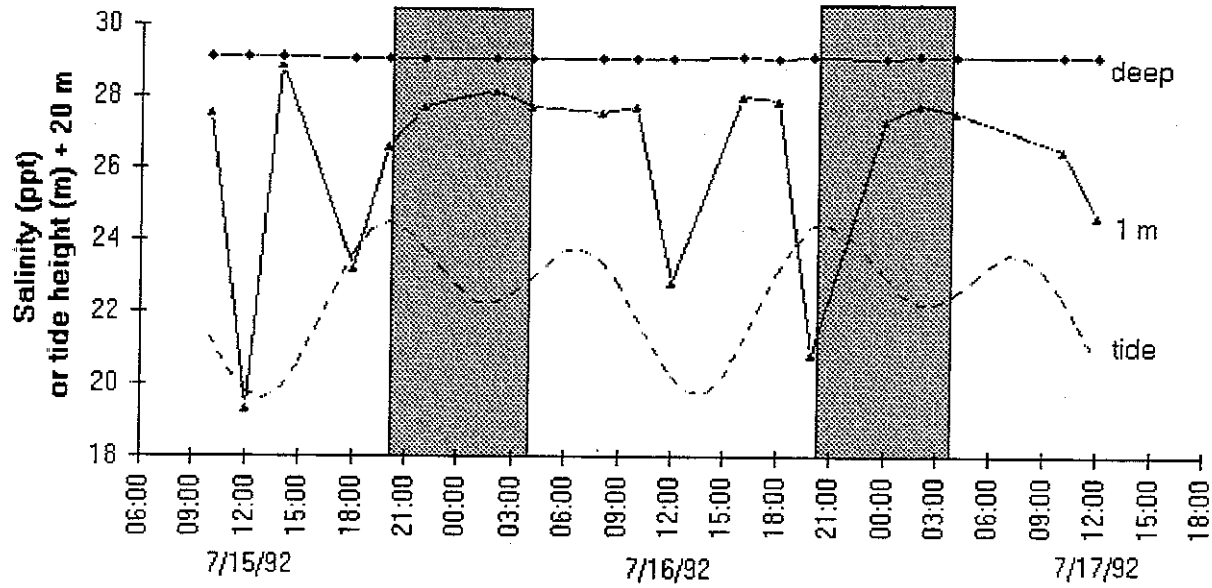


Figure 11. Temperature (°C) versus time over the 52-h tidal cycle survey on 15 to 17 July 1992 in Budd Inlet for 1 m (triangles) and deep (1 m above seabed; diamonds) samples at a) Station BI-5 in the inner bay and b) Station BD-2 in the central bay. Shading represents night.

a)



b)

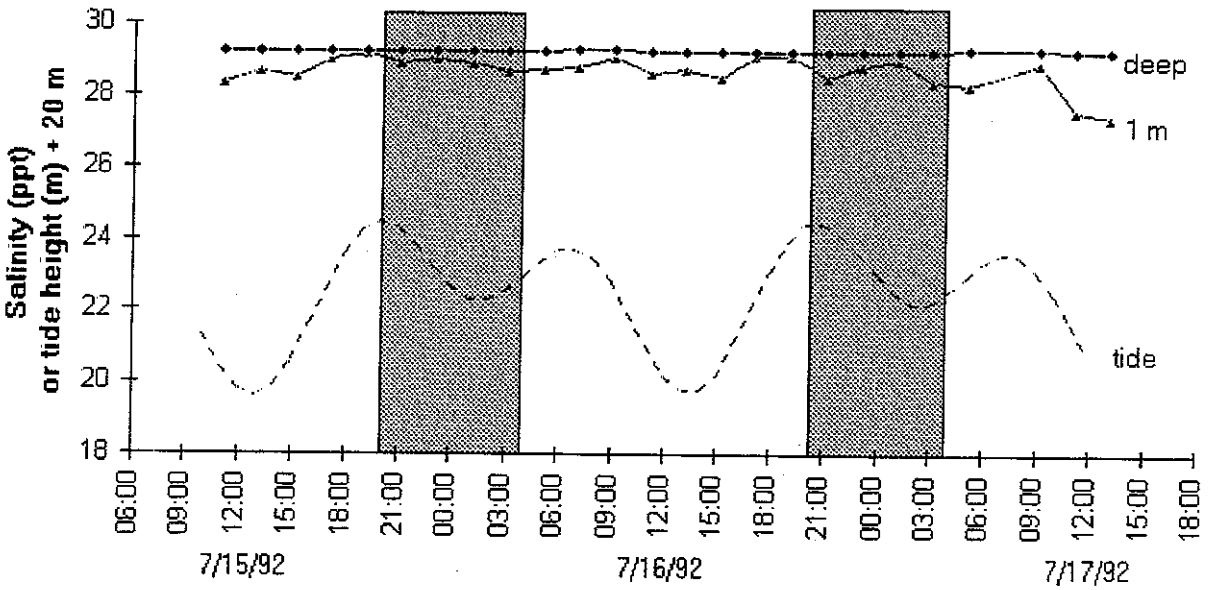


Figure 12. Salinity (ppt) versus time over the 52-h tidal cycle survey on 15 to 17 July 1992 in Budd Inlet for 1 m (triangles) and deep (1 m above seabed; diamonds) samples at a) Station BI-5 in the inner bay and b) Station BD-2 in the central bay. Shading represents night.

prior to the start of the survey) and 15 July; backflushing occurred during flood tide from approximately 1900 until high tide on July 16. Salinities may be influenced by other freshwater inputs such as LOTT effluent releases and drainage from Moxlie Creek, Ellis Creek or Gull Harbor (Figure 1). One-meter salinities ranged from 19.3 to 28.9 ppt in the inner bay, and from 27.4 to 29.1 ppt in the central bay (Figure 12). The low variation in surface salinities in the central bay implies that the effect of the Capitol Lake drainage, was dramatically reduced in the central bay at Station BD-2.

The near-bottom values of salinity averaged 29.1 and 29.2 ppt in the inner and central bay, respectively, indicating saltier water toward the mouth of the bay. No noticeable changes with time were discernible in the near-bottom data over the sampling period.

Density

Density (Figure 13) tracked salinity in its variation through time and space. The warmer temperatures of the fresher surface waters resulted in strong density gradients. Density gradients were greatest in the inner bay (Station BI-5) (Figure 13). The mean relative statification (the difference between near-bottom and 1-m density (sigma-t) values) was 2.9 (s.d. =2.6) at Station BI-5 and 1.1 (s.d. = 0.6) at Station BD-2 .

Euphotic Zone Depth

The extinction coefficient of light can be calculated from the Secchi disk depth (the depth at which the disk disappears), and then used to derive the depth of the euphotic zone (the depth to which light penetrates in the water column). The depth of the euphotic zone is typically defined as the depth at which 1% of the incident radiation is available (e.g., Steemann Nielsen, 1975), and is considered the portion of the water column where there is sufficient light for photosynthesis to occur.

To calculate the euphotic zone depth, the extinction coefficient, k, was determined with the equation:

$$k = 1.6/\text{Secchi disk reading (m)}$$

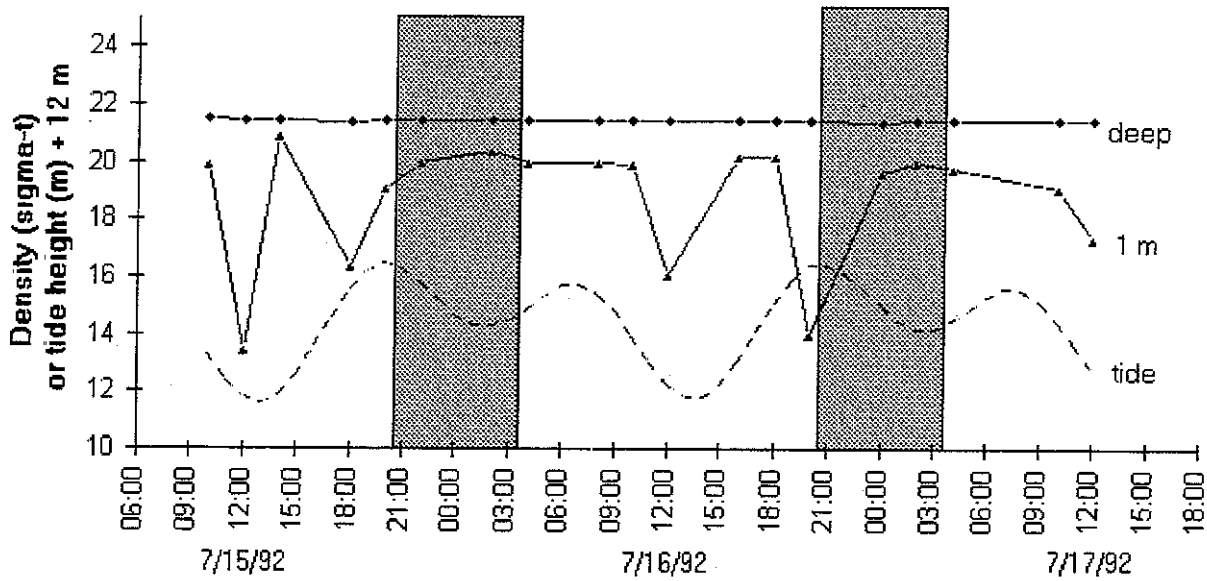
This equation was originally derived by Poole and Atkins (1929) for the English Channel, but has been modified for Puget Sound waters by substituting a value of 1.6 for 1.7.

The euphotic zone depth (1% light level) was derived using the formula for light extinction in water:

$$I_z/I_0 = e^{-kz}$$

substituting 0.01 (*i.e.*, 1%) for I_z/I_0, solving for z, the depth (m) at which 1% of the surface light (I_0) is found.

a)



b)

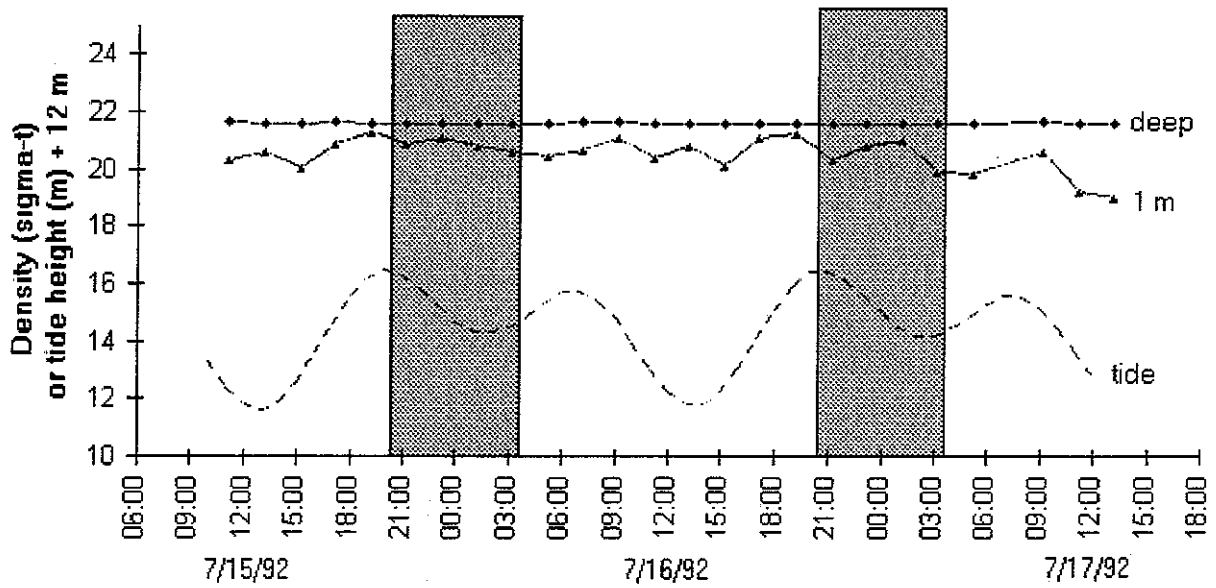


Figure 13. Density (sigma-t) versus time over the 52-h tidal cycle survey on 15 to 17 July 1992 in Budd Inlet for 1 m (triangles) and deep (1 m above seabed; diamonds) samples at a) Station BI-5 in the inner bay and b) Station BD-2 in the central bay. Shading represents night.

Figure 14 displays the euphotic zone depths (depths of 1% light levels) for West Bay and longitudinal transect stations during low tide. Average bottom depths were 5 m at Station BI-6, 7 m at Station BB-2, and 9 to 12 m at the remaining stations. Deep euphotic zones reflect the absence of particles which attenuate light. Shallower euphotic zones reflect the presence of suspended particles, which are typically either of sedimentary or phytoplankton origin. The euphotic zone depths were shallower in the inner bay than in the central and outer bay for the majority (12 out of 16) of surveys, indicating that phytoplankton growth may be more light-limited in the inner bay than in the central and outer bay. These shallower depths are likely due to the increased sedimentary load from the Deschutes River/Capitol Lake outlet and inputs from LOTT, since phytoplankton biomass was not as large in the inner bay as in the central bay (see Phytoplankton Concentration and Distribution section). A reduction in the euphotic zone depth as a result of high phytoplankton concentrations is indicated in the August 13 data, with depths at least 2 m shallower at central bay stations than at inner bay stations (Figure 14). The corresponding chlorophyll *a* concentrations (collected at the Secchi disk depths) were much higher in the central bay ($\sim$50 μg/L (mg/m^3)) than in the inner bay ($\sim$5 mg/m^3; Figure 31).

In general, throughout the bay, euphotic zone depths were shallower during occurrences of phytoplankton blooms (chlorophyll *a* > 10 mg/m^3) and deeper during periods of low chlorophyll *a* concentrations (Figures 14 and 31). The deepest euphotic zone depths (Figure 14) were seen on 28 May, corresponding with the lowest chlorophyll *a* concentrations (Figure 31) observed for the season. According to data collected at the Olympia Airport by the National Weather Service, two moderate wind events (daily wind speed averages of $\sim$16 km/h (10 mph)) occurred from 18 to 20 May and 25 to 26 May. These winds could have mixed the phytoplankton throughout the water column, thus reducing their population in the euphotic zone, and consequently increasing the depth of light penetration.

Dissolved Oxygen

Summary tables of surface and near-bottom D.O. concentrations during the 1992 seasonal monitoring of Budd Inlet are located in Appendix A. Dissolved oxygen concentrations in surface waters (1 m) ranged from a low of 3.8 mg/L on 7 October in West Bay to a high of 20.9 mg/L on 25 March in the central bay. Dissolved oxygen concentrations in the near-bottom waters ranged from a low of 2.2 mg/L on 7 October in East Bay to a high of 18.2 mg/L on 15 May in East Bay. Dissolved oxygen concentrations were generally higher at 1 m than at near-bottom depths and in the central and outer bay than in the inner bay. Dissolved oxygen results at different tidal stages for the same station during bi-weekly sampling often differed by 1 mg/L or more during the same survey (Appendix A). Therefore, tidal stage (low, high, flood, or ebb) should be considered in the evaluation of D.O. results.

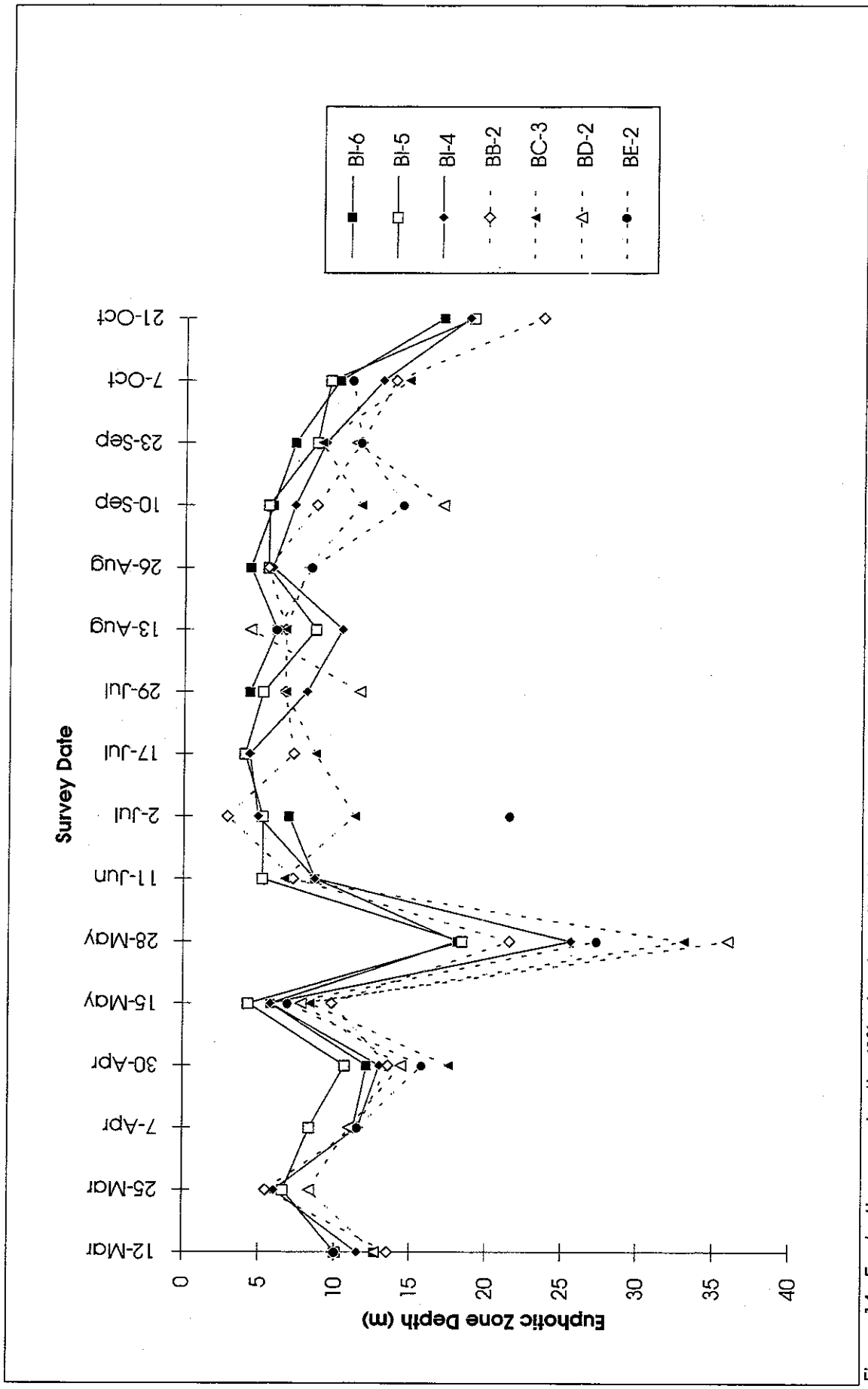


Figure 14. Euphotic zone depths (1% of surface light levels) calculated from Secchi disk depths for Budd Inlet during 1992. Data collected at low tide, except 1st 3 surveys at ebb tide and last survey at high tide. Solid line = West Bay (inner bay). Dashed line = central and outer bay. Bottom depths were used for Secchi depth values for Stations BB-2 and BE-2 on 28 May since the Secchi disk hit bottom before disappearing. Average bottom depths were 5m at Station BB-2, and 9 to 12 m at Stations BI-5, BI-4, BC-3, BD-2 and BE-2.

Low Dissolved Oxygen

In this report, D.O. concentrations less than 5.0 mg/ L are termed low, and D.O. concentrations less than 3.0 mg/L are termed near-hypoxic, since a concentration of 2.0 mg/L is usually considered hypoxic (Llansó, 1992; Smith, *et al.*, 1992). Hypoxia, the presence of very low D.O. concentrations in the water column, is associated with detrimental effects to organisms such as fish causing reduced feeding and growth, and mortality as oxygen decreases to 0 mg/L (Harding *et al.*, 1992). Low D.O. concentrations were most frequently observed in the inner bay at near-bottom depths (Figures 15, 16, and 17). During low tide in West Bay, near-bottom D.O. was measured at concentrations less than 5.0 mg/L from 17 July through 7 October, and less than or equal to 3.0 mg/L on 29 July and 26 August (Figures 15 and 18). Low near-bottom D.O. values occurred less frequently in East Bay than in West Bay. In East Bay, near-bottom D.O. concentrations were recorded less than 5.0 mg/L during low tide from 13 August through 7 October, and less than 3.0 mg/L during high tide on 7 October (Appendix A and Figure 16).

Some inner bay stations also occasionally showed low D.O. values at depths as shallow as 1 m. One-meter values less than 5.0 mg/L were observed during low tides at stations in both West and East Bays on 26 August and 7 October (Appendix A and Figure 18). One-meter values less than 5.0 mg/L also occurred during high tide at the innermost West Bay station on 26 August and the innermost East Bay station on 7 October (Appendix A). At times, in the central bay, near-bottom D.O. concentrations less than 5.0 mg/L were measured during flood tides along the eastern shore at the BC or BB transects. This occurred at the BC transect on 13 and 26 August (Figure 17) and at the BB transect on 7 October (Figure 16). The D.O. data collected during the bi-weekly seasonal monitoring surveys may not reflect the lowest D.O. conditions, since samples were taken during the day, in a year without much rainfall and hence a lesser degree of stratification.

High Dissolved Oxygen

At 100% saturation, the D.O. concentration in the water is equilibrated with the atmosphere. The data collected during the sampling season (March to October) had a salinity range of approximately 19 to 30 ppt and a temperature range of approximately 9.5 to 23°C (Table 5). One hundred percent saturation concentrations for a salinity of 30 ppt and temperatures of 9.5 and 23°C were 9.4 and 7.2 mg/L respectively. At a salinity of 19 ppt over the same temperature range (9.5 and 23°C), D.O. saturation concentrations were 10.1 and 7.6 mg/L, respectively. Phytoplankton photosynthesis can cause the water to become supersaturated, with D.O. concentrations above saturation levels observed. Supersaturated (high) D.O. concentrations are defined as greater than 12 mg/L in this report, since this is well above the possible 100% saturation concentrations. High D.O. concentrations (>12 mg/L) were observed at 1 m on 11 out of 16 surveys. Dissolved oxygen concentrations during low tide were generally highest in the central bay near Stations BB-2 and BC-3. Maximum D.O.

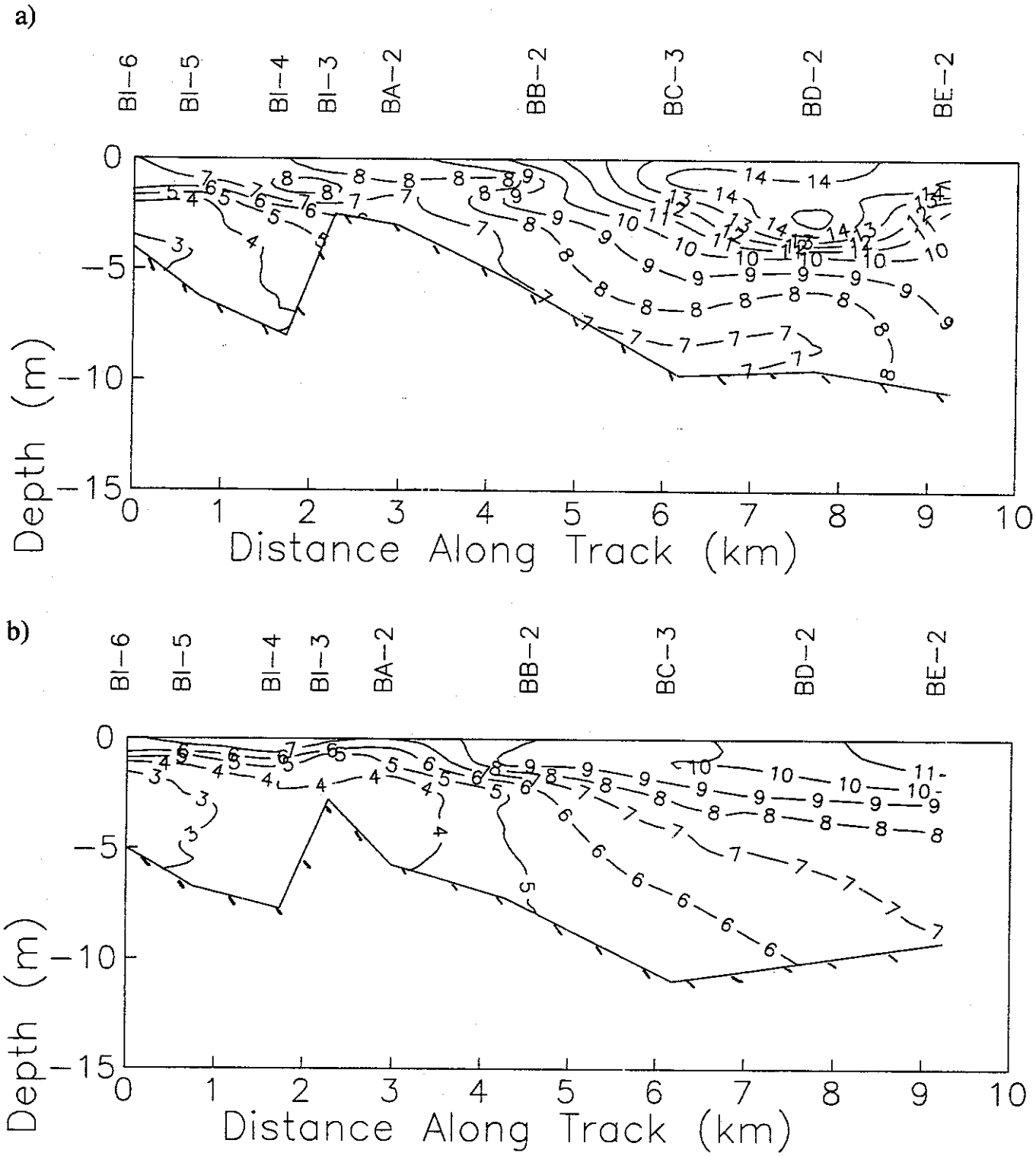


Figure 15. Dissolved oxygen (mg/L) vertical contour plots for Station BI-6 out to Station BE-2 in Budd Inlet during low tide on a) 29 July 1992 and b) 26 August 1992. ⟵⟵ indicates bottom contour.

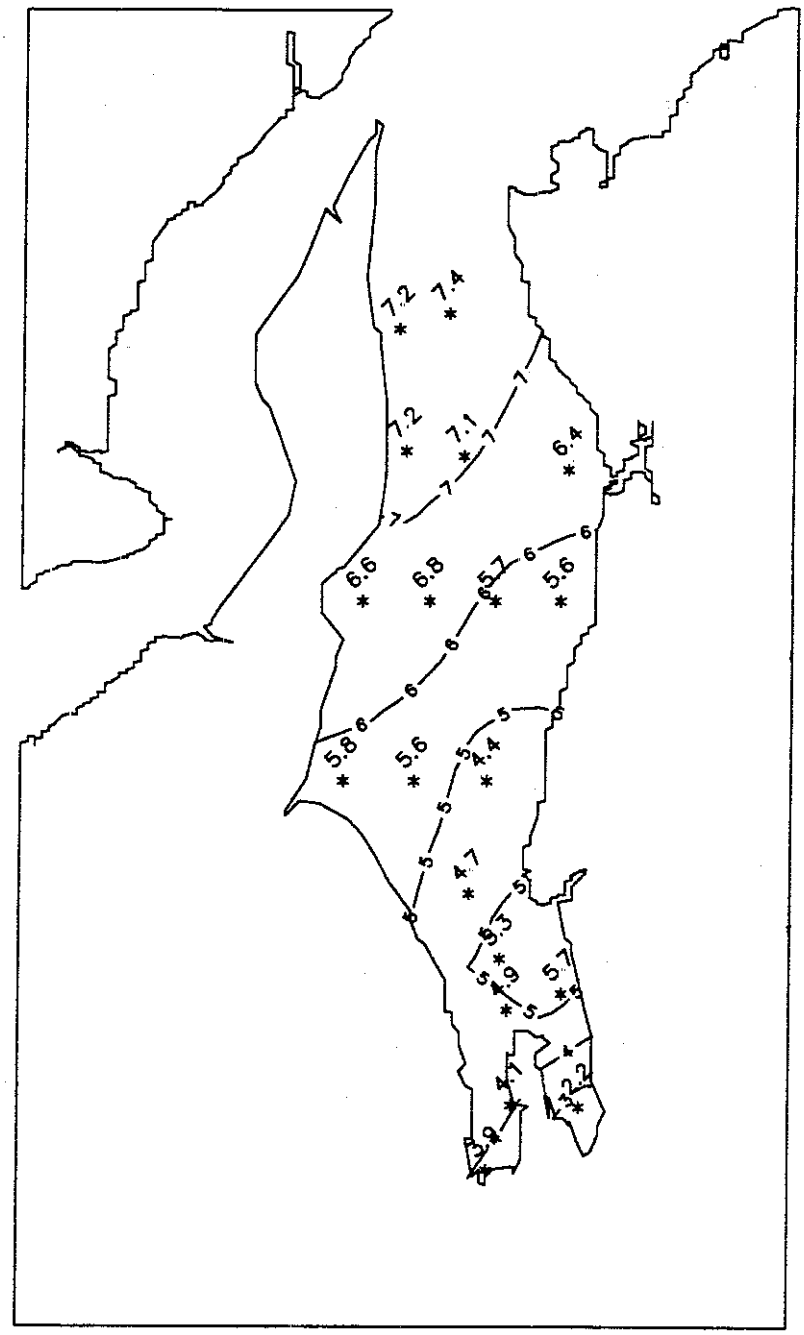


Figure 16. Near-bottom dissolved oxygen (mg/L) concentrations in Budd Inlet on 07 October 1992 during flood tide (central and outer bay) and high tide (inner bay).

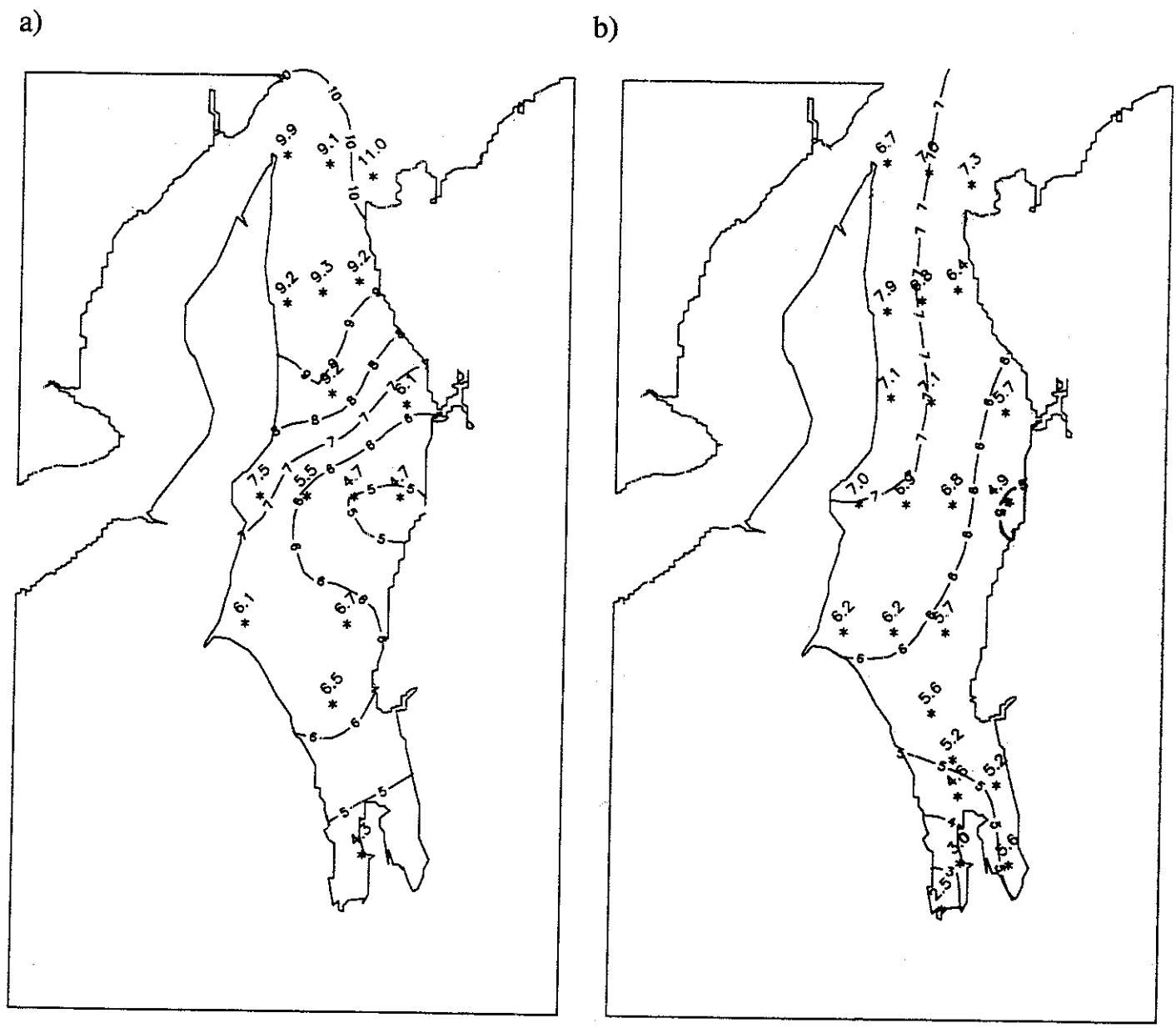


Figure 17. Near-bottom dissolved oxygen (mg/L) concentrations in Budd Inlet during flood tide (central and outer bay) and high tide (inner bay) on a) 13 August 1992 and b) 26 August 1992.

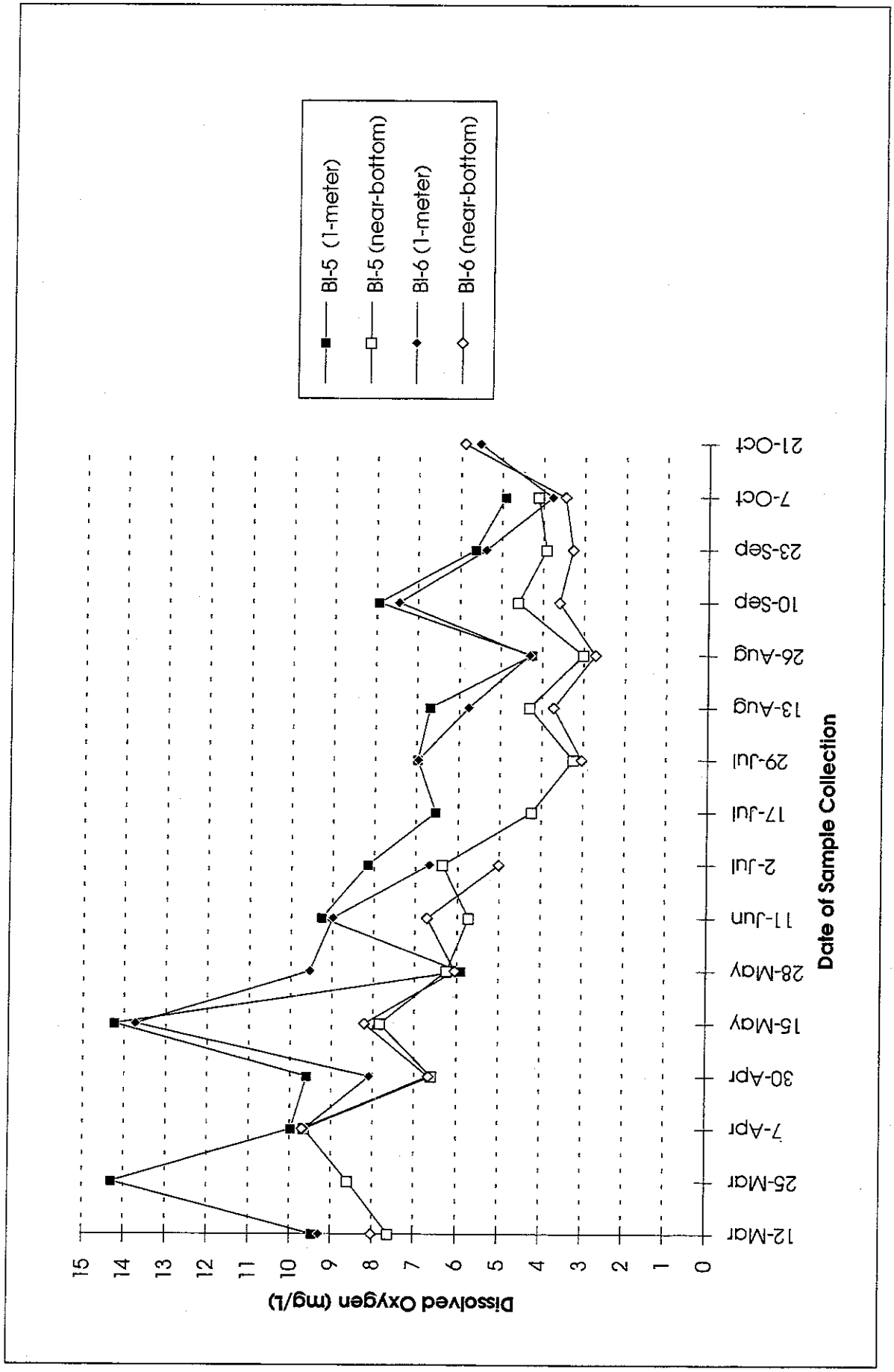


Figure 18. Dissolved oxygen concentrations at West Bay Stations Bl-5 and Bl-6 from March to October 1992 in Budd Inlet. Low tide data except for first 3 surveys (ebb tide) and last survey (high tide).

concentrations in the central bay during low tide occurred at the surface in the spring and at 1-2 m depth from mid-July through mid-August, and were likely due to runoff (during high flow periods) and biological activity.

The highest D.O. concentrations observed in the near-surface waters during flood tide were close to the eastern shoreline north of Priest Point Park (Figure 19). This same pattern was often observed in the near-bottom waters during the early season surveys. In general, the highest D.O. values (>12 mg/L) corresponded to times of phytoplankton blooms (chlorophyll a > 10 mg/m^3) in the central inlet and inner bay areas.

Dissolved Oxygen: Tidal and Diel Effects

Bi-Weekly Results

The bi-weekly sampled D.O. concentrations presented above were likely influenced by the stage of the tide during the time of collection. Dissolved oxygen concentrations were approximately 1 mg/L higher throughout the water column during high tide than at low tide, according to limited data evaluated (three comprehensive comparisons). For example, on 10 September, high tide D.O. concentrations below 5.0 mg/L were observed only at West Bay Stations BI-6 and BI-5 (Figure 20b). The corresponding low tide data on that date showed concentrations below 5.0 mg/L at shallower depths and over a larger area (Stations BI-6, BI-5, and BI-4) (Figure 20a). It is unknown whether the differences between low and high tide data, varying on 6-h time scales, are due solely to tidal effects or to a combination of diel (e.g., photosynthesis, respiration) and tidal (e.g., advection, mixing) effects. For instance, photosynthesis by phytoplankton produces D.O. and occurs only during daylight. The surface increase in D.O. between 1130 and 1800 on 10 September is possibly due to phytoplankton growth (Figure 20).

Tidal Cycle Survey Results

Distinct variation was observed between surface and near-bottom D.O. concentrations at all three stations during the 52-h tidal cycle survey on 15-17 July (Figures 21 and 22). At inner bay Station BI-5, the mean 1-m D.O. value was 6.5 mg/L (s.d. = 1.0), and the mean near-bottom value was 3.3 mg/L (s.d. =0.6), (n=19). At central/inner bay Station BA-2, the mean 1-m D.O. value was 10.1 mg/L (s.d. =1.7), and the mean near-bottom value was 6.1 mg/L (s.d. =1.5), (n=23). At central bay Station BD-2, the mean 1-m D.O. value was 9.7 mg/L (s.d. =1.1), and the mean near-bottom value was 7.3 mg/L (s.d. =0.6), (n=25). Figure 22 suggests the movement of the high D.O. concentration shifts in the direction of the tide, moving further seaward during ebb tide (~0700 to 1230) and back during flood tide (~1430 to 1930). This may indicate advection of water with a high concentration of phytoplankton, in response to the tide.

The lowest D.O. value during the tidal cycle survey conducted from 15-17 July was 2.5 mg/L, found at near-bottom depths at West Bay Station BI-5, on 16 July between 1000

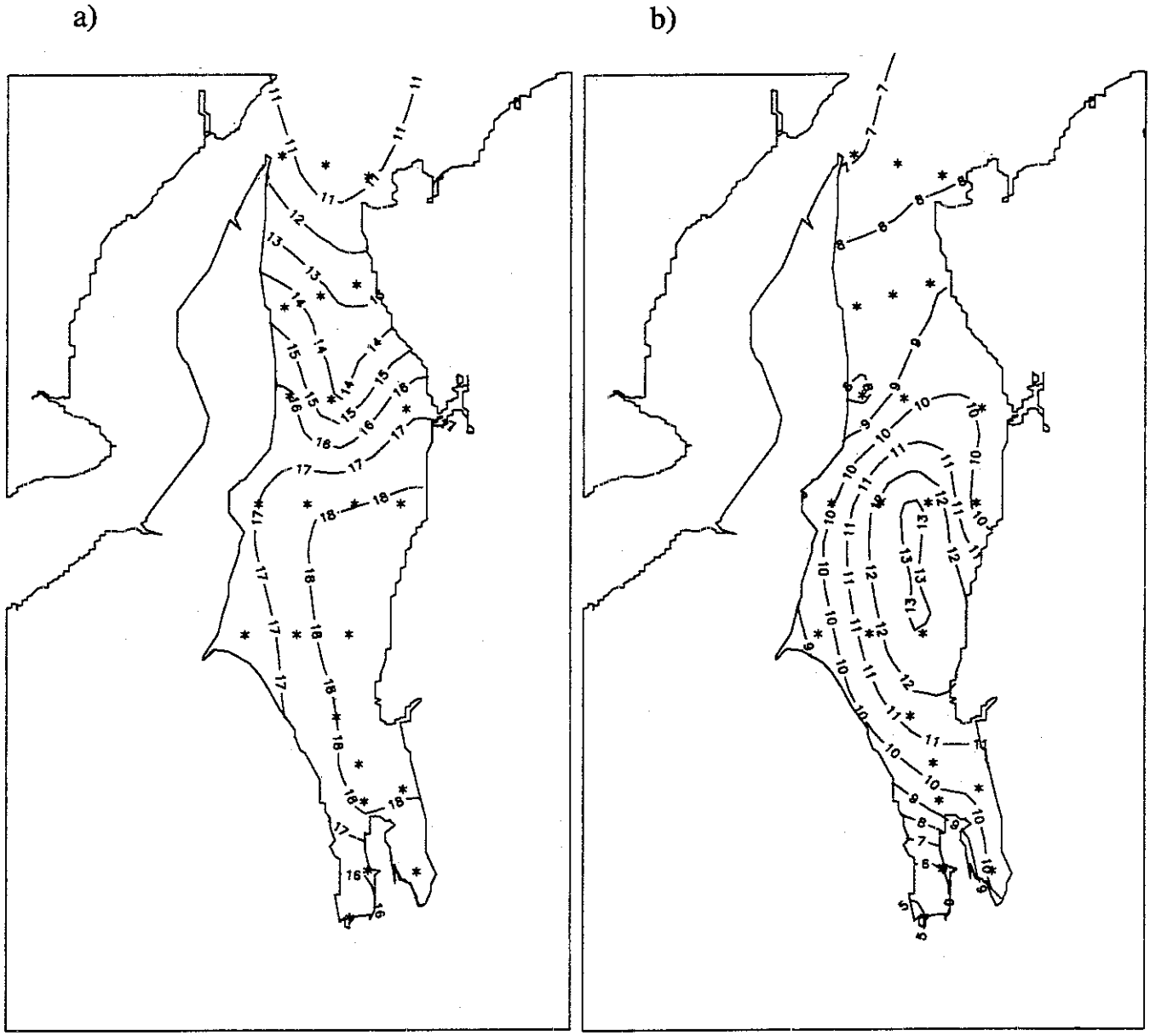


Figure 19. One-meter dissolved oxygen (mg/L) concentrations in Budd Inlet during flood tide (central and outer bay) and high tide (inner bay) on a) 15 May 1992 and b) 26 August 1992.

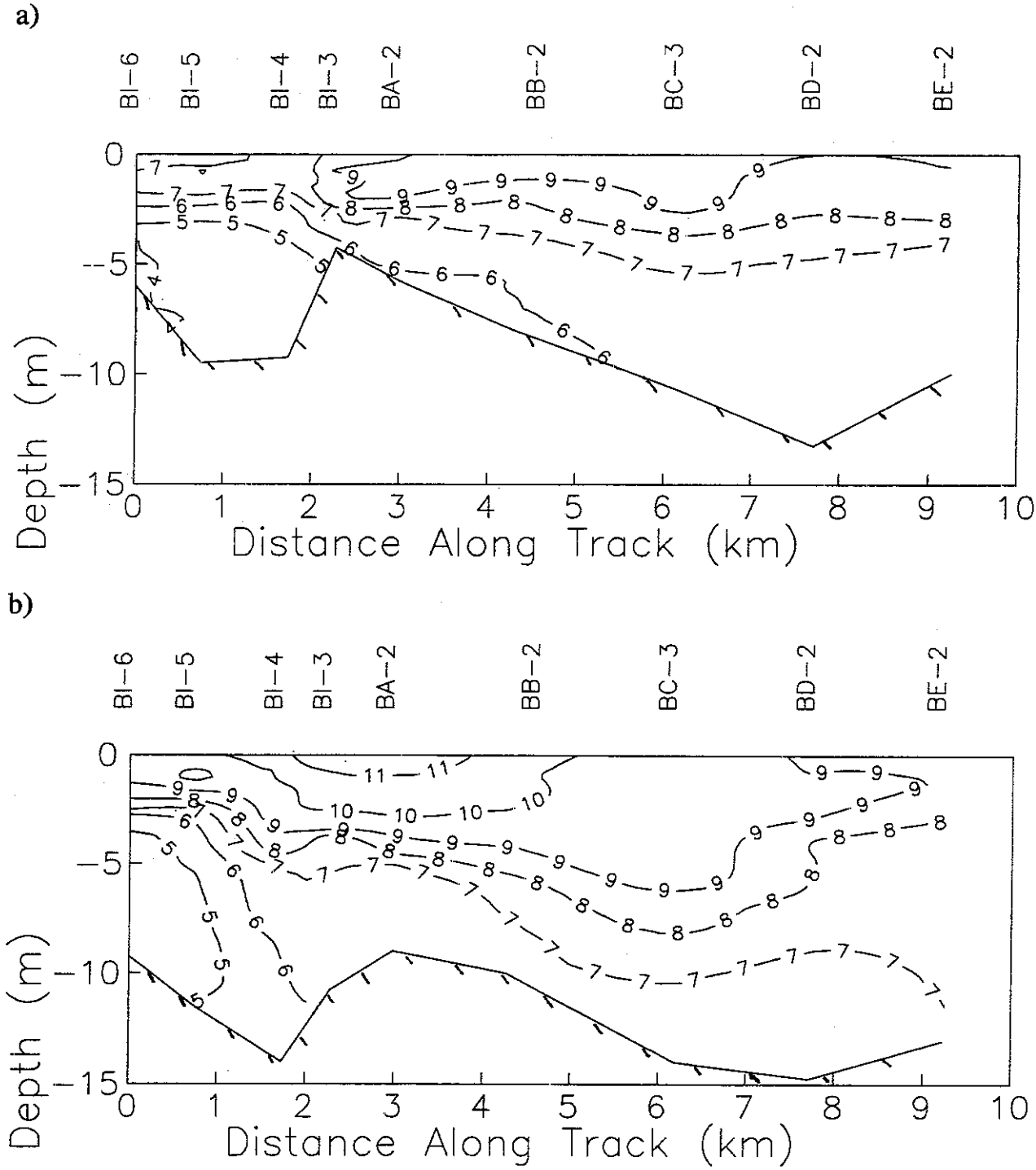
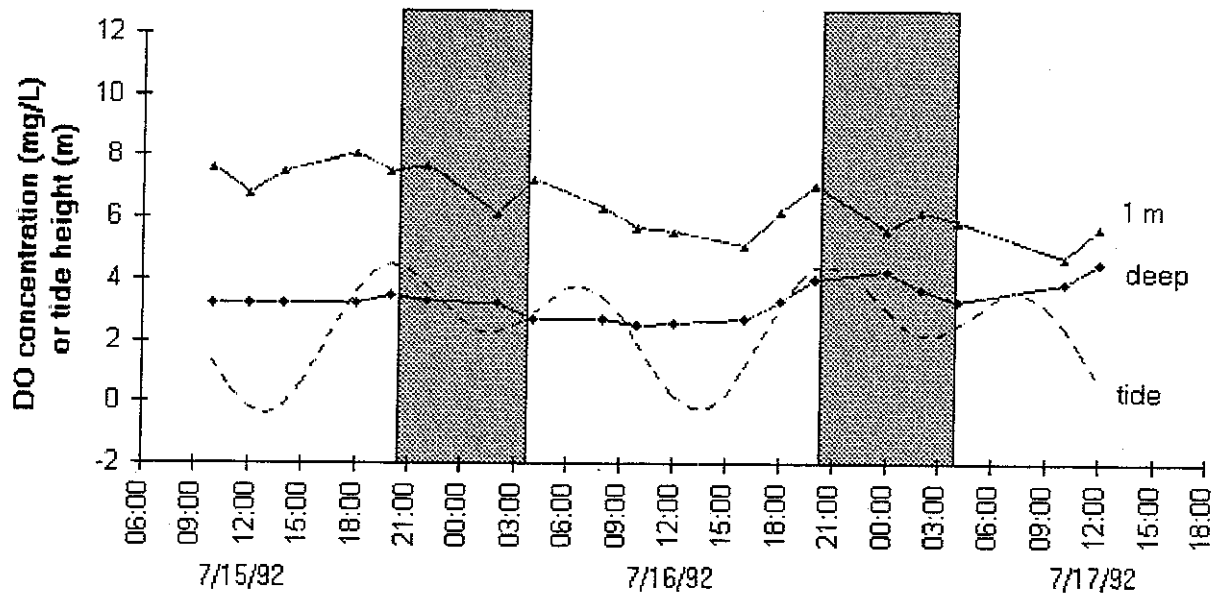


Figure 20. Dissolved oxygen (mg/L) vertical contour plots for Station BI-6 out to Station BE-2 on 10 September 1992 during a) low tide and b) flood tide (central and outer bay) and high tide (inner bay). Low tide occurred at ~11:30 and high tide occurred at ~18:00. ⟍⟍⟍ indicates bottom contour.

a)



b)

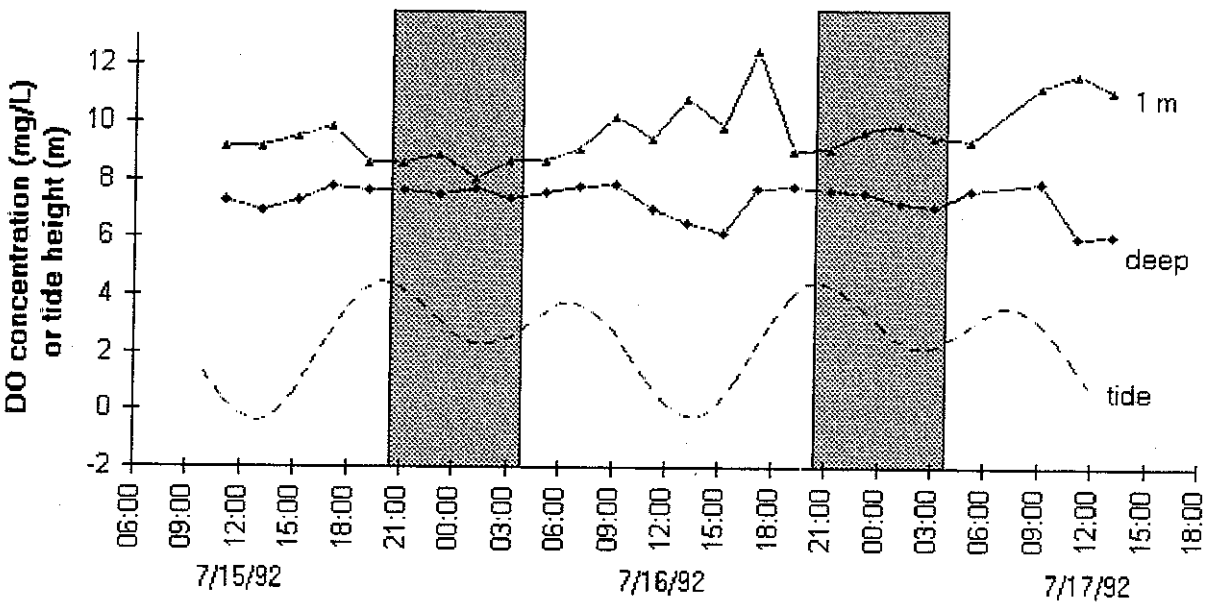
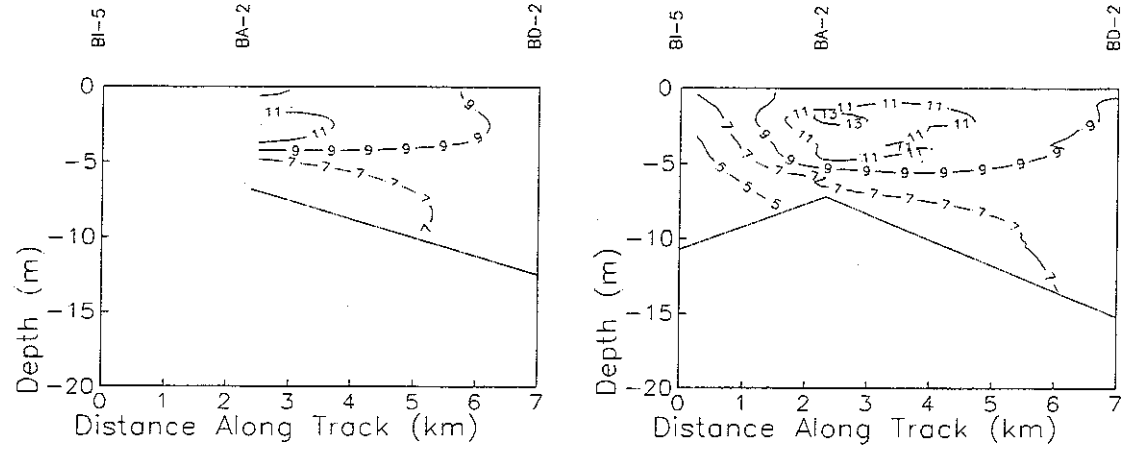
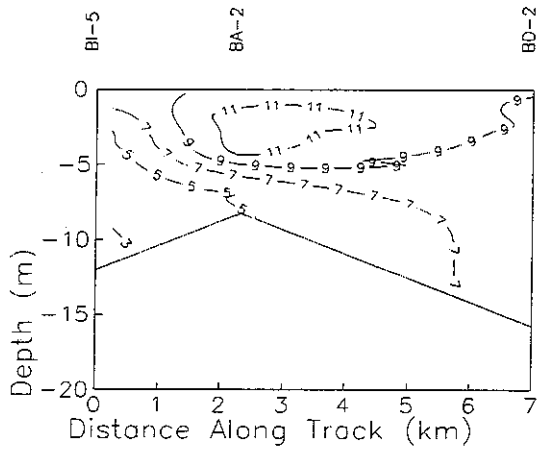


Figure 21. Dissolved oxygen (DO) concentration versus time over the 52-h tidal cycle survey on 15 to 17 July 1992 in Budd Inlet for 1 m (triangles) and deep (1 m above seabed; diamonds) samples at a) Station BI-5 in the inner bay and b) Station BD-2 in the central bay. Shading represents night.

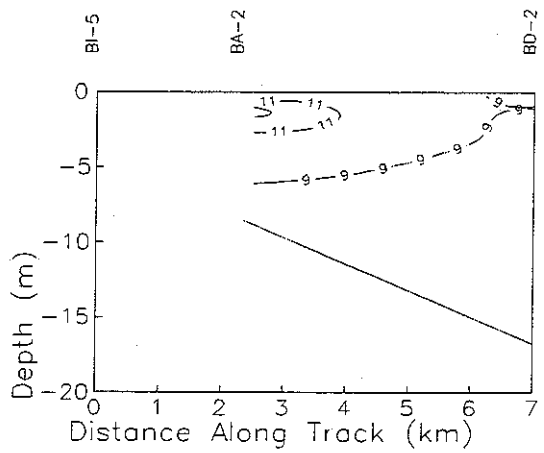


24:00 - 01:10

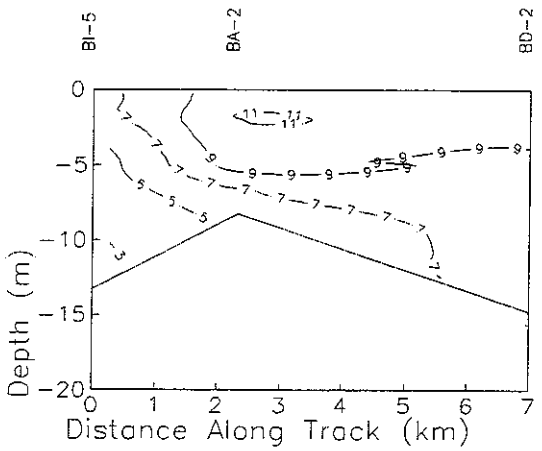
02:00 - 03:10



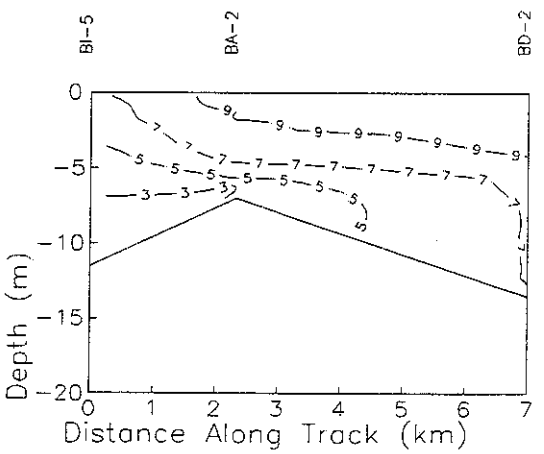
04:00 - 05:10



06:00 - 07:10

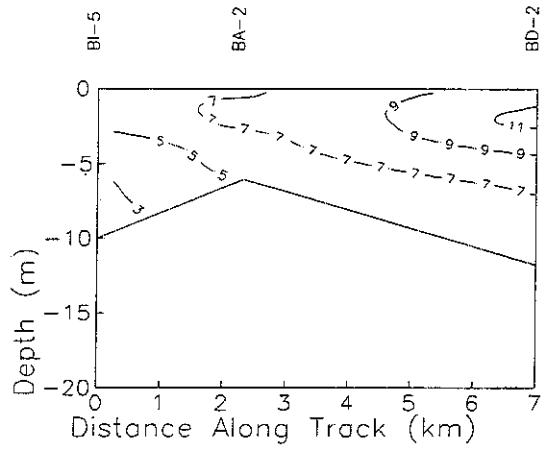


08:00 - 09:10

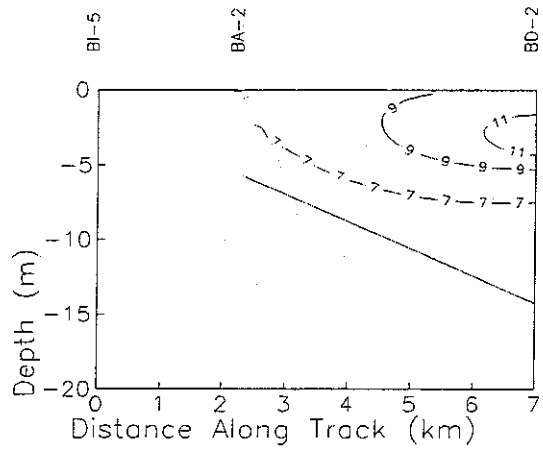


10:00 - 11:10

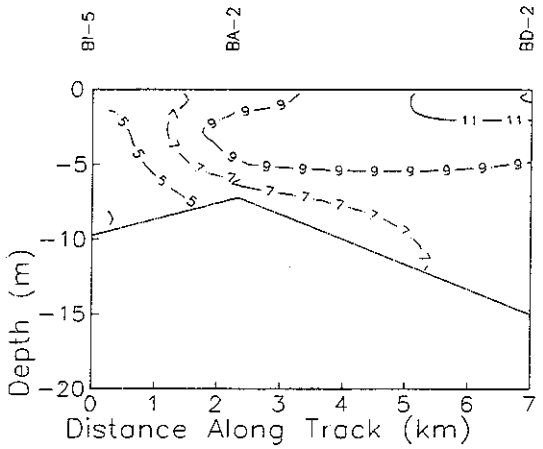
Figure 22. Dissolved oxygen (mg/L) vertical contour plot sequence from the tidal cycle survey in Budd Inlet on 16 July 1992. Order of sampling was Station BI-5, Station BA-2 then Station BD-2. Starting time indicates sampling at Station BI-5. Ending time indicates sampling at Station BD-2.



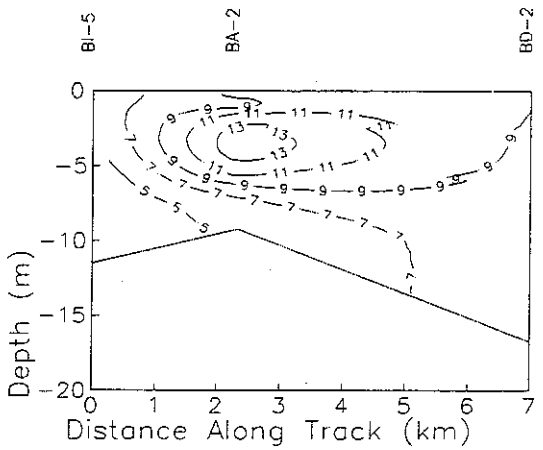
12:00 - 13:10



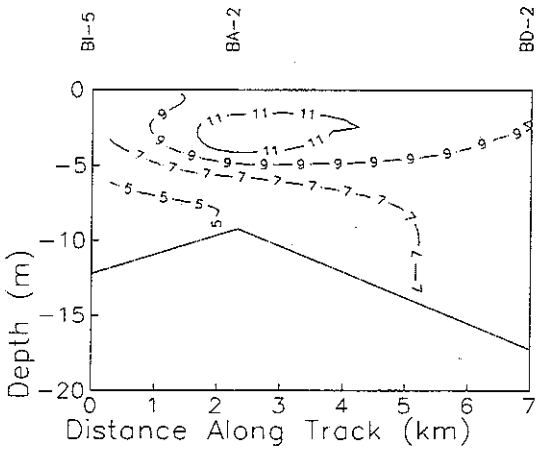
14:00 - 15:10



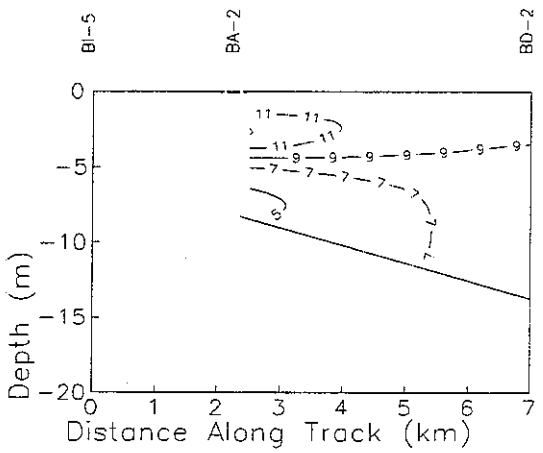
16:00 - 17:10



18:00 - 19:10



20:00 - 21:10



22:00 - 23:10

Figure 22: Continued

and 1250 during ebb tide (Figure 21a). In contrast, the highest D.O. value was almost 12.5 mg/L, found near the surface at central bay Station BD-2, on 16 July around 1500 during flood tide (Figure 21b).

As with the variation seen in the bi-weekly results, the observed changes in D.O. concentrations over the short (*i.e.*, few hours) time scales observed during the tidal cycle survey (Figures 21 and 22) could have originated from many processes: physical forcing (e.g., mixing from tides or winds, drainage of Capitol Lake), chemical reactions (e.g., binding of oxygen by sulfides) and biological activity (e.g., photosynthesis, respiration, bacterial remineralization). Likely, a combination of these processes are responsible. In the inner bay, D.O. values (particularly at 1-m depths) varied somewhat with tidal stage, with lower values near low tide and higher values near high tide (Figure 21a). In the central bay, however, the 1-m D.O. values were highest during the daylight hours and did not vary with tidal stage, indicating photosynthetic oxygen production, as later shown by chlorophyll *a* concentrations at these locations.

Range of Dissolved Oxygen Variation

Variation of D.O. was evaluated over temporal (seasonal, tidal cycle) and spatial (horizontal and vertical) scales. The most substantial variation in D.O. was seen over the seasonal cycle. For stations sampled during low tide, the maximum seasonal difference in D.O. concentration was 15.9 mg/L at 1-m depths and 12.6 mg/L at near-bottom depths over the time period between April to October. Spatial variation was about the same for both horizontal and vertical scales. Horizontal gradients from the inner to central bay (Station BI-5 values subtracted from Station BC-3 values) during low tide ranged from 0.4 to 7.6 mg/L at 1-m depths and from -0.3 to 6.4 mg/L at near-bottom depths. Vertical D.O. gradients (near-bottom values subtracted from 1-m values) during low tide ranged from 1.6 to 9.0 mg/L in the inner bay (Station BI-5) and from -0.3 to 6.4 mg/L in the central bay (Station BC-3) with the lowest gradients observed on 28 May and the highest observed on 15 May. Dissolved oxygen variation due to the tides (low tide values subtracted from high tide values) was the smallest, with differences of approximately 1 mg/L.

Nutrients

Nutrient limitation of phytoplankton growth has been found to vary widely with species, and has not been extensively studied in local waters. Thus, it is not possible to link the existence of nutrient limitation in the field with a particular nutrient concentration. Nonetheless, decreasing concentrations of nutrients with time indicate where phytoplankton uptake has exceeded nutrient supply and regeneration. Nutrient concentrations below reporting limits (0.01 mg/L; Table 4; Ecology, 1994) indicate where this draw down has occurred.

Surface and near-bottom dissolved nutrient concentrations at select stations during (mostly) low slack tide are presented in Figures 23, 24, and 25. In general, surface nitrite+nitrate-N, ammonium-N and orthophosphate-P concentrations were higher at the inner bay stations than at the central and outer bay stations during low slack tide (Figures 23a, 24a, and 25a). Surface nutrient fluctuations with time were similar among the central and outer bay stations (BB-2, BC-3 and BE-2), but varied among stations in the inner bay, likely due to variable inputs. Station BI-4, located near the LOTT outfall (Figure 1), generally displayed much higher surface nutrient levels than all other stations, particularly for ammonium-N. Station BA-2 located at the border of the inner and central bay (termed inner/central bay), displayed nutrient concentration changes similar to either inner or central and outer bay stations depending on the survey. Surface nutrients from the cross bay transect stations which were collected during ebb tides on the first three surveys only, showed little variability from east to west across the bay.

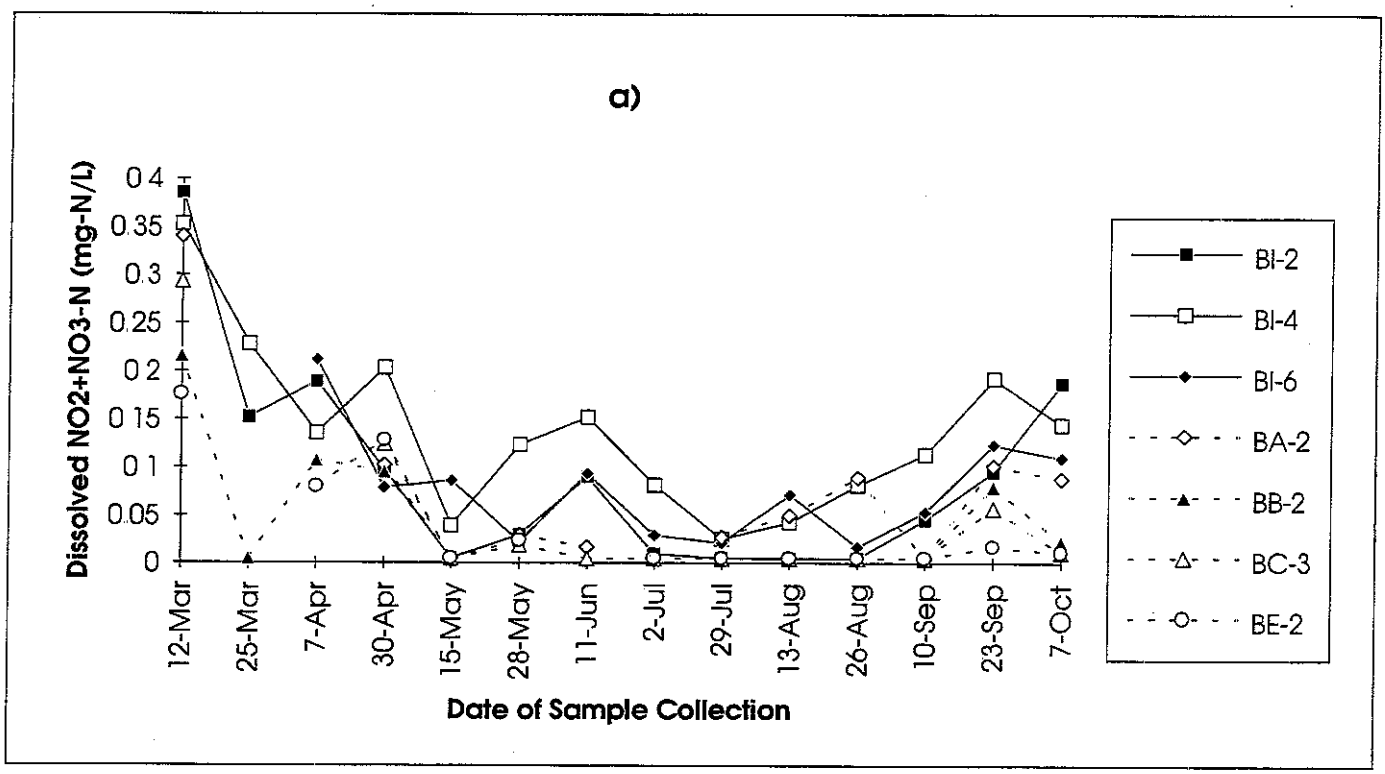
The seasonal fluctuation of surface ammonium-N was similar to that of orthophosphate-P at both the inner bay stations and the central and outer bay stations. Surface nitrite+nitrate-N concentrations fluctuated independently from surface ammonium-N and orthophosphate-P concentrations. These differences were likely due to biological influences, for example, variable phytoplankton uptake rates and microbial processes. In addition, the concentration of nitrite+nitrate-N in LOTT effluent was much lower than that of ammonium-N and usually somewhat lower than that of orthophosphate-P (City of Olympia, 1992; Figure 26).

Overall, the seasonal fluctuations in the near-bottom concentration of a particular nutrient were consistent at all stations throughout the inlet. However, the near-bottom concentrations of nitrite+nitrate-N tended to be lower, and of ammonium-N and orthophosphate-P tended to be higher in the inner bay (Station BI-4) (Figures 23b, 24b, and 25b).

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

Surface

At all stations, surface nitrite+nitrate-N concentrations were highest during the 12 March survey (Figure 23a). At central and outer bay stations (except for BA-2), surface nitrite+nitrate-N concentrations below the reporting limit (<0.01 mg/L) were observed during mid-May and from mid-June through mid-September. In the inner bay, concentrations of surface nitrite+nitrate-N below the reporting limit were observed during mid-May and from the end of July through the end of August at East Bay Station BI-2. Below reporting limit concentrations were not observed at West Bay Station BI-4, which is near the LOTT outfall (Figure 23a). Surface nitrite+nitrate-N concentrations showed similar fluctuation patterns at Stations BI-4, BI-2 and BI-6 (somewhat), although concentrations were typically 0.05 to 0.10 mg/L higher at Station BI-4.



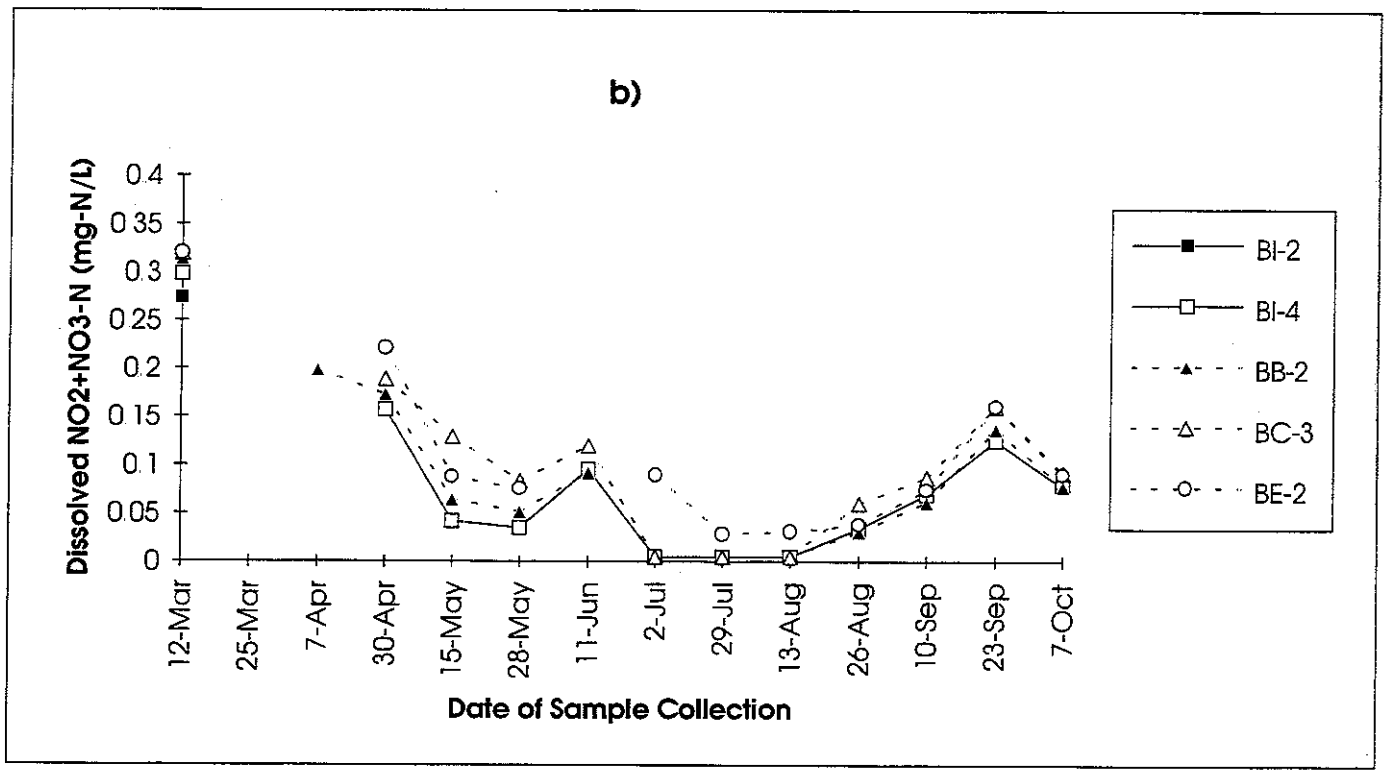


Figure 23 Concentrations of dissolved nitrite+nitrate-N (NO2+NO3-N) for a) surface and b) near-bottom depths in Budd Inlet during 1992 Inner bay stations represented with a solid line. Central and outer bay stations represented with a dashed line Data collected at low tide, except first 3 surveys at ebb tide

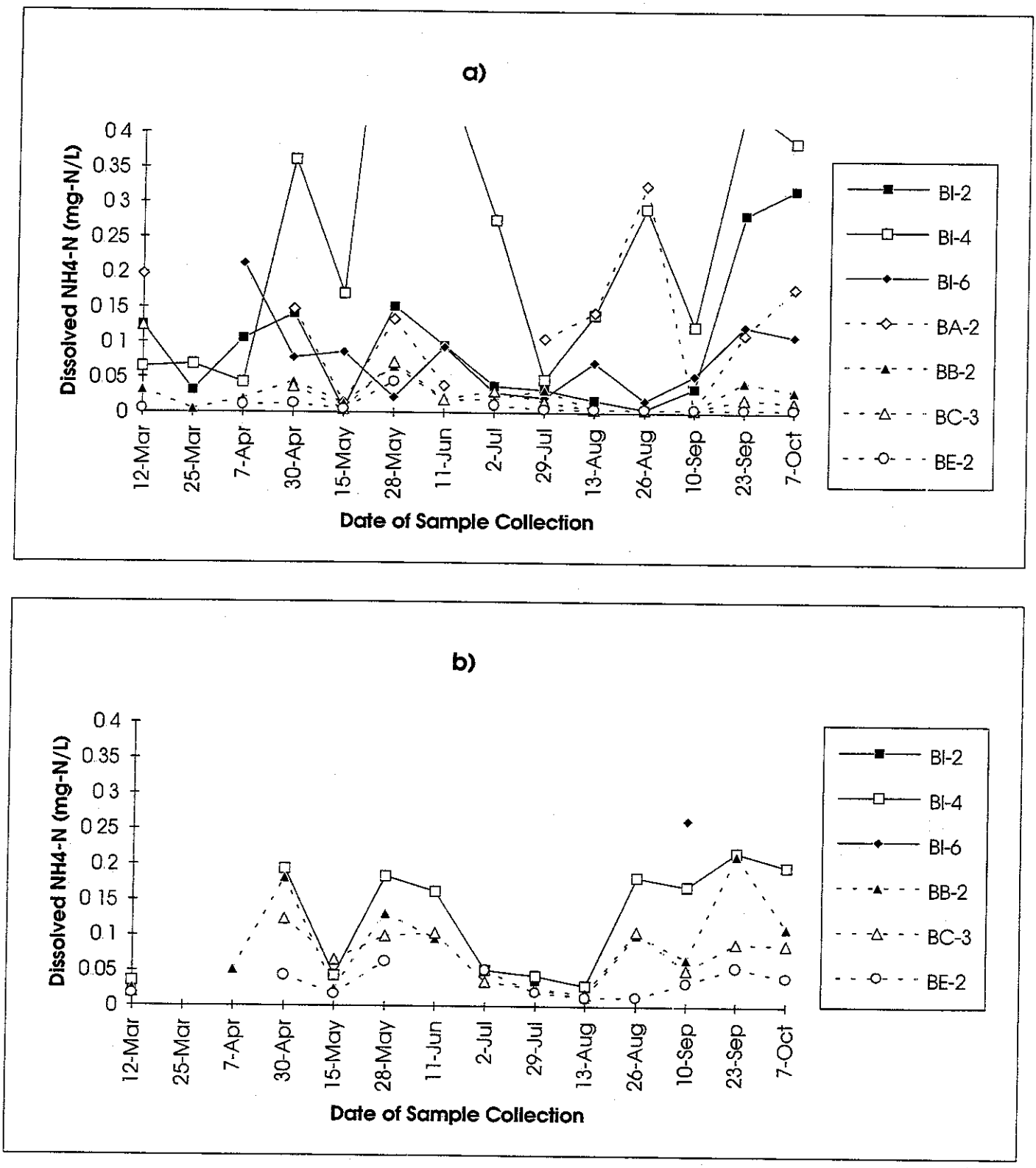


Figure 24. Concentrations of dissolved ammonium-N (NH4-N) for a) surface and b) near-bottom depths in Budd Inlet during 1992. Inner bay stations represented with a solid line. Central and outer bay stations represented with a dashed line. Data collected at low tide, except first 3 surveys at ebb tide

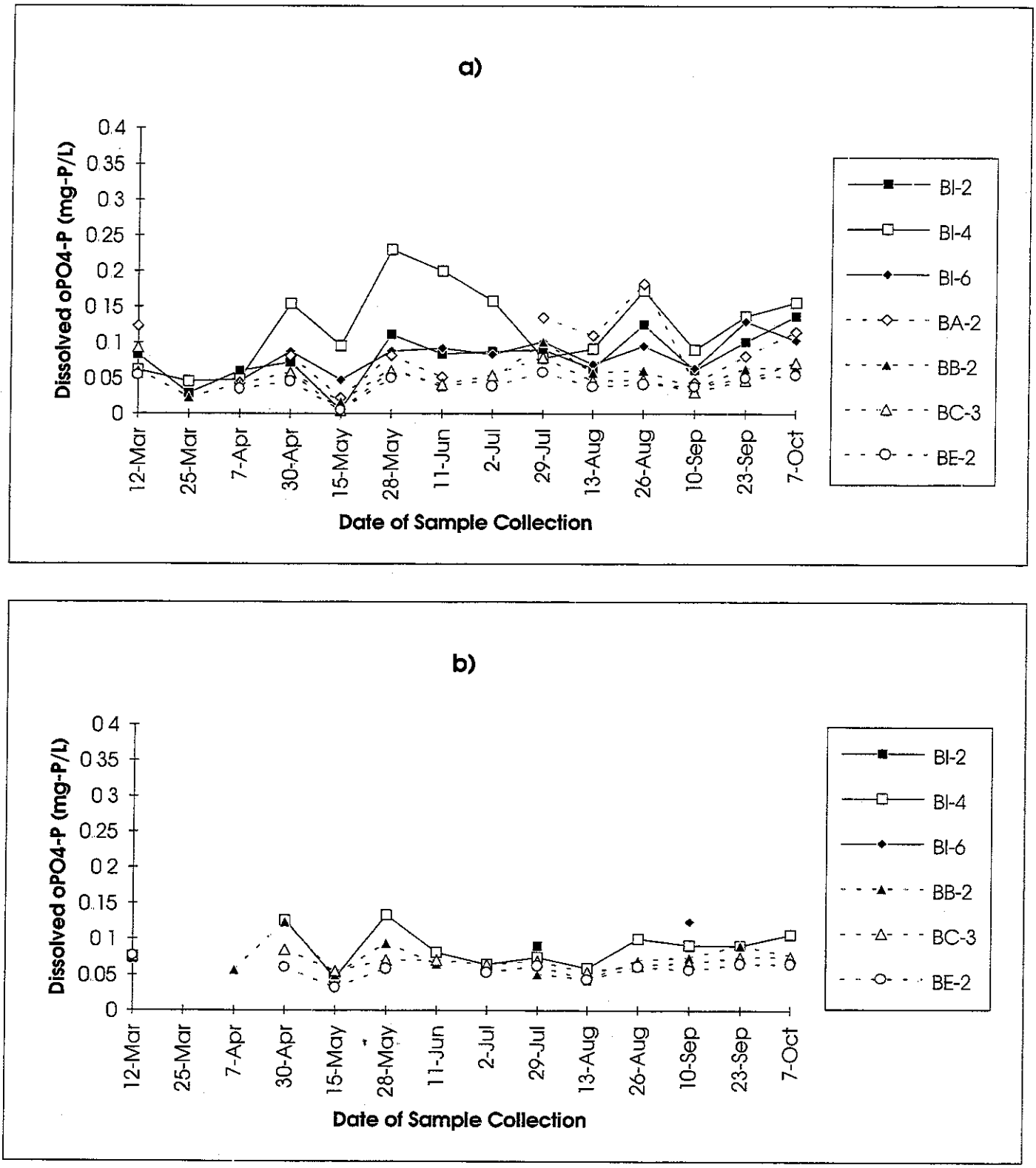


Figure 25 Concentrations of dissolved orthophosphate-P (oPO4-P) for a) surface and b) near-bottom depths in Budd Inlet during 1992 Inner bay stations represented with a solid line. Central and outer bay stations represented with a dashed line Data collected at low tide, except first 3 surveys at ebb tide.

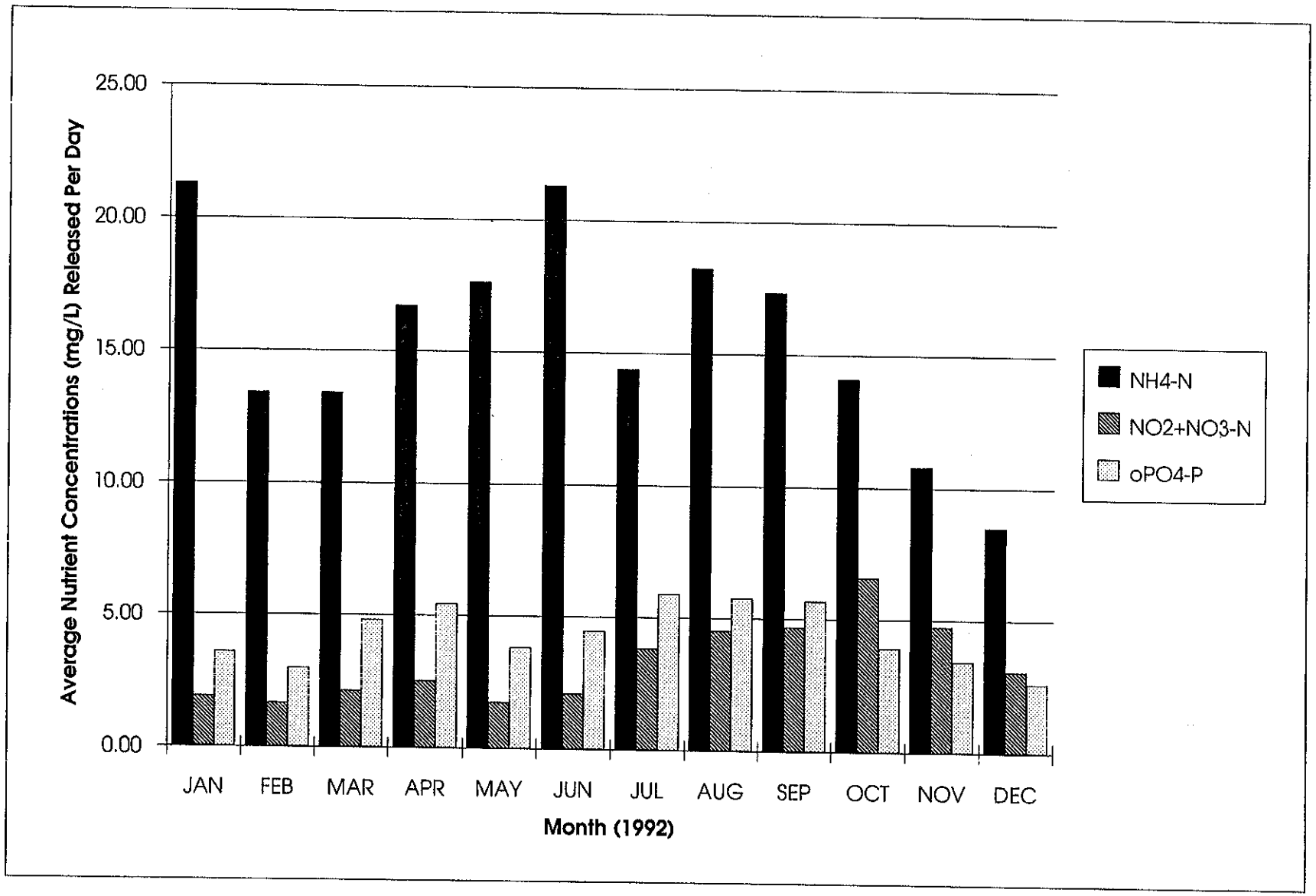


Figure 26. LOTT (Lacey, Olympia, Tumwater, Thurston County) Waste Water Treatment Plant final effluent: monthly averages of nutrients released per day during 1992. From the City of Olympia, Dept. of Public Works, Final Effluent, Yearly Report.

Near-Bottom

At the central and outer bay stations, near-bottom nitrite+nitrate-N had a seasonal fluctuation pattern somewhat similar to surface nitrite+nitrate-N. However, near-bottom nitrite+nitrate-N concentrations were not below reporting limit for as long a duration as surface nitrite+nitrate-N concentrations (Figure 23). Near-bottom nitrite+nitrate-N concentrations in the inner bay showed the same seasonal fluctuations as in the central and outer bay. At West Bay Station BI-4, near-bottom nitrite+nitrate-N concentrations were below reporting limit from early July through mid-August (Figure 23b). Therefore, below reporting limit concentrations of nitrite+nitrate-N at Station BI-4 were observed more often at near-bottom depths than at the surface, reflecting a surface input of nitrite+nitrate-N at Station BI-4. This is the opposite of that observed at the central and outer bay stations where below reporting limit concentrations of nitrite+nitrate-N were observed more frequently at the surface than at near-bottom depths (Figure 23).

Ammonium-N (NH_4-N)

Surface

At the central and outer bay stations (except for BA-2), surface ammonium-N concentrations were fairly low during the entire sampling season. Concentrations below reporting limits were observed at one or more central or outer bay stations during March, mid-May, and late July through early October (Figure 24a). In contrast, at West Bay Station BI-4, extremely high surface ammonium-N concentrations (0.139 to 0.844 mg/L) were observed from late April through early October (excluding the 29 July survey). Concentrations below reporting limits were never observed at Station BI-4 during any of the seasonal surveys (Figure 24a). Station BA-2 and often Station BI-2 showed seasonal fluctuations similar to Station BI-4, although ammonium-N concentrations were typically 0.10 to 0.20 mg/L higher at Station BI-4 (Figure 24a). Surface ammonium-N concentrations at Station BI-6 showed slightly different fluctuation patterns (particularly during spring) than other inner bay stations, likely due to its proximity to the Deschutes River/Capitol Lake outlet. Overall, inner bay surface ammonium-N concentrations were much higher than surface nitrite+nitrate-N concentrations (Figures 23a and 24a), which is the reverse of what is typically expected in ambient marine waters (away from nutrient inputs).

Near-bottom

For all stations, periods of below reporting limit concentrations of both near-bottom ammonium-N and near-bottom nitrite+nitrate-N corresponded with each other, for the most part (Figures 23b and 24b). Central, outer, and inner bay stations had the same general near-bottom ammonium-N fluctuations although concentrations were usually higher at the inner bay stations (Figure 24b).

Orthophosphate-P (oPO_4-P)

Surface

At central and outer bay stations (except for BA-2), observed surface orthophosphate-P concentrations were fairly consistent throughout the season. Surface concentrations below reporting limit were observed only during mid-May (Figure 25a). For all the inner bay stations, surface orthophosphate-P concentrations fluctuated at the same time as surface ammonium-N, however, the magnitude of the fluctuations were smaller for orthophosphate-P than for ammonium-N (Figures 24a and 25a). The highest surface orthophosphate-P concentrations were observed at Station BI-4 (Figure 25). Surface orthophosphate-P concentrations were below reporting limits in the inner bay only at Station BI-2 during mid-May.

Near-Bottom

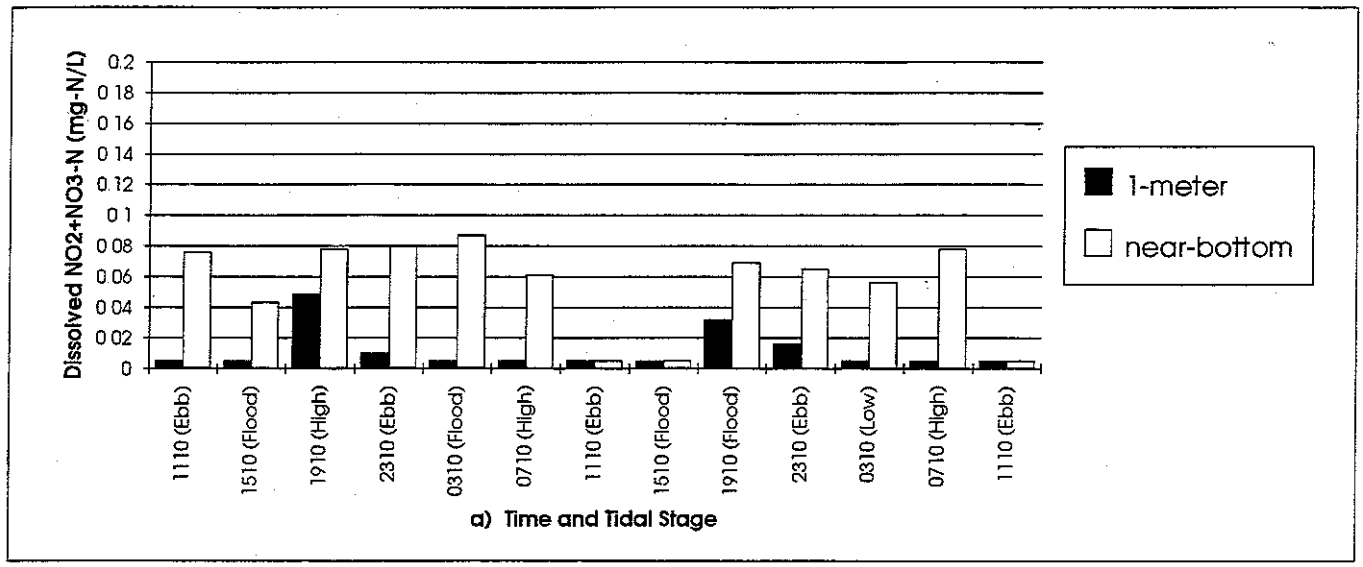
At central and outer bay stations near-bottom orthophosphate-P concentrations were similar to surface orthophosphate-P concentrations, with the near-bottom concentrations slightly higher (Figure 25). As with near-bottom ammonium-N, central, outer, and inner bay stations had the same general near-bottom orthophosphate-P fluctuations although concentrations were usually higher at the inner bay stations. (Figure 25).

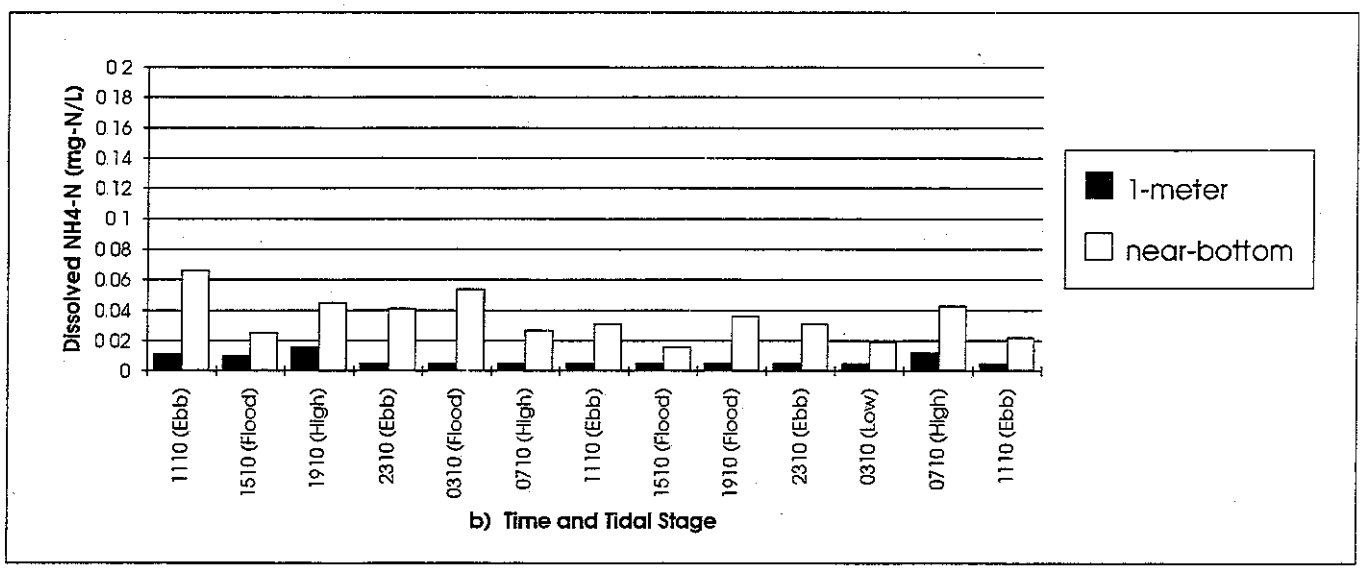
Tidal Cycle Survey Fluctuations

Different nutrient dynamics were seen for the two stations (BD-2 in the central bay and BA-2 in the inner/central bay) sampled during the mid-July tidal cycle survey.

Central Bay (Station BD-2)

At Station BD-2, surface nitrite+nitrate-N concentrations were below reporting limit during the entire survey except at 1910 on 15 July during high tide and at 1910 and 2310 on 16 July during flood and ebb tides, respectively (Figure 27a). Near-bottom nitrite+nitrate-N concentrations were generally higher than surface concentrations and were observed below reporting limit only on three occasions (Figure 27a). Surface ammonium-N concentrations at Station BD-2 remained below reporting limit during all but four samplings when concentrations were only slightly above the reporting limit (0.010 to 0.016 mg/L; Figure 27b). Near-bottom ammonium-N concentrations were somewhat higher than surface ammonium-N concentrations with values above reporting limit measured during all samplings (Figure 27b). Surface and near-bottom orthophosphate-P concentrations fluctuated very little. Near-bottom orthophosphate-P concentrations were always slightly higher than those on the surface (Figure 27c); however, observed concentrations for both surface and near-bottom depths were well above reporting limits throughout the tidal cycle survey. Overall, nutrient fluctuations did not show obvious tidal stage relationships at Station BD-2, however a longer survey is needed to identify statistically significant trends.





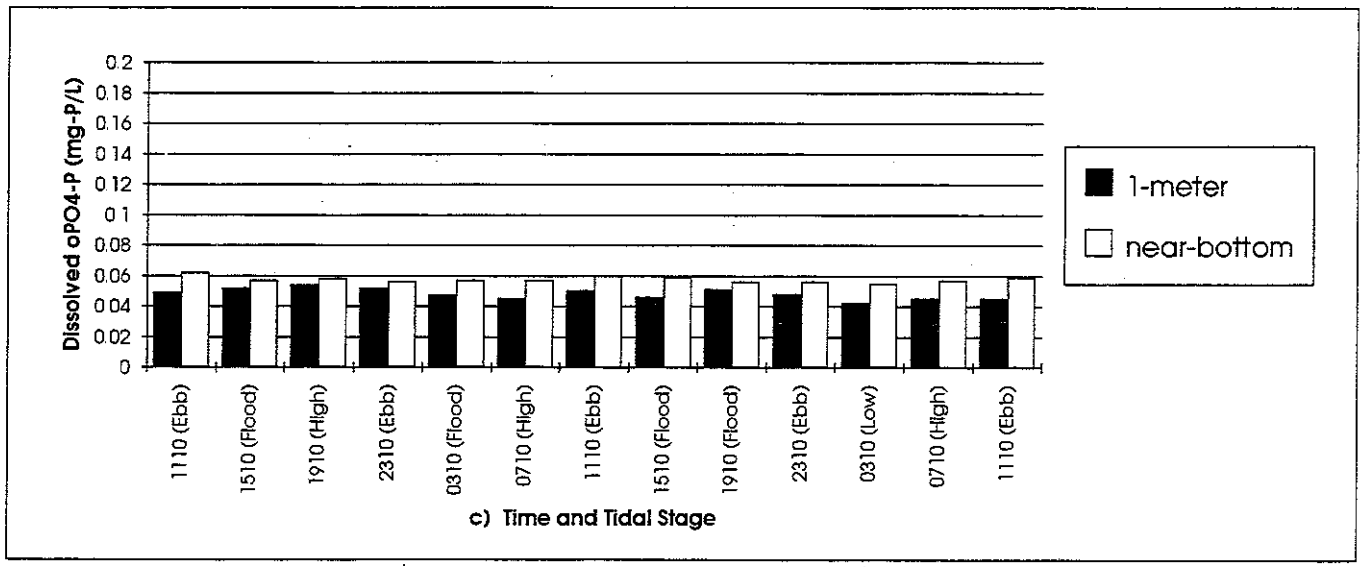


Figure 27. Central bay Station BD-2: a) NO2+NO3-N, b) NH4-N, and c) oPO4-P concentrations during the tidal cycle survey on 15-17 July 1992 in Budd Inlet.

Inner/Central Bay (Station BA-2)

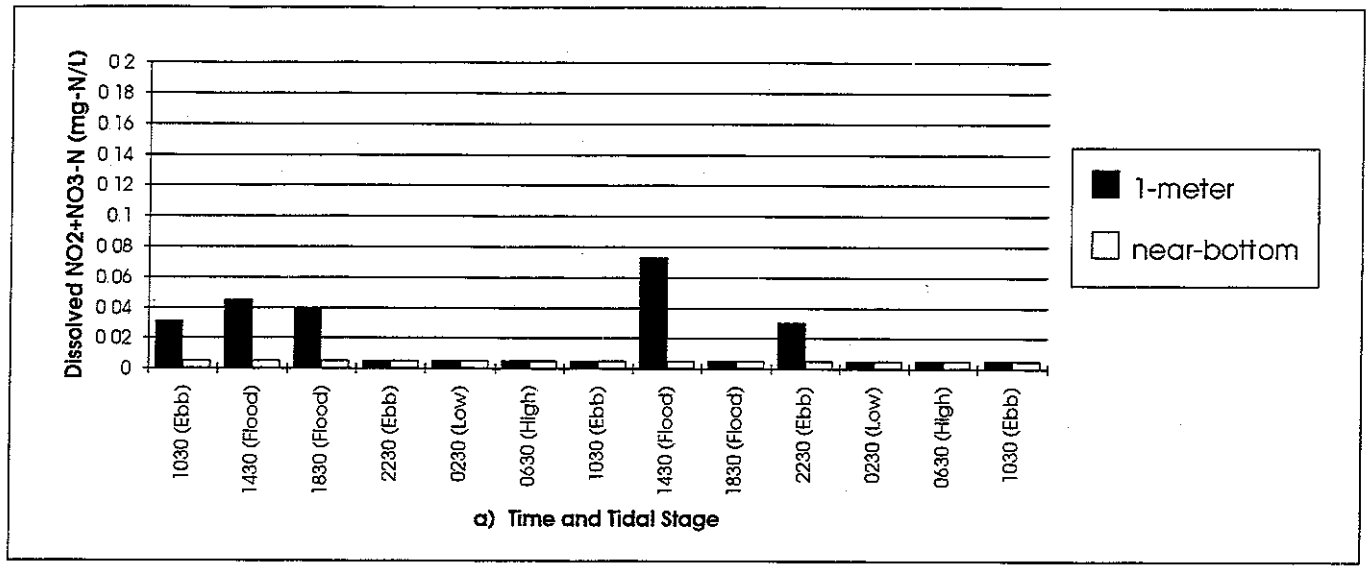
At Station BA-2, surface nitrite+nitrate-N, ammonium-N and orthophosphate-P showed large fluctuations (Figure 28), most likely due to inputs from LOTT and the Deschutes River/Capitol Lake outlet. Near-bottom nitrite+nitrate-N concentrations remained below reporting limit at Station BA-2 during the entire tidal cycle survey (Figure 28a). Near-bottom ammonium-N and orthophosphate-P fluctuated somewhat during the survey with ammonium-N fluctuating slightly more than orthophosphate-P (Figure 28b and c). Near-bottom ammonium-N and orthophosphate-P concentrations were not measured below reporting limit during the tidal cycle survey. As with Station BD-2, nutrient fluctuations did not vary directly with tidal cycle fluctuations at Station BA-2.

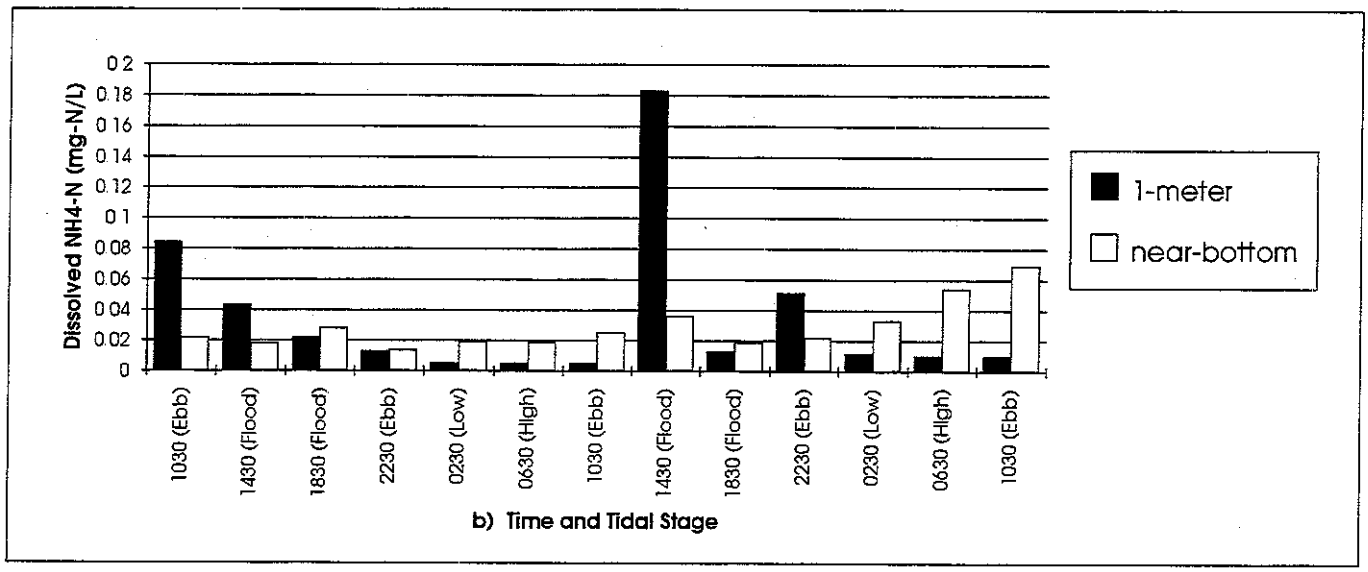
Comparisons Between Stations BD-2 and BA-2

At Station BD-2, in the central bay, nutrient concentrations were lower in the surface than near-bottom, whereas the opposite was found for Station BA-2, in the inner/central bay. Because nutrients are typically utilized in the surface, following phytoplankton growth, this reverse pattern found at Station BA-2 indicates a nutrient supply within the surface waters, likely from Lott and/or the Deschutes River/Capitol Lake outlet. This pattern was also observed in the bi-weekly data when central and outer bay stations were compared to West Bay Station BI-4 (Figures 23, 24, and 25).

Phytoplankton Concentration and Distribution

A summary table of the chlorophyll *a*, transmissometer and D.O. data used to indicate phytoplankton concentration and distribution during the 1992 seasonal surveys in Budd Inlet is located in Appendix B. A phytoplankton "bloom" signifies a population that is actively growing and thus large. Chlorophyll *a* concentrations greater than 10 μg/L (mg/m^3) are defined in this report as blooms. According to the seasonal data, phytoplankton blooms occurred baywide throughout the growing season (March through October 1992), with maximum concentrations in the central and occasionally inner bays. The first observed bloom of the season was on 25 March. The last observed bloom of the season was on 7 October. In the central bay, flood tide fluorometer data indicated chlorophyll *a* concentrations were highest at stations on the east side of the bay. Overall, chlorophyll *a* concentrations were highest in the central bay and covered a larger horizontal and vertical area than in the inner bay. Fluorometric data from the tidal cycle survey (15-17 July) indicate that phytoplankton vertical migration likely occurred at central bay Station BD-2 and to a lesser degree at inner/central bay Station BA-2.





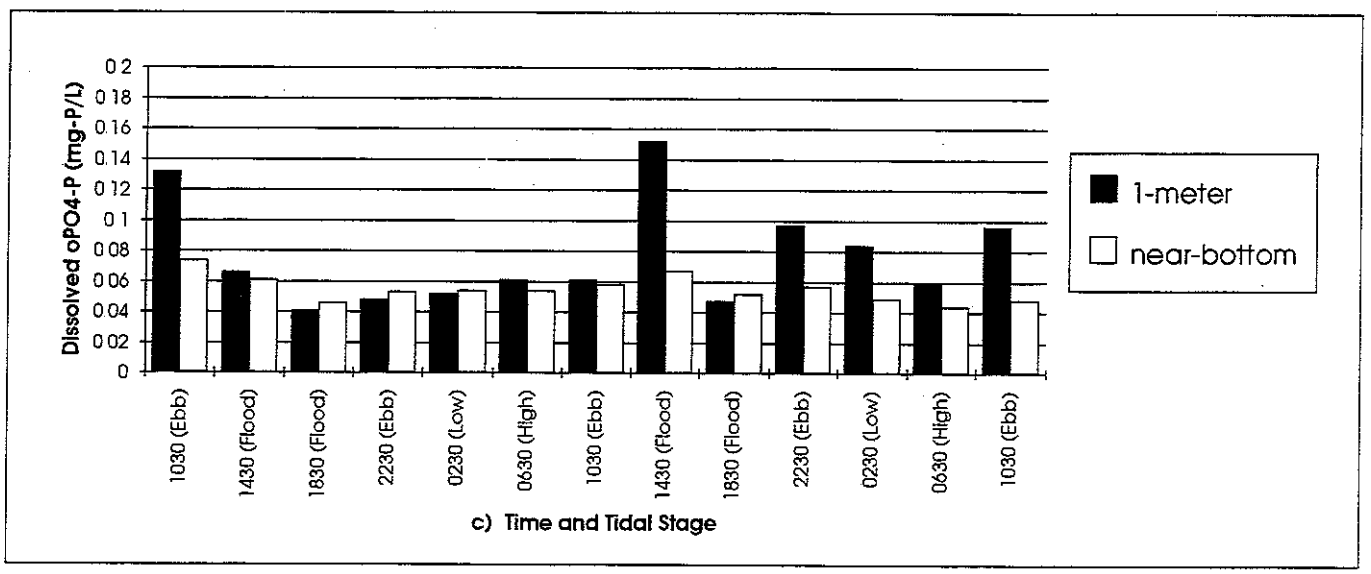


Figure 28 Inner/central bay Station BA-2: a) NO2+NO3-N, b) NH4-N, and c) oPO4-P concentrations during the tidal cycle survey on 15-17 July 1992 in Budd Inlet.

Horizontal Distribution

Baywide Distribution During Flood and High Tides

During flood and high tides the maximum chlorophyll *a* concentrations were frequently in the central bay close to the east side between transects BA and BC (Figure 29). Chlorophyll *a* concentrations were lowest at central bay stations close to the west side of the inlet (BC-4 and BD-3), and at the outer bay stations (transects BE and BF). Inner bay chlorophyll *a* concentrations were usually equal to or lower than central bay concentrations and higher than outer bay concentrations.

Longitudinal Distribution During Low Tide

During low tide, maximum chlorophyll *a* concentrations were observed in the central bay generally at Stations BB-2 and BC-3 (Figure 30). Phytoplankton blooms were somewhat smaller in size and generally had lower peak concentrations at inner bay stations than at central bay stations (Figure 31). Exceptions to this pattern occurred on 15 May and 10 September.

Phytoplankton distributions were influenced by tidal action. The high phytoplankton concentrations seen in the central bay appear to have been advected into the inner bay during flood tides. Transmissometer contour plots from the 11 June survey indicate that the phytoplankton concentration maximum, as shown by low transmissometer values, extended further into the inner bay at flood and high tides than at low tides (Figure 32).

Vertical Distribution (Depth of Bloom)

Seasonal data summarized in Appendix B show the maximum concentration of phytoplankton was typically located deeper in the water column during high tide than during low tide. At low tide, inner bay phytoplankton concentration maxima were generally just below the surface layer (1.5 to 2.5-m depths) during March through mid-July and about 1-2 m deeper (2.5 to 4.5-m depths) from the end of July through September. Central and outer bay maxima were generally near the surface (0.5 to 2-m depths) during March through June, and then deeper in the water column (2 to 6-m depths) from July through mid-September. Overall, central and outer bay blooms tended to be located at shallower depths than inner bay blooms during the spring and early summer, and at deeper depths than the inner bay blooms during the mid-summer to early fall. Large blooms in the inner bay were not evidenced in the top 0.5-m of the water column, likely due to the freshwater surface runoff present at these stations. The vertical extent of phytoplankton blooms was deeper in the central and outer bay than in the inner bay, possibly due to deeper euphotic zone depths in the central and outer bay than in the inner bay (Figure 14).

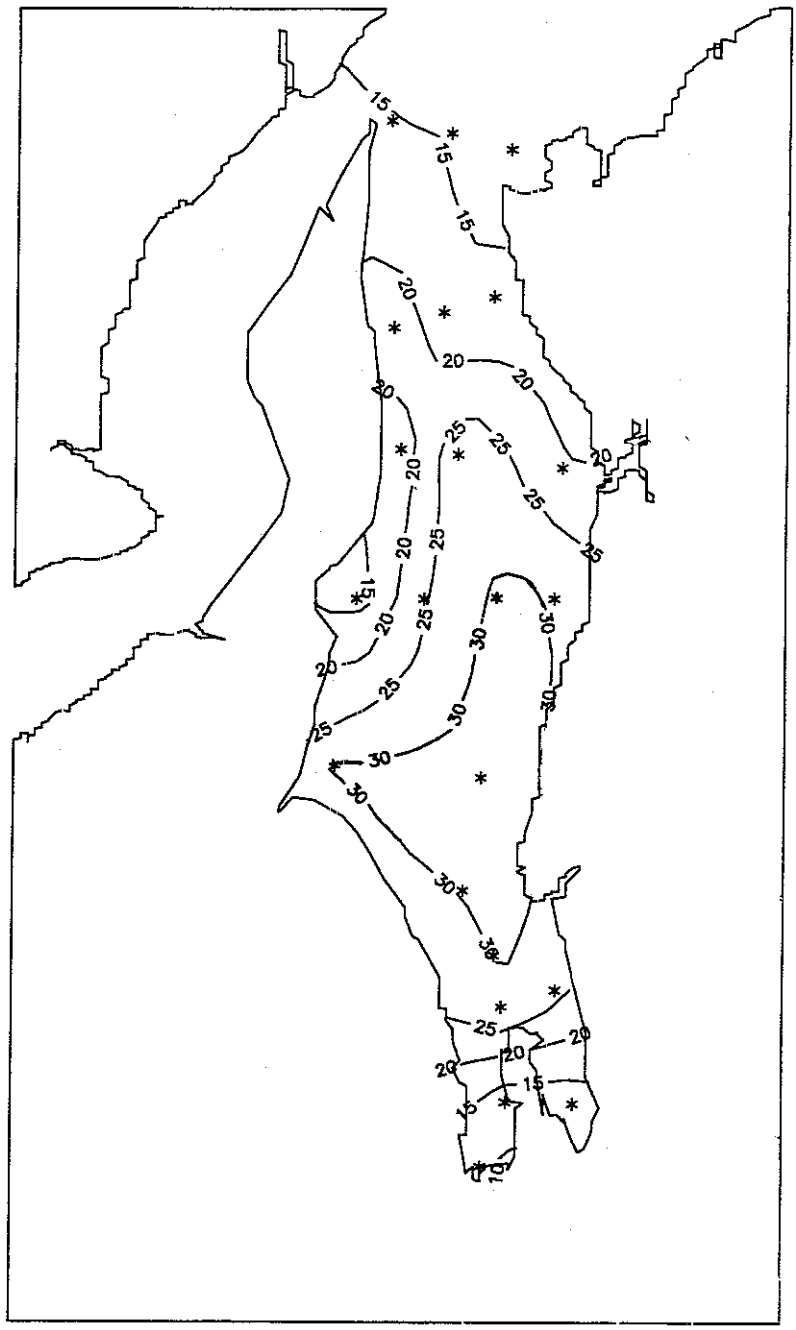


Figure 29. *In situ* fluorometer measurements of chlorophyll *a* (mg/m^3) in Budd Inlet on 26 August 1992 at 4 m depth during flood tide (central and outer bay) and high tide (inner bay). Fluorometer maximum = 30 mg/m^3.

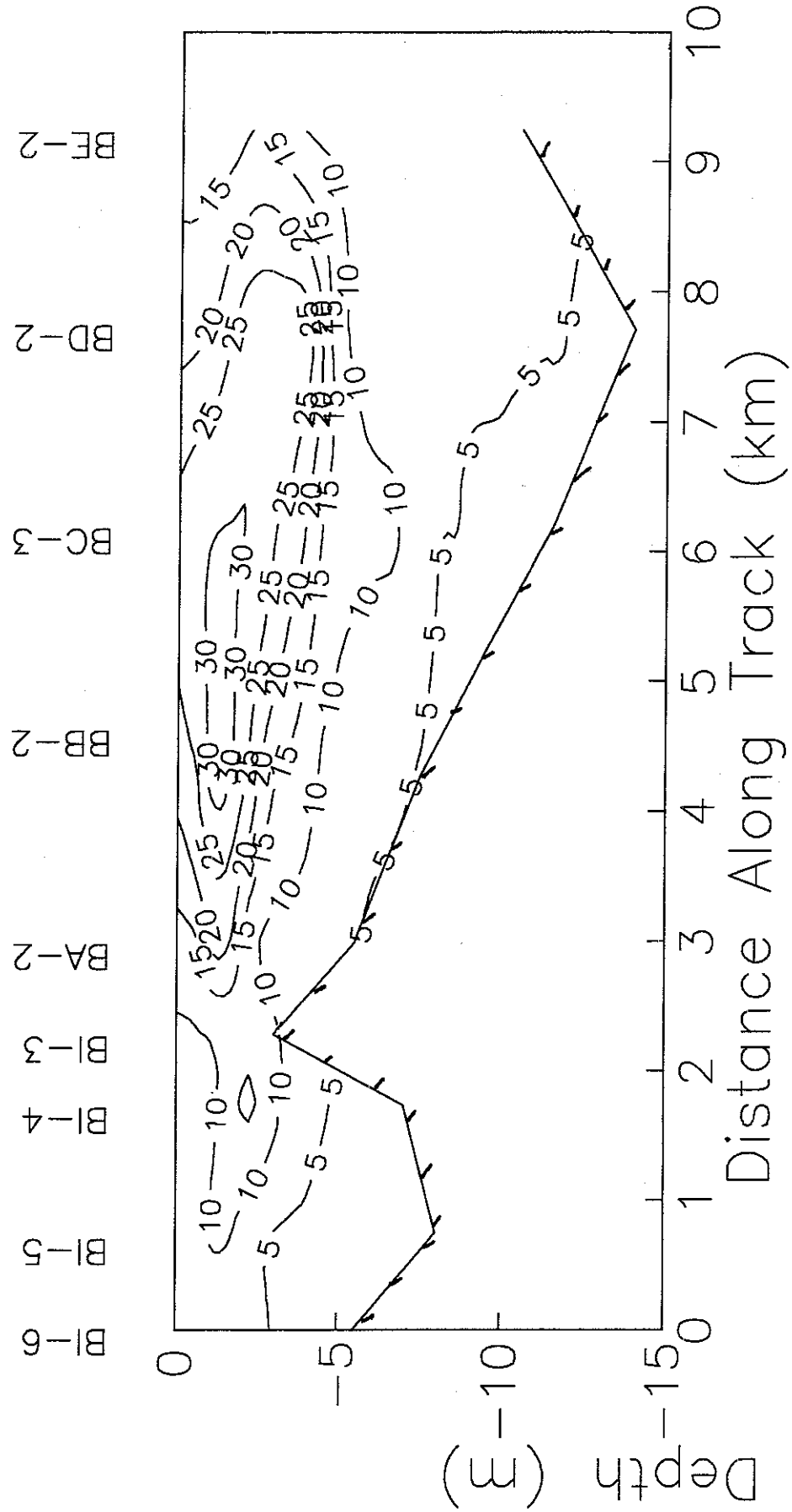


Figure 30. Vertical contour plot of *in situ* fluorometer measurements of chlorophyll *a* (mg/m^3) from Station BI-6 out to Station BE-2 in Budd Inlet on 23 September 1992 during low tide. ⌇⌇⌇ indicates bottom contour.

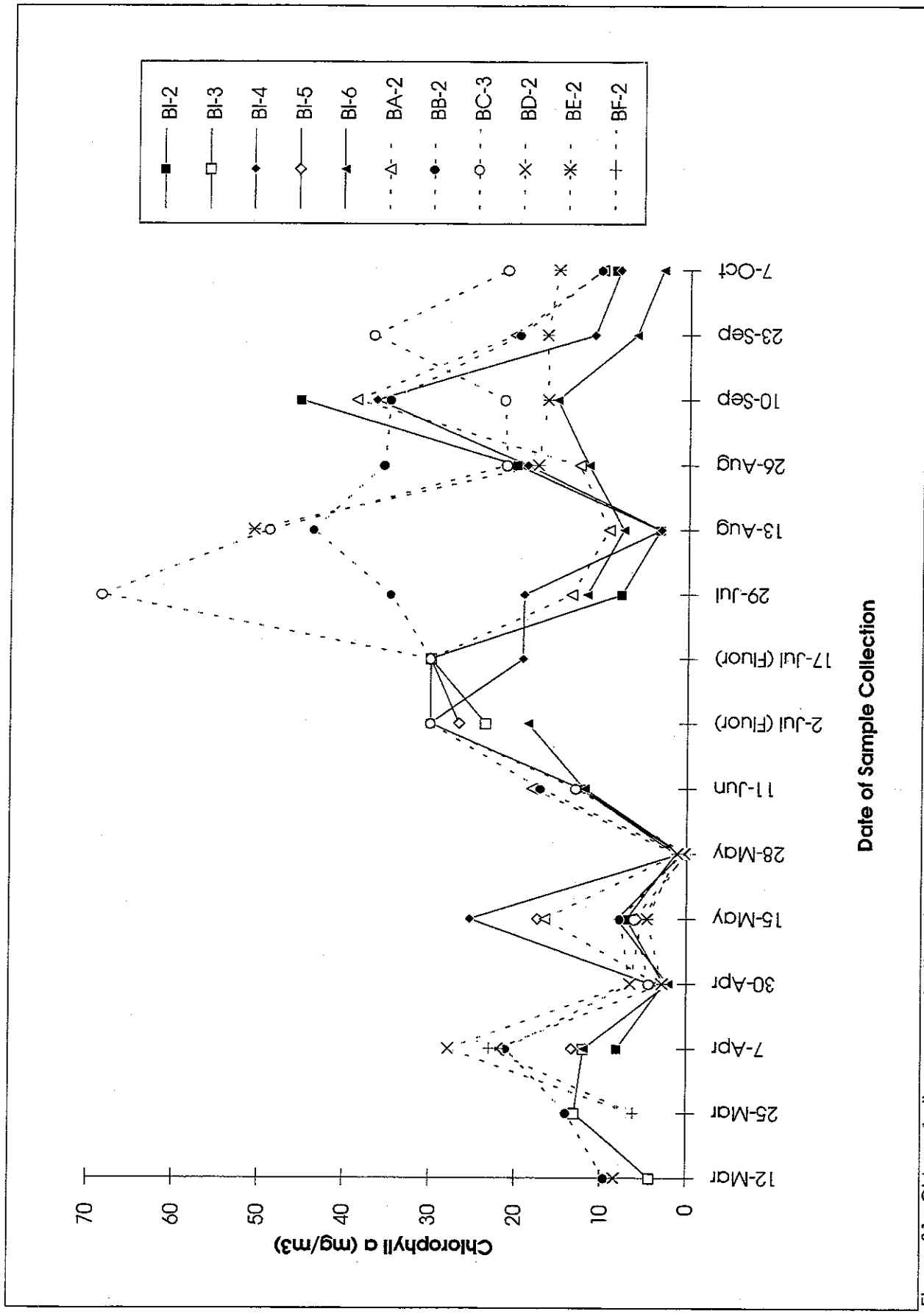


Figure 31. Chlorophyll a concentrations from discrete lab analyses of samples collected in Budd Inlet during 1992. Low tide samples, except first 3 surveys which were at ebb tide. In situ fluorometer results replace lab results for 2-17 July (fluorometer max = 30 mg/m3). Solid line = inner bay. Dashed line = central and outer bay.

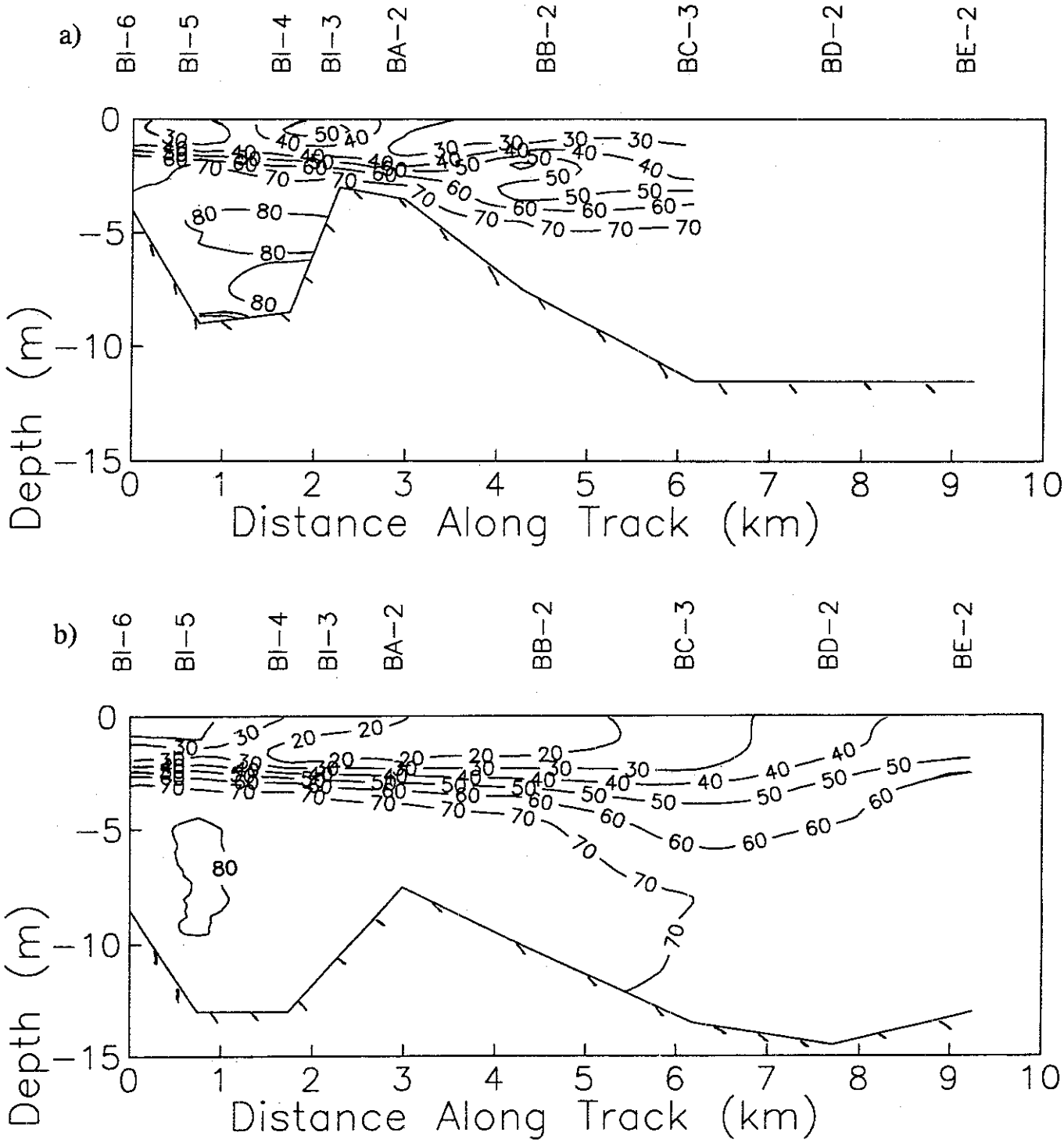


Figure 32. Transmissometer (% light transmission per 25 cm path length) vertical contour plots for Station BI-6 out to Station BC-3 or BE-2 in Budd Inlet on 11 June 1992 during a) low tide (no data included for Stations BD-2 and BE-2) and b) flood tide (central and outer bay) and high tide (inner bay) (no data included for Station BI-3). ⌐¬⌐¬ indicates bottom contour.

Timing of Phytoplankton Blooms

Phytoplankton blooms, where chlorophyll *a* concentrations exceeded 10 mg/m^3, were evident during all surveys except for 12 March, 30 April, 28 May, and 21 October (Figure 31). The highest laboratory chlorophyll *a* concentrations (36 to 45 mg/m^3) for inner bay stations were measured on 10 September. The highest laboratory chlorophyll *a* concentrations (35 to 68 mg/m^3) for central and outer bay stations were measured on 29 July and 13 August. The lowest laboratory chlorophyll *a* concentrations (0.1 to 1.3 mg/m^3) for central, outer, and inner bay stations were recorded on 28 May. Average daily wind speeds of 16 km/h (10 mph) were observed on 18 to 20 May and 25 to 26 May (Olympia Airport National Weather Service data), and likely produced vertical mixing of the water and a decrease in phytoplankton growth. Generally, the highest chlorophyll *a* concentrations in Budd Inlet were observed during the summer and early fall. However, this trend may be biased because samples were collected at 1 m prior to July and at depths of maximum chlorophyll *a* concentrations from July through October.

The seasonal fluctuation in chlorophyll *a* during low tide showed a similar pattern for all inner bay stations except for Station BI-6, where chlorophyll *a* was occasionally somewhat lower (5 to 30 mg/m^3 lower) than at the other inner bay stations, particularly towards the end of the season (Figure 31). Chlorophyll *a* fluctuations in the outer bay had generally the same seasonal pattern as those in the central bay; although, outer bay concentrations were typically lower with higher variability in July-October (Figure 31).

Tidal Cycle Survey Vertical Migration

In the tidal cycle survey, *in situ* fluorometer profiles were obtained during a 52-h period at three stations (BD-2, BA-2 and BI-5) on 15-17 July 1992. Fluorometer data from only low slack tides were evaluated in order to minimize advection effects and more easily assess possible phytoplankton vertical migration caused by diel changes. Lower-low tides occurred during mid-day while higher-low tides occurred in the middle of the night (Figure 2).

Central Bay (Station BD-2)

Low tide fluorometer data at Station BD-2 on 15 and 16 July indicated that chlorophyll *a* maxima were at shallower depths during the day (3 to 5 m) than during the night (7 to 9 m) (Figure 33a, b, and c). Fluorometer data from 17 July (Figure 33d and e) showed the same general patterns; however, the chlorophyll *a* maxima had a broader depth distribution than shown in the 15 and 16 July data. The chlorophyll *a* distribution was split during the nighttime collection on 17 July, which may indicate patchiness, or the presence of two separate phytoplankton populations (Figure 33d).

Inner/Central Bay (Station BA-2)

Low tide fluorometer data for Station BA-2 indicated a more complex distribution than was observed at Station BD-2. The peak phytoplankton concentration was located at 2 to 4 m during mid-day (Figure 34a, c, and e), then split into two distinct depth maxima at night, with peaks occurring at 1 to 2 m and at approximately 4 to 6 m (Figure 34b and d). This may indicate that two populations of phytoplankton were located at the same depth during mid-day, with one migrating to the bottom and one migrating closer to the surface during the night. It is also possible that phytoplankton may have advected in from elsewhere in the bay in the surface and/or near-bottom waters.

Inner Bay (Station BI-5)

Low tide fluorometer data for Station BI-5 gave no indication of phytoplankton vertical migration at this site. The peak phytoplankton concentration depth was between 1 and 2 m for all low tide mid-day and nighttime observations (Figures 35a-e). Maximum chlorophyll *a* concentrations at Station BI-5 were lower and had a narrower depth distribution than at Stations BD-2 and BA-2.

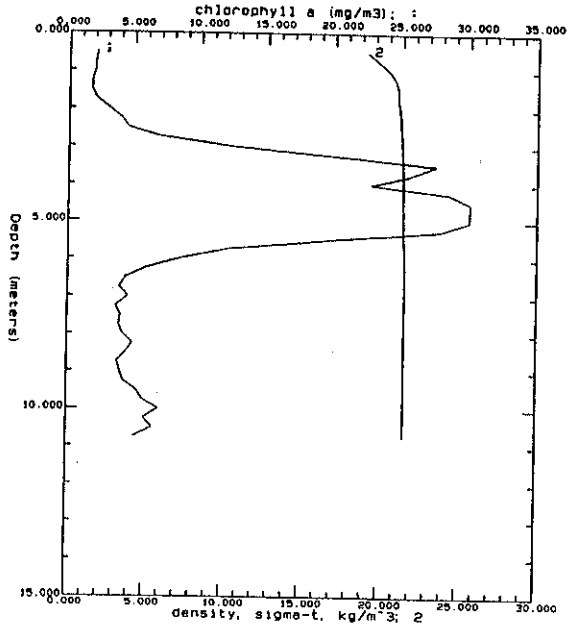
Vertical Migration vs. Physical Advection

In summary, chlorophyll *a* maxima were located at greater depths during the night than during the day at Stations BD-2 (central bay) and BA-2 (central/inner bay) but not at Station BI-5 (inner bay). The diel differences seen at Stations BD-2 and BA-2 could be due to phytoplankton vertical migration and/or to physical advection. No indication of water mass layering due to density differences was seen (Figures 33 and 34), indicating that the layering of chlorophyll *a* at Stations BD-2 and BA-2 was not dominated by physical effects. Alternatively, microscopic observation of a phytoplankton sample collected at Station BA-2 showed the presence of a dinoflagellate species known to migrate vertically (see Phytoplankton Species section), indicating that the vertical migration of phytoplankton are likely responsible for the observed diel changes in the depths of the fluorometric maxima.

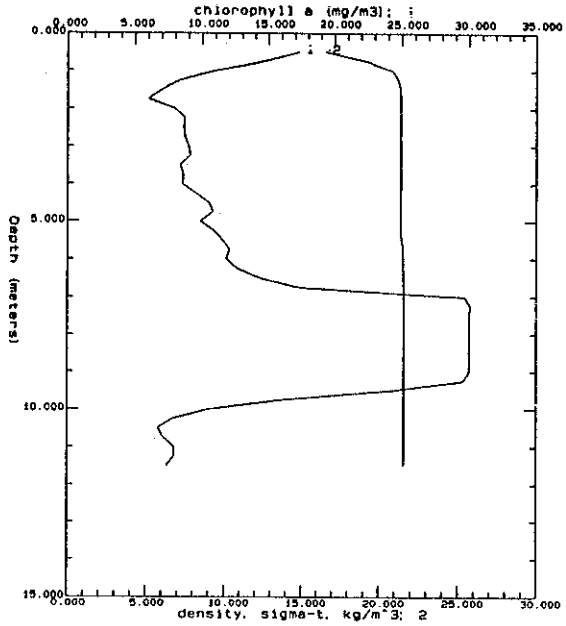
Phytoplankton Species

Diatoms vs. Dinoflagellates

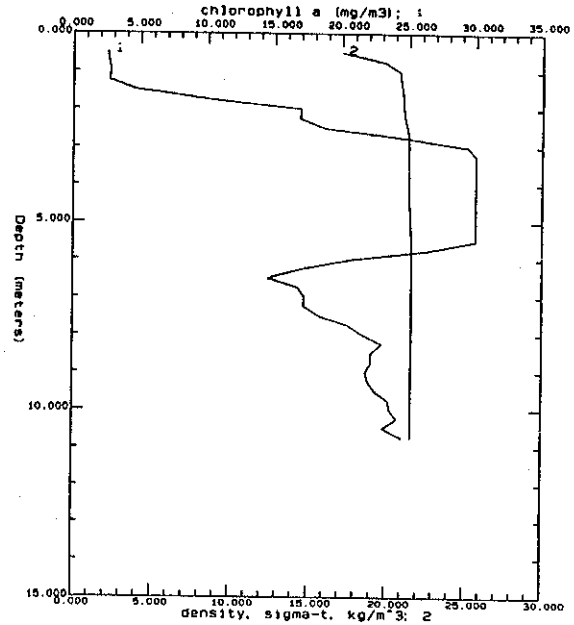
Total diatom, dinoflagellate, and phytoplankton concentrations at the monthly central Budd Inlet Station (BUD005) and at an inner Budd Inlet station (primarily BI-4) are shown in Figure 36 (note log scale). At both locations, diatoms predominated over dinoflagellates from March through mid-June and from late August or mid-September through October. Dinoflagellates predominated over diatoms from early July through mid-August at Station BUD005 and from early to late July at the inner bay station.



a) 1310 (Day) on 15-Jul-92: Low Low Tide

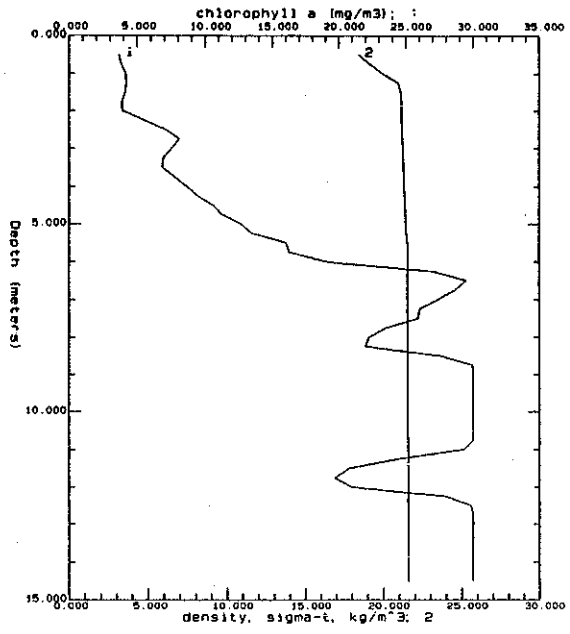


b) 0110 (Night) on 16-Jul-92: High Low Tide

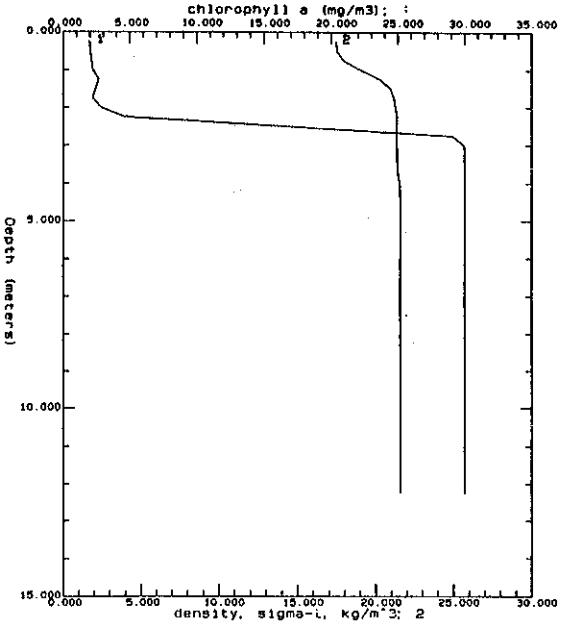


c) 1310 (Day) on 16-Jul-92: Low Low Tide

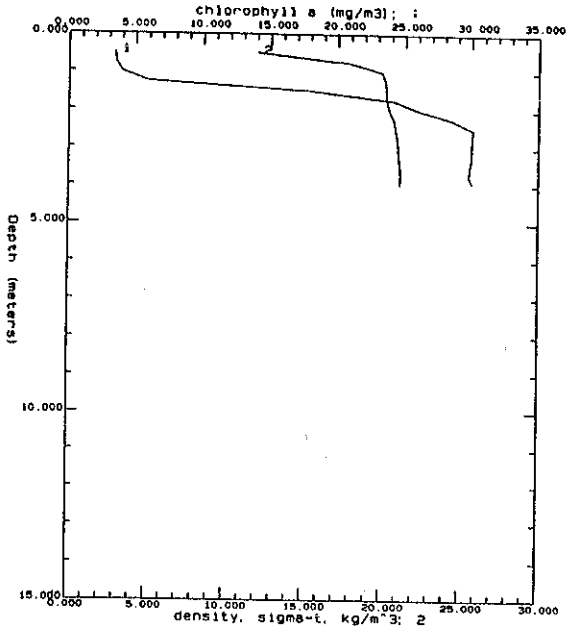
Figure 33. *In situ* fluorometer (1) and density (2) profile data for central bay Station BD-2 at low tide during tidal cycle survey 15-17 July 1992. Fluorometer chlorophyll *a* maximum = 30 mg/m^3.



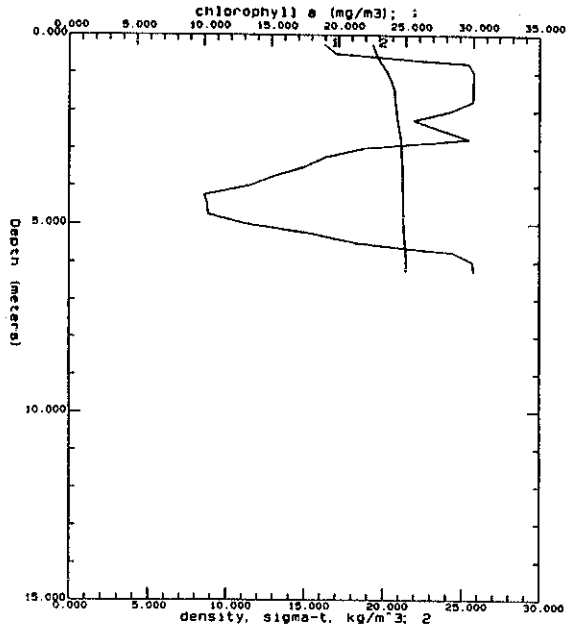
d) 0310 (Night) on 17-Jul-92: 1 Hour After High Low Tide



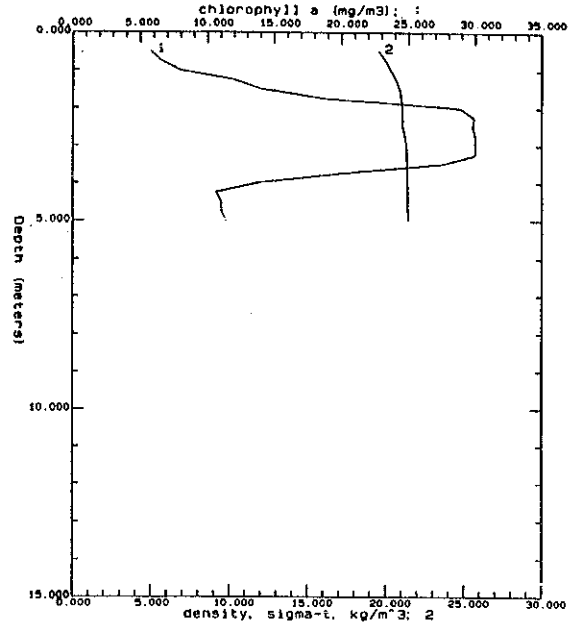
e) 1310 (Day) on 17-Jul-92: Low Low Tide



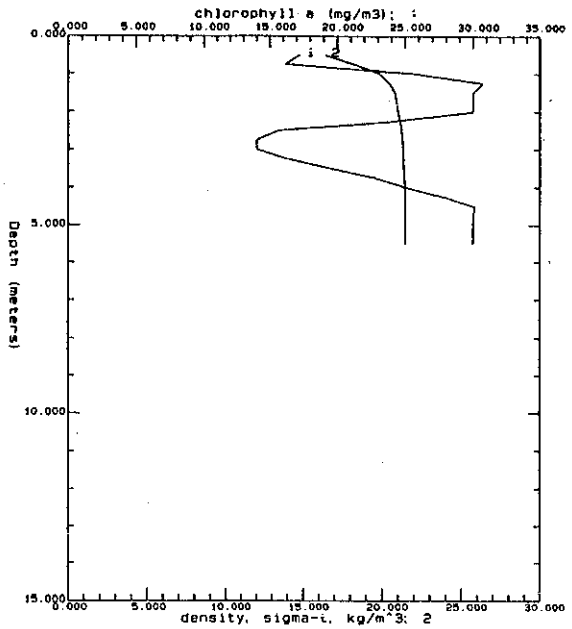
a) 1230 (Day) on 15-Jul-92: Low Low Tide



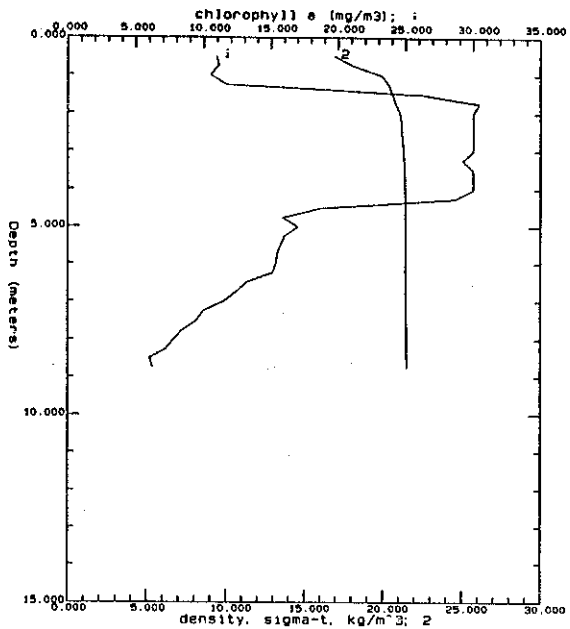
b) 0230 (Night) on 16-Jul-92: High Low Tide



c) 1230 (Day) on 16-Jul-92: Low Low Tide

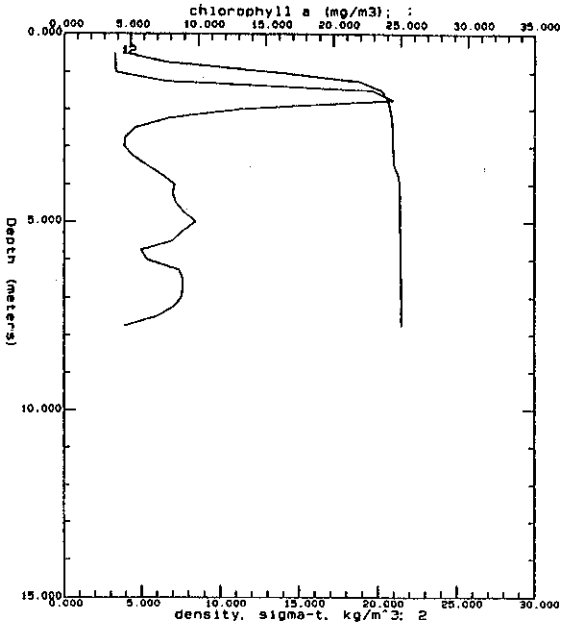


d) 0230 (Night) on 17-Jul-92: High Low Tide

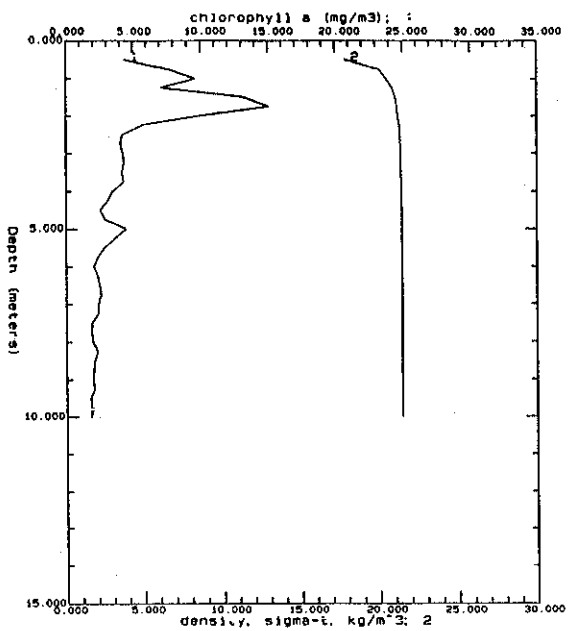


e) 1230 (Day) on 17-Jul-92: 1.5 Hours Before Low Low Tide

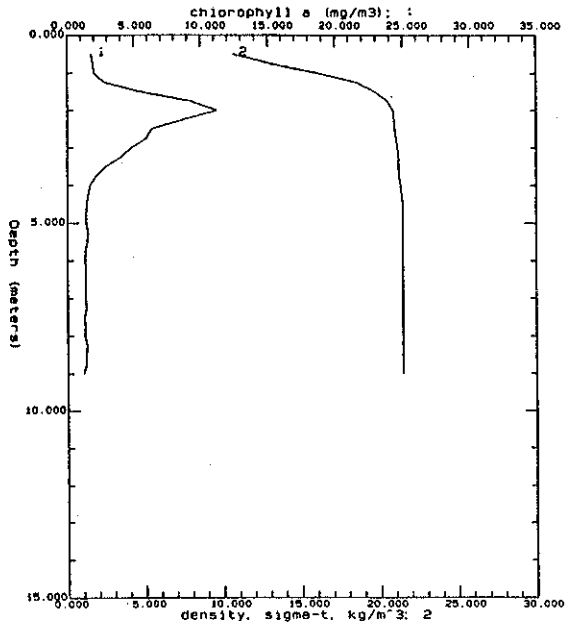
Figure 34. *In situ* fluorometer (1) and density (2) profile data for inner/central bay Station BA-2 at low tide during tidal cycle survey 15-17 July 1992. Fluorometer chlorophyll *a* maximum = 30 mg/m^3.



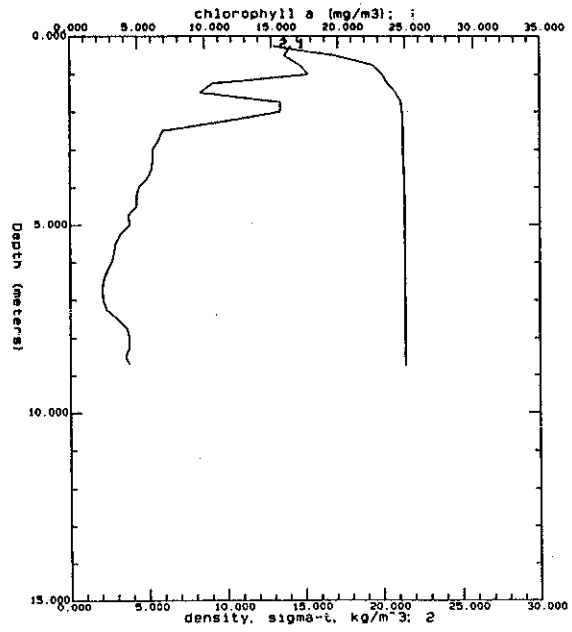
a) 1200 (Day) on 15-Jul-92: Low Low Tide



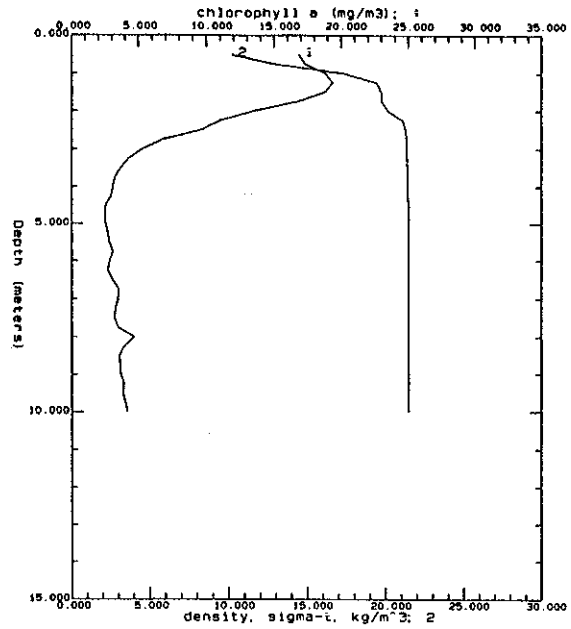
b) 0200 (Night) on 16-Jul-92: High Low Tide



c) 1200 (Day) on 16-Jul-92: 1.5 Hours Before Low Low Tide



d) 0200 (Night) on 17-Jul-92: High Low Tide



e) 1200 (Day) on 17-Jul-92: 3 Hours Before Low Low Tide

Figure 35. *In situ* fluorometer (1) and density (2) profile data for inner bay Station BI-5 at low tide during tidal cycle survey 15-17 July 1992. Fluorometer chlorophyll *a* maximum = 30 mg/m^3.

Diatoms

Diatom species with concentrations greater than 10,000 cells/L on one or more occasions at Station BUD005 and in the inner bay are shown in Figure 37. For the majority of collections, *Chaetoceros* spp., centric chain-forming diatoms with long spines, were the most abundant species.

The highest diatom concentrations ($\sim 1 \times 10^7$ cells/L) occurred during mid-May at Station BUD005 and during mid-May and mid-June at the inner bay station. At both locations, *Skeletonema costatum*, also a chain-forming centric diatom, was the dominant species during May and *Chaetoceros* spp. were the dominant species during June. High diatom concentrations ($> 1 \times 10^6$ cells/L) were also observed on 11 May at Station BUD005 and on 25 March, 26 August, and 10 September in the inner bay. The lowest diatom concentrations ($\sim 2 \times 10^4$ cells/L) were recorded during early and mid-July.

Dinoflagellates

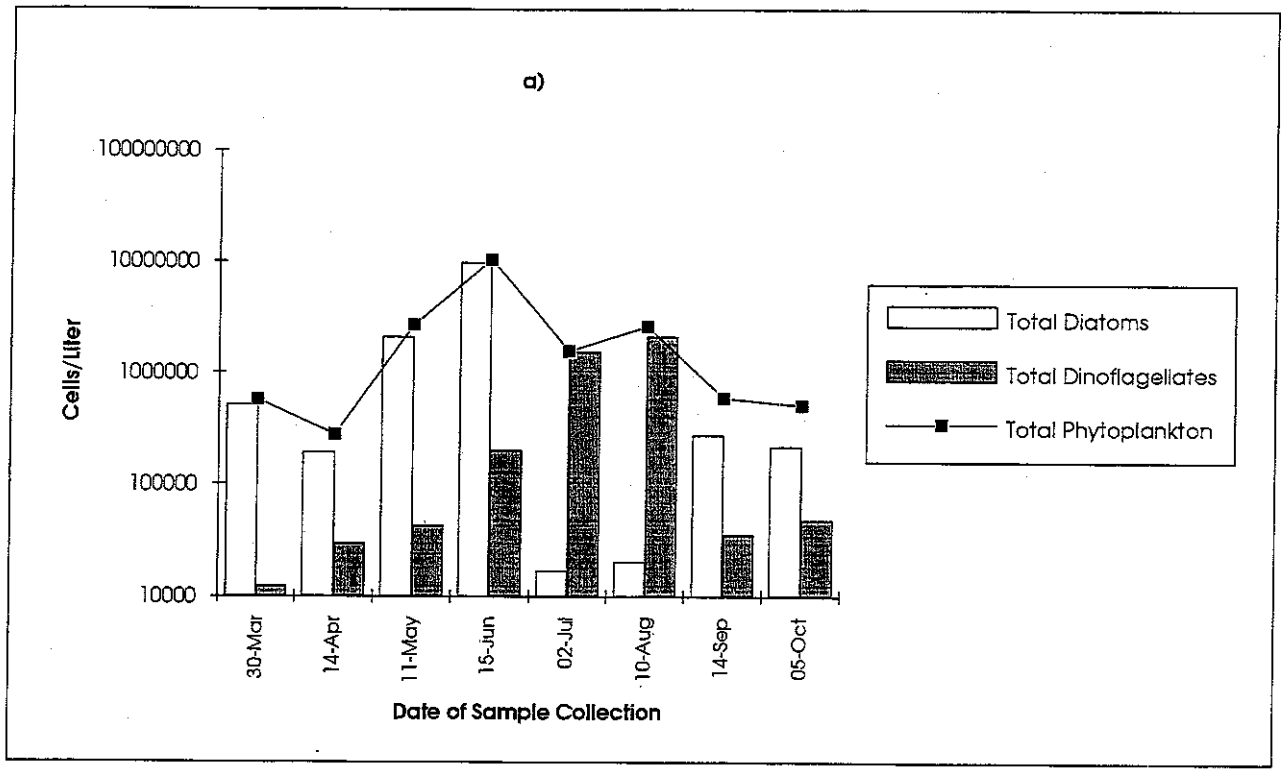
Dinoflagellate species with concentrations greater than 10,000 cells/L on one or more occasions at Station BUD005 and in the inner bay are shown in Figure 38. Miscellaneous colorless dinoflagellates, as a whole, had a higher concentration than other dinoflagellates except for the surveys during July and August (and September at Station BI-4). Colorless dinoflagellates do not photosynthesize, but rather are heterotrophic (they eat phytoplankton and other organisms). The highest dinoflagellate concentrations ($> 1 \times 10^6$ cells/L) were observed during July through the beginning of August and were composed primarily of *Ceratium fusus*, a large 200-μm long photosynthetic species known to undergo vertical migration (Staker and Bruno, 1980). The lowest dinoflagellate concentrations ($\sim 2 \times 10^4$ cells/L or less) were observed during early spring and fall.

Other Phytoplankton

Phytoplankton species other than diatoms and dinoflagellates with concentrations greater than 10,000 cells/L on one or more occasions at Station BUD005 and in the inner bay are shown in Figure 39. Microflagellates less than 10 μm in diameter had higher concentrations than other miscellaneous species or species groups except at Station BUD005 during May, July, and October. Concentrations of other phytoplankton were less variable than concentrations of diatoms or dinoflagellates and were never above 1×10^6 cells/L at either Station BUD005 or the inner bay station.

Harmful or Toxic Phytoplankton

Pseudonitzschia pungens, a pennate diatom, occurs in two forms, one toxic and one non-toxic, that cannot be distinguished with a light microscope. The toxic form, forma *multiseries*, may produce domoic acid, a neurotoxin that can accumulate in shellfish and other organisms and pose health threats to humans. *P. pungens* was observed on 30 March



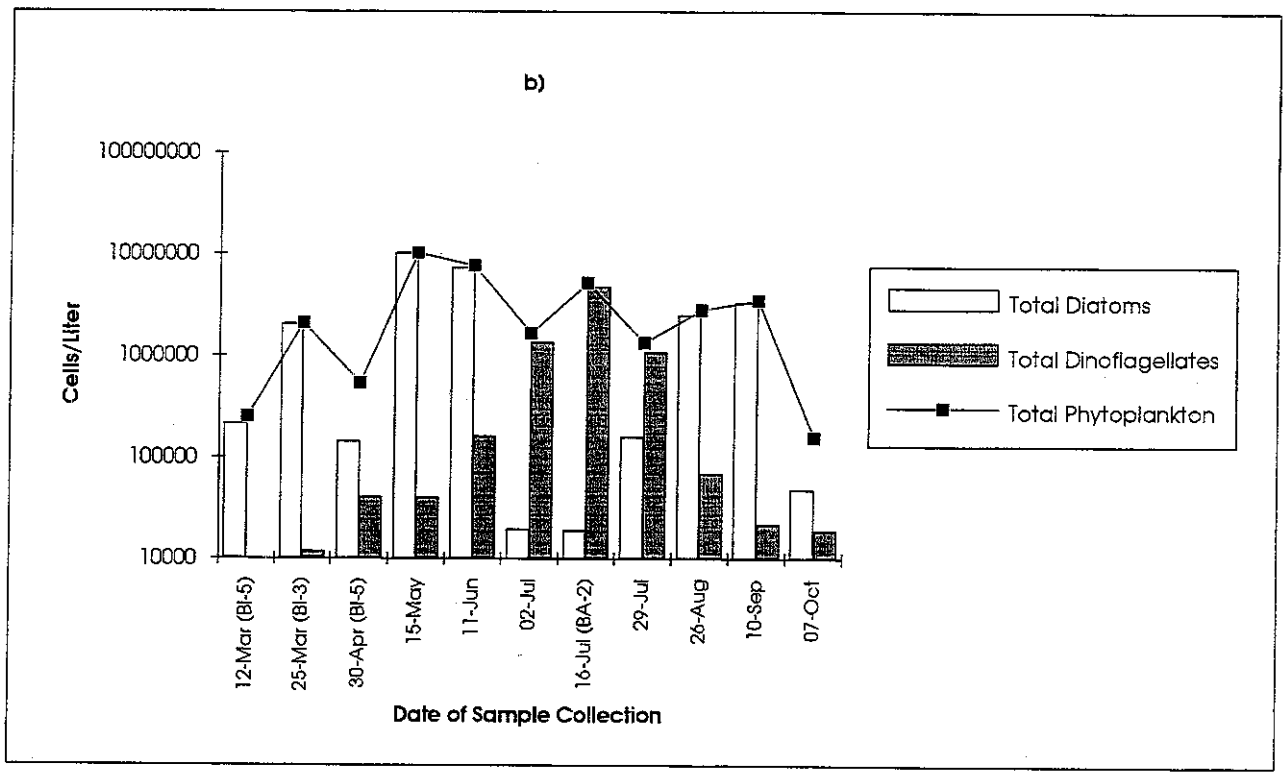
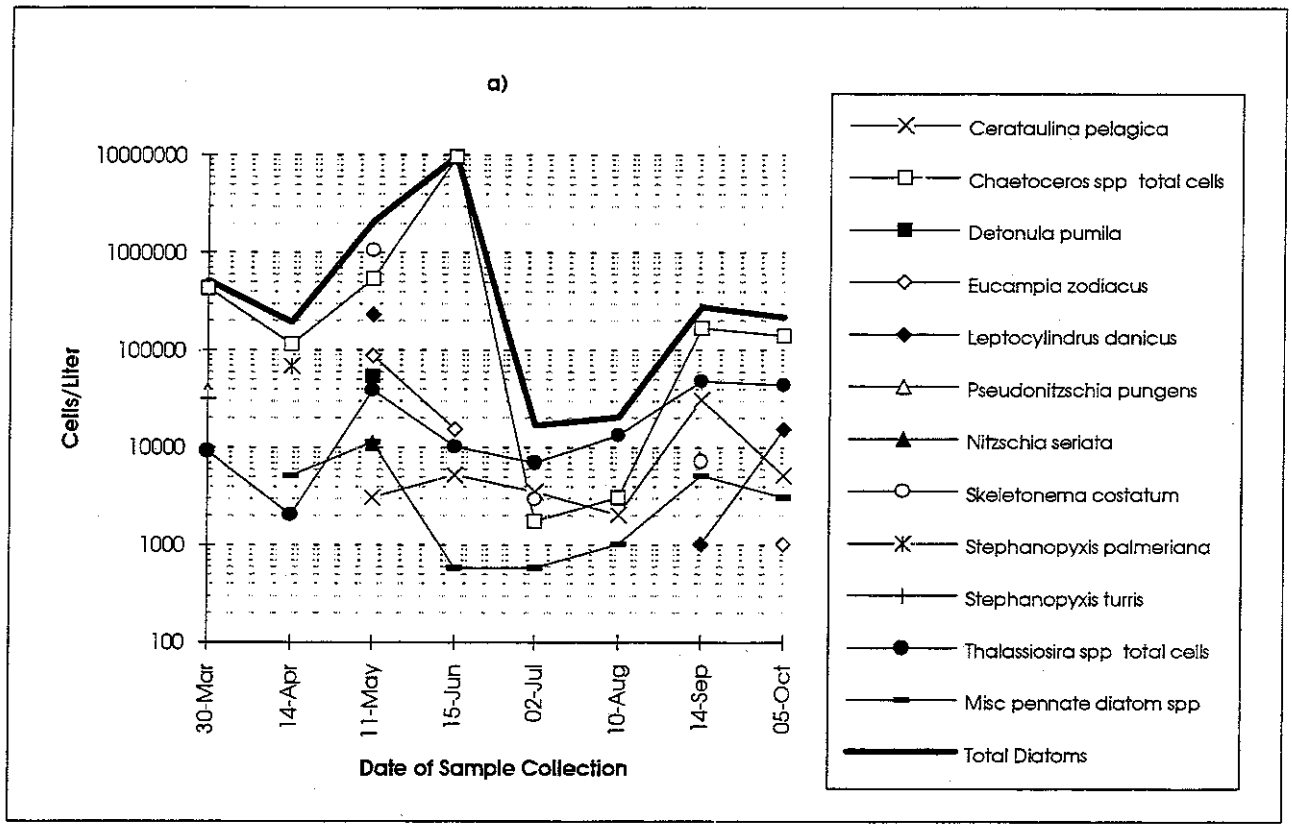


Figure 36. Diatom, dinoflagellate and total phytoplankton concentrations during March to October 1992 in a) central Budd Inlet (Station BUD005) and b) inner Budd Inlet (Station BI-4 unless otherwise indicated). Central Budd Inlet samples collected at 0 5 m except 10 August sample which was at 2 5 m. Inner Budd Inlet samples collected at 1 m 12 March to 2 July and at bloom maximum depths 16 July to 7 October



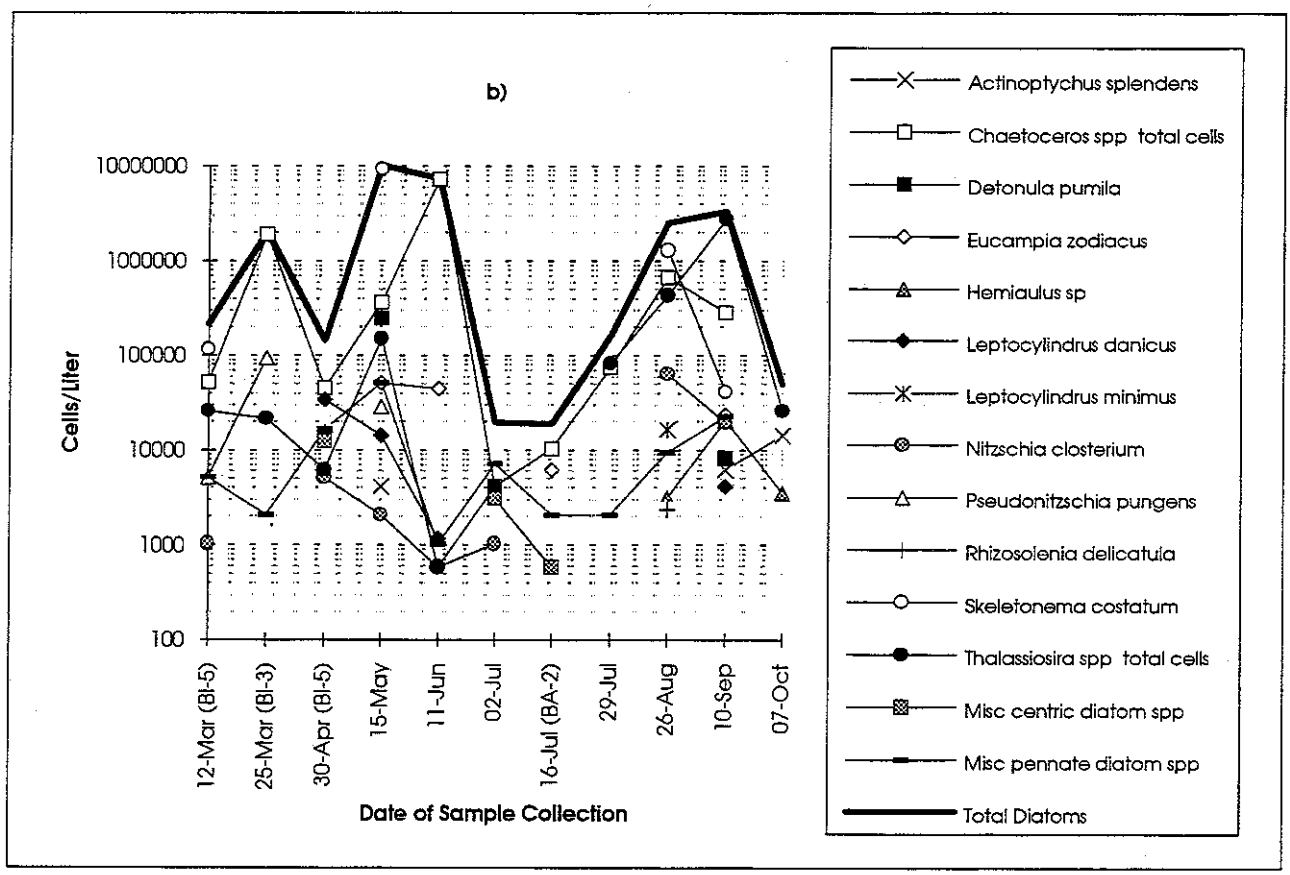
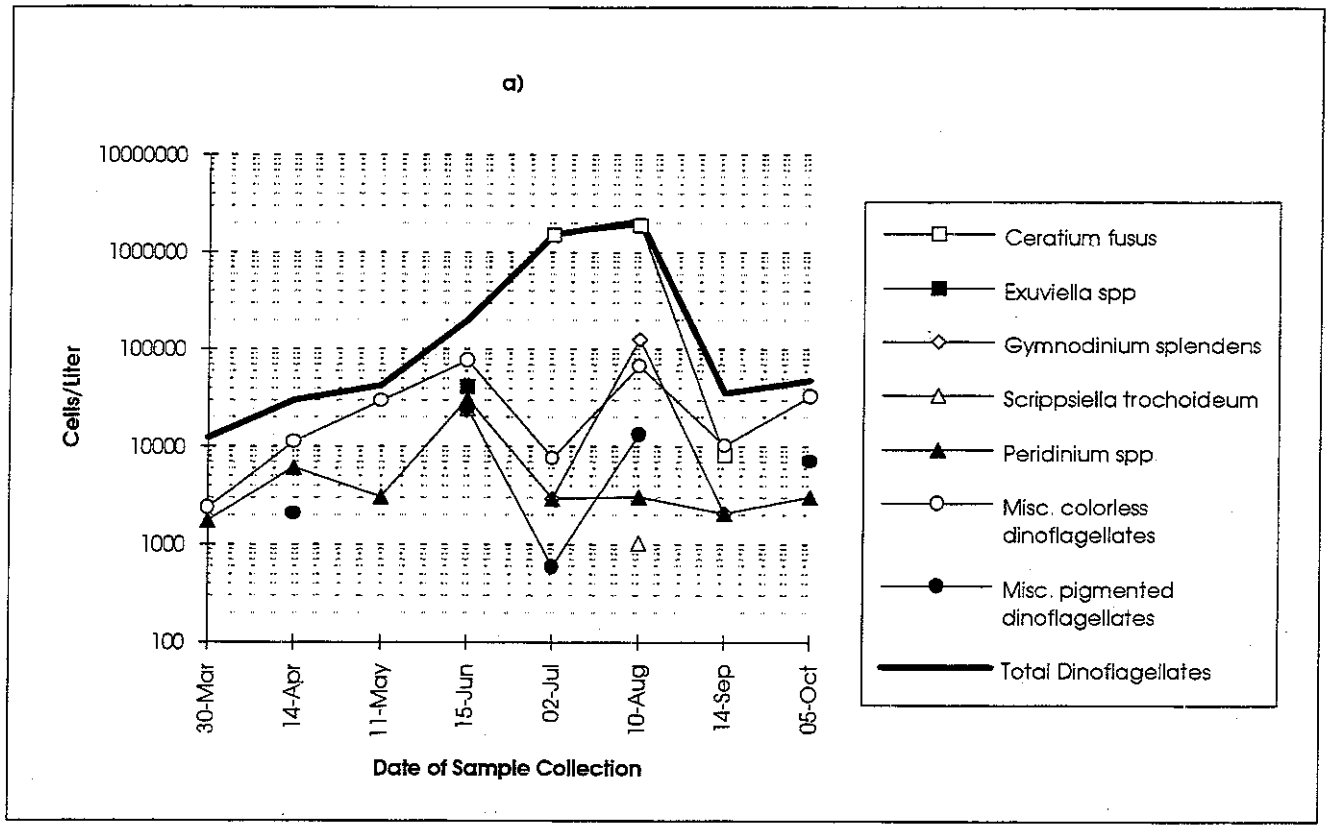


Figure 37 Diatom species with concentrations > 10,000 cells/L during March to October 1992 in a) central Budd Inlet (Station BUD005) and b) inner Budd Inlet (Station BI-4 unless otherwise indicated). Central Budd Inlet samples collected at 0.5 m except 10 August sample which was at 2 5 m Inner Budd Inlet samples collected at 1 m 12 March to 2 July and at bloom maximum depths 16 July to 7 October



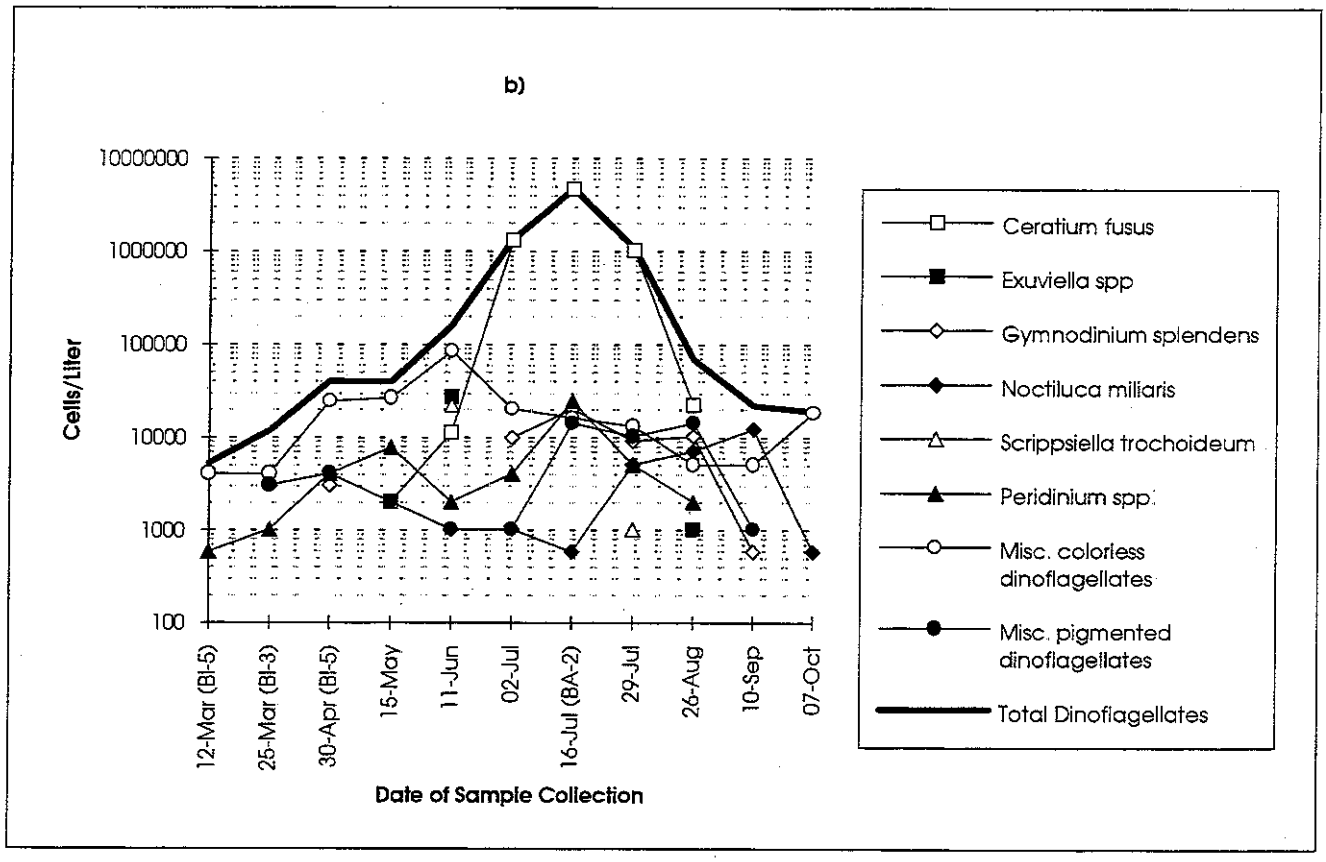
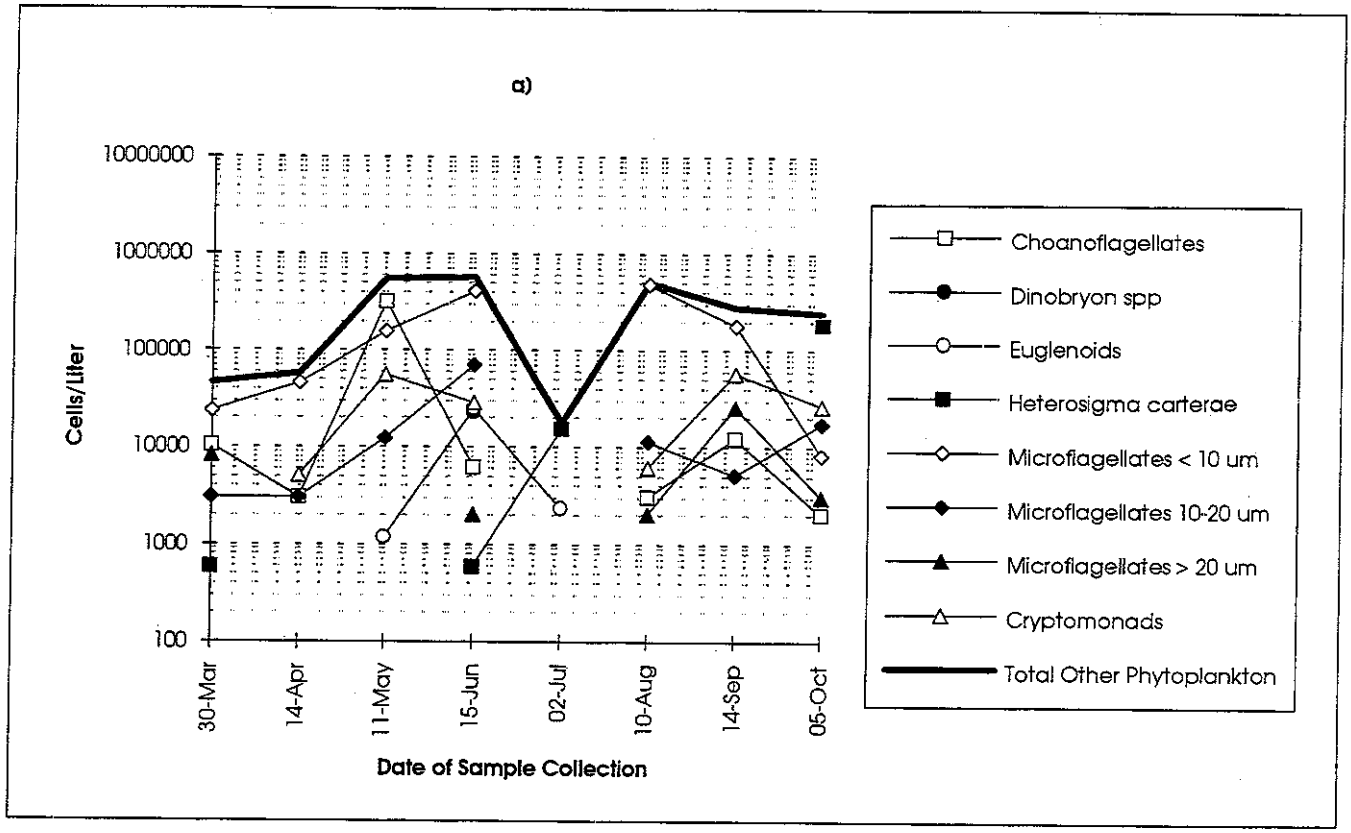


Figure 38. Dinoflagellate species with concentrations > 10,000 cells/L during March to October 1992 in a) central Budd Inlet (Station BUD005) and b) inner Budd Inlet (Station BI-4 unless otherwise indicated). Central Budd Inlet samples collected at 0.5 m except 10 August sample which was at 2.5 m. Inner Budd Inlet samples collected at 1 m 12 March to 2 July and at bloom maximum depths 16 July to 7 October.



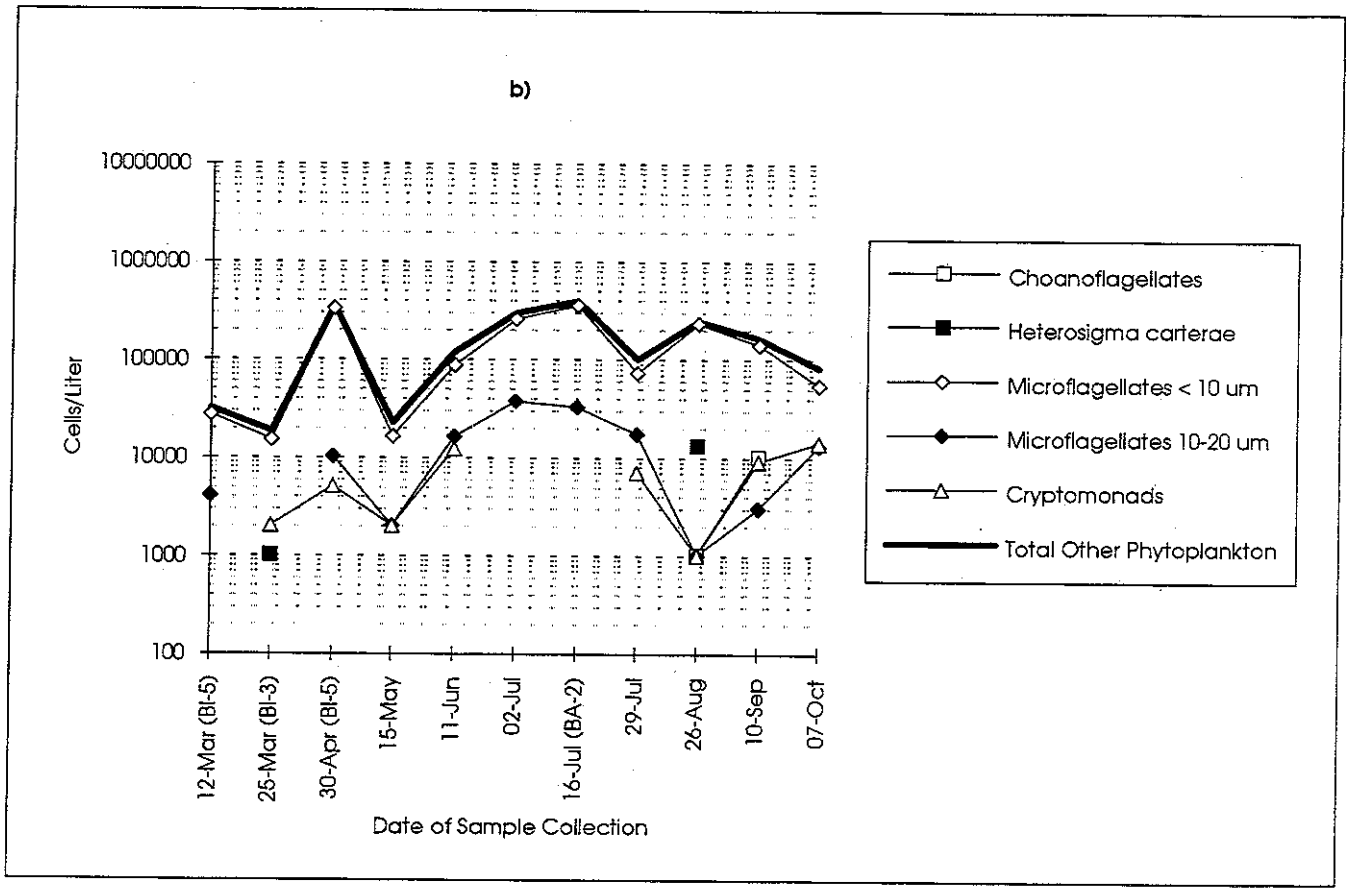


Figure 39. Other phytoplankton species with concentrations > 10,000 cells/L during March to October 1992 in a) central Budd Inlet (Station BUD005) and b) inner Budd Inlet (Station BI-4 unless otherwise indicated). Central Budd Inlet samples collected at 0.5 m except 10 August sample which was at 2.5 m. Inner Budd Inlet samples collected at 1 m 12 March to 2 July and at bloom maximum depths 16 July to 7 October

at Station BUD005 and on 12 and 25 March, 15 May, and 26 August in the inner bay (Figure 37). The concentration of cells where harmful effects become evident is not known (Horner, 1994) and toxicity concentrations within cells have shown to be variable depending on factors such as stage of cell growth (Douglas and Bates, 1992). Thus, the threat to human health implied by these observations cannot be assessed.

Heterosigma carterae is a small photosynthetic flagellate that can cause fish kills, although the mechanism is unknown. *H. carterae* was observed on 30 March, 15 June, 2 July, and 5 October at Station BUD005, and on 25 March and 26 August in the inner bay (Figure 39). As with *P. pungens*, the concentration at which harm can occur is unknown. No toxic or harmful dinoflagellate species were recorded at Station BUD005 or in the inner bay.

DISCUSSION

Budd Inlet can be separated into inner bay, and central and outer bay areas with somewhat different physical and biological processes occurring in both. Water quality parameters in the central and outer bay are more representative of the ambient conditions seen in greater Puget Sound, whereas water quality parameters in the inner bay are affected by the Deschutes River/Capitol Lake inputs, discharges from LOTT and other anthropogenic sources. In addition, there is greater stratification and a lower flushing efficiency for water in the inner bay than in the central and outer bay (URS, 1986). The combination of these and other factors results in poorer water quality for inner Budd Inlet than is observed in the central and outer bay. These poor water quality conditions include eutrophication and the prevalence of low D.O. conditions, resulting in habitat degradation and the potential for fish kills (URS, 1986). Fecal coliform contamination has also been recorded throughout Budd Inlet (Tetra Tech, 1988a); however this parameter was not evaluated in this study.

Eutrophication and Depletion of Dissolved Oxygen

Water quality parameters combined, rather than observed independently, show a more complete picture of the sequence of events producing eutrophication and subsequent D.O. depletion in Budd Inlet waters.

Eutrophication, that is enrichment with nutrients, results in large populations of phytoplankton in environments where nutrients normally limit phytoplankton growth. The organic material produced by phytoplankton eventually becomes oxidized, and in this process, D.O. concentrations decrease. Low D.O. concentrations typically are found in the deeper waters, where the bulk of the organic material has settled. Settling of this organic matter may be from either from the direct sinking of senescent cells, or through grazing by herbivorous zooplankton that produce large fecal pellets that sink.

Eutrophic conditions in Budd Inlet are somewhat complex because of differences between the inner versus the central and outer bays. The highest nutrient concentrations and lowest D.O.

concentrations were seen in the inner bay, yet chlorophyll *a* concentrations were maximum in the central bay. In the central and outer bay, the seasonal sequence of events starts with high nutrient concentrations in the early spring, reflecting stronger vertical mixing and reduced algal growth during the winter months. Stratification of the water column along with increases in light and temperature promote phytoplankton blooms dominated by diatoms (Figure 36), and lead to the eventual decline of surface nutrients to concentrations below reporting limits by early summer as observed in the central and outer bay (Figure 23). Phytoplankton blooms dominated by dinoflagellate species are found during mid to late summer (Figure 36); these species can move deeper in the water column to utilize near-bottom nutrients. Migrating dinoflagellate species would contribute to low D.O. concentrations in near-bottom waters since these organisms respire at night while at depth. During the fall, an influx of nutrient-rich Puget Sound water (Tetra Tech, 1988a) and mixing of the water by strong winds make nutrients again available in surface waters. Fall diatom blooms utilize these nutrients resulting in the temporary drop of nutrient concentrations to levels near reporting limits at some stations (Figure 23). During the late fall, as day length decreases and storms continue to deepen the mixed layer, the phytoplankton mix down in the water column and become light-limited, and growth decreases. In the inner bay, however, nutrients never fell below reporting limits, and migration of dinoflagellates was not evident. The high nutrient enrichment coupled with increased stratification may contribute to these observed deviations.

The increased stratification of the inner bay may account for why the lowest D.O. concentrations were observed there in spite of lower phytoplankton biomass. Decomposition of settled organic matter reduces the D.O. concentration of near-bottom waters. Stratification impedes the diffusion of oxygen from the surface into bottom waters and reduces vertical mixing of the water masses since energy is required to overcome the density gradient. Thus, under stratified conditions in summer months, low oxygenated water cannot easily be replenished with higher oxygenated water. The near-bottom low D.O. conditions will continue to worsen, as phytoplankton continue to bloom, sink and decay, until fall storms promote mixing of the water column or until bottom water is replaced by advection from the outside, producing an increase in D.O. content. The intense salinity-induced stratification of the inner bay impedes this process.

Nutrient and Phytoplankton Dynamics

Eutrophic conditions result from nutrient enrichment followed by uptake and growth by phytoplankton. Large phytoplankton blooms can be induced by natural or anthropogenic sources of nutrients. An increase in nutrient concentration with time indicates nutrient input in excess of phytoplankton uptake, whereas, a decrease indicates phytoplankton utilization in excess of nutrient input. Below reporting limit (<0.01 mg/L) nutrient concentrations and high (>10 mg/m^3) chlorophyll *a* concentrations were used to indicate phytoplankton bloom occurrence and location in Budd Inlet. Since phytoplankton species composition can affect the level of nutrient depression and vice versa, shifts in algal class (*i.e.*, diatoms vs. dinoflagellates) were also useful for understanding nutrient dynamics (Figure 36). Other

factors (not addressed) which influence nutrient dynamics and bloom occurrence include bacterial uptake and regeneration of nutrients, and grazing of phytoplankton and bacteria by zooplankton and other heterotrophs.

Nutrient Concentration and Phytoplankton Bloom Location

Phytoplankton blooms were associated with below reporting limit concentrations of nitrite+nitrate-N and ammonium-N in the surface waters of the central and outer bay during mid-May and from mid-June until mid-September (Figures 23 and 24). Surface nitrite+nitrate-N and ammonium-N were seldom below reporting limits in the inner bay (particularly in West Bay), probably due to continual inputs of nutrients from LOTT and the Deschutes River/Capitol Lake outlet. Surface ammonium-N and orthophosphate-P concentrations were particularly high in the inner bay on 28 May (Figures 24 and 25). This may reflect high nutrient inputs as well as a lack of nutrient utilization due to the very low phytoplankton abundance (chlorophyll *a* ~ 1 mg/m^3 throughout the bay; Figure 31).

Phytoplankton blooms occurred throughout the bay but tended to be largest in the central bay, implying high nutrient utilization in this area. In spite of the higher nutrient levels in the inner bay, observed phytoplankton blooms were smaller in the inner bay than in the central bay. These lower biomass levels in the inner bay may be caused by lower growth rates or by higher loss rates for the phytoplankton populations. Low growth rates could be from unsuitable growth conditions, perhaps due to the large freshwater lens observed in the inner bay. This lens may reduce the area of the water column suitable for marine phytoplankton growth, due to lower salinity or higher turbidity (Figure 14). Alternatively, loss processes may be more intensive in this area, such as a higher flushing rate in the surface layer, so that the residence time for phytoplankton in the surface layer of the inner bay is short. A box model (Figure 4.4 in URS, 1986) showed residence times in the surface 3-m layer were shorter for the area from inner bay Station BI-3 to central bay Station BB-2 (1.05 d) than for either the area within the central bay from Station BB-2 to Station BC-3 (1.11 d) or the area from central bay Station BC-3 to outer bay Station BE-2 (1.61 d). Residence times further into the inner bay were not determined. It should also be noted that the observed bloom locations may be somewhat biased since inner bay sample collection occurred predominantly during low tide when the blooms were likely located further out in the bay than during flood or high tides.

Nutrient Concentration and Phytoplankton Species Changes

Diatoms were dominant in spring when the reduction of surface nitrite+nitrate-N concentrations occurred in the inner and central bays (Figures 23, 24, and 36). The dominant phytoplankton changed from diatoms to dinoflagellates during the end of June (Figure 36). Following the decrease in surface water nitrite+nitrate-N (Figure 23), there was a substantial increase in *Ceratium fusus* (Figure 38), a dinoflagellate known to vertically migrate, and thus able to exploit nutrients at depth. During July and August, near-bottom

nitrite+nitrate-N was below reporting limit throughout the inner and central bay (Figure 23). This decrease in near-bottom nitrite+nitrate-N may have been due to utilization by *C. fusus*.

Near-bottom nitrite+nitrate-N increased during late summer/early fall (Figure 23). Phytoplankton species dominance changed from dinoflagellates back to diatoms during this time (Figure 36). Conditions such as water column mixing may have precipitated this change by re-injecting nutrients into the surface waters (Figure 23) for utilization by non-migrating phytoplankton such as diatoms.

Factors Affecting Low Dissolved Oxygen Concentrations

One of the most critical parameters monitored, in terms of water quality, was D.O. concentration. Dissolved oxygen values of 5.0 mg/L may begin to stress many organisms, especially fish, and when D.O. values approach 2.0 mg/L in the water column, organisms may show avoidance behavior (Harding *et al.*, 1992). Mortality can occur at D.O. concentrations of less than 0.5 to 2.0 mg/L depending on species, life history stage and duration of exposure (Harding *et al.*, 1992). Large fish kills were last observed in Budd Inlet during 1981 due to influxes of anoxic water from the bottom of Capitol Lake, which contained high concentrations of hydrogen sulfide. A siphon from the bottom of Capitol Lake into Budd Inlet was installed in 1987 to prevent lake bottom water from stagnating and becoming anoxic, and has appeared to rectify this problem (Tetra Tech, 1988a). However, in this study, D.O. concentrations below 5.0 mg/L were consistently observed in late summer/early fall with values occasionally dropping below 3.0 mg/L (Figures 16 and 18). It is therefore important to evaluate which factors promote low D.O. conditions in Budd Inlet.

The lowest D.O. concentrations were at near-bottom depths in the inner bay (predominantly West Bay) and, to a lesser degree, in the central bay near the eastern shore. This portion of the central bay had the largest phytoplankton blooms and the greatest degree of stratification (aside from the inner bay). Low D.O. concentrations were likely due to a combination of biological, biochemical, and physical factors. The impact of any one factor can be variable over tidal and/or diel cycles.

Biological Factors

There were significant phytoplankton blooms (chlorophyll a > 10 mg/m^3) during most of the growing season with the largest blooms recorded from July through September. Near-bottom D.O. concentrations were also found to be lowest during this period. These low D.O. concentrations may be partially due to oxygen consumption by bacteria during phytoplankton decomposition and by respiration of benthic organisms (URS, 1986).

Another biological factor promoting low D.O. concentrations may be the downward vertical migration of dinoflagellates during the night (URS, 1986). While in the dark at depth, photosynthesis cannot occur; however, respiration will continue, and thus reduce near-bottom D.O. concentrations. Near-bottom D.O. concentrations were lowest during and following

blooms of *Ceratium fusus* (Appendix A and Figure 38), the dominant species found during the tidal cycle survey. Fluorometer data from the tidal cycle survey indicated that vertical migration occurred in the central bay (Figures 33 and 34), but did not occur in the inner bay where D.O. concentrations were lowest (Figures 22 and 35). The lowering of near-bottom D.O. in the central bay may partially contribute to the low D.O. concentrations seen in the inner bay since less oxygen would be available to replenish the near-bottom inner bay waters during tidal advection. The magnitude of the reduction in the near-bottom D.O. from migrating dinoflagellates is unknown and should be resolved.

Biochemical Factors

Additional processes, outside the scope of this study, that may contribute to D.O. depletion in the inner bay are oxygen demand within the sediments, nitrification, binding of oxygen by sulfides, decomposition of other organic materials (such as wood or wood products), and other oxygen consuming processes within the water column.

Physical Factors

Physical factors that likely contribute to near-bottom D.O. depletion are stratification, which inhibits mixing, and slow rates of horizontal advection. Stratification was strongest in the inner bay, largely due to freshwater from the Deschutes River/Capitol Lake outlet (Figure 9). No direct measurement of advection exist for all of the areas in this study. However, the relative residence times for D.O. calculated by URS (1986), do not show differences in the accumulation of D.O. in the area between Stations BI-3 and BB-2 versus the area between Stations BB-2 and BC-3. Unfortunately, no measurements or calculations exist for the inner bay stations south of Station BI-3, where the lowest D.O. concentrations were observed in this study.

Near-bottom D.O. concentrations below 5.0 mg/L persisted at some inner bay stations from July through mid-October, when strong fall winds would be expected to cause mixing and increase D.O. concentration. Mixing will only occur when the kinetic energy from the wind and tides exceeds the potential energy represented by stratification. The stronger stratification of the inner bay apparently acts as an effective inhibitor of vertical mixing.

Tidal and Diel Influences

The effects of tidal and diel cycles on D.O. concentrations were somewhat quantified. In general, D.O. levels were higher during high tide than during low tide (Figures 20 and 21a), and higher during the daytime than at night in near-surface waters (Figure 21b). The higher D.O. levels during high tide may be due to the influx of higher oxygenated waters coming in from the Sound during the preceding flood tide. The higher near-surface D.O. levels during the daytime were likely due to phytoplankton photosynthetic activity during the daylight hours.

The effects of tidal and diel influences were difficult to separate over a 52-h tidal cycle period since the lengths of one day and one complete (mixed) tidal cycle are similar (~24 and 25 h, respectively). The tidal and diel periods would be more distinguishable over a longer time period (*i.e.*, weeks) and thus allow the contributions from each component to be more easily resolved.

The sporadic releases and back-flushes of Capitol Lake during the tidal cycle survey also made the interpretation of the tidal and diel variability in the inner bay difficult. The effect of these episodes needs to be better resolved.

Summary of Project Objectives

Specific project objectives were identified at the beginning of this report. How the study results have answered these objectives are summarized in this section.

1. Stratification was strongest in the inner bay and decreased from the head to the mouth of Budd Inlet. Stratification was predominantly salinity driven. Stratification between 1 m and near-bottom was strongest during March and July in the inner bay. Throughout the inlet, some degree of stratification existed during the sampling season (March-October), as indicated by changes in sigma-t with depth. Typically the major pycnocline was above 2 m.

2. Low dissolved oxygen (D.O.) concentrations (< 5.0 mg/L) were found in Budd Inlet, occurring from July through October predominantly in the inner bay. The majority of occurrences were in West Bay at near-bottom depths. Dissolved oxygen concentrations less than 5.0 mg/L were also seen in the central bay near the eastern shore. Near-hypoxic D.O. concentrations (< 3.0 mg/L) were observed during late August and early October at inner bay stations in both East Bay and West Bay at near-bottom depths. The conditions resulting in low D.O. are likely a combination of organic loading and persistent stratification.

3. Surface nutrients below reporting limits were observed in the central and outer bay during mid-May and from mid-June through mid-September. In the inner bay, this condition was observed during mid-May and from late July through late August at East Bay Station BI-2, but never at West Bay Station BI-4. The highest nutrient concentrations (particularly for ammonium-N) were consistently recorded at West Bay Station BI-4. Station BI-4 is located near the primary LOTT outfall. The decrease in surface nutrients was associated with the seasonal increase of phytoplankton. The persistence of high surface nutrient concentrations in the inner bay is likely due to nutrient input from LOTT or other anthropogenic sources. Whether the phytoplankton nutrient demand is lower in the inner bay cannot be determined from biomass data (chlorophyll *a*) alone, but would require production (growth rate) measurements.

4. Bloom concentrations (chlorophyll *a* > 10 mg/m^3) occurred throughout the bay during the growing season (March-October); however, the largest phytoplankton blooms (chlorophyll *a* > 30 mg/m^3) were generally seen in the central bay during July through September. Phytoplankton concentrations were consistently highest in the central bay, although higher nutrient levels were found in the inner bay. Other conditions possibly inhibited phytoplankton growth in the inner bay, or reduced their population there.

5. Dinoflagellate blooms of species known to migrate vertically occurred during July and August at central and inner bay stations. During the mid-July tidal cycle survey, chlorophyll *a* were located deeper in the water column during the night than during the day at the central bay stations, but not at the inner bay station. The density profiles indicated that an *in situ* process (*i.e.*, vertical migration) not physical advection of water masses along density surfaces affected the vertical location of the chlorophyll *a* maximum.

6. Potentially harmful phytoplankton species (*Pseudonitzschia pungens* and *Heterosigma carterae*) were present at both central and inner bay stations at various times during the sampling period (March-October), in concentrations ranging from 10^3 to 10^5 cells/L. These species have been associated with harm to humans and fish; however, the necessary concentration for effects to be evident and the conditions that promote toxicity (for *P. pungens*) are not presently known.

7. The effect of tidal stage was evident on many parameters. The freshwater lens from the Deschutes River/Capitol Lake outlet extended further out in the bay at low tide than at high tide. Limited comparisons indicated that D.O. concentrations were lower during low tide than during high tide. Phytoplankton blooms tended to be located further out in the bay during low tide than during high tide. In addition, diel variation was seen in some parameters. During the mid-July tidal survey phytoplankton were located at deeper depths during the night than during the day. In general, D.O. concentrations were higher during the day than at night. The effects of tidal and diel variation on D.O. could not be resolved in this study.

8. Budd Inlet showed eutrophic conditions at times, especially in the inner bay. The effect of the reduction of nutrient input when LOTT effluent has approximately 90% nitrogen removal (slated for spring 1994) cannot be predicted from these data. However, these data provide a solid baseline with which to compare post nitrogen removal conditions.

Conclusions

Budd Inlet is a productive and dynamic estuary. Physical and biological conditions within the inlet are influenced by tides and freshwater input. At a particular station, tidal stage appeared to influence the D.O. concentration, although some of the change may also have been due to diel variation. The freshwater input at the head of the estuary effects a persistent stratification within the estuary which is most pronounced in the inner bay. In

addition to the stronger stratification, the inner bay exhibited different water quality conditions than the rest of the inlet. Addition of nutrients to the inner bay, primarily from LOTT, may explain why nutrient concentrations did not fall below reporting limit concentrations during the summer and early fall months, as was seen in all other regions of the inlet. Nutrient uptake and input rates would be necessary to evaluate this scenario, however. The lowest D.O. concentrations were found in the near-bottom waters of the inner bay, sometimes approaching hypoxic levels (2.0 mg/L). Existence of these conditions is likely affected by the strong stratification and perhaps the abundance of nutrients in the inner bay. However, without determination of the phytoplankton production and flushing rates of the inner bay (south of Station BI-3), the mechanism for the occurrence of these low D.O. conditions cannot be identified. In summary, the distribution of phytoplankton biomass, nutrients and D.O. in the inner bay is different than in the rest of the inlet. Observation of these same parameters after nitrogen nutrients have been removed from the LOTT effluent would provide instrumental information on the effects of nutrient loading in an estuary of this type.

Recommendations

1. Explain the observed distribution of phytoplankton, which shows a lower concentration in the inner bay than in the central bay. The phytoplankton concentration is the net balance of growth and loss processes, so it is necessary to determine whether growth is less in the inner bay or if loss processes are greater there. The primary productivity of the inner versus central bays should be measured, and then the biomass-normalized production rates (mg C mg chl^{-1} d^{-1}) compared to determine if growth is inhibited. To assess loss processes, the residence times of water at the depth of the chlorophyll maximum for the inner versus central bays should be determined. A residence time for the inner bay, south of BI-3 was not determined by URS (1986). Also, tidal influences on the location of phytoplankton blooms should be investigated to ascertain whether blooms are simply advected in and out according to the tidal cycle, and thus tend to aggregate in an area. Limited high slack tide data indicated that the blooms tended to be located further in toward the head of the inlet during high tide as opposed to low tide.

2. Constrain the sources of variability on D.O. Investigate tidal versus diel influences on D.O. Since these processes operate on 25-h and 24-h cycles respectively, a moored sensor that can record data for weeks would be necessary to deconvolute these effects. In addition, other sources of D.O. variation, such as sediment oxygen demand and dinoflagellate vertical migration should be quantitatively assessed. The coupling of water column processes with benthic processes, particularly for D.O. concentrations, needs to be investigated.

3. Better resolve the cause of the low D.O. in the inner bay, which is observed in spite of the lower chlorophyll *a* concentrations there. Quantitatively determine the importance of stratification in the persistence of these low D.O. conditions.

4. Assess the connection between annual variations of water quality conditions to variations in climatic forcing, such as precipitation, solar radiation, winds.

5. Monitoring should continue following implementation of the removal of nitrogen from the LOTT effluent slated for spring 1994. This will allow a comprehensive assessment of the effects of nitrogen removal on water quality parameters in Budd Inlet. This information may have future implications regarding the construction of similar Waste Water Treatment Plants (WWTPs). WWTPs are a significant source of nutrients, yet whether nutrient addition leads to eutrophication in local estuaries varies according to whether nutrients or light or mixing controls the primary production and decrease in D.O. concentration. It is difficult to ascertain the effect of nutrient addition by LOTT into Budd Inlet without a mass balance model. Accurate estimates of all of the fluxes necessary for construction of such a model have not been determined. These include: nutrient uptake by phytoplankton and bacteria, efflux from the sediments, regeneration, advection, and external inputs to Budd Inlet (e.g., runoff). While construction of such a model would be useful for better understanding the dynamics within Budd Inlet, the impact of WWTP effluent on water quality could best be determined from direct measurement of parameters before and after this significant change.

REFERENCES

APHA-AWWA-WPCF (American Public Health Association - American Water Works Association - Water Pollution Control Federation), 1989. Standard Methods for the Examination of Water and Wastewater, 17th Edition.

Bortleson, G.C., N.P. Dion, J.B. McConnell and L.M. Nelson, 1976. Reconnaissance data on lakes in Washington. Washington State Department of Ecology, Water Supply Bulletin 43, Vol. 4.

City of Olympia, Department of Public Works, 1992. Final Effluent, 1992 Yearly Report.

Douglas, D.J. and S.S. Bates, 1992. "Production of domoic acid, a neurotoxic amino acid, by an axenic culture of the marine diatom *Nitzschia pungens* f. *multiseries* Hasle," Canadian Journal of Fish and Aquatic Sciences. Vol. 49, pp. 85-90.

Ecology (Washington State Department of Ecology), 1988. Quality Assurance Manual. Manchester Environmental Laboratory, Manchester, WA.

Ecology (Washington State Department of Ecology), 1994. Laboratory Users Manual, Fourth Edition. Manchester Environmental Laboratory, Manchester, WA.

EPA (Environmental Protection Agency), 1984. Methods for Chemical Analysis of Water and Waste. 6/4/79/020.

Harding, L.W. Jr., M. Leffler and G.E. Mackiernan, 1992. Dissolved Oxygen in the Chesapeake Bay: A Scientific Consensus. Maryland Sea Grant, College Park, Maryland.

Horner, R.A., 1994. "Harmful Phytoplankton in Puget Sound," Puget Sound Notes. No. 34, pp. 1-4.

Janzen, C.D., 1992. Marine Water Column Ambient Monitoring Plan: Final Report. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program and the Puget Sound Water Quality Authority, Publication 92-23, Olympia, WA.

Jay, D., 1991. "Internal asymmetry and anharmonicity in estuarine flows," *In* Progress in Tidal Hydrodynamics. Wiley-Interscience. pp 521-546.

Lavelle, J.W., H.O. Mofjeld, E. Lempriere-Doggett, G.A. Cannon, D.J. Pashinski, E.D. Cokelet, L. Lytle and S. Gill, 1988. A Multiply-Connected Channel Model of Tides and Tidal Currents in Puget Sound, Washington and a Comparison with Updated Observations. NOAA technical memorandum ERL PMEL -84.

Llansó, R.J., 1992. "Effects of hypoxia on estuarine benthos: the lower Rappahannock River (Chesapeake Bay), a case study," Estuarine, Coastal and Shelf Science. Vol. 35, pp. 491-515.

Lorenzen, C.J., 1966. "A method for the continuous measurement of in vivo chlorophyll concentration," Deep Sea Research. Vol. 13, pp 223-227.

NOAA (National Oceanographic and Atmospheric Association), 1993. Local Climatological Data, 1992 Annual Summary with Comparative Data. National Climate Data Center, Ashville, N.C.

Pond, S. and G.L. Pickard, 1983. Introductory Dynamical Oceanography, Second Edition. Pergamon Press.

Poole, H.H. and W.R.G. Atkins, 1929. "Photoelectric measurements of submarine illumination throughout the year," Journal of the Marine Biological Association. Vol. 16, pp. 297-324.

PSEP (Puget Sound Estuary Program), 1990. Recommended Protocols and Guidelines for Measuring Selected Environmental Variables in Puget Sound. U.S. Environmental Protection Agency, Region 10, Seattle, WA.

PSWQA (Puget Sound Water Quality Authority), 1988. 1988 Puget Sound Water Quality Management Plan. Seattle, WA.

Sea-Bird Electronics, Inc., 1990. Seacat SBE 19 Conductivity, Temperature, Depth Recorder Operating Manual. Sea-Bird Electronics, Inc., Bellevue, WA.

------, 1992a. SBE 25-03 Sealogger CTD Operating Manual. Sea-Bird Electronics, Inc., Bellevue, WA.

------, 1992b. CTD Data Acquisition Software, SEASOFT Version 4.015. Sea-Bird Electronics, Inc., Bellevue, WA.

Smith, D.E., M. Leffler and G.E. Mackiernan [eds.], 1992. Oxygen Dynamics in the Chesapeake Bay. Maryland Sea Grant, College Park, Maryland.

Staker, R.D. and S.F. Bruno, 1980. "Diurnal vertical migration in marine phytoplankton," Botanica Marina. Vol. 23, pp. 167-172.

Steemann Nielsen, E., 1975. Marine Photosynthesis. Elsevier Scientific Publishing Co.

Tetra Tech, Inc., 1988a. Puget Sound Estuary Program, Budd Inlet Action Plan: Initial Data Summaries and Problem Identification. Prepared for U.S. Environmental Protection Agency, Region 10, Seattle, WA, by Tetra Tech, Bellevue, WA, TC-3338-27.

------, 1988b. Puget Sound Estuary Program, Characterization of Spatial and Temporal Trends in Water Quality in Puget Sound. Submitted to U.S. Environmental Protection Agency, Region 10, Seattle, WA, EPA 503/3-88-003.

Throndsen, J., 1978. "Preservation and storage," *In* A. Sournia [ed.] Phytoplankton Manual. Monograph of Oceanographic Methodology, Unesco, pp. 69-74.

URS Corporation, 1986. Southern Puget Sound Water Quality Assessment Study, Final Report: Comprehensive Circulation and Water Quality Study of Budd Inlet. Prepared for Washington State Department of Ecology, Olympia, WA, by URS Corporation, Seattle, WA.

APPENDIX A

Narrative summaries of 1-m and near-bottom dissolved oxygen distribution in Budd Inlet during March-October 1992

Table A.1 Narrative summary of surface (1-m) DO distribution in Budd Inlet from March through October 1992.

Date	DO Range (mg/L)	Tide	Comments
12-Mar-92	8.3 to 13.0	Ebb	High values (>12 mg/L) in central bay at Stations BC3, BC4, BD1 and BD2 Lowest values (<10 mg/L) in East and West Bay
25-Mar-92	12.4 to 20.9	Ebb	Highest values in central bay toward the eastern shore High values (>12 mg/L) over entire bay
7-Apr-92	9.6 to 13.3	Ebb	High values (>12 mg/L) from BB transect to mouth of bay
30-Apr-92	9.7 to 11.1	Flood/High*	Fairly uniform concentrations all over bay No inner bay data plotted
	8.1 to 10.9	Low	Fairly uniform concentrations all over bay
15-May-92	10.0 to 18.8	Flood/High*	Highest values along eastern shore from inner bay at Stations BI2 and BI3 out to central bay at Stations BD1 and BD2 High values (>12 mg/L) over entire bay excluding BF transect
	12.5 to 19.7	Low	Highest values (17.2 to 19.7 mg/L) in central/outer bay (Stations BA2 to BE2) High values (>12 mg/L) over entire bay
28-May-92	7.2 to 10.7	Flood/High*	Lowest value at West Bay Station BI6 Fairly uniform concetrations throughout bay
	5.9 to 10.7	Low	Lowest value at West Bay Station BI5 Fairly uniform concentrations (9.1 to 10.7 mg/L) at all other stations
11-Jun-92	10.8 to 15.3	Flood/High*	Highest concentration in central bay near BB and BC transects High values (>12 mg/L) over entire bay excluding West Bay Station BI5, and outer bay near Station BE1 and BF transect
	8.1 to 13.7	Low	High values (>12 mg/L) in central bay from Stations BA2 to BC3 Lowest value in East Bay at Station BI1
2-Jul-92	7.2 to 14.1	Ebb	High values (>12 mg/L) in central bay at BB transect and along eastern shore at Stations BC1 and BC2 Lowest values in East Bay
	6.7 to 14.4	Low	Highest value in central bay at Station BB2 Lowest value in West Bay at Station BI6 DO values slightly higher at central bay than at inner bay stations
17-Jul-92	6.5 to 14.2	Low	Highest values (>12 mg/L) in central bay Lowest value at West Bay Station BI5 No sampling out past Station BC3 No cross bay transects conducted

* Indicates that the central and outer bay stations were sampled on the flood tide and the inner bay stations were sampled on the following high tide

Table A.1 continued

Date	DO Range (mg/L)	Tide	Comments
29-Jul-92	9.2 to 16.0	Flood	No inner bay values available Highest value at Station BB2 High values (>12 mg/L) in central and outer bay from Stations BB1 and BB2 to Station BC3 and BE transect
	6.6 to 14.4	Low	Highest values (>14 mg/L) in central/outer bay at Stations BC3 to BE2 Lowest value in East Bay at Station BI2 Fairly uniform values (7.0 to 8.5 mg/L) at other inner and central bay stations
13-Aug-92	9.2 to 15.0	Flood/High*	Inner bay values available only at Station BI5 Highest value at Station BC3 High values (>12 mg/L) in central and outer bay from Station BA2 out to Stations BE1 and BE3
	5.1 to 13.7	Low	Highest values (11.9 to 13.7 mg/L) in central/outer bay Lowest values (<6.0 mg/L) at East and West Bays at Stations BI1, BI6 and BI4
26-Aug-92	4.6 to 13.4	Flood/High*	High values (>12 mg/L) in central bay near eastern shore at Stations BB1, BC2 and BC3 Lowest values (4.6 and 5.3 mg/L) at West Bay Stations BI6 and BI5
	4.2 to 11.1	Low	Highest values (9.4 to 11.1 mg/L) in central/outer bay Lowest values (<5.0 mg/L) in East and West Bays at Stations BI2, BI3, BI5 and BI6 Low values (5.0 to 6.0 mg/L) at inner bay Stations BI4 and BA2
10-Sep-92	6.6 to 10.8	Flood/High*	Lowest values at BF transect Fairly uniform concentrations throughout the bay
	7.0 to 9.8	Low	Highest values in central/outer bay Lowest value at West Bay Station BI4 Fairly uniform concentrations throughout the bay
23-Sep-92	5.2 to 8.9	Low	No cross bay transects conducted Lowest values (<6.0 mg/L) in East and West Bays
7-Oct-92	4.7 to 14.8	Flood/High*	Highest values in central bay at Stations BC2 and BC3 High values (>12 mg/L) in central and outer bay concentrated around center transect Lowest value at East Bay Station BI1 Low values (<7.0 mg/L) at West Bay Stations BI6 and BI5
	3.8 to 10.9	Low	Highest values (9.5 to 10.9 mg/L) in central/outer bay Lowest values (<5.0 mg/L) in East and West Bays at Stations BI2, BI5 and BI6 Low values (5.0 to 6.0 mg/L) at remaining inner bay stations
21-Oct-92	5.2 to 7.4	High	Lowest values (<6.0 mg/L) at East Bay Stations BI1 and BI2 and at West Bay Station BI6 Low values (<7.0 mg/L) in inner bay out to Stations BA2 and BB1 Did not sample north of BB transect

* Indicates that the central and outer bay stations were sampled on the flood tide and the inner bay stations were sampled on the following high tide

Table A.2 Narrative summary of near-bottom DO distribution in Budd Inlet from March through October 1992.

Date	DO Range (mg/L)	Tide	Comments
12-Mar-92	7.6 to 11.3	Ebb	Higher DO values along the eastern shore in the central inlet Lowest values in West Bay
25-Mar-92	8.4 to 16.3	Ebb	Higher DO values along the eastern shore in the central inlet
7-Apr-92	9.7 to 11.5	Ebb	Fairly uniform concentrations throughout the bay Highest concentrations in the central to outer inlet
30-Apr-92	7.1 to 10.6	Flood/High*	Fairly uniform concentrations throughout the bay Higher DO values along the eastern shore in the central inlet
	6.6 to 9.5	Low	Fairly uniform concentrations throughout the bay Lowest values (<7.0 mg/L) in West Bay at Stations BI5 and BI6
15-May-92	8.1 to 18.2	Flood/High*	Highest values in East Bay Lowest values in West Bay Remainder of the inlet fairly uniform and measured within 1-2 mg/L of adjacent stations
	7.8 to 15.3	Low	Highest values at Station BA2 (border of inner/central bay)
28-May-92	5.9 to 10.5	Flood/High*	Highest value at Station BI2 in East Bay Lowest value at Station BI5 in West Bay Concentrations increased outward form the head of the inlet Near bottom and surface values were similar for central and outer bay stations
	6.0 to 10.5	Low	Highest value at Station BA2 in inner/central bay Lowest value at Station BI6 in West Bay Concentrations increased outward form the head of the inlet
11-Jun-92	6.4 to 10.9	Flood/High*	Highest values near mouth of inlet with values >7.0 mg/L at Station BA2 outward Lowest values at Stations BI6 and BI5 in West Bay
	5.7 to 9.4	Low	Highest values in the central and outer bay Lowest values (<7.0 mg/L) at West Bay Stations BI6 and BI5
2-Jul-92	5.6 to 13.4	Ebb	Higher values along the eastern shore in the central inlet Lowest values at Stations BI4 (West Bay) and BI2 (East Bay) Low value (5.8 mg/L) at Station BC2 in central inlet
	5.2 to 9.2	Low	Lowest values at Stations BI6 and BI4 in West Bay
17-Jul-92	4.2 to 9.7	Low	Lowest values (<5.0 mg/L) at Stations BI5 and BI4 in West Bay No cross bay transects conducted

* Indicates that the central and outer bay stations were sampled on the flood tide and the inner bay stations were sampled on the following high tide

Table A.2 continued

Date	DO Range (mg/L)	Tide	Comments
29-Jul-92	5.1 to 11.3	Flood	No inner bay values available Lowest values at Stations BC2 and BC3 in central inlet
	3.0 to 8.6	Low	Lowest values (<5.0 mg/L) at Stations BI6, BI5 and BI4 in West Bay
13-Aug-92	4.3 to 11.0	Flood/High*	Lowest value at Station BI5 in West Bay Low values at central inlet Stations BC1 and BC2 (4.7 mg/L) and BC3 (5.8 mg/L) The low DO distribution reached out past the BC transect toward the eastern shore
	3.7 to 8.5	Low	Lowest DO values (<5.0 mg/L) at Stations BI6 and BI5 in West Bay and at BI2 in East Bay
26-Aug-92	2.5 to 7.9	Flood/High*	Lowest value (<3.0 mg/L) in West Bay at Station BI6 Low values (<5.0 mg/L) at all West Bay Stations BI6, BI5 and BI4 Low value (4.9 mg/L) at Station BC1 on the east side of the central inlet
	2.7 to 7.2	Low	Lowest values (<3.0 mg/L) in West Bay at Stations BI5 and BI6 Low values (<5.0 mg/L) in East and West Bays out to Station BB2 in the central inlet
10-Sep-92	4.5 to 7.4	Flood/High*	Lowest values (<5.0 mg/L) in West Bay at Stations BI6 and BI5
	3.9 to 7.0	Low	Low values (<5.0 mg/L) in East and West Bays with lowest concentrations at Stations BI6 and BI5
23-Sep-92	3.3 to 6.9	Low	Lowest values (3.3 to 4.3 mg/L) in West Bay at Station BI6 out to Station BI4 Low value (4.4 mg/L) in East Bay at Station BI2 No cross bay transects conducted
7-Oct-92	2.2 to 7.4	Flood/High*	Lowest value (<3.0 mg/L) at Station BI1 in the East Bay Low values (3.0 to 5.0 mg/L) in West Bay at Stations BI6 to BI4 and in the central inlet at Stations BA2 and BB1 Concentrations increased northward out of the bay once past the BB transect
	3.5 to 7.1	Low	Low values (<5.0 mg/L) in East and West Bays with lowest concetrations at Stations BI6 and BI5
21-Oct-92	5.6 to 6.5	High	Lowest value at Station BI1 in East Bay Did not sample north of BB transect

* Indicates that the central and outer bay stations were sampled on the flood tide and the inner bay stations were sampled on the following high tide

APPENDIX B

Narrative summary of phytoplankton distribution in Budd Inlet during March-October 1992

Table B.1 Narrative summary of chlorophyll a (from discrete laboratory fluorometry analyses and in-situ fluorometer profile data), transmissometer and DO data used to indicate phytoplankton distribution in Budd Inlet from March through October 1992.

Date	Lab Chl Max (mg/m3)	Station and Depth of Lab Chl Max	Tide	Comments
12-Mar-92	9.5	BB2 at 1 m	Ebb	Low phytoplankton conc. indicated by transmissometer and lab fluorometry data
25-Mar-92	13.9	BB2 at 1 m	Ebb	Some bloom activity indicated by transmissometer and lab fluorometry data Bloom max at Stations BI2 and BI5 out to Station BI3 at 2 m Bloom max from Station BI5 out to Station BB2 at 1.0 to 0.5 m
7-Apr-92	27.7	BD2 at 1 m	Ebb	Bloom indicated by transmissometer and lab fluorometry data Bloom max at Stations BI5 and BI6 at 2.5 m and 1.5 m respectively Blooms at Stations BB2 to BE2 at 1 to 4 m with highest values at Station BD2 (2.5 m)
30-Apr-92	6.6	BB2 at 1 m	Low	Low phytoplankton conc. indicated by DO and lab fluorometry data Highest DO (10 mg/L) at Stations BC3 to BE2
15-May-92	25.3 and 25.2	BB2 at near-bottom and BI4 at 1 m	Low	Bloom indicated by DO and lab fluorometry data Bloom throughout bay from Stations BI6 to BE2 DO values >15 mg/L from 0.5 to 2 m (inner bay) and 0.5 to 4 m (central bay)
	23.7	BI4 at near-bottom	High	DO values >15 mg/L in inner bay out to Station BA2 from 0.5 m to 3-4 m No central or outer bay high tide data
28-May-92	1.9	BE2 at near-bottom	Low	Very low phytoplankton conc. indicated by DO and lab fluorometry data
11-Jun-92	18.1	BA2 at 1 m	Low	Bloom indicated by transmissometer and lab fluorometry data Bloom max at Station BA2 out to Station BC3 at 0.5 to 2 m
	41.0	BI4 at 1 m	Flood/High*	Bloom max at Stations BI2 and BI6 out to BC transect and Station BD1 at 1 m
2-Jul-92	No Lab Data	No Lab Data	Low	Large bloom indicated by in-situ fluorometer data Conc. >10 mg/m3 from Station BI6 to ~Station BD2 Max conc. (>25 mg/m3) at Stations BB2 to BC3
	No Lab Data	No Lab Data	Ebb	Max conc. (>25 mg/m3) at Station BA2 out to Stations BC1, BC2 , BC3, BD1 and BE1 at 3 m Max conc. (>25 mg/m3) at Stations BI2 and BI4 out to BB transect at 1 m
17-Jul-92	No Lab Data	No Lab Data	Low	Large bloom indicated by in-situ fluorometer data In-situ fluorometer >10 mg/m3 from Station BI6 out to Station BC3 (no data further out) Max conc. (>30 mg/m3) from Stations BB2 to BC3 In-situ fluorometer values > 25 mg/m3 from Stations BA2 to BB2

* Indicates that the central and outer bay stations were sampled on the flood tide and the inner bay stations were sampled on the following high tide

Table B.1 continued

Date	Lab Chl Max (mg/m3)	Station and Depth of Lab Chl Max	Tide	Comments
29-Jul-92	68.4	BC3 at 3 m	Low	Very large bloom indicated by lab and in-situ fluorometry data Highest conc. in central and outer bay with slightly lower values in the inner bay In-situ flurometer conc. >10 mg/m3 from Stations BI6 to BE2 at 3-5 m In-situ flurometer conc. >30 mg/m3 at Stations BA2 to BE2 and >25 mg/m3 at Station BI4
	No Lab Data	No Lab Data	Flood	No inner bay flood tide data In-situ fluorometer conc. >10 mg/m3 over the central and outer bay at 3-5 m Max conc. (>30 mg/m3) at Station BA2 out to Stations BC1, BC2 and BC3
13-Aug-92	50.7	BE2 at 2 m	Low	Very large bloom indicated by transmissometer and lab fluorometry data Low transmissometer readings at Station BB2 out to Station BE2 at ~1-3.5 m Lowest transmissometer readings at Station BD2 at 1.5 m
	No Lab Data	No Lab Data	Flood/High*	Bloom indicated by transmissometer data from Stations BI5 to BC1, BC2 and BC3 at ~3-4 m Lowest transmissometer readings at Station BC1 at 4 m
26-Aug-92	35.6	BB2 at 3 m	Low	Large bloom over entire bay indicated by in-situ and lab fluorometry data In-situ fluorometer conc. >10 mg/m3 from Stations BI6 to BE2 In-situ fluorometer conc. >25 mg/m3 at Station BI4 and from Station BA2 out to ~Station BD2 In-situ fluorometer max at 1-5 m at Station BB2 and at 3-6 m at Station BC3
	No Lab Data	No Lab Data	Flood/High*	In-situ fluorometer conc. >10 mg/m3 over entire bay at 3-4 m In-situ fluorometer conc. >25 mg/m3 at Stations BI2 and BI6 to BC1, BC2, BC3 and BD2 Depth of in-situ fluorometer max ranged from 2 m (inner bay) to 4 m (central bay)
10-Sep-92	38.8	BA2 at 3.5 m	Low	Large bloom over entire bay indicated by in-situ and lab fluorometry data In-situ fluorometer conc. >25 mg/m3 at Stations BI6 to BC3 and at Station BE2 In-situ fluorometer max at 2-4 m in inner bay and at 4-5 m in central bay
	No Lab Data	No Lab Data	Flood/High*	In-situ flurometer conc. >10 mg/m3 from the inner bay out to Stations BE1 and BE2 at 3-6 m In-situ fluorometer conc. >25 mg/m3 at inner bay stations out to Stations BC1, BC2 and BC3 Depth of in-situ fluorometer max ranged from 2-5 m in inner bay to 5-7 m in central bay
23-Sep-92	36.8	BC3 at 1 m	Low	Bloom over most of bay indicated by in-situ and lab fluorometry data In-situ fluorometer conc. >10 mg/m3 from Station BI5 out to Station BE2 at 1-3 m In-situ fluorometer conc. >25 mg/m3 from Station BA2 out to Station BD2
7-Oct-92	21.2	BC3 at 1.5 m	Low	Some bloom activity over entire bay indicated by in-situ fluorometer data In-situ fluorometer conc. >10 mg/m3 from Station BI3 out to Station BF2 In-situ fluorometer max conc. (20 mg/m3) at Station BB2 out to Station BE2 at ~2 m
	No Lab Data	No Lab Data	Flood/High*	Low transmissometer readings at Stations BI6 to BI4 at 1 m and BC2 and BC3 to BE2 at 1-2 m
21-Oct-92	No Lab Data	No Lab Data	High	Low phytoplankton conc. indicated by transmissometer data

* Indicates that the central and outer bay stations were sampled on the flood tide and the inner bay stations were sampled on the following high tide