WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

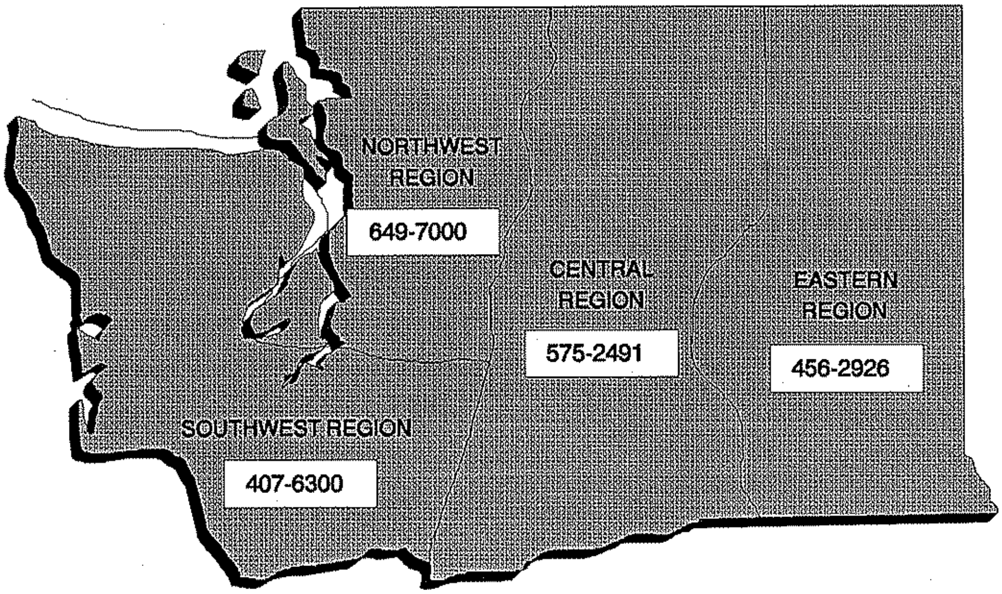
1992 Sinclair and Dyes Inlet Seasonal Monitoring Report

August 1995

Publication No. 95-345

For additional copies of this report, contact:

Department of Ecology
Publications
P.O. Box 47600
Olympia, WA 98504-7600
Telephone: (360) 407-7472



The epartment of Ecology is an equal opportunity agency and does not discriminate on the basis of race, creed, color, disability, age, religion, national origin, sex, marital status, disabled veteran's status, Vietnam Era veteran's status, or sexual orientation.

For more information or if you have special accommodation needs, please contact Kim Douglas at (206) 407-6677. Ecology Headquarters telecommunications device for the deaf (TDD) number is (206) 407-6006. Ecology Regional Office TDD numbers are as follows:

SWRO (TDD) (360) 407-6306
NWRO (TDD) (206) 649-4259
CRO (TDD) (509) 454-7673
ERO (TDD) (509) 458-2055

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Sinclair and Dyes Inlet Seasonal Monitoring Report

---

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

Environmental Investigations
and Laboratory Services Program
Olympia, Washington 98504-7710

August 1995

Publication No. 95-345

printed on recycled paper

Table of Contents

List of Tables

List of Figures

Acknowledgments

Authorship on this report reflects various instrumental input. The Sinclair and Dyes Inlet project was planned by Carol Janzen and conducted primarily by Storrs Albertson, Lisa Eisner, Sharon Bell, and Carol Janzen. Lead authorship was by Storrs Albertson, with contributions from Jan Newton and Lisa Eisner.

Many people assisted the authors of this report collecting data. These include: Bernard Strong, Kelly Carruth, and Mark Golliet, all from the Ecology's Environmental Investigations and Laboratory Services (EILS) Program. Their efforts are greatly appreciated.

We would like to acknowledge the Manchester Environmental Laboratory and specifically 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.

Bernard Strong provided valuable support in the construction, maintenance, and trouble shooting of our field equipment. Mark Golliet and Angie Thomson finalized some of the graphics, and Kati Brown helped to process CTD data for this report. Rita Horner (University of Washington) conducted the phytoplankton taxonomy. Jeff Dairiki (University of Washington) verified some of the numerical calculations. Kim Douglas conducted the final word processing and formatting for report preparation.

Review was kindly done by: Curt Ebbesmeyer (Evans-Hamilton, Inc.), Kaye V. Ladd (The Evergreen State College), Randy Shuman (King County Department of Metropolitan Services), and Will Kendra (Ecology).

Abstract

Sinclair and Dyes Inlets are semi-enclosed partially mixed embayments located in central Puget Sound. Both inlets were designated as sensitive to eutrophication (*i.e.*, nutrient enrichment) by an assessment of long-term water quality data conducted by Tetra Tech (1988a) and in the Urban Bay Action Plan for Sinclair and Dyes Inlets (Jacobson and Booth, 1990) for the Puget Sound Estuary Program (PSEP). An additional water quality problem, noted in the former report, was the presence of occasional low dissolved oxygen (DO) concentrations (*e.g.*, 21 September 1987). The low DO concentrations are partially due to persistent (density) stratification and decay of organic matter. In order to better quantify the timing and extent of these problems, a seasonal monitoring project was conducted from March through October 1992, with biweekly surveys conducted at up to 23 stations in Sinclair and Dyes Inlets. Measured parameters included temperature, salinity, depth, DO, dissolved nutrients (nitrate+nitrite-N, ammonium-N, and orthophosphate-P), Secchi disk depth, chlorophyll *a* (*in situ* fluorometry and discrete laboratory analyses), phaeopigment, light transmission, and phytoplankton taxonomy.

Precipitation in 1992 was notably less than normal (NOAA, 1993) which likely minimized the strength of salinity-induced stratification in both inlets. Stratification in the Sinclair Inlet during 1992 was strongest in the inner inlet, between the inlet head and Bremerton and was driven by changes in both salinity and temperature. As in the Tetra Tech (1988a) study, low DO concentrations (DO < 5.0 mg/L) were observed infrequently (2 of 14 surveys) and only in the inner portion of the inlet, near Port Orchard. The lowest DO concentrations were recorded at stations where phytoplankton concentrations were highest, though not necessarily simultaneously. Near-surface (1-m) nitrate+nitrite-N concentrations fell below reporting limits (0.01 mg/L) in inner and central Sinclair Inlet from early-May to mid-September, with a notable exception occurring on 8 July after a period of precipitation and when phytoplankton concentrations were unseasonably low. The highest nutrient concentrations (particularly ammonium-N) were recorded in the inner Sinclair Inlet, near Port Orchard and south of Bremerton. Phytoplankton blooms (chlorophyll *a* >10 mg/m^3) occurred throughout the Sinclair Inlet during March through October, however, the highest chlorophyll *a* concentrations were consistently in the inner inlet, between the inlet head and Bremerton. Blooms of dinoflagellate species known to migrate vertically (*Gymnodinium splendens*) occurred during early-August at inner Sinclair stations. This migration may be linked to nutrient availability. Potentially harmful (*e.g.*, to vertebrates including fish or humans) phytoplankton species (*Pseudonitzschia pungens, Pseudonitzschia pseudodelicatissima, Alexandrium (Gonyaulax) catenella,* and *Heterosigma carterae*) were present in varying quantities in both Sinclair and Dyes Inlets, though no reports of toxicity or fish kills occurred during this time.

Low DO conditions do not appear to be problematic in either Sinclair or Dyes Inlets; however, Sinclair Inlet does exhibit isolated events of low DO concentrations. Further water quality investigation of low DO conditions should focus on inner Sinclair Inlet, in the vicinity of Port Orchard. At times, this portion of the inlet showed elevated ammonium-N and phytoplankton concentrations as well as low near-bottom DO concentrations (*e.g.*, 19 August 1992 data). More frequent sampling at that location in the late-summer to early-fall period would be necessary to assess how sporadic low DO concentrations are and, thus, whether these observations represent a

significant water quality problem. Sampling of the benthic community in this area would be useful in determining impact of low DO concentration events on biota. Measured DO concentrations were different during low tide than during high tide in this study. A near-bottom moored sensor, capable of recording hourly data, could be used to determine the magnitude, temporal extent and variability of low DO concentrations. Monthly data available from the long-term monitoring stations SIN001 and DYE004 do not resolve short-lived changes in DO concentrations nor adequately reflect water quality conditions elsewhere in these inlets.

Introduction

The Washington State Department of Ecology (Ecology) conducts long-term and focused monitoring projects in Puget Sound and the coastal estuaries of Grays Harbor and Willapa Bay. An assessment of spatial and temporal water quality trends in Sinclair and Dyes Inlets by Tetra Tech (1988b) and the Urban Bay Action Plan (Jacobson and Booth, 1990) identified them as two of the embayments in Puget Sound more sensitive to eutrophication *(i.e.*, nutrient enrichment). Consequently, they were selected as one of the first two focused studies to be undertaken by Ecology in 1992, along with Budd Inlet in south Puget Sound. Results of the Budd Inlet monitoring project are summarized in Eisner *et al.* (1994).

This report, prepared as part of Ecology's Marine Water Column Monitoring Program, contains results of the Sinclair and Dyes 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 Marine Water Column Unit of Ecology's Ambient Monitoring Section (AMS).

Study Area

Sinclair and Dyes Inlets lie in central Puget Sound in a region referred to collectively as the Port Orchard system (Figure 1). The city of Bremerton and the Puget Sound Naval Shipyards are located on the northern shore of Sinclair Inlet while Port Orchard is situated on its southern shore. The smaller city of Silverdale sits on the northern shore of Dyes Inlet. Both inlets have fairly extensive shoreline development, with Sinclair Inlet being the most urbanized. Potential sources of contamination in the study include wastewater treatment plants (WWTPs), combined sewer overflows, emergency overflows, surface water runoff, groundwater, industrial sources and accidental spills. The Bremerton WWTP (effluent limitation of 10.1 million gallon per day) and the Port Orchard/KCSD No. 5 WWTP are permitted under the Clean Water Act, section 301(h) of the National Pollution Discharge Elimination System (NPDES) (locations in Figure 1). Detailed information on these sources is available in Tetra Tech (1988a).

Sinclair Inlet is roughly 5.6 km long extending in a west-southwest direction from Point Herron (east Bremerton) to Gorst Creek at its head, although if measured from Waterman Point, this funnel-shaped inlet is almost 11 km long. Dyes Inlet is about 9.2 km across its widest dimension, from North Bremerton to Silverdale. The two inlets are interconnected by a channel called Port Washington Narrows (Figure 1). Sinclair Inlet has a relatively smooth, muddy bottom (Tetra Tech, 1988a) with depth decreasing gradually from its head (about 3 m at lower-low tide) to its mouth (over 50 m off Waterman Point). Sinclair and Dyes Inlets exhibit a relatively modest two-layer estuarine mean flow pattern (Tetra Tech, 1988a) with saltier, generally colder water entering at depth from outer Puget Sound, and fresher, typically warmer water exiting at the surface. This slow "conveyor belt" of water flow is modified by a large mixed-tide signal. The tidal range in

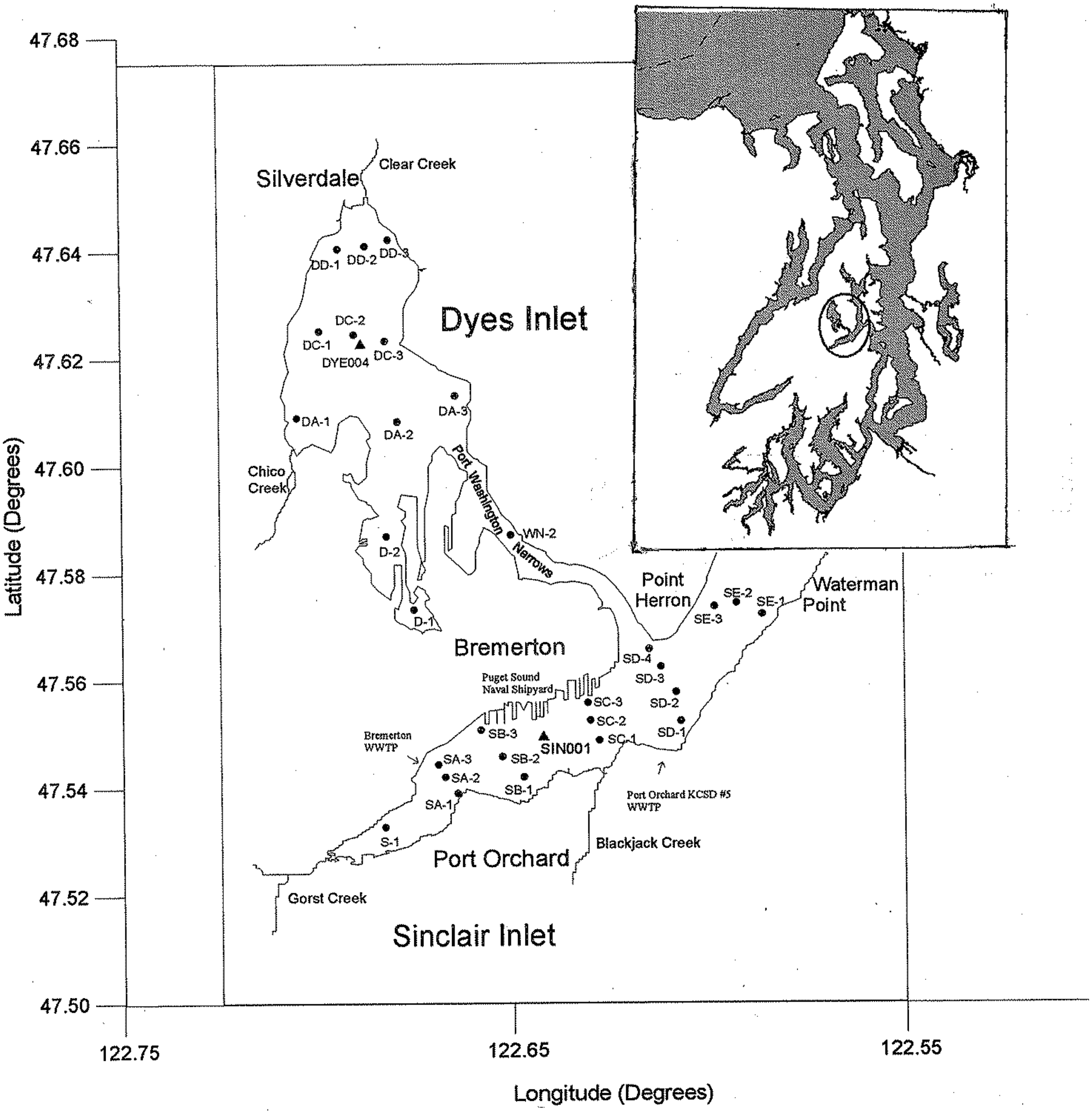


Figure 1. Station locations of the Sinclair and Dyes Inlet study area from March to October 1992. Stations SIN001 and DYE004, from Ecology's long-term monitoring program, are also shown.

Sinclair Inlet is about 3 m (Lavelle *et al.*, 1988). Interactions between tidal forcing, density stratification, bottom topography (friction) and wind stress result in a complex pattern of water flow.

Currents in both inlets are tidally dominated, though the effects of wind may be significant in some portion of the inlets. Maximum currents of > 2 knots occur in Port Washington Narrows (Lavelle *et al.*, 1988). Maximum current speeds in Sinclair Inlet are 0.2 to 0.3 knots (Lincoln and Collias, 1975). Mixing has been noted to be more active in Dyes Inlet than in Sinclair Inlet (Lincoln and Collias, 1975) because of the high currents in Washington Narrows which is the source water for Dyes Inlet. The estimated residence (flushing) time is on the order of 14 days in Sinclair Inlet (U.S. Navy, 1983), and on the order of four days in Dyes Inlet (Lincoln and Collias, 1975).

Flushing rates are lowest near the head of the inlet where a variety of point and non-point sources of pollution are located (Tetra Tech, 1988a). The most significant freshwater drainage into these inlets include: 1) Blackjack Creek that discharges into the south-central portion of Sinclair Inlet near Port Orchard (0.1-1.3 m^3/s), 2) Gorst Creek that discharges into the head of Sinclair Inlet (flow unrecorded), 3) Chico Creek that discharges into Dyes Inlet near the city of Chico (0.0-11.7 m^3/s), and 4) Clear Creek that discharges into the head of Dyes Inlet (0.1- 4.0 m^3/s) (Tetra Tech, 1988a). Overall, freshwater input to this system appears to be relatively low and highly variable, making it difficult to construct suitable box models of estuarine circulation from hydrographic data. Additional information and references on the Port Orchard system can be found in Lincoln and Collias (1975) and in Tetra Tech (1988a).

This study was focused on detecting the effects of eutrophication. The term "eutrophication" implies a process of becoming eutrophic, which means changing from a state of lesser nutrient input to one of greater nutrient input (Edmondson, 1991). Elevated levels of phytoplankton (production and abundance) and depressed dissolved oxygen (DO) concentrations in near-bottom waters are typical results of eutrophication, but not the process itself. Many of these subsequent consequences are often easier to detect. Other water quality problems (*e.g.*, chemical contamination) may exist in these inlets but were outside the scope of this project. Sediment concentrations of metals, volatile, and semi-volatile organic compounds, pesticides, PCBs, and total sulfides, from Sinclair and Dyes Inlets are available most recently in Dutch *et al.* (1992) and Johnston (1993). Elevated concentrations of mercury, copper, lead, and silver, above the mean of all PSAMP stations have occurred in Sinclair Inlet (Llansó, 1995) and of some metals and Polycyclic Aromatic Hydrocarbons in Dyes Inlet as well.

Both Sinclair and Dyes Inlets were designated sensitive to eutrophication by an assessment of long-term water quality data conducted by Tetra Tech (1988a) and in the Urban Bay Action Plan for Sinclair and Dyes Inlets (Jacobson and Booth, 1990) for the Puget Sound Estuary Program (PSEP). Dissolved oxygen concentrations for Ecology's long-term monitoring station SIN001 in Sinclair Inlet (Figure 1) at 0 and 10 m depths have not fallen below WAC (1992) water quality standards (< 6 mg/L DO). However, the presence of occasional low DO concentrations (*e.g.*, 21 September 1987) have been noted in Tetra Tech (1988a). The areal extent and timing of low DO concentration events have not been well-defined for regions of Sinclair or Dyes Inlets (Jacobson and Booth, 1990).

Low DO concentrations in various areas of both Sinclair and Dyes Inlets 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; phytoplankton blooms that die off, sink to the bottom, and result in oxygen consumption due to organic material decay; enhancement of phytoplankton blooms by nutrient (especially nitrogen) inputs from Port Orchard, Bremerton, Silverdale, and the surrounding developed areas; blooms of vertically migrating dinoflagellates that have a net production of oxygen in the surface waters during the day, but consume oxygen at depth during the night; high sediment oxygen demand (SOD; and high biological oxygen demand (BOD) from pollutant sources.

In order to better assess eutrophication in Sinclair and Dyes Inlets, a study entailing frequent sampling during the growing season and spatially comprehensive monitoring of the embayments was conducted.

Project Objectives

The overall goal of the 1992 Sinclair and Dyes Inlet project 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 was to have a working knowledge of physical and biological processes within the inlets and their dynamics.

Specific objectives to meet the project goal were to:

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

2. determine the onset, duration, and location of low DO 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* during the phytoplankton 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 DO (Staker *et al*, 1980, and Kamykowski, 1981); and

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).

Methods

Monitoring Approach and Design

The 1992 Sinclair and Dyes Inlet project was designed to document spatial and temporal patterns in physical, biological, and chemical conditions within both inlets. Table 1 lists each station, its latitude and longitude, parameters sampled, and number of vertical CTD (conductivity, temperature, depth) profiles taken.

Field surveys were planned every two weeks between 26 March and 14 October 1992, though logistical constraints occasionally prevented this regular sampling interval from being accomplished. Up to 32 stations were monitored in the study area, 20 in Sinclair Inlet, 11 in Dyes Inlet, and one in the Port Washington Narrows (Figure 1).

Sinclair Inlet Sampling

Sinclair Inlet was divided into inner, central, and outer areas. Inner Sinclair stations include those on the SA and SB transects and station S-1 (area west of Port Orchard). Outer Sinclair stations include those on the SD and SE transects (area east of Washington Narrows (Point Herron), and the central Sinclair stations were those on the SC transect. These zones are slight modifications from those of Lincoln and Collias (1975).

Two principal sampling strategies were employed:

1. biweekly along-channel transects (meaning from the inlet head toward its mouth), conducted to detect gradients in physical, biological, and chemical parameters emanating outward from the head of the inlet; and
2. biweekly cross-channel transects, conducted to characterize the distribution of most of these parameters over the entire inlet.

Along-Channel Transects

Along-channel transects consisted of six stations (S-1, SA-2, SB-2, SC-2, SD-2, SE-2) from the head of the inlet to the mouth along the central axis of the inlet (Figure 1). The transect was sampled during slack tide in order to minimize the influence of dynamics resulting from the tidal mixing and movement of water in and out of the inlet. Five high slack periods and nine low slack periods were sampled in Sinclair Inlet during 1992 (Table 2). For these purposes, a slack tide was defined as a period lasting from one hour before until one hour after either a high or low tide. In order to compare data throughout the season, sampling on the low slack tide was targeted. The resultant sampling scheme, however, was as much a function of what was logistically feasible as it was logically ideal.

Table 1. Sinclair and Dyes Inlets' station locations, parameters sampled, and number of casts made during 1992. An ‘A’ after the station name indicates it was included on slack tide along-channel transects. Where ‘CTD’ is indicated, this includes a continuous depth profile of conductivity, temperature, dissolved oxygen, and transmissometer (and pH) or fluorometer readings. Also, ‘chl *a*’ indicates both chlorophyll *a* and phaeopigment analyses; ‘nutrients’ indicates dissolved nitrate+nitrite-N, ammonium-N and orthophosphate-P analyses and ‘phyto’ indicates water samples were taken for enumeration and speciation of phytoplankton.

Station	*Latitude (N)*	*Longitude (W)*	*Parameters Sampled*	*# of CTD Casts Made*
Dyes Inlet				
D-1	47° 34.40’	122° 40.52’	CTD, nutrients, chl *a*	5
D-2	47° 35.22’	122° 40.91’	CTD	8
DA-1	47° 36.54’	122° 42.28’	CTD	3
DA-2	47° 36.50’	122° 40.73’	CTD, nutrients, chl *a*	8
DA-3	47° 36.78’	122° 39.86’	CTD, nutrients, chl *a*	4
DC-1	47° 37.51’	122° 41.95’	CTD	5
DC-2	47° 37.47’	122° 41.39’	CTD, nutrients, chl *a*, phyto	8
DC-3	47° 37.40’	122° 40.92’	CTD	5
DD-1	47° 38.43’	122° 41.65’	CTD, nutrients, chl *a*	4
DD-2	47° 38.48’	122° 41.22’	CTD, nutrients, chl *a*	8
DD-3	47° 38.53’	122° 40.87’	CTD	4
Wash- WN-2*	47° 35.23’	122° 38.98’	CTD, nutrients, chl *a*	4
Sinclair Inlet				
S-1, A	47° 31.96’	122° 40.97’	CTD, nutrients	20
SA-1	47° 32.34’	122° 39.85’	CTD	13
SA-2, A	47° 32.52’	122° 40.03’	CTD, nutrients, chl *a*	21
SA-3	47° 32.66’	122° 40.14’	CTD	12
SB-1	47° 32.52’	122° 38.85’	CTD, nutrients, chl *a*	13
SB-2, A	47° 32.75’	122° 39.15’	CTD, nutrients, chl *a*, phyto	26
SB-3	47° 33.04’	122° 39.46’	CTD, nutrients, chl *a*	13
SC-1	47° 32.92’	122° 37.68’	CTD	12
SC-2, A	47° 33.15’	122° 37.82’	CTD, nutrients, chl *a*	25
SC-3	47° 33.35’	122° 37.88’	CTD	11
SD-1	47° 33.14’	122° 36.43’	CTD, nutrients, chl *a*	12
SD-2, A	47° 33.46’	122° 36.49’	CTD, nutrients, chl *a*, phyto	22
SD-3	47° 33.75’	122° 36.69’	CTD	11
SD-4	47° 33.95’	122° 36.87’	CTD, nutrients, chl *a*	10
SE-1	47° 34.33’	122° 35.15’	CTD	12
SE-2, A	47° 34.46’	122° 35.55’	CTD, nutrients, chl *a*	16
SE-3	47° 34.42’	122° 35.85’	CTD	10
SF-1	47° 35.12’	122° 34.40’	CTD	2
SF-2, A	47° 35.25’	122° 34.90’	CTD, nutrients, chl *a*	3
SF-3	47° 35.39’	122° 35.36’	CTD	2

* Same location as long-term monitoring station DYE003

Table 2. Date and tidal stage of Sinclair and Dyes Inlet seasonal surveys; March-October 1992. Slack tide (low or high) was considered to be within +/- one hour of the peak low or high tide. Tidal range and exchange data relate to a 24-hour period beginning at midnight (local time) on the survey date. "ND" indicates "No Data" (survey not done).

Date of Survey	*Sinclair Inlet Along-channel Transect Tidal Stage*	*Sinclair Inlet Cross-channel Transect Tidal Stage*	*Dyes Inlet Tidal Stage*	*Primary CTD Used*	*Tidal Range (m) @ Port Orchard*	*Tidal Exchange (m) @ Port Orchard*
26-Mar-92	Low	Low	Ebb	SBE 19	0.4 - 3.2	2.8
21-Apr-92	Low	ND	Ebb	SBE 19	-0.2 - 3.5	3.7
6-May-92	Low	Flood	Ebb	SBE 19	-0.7 - 3.8	4.5
20-May-92	Low	Ebb	ND	SBE 19	-0.3 - 3.7	4.0
10-Jun-92	High	Flood	Flood	SBE 19	0.0 - 3.7	3.7
24-Jun-92	High	Ebb	Flood	SBE 19	0.6 - 3.5	2.9
8-Jul-92	High	Flood	Flood	SBE 25	0.1 - 3.7	3.6
22-Jul-92	High	Ebb	ND	SBE 25	0.7 - 3.4	2.7
5-Aug-92	High	Ebb	Flood	SBE 25	0.1 - 3.5	3.4
19-Aug-92	Low	Ebb	ND	SBE 19	0.5 - 3.4	2.9
3-Sep-92	Low	Ebb	High	SBE 25	0.0 - 3.2	3.2
16-Sep-92	Low	Ebb	ND	SBE 25	0.1 - 3.3	3.2
30-Sep-92	Low	Flood	Ebb	SBE 19	-0.4 - 3.5	3.9
14-Oct-92	Low	Flood	ND	SBE 25	-0.2 - 3.5	3.7

CTD profiling casts and Secchi disk measurements were conducted at each station in the along-channel transect. These six stations 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 areas with minimal dynamic influences from the tides. In addition, phytoplankton samples were collected, predominantly at station SB-2, and analyzed for species composition.

Cross-Channel Transects

To better characterize the entire inlet, cross-channel sampling was conducted at five transects (SA, SB, SC, SD, SE), each with three or four stations spanning the width of the inlet (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-channel transect sampling. Although ideal sampling conditions occur during the least amount of dynamic change, as during slack tide periods or during small tidal exchanges, the majority of the Sinclair Inlet cross-channel transects took place during flood or ebb tide. Most of the sampling occurred during the larger exchange of neap tide events (Table 2). Thus, these data may show influences due to tidal advection as well as location. CTD profiling and Secchi disk measurements were conducted at each station in the cross-channel transects. No additional water samples were collected during this portion of the monitoring, except during the first survey, when all stations were sampled for nutrients.

Dyes Inlet Sampling

Dyes Inlet was sampled every other week from 26 March through 8 July 1993 (excluding 20 May) on the same days as Sinclair surveys. Due to the lack of conventional water quality information in Dyes, sampling during the first survey consisted exclusively of cross-channel transects, with all stations sampled for nutrients, Secchi depths, and CTD profiles. The temporal and spatial variability in Dyes Inlet was less than in Sinclair Inlet, and since reduction in the scope of work for these two inlets was necessary for logistical reasons, less frequent sampling was adopted. Thus, the number of monitoring stations in Dyes Inlet was reduced and the sampling period was increased from biweekly to monthly.

Eleven stations in Dyes Inlet were established for water quality sampling (Figure 1). Stations DD-1, DD-2, DC-2, DA-2, and D-1 were typically sampled during each survey and were sampled for nutrients, chlorophyll *a*, phaeopigment, Secchi disk depth and CTD profiles. In addition, phytoplankton samples, predominantly collected at station DC-2, were analyzed for species composition. Dyes Inlet cross-channel transects, when completed, consisted of three transects (DD, DC, DA), each with three stations (Figure 1). Only CTD profiles and Secchi depths were conducted at the cross-channel transect stations. All but one of the Dyes Inlet surveys occurred during ebb or flood tides (Table 2).

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 pre-positioned Ecology or navigational buoys also were used to facilitate station location.

Either a Sea-Bird Electronics, Inc., Sealogger® SBE-25 CTD or a Seacat® SBE-19 CTD profiler were used to collect continuous water column profile data (Table 2). Parameters measured by sensors on the SBE-25 included conductivity (used to compute salinity), temperature, pressure (used to calculate depth), DO, and fluorescence (to estimate chlorophyll *a* concentration). Density was derived from salinity and *in situ* temperature. The Seacat® SBE-19 CTD profiler was used in the early surveys (through June), and as a backup instrument when the SBE-25 was being calibrated. The SBE-19 CTD measured conductivity, temperature, pressure, DO, 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. Real-time observation of the profiles was obtained with a data link to a lap-top computer and aided the determination of discrete sampling depths. Profiling 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 disk depths were used to indicate water clarity based on the extinction of light in the water column. Derivation of the light extinction coefficient allows calculation of the approximate euphotic zone depth.

A 1.2-L Niskin® bottle was manually deployed to collect discrete water samples for dissolved nutrients (ammonium-N, nitrate+nitrite-N, and orthophosphate-P), chlorophyll *a*, phaeopigment, phytoplankton enumeration and taxonomy, DO, 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 DO sensor attached to the CTD profiling unit. A Beckman sensor was used on the SBE-19 CTD and a YSI sensor was used on the SBE-25 CTD. An integral pump kept a continual flush of sample water washing over the sensor membrane surface. Combining DO data from two different CTD units (see Table 2) is not ideal. However, both instruments were routinely calibrated (monthly) at the same lab and time, with two-point calibrations (*i.e.*, 0 mg/L and saturated). These procedures are described in the Quality Assurance section.

Discrete DO samples (N=11) were collected for comparison to CTD sensor values and analyzed at Ecology using the Winkler Method with the azide modification (APHA-AWWA-WPCF, 1989). These results and the differences between the CTD and Winkler DO data are listed in Table 3. Comparison of the two methods is only available for DO concentrations ranging 6 to 12 mg/L. The mean of the differences is relatively low (less than 0.5 mg/L); however, standard deviation is quite high (~1 mg/L), and on three occasions the two methods differed by nearly 2 mg/L (Table 3). No bias was apparent in the data. The result of a two-tailed paired-sample *t*-test was that there was no consistent difference between the means of the Winkler and CTD DO data (the null hypothesis) at the 95% confidence level. However, the probability of Type II error (not rejecting the null hypothesis when it is false) was very high with this small sample size. Thus, bias was low, but random variation was quite high.

Table 3. A comparison of dissolved oxygen data by Winkler titration and from CTD sensor values collected during 1992 Sinclair and Dyes Inlets surveys. Results from a paired-sample, 2-tail *t*-test are shown. The null hypothesis, H_o, for the *t*-test is that there is no difference between the means of the two methods.

Survey #	*Date*	*Station*	*Depth (m)*	*Winkler DO (mg/L)*	*CTD DO (mg/L)*	*Diff. = Wink. - CTD*
3	5/6/92	SF-2	0.0	11.44	11.96	-0.52
3	5/6/92	SF-2	10.0	11.65	12.05	-0.40
9	8/5/92	D-1	1.0	13.47	11.56	1.91
10	8/19/92	SA-2	5.0	7.92	7.35	0.57
11	9/3/92	SD-2	1.0	8.55	6.82	1.73
11	9/3/92	SD-2	10.0	8.44	6.77	1.67
12	9/16/92	SA-2	4.0	6.07	6.56	-0.49
12	9/16/92	SB-2	5.0	6.17	6.40	-0.23
12	9/16/92	SB-2	5.0	5.87	6.40	-0.53
14	10/14/92	SB-2	3.0	8.97	8.74	0.23
14	10/14/92	SB-2	3.0	8.56	8.74	-0.18
					mean	0.34
					standard deviation	0.98
					$T_{calculated}$	1.16
					standard error	0.29

Such random variation in the agreement between the two methods may be due to several sources:

1. Different water masses sampled. Water bottles are deployed after the CTD profile is taken. Drifting by the boat and water advection can result in different water sources. The length (vertical extent) of the water bottle is also a problem when the magnitude of the vertical DO gradient is large (as on 5 August and 3 September at a depth of 1 m).

2. Insufficient reagents. The Hach, Inc., powdered chemical reagents used for the Winkler analyses are not recommended for DO concentrations greater than 10 mg/L.
3. Operator error in sampling or titration of Winkler samples.
4. DO sensor inaccuracies that are not detected by manufacturer recommended two point calibrations (*e.g.*, non-linearity of response, effect of temperature lags).
5. DO sensor data processing (*e.g.*, offsets).

Although this comparison was made on a very limited number of samples, in some cases (*e.g.*, 3 September 92 data), the agreement obtained was unacceptably poor. Such results have illuminated a problem in the current procedures used to measure DO and to assess sensor accuracy that is presently under evaluation at Ecology. More samples (larger N) and comprehensive sampling over the water column are required. Winkler analyses should be conducted on discrete samples from numerous depths at one station for regression with data from the CTD DO sensors in order to assess the agreement between these two methods and discern sources of variation.

Nutrients

Discrete nutrient samples were collected biweekly at both 1-m and near-bottom depths. Near-bottom sampling was at 10 m, or at 1 m above the bottom in waters less than 10 m. Sub-samples 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 frozen for preservation. Frozen samples were delivered to Ecology's Manchester Environmental Laboratory (MEL) for analysis of dissolved nitrate+nitrite-N (NO_3+NO_2-N), ammonium-N (NH_4-N) and orthophosphate-P (oPO_4-P) using an Alpkem® series 300 autoanalyzer following analytical method numbers 353.2, 350.1 and 365.3 (US EPA, 1984), respectively.

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 depths or at the Secchi disk depth. The depths of maximum phytoplankton abundance for the early surveys (March through June), inferred from the transmissometer and DO profiles, varied from 0.5 to 2.5 m. Therefore, the 1-m chlorophyll *a* samples from these survey provide a reasonable estimate of peak chlorophyll *a* values. Chlorophyll *a* samples from 0.5-m depth were also collected monthly in central Sinclair Inlet (station SIN001) and Dyes Inlet (station DYE004) (Figure 1), as part of the long-term monitoring program conducted by Ecology.

Samples were filtered at the end of the survey day at the field laboratory. Fifty-mL sub-samples 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 MEL 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

Phytoplankton samples were taken at 1 m from 26 March to 24 June, and at the depth of the fluorescence maximum from 8 July to 14 October. These samples were always accompanied by a chlorophyll *a* sample. Phytoplankton samples from long-term stations, SIN001 and DYE004, were collected at 0.5 m. Phytoplankton 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) according to Hasle (1978).

Data Processing

CTD data were processed using SEASOFT® Software, versions 4.006 and 4.015 with the most recent calibration coefficients (see QA section). CTD data were averaged over 0.5-m depth intervals for both the SBE-25 Sealogger® CTD and the SBE-19 Seacat® CTDs. Profiles of salinity and density (σ_t) were derived using these averaged 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, DO, and chlorophyll *a* values were made using Golden Software's SURFER® package program. Data were first gridded by kriging (a form of radial basis function interpolation or spline) 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 (*e.g.*, within 100 m).

Phytoplankton Abundance

A direct measurement of phytoplankton abundance was obtained from phytoplankton cell counts. However, due to financial constraints, these were done only for one station in inner Sinclair Inlet and one in Dyes Inlet per survey. Another measurement of phytoplankton was chlorophyll *a*. Fluorometric determination of chlorophyll *a* was conducted both *in situ* and by laboratory analysis of 90% acetone extracts from discrete water samples. Unfortunately, the *in situ* fluorometer was not available for all surveys and so transmissometry and DO readings were used as indirect indicators of phytoplankton biomass. Table 4 shows the methods used to evaluate phytoplankton/chlorophyll *a* distribution and concentration for each survey date. All of these methods have associated imprecision for estimating phytoplankton biomass.

Table 4. Methods used to evaluate phytoplankton biomass in Sinclair and Dyes Inlet surveys during 1992. The transmissometer was removed for repair during May 1992.

	Field measurements with CTD sensors			*Lab analysis*
Survey Date	*Fluorometer (Chlorophyll a)*	*Transmissometer*	*Dissolved Oxygen*	*Chlorophyll a*
26-Mar-92		X	X	X
21-Apr-92		X	X	X
6-May-92			X	X
20-May-92			X	X
10-Jun-92		X	X	X
24-Jun-92		X	X	
8-Jul-92	X		X	X
22-Jul-92	X		X	X
5-Aug-92	X		X	X*
19-Aug-92		X	X	X*
3-Sep-92	X		X	X*
16-Sep-92	X		X	X*
30-Sep-92		X	X	X*
14-Oct-92	X		X	X*

* Indicates result was qualified as an estimate

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, light, nutrient, and physiological conditions. Thus, chlorophyll *a* concentration is specific for phytoplankton biomass but the exact amount of phytoplankton (*e.g.*, mg C or # cells) 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. Phaeopigments are degradation products of chlorophyll *a* and are primarily produced during zooplankton herbivory. 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 material in the water column that may either quench or contribute to the *in situ* fluorescence signal. 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. In addition, all chlorophyll *a* samples from this project were stored in air instead of acetone prior to analysis. Subsequent evaluation showed that storage of filtered cells in air can result in pigment degradation of approximately 22% over replicates stored in acetone (Eisner, 1994). These 1992 laboratory chlorophyll *a* results may consequently be somewhat lower than the true extracted pigment values.

For surveys when fluorometry data were not available, transmissometer and/or DO data were used to indicate phytoplankton biomass, although both measurements are not specific for phytoplankton. Low transmissometer readings indicate high concentrations of suspended particles. However, the percent of the suspended particles which 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 DO concentrations (> 100% saturated DO value) 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 DO is also affected by many other physiological and biological factors, such as, mixing with deep water and respiration, DO data can only be considered as very imprecise indicators of phytoplankton.

Quality Assurance

Data Quality Objectives

Data quality objectives for reporting limits and precision for the Sinclair and Dyes Inlet Seasonal Monitoring Study are listed in Table 5. 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; MEL objective 0.01 mg/L); and

2. the precision (relative standard deviation) for chlorophyll *a* (PSAMP requests +/- 10%; MEL objective +/- 20%).

Table 5. Marine water column quality assurance/quality control objectives. PSAMP units of microgram-atom/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%
Nitrate+Nitrite-N	mg/L	0.01	* 10%
Orthophosphate-P	mg/L	0.01	* 10%
Chlorophyll *a* and Phaeopigments	mg/m^3	0.05	20%
CTD Parameters			
Conductivity / Salinity	ppt	0.01	8%
Temperature	°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/m^3 (chl *a*)	Not Determined	Not Determined

* maximum RSD expected near the reporting limit

Laboratory Quality Control (QC) Procedures and Results

Laboratory QC Procedures

Manchester Environmental Laboratory's QC procedures are described in the Manchester Quality Assurance Manual (Ecology, 1988) and their procedures specific to the analyses conducted in this study are found in Marine Water Column Ambient Monitoring Plan (Janzen, 1992). Calibrations of the autoanalyzer and fluorometer are maintained by the MEL.

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. This also made a comparison of lab versus field chlorophyll *a* determinations difficult because the fluorometer was not available until the 8 July survey.

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 x (standard deviation/mean). Results that fell below reporting limits were not included in the precision estimates. Reporting limits, the minimum concentration at which a predetermined level of precision is attainable, are shown for all parameters in Table 5. 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 6 shows the estimated precision of dissolved nutrients (nitrate+nitrite-N, ammonium-N, orthophosphate-P), chlorophyll *a* and phaeopigment data. For nutrients, nearly 85% of the orthophosphate-P and nitrate+nitrite-N, and over 60% of the ammonium-N data were within the targeted RSD range. The estimated precision for phaeopigments was quite poor; however, the number of samples was also very small. Numerous samples were omitted from this tabulation due to their qualification by MEL as "estimated value."

Table 6. Relative Standard Deviation (RSD) for nutrient, chlorophyll *a*, and phaeopigment results in Sinclair and Dyes Inlets from March-October 1992: lab duplicate results. Below reporting limit data are excluded. RSD = 100 x standard deviation / mean. Shaded areas indicate the target RSD range (Janzen, 1992) for each parameter.

RSD (%)	*Nitrate+Nitrite -N (% total)*	*Ammonium -N (% total)*	*Orthophosphate -P (% total)*	*Chlorophyll a (% total)*	*Phaeopigment (% total)*
0-10	83.3%	62.5%	84%	75%	0%
10-20	0%	18.8%	12%	25%	33.3%
20-30	0%	6.3%	4%	0%	0%
30-40	5.6%	12.5%	0%	0%	66.7%
40-50	0%	0%	0%	0%	0%
50-60	0%	0%	0%	0%	0%
60-70	0%	0%	0%	0%	0%
70-80	0%	0%	0%	0%	0%
80-90	5.6%	0%	0%	0%	0%
90-100	0%	0%	0%	0%	0%
> 100	5.6%	0%	0%	0%	0%
Total #	18	16	25	4	3

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).

Calibration coefficients for temperature, conductivity, and pressure sensors were determined at Sea-Bird Electronics, Inc., during routine annual factory calibrations. These coefficients were applied during data processing. Sea-Bird's published specifications (Sea-Bird, 1992c) for precision and/or accuracy, in all cases met or exceeded the project objectives (*i.e.*, conductivity +/- 0.001 S/m, temperature +/- 0.01°C and depth +/- 0.25%). In addition, annual measurement of calibration standards show that sensors have drifted less than 0.0003 S/(m-month) for conductivity and 0.005°C/year for temperature. The *in situ* fluorometer was calibrated annually by Sea Tech, Inc. Monthly two-point (*e.g.*, zero and saturated) laboratory calibrations for the *in situ* DO sensors were conducted at Ecology by AMS staff to obtain calibration coefficients.

Results

Hydrography

Sinclair Inlet

Variations in the hydrographic parameters were evident spatially, primarily in the along-channel direction of the inlet, and temporally, both with season and over tidal cycles. Sinclair Inlet along-channel transect hydrographic data, collected primarily during low tides at station SA-2, are summarized in Table 7. A comparison of data from station SB-2 collected during slack tide versus during either flood or ebb tides is shown in Table 8. Most of the data represent daytime and light wind (less than 10 km/h) conditions.

Temperature

Sinclair Inlet went from being thermally well-mixed in early-spring (*e.g.*, 21 April slack tide data with a temperature difference from a depth of 1 m to the near-bottom of only 1°C) (Figure 2a) to being thermally stratified by the 24 June survey (temperature difference from a depth of 1 m to the near-bottom of 8°C) (Figure 2b). Throughout the summer, thermal stratification increased in extent and intensity. The water column remained thermally stratified until early-September, with temperatures at a depth of 1 m ranging from 16 to 22°C (Table 7). Near-bottom temperatures varied by only about one degree during the period, ranging from 14 to 15°C. The most thermally stratified conditions in inner Sinclair Inlet were observed on 24 June, 19 August, 3 September and 6 May (Tables 7 and 8). Of these dates, the first two were when the warmest temperatures at a depth of 1 m were recorded (Figure 3). From mid-September through October, the thermocline became deeper and weaker (Figure 2c).

During surveys taken closer to high tide (10 June through 05 August), warmer surface waters tended to remain in the inner areas, from the head of the inlet (station S-1) to the SC transect (Figure 3a). During surveys taken closer to low tide (26 March through 20 May, and 19 August through 14 October), warmer surface waters tended to extend further towards the outer stations in the SD and SE transects (Figure 3b, d). Overall, thermal stratification was greatest in inner Sinclair Inlet (Figure 3c) where shallow depths and lower circulation allows increased solar heating.

Table 7. Summary of biweekly hydrographic data collected during 1992 slack tide along-channel surveys at inner bay station SA-2 in Sinclair Inlet. Larger values in the relative stratification column indicate greater stratification. The depth of the thermocline (and pycnocline) was determined as the depth at which the absolute value of the gradient in temperature (and density) was maximum. Relative stratification was calculated as the difference between near-bottom and 1-m sigma-*t* values; larger values indicate greater stratification between these depth strata. Potential energy was calculated as the difference in gravitational energy between the as-stratified water column and that same water column when mixed to achieve homogeneity. The larger the magnitude of this number, the greater the stratification throughout the water column. Average density, $\overline{\rho}$, is the mean of all CTD values from all depths of a cast, as described in the text. Numbers in parenthesis (in final two columns) indicate overall rank due to stratification.

1992 Survey Date	*Tidal Stage*	*Minimum Temperature (^oC)*	*Maximum Temperature (^oC)*	*Minimum Salinity (ppt)*	*Maximum Salinity (ppt)*	*Average Density (sigma-t)*	*Depth of Thermocline (m)*	*Depth of Pycnocline (m)*	*Relative Stratification (sigma-t)*	*Potential Energy (PE) per Volume (Joule/m^3)*
3/26	Low	9.7	10.7	28.3	28.7	21.93	3.3	1.8	0.51	-3.9
4/21	Low	10.2	11.2	28.7	29.1	22.10	3.8	3.8	0.41	-3.8
5/6	Low	12.2	15.8	28.5	28.8	21.36	3.3	3.3	0.94	-8.7
5/20	Low	12.1	13.1	29.0	29.1	21.81	6.8	7.3	0.28	-2.4
6/10	High	13.1	15.0	28.9	29.2	21.70	1.3	1.8	0.66	-5.4
6/24	High	14.9	21.7	28.6	29.2	20.79	2.8	2.8	2.06 (1)	-20.0 (1)
7/8	High	14.3	16.2	28.5	29.5	21.52	3.3	1.8	1.11	-8.6
7/22	High	14.5	16.2	29.1	29.6	21.64	1.8	1.3	0.77	-7.1
8/5	High	14.7	16.2	29.6	29.8	21.83	1.3	1.3	0.45	-3.8
8/19	Low	15.5	19.0	29.4	29.8	21.40	2.8	2.8	1.14 (3)	-11.9 (2)
9/3	Low	15.0	18.8	29.3	30.0	21.76	1.8	1.8	1.42 (2)	-10.2 (3)
9/16	Low	14.7	15.7	29.7	30.1	22.14	1.3	1.3	0.54	-4.0
9/30	Low	13.9	15.0	30.0	30.2	22.40	1.3	1.3	0.44	-3.2
10/14	Low	13.6	13.9	30.1	30.3	22.51	1.4	7.9	0.23	-1.7

Table 8. A comparison of biweekly hydrographic data collected during 1992 at slack tide and during exchange at inner bay station SB-2 in Sinclair Inlet. Larger values in the relative stratification column indicate greater stratification. Relative stratification was calculated as the difference between near-bottom and 1-m sigma-*t* values; larger values indicate greater stratification between these depth strata. "ND" indicates "No Data" (Not Done).

1992 Survey Date	*Tidal Stage*	*Min/Max Temperature (^oC)*	*Min/Max Salinity (ppt)*	*Relative Stratification (sigma-t)*	*Tidal Stage*	*Min/Max Temperature (^oC)*	*Min/Max Salinity (ppt)*	*Relative Stratification (sigma-t)*
3/26	Low	9.6/10.9	28.2/28.8	0.7	ND	ND	ND	ND
4/21	Low	10.2/11.5	28.5/29.1	0.6	ND	ND	ND	ND
5/6	Low	11.4/15.0	28.4/29.0	1.1	Flood	11.2/14.7	28.6/29.0	0.9
5/20	Low	11.9/13.7	28.0/29.5	1.6	Ebb	12.0/14.3	28.7/29.1	0.8
6/10	High	13.1/14.9	28.8/29.2	0.7	ND	ND	ND	ND
6/24	High	14.6/20.7	28.6/29.2	1.9	Ebb	14.2/21.3	28.7/29.2	2.0
7/8	High	13.9/16.1	28.7/29.5	1.0	Flood	13.9/16.4	28.6/29.5	1.2
7/22	High	14.4/16.3	29.3/29.6	0.6	Ebb	14.6/16.2	29.3/29.6	0.6
8/5	High	14.7/15.7	29.5/29.8	0.4	Ebb	14.7/16.2	29.5/29.8	0.6
8/19	Low	15.3/19.1	29.3/29.8	1.2	Ebb	15.2/18.6	29.3/29.9	1.2
9/3	Low	15.0/18.4	29.4/30.1	1.3	Ebb	15.0/18.3	29.3/30.0	1.4
9/16	Low	14.5/15.7	29.7/30.1	0.5	Ebb	14.5/15.5	29.8/30.1	0.6
9/30	Low	13.8/15.5	29.9/30.3	0.7	Flood	13.8/15.4	29.9/30.3	0.5
10/14	Low	13.4/13.5	29.9/30.3	0.3	Flood	13.4/13.7	29.9/30.0	0.3

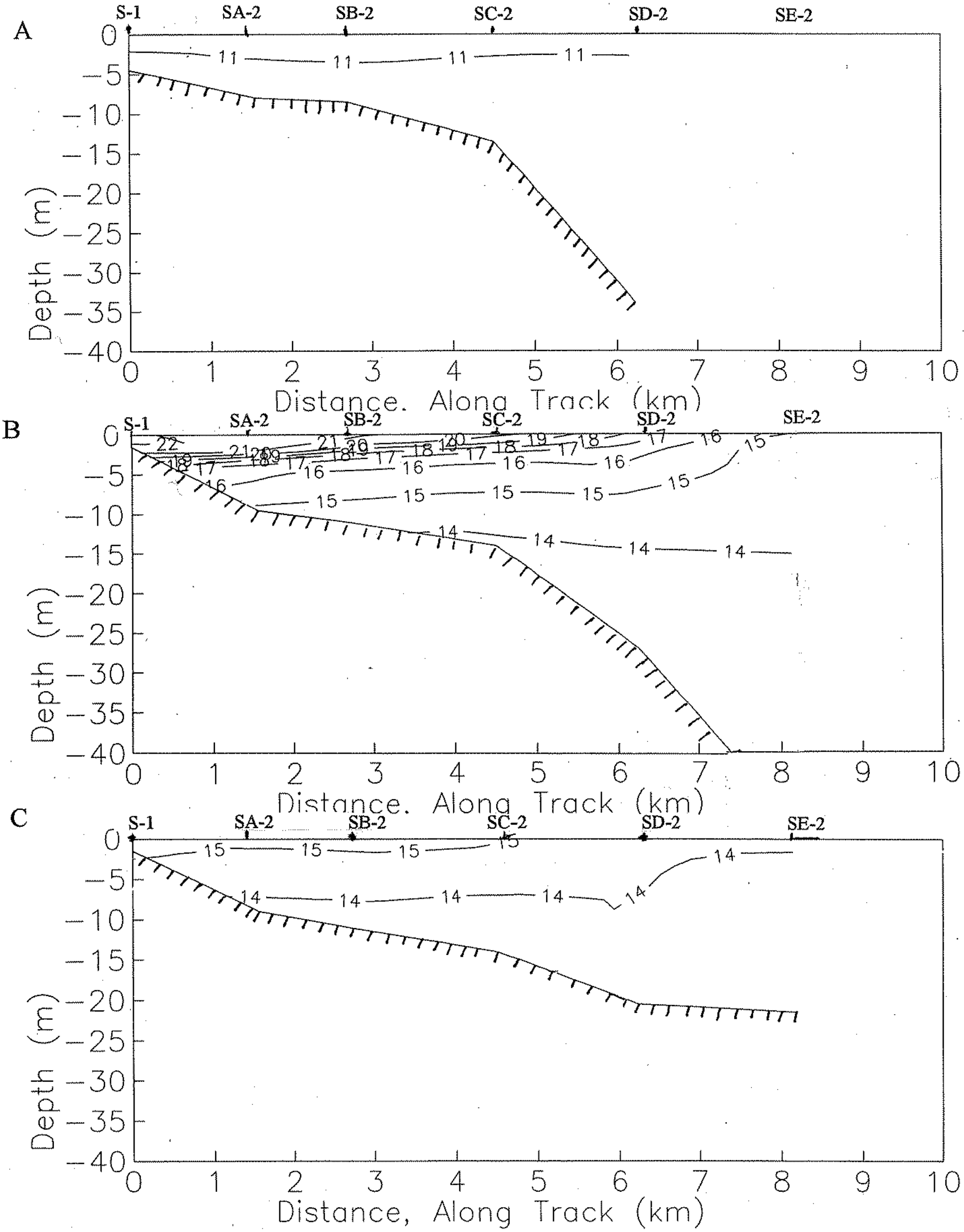


Figure 2. Contour plots of vertical temperature (°C) profiles for station S-1 out to station SE-2 during slack tide in Sinclair Inlet on (a) 21 April (low tide), (b) 24 June (high tide), and (c) 30 September 1992 (low tide). //// represents bottom contour.

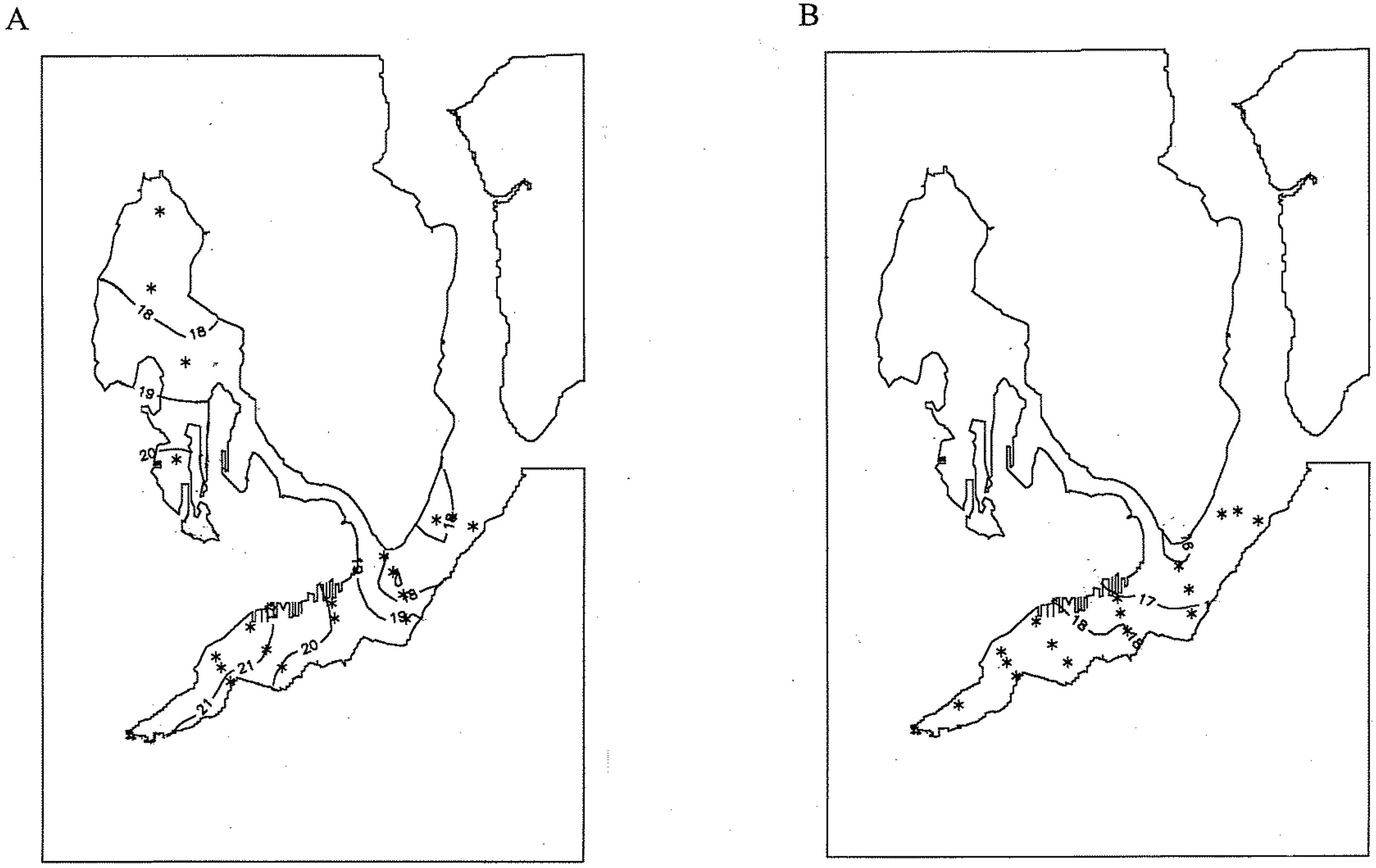


Figure 3. Contour plots of (a) 1-m temperatures (°C) on 24 June during ebb tide (Sinclair) and flood tide (Dyes), (b) 1-m temperatures on 19 August during ebb tide (Sinclair), (c) temperature difference (ΔT) from 1 to 5 m on 24 June, and (d) temperature difference (ΔT) from 1 to 5 m on 19 August 1992. Data from cross-channel transects. Stations with data used for contouring are indicated by "*".

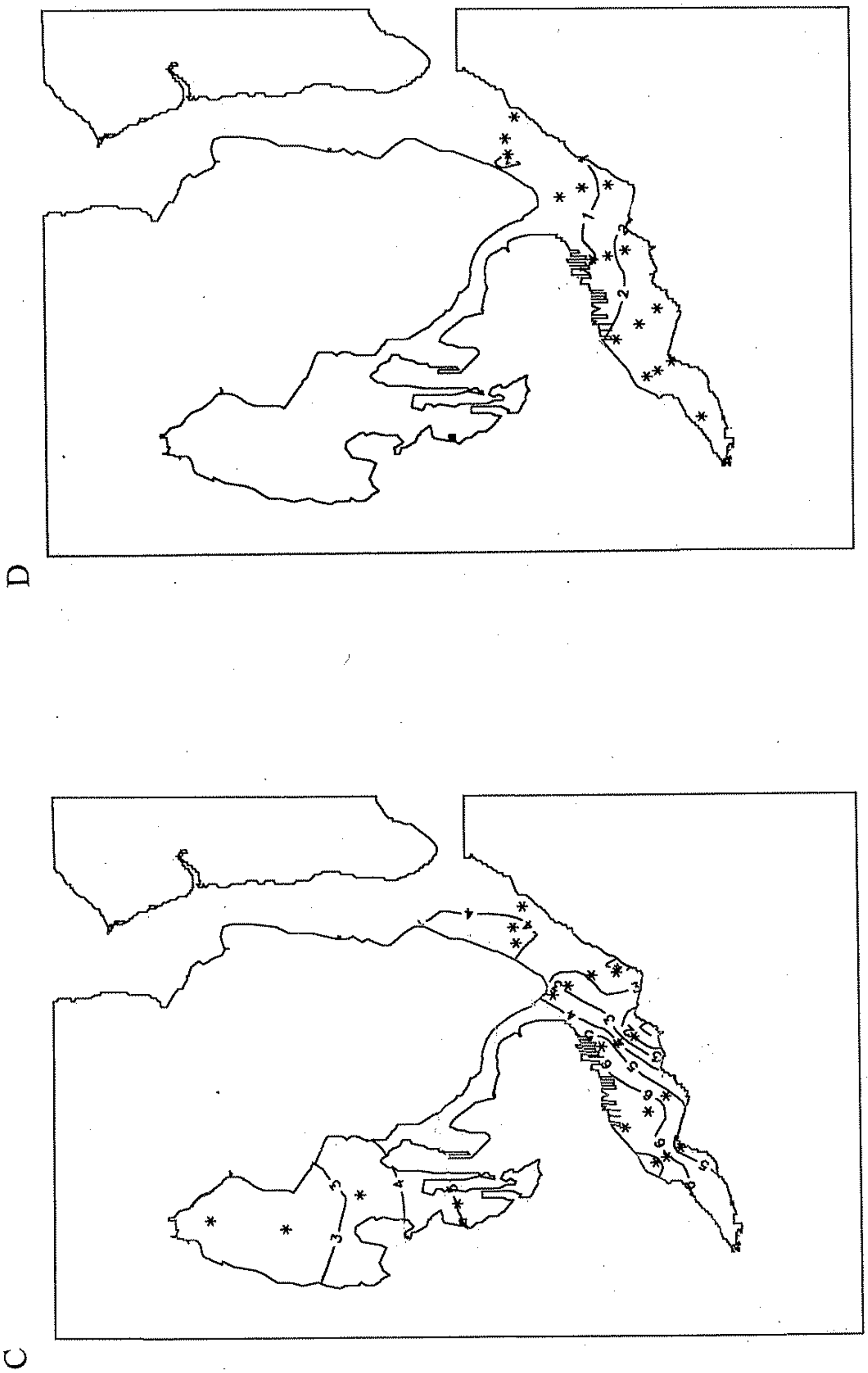


Figure 3. continued.

Salinity

The influence of salinity on density stratification was not as great in Sinclair and Dyes Inlets as it is in locations elsewhere in Puget Sound that are close to larger freshwater sources (*e.g.*, Budd Inlet, Eisner *et al.,* 1994). The water column was nearly isohaline for most of the surveys, with only minor salinity stratification (1-2 ppt difference between upper and lower water column) occurring during the slack tide transects on 24 June and 8 July (Figure 4). The most significant salinity stratification observed in inner Sinclair Inlet were on 24 June, 8 July, and 3 September (Tables 7 and 8). On 5 August, there was a significant freshwater signature in the vicinity of station SD-1, the next cove east of Blackjack Creek (Figure 1).

Salinities from a depth of 1 m ranged from just below 24 ppt (5 August) to slightly over 30 ppt (14 October). Near-bottom salinities ranged from 28.5 ppt in the spring to slightly over 30 ppt in the fall, and generally increased as the season progressed. This steady increase in salinity most likely reflects the reduced freshwater input to the inlet during the summer months. Salinity increases may also be affected by saltier oceanic waters entering the Sound in late-summer and fall months from coastal upwelling events (Lavelle *et al.*, 1991). The largest vertical variation in salinity observed on the along-channel transect (1 ppt) was on 8 July at inner Sinclair station SA-2 (Table 7). This variation was not as strong at station SB-2 and varied with tidal cycle (Table 8). Rain occurred periodically from 3 to 8 July (AMS field log), which may have influenced salinities on the 8 July survey.

The effects of variation in the magnitude and location of freshwater inflow is evident in Figure 5, where possibly Blackjack Creek, the KCSD #5 WWTP or groundwater inflow (Tetra Tech, 1988a) on salinity is clearly evident in August and not in June. This variability makes it difficult to generate useful box models for the Port Orchard system from the data taken in this study. With accurate freshwater inputs, or adequate current meter data, such a model could prove useful in calculating residence times for a given period, as has been done previously (US Navy, 1983; Lincoln and Collias, 1975). The variation in freshwater inflow may substantially alter residence time values.

Pooling all data (low, flood, and high tide) measured on 24 June, a time of fairly high precipitation and run-off, the Temperature/Salinity (T/S) diagram (Figure 6) reveals a relatively low spread of salinities compared with Budd Inlet (Eisner *et al.*, 1994), a Puget Sound estuary with substantial freshwater input. This is indicative of lower freshwater input into the Port Orchard system. The distinct endpoint (T = 13°C, S=30 ppt) indicates the temperature and salinity of the densest water in Sinclair Inlet, from oceanward Puget Sound. Water with different T/S properties than this endpoint were the result of heat or freshwater inputs, primarily from solar radiation or mixing with riverine water, respectively. More salinity variation was seen in warmer than in colder water. These warmer, less saline waters were located near the surface.

The seasonal trend of warming temperature and increasing saltiness during the summer months is evident in plots of the T/S endpoint, progressive with time over one year (Figure 7). By using deep water values, short-term variability (*e.g.*, tidal) is suppressed and long-term trends become evident. Aside from a slight inflection in salinity between March and May, seen in both seasonal

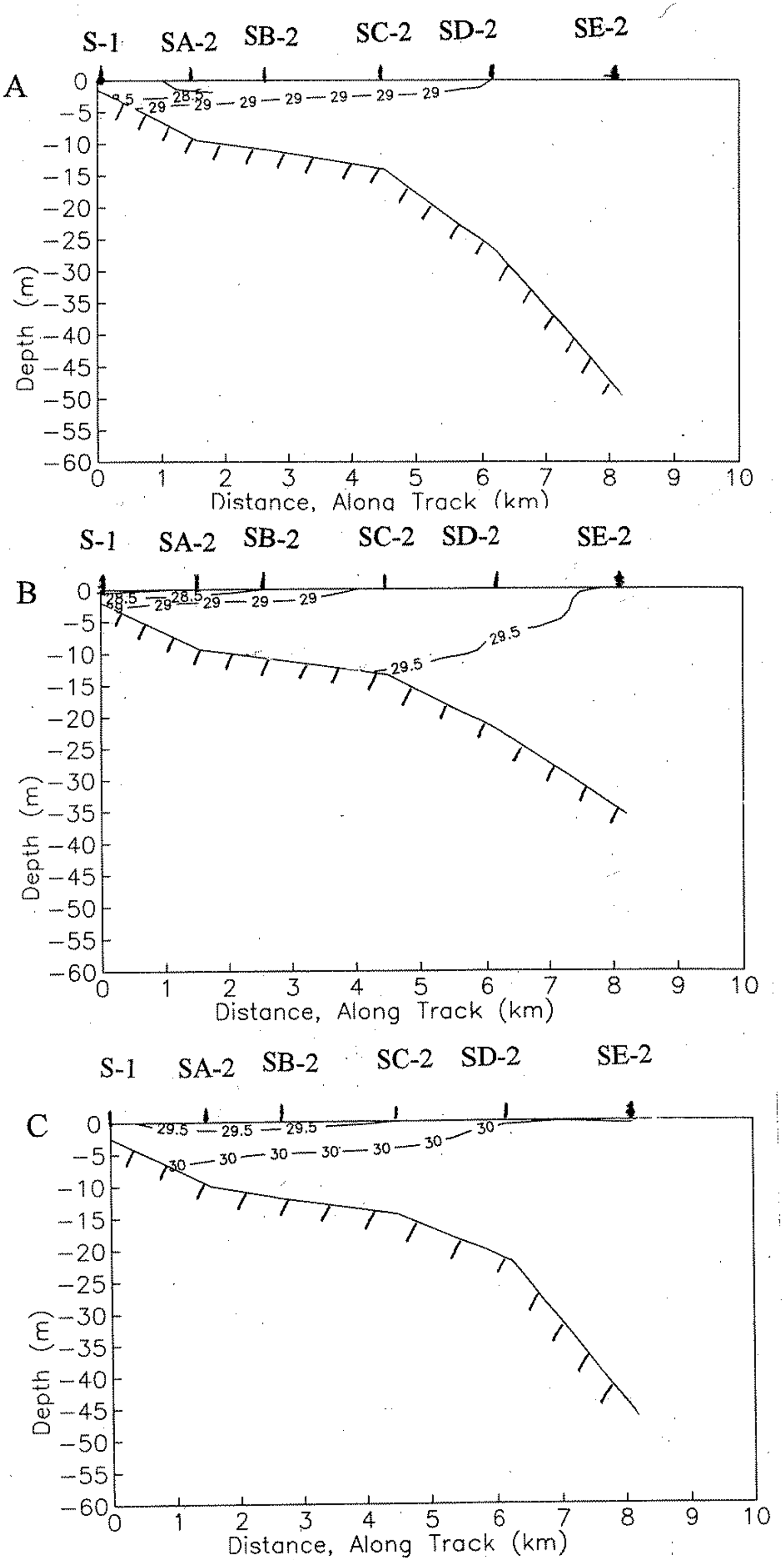


Figure 4. Contour plots of vertical salinity (ppt) profiles for station S-1 out to station SE-2 in Sinclair Inlet on (a) 24 June at high tide, (b) 8 July at high tide, and (c) 3 September 1992 at low tide. //// represents bottom contour.

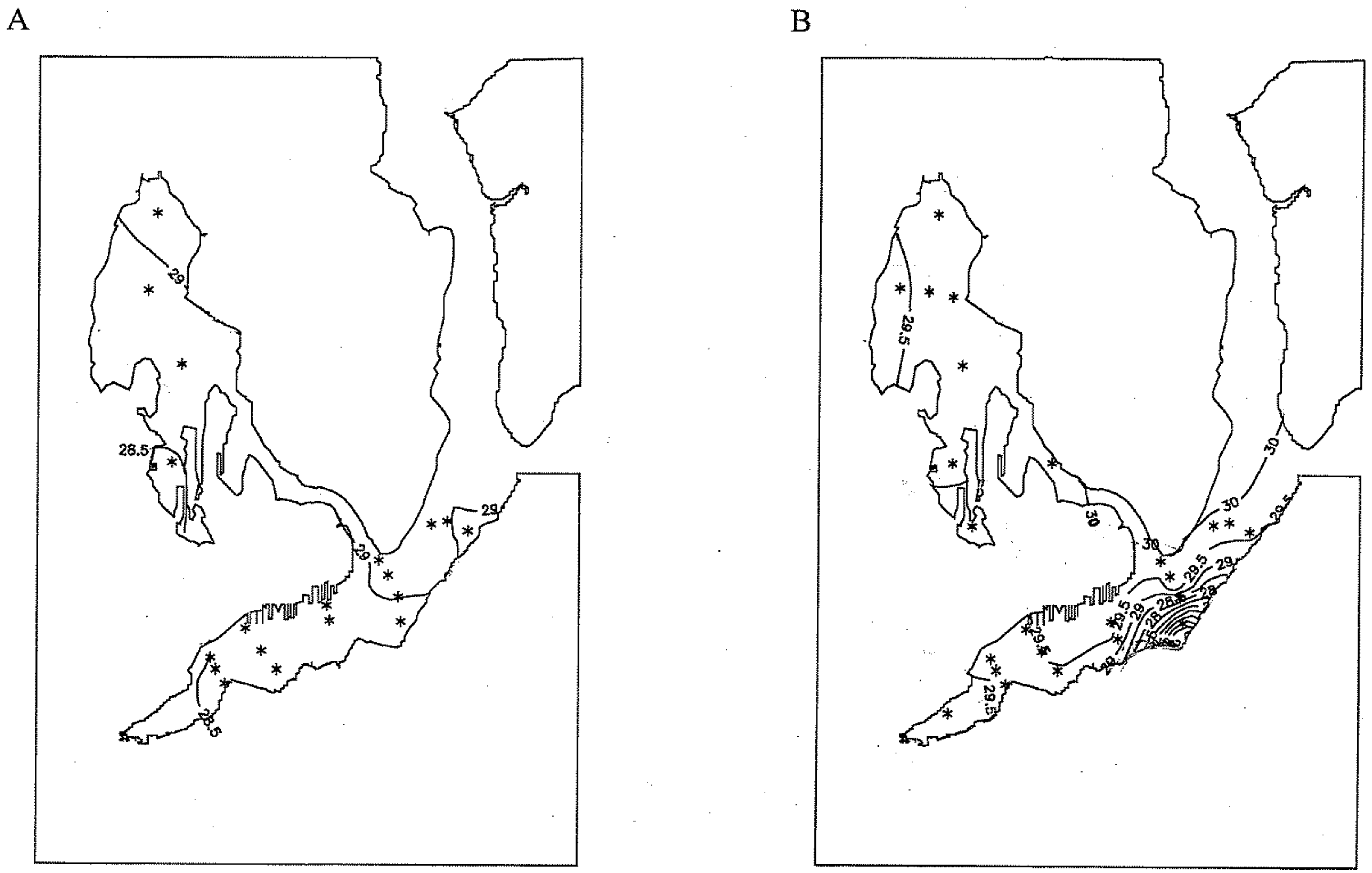


Figure 5. Contour plots of 1-m salinities (ppt) in Sinclair (ebb tide) and Dyes (flood tide) Inlets from (a) 24 June, and (b) 5 August 1992. Data from cross-channel transects. Stations with data used for contouring are indicated by "*".

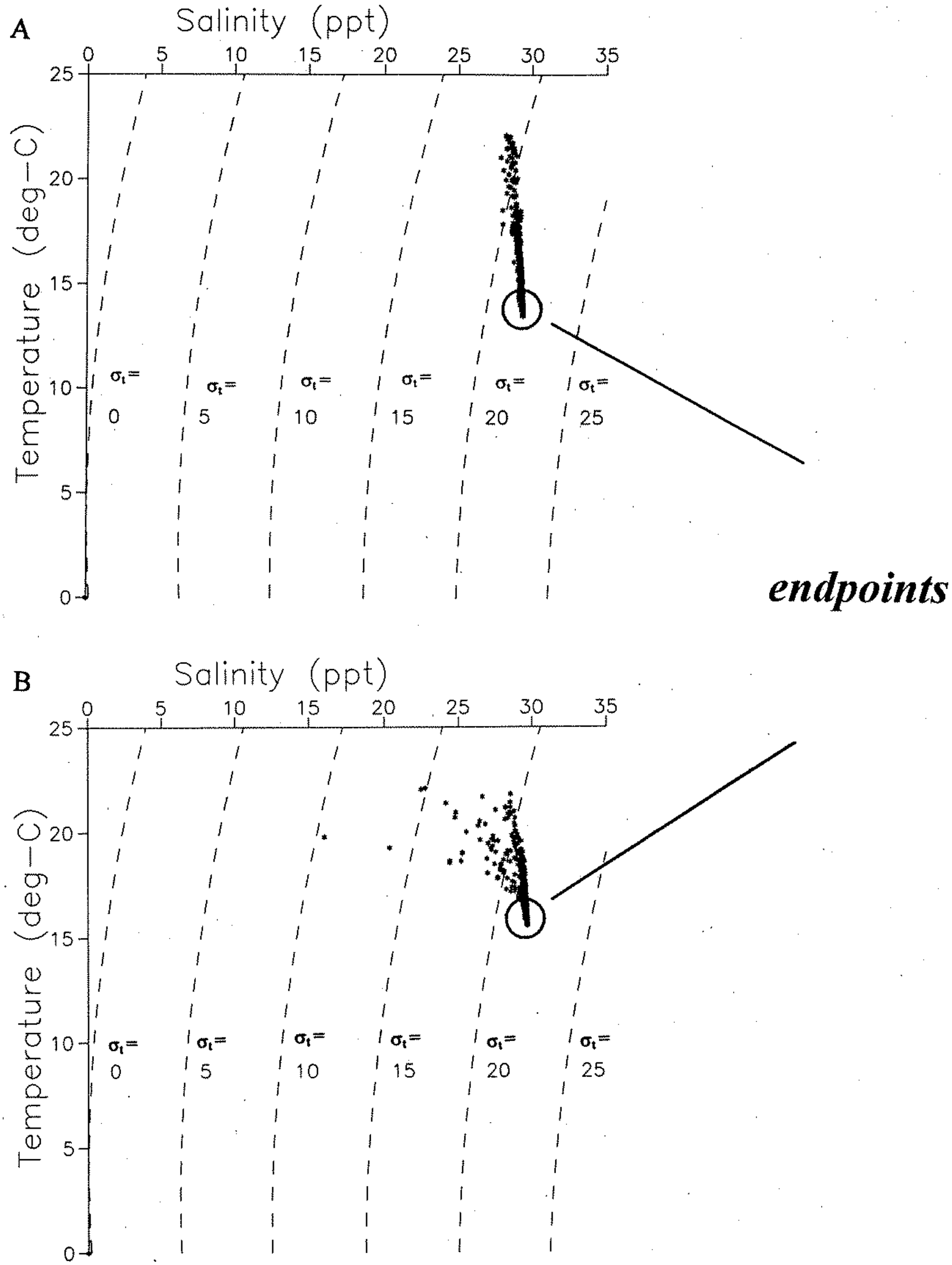


Figure 6. T/S (temperature/salinity) diagrams for data collected on (a) 24 June 1992, in Sinclair and Dyes Inlets, and (b) 26 August 1992, in Budd Inlet. Data from all depths (˜0.25 m to bottom) combined from CTD casts at all stations.

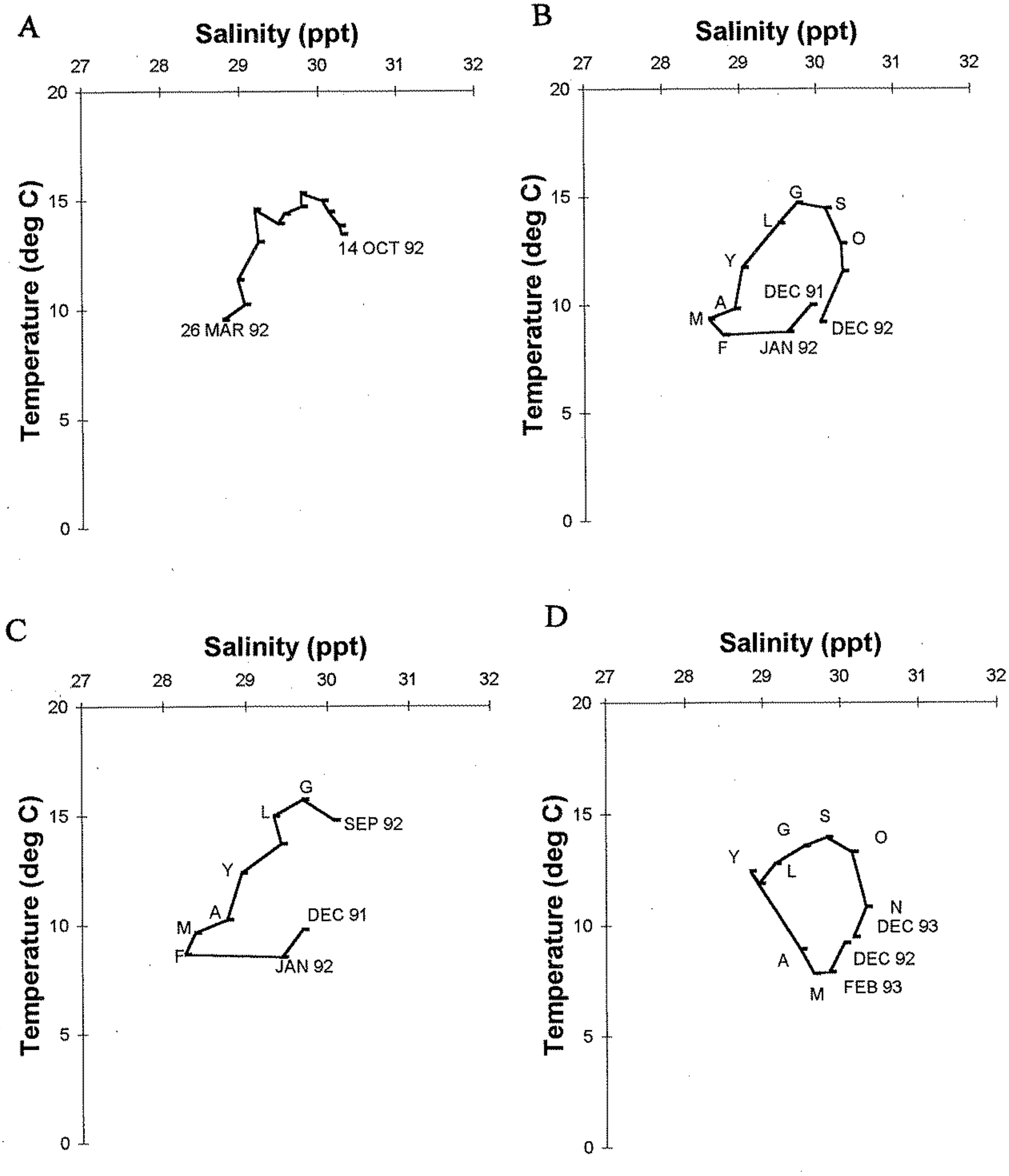


Figure 7. Progressive T/S (temperature/salinity) endpoint diagrams from 1992 for (a) seasonal surveys, (b) long-term monitoring station SIN001, (c) long-term monitoring station DYE004, and from 1993 for (d) station SIN001. “J” = January, “F” = February, “M” = March, “A” = April, “Y” = May, “U” = June, “L” = July, “G” = August, “S” = September, “O” = October, “N” = November, and “D” = December.

and long-term monitoring data (stations SIN001 and DYE004), successive warmer and saltier conditions prevail until 19 August, when the temperatures began to decrease. Seasonally, bottom waters became colder first before they became less saline. Data from 1993 are provided from SIN001 for contrast. The shapes of these T/S endpoint ellipses appear to be more distinct between years than between nearby locations (*e.g.*, SIN001 and DYE004).

Density

In this report, density (ρ, units of kg/m^3) is indicated by the oceanographic convention, sigma-*t* (σ_t), where $\sigma_t \equiv [\rho_{(\text{salinity, temperature, pressure} = 1\text{ atm})} - 1000]$. A 1 ppt increase in salinity affects density as much as a 5°C decrease in temperature. An estuary derives most of its stratification (density layering) from variations in salinity, in contrast to the ocean, where the salinity range is small and temperature becomes more important in controlling stratification. In Sinclair and Dyes Inlets, however, both salinity and temperature significantly affect density, to varying degrees, throughout the season. Density stratification in 1992 was less significant in Sinclair and Dyes Inlets compared with other embayments in Puget Sound (*e.g.*, Budd Inlet, Eisner *et al.*, 1994). Precipitation for 1992 was below normal (see Discussion), which would likely result in lower stratification overall.

Less dense surface water was usually found on the north side of Sinclair Inlet during flood tides (Figure 8). During ebb tides this was less apparent (Figure 9). The casts taken at stations SA-3 and SA-2 on 24 June reveal an unstable sub-surface watermass, since denser water is overlying less-dense water, at depths of approximately 3 to 4 m (Figure 9a). This instability in density was driven by both temperature and salinity, reflecting a layer of warmer, fresher water at depth. Possibly this feature was related to discharge from the Bremerton WWTP.

Relative Stratification

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 1-m depth sigma-*t* values from the near-bottom sigma-*t* values. As shown by the relative stratification (Tables 7 and 8), the days with strongest density stratification in Sinclair Inlet were: 24 June (mostly temperature driven), 3 September (mostly salinity driven) and 19 August (temperature and salinity driven).

Density stratification generally was strongest in inner Sinclair Inlet around the SB transect (Figures 8, 9 and 10)

Potential Energy

Vertical profiles of density data were also used to calculate the potential energy (PE) represented by stratification by integrating the entire density profile. Potential energy is a more complete description of water column stability than relative stratification since it includes information about the entire water column (*i.e.*, indicates more about mixing). Without current meter data, not much can be said about kinetic energy (KE) or PE/KE ratios (*i.e.*, Richardson number). The

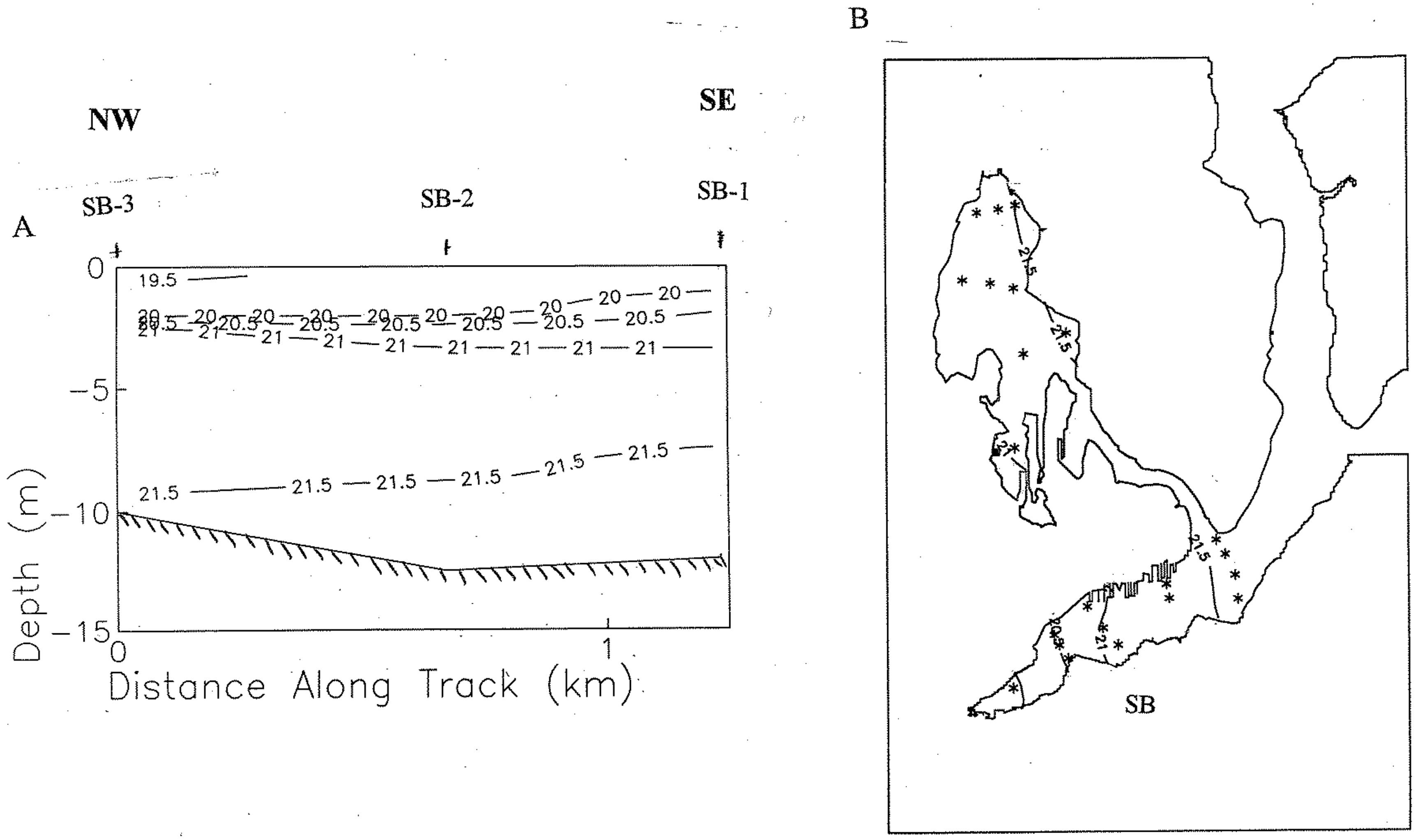


Figure 8. Density (sigma-*t*) contour plots from Sinclair Inlet during flood tide on 6 May 1992: (a) along the SB cross-channel transect (looking northeast); and (b) horizontal plan view at 1 m. Stations with data used for contouring are indicated by "*". //// represents bottom contour.

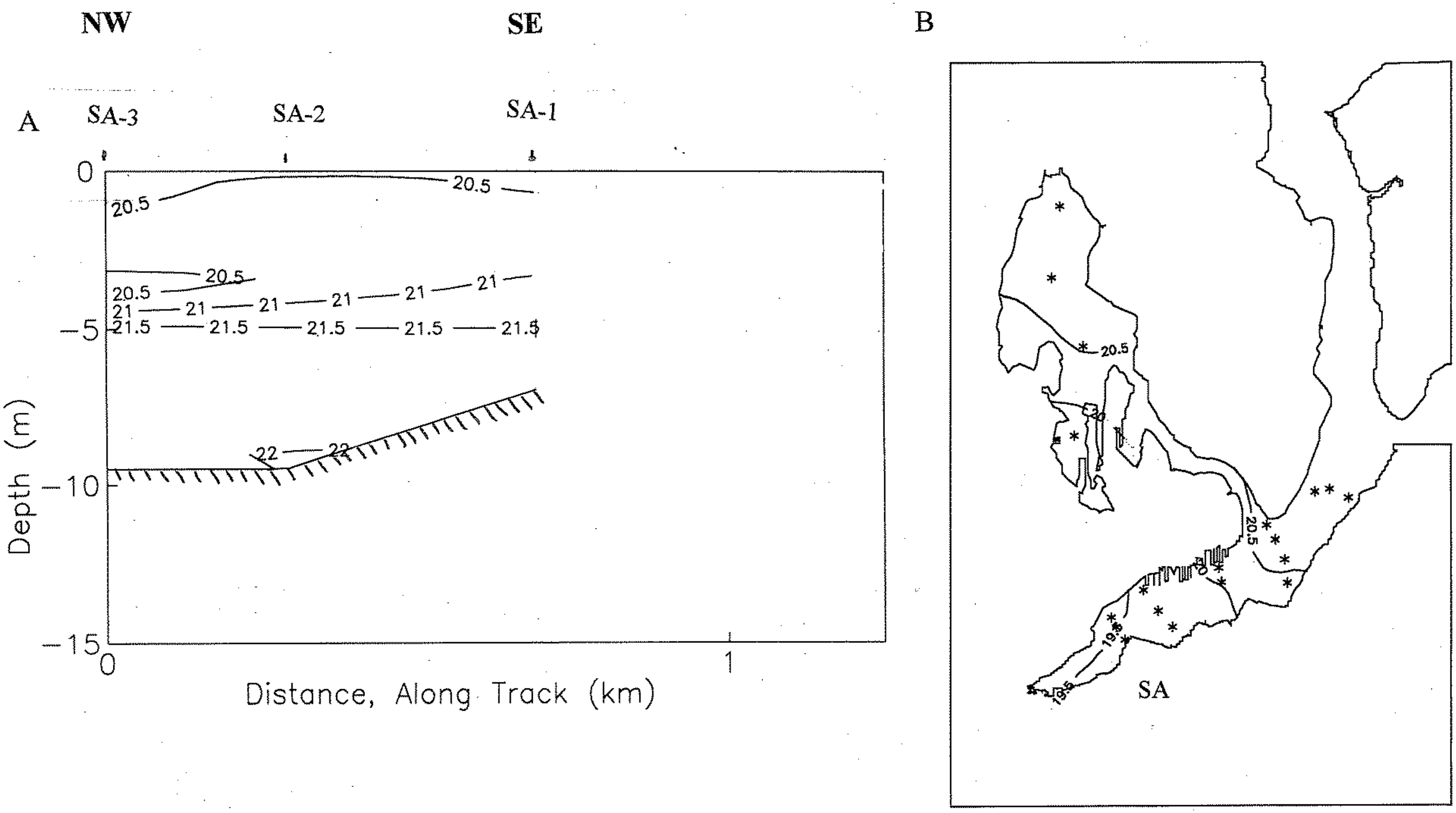


Figure 9. Density (sigma-*t*) contour plots from Sinclair Inlet during ebb tide on 24 June 1992: (a) along the SA cross-channel transect (looking northeast); and (b) horizontal plan view at 1 m. Stations with data used for contouring are indicated by "*". //// represents bottom contour.

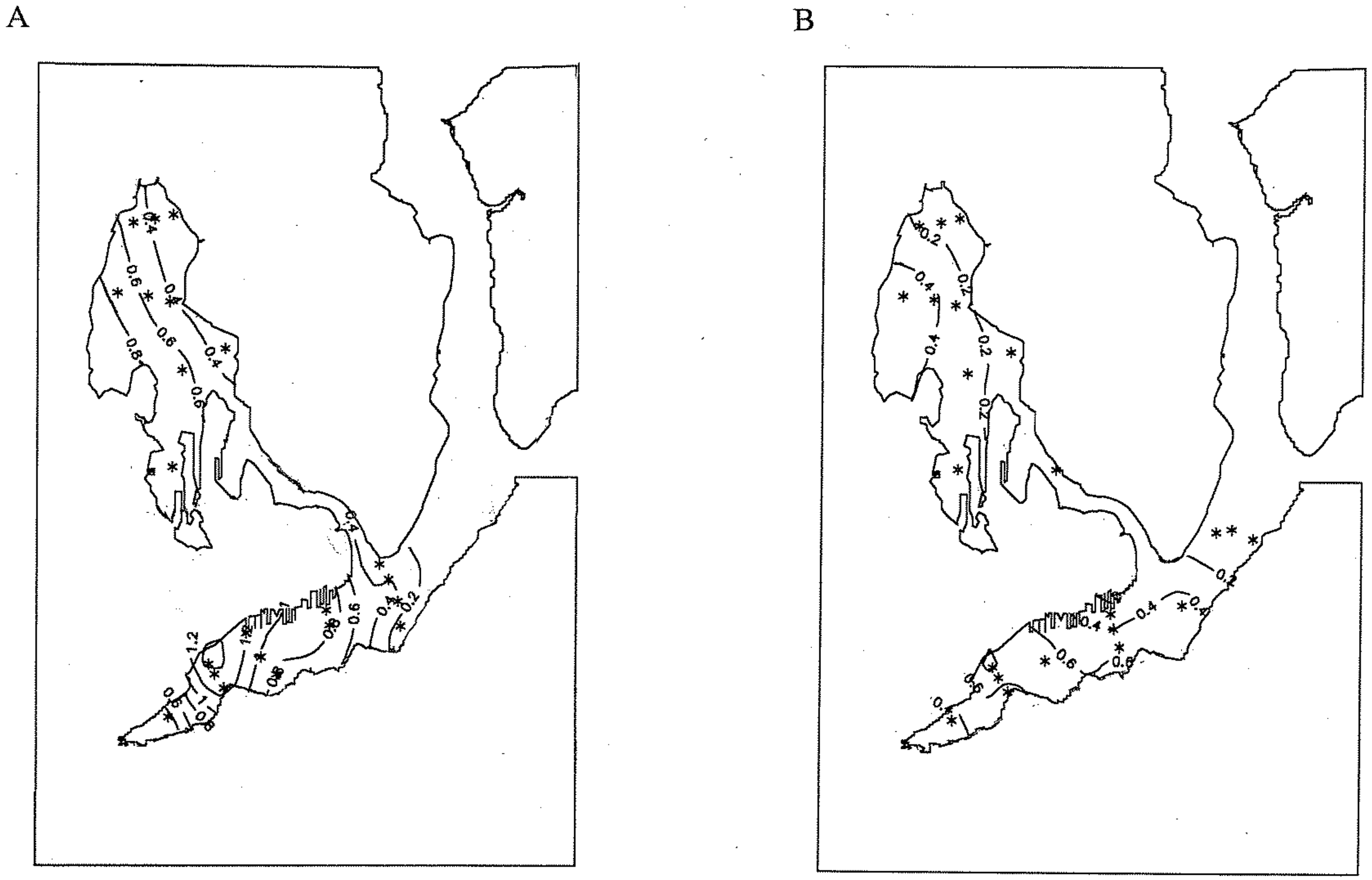


Figure 10. Relative stratification (units of sigma-*t*) in Sinclair and Dyes Inlets on (a) 6 May, during flood tide (Sinclair) and ebb tide (Dyes), (b) 10 June, during flood tide, and (c) 3 September, during ebb tide (Sinclair) and high tide (Dyes), and potential energy on (d) 3 September 1992. Relative stratification values were obtained by subtracting the 1-m density value from the near-bottom density value. The potential energy function is defined in the text. Larger magnitudes in either parameter indicate greater stratification. Stations with data used for contouring are indicated by "*".

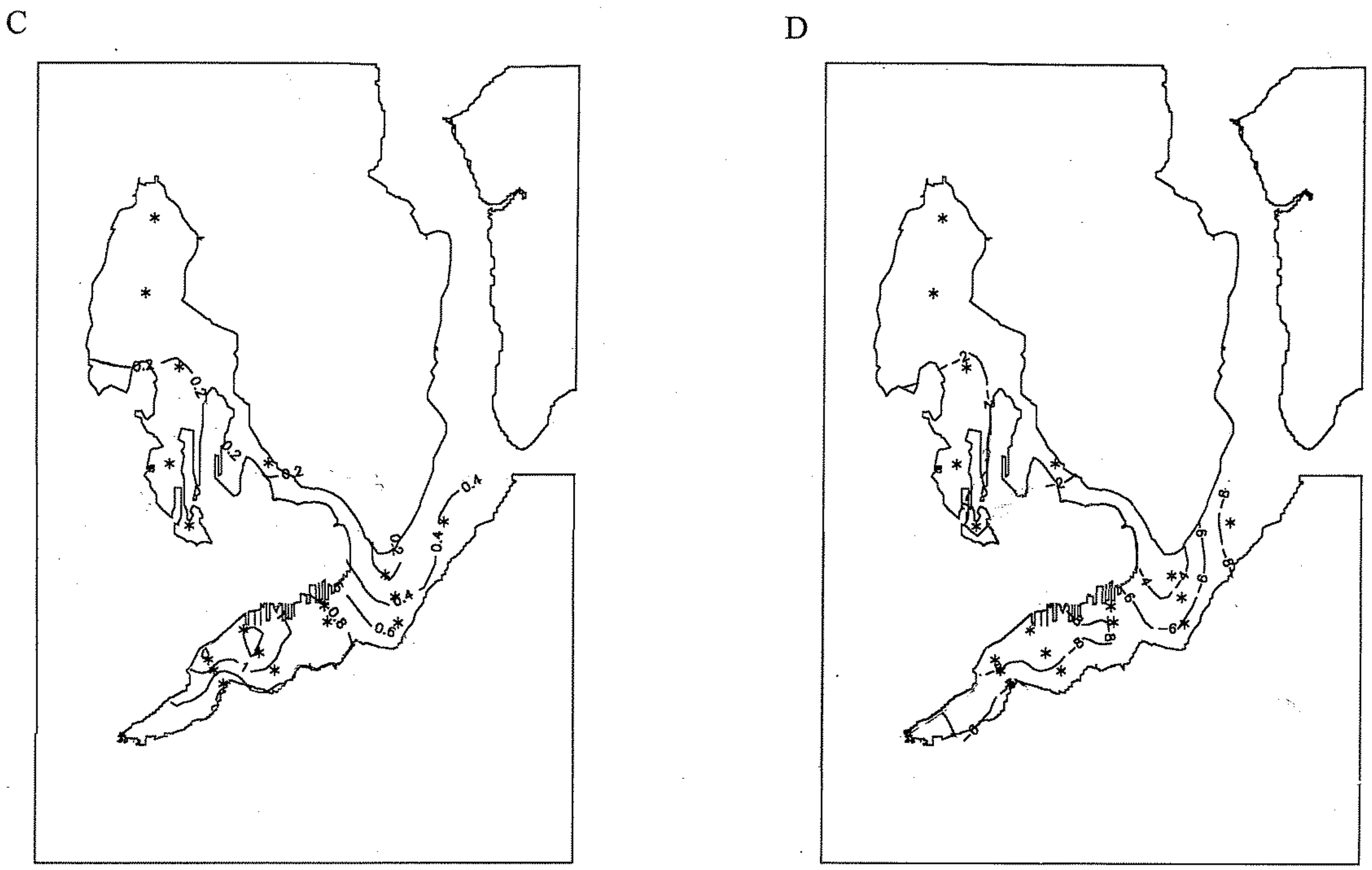


Figure 10. continued.

derived ΔPE values (Tables 7 and 8) are defined on a per volume basis, and were calculated as the difference in potential energy between the stratified water column and the same water column had it been thoroughly stirred to a homogeneous density:

$$\Delta PE = PE_{\text{mixed}} - PE_{\text{stratified}}$$

$$PE_{\text{mixed}} = g/H \int_{-H}^{0} \bar{\rho}\, z\, dz = (g\, \bar{\rho} / H)\left[\ (z^2/2)\ \right]_{-H}^{0} = -\,\bar{\rho}\, g\ (H/2)$$

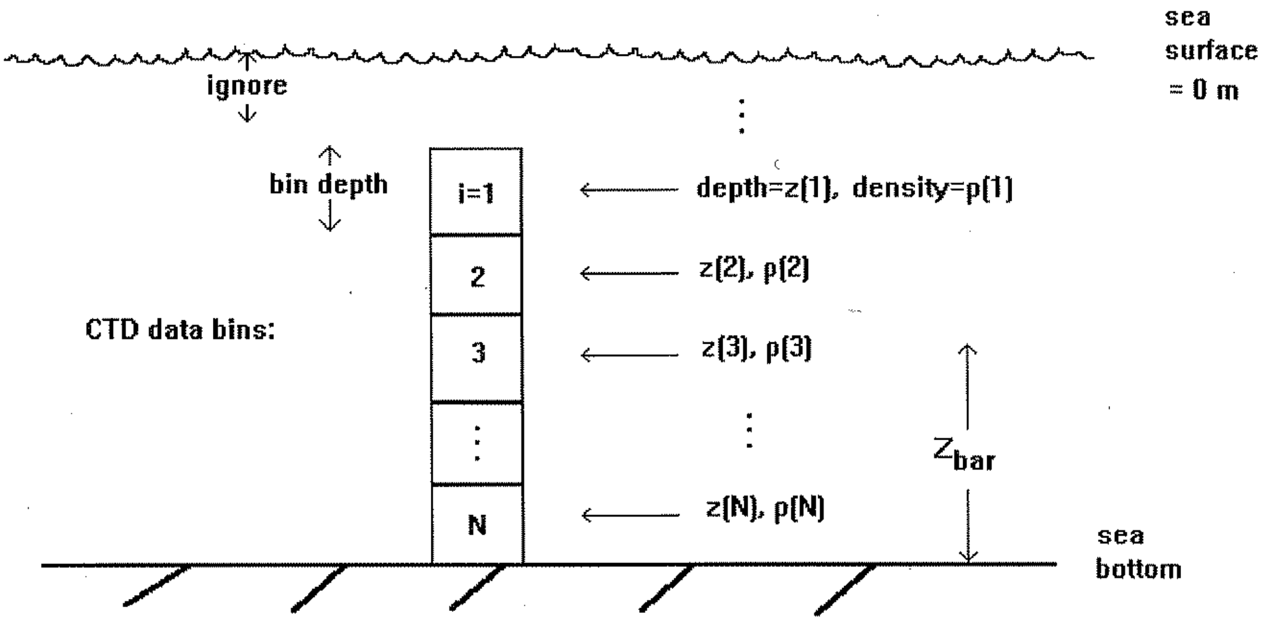
$$PE_{\text{stratified}} = g/H \int_{-H}^{0} \rho(z)\, z\, dz$$

where:

$\rho(z)$ = density (kg/m^3);
g = acceleration of gravity = 9.8 m/s^2;
z = depth (m);
H = total depth (m);
$\bar{\rho}$ = average density = $1/H \int_{-H}^{0} \rho(z)\, dz$;
$\bar{z}$ = average depth = $1/H \int_{-H}^{0} z\, dz = -H/2$.

The scheme for numerically integrating the discrete density (sigma-*t*) values available from the CTD to obtain ΔPE is outlined in Figure 11. The well-mixed (homogeneous) water-column represents a higher energy state, with a higher center of mass. The stratified fluid, with denser water beneath fresher and warmer surface water, has a lower center of mass and hence a lower PE relative to the well-mixed state. The energy to mix the water column vertically, can come from a variety of sources such as wind, tides, solar heating, etc. Since this integration is somewhat depth-sensitive, the most valid comparisons of ΔPE are between biweekly surveys at the same stations, with the same depths.

The plan view contour patterns of potential energy (Figure 10d) are similar to those of relative stratification (Figure 10c). Summarizing the potential energy data from Table 7, the most stratified days during the 1992 seasonal project were 24 June, 19 August, and 3 September, in descending order. While the first of these dates agrees with the relative stratification calculation used previously, the second and third do not. September 3 had a greater surface to-bottom density difference, but 19 August required a greater total (integrated) energy input (ΔPE) to overturn. Looking at both relative stratification and potential energy, therefore, gives a better idea of how much mixing has occurred for a given amount of freshwater present. A consequence of this lower mixing ratio would have been a longer residence time of water, and all dissolved or suspended constituents, in the inlet. The value of -20 J/m^3 from 24 June 1992 (a relatively high value) corresponds to a required kinetic energy of 3,100 MegaJoules to mix Sinclair Inlet based on a total volume of 1.55×10^8 m^3 (5.47×10^9 ft^3 at Mean Lower Low Water (MLLW) from Lincoln and Collias, 1975). Greater amounts of stratification trap volumes of water with low DO at depth and can also influence plankton populations.



where,

$$g = 9.8 \text{ m/s}^2$$

$$\text{sea-bottom depth} = Z_N + (\text{bin depth} / 2)$$

$$Z_{bar} = (Z_N - Z_1 + \text{bin depth}) / 2$$

$$\rho_{avg} = \frac{1}{N} \sum_{i=1}^{N} \rho_i$$

$$PE_{mixed} = g * Z_{bar} * \rho_{avg}$$

$$PE_{stratified} = \frac{1}{N} \sum_{i=1}^{N} \rho_i z_i$$

$$\Delta PE = PE_{mixed} - PE_{stratified}$$

Figure 11. Numerical integration scheme for discrete CTD density values to determine potential energy (Joule/m^3) in a stratified water column.

Baroclinic and Barotropic Flows

The data collected in Sinclair Inlet during the 1992 monitoring showed that isopycnals (surfaces of constant density) not only varied along the along-channel transects (southwest-northeast) at constant depth, but along the cross-channel transects (north-south) as well. Isopycnals were generally sloped relative to isobars (surfaces of constant pressure/depth), 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, with an external signature at the surface. In a fluid of constant density, only barotropic flow is possible; in a fluid with two or more density layers, there may be barotropic as well as baroclinic flow.

In Sinclair Inlet, during both ebb and flood tides at the SA and SB transects, less dense water was observed along the north (Bremerton) side of the inlet (Figures 8 and 9). During some ebb tides surveyed, lower density water also occurred along the south (Port Orchard) side of the inlet (Figure 9). Understanding the cause of this flow could help explain the distribution of phytoplankton and other parameters throughout the inlet. Perhaps there is a counterclockwise gyre in inner Sinclair with periodic freshwater inflows from Gorst and Blackjack Creeks. 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. The northerly wind on 24 June (field observation) would cause a "pile-up" of water at the southern shore, producing a surface slope up toward the south and a resulting pressure gradient force toward the north. The surface layer will be thicker in the south with the pycnocline sloping opposite to the surface slope (*i.e.*, upward to the north, as in Figure 8a). Baroclinic flow would exhibit an eastward surface component relative to the westward barotropic flow of the flood tide.

Wind and tidal effects are not the only forces that may be influencing water circulation. To evaluate the importance of the earth's rotation on both baroclinic and barotropic flows, calculation of the Rossby radius is used (Pond and Pickard, 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.*, 6 May), using the equation from Pond and Pickard (1983):

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

where:

g = force of gravity (9.8 m/s^2);
ρ = density (1.021 kg/m^3);
$\Delta\rho$ = density change between layers (0.01 kg/m^3 on 6 May);
h1 = height of upper layer (2 m);
h2 = depth of lower layer (8 m);
f = Coriolis force (1.07E-04 at this latitude).

The Internal Rossby Radius was about 3.7 km. This value is close to the dimensions of Sinclair Inlet (2-3 x 11 km), indicating that rotation could be important internally. There would be no observable effect of rotation at the surface, but internally, the slope of isopycnals relative to isobars could be affected. The significance of this effect depends on the strength of other mixing forces, such as inertial, buoyancy, or wind forcing.

Tidal Variability

Tidal variability in inner Sinclair Inlet is summarized in Table 8. Data at station SB-2 showed that on some days (*e.g.* 20 May), changes between tidal stages for some parameters were more extreme than between biweekly surveys. Salinities at a depth of 1 m, for example, changed more in four hours from ebb to low tide on 20 May (28.7 to 28.0 ppt, respectively) than between low tides on that day and the previous survey of 6 May (28.0 to 28.4 ppt, respectively). In contrast, near-bottom values did not exhibit as much tidal variability, nor did parameters that were not depth-varying (*i.e.*, not stratified).

Dyes Inlet

Not as many surveys occurred in Dyes Inlet as in Sinclair. The most complete survey dates in Dyes Inlet were: 26 March, 21 April, 6 May, 10 June, 5 August, and 3 September.

Temperature

An accurate comparison between temperatures in Dyes & Sinclair Inlets is not possible since Dyes Inlet was routinely sampled earlier in the day than Sinclair. Nevertheless, observed temperatures during the summer were often just slightly warmer on the surface in Dyes Inlet than those in Sinclair Inlet.

Thermal stratification was greatest in the May through August surveys and least in March, April, and in September (Table 9). On dates where cross-channel (east to west) transects were conducted, temperatures were consistently greater on the west side of the inlet (Figure 12).

This could be a result of colder (and saltier) waters entering through Washington Narrows and corresponding circulation patterns.

Salinity

Salinity in Dyes Inlet increased from the north, by Silverdale the south by modest amounts (0.1-0.3 ppt) at a depth of 1 m. Some minor cross-channel variations were also observed (*e.g.*, Figure 5b), primarily that salinity increased to the east. Since the inflow from Chico Creek is known to be highly variable, and these data were collected in a drier than normal year, the observed pattern may not always prevail.

Table 9. Summary of biweekly hydrographic data collected during 1992 surveys at station DA-2 in Dyes Inlet. Larger values in the relative stratification column indicate greater stratification. The depth of the thermocline (and pycnocline) was determined as the depth at which the absolute value of the gradient in temperature (and density) was maximum. Relative stratification was calculated as the difference between near-bottom and 1-m sigma-*t* values; larger values indicate greater stratification between these depth strata. "ND" indicates "No Data" (Not Done).

1992 Survey Date	*Tidal Stage*	*Minimum Temperature (°C)*	*Maximum Temperature (°C)*	*Minimum Salinity (ppt)*	*Maximum Salinity (ppt)*	*Depth of Thermocline (m)*	*Depth of Pycnocline (m)*	*Relative Stratification (sigma-t)*
3/26	Ebb	10.0	10.7	28.5	28.6	4.8	6.3	0.20
4/21	Ebb	10.8	11.8	28.7	28.9	3.8	4.3	0.31
5/6	Ebb	12.3	14.1	28.5	28.9	1.3	1.3	0.70
5/20	ND	ND	ND	ND	ND	ND	ND	ND
6/10	Flood	14.3	15.1	29.1	29.1	3.3	3.3	0.23
6/24	Flood	15.1	18.2	28.9	29.2	1.3	1.3	0.93
7/8	Flood	14.7	16.0	29.2	29.4	1.3	1.1	0.43
7/22	ND	ND	ND	ND	ND	ND	ND	ND
8/5	Flood	15.8	17.4	29.6	29.7	1.3	1.3	0.45
8/19	ND	ND	ND	ND	ND	ND	ND	ND
9/3	High	15.8	16.6	29.9	30.0	1.3	1.3	0.22
9/16	ND	ND	ND	ND	ND	ND	ND	ND
9/30	ND	ND	ND	ND	ND	ND	ND	ND
10/14	ND	ND	ND	ND	ND	ND	ND	ND

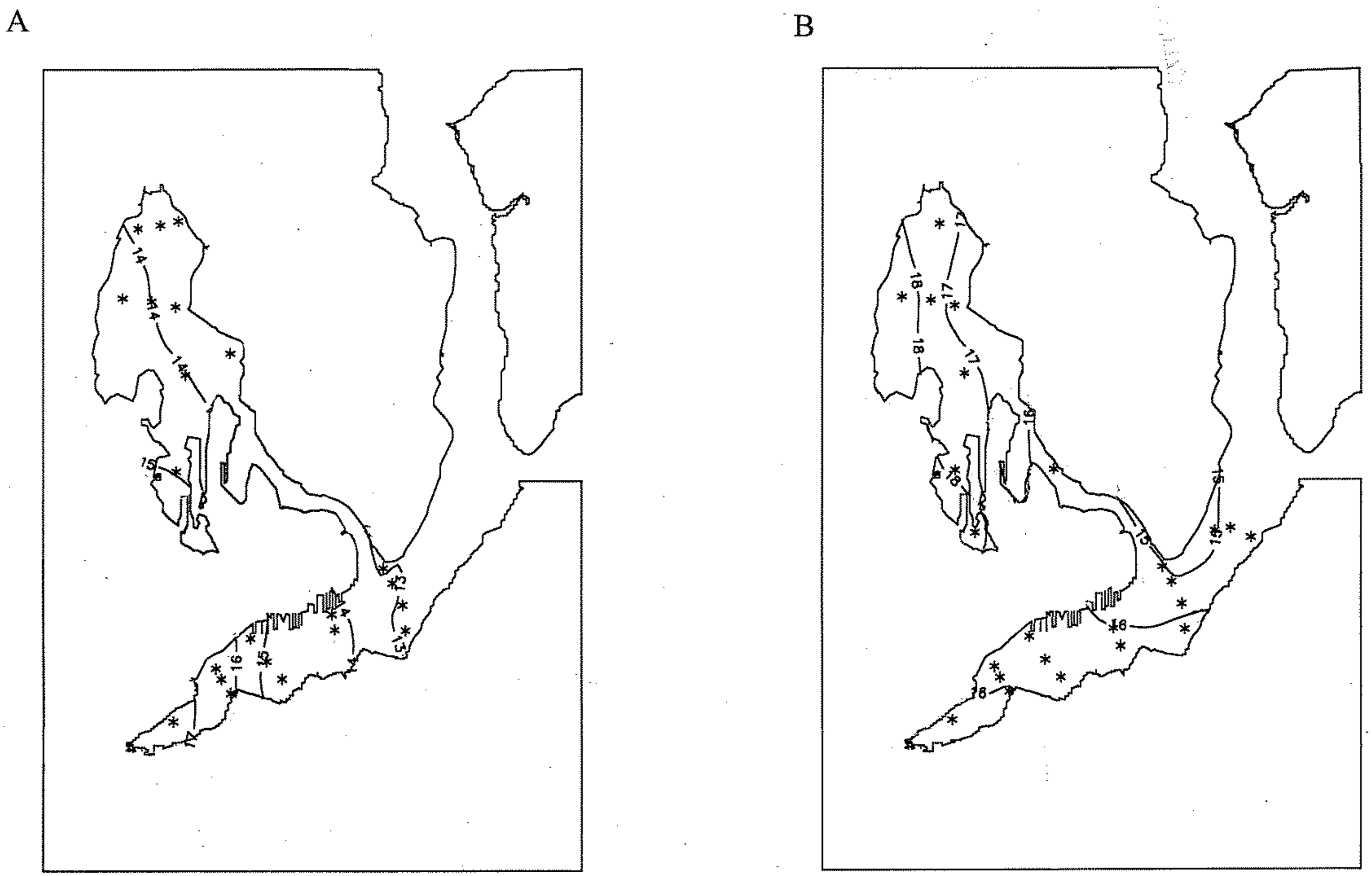


Figure 12. One-meter temperatures (°C) in Sinclair and Dyes Inlets on (a) 6 May, during flood tide (Sinclair) and ebb tide (Dyes), and (b) 5 August 1992, during ebb tide (Sinclair) and flood tide (Dyes). Stations with data used for contouring are indicated by "*".

Density

On dates when cross-channel transects were done, density stratification in Dyes Inlet was greatest along the western shore due to the thermal and haline variations discussed above. This was evident during both ebb (Figure 13a) and flood (Figure 13b) tidal stages. Relative stratification was strongest on 24 June and 6 May. Values of relative stratification were lower than those observed in inner Sinclair Inlet, indicating a more mixed water-column throughout Dyes Inlet.

Euphotic Zone Depth

The depth of the euphotic zone is typically defined as the depth at which 1% of the surface 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. The equation that describes the proportional rate of change of light intensity with depth is:

$$I(z) = I_o\, e^{-kz}$$

where:

I_o = 100% (*i.e.*, surface) radiation
z = depth
k = light extinction coefficient
$I(z)$ = light at depth z.

The light extinction coefficient can be determined from Secchi disk depth (the depth at which the disk disappears) using the equation developed by Poole and Atkins (1929) from English Channel data:

$$k = 1.7 \,/\, \text{Secchi disk depth (m)}.$$

This relationship has been modified empirically for Puget Sound waters by substituting a value of 1.6 for 1.7 (Newton *et al.*, 1994). The depth of the euphotic zone can be derived from the former equation, using k as obtained from Secchi data, substituting 0.01 for $I(z) / I_o$ (*i.e.*, 1% of surface radiation), and solving for z, the depth (m) at which 1% of the surface light (I_o) is found. Figure 14 displays the euphotic zone depths (depths of 1% surface light levels) for along-channel transect stations in Sinclair Inlet during slack tide. Shallower euphotic zones reflect the presence of suspended particles, which are typically either of sedimentary or planktonic origin.

During every survey in Sinclair Inlet, the euphotic zone depths were shallower in the inner and central inlet than in the outer inlet. These shallower euphotic zone depths indicate a higher particulate concentration that was likely due to the increased phytoplankton biomass in inner and central Sinclair Inlet (see Phytoplankton Concentration and Distribution section) or possibly sedimentary load from Gorst Creek. Also, in a shallower area, the potential for sediment resuspension can add to the particulate load. A reduction in the euphotic zone depth as a result of high phytoplankton concentrations is indicated in the 5 August data, with depths at least 2 m shallower at station SB-2 than at other inner Sinclair stations (Figure 14). The corresponding

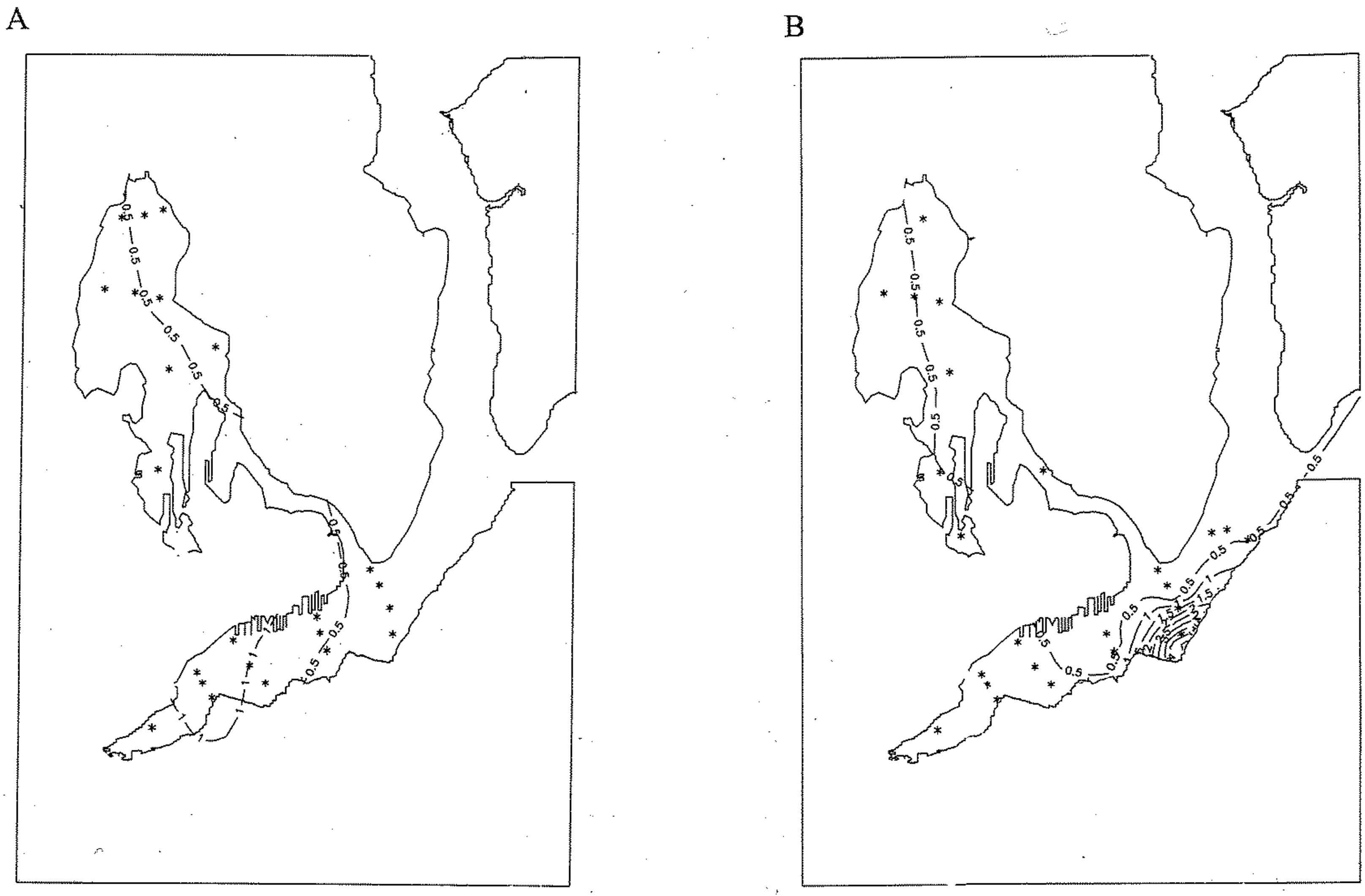


Figure 13. Relative stratification (units of sigma-*t*) in Sinclair and Dyes Inlets on (a) 6 May, during flood tide (Sinclair) and ebb tide (Dyes), and (b) 5 August 1992, during ebb tide (Sinclair) and flood tide (Dyes). Relative stratification values were obtained by subtracting the 1-m density (sigma-*t*) value from the near-bottom density (sigma-*t*) value. Higher numbers indicate greater relative stratification (contour interval = 1.0); see 6 May in Figure 10a for finer interval. Stations with data used for contouring are indicated by "*".

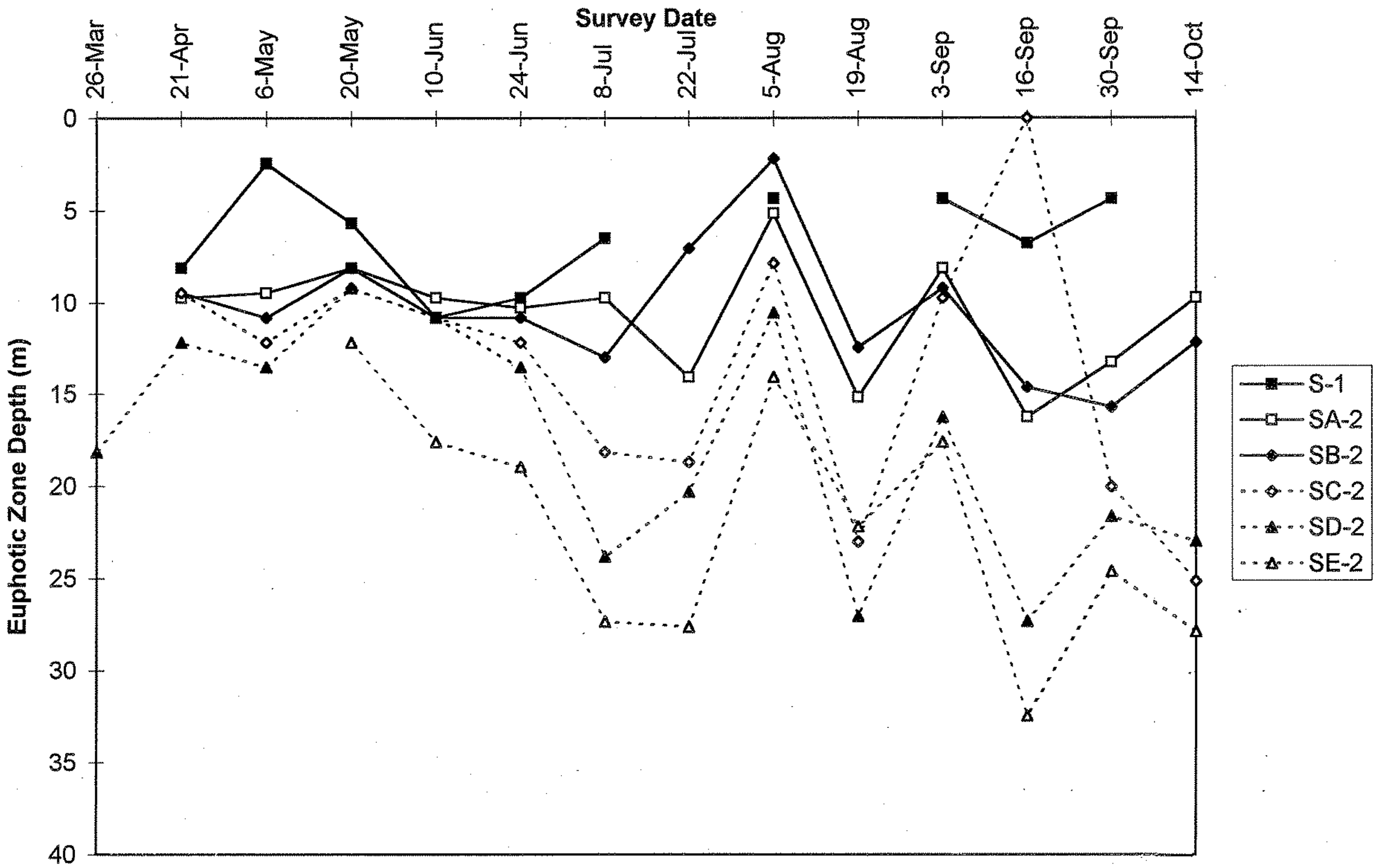


Figure 14. Euphotic zone depths (1% of surface light levels) calculated from Secchi disk depths for Sinclair Inlet during 1992. Data collected at slack tide. Solid line = inner bay (stations S-1, SA-2, and SB-2). Dashed line = central and outer bay (stations SC-2, SD-2, and SE-2). Data are discrete.

chlorophyll *a* concentrations (collected at the Secchi disk depths) were much higher at station SB-2 (~50 mg/m^3) than elsewhere (~10 mg/m^3; see Phytoplankton Concentration and Distribution section).

Euphotic zone depths were typically shallower during occurrences of phytoplankton blooms (chlorophyll $a > 10$ mg/m^3) and deeper during periods of low chlorophyll *a* concentrations (Figure 14 and Phytoplankton Concentration and Distribution section). Some of the deepest euphotic zone depths in inner Sinclair Inlet (10 June, 19 August, and 16 September; Figure 14), corresponded with the lowest chlorophyll *a* concentrations observed during mid-season (Phytoplankton Concentration and Distribution section). According to Ecology AMS logbooks, moderate wind events (daily wind speed averages of >8 km/h (>5 mph)) occurred from 7 to 10 June and on 19 August. 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.

Nutrients

Nutrient availability and sunlight are the main factors that regulate the growth of phytoplankton. Nitrate+nitrite-N are the principle sources of dissolved inorganic nitrogen (DIN) in seawater; together with ammonium-N and dissolved organic nitrogen (DON), these provide the nitrogen necessary for phytoplankton growth. The main source of nitrate+nitrite-N is from remineralization at depth and diffusion or mixing across the pycnocline, whereas ammonium-N is produced in the euphotic zone, primarily from excretion and exudation by organisms. Ecology does not measure DON. All nitrogen forms also can be inputted from anthropogenic sources, such as WWTPs, septic tanks, and agricultural runoff. Ammonium-N, however, is the most common form in these anthropogenic sources. Thus high ammonium-N concentrations are generally indicative of exogenous sources, such as sewage or land-applied fertilizers contained in runoff. Ammonium-N is a preferred nitrogen source for many phytoplankton, so its addition can result in a rapid increase of phytoplankton populations.

Phosphorous is required by phytoplankton in an approximate molar ratio of 1/16 the nitrogen requirement. In marine systems, nitrogen is most often the growth-limiting nutrient, as opposed to phosphorous. While usually in plentiful supply in seawater, phosphorous can become the limiting nutrient to phytoplankton growth in less saline environments or in locations heavily influenced by anthropogenic input of nitrogen. Nutrient limitation of phytoplankton growth has been found to vary widely with species and has not been extensively studied in local waters. Because the nitrogen concentration required by phytoplankton to attain maximum growth rate depends on many factors, both physiological and environmental, low concentrations measured in water samples cannot be used as evidence of limiting conditions for a particular phytoplankton population. In addition, a major difficulty in evaluating nutrient availability is due to patchiness of the nutrient supply and rapid uptake rates by phytoplankton. Given these constraints, only general patterns of temporal change can be determined from analysis of discrete water samples. Despite this, decreasing concentrations of field measured nutrients with time, coupled with increases in phytoplankton abundance, indicate where phytoplankton uptake has exceeded nutrient supply and regeneration. Nutrient concentrations below reporting limits (0.01 mg/L; Table 5; Ecology, 1994) indicate where this draw-down has occurred (Figure 15) and consequently reveal important information about the onset and decline of phytoplankton blooms.

Nutrients results are presented for Sinclair Inlet stations only, due to the less complete coverage for Dyes Inlet. Near-surface (1-m) and near-bottom dissolved nutrient concentrations from selected Sinclair Inlet stations during (mostly) low slack tide are presented in Figures 16, 17, and 18.

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

At all stations, 1-m nitrate+nitrite-N concentrations were highest during the 26 March survey (Figure 16a). In inner and central Sinclair (S-1, SA-2, SB-2 & SC-2), 1-m nitrate+nitrite-N concentrations below the reporting limit (<0.01 mg/L) were observed at one or more stations from early-May through mid-September, excluding 10 June and 8 July. At the outer stations (except for SE-2), 1-m nitrate+nitrite-N concentrations below the reporting limit were observed only on 24 June. Nutrient concentrations near the surface would be influenced by phytoplankton uptake as well as mixing with Puget Sound or freshwater sources.

Near-bottom nitrate+nitrite-N had a seasonal fluctuation pattern somewhat similar to 1-m nitrate+nitrite-N at inner Sinclair stations SA-2 and SB-2. However, near-bottom nitrate+nitrite-N were not below reporting limit for as long a duration as 1-m nitrate+nitrite-N concentrations (Figures 15 and 16). Below reporting limit concentrations of nitrate+nitrite-N occurred on 5 August and 19 August. In outer Sinclair Inlet, near-bottom nitrate+nitrite-N tracked near-surface values reasonably well.

Ammonium-N (NH_4-N)

At most stations, 1-m ammonium-N concentrations were fairly low during the entire sampling season. Higher concentrations were observed at station S1 on 10 June and at several stations on 8 July (Figure 17a).

For most stations, periods of below reporting limit concentrations of near-bottom ammonium-N and near-bottom nitrate+nitrite-N corresponded with each other (Figures 15, 16b, and 17b). All stations had the same general seasonal near-bottom fluctuations, although ammonium-N concentrations were often highest at inner Sinclair stations SA-2 and SB-2 (Figure 17b). Overall, ammonium-N concentrations were much lower than nitrate+nitrite-N concentrations (Figures 16 and 17), which is typical of marine waters.

Orthophosphate-P (oPO_4-P)

At most stations (aside from SB-2), 1-m and near-bottom orthophosphate-P concentrations were fairly constant throughout the season (Figure 18). At station SB-2, there were some peaks in orthophosphate-P concentration at a depth of 1 m on 5 August and in the near-bottom on 22 July and 19 August. Near-bottom orthophosphate-P peaks corresponded with near-bottom

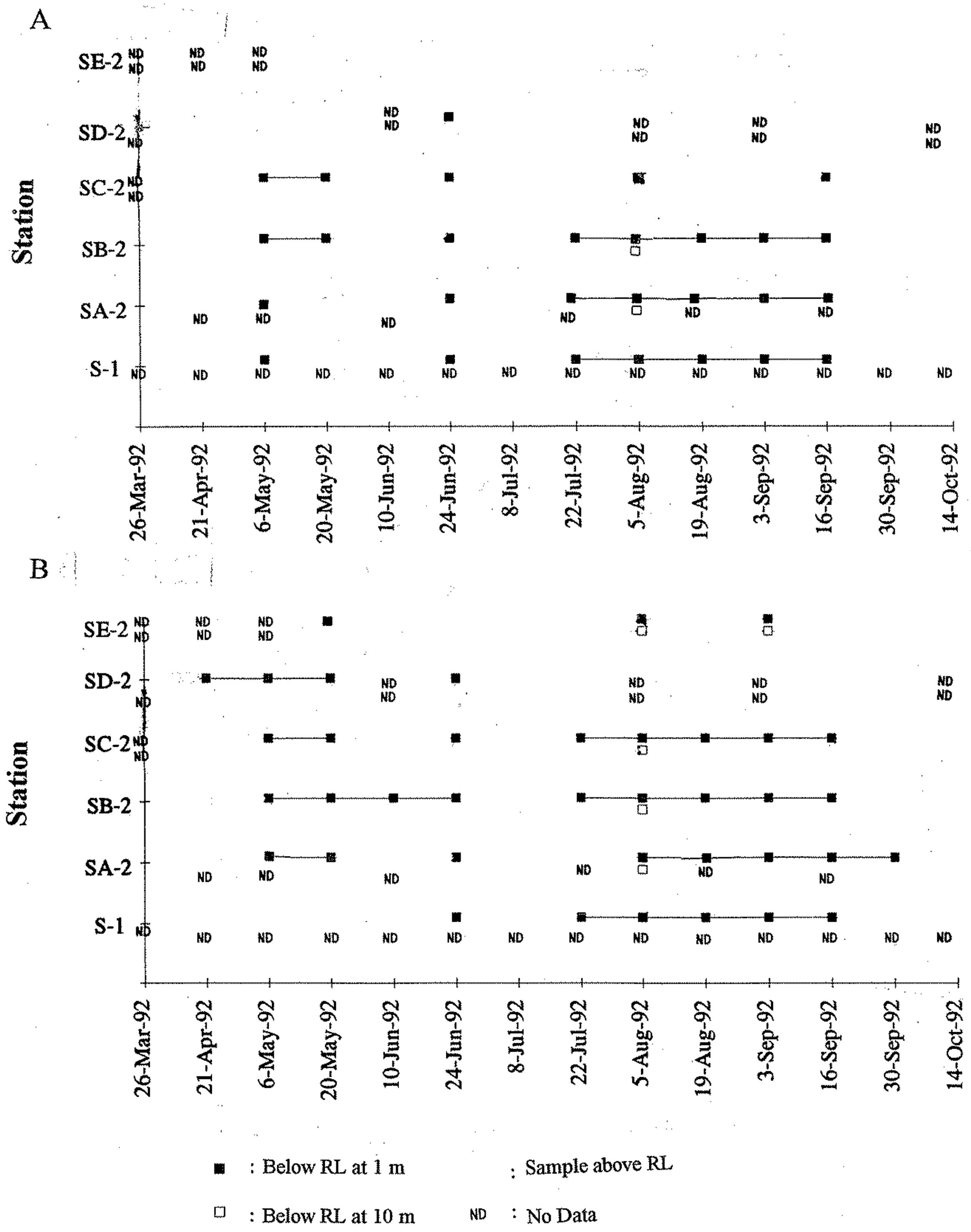
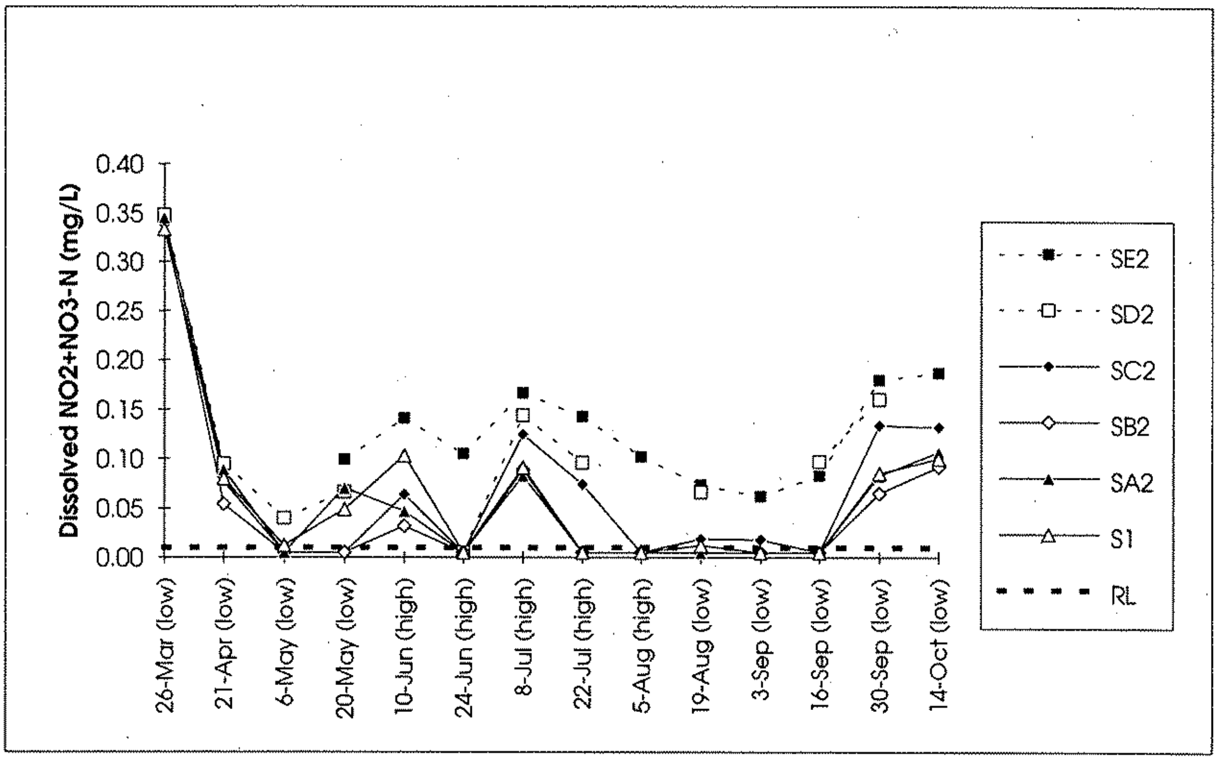


Figure 15. Nutrient concentrations below reporting limit (0.01 mg/L) at slack tide for the 1992 season in Sinclair Inlet of (a) dissolved nitrate+nitrite-N (mg/L) and (b) dissolved ammonium-N (mg/L). Data are discrete. "RL" indicates reporting limit.

A



B

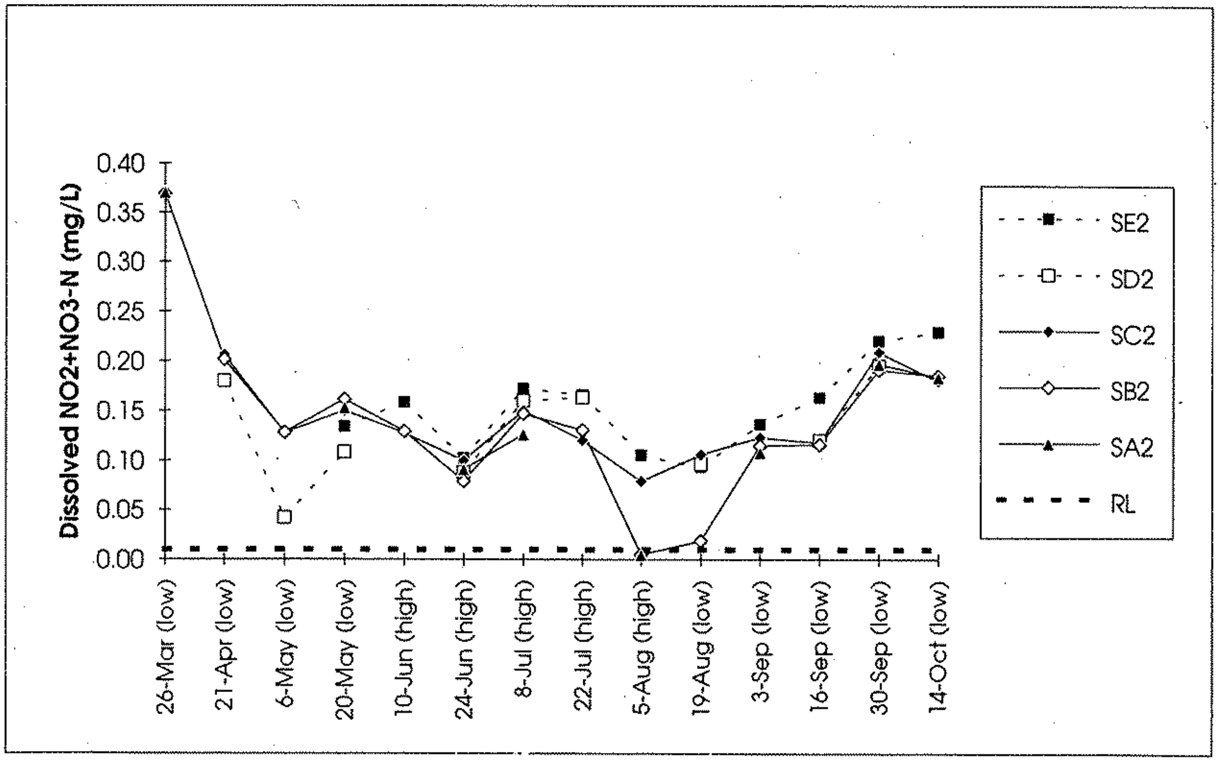
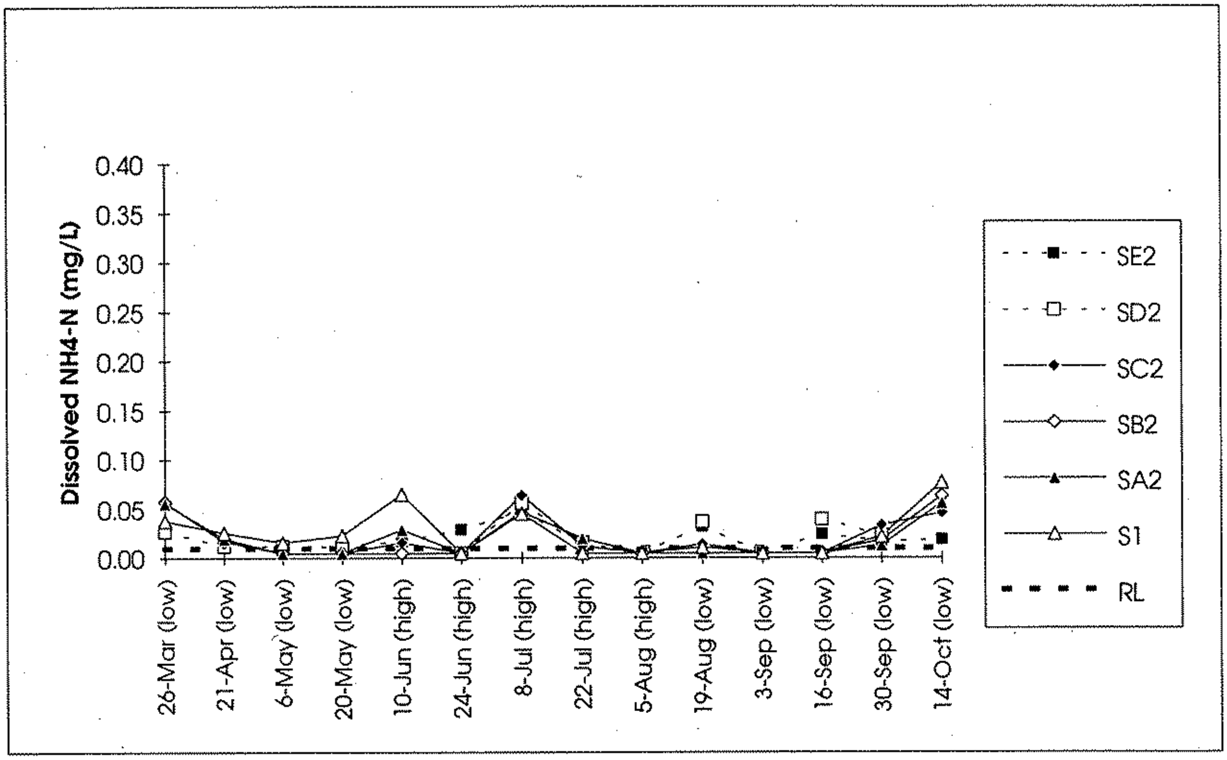


Figure 16. Concentrations of dissolved nitrate+nitrite-N (mg/L NO_3+NO_2-N) for (a) near-surface and (b) near-bottom depths in Sinclair Inlet on survey dates during 1992. Inner bay stations represented by a solid line. Central and outer bay stations represented with a dashed line. Samples collected at low tide, except for surveys between 10 June and 5 August, inclusive, which were collected at high tide. Data are discrete. "RL" indicates reporting limit.

A



B

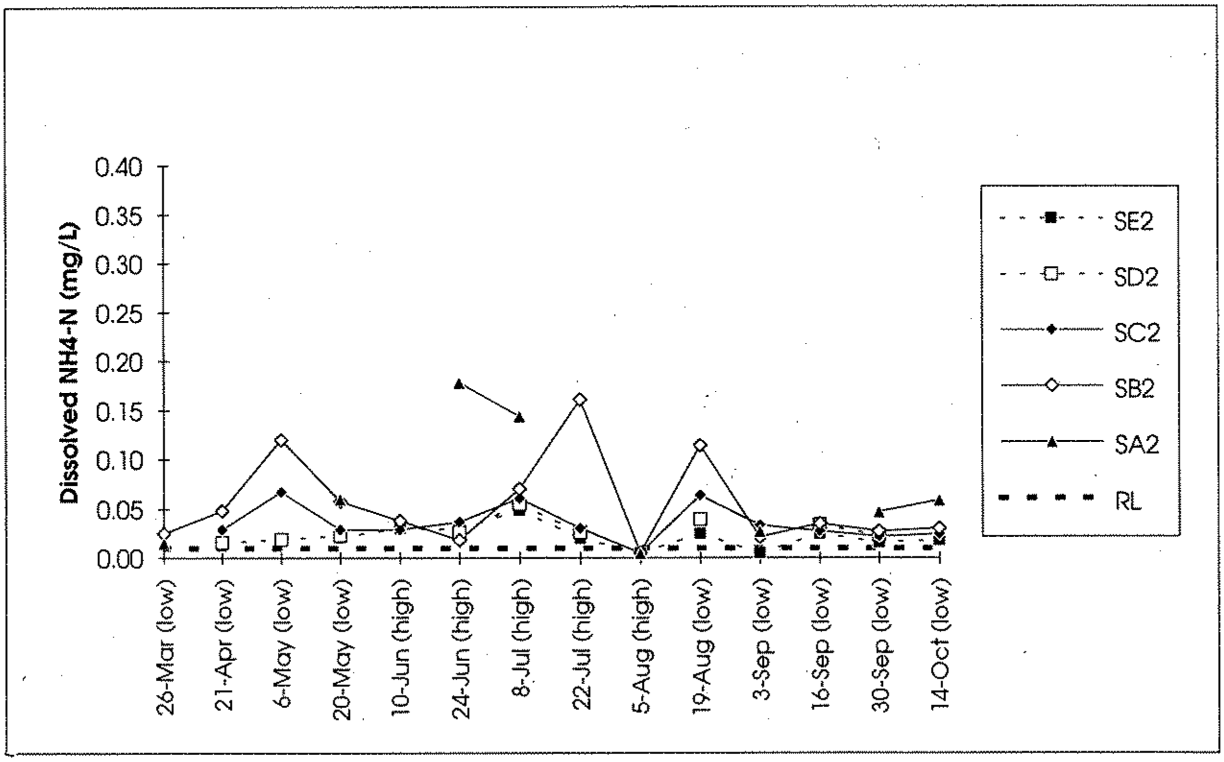


Figure 17. Concentrations of dissolved ammonium-N (mg/L NH_4-N) for (a) near-surface and (b) near-bottom depths in Sinclair Inlet during 1992. Inner bay stations represented by a solid line. Central and outer bay stations represented with a dashed line. Samples collected at low tide, except for surveys between 10 June and 5 August, inclusive, which were collected at high tide. Data are discrete. "RL" indicates reporting limit.

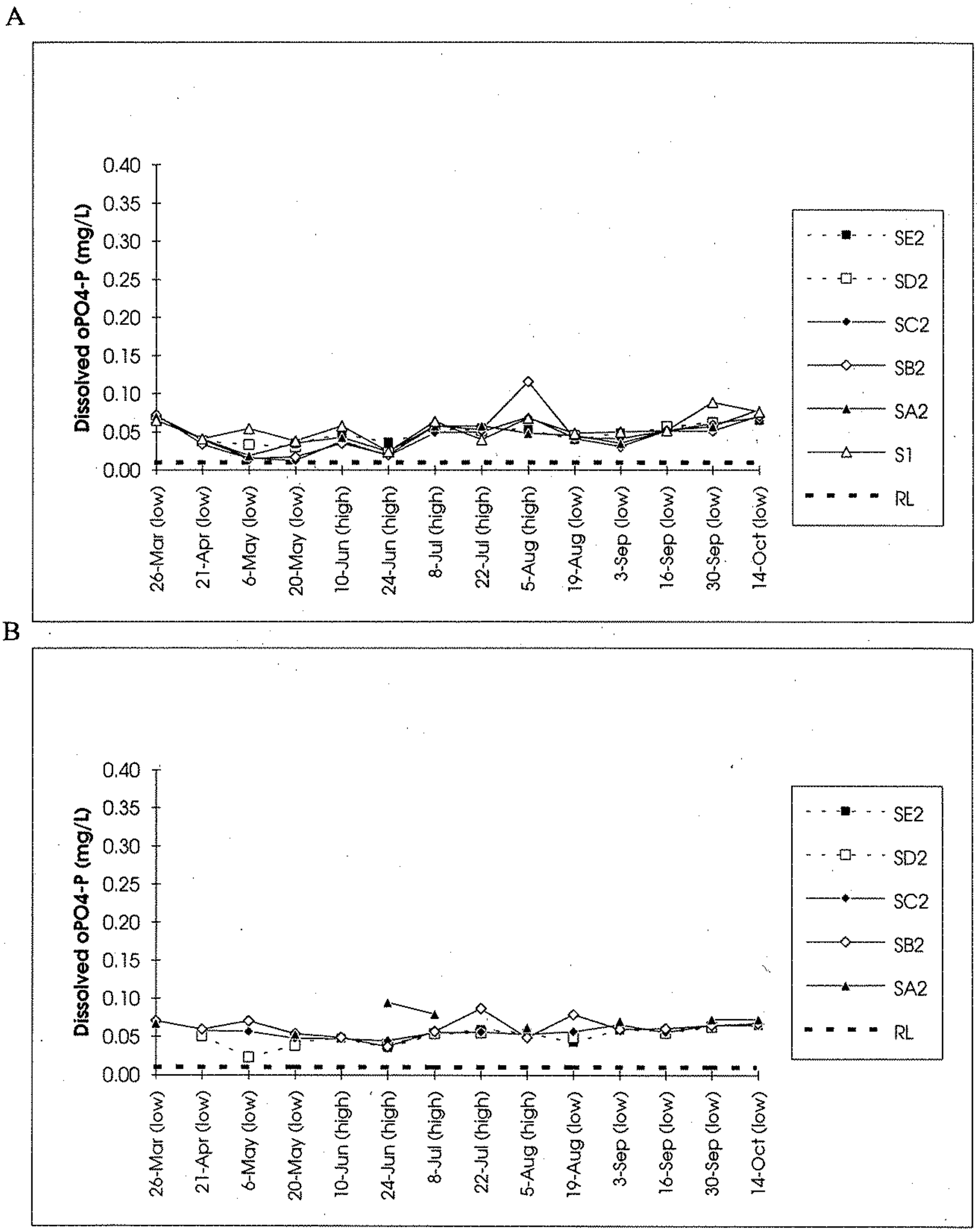


Figure 18. Concentrations of dissolved orthophosphate-P (mg/L oPO_4-P) for (a) near-surface and (b) near-bottom depths in Sinclair Inlet during 1992. Inner bay stations represented by a solid line. Central and outer bay stations represented with a dashed line. Samples collected at low tide, except for surveys between 10 June and 5 August, inclusive, which were collected at high tide. Data are discrete. "RL" indicates reporting limit.

ammonium-N peaks at station SB-2 further suggesting an anthropogenic source. Based on the persistence of measurable orthophosphate-P throughout the season, it is unlikely that phosphorous limited phytoplankton growth.

Spatial Patterns

During low slack tide in Sinclair Inlet, nitrate+nitrite-N concentrations were higher at the outer stations than at inner and central stations, while ammonium-N values tended to be highest near inner stations (*e.g.*, SA-2, SB-2). High nitrate+nitrite-N concentrations at the outer stations are influenced by greater proximity to upwelled oceanic nutrients as well as less loss to the phytoplankton population, which is less abundant at the outer stations (see Phytoplankton Concentration and Distribution section). The high ammonium-N concentrations, observed in May, July, and August at the inner stations, may have been influenced by inputs from Bremerton WWTP and run-off.

To evaluate the importance of ammonium-N (NH_4-N) input from the Bremerton WWTP to Sinclair Inlet, a simple estimation was calculated, as follows.

Assume: steady-state (ignore tides), complete mixing, water and NH_4-N are conserved.

Where: V = volume of water;
$\dot{V}$ = dV/dt, time rate-of-change (derivative) of water volume.

If: residence time = 14 days for Sinclair Inlet (US Navy, 1983); and
$V_{MLLW} = 1.55 \times 10^8\ m^3$, the volume of Sinclair Inlet at mean lower-low water;
then, $\dot{V}_{IN} = 1.55 \times 10^8\ m^3 / 14\ days = 1.11 \times 10^7\ m^3/day$.

Using: $\dot{V}_{WWTP} = 6 \times 10^6$ gal/day (22,710 m^3/day), annual average flow of WWTP (Tetra Tech, 1988a);
C_{WWTP} = 20 mg/L, NH_4-N concentration in WWTP effluent (Reif, 1988);
C_{IN} = 0, assume NH_4-N concentration of water replenishing the inlet is 0 mg/L;
C_{OUT} = resultant (unknown) NH_4-N concentration.

For conservation of water:

$$\dot{V}_{WWTP} + \dot{V}_{IN} = \dot{V}_{OUT}.$$

For conservation of NH_4-N:

$$C_{WWTP}\,\dot{V}_{WWTP} + \cancel{C_{IN}}\dot{V}_{IN} = C_{OUT}\dot{V}_{OUT}.$$

Therefore:

$$C_{OUT} = (C_{WWTP}\,\dot{V}_{WWTP}) / \dot{V}_{OUT} = (C_{WWTP}\,\dot{V}_{WWTP}) / (\dot{V}_{WWTP} + \dot{V}_{IN}).$$

Thus, the calculated concentration of the ammonium-N input from the Bremerton WWTP is = 0.04 mg/L. Although this is a very approximate calculation, the result indicates that the WWTP discharge at Bremerton would be detectable in Sinclair Inlet.

Temporal Patterns

Nitrate+nitrite-N data exhibit a clear seasonal pattern, reflecting vertical mixing in both spring and late-fall, and water column stratification between nutrient-poor surface water and deeper nutrient-rich water during summer and early-fall. Both ammonium-N and orthophosphate-P data show this pattern slightly; however, both also exhibit short-lived summer concentration maxima.

Near-surface (1-m) nitrate+nitrite-N and ammonium-N concentrations were relatively high on 8 July (Figures 16 and 17). This may reflect high nutrient inputs, possibly in association with high precipitation or runoff, as well as a lack of nutrient utilization due, to the unseasonably low phytoplankton abundance (chlorophyll *a* ~1 mg/m^3 in central and outer Sinclair Inlet; see Phytoplankton Concentration and Distribution section).

Overall, the seasonal fluctuations in the near-bottom concentration of a particular nutrient were consistent at all stations throughout the inlet, except as noted in the inner inlet (stations SA-2, SB-2), possibly influenced by the Bremerton WWTP outfall. The near-bottom concentrations of nitrate+nitrite-N, however, were typically higher than 1-m concentrations, reflecting accrual at depth (remineralization) and uptake in the euphotic zone. Orthophosphate-P was consistently present at concentrations above the reporting limit, in accordance with its role as non-limiting to phytoplankton growth in marine systems.

Phytoplankton Concentration and Distribution

Sinclair Inlet

Horizontal Distribution

Low and high (slack) tide along-channel transect data indicate maximum phytoplankton concentrations were generally centered around station SB-2 (Figure 19a, c) and sometimes station SA-2 (Figure 19d). Ebb and flood tide cross-channel transect data also indicate that maximum phytoplankton concentrations were generally located at the SB and SA transects (Figure 20). Though centered in inner Sinclair Inlet, at times, high concentrations of phytoplankton extended throughout much of the inlet (*e.g.*, Figure 19b). Bloom concentrations (defined here as > 10 mg/m^3) were often observed from station S-1 out to stations SC-2 or SD-2 (Figures 19b and 21). This pattern was observed during slack as well as ebb and flood tides. Overall, inner Sinclair stations had higher phytoplankton concentrations than outer stations, likely due to stronger stratification in the inner inlet.

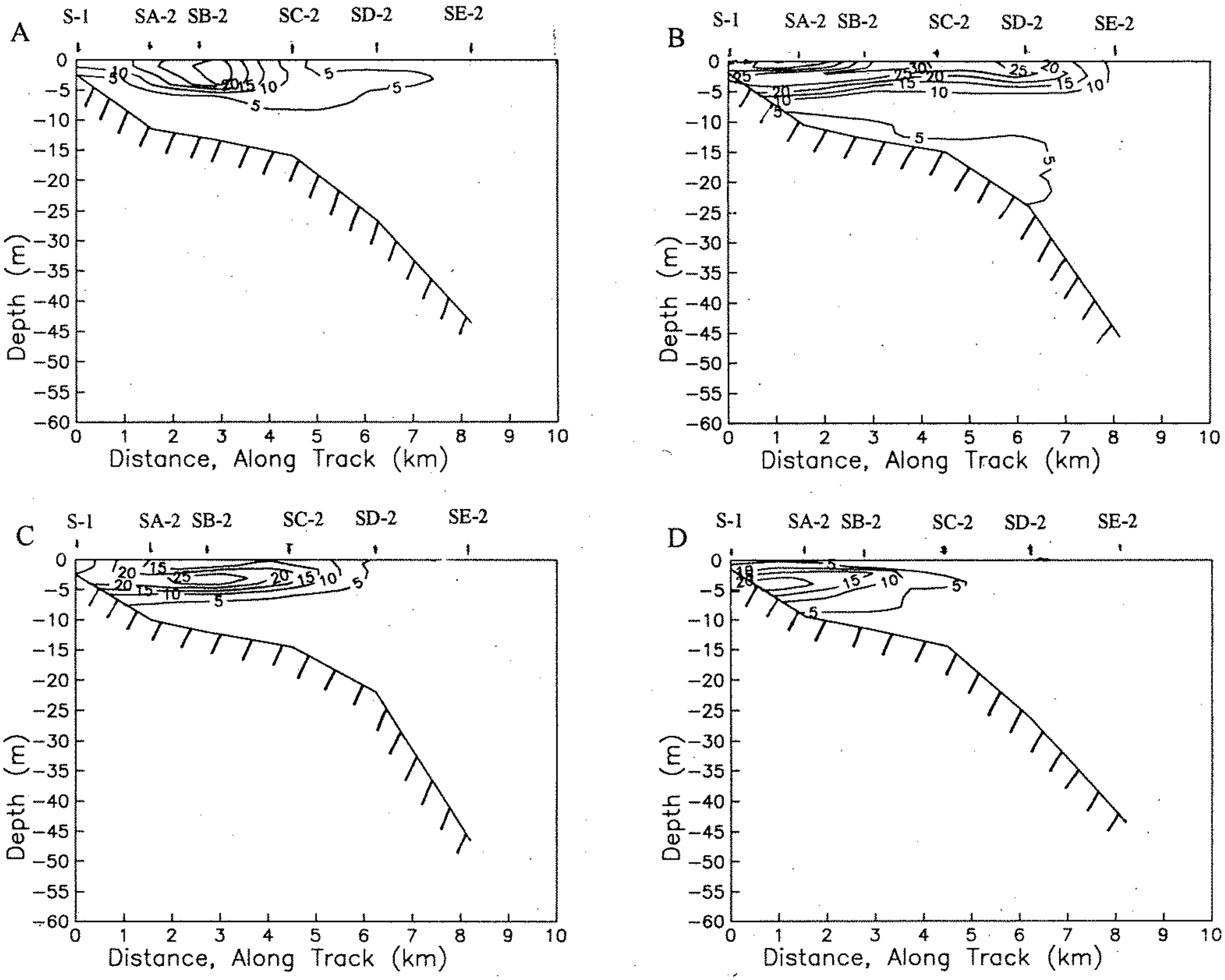


Figure 19. Vertical contour plots of *in situ* fluorometer measurements of chlorophyll *a* (mg/m^3) from station S-1 out to station SE-2 at slack tide in Sinclair Inlet on (a) 22 July (high tide), (b) 5 August (high tide), (c) 3 September (low tide), and (d) 14 October (low tide) 1992. //// represents bottom contour.

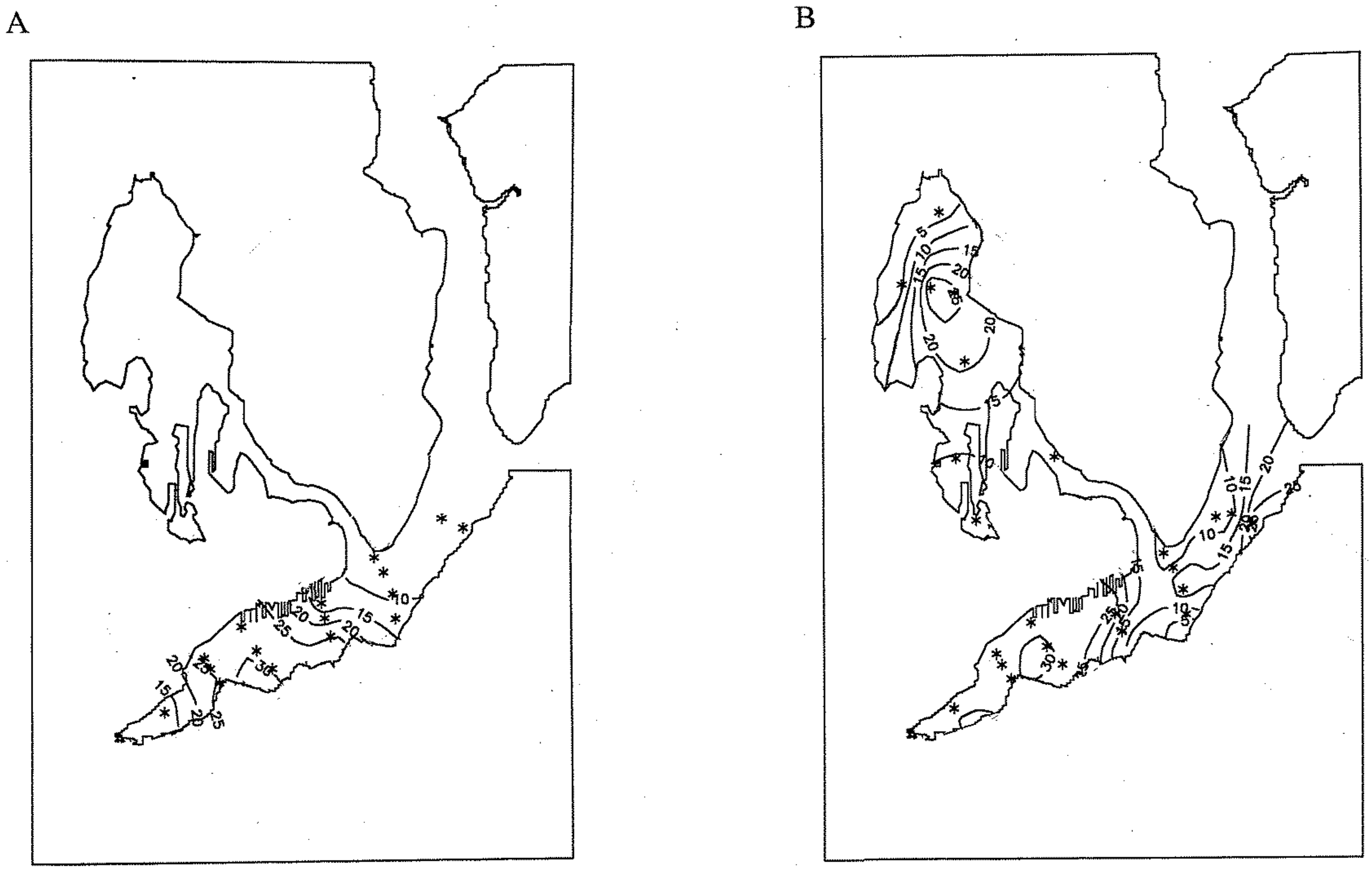


Figure 20. Contour plots of *in situ* fluorometer measurements of chlorophyll *a* (mg/m^3) on (a) 22 July, at a depth of 1 m (ebb tide), (b) 5 August, at a depth of 2 m (ebb tide), (c) 3 September, at a depth of 3 m (ebb tide), and (d) 14 October 1992, at a depth of 3 m (flood tide). Stations with data used for contouring are indicated by "*".

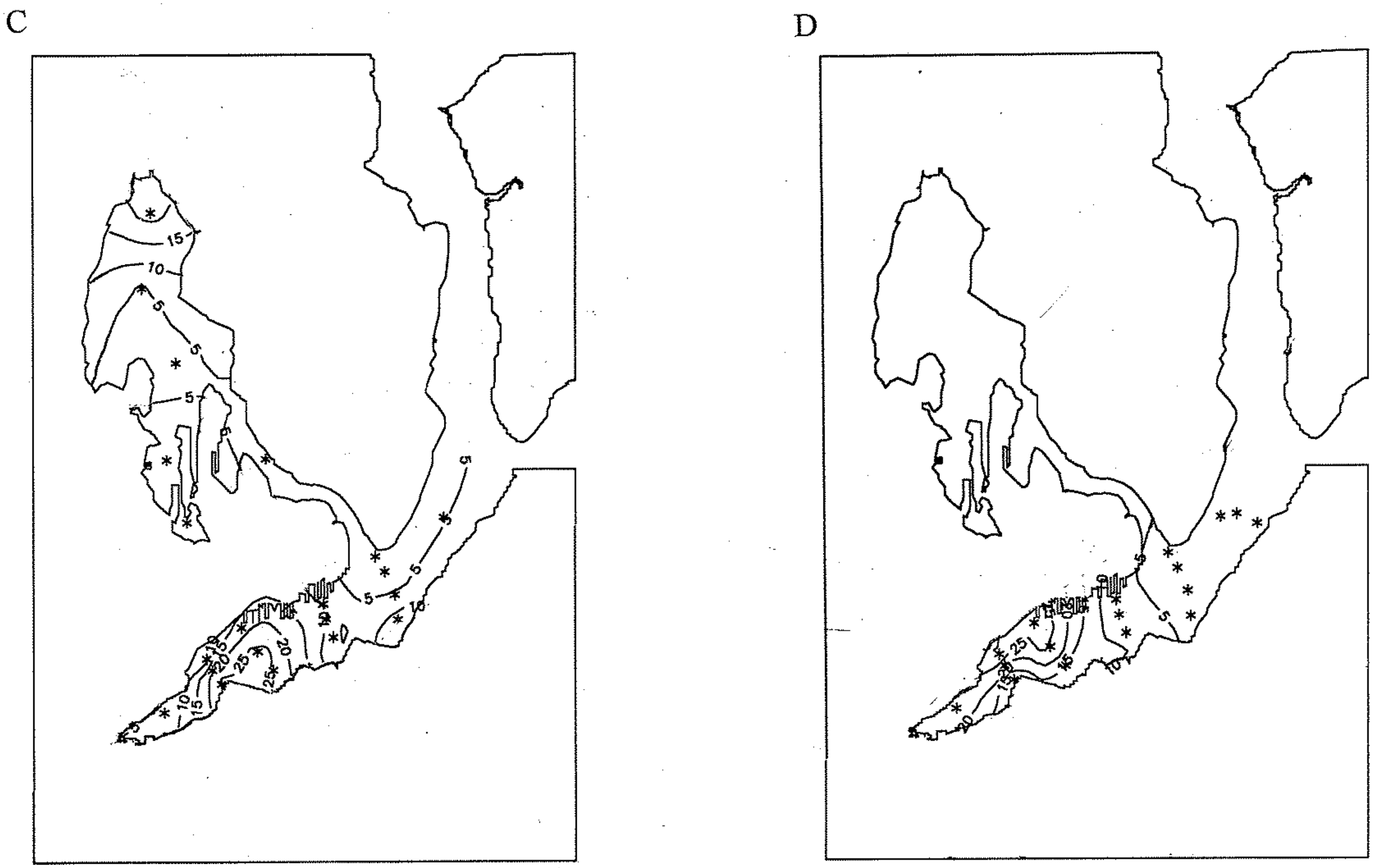


Figure 20. continued.

Vertical Distribution

During slack tides, phytoplankton abundance maxima were located in surface waters (0.5 to ~3 m) during spring and early-summer surveys, as indicated by transmissometer and DO data (Figures 22 and 23). During mid-summer, maximum concentrations were generally observed between 0 to 5 m (Figure 19a,b). Maximum concentrations were observed at slightly deeper depths (2 to 6 m) during late-summer and fall surveys (Figure 19c,d). Ebb and flood tide data indicate similar vertical distributions.

Timing of Phytoplankton Blooms

Biweekly slack tide data indicate phytoplankton bloom concentrations were observed for at least one station in Sinclair Inlet during all surveys except 26 March and 19 August (Figure 21). Chlorophyll *a* concentrations >25 mg/m^3 were observed from late-July through mid-October excluding the 19 August survey. The highest concentration (51 mg/m^3) was observed on 22 July 1992 at station SB-2.

Dyes Inlet

Dyes Inlet data were collected during flood or ebb tides except for one survey conducted during high slack tide (Table 3).

Horizontal Distribution

Lab chlorophyll *a* concentrations were highest at station DA-2 during two summer surveys and highest at station DD-2 during two fall surveys (Figure 24). However, there was not a consistent location of maximum phytoplankton concentration in Dyes Inlet (such as for inner Sinclair Inlet). Bay-wide *in situ* fluorometer, transmissometer, and DO data also support this conclusion.

Vertical Distribution

Maximum phytoplankton concentrations were located close to the surface (0.5 to ~3 m) during spring and mid-summer surveys (Ecology AMS logbook). Maximum concentrations were observed at slightly deeper depths (2 to 4 m) during late-summer and fall surveys (Figure 25).

A direct comparison of early- and late-season data was hampered by changes in methods (*i.e.*, early surveys were executed without an *in situ* fluorometer and lab samples were taken at a depth of 1 m, instead of at the depth of the fluorometric peak). All chlorophyll *a* concentrations taken after 5 August had values below 10 mg/m^3 at a depth of 1 m (Figure 25). In contrast, lab 1-m chlorophyll *a* concentrations from 21 April and 10 June were above 10 mg/m^3.

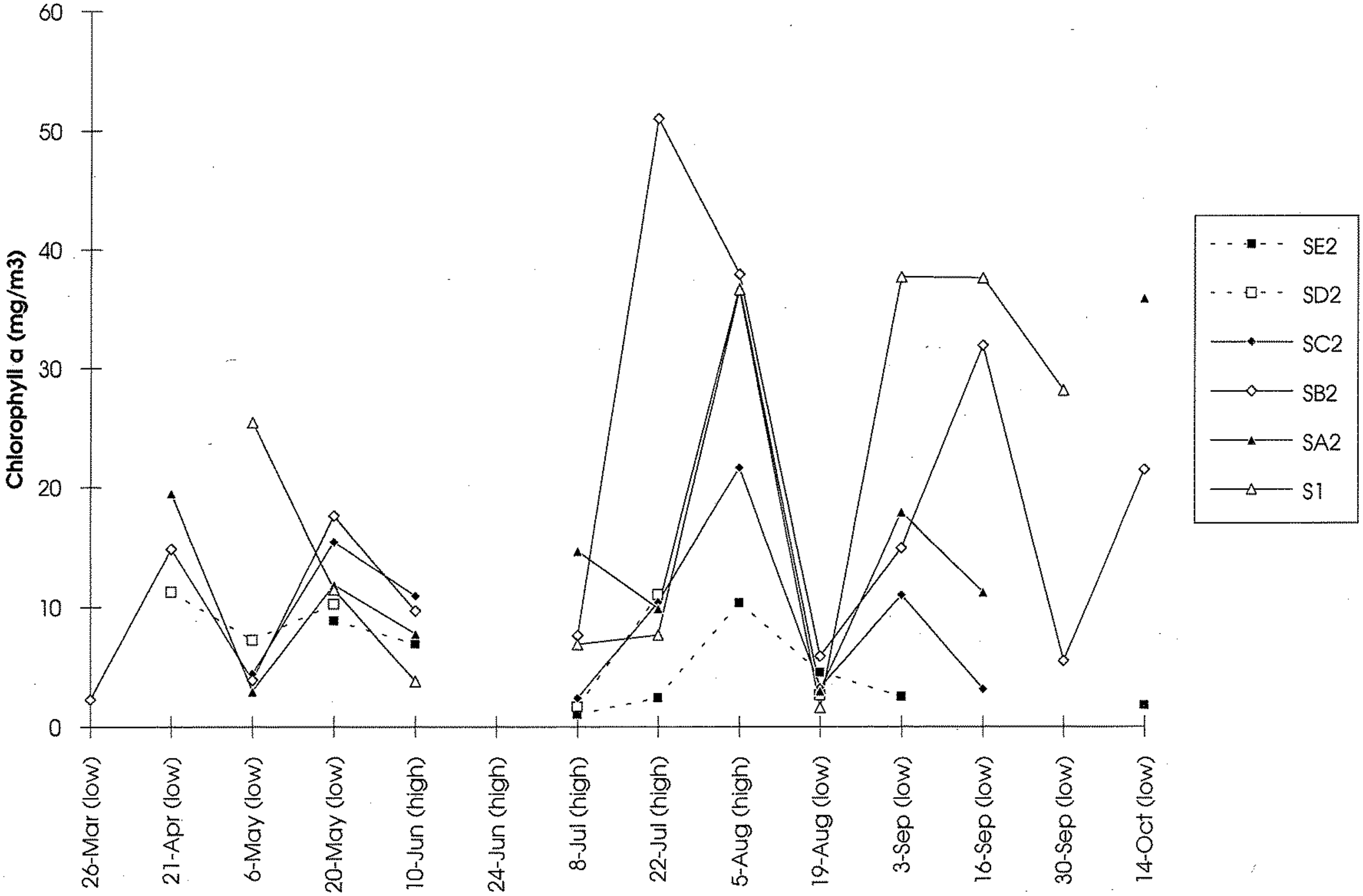


Figure 21. Lab chlorophyll *a* concentrations (mg/m^3) in Sinclair Inlet during 1992. Tidal stage is listed next to the survey date on the abscissa. Solid line = inner bay, dashed line = outer bay. Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth. Data are discrete. No lab chlorophyll *a* data were available for 24 June due to breakdown of the lab fluorometer.

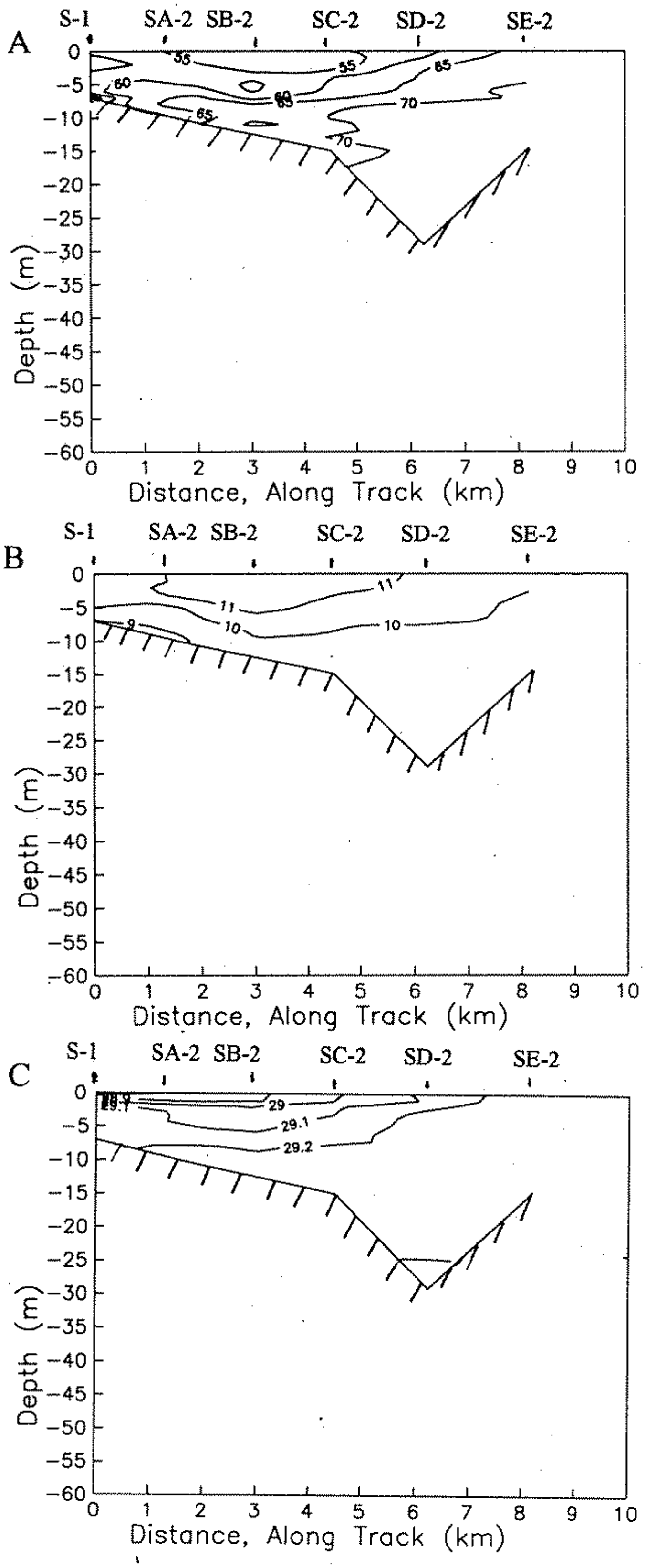


Figure 22. Vertical contour plots from station S-1 out to station SE-2 at high tide in Sinclair Inlet on 24 June 1992 of (a) transmissometer (% light transmission), (b) dissolved oxygen (mg/L), and (c) salinity (ppt). //// represents bottom contour.

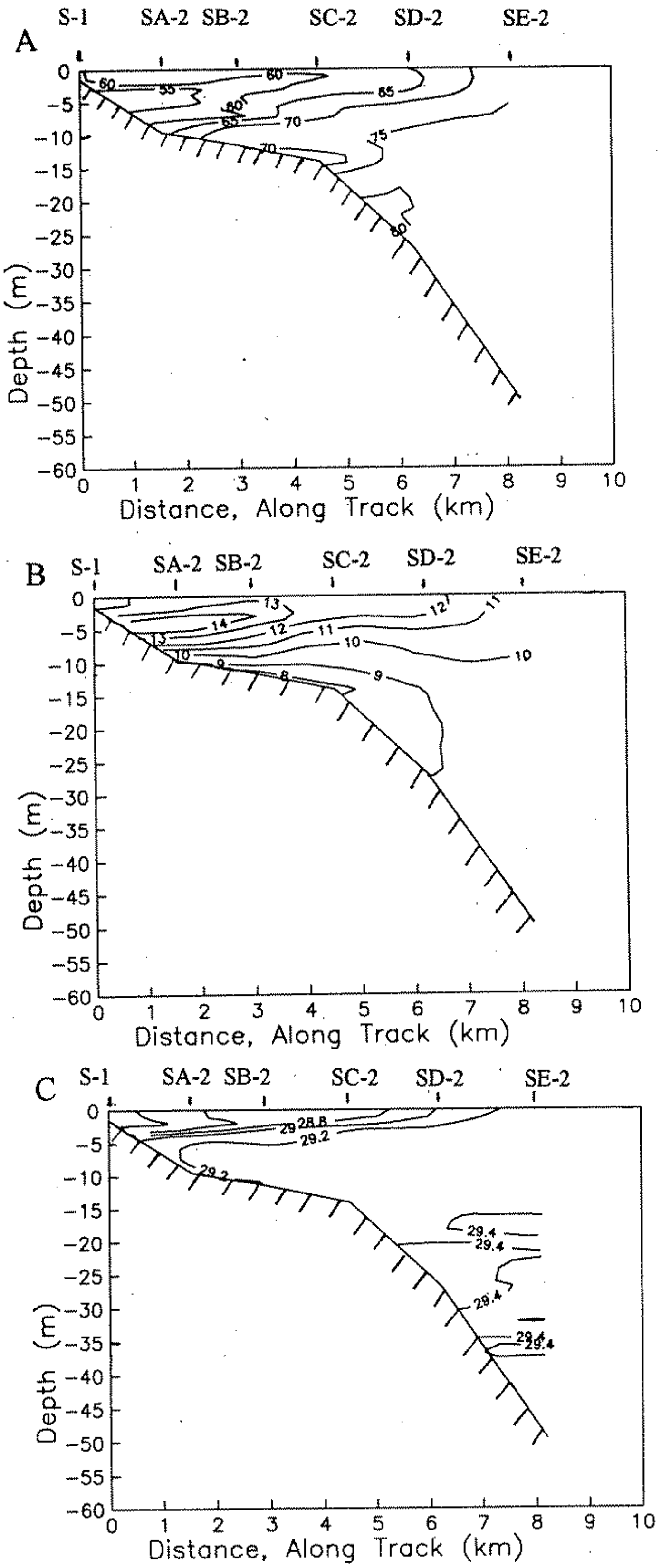


Figure 23. Vertical contour plots from station S-1 out to station SE-2 at high tide in Sinclair Inlet on 8 July 1992 of (a) transmissometer (% light transmission), (b) dissolved oxygen (mg/L), and (c) salinity (ppt). //// represents bottom contour.

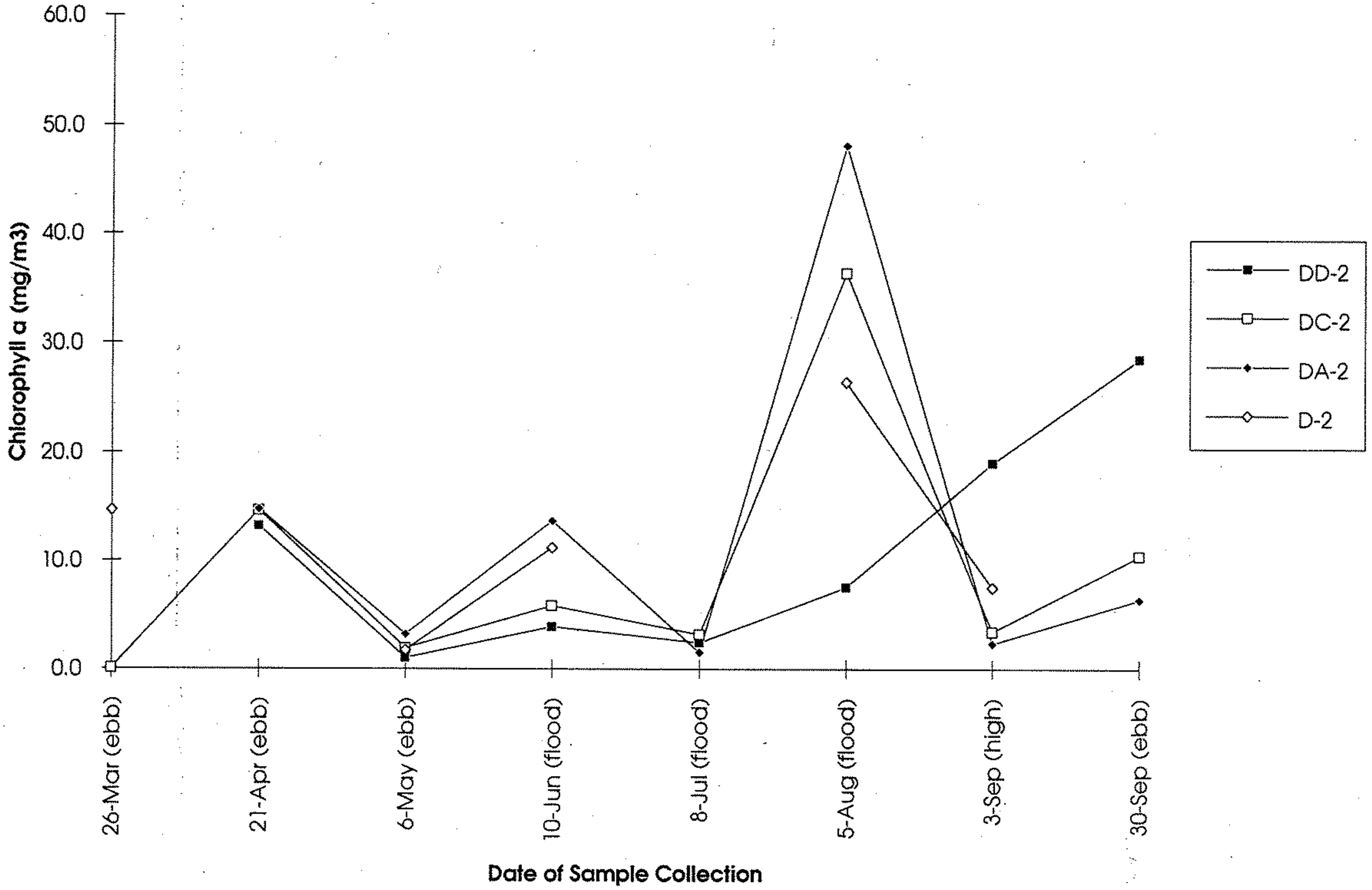


Figure 24. Lab chlorophyll *a* concentrations (mg/m^3) in Dyes Inlet during 1992. Tidal stage is listed next to the survey date on the abscissa. Solid line = inner bay, dashed line = outer bay. Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth. Data are discrete.

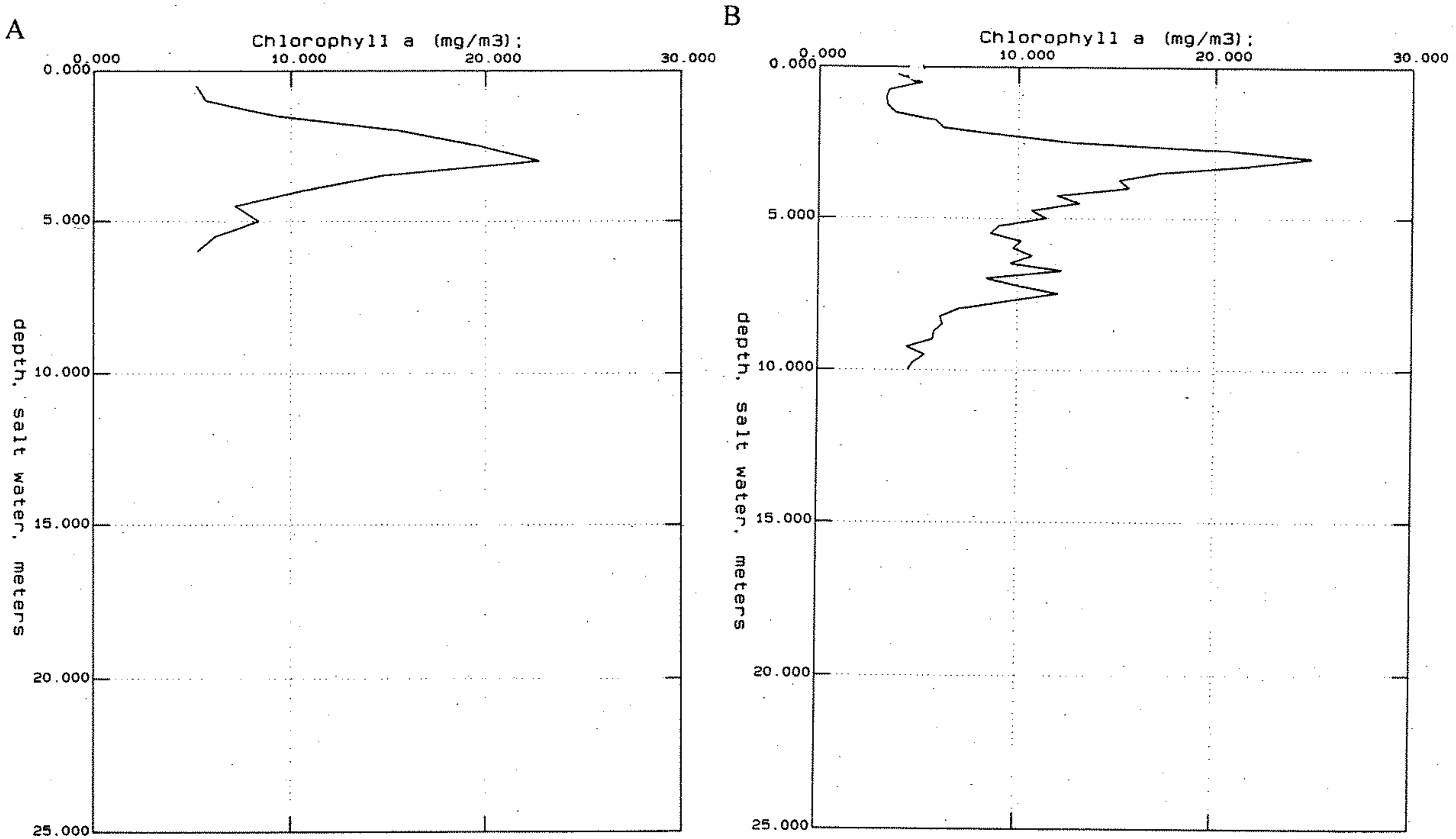


Figure 25. Vertical profiles of fluorometer data (mg chl *a*/m^3) at station DD-2 in Dyes Inlet from (a) 3 September and (b) 30 September 1992.

Timing of Phytoplankton Blooms

Phytoplankton blooms were observed at one or more stations during five out of eight surveys (Figure 24). Chlorophyll *a* concentrations > 25 mg/m^3 were observed on the 5 August and 30 September surveys. The highest concentration (48 mg/m^3) was observed during the 5 August survey at station DA-2.

Comparison of Sinclair and Dyes Inlets

Lab chlorophyll *a* concentrations were similar for both Sinclair and Dyes Inlets for surveys conducted on the same date (Figures 21 and 24).

During the September surveys, the highest phytoplankton concentrations were observed at the stations located in shallow water inner portions of both Sinclair (Figure 21) and Dyes (Figures 20c and 24) Inlets. During the spring and summer months the highest concentrations were generally located slightly further out in the inlet for both Sinclair (SA and SB transects) and Dyes (stations DA-2 and DC-2) Inlets, although generalizations are somewhat difficult to make for Dyes Inlet.

In summary, in Sinclair Inlet, the maximum phytoplankton concentrations were generally located in the inner inlet; whereas, in Dyes Inlet, maximum concentrations were located in different areas of the inlet depending on the survey. Lack of current meter data prevents a makes a mechanistic explanation of this observation. Sinclair and Dyes Inlets had similar seasonal lab chlorophyll *a* concentrations indicating that the timing of bloom occurrences may have been similar for both inlets. Similar phytoplankton species compositions were observed in both Sinclair and Dyes Inlets; although, some differences existed (see Phytoplankton Species section). In both Sinclair and Dyes Inlets, maximum phytoplankton concentrations were located near the surface during spring and early summer months and at slightly deeper depths during the late-summer and fall months. This may be in response to nutrient availability, since nitrogenous nutrients dropped below reporting limits at 1-m depths but were replete in the near-bottom waters during these months (Figure 15).

Dissolved Oxygen

Dissolved oxygen concentrations measured at 1-m ranged from a low of 6.4 mg/L on 3 September in Washington Narrows, to a high of 16.6 mg/L on 6 May at station SA-2 in Sinclair Inlet. Dissolved oxygen concentrations measured in the near-bottom waters ranged from a low of 2.2 mg/L on 19 August at Sinclair Inlet station SB-1, to a high of 15.9 mg/L on 6 May at Sinclair Inlet station S-1 (~ 2-3 m). Dissolved oxygen results at different times of the day for the same station often differed by 1.0 mg/L or more during the same survey (Table 10). The proportion of temporal dependency due to physical (*e.g.*, tidal) versus biochemical effects (*e.g.*, photosynthesis, respiration and decay) is not known.

Table 10. A comparison of dissolved oxygen concentration data collected at central Sinclair Inlet station SB-2 at slack tide and during exchange. Near-bottom data are from the next-to-bottom data bin in the CTD cast. "ND" indicates there are "No Data" (Not Done).

1992 Survey Date	*Tidal Stage*	*1-m DO (mg/L)*	*Near- bottom DO (mg/L)*	*Tidal Stage*	*1-m DO (mg/L)*	*Near- bottom DO (mg/L)*
3/26	Low	9.1	8.0	ND	ND	ND
4/21	Low	13.1	9.3	ND	ND	ND
5/6	Low	15.9	10.2	Flood	15.6	8.6
5/20	Low	11.8	9.2	Ebb	12.6	8.6
6/10	High	11.8	9.5	ND	ND	ND
6/24	High	13.2	8.6	Ebb	12.6	7.9
7/8	High	8.2	6.6	Flood	8.2	6.2
7/22	High	11.8	5.1	Ebb	11.7	5.4
8/5	High	10.4	8.0	Ebb	13.9	8.0
8/19	Low	11.1	4.2	Ebb	11.1	5.5
9/3	Low	10.5	7.2	Ebb	9.8	7.0
9/16	Low	11.2	6.8	Ebb	9.6	6.4
9/30	Low	10.7	7.3	Flood	13.0	7.0
10/14	Low	7.8	6.8	Flood	10.7	7.4

Low Dissolved Oxygen

In this report, DO concentrations below 5.0 mg/ L are termed low, and DO concentrations below 3.0 mg/L are termed hypoxic, since a concentrations of 2 to 3 mg/L are usually considered hypoxic (*e.g.*, Llansó, 1992; Smith *et al.*, 1992). Hypoxia, the presence of very low DO 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).

The lowest DO concentrations were most frequently observed in the inner portion of Sinclair Inlet at near-bottom depths (Figures 26 and 27). The only observation of hypoxic DO concentrations was on 19 August at stations SA-1 and SB-1 (Figure 27b). At station SB-1, the near-bottom (10 m) DO concentration fell to a minimum of 2.2 mg/L (Figure 28); at station SA-1, the lowest DO concentration observed (2.9 mg/L) was found mid-depth (5 m), while the near-bottom (8 m) concentration was 3.9 mg/L. The spatial extent of low DO conditions appeared to be small; however, its variation with time (and tide) is not known. Dissolved oxygen concentrations below 5.0 mg/L were recorded only during two surveys (22 July at SB-2; 19 August at SA-2 and SB-2), but were no lower than 4.7 mg/L in all instances.

Because the low DO conditions observed in inner Sinclair Inlet were infrequent and relatively mild, detrimental effects to the biota from these conditions are probably not serious. It should be noted, however, that the DO data collected during this 1992 project may not reflect the lowest

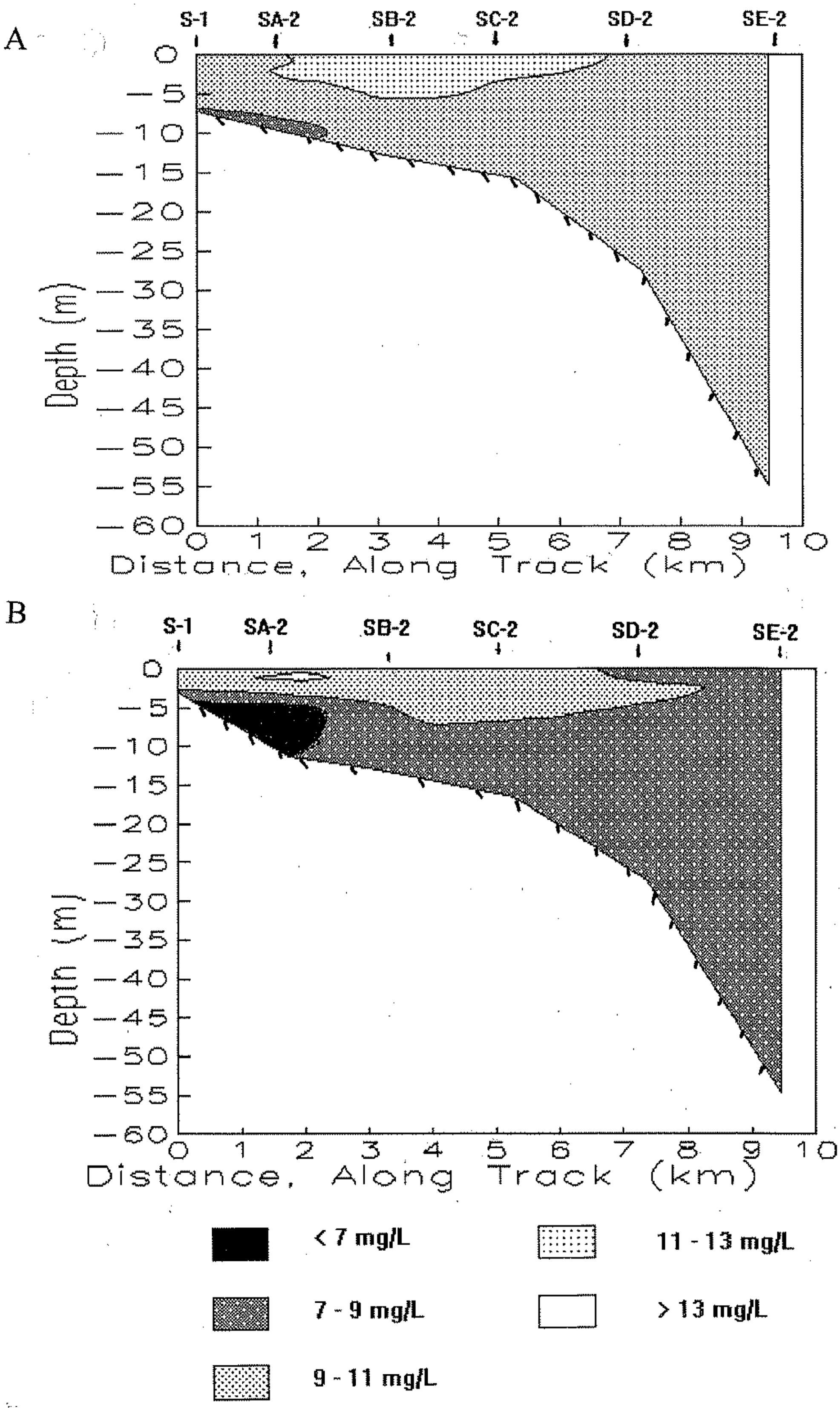


Figure 26. Dissolved oxygen (mg/L) vertical contour plots for station S-1 out to station SE-2 in Sinclair Inlet during high tide on (a) 10 June and (b) 5 August 1992. ⫽⫽ represents bottom contour.

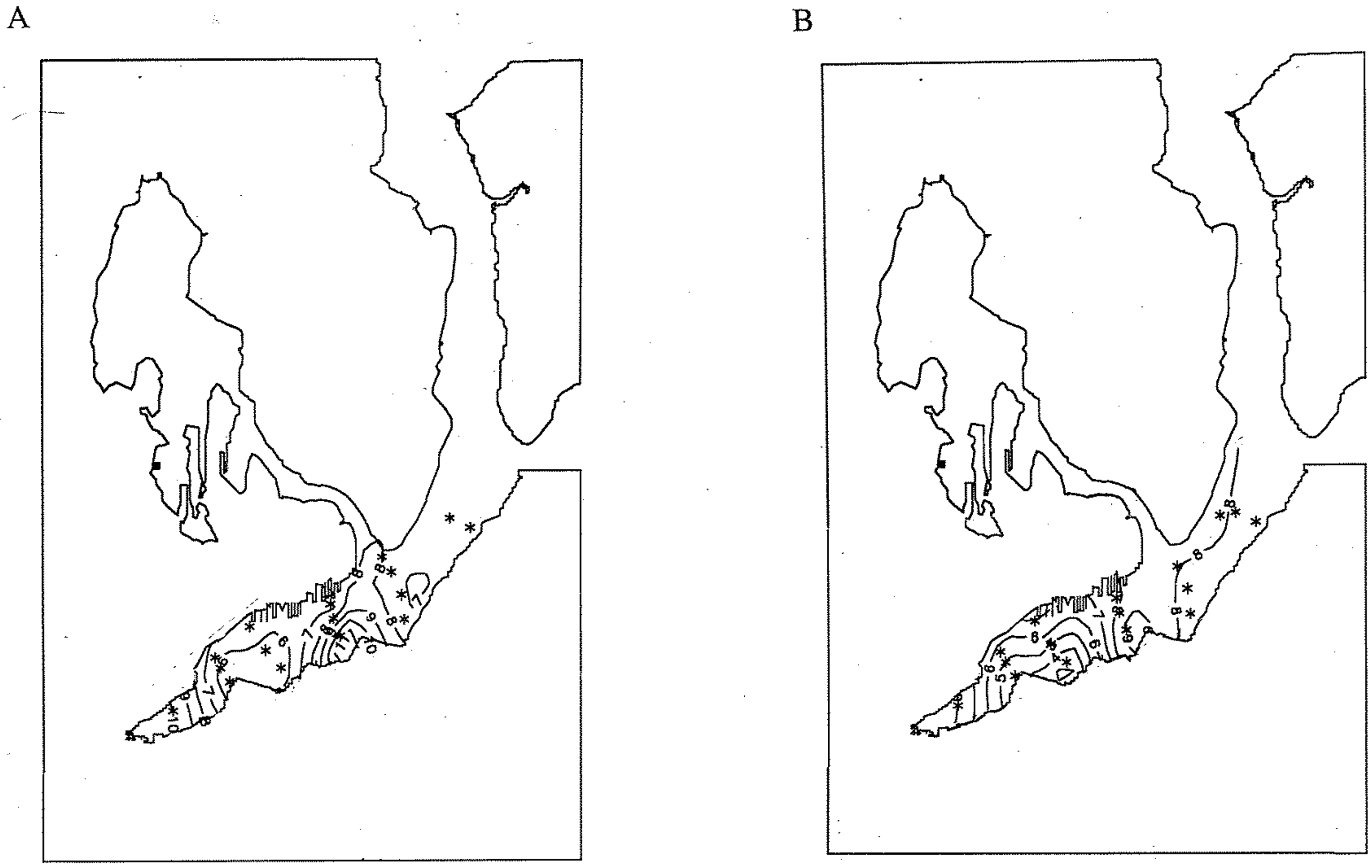


Figure 27. Near-bottom dissolved oxygen concentrations (mg/L) in Sinclair Inlet during ebb tide on (a) 22 July and (b) 19 August 1992. Stations with data used for contouring are indicated by "*".

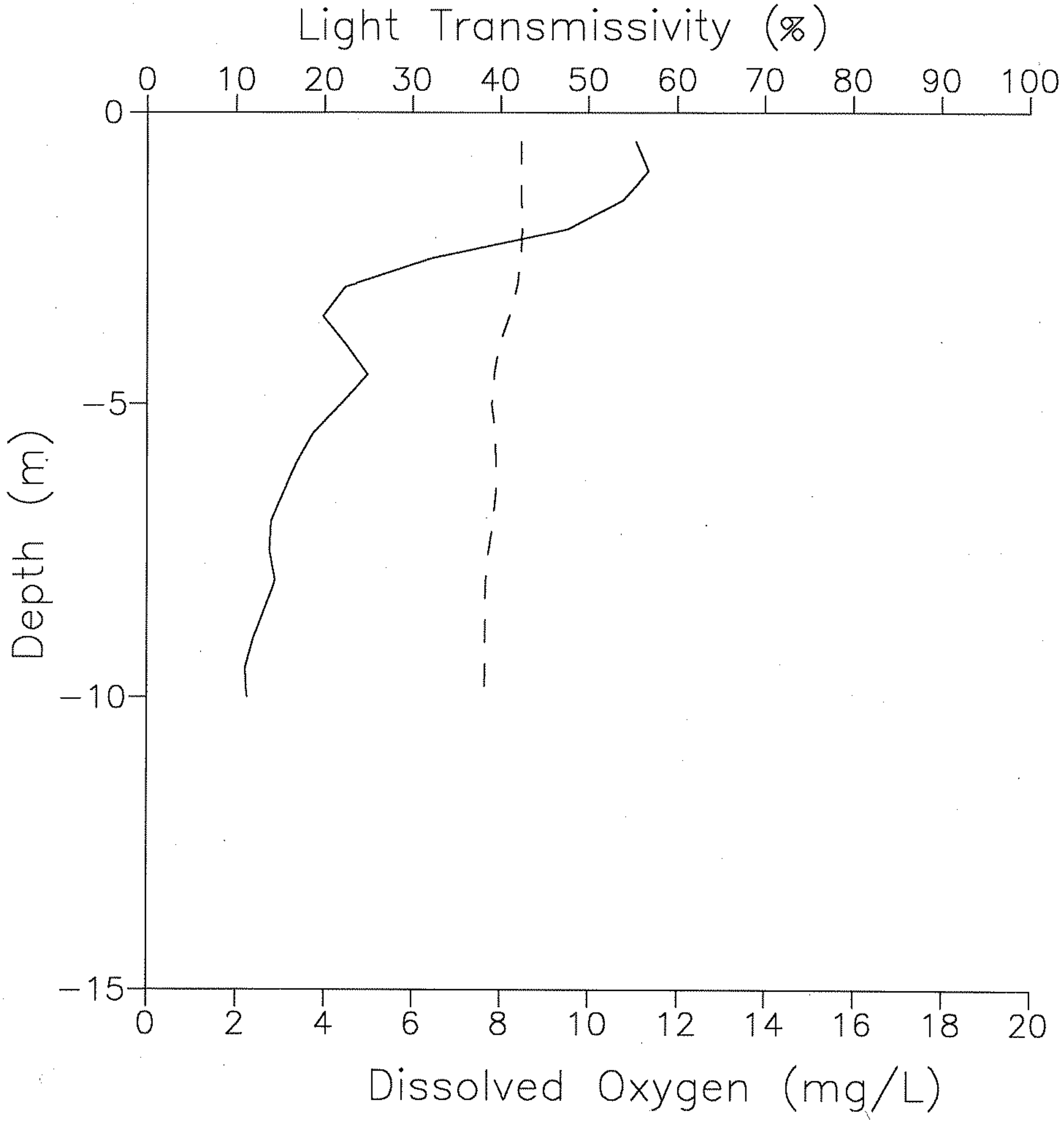


Figure 28. Vertical profile of dissolved oxygen (mg/L), solid line, and transmissometer data (% light transmission), dashed line, from 19 August 1992 at station SB-1 during ebb tide. Low light transmissivity may indicate higher phytoplankton concentrations.

DO conditions, since samples were taken during the day, in a year without much rainfall and hence with a lesser degree of stratification. To learn more about DO variability, sampling over tidal cycles and during a wet year would be required.

Both Sinclair and Dyes Inlets are rated as class "A" waters by the WAC (1992) code, thus are ascribed a water quality standard that DO concentrations shall exceed 6.0 mg/L. During the 1992 project, observed DO concentrations were in accordance with the WAC (1992) standard for all surveys in Dyes Inlet, and for surveys during March through June in Sinclair Inlet. However, observed DO concentrations in Sinclair Inlet fell below 6.0 mg/L on six dates between July and October: at stations along the SA and SB transects on 8 and 22 July, 19 August, and 14 October, and along the SA transect on 3 and 16 September. Although these represent excursions from WAC (1992) water quality standard, reports of deleterious effects to the biota from DO concentrations between 5 and 6 mg/L have not been noted in the literature.

Sinclair Inlet

A continuous biweekly time-series of DO concentration data for inner Sinclair station SA-2 is shown in Figure 29. Near-bottom DO concentrations were much lower in July through October (5-7 mg/L) than from March through June (8-14 mg/L). Variation of DO with depth changed throughout the season, influenced by both biological (phytoplankton blooms) and physical (degree of stratification) processes, and was maximum from July through September.

Water with a DO concentration that is in equilibrium with the atmosphere is referred to as 100% saturated. The biological processes of respiration and organic material decay consume oxygen, resulting in waters with less than 100% DO saturation. Conversely, photosynthesis produces oxygen and when this rate is high, and in excess of oxygen loss rates, water can become super-saturated. Super-saturation of water with DO is also a function of temperature and salinity. For the range of salinities and temperatures observed in Sinclair and Dyes Inlets during 1992, super-saturated (high) DO concentrations would be indicated by values greater than 10 mg/L.

High surface DO concentrations (> 10 mg/L) were observed on 9 out of 14 surveys. Dissolved oxygen concentrations were generally highest near the surface in inner Sinclair Inlet, by the SA and SB transects. In general, the highest DO values corresponded to phytoplankton blooms (chlorophyll *a* > 10 mg/m^3), and were observed in inner Sinclair Inlet.

Dyes Inlet

All of the DO concentrations measured in Dyes Inlet (Table 11) were greater than or equal to 6.8 mg/L. The lowest value (6.8 mg/L) was found at Oyster Bay (station D-1). It was somewhat surprising that lower DO values were not observed in Oyster Bay. Since Oyster Bay is ostensibly cut-off from the main section of Dyes Inlet, and thus, may have poor flushing, low DO values were anticipated.

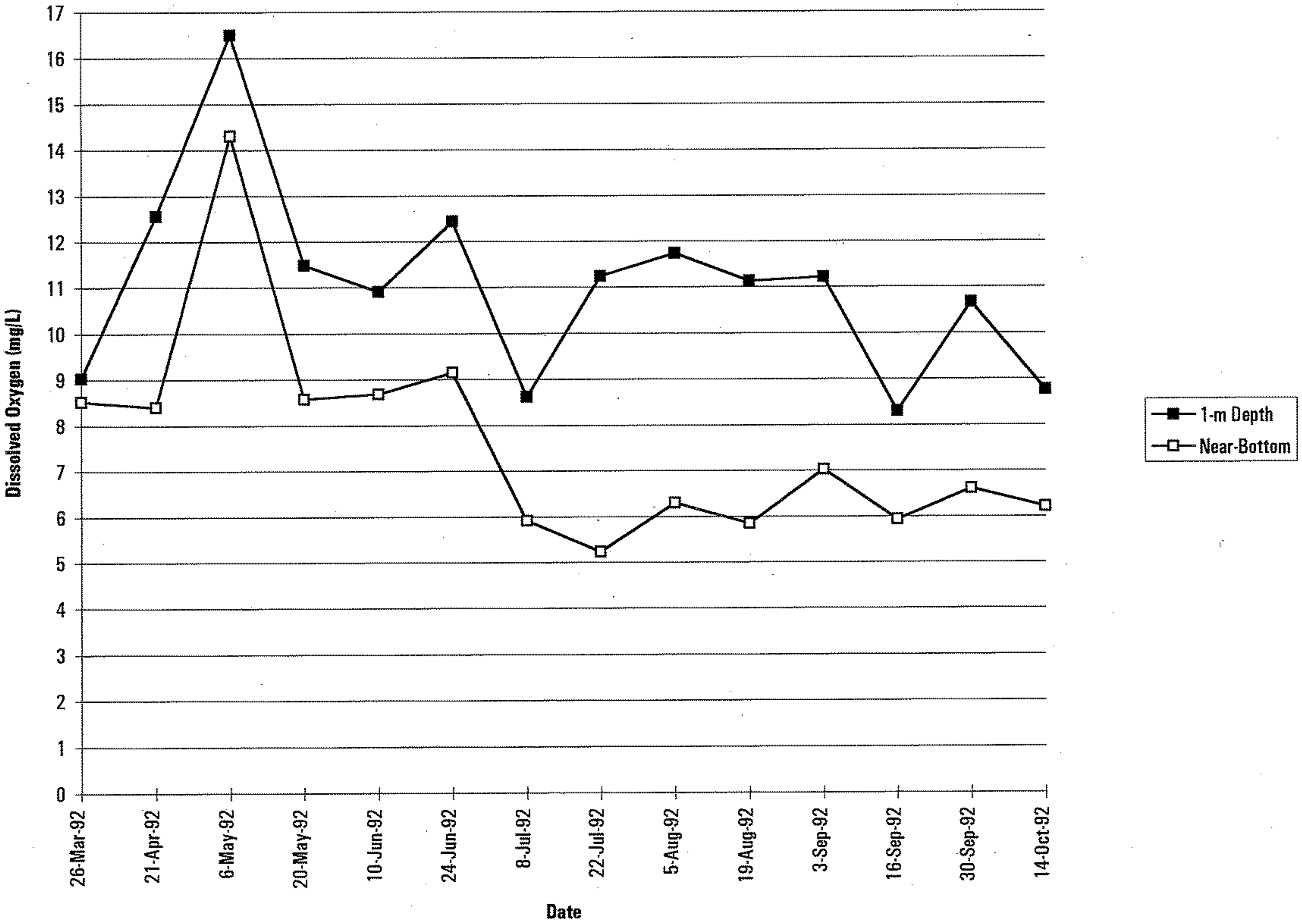


Figure 29. Dissolved oxygen concentrations (mg/L) from Sinclair Inlet station SA-2 at 1 m and near-bottom depths during March to October 1992 slack tides. Low tide except for surveys between 10 June and 5 August, inclusive, which were collected at high tide. Data are discrete.

Table 11. Summary of dissolved oxygen concentration data from two locations in Dyes Inlet. Near-bottom data are taken from the next-to-last data bin in the CTD downcast. Note that dissolved oxygen concentrations were not excessively low in Oyster Bay. "ND" indicates there are "No Data" (Not Done).

1992 Survey Date	*Tidal Stage*	*Near-bottom DO (mg/L) at Oyster Bay (station D-1)*	*Near-bottom DO (mg/L) at station DA-2*
3/26	Ebb	9.3	8.4
4/21	Ebb	ND	10.2
5/6	Ebb	ND	11.6
5/20	ND	ND	ND
6/10	Flood	12.5	10.5
6/24	Flood	ND	8.5
7/8	Flood	6.8	6.7
7/22	ND	ND	ND
8/5	Flood	11.6	10.0
8/19	ND	ND	ND
9/3	High	8.6	6.9
9/16	ND	ND	ND
9/30	Ebb	9.7	ND
10/14	ND	ND	ND

Maximum DO concentrations in Dyes Inlet occurred at the surface in the spring and at 1-2 m depth from mid-July through mid-August and generally corresponded with the occurrence of phytoplankton blooms.

Phytoplankton Species

Sinclair Inlet

Total diatom, dinoflagellate, and phytoplankton concentrations at the inner Sinclair Inlet stations are shown in Figure 30. The diatoms, dinoflagellates, and miscellaneous phytoplankton (*i.e.*, other than diatoms and dinoflagellates) that were observed in concentrations greater than 10^4 cells/L during any of the Sinclair surveys are shown in Figures 31, 32, and 33, respectively.

Diatoms predominated over dinoflagellates from April through late-June and from mid-August to late-September (Figure 30). Dinoflagellates predominated over diatoms from early-July through early-August and during mid-October.

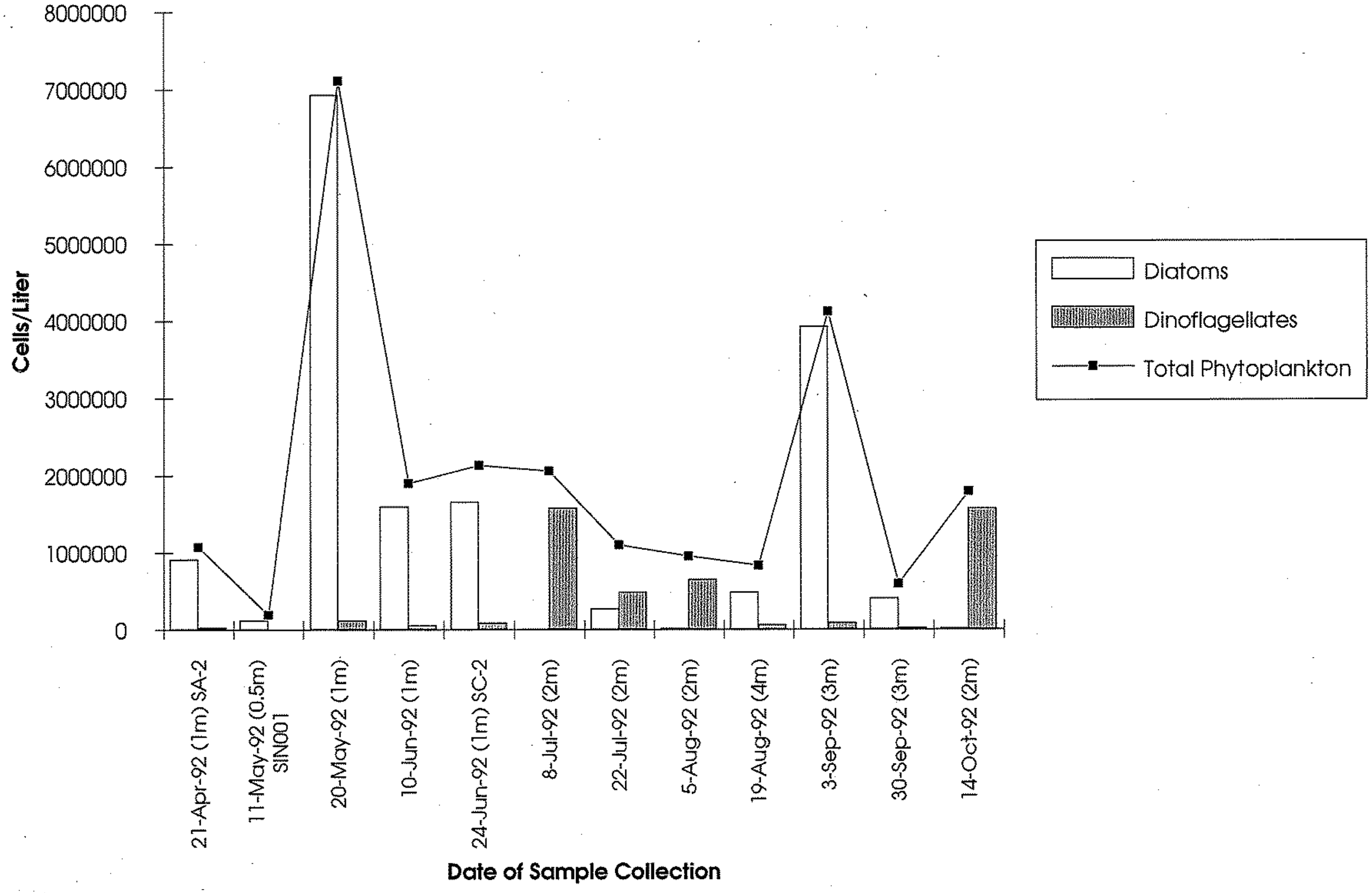


Figure 30. Diatom, dinoflagellate, and total phytoplankton concentrations (cells/L) during April to October 1992 from inner Sinclair Inlet (station SB-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

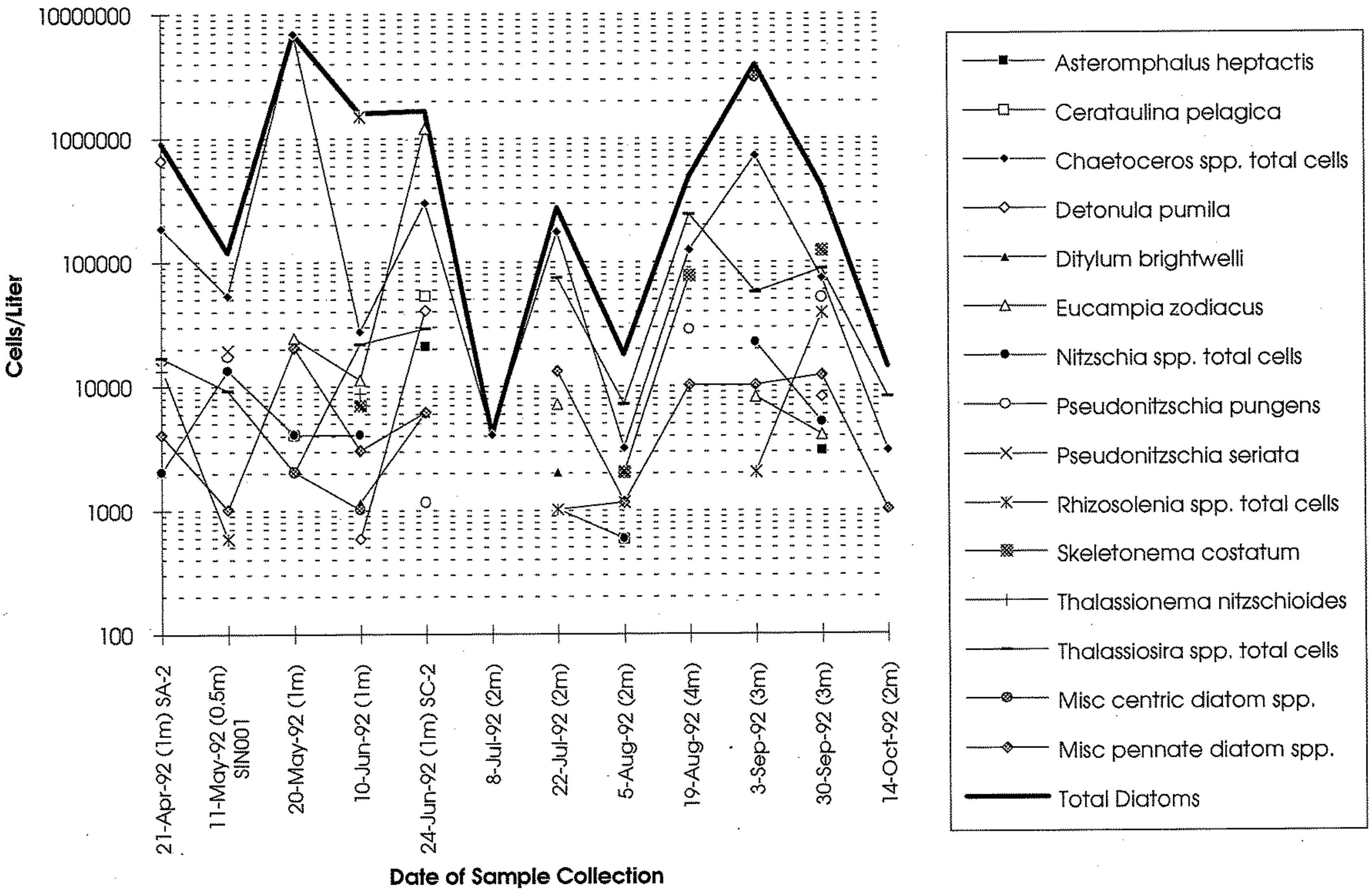


Figure 31. Diatom species with concentrations > 10,000 cells/L during April to October 1992 from inner Sinclair Inlet (station SB-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

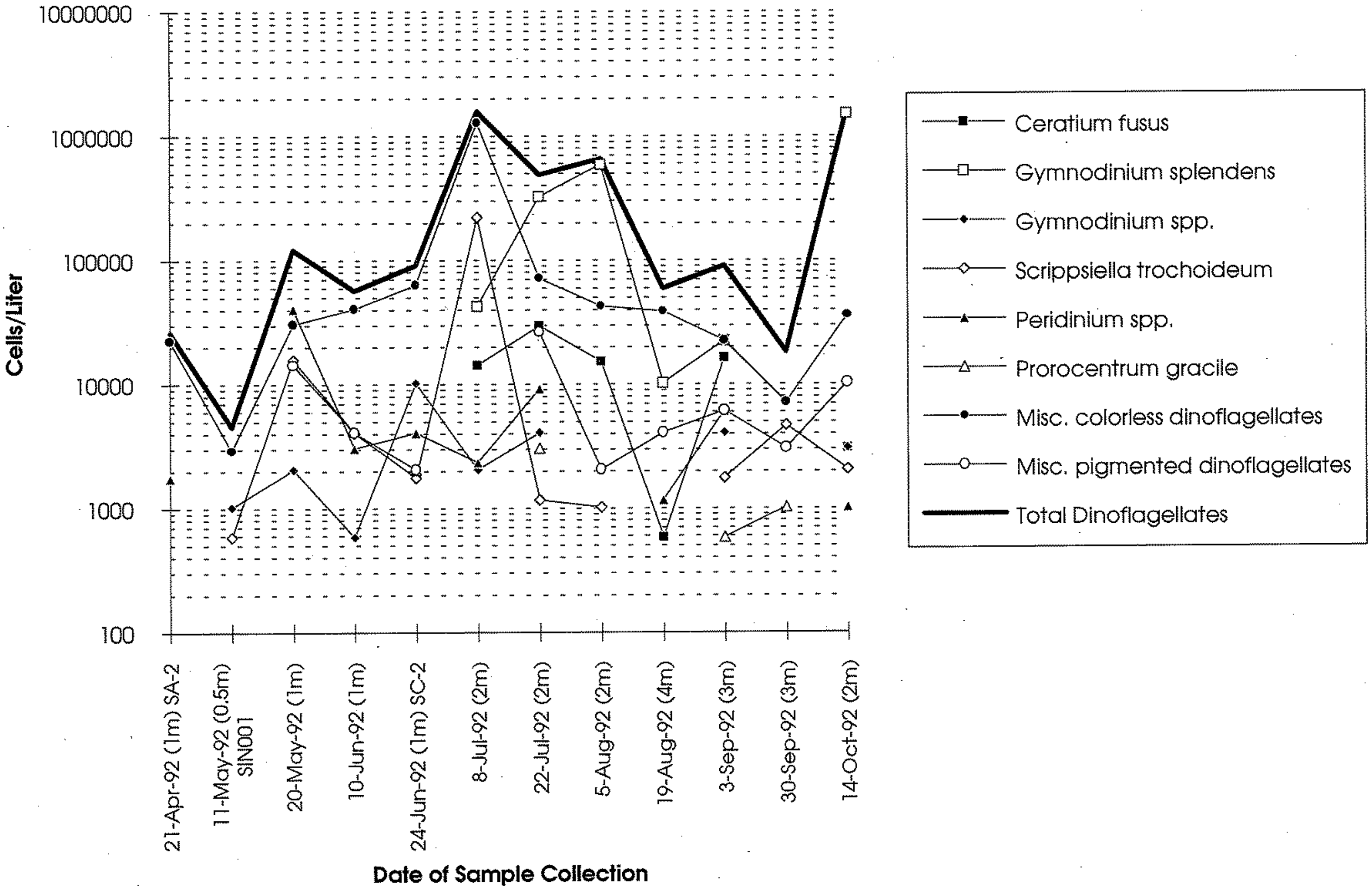


Figure 32. Dinoflagellate species with concentrations > 10,000 cells/L during April to October 1992 from inner Sinclair Inlet (station SB-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

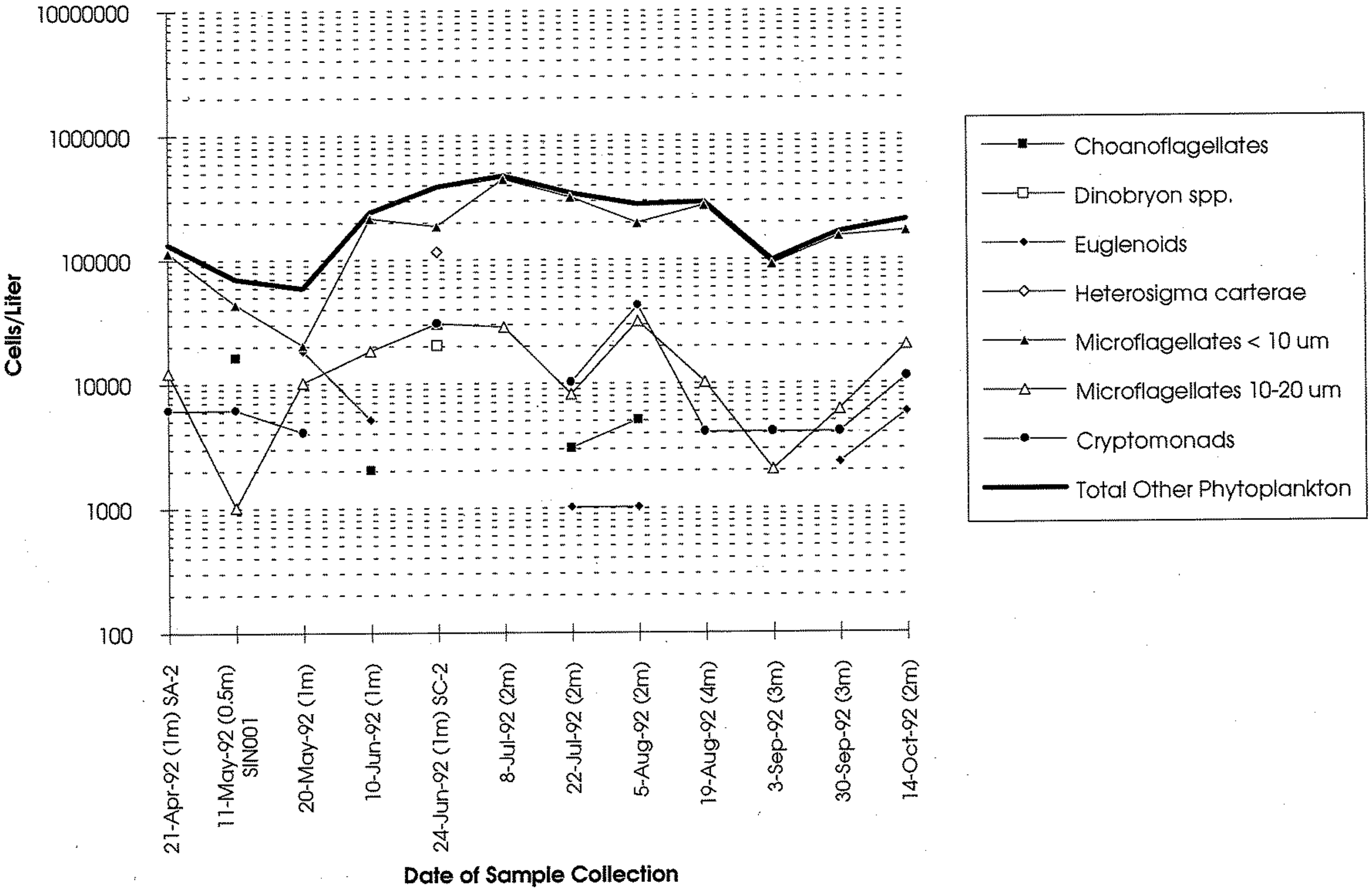


Figure 33. Miscellaneous phytoplankton species with concentrations > 10,000 cells/L during April to October 1992 from inner Sinclair Inlet (station SB-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

Diatoms

Chaeotoceros spp., centric chain-forming diatoms with long spines, were the most abundant diatom species present on five out of 12 surveys (Figure 31). Other species with the highest abundance were *Detonula pumila*, *Rhizosolenia* spp., *Eucampia zodiacus*, *Thalassiosira* spp., and miscellaneous centric diatom species.

High diatom concentrations ($> 1 \times 10^6$ cells/L) were observed from 20 May to 24 June and on 3 September. The highest diatom concentration ($\sim 7 \times 10^6$ cells/L), found on 20 May, was composed primarily of *Chaeotoceros* spp. The lowest diatom concentrations ($\sim 4 \times 10^3$ cells/L) were observed on 8 July.

Dinoflagellates

Miscellaneous colorless (unpigmented) dinoflagellates, as a whole, had concentrations higher than or equal to other dinoflagellate species except for surveys during late-July to early-August and during mid-October when *Gymnodinium splendens* was the most abundant species (Figure 32). Colorless dinoflagellates do not photosynthesize, but rather are heterotrophic (they eat phytoplankton and other organisms).

The highest dinoflagellate concentrations ($\sim 2 \times 10^6$ cells/L) observed were on 8 July (composed of colorless dinoflagellates) and 14 October (composed of *Gymnodinium splendens*). The lowest dinoflagellate concentration ($\sim 5 \times 10^3$ cells/L) observed was on 11 May.

Miscellaneous Phytoplankton

Microflagellates less than 10 μm in diameter were present in higher concentrations than any other species or species group in this category, except on 20 May when an equal number of Euglenoids were observed (Figure 33). Concentrations of miscellaneous phytoplankton were less variable than concentrations of diatoms and dinoflagellates and were never greater than 5×10^5 cells/L.

Dyes Inlet

Total diatom, dinoflagellate, and phytoplankton concentrations typical of Dyes Inlet stations are shown in Figure 34. Diatom, dinoflagellate, and miscellaneous phytoplankton with concentrations greater than 10,000 cells/L during any of the Dyes Inlet surveys are shown in Figures 35, 36, and 37, respectively.

Diatoms predominated over dinoflagellates from April through late-June and during September (Figure 34). Dinoflagellates predominated over diatoms from early-July through early-August.

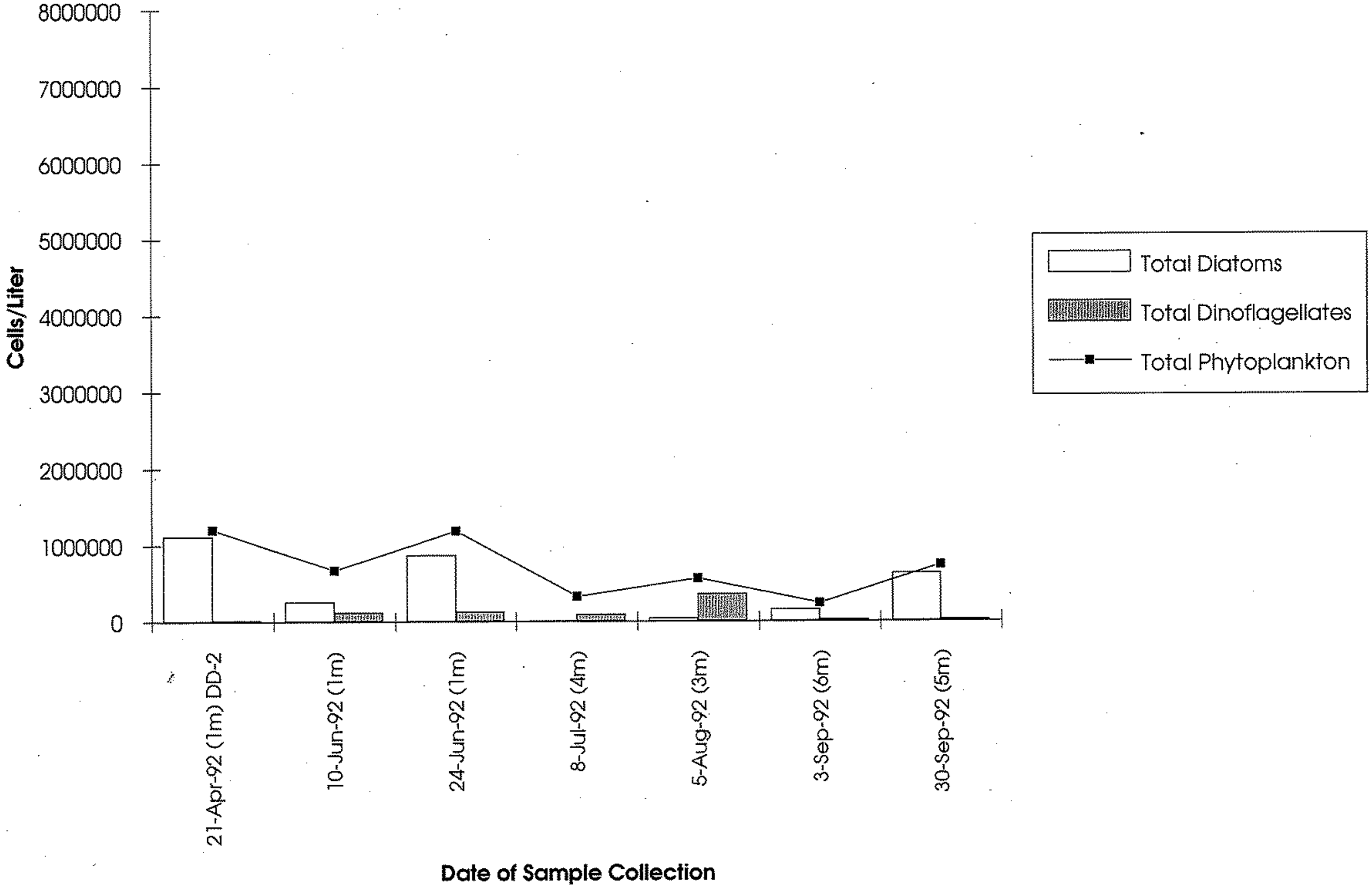


Figure 34. Diatom, dinoflagellate, and total phytoplankton concentrations (cells/L) from April to September 1992 in Dyes Inlet (station DC-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

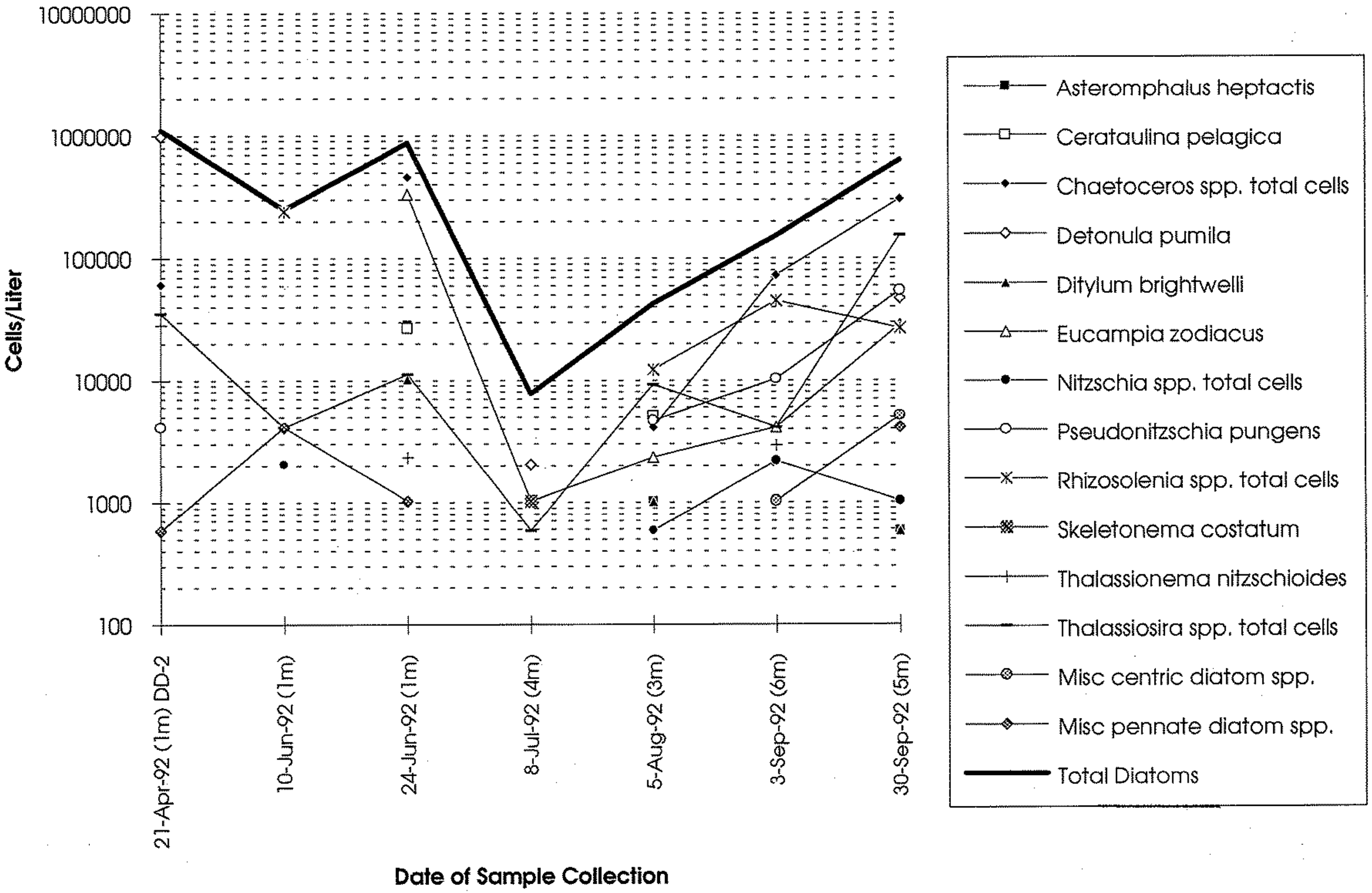


Figure 35. Diatom species with concentrations > 10,000 cells/L from April to September 1992 in Dyes Inlet (station DC-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

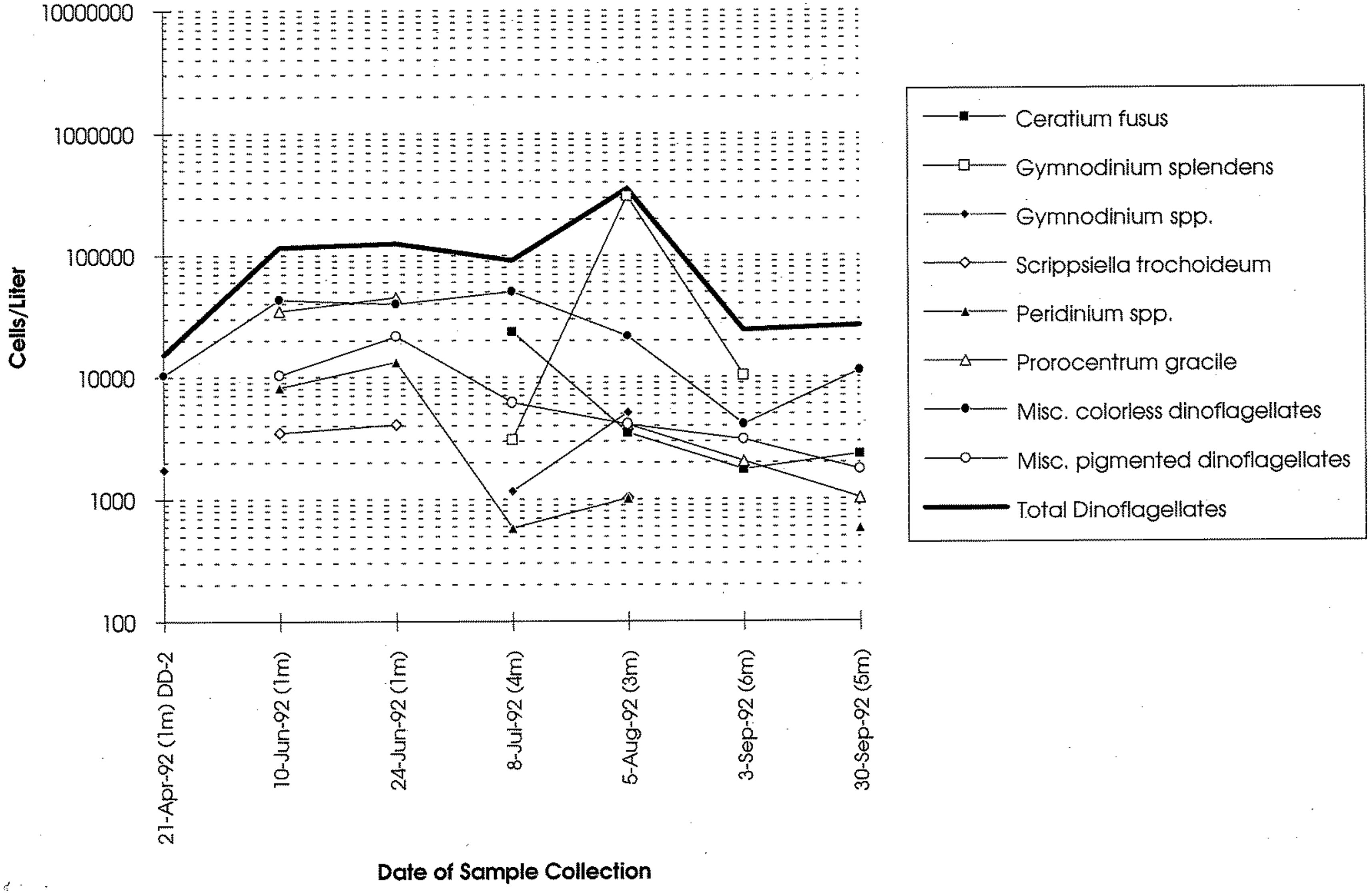


Figure 36. Dinoflagellate species with concentrations > 10,000 cells/L from April to September 1992 in Dyes Inlet (station DC-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

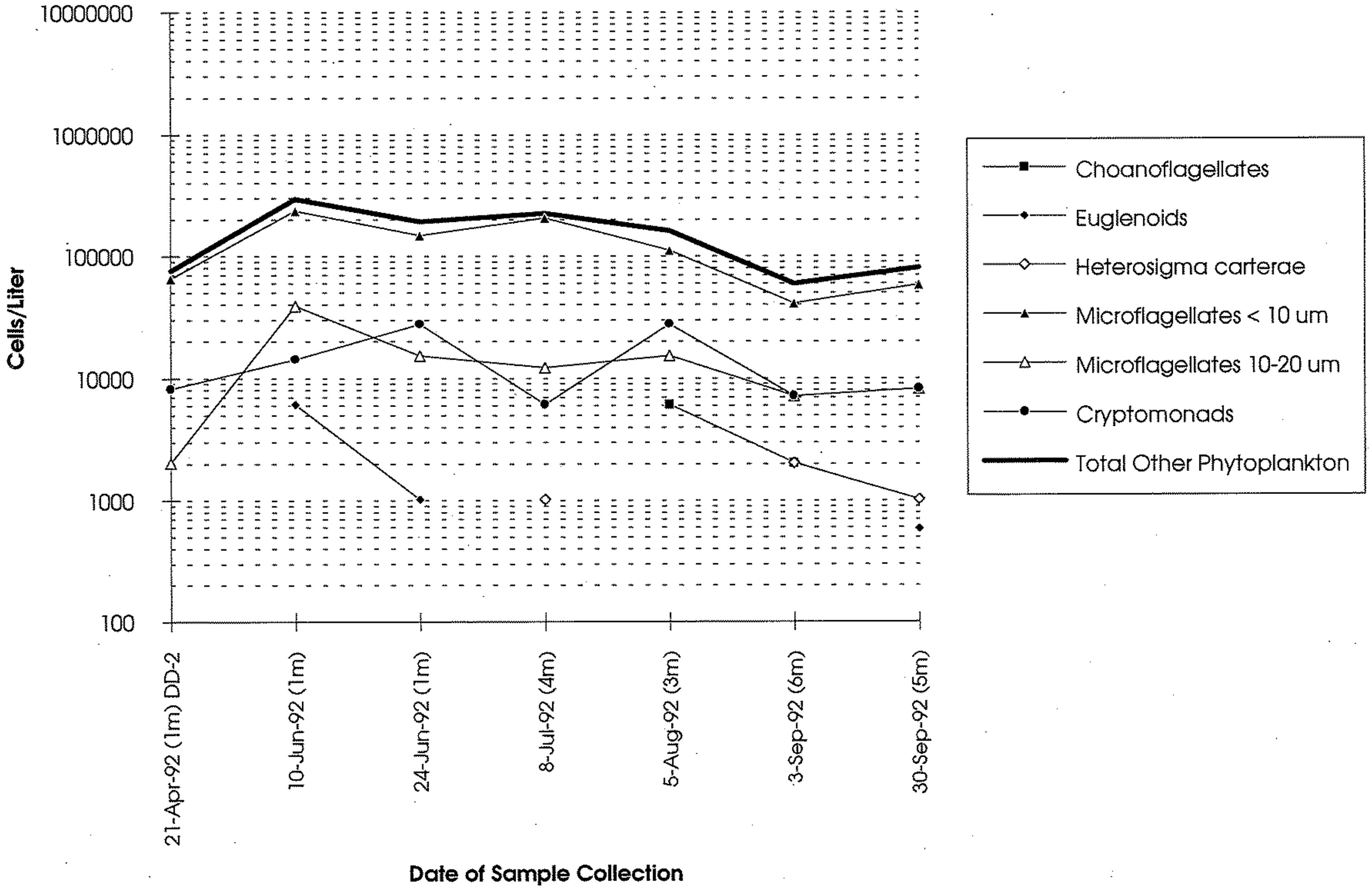


Figure 37. Miscellaneous phytoplankton species with concentrations > 10,000 cells/L from April to September 1992 in Dyes Inlet (station DC-2, unless otherwise indicated). Samples for 26 March to 10 June were collected at a depth of 1 m. Samples from 8 July to 14 October were collected at the depth of the fluorescence maximum, which ranged between 0.5 m and 10 m in depth.

Diatoms

Chaeotoceros spp., were the most abundant diatom species present on three out of seven surveys. Other species with the highest abundance were *Detonula pumila* and *Rhizosolenia* spp.

The highest diatom concentrations (~1 x 10^6 cells/L) were observed on 21 April and were composed primarily of *Detonula pumila*. The lowest diatom concentrations (~8 x 10^3 cells/L) were recorded on 8 July.

Dinoflagellates

Miscellaneous colorless dinoflagellates, as a whole, had concentrations higher than or equal to other dinoflagellate species except for surveys during early-August and early-September when *Gymnodinium splendens* were the most abundant species (Figure 36).

The highest dinoflagellate concentrations (~4 x 10^5 cells/L) were observed on 5 August and were composed primarily of *Gymnodinium splendens*. The lowest dinoflagellate concentrations (~ 2 x 10^4 cells/L) were recorded on 21 April.

Miscellaneous Phytoplankton

Microflagellates less than 10 µm in diameter were found in higher concentrations than other species or species group on all seven survey dates (Figure 37). Concentrations of miscellaneous phytoplankton were less variable than concentrations of diatoms and dinoflagellates and were never observed in concentrations greater than 3 x 10^5 cells/L.

Potentially Harmful Phytoplankton

Sinclair Inlet

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 (Douglas and Bates, 1992; Horner, 1994). *Pseudonitzschia pungens* were observed on 11 May, 24 June, 19 August, and 30 September (Figure 31). *Pseudonitzschia pseudodelicatissima*, another species of pennate diatom which may produce domoic acid, were found in low concentrations (2 x 10^3 cells/L) on 11 May.

Alexandrium (Gonyaulax) catenella is a "red-tide" dinoflagellate that produces PSP (Paralytic Shellfish Poison). As with *Pseudonitzschia pungens*, these toxins can accumulate in shellfish and pose health threats to humans (as well as fish and invertebrates). *Alexandrium catenella* were recorded in low concentrations on 24 June (2 x 10^3 cells/L) and 14 October (7 x 10^3 cells/L).

Heterosigma carterae is a small flagellated species that can cause fish kills although the mechanism is unknown. *Heterosigma carterae* were observed on 24 June in concentrations above 10^5 cells/L (Figure 33).

It is not known if the concentrations of any of these potentially harmful species in Sinclair Inlet were high enough to pose a marine or human health threat.

Dyes Inlet

Pseudonitzschia pungens and *Pseudonitzschia pseudodelicatissima* were observed in Dyes Inlet during 1992. *Pseudonitzschia pungens* were observed on 21 April, 5 August, 3 September, and 30 September (Figure 35). *Pseudonitzschia pseudodelicatissima* were found in low numbers (3×10^3 cells/L) on 8 July.

Alexandrium catenella were observed in low concentrations on 10 June (4×10^3 cells/L) and 30 September (5×10^3 cells/L).

Heterosigma carterae were observed in low numbers on 8 July, 3 September, and 30 September (Figure 37).

As in Sinclair Inlet, it is not known if the concentrations of any of these potentially harmful species were high enough in Dyes Inlet to pose a marine or human health threat.

Comparisons Between Sinclair and Dyes Inlets

Phytoplankton collection occurred in both Sinclair and Dyes Inlets on seven survey dates. Total phytoplankton concentrations were higher in Sinclair Inlet than in Dyes Inlet except during the 21 April and 30 September surveys when concentrations were slightly higher in Dyes Inlet (Figures 30 and 34).

The changes from diatom to dinoflagellate dominance (early July) and from dinoflagellate back to diatom dominance (mid-August and early-September) occurred during the same time in both Inlets (Figures 30 and 34). Due to a lack of data, it is not known if a fall dinoflagellate bloom, similar to the one in Sinclair Inlet, also occurred in Dyes Inlet.

Generally, the same species were dominant in both Sinclair and Dyes Inlets during a particular survey (Figures 31, 32, 33, 35, 36, and 37), although some differences existed for the diatom data collected from 8 July to 30 September. These differences may be partially due to differences in the depth of sample collection between Sinclair and Dyes Inlets. The phytoplankton cell counts were generally lower in Dyes Inlet than in Sinclair Inlet. This difference in cell counts may be due to the area of maximum bloom concentration (inner Sinclair Inlet) being located near the stations where phytoplankton samples were collected in Sinclair Inlet. Whereas, the area of maximum phytoplankton concentration was not always located near the station where phytoplankton were collected in Dyes Inlet.

Potentially harmful phytoplankton species were observed at different times in Sinclair Inlet than in Dyes Inlet. These species were never the most abundant species observed; therefore, differences could be partially due to limited sample collection (one station at one depth per survey in each inlet).

Plankton Observations

Other planktonic organisms (*i.e.*, non-phytoplankton) were not monitored in this study. However, field staff noted an unusual occurrence that is reported here. Large quantities of the scyphozoan *Aurelia aurita*, a common jellyfish, were found between the SA and SB transects in Sinclair Inlet during much of the summer. In their normal configuration, the medusae have four concentrically arranged U-shaped gonads that bear resemblance to a cloverleaf. Individuals with six to seven gonads were observed on several occasions around station SB-2. Individuals with five gonads were quite common (perhaps 1 in 10). These observations are highly unusual (pers. comm., Dr. Claudia Mills, Friday Harbor Laboratory) and may be a cause of concern.

The life-cycle of these jellyfish include a demersal larval stage, which selects or deposits in particular microhabitats (*e.g.*, wood-pilings) (Keen, 1987). Planulae metamorphose into polyps after recruitment and deposition. A subsequent metamorphosis transforms these polyps to immature medusae called ephyrae, which are shaped differently than the polyps. Effects of hydrocarbons on *Aurelia* development were noted by Spangenberg (1984). It is possible that toxic substances in direct contact with the polyps or in their diet caused these significant abnormalities. Toxic substances observed in Sinclair Inlet sediments include mercury and some organic chemicals (Dutch *et al.*, 1992).

Discussion

Sinclair Inlet showed different physical and biological conditions in the inner versus the central and outer portions of the inlet. Water quality parameters in the central and outer Sinclair Inlet and in Dyes Inlet were more representative of the ambient conditions seen in the main basin of Puget Sound. Inner Sinclair Inlet, however, showed greater stratification (Figure 10) and has a lower flushing efficiency (Tetra Tech, 1988a) than the central and outer inlet. Water quality conditions of concern observed in inner Sinclair Inlet included high phytoplankton abundance and sporadic low DO concentrations. This discussion will be focused on conditions in inner Sinclair Inlet. However, first, it is important to establish how different conditions there are from the rest of the inlet.

Independence of CTD Data from Sinclair Along-Channel (Slack Tide) Survey Stations

There were six stations along the slack tide transect in Sinclair Inlet in this study. The question of how many of these stations were "necessary" (*i.e.*, presented information that was not revealed at the other stations) should be determined, particularly since Ecology only routinely maintains a single long-term station in the area (SIN001).

The biweekly data from this project were examined with principle component analysis (*a.k.a.* eigenvector or factor analysis, empirical orthogonal functions) to determine station independence over that time scale (Fukumori and Wunsch, 1991). Values of 1-m and near-bottom temperature, salinity, and DO were entered into input matrices (Sij), with "i" rows (14 surveys) and "j" columns (six stations). A correlation matrix was computed as follows:

1) The mean of each column was subtracted from each entry in that column.
2) Each entry in each column was divided by the sample standard deviation of all entries in that column. Doing this makes it possible to compare different parameters (*e.g.*, temperature and DO).
3) The resulting matrix was pre-multiplied by its transpose, resulting in the desired correlation matrix.

Further details are described in Albertson (in press).

The results for temperature, salinity, and DO are contained in Table 12. The first PCA component, accounting for over 90% of the total seasonal variability in temperature and salinity (T/S), was the "free body" mode where all parameters changed together at all locations.

Using this result to predict future monitoring needs for physical (T/S) parameters, a single station (*e.g.*, SIN001) most likely will measure about 90% of the total variability in temperature and salinity in the inlet. Is that good enough? The answer depends on what is being asked. An engineer at a WWTP concerned about the corrosivity of seawater on a discharge pipe would need to know salinity to fewer significant digits than a physical oceanographer studying circulation patterns in the area.

In contrast, the first PCA component for DO at both 1-m and near-bottom depths only accounted for 60-70% (Table 12) of the total variability, indicating the greater independence of each station. The DO concentrations farther out in the inlet are not representative of the inner inlet. This also implies that the processes involved in maintaining DO concentrations are more complex than mere physical mixing (*e.g.*, photosynthesis, respiration, and oxidation). As has already been shown, there is a positive correlation between seasonal DO and density stratification, but it is a weak one ($r = 0.4$).

PCA analysis of near-bottom DO from all stations in Sinclair Inlet (not shown) similarly reveal that less than 70% of the seasonal variability observed was accountable by a primary factor. Stations S-1 and SC-1 had higher loadings on other factors (beside the main one) probably because they were shallow. Stations such as SB-1, SB-2 and SC-1 had higher loadings on other PCA factors because occasional low DO concentrations were observed there. It is at these inner

Table 12. Principal component (empirical orthogonal function) analysis of 1992 survey slack tide (seasonal) data from Sinclair Inlet at 1-m and near-bottom (next-to-bottom bin) depths. All data were mean-centered and standardized (normalized by their sample (N-1) standard deviations). The underlined percentage at the top of each column indicates how much variability is explained by that factor. The values (loadings) in each column explain how much the corresponding factor is represented at that station. A loading of 1.000 would mean that all the variability at a station was explained by the corresponding factor. The sum of the squares of all loadings, as well as the percentages of all factors (smaller ones are not shown), should add to 1.

Parameter	Temperature				Salinity				Dissolved Oxygen				
	1-m		Near-bottom		1-m		Near-bottom		1-m		Near-bottom		
Station	*92.9%*	*3.7%*	*96.1%*	*3.2%*	*92.1%*	*3.6%*	*93.5%*	*6.4%*	*62.2%*	*23.3%*	*70.8%*	*15.4%*	*12.4%*
S1	0.948	0.072	0.917	0.398	0.949	0.269	0.815	0.580	0.614	0.717	0.507	0.753	-0.414
SA2	0.989	0.139	0.995	-0.052	0.975	0.186	0.996	-0.081	0.670	0.484	0.829	0.058	0.544
SB2	0.982	0.132	0.995	-0.061	0.945	-0.086	0.995	-0.088	0.828	0.207	0.869	0.302	0.377
SC2	0.989	0.076	0.992	-0.083	0.984	0.049	0.993	-0.113	0.961	-0.053	0.968	-0.060	-0.165
SD2	0.967	-0.036	0.988	-0.134	0.935	-0.266	0.995	-0.089	0.801	-0.573	0.914	-0.288	-0.263
SE2	0.907	-0.415	0.993	-0.038	0.968	-0.160	0.994	-0.105	0.810	-0.525	0.882	-0.421	-0.191

Sinclair Inlet locations where future monitoring for low bottom DO would be most useful. Based on this PCA analysis, a single station in the central or outer inlet (*e.g.*, SIN001) would represent DO dynamics of the inner inlet only about two-thirds of the time. Data from this study show that the occasional low DO concentrations in inner Sinclair Inlet are not observed at SIN001.

For the T/S analysis, most of the secondary components in Table 12 have one sign-reversal in their component loadings. These components account for an additional 5% of the observed variability. They seem to be related to the influence of outer Puget Sound (*e.g.*, stations toward the mouth of the estuary have a negative thermal anomaly in summer). A second monitoring station near station SE-2 (the "antinode" of the component loadings) would pick-up an additional 5% of T/S variance. Caveats pertaining to tidal variability and the representativeness of 1992 data apply.

In summary, while temperature and salinity are adequately described by the data from any one of the stations monitored, the DO concentration in inner Sinclair is not described by data from the central or outer inlet.

Nutrient and Phytoplankton Dynamics in Inner Sinclair Inlet

Phytoplankton blooms (Figure 21) were associated with below reporting limit concentrations of nitrate+nitrite-N and ammonium-N observed in the surface waters of the inner and central Sinclair Inlet from early-May through mid-September (Figures 16 and 17). The correlation coefficient (r) between 1-m nitrate+nitrite-N and chlorophyll *a* (1-m or fluorometric peak) data for station SB-2 throughout the season was -0.40, indicating an inverse but weak relationship. Phytoplankton blooms occurred throughout the inlet, but tended to be largest in the inner portion near the SB transect, implying high nutrient utilization in this area. This area is proximate to the discharge from the Bremerton WWTP. It should be noted that other factors, not addressed here, influence nutrient dynamics and bloom occurrence, such as, bacterial uptake and regeneration of nutrients, and grazing of phytoplankton and bacteria by zooplankton and other heterotrophs.

Since phytoplankton species composition can affect the level of nutrient depression and vice versa, shifts in phytoplankton class (*i.e.*, diatoms vs. dinoflagellates) were also useful for understanding nutrient dynamics. Diatoms were dominant in spring when the reduction of 1-m nitrate+nitrite-N concentrations occurred at inner and central Sinclair stations (Figures 16, 30, and 34). The dominant phytoplankton changed from diatoms to dinoflagellates during the end of June (Figures 30 and 34). Following the decrease in 1-m nitrate+nitrite-N starting on 8 June (Figure 16a), there was a substantial increase in *Gymnodinium splendens* (Figure 32), a dinoflagellate known to vertically migrate, and thus able to exploit nutrients at depth. On 5 August, near-bottom nitrate+nitrite-N was below reporting limit at inner Sinclair stations SA-2 and SB-2 (Figure 16), which may reflect utilization by *Gymnodinium splendens*. Near-bottom nitrate+nitrite-N increased during late-summer and early-fall (Figure 16). Phytoplankton species dominance changed from dinoflagellates back to diatoms during this time. Conditions such as water column mixing may have precipitated this change from dinoflagellates to diatoms by re-injecting nutrients into the surface waters (Figure 16) for utilization by non-migrating phytoplankton such as diatoms. An exception to this pattern was a late-season dinoflagellate bloom on 14 October (Figures 30 and 34).

Eutrophication, Stratification, and Low Dissolved Oxygen

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, DO concentrations decrease. Low DO 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 the direct sinking of senescent cells, or through grazing by herbivorous zooplankton that produce large fecal pellets that sink.

The highest ammonium-N and chlorophyll *a* concentrations and the lowest DO concentrations were seen at the inner Sinclair stations. The increased stratification and higher phytoplankton biomass of the inner inlet both contribute to the lower DO concentrations observed there. 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. The near-bottom low DO 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 DO content. The greater stratification of inner Sinclair Inlet impedes this process.

It should be noted that Wateryear 1992 (WY 1992 ≡ October 1991 to September 1992) was drier than the 30-year average (precipitation anomaly = -1.42 cm; NOAA, 1993), and consequently might have developed less stratification than normal. WY 1992 was also warmer than normal (air temperature anomaly = +1.35°C; NOAA, 1993), which would have conversely helped to stratify the water column. As noted in the density section, however, a small decrease in salinity can have a greater effect on stratification than a larger change in temperature. The effect of the drier weather in 1992 on decreasing stratification during this study is not known.
One of the most critical parameters monitored, in terms of water quality, was DO concentration. Dissolved oxygen values below 5.0 mg/L may begin to stress many organisms, especially fish, and when DO values approach 2.0 mg/L, organisms may show avoidance behavior (Harding *et al.*, 1992). Mortality can occur at DO 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).

In Sinclair Inlet, DO concentrations that may cause stress to organisms were observed on only two surveys during 1992 (DO < 5.0 mg/L on 22 July; DO < 3.0 mg/L on 19 August). Such low DO concentrations were never recorded in Dyes Inlet, where DO concentrations always were observed above 6.0 mg/L during this study. The possibility that DO concentrations lower than those observed may occur in Dyes Inlet during a year of higher freshwater input from Chico Creek, however, cannot be dismissed.

The lowest DO concentrations were at near-bottom depths in inner Sinclair Inlet. This portion of the inner inlet had the largest phytoplankton blooms and the greatest degree of stratification. Previous studies (Tetra Tech, 1988a) have indicated that variable residence times occur in this area (*e.g.*, residence time in Oyster Bay varies from one to five days). Also, the nearby Bremerton WWTP outfall inputs additional nutrients (~ 0.04 mg/L NH_4-N), possibly enhancing phytoplankton growth. Additional processes, outside the scope of this study, that may contribute to DO depletion in inner Sinclair Inlet are oxygen demand within the sediments, nitrification, binding of oxygen by sulfides, and decomposition of anthropogenic organic materials. Low DO 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. The timing of low DO concentrations during the late summer / early fall may be due to continued accumulation of organic matter beyond the period of peak production.

Neither inlet exhibited a severe low DO problem, although Sinclair Inlet, in particular, exhibits conditions that make it sensitive to eutrophication. Data from this study indicate that DO concentrations in inner Sinclair Inlet might be affected by anthropogenic nutrient input. During this project in 1992, there were six observations of DO < 6 mg/L at station SA-2, in inner Sinclair Inlet, from July through October. Lincoln and Collias (1975), however, did not observe any DO concentrations < 6 mg/L for six surveys between 24 April to 4 August 1975 that included two stations in Sinclair Inlet, corresponding to Ecology's 1992 stations SA-2 and (roughly) SD-2. Sampling differences, interannual variation, and weather effects must be considered and prevent a conclusion regarding water quality changes.

The long-term Ecology monitoring station, SIN001, in central Sinclair Inlet has not shown DO concentrations below the WAC (1992) standard of 6 mg/L in monthly data from 1973-1993 (Ecology AMS database). All of the stations where low DO concentrations were observed during this project were along either the SA or SB transects. Station SIN001 is only 1 km west of transect SB, at a similar water depth as station SB-2 (10-15 m). Visual observations during this project were that plankton were typically interior to a front somewhere around the SB transect. Possibilities for the differences in observed DO concentrations include better physical flushing at station SIN001, a lower biological population at SIN001 (as noted above), or greater shipping activity (prop wash) around Bremerton that may mix the water column in the vicinity of SIN001 but not at the SB or SA stations.

It is possible that DO concentrations could become even lower in a more typical year if stratification is normally stronger. Changes in salinity from the surface to bottom layers have long been known to relate to mixing and residence times in estuaries (Knudsen, 1900). Although long-term monitoring station SIN001 (Figure 1) is further toward the outer inlet from the region with the lowest DO, it can still be used as a gauge for interannual variability. Figure 38a shows density stratification (difference between sigma-*t* at 10 m and 0.5 m) versus DO stratification (difference between DO at 0.5 m and 10 m) for a period of 20 years at this location between April and September each year. The data show a weak correlation ($r = 0.4$ for data measured with CTD) between DO and density stratification over the 20-year period. The fact that the correlation is not higher is most likely due to DO stratification being affected by additional factors beside density (*e.g.*, biological). Figure 38b illustrates that density stratification at SIN001 was in general lower in 1992 than in 1993 or 1994. Higher surface-to-bottom DO differences can be seen in 1993.

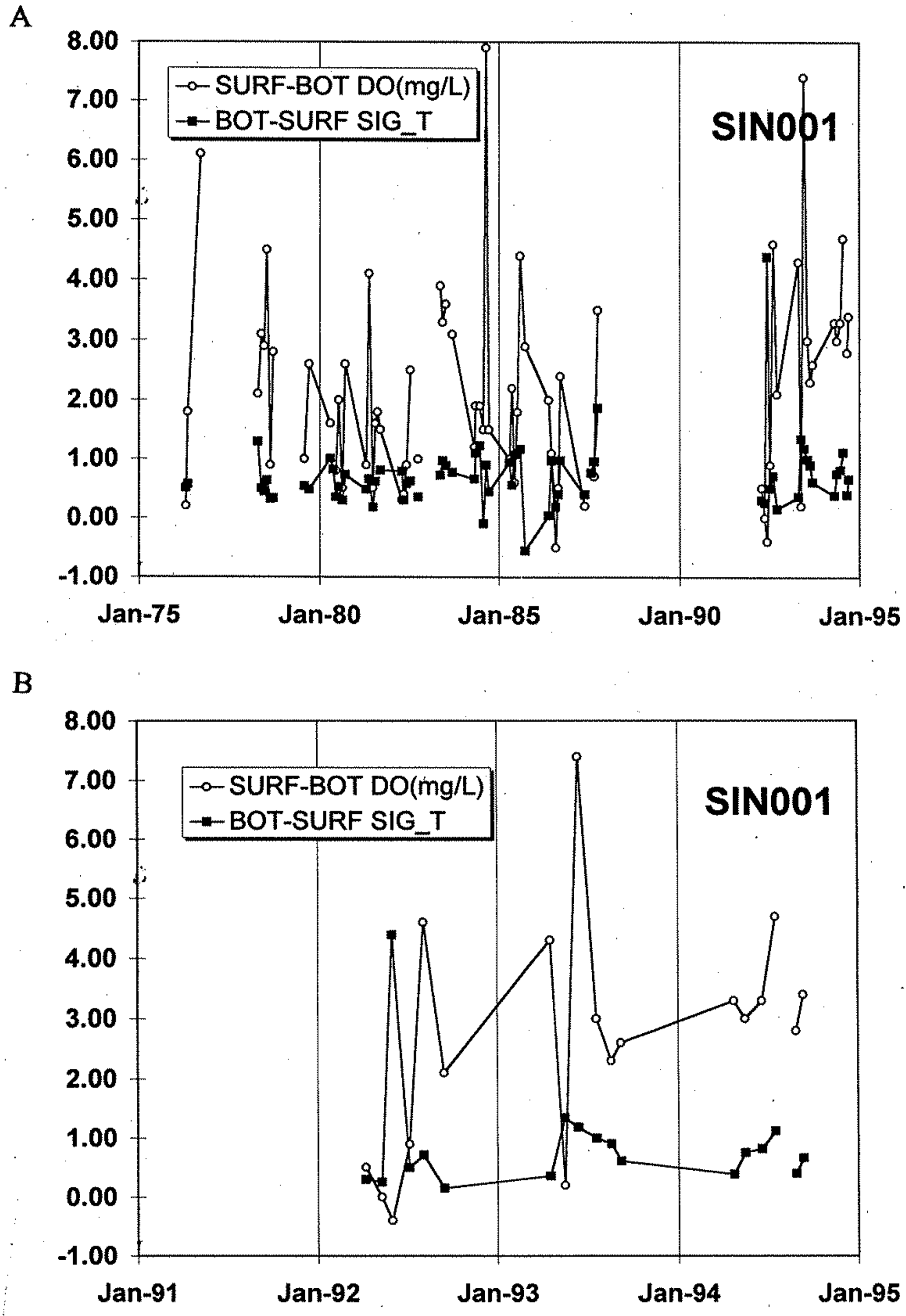


Figure 38. Differences between 0.5-m and 10-m values of seasonal (April to September) DO (mg/L) and density (sigma-*t*) at long-term monitoring station SIN001 from (a) 1975 to 1995, and (b) 1991 to 1995.

Summary of Project Objectives

Specific project objectives were identified at the beginning of this report. A summary of how the 1992 monitoring in Sinclair and Dyes Inlets met these objectives is presented here.

1. Stratification in the Port Orchard system was driven by both salinity and temperature, unlike some estuaries where freshwater is the primary source of density variation. Since 1992, precipitation was below normal, temperature-induced stratification was more important to density than normal. Observed stratification was strongest in inner Sinclair Inlet around the SB transect. Previous literature (Tetra Tech, 1988a) suggests that perhaps greater stratification occasionally exists in Dyes Inlet near the outlet of Chico Creek, since it sporadically is the largest freshwater input to the system, but this was not observed in 1992. During the monitoring season, stratification was strongest in Sinclair Inlet on two distinct occasions: from late-June to early-July, a period of significant precipitation (and also when diatom predominance gave way to dinoflagellates); and from August to early-September, during and following a hot weather period. Observed stratification between 1-m and near-bottom in inner Sinclair Inlet was strongest on 24 June, 19 August, and 3 September 1992. Throughout the inlet, some degree of stratification existed during the entire sampling season (March-October), as indicated by changes in sigma-*t* with depth. Typically the pycnocline was above 3 m.

2. Low DO concentrations (DO < 5.0 mg/L) were found in inner Sinclair Inlet during two surveys: 19 August (minimum DO = 2.2 mg/L) and 22 July (minimum DO = 4.7 mg/L). On these dates, low DO concentrations were observed at three stations (SA-1, SA-2 and SB-1) and one station (SB-2), respectively. Low DO concentrations were not found in Dyes Inlet, Washington Narrows, or Oyster Bay during the study. The conditions resulting in low DO were likely a combination of persistent stratification, settling of phytoplankton blooms, and organic loading.

3. Near-surface (1-m) nutrients below reporting limits (< 0.01 mg/L) were observed in inner and central Sinclair Inlet from early-May through mid-September. The highest nitrate+nitrite-N concentrations were consistently in outer Sinclair Inlet. The highest ammonium-N concentrations were often around inner Sinclair Inlet station SB-2, which is close to the Bremerton WWTP discharge. The decrease in surface nutrients was associated with the seasonal increase of phytoplankton. Whether the phytoplankton nutrient demand is higher in the inner inlet cannot be determined from biomass data (chlorophyll *a*) alone, but would require primary production (growth rate) measurements.

4. Bloom concentrations (chlorophyll $a > 10$ mg/m^3) occurred throughout the Sinclair Inlet during the growing season (March-October); however, the largest phytoplankton blooms (chlorophyll $a > 30$ mg/m^3) were generally seen near the SB transect, where lower nutrient levels also were found.

5. Dinoflagellate blooms of species known to migrate vertically occurred from July to mid-August and in mid-October at inner Sinclair Inlet stations. Their abundance was high during times of low 1-m nutrient concentrations and low near-bottom DO concentrations.

6. Potentially harmful phytoplankton species (*Pseudonitzschia pungens, Pseudonitzschia Pseudodelicatissima, Alexandrium (Gonyaulax) catenella,* and *Heterosigma carterae*) were present in varying quantities (10^3 to 10^5 cells/L) in both Sinclair and Dyes Inlets, though no reports of toxicity or fish kills occurred during this time. 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 are not presently known.

Conclusions

Inner Sinclair Inlet, between Port Orchard, and Bremerton and westward to the head of the inlet, in addition to having stronger stratification, exhibited different water quality conditions than the rest of the inlet. Water quality parameters in the central and outer Sinclair Inlet and in Dyes Inlet were more representative of the ambient conditions seen in the main basin of Puget Sound.

Low DO concentrations (< 5 mg/L) were found only in inner Sinclair Inlet. Observed DO concentrations in Dyes Inlet and the rest of Sinclair Inlet were above 6.0 mg/L throughout the project. Anthropogenic addition of nutrients, possibly from the Bremerton WWTP, the Port Orchard marina or non-point sources, were suggested by occasional high concentrations of ammonium-N in the near-bottom waters of inner Sinclair Inlet. Reduction of surface nitrogen nutrient concentrations to below reporting limit levels occurred in inner Sinclair Inlet from late-June through September (excluding 8 July), reflecting uptake by phytoplankton. Surface concentrations of nitrogenous nutrients at stations in outer Sinclair Inlet remained above reporting limits throughout the study. Phytoplankton bloom concentrations (chlorophyll $a > 10$ mg/m^3) occurred in inner and central Sinclair during the growing season (March-October). The lowest DO concentrations were found in the near-bottom waters of inner Sinclair Inlet, approaching hypoxic levels (~2.0 mg/L) just once at station SB-1 on 19 August 1992. Observed low DO concentrations in inner Sinclair Inlet (DO < 5.0 mg/L) were rare (2 of 14 surveys) and did not persist between biweekly sampling surveys. Existence of these conditions is a combination of the strong stratification, biological production, and perhaps excess nutrient input into the inner inlet.

Because the low DO conditions observed in inner Sinclair Inlet during this project were infrequent and relatively mild, detrimental effects to the biota from these conditions are probably not serious. Freshwater input was below normal during 1992; the influence of a more typical year's weather on stratification and DO concentrations in either inlet is not known. Principle component analysis of the data showed that the dynamics of DO concentration variation in inner Sinclair Inlet are not reflected by that of the central and outer stations. In contrast, physical parameters (*e.g.*, temperature and salinity) exhibit variation similarly throughout Sinclair Inlet. Ecology's long-term monitoring station does not adequately describe DO conditions in inner Sinclair Inlet.

Other water quality concerns include the occurrence of potentially harmful phytoplankton species and jellyfish medusae with abnormal numbers of gonads. The latter observation could be of importance, if these mutations were due to chemical contamination.

Recommendations

1. Any future monitoring for eutrophication or low DO concentrations should concentrate on inner Sinclair Inlet (between the SA and SB transects in this study). Additionally, some investigation of stratification effects in Dyes Inlet during a year of relatively high precipitation should be considered.

2. Since low DO conditions in inner Sinclair Inlet are short-lived and sporadic, more frequent sampling during the late-summer to early-fall period is indicated. A near-bottom moored sensor array, capable of recording hourly DO data, would be necessary to determine the magnitude and temporal extent of minimum DO concentrations. Monthly data, available from long-term monitoring stations SIN001 and DYE004, may not be resolving short-lived changes in freshwater input and residence times or other parameters that affect DO.

3. Analysis of the benthic community in inner Sinclair Inlet would yield information on the severity of low DO concentrations and its impact to biota.

4. Assess the degree to which nutrients limit phytoplankton production in inner Sinclair Inlet.

5. Assess the prevalence of the abnormalities observed in jellyfish in Sinclair Inlet and whether toxins may be responsible.

6. Because freshwater input to Sinclair Inlet is highly variable, assess flushing rates under different conditions of weather and tide.

References

Albertson, S.L, 1995 (in press). "Principle Component Analysis of Hydrographic Data in Sinclair and Budd Inlets," 1995 Puget Sound Research Conference Proceedings.

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.

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.

Dutch, M., H. Dietrich, and P.L. Striplin, 1992. Puget Sound Ambient Monitoring Program 1992: Marine Sediment Monitoring Task, Annual Report 1992. Washington State Department of Ecology, Olympia, WA, Publication No. 93-87.

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

------, 1994. Laboratory Users Manual, Fourth Edition. Manchester Environmental Laboratory, Manchester, WA.

Edmondson, T., 1991. "The Uses of Ecology: Lake Washington and Beyond". University of Washington Press.

Eisner, L.B., C.D. Janzen, S.L. Albertson, S.A. Bell, and J.A. Newton, 1994. 1992 Budd Inlet Seasonal Monitoring Report. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program, Olympia, WA, Publication No. 94-132, 86 pp. + appendices.

Fukumori I., and C. Wunsch, 1991. "Efficient Representation of the North Atlantic Hydrographic and Chemical Distributions." Progressive Oceanography, Vol. 27, pp. 111-195.

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.

Hasle, G.R., 1978. "Using the inverted microscope" *In* A. Sournia (ed.) Phytoplankton Manual. Monographs on Oceanographic Methodology 6, Uesco, Paris.

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

Jacobson, M.A. and P.N. Booth, 1990. Sinclair and Dyes Inlets Urban Bay Action Program: 1990 Action Plan. PTI Environmental Services for US EPA contract 68-D8-0085

Janzen, C.D., 1992. Marine Water Column Ambient Monitoring Plan: Final Report. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program, Publication No. 92-23, Olympia, WA.

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

Johnston, R.K. Acid Volatile Sulfides and Simultaneously Extracted Cooper, Lead, and Zinc in Sediments of Sinclair Inlet, Washington. US Navy, Technical Report 1552.

Kamykowski, D., 1981. "Laboratory experiments on the diurnal vertical migration of marine dinoflagellates through temperature gradients." Marine Biology, Vol. 62, pp. 57-64.

Keen, S.L., 1987. "Recruitment of Aurelia aurita (Cnidaria: Scyphozoa) larvae is position-dependent, and independent of conspecific density within a settling surface," Mar. Ecol. Prog. Ser., Vol. 38, pp. 151-160.

Knudsen, M., 1900. "Ein Hydrographische Lehrsatz, Annalen der Hydrographie und Marinen Meteorologie", Vol. 28, pp. 316-320.

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.

------, E.D. Cokelet, and G.A. Cannon, 1991. "A model study of density intrusions into and circulation within a deep, silled estuary: Puget Sound," Journal of Geophysical Research, Vol. 96, Number C9, pp. 16,779-16,800.

Lincoln, J.H. and E. Collias, 1975. An Oceanographic Study of the Port Orchard System. URS.

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.

------, 1995. Puget Sound Ambient Monitoring Program Marine Sediment Questions, Issues, and Recommendations. Puget Sound Water Quality Authority, Olympia, WA.

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.

Newton, J.A., S.A. Bell, and M.A. Golliet, 1994. Marine Water Column Ambient Monitoring Program: Wateryear 1993 Data Report. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program, Olympia, WA, Publication No. 94-210, 57 pp. + appendices.

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. US Environmental Protection Agency, Region 10, Seattle, WA.

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

Reif, D., 1988. Bremerton Wastewater Treatment Plant Class II Inspection. Washington State Department of Ecology, WA-15-0040.

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.

------, 1992c. The Fundamentals of CTD Accuracy. 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.

Spangenberg, D.B., 1984. "Use of the *Aurelia* metamorphosis test system to detect subtle effects of selected hydrocarbons and petroleum oil, responses of marine organisms to pollutants." Stegeman, J.J. ed., Mar. Environ. Res. Vol. 14, pp. 281-303.

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, Sinclair and Dyes Inlets Action Program: Initial Data Summaries and Problem Identification. Prepared for U.S.

Environmental Protection Agency Region X - Office of Puget Sound, Seattle, WA, TC-3338-13, Final Report.

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

U.S. Department of the Navy, 1983. Initial Assessment Study of Naval Shipyard Puget Sound, Bremerton, Washington. EESA 13-022, Prepared for US Navy Assessment and Control of Installation Pollutants (NACIP) Department, Port Hueneme, CA.

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

WAC (Washington Administrative Code), 1992. Chapter 173-201 WAC. Olympia, WA.