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CIRCULATION AND WATER PROPERTY STUDY OF PRINCE RUPERT HARBOUR, Summer 1992

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ABSTRACT

Stucchi, D.J. and U. Orr 1993. Circulation and Water Property Study of Prince Rupert Harbour, Summer 1992. Can. Tech. Rep. Hydrogr. Ocean Sci. 154: 46p.

We present and analyse the current meter record and water property data from 10 surveys obtained during the summer of 1992. The circulation in the harbour is active with speeds typically in the range 5 to 15 cm/s and burst to 25 cm/s. At 17 m depth, there is a 2 cm/s mean flow toward the southwest (out of the harbour). Tidal currents dominate the current record, and the principal tidal constituent is M2 having an amplitude of 11 cm/s. The calculated barotropic M2 current agrees well with the observed amplitude of M2 constituent. The prominence of shallow water constituents suggests that tidal mixing is important. The neap-spring modulation in the strength of the tidal currents produces a conspicuous fortnightly variation in water properties and MSF currents of 1.6 cm/s. Water property variations between consecutive surveys show that flushing of the bottom half of the harbour can occur in about 12 days. A review of historical data and our survey data shows that there is no evidence of widespread, long-lasting detrimental dissolved oxygen depletion inside the harbour. Furthermore, we estimate that there is a negligible effect on dissolved oxygen levels caused by the sewage effluent's BOD and organic enrichment of the sediments. We also estimate that the incremental increase in dissolved inorganic nitrogen caused by the sewage effluent is small. Nutrient concentrations inside the harbour were not significantly different from those outside.

Key words: Circulation, sewage, Prince Rupert Harbour B.C.

RÉSUMÉ

Stucchi, D.J. et U. Orr 1993. Étude de la circulation et des propriétés de l'eau dans le port de Prince Rupert, été 1992. Rapp. tech. can. hydrogr. sci. océan. 154: 46p.

Nous présentons et nous analysons les enregistrements de courantomètre et les données des propriétés de l'eau de 10 relevés faits pendant l'été 1992. L'eau dans le port circule à des vitesses typiques qui varient de 5 à 15 cm/s avec des écarts allant jusqu'à 25 cm/s. A une profondeur de 17 m, il y a un courant qui se dirige vers le sud-ouest (hors du port) à une vitesse moyenne de 2 cm/s. Les courants de marée dominent les enregistrements de courant, la principale composante de marée étant M2 avec une amplitude de 11 cm/s. Le courant barotropique M2 calculé correspond bien à l'amplitude observée de la composante M2. La quantité importante de constituants d'eau peu profonde suggère un important brassage des eaux par la marée. La modulation des marées de morte eau - vive eau dans l'intensité des courants de marée produit une variation bimensuelle remarquable sur les propriétés de l'eau et un courant MSF de 1.6 cm/s. Les variations dans les propriétés de l'eau entre les relevés consécutifs montrent que le changement de l'eau de la moitié inférieure du port peut se produire à intervalle de 12 jours. Une étude des données historiques et de nos données de relevés ne montre aucune évidence de diminution d'oxygène dissout à l'intérieur du port, diminution soit nuisible, étendue ou durable. De plus, nous estimons qu'il y a un effet négligeable sur le niveau d'oxygène dissout causé par la demande biochimique en oxygène des eaux d'égouts et par l'enrichissement organique des sédiments. Nous estimons aussi que l'augmentation additionnelle en azote inorganique dissout causée par les eaux d'égouts est faible. La différence entre les concentrations d'éléments nutritifs à l'intérieur et à l'extérieur du port n'était pas significative.

Mots clés: Circulation, eaux d'égouts, le port de Prince Rupert, C.-B.

1.0. INTRODUCTION

At present, the city of Prince Rupert discharges municipal sewage effluent to the harbour through twelve outfalls. Eleven of the outfalls discharge untreated sewage (several discharge comminuted sewage), and only one outfall receives primary treatment. This practice of sewage disposal to the harbour has created high coliform counts near shore and is aesthetically unpleasant. To address these concerns the city is proposing to extend three of the present outfalls to deeper waters. A local citizens group, "Friends of the Harbour" concerned about the impact of the city's sewerage extension program is advocating that several studies be conducted and is calling for an environmental impact assessment. In response to these concerns, the Institute of Ocean Sciences (IOS) of the Department of Fisheries and Oceans (DFO) funded a review of the oceanography and marine ecology of Prince Rupert Harbour (Akenhead 1992). In his report, Akenhead (1992) identified several areas of concerns and deficiencies in the database for Prince Rupert Harbour. To address some of these concerns as well as the identified deficiencies in our knowledge, IOS and the North Coast Division of Habitat Management (DFO) collaborated on an oceanographic study of the harbour during the summer of 1992.

In general, the goal of the study was to identify and improve our understanding of the oceanographic processes that are dominant in the harbour. More specifically, one of our goals was to obtain a better description and understanding of the circulation including an estimate of the degree of flushing or exchange that the harbour waters experience. A second goal was to add to our database of oceanographic observations from the harbour as summer observations are few in number. We wanted to determine if the concern expressed by Akenhead (1992) that dissolved oxygen levels in the harbour could be significantly depressed below levels observed outside the harbour was warranted.

The report on the 1992 study begins with a section that contains a review of previous studies and describes the relevant physical features of the area, the tides, winds and runoff. Following is a section that contains a description of the sampling program, methods and instrumentation that we used to collect the data. The next two sections deal with the two main components of the summer 1992 program; the circulation study (current meter data) and the monitoring of water properties (hydrography). These sections contain a presentation of the data, their analysis and interpretation. The report ends with separate sections on conclusions and recommendations for future work. We have included appendices to the report that contain most of the data that we discuss in this report. Appendix A of the report contains plots and statistical summaries of the current meter record from the Associated Engineering Services Ltd.'s 1977 marine study (AES Ltd. 1977). Appendices B and C contain most of the water property data that we collected over the summer of 1992 in Prince Rupert Harbour.

2.0. REVIEW AND BACKGROUND

2.1 REVIEW OF STUDIES

The earliest study (1948) in the region was of the oceanography of Chatham Sound (fig. 2.1). Because the harbour opens directly onto Chatham Sound the oceanography of the sound directly influences that of the harbour. Chatham Sound provides the source waters for Prince Rupert Harbour. Most of the investigations in the Prince Rupert region have dealt with the water quality problems created by the pulp mill located in Port Edward (fig. 2.2). Though most of the data were collected near the pulp mill some observations were collected inside Prince Rupert Harbour and in Chatham Sound near the entrance to the harbour. The only study that we are aware of that concentrated on Prince Rupert Harbour was that of Associated Engineering Services Ltd. (1977). Drinnan and Webster (1974) reported on the water quality and oceanography as part of an interagency study of the harbour and environs. McGreer *et al* (1980) and more recently

Akenhead (1992) reviewed the oceanography of the region and provided an extensive bibliography of relevant data and studies. We will highlight in this review the main physical oceanographic features of the area.

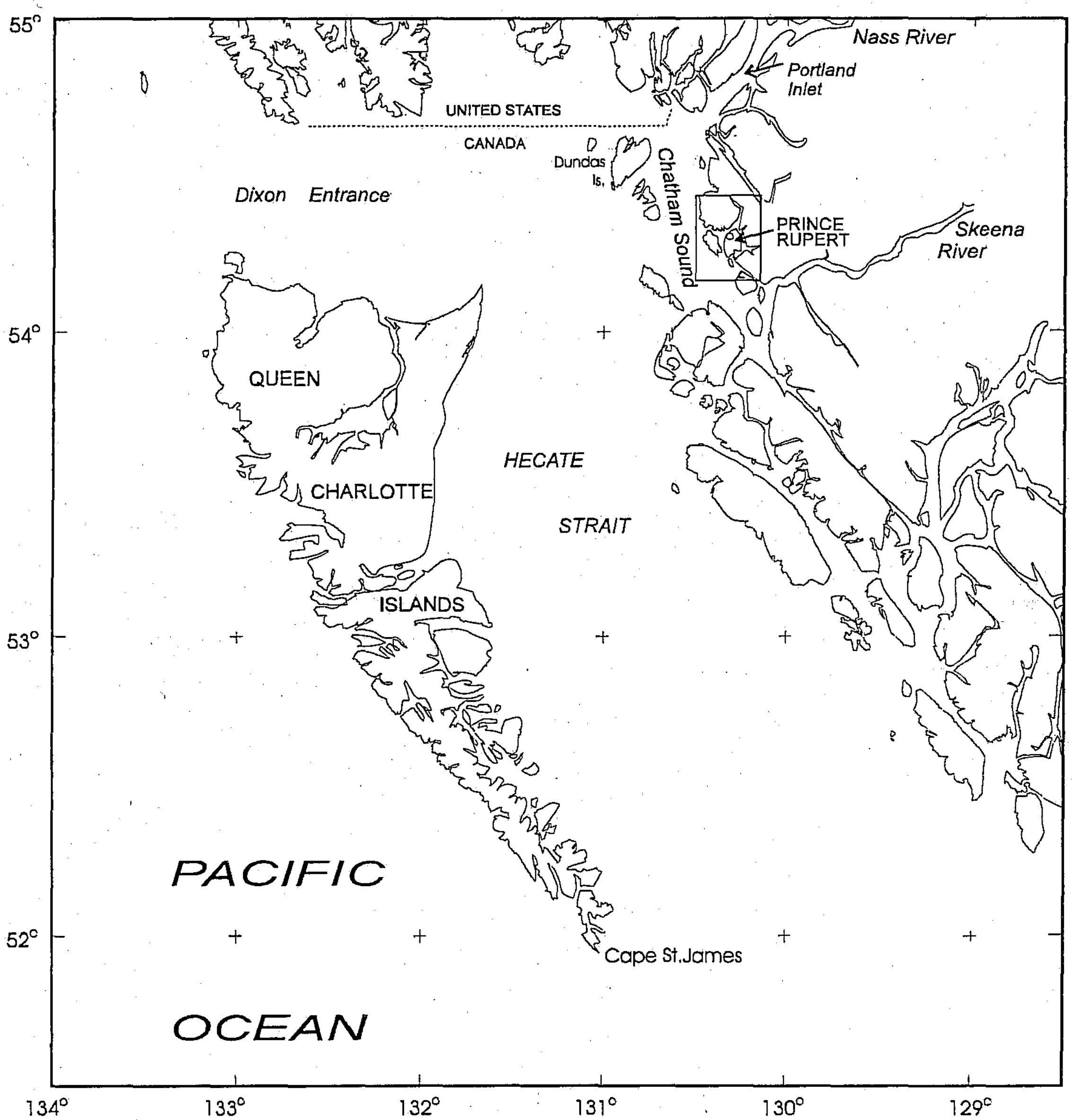


Figure 2.1 General map of the north coast showing the Chatham Sound and Prince Rupert Harbour study area in the small box.

The Pacific Oceanographic Group under the direction of Drs. J.P. Tully and W.M. Cameron carried out an extensive oceanographic survey of Chatham Sound. The purpose of the survey was to investigate the relationship between water properties and the migration pattern of salmon to their spawning grounds. During the spring and summer, water property measurements were taken at over 700 stations in the sound. Trites (1953) performed a detailed analysis of the 1948 data set focusing on the distribution and circulation of fresh water in Chatham Sound over the period of the survey. From his analysis Trites (1953) deduced that, during non-freshet conditions, the fresh water from the Skeena River moves northward along the Tsimpsean Peninsula and merges with the Nass River water at the mouth of Portland Inlet and then flows westward into

Dixon Entrance through Dundas Passage. During freshet conditions (late May and early June), the flow of Skeena River water northward past Tugwell Island is blocked by Nass River water in the northern part of the sound. Trites (1953) noted that tides and winds also exerted a significant influence on water properties and circulation in the sound.

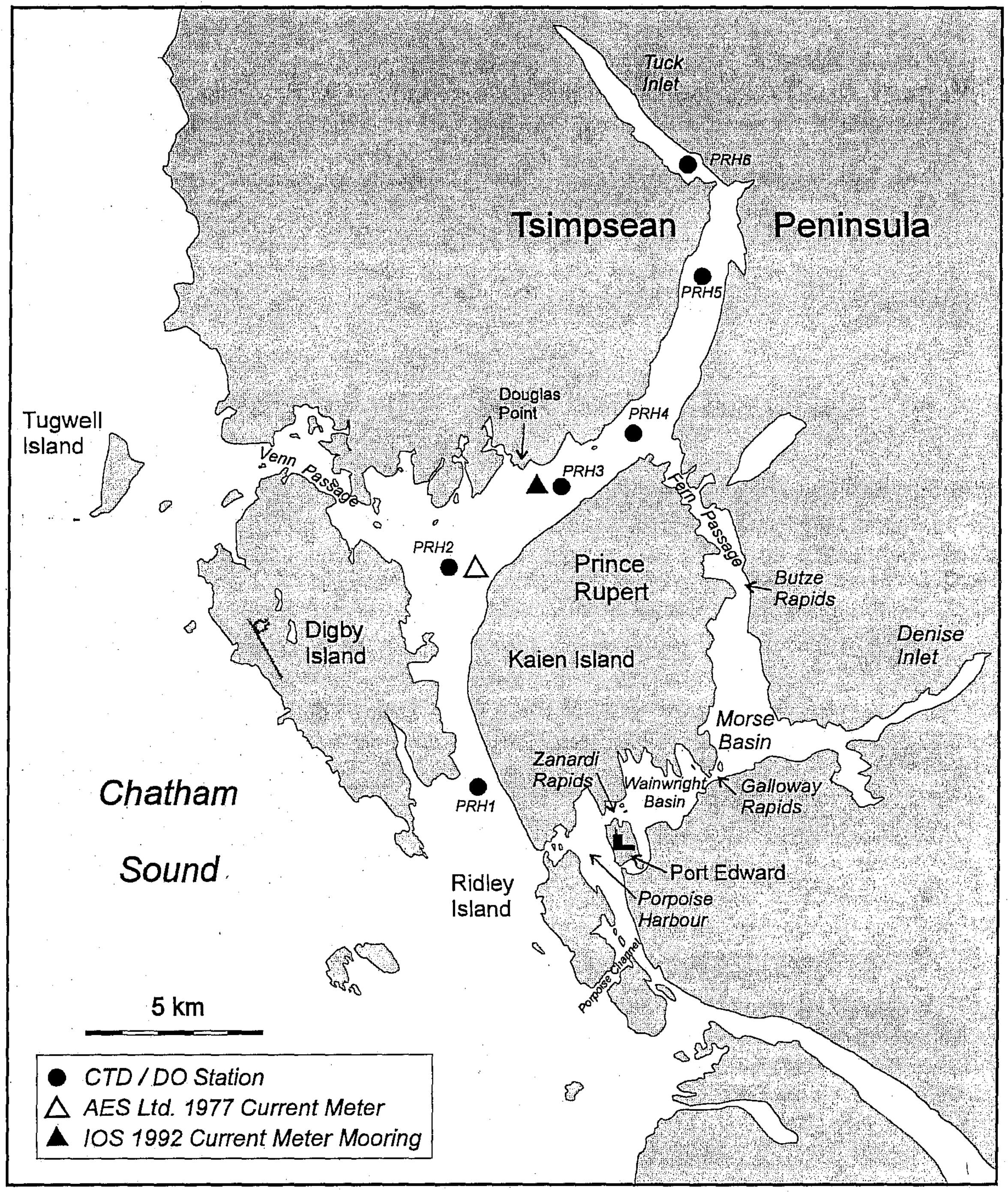


Figure 2.2. Map of Chatham Sound and Prince Rupert Harbour showing the location of water sampling stations (1992) and current meter measurements.

Waldichuk (1962) reported on the severe oxygen depletion problems observed in Porpoise Harbour and Wainwright Basin caused by the effluent from the Port Edward sulphite pulp mill (fig. 2.2). Waldichuk *et al* (1968) conducted several oceanographic surveys from 1961 to 1967 to study the effects of pulp mill effluent on the surrounding receiving waters. During his pollution cruises Waldichuk sampled several stations inside Prince Rupert Harbour and outside in Chatham Sound. Drinnan and Webster (1974) reported the oceanographic and water quality data that they collected on three sampling trips; April, July and October 1973. They made measurements of temperature, salinity and dissolved oxygen, and obtained samples for nutrient analysis (ortho-phosphate, nitrate and ammonia). These two references provide most of the available data base of water properties and water quality for the harbour.

In later years, the Environmental Protection Service (EPS) of Environment Canada conducted several surveys in the region to assess the environmental impact of the pulp mill at Port Edwards (Packman 1977). Also the pulp mill maintained a marine receiving water monitoring program (Ho 1978). In both cases, most of the sampling stations were near the pulp mill, but there were several control stations outside Porpoise Harbour in Chatham Sound. These control stations are useful in that they provide a partial description of dissolved oxygen variations outside Prince Rupert Harbour. Ho (1978) reviewed the water quality in the region and reported that in Chatham Sound the surface DO levels are near saturation most of the time except for the August to October period when DO concentrations decrease from 9 ppm to about 6.5 ppm. The lowest DO levels (6.5 ppm) inside the harbour occurred near the bottom, seaward of Tuck Narrows (McGreer *et al* 1980). However it should be noted that there are few observations of DO inside the harbour and near the bottom in Chatham Sound.

More recently Seaconsult Marine Research Ltd. (Hodgins and Knolls 1990) conducted a pulp mill effluent dispersion study for Skeena Cellulose Inc. They observed that the movement of the dye once it left Porpoise Harbour was to the northwest along the coastlines of Ridley and Digby Islands. Their observations confirm the circulation deduced by Trites (1953). Seaconsult personnel did not obtain water property profiles inside Prince Rupert Harbour. They did however obtain some profiles of temperature and salinity near the mouth of the harbour as they were tracking the movement of the dye patch.

As part of their study of the city's sewage disposal plan, AES Ltd. (1977) conducted an oceanographic investigation of Prince Rupert Harbour from July 4 to 15, 1977. AES Ltd.'s marine program consisted of three components; measurements of the temperature and salinity profiles at several stations inside and outside the harbour; the deployment of a current meter 0.8 m off the bottom in the harbour (fig. 2.2); and measurement of the surface circulation using several surface drogues.

The current meter collected observations every 5 minutes over the deployment period from July 4 to 15. (Appendix A contains plots and summaries of these data.) The 10-day duration of the current meter record is too short for a comprehensive analysis of the currents. Nevertheless the current meter record reveals that there are significant (22 cm/s max.) bottom currents. The currents are primarily tidal in nature and there is evidence of much higher frequency motions as well. The average current over the deployment period was about 1 cm/s heading to the southwest i.e. out of the harbour. The harmonic analysis report on this current meter record contained in Akenhead (1992) is incorrect. A re-analysis of the current meter record (using the correct sampling interval) shows that the amplitude of M2, the lunar semidiurnal tidal constituent, is not 0.7 cm/s but rather 8 cm/s - more than 10 times larger.

To observe the motion of the surface currents in the harbour AES Ltd. constructed surface drogues designed to follow the top 1.5 m of the water column. In total, AES Ltd. released 62 drogues in five release periods. One drogue release just outside the harbour mouth during a flooding tide travelled the length of the harbour entrance channel at an average speed of 90 cm/s (1.7 knots) (AES Ltd. 1977). Inside the harbour, surface currents were typically in the range 15 to 46 cm/s (0.3 to 0.9 knots), but they were not always in phase with the tidal currents. Unexpected northeasterly heading surface currents, with speeds up to 36 cm/s (0.7 knots), were observed in the harbour during the ebbing tide. Though southwesterly winds were present at the time, AES Ltd. (1977) believed that their strength was too weak to totally account for the NE flow of the surface currents. Instead they hypothesised that the currents might have been caused by the invasion of Skeena River water from Chatham Sound.

2.2. BACKGROUND INFORMATION

Geography

The city of Prince Rupert (pop. 16,000) occupies the northwest part of Kaien Island (fig. 2.2). Prince Rupert Harbour lies between Kaien and Digby Island and the Tsimpsean Peninsula and extends north to Tuck Inlet. To the west Digby Island shelters the harbour from Chatham Sound. Digby Island is a low flat island that offers little protection from the winds. It is also the location of the airport.

The narrow (600 m) channel between Digby Island and Kaien Island is the main, navigable entrance to the harbour. Depths through this 5 km long entrance channel are about 45 m with tidal currents up to 3 knots (150 cm/s) reported. Water depths inside the harbour are generally in the range 40 to 60 m, but there are a few small but deep (90 m) holes (fig. 2.3). There is no prominent sill in Prince Rupert Harbour, except Tuck Narrows 20 km inland from the mouth.

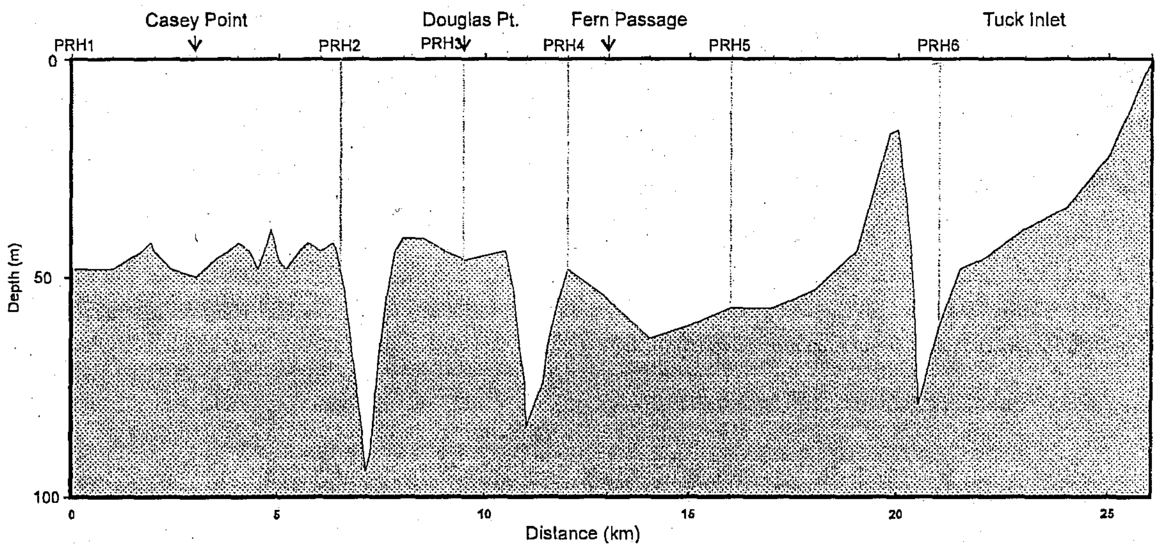


Figure 2.3 Axial depth profile of Prince Rupert Harbour from the mouth to Tuck Inlet showing the location of the water sampling stations (PRH1 to PRH6).

Access to the harbour is possible through Venn Passage between the north end of Digby Island and the Tsimpsean Peninsula (fig. 2.2), but this narrow and shallow passage is only suitable for small boats. There is a waterway around the southern and eastern sides of Kaien Island but several rapids punctuate this tortuous route. The southern entrance is via Porpoise Channel then through Zanardi Rapids at the pulp mill into Wainwright Basin that connects to the much larger Morse Basin and Denise Inlet via Galloway Rapids. Butze Rapids connects Morse Basin to Fern Passage to the north. Fern Passage then opens into the harbour. Tidal currents through these passages are violent.

Tides

The most conspicuous characteristic of the tides in this region is their large amplitude. Tides in Chatham Sound and Prince Rupert Harbour are mixed mainly semidiurnal (two high and two low waters per lunar day). Tidal analysis of water level records is usually done by harmonic analysis (see Foreman 1978). In harmonic analysis the observed tidal record is treated as the sum of a finite number of harmonic constituents of the form

$$H_n \cos(\omega_n t - \theta_n)$$

where H_n, ω_n and θ_n are the amplitude, angular frequency (= $2\pi/T_n$, where T_n is the period) and phase of the nth tidal constituent.

Table 2.1 Top ten tidal constituents from harmonic analysis of Prince Rupert water level (Index No. 9354).

Rank	Constituent	Period (hr.)	Frequency (cph)	Amplitude (m)	Greenwich Phase (°)
	Z0		Mean	3.849	0
1	M2	12.42	0.080511	1.943	267.4
2	S2	12.00	0.083333	0.636	299.2
3	K1	23.93	0.041781	0.508	259.7
4	N2	12.66	0.078999	0.390	242.8
5	O1	25.82	0.038731	0.308	243.8
6	K2	11.97	0.083562	0.173	291.8
7	P1	24.07	0.041553	0.159	256.3
8	SA	8764.24	0.000114	0.111	348.3
9	NU2	12.63	0.079202	0.076	246.5
10	Q1	26.87	0.037219	0.054	235.3

The lunar semidiurnal constituent M2 (12.42 hour period) has the largest amplitude (1.94 m) followed by the solar semidiurnal tidal constituent S2 (12 hour period) at 0.64 m (Table 2.1). In cases where the ratio of the amplitudes of the S2 and M2 tidal constituents is appreciable, the beating together of these two constituents produces a pronounced neap-spring or fortnightly variation in the tidal amplitudes. For Prince Rupert Harbour the ratio S2/M2 is equal to 0.33 (Table 2.1). During the largest tides the tidal range is 7.7 m, and during average tides the range is 4.9 m.

The large amplitude of the tides together with the constricted passages in and around the Prince Rupert Region creates some swift tidal streams. Currents in the rapids mentioned above may reach speeds up to 5 knots, while currents in the channels may be as large as 3 knots (Canadian Hydrographic Service, 1991).

Winds

The prevalent wind direction at Prince Rupert Airport is from the SE. For 10 months of the year the most frequent wind direction is SE, while for two months, June and July the most frequent direction is W (Atmospheric Environment Service, 1993). Detailed wind statistics for January show (Table 2.2) that not only do SE winds predominate but also that this direction has the strongest mean winds. In July, (Table 2.3) there is a bimodal frequency distribution in the wind direction. Westerly winds occur most often followed closely by SE winds. Mean winds are 50% higher in January than in July. Also, not surprisingly, extreme hourly wind speeds are highest in the winter (89 km/h) and lowest in the summer (55 km/h), but the direction of these extreme winds is the same, namely SE. Calm periods occur 12% of the time in winter months and 14% of the time in the summer.

Wind statistics at Lucy Island, 11 km due west of the Prince Rupert Airport, in Chatham Sound have similar direction statistics (Atmospheric Environment Services 1983). However, the mean wind speeds are about 50% higher.

Table 2.2 Statistical analysis of wind speed versus direction for the month of January (1962 - 1987).

Wind Direction	JANUARY % Occurrence by Wind Speed Class (km/h)								Mean Wind Speed (km/h)	% Occurrence by Direction
	1-9	10-19	20-30	31-42	43-55	56-69	70-84	85-100		
NE	7.87	8.05	0.40	0.03					10.1	16.4
E	8.69	10.67	2.93	0.47	0.06	0.03	0.01		13.0	22.8
SE	2.12	10.18	9.78	5.07	1.38	0.30	0.03	0.01	23.5	28.8
S	0.75	1.07	1.70	0.88	0.23	0.06	0.01		23.3	4.7
SW	0.51	1.10	1.33	0.62	0.08	0.01			21.8	3.7
W	0.73	1.14	1.01	0.65	0.07	0.02			20.6	3.6
NW	1.59	1.24	0.58	0.17	0.01				13.2	3.6
N	2.53	1.78	0.12						9.7	4.4
CALM										12.0
TOTAL									14.94	100.0

Table 2.3 Statistical analysis of wind speed versus direction for the month of July (1962 - 1987).

Wind Direction	JULY % Occurrence by Wind Speed Class (km/h)								Mean Wind Speed (km/h)	% Occurrence by Direction
	1-9	10-19	20-30	31-42	43-55	56-69	70-84	85-100		
NE	2.94	0.95	0.01						7.7	3.9
E	5.54	2.32	0.18	0.02					8.6	8.1
SE	3.97	9.42	4.63	0.98	0.06	0.01			16.5	19.1
S	6.08	6.33	0.92	0.12	0.01				11.4	13.5
SW	4.81	5.25	0.27	0.02					10.5	10.3
W	5.90	13.67	2.70	0.06					13.5	22.3
NW	2.75	3.11	0.58	0.01					11.5	6.4
N	1.46	0.51	0.02						8.0	2.0
CALM										14.4
TOTAL									10.68	100.0

Runoff

The two dominant riverine sources of fresh water to the region, are the Skeena River just to the south of Prince Rupert and the Nass River to the north in Portland Inlet (fig. 2.1). The snow melt inland in late May and June produces a dramatic increase in discharge (termed a freshet) in both rivers (fig. 2.4). A secondary peak in runoff occurs in the early fall as air temperatures associated with the fall storms are still high enough to cause precipitation in the form of rain. Once the air temperature cools in the inland regions most of the precipitation falls as snow during the winter months and runoff in the Nass and Skeena Rivers is at it lowest levels of the year.

Although no major rivers discharge into the harbour we can estimate the amount of fresh water draining directly to the harbour using the catchment area and rainfall records. Using an average annual precipitation for Prince Rupert of 3.15 m (Atmospheric Environment Services 1993) and a catchment basin area of 225 km^2 the annual volume of fresh water draining into the harbour is approximately 709 x 10^6 m^3. This volume of fresh water is equivalent to a average annual flow of 22.5 m^3 s^{-1} and is much smaller than the flow of either the Skeena or Nass Rivers. During the drier summer months (May to August) the average monthly fresh water flow is about 16 m^3 s^{-1}.

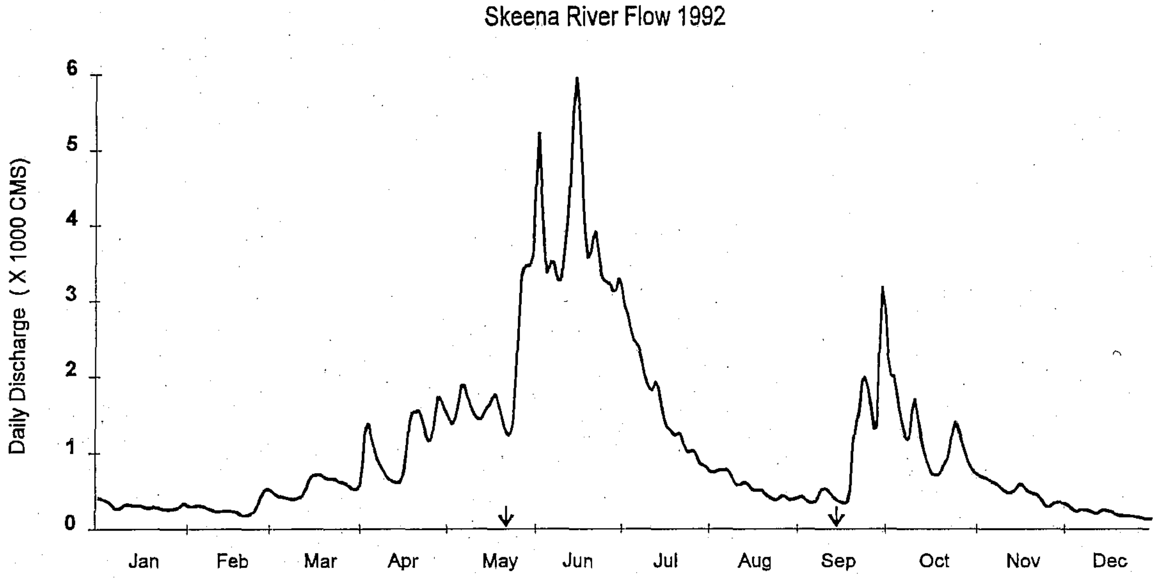


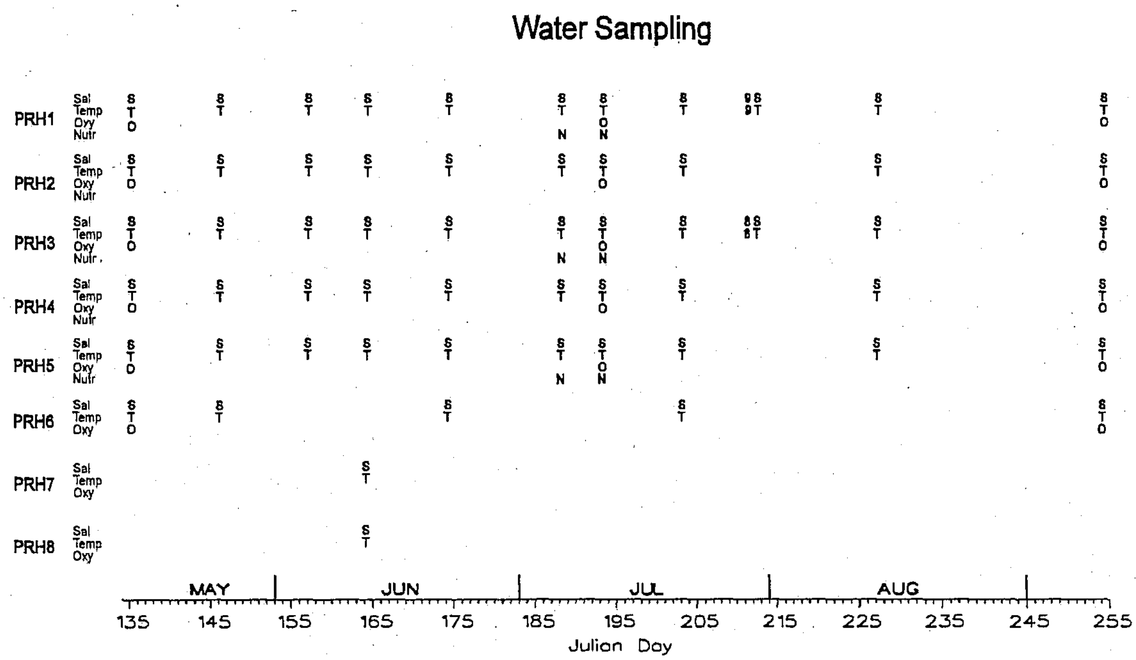
Figure 2.3 Time series plot showing the daily discharge of the Skeena River at Usk for 1992. The arrows on the time axis mark the beginning and end of the study period.

3.0. SAMPLING PROGRAM, DATA AND METHODS

The sampling program that we carried out during the summer of 1992 had two main components; water property sampling and current meter measurements. In addition, we conducted several special sampling programs including two nutrient sampling surveys, sediment sampling, and a 12-hour time series at two stations.

The water property sampling component consisted mainly of obtaining temperature, salinity and dissolved oxygen profiles at six stations in Prince Rupert Harbour and vicinity (see fig. 2.2). Four of the stations were inside the harbour, while one station (PRH1) was just outside the harbour near Barrett Rock, and another station (PRH6) was in Tuck Inlet. Our intention was to sample these stations weekly throughout the summer but for several reasons (instrument problems, weather, time constraints, etc.) regular sampling of all parameters at all stations was not possible. Table 3.1 summarises the water property data that were collected over the summer. The special sampling programs for nutrients and the time series are also shown in Table 3.1. In spite of the difficulties encountered personnel from the North Coast Division of DFO conducted a total of 10 surveys during the 100-day period from early May to early September.

Table 3.1 Summary of the dates, locations and water properties measured during the water sampling surveys.



In all but one of the surveys we used an Applied Microsystems STD12 to collect the temperature and salinity profiles. The July 4, 1992 survey was done from the CSS JOHN P TULLY using a Guildline Instruments Ltd., model 8705 CTD. Calibration checks on the STD12 were taken at several stations on each survey and used to correct the STD12 salinity and temperature data. The AMS STD12 performed consistently during the summer and the mean difference between it and the samples was 0.02 psu (practical salinity units) and 0.02°C. Table 3.2 lists the instrumentation used and their accuracy specifications.

Table 3.2 List of instrumentation and manufacturers' accuracy specifications.

Applied Microsystems Ltd. STD-12	Pressure	±0.5 db (±0.1%FSP)
	Temperature	±0.01 °C
	Salinity	±0.01 psu
Guildline Instruments Ltd. Model 8705 CTD	Pressure	±3. db(±0.15%FSP)
	Temperature	±0.005 °C
	Salinity	±0.005 psu

We obtained samples for dissolved oxygen determination at standard depths (0, 2, 5, 10, 15, 20, 25, 30, 40, 50 m) using 1.7 litre Niskin water sampling bottles. The water samples we obtained were "fixed" and analysed within 24 hours. A modified Winkler titration method (Strickland and Parsons 1965) was used to determine the DO content of the sample. The accuracy of the DO determination is about ±0.05 mg/l under ideal laboratory conditions. A Yellow Springs (YSI) polarographic oxygen sensor was used on most of the surveys but problems with calibrations discovered in July data make most of the data untrustworthy.

Nutrient sampling was carried out on two consecutive surveys (July 6 and 12) at stations PRH1, PRH2 and PRH3. Water samples were collected using 1.7 litre Niskin bottles from which we drew duplicate tubes of sea water for nutrient analysis. The samples were frozen and taken to IOS for analysis. Personnel from the Climate Chemistry Division of IOS performed the analysis of the nutrient samples using a four-channel Autoanalyzer. A malfunction in the phosphate channel precluded measurement of this nutrient. Nitrate, nitrite and silicate channels produced excellent responses to standard solutions. Appendix C contains the nutrient data.

We deployed a single current meter mooring in the harbour near Douglas Point (fig. 2.2) from May to September 1992 - a 119 day deployment. On this subsurface mooring we positioned two Aanderaa RCM4 current meters, one at 17 m depth and the other at 41 m depth (fig. 3.2). Each of the current meters had temperature, conductivity and pressure sensors and sampled every 15 minutes. Unfortunately the data return from this mooring was poor - less than 50%. The deeper of the two current meters malfunctioned from the outset. The current meter at 17 m depth collected current speed and direction data for only the first 63 days (1522 hr) of the deployment after which time the speed data stopped abruptly. The heavy biological growth on the current meter which we observed upon recovering the instrument blocked the rotor. However there was no indication of a progressive attenuation of the speed signal. This current meter however collected good temperature and salinity data throughout the 119-day deployment.

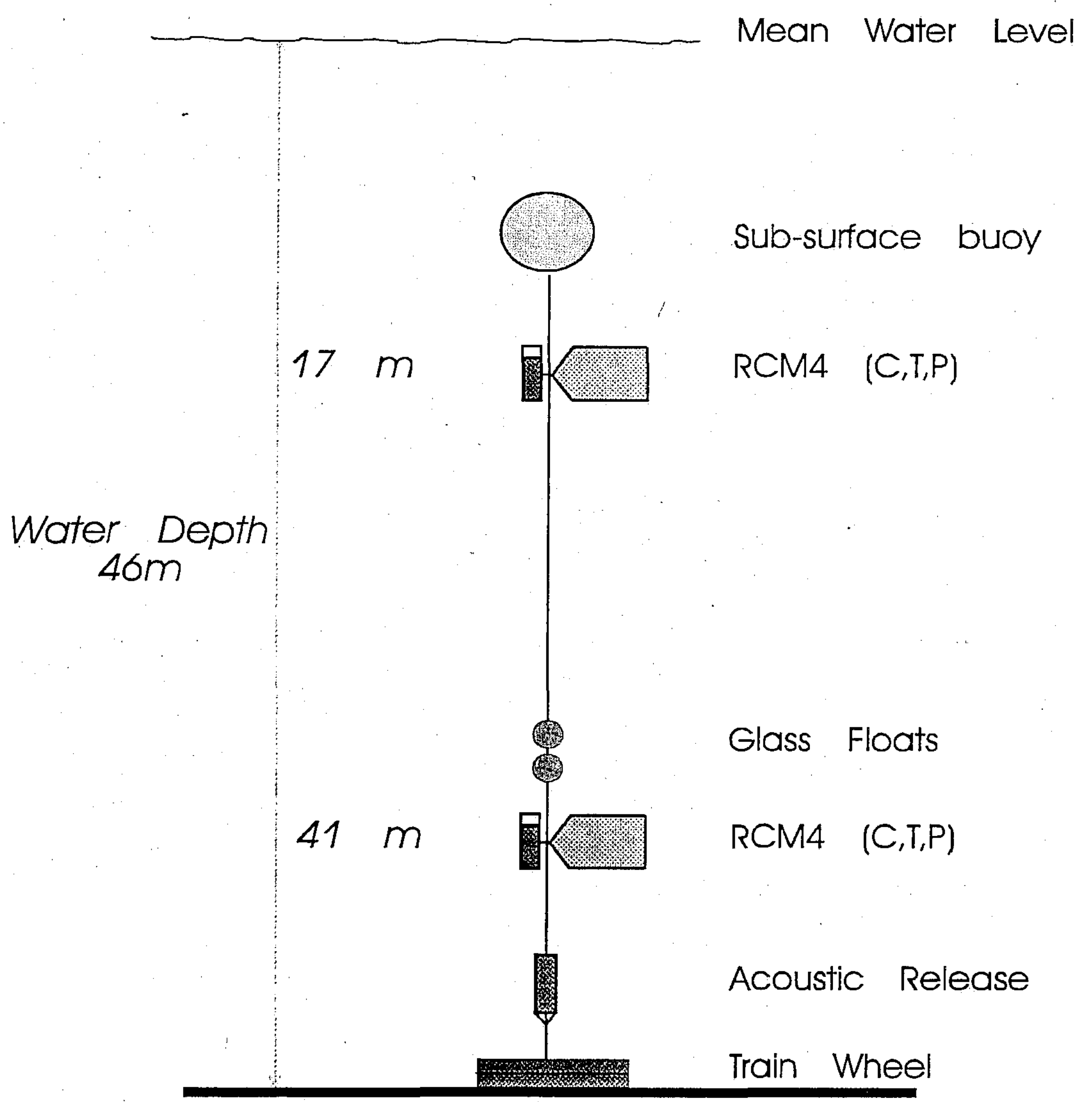


Figure 3.2 Diagram of the Prince Rupert Harbour current meter mooring deployed in 1992 near Douglas Point (54° 19.57'N 130° 19.83'W).

4.0. CURRENT METER MOORING

4.1. TIDAL CURRENTS

A statistical summary of the current velocity data from the 17 m instrument shows that the principal axis of motion for the currents was 29° true. This orientation is approximately aligned with the northeast-southwest (45°-225°) orientation of the harbour axis. Maximum speeds along this axis were as high as 26 cm/s; average speeds were -1.9 cm/s (-ve sign indicates flow out of the harbour or to the SW); and the standard deviation was 9.8 cm/s. In the cross-channel direction, maximum speeds were about 12 cm/s with an average speed of -0.4 cm/s (-ve sign is flow to the SE) and standard deviation of 3.1 cm/s. The basic statistics for this current meter data are similar to those of AES Ltd.'s 10-day current meter record of July 1977.

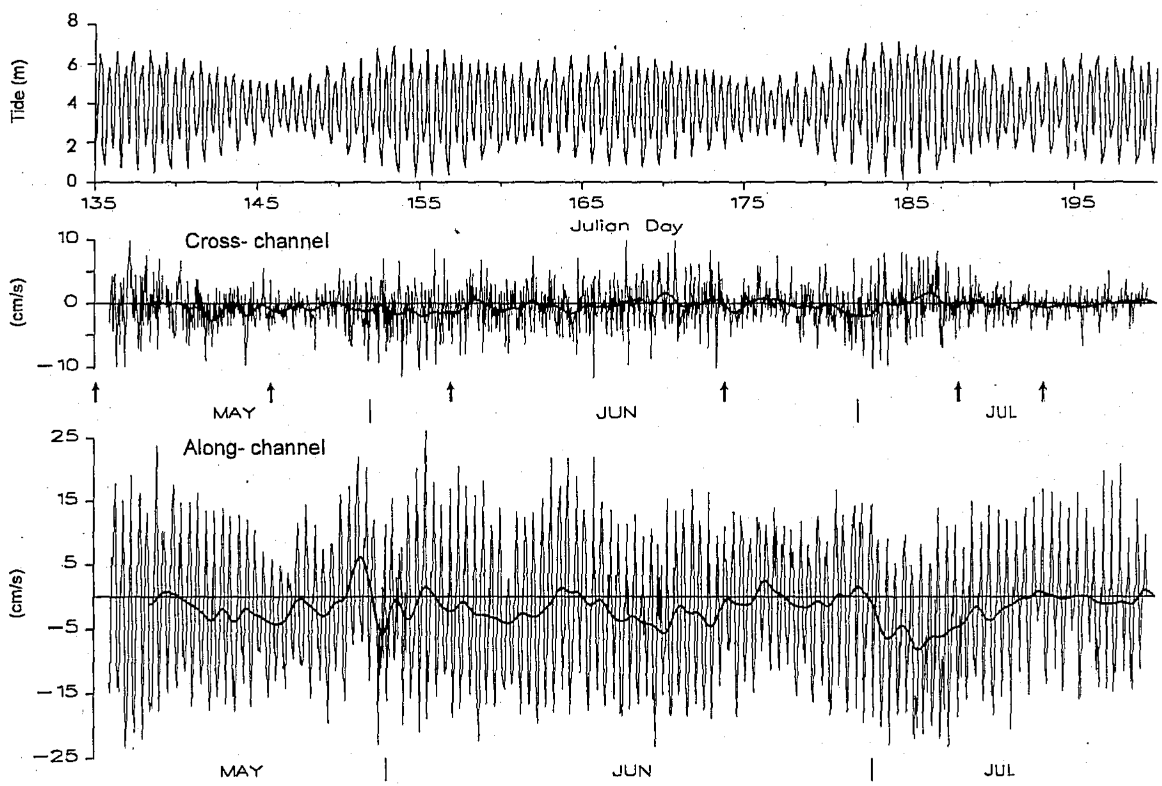


Figure 4.1 Time series plot showing the along-channel and cross-channel currents (hourly and low-passed) from the 1992 Douglas Point mooring, and the observed surface tide in Prince Rupert Harbour.

Visual inspection of the time series plot of the currents (fig. 4.1) reveals that the semidiurnal tidal signal is conspicuous in the along-channel component. The cross-channel component appears to have a higher than semidiurnal tidal frequency signal. Harmonic analysis of the currents using the programs of Foreman (1978) confirm the prominence of the tidal signal in these data as the 36 tidal constituents in the analysis account for about 80% of the variance in the currents.

Table 4.1 The top 10 tidal constituents from the harmonic analysis of 1522 hours of current data at 17 m depth from the Douglas Point mooring.

Rank	Constituent	Period (hr.)	Major Semi-Axis (cm/s)	Minor Semi-Axis (cm/s)	Inclination (° from East)	Greenwich Phase(°)
	Z0		1.961	0	42.3	180
1	M2	12.42	11.251	-0.599	29.6	181.7
2	M4	6.21	1.895	0.031	38.1	102.8
3	K1	23.93	1.833	0.005	34.2	182
4	N2	12.66	1.717	-0.233	25.2	182.2
5	MSF	354.37	1.61	0.009	22.8	294.4
6	S2	12.00	1.477	-0.389	16.7	257
7	MS4	6.10	1.34	-0.18	23.6	164
8	MU2	12.87	1.245	0.339	15.9	284.2
9	L2	12.19	1.043	0.267	22.1	152.4
10	O1	25.82	0.938	0.322	9.8	150

By far the dominant tidal constituent is the astronomical constituent M2, the lunar semidiurnal tide of period 12.42 hours, followed by M4 (6.21 hour period) a shallow water constituent (Table 4.1). The prominence of M4 is surprising given the fact that S2 is the second largest constituent of the tidal elevation (Table 2.1). Of the top five tidal constituents, two are shallow water constituents; M4 is the biharmonic or overtide of M2, and MSF (14.76 day period) is the long period shallow water constituent that is the beat frequency of M2 and S2. Shallow water constituents are generated by frictional and non-linear effects and their prominence is indicative of the energetic tidal mixing and the importance of frictional effects in this harbour system.

The M2 currents and the surface tide are almost in quadrature (90° out of phase) as the M2 current extremes lead tidal elevation extremes by 86° (267.4°-181.7°). Thus the tides in the harbour are standing waves and not progressive waves. The tidal currents are primarily rectilinear as the semi-minor axes are usually much smaller than the semi-major axes. The inclinations of the tidal ellipses for the individual constituents are approximately aligned with the orientation of the harbour axis.

Although we do not have any description of the vertical structure of the currents we can compare the observed tidal currents at 17 m with the barotropic currents based on continuity (conservation of volume). The sectionally averaged (width and depth averaged across the section) current from continuity is given by the following equation

$$u(t) = \frac{A_{srf}}{A_x} \cdot \frac{dH(t)}{dt} \qquad (1)$$

where A_{srf} is the surface area landward of the cross-section, A_x is the area of the cross-section, and H(t) is the time dependant water level.

If we examine only the dominant tidal constituent M2 then the above equation can be rewritten as

$$u(t) = \frac{1}{A_x} \cdot \left[A_{srf} \cdot \omega \cdot H_o \cos(\omega t + \theta)\right] \qquad (2)$$

where H_o and θ are the amplitude and phase of the M2 tide, and ω is the angular frequency of the M2 tide. The term in the brackets on the right-hand side of the above equation is the volume flux through the cross-section.

The determination of the volume flux is problematic because the tidal waters that flow into Denise Inlet and Morse Basin flow through both Fern Passage to the north and Porpoise Harbour to the south. To calculate the sectionally averaged currents through the Douglas Point section we need to know the volume of water passing through Fern Passage into Morse Basin and Denise Inlet. Using the observed maximum flood and ebb currents at the western end of Fern Passage and through Galloway Rapids (C.H.S. 1991) AES Ltd. (1977) estimated that about 80% of the tidal prism in Morse Basin and Denise Inlet entered through Fern Passage. The observations of the maximum flood and ebb current are neither precise nor representative of the entire flow through the passages (personal communication Mr. M. Woodward, Tides and Currents Division, IOS). Consequently the determination of the relative volume fluxes through Fern Passage and Porpoise Harbour is at best coarse.

The calculation is further complicated by the tidal choking effect of the narrow and shallow constrictions in both the north and south passages to Morse Basin. Frictional effects in these constrictions (Butze, Galloway and Zanardi Rapids) result in not only an attenuation of the tidal amplitude in Morse Basin but also a phase shift in the tidal constituents. Rewriting (2) by splitting the volume flux through the Douglas Point section into two parts; the flux for Prince Rupert Harbour proper (first term inside the rectangular brackets) and the flux through Fern Passage (second term inside the rectangular brackets) we get

$$u(t) = \frac{1}{A_x}\left[A_{hbr} \cdot \omega \cdot H_{hbr} \cos(\omega t + \theta_{hbr}) + f \cdot A_{MB} \cdot \omega \cdot H_{MB} \cos(\omega t + \theta_{MB})\right] \qquad (3)$$

where A_{hbr} and A_{MB} are the surface areas of the harbour and Morse Basin respectively; H_{hbr} and θ_{hbr} are the M2 amplitude and phase in the harbour; H_{MB} and θ_{MB} are the M2 amplitude and phase in Morse Basin; and f is the fraction of the Morse Basin tidal prism entering through Fern Passage.

We may now calculate the sectionally averaged current through the Douglas Point section given the following values of the parameter in the above equation:

$A_x = 5.6 \times 10^4\ m^2$.
$A_{hbr} = 16.2 \times 10^6\ m^2$
$H_{hbr} = 1.94$ m
$\theta_{hbr} = 177.4°$
$A_{MB} = 13 \times 10^6\ m^2$
$H_{MB} = 1.56$ m
$\theta_{MB} = 207.2°$
$\omega = 1.41 \times 10^{-4}$ radians s^{-1}
f = 0.8

The maximum current due to the volume flux is about 12 cm/s of which 4 cm/s is attributed to the volume flux through Fern Passage. This compares well with the observed 11 cm/s amplitude of the M2 constituent. Given the uncertainty in the contribution of tidal volume through Fern Passage and Porpoise and the expected vertical and lateral shear in the currents the agreement between observations and the computed currents based on continuity is remarkable. This simple calculation suggests that continuity can explain a large portion of the current signal and that the currents are primarily barotropic in this harbour. The tidal excursion of a water particle based solely on the M2 constituent is approximately 2.5 km.

4.2. SUB-TIDAL CURRENTS

Over the 63 days of current velocity record there was a mean current of 1.9 cm/s directed to the southwest. At this mean velocity, a water particle would move 1.64 km to the southwest in one day. It would take approximately 6 days for a particle to travel 9.5 km the distance to the mouth of the harbour at PRH1. This mean drift may be part of a net circulation around Kaien Island or residual currents set up by non-linear effect of the tidal flow interacting with the geometry of the harbour system. With only one current meter record, the causes for and detailed description of this residual flow are precluded.

The low-frequency currents or sub-tidal currents (frequencies lower than 1/24 hours) are typically less than 5 cm/s in magnitude and oriented in along the harbour axis (fig. 4.1). There is a conspicuous 5 to 10 day-long event in early July when the sub-tidal current intensifies reaching peak speed of 8 cm/s and above 5 cm/s for 5 days. In an attempt to discover the processes responsible for this event we have examined the local winds and fluctuations in the mean sea level.

Climate Services of the Atmospheric Environment Service of Environment Canada provided the hourly wind observations from the Prince Rupert Airport, and the Tidal Officer at IOS provided hourly sea level observations (fig. 4.2).

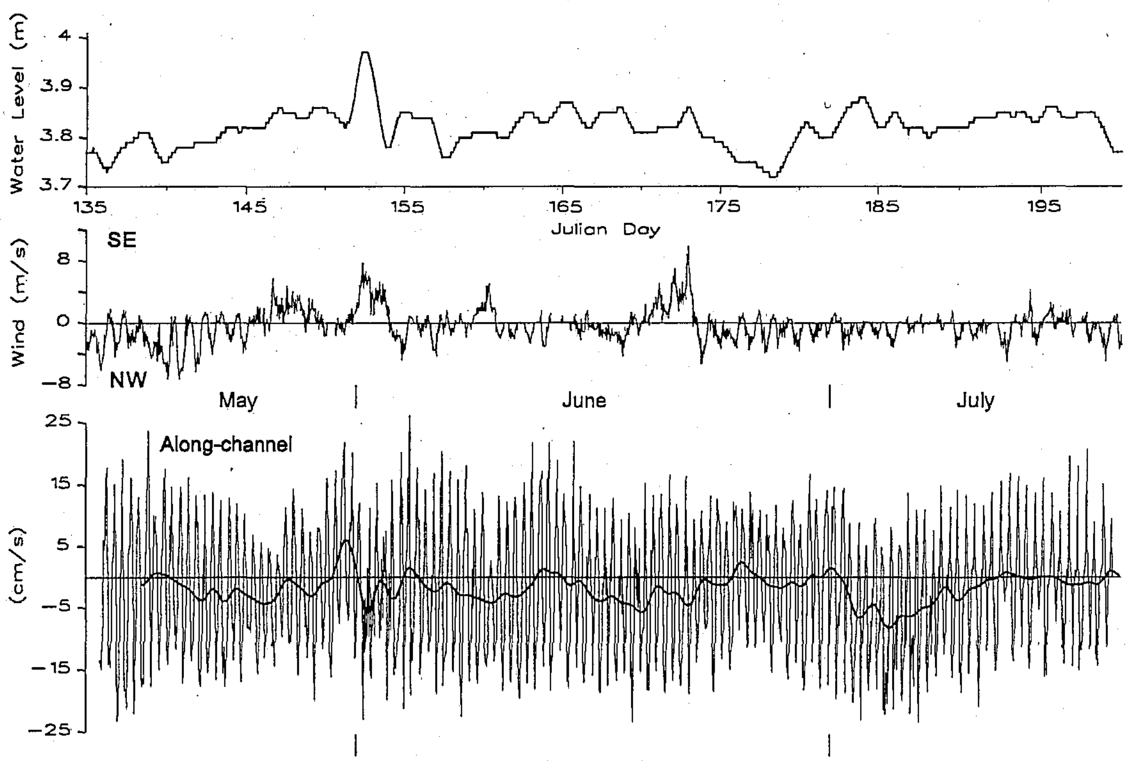


Figure 4.2 Time series showing the along-channel currents at 17 m, the airport winds and low-passed water level from Prince Rupert Harbour during the summer of 1992.

There is no apparent relationship between the local winds and sub-tidal currents or between low-passed sea level and the sub-tidal currents. There is however some evidence of a correlation between winds and sea level. During periods of strong southeasterly winds at the beginning of June and during the third week in June mean sea level in the harbour rises. It appears that these

SE winds set up the sea surface but there is no clear indication of corresponding flow in the harbour or the opposite effect during northwesterly winds.

4.3. TEMPERATURE AND SALINITY TIME SERIES

The time series of salinity and temperature collected by the current meter at 17 m depth are remarkable with respect to the prominence of the fortnightly fluctuations they exhibit (fig. 4.3). Harmonic analyses of both the salinity and temperature time series (Table 4.2) confirm the dominance of the MSF and MM constituents. In the salinity time series, MSF is the largest constituent (0.46 psu) followed by M2 (0.32 psu) and then MM (0.20 psu). Tidal constituents account for about 50% of the variance in the salinity time series.

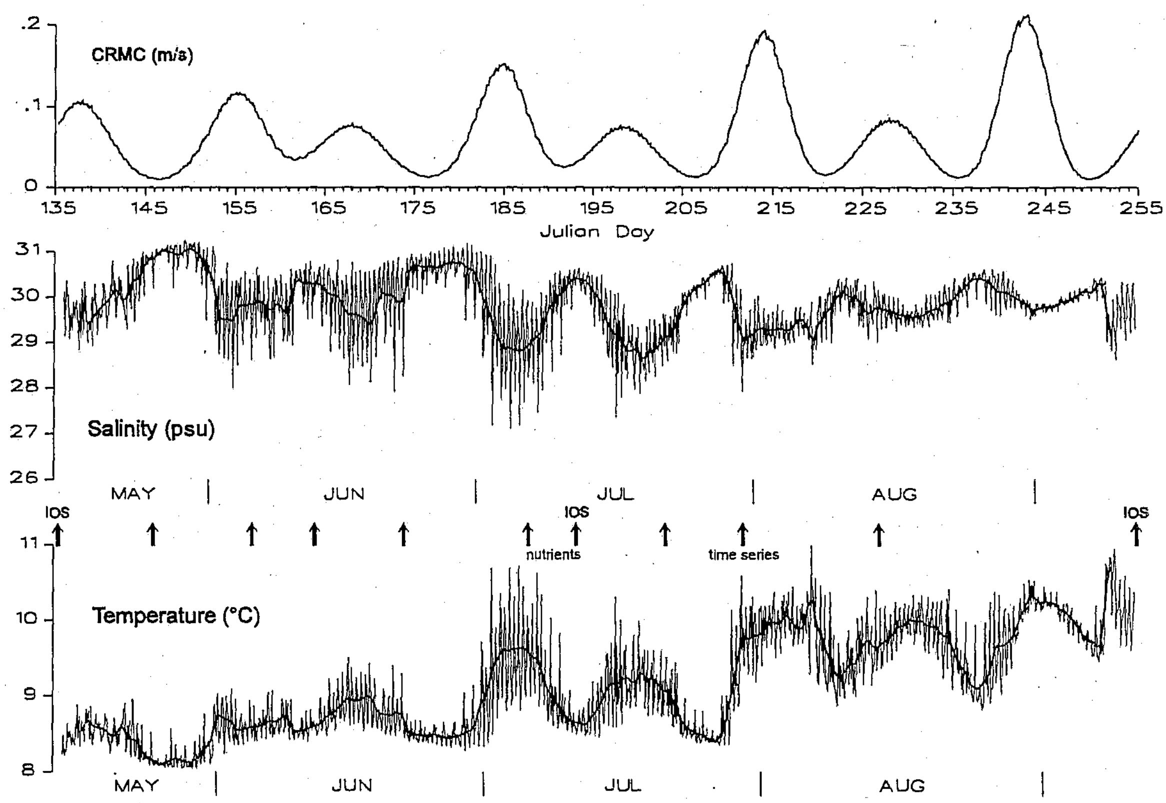


Figure 4.3 Time series showing the temperature and salinity data from the current meter at 17 m depth on the 1992 Douglas Point mooring. Also shown is the cube root of the mean cubed (CRMC) tidal current through the harbour entrance channel. The vertical arrows indicate the times of the water quality surveys.

In the temperature time series, MM and MSF constituents are the largest with a comparable amplitude of 0.25 °C, followed by M2 with an amplitude of 0.19°C. Tidal constituents account for only 22% of the variance in the temperature time series. The phase relationship between the salinity and temperature signal is straightforward. They are 180° out of phase. This is consistent with the vertical gradients in temperature and salinity in this time period. Warmer fresher water overlies colder more saline sea water.

Table 4.2 The top 10 constituents from the harmonic analysis of 2849 hours of salinity and temperature data at 17 m depth from the Douglas Point mooring

Salinity			Temperature		
Constituent	**Amplitude (psu)**	**Greenwich Phase (°)**	**Constituent**	**Amplitude (°C)**	**Greenwich Phase (°)**
Z0	29.891	0.0	Z0	9.129	0.0
MSF	0.465	261.2	MM	0.266	69.8
M2	0.322	329.1	MSF	0.254	96.9
MM	0.199	258.5	M2	0.194	150.5
S2	0.122	14.1	K1	0.064	127.3
K1	0.104	304.7	S2	0.062	189.5
N2	0.076	321.0	N2	0.059	146.4
O1	0.075	282.6	O1	0.052	108.6
M4	0.050	38.4	2MS6	0.032	138.3
M6	0.047	256.4	M4	0.031	245.4
2MS6	0.047	310.0	M6	0.031	89.2

The dominance of the MM and MSF constituents in the water properties of Prince Rupert Harbour confirm our expectations that tidal mixing is important in this harbour system. The currents through Fern Passage at the northern end of Kaien Island can attain speeds of 100 cm/s and enter the harbour at right angles as a tidal jet. Tidal currents in the harbour entrance channel approach 100 cm/s and the flow is visibly turbulent. The hydrographic chart of the harbour notes tidal current of up to 2.5 knots (130 cm/s) at the harbour.

The rate of dissipation of turbulent kinetic energy from tidal currents is proportional to their speed cubed (Simpson and Hunter 1974). We expect a large difference in the energy available for mixing between neap and spring tides in this harbour. By taking a 25 hour running mean of the absolute value of the current speed cubed we bring out the significant spring-neap modulation in energy dissipation from the tides. We use the mean of the cubed speed as an index of the strength of the tidal mixing in this harbour system much as Griffin and LeBlond (1990) did in their analysis of the variation in surface salinity in Georgia Strait. We computed the sectionally-averaged tidal current in the southern portion of the entrance channel using the predicted surface tide for Prince Rupert.

The relationship between the spring-neap envelope and the variations in salinity (fig.4.2) is such that during spring tides the salinity is lowest (temperature highest) and during neap tides salinity increases (temperature decreases). This is consistent with the model in which the much stronger spring tidal currents mix down the fresher and warmer waters near the surface. Thus at or shortly after spring tides the salinity signal at 17 m reaches a local minimum and the temperature signal reaches a local maximum. Presumably at some level closer to the surface the opposite occurs. During periods of neap tides mixing is not nearly as effective and may not penetrate to 17 m. Closer examination reveals that salinity and temperature lag the spring-neap modulation of the tidal currents by a few days.

The above described relationship is in keeping with a model of mixing in which a stratified fluid column is partially mixed and allowed to restratify given the persistent source of buoyancy (both fresh water and heat) supplied to the harbour.

5.0. HYDROGRAPHIC DATA

In this section, we discuss several noteworthy features of the temperature and salinity properties observed during the 11 surveys conducted over the May to September period. We also discuss the dissolved oxygen and nutrient content of the harbour waters and the impact of the sewage discharge on their concentrations. Appendix B contains depth - distance contour plots of temperature and salinity of all the harbour surveys.

5.1. TEMPERATURE AND SALINITY DATA

Using Pickard's (1961) classification scheme for salinity profiles, the salinity profiles from Prince Rupert Harbour are of Type 2 (fig. 5.1). Near-surface salinity in the harbour and at the station at the mouth (PRH1) are generally high, in the 20 to 25 psu range. This is because there is no major source of fresh water in the harbour system. The surface salinity in the harbour is similar to that found along the eastern side of Chatham Sound during non-freshet conditions. During freshet condition, Trites (1966) reported surface salinity in the range 14 to 20 psu along the eastern side of Chatham Sound. We did not observe salinity this low at station PRH1 except the profile taken on June 12, 1992 when the surface salinity was just below 20.0 psu.

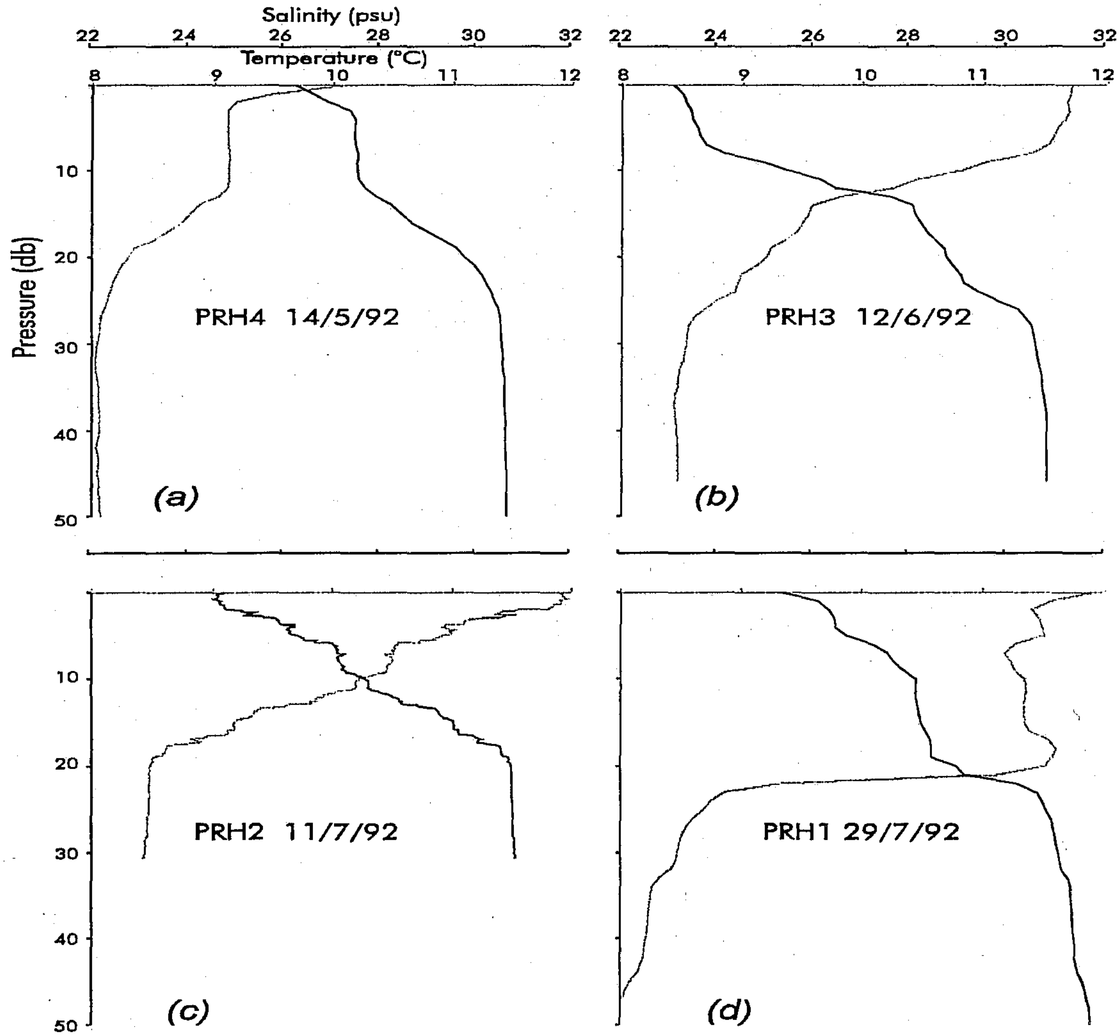


Figure 5.1 Temperature and salinity depth profiles from Prince Rupert Harbour.

A feature of both the temperature and salinity profiles inside the harbour is the general absence of a sharp, clearly defined thermocline and halocline (fig. 5.1). The halocline and thermocline, which more closely resemble a linear gradient than an exponential one, may extend as deep as 25 m and often contain many steps or mixed layers of varying thickness (fig 5.1a). In the one survey when we used a rapidly sampling CTD (Guildline 8075) the profiles on either side of the harbour entrance channel exhibited a significant amount of fine structure (fig. 5.1 c). This fine structure that was not resolved with the slower sampling AMS STD-12 is probably ubiquitous in the harbour.

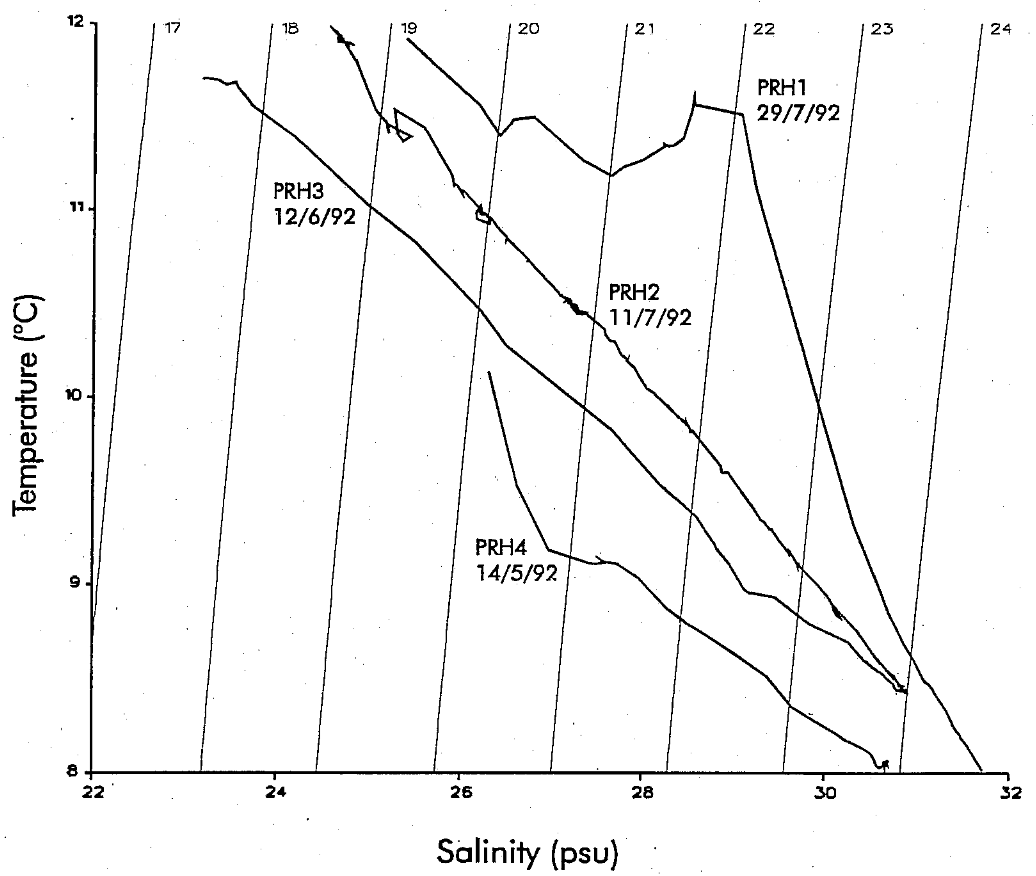


Figure 5.2 Temperature-salinity plots of the four profiles shown in figure 5.1. The regularly spaced curved lines are lines of constant density.

Temperature-salinity (TS) plots of the harbour data are remarkable because they are usually linear (fig. 5.2) or very nearly so. The interpretation of a linear TS diagram is that it represents a water mass that results from the mixing of only two water types. The more saline and colder deep waters mix with the fresher and warmer surface waters. The small scale structures (temperature and salinity inversions) in figure 5.1c collapses onto a straight line when we plot them on a TS diagram. This is not instrument noise but the signature of a turbulent flow, one in which there is overturning of water parcels. Again this is evidence that active mixing is occurring in the narrow entrance channel. By contrast some TS plots from water outside the harbour (PRH1) deviate noticeably from the linear curve indicating that these water are not as well mixed.

Another feature of note is that salinity in the bottom half of the water column at PRH1 is usually higher than that in the harbour. This produces an along-channel gradient of salinity over the length of the harbour entrance channel, i.e. between station PRH1 and PRH2, such that it suggests a high salinity inflow layer at depth. The bottom waters outside the harbour in Chatham

Sound are poised to enter the harbour but unable to transit the harbour entrance channel without undergoing significant mixing. The entrance channel acts as a barrier to the higher salinity water.

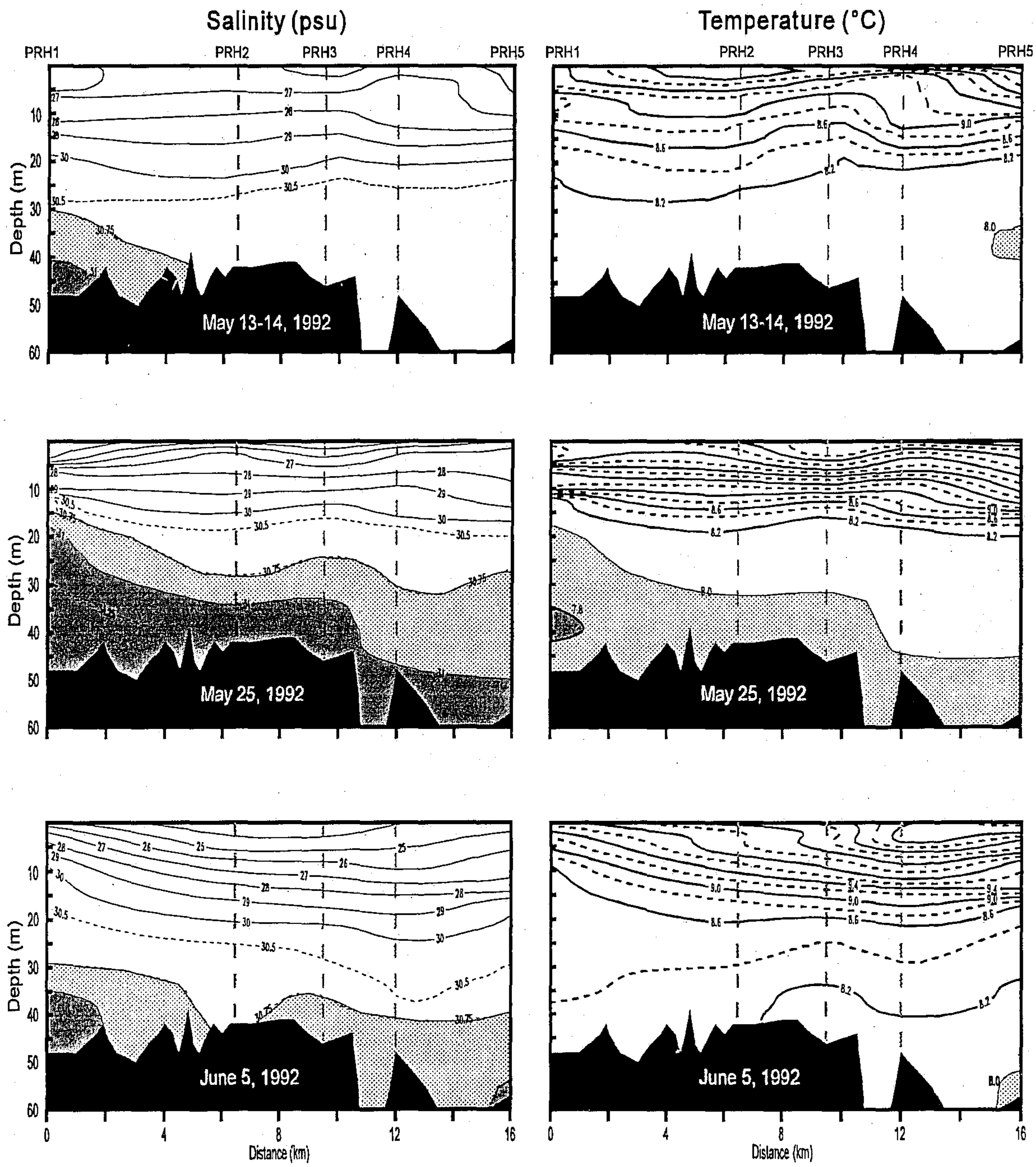


Figure 5.3 Depth-distance contour plots of salinity and temperature for the first three surveys. Dark grey areas are >31 psu and <7.8°C. Light grey areas are >30.75 psu and < 8.0°C.

The first three harbour surveys (May 13-14, May 25 and June 5) illustrate the dynamic nature of deep waters of the harbour (fig. 5.3). In the first survey (May 13-14) no water in the harbour had a salinity greater than 30.75 psu or a temperature less than 8°C. In the second survey, twelve days later, salinities greater than 30.75 were present throughout the harbour below 25 m depths, as were temperatures less than 8.0°C. In the twelve days between the surveys, colder more saline waters from Chatham Sound replaced approximately half the volume of the harbour waters. By June 5, eleven days later, the salinity of the deep waters of the harbour was lower and their temperature higher. Only a small pocket of 31.0 psu water remained at the bottom of PRH5, and 30.75 psu water occupied depth at or below 40 m. The temperature of the deep waters had increased and was greater than 8.0°C throughout the harbour except the small pocket at the bottom of PRH5.

Only the replacement of the deep waters by advection (horizontal movement of water) can increase salinity in the harbour. In the case of decreasing salinity, either advection or mixing processes may be responsible. In any event, the waters in the bottom half of the harbour appear to exchange with the outside on a time scale of 12 days. Interestingly the salinity of the deep waters in the harbour was higher during neap tides (May 25) and lower during spring tides (May 13 and June 5) (fig. 4.1). Tidal mixing may modulate the replacement of the deep waters of the harbour in much the same way as reported by Geyer and Cannon (1982) in Puget Sound and Stucchi and Giovando (1984) in Saanich Inlet.

The model for water replacement suggested is one in which the neap-spring modulation of the tidal mixing in the entrance channel acts as a barrier to the passage of the usually higher density sea water found at the mouth of the harbour. During neap tides tidal mixing is at a minimum and dense water from Chatham Sound can transit the entrance channel with comparatively little modification to its properties. During spring tides denser water from outside the harbour is unable to transit the entrance channel without undergoing substantial mixing. Given this model the temperature and salinity properties of the harbour water should exhibit a neap-spring variation. Indeed the data from the current meter at 17 m depth near Douglas Point shows this type of behaviour. Unfortunately with only one current meter at mid-depth, we cannot know the vertical structure of the neap-spring circulation.

On July 29, 1992 we repeatedly occupied stations PRH1 and PRH3 over a 12 hour period. Figure 5.4 shows the time-depth contour plots of temperature and salinity for both stations. Several features are of interest. First, these time series data confirm that the waters in the bottom half of the water column at PRH1 are more saline than those in the harbour. Second, the vertical excursion in isotherms and isohalines is appreciably larger at PRH1 than at PRH3. At PRH1 the 10°C isotherm and the 30 psu isohaline move vertically almost 20 m while at PRH3 the vertical excursion is less than 10 m. Third, the 27 psu isohalines at PRH1 intersect the surface around 1800 UTC July 29 and again around 2300 UTC. These surfacing isohalines suggest a mixing up of more saline water and they coincide with the times of the maximum flooding and ebbing currents.

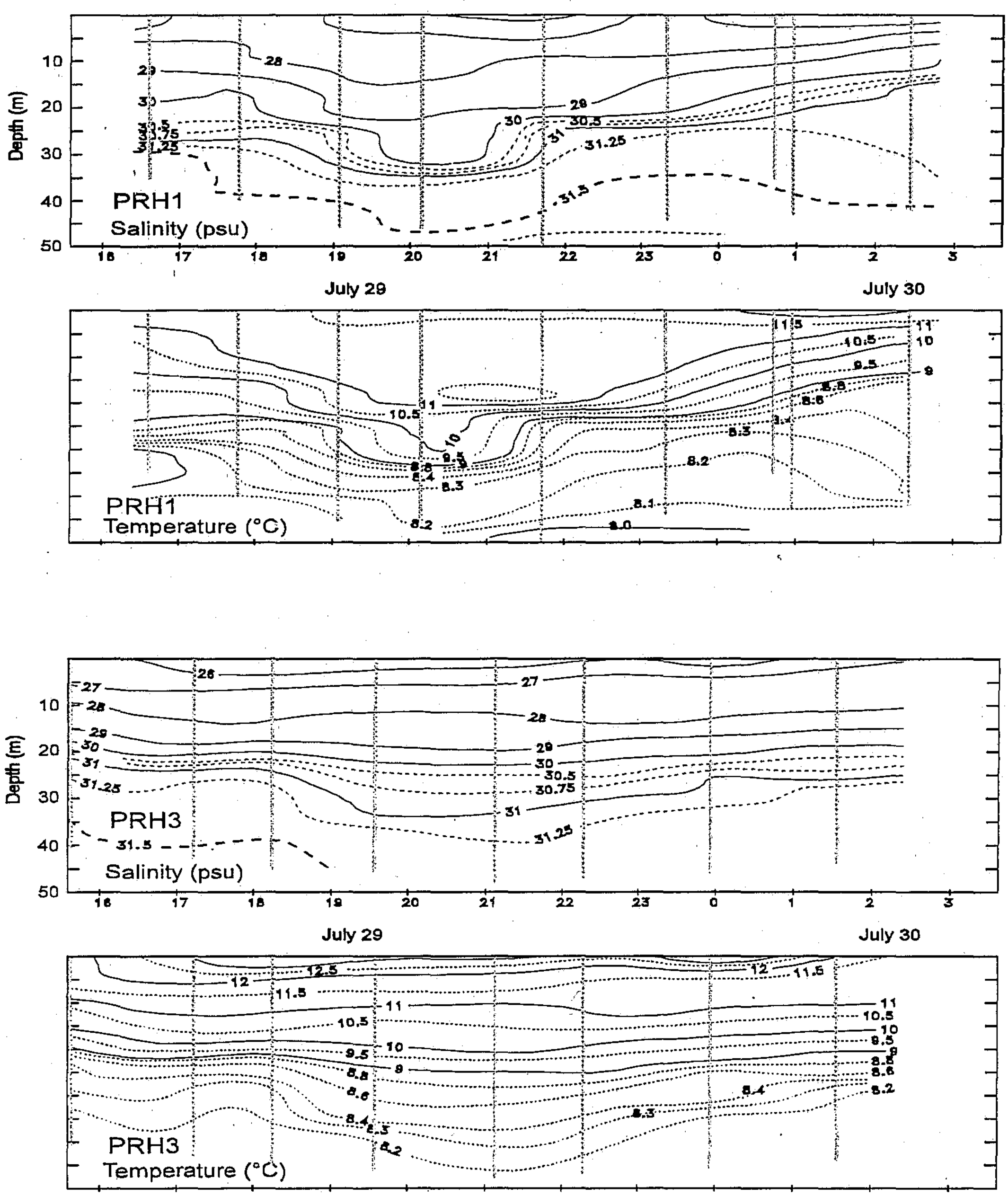


Figure 5.4 Time-depth contour plots of temperature and salinity obtained at stations PRH1 and PRH3 during the 12-hour time series.

5.2. DISSOLVED OXYGEN DATA

Adequate DO levels are necessary for the survival and growth of healthy fish populations. Davis (1975) in his review of the oxygen requirements of aquatic life has stated that low oxygen levels adversely affect growth, and have marked effects on the physiological, biochemical and behavioural processes in fish. He developed oxygen criteria for various fish populations and from these he devised three levels of protection. Level A represents ideal conditions and assures a high degree of safety. Level B represents the level where the fish start to exhibit some symptoms of oxygen distress. At level C large portions of the fish population are affected, and deleterious effects may be serious. The protection levels for anadromous marine species including salmonids are 9.0, 6.5 and 4.0 ppm O_2 for levels A, B, and C respectively.

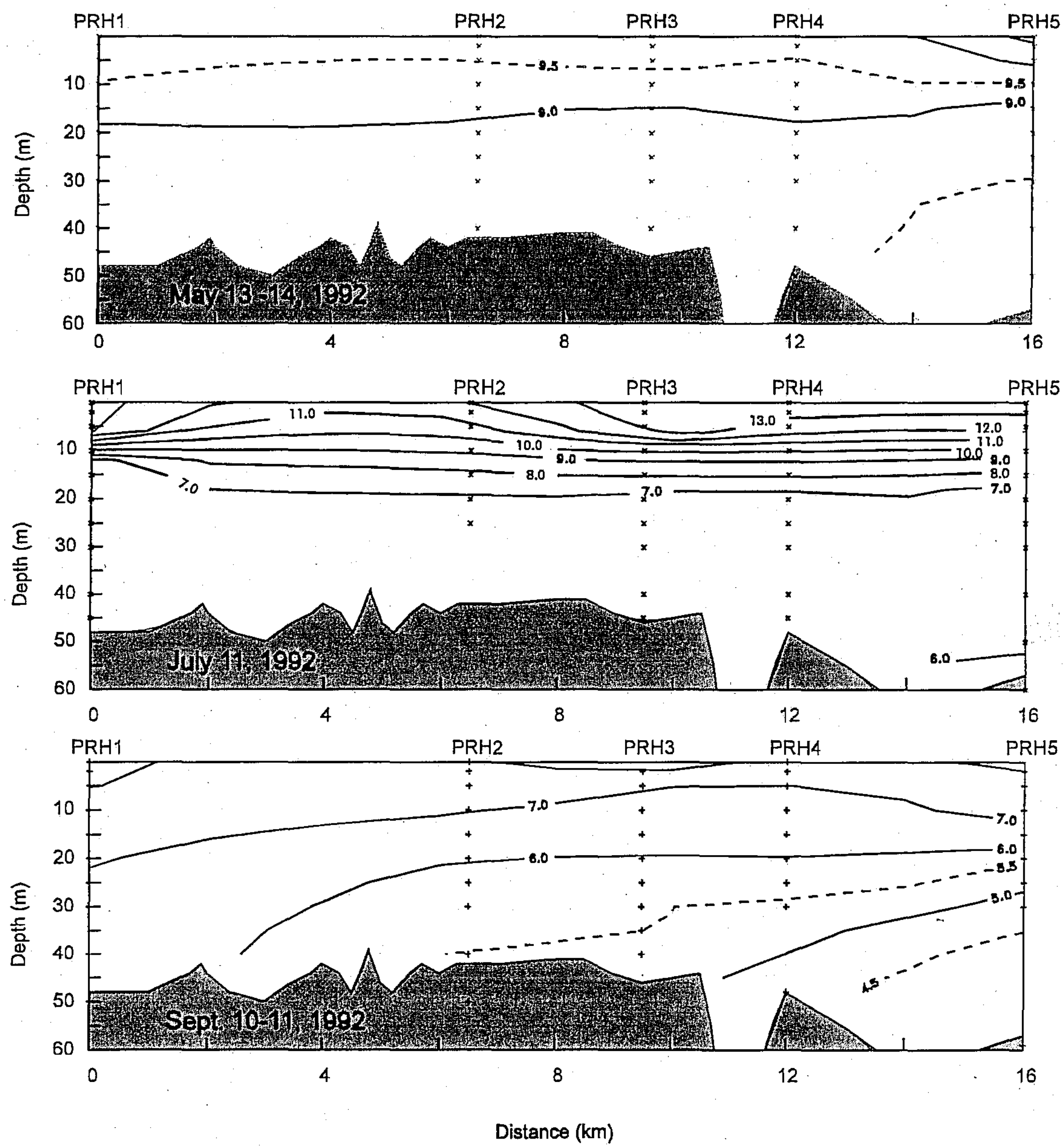


Figure 5.5 Time-depth contours of dissolved oxygen concentration for the first, middle and last surveys of the program.

The dissolved oxygen concentrations in the harbour did not fall below protection level C concentrations. The deep water of the harbour generally had DO concentrations greater than 5 ppm. In each of the three surveys, the water at the bottom of PRH5 had the lowest DO levels. This suggests that the bottom water in the inner reaches of the harbour has a longer residence time here. The highest deep water DO concentration (8.5 to 9 ppm) occurred in May while the lowest concentration occurred in September (fig. 5.5). The lowest values (less than 4.5 ppm) occurred near the bottom at the PRH5, the innermost station in September 1992. McGreer *et al* (1980) also reported that the DO concentrations were lowest (less than 6.5 mg/l) in the fall at the bottom in the upper reaches of the harbour. Outside the harbour, PRH1, DO levels were also lower (6 to 8 ppm) in the fall but not as low as measured at PPR5.

The near surface DO concentration were above protection level B on all three surveys. The highest near surface concentration (10 to 13 ppm) occurred in July while the lowest (7 to 8 ppm) occurred in September (fig. 5.5). In his analysis of a seven-year time series of DO measurement at a station not too distant from PRH1, Ho (1978) reported a similar seasonal depression of DO levels that he attributed to wind induced upwelling. The July surface DO concentrations are noteworthy because of their high levels. In the top 10 m, DO saturation levels ranged from 100 to 150%. Super-saturated concentrations of DO in the euphotic zone suggest that an active phytoplankton bloom was in progress (Pickard 1961).

Based on our three surveys and the reports of McGreer *et al* (1980) and Ho (1978), the concern of Akenhead (1992) that significant DO depression might occur in the harbour is not substantiated. It does appear that the seasonally lower DO content of the source water combined with the slower flushing rate of the deep water in the inner reaches of the harbour produces the lowest DO levels here. However the low DO concentrations we observed were neither widespread nor low enough to cause concern. Nevertheless more observations especially in the fall would provide us with a better picture of the DO variation in the harbour system and in Chatham Sound.

5.3. IMPACT OF SEWAGE ON DISSOLVED OXYGEN

We can undertake an approximate calculation of oxygen uptake that results from the organic matter in the sewage effluent using the time scale of 12 days for harbour water replacement. There are two components to the effluent related oxygen uptake to consider. One component arises from the biochemical oxygen demand (BOD) of the effluent. This is the oxygen uptake caused by the metabolism of micro-organisms as they feed on the dissolved organic constituents in the sewage effluent. The BOD bioassay is a standard test that is routinely used to characterise the oxygen demand potential of various domestic and industrial effluents. The second component is the sediment oxygen demand (SOD). This oxygen uptake is also caused by the metabolism of micro-organisms as they feed on the organic constituents of the sewage effluent deposited on the bottom. There is no standard test to assess the SOD potential of an effluent but the measurement of the total suspended solids (TSS) concentration in an effluent stream is often used as an indicator. The most direct way to assess the importance of SOD is to measure, usually *in situ*, the rate of oxygen uptake by the sediments. This is accomplished by measuring the rate of decline of dissolved oxygen in a known volume of water trapped by a bell jar or benthic chamber over a known sediment surface area.

BOD

The BOD(5) test measures the amount of DO consumed or exerted at 5 days by micro-organisms while metabolising or stabilising a given amount of organic material. This process of stabilisation is often modelled as a first order reaction - a reaction in which the rate is directly proportional to the amount of organic material present. The amount of oxygen uptake (BOD) at any time t for a first order reaction is given by

$$\mathrm{BOD}(t) = L_M \cdot (1 - e^{-Kt}) \qquad (4)$$

where K is the reaction constant that characterises how easily the organic matter is metabolised by the micro-organism, and L_M is the ultimate BOD potential of a given amount of effluent. Equation (5) expresses the ultimate BOD potential L_M given the BOD(5) of the effluent.

$$L_M = \frac{\mathrm{BOD}(5)}{(1 - e^{-K \cdot 5})} \qquad (5)$$

If we assume that the daily BOD(5) discharged to the harbour is constant and accumulates for 12 days, then the time integral of (4) gives the total uptake of dissolved oxygen, O_{Total}.

$$O_{Total} = L_M \int_0^{12} (1 - e^{-Kt})\,dt \qquad (6)$$

$$= 12 \cdot L_M + \frac{L_M}{K}(e^{-K \cdot 12} - 1)$$

In order to evaluate equation (6) we need to know the daily discharge of BOD(5) into Prince Rupert Harbour, but there are no direct measurements of either BOD(5) concentration or daily effluent flow for sewage effluent from the city of Prince Rupert. Instead, we use the average BOD(5) concentration of 180 mg O_2/l for untreated municipal wastes from Thomann and Mueller's (1987) tabulation of selected waste inputs parameters in the United States, and for flow volumes we use AES Ltd.'s (1977) estimate of 1730 m^3 day^{-1}. Thus the total daily discharge of BOD(5) to the harbour is about 311 kg. Using a first order reaction rate K of 0.35 day^{-1} at 20°C, for untreated domestic sewage (Thomann and Mueller 1987) the ultimate BOD potential, L_M, discharged daily to the harbour is about 376 kg. Substituting for K and L_M in the equation (6), the accumulation of 12 days of sewage discharge produces a total dissolved oxygen uptake of about 3500 kg.

To calculate the incremental change in DO concentration we assume that the sewage is mixed into the top 10 m of the harbour waters. Using a harbour area (entrance to Tuck Narrows) of 28 km^2, the BOD of the sewage effluent would cause a decrease in DO concentration of about 0.01 ppm. Clearly the impact on DO concentrations in the harbour is negligble and unlikely to change significantly if we improve estimates of the effluent parameters or time scales for harbour water replacement.

SOD

We can only make an approximate calculation of the impact of SOD on dissolved oxygen levels because there are no direct SOD measurements from Prince Rupert Harbour. Instead we calculate the amount of oxygen uptake based on uptake rates from other marine areas. The calculation uses two uptake rates. At the low end, the SOD rate of 0.1 g O_2 m^{-2} day^{-1} typifies an unpolluted benthic environment with low sedimentation rates of organic solids. At the high end, the SOD rate of 1 g O_2 m^{-2} day^{-1} represents a polluted benthic environment, one in which there is a large flux of organic solids. We further assume that the deep harbour waters are replaced every 12 days and well mixed in the bottom 20 m of the harbour. Using these assumption and bounds for the SOD, the DO concentration deficit after 12 days, for a water column 20 m high resting on one square metre of bottom area would be 0.06 and 0.6 ppm for the pristine and polluted benthic environment respectively.

Based on Thomann and Mueller's (1987) tabulation of an average TSS concentration of 300 mg/l for general municipal wastes and AES Ltd.'s (1977) estimate of daily effluent flow 1730 m^3, the daily load of solids deposited in the harbour is about 520 kg. This is low in comparison to the typical discharges of 10,000 kg day^{-1} (Colodey and Wells 1992) from B.C. pulp mills or large urban centres. Consequently we may argue that the SOD rate for the whole of Prince Rupert Harbour should be closer to the lower of the SOD rates used above. In this case the effects of SOD on the DO levels in the harbour are also negligble ~ 0.06 ppm. Even for the case of high SOD rates the 12-day replacement time for the harbour waters precludes the severe depletion of DO in the deep harbour waters. The lower DO levels at PRH5 may be explained by a combination of longer residence time of the bottom waters here and elevated SOD rates at this end of the harbour.

5.4. NUTRIENTS

In all of the stations we sampled during the two surveys for nutrients, the concentrations of nitrates plus nitrites were very low in the top 5 m. (Appendix C contains tabulations and profile plots of all our nutrient data.) In the top 2 m of three stations, nitrates plus nitrites were not detectable. Silicate concentrations were also low in the top 5 m of the water column though never absent. Nutrient concentrations near the surface did not show any significant differences between stations inside and outside the harbour, nor were there any significant difference between the two surveys. Nutrient concentrations for both silicates and nitrates plus nitrites were highest in the deep waters at all five stations. Nitrate plus nitrite concentrations in the deep waters were in the 18 to 21 μmole/l range and exhibited no changes between locations inside and outside the harbour, or between samples collected 4 or 5 days apart. Silicate concentrations in the deep waters were in the range 24 to 36 μmole/l. Unlike the concentrations of nitrate and nitrite, silicate concentrations in the deep waters did appear to change between the two sampling surveys. The change is most pronounced at PRH1 where concentrations increase from the 24 to 27 μmole/l range to 31 to 36 μmole/l range in 5 days.

Our nitrate concentrations exhibit a similar pattern to the July 1973 measurements taken by Drinnan and Webster (1974) in Prince Rupert Harbour. In July 1973, nitrate concentrations at the surface were low and in the deeper waters (30m) concentrations were much higher and within the range of winter time concentrations for coastal areas (Drinnan and Webster 1974). Also, our observations of the deep water nitrate plus nitrite concentrations are similar to summer time concentrations at the mouth of Portland Inlet reported by Macdonald *et al* (1984). However, the silicate concentrations they measured at depths below 50 m were much higher, in the range 46 to 59 μmole/l. Only the silicate concentrations at 25 m reported by Macdonald *et al* (1984) were comparable to those we observed.

If we adopt a simple mixing model for Chatham Sound waters involving two water types in which the nutrients are assumed to be conservative quantities, then the resulting nutrient - salinity curve should be a straight line. One water type is the Skeena River water, and it has low (1 to 2 μmol/l) nitrate plus nitrite concentrations from June to October (Environmental Operations Branch, Environmental Surveys Branch, Environment Canada). The second water mass is the nutrient rich (20 μmol/l nitrate plus nitrite) Chatham Sound bottom waters (salinity ~31 psu). Plots of nutrient concentration versus salinity (fig 5.6) show that the nutrient data from the harbour fall well below simple mixing line mentioned above indicating a depletion of nutrients most likely by biological processes.

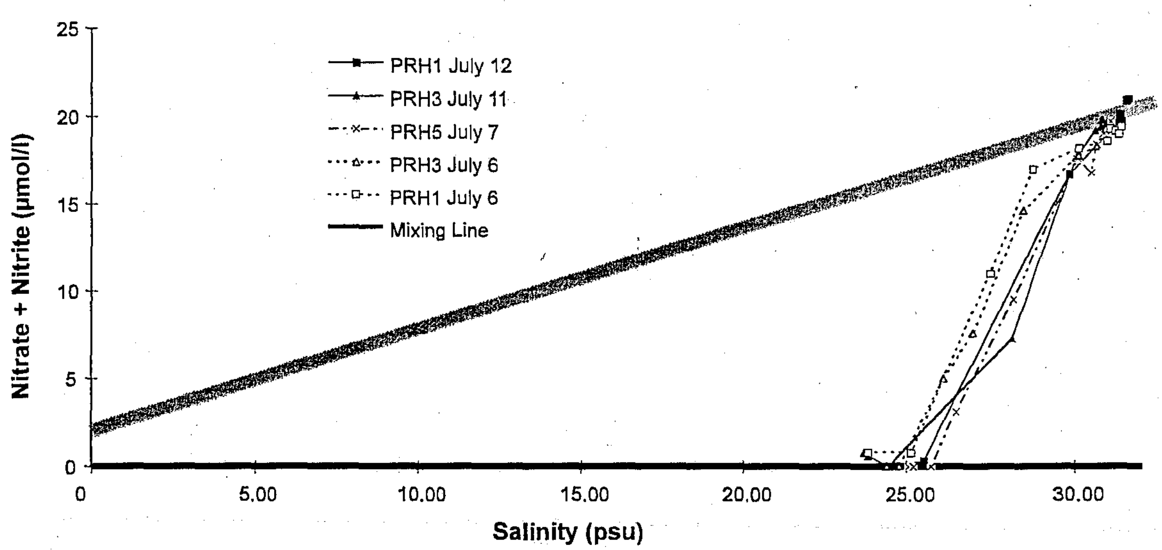


Figure 5.6 Prince Rupert Harbour nitrate+nitrite concentration plotted against salinity.

The surface nutrient depletion along with the supersaturated dissolved oxygen concentrations are strong evidence that significant biological production, i.e., a phytoplankton bloom was occurring at the time we collected these nutrient samples. Although we do not have phosphate measurements, the almost complete depletion of nitrates and nitrite in the surface water indicates that the biological processes are nitrogen limited.

Under conditions of an active phytoplankton bloom and with only two surveys we cannot determine if there is any evidence of nutrient enrichment from the discharge of sewage. However comparing nutrient concentrations inside the harbour with those from outside (PRH1) we could not determine significant difference that could be explained by sewage discharge inside the harbour.

We may, however, calculate the incremental increase in inorganic dissolved nitrogen that originates from the 12 sewage outfalls. Our calculation is approximate since there are no direct measurements of either the characteristics or volumes of the sewage effluent discharged into the harbour. For sewage effluent characteristics we chose the city of Victoria as a proxy for Prince Rupert since both cities do not treat their effluent. For flow volumes we use the average annual flow, Q, of 7.2 cfs (0.2 $m^3 s^{-1}$ or 1730 $m^3 day^{-1}$) estimated by AES Ltd. (1977). Furthermore we assume that most of the inorganic dissolved nitrogen in the effluent is in the form of ammonia (NH_4), and the concentrations are between 15 and 30 mg/l (EVS Consultants 1992). We further assume that the sewage is mixed into the top 10 m of the harbour waters and that this 10 m surface layer flushes completely in 12 days.

Based on the preceding assumptions and effluent characteristics the total daily discharge of dissolved inorganic nitrogen, N_{tot}, to the harbour ranges from 20 to 40 kg NH_4-N. If we accumulate the discharge for 12 days in the top 10 m then the incremental change in concentration of nitrogen provided by the sewage effluent ranges from 0.06 to 0.12 μmol/l. In comparison to the natural nitrate plus nitrate levels of 20 μmol/l the contribution from the sewage effluent is negligible, i.e., less than 1%.

6.0. CONCLUSIONS

Based on the 63-day record of currents at 17 m depth near Douglas Point, the currents in the harbour are not sluggish. Speeds in the range 5 to 15 cm/s are typical with the occasional burst to 25 cm/s (half a knot). The currents generally align themselves with the harbour axis, that is in a southwest - northeast direction. The mean flow is toward the southwest (out of the harbour) at a speed of about 2 cm/s. The currents are primarily tidal in nature since the tidal constituents account for about 80% of the variance in the currents. The dominant tidal constituent is the lunar semidiurnal tide M2 (period 12.42 hours) having an amplitude of 11 cm/s. The amplitude of the barotropic M2 tidal currents, calculated from sea level variations and continuity, agrees well with observed amplitude of the M2 tidal currents.

Tidal mixing is an active and important process determining the circulation and water properties of Prince Rupert Harbour. Harmonic analysis of the currents shows that the shallow water constituents are significant. The neap - spring or fortnightly variation of tidal energy produces an appreciable signal (1.6 cm/s MSF constituent) in the harbour circulation. In the temperature and salinity record collected by the current meter, the low frequency shallow water constituents MSF and MM are dominant. This indicates that the neap-spring modulation in the strength of the tides produces significant water property variations in the harbour.

Based on water property variations between surveys, the advective replacement of the bottom half of the harbour waters can occur in a time scale of about 12 days.

Based on our review of the historical water quality data and on our observations of DO conditions in and around the harbour, concerns about a catastrophic depletion of DO are not substantiated.

There is no evidence of widespread, long-lasting detrimental DO depressions inside the harbour. DO concentrations in the deep water of the harbour generally had concentrations greater than 5 ppm. The lowest DO concentrations (~5 ppm) occurred in the fall, near the bottom, at the innermost end of the harbour. Estimates of the oxygen demand of sewage effluent discharged into the harbour indicate that the impact from BOD in the surface waters and sediment oxygen demand in the bottom waters are small.

Our near surface measurements of nutrient concentrations reveal that an active phytoplankton bloom was in progress. At depth, nutrient concentrations fell within the range of winter time concentrations for coastal areas. With only two surveys it is difficult to determine if there is any evidence of nutrient enrichment inside the harbour. But we could not detect any significant differences between concentrations inside and those outside the harbour. Furthermore, estimates of the incremental change in nutrient concentration (dissolved inorganic nitrogen) caused by sewage effluent indicate that they would cause a change of less than 1%.

7.0. RECOMMENDATIONS

Our current meter measurements in Prince Rupert Harbour provide new and interesting information about the circulation in this harbour. However, the lack of observations of the vertical structure of the currents is the most conspicuous deficiency in our description and understanding of the harbour circulation. We know from the surface drogue measurements of AES Ltd. (1977) that the surface currents can be large and not always tidal in character. To describe the circulation and understand the driving forces generating not only near surface but also the near bottom currents, we recommend season long time series measurements of the vertical structure of the currents.

However, measurement of the current profile in the top 20 m would be a risky undertaking if we used conventional current meters because of the likelihood of collisions with the deep draft (15 m) vessels that anchor in the harbour. Also, vertical resolution would be coarse given the limited number of current meters prudent to mount on any one mooring. We recommend the use of an alternate technology, a bottom mounted acoustic Doppler current meter, that would provide good vertical resolution of currents while remotely measuring the current profile from the bottom.

The calculation of the barotropic tidal current in the harbour is uncertain because we have only a coarse estimate of the volume of water passing through Fern Passage into Morse Basin and Denise Inlet. We recommend that a more precise estimate of the amount of the Morse Basin and Denise Inlet tidal volume that enters via Fern Passage. Determination of the relative flow through Fern Passage may be useful in specifying boundary conditions or testing numerical models of the harbour circulation.

To extend our description and understanding of the harbour circulation we recommend that a 3-dimensional tidal model of harbour and surrounding waterways be constructed. The model, once tested and verified with actual current measurements, could be used as a tool to track the dispersal and movement of effluent and contaminants introduced to the system. We could use the detailed description of currents provided by the model to optimise locations and configurations of effluent discharge. Also, model predictions would be useful in the specification of boundary conditions in diffuser models that attempt to predict the trajectory of the sewage plume, dilution and trapping depth.

Our sampling program during the summer of 1992 greatly increased our data base of water property and water quality measurements for the harbour. We now have a good description of the summer and early fall conditions. We recommend the extension of the measurements to the winter and spring in order to provide us with the full annual range of variations in stratification, water properties and water quality. Nevertheless, more DO measurements of deep water especially in the fall of the year would add more credibility and confidence to our understanding of the DO variations at this critical time of the year.

In an attempt to estimate the impact of the sewage effluent on the water quality in the harbour, we estimated the amount of oxygen demand and nutrient enrichment produced by the discharge of sewage into the harbour. Lacking direct measurements of effluent characteristics for Prince Rupert we used the effluent characteristics of untreated domestic sewage and Victoria sewage as a proxy. These calculations would be more credible and relevant if we could use effluent characteristic and discharge rates for Prince Rupert sewage. We recommend the measurement of effluent characteristics (BOD(5), total suspended solids (TSS), ammonia, and phosphates) and flow rates of Prince Rupert sewage at the 12 outfalls.

The main source of industrial pollution (BOD, TSS and toxic compounds) in the area is the Skeena Cellulose Inc. pulp mill at Port Edwards. The advection of the pulp mill's effluent plume into the harbour could also be a major input of contaminants. Hodgins and Knolls (1990) have studied the dispersion and movement of the pulp mill's effluent plume using an ebb tide dye release, and found that pulp mill effluent did not spread into the harbour. However, on the flood tide the possibility exists that pulp mill effluent may enter the harbour through the "backdoor", i.e., through Fern Passage via Morse Basin. To our knowledge, no study exists for a flood tide dye release. Consequently, we recommend a study of the movement and dispersal of the pulp mill's effluent plume using a flood tide dye release to assess the transport of effluent to the harbour through Fern Passage via Morse Basin.

In the Victoria sewage experience, the replacement of the Macaulay Point shoreline outfall with offshore submerged diffusers produced improvements in several water quality indicators (coliform counts, nutrients, colour etc.) at and near the Macaulay Point shoreline (Balch *et al* 1976). If the citizens of Prince Rupert decide to proceed with the proposed sewerage extension program we recommend that an intensive monitoring program be undertaken. The detailed objectives, design, methods and parameters of the monitoring program should be carefully considered and tailored to the site. The general objective of the monitoring program should be to assess the impact of the sewerage extension program on the receiving waters both along the harbour shoreline and away from shore. The monitoring program should be in place for at least one year before and after the sewerage extension program is completed. Important indicators such as coliform counts at the surface and at depth, and visible occurrence of sewage wastes along the shoreline should be included in the monitoring program. Historic coliform monitoring data should be examined and summarised to document the present impact of shoreline outfalls, and assist in the design of future monitoring programs.

Clearly there are many other concerns regarding the discharge of sewage that are beyond the scope of our 1992 study and not addressed in this report. These concerns relate to the discharge of toxic chemicals, their accumulation in the sediment and harbour waters as well as their effects on marine organisms. Toxic substances are not only introduced by domestic sewage effluent but also in the effluents from industrial activities as well as from surface runoff. As a first step, we recommend a review of knowledge and measurements of toxic compounds in the sediments and marine organisms of the harbour and their sources. A second step would be to carry out a comprehensive chemical analysis of the effluent stream from each outfall to identify toxic chemicals, their sources and variations in time. This effluent chemistry work could be used to direct a source control program for those toxic substances that are present in abnormally high concentrations. A third step would be to carry out a sediment chemistry program to identify and quantify the concentration as well as the geographical distribution of toxic substances. The fourth step would examine the health of the ecosystem using indicators such species diversity and abundance, health of marine organisms, i.e., incidence of diseases, lesions, tumours etc., and the accumulation of toxic substances in the tissues of marine organisms - bioaccumulation.

8.0. ACKNOWLEDGEMENTS

The 1992 summer study was a co-operative endeavour, comprising several groups and many individuals from the department. At the outset we would like to acknowledge and thank the personnel in Marine Division (DFO Marine Base, Prince Rupert) for making time available for our work on the Fisheries Patrol vessels, and the crews of the vessels we used for their enthusiastic co-operation and assistance. We acknowledge the considerable effort and contribution made by summer student Mr. Harry Jussinoja to the sampling program. We thank and recognise the competent work of the IOS oceanographic technicians; Tom Juhasz, Bernard Minkley and Darren Tuele. Finally, we thank Dr. R.E. Thomson for reviewing the manuscript.

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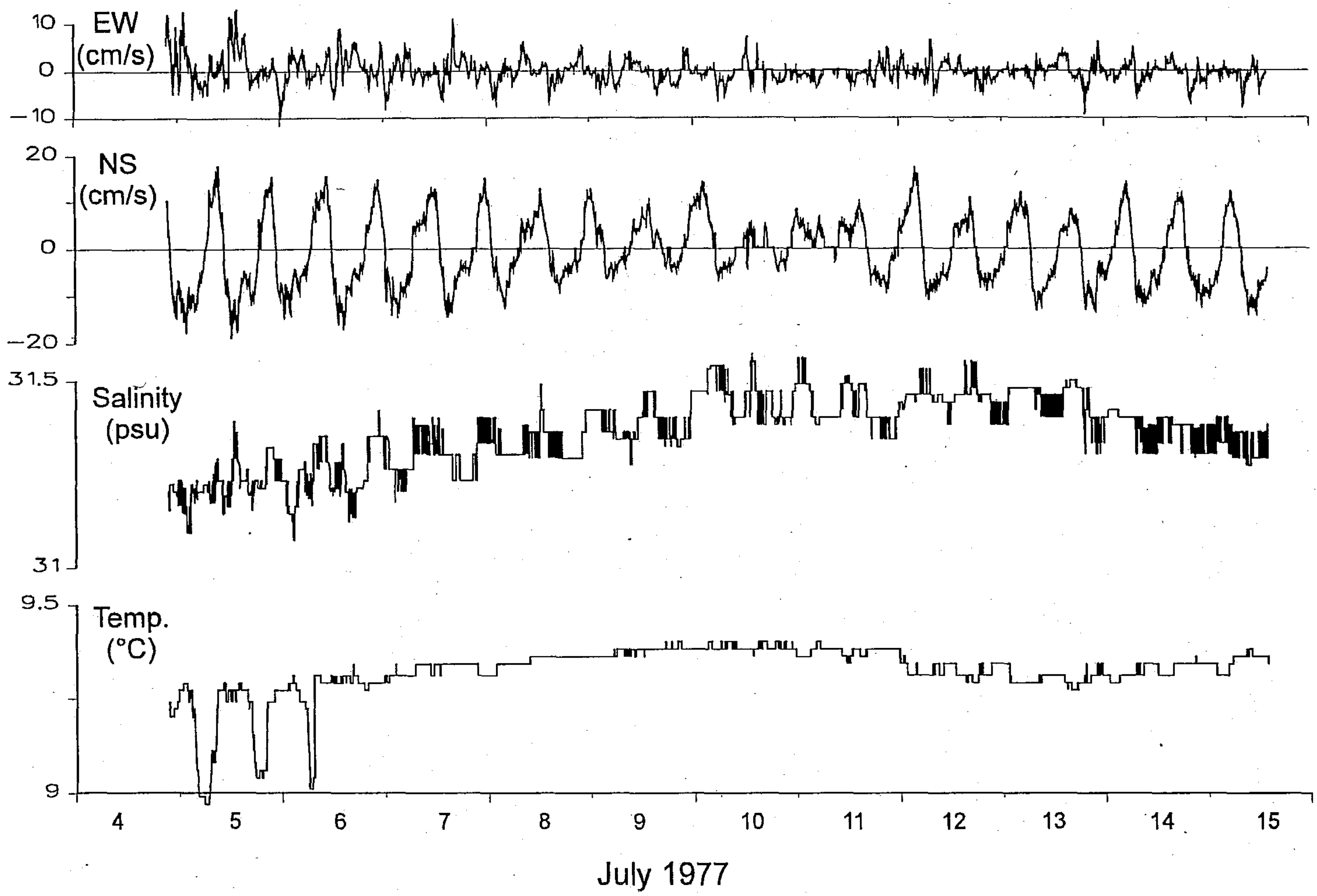

Figure A.1. Time series plot showing the current meter data collected by Associated Engineering Services Ltd., in 1977 inside Prince Rupert Harbour, 0.8 m off the bottom in a water depth of 40 m.

APPENDIX A (continued)

Table A.1 Tombstone information on AES Ltd. current meter mooring

Location:	54° 18.8'N 130° 20.8'W
Depth:	39.5 m (0.8m off bottom)
Water Depth:	40m
Instrument Type:	Aanderaa Instruments Ltd. RCM4
Sampling Interval:	5 minutes
Deployment Date:	July 4 1977
Recovery Date:	July 15, 1977
Duration of deployment:	10.7 days
Comments:	The current meter was mounted in a cage 0.8m off the bottom

Table A.2 Statistics for the Prince Rupert Harbour deployed by Associated Engineering Services Ltd.

Parameter	**Accuracy**	**Mininum**	**Maximum**	**Average**	**Standard Deviation**
Speed (cm/s)	± 1 cm/s	0.0	21.7	6.7	3.8
Direction (° True)	± 0.5 °	0.0	359.	154.1	102.9
Temperature (°C)	± 0.02 °C	8.97	9.40	9.32	0.06
Salinity (psu)	± 0.1 psu	31.07	31.56	31.36	0.23
Pressure (dbar)	± 0.7 dbar	37.3	41.0	39.5	0.9
Sigma-t	± 0.1	24.18	24.56	24.40	0.09
NS component (cm/s)	± 1 cm/s	-21.4	16.0	-0.7	6.6
EW component (cm/s)	± 1 cm/s	-14.1	11.6	-0.7	3.8

Table A.3 Harmonic analysis of current meter record.

		Current Ellipse			
Constituent	**Frequency (cycles/hour)**	**Major (cm/s)**	**Minor (cm/s)**	**Inclination(°)**	**Phase (°) (local time)**
Z0	0.000	0.9	0.0	44.4	
K1	0.0417807	0.8	-0.4	94.5	244.9
M2	0.0805113	8.0	0.6	64.3	358.0
M3	0.1207671	0.7	-0.1	60.5	189.3
M4	0.1610227	2.1	0.3	55.9	326.4
2MK5	0.2028035	0.7	-0.2	49.2	287.1
2SK5	0.2084474	0.4	0.0	20.9	272.4
M6	0.2415342	0.6	-0.1	23.0	311.6
3MK7	0.2833149	0.5	-0.1	101.9	317.9
M8	0.3220455	0.5	-0.2	113.6	293.4

Appendix B Temperature and Salinity Sections

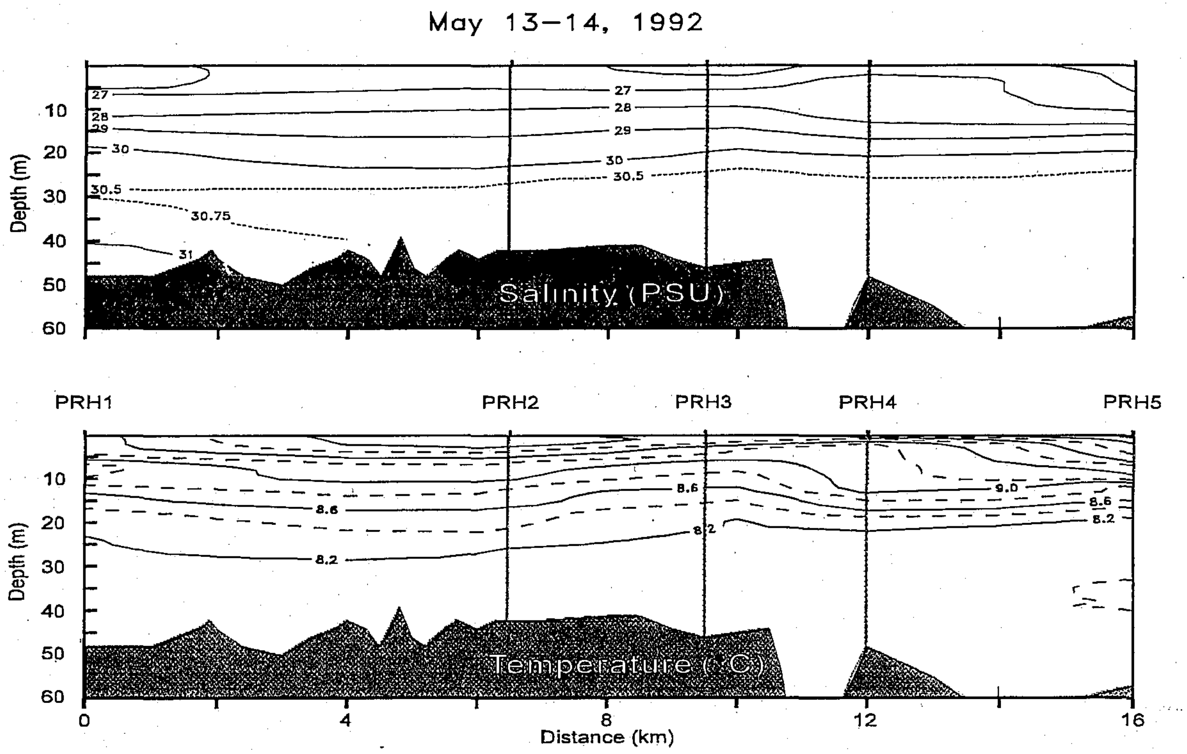

Figure B.1 Temperature and salinity sections for May 13, 1992.

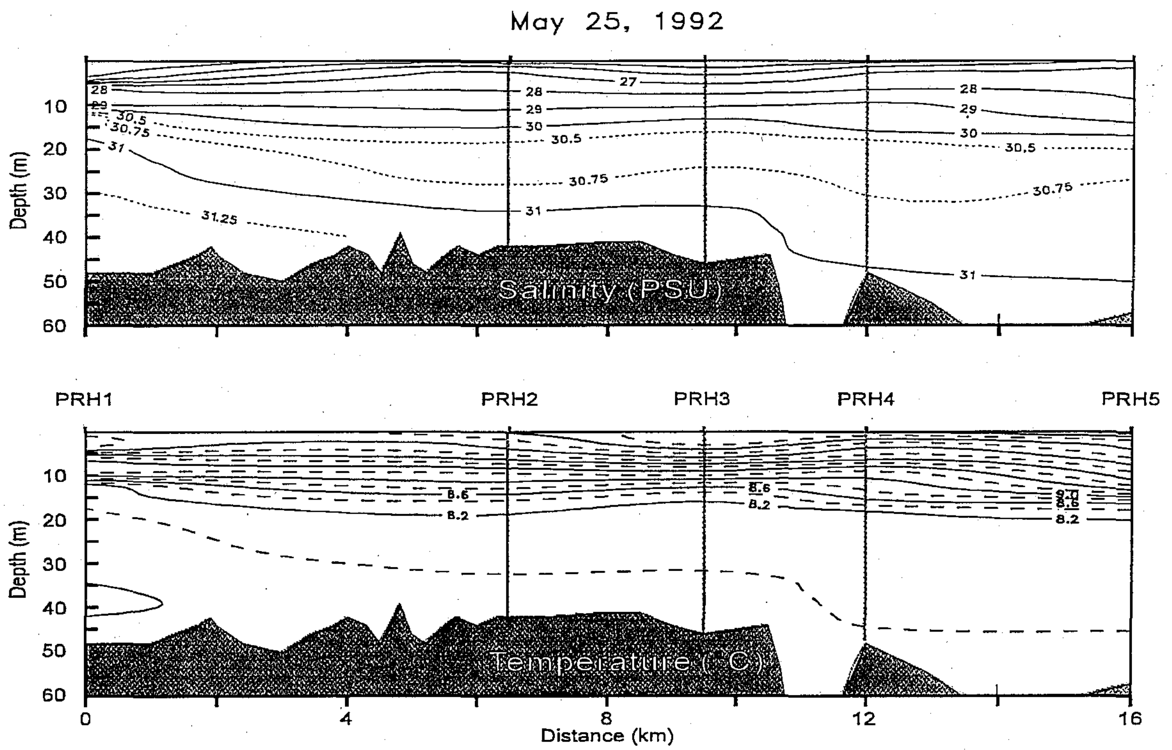

Figure B.2 Temperature and salinity sections for May 25, 1992.

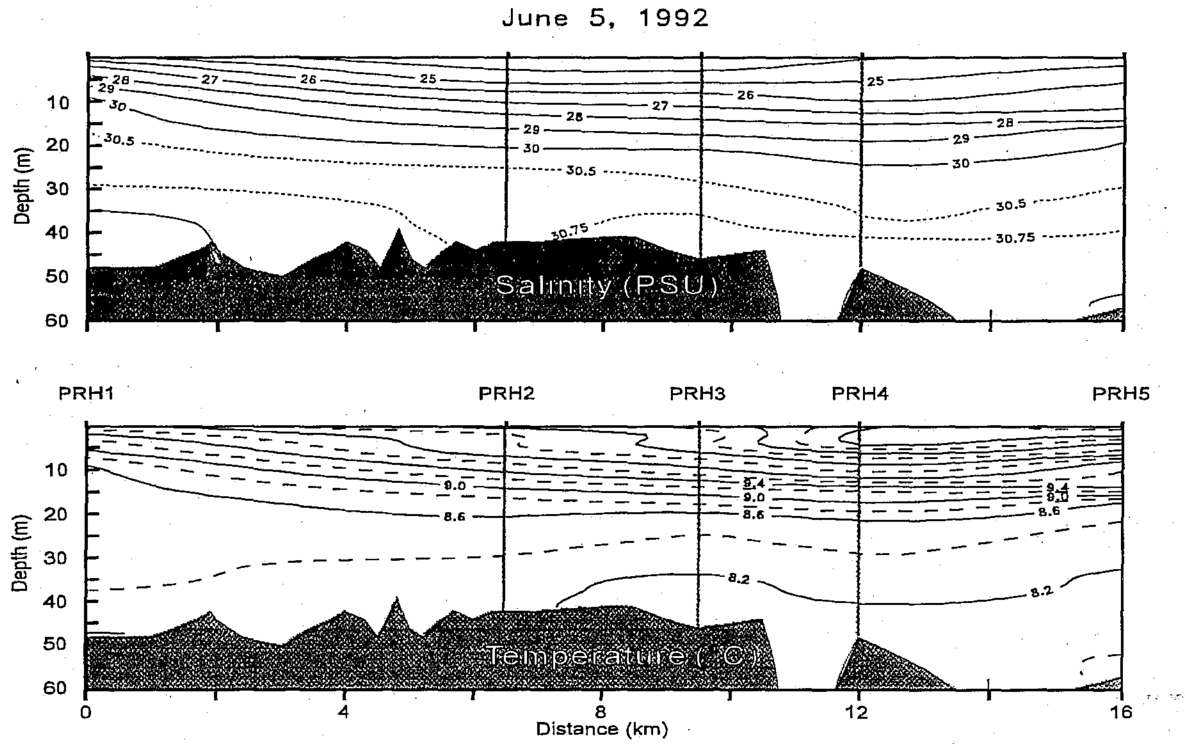

Figure B.3 Temperature and salinity sections for June 5, 1992.

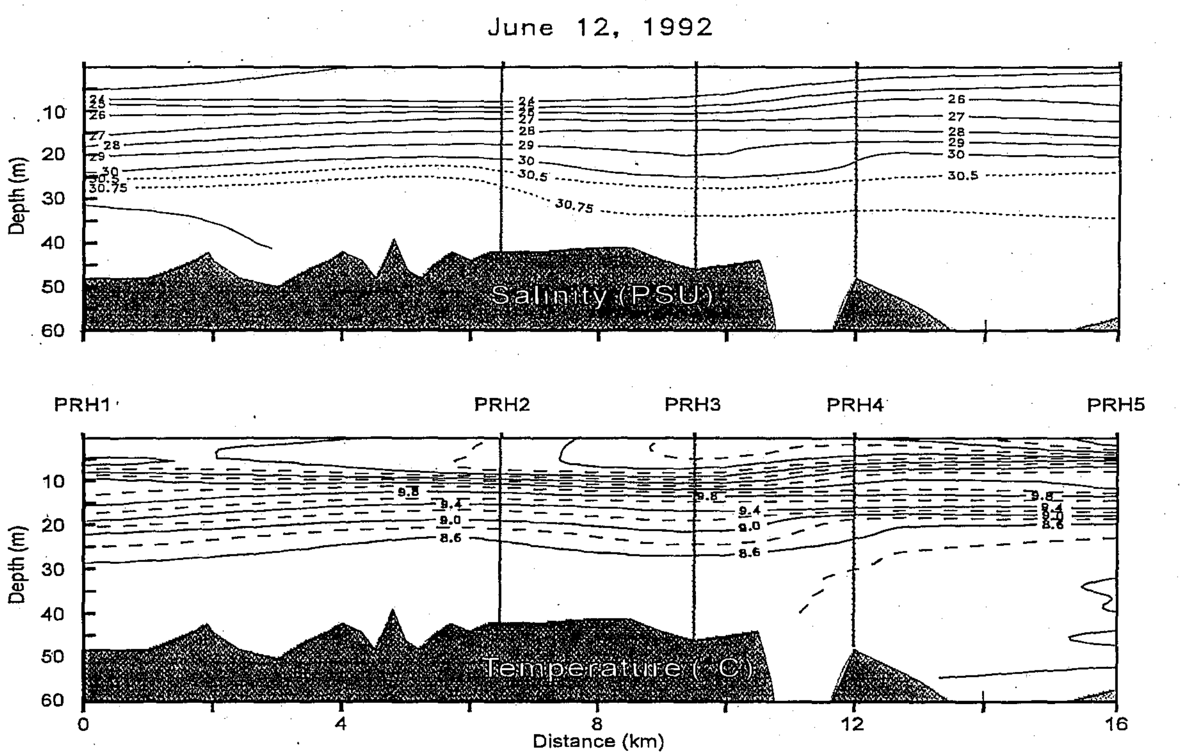

Figure B.4 Temperature and salinity sections for June 12, 1992

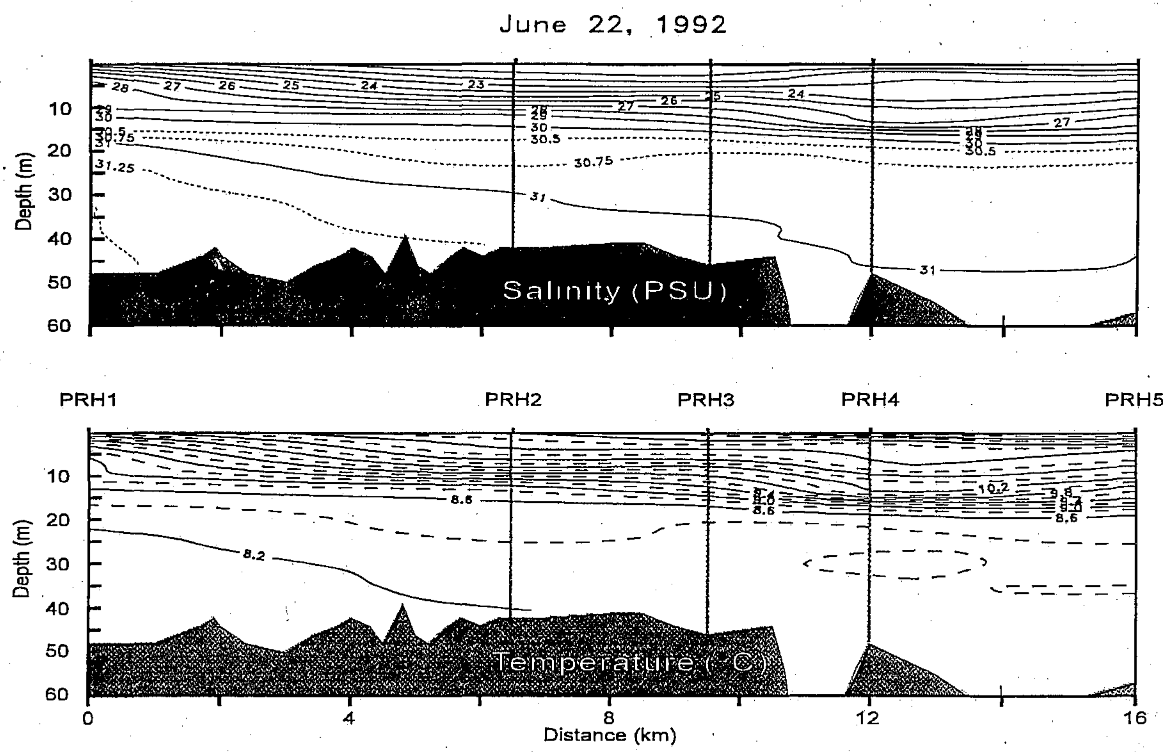

Figure B.5 Temperature and salinity sections for June 22, 1992.

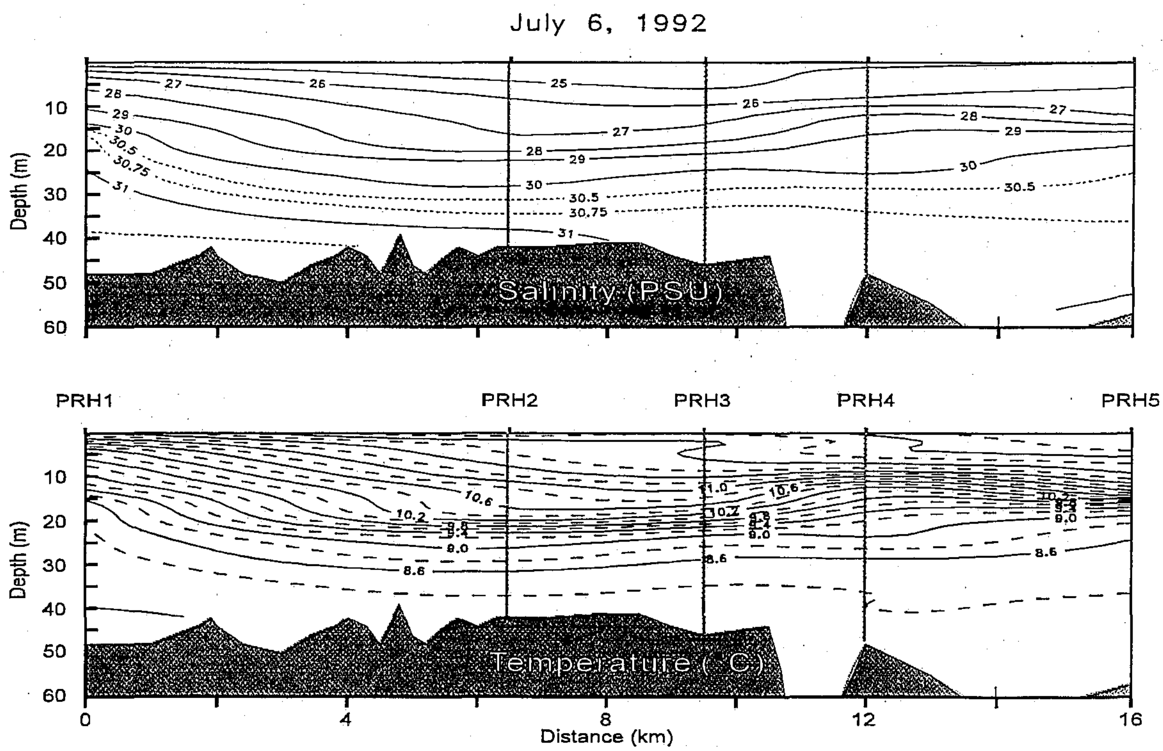

Figure B.6 Temperature and salinity sections for July 6, 1992.

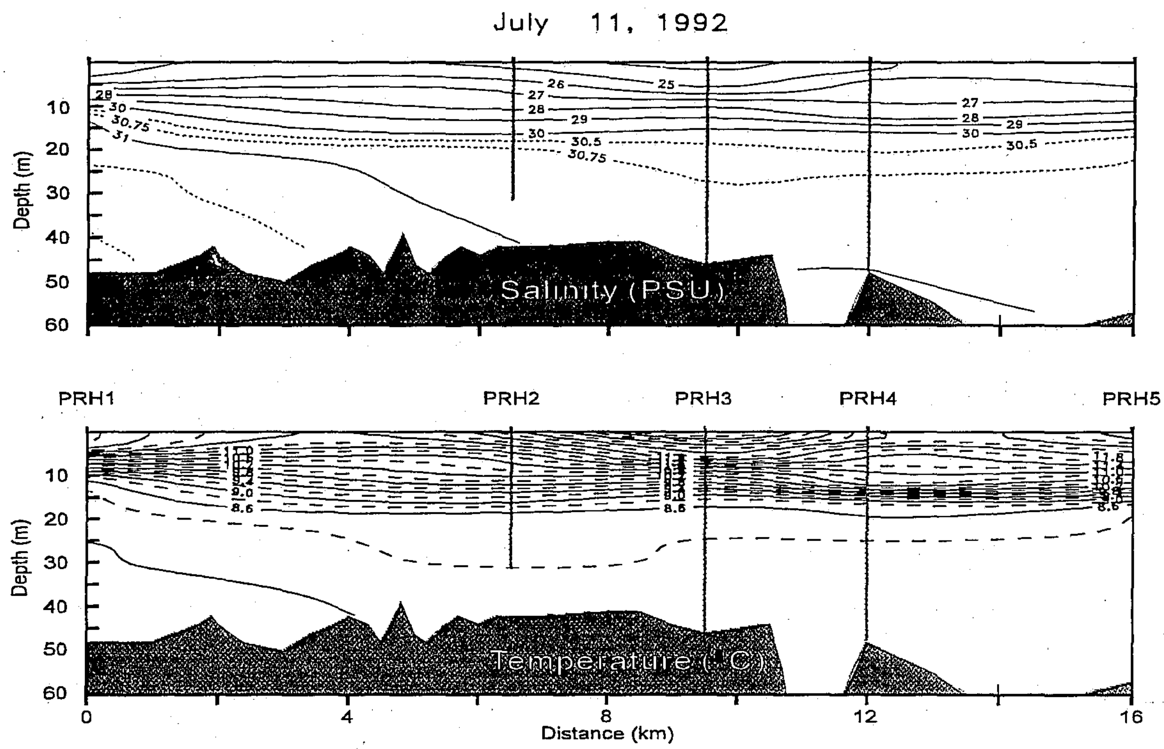

Figure B.7 Temperature and salinity sections for July 11, 1992.

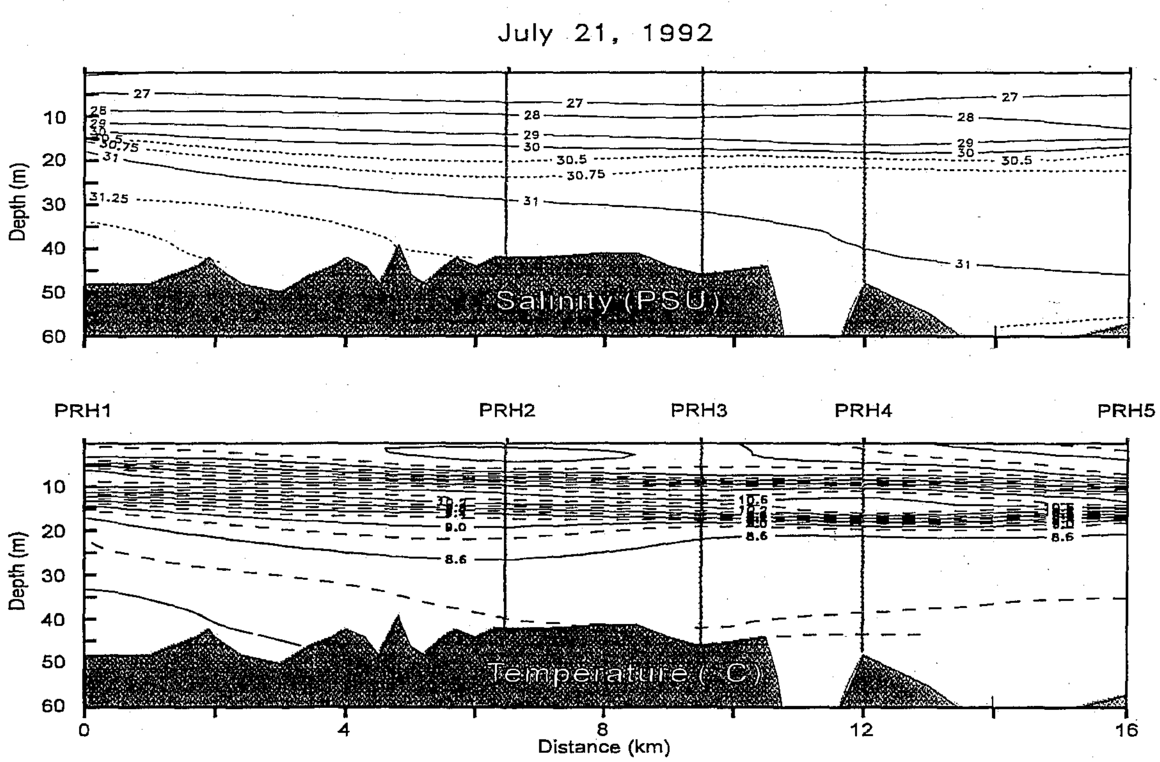

Figure B.8 Temperature and salinity sections for July 21, 1992.

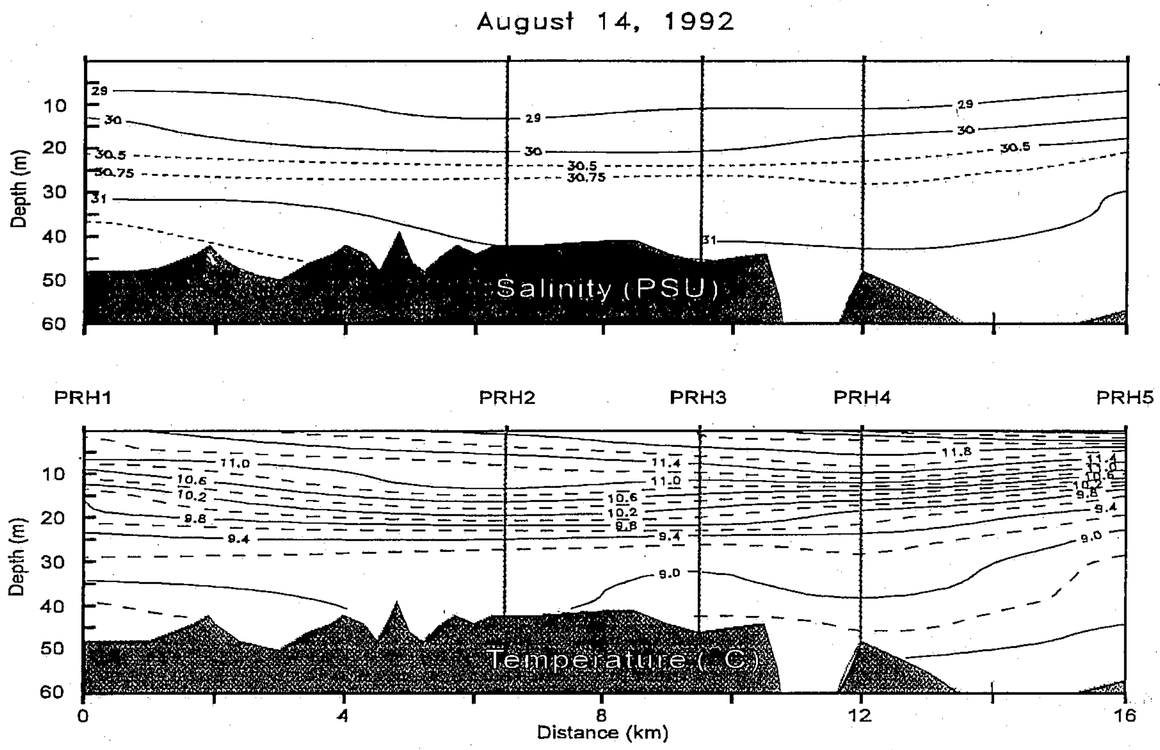

Figure B.9 Temperature and salinity sections for August 14, 1992.

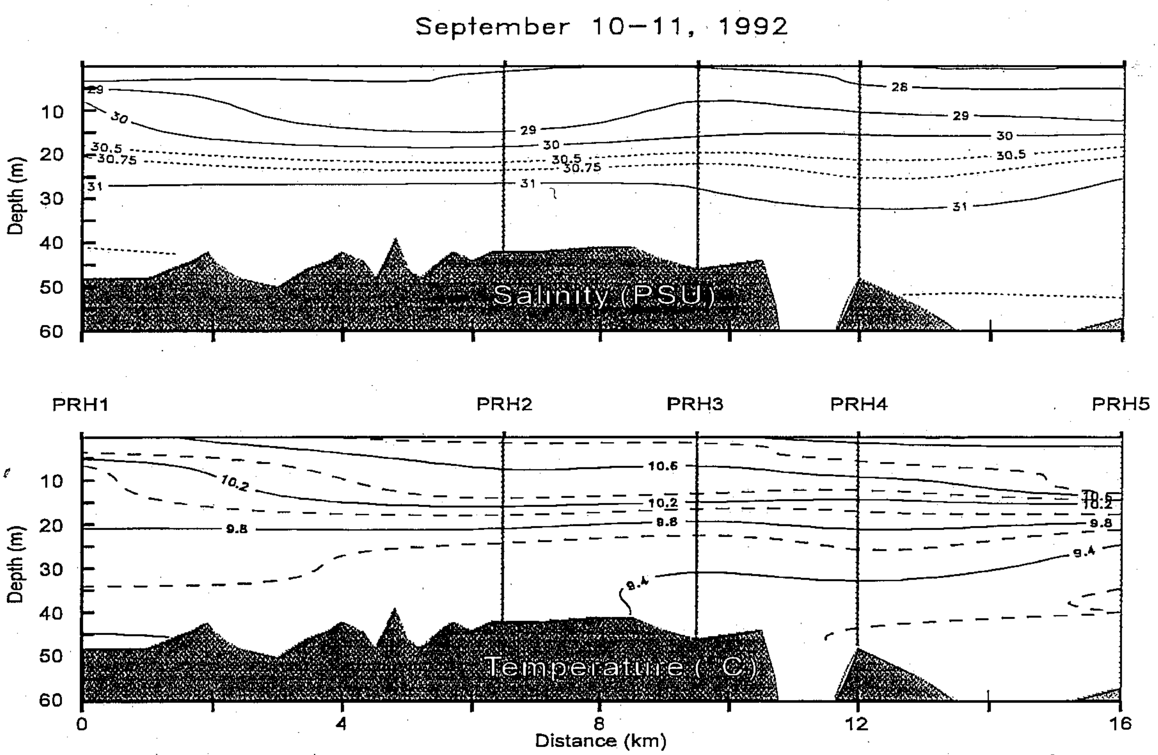

Figure B.10 Temperature and salinity sections for September 10-12, 1992.

Appendix C Nutrient Data

Table C.1 Nutrient samples collected July 6 and 7, 1992

STATION Date Time (UTC)	DEPTH (m)	SALINITY (psu)	$NO_3 + NO_2$ (µmol/l)	SILICATE (µmol/l)
PRH1	0	23.81	0:8	6.1
July 6, 1992	2	25.15	0.8	3.6
16:36-18:10	5	27.50	11	17.9
	10	28.75	17	24
	15	30.10	18.2	25.8
	20	30.92	18.6	24.8
	25	31.02	19.3	27
	30	31.16	19.2	26.3
	40	31.27	19	25.5
	47	31.34	19.4	25.6
PRH3	0	24.32	0	2.5
July 6, 1992	2	24.40	0	2.2
21:46-22:35	5	24.78	0	0.1
	10	26.13	5	6.5
	15	27.00	7.6	10.4
	20	28.48	14.6	21.3
	25	30.10	17.8	26.2
	30	30.61	18.3	27.6
	40	30.88	19.3	29.3
	44	30.89	19.3	30.2
PRH5	0	25.06	0	1.1
July 7, 1992	2	25.22	0	0.6
01:20-01:50	5	25.74	0	1.1
	10	26.49	3.1	5.1
	15	28.18	9.5	12.7
	20	30.08	17.6	27.5
	25	30.47	16.8	26.8
	30	30.62	18.4	28.7
	40	30.80	19	30.3
	58	31.04	19.7	34.4

Table C.2 Nutrient samples collected July 11 and 12, 1992

STATION Date Time (UTC)	DEPTH (m)	SALINITY (psu)	$NO_3 + NO_2$ (µmol/l)	SILICATE (µmol/l)
PRH3	0	23.68	0.8	1.1
July 11, 1992	2	23.82	0.6	1.2
21:38	5	24.46	0	4.1
	10	28.16	7.3	10.6
	15	30.03	17.7	28
	20	30.57	19.2	30.2
	25	30.73	19.4	30.8
	30	30.77	19.8	31.8
	40	30.87	19.5	32
	45	30.92	19.7	33.2
PRH1	0	24.71	0	1.7
July 12, 1992	2	24.69	0	1.6
01:33	5	25.54	0.3	2
	10	29.83	16.7	26.9
	15	31.06	19.3	31.1
	20	31.12	19.7	31.9
	25	31.31	20.1	33.2
	30	31.37	19.7	32.1
	40	31.51	20.9	35.8
	45	31.56	21	35.4

Appendix C (continued)

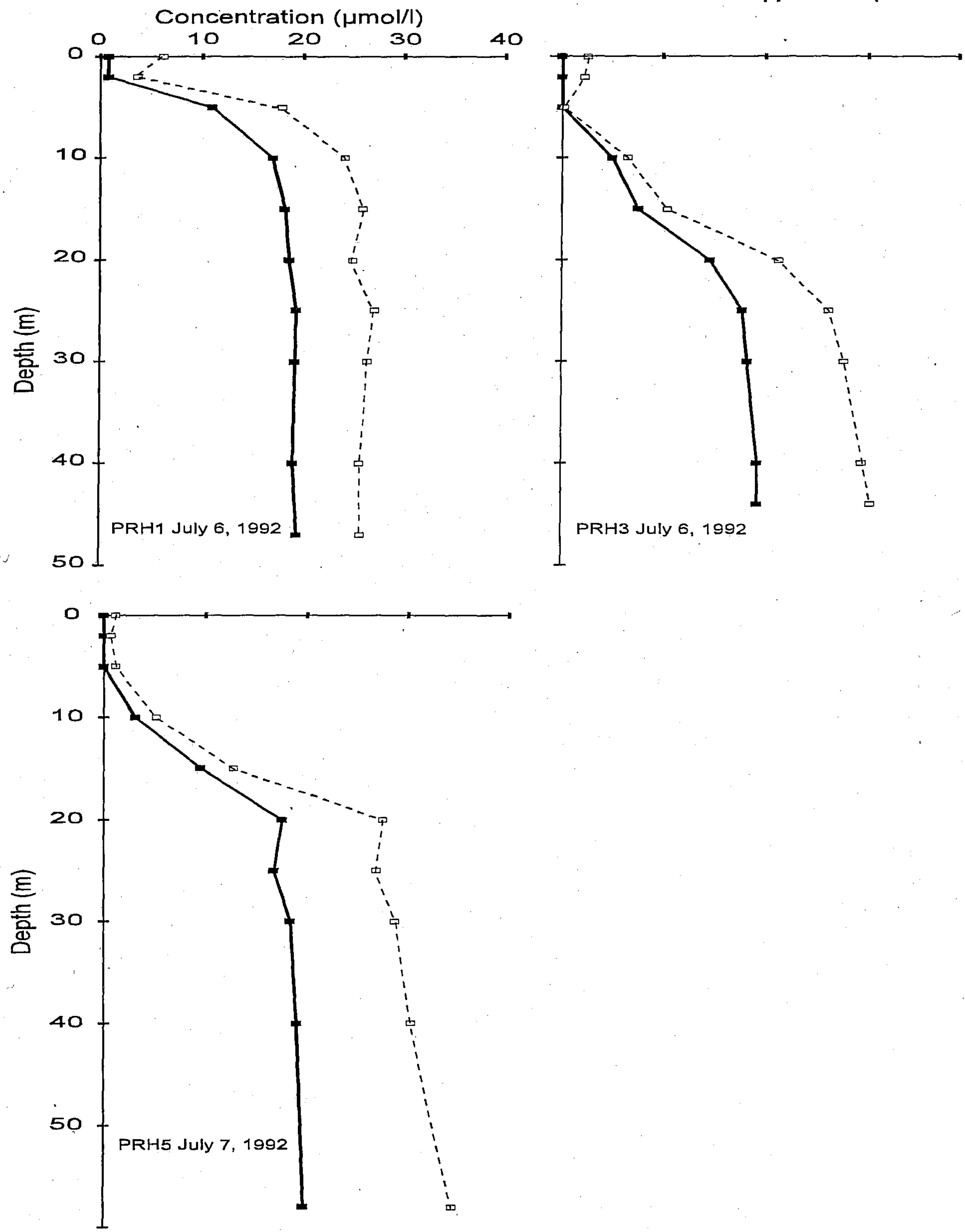

Figure C.1 $NO_3 + NO_2$ (solid line) and silicate (dashed line) depth profiles at station PRH1, PRH3 and PRH5 July 6-7, 1992.

Appendix C (continued)

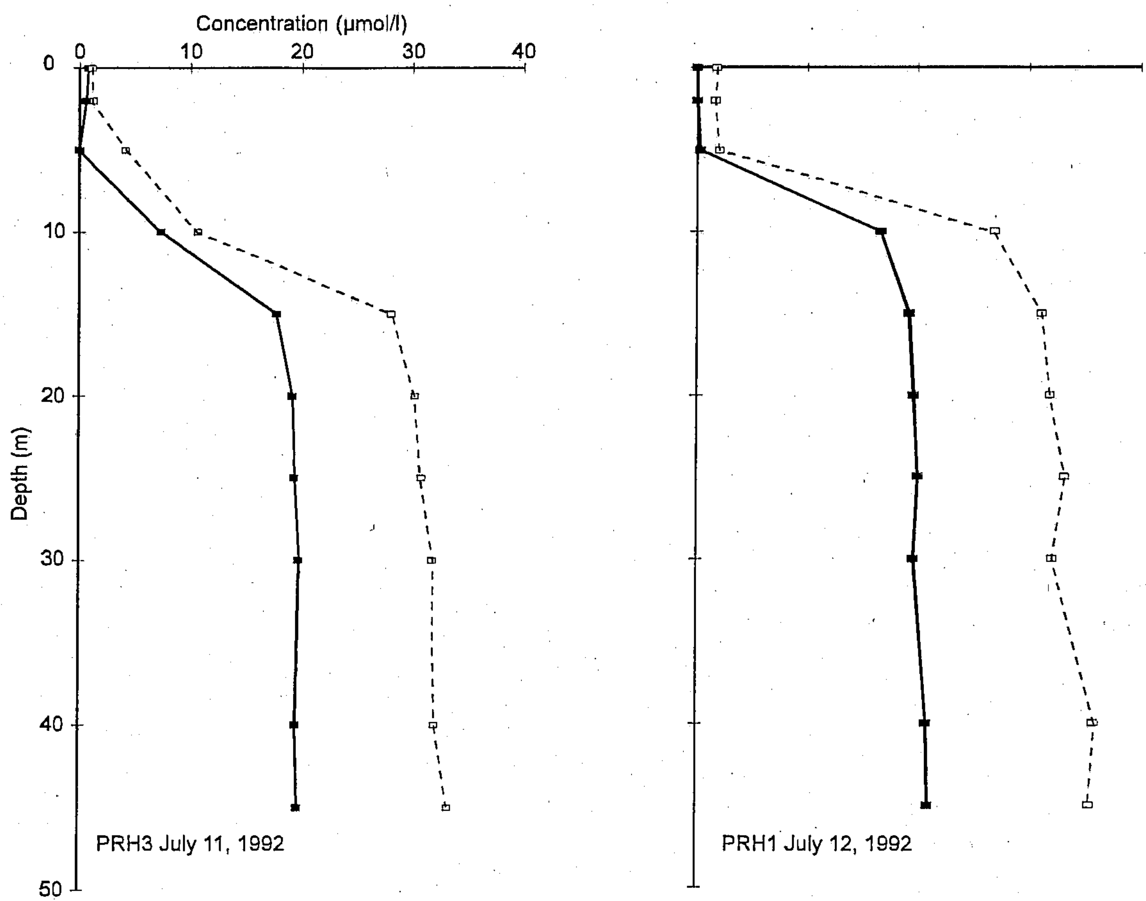

Figure C.2 $NO_3 + NO_2$ (solid line) and silicate (dashed line) depth profiles at station PRH3 And PRH1 July 11-12, 1992.