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OBSERVATIONS FROM THE WASHINGTON STATE FERRY WALLA-WALLA OF NEAR SURFACE TEMPERATURE AND SALINITY ACROSS PUGET SOUND'S MAIN BASIN

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ABSTRACT

Near surface temperature and salinity were observed across Puget Sound, Washington, a fjord-like estuary, during 6 August-6 September 1979. Water from approximately 6 m depth was sampled every 4 seconds (30-40 m at full speed) aboard a Washington State Ferry as it crossed the Main Basin of Puget Sound and entered adjoining bays and inlets. A total of nearly 600,000 triplets of temperature, salinity, and position were recorded during the study.

Presented herein are: 1) cross channel profiles of temperature, salinity, and density for each crossing using all data; 2) listings of temperature, salinity, density, date, and time of all observations at 40 selected sites; 3) time series of temperature, salinity, and density at the 40 selected sites; and 4) contours of cross-channel temperature, salinity, and density versus time using data at the 40 selected sites.

The data set shows consistent cross-channel variations of temperature, salinity, and density which can be attributed to solar heating of water in shallow bays and inlets, discharge of vertically mixed water through a preferred channel during ebb, and discharge of freshwater into a large bay. Tidal oscillations of the characteristically different waters cause variability of water properties at several of the 40 selected sites. The cross-channel variability of water properties observed in Puget Sound's Main Basin during the study is much greater than historical long-channel variability. The gradual increase in salinity and decrease in temperature compare favorably with historical data.

The volume and quality of data collected during the study suggests that the use of ferries as oceanographic vessels is a feasible and reliable way to obtain valuable water property measurements and advance our understanding of circulation patterns in Puget Sound.

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1. INTRODUCTION

An oceanographic experiment was conducted aboard the Washington State Ferry Walla-Walla (hereafter Ferry) during 6 August-6 September 1979. The purpose of the experiment was to sample temperature and conductivity (salinity) of the near surface water as the Ferry crossed the Main Basin of Puget Sound (Fig. 1). Each weekday the Ferry made 24 crossings over the route from Seattle to Winslow (hereafter Winslow route; 15 km) and on weekends 16 crossings each day over the route from Seattle to Bremerton (hereafter Bremerton route; 27 km; Fig. 2). Both routes cross the Main Basin near midway along its length.

Approximately 5 km of each Ferry route transects the Main Basin. To the east both routes traverse Elliott Bay; to the west the Winslow route enters the outer portion of Eagle Harbor while the Bremerton route traverses Rich Passage, southern Port Orchard, and the outer part of Sinclair Inlet, the Ferry terminal being near the junction of Sinclair Inlet and Dyes Inlet (Fig. 3). Figure 4 shows bathymetry along each route.

The Main Basin of Puget Sound ($\sim$ 60 km x 5 km x 200 m) is a stratified estuary with a deep surface layer ($\sim$ 50 m) and a large net transport of $3 \times 10^4\ m^3\ sec^{-1}$ seaward in the surface layer and landward in the lower layer (Ebbesmeyer and Barnes, 1979; Fig. 5). Mid-channel circulation and water properties are strongly influenced by vertical mixing of surface and bottom water over sills at each end of the Main Basin (Fig. 1). To the north in Admiralty Inlet (64 m sill depth) a large fraction of surface water is mixed to depth where it re-enters the Main Basin (Ebbesmeyer and Barnes, 1979). To the south the orientation of the East Passage - Colvos Passage waterways and The Narrows sill (44 m sill depth) contribute to a net flow clockwise around Vashon Island (Barnes and Ebbesmeyer, 1979; Fig. 6). Deep East Passage water is pumped upward by flood tides, mixed with surface water in The Narrows, and the mixture is discharged into the large Terminal Basin to the south. The returning ebb contains variable amounts of Terminal Basin resident and river water, as well as refluxing Main Basin water. This mixed water flows seaward through Colvos Passage (53 m sill depth) where current measurements show a predominant ebb and weak flood. The mixture discharges into the Main Basin both north and south of Blake Island, below local river plumes and above the level of no-net-motion ($\sim$ 50 m). Some of the Colvos Passage water returns southward through East Passage contributing to a clockwise circulation around Vashon Island and the remainder continues northward in the Main Basin.

Elliott Bay opens to the Main Basin, covers approximately 14.1 km^2, and has an average depth of 58 m. The predominant freshwater flow into

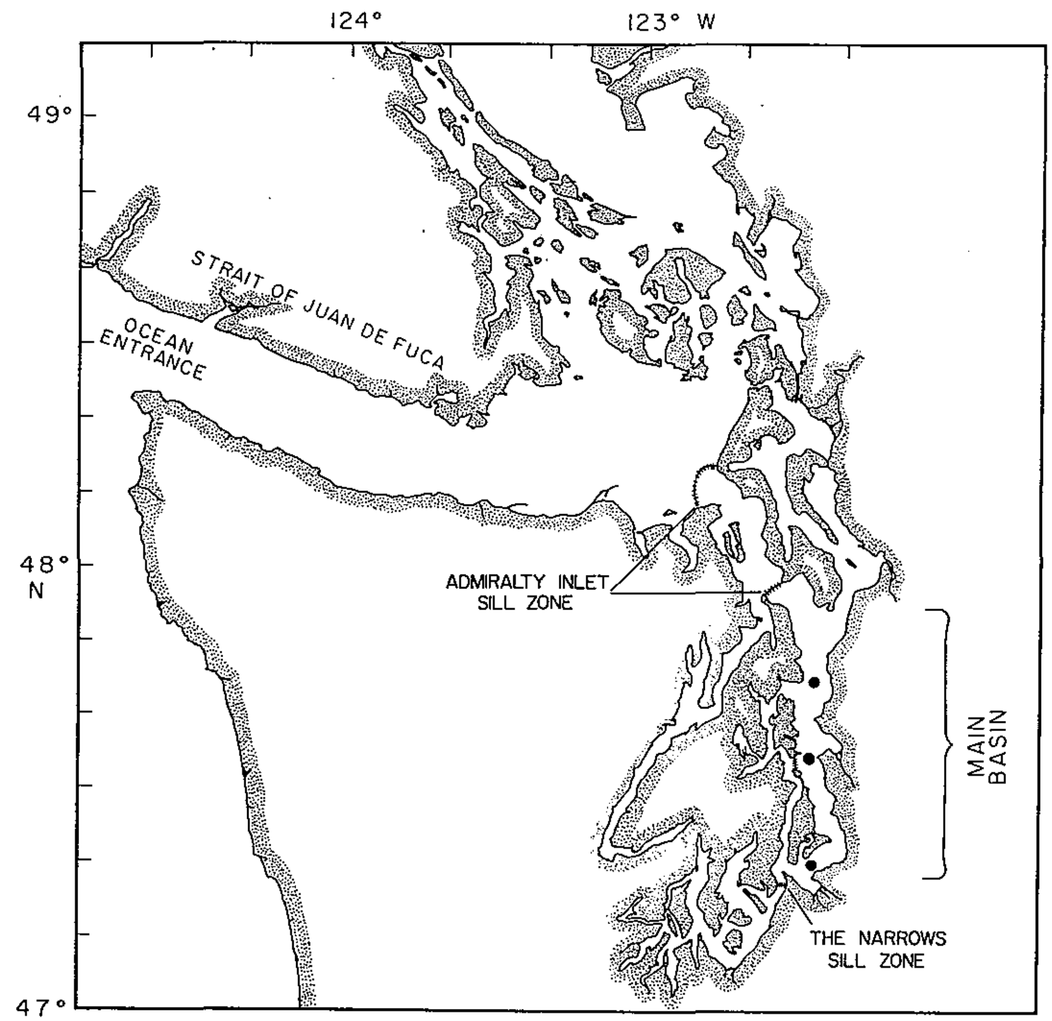

Figure 1. Puget Sound and approaches. Notation: hatched lines, sills; and dots, historical stations Point Jefferson (north), Alki Point (central), and Browns Point (south).

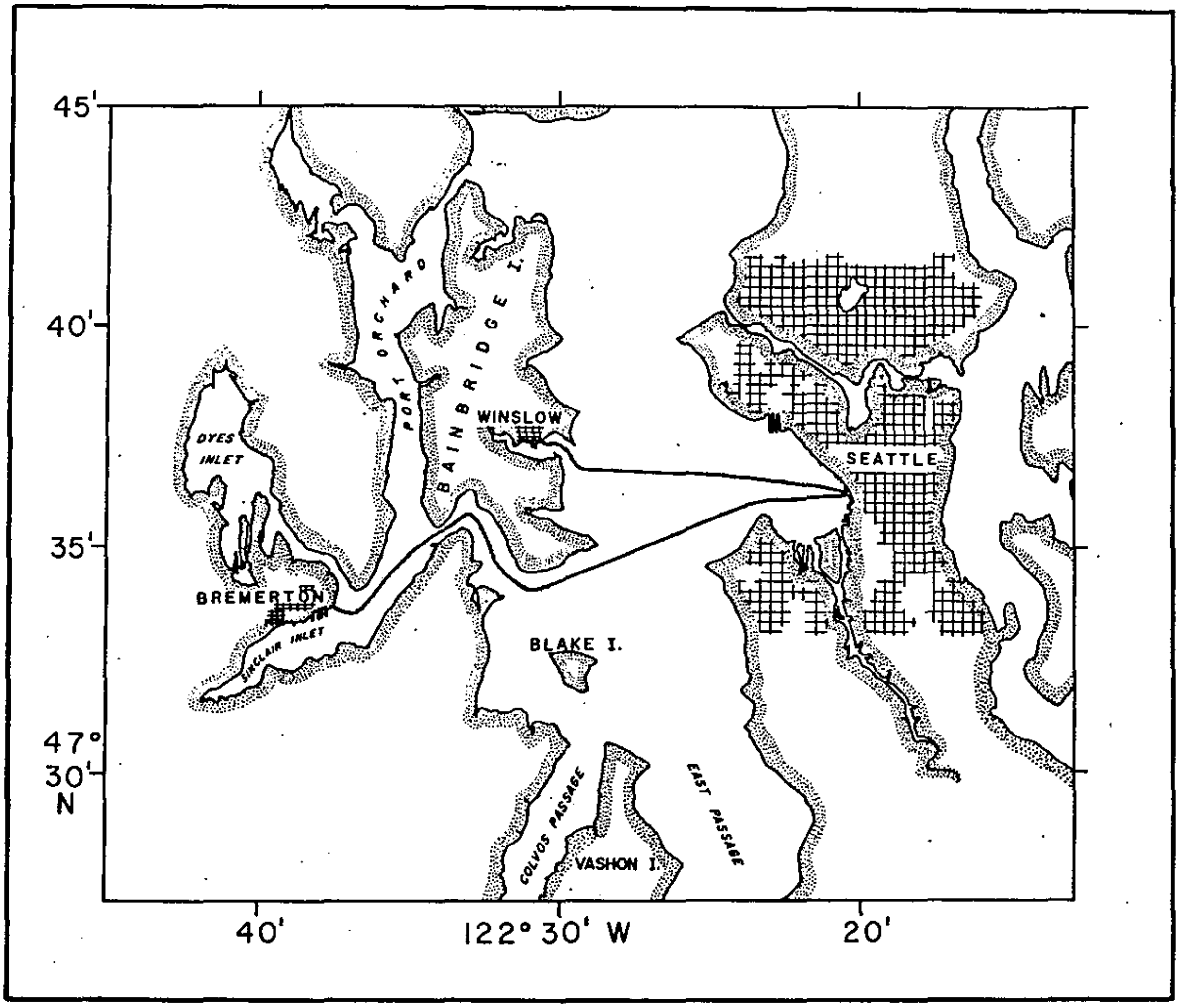

Figure 2. Seattle - Winslow and Seattle - Bremerton Ferry routes (lines). Routes shown are mean routes. The Ferry's westward routes are approximately 200 m north of its eastward routes to avoid collision with other ferries.

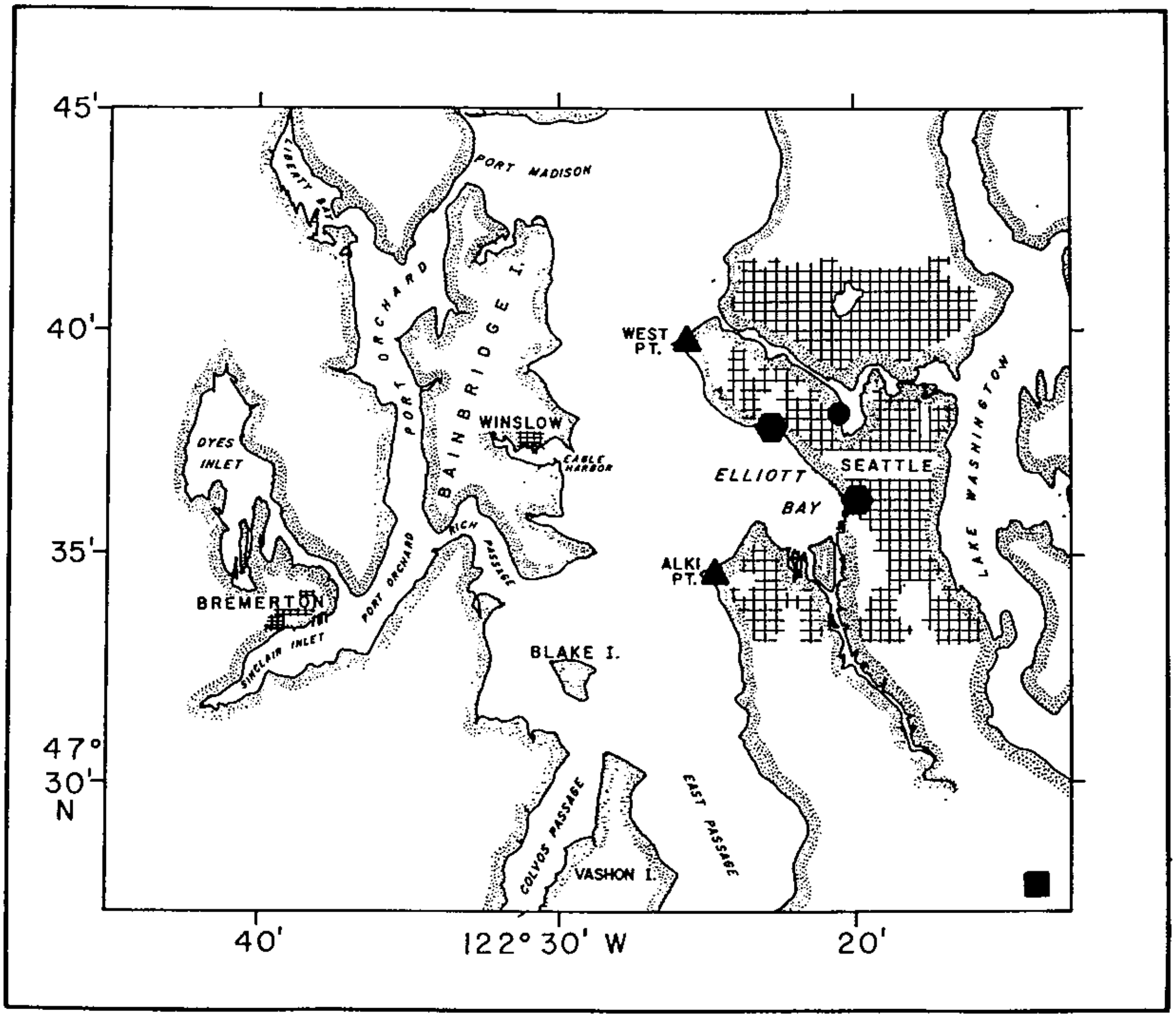

Figure 3. Locations of wind gauging stations (▲), Seattle weather station (●), approximate location Duwamish River gauging station (■), and Mini Ranger transponder locations (⬢).

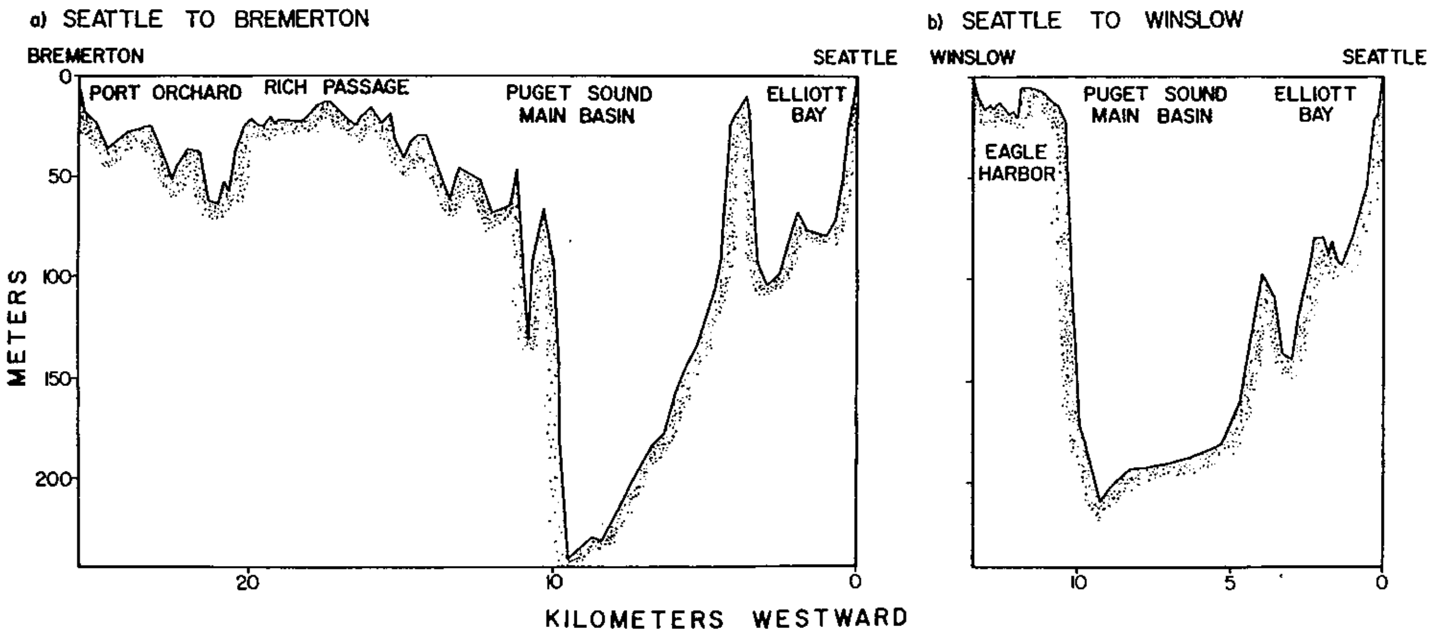

Figure 4. Bottom profiles along Seattle - Bremerton (a) and Seattle-Winslow (b) ferry routes.

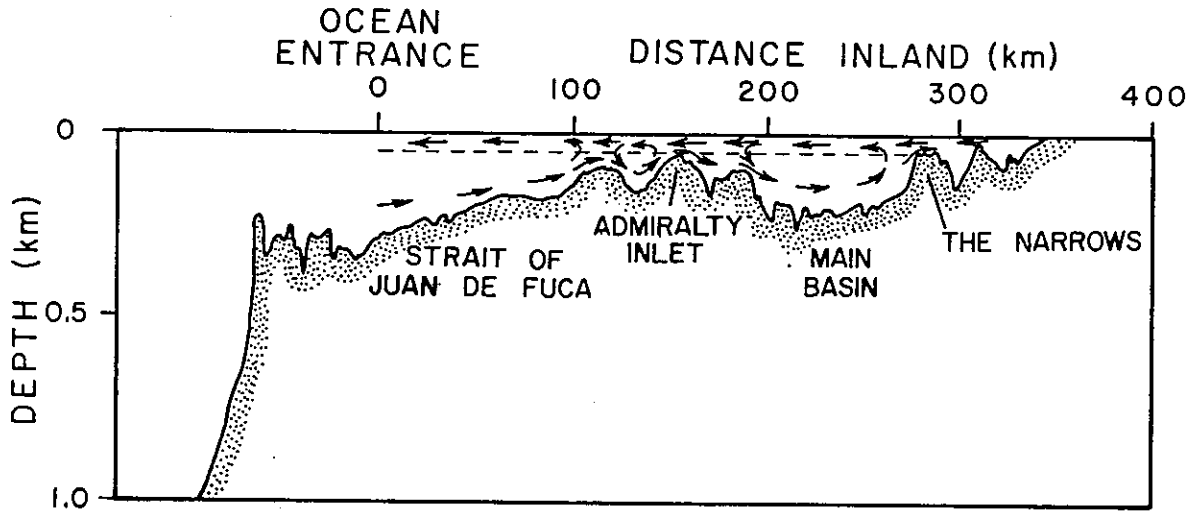

Figure 5. Profile view of net circulation at mid-channel in summer between the Pacific Ocean and the head of Puget Sound (adapted from Ebbesmeyer and Barnes, 1979). Notation: dashed line, depth of no-net-motion (approximately 50 m).

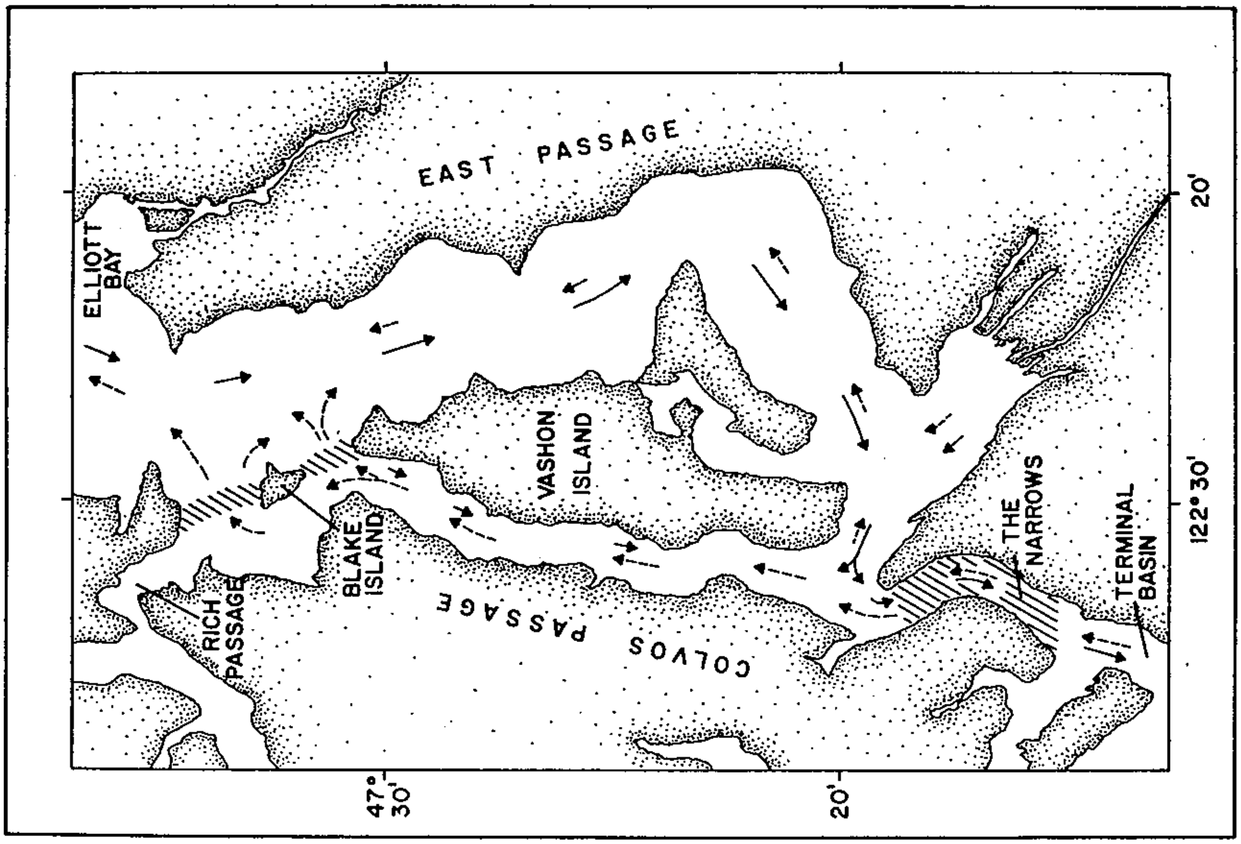

Figure 6. Horizontal circulation around Vashon Island (adapted from Barnes and Ebbesmeyer, 1979). Notation: hatched areas, sill zones; solid arrows, flood currents; and dashed arrows, ebb currents. Difference in length of arrows for flood and ebb currents indicates net transport.

Elliott Bay is the Duwamish River which enters at the southeast extremity. This input creates strong salinity gradients in portions of Elliott Bay.

Eagle Harbor is relatively small (~1.4 km^2) and shallow (average depth ~12m) with little freshwater inflow.

Rich Passage serves as the connection between the Main Basin and Port Orchard, Sinclair Inlet, and Dyes Inlet. It is approximately 1 km x 5 km x 25 m with a 14 m sill near midpassage. Currents are strong and often reach 3 knots during flood and ebb (National Ocean Survey, 1979). Port Orchard is oriented north-south, is approximately 17 km long, 20 m deep, and covers 33.4 km^2. Sinclair Inlet is a wide mouthed bay covering approximately 7.2 km^2 with an average depth of 6.5 m, and is connected to Port Orchard and Sinclair Inlet by a narrow mouth through which current speeds commonly approach 1.5 m sec^{-1}. There is no major freshwater input to Rich Passage, Port Orchard, Sinclair and Dyes Inlets. All areas and depths are at mean lower low water and are computed or taken from McLellan (1954; Table 1).

TABLE 1. CHARACTERISTIC DIMENSIONS AND RATIOS OF BAYS AND INLETS ALONG THE FERRY ROUTES.

Dimensions	Elliott Bay	Port Orchard	Dyes Inlet	Sinclair Inlet	Eagle Harbor
Volume below MLLW (x 10^8 m^3)	8.19	6.56	1.55	0.72	
Volume between MLLW and MHHW (x 10^7 m^3)	4.75	11.20	5.21	1.13	0.51
Surface area at MLLW (x 10^7 m^2)	1.41	3.34	2.58	0.72	0.14
Cross-sectional area at entrance (x 10^4 m^2)	30.2	south entrance 0.98	0.30	2.02	0.45
Length, entrance to head (km)	7.3	17.4	5.6	5.5	3.1
Ratios					
Bulk residence period (Volume/Tidal Prism)	17.3	5.9	3.0	6.4	
Mean Tidal Transport Tidal Prism(2)/½ tidal day (x 10^3 m^3 sec^{-1})	2.1	5.0	2.3	0.5	0.23
Mean Depth (m) Volume(1)/Area(3)	58.4	19.6	6.0	10.0	

2. EXPERIMENT DESCRIPTION

2.1 TEMPERATURE AND CONDUCTIVITY

Sea water was drawn into the Ferry at approximately 6 m depth through two 0.46 m diameter pipes. These pipes connect to the engine cooling tank (i.e., sea chest) and samples for analysis were extracted near one of the pipes. The sample water was pumped at 315 cm^3 sec^{-1} from the sea chest into an 8.5 liter plexiglass container where temperature and conductivity were measured (Fig. 7).

The system for measuring temperature and conductivity was manufactured by Ocean Data Equipment. The system consisted of model CT-102 temperature and conductivity sensors and electronics that provided a linear voltage proportional to temperature and conductivity. The output signals were recorded every 4 seconds using a Sea Data model 1250 data logger. The system was calibrated before and after the experiment by the Northwest Regional Calibration Center and no equipment drift was found (Fig. 8).

Based on sensor resolution of 0.001 volt, resolutions of temperature, conductivity, and corresponding salinity are 0.013°C, 0.027 mhos cm^{-1}, and 0.022°/oo, respectively. During the calibration tests, variations of temperature, conductivity, and corresponding salinity around the stable bath properties were approximately twice the resolution of each sensor. Features observed in Puget Sound during the study are characterized by variations in water properties at least several times greater than the resolution of these properties.

An important consideration is the time required for a water parcel to flow through the intake pipes, sea chest, and sampling arrangement. This lag between the time when source water is drawn and when it is sampled may be computed from the bulk residence time for the components where bulk residence time is defined as volume divided by flow rate. For the intake pipes and sea chest the bulk residence time is estimated at approximately one minute. For the plexiglass sensor container the bulk residence time is approximately 27 seconds. Thus a conservative estimate of the overall time required for a water parcel to enter the Ferry and arrive at the sensors is approximately 1.5 minutes. This time lag was used to adjust the measured variables to the position where the respective water was first drawn into the Ferry.

Because of the Ferry's speed (9.5 m sec^{-1}) the 90 second lag and 4 second sampling interval correspond to significant distances of 850 m and 40 m, respectively. The latter distance is the shortest distance that can be resolved at the 4 second sampling rate. Some Ferry crossings

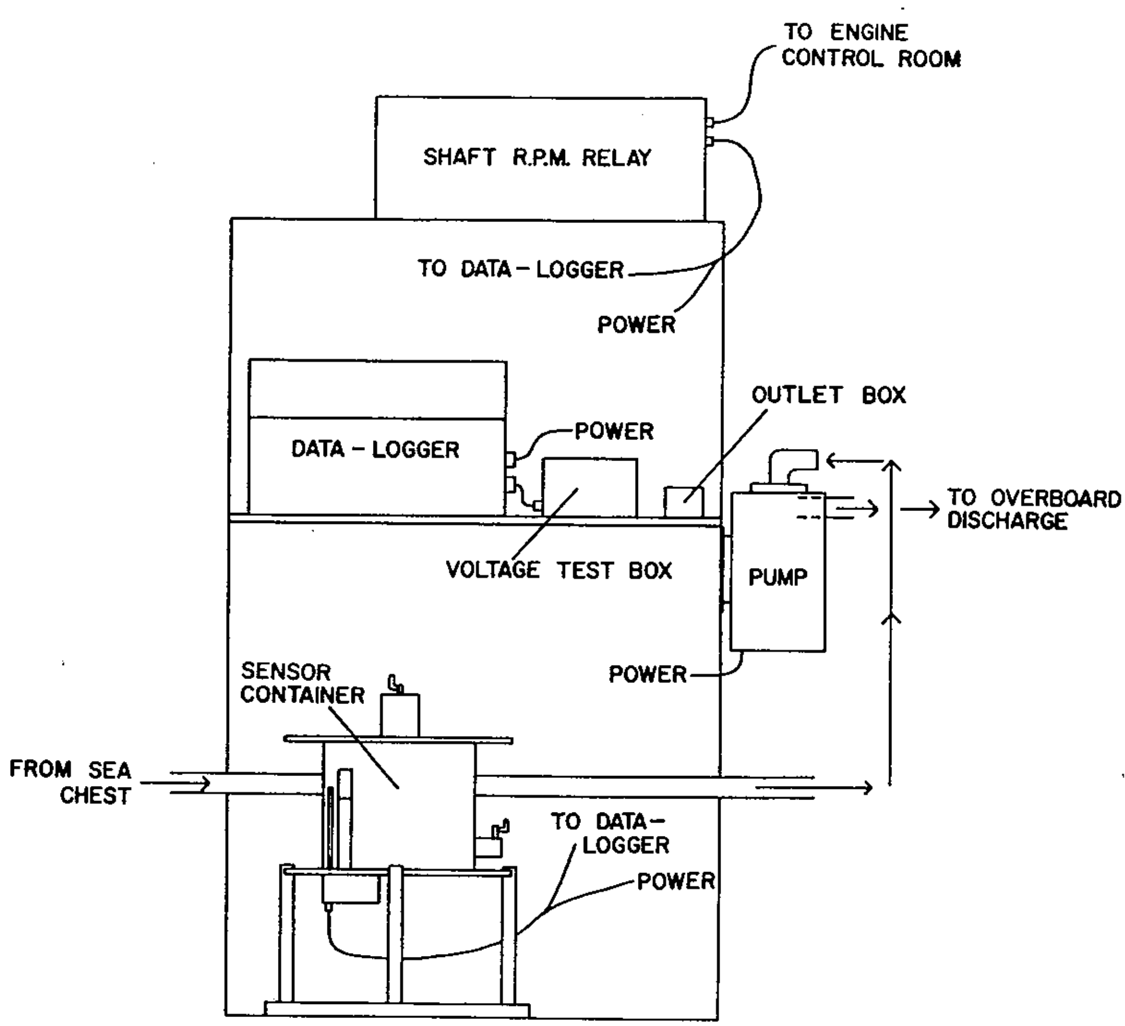

Figure 7. Schematic of sampling system. Notation: arrows, pathway of water flow.

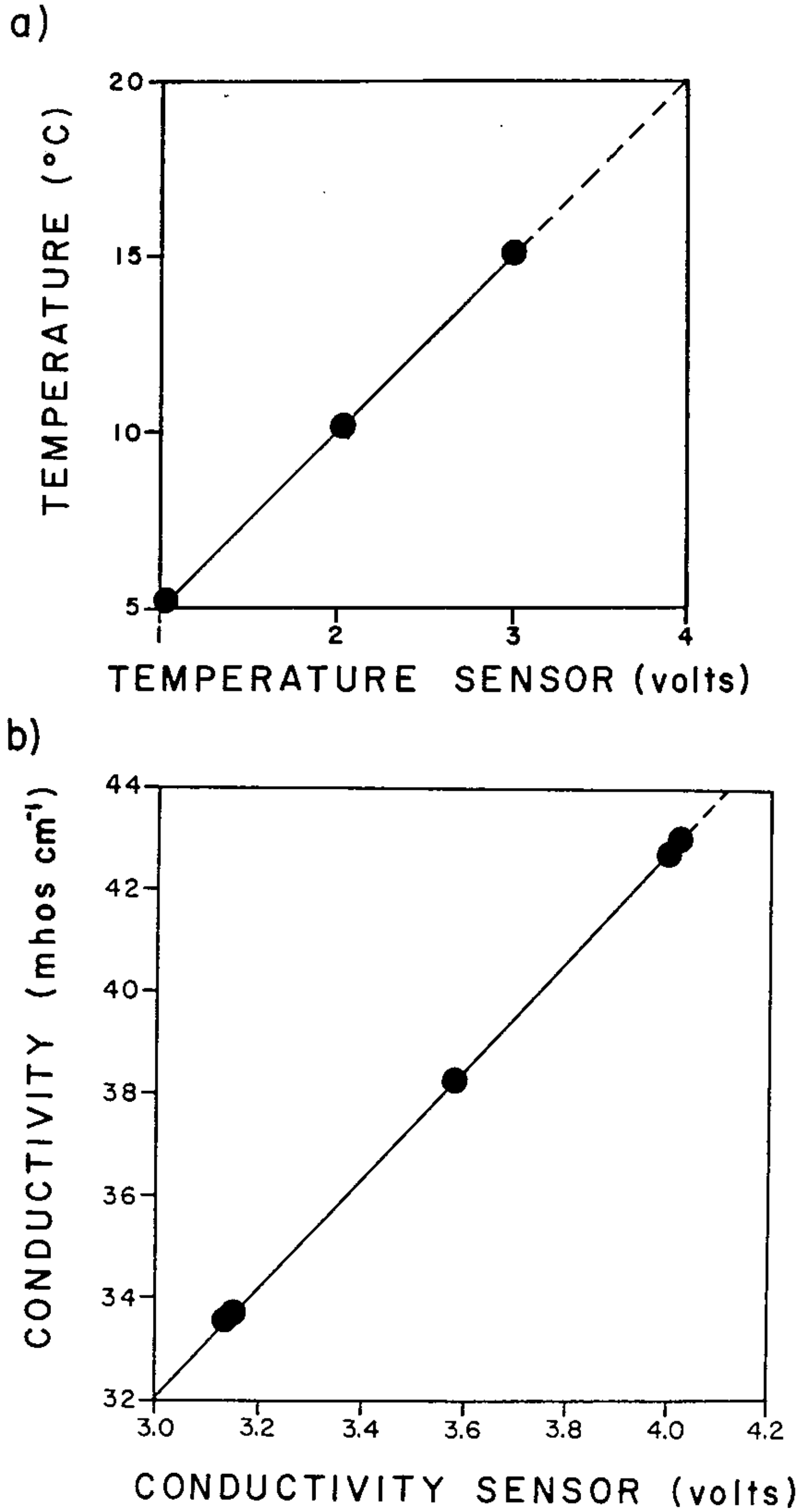

Figure 8. Sensor voltage versus temperature (a) and conductivity (b). Notation: dots, calibration measurements; dashed lines, assumed calibration curve extension.

were recorded at one second intervals to determine if finer resolution was possible and comparison of data at 1 and 4 second intervals did not show significant differences. As a result, most recordings were made at the 4 second interval.

The sampling depth of 6 m is within a region of strong vertical gradients as shown by the vertical profiles of August mean temperature, salinity, and density at nearby historical stations Point Jefferson and Browns Point (Fig. 9). As a result small variations in the depth of the intake can result in sizeable variations in the measured water property. For example, intake depth can vary with different loads (i.e., number of cars aboard, fuel load, etc.). The effects of these factors have not been addressed in this study.

2.2 POSITIONING

During this experiment the position of the Ferry was determined using a Mini-Ranger III system (abbreviated MRS) manufactured by Motorola Inc. The MRS operates on the principle of pulse radar and uses a mobile transmitter to interrogate two transponders within line-of-sight located onshore at known positions. The transmitter was mounted above the Ferry pilothouse and wired to the MRS display console inside the pilothouse. The display console was connected to a Fluke data recorder and the ranges were recorded at 10 second intervals. The transponders were located atop the Old Federal Building and near the offshore end of Pier 91 (Fig. 3). The range accuracy of the MRS system as stated by the manufacturer is 3 m when stationary. As used in this experiment the range accuracy is approximately 10 m.

The rotation rate of the Ferry's bow propeller as recorded by the datalogger was found to be closely proportional to Ferry speed as determined using MRS positions (Fig. 10). Consequently the rotation rate was used to determine Ferry position along each crossing route when MRS positions were not obtained.

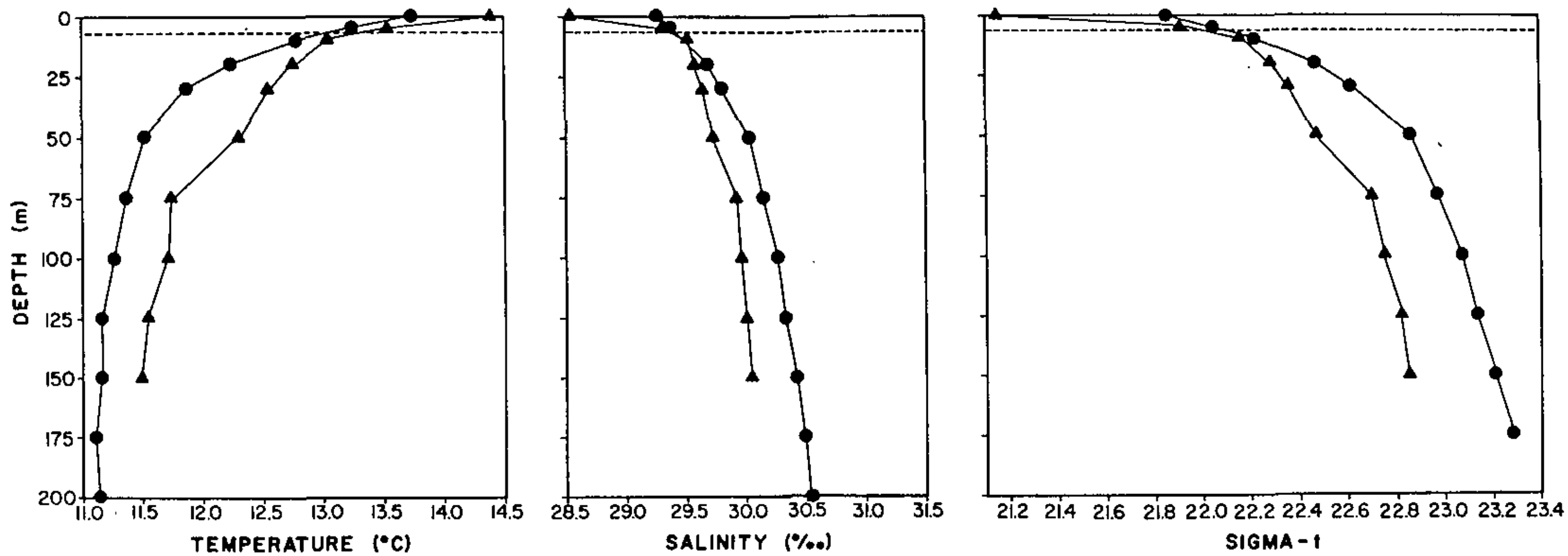

Figure 9. Vertical profiles of August mean temperature, salinity, and density at the historical stations Point Jefferson (●) and Browns Point (▲). Notation: dashed line, sampling depth.

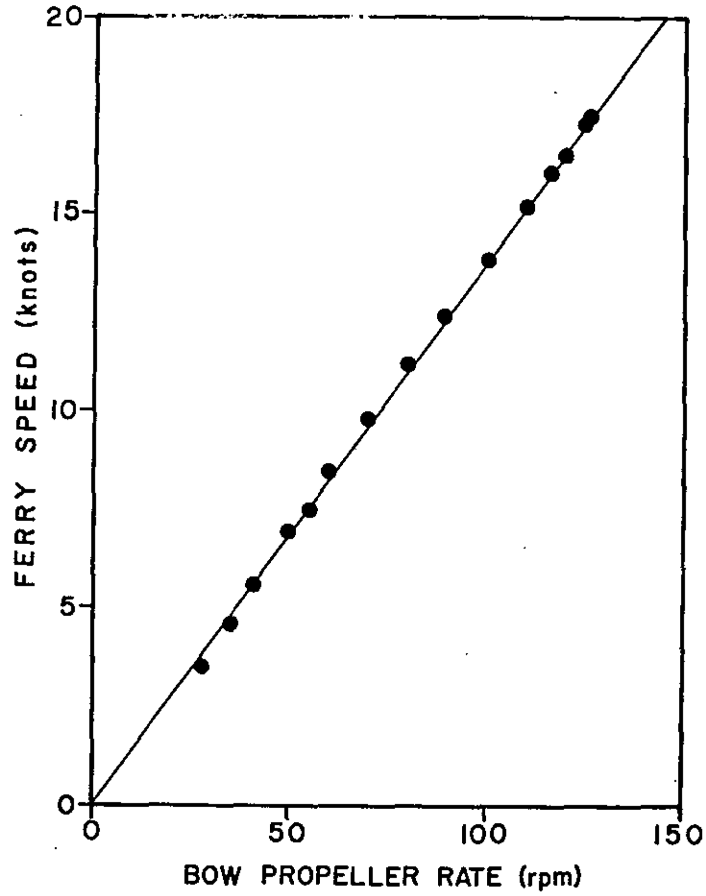

Figure 10. Plot of bow propeller rotations per minute versus Ferry speed. Notation: dots, measurements.

3. DATA REDUCTION AND PRESENTATION

Initially the triplets of temperature, conductivity, and position were transformed into sets of temperature, salinity, density (expressed as sigma-t units), and position. From 530 crossings between Seattle and Winslow and 144 crossings between Seattle and Bremerton approximately 600,000 data sets were obtained. Several data gaps occurred when the recording system was inadvertently disconnected. The longest gap is 1.5 days during 30-31 August. For each crossing all of the salinity, temperature, and density observations are shown as cross-channel profiles in Appendix A.

Due to the large amount of data, observations at 1 km intervals were used for further analysis. Figure 11 and Table 2 show the 40 positions of the reduced data set. Reckoned eastward, sites 1-26 represent the Bremerton route and 27-40 represent the Winslow route.

The means and standard deviations were determined for each of the measured water properties at each site (1-40; Fig. 12). Some effects of data trends were removed by computing the standard deviation as the mean of the standard deviation of each day.

The reduced data set has been shown three different ways: 1) Appendix B - listings of temperature, salinity, and density at each site for each crossing; 2) Appendix C - time series of temperature, salinity, and density at each site; 3) Figure 18 - contours of temperature, salinity, and density in the space of time and cross-channel distance.

Wind speed and direction were recorded every 3 hours at West Point and Alki Point (Figs. 3 and 13; Table 3) by the National Oceanic and Atmospheric Administration. Air temperature was recorded at the Seattle weather station (Fig. 3) and the daily mean and extremes are shown in Figure 14 and Table 4. Precipitation was recorded at the Seattle weather station and the daily totals are shown in Figure 14 and Table 5. Discharge of the Green River (Duwamish River) was determined by the U.S. Geological Survey at a location shown in Figure 3. The daily average discharge is shown in Figure 14 and Table 5.

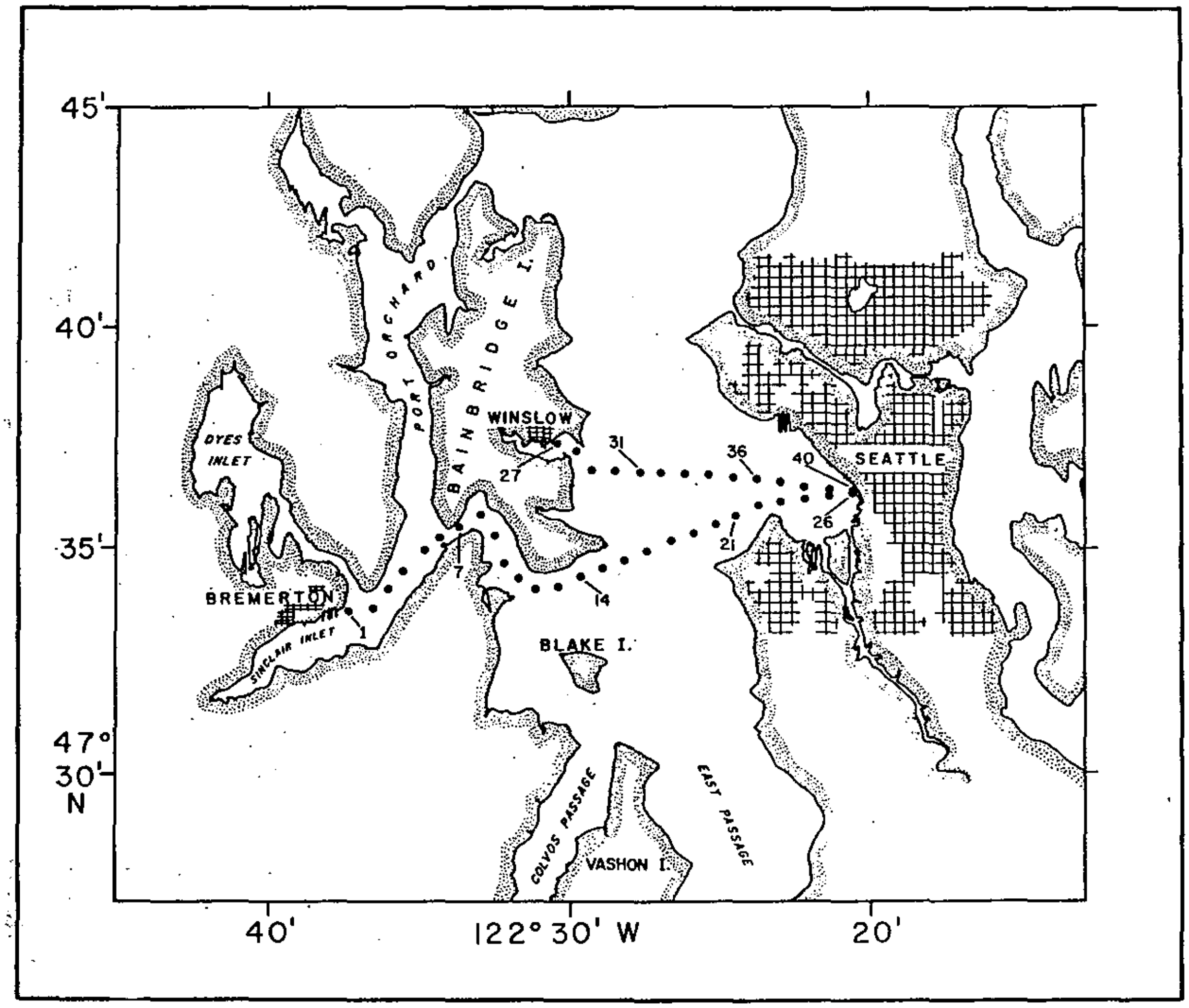

Figure 11. Sites (●) selected for the reduced data set spaced at 1 km intervals. Notation: sites 1-26, Seattle - Bremerton route; sites 27-40, Seattle - Winslow route.

TABLE 2. POSITIONS OF THE 40 SITES SELECTED FOR THE REDUCED DATA SET.

Station	Latitude	Longitude
1	47° 33.60'	122° 37.25'
2	47° 33.66'	122° 36.51'
3	47° 34.07'	122° 36.00'
4	47° 34.48'	122° 35.46'
5	47° 34.88'	122° 34.93'
6	47° 35.19'	122° 34.31'
7	47° 35.48'	122° 33.66'
8	47° 35.69'	122° 32.95'
9	47° 35.26'	122° 32.49'
10	47° 34.76'	122° 32.20'
11	47° 34.33'	122° 31.77'
12	47° 34.02'	122° 31.10'
13	47° 34.17'	122° 30.35'
14	47° 34.32'	122° 29.58'
15	47° 34.52'	122° 28.81'
16	47° 34.71'	122° 28.08'
17	47° 34.90'	122° 27.35'
18	47° 35.10'	122° 26.59'
19	47° 35.29'	122° 25.85'
20	47° 35.48'	122° 25.11'
21	47° 35.67'	122° 24.38'
22	47° 35.87'	122° 23.62'
23	47° 36.00'	122° 22.89'
24	47° 36.03'	122° 22.12'
25	47° 36.09'	122° 21.33'
26	47° 36.14'	122° 20.54'
27	47° 37.33'	122° 30.35'
28	47° 37.15'	122° 29.69'
29	47° 36.72'	122° 29.23'
30	47° 36.69'	122° 28.44'
31	47° 36.68'	122° 27.64'
32	47° 36.64'	122° 26.85'
33	47° 36.61'	122° 26.07'
34	47° 36.59'	122° 25.27'
35	47° 36.53'	122° 24.48'
36	47° 36.46'	122° 23.68'
37	47° 36.38'	122° 22.89'
38	47° 36.39'	122° 22.08'
39	47° 36.25'	122° 21.29'
40	47° 36.18'	122° 20.53'

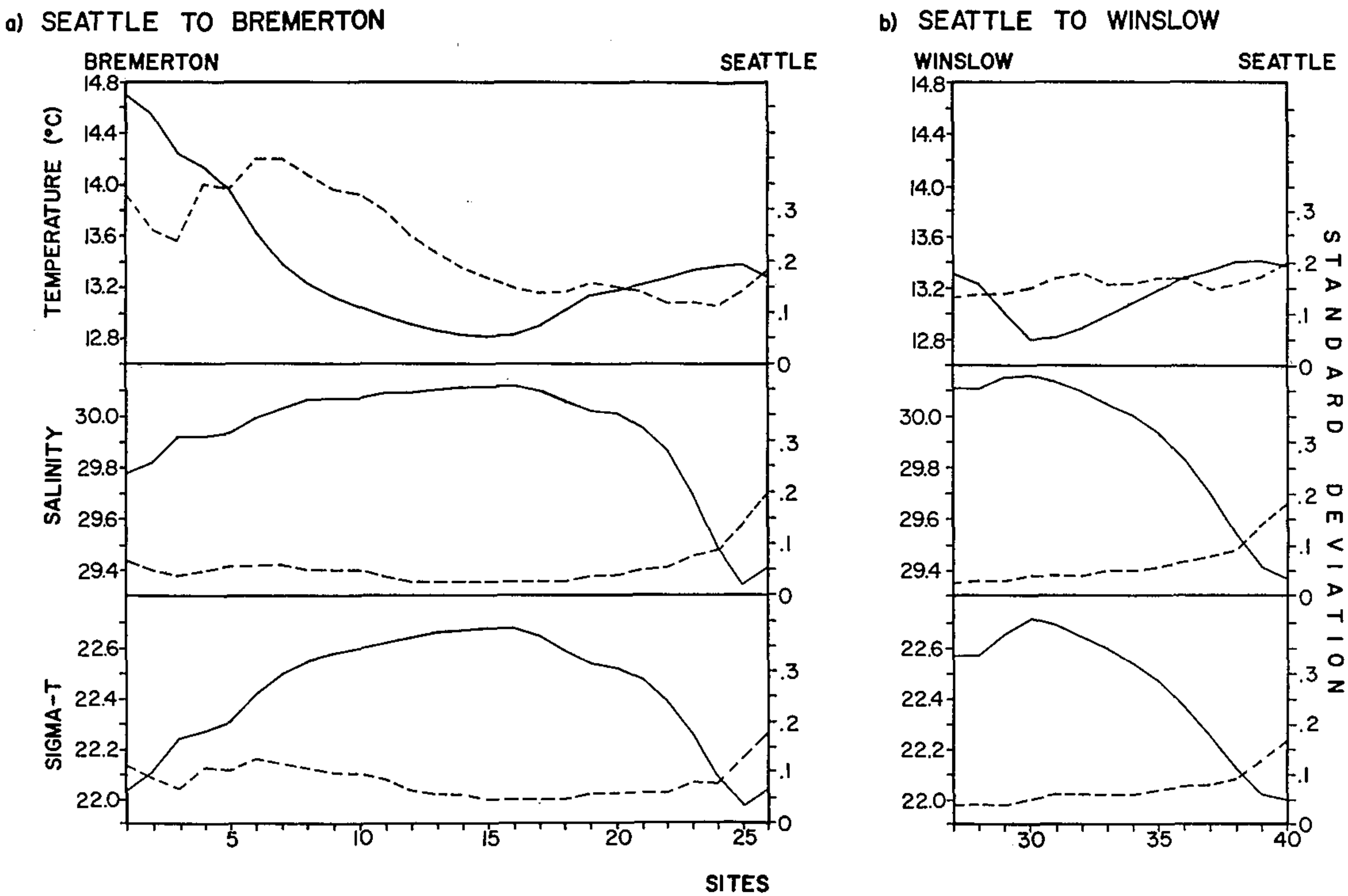

Figure 12. Mean (solid line) and standard deviation (dashed line) of temperature, salinity, and density (sigma-t) from Seattle to Bremerton (a) and Seattle to Winslow (b) for the reduced data set from 6 August-6 September, 1979. Sites listed at bottom.

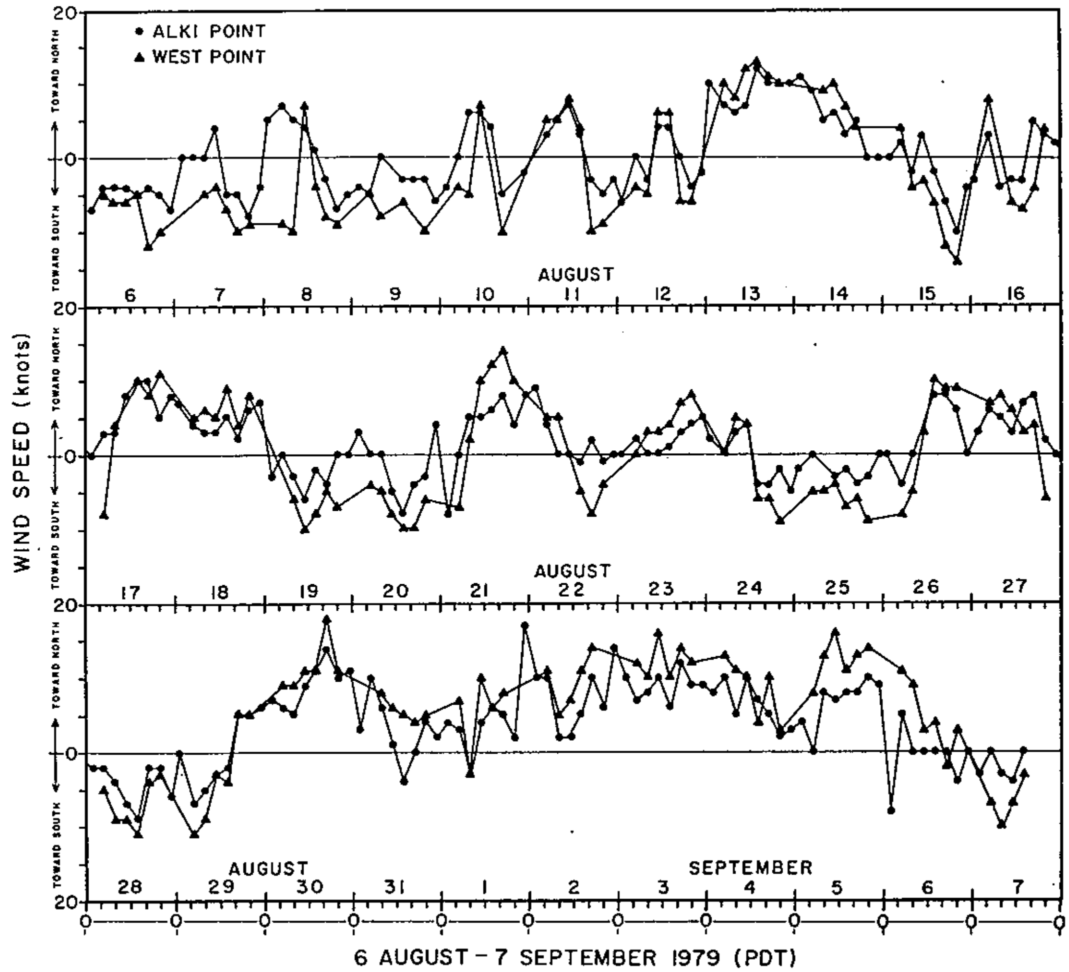

Figure 13. Wind speed at Alki Point (●) and West Point (▲). Notation: toward north, 270° through 089°; toward south 090° through 269°.

TABLE 3. WIND DIRECTION AND SPEED RECORDED AT WEST AND ALKI POINTS DURING 6 AUGUST - 6 SEPTEMBER, 1979.

	August 6		7		8	
Hour (PDT)	Alki Point	West Point	Alki Point	West Point	Alki Point	West Point
0200	NE 07		calm		S 05	
0500	NE 04	N 05	calm		S 07	N 09
0800	NE 08	N 06	calm	N 05	S 05	N 10
1100	N 04	NNW 06	S 04	N 04	S 04	WSW 07
1400	N 05	N 05	N 05	N 07	S 01	N 04
1700	N 04	N 12	N 05	N 10	N 03	N 08
2000	NE 05	N 10	NE 08	NNE 09	N 07	N 09
2300	N 07		N 04		N 05	

	August 9		10		11	
0200	N 04		N 04		W 04	
0500	N 05	N 05	calm	N 04	S 03	SSE 05
0800	calm	NNW 08	S 06	NE 05	S 05	S 05
1100			S 06	S 07	S 07	SSE 08
1400	NNE 03	N 06	S 04		S 03	SSW 04
1700	NE 03		NE 05	NNE 10	N 03	NNE 10
2000	NE 03	N 10			NE 05	NNE 09
2300	N 06		NE 02		N 03	

	August 12		13		14	
0200	N 06		SW 10		S 11	
0500	calm	NNW 04	S 07	S 10	S 09	
0800	N 03	NNW 05	S 06	SSE 08	S 05	SSE 09
1100	S 04	S 06	S 07	S 12	S 06	S 10
1400	S 04	S 06	S 12	SSE 13	S 03	SE 07
1700	calm	NNE 06	S 10	SE 11	S 05	SSE 04
2000	N 04	NNE 06	S 10	SSE 10	calm	
2300	N 02		S 10		calm	

TABLE 3 (continued)

	August 15		16		17	
Hour (PDT)	Alki Point	West Point	Alki Point	West Point	Alki Point	West Point
0200	calm		N 03		calm	
0500	S 02	SW 04	S 03	SSE 08	SE 03	NE 08
0800	N 02	NNE 04	NE 04	W 06	S 03	SSE 04
1100	S 03	N 03	N 03	NNE 06	S 08	
1400	N 02	NNE 06	NE 03	NNE 07	S 10	SE 10
1700	N 06	NNE 12	S 05	N 04	S 10	SSE 08
2000	N 10	NNE 14	S 03	SSE 04	S 05	SW 11
2300	NE 04		S 02		S 08	
	August 18		19		20	
0200	S 07		NNE 03		S 03	
0500	S 04	SSE 05	calm		calm	NNE 04
0800	S 03	SE 06	N 03	NNE 06	calm	NNE 05
1100	S 03	SSE 05	N 06	NNE 10	N 05	NNE 08
1400	S 05	SSE 09	N 02	N 08	N 08	NNE 10
1700	S 02	S 04	NE 04	NNE 05	N 04	NNE 10
2000	S 06	SSE 08	calm	NNE 07	NE 03	NNE 06
2300	S 07		calm		S 04	
	August 21		22		23	
0200	N 08		S 09		calm	
0500	calm	NNW 07	S 04	SSE 05	S 02	calm
0800	S 05	SSW 02	calm	S 05	calm	S 03
1100	S 05	S 10	calm		calm	S 03
1400	S 06	SSE 12	N 01	NNE 05	S 01	S 04
1700	S 08	SE 14	S 02	NNE 08	S 03	S 07
2000	S 04	SSE 10	NE 01	NNE 04	S 04	SE 08
2300	S 08		calm		S 05	

TABLE 3 (continued)

	August 24		25		26	
Hour (PDT)	Alki Point	West Point	Alki Point	West Point	Alki Point	West Point
0200	S 02		N 02		calm	
0500	calm	calm	calm	NNE 05	N 04	N 08
0800	S 03	S 05	E 02	NNE 05	calm	NNE 05
1100	S 04	SSW 04	N 03	NNE 04	W 03	S 03
1400	N 04	N 06	N 02	NNE 07	S 08	SSE 10
1700	N 04	NNE 06	NE 04	N 06	S 08	SSE 09
2000	N 02	NNE 09	N 03	NNE 09	S 06	SSE 09
2300	N 05		calm		calm	
	August 27		28		29	
0200	S 03		N 02		calm	
0500	S 06	S 07	N 02	NNE 05	N 07	N 11
0800	S 05	SSE 08	N 04	N 09	N 05	NNW 09
1100	S 03	SSE 06	N 07	N 09	N 03	NW 03
1400	S 07	S 03	N 09	NNE 11	N 02	N 04
1700	S 08	SSE 04	N 02	N 04	S 05	S 05
2000	S 02	NNE 06	N 02	NW 03	S 05	SSE 05
2300	calm		N 06		S 06	
	August 30		31		September 1	
0200	S 07		S 03		S 04	
0500	S 06	SE 09	S 10		S 03	SE 07
0800	S 05	SSE 09	S 06	SSE 08	NE 03	ENE 03
1100	S 09	S 11	S 01	SSE 06	S 04	SSE 10
1400	S 11	SSE 11	NE 04	SSE 05	S 06	SSE 06
1700	S 14	S 18	calm	SSE 04	S 05	SE 08
2000	S 10	SSE 11	S 04	SSE 05	S 02	
2300	S 11		S 02		S 17	

TABLE 3 (continued)

Hour (PDT)	September 2 Alki Point	September 2 West Point	3 Alki Point	3 West Point	4 Alki Point	4 West Point
0200	S 10		S 10		S 08	
0500	S 10	SE 11	S 07	SSE 12	S 10	SSE 13
0800	SW 02	SSE 05	S 08	SSE 10	S 05	S 11
1100	SE 02	SSE 07	S 10	S 16	S 10	SSE 10
1400	S 05	S 11	S 06	S 10	S 07	SSE 04
1700	S 10	SSE 14	S 12	SSE 14	S 05	SSE 10
2000	S 06		S 09	SSE 12	S 02	SE 03
2300	S 14		S 09		S 03	

Hour (PDT)	September 5 Alki Point	September 5 West Point	6 Alki Point	6 West Point	7 Alki Point	7 West Point
0200	S 04		ENE 08			
0500	calm	S 08	S 05	SSE 11		
0800	S 08	SSE 13	calm	S 09		
1100	S 07	SSE 16	calm	SSW 03		
1400	S 08	SE 11	calm	S 04		
1700	S 08	SSE 13	calm	NE 02		
2000	S 10	SSE 14	NE 04	WSW 03		
2300	S 09		calm			

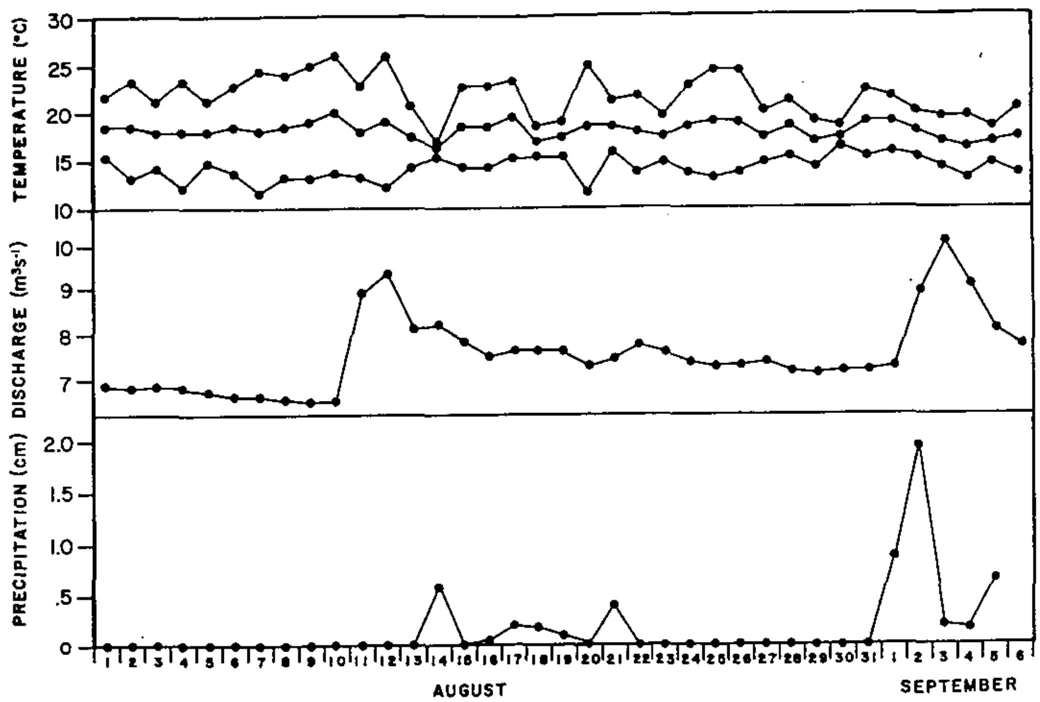

Figure 14. Air temperature, Duwamish River discharge, and Seattle precipitation recorded at locations shown in Figure 3. In temperature panel: upper, middle, and lower lines denote maximum, mean, and minimum temperatures, respectively.

TABLE 4. AIR TEMPERATURE RECORDED AT THE SEATTLE WEATHER STATION DURING 6 AUGUST - 6 SEPTEMBER, 1979

DATE	MAXIMUM	MINIMUM	MEAN	DATE	MAXIMUM	MINIMUM	MEAN	DATE	MAXIMUM	MINIMUM	MEAN
AUGUST				AUGUST				SEPTEMBER			
1	72	60	66	17	75	60	68	1	72	61	67
2	75	56	66	18	66	60	63	2	69	60	65
3	71	58	65	19	67	60	64	3	68	58	63
4	75	54	65	20	78	53	66	4	68	56	62
5	71	59	65	21	71	61	66	5	66	59	63
6	74	57	66	22	72	57	65	6	70	57	64
7	77	53	65	23	68	59	64				
8	76	56	66	24	74	57	66				
9	78	56	67	25	77	56	67				
10	80	57	69	26	77	57	67				
11	74	56	65	27	69	59	64				
12	80	54	67	28	71	60	66				
13	70	58	64	29	67	58	63				
14	63	60	62	30	66	62	64				
15	74	58	66	31	73	60	67				
16	74	58	66								

TABLE 5. PRECIPITATION RECORDED AT THE SEATTLE WEATHER STATION, AND DISCHARGE OF THE GREEN RIVER (DUWAMISH RIVER) RECORDED AT AUBURN DURING 6 AUGUST - 6 SEPTEMBER, 1979.

Date	Precip. (in.)	Discharge (m^3/sec)	Date	Precip. (in.)	Discharge (m^3/sec)
August			August		
6		6.6	22		7.8
7		6.6	23		7.6
8		6.6	24		7.4
9		6.5	25		7.3
10		6.5	26		7.3
11		8.9	27		7.4
12		9.4	28		7.2
13		8.2	29		7.2
14	0.25	8.2	30		7.2
15		7.8	31		7.2
16	0.03	7.5	September		
17	0.1	7.7	1	0.36	7.3
18	0.08	7.5	2	0.76	9.0
19	0.06	7.5	3	0.08	10.1
20		7.3	4	0.07	9.1
21	0.18	7.5	5	0.25	8.1
			6		7.8

4. DISCUSSION

The data obtained during the month long experiment provides insight into the spatial and temporal variability of near surface temperature, salinity, and density in Puget Sound's Main Basin and its adjoining channels, bays, and inlets. Using the Main Basin net circulation discussed by Ebbesmeyer and Barnes (1979) as a framework, the spatial variations of temperature, salinity, and density can be accurately associated with source waters and a more detailed description of Puget Sound's circulation obtained. Temporal variations of these water characteristics provide further insight into the seasonal changes occurring within Puget Sound. Both spatial and temporal variations compare favorably with historical data taken since 1932 (Collias, 1970).

4.1 SPATIAL (CROSS-CHANNEL) VARIABILITY

The variation of temperature, salinity, and density across channel can be seen in Appendix A which contains the entire data set from each transect. In addition these variations can be seen in the reduced data set in the following three ways: a) cross-channel profiles of mean temperature, salinity, and density; b) daily mean temperature-salinity diagrams; and c) cross-channel profiles of temperature, salinity, and density gradients.

Figure 12 shows cross-channel profiles of mean temperature, salinity, and density for the Bremerton and Winslow routes. The maximum mean temperature on the Bremerton route occurs in Port Orchard. Eastward the mean temperature decreases rapidly in Rich Passage to a minimum near site 15 (see Figs. 11 and 12). The mean temperature then increases sharply in mid-channel of the Main Basin to an intermediate mean temperature in Elliott Bay.

The Bremerton route cross-channel profile of mean salinity shows lowest values occurring in eastern Elliott Bay, a rapid increase in salinity near the middle of Elliott Bay, and a more gradual increase in salinity in the Main Basin to a broad salinity maximum from mid-channel in the Main Basin to the mouth of Rich Passage (see Figs. 11 and 12, stations 11-17).

The mean density pattern along the Bremerton route follows that of mean salinity, an exception being a narrower maximum.

On the Winslow route the mean temperature is approximately the same in Eagle Harbor and Elliott Bay with the minimum mean temperature in the western half of the Main Basin (see Figs. 11 and 12, stations 30 and 31). The mean salinity profile is very similar to that of the eastern half of the Bremerton route, with the maximum mean salinity along Bainbridge Island (see Figs. 11 and 12, stations 29-31). The density curve parallels that of salinity but with a slightly more pronounced peak in the western Main Basin.

Figure 15 shows the mean temperature (T) versus salinity (S) across the Basin. The characteristic "V" shape of the T-S curve for the Bremerton route may be described as follows: the highest temperatures occur in Port Orchard and the lowest occur in the Main Basin with intermediate values in Elliott Bay; and the highest salinities occur in the Main Basin and lowest occur in Elliott Bay with intermediate values in Port Orchard.

The mean temperature peak seen where the Bremerton route crosses Port Orchard is a result of solar heating as water circulates through relatively shallow Port Orchard and Sinclair and Dyes Inlets. The elevated temperatures seen through Port Orchard are not observed in Elliott Bay and Eagle Harbor, both of which are more directly and openly connected to the Main Basin. Table 1 shows the mean depth and other dimensions of Port Orchard, Sinclair Inlet, Dyes Inlet, Eagle Harbor, and Elliott Bay.

The colder temperatures and greater salinity seen at the mouth of Rich Passage indicate the presence of deep East Passage water which has been upwelled and vertically mixed with Terminal Basin water in the Narrows and discharged north through Colvos Passage.

The low salinity values observed in Elloitt Bay are a result of Duwamish River discharge into the Bay. Although a salinity difference of $0.8^{o}/oo$ is often seen across Elliott Bay the freshwater plume was probably near its yearly minimum size during this study. Observations occurred during a long, warm, dry spell and average Duwamish River discharge was only 8.8 m^3 sec^{-1} (Fig. 14; Table 5). Dye studies using the Puget Sound model at the University of Washington have suggested that Duwamish River water entering through the East waterway hugs the eastern shore while water entering the West waterway is more rapidly flushed outward around Duwamish Head (Rogers, 1955). Thus, the river input most responsible for the observed freshwater plume is probably that which enters through the West waterway and may be as small as half of the total discharge.

Figure 16 shows cross-channel profiles of the gradients of temperature, salinity, and density. The gradients were computed as differences between mean values at adjoining stations by subtracting easterly values from westerly values. The peaks indicate positions of strongest gradients. Although there are peak temperature and salinity gradients at similar locations, the strongest ones do not occur at the same positions. The strongest temperature gradients occur at the junction of Rich Passage and Port Orchard and at mid-channel. The strongest salinity gradients occur within Elliott Bay. The effect of temperature and salinity on opposite sides of the Basin both act in the same sense and there are pronounced density gradients on both sides of the Basin. The cross-channel profiles of temperature, salinity, and density gradients again show the effects of river discharge into Elliott Bay, Colvos Passage discharge into the Main Basin south of Bainbridge Island, and solar heating of water in Port Orchard, Sinclair and Dyes Inlets.

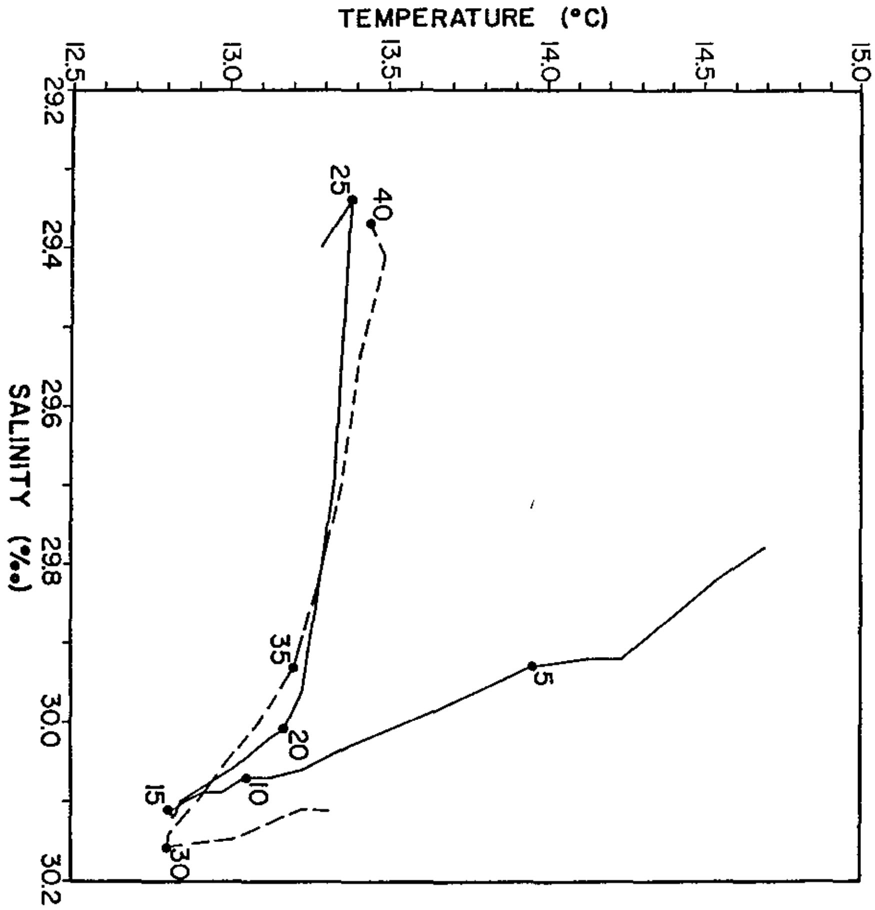

Figure 15. Mean temperature versus salinity curves of the reduced data set from Seattle to Bremerton (solid line) and Seattle to Winslow (dashed line) during 6 August-6 September, 1979. Notation: dots and associated numbers, selected sites of the reduced data set.

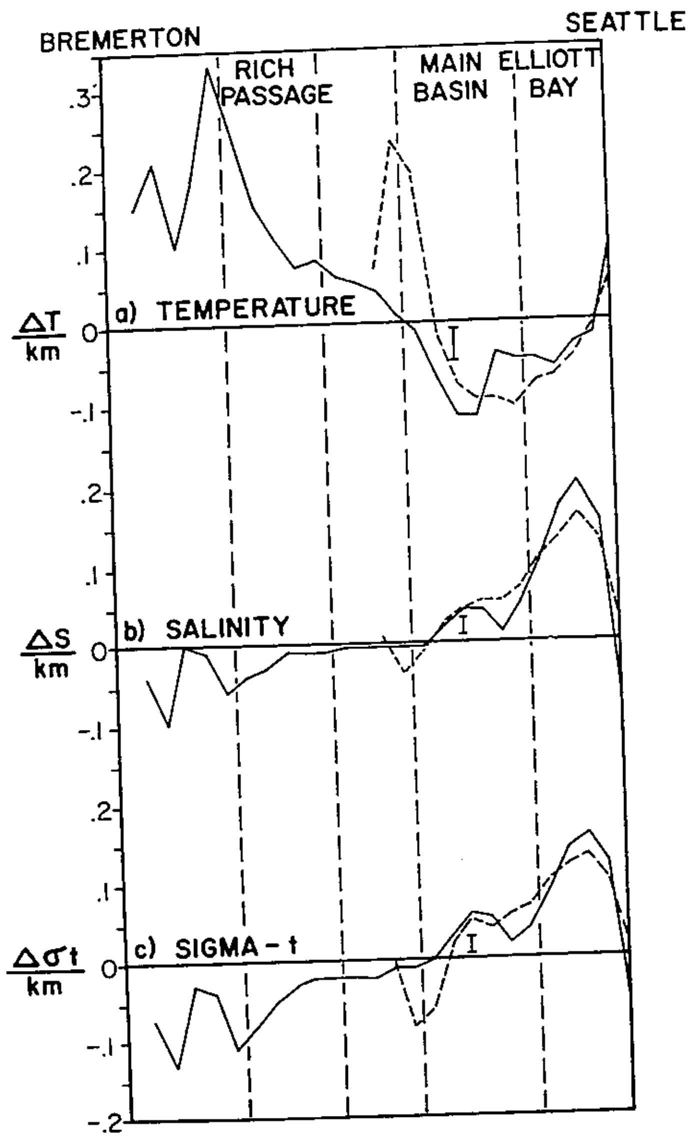

Figure 16. Mean gradients of temperature (a), salinity (b), and density (c) for the reduced data set from Seattle to Bremerton (solid line) and Seattle to Winslow (dashed line) during 6 August-6 September, 1979. Gradients were computed as the difference between values at adjoining stations; easterly values were subtracted from westerly values. Vertical bars within Main Basin section of curve indicate range of long-channel gradient between historical stations Point Jefferson and Alki Point (see Fig. 1).

It is useful to contrast the long-channel gradients with those computed across channel. The long-channel gradient was computed from the historical data between stations located off Point Jefferson and Alki Point (Fig. 1). Comparison of gradients show that the peak cross-channel gradients are severalfold greater than the long-channel gradients computed from the historical data (Fig. 16).

4.2 TEMPORAL VARIABILITY

The study was conducted during a period of usually increasing salinity and near peak temperature in the Main Basin. Figure 17 shows the annual cycle of mean temperature, salinity, and density at Point Jefferson computed from University of Washington cruise data taken since 1932 (Collias, 1970).

Temporal variations in the measured water properties may be characterized by the standard deviations of the properties at each site (Fig. 12). The greatest standard deviation of temperature occurs in Rich Passage and the greatest salinity standard deviation occurs in Elliott Bay. The standard deviation of density has peaks in both Rich Passage and Elliott Bay. In Eagle Harbor the standard deviations of temperature, salinity, and density are comparatively small.

Tidal oscillations of temperature, salinity, and density can be seen in the cross-channel contours of these properties versus time (Fig. 18). Strong horizontal oscillations of up to 6 km occur through Rich Passage where colder, more saline Colvos Passage water fills the Passage on floods and warmer, fresher water from Port Orchard fills the Passage on ebbs. Similar oscillations occur within Elliott Bay and little cross-channel tidal effect is seen near mid-channel. A salinity front occurred near the mouth of Elliott Bay throughout the study. Tidal oscillations in areas of strong horizontal gradients cause the large standard deviations of temperature, salinity, and density observed at sites in these areas.

It is useful to inspect the daily average T-S curves across channel (Fig. 19). In general the characteristic shapes shown by the mean data are preserved in the profiles of the daily average data. Over the study period a gradual increase in salinity and decrease in temperature was observed in the Main Basin. This conforms to the normal trends at this time of year as observed at Point Jefferson (Fig. 17).

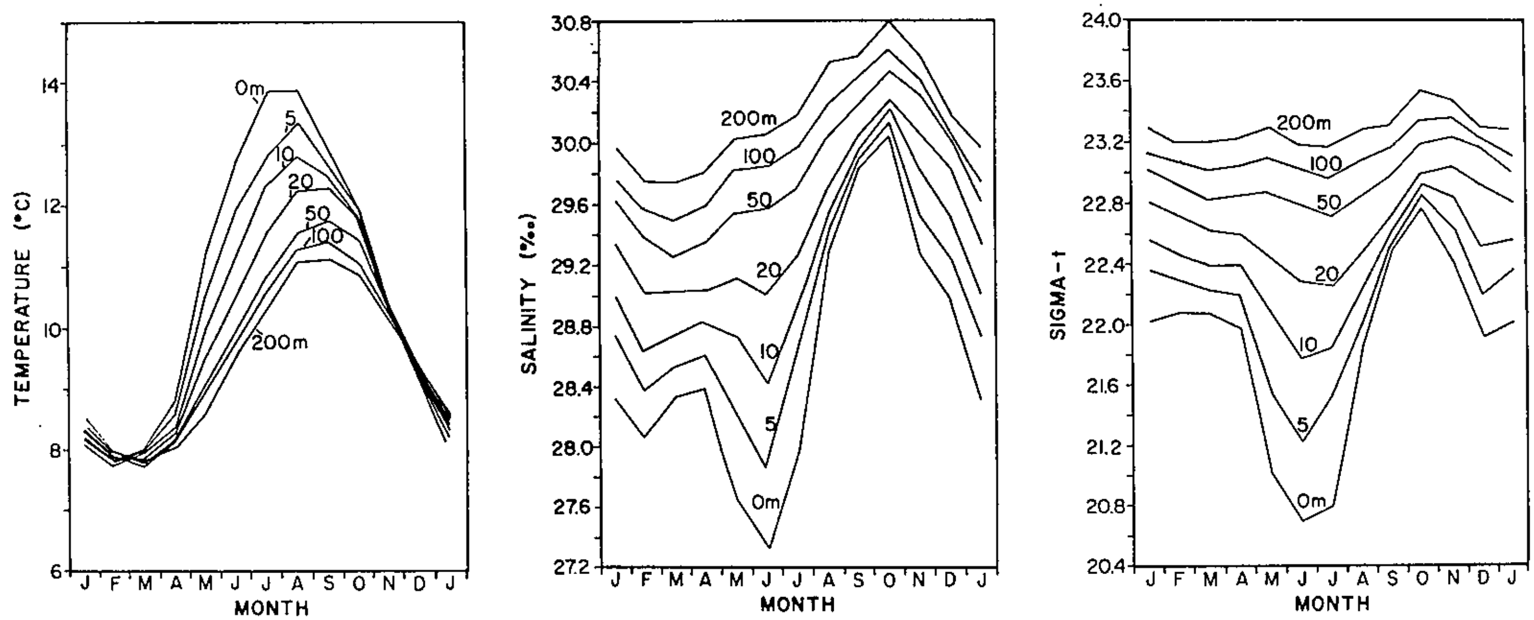

Figure 17. Yearly cycles of temperature, salinity, and density for standard depths at the historical station Point Jefferson.

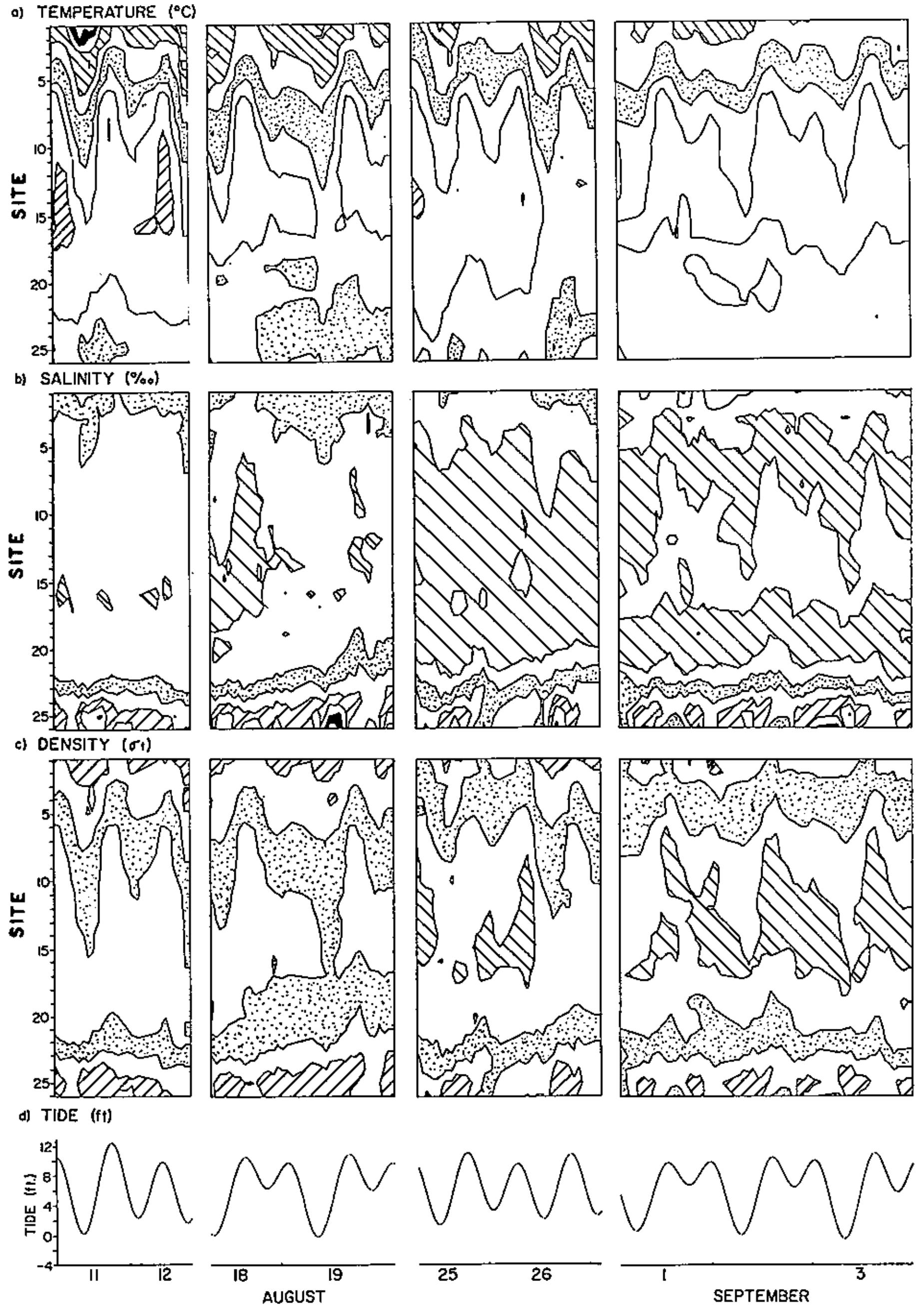

Figure 18a. Contours of temperature, salinity, and density in the space of time and cross-channel distance for the Bremerton route. Contours are plotted from data taken at 1 km intervals. The coding legend is shown in Figure 18b. The locations of the sites are shown in Figure 11.

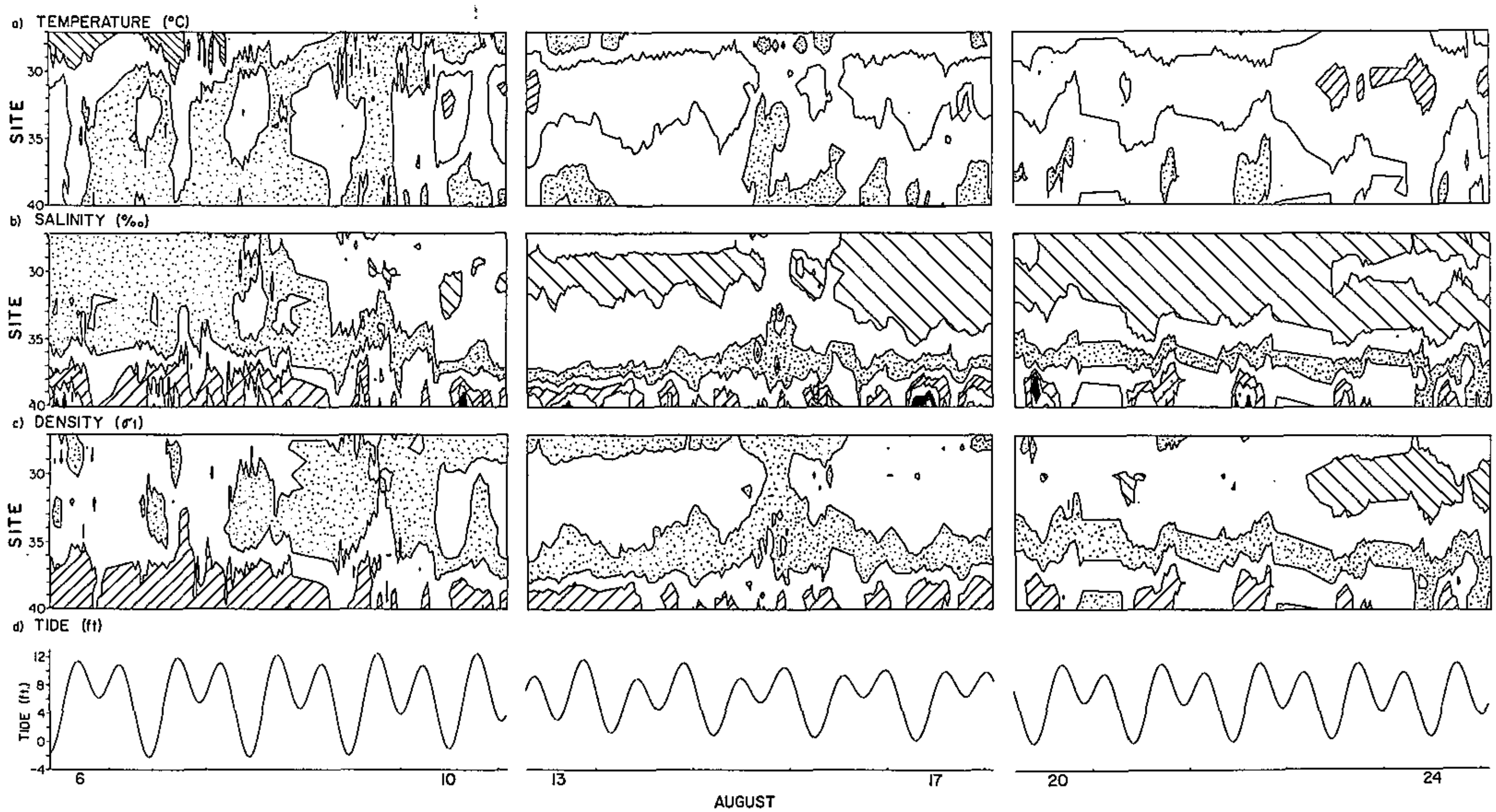

Figure 18b. Contours of temperature, salinity, and density in the space of time and cross-channel distance for the Winslow route. Contours are plotted from data taken at 1 km intervals. Legend illustrates coding used to label different water types. The locations of the sites are shown in Figure 11.

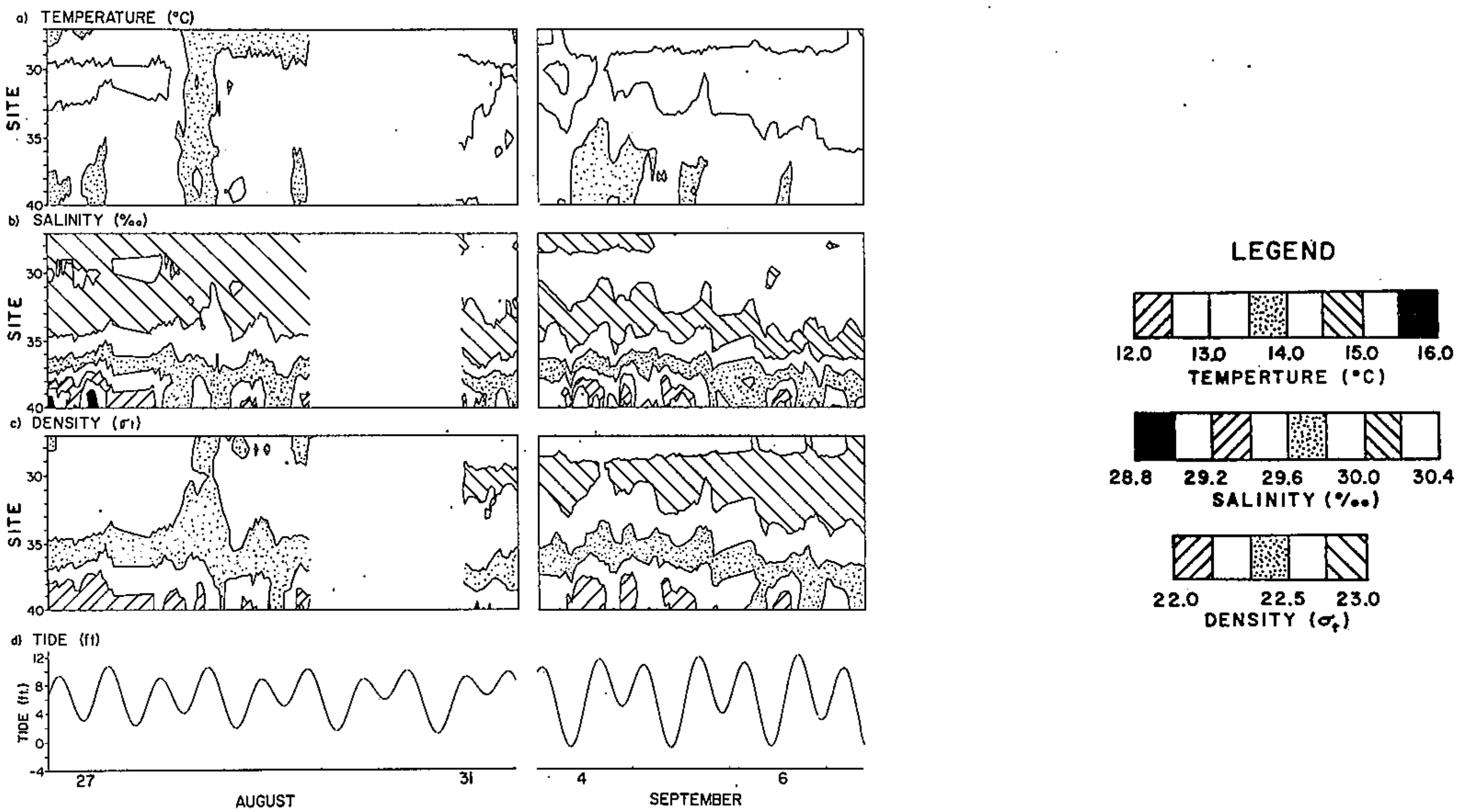

Figure 18b. continued.

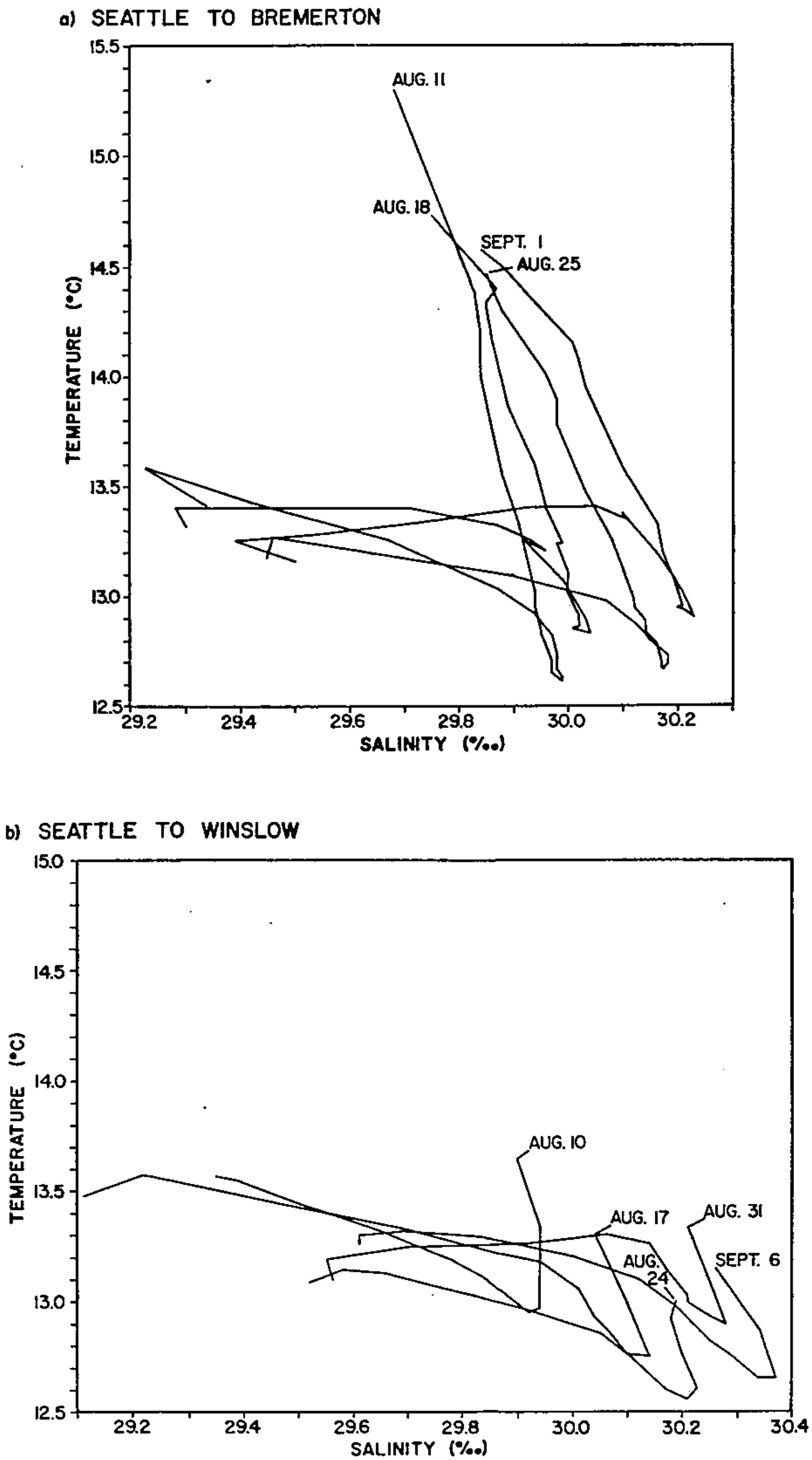

Figure 19. Selected daily mean temperature versus salinity curves of the reduced data set from Seattle to Bremerton (a) and Seattle to Winslow (b).

5. CONCLUSIONS

As a first trial at using ferries as oceanographic vessels, the results are quite encouraging. The month-long data set collected aboard the Washington State Ferry Walla-Walla during the period 6 August-6 September consistently shows large cross-channel variations of water properties. Colder and more saline water entering the western half of the Main Basin from Colvos Passage separates the warmer, intermediate salinity water of Port Orchard, Sinclair and Dyes Inlets from mid-channel water of intermediate temperature and salinity and the fresher, intermediate temperature water of the Duwamish River plume in Elliott Bay.

Cross-channel gradients of mean temperature, salinity, and density observed when traversing these water types are much greater than long-channel gradients computed from historical means at Point Jefferson and Alki Point.

Strong tidal oscillations occur in the regions of highest horizontal gradients: Rich Passage and Elliott Bay. Water alternately enters Rich Passage from Port Orchard during ebb and the Main Basin during flood, water from either source often moving up to 6 km through the Passage. In Elliott Bay tidal oscillations of the fresher Duwamish River plume are smaller.

The gradual decrease in temperature and increase in salinity seen during the study period are consistent with trends in the historical data for August and September in the Main Basin. The Main Basin water was warmer and more saline during the study than the historical data for the same period. This is indicative of the unusually warm, dry weather before and during the study.

An important conclusion of this study is that the bow rpm measurement is an excellent indicator of ferry speed. As the ferries routinely follow an exact route noting times of passage of major channel markers, a simple measurement of rpm obviates the need of the expensive MRS navigation system. This now allows placement of the sampling system aboard ferries on routes where logistics or cost previously prohibited the use of the MRS navigation system.

Ferry routes across Puget Sound and its approaches are shown in Figure 20. By instrumenting ferries on several of these routes, a more detailed description of the circulation patterns in Puget Sound over extended periods of time may be obtained.

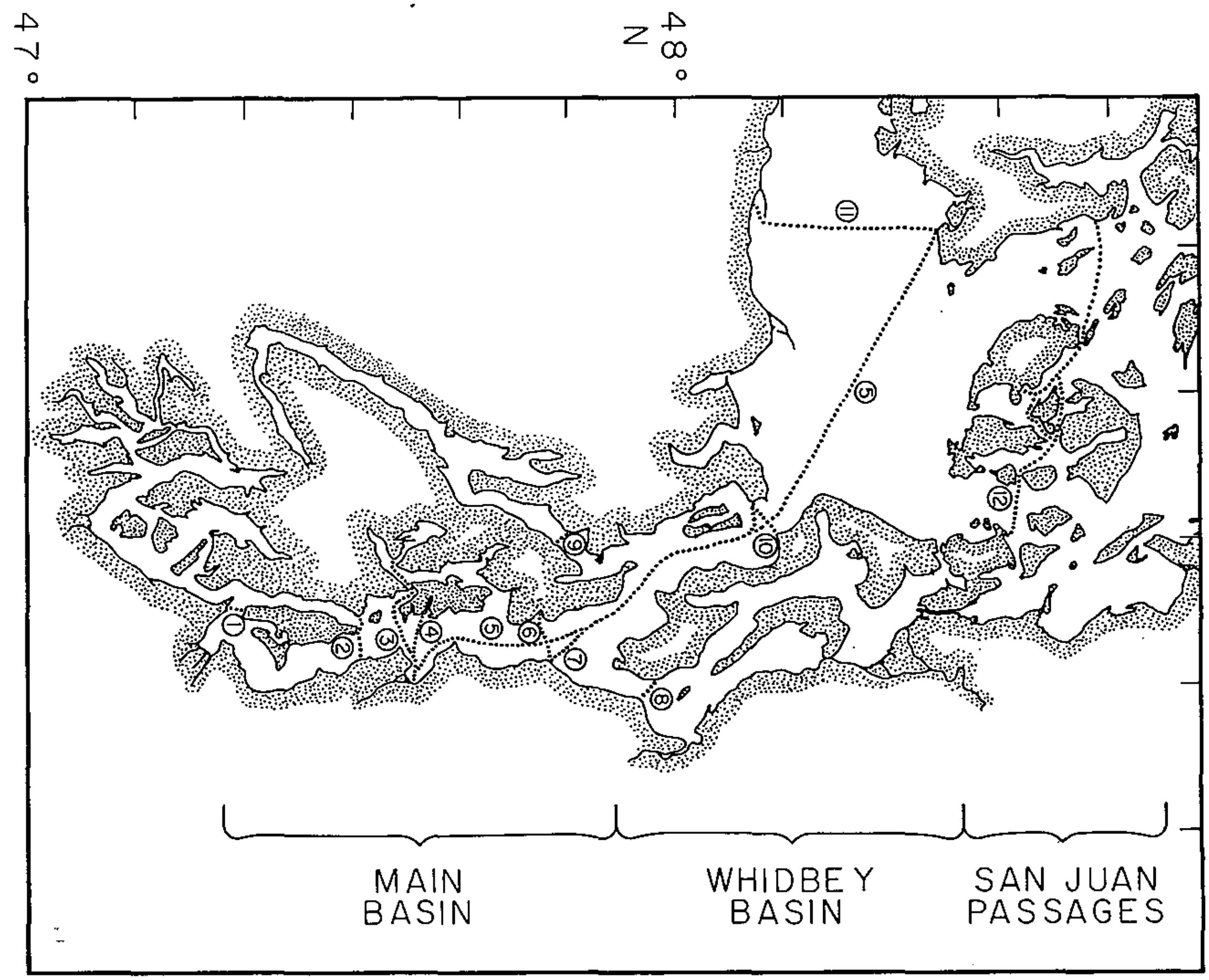

Figure 20. Twelve ferry routes crossing Puget Sound and approaches.

6. ACKNOWLEDGMENTS

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