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# PUGET SOUND CIRCULATION: FINAL REPORT FOR FY77-78

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Marine Ecosystems Analysis Program
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UNITED STATES
DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

NATIONAL OCEANIC AND
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Richard A. Frank, Administrator

Environmental Research
Laboratories
Wilmot N. Hess, Director

Report Submitted to
MESA Puget Sound Project
MARINE ECOSYSTEMS ANALYSIS PROGRAM
ENVIRONMENTAL RESEARCH LABORATORIES

BY

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# PREFACE

This report represents the Final Report to the MESA Puget Sound Project for research sponsored in the main basin of Puget Sound by PMEL during FY77 and FY78. Their support is gratefully acknowledged. This research included experiments to better describe the oceanographic characteristics of The Narrows in February-March 1977 and of Admiralty Inlet in September-October 1977.

The primary purpose of this report is to describe these two experiments and to summarize the observations as of about November 1978. As background for these descriptions, a summary of results from the earlier main basin studies is given in the Introduction. More details of the earlier work may be found in the referenced papers and in a previous report to MESA (NOAA Technical Memorandum ERL MESA-18). Partial analysis of The Narrows data was used by Mr. Terry Keefer as partial fulfillment of the requirements for a MA degree in Oceanography at the University of Washington in 1978.

This research now has evolved into a PMEL project, and further analysis of these data is continuing. Presentation of some of the results is expected at an international fjord oceanographic conference next summer in Canada. Additional field studies are anticipated late next summer and the following winter to continue increasing understanding of the replacement processes occurring in Puget Sound. These studies may be combined with a new MESA project to study other aspects of Puget Sound oceanography.

Many discussions over the years with professors Clifford Barnes and Maurice Rattray at the University of Washington have provided much insight regarding estuarine circulation and Puget Sound. Supporting services by many in our Coastal Physics group are gratefully acknowledged. In particular, the great care in instrument maintenance by Richard Carlone has been a major factor producing the relatively high data return.

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ABSTRACT

Physical oceanographic research in Puget Sound has focused on describing deep water flow through the main basin and on determining its principle driving mechanisms. Observations, however, have been made throughout the water column using moored current meters and shipboard STD surveys. The main experimental site has been located near the largest single wastewater discharge point in Puget Sound. Hence, some of the results should be applicable in determining physical factors influencing the transport and dispersions of effluents. Additional observations were made in 1977 in The Narrows and in Admiralty Inlet, the two major sills located at opposite ends of the main basin.

Observations during winter near The Narrows and Vashon Island confirmed earlier hydraulic model data and showed a clockwise tidally averaged flow around Vashon Island. Strong flood tides advected deeper water from the main basin onto The Narrows sill. Apparently, relatively large northward currents in Colvos Passage also can cause some main basin deep water to be advected to shallower depths. There may be some minimum speed required in Colvos Passage to produce this effect. These observations were made during an extremely dry spell in Puget Sound region resulting in very uniform water properties. Thus, it was not possible to determine the depth from which main basin water was being advected onto The Narrows sill. Observations in late summer, however, indicated a source depth of at least 120 m.

Observations during late summer to early fall in Admiralty Inlet showed new bottom water entering Puget Sound both when flood tides ranges did and did not exceed 3.5 m. Water property sections in the Inlet showed up and down slopes of the isolines approximately following the bathymetry during strong flooding currents. During low flood tide ranges, new bottom water inflow was characterized by lower maximum tidal currents, but for longer duration, than when no new water was entering. Tidally averaged flow during intrusions of saltier and colder bottom water was characterized by increased bottom inflow and increased outflow of upper water at approximately fortnightly intervals. The bottom flow was always into the estuary. Step decreases in bottom-water temperature indicative of new bottom water, were observed at two locations in the main basin with time lags of about 7 days from Seattle to Tacoma, thus confirming earlier estimates from a single location.

## 1. Introduction and Main Basin Summary

Puget Sound is a fjord-like estuary connecting through Admiralty Inlet and Deception Pass to the Strait of Juan de Fuca and then to the Pacific Ocean (Figure 1). It is entirely within the State of Washington in the United States and is part of a larger estuarine system contiguous to several major population centers in the United States and Canada. About 98% of the tidal prism flows through Admiralty Inlet over a sill of about 64 m depth near Port Townsend. The main basin has depths exceeding 200 m and extends south about 60 km from the major junction with Admiralty Inlet near Possession Point to The Narrows, a constriction of about 44 m sill depth separating a southern basin. Within the main basin, the 183-m contour deliniates a deeper section approximately 50 km long and 3-5 km wide. The other main subdivisions include Hood Canal and Whidbey basin, the latter extending from Possession Point to Deception Pass through Saratoga Passage. Numerous rivers enter the Puget Sound system, but the Skagit entering in the north supplies more than 60% of the freshwater.

During 1975-76 a year-long mooring to record currents, temperature, and salinity at several levels was maintained at a location in the main basin just north of West Point as an outgrowth of month-long observations made at the same location during the winters of 1972 and 1973 (Figure 1). Prior to this time replacement of Puget Sound bottom water with more saline, hence denser, water primarily had been thought to occur in July-October in response to northerly summer winds along the Pacific coast (Barnes and Collias, 1958). Northerly winds induce upwelling of denser oceanic water to shallow depths which then could be transported along the bottom of the Strait of Juan de Fuca into Puget Sound. Additionally, long-term hydrographic observations showed that bottom-water density in the Sound also increased during April-May and decreased during May-June and October-February. During the lowering of density in winter, mixing and/or replacement results in the deeper water in the main and Whidbey basins becoming relatively isothermal, less saline, and higher in dissolved oxygen. Deep water replacement previously only had been documented at about monthly intervals with water properties.

Observations during winter 1973 (Cannon and Ebbesmeyer, 1978) showed that water near the bottom was cooled in a series of step decreases of temperature of up to 0.6$^{\circ}$ C at about 2-week intervals coincident with the onset of about 5-day intervals of net landward flow near the bottom (Figure 2). Between these intervals, bottom flow was tidal with a small seaward component. Temperature sections along the axis of the Sound showed a vertical temperature front close to the mooring following the first step, but at the beginning and end of the month there was no evidence of this front. Density (sigma-t) sections showed that less dense water (colder but less saline) was intruding to near bottom just north of the mooring and the passing temperature front, and that an overall decrease in density occurred during the month.

Intrusion of new deep water was shown to occur when flood-tide ranges at Seattle exceeded 3.5 m. At this range, Strait of Juan de Fuca water had been shown by hydraulic model studies to completely transit Admiralty Inlet sill (about 17 nautical miles) in one flood period and thus be least

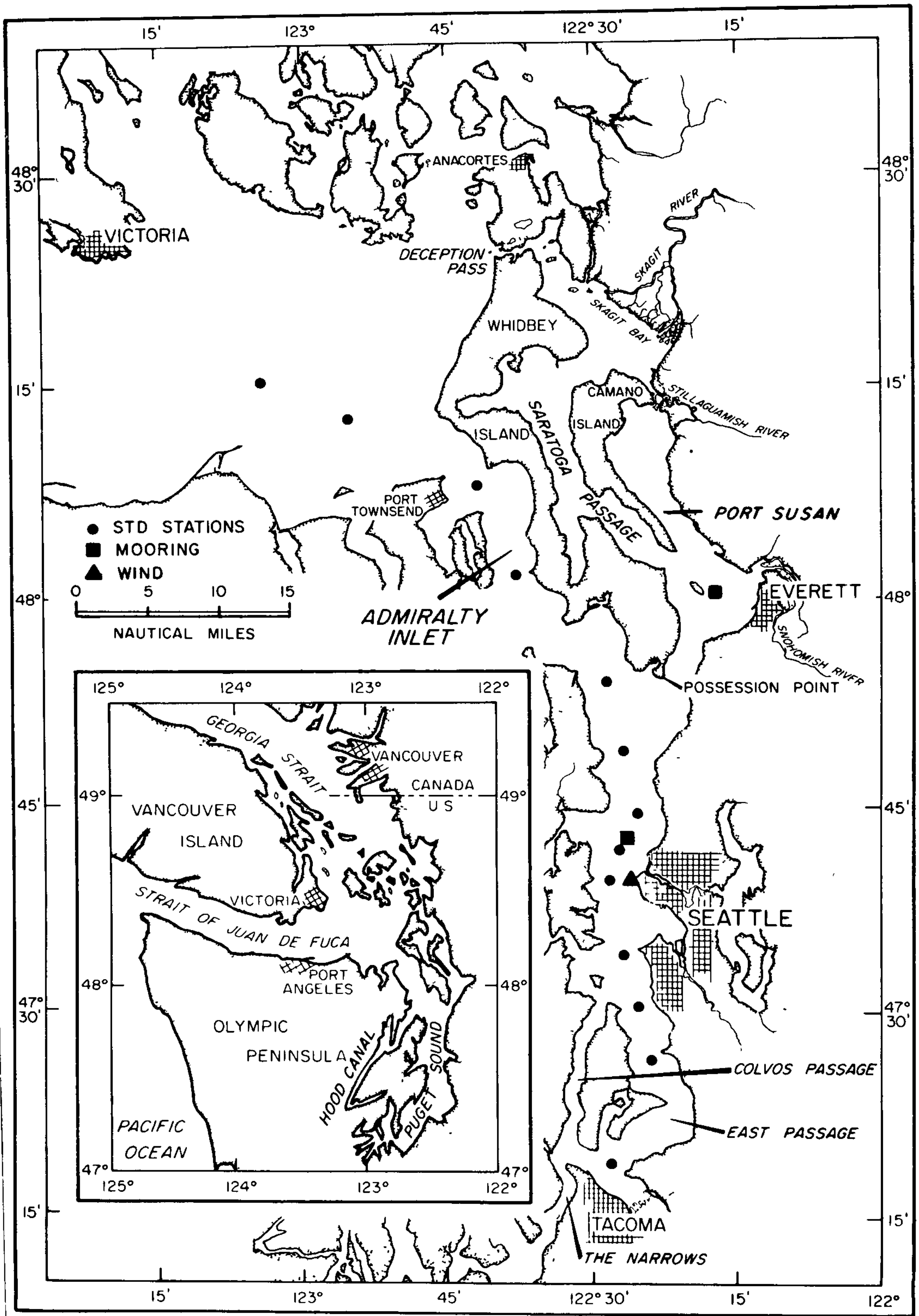


Figure 1. Puget Sound region showing station locations.

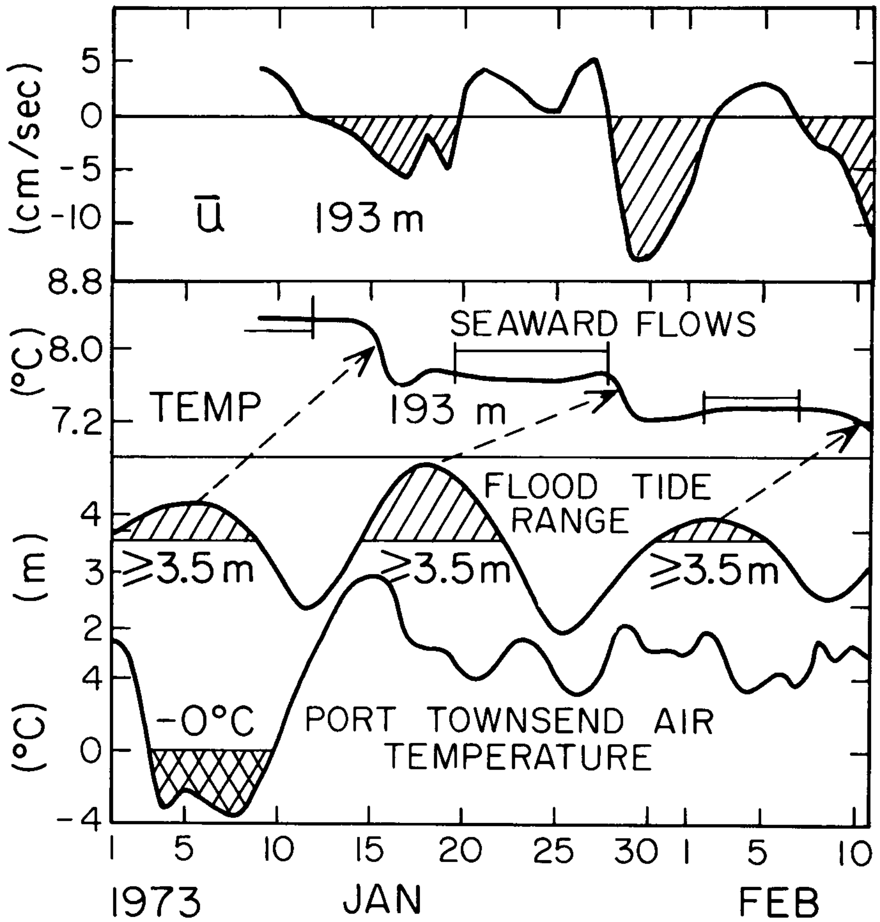


Figure 2. Daily average longitudinal bottom currents and temperature in Puget Sound; range of greatest daily Seattle flood tide; and daily average Port Townsend air temperature (from Cannon and Ebbesmeyer, 1978).

mixed (Farmer and Rattray, 1963). In this study an 8 to 10-day time lag was required to transit the distance from sill to mooring, and the largest temperature decrease occurred following flood tides concurrent with below-freezing air temperatures over Admiralty Inlet. Density differences during the temperature steps were small, and it was not possible to determine whether the new water initially was more dense.

Finally, it was speculated that a similar process might occur in late summer when the most dense bottom water can enter the Sound. Confirming current observations on the sill of Port Susan, a secondary basin in Puget Sound, showed flow into that basin at about fortnightly intervals lasting about 5 days each time (Cannon, 1975). It also was speculated that deep water might be added quasi-continuously at about 2-week intervals.

The addition of deep water in Puget Sound during the year-long observations (Cannon and Laird, 1978), as in the earlier observations, showed the winter intrusions (December-February) to occur 8 to 10 days following periods when the tidal ranges exceeded 3.5 m (Figure 3). The time of high tidal range predicts when the flooding tides will be greatest in Admiralty Inlet over the sill. Similar time lags had been observed for about fortnightly renewal during summer-fall in the Port Susan estuary (Cannon, 1975). About a week was required for water to flow from the Admiralty Inlet sill to the sill of Port Susan. Characteristics of water properties along the Sound during an intrusion usually show a tongue-like contour or a single contour near bottom extending southward from the south end of Admiralty Inlet (Figure 4). However, note that an intrusion does not necessarily imply that all deep water is replaced.

An overall rate of replacement of intermediate and deep water, south of the mooring was approximated for the 1973 observations using the net landward transport and assuming negligible effects of entrainment and diffusion (Cannon and Ebbesmeyer, 1978). Computations were made using average daily currents, assumed uniform across-channel. The landward transport was divided into the volume beneath the average depth of no-net-motion (about 35 $km^3$ beneath 52 m), yielding an effective replacement time of about 9 days. This value also is applicable for the year-long observations for all the major intrusions. However, it is still unclear how much water is actually replaced during any given intrusion. But, a possible deep-water renewal rate of 1 to 2 weeks indicated by these studies is significantly quicker than earlier estimates for all of Puget Sound of 2 to 10 months based on water property observations (Friebertshauser and Duxbury, 1972).

Friebertshauser and Duxbury estimated flushing for the entire Puget Sound basin inside the Admiralty Inlet entrance and for the total water column. Also, they delt with monthly averages of properties. Their overall averages were significantly influenced by the particularly slow renewal of the Hood Canal basin, and they were unable to make specific estimates for the main basin. However, they indicated a possible quick renewal during late summer bottom-water intrusions. Thus, the results here are not contradictory, but provide added information for the deep water in the main basin of Puget Sound.

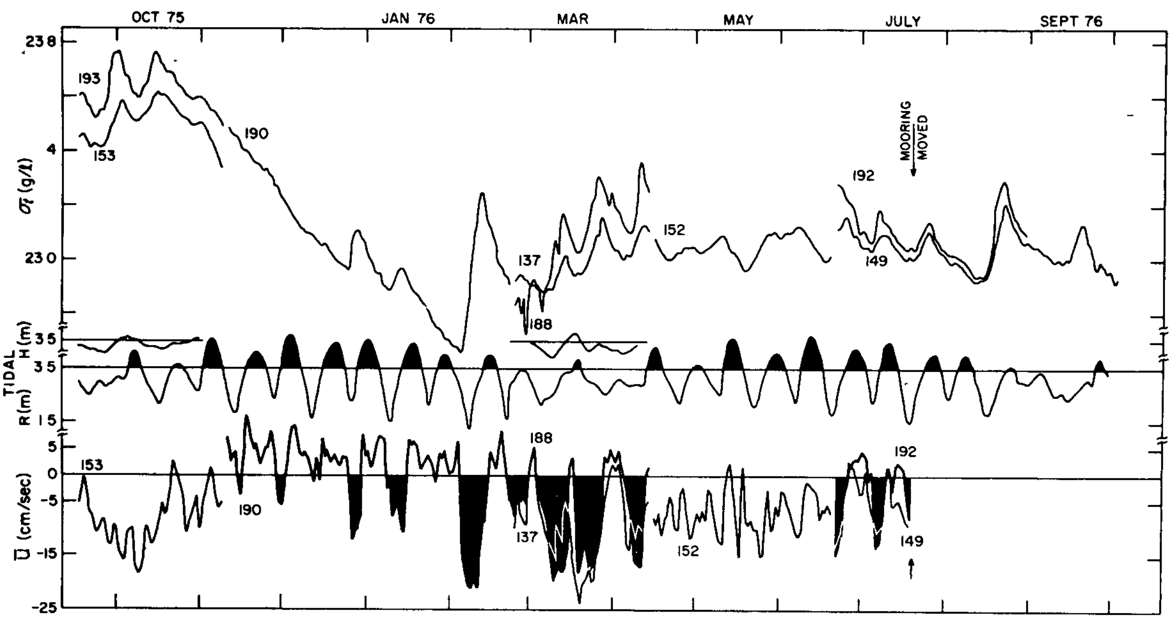


Figure 3. Daily average sigma-t at 5 and 50 m above the bottom in Puget Sound; range (R) and height (H) of greatest daily Seattle flood tide; and daily average along-channel currents at 5 and 50 m above the bottom (from Cannon and Laird, 1978).

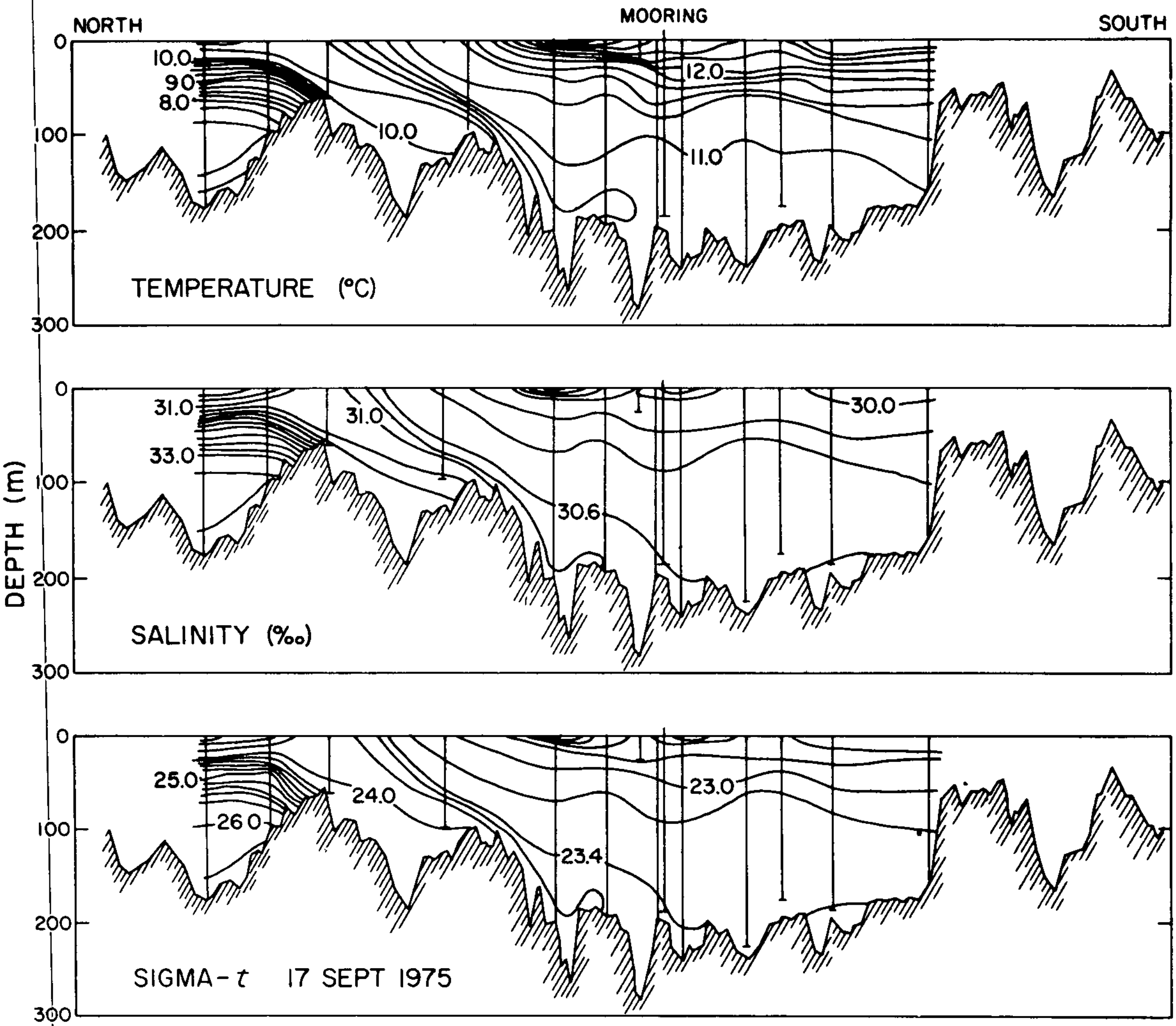


Figure 4. Temperature, salinity, and sigma-t along Puget Sound (from Cannon and Laird, 1978).

The depth of no-net-motion along channel for averages of a month or longer in all seasons except summer, when there were insufficient observations, occurred in the range of 45-55 m (Cannon and Laird, 1976). However, significant variations in this depth have been observed in mean daily along-channel current profiles (Figure 5). During the predominant southerly winds (blowing out estuary) in winter, a quasi-steady profile was established with a depth of no-net-motion of 40-50 m. However, relaxation of the wind or reversal to northerly (blowing in-estuary), even for brief intervals, resulted in deepening of the depth of no-net-motion. The change in this depth at times was considerable, from about 50 m to as much as 100 m (in the 1972 observations not shown here) in about 200 m total depth. Return to southerly winds resulted in return of the depth to about the previous quasi-steady level. There apparently was a delicate balance of forces along the estuary. These relative changes caused by wind stress were consistent with general theory (Rattray, 1967) as were the magnitudes of the mean currents (Winter, 1973; Winter et al., 1975). However, Winter's first approximations of the depth of no-net-motion by theory were 10-20 m shallower than observed, and more study is needed to resolve this difference.

The year-long observations, however, indicated some major differences from the earlier winter-replacement observations. First, there were occurrences of large tidal ranges during November-January with almost no or very small inflow and, particularly, with no apparent changes in water properties. Second, there were occurrences of inflow during low tidal ranges during August-October and during March-April. These latter two periods also were different in that the summer-fall interval was when the most dense water could enter the Sound, and the winter-spring interval was about when the least dense water was in the Sound.

Thus, other factors must be important in determining when there will be intrusions of deep water. One apparent factor is the degree of mixing which takes place when crossing the finite-length entrance sill (17 nautical miles). During summer-fall the water apparently is sufficiently salt (dense) that it apparently does not matter that more than one tide is required to transport it across the sill. Also, there is minimum fresh water entering the Sound to be available for mixing over the sill. However, the flows still occurred at about fortnightly intervals. On the contrary, the lack of significant inflow during fall when there are large tides probably is influenced by having an abundance of fresh water available for mixing over the sill. The largest temperature step decrease in December 1975 occurred following an extreme cold spell coincident with the large tidal range. This cold spell also was characterized by clear weather and a lack of fresh water, as was the case in winter 1973 (Figure 2).

Finally, the two large intrusions in March occurred during small tides. They represented excusions as large as the one in February. This case is least well understood. Apparently the combination of greater density outside and minimum inside is sufficient to cause the intrusion, even though more than one tidal cycle is required to cross the sill, but still at fortnightly intervals. This period of renewal was observed

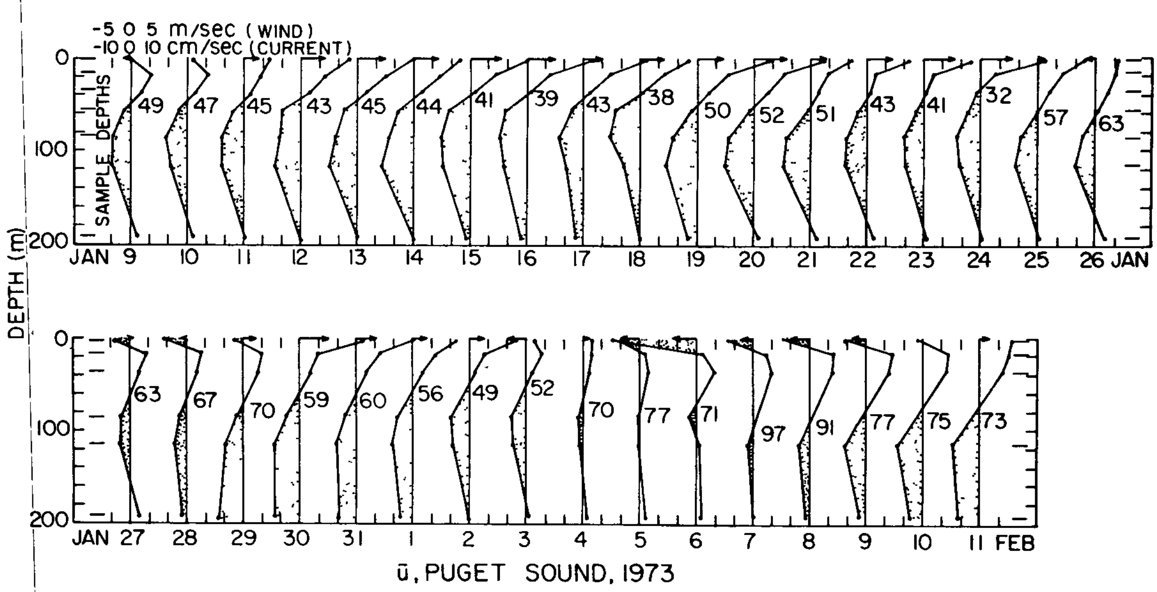


Figure 5. Daily average along-channel current profiles. Daily average north-south winds are shown by the vectors at 0 m on each profile. Positive speeds are flow to the north (out-estuary). Depths of no-net-motion are given for each profile (from Cannon and Laird, 1976).

to be most important in other years and needs additional study. Earlier work (Cannon, 1975) showed it to be the dominant time of renewal of oxygen in the secondary basin of Port Susan (Figure 6).

There have been a variety of studies of renewal of deep water in other fjords in western North America and Norway and in the deep ocean in the Caribbean. None so far show the fortnightly characteristics similar to what has been described here for Puget Sound, although there are possible indications. One difference is the relatively long entrance sill in Admiralty Inlet. Perhaps another difference is that the head of the main basin of Puget Sound is really a relatively narrow, shallow passage, The Narrows, entering another basin.

There are extremely high tidal currents through The Narrows which appear to be capable of pumping deep water up from about twice the depth of the sill. Physically, the process would be explained by application of Bernoulli's principle, and it has been shown in Puget Sound using the hydraulic model at the University of Washington. It is not yet known whether the process occurs continuously on all flood tides, or whether it occurs only on the largest, fortnightly tides. In either case, the effect of The Narrows is to greatly assist the movement of deep water through Puget Sound. This partly was the subject of a study in winter 1977 and is described in Section 2.

In late summer-early fall 1977 observations were made to describe the characteristics over the Admiralty Inlet entrance sill during flow of the most dense bottom water into Puget Sound. These observations also partly included the smaller tidal ranges noted from the year-long observations and are described in Section 3.

In addition, a mooring was maintained at the bottom in the Puget Sound main basin during winter and summer 1978 concurrent with other studies in the Strait of Juan de Fuca. Its purpose was to observe characteristics outside the entrance sill during bottom water intrusions. These data are still being analyzed.

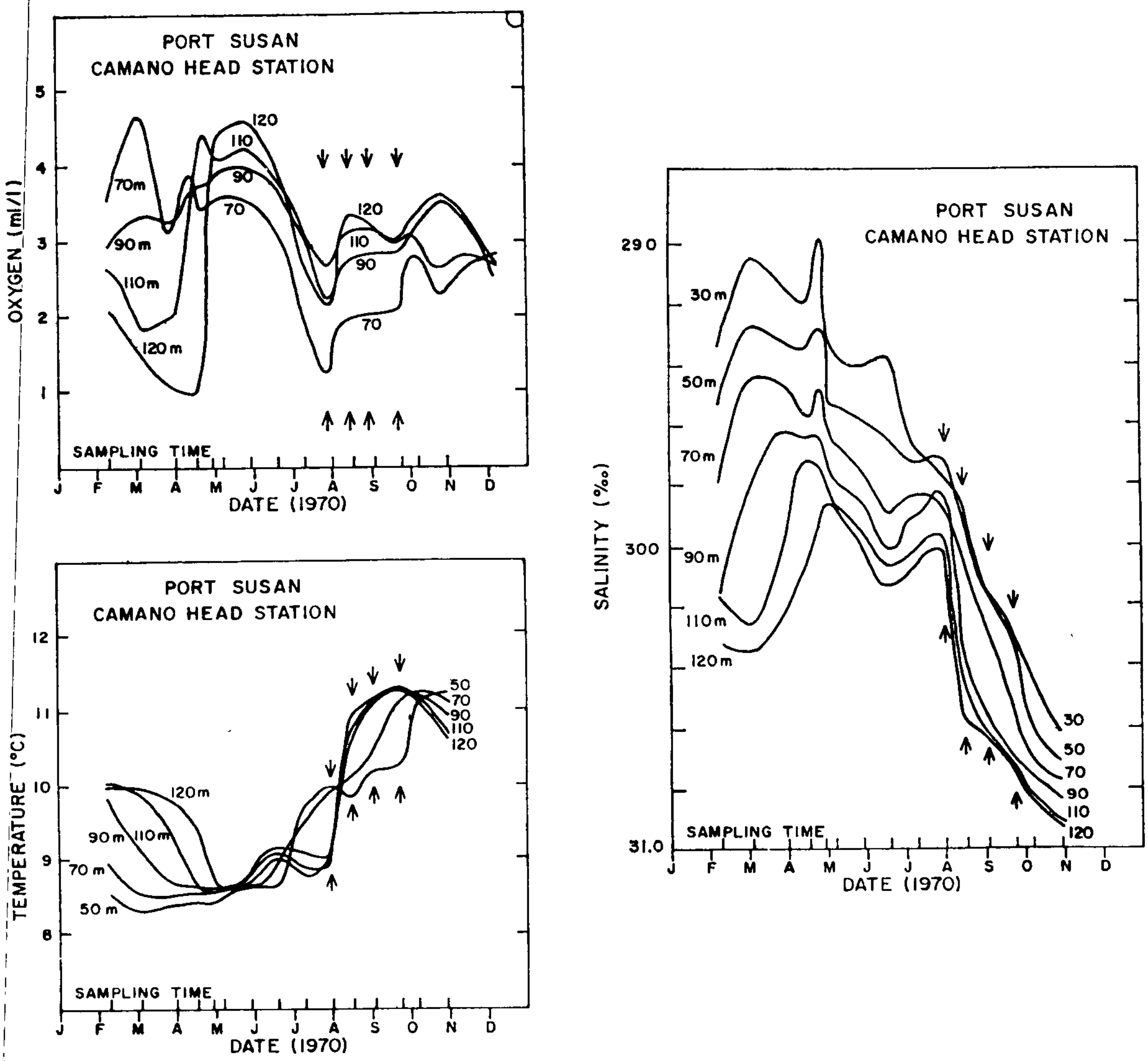


Figure 6. Dissolved oxygen, temperature, and salinity in Port Susan. Arrows indicate STD sections (from Cannon, 1975).

## 2. The Narrows

### 2.1 Experiment Description

To begin to determine the effect of The Narrows on the circulation in the main basin of Puget Sound, a month-long series of observations was made in February-March 1977 both in the vicinity of The Narrows and extending into the main basin (Figure 7). As will be seen, it was not possible to determine as much as had been planned because the abnormally dry year due to lack of precipitation resulted in extremely uniform water properties throughout the Sound. However, significant new observations were obtained in that this was the first extended set of current and water property observations in and around The Narrows. Additional information, however, was obtained in September-November during the observations in Admiralty Inlet described in Section 3.

Seven subsurface current meter moorings were deployed by the NOAA ship McArthur on 23-24 February for approximately one month and recovered on 28 March (Figure 7). Depths of functioning meters are given in Table 1. All were Aaneraa meters with sensors to measure average values of speed and instantaneous values of direction, conductivity, temperature and pressure at 10-minute intervals. Aanderaa pressure gauges were installed on moorings 5 and 6 and recorded at 15-minute intervals. In addition, the University of Washington had a current-meter mooring in Colvos Passage (UW in Figure 7; Larsen et al., 1977).

Wind speed and direction were recorded during the study at West Point near mooring 6 where winds seem representative of the main basin and, for comparison, at Point Robinson in East Passage (main basin water east of Vashon and Maury Islands) on Maury Island (appears to be southeast part of Vashon Island). Wind direction throughout the study, however, was typical of winter and generally from the south with only scattered instances of northerly winds.

STD surveys were made in The Narrows region (Figure 7) during neap tides on 1-2 March using the charter vessel Snow Goose and, including all of the Sound from the Strait of Juan de Fuca (Figure 1), during spring tides on 8-9 March using the McArthur.

### 2.2 Water Properties

Temperature and salinity (density) sections along Puget Sound taken on March 1977 run along the main basin from outside the Admiralty Inlet sill in the Strait of Juan de Fuca to south of The Narrows in the southern basin (Figures 1 and 8). Because of the very uniform temperatures, salinity and density contour patterns would be identical. Water outside the sill can be seen to be more saline, colder and highly stratified. Isohalines were nearly horizontal in the Strait. Isohalines within Admiralty Inlet intersected both surface and bottom and sloped

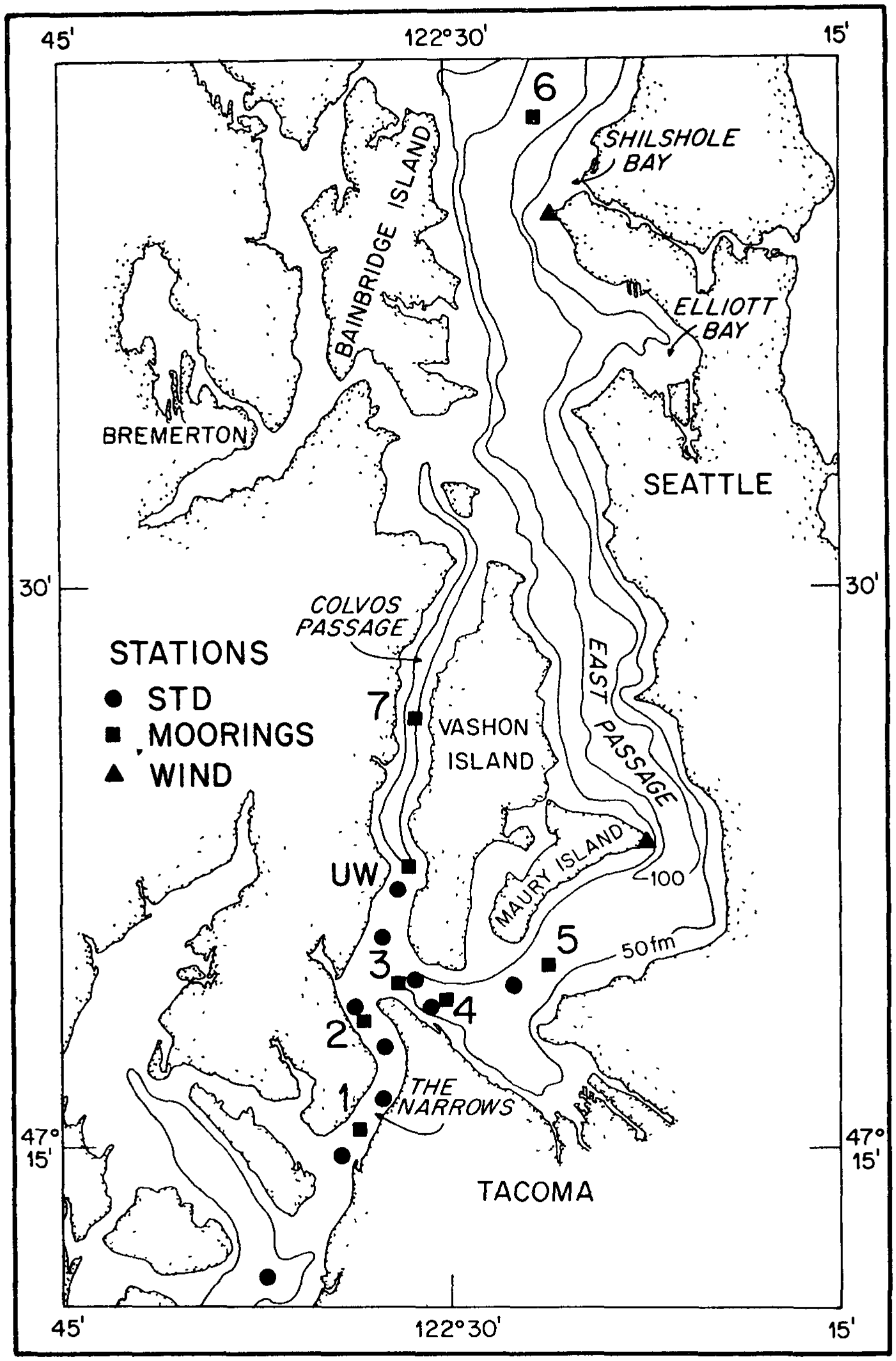


Figure 7. Station locations for The Narrows experiment. Contours are 50 and 100 fm (92 and 183 m).

Table 1. Summary of Narrows moorings, Feb-Mar 1977.

| No. | Depth m | Meter # | Lat., Long. N,E | Bottom m | Mean cm/sec | Speed °T | Tot. Var. $(c/s)^2$ |
|---|---|---|---|---|---|---|---|
| 1 | 45 | 2157 | 47° 15.6' | 51 | 5.7 | 205 | 5815 |
| | | | 122° 33.5' | | | | |
| 2 | 43 | 2162 | 47° 18.4' | 73 | 48.2 | 153 | 4830 |
| | 67 | 1830 | 122° 33.4' | | 42.8 | 144 | 3173 |
| | 68 | 1831 | | | 41.2 | 141 | 2923 |
| 3 | 19 | 2164 | 47° 19.4' | 102 | 35.3 | 294 | 633 |
| | 39 | 1832 | 122° 31.8' | | 33.1 | 297 | 630 |
| | 72 | 1833 | | | 30.7 | 299 | 768 |
| | 97 | 1834 | | | 21.6 | 293 | 550 |
| 4 | 15 | 2252 | 47° 18.9' | 152 | 14.0 | 276 | 242 |
| | 43 | 1835 | 122° 30.2' | | 15.5 | 280 | 198 |
| | 92 | 1987 | | | 14.8 | 290 | 240 |
| | 147 | 2166 | | | 10.3 | 286 | 368 |
| 5 | 29 | 2160 | 47° 20.0' | 181 | 12.2 | 237 | 135 |
| | 57 | 2159 | 122° 26.1' | | 12.5 | 233 | 146 |
| | 71 | 1825 | | | 10.3 | 233 | 148 |
| | 111 | 1803 | | | 8.3 | 232 | 187 |
| | 176 | 2478 | | | 6.6 | 220 | 129 |
| 6 | 19 | 1973 | 47° 42.3' | 203 | 6.9 | 031 | 188 |
| | 34 | 2502 | 122° 26.6' | | 4.4 | 044 | 149 |
| | 47 | 2503 | | | 3.5 | 053 | 146 |
| | 72 | 2504 | | | 1.1 | 346 | 163 |
| | 113 | 2505 | | | 6.1 | 244 | 204 |
| | 198 | 2488 | | | 9.5 | 228 | 138 |
| 7 | 15 | 1977 | 47° 26.5' | 115 | 30.1 | 356 | 535 |
| | 43 | 2258 | 122° 31.4' | | 27.8 | 357 | 469 |
| | 92 | 1827 | (no t, s) | | 26.4 | 353 | 483 |

Notes: Moorings 4 and 5 started on 23 Feb.; all others, on 24 Feb. Records exceeded 32 days except mooring 4 which was 31 days.

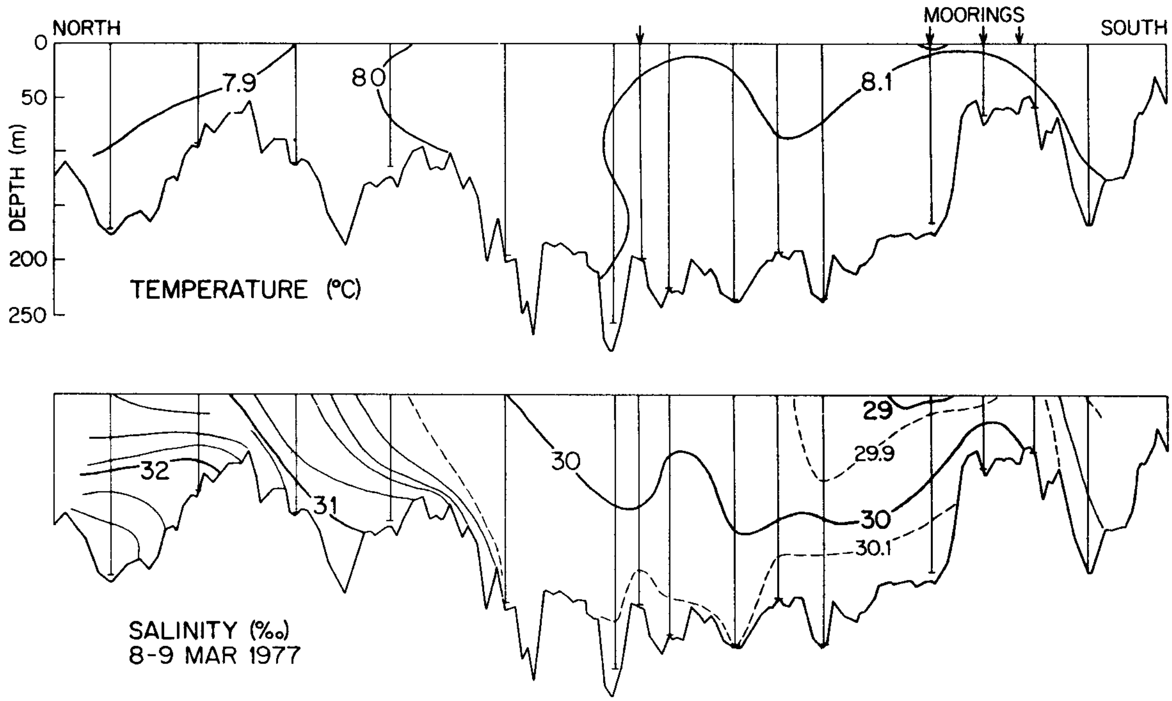


Figure 8. Temperature and salinity along Puget Sound. Arrows indicate mooring locations.

downward from north to south as a result of mixing over the sill. They resembled patterns observed in coastal plain estuaries.

Salinity and temperature were extremely uniform within the basin. Top to bottom salinity differences were 0.05-0.20 $^{o}$/oo. However, the existence of 30 $^{o}$/oo water during March was somewhat high for this time of year. Historically, 30 $^{o}$/oo water has been observed in the main basin during late winter-early spring only once in February-March 1953 (Collias et al., 1974). The 1953 and 1977 winters were similarly extremely dry. However, the 30 $^{o}$/oo water in 1977 occurred at even shallower depths than in 1953 and even penetrates into The Narrows.

Temperature variation from surface to bottom was about 0.05$^{o}$C. This is in agreement with historical data (Collias et al., 1974) and with the 1975-76 observations showing the main basin becoming isothermal by February-March (Cannon and Laird, 1978). However, these temperatures were about 0.5$^{o}$C warmer than those in the 1975-76 data. A surface lens of slightly colder and fresher water observed at the southern end of East Passage is attributed to runoff from the Puyallup River into Commencement Bay.

Daily average salinities from some of the moorings indicated a general decrease in salinity during the month (Figure 9). At the southern end of the main basin this decrease at the bottom was about 0.3 $^{o}$/oo. In The Narrows it was slightly less than 0.2 $^{o}$/oo, and in Colvos Passage, about 0.15 $^{o}$/oo. Temperatures were uniform everywhere to about 0.1$^{o}$C and showed variations of less than 0.1$^{o}$C during the month. Only at mooring 6 was there any systematic change, and it was a slight decrease. However, apparent small step decreases in temperature occurred starting on 25 February and on 9 March and are possible indications of new bottom water. The second was larger with a decrease of about 0.1$^{o}$C in two days. If these decreases were due to new bottom water, then the density differences were extremely small. They probably were similar to winter 1973 when density decreases could not be observed during bottom water intrusions and the overall salinity (density) decreased during the month-long observations (Cannon and Ebbesmeyer, 1978).

Observations of water properties through The Narrows on 9 March were very similar on ebb and flood tides (Figure 10). Salinities greater than 30 $^{o}$/oo existed in the north end of The Narrows during both tides. Properties were very uniform in The Narrows due to mixing by the large tidal currents which at times exceeded about 2 m/sec. A tongue of relatively denser water was observed along the bottom entering The Narrows from the north. This feature had been expected only during flooding currents Apparently, during ebbing currents the flow northward into Colvos Passage is large enough to maintain this upward flow of deeper water. If this is so, then there is a large fraction of the tidal day when deep water can be removed from the main basin. Observations on 1 March during smaller tides were similar.

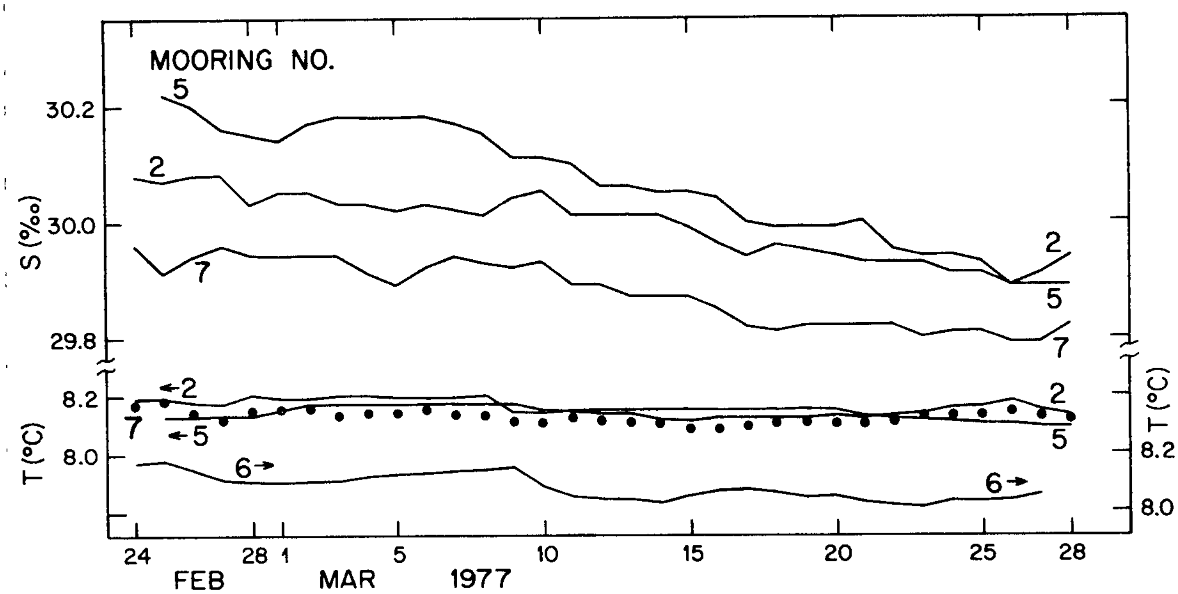


Figure 9. Daily average water properties from near bottom sensors on the indicated moorings. Mooring 7 is shown only by dots.

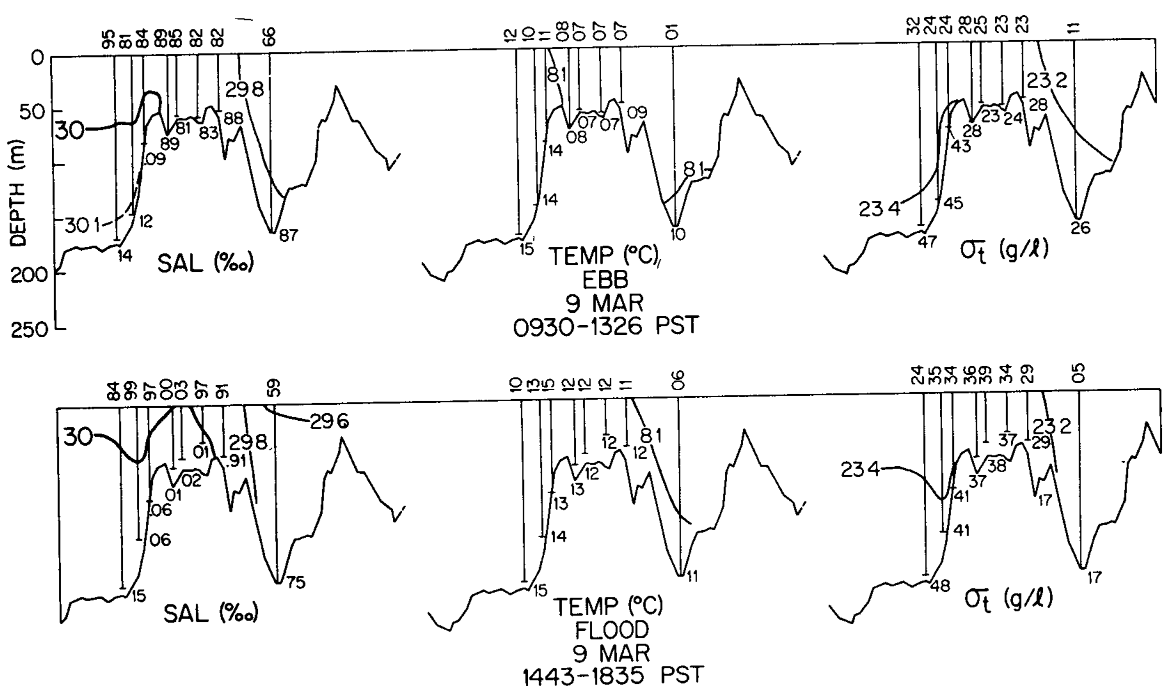


Figure 10. Temperature, salinity, and sigma-t through The Narrows during an ebb and the following flood tide. Decimal fractions of surface and near-bottom values are given.

## 2.3 Mean Flow

Hourly average current vectors were sequentially added to produce progressive vector diagrams (PVD) for each record. A vector from the start to the end of each PVD represents the mean direction and speed for the approximate month's duration (Figure 11). The PVD's all were reasonably linear except at 72 m at mooring 6 which apparently was alternately above and below the level of no-net-motion. Thus, the month-long mean is a reasonable concept. The vertical profile from the total record of along-channel speeds in the main basin at mooring 6 showed seaward flowing water in the upper layers and landward flowing water in the lower layers. The level of no-net-motion appeared near 70 m and was deeper than the 50 m depth determined in prior studies (Cannon and Ebbsemeyer, 1978; Cannon and Laird, 1978).

The reversal in mean current direction with depth observed at mooring 6 was absent from all records at the moorings in the Vashon Island area (3, 4, 5 and 7). Currents at each of these moorings displayed nearly uniform direction with depth extending from about 15 or 20 m to the bottom. It is assumed that the surface currents were similar. The slight turning of the currents with depth is attributed to changes in bathymetry with depth. Thus, it is concluded that there was a mean circulation clockwise around Vashon Island as has been deduced in the Puget Sound hydraulic model (Farmer and Rattray, 1963). Inflowing water in East Passage was compensated by outflowing water in Colvos Passage. This is, as far as the authors know, the first documentation in the field and over an entire month.

Mean current reversal with depth was not observed in The Narrows (moorings 1 and 2) mainly because the shallow instruments failed. In addition, large lateral changes are known near mooring 2 because of bathymetric effects. Tidal current tables indicate for the northern reaches of The Narrows that tides flood on the west and ebb on the east. Charts of surface currents produced using the hydraulic model of Puget Sound showed this same pattern (McGary and Lincoln, 1977). Mooring 2 was placed on the deeper, western side of The Narrows in order, hopefully, to measure deep water from the main basin flowing into The Narrows. Outflow either may have been at the surface or on the eastern side or both. Mean outflow at mooring 1 must have occurred in the surface layers in order to transport freshwater out of the southern basin.

Thus, main basin deep water on the average flows southward through Puget Sound and up into The Narrows. Here it is mixed with other water and becomes less dense. It is then refluxed northward through The Narrows and Colvos Passage and into the main basins but north of Vashon Island. From here, part may recirculate southward through East Passage, and part may flow northward in the upper layers of the main basin (Barnes and Ebbesmeyer, 1978). Still unanswered, however, is how often and under what circumstances the deep water flows up into The Narrows.

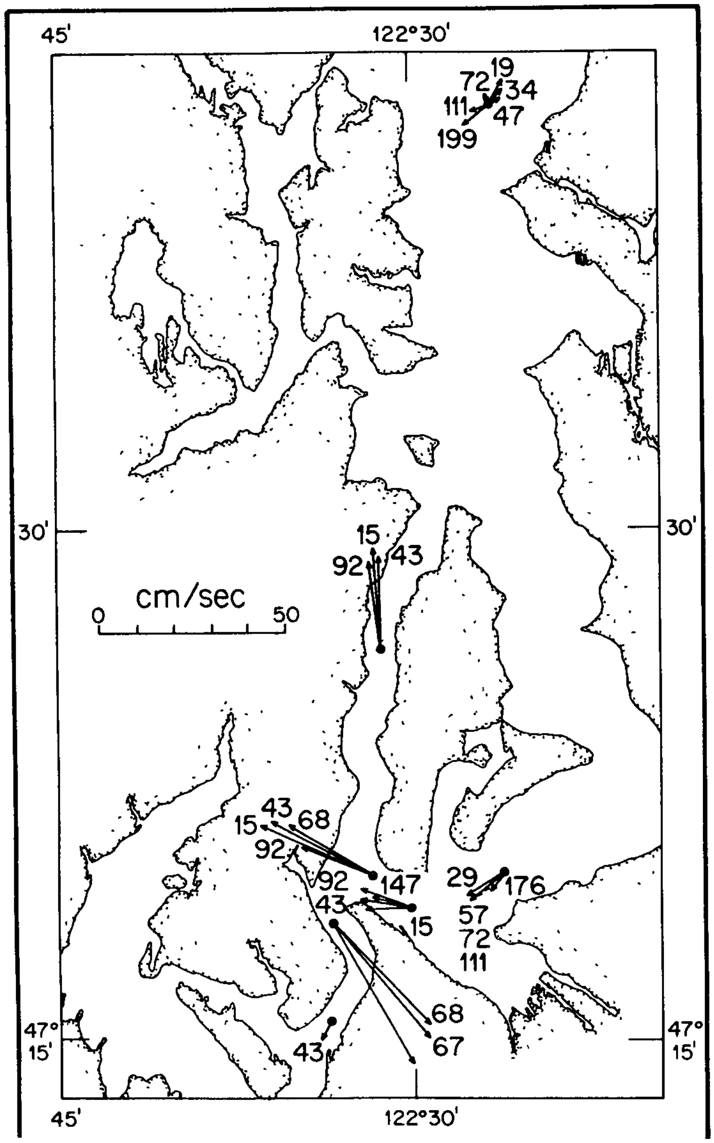


Figure 11. Vector average currents for total records at the indicated depths.

Daily average currents showed relatively large variations about the monthly means particularly near bottom (Figure 12). The largest variations were observed at mooring 6 in the northern part of main basin off Shilshole. Maximum southward daily average flows exceeded 15 cm/sec and occurred at about fortnightly intervals. The slight temperature step decreases (Figure 9) were simultaneous with the maximum southward flows. The relationship between bottom currents and the Puget Sound flood tidal range was the same as in the winter of the 1975-76 observations (Cannon and Laird, 1978). During this time of year the flood tidal range in Puget Sound was less than 3.5 m, yet significant and possibly some of the largest southward bottom currents occurred in the northern part of the main basin. There also was an approximate fortnightly cycle in the bottom currents at the southern end of the main basin off Tacoma at mooring 5. The maximum southward flow at mooring 5 lagged the maximum at mooring 6. by 5-9 days. Of special note was that neap tides on 2 March occurred during maximum southward daily average currents (10 cm/sec) at mooring 5, and that spring tides on 9 March occurred during minimum southward average currents (5 cm/sec). It is not yet clear whether this is more than coincidence.

## 2.4 Tidal Currents

The average currents discussed in the previous section had the tidal components removed. However, flow throughout Puget Sound is dominated by tidal currents, thus tidal characteristics must be included to examine particular circumstances, such as flow into The Narrows during flood current. The two pressure sensors on moorings 5 and 6, as well as tide tables, showed no difference between tidal heights and between times of high water throughout the main basin. Tidal flow through The Narrows is an hydraulic flow, and the largest currents occurred during the highest tides in the main basin (Figures 12 and 13). Note that the largest daily averaged flow through The Narrows also occurred during the highest main basin tides (opposite that noted above for mooring 5). The STD observations through The Narrows on 1-2 March were during the smaller currents and on 8-9 March were during larger currents.

Currents at mooring 1 behaved much like those forced by a standing wave reversing at high and low water (Figure 14). Speeds during flood were up to 200 cm/sec and were higher than during ebb by about 50 cm/sec representing the net in-estuary flow near bottom. The flow reversed direction quickly, and speeds exceeded 50 cm/sec within an hour of the reversal. This pattern was consistent throughout the month during spring (Figure 14) and neap (not shown) tides, although the speeds were smaller during neap tides.

Currents at mid depth and near bottom at mooring 2 behaved nearly identically. Each changed direction at the same time, and directional variations were within 10° throughout the record. Current speeds at mooring 2 were different than those observed at mooring 1 in that the maximum speeds during falling tide were noticably smaller and of shorter duration (Figure 14). The flow at mooring 2 primarily was in the flood direction and the ebbs were of relatively shorter duration. Outflow

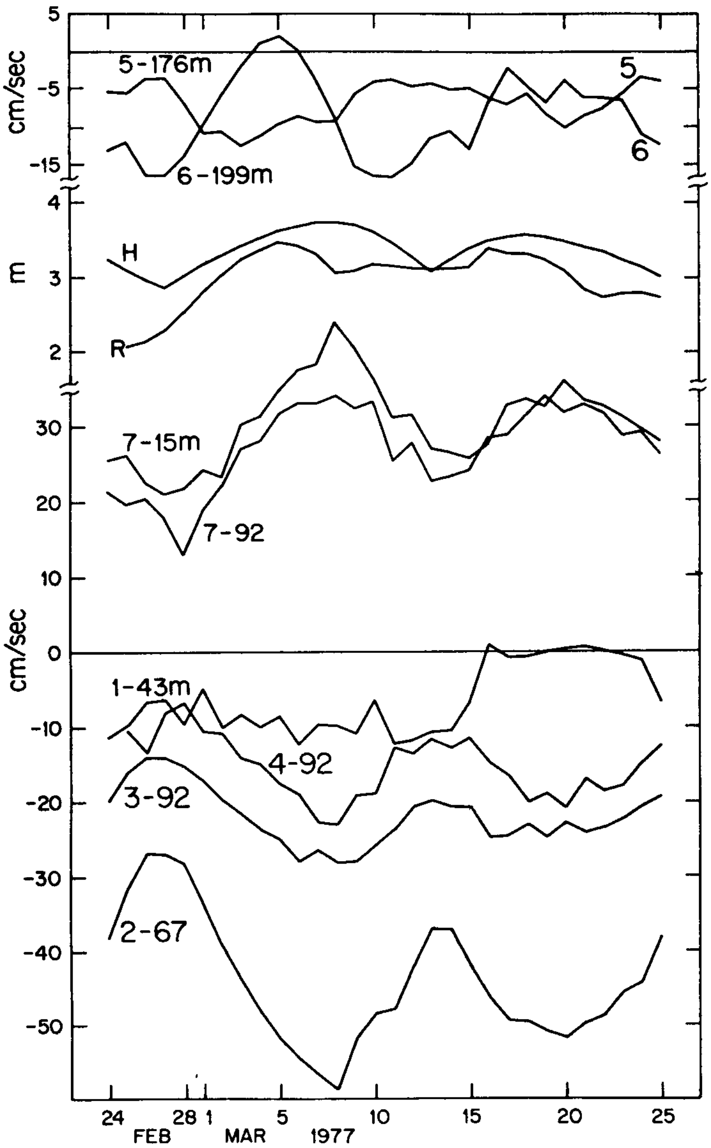


Figure 12. Daily average along-channel currents at the indicated moorings and depths; and range (R) and height (H) of greatest daily Seattle flood tide.

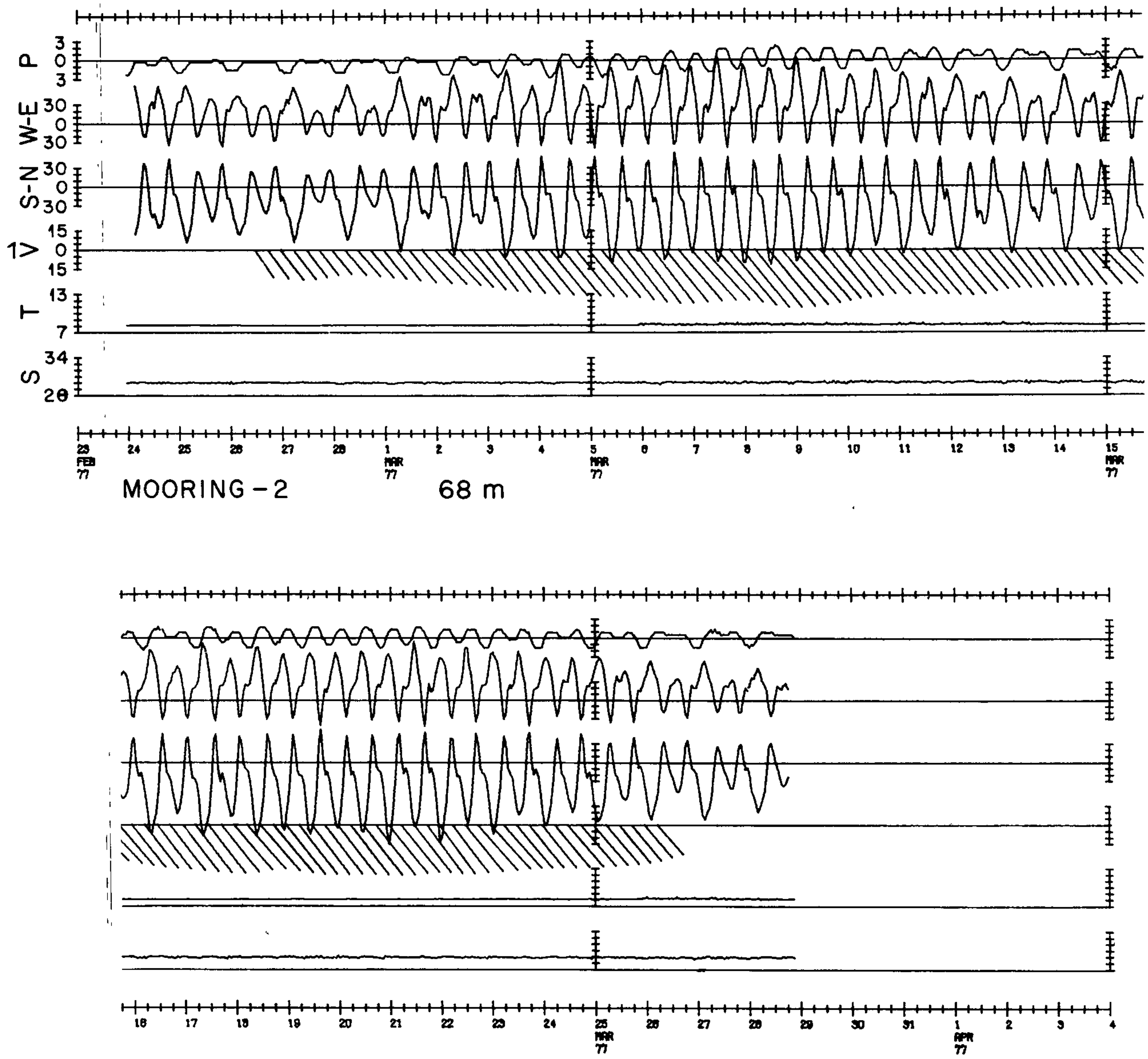


Figure 13. Pressure changes (m), currents (cm/sec), temperature ($^{o}C$), and salinity ($^{o}/oo$) for the near bottom meter at mooring 2 in The Narrows.

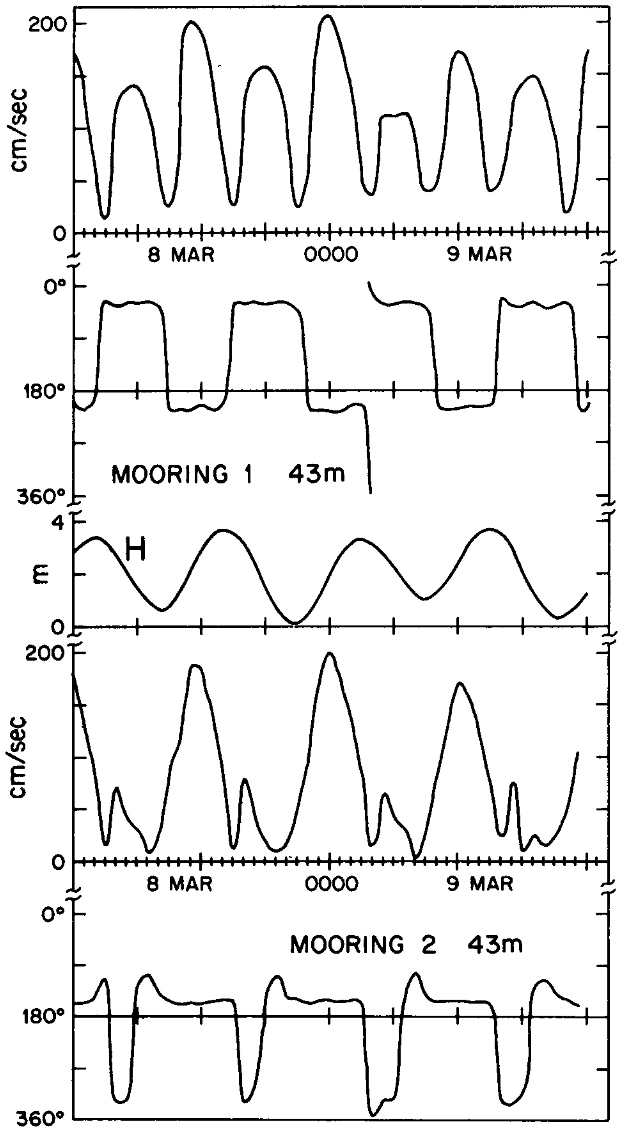


Figure 14. Hourly average speed and direction during spring tides at moorings 1 and 2; and tide height from mooring 5.

began slightly after high water and lasted only 2-3 hours reaching a maximum speed of about 75 cm/sec. Then while the tide was still falling, the flow reversed to inflow, although relatively weakly until after low water. Maximum speeds were up to about 150 cm/sec during the rising tide. The tidal current phases were similar for spring and neap tides. Because of the geometry of The Narrows near mooring 2, there is a large lateral variation in the tidal currents, and outflow primarily occurs on the east side (McGary and Lincoln, 1977). The mooring was located to measure the inflow.

Mean flow in Colvos Passage at mooring 7 was northerly or out-estuary at all depths (15, 43 and 91 m), and there were only about 2% instances of southerly flow in the original time series. Maximum speeds at mid depth were about 40 cm/sec during neap tides and about 80 cm/sec during spring tides. Daily average currents ranged from about 18-40 cm/sec during neap and spring tides, respectively, about half the maximum current.

East Passage mean flow was in-estuary as shown previously. Tidal currents, however, behaved somewhat differently than in The Narrows or in Colvos Passage. The variations at mooring 3 were nearly identical at all depths, and flow at mid depth at mooring 3 (68 m) is used as an example (Figure 15). Following high tide, ebb flow commenced out-estuary into East Passage from The Narrows. However, this out-estuary flow lasted only for 1-2 hours attaining maximum speeds of about 20 cm/sec. Then, while the tide was still falling, the currents reversed and flowed in-estuary. This inflowing current persisted through low water and the entire following rising tide until high water. These short-duration outflows were characteristic throughout the month. Following reversal to inflow, the speed continued to increase slightly and then decreased to less than 10 cm/sec just before low water. Inflow then continued during the rising tide reaching maximum speeds of about 100 cm/sec at all depths except right near the bottom. Slack water occurred at high water. It is important to note that the smaller increase in inflowing speed occurred during falling tide in the main basin, but flow in Colvos Passage was nearing maximum speeds flowing northward or out-estuary. This current reversal was characteristic at all depths at mooring 3 (15, 43, 68 and 93 m). The only difference was the duration of out-estuary flow. At the surface it was less than 1 hour and at the bottom it was up to 3 hours.

The secondary or smaller maxima in speed at mooring 3 were most obvious during spring tides from 7-11 March and occurred between each pair of the major or larger speed maxima. During neap tides of 24 February - 1 March these secondary speed maxima were not as obvious nor as regular. There apparently is a correlation between the higher speed outflows in Colvos Passage and the in-estuary flows occurring in East Passage during falling tide (Figure 16). Currents in Colvos Passage at mooring 7 were considered to be flowing out-estuary and were out-of-phase with the maximum speeds at mooring 7. During spring tides, the secondary speed

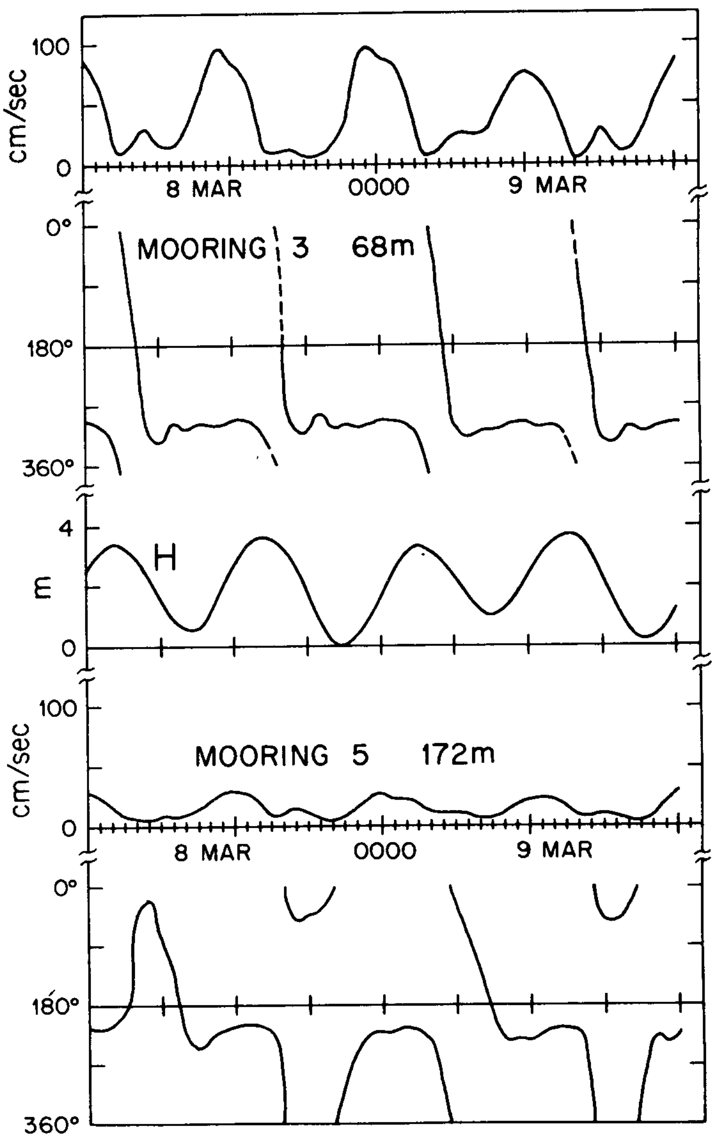


Figure 15. Hourly average speed and direction during spring tides at moorings 3 and 5; and tide height from mooring 5.

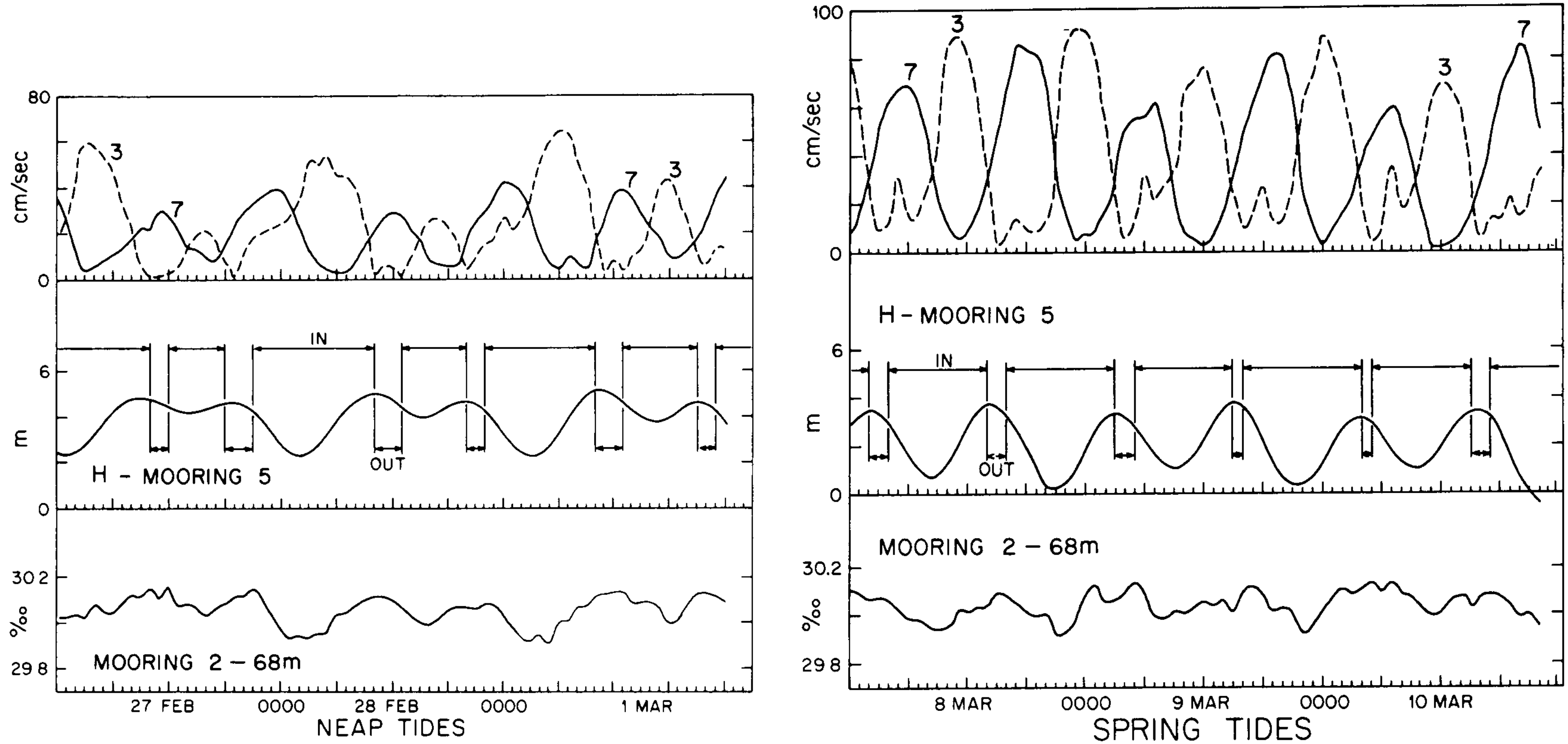


Figure 16. For neep and spring tides; hourly average speeds at moorings 3 and 7; tide height from mooring 5 indicating inflow (into The Narrows) or outflow at mooring 3; and salinity from near bottom at mooring 2.

maxima at mooring 3 were present under each speed maximum at mooring 7. However, during neap tides, these secondary maxima at mooring 3 were absent or of much smaller magnitude. It appeared that some minimum speed in the outflow in Colvos Passage must be reached to cause the inflow in East Passage during the falling tide in the main basin. This flow pattern would explain the similarities in water properties between ebb and flood during spring pattern tides (Figure 10).

Currents farther east in East Passage at moorings 4 and 5 were similar to those at mooring 3, but due to greater channel width and depth, they were of smaller magnitude. The near-bottom meter at mooring 5 (172 m) showed the largest deviations from mooring 3, and the currents were weak and variable during the falling tide (Figure 15). All other observations at moorings 3, 4 and 5 indicated that during the falling tide, flow was in the same direction as during flood or rising tide. Thus, water is advected southward toward The Narrows-Colvos Passage channel at all depths below about 15 m. Above that depth, there were no observations.

Salinity at the bottom of mooring 2 during both neap tides (27 February - 1 March) and spring tides (8-10 March) increased 0.1-0.2 $^{o}/oo$ during each rising tide (Figure 16). Salinity increased to nearly the same value (about 30.1 $^{o}/oo$) during each rising tide, and dropped to below 30 $^{o}/oo$ on each falling tide. These data implied that deeper water from East Passage was advected into The Narrows during flood, because the larger salinity changes (greater than 0.2 $^{o}/oo$) represented a significant fraction of the water column (Figure 10). However, it is not possible to determine from these data whether water from the bottom near mooring 5 was actually getting into The Narrows. If so, it was mixed to slightly lower values during transit. During the experiment primarily in Admiralty Inlet the following fall (discussed in Section 3), it was possible from STD observations to infer that water from deeper than about 120 m was being advected into The Narrows on flood tides.

### 2.5 Tidal Pumping

Previous sections have described water from East Passage being advected up into The Narrows-Colvos Passage channel and mixed with ambient water during both falling and rising tides in the main basin. The process producing aspiration of East Passage water probably is similar to that described by Stommel et al. (1973), who applied Bernouillis' principle to explain the passage of Mediterranean deep water over its shallow sill and into the open Atlantic Ocean. It was initially thought that the Puget Sound main basin deep water was advected into The Narrows only during flood tide, but it now appears that the ebb flow northward into Colvos Passage also advects water into Colvos Passage.

Intense mixing during transit through The Narrows-Colvos Passage channel yields a mixture less dense than the original deep water of the main basin. This homogeneous effluent from the north end of Colvos

Passage will assume an equilibrium level determined by the main basin stratification. Depth of this equilibrium level will not be in the deep water, but it may have significant consequences on the net circulation in the main basin. If the effluent density is above the level of no-net-motion, it will continue moving seaward. Thus deep water has been removed from the main basin, and increased southward flow must occur in the main basin deep water to replace it. However, if part of the effluent density is below the level of no-net-motion, that part will move landward and recirculate through East Passage. The southward flow of main basin deep water from farther north will then be reduced. Additional study is required to determine the fate of the effluent from the north end of Colvos Passage where the sill depth is about 53 m, which is the same as various long-term averages of the depth of no-net-motion farther north in the main basin (Cannon and Laird, 1976; also in NOAA Technical Memorandum ERL MESA-18).

To quantify the contribution to main basin circulation made by the tidal pumping of The Narrows, Helseth et al. (1976) conducted an experiment in the Puget Sound hydraulic model. Portions of the southern basin, The Narrows and Colvos Passage alternately were blocked from tidal action, and the resulting net circulation in the main basin deep layers were measured. Assuming that the volume of East Passage deep water pumped into The Narrows is related to the tidal prism received by the southern basin, then reducing the tidal prism in the southern basin likewise reduces the volume of East Passage deep water advected into The Narrows. Blocking The Narrows completely resulted in the largest reduction in volume transport by about 75%. Apparently,circulation in the main basin is extremely sensitive to the flow in The Narrows. Blocking the southern end of Colvos Passage permitted flow through The Narrows, but it did not allow ebbing currents to flow through Colvos Passage. In this case the reduction in transport was about 55%, and it supported the conclusion here that the flow into The Narrows-Colvos Passage channel from East Passage during falling tide in the main basin does contribute to transport of deep water out of the main basin.

Another possible consequence of the level of the Colvos Passage effluent in the main basin is related to the relatively large southward bottom currents observed during February-March during periods of small tides (Cannon and Laird, 1978). Bottom currents during February-March 1976 and February-March 1977 at mooring 6 showed weak seaward flow for 2-3 day periods between much longer periods of strong landward flow. Similar events were implied from data for Port Susan in winter 1970 (Cannon, 1975). As salinity drops during the winter rainy season, deep water tidally pumped from the main basin will mix with fresher water from the Puyallup and Nisqually rivers in The Narrows-Colvos Passage channel. The result may be an effluent from Colvos Passage which will remain above the level of no-net-motion producing the relatively large currents during winter-spring intrusions. During other seasons, the effluent density may be such that some is below and above the level of no-net-motion. However, this particular winter was extremely dry implying a more dense mixture, and the relatively large bottom currents were still observed. Thus, additional study is required.

2.6 Summary

Analysis of current and hydrographic data collected in February-March 1977 near The Narrows and Vashon Island showed a clockwise mean flow (averaged over the study period) around Vashon Island with currents flowing south through East Passage and returning north through Colvos Passage (Figure 11). This mean flow was observed from near surface to the bottom. During rising tide in the main basin, water flowed southward through East Passage, over the sill in The Narrows, and into the southern basin. On ebb, water flowed from the southern basin, through The Narrows and Colvos Passage, and into the main basin north of Vashon Island.

One new observation was that deep water could flow into The Narrows-Colvos Passage channel during falling tides as well as during rising tides (Figure 15). This appeared to be a consequence of the large northward currents in Colvos Passage. Although not determined, there may be a threshold speed in Colvos Passage during outflowing currents which must be reached before current reversal in East Passage takes place during falling tides. During the smaller neap tides, this current reversal did not always occur in East Passage.

The water property observations indicated that water deeper than sill depth was being advected into The Narrows (Figures 10 and 16). However, it was not possible to determine if water from the very bottom was being advected into The Narrows. This was because of the unusually dry year resulting in very uniform water properties. Observations in autumn 1977 when the Sound had returned to more normal stratification, discussed in Section 3, did indicate water from at least as deep as 120 m at mooring 5 was getting into The Narrows at mooring 2 during flood tides.

Although beyond the scope of these observations, it has been speculated that the mixed effluent from the north end of Colvos Passage also may influence the deep circulation. This effect would vary depending on the density of the effluent. If it is less than at the level of no-net-motion in the main basin, it would move seaward. If greater, it would move southward with the upper part of the deep water. During the latter case, less deep water from farther north would be able to move southward, and flow near mooring 6 should diminish. The opposite would occur if the effluent moved seaward, and may help explain the relately large bottom currents observed near mooring 6 during several winters.

Finally, it should be noted again that this study was conducted during an anomalously dry year. The low freshwater runoff into Puget Sound apparently allowed relatively higher than normal salinity water to persist throughout winter-spring. It also greatly reduced stratification in the estuary, producing anomalously uniform water at least during this month. The results of this experiment may be different under more normal conditions. Also, because of the uniformity it was not possible to determine from water properties the depth from which main basin water could be tidally pumped into The Narrows.

## 3. Admiralty Inlet

### 3.1 Experiment Description

During the fall of 1977 current meter and STD measurements were made to investigate the exchange of water through Admiralty Inlet into Puget Sound. Admiralty Inlet is the principle connection between Puget Sound and the Strait of Juan de Fuca and has relatively shallow water over its approximately 17 nautical-mile long sill. The shallowest depth of about 64 m is located near Port Townsend and results in intense mixing in the Inlet.

Seven subsurface current meter moorings were deployed by the NOAA ship McArthur in Admiralty Inlet and Puget Sound on 14-15 September for approximately two months and were recovered at various times in mid-November. Five moorings (8-12) were located in Admiralty Inlet (Figure 17), and two were in the main basin of Puget Sound at the same locations as moorings 5 and 6 during The Narrows experiment (Figure 7). In addition, one current meter without a vane was suspended from the Coast Guard buoy "SC" near the middle mooring (10) of the cross section in Admiralty Inlet. The primary function of this instrument was to measure near-surface temperature and salinity. Winds were monitored on land at West Point in the main basin and at Bush Point at the cross section in Admiralty Inlet. Pressure gauges were installed on moorings 12 and 6.

All moorings were deployed buoy first, and the anchors were lowered to the bottom and released by tension trip hook. Subsurface flotation was provided by a 50-inch diameter "clam shell" buoy just above the top current meter and by two 28-inch diameter spherical buoys above the bottom current meter. The clam shaped buoys were an experiment to decrease drag and tilt of the moorings in the high currents in Admiralty Inlet. The pressure gauges were clamped to the acoustic releases. All sensing instrumentation was manufactured by Aanderaa. The current meters recorded average speed and instantaneous direction, temperature, salinity, and pressure at 10-min intervals. Wind sensors recorded average speed and instantaneous direction every 20 minutes.

The current measurements were made at various levels at each mooring, but measurements near surface at 15 m and 5 m above bottom were planned to be common at each location. Mooring 6 was accidentally released about two weeks prior to recovery. However, it was sighted and reported by a commercial ship at the same time of planned recovery. Also, the main subsurface flotation on mooring 12 collapsed just after deployment, and the bottom meter was the only one which functioned. A summary of the functioning meters is given in Table 2.

Temperature and salinity measurements were made twice, during low flood tidal ranges on 19-22 September using the charter vessel Snow Goose and the McArthur, and during higher tidal ranges on 17-18 October

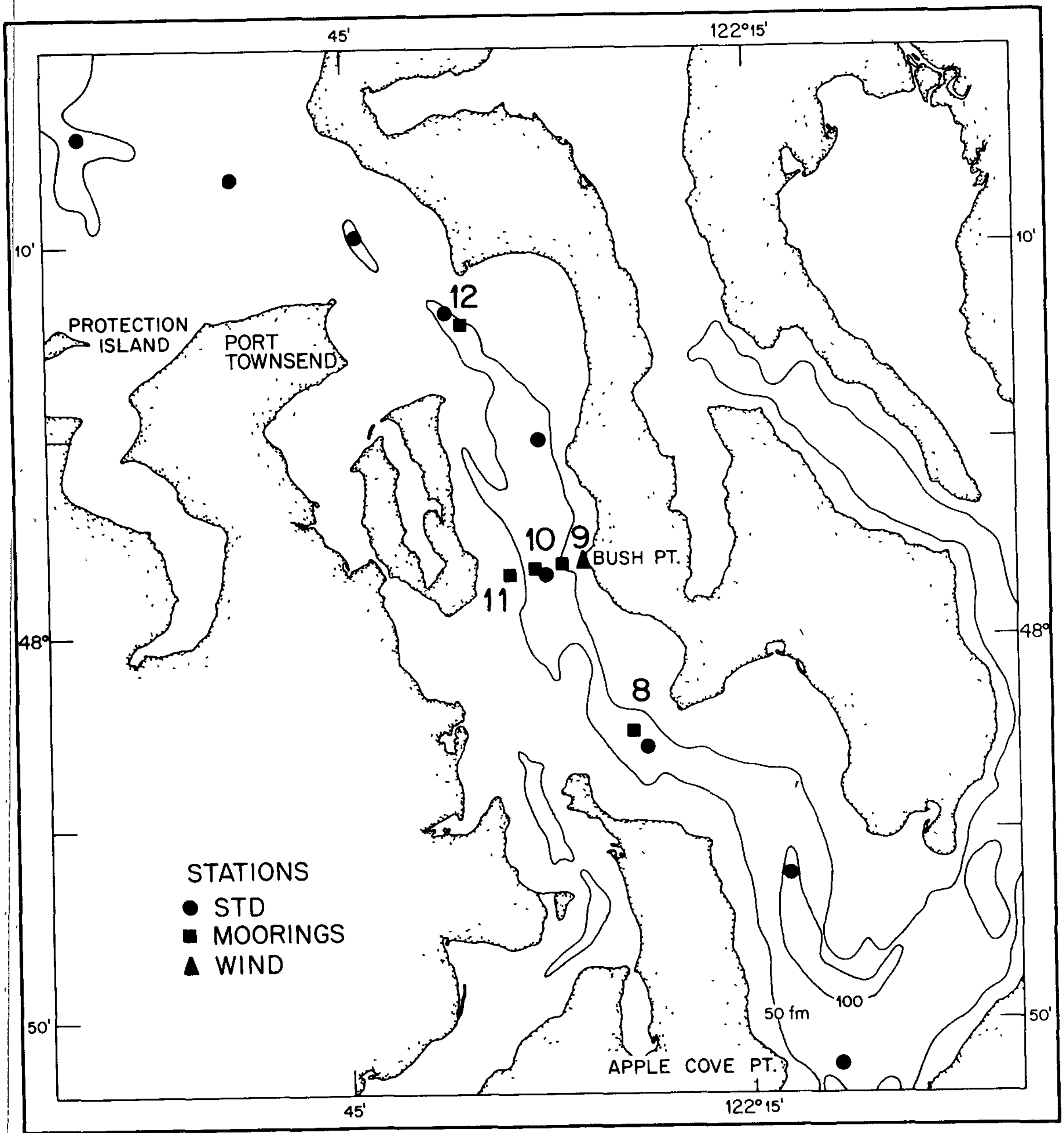


Figure 17. Station locations for the Admiralty Inlet experiment. Contours are 50 and 100 fm (92 and 183 m).

Table 2. Summary of Admiralty Inlet moorings, Sept-Nov 1977.

| No. | Depth m | Meter # | Lat., Long. N,E | Bottom m | Length days | Mean Speed cm/sec | $^{o}$T |
|---|---|---|---|---|---|---|---|
| 12 | 89 | 1669 | 48$^{o}$ 08.7' 122$^{o}$ 41.9' | 104 | 57 | 14.8 | 152 |
| 11 | 18 | 2157 | 48$^{o}$ 01.6' | 60 | 57 | 25.7 | 008 |
| | 52 | 2499 | 122$^{o}$ 38.9' | | 57 | 7.0 | 056 |
| 10 | 2 | 2445 | 48$^{o}$ 01.7' | 108 | 57 | -- | -- |
| | 16 | 2156 | 122$^{o}$ 38.0' | | 57 | 18.5 | 341 |
| | 32 | 2167 | | | 57 | 7.2 | 342 |
| | 55 | 1809 | | | 57 | 11.7 | 249 |
| | 72 | 1671 | | | 57 | 12.0 | 164 |
| | 103 | 2496 | | | 57 | 12.6 | 185 |
| 9 | 23 | 2511 | 48$^{o}$ 01.8' | 112 | 57 | 18.2 | 274 |
| | 107 | 1676 | 122$^{o}$ 37.2' | | 57 | 20.9 | 193 |
| 8 | 18 | 2493 | 47$^{o}$ 57.5' | 109 | 55 | 16.1 | 289 |
| | 30 | 1828 | 122$^{o}$ 34.5' | | 51 | 11.5 | 290 |
| | 70 | 1820 | | | 55 | 6.6 | 152 |
| | 104 | 2492 | | | 38 | 14.1 | 114 |
| 6 | 18 | 2252 | 47$^{o}$ 41.8' | 200 | 45 | 10.0 | 035 |
| | 54 | 1807 | 122$^{o}$ 26.9' | | 45 | 3.4 | 029 |
| | 110 | 1675 | | | 45 | 6.7 | 289 |
| 5 | 16 | 2513 | 47$^{o}$ 20.0' | | 56 | 5.5 | 239 |
| | 55 | 1814 | 122$^{o}$ 26.2' | | 61 | 9.9 | 235 |
| | 176 | 1805 | | | 61 | 8.6 | 225 |

Notes: Moorings 12-9 started on 14 Sept.; 8-5, on 15 Sept. Mooring 11 was moved on 12 Oct.; 18-m vane broken, thus velocity shorter than 57 days.

using the Snow Goose. The plan was to obtain one set of STD observations when the flood tide range exceeded 3.5 m, hence during inflow of bottom water into Puget Sound, and one during much smaller tidal ranges and no inflow of bottom water (Figure 18). As it turned out, inflow occurred during both sets of STD's. The low tidal range case was analogous to the 1975-76 year-long observations when inflow also occurred in late summer during low tidal ranges. Also of significance was the good agreement between the measured tidal range and that predicted from tide tables.

Unfortunately, the data logger failed both times aboard the Snow Goose, so analog CTD records were hand digitized at 6-m intervals. The McArthur STD data were averaged to provide values at 1-m intervals. On the Snow Goose a Plessey 9400 was used and on the McArthur, a Plessey 9006. Nansen-cast data were used to calibrate both instruments.

## 3.2 Water Properties

Temperature, salinity, and sigma-t sections were made through Puget Sound from the Strait of Juan de Fuca to south of The Narrows on 22-23 September (Figure 1). This section had been planned when bottom water was not expected to be entering Puget Sound; however, both water properties and currents indicated such a flow to exist. Although the previous winter had been dry and water properties were uniform and higher than usual, the sections here indicated the Sound had returned to more normal conditions. Water just outside the Admiralty Inlet still had a salinity only slightly less than 33 $^{o}/oo$ at the bottom. Historically, that water outside the Admiralty Inlet at times has salinity slightly exceeding 33 $^{o}/oo$, but this usually occurs earlier than mid-September (Collias et al., 1974).

More detailed STD sections were made through Admiralty Inlet on 19-20 September to assess the differences in structure during ebb and flood currents. The section during ebb showed a fairly uniform tilt to the isolines through Admiralty Inlet. The section was made from Puget Sound to the Strait of Juan de Fuca, and maximum ebb occurred during occupation of the middle stations. Relatively colder and saltier water appeared to be held just outside the shallowest part of the sill at Port Townsend. Water colder than 9$^{o}$C and saltier than 32 $^{o}/oo$ was at depths shallower than the sill depth, almost like it was being piled up there. At the other end of the Inlet, water colder than 11$^{o}$C and saltier than 31 $^{o}/oo$ was not getting into Puget Sound proper.

The section during flood was made the following day in the reverse direction, and maximum currents occurred during occupation of the first stations near the shallowest part of the sill. The 9$^{o}$C and 32 $^{o}/oo$ isolines in the Strait were now below sill depth, sloped up over the sill, and then down into the deeper water inside the sill. The upward trend probably is a Bernoulli effect much as was described earlier for The Narrows. Various isolines indicated deeper water flowing down into the deep hole midway across the sill and then up over the next shallower region. Water slightly colder than 11$^{o}$C and slightly saltier than 31 $^{o}/oo$ is seen getting

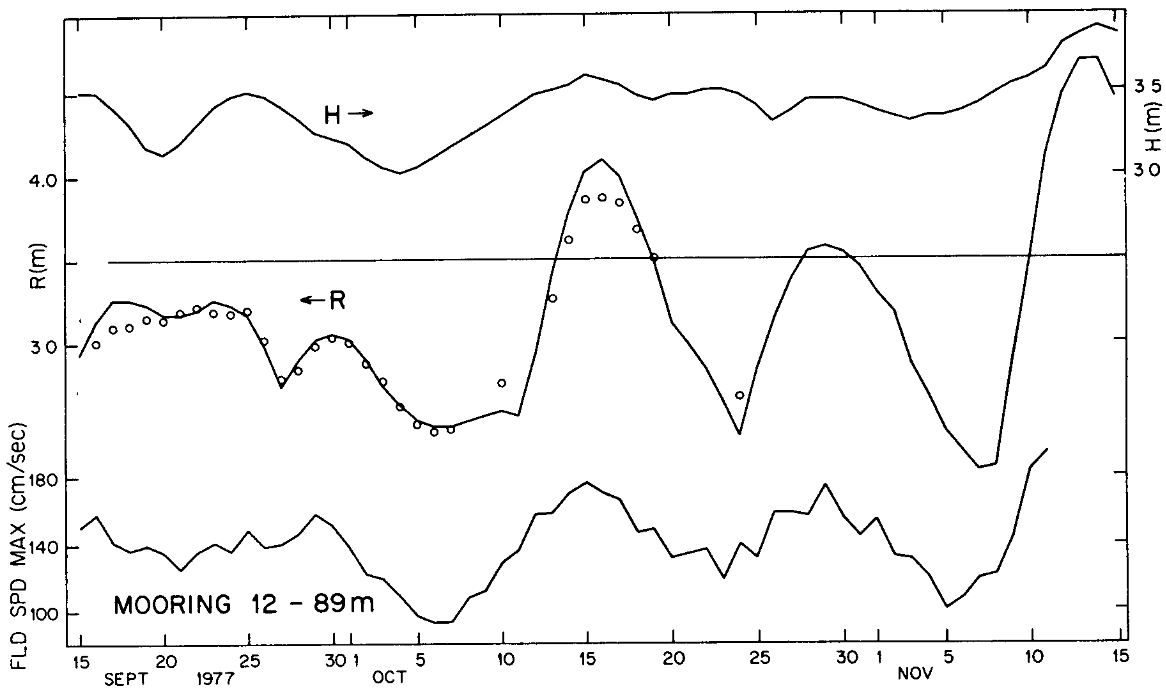


Figure 18. Range (R) and height (H) of greatest daily Seattle flood tide; and maximum flood tide near bottom at the entrance to Admiralty Inlet at mooring 12. Circled values of R are from pressure gauge on mooring 6, otherwise R and H from tide tables.

into the northern end of the main basin of Puget Sound, but it is confined there. Of greater significance was water represented by the 11.4 and 11.6°C and the 30.8 $^{0}/oo$ isolines which did not appear in the main basin during the 19 September ebb section. These isolines extended into the main basis on the flood section during 20 September, and then extended partway down the Sound to mid-Seattle during the longer section on 23 September (Figure 19). This distance of about 16 nautical miles in 3 days implied a mean speed of about 10 cm/sec. which is very realistic from previous studies.

The flood section through Admiralty Inlet was repeated a month later on 19 October and showed the same up and down contours as in Figure 20. This perhaps is characteristic of large flood currents through the Inlet when new bottom water enters the main basin. The long section on 23 September was made through Admiralty Inlet during the last half of a weak flood (0.9 knots predicted maximum at Bush Point) and resembled more the ebb transect. Thus, the contours in the main basin indicating new bottom water at this time probably represented water that had already entered on previous larger floods. One major difference on the 19 October section was that 11°C water extended almost to mooring 6 off Seattle. As will be seen later, this water eventually extended the entire length of the main basin to mooring 5 at Tacoma. Also, the deep water in the Sound cooled during the month interval. A section made on 17-18 October showed that the 11.4°C isotherm extended along the entire length of the main basin. Previously the 11.8°C isotherm was the coldest spanning the entire basin. Salinity, however, remained about as before, except that the saltier 30.8 $^{0}/oo$ water was entirely absent.

A 24-hr STD time series at mooring 11 in Admiralty Inlet on 22 September showed that the 11°C isotherm moved seaward of the location during ebbs and the 10°C isotherm moved landward on one flood. Bottom salinity varied from about 31.0 $^{0}/oo$ to greater than 31.4 $^{0}/oo$. A similar series in the main basin at mooring 6 off Seattle on 21 September showed the arrival during flooding currents of bottom water colder than 11.6°C and saltier than 30.8 $^{0}/oo$.

Of special significance was the third STD time series on 20 September at the location of mooring 2 in The Narrows (Figures 7 and 21). Bottom salinities greater than 30.6 $^{0}/oo$ and temperatures colder than 12°C were observed during flooding currents. This time series, when considered with the STD section along the Sound 3 days later on 23 September (Figure 19), indicated that this water came from depths greater than 120 m in the main basin (the limit of the southernmost STD) and was being observed at about 70 m in The Narrows. The bottom water at the southern end of the main basin at that time was about 11.8°C and 30.7 $^{0}/oo$ as measured by the Aanderaa meters on mooring 5.

More details of the variations in water properties throughout the approximate 2-month interval can be seen in daily averages from the Aanderaa neters. Three occurrences of inflow at approximately fortnightly intervals represented by increasing salinity (density) and decreasing temperature were observed at the bottom of mooring 12 just inside the

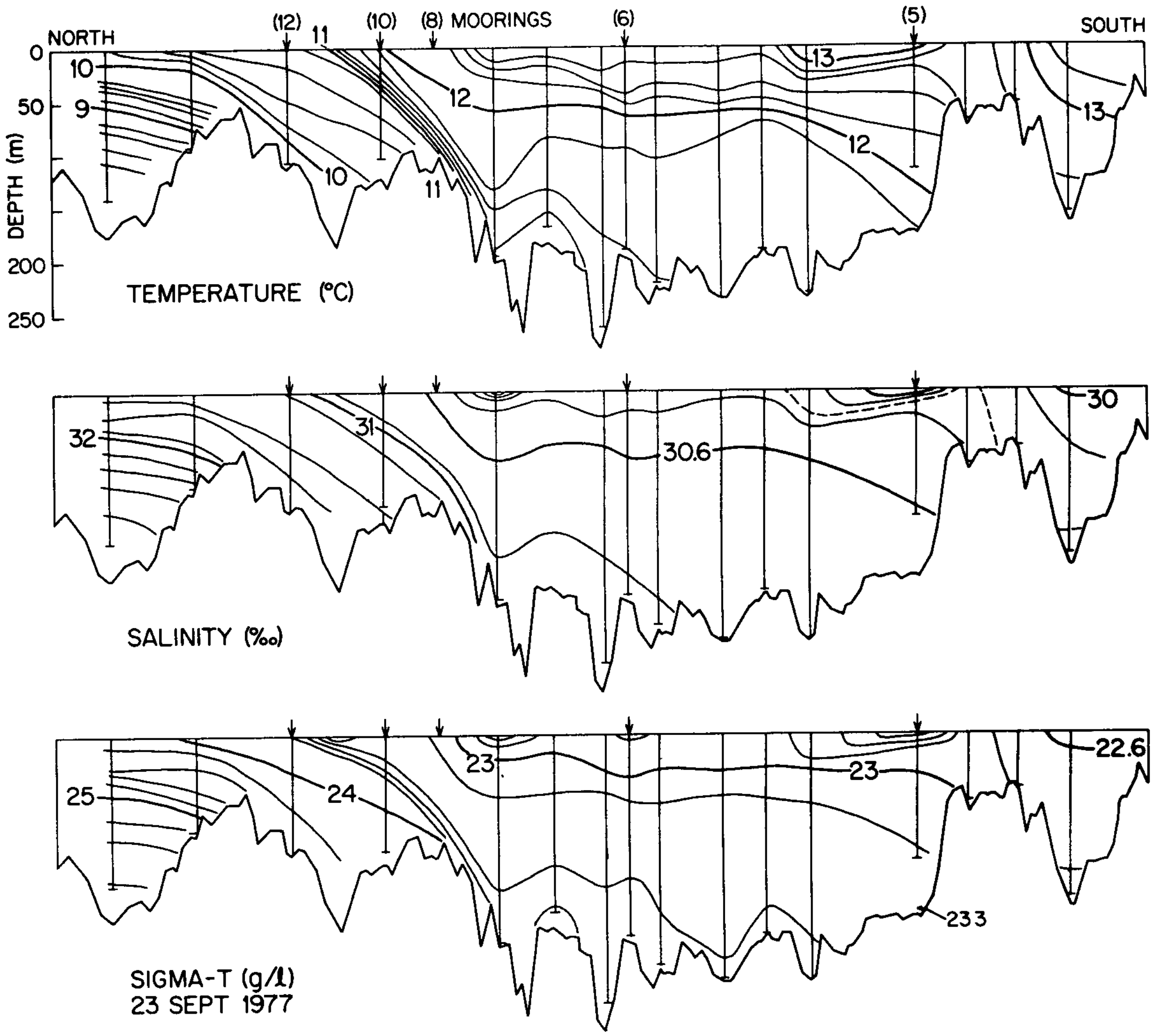


Figure 19. Temperature, salinity, and sigma-t along Puget Sound. Arrows indicate mooring locations.

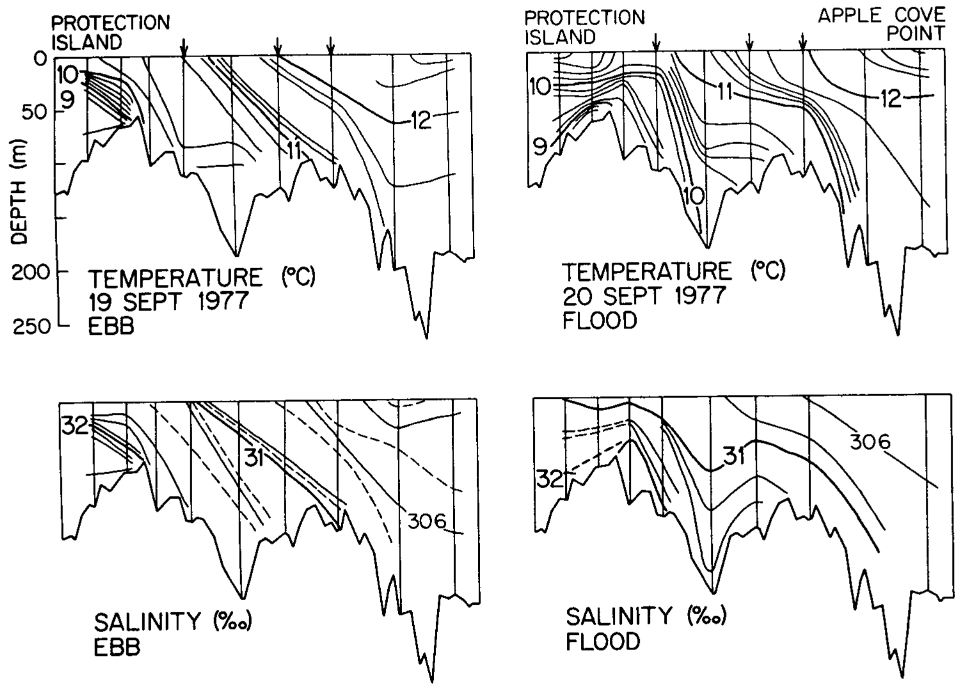


Figure 20. Temperature and salinity through Admiralty Inlet during an ebb and a flood tide.

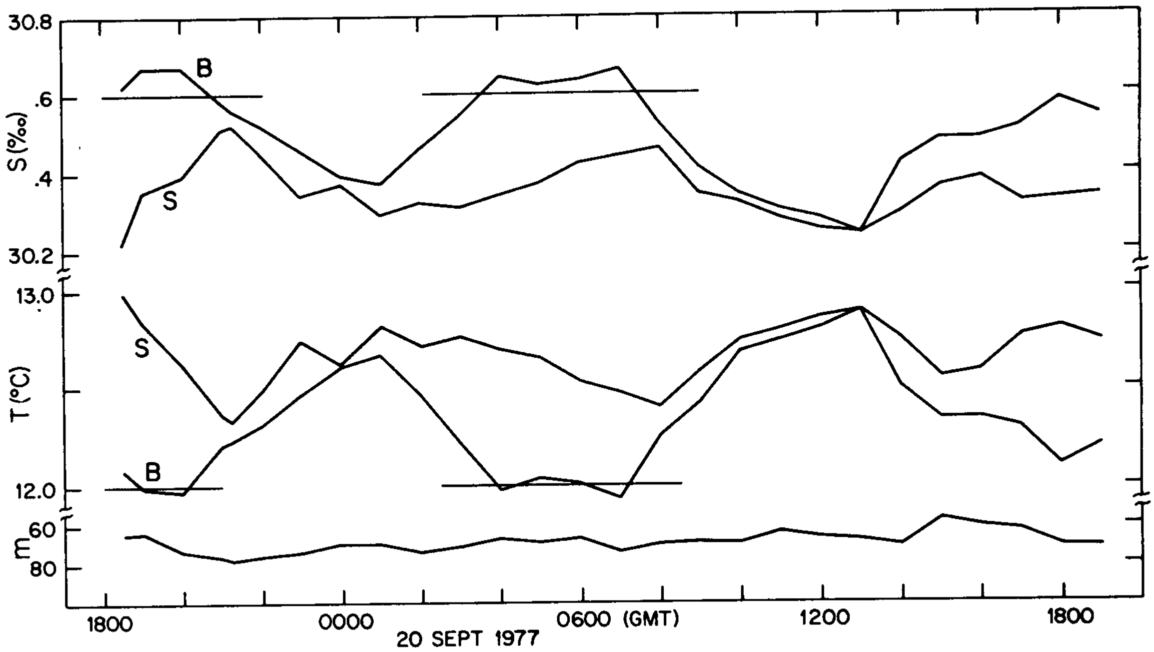


Figure 21. Temperature and salinity at the surface and bottom in The Narrows at mooring 2 shown on Figure 7. Depth of bottom also is given.

shallowest part of the sill near Port Townsend (Figure 22). The largest changes were during the second interval when salinity increased 0.7 $^{0}$/oo and temperature decreased 0.6$^{o}$C in 5 days. It will be shown later that these changes actually occurred during increases in landward bottom flow, which always was directed into the estuary. There was a general decrease in temperature during the two months, and except at the end of the records, salinity returned to about the same values following the first two increases. The apparent continual decreasing salinity following the third increase may be the commencement of the relatively large autumn decrease shown in the 1975-76 observations. The first set of STD observations during 19-23 September were made at the end of the first inflow, while those during 17-19 October were made at the onset of the third inflow. Hence,new bottom water was observed midway along the main basin of Puget Sound during the first STD's but only at the extreme north end during the second.

Midway through Admiralty Inlet at mooring 10 off Bush Point, the meters in the bottom 30 m of water showed similar characteristics to those at mooring 12 (Figure 23). Instruments in the upper 50 m of water, however, indicated a reverse effect, temperature increased and salinity decreased during the increased bottom-water inflows, particularly during the first two. Average bottom temperatures were about 0.5$^{o}$C higher and average bottom salinities about 0.1 $^{o}$/oo lower at morring 10 than at mooring 12.

At the south end of the Admiralty Inlet sill at mooring 8, just past the entrance to Hood Canal, modulation in the temperature and salinity observations was similar to those at mooring 10 (Figure 24). Colder and saltier water during increased inflow also occurred in the bottom 30 m of water. However, average bottom temperatures had increased about 0.3$^{o}$C over those at mooring 10, but salinities were about the same.

Observations midway along Puget Sound at mooring 6 during the first month showed a general decrease in temperature in the upper 100 m (Figure 25). Salinity increased slightly near surface, remained about the same near 50 m (the long-term approximate depth on no-net-motion), and decreased slightly at mid-depth near 100 m. The bottom instrument failed completely, and all observations ceased at the end of October when the mooring was released prematurely.

Observations at the south end of Puget Sound at mooring 5 near Tacoma also showed a general decrease in temperature and fairly uniform salinity (except near surface) during the 2-month observation interval (Figure 27). Temperature became uniform throughout the water column about the end of October. Near-surface salinity showed a large decrease commencing about 22 October, probably indicating increased outflow of the Puyallup River into Commencement Bay at Tacoma.

Of special significance at mooring 5 were the step decreases in bottom-water temperature. These were identical to those observed farther north near mooring 6 during winter 1973 and during autumn 1975, and they are the first observation of step decreases at any other location in the main basin. Although the bottom Aanderaa current meter failed at

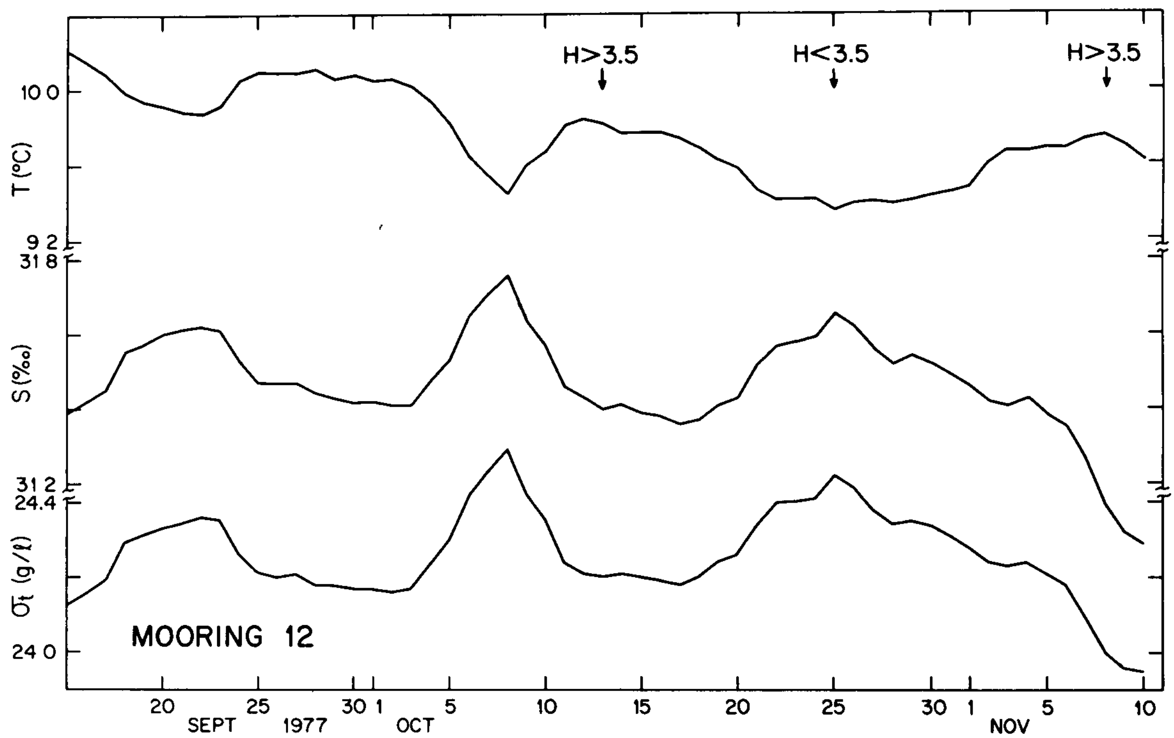


Figure 22. Daily average temperature, salinity, and sigma-t from near bottom at mooring 12.

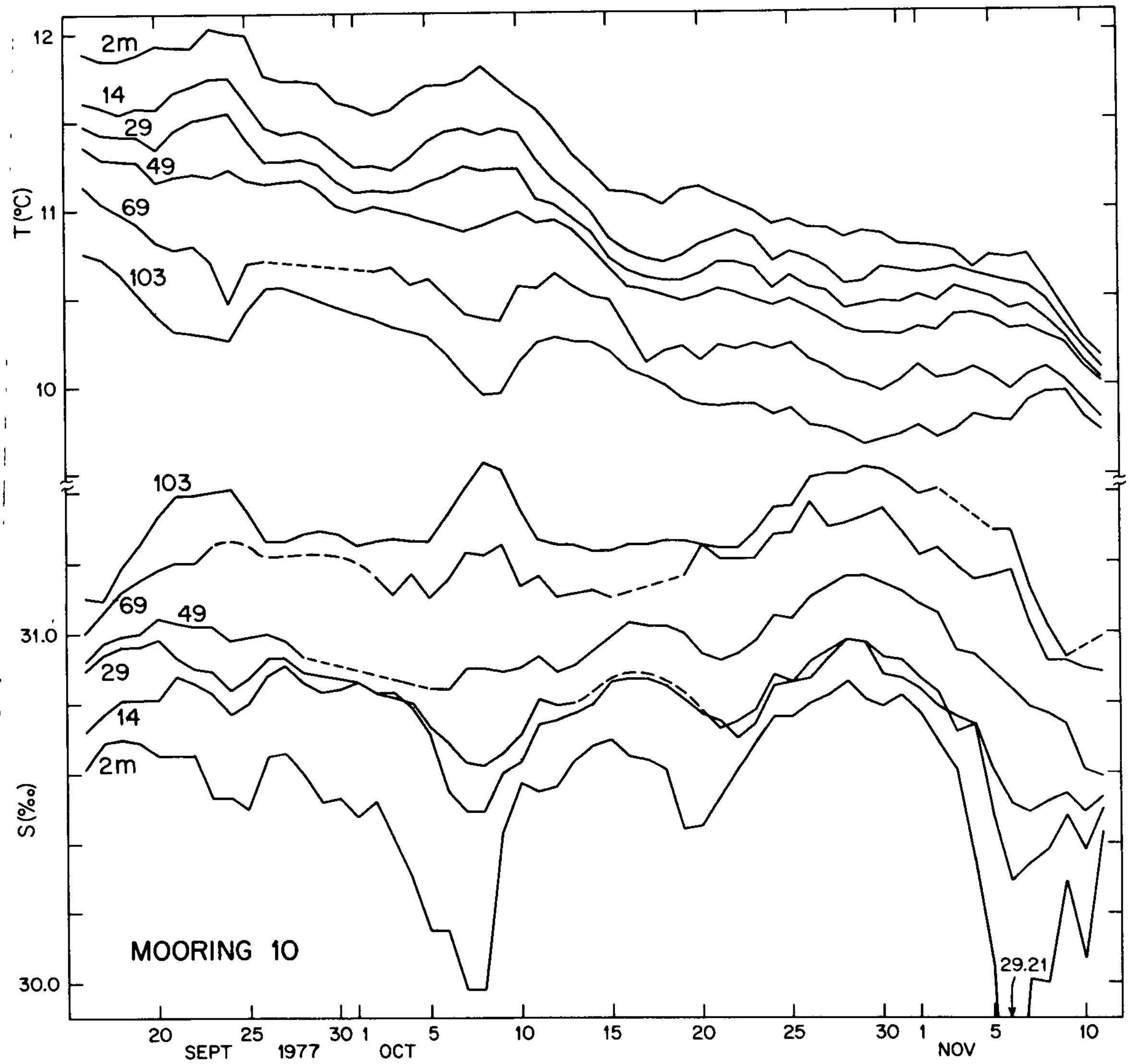


Figure 23. Daily average temperature and salinity from mooring 10 at the indicated depths.

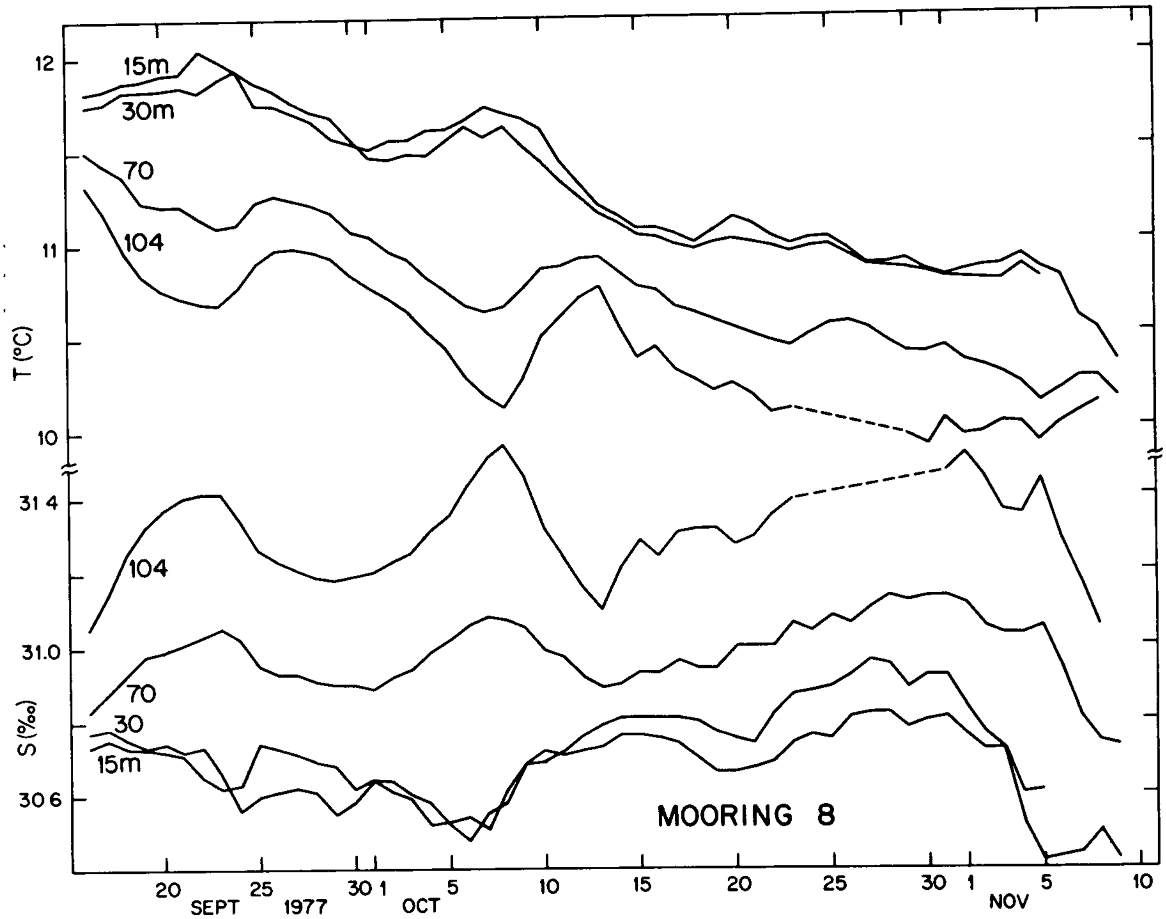


Figure 24. Daily average temperature and salinity from mooring 8 at the indicated depths.

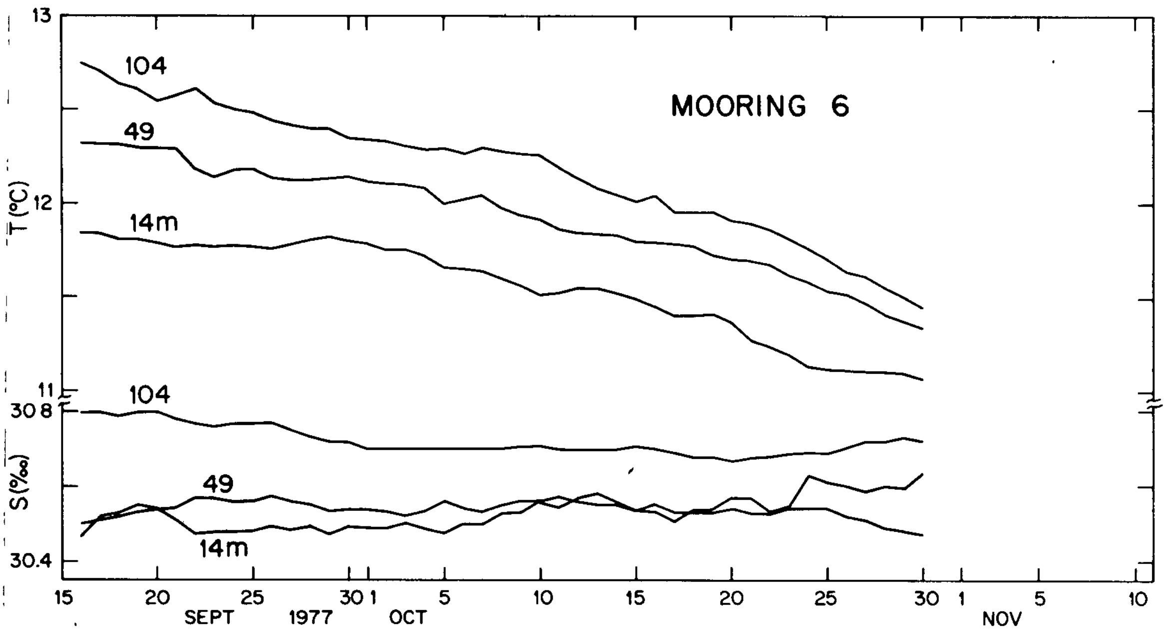


Figure 25. Daily average temperature and salinity from mooring 6 at the indicated depths.

mooring 6, there was a temperature sensor on the pressure gauge which was attached to the acoustic release at the bottom. Daily average temperatures from part of this record have been included in Figure 26. About 7 days were required for the step decreases to transit the approximately 25 nautical miles between the two moorings, implying an average speed of about 8 cm/sec. The minima temperatures during these decreases were 0.4-0.5°C warmer by the time the southern end of the main basin was reached.

Total-record average temperatures decreased with depth and increased from the Strait of Juan de Fuca into Puget Sound (Table 3). Little variation at comparable depths was indicated along Puget Sound between moorings 6 and 5. Generally, smaller standard deviations were in Puget Sound proper. The higher value at 16 m at mooring 5 is attributed to influence of the Puyallup River outflow. Salinities increased with depth and decreased from the Strait into the Sound. The decreases at 32 m at mooring 10, at 30 m at mooring 8, and at 55 m at mooring 5 were due to partial record errors. Standard deviations were much lower in Puget Sound than in Admiralty Inlet. The higher standard deviation at 72 m at mooring 10 was the result of partial record errors.

### 3.3 Currents

Because of the geometry associated with Admiralty Inlet, some of the total-record vector average currents indicated directions across channel which are not realistic (Table 3). They are the result of ebb and flood currents not being 180° out-of-phase. The records were rotated such that +u was seaward along the direction of maximum variance. All moorings, except 5, have average seaward flow (+) in the surface water and average flow into the estuary (-) in the deeper water. The depth of no-net-motion at mooring 6 was somewhat deeper than 49 m and, although it is difficult to tell from three points, it may have been about 60 m. This is about the same depth as in September-November 1975 during the year-long observations. The flow at mooring 5 was southward at all depths as was described in The Narrows experiment. The level of no-net-motion was at about 40 m at mooring 10 in Admiralty Inlet. It was shallower on the east side and deeper on the west side which indicated curvature effects exceeded Coriolis effects. Along-channel variances in speed were significantly greater in Admiralty Inlet than in Puget Sound and were largest near Bush Point. Also, there was a decrease in variance with depth at the midchannel moorings (8 and 10) in Admiralty Inlet.

The records were low-pass filtered for periods greater than 30 hr, and then daily averages were computed for conceptual convenience (Figure 27). Of significance is the relatively large fortnightly variation in the currents in Admiralty Inlet. It is most obvious at mooring 8 where the upper two current meters showed increased outflow when the lower two meters showed increased inflow. The increased inflow in the deeper water corresponded directly with the intervals of increasing

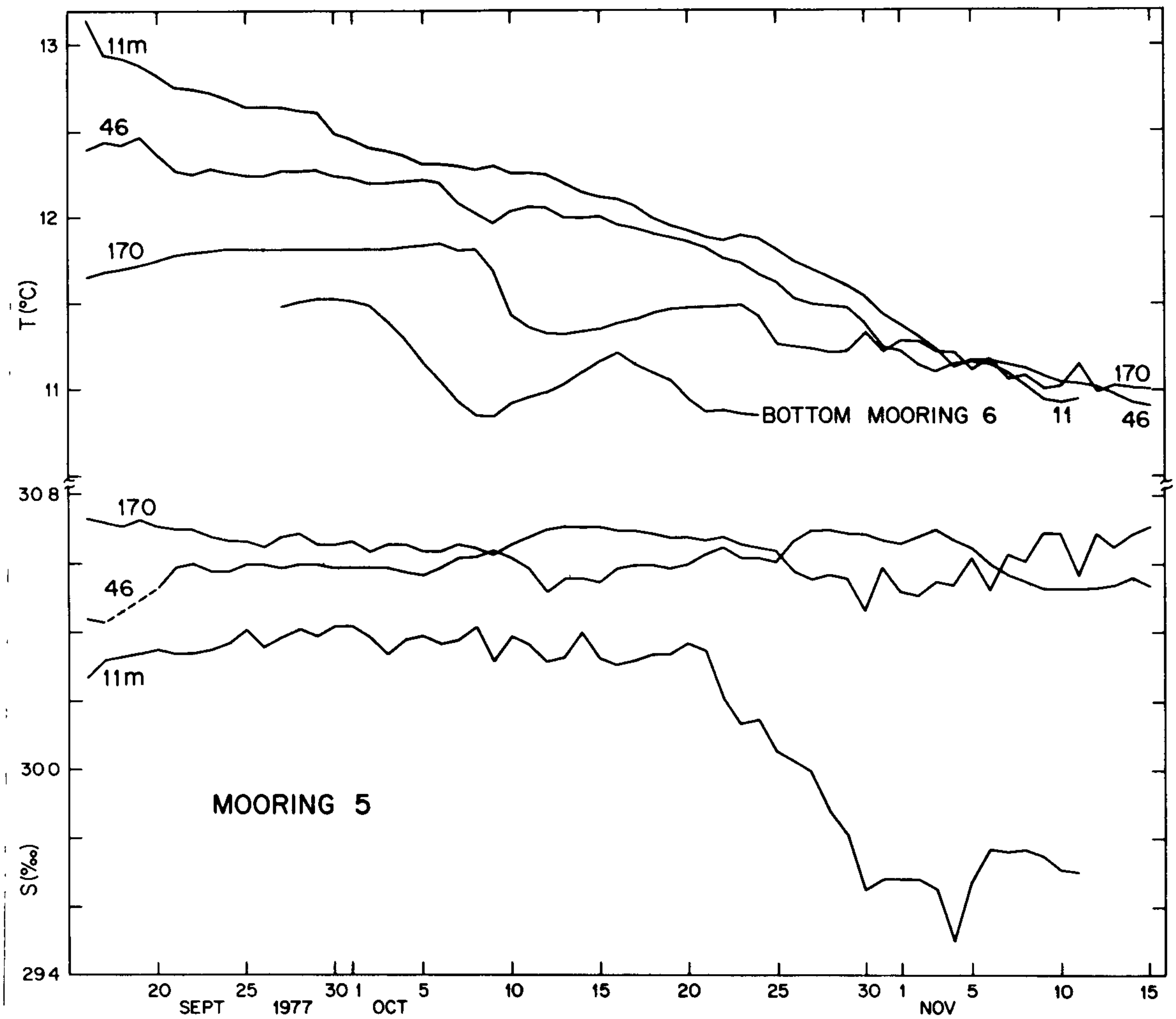


Figure 26. Daily average temperature and salinity from mooring 5 at the indicated depths. Also shown are daily average near-bottom temperatures from the pressure gauge on mooring 6.

Table 3. Total-record statistics.

| No. | Depth m | Dir +u | $\bar{u}$ cm/s | u, var $(c/s)^2$ | $M_f$ c/s | $\bar{t} \pm$ s.d. °C | $\bar{s} \pm$ s.d. °/oo | |
|---|---|---|---|---|---|---|---|---|
| 12 | 89 | -46° | -14.2 | 5564 | 5.0 | 9.76±.5 | 31.60±.3 | |
| 11 | 18 | - 6° | 8.0 | 4320 | 9.2 | 11.01 .5 | 30.75 .2 | |
| | 52 | - 4° | 3.4 | 4720 | .9 | 10.58 .5 | 31.20 .2 | |
| 10 | 2 | -- | -- | -- | -- | 11.35 .5 | 30.53 .4 | |
| | 16 | -10° | 18.2 | 6940 | 1.8 | 11.10 .5 | 30.74 .2 | |
| | 32 | - 6° | 6.9 | 6476 | .7 | 10.94 .5 | 30.72 .4 | * |
| | 55 | - 2° | -3.8 | 6042 | 2.0 | 10.78 .5 | 30.96 .2 | |
| | 72 | - 4° | -12.0 | 5739 | 3.7 | 10.42 .5 | 31.21 .5 | |
| | 103 | - 5° | -12.4 | 2977 | .5 | 10.13 .4 | 31.29 .2 | |
| 9 | 23 | - 8° | 3.9 | 7267 | 2.2 | 11.17 .5 | 30.29 .2 | |
| | 107 | - 2° | -19.9 | 3707 | 3.8 | 10.18 .4 | 31.4 | * |
| 8 | 18 | -50° | 15.2 | 5930 | 2.4 | 11.34 .5 | 30.72 .2 | |
| | 30 | -49° | 8.9 | 5619 | 1.5 | 11.31 .5 | 30.69 .2 | |
| | 70 | -42° | - 6.3 | 4277 | 5.8 | 10.78 .5 | 30.99 .2 | |
| | 104 | -39° | -12.4 | 1996 | 6.8 | 10.61 .5 | 31.29 .2 | |
| 6 | 18 | 21° | 9.8 | 277 | 3.5 | 12.17 .4 | 30.53 .1 | |
| | 54 | 24° | 3.4 | 154 | .9 | 11.91 .3 | 30.54 .04 | |
| | 110 | 46° | - 6.5 | 186 | 1.6 | 11.54 .3 | 30.72 .05 | |
| 5 | 16 | 60° | - 5.6 | 64 | 1.2 | 12.13 .5 | 30.19 .3 | * |
| | 55 | 51° | - 9.4 | 122 | 2.2 | 11.91 .4 | 30.63 .2 | |
| | 176 | 40° | - 8.7 | 222 | 4.6 | 11.54 .3 | 30.65 .1 | |

Notes: Mooring 10, 32 m salinity low 13-18 Oct. Mooring 9, 107 m salinity bad 18-22 Sept. and rotor fouled 26-28 Sept. Mooring 5, 16 m speeds low 19-22 Oct. $M_f$ is approximate fortnightly amplitude.

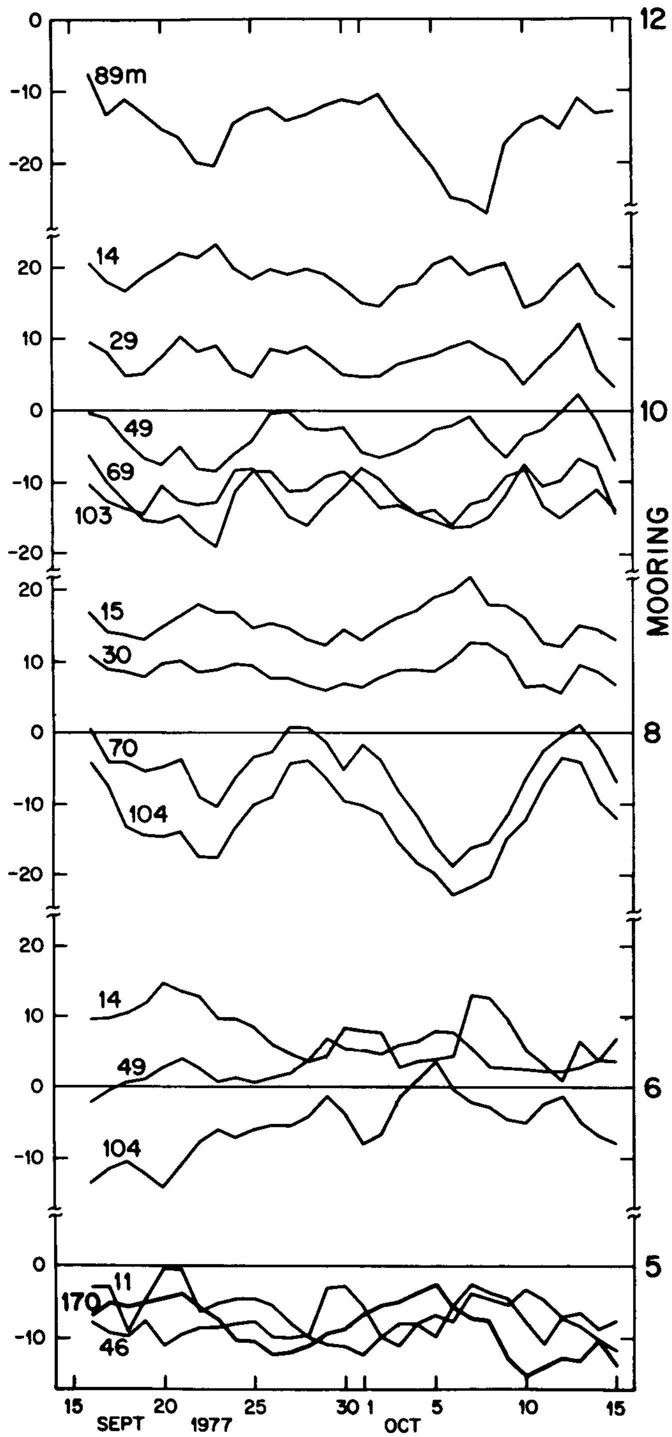


Figure 27. Daily average along-channel currents at the indicated moorings and depths. Speeds are cm/sec.

salinity and decreasing temperatures discussed earlier. The maximum inflow occurred simultaneous with the property extremes. The only exception was at the bottom (103 m) at mooring 10 where inflow increased around 28 September but was minimum at the bottom at moorings 12 and 8 to the north and south, respectively. The 69-m record at mooring 10 was more similar to those at the bottom at moorings 8 and 12, but it also showed a small increased inflow on 17-28 September analogous to the larger increase at 103 m. The amplitudes of the approximate fortnightly signals were determined from a fast Fourier transform of the initial 30-day records (Table 3). They were a few cm/sec except at 103 m at mooring 10. It is unclear if the differences at the bottom between mooring 10 and moorings 8 and 12 were real or a result of instrument malfunction. The bottom meter nearby on mooring 9 failed during the days in question. The first increasing bottom inflow interval which peaked on 23 September occurred during winds blowing out-estuary, but the second and largest which peaked on 6-8 October occurred during winds blowing in-estuary (Figure 28).

The daily average currents in the main basin at mooring 6 showed similar increasing outflow near surface at 14 m and increasing inflow at mid-depths at 104 m. However, the signal was smaller than in Admiralty Inlet. Also during the 30 days, there were trends which indicated increasing seaward flow at 49 m and decreasing landward flow at 104 m, and on 4-5 October seaward flow existed at 104 m and shallower. Outflow was greatest at 49 m, and about equal at 14 and 104 m. Winds during the preceeding 5 days had been the strongest from the north (Figure 28), and the level of no motion deepened significantly as was seen in the 1972 and 1973 winters (Cannon and Laird, 1976). Probably some amount of surface water was flowing southward as seen in 1973. Outflow also was greatest at 49 m on 29 September and 12 October when relative minima occurred at 104 m.

At mooring 5 at the southern end of the main basin, near-surface flow was variable, but always southward. Flow at the bottom, however, had a large fortnightly variation of about 5 cm/sec. The largest bottom flow occurred on 10 October and was coincident with the arrival of the temperature step decrease on 9-10 October (Figure 26). The average speed at the bottom at mooring 5 from 5-10 October was 8 cm/sec, which was what was required to transport the temperature front from mooring 6 to mooring 5 in about 7 days.

### 3.4 Replacement Processes

Still unanswered is when do some of the flows of new bottom water into Puget Sound commence. The increased inflow commencing about 13 October as shown by the bottom temperature decrease at mooring 12 (Figure 22) occurred about when the Puget Sound flood tide range exceeded 3.5 m (Figure 18). This is the primary process discussed for field observations by Cannon and Laird (1978) and for model observations by Farmer and Rattray (1963). However, it was indicated in the 1975-76

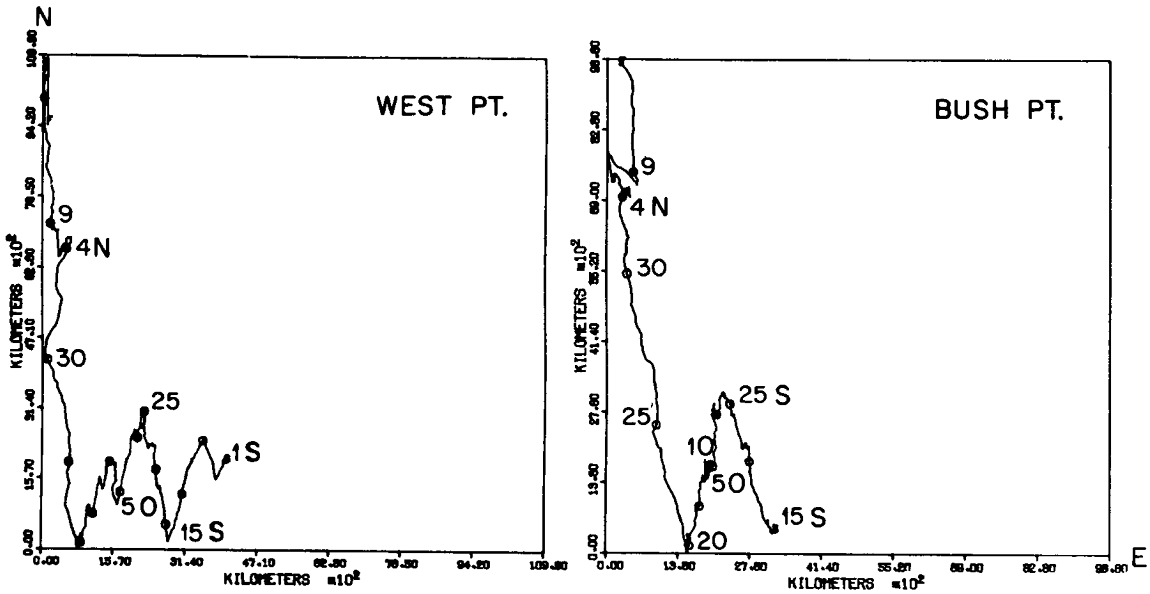


Figure 28. Progressive vector diagrams of winds at Bush Point in Admiralty Inlet and at West Point in Puget Sound. Circles are at 5-day intervals, and the dates are indicated by the day and first letter of the month.

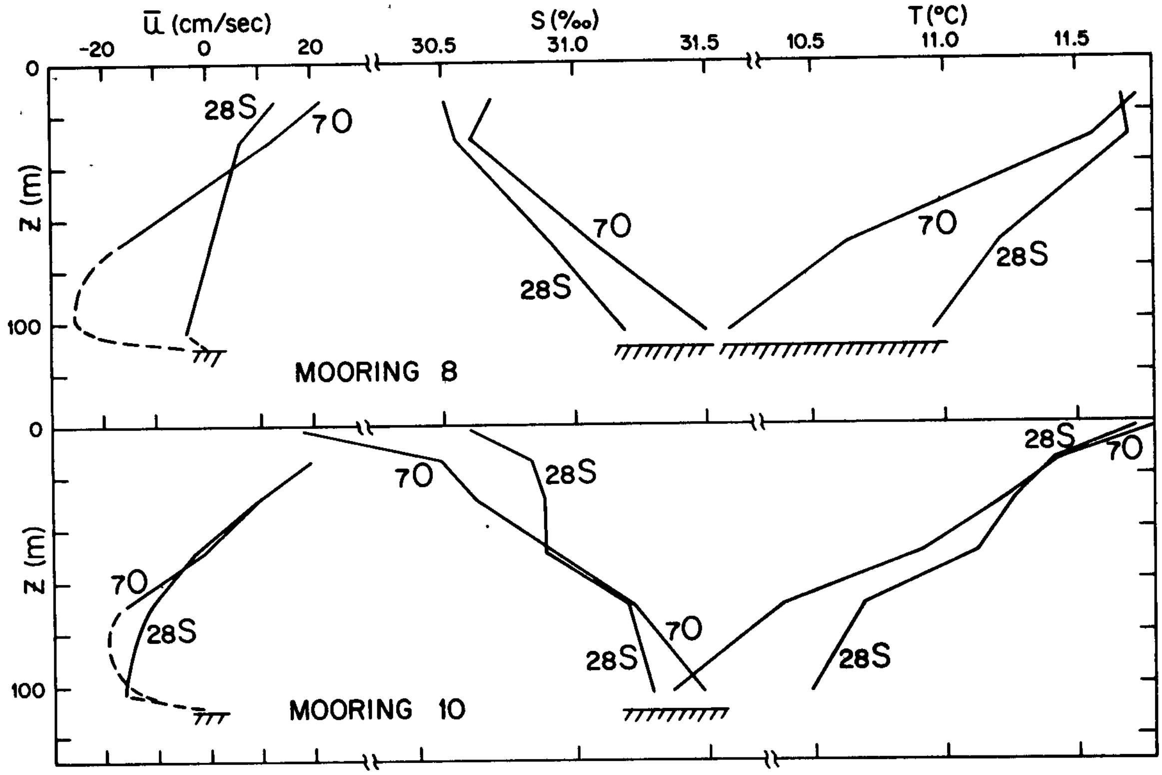


Figure 29. Daily average profiles of currents, salinity, and temperature at moorings 10 and 8 during a maximum bottom inflow (7 October) and during a minimum bottom inflow (28 September).

observations by Cannon and Laird that inflows also occurred when the flood tide range did not exceed the 3.5 m, one interval was in winter and one was in late summer-early fall. This latter time was repeated here, and two inflows were observed during the low tidal ranges. The first inflow peaked about 23 September and was documented with STD and current meter observations. The second peaked about 8 October as shown by current meter observations.

These two inflows occurred during minimum amplitudes in tidal currents at the bottom at mooring 12 (Figure 18). However, the duration of the flooding currents appeared inversely related to their maximum amplitude. At mooring 12 on 20 and 29 September and on 7 October, the durations and amplitudes were about 8½, 7, and 8½ hr, and 134, 158, and 93 cm/sec, respectively. No increased bottom inflow occurred during 29 September. The durations and amplitudes at the other end of Admiralty Inlet at mooring 8 were about 10½ and 6 hr, and 100 and 90 cm/sec on 20 and 29 September, respectively. Finally, both duration and maximum amplitude of the flooding current were large when the flood tide range exceeded 3.5 m. On 16 October they were about 8 hr and 170 cm/sec at mooring 12.

This situation was similar to one described for inflow across the Port Susan sill (Cannon, 1975) which occurred similutaneous with minimum variance in the flow. It was speculated there that perhaps the term in the averaged equation of motion which includes the horizontal gradient of the square of the rms tidal velocity (Rattray, 1967) was important under some circumstances. However, there were insufficient data for the Port Susan observations to make such an estimate. There are sufficient data for the Admiralty Inlet observations and these gradients will be estimated in the near future to attempt to better understand why new bottom water enters Puget Sound during these low tidal ranges. One possibility speculated by Cannon and Laird (1978) was that the water was sufficiently dense that it did not matter that more than one tidal cycle was required to transit the sill causing further mixing and reduction in density. If this is so, then it is still unanswered as to why the fortnightly cycle.

Finally, mean daily profiles at moorings 8 and 10 show some differences during a maximum bottom inflow on 7 October and during a minimum bottom inflow on 28 September. The maximum was greater at mooring 8, but the minimum was greater at mooring 10. Larger top-to-bottom gradients existed in both temperature and salinity during the maximum inflow.

### 3.5 Summary

Observations of currents and water properties were made in Admiralty Inlet and in the main basin of Puget Sound during September-November 1977. The primary purpose was to provide a better description of characteristics over the entrance sill during some intervals of new bottom water flowing into Puget Sound. The observational interval included occurrences of inflow both when flood tide ranges in the main basin exceeded 3.5 m and when 3.5 m was not exceeded (Figure 18). Late summer-early fall also was one of the two times during 1975-76 year-long observations in the main basin when inflow occurred during low tidal ranges. The other was during late winter.

Temperature-salinity sections through Admiralty Inlet showed alternating up and down slopes of the isolines approximately following the bathymetry during flooding currents when new bottom water was entering Puget Sound (Figure 20). This characteristic occurred during flood currents both with low flood tidal ranges (20 September) and with high ranges (19 October). During ebb currents or weak floods, there was a more uniform slope of the isolines upward toward the north which intersected both the surface and the bottom. In this situation water appeared to be held just outside the entrance sill. Agreement between water properties from the STD (Figure 19) and from the Aanderaa sensors on the same day was excellent. During low tidal ranges new bottom water inflow was characterized by relatively lower maximum tidal currents, but for longer durations, than when no new bottom water was entering the Sound. Inflow during large tidal ranges showed both large durations and maximum currents.

Daily average water properties from the Aanderaa sensors showed that three intervals of inflow occurred (Figure 22). These were represented by increasing salinity and decreasing temperature through Admiralty Inlet. Flow characteristics in Admiralty Inlet during these inflows indicated increased bottom inflow and increased outflow in the upper water (Figure 27).

Observations in the main basin showed step decreases in temperature at the bottom similar to what had been observed in 1973 and in 1975-76 when new bottom water entered the Sound. However, for the first time these steps were observed at two locations, moorings 6 and 5 (Figure 26). These moorings were about 25 nautical miles apart. The 7 days required to transit this distance on each of two occasions implied a mean speed of about 8 cm/sec. Current meter observations also indicated about the same average speed during the transit interval.

Finally, time series STD observations for one day in The Narrows indicated water from deeper than 120 m in the main basin was entering The Narrows at 60-70 m on flood tides (Figures 19 and 21).

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