Washington State
Department of Ecology

Southern Puget Sound
Water Quality Assessment
Study

CIRCULATION AND **FLUSHING IN** SOUTH PUGET SOUND

URS Company

July 1986

ERRATA SHEET

For: Circulation and Flushing in South Puget Sound, URS Company and Evans Hamilton, July 1986.

page *36*

Equations should read:

$$\alpha 21 = \left(\frac{S_1}{S_2}\right)\frac{S_2 - S_4}{S_1 - S_4} \qquad \alpha 24 = \left(\frac{S_1}{S_3}\right)\frac{S_3 - S_4}{S_1 - S_4}$$

$$\alpha 31 = \left(\frac{S_4}{S_2}\right)\frac{S_1 - S_2}{S_1 - S_4} \qquad \alpha 34 = \left(\frac{S_4}{S_3}\right)\frac{S_1 - S_3}{S_1 - S_4}$$

CIRCULATION AND FLUSHING IN SOUTHERN PUGET SOUND

URS Corporation and Evans-Hamilton, Inc.

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INTRODUCTION

Population growth estimates indicate that Southern Puget Sound will be one of the fastest growing areas in the Puget Sound basin. Present population and future growth will put increasing demands on wastewater systems. The Washington Department of Ecology will continue to be faced with difficult decisions on the location and allowable limits of wastewater discharges. One of the goals of the Southern Puget Sound Water Quality Assessment Study was to compile information regarding circulation and flushing to be used to guide decisions on where new or expanded effluent outfalls could be located in Southern Puget Sound. This report contains information on circulation and flushing in Southern Puget Sound. A simple model was used to estimate the maximum discharge rate allowable to achieve given dilutions within an inlet. The maximum discharge rate is dependent upon the volume transport of water out of an inlet and on the refluxing of water which may occur at the mouth of an inlet.

Previous investigators have calculated flushing for several areas of Southern Puget Sound using two methods. Those methods and the results are described herein. We also have discussed the data collected as part of this project and the availability of other data for use in estimating transport and flushing. Transports are presented based on two methods: current meter measurements and a water budget analysis. Transports calculated from the water budget method differ from previous estimates although the same method was used. Refluxing and its effect on flushing is also discussed. A simple expression for the maximum discharge rate is also presented along with methods for determining the design dilution of a diffuser and the background concentration of effluent in an inlet.

The data used to perform these calculations is very limited. Assumptions were made concerning net transport and circulation patterns in the Southern Sound and which locations in an inlet are representative of various flow regimes. Sometimes a small change in an assumption can have a large effect on the result. We have made our estimates based on available data and what we

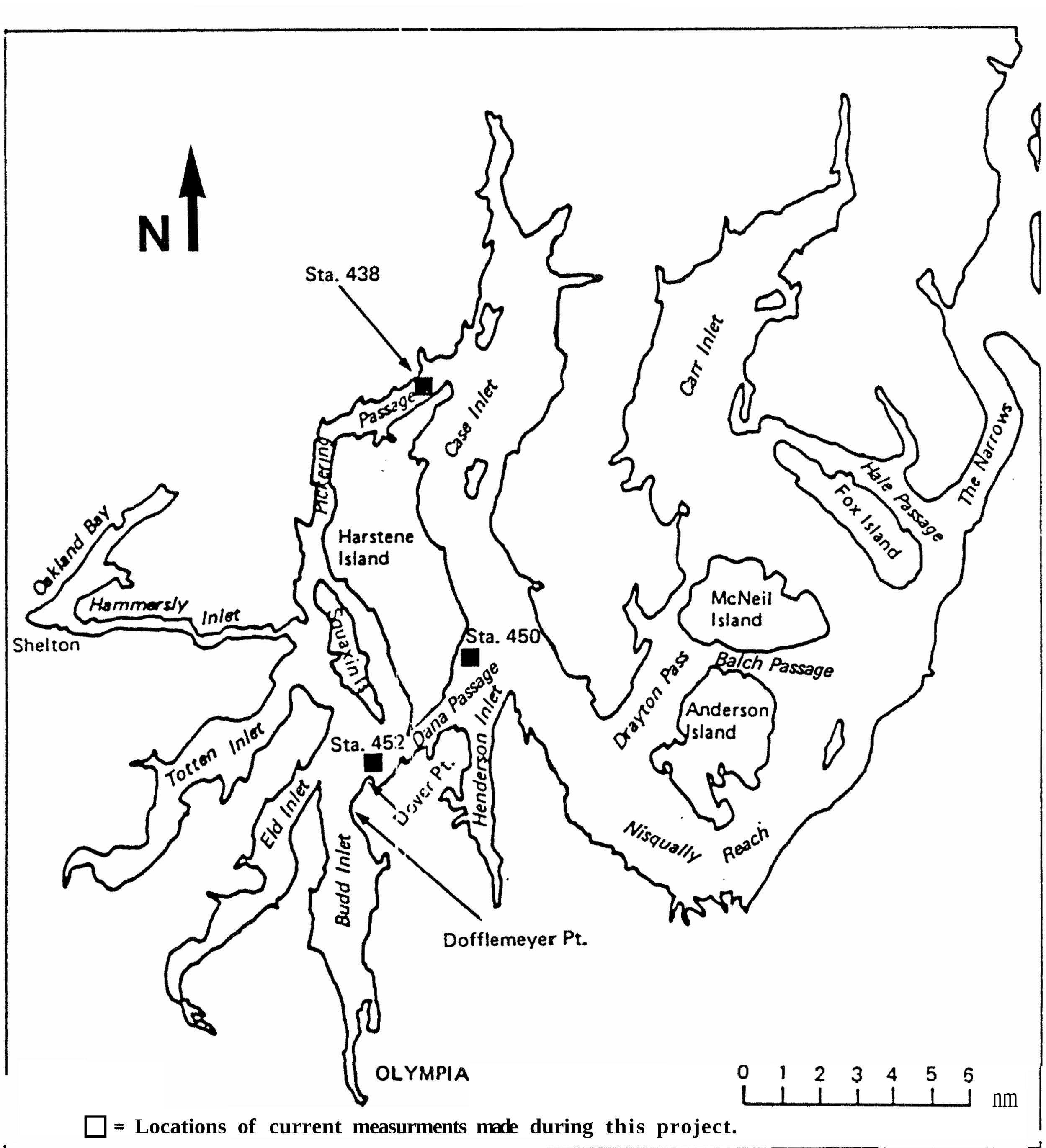


Figure 1. Area map of Southern Puget Sound.

consider to be reasonable assumptions. This report is intended to provide indications of allowable loads but not to set strict limits. Some policy decisions and site-specific work would need to be conducted to more accurately define maximum discharge rates.

PREVIOUS FLUSHING ESTIMATES

Estimates of flushing previously have been made for Southern Puget Sound and other areas of Puget Sound. The methods utilized fall into two general categories -- tidal prism and water budgets. Tidal prism methods assume that water replacement during each tidal cycle is the factor driving flushing. Various assumptions have been made concerning the amount of water replaced with each tidal cycle and the degree of mixing within the inlet. Three variations of tidal prism methods are discussed below. The budget approach requires that the masses of freshwater and saltwater entering and leaving the estuary must balance.

Tidal Prism Methods

Estimates of the flushing rates of Budd, Eld, Totten, Hammersley, and Henderson inlets have been made previously by the University of Washington (1971) and Duxbury et al. (1972) based upon the ratio of inlet volume to intertidal volume (tidal prism). These estimates, presented in Table 1, assume that the water entering an inlet on a flood tide displaces an equal volume of water in the inlet, which exits on the ebb tide. These estimates also assume that water exiting on ebb tides does not return on ensuing flood tides. This results in the fastest possible flushing of each inlet by tidal actions. The flushing rate using this method would be $F1 = V/\Delta V \times 0.52$ days/tidal cycle. F1 is the amount of time (in days) required to completely displace the original (old) water with new water. V is the average volume of the inlet at mean high water (MHW) and ΔV is the average intertidal volume of the inlet, i.e., the volume at MHW minus the volume at mean low water (MLW). The exact volumes they used to make these calculations are not known with the exception of Budd Inlet (Duxbury et al., 1972), but should be close to the volumes calculated by McLellan (1954). Flushing estimates for the other areas listed in Table 1 were made using the same equations and using volumes from McLellan (1954). The net seaward transport, which must be occurring to produce these flushing rates, is calculated by dividing the flushing rates, provided in Table 1, into each inlet's volume at MHW (see Table 1).

Table 1. Summary of flushing rates and net seaward transports calculated for several areas of Puget Sound.

	Budd Inlet	Eld Inlet	Totten Inlet	Hammersley Inlet and Oakland Bay	Henderson Inlet	Pickering	Case Inlet	Carr Inlet	Southern Sound
Volume ($x10^8 m^3$)									
Total to MHW	2.52	1.59	2.13	1.48	0.55	5.56	23.92	46.24	158.26
Total to MLLW	1.65	0.99	1.22	0.68	0.31	4.09	20.74	42.49	141.65
Intertidal	0.88	0.60	0.91	0.79	0.24	1.50	3.18	3.75	16.61
$\Delta V/V$ (o/o)	35	38	43	53	44	27	13	8	11
Tidal Prism Method									
Flushing Rate (1) (tidal cycles)	2.8	2.7	2.4	1.7	2.3	3.7	7.5	12.3	9.5
Flushing Rate (days)	1.4	1.4	1.2	.9	1.2	1.9	3.9	6.4	4.9
Net Seaward Transport ($10^3 m^3/s$)	2.0	1.3	2.0	1.9	0.5	3.4	7.1	8.4	37.3
Water Budget Method									
Flushing Rate (2) (days)	2.4								
Net Seaward Transport ($10^3 m^3/s$)	1.2								

(1) Budd, Eld, Totten, Hammersley, and Henderson
From University of Washington (1971) and Duxbury et al. (1972)

(2) From Duxbury (1972)

As bulk replacement of old water with new is most likely not occurring at these rates, Duxbury (1983) tried to refine the estimates by making two changes. First he assumed that the water entering the flood tide mixed completely with old water, already in the inlet, and that the next flood tide displaced this mixture of new and old water, not only old water as was assumed previously. This has the effect of displacing less and less of the initial (old) water mass each consecutive tide cycle (Figure 2). As an example Duxbury states:

"If, for example, the intertidal volume is 20 percent of the mean volume of an embayment then after 1 tide cycle, ebb and flood, 80 percent of the initial water in the embayment remains. On the next tide cycle 80 percent of 80 percent of the initial water remains. After 3.1 tide cycles 50 percent of the initial water remains or 3.1 tide cycles represents the half life of the initial water."

The amount of original water remaining at any time is:

$$\text{Water Remaining} = V \exp((-\Delta V/V)(t/0.52)),$$

where ΔV and V are as defined above and t is the time in days. Expressed as a percentage, this equates to

$$\%\ \text{Water Remaining}/100 = \exp((-\Delta V/V)(t/0.52))$$

This half-life method of describing flushing does not produce a specific flushing time that can be compared with results from other methods. However, it can be used to provide a useful comparison of water replacement in different inlets. For Budd Inlet, the intertidal volume (tidal prism) is 35 percent of the volume of Budd Inlet at MHW (from McLellan, 1954). The half life of the initial water in Budd Inlet is therefore 1.6 tidal cycles (0.8 days), while it would take 7 tidal cycles (3.62 days) to replace 95 percent of the initial water. This type of calculation is useful for determining the length of time required for the removal of a specific input. While the amount of material removed with each tidal cycle decreases, the transport of water remains constant.

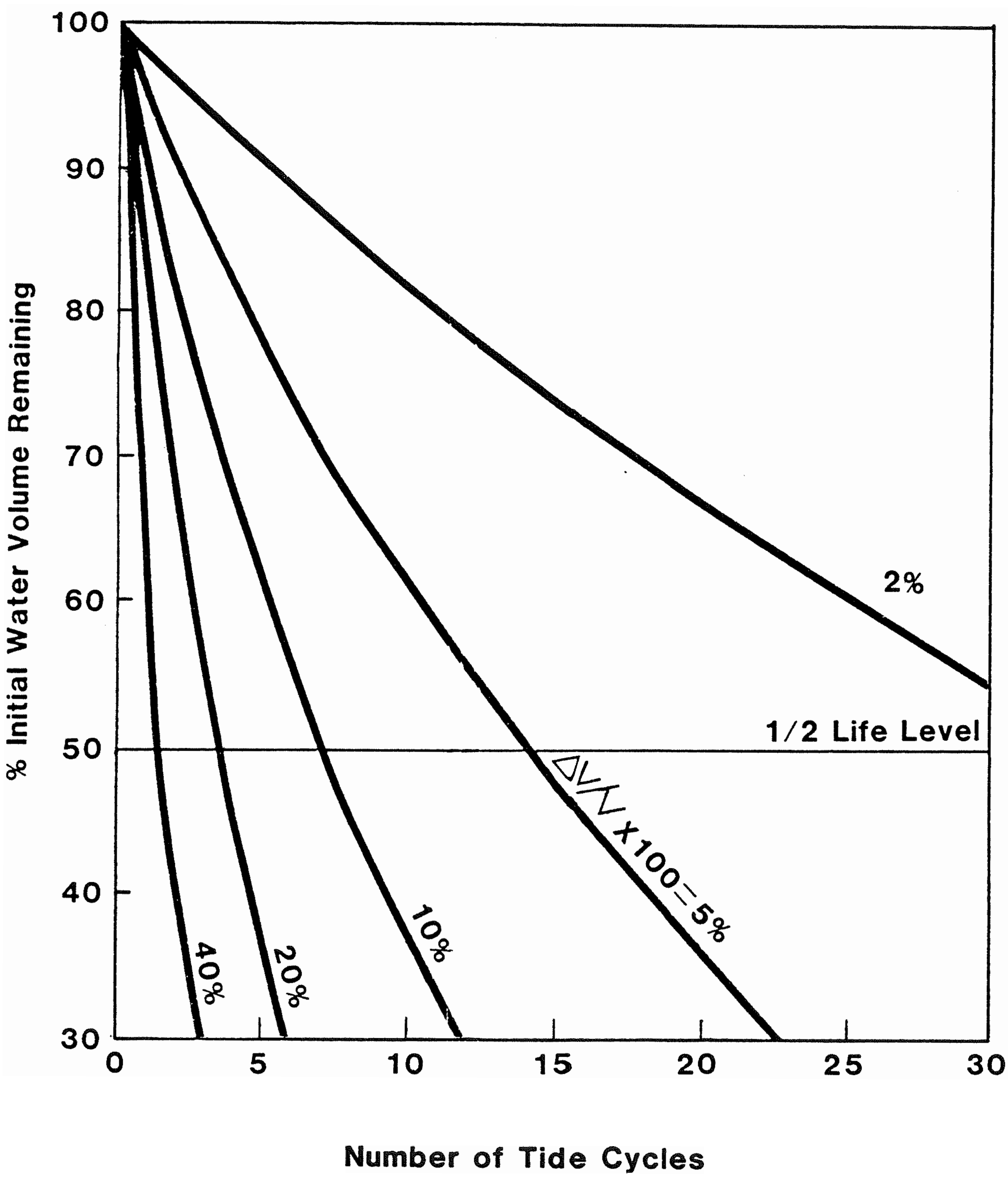


Figure 2. Percent of initial water remaining in an inlet versus the number of tidal cycles for several values of intertidal volume. Source: Duxbury, 1983.

Duxbury's second change from his 1972 calculations was to include an estimate of the amount of ebbing water which re-entered Budd Inlet on the ensuing flood tide (i.e., refluxing). The aforementioned half-life calculations assumed no ebbing water was refluxed back into the inlet. He also calculated the half-life of water in Budd Inlet if different percentages of the ebbing water was refluxed back into the inlet. Refluxing increases the time it takes to flush Budd Inlet, but it does not change the transport calculations.

Water and Salt Balance

All the previous flushing estimates presented in this chapter are based upon assumptions of mixing processes and water replacement due to tidal action. The University of Washington (1971) and Duxbury (1972) presented flushing estimates based upon net seaward transports calculated from actual runoff and salinity measurements. This method, called a water and salt budget study, essentially says that the mass or volume of water in an inlet does not change, therefore the freshwater inputs to the system (runoff and precipitation) must exit seaward. In addition, this net movement seaward of the fresher water, and the net movement landward of the deeper marine water can be calculated by balancing water and salt budgets reflected in the measurements of freshwater and seawater entering, within, and outside the inlet.

The water budget equations for this analysis are:

(1) Total Water Budget: $T_i + R - T_o - AW = 0$

(2) Freshwater Budget: $F = R + \left(\frac{S_b - S_i}{S_b}\right) T_i - \left(\frac{S_b - S_o}{S_b}\right) T_o$

(3) Seawater Budget: $P = AW - \Delta F = \left(1 - \frac{S_b - S_i}{S_b}\right) T_i - \left(1 - \frac{S_b - S_o}{S_b}\right) T_o$

where:

T_i = Net rate of inflow (volume/time) of seawater to the inlet.

T_o = Net rate of outflow (volume/time) of seawater from the inlet.

R = Freshwater input (volume/time).

AW = Change in the water volume of the inlet (volume/time) as indicated by a change in sealevel. In this analysis the volume of an inlet is assumed to remain the same, thus AW = 0.

AF = Change in the freshwater content of the inlet (volume/time).

P = Change in the seawater content of the basin, AW-AF (volume/time).

S_b = Mean salinity of seawater available to fill the inlet if no freshwater were present, a reference salinity for the Pacific Ocean, taken to be $33.8^o/oo$.

S_i = Mean salinity of the inflowing water, from field measurements.

S_o = Mean salinity of the outflowing water, from field measurements.

S_p = Average salinity of the water in the inlet as calculated from field measurements.

The above equations can be rearranged to give the landward (T_i) and seaward (T_o) net transports and the flushing rate of an inlet:

(4) $T_i = \dfrac{S_o}{S_i - S_o}(R) - \dfrac{S_b}{S_i - S_o}(\Delta F)$

(5) $T_o = T_i + R$

(6) $\text{Flushing Rate} = \dfrac{\text{Volume at MHW}}{T_o}$

To perform this analysis accurate field measurements are required of the salinities of the inlet, the water at depth flowing into it, and the water near surface flowing outward, as well as the total freshwater input to the inlet between the salinity sampling dates. Selection of the depth range over which net transport seaward and landward occur and the corresponding salinities are critical. In addition, sufficient sites must be measured within an inlet to insure that an accurate average salinity can be calculated for the inlet.

The most complete synoptic set of water property measurements of the Southern Sound were made by the University of Washington and were reported by Olcay (1959). These measurements were made monthly from approximately September 1957 through December 1958 at stations throughout the Southern Sound. Duxbury (1972) calculated the monthly flushing rate of Budd Inlet based upon Olcay's salinity measurements and runoff data provided by the U.S. Geological Survey. The results of these calculations are shown in Table 2. In his calculations, he chose the salinity of the upper 10 meters at Dover Point to be representative of the outflowing water (T_o) and the salinity at the 50 m depth at Dover Point to be representative of the inflowing water (T_i). S_p was calculated from salinity measurements at Gull Harbor, Olympic Shoal, and Budd Inlet Buoy No. 12. The locations of these stations are shown in Figure 3. Net seaward transport ranges from 3000 m^3/s (February) to 200 m^3/s (November) and averages 1100 m^3/s, while flushing rates vary from 0.9 days (February) to 12.0 days (November). The average flushing rate based upon the average net seaward transport is 2.4 days. This rate is 70 percent slower than the rate calculated using the tidal prism method (Table 1).

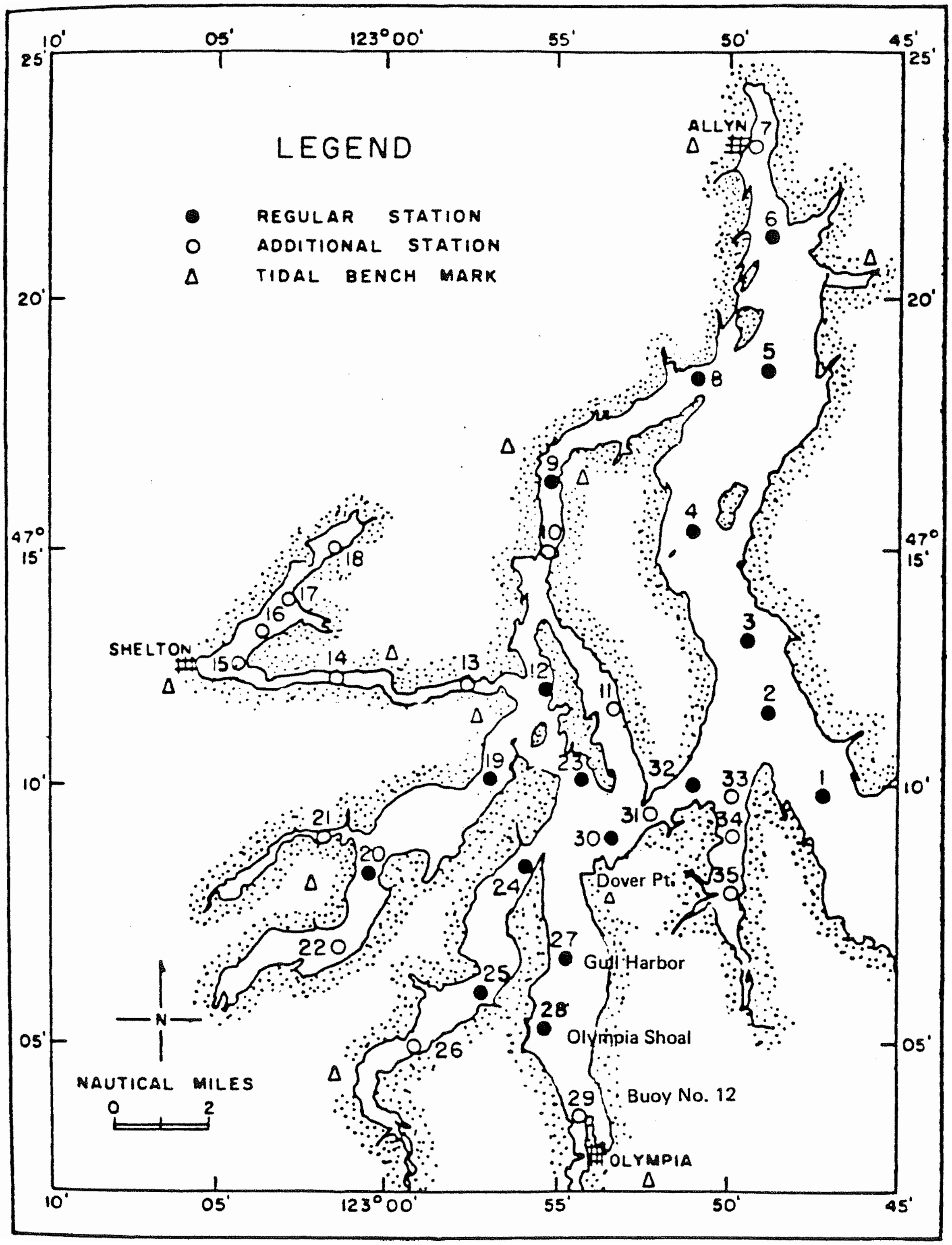


Figure 3. Locations of water property measurements reported by Olcay(1959) and the four stations used by Duxbury et al. (1972) for a water budget analysis.

Table 2. Monthly transport and flushing rates for Budd Inlet adapted from Duxbury (1972)

	T_i (10^3 m^3/s)	T_o (10^3 m^3/s)	Replacement Time (Days)
January	2.0	2.0	1.2
February	2.9	3.0	0.9
March	1.7	1.8	1.5
April	1.6	1.7	1.6
May	.8	0.8	3.6
June	.4	0.4	6.9
July	1.3	1.3	2.1
August	0.9	0.9	2.7
September	0.4	0.4	6.9
October	0.3	0.3	8.7
November	0.2	0.2	12.0
December	0.5	0.5	5.1
MEAN	1.1	1.1	2.4

Duxbury et al. (1972) did not calculate flushing of various inlets in Southern Puget Sound, but did calculate flushing for the whole of Southern Puget Sound as well as Whidbey Basin, Hood Canal, and the entire Puget Sound based on this water budget study. The sampling stations, periods, and salinities they used in their calculations were not presented, but were obtained from Collias (1970). Table 3 shows the flushing times they calculated for various months, and the associated net seaward transports derived from the replacement times. Volumes for the transport calculations were obtained from McLellan (1954). The flushing time of all of southern Puget Sound averages 56 days according to the water and salt budget analysis. For perspective, Whidbey Basin flushes an average of every 40 days, while Hood Canal and the entire Sound average 177 and 152 days, respectively.

Olcay (1959) estimated the flushing of Oakland Bay within Hammersley Inlet in yet another manner. During April 1958 he noticed a large input of freshwater to Oakland Bay. From April through June the salinity of the Bay increased rapidly diluting the new freshwater while the salinity outside of the Bay in Case Inlet remained relatively constant. Based on the rate of salinity increase in Oakland Bay, Olcay estimated the half-life of the water

Table 3. Replacement time (University of Washington, 1971) and associated transport for several areas in Puget Sound

	Replacement Time (days)				Net Seaward Transport ($10^3 m^3/s$)			
	Whidbey Basin	Southern Puget Sound	Hood Canal	Entire Puget Sound	Whidbey Basin	Southern Puget Sound	Hood Canal	Entire Puget Sound Area
January-February	46	33	272	113	7.3	5.5	1.1	17.2
February-March	32	45	85	62	10.5	4.1	3.4	31.4
March-April	54	41	202	582	6.2	4.5	1.4	3.3
April-May	30	28	97	166	11.2	6.5	3.0	11.7
May-June	44	114	672	184	7.7	1.6	0.4	10.6
June-July	25	54	328	99	13.5	3.4	0.9	19.7
July-August	30	80	152	124	11.2	2.3	1.9	15.7
August-September	47	70	191	132	7.2	2.6	1.5	14.8
September-October	93	80	149	407	3.6	2.3	1.9	4.8
October-November	57	51	215	120	5.9	3.6	1.3	16.2
November-December	76	174	183	480	4.4	1.1	1.6	4.1
December-January	18	35	101	146	18.7	5.2	2.9	13.3
MEAN	40	56	177	152	8.4	3.3	1.6	12.8

replacement of Oakland Bay to be approximately eight days. Based on this rate he estimated 90 percent of Oakland Bay's volume would be replaced in approximately 5 weeks.

Summary

Estimates of flushing have been made by previous investigators using two methods -- tidal prism and water budget. These previous estimates are presented in Tables 1, 2 and 3.

The tidal prism method considers replacement of water in an inlet due to the rise and fall of the tide. This method is based on the ratio of the volume of seawater in the inlet and the intertidal volume. Various assumptions have been made concerning the amount of mixing of old and new water with each tidal cycle. This method could provide good flushing estimates if the ratio of old and new water leaving the inlet were known. However, we have not established an accurate way of determining this ratio. The fastest flushing would occur if no mixing took place and new water replaced an equal volume of old water. The rate of flushing decreases as the amount of old water in the out-going volume decreases. No flushing occurs when the new water enters and leaves without carring any old water with it.

The water budget method is based on a balance of water and salt in the inlet. This method considers fresh water input and changes in the amount of salt in the inlet and calculates the advective transports necessary to attain the salinity distribution. This method does not consider the turbulent transport of salt into or out of the inlet or between the upper and lower layers. This process could be important in some areas of the Southern Sound where the tidal currents are strong and the tidal range is large compared to the water depth.

Both of these methods involve assumptions and uncertainties in measured values. The water budget method can be very sensitive to small changes in salinity values. This issue is further discussed in the Transport section.

AVAILABLE DATA

The lack of flushing and transport estimates for areas other than Budd and Hammersley inlets prompted us to make the calculations for several other areas described below. These were done using the water budget technique described earlier, and also based upon net currents calculated from current meter records and the cross-channel area through which the net current passes. We have also recalculated the flushing rate and transport occurring in Budd Inlet using the water budget method. Current meter measurements collected during this project have more clearly defined the vertical extent of the seaward and landward flowing layers, thereby enabling a clearer selection of appropriate salinities.

Water Property Data

Data were collected by the University of Washington over several years and have been indexed by Collias (1970). The sites where water property data were collected by the University of Washington in Southern Sound are shown in Figure 4. For the waters landward of the Nisqually River Delta, monthly sampling was most consistently done during 1957-1958 (Olcay, 1959; Figure 3). Carr Inlet was most consistently sampled during 1954-1955. The accuracy of the data collected by the University of Washington is considered to be quite good. The water samples were collected in Nansen bottles, and the salinities were determined using an accurate conductivity bridge.

Current Measurements

The sites of available current measurements are shown in Figure 5. Measurements were made by several investigators using a variety of instruments. The measurements vary in length, sampling interval, and quality. Cox et al. (1984) have indexed the majority of these measurements and their sources, and also provided net speed and direction of the current computed over a tidal day (24.84 hrs) and the length of the record. The older records (prior to 1970) listed by Cox et al. (1984) relied both upon

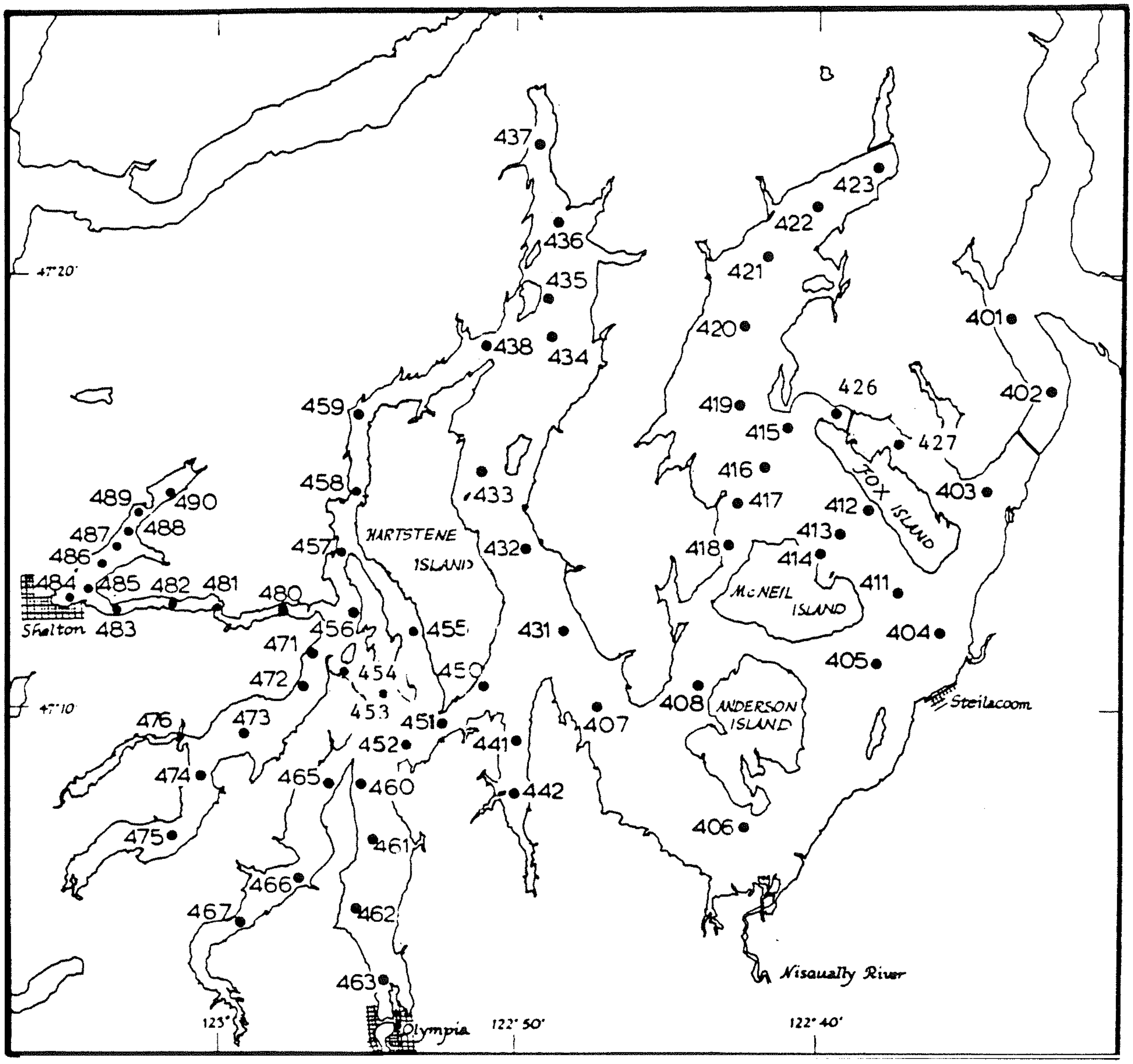


Figure 4. Location of water property measurements taken in the Southern Sound from 1932-1966 by the University of Washington (From Collias, 1970)

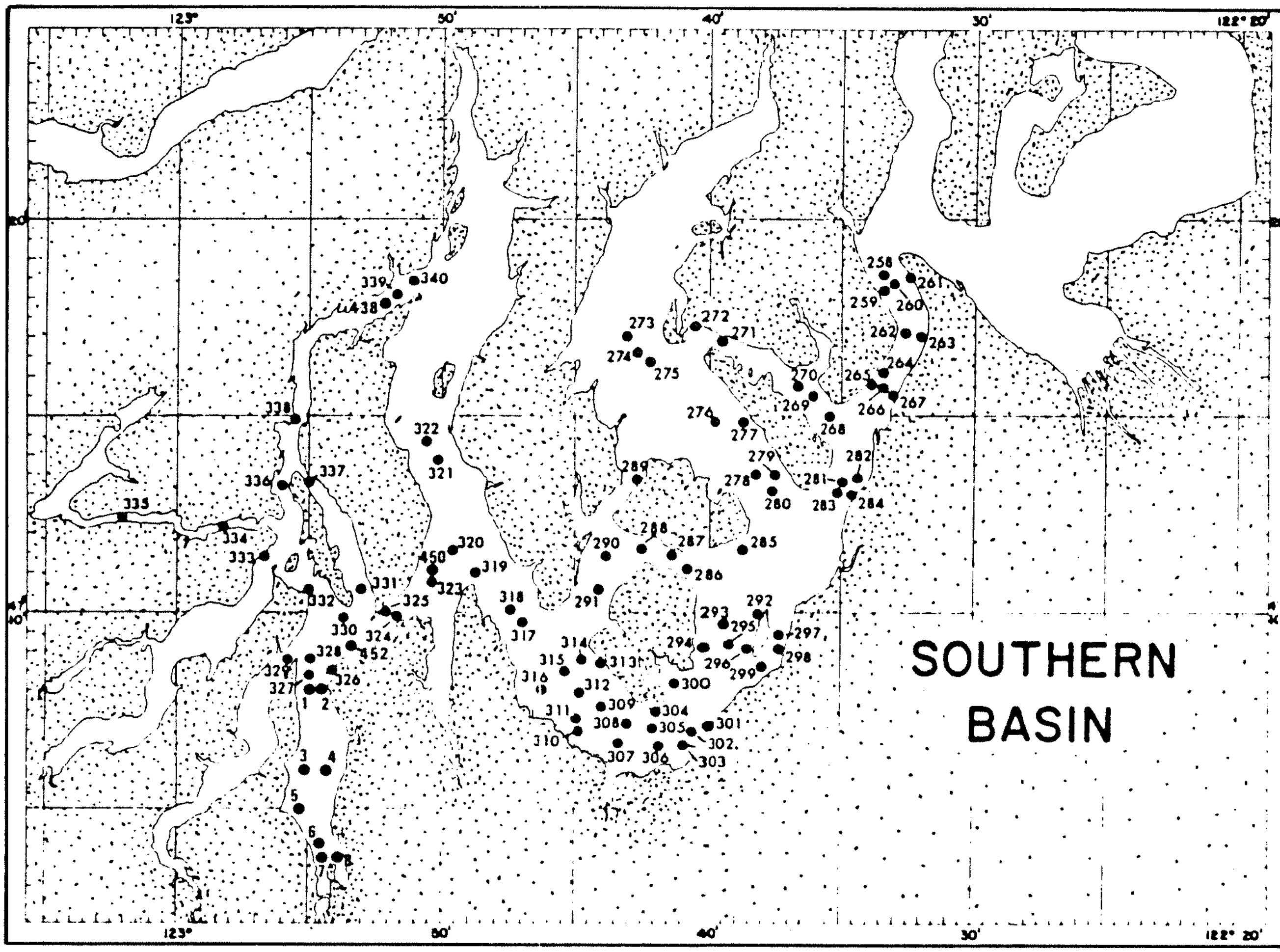


Figure 5. Locations of current measurements collected in Southern Sound(from Cox et al.,1984).

the operator and the instrument utilized for the accuracy of the measurement. The accuracy of the instruments has improved over time, and therefore more recent (after 1970) current measurements are generally more accurate, collect data over longer periods of time, and have shorter time intervals between measurements. Older measurements are generally useable but last only a few days with measurements taken only at half hour or longer time intervals.

For this project current meters were deployed at the east and west ends of Dana Passage and the northern end of Pickering Passage. These measurements were made using Aanderaa models RCM4 current meters. The timing of these measurements coincided with field surveys conducted in Budd Inlet for another part of this project. The Budd Inlet work is described in URS (1986).

Current meters were attached to subsurface moorings and left in the water for approximately 90 days. Moorings were placed at historical water stations, property 450, 452, and 438 (see Figure 4). The upper portion of the mooring (at site 452) parted under strain on the 39th day of the deployment and was found floating on the surface. The meters on the two remaining moorings were fouled with marine growth after approximately 38 days; data obtained after these dates were considered questionable and were not used in our calculations. Details of the mooring locations, sampling depths, and statistical analysis of meter data are given in Appendix A.

The net current speed and direction over a total of 28 days was computed. Net current speed and direction for earlier measurements were obtained from Cox et al. (1984) who excluded the records containing small gaps. Several of those records have been re-examined and, where possible, the gaps have been filled with interpolated values and a new net current computed for the longest length current record lasting an integer number of tidal days. Net current speed and direction for the new current measurements are provided in Table 4.

Table 4. Net current speed and direction of current measurements made in Pickering and Dana Passages

Site no.	Meter depth (m)	Observation period	Mean speed (cm s^{-1})	Net speed (cm s^{-1})	Net dir. (°True)	Variance (cm2 s-2)
Pickering Passage						
438	9	4/17-5/14/1985	19.6	0.2	288	555
	16	4/17-5/14/1985	18.0	2.3	238	462
	23	4/17-5/14/1985	15.9	3.4	240	345
Dana Passage						
450	9	4/17-5/14/1985	20.2	3.1	169	513
	16.5	4/17-5/14/1985	18.3	6.6	224	402
	24	4/17-5/14/1985	17.9	10.8	216	330
	31.5	4/17-5/14/1985	18.0	12.7	214	280
	39	4/17-5/14/1985	17.1	12.7	209	227
452	15	4/17-5/14/1985	25.9	17.8	246	1,090
	24	4/17-5/14/1985		No Data		
	33	4/17-5/14/1985	29.2	21.0	258	1,384
	41	4/17-5/14/1985	28.2	21.6	254	1,365
	50	4/17-5/14/1985	27.4	21.0	255	1,188

CIRCULATION

The net currents calculated from current meter measurements made in Southern Puget Sound are presented in plan view in Figure 6. To suppress tidal bias, these net currents have been calculated from data covering an integer number of tidal cycles. Biases due to fortnightly or longer changes in the strength of the tides (e.g., spring versus neap tides) are present to varying degrees because of the varying record lengths.

The pattern of net circulation shown in Figure 6 confirms that a two-layer flow exists in the majority of basins, bays, and inlets in the Southern Sound. Generally the net flow is directed out of these inlets near surface and into the inlets near bottom. Areas of intense mixing such as Dana Passage, Nisqually Reach, and The Narrows show rather confused flow patterns. In some areas such as Eld and Totten inlets, little or no data exists making the deduction of the net flow difficult.

Of particular interest to this study is the flow north of Dover and Dofflemeyer points. Directly north of Dover Point the net flow is extremely strong (approximately 20 cm/s), directed westward (inland), and does not appear to reverse near surface. A bit farther north (site 330, Figure 5), a 5-day record taken in 1945 at 5 meters of depth indicates that a strong flow (approximately 24 cm/s) exists directed eastward. While no data exists below 5 meters, it is likely that net flow is eastward top to bottom in that area to compensate for the net westward flow at station 452. To determine if this feature was real, we compared the 5 days of record at the northern site to 5 days of the shallowest record at the southern site during similar types of tides. At each site the current reaches approximately 2 knots during one tidal phase (north site during ebb; south site during flood), then is slow during the opposite tidal phase.

This flow pattern was confirmed by visual observation of dye released in the University of Washington's hydraulic model of Puget Sound. The model showed that water exiting Budd Inlet on an ebb tide, moved more strongly out on the west side. This water then moved out across the mouth of Eld Inlet

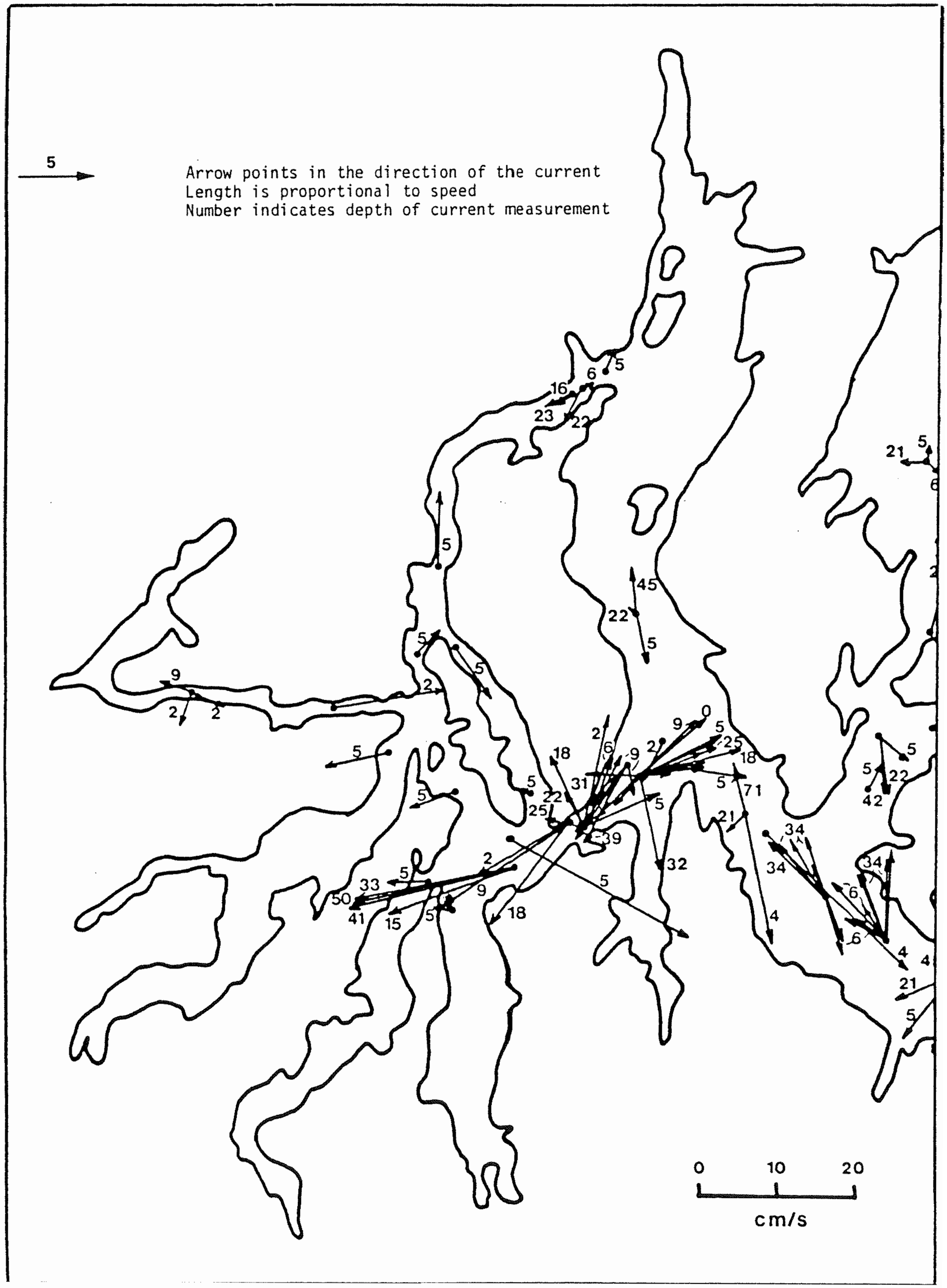


Figure 6. Net current speed and direction of current measurement made within Southern Puget Sound. Data from Cox et al.(1984)

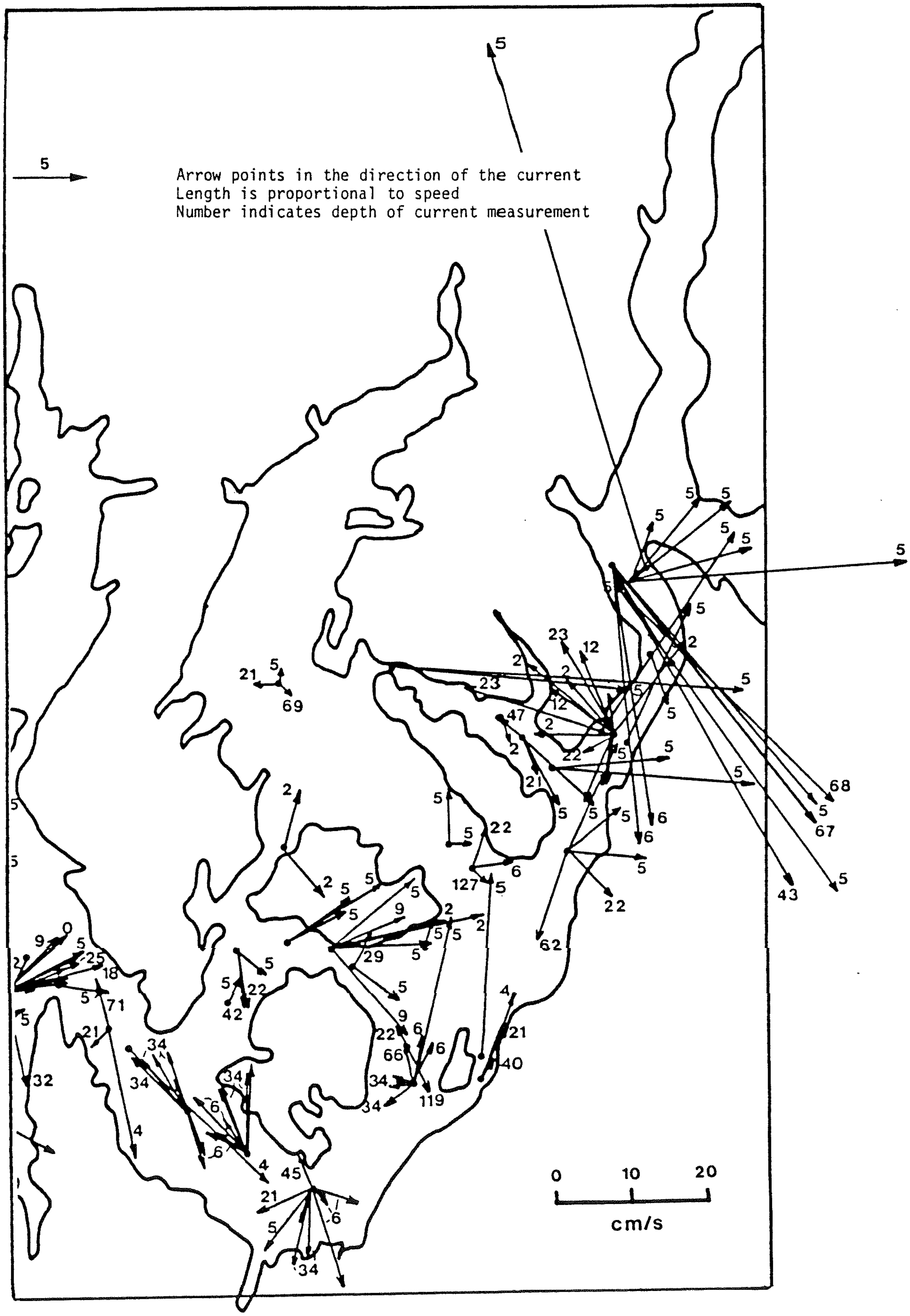


Figure **6.** cont.

before turning eastward toward the southern tip of Squaxan Island. Much of the water which had just left the Inlet would re-enter on a flood tide. The water would work its way back, forth and around until it reached Dana Passage. Figure 7 shows the general circulation patterns in this area and in Budd Inlet.

The data collected in Pickering Passage indicate large tidal currents (typically 15 to 20 cm/s) oriented predominantly along-channel. The net velocities were small and directed southwesterly below about 8 meters. Data collected previously indicates northeasterly net flows above this level (see Cox et al.,1984 and Appendix B). Large tidal currents and small net velocity means that water in the area oscillates back and forth with the tides while slowly moving along the channel. The net northeasterly flow in the surface layer provides a pathway for water from the inlets (i.e., Budd, Eld, Totten, and Hammersly) to exit the Sound without going through Dana Passage. However, since the total transport through Pickering Passage is much smaller than that through Dana Passage, the bulk of the water from these inlets must go through Dana Passage.

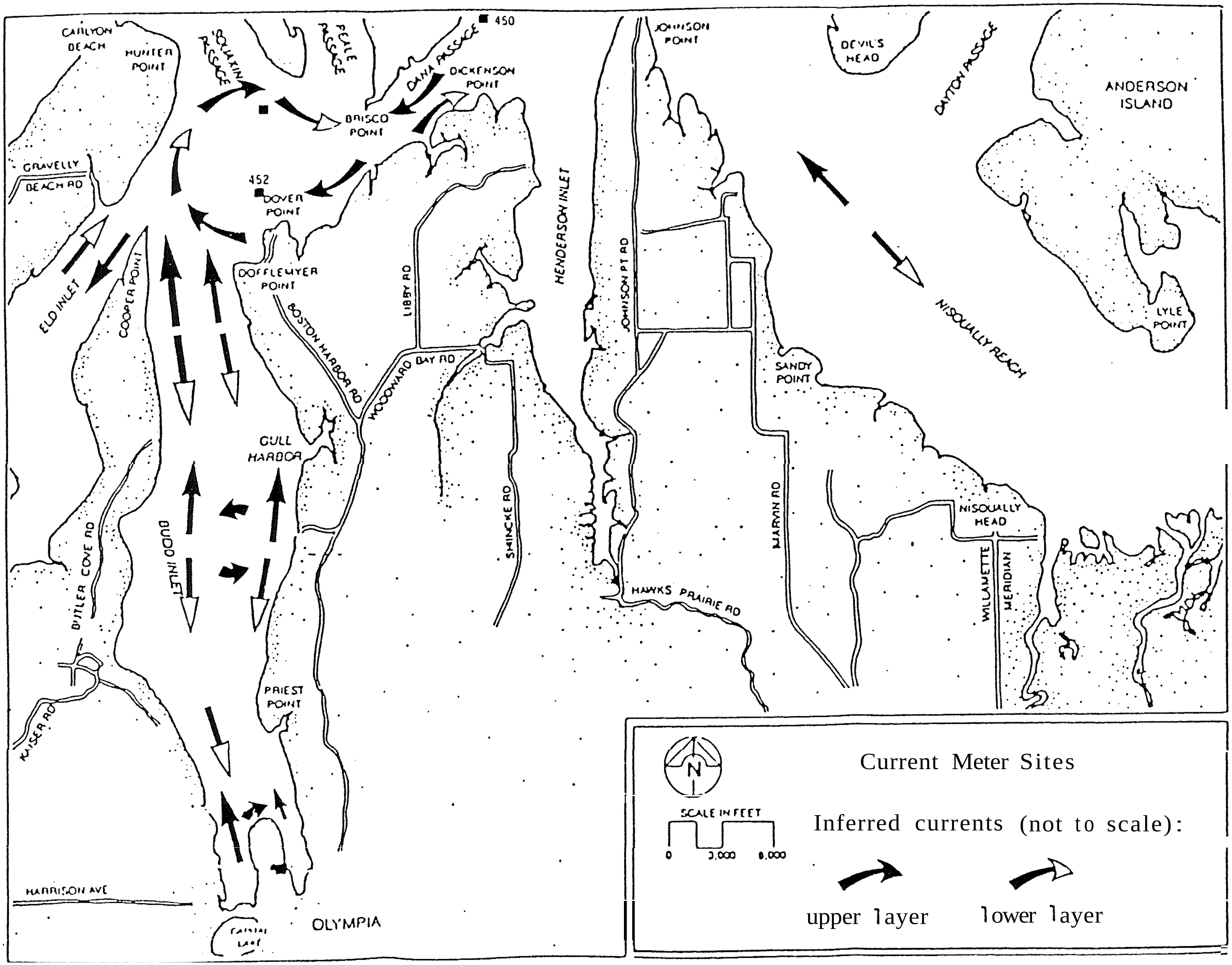


Figure 7. Circulation patterns for Budd inlet and approaches.

Transports Calculated From Current Measurements

The net transport occurring in the Southern Sound can be calculated by comparing the net along-channel currents with the cross-channel area through which they pass as follows:

$$\text{Net Current Speed (m/s)} \times \text{Cross-channel Area } (m^2)$$
$$= \text{Net Transport } (m^3/s)$$

This method of calculating transport involves assumptions and limitations. Currents have been measured at only a few depths at any one location so currents at other depths are interpolated values. It is assumed that the current measured at mid-channel applies to the entire cross-section. Also, the current measurements span 1-60 days; therefore while tidal phase (flood versus ebb) or fortnightly (spring versus neap) biases can in some cases be suppressed by averaging, seasonal fluctuations of the transport have not been determined. Therefore, the transport calculated for each inlet may not be an average condition.

The cross-sections selected for the computation of transport are shown in Figure 8. Since net transport varies with depth, the net flow within selected depth ranges was multiplied by the cross-sectional area of water within those depth ranges, and then the transports were summed for all depth ranges within the outflowing and inflowing layers. The current speeds were selected from vertical profiles of the net current (Appendix B) and the cross-sectional area from cross-channel bathymetry profiles developed from National Ocean Survey (NOS) hydrographic charts NOS. 18456, 18457, and 18448. Depth ranges were selected so that both the net current and bathymetry changed linearly within the depth ranges.

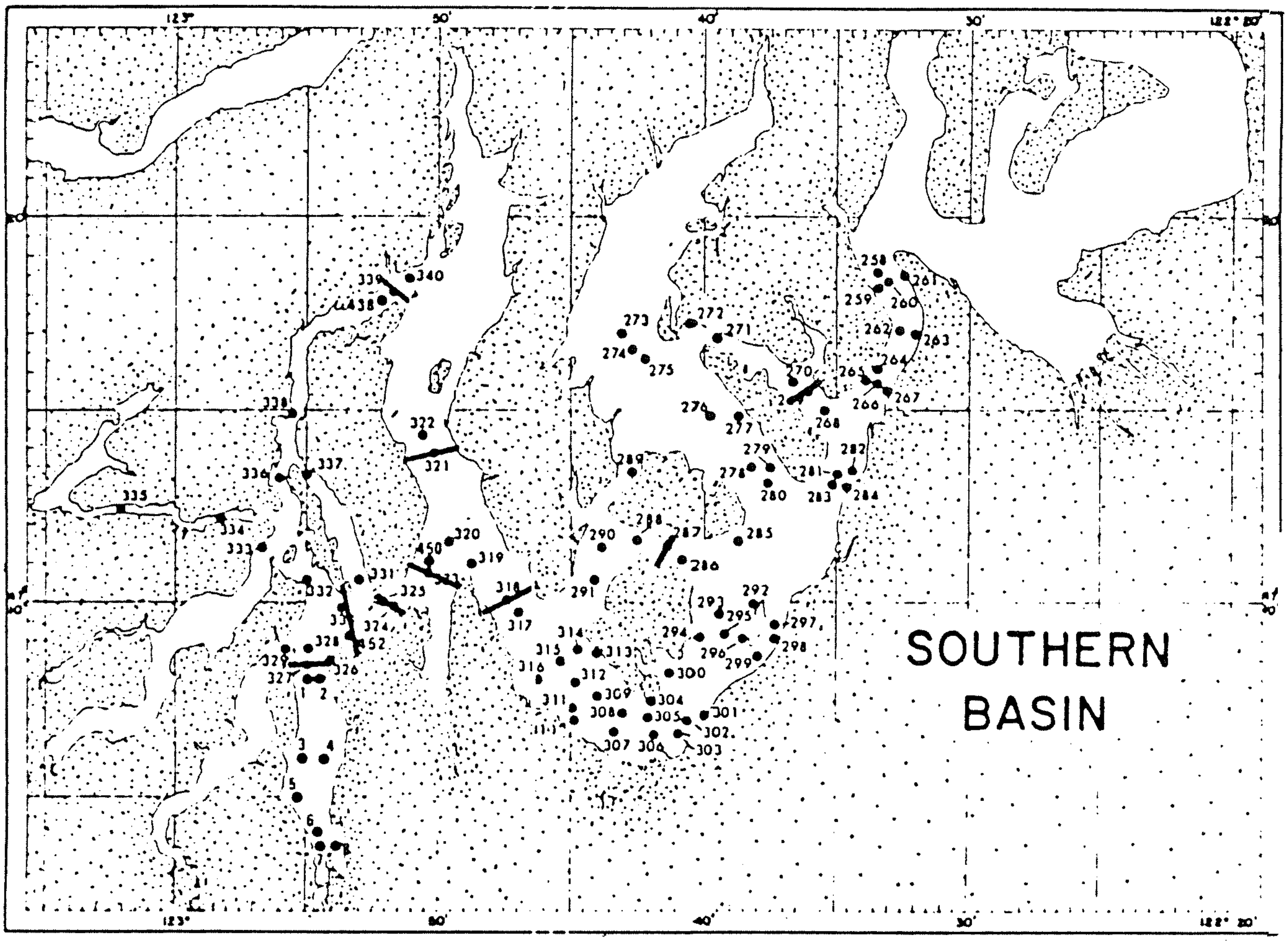


Figure 8. Locations of cross-channel sections used to compute transport based upon current measurements.

Horizontal variation of the net transport (i.e., across the cross section) also can occur. Only in a few cases were there sufficient measurements to calculate the horizontal variation. In these cases (Dana Passage and north of Dofflemeyer Point) the net flow appears to reverse across channel and does not reverse with depth. Where only mid-channel measurements were taken, these measurements were assumed to be representative of the currents across the section. No factor was used to account for slowing of the currents near land and therefore the transports are probably somewhat large. The calculated net transports are provided in Table 5. In several areas there were insufficient data to calculate transport.

Table 5. Net seaward (T_o) and landward (T_i) transport calculated from current measurements and cross-channel areas. Transport units are $10^3 m^3/s$.

Location	Measurement Sites	Measurement Dates	T_o	T_i
Hale Passage	269	3/10-15/1947 2/09-28/1978	2.6	0.3
Balch Passage .	287	2/10-14/1945 5/21-25/1952	1.4	
Nisqually-Dana Basin	318	3/27-4/12/1978	5.0	3.9
Case Inlet	321	3/28-4/12/1978	1.9	1.4
East of Dana Passage	450 323	4/17-5/14/1985 10/5-6,12-13/1972	1.2	1.5
Center of Dana Passage	325, 324	5/25-31/52,1/30-2/3/45 9/23-25/25,5/26-31/52. 3/8-4/10/78	Insuff. Data	1.2
West of Dana Passage	452 453	4/17-5/14/1985	5.0	5.4
Budd Inlet		9/20-23/1984	0.5	0.4
N. Pickering Passage	339 438	3/28-4/12/1978 4/17-5/14/1985	0.15	0.13

In general, basins with two layer flows which are divided vertically show T_o and T_i values which are close in magnitude. Hale and Balch Passages have nearly unidirectional transport of water through them. Dana Passage has a two directional transport as does the area north of Dofflemeyer Point, but these flows are divided horizontally. Therefore, this area was divided into east, center and west of Dana Passage for calculation of T_o and T_i. For both east and west of Dana Passage, the selection of the horizontal dividing line between the opposite net flows was difficult to establish due to sparse data coverage. As a result T_i exceeds T_o slightly. This is probably an artifact of the selection of the division point between the two flow layers and not actually occurring. The numbers are useful in determining the net transport (both T_o and T_i) east and west of Dana Passage to be approximately 1,400 and 5,300 m^3/s, respectively. The large transports west of Dana Passage are due to water recirculation caused by an eddy in that area. Approximately 1,200 m^3/s appear to be passing through Dana Passage.

Transports Calculated Using the Water Budget Method

Transports were also calculated using the water budget method to provide transport estimates for several areas of Southern Puget Sound, to provide an independent check of the transports derived from current measurements, and to estimate the seasonal variability of transport within the inlets. The stations and depths of the measurements used to calculate transport for each inlet are given in Table 6. To compute the average salinity of the water in an inlet (Sp), data within each inlet were first averaged horizontally at common depths, then averaged vertically using the average salt content, within specific depth intervals, and the volume of water within those intervals. The volumes of water within the depth intervals were obtained from McLellan (1954).

Table 6. Station numbers and depths of salinity measurements used to calculate transport

Inlet	Sp		So		Si	
	Station*	Depth (m)	Station	Depth (m)	Station	Depth (m)
Budd Inlet	461,463	0-15	461	2	452	30
Eld Inlet	465,466,467	0-25	465	2	452	30
Totten Inlet	472,474,475,476	0-30	472	2	453	15
Oakland Bay/ Hammersley Inlet	482,485,488	0-15	482	2	456	10
Henderson Inlet	441	0-13	441	2	431	20
Case Inlet	431,433,436,437, 438	0-70	431	5	431	50
Carr Inlet	411,413,416,419, 420, 421,422,423	0-160	411	5	411	50

*See Figure 4 for station locations.

Runoff and precipitation data were obtained for the periods when water properties were measured. Gaged runoff was obtained from Washington State Streamflow records (United States Geological Survey, 1957-1959). Gaged rivers entering the inlet are:

Budd Inlet	Deschutes River
Eld Inlet	None
Totten Inlet	Skookum Creek
Hammersley Inlet	Goldsborough Creek
Henderson Inlet	Woodland Creek
Case Inlet	None
Carr Inlet	Minter Creek

Ungaged runoff was calculated in a manner similar to the technique used by Lincoln (1977). This technique establishes a ratio of gaged discharge to drainage area, and applies that ratio to calculate the runoff discharge from ungaged drainage areas. The drainage basin areas were supplied by the WDOE (Michaud and Chamberlain, 1984).

Daily precipitation at Shelton, Olympia, and Tacoma were obtained from the National Weather Bureau (1957-1959). The total precipitation entering each inlet during the sampling intervals was computed based upon the following combination of Olympia, Shelton, and Tacoma rainfall:

Budd Inlet	100% Olympia;	
Eld Inlet	67% Olympia;	33% Shelton
Totten Inlet	33% Olympia;	67% Shelton
Hammersley Inlet	100% Shelton	
Henderson Inlet	100% Olympia	
Case Inlet	100% Shelton	
Carr Inlet	100% Tacoma	

The monthly net seaward transports calculated using the water budget analysis are presented in Table 7 and graphed in Figure 9. The minimum transports within four of the seven inlets occurs in late August - early September, a time of low runoff. Maximum transports occur during several different months. The average transports calculated from these data range from 130 m^3/s in Henderson Inlet to 2380 m^3/s in Carr Inlet.

The values presented for Budd Inlet are generally lower than the estimates provided by Duxbury (1972) although the same equations and data base were used. As previously described, several of the assumptions we made were different than Duxbury's. However, the choice of a representative salinity for the outflowing upper layer (S_0) has the greatest effect on the transport calculation. Duxbury (1972) used the average salinity of the upper 10m. Based on our recent current meter surveys in Budd Inlet, it appears that the upper layer is much shallower and therefore salinity values at 2m were used.

Table 7. Net seaward (T_o) and landward (T_i) transports (10^3 m^3/s) for seven inlets calculated from a water budget analysis

Sampling Dates[a]		Henderson Inlet	Budd Inlet	Eld Inlet	Totten Inlet	Hammersley Inlet	Case Inlet	Carr Inlet	Sampling Dates[b]
8/3/57	T_o				0.1				
	T_i				0.1				
8/19/57	T_o				0.1	0.3			
	T_i				0.1	0.3			
9/4/57	T_o								
	T_i								
11/3/57	T_o				0.3	0.3			
	T_i				0.3	0.3			
11/23/57	T_o			0.2		0.2			
	T_i			0.2		0.2			
12/27/57	T_o			0.2		0.3	0.1		
	T_i			0.2		0.2	0.0		
1/25/58	T_o			0.3	0.4	0.3	1.9		
	T_i			0.2	0.4	0.2	1.9		
2/11/58	T_o			0.4	0.5		0.3	1.1	2/15/54
	T_i			0.4	0.5		0.3	1.1	
3/8/58	T_o			0.3			1.1	3.2	3/22/54
	T_i			0.3			1.1	3.2	
4/5/58	T_o	0.1		0.2		0.2	2.1		
	T_i	0.1		0.2		0.1	2.1		
4/26/58	T_o	0.1	1.1	0.1		0.2	2.6	1.7	4/23/54
	T_i	0.1	1.1	0.1		0.2	2.6	1.7	
5/24/58	T_o	0.2	0.7	0.1	0.2	0.4	1.1	1.9	5/13/54
	T_i	0.2	0.7	0.1	0.2	0.3	1.0	1.9	
6/16/58	T_o	0.1	0.3	0.2	0.3	0.3	2.7	1.1	6/23/54
	T_i	0.1	0.3	0.2	0.3	0.3	2.7	1.0	
7/8/58	T_o	0.1	0.5	0.3	0.1	0.3	1.0	2.4	7/10/54
	T_i	0.1	0.5	0.3	0.1	0.3	1.0	2.4	8/10/54

Table 7. (Continued)

Sampling Dates		Henderson Inlet	Budd Inlet	Eld Inlet	Totten Inlet	Hammersley Inlet	Case Inlet	Carr Inlet	Sampling Dates[b]
7/31/58	T_o	0.1	0.5	0.5	0.2	0.4	2.4		
	T_i	0.1	0.5	0.5	0.2	0.4	2.3		
8/19/58	T_o	0.1	0.1	0.1	0.2	0.3	1.6		
	T_i	0.1	0.1	0.1	0.2	0.3	1.6		
9/9/58	T_o	0.2	0.7	0.7	0.4	0.6	1.0	4.0	9/29/54
	T_i	0.2	0.7	0.7	0.4	0.6	1.0	4.0	
10/4/58	T_o						0.6	3.9	10/19/54
	T_i						0.6	3.8	
11/21/58	T_o								11/15/54
	T_i								
Average	T_o	0.1	0.6	0.6	0.3	0.3	1.4	2.4	
	T_i	0.1	0.6	0.6	0.3	0.3	1.4	2.4	

a. Transport values represent the average transport between sampling dates.

b. This set of sampling dates is for Carr Inlet only.

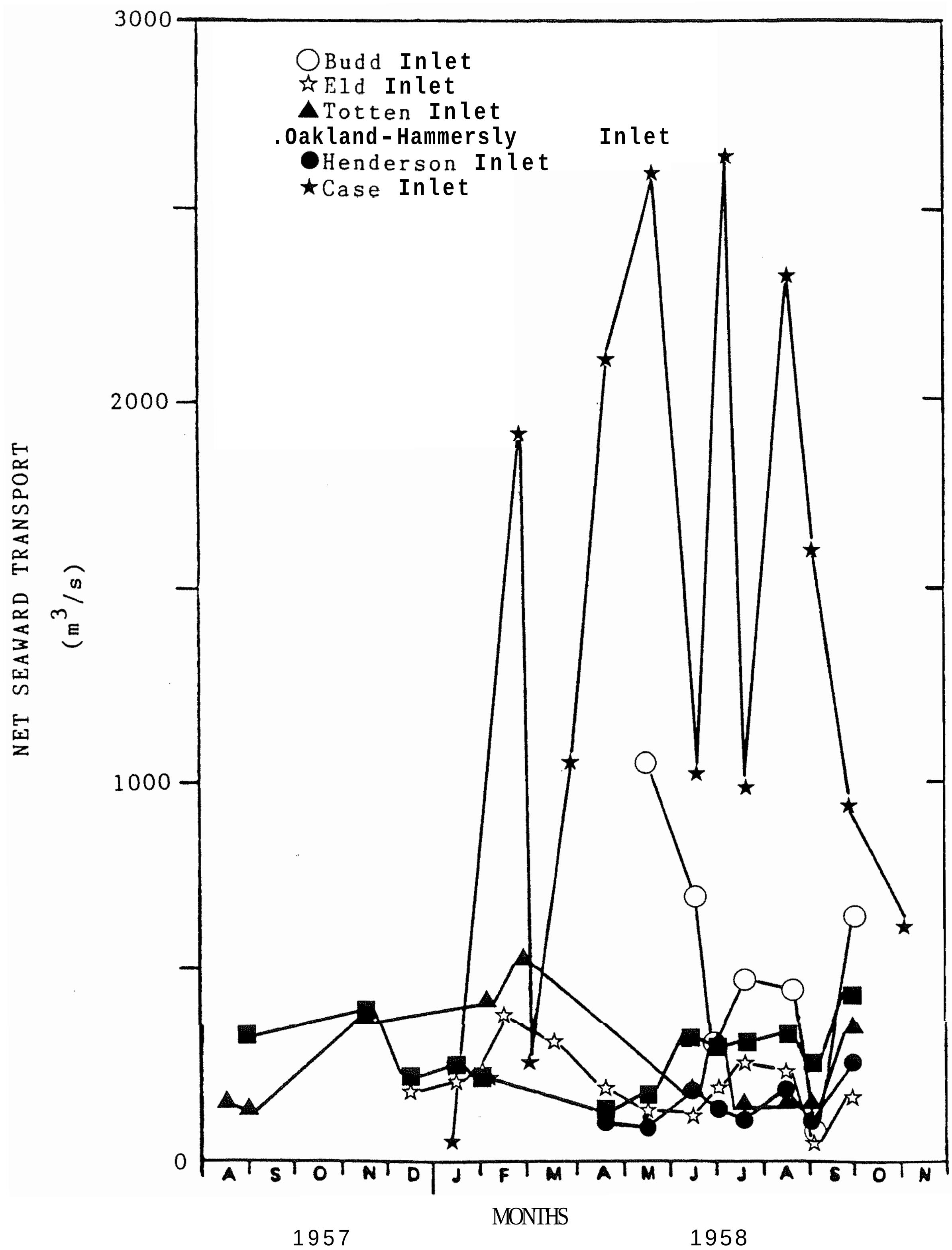


Figure 9. Monthly net seaward transport calculated from a water budget analysis.

For all the inlets except Case Inlet, the monthly values vary somewhat gradually from month to month. For Case Inlet, the numbers change significantly, and probably unrealistically between May to August of 1958.

The effect of changing S_0 can be seen in the following example. For the July time period, Duxbury used $S_0=29.0$ and we used 28.44, which is a difference of only 0.56 $^o/oo$. This is less than expected seasonal changes in salinity. Using $S_0=29.0$, Duxbury (1972) calculated $T_0=1274\ m^3/s$. Using $S_0=28.44$ and keeping all other factors constant, $T_0=196\ m^3/s$. This is a good example of how a small change in a measured value can produce a large change in the result.

Net Transport

Figure 10 summarizes the estimates of the average net seaward transports for the Southern Sound. This figure presents values calculated from both methods described above. Transport estimates for Budd and Case Inlets were made both from current measurements and a water budget analysis. In both cases, transports calculated from the two methods were reasonably close. For Budd Inlet, the estimates were 600 and 500 m^3/s using the water budget and current measurements methods, respectively. For Case Inlet, the estimates were 1900 and 1400 m^3/s. Figure 10 shows the water budget value in each case since this volume represents a longer term average and because the other inlet values are based on the water budget method.

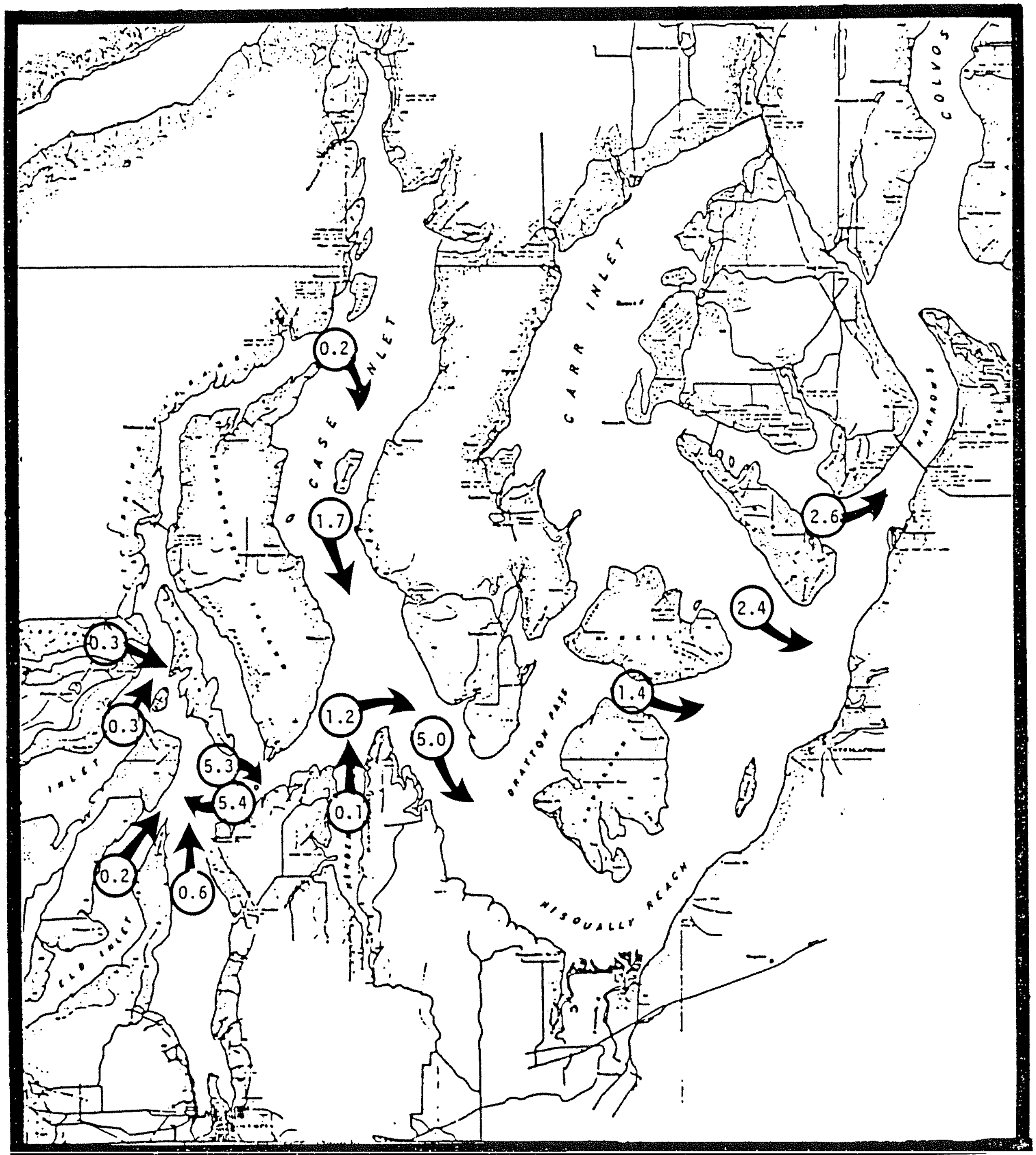


Figure 10. Average net seaward transport (10^3 m^3/s) for several areas in the Southern Sound.

REFLUXING

The estimates of transport compiled thus far in this report do not take refluxing into account. The effect of refluxing is to return a portion of the outflowing surface layer to the inflow, thereby increasing the flushing time of an inlet. This refluxing generally occurs within mixing zones and not within the basins and inlets of the Sound. The majority of these mixing zones are relatively shallow constrictions (sills) separating the deeper basins. The refluxing which occurs in these mixing zones is illustrated in Figure 11. The flow exiting any layer is divided into two parts when it enters a mixing zone. The part which mixes and returns into the opposite layer of its original source basin is the refluxed portion (e.g., fraction α_{34}) Those fractions continuing out of the basin (e.g. α_{31} and α_{24}) are said to be effluxed (see Cokelet and Stewart, 1985).

The refluxed and effluxed fractions can be calculated based upon the transport weighted average salinities (S_1, S_2, S_3, S_4) of the layers of the two reaches adjoining the mixing zone. Based upon the conservation of mass and salt, and using Knudsen's Hydrographic Theorem, Cokelet and Stewart (1985) derived the following equations to represent the reflux and efflux coefficients:

$$\alpha_{21} = \frac{S_1 \; S_2 - S_4}{S_2 \; S_1 - S_4} \qquad \alpha_{24} = \frac{S_1 \; S_3 - S_4}{S_3 \; S_1 - S_4}$$

$$\alpha_{31} = \frac{S_4 \; S_1 - S_2}{S_2 \; S_1 - S_4} \qquad \alpha_{34} = \frac{S_4 \; S_1 - S_3}{S_3 \; S_1 - S_4}$$

Salinities in these equations are flux weighted salinities. The sum of all coefficients for water emanating from a layer must equal 1 (i.e., the amount of water refluxed plus effluxed is 100 percent of the water leaving a layer).

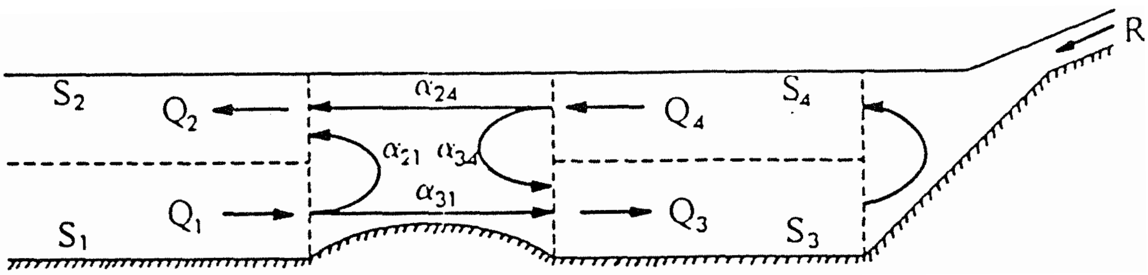
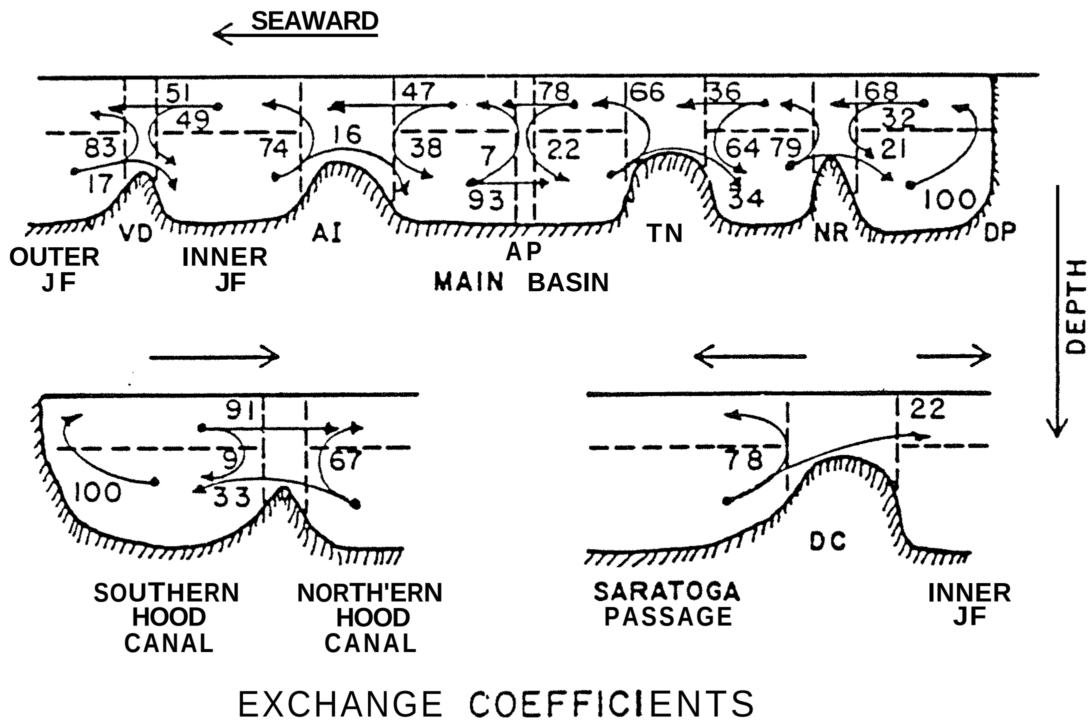


Figure 11. Two reaches meeting at a simple junction mixing zone (From Cokelet and Stewart, 1985). Q represents the average transport of water, S the transport weighted average salinity of a layer, R the runoff, and α the refluxing and effluxing fractions.

Stewart et al. (in-preparation) have calculated refluxing and effluxing percentages for a number of Puget Sound's mixing zones (Figure 12) based upon an annual average salinity and transport calculated each layer within each reach. The annual average salinities were calculated based upon University of Washington hydrographic measurements taken during 1953-54. Transport was calculated from current measurements taken usually near mid-basin. Reflux coefficients for The Narrows and Nisqually Reach were estimated to be 0.64 and 0.32, respectively. Because of limited current measurements embracing Dana Passage, Stewart et al. (in preparation) did not calculate refluxing and effluxing percentages for this location.

Refluxing does occur in Da'na Passage, One way to estimate refluxing, without using transport data, is to estimate the depths at which the majority of the transport is occurring into and out of each basin, and then to use the average annual salinities at those depths in the refluxing equation realizing these salinities are not flux-weighted and that the depths of greatest transport may be incorrect. Using salinity data from UW sites 431 and 452 which embrace Dana Passage, we estimate a refluxing coefficient (α_{34}) of about 68 to 70 percent.

To more accurately calculate the refluxing in Dana Passage, we attempted to obtain transport weighted salinities to use in the refluxing equation. Currents and salinities were measured at five depths (Table 4) east and west of Dana Passage near UW hydrographic station numbers 450 and 452. Good current data was recorded for each meter except the meter at 24m depth at site 452. Net currents were calculated for the data from each current meter record and the along-channel portion of the net current plotted versus depth. As stated earlier, the net flow at these two locations was not typical of two layer flow basins, but was more typical of a uniform net flow at all depths, especially at site 452. At site 450, the net current is inland except near surface, and at site 452, it is very strong and also directed inland. Re-examination of historical current measurements taken at surrounding sites (Figure 5, sites 323 and 330) indicate the net currents south of site 450 and north of site 452 are predominantly seaward. It appears that the four layers which mix in Dana Passage are separated horizontally, not vertically, within the two basins.



LEGEND

JF STRAIT OF JUAN DE FUCA
AI ADMIRALTY INLET
AP ALKI POINT
TN 'THE NARROWS
NR NISQUALLY REACH
DP DANA PASSAGE
DC DECEPTION PASSAGE
VD VICTORIA–DUNGENESS

Figure 12. Exchange coefficients in major reaches and sill zones of Puget Sound. Number indicate the percentage of water traveling between reaches(From Quinlan et al.,1985). Numbers at Admiralty Inlet do not equal 100 due to transport into Whidbey Basin and Hood Canal.

While we were able to calculate transports associated with this type of flow regime, salinities were only measured within two of the four layers by the current meters deployed for this project. In addition, plots of the average salinities recorded at each site versus depth suggest some of the salinity data may not be accurate. Figure 13 presents the recent salinity measurements versus the annual average of UW historical salinity measurements taken at sites 431 and 452. The questionable recent salinity data is at mid-depth at both sites. The salinity data would indicate the least dense water at middepth which is not realistic. The overall profiles of the new measurements, though offset some, parallel the profiles of nearby historical measurements. Therefore the historical salinity measurements were combined with the recent and historical current measurements to compute the refluxing coefficients.

To assess whether or not the salinity measurements at sites 431 and 452 represent all four layers (S_1, S_2, S_3, S_4), we compared salinity measurements at site 453 with 452 (Figure 12). No cross channel site was available to compare with site 431. The annual average salinities versus depth at site 453 are quite different than at site 452 for the same averaging period. Therefore, we felt the salinity measurements at site 453 were representative of the seaward flowing layer and salinities at site 452 more representative of the landward flowing layer. Salinities at site 431 were used for both layers of the basin east of Dana Passage.

The transport weighted salinities which result from the mix of the net flows calculated from the recent current measurements and the annual average salinities at UW stations 431, 452, and 453 are:

$$S_1 = 29.141$$
$$S_2 = 29.040$$
$$S_3 = 28.871$$
$$S_4 = 28.708$$

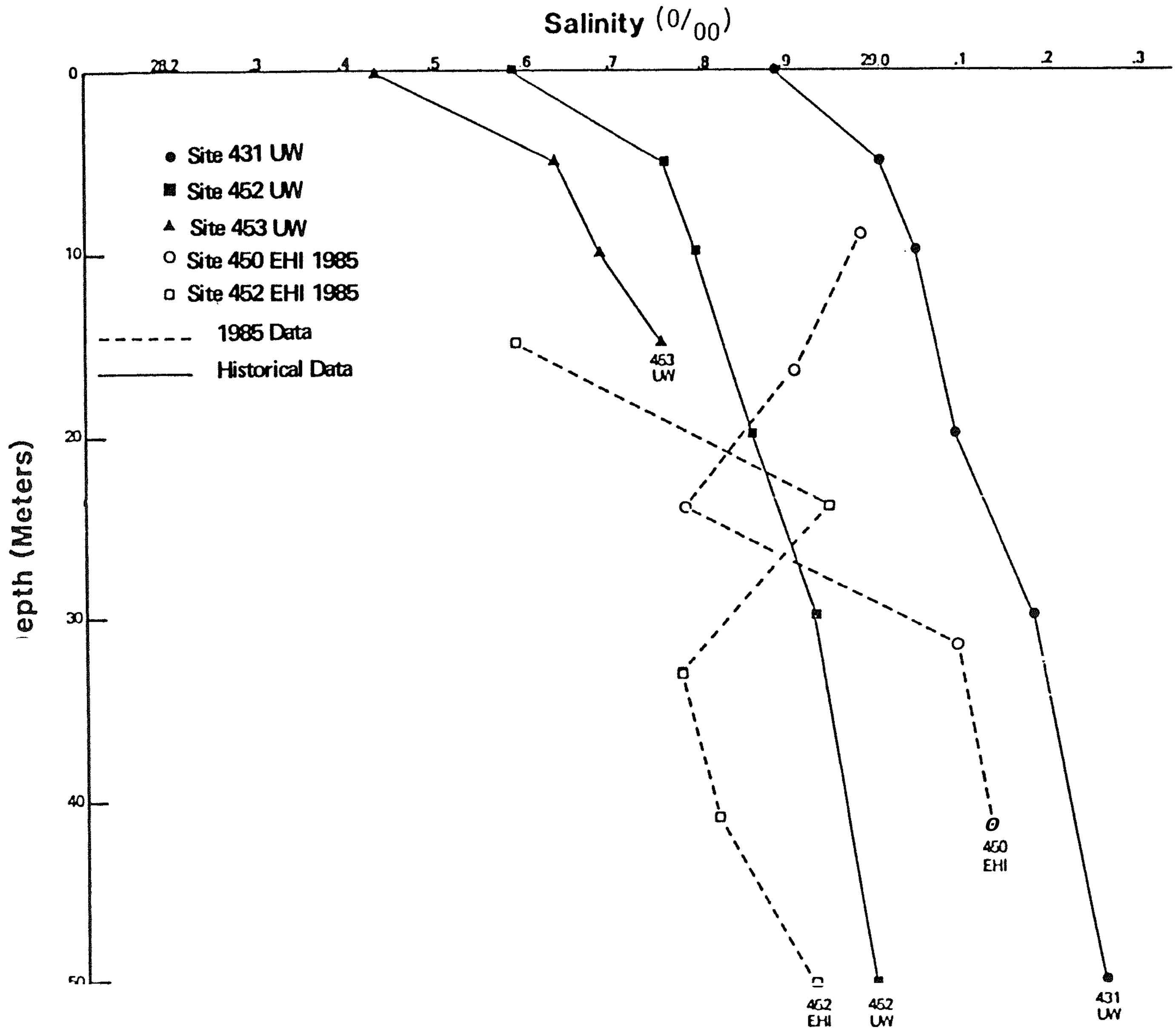


Figure 13. Salinity profiles based on current meter data and University of Washington historical data.

Using these flux-weighted salinities in the refluxing equation (α_{34}) results in a refluxing coefficient of 0.62 or 62 percent for Dana Passage. This value will be used to represent the reflux coefficient for all inlets west of Dana Passage.

Water from Budd, Eld, Totten and Hammersley Inlets all exit through Dana Passage. It is difficult to determine how much of the water from each Inlet is refluxed back into the same Inlet. As a first approximation, we assumed that the refluxing for each Inlet was 0.6. This value is probably high considering the waters from all the Inlets mixed to some degree and are returned to other Inlets. However, observations of the hydraulic model indicate that some of the water is refluxed into the Inlet before it even reaches Dana Passage. A minimum value could be derived by assuming that water from Budd, Eld, Totten and Hammersley Inlets completely mix, that 0.6 of the mixture is refluxed at Dana Passage and that the refluxed portions are redistributed to the Inlet proportional to their transports. According to previous estimates the ratio of Budd Inlet transport to Dana Passage transport is 600 m^3/s to 1200 m^3/s or 0.5. Combined with the reflux coefficient for Dana Passage, this would result in a minimum reflux of 0.3 for Budd Inlet. This would also mean that the rest of the refluxed Budd Inlet water (the other 0.3) is transported into Eld, Totten and Hammersley Inlets.

MAXIMUM DISCHARGE RATE MODEL

Ideally, we would like to determine a maximum discharge rate of effluent into an embayment by combining information on flushing rates and assimilative capacity. Assimilative capacity is something people have been working on for a long time and no clear results have been produced so far. We just do not know the levels of contaminants which cause sublethal or chronic effects. In addition, there are indications that bacteria behave differently than we had thought. Some bacteria thought to be dead due to exposure to the marine environment appear to grow again once placed in a host organism. This may change our present thoughts about bacterial die-off. Definitive explanations of assimilative capacity and bacteria die-off are probably not forthcoming in the near future. Meanwhile, some guidelines for maximum total discharge rates into an area are needed.

One reasonable and simple approach is to set the maximum discharge rate such that the volume transport of diluted effluent is less than or equal to the average transport out of the area (average transport must include adjustment for refluxing). In other words,

$$(7) \quad Imax \times D \le T_o - T_o R \quad \text{or} \quad Imax = \frac{T_o(1-R)}{D}$$

where D = effective dilution; Imax = maximum discharge rate, T_o = surface transport out of the embayment; and R = refluxing coefficient.

Transport and refluxing estimates for areas of the Southern Sound were presented in previous sections. A discussion of dilution and the effects of mixing with contaminated seawater is presented below.

Dilution

Dilution (D) is defined as one part effluent in D parts mixture of effluent and seawater. So, when mixing effluent with uncontaminated seawater the following equation applies:

$$(8) \qquad \frac{1}{D} = \frac{1}{X+1} = C$$

where C equals the concentration of effluent in the mixture and X equals the number of parts of seawater which must be mixed with one part effluent to result in a dilution of D. For example, if $D = 100$, $C = 0.01$ and $X = 99$ i.e., 1 part effluent + 99 parts seawater = 100 dilution.

If effluent is being mixed with contaminated seawater, the background concentration should be accounted for in the dilution calculation. When mixing effluent with contaminated seawater, the following equation applies:

$$(9) \qquad \frac{1}{D} = \frac{X \cdot BC+1}{X+1} = C$$

where BC equals the background concentration of "old" effluent in the seawater which is being mixed with the "new" effluent. If BC=0, Equation (9) reduces to Equation (8). This means that if the receiving water is contaminated, the diffuser must be designed to produce a larger dilution to achieve the desired effective dilution. As the background concentration increases, it will require mixing with more seawater to achieve the same effective dilution. Examples of dilution requirements for several different background concentrations are listed in Table 8. The examples all assume a desired effective dilution of 100.

Table 8. Design dilutions required to achieve an effective dilution of 100

Background Concentration (BC)	Background Dilution	Design Dilution (X+1)	Effective Dilution (D)
0.0000		100	100
0.005	2000	105	100
0.001	1000	111	100
0.002	500	125	100
0.005	200	199	100
0.01	100	Can't Do	100

Based on the table, it appears that if the background concentrations are low, they probably do not need to be considered in diffuser design. However, background concentrations greater than approximately 0.001 should be considered in diffuser design calculations.

Background Concentration

This section describes a simple method for calculating the background concentration resulting from a new effluent input into an embayment with a two-layer flow (Figure 14).

Assume that a constant input (I) is introduced at point A and that it moves from A to B in time t. For modeling purposes, it is easier to assume that the input comes in pulses such that there is one pulse of quantity q in time t and therefore,

$$(10)\quad q = tI$$

The following assumptions are also made:

1. There is some refluxing of water at point B such that a percentage of effluent R is refluxed from B to point C.

2. Water is transferred between the upper and lower layers only at the head and mouth of the embayment, therefore all water at A moves to B and all water at C moves to D.

We can now trace the movement and amount of effluent in the embayment as it reaches equilibrium. Table 9 shows the amount of effluent at four points in the embayment at various times. The development shown is based on a transit time of t between C and D. This is certainly not true for many embayments. However this assumption does not affect the final background concentration, only the amount of time required to achieve it. For conservative quantities the actual transit time is of no consequence. For

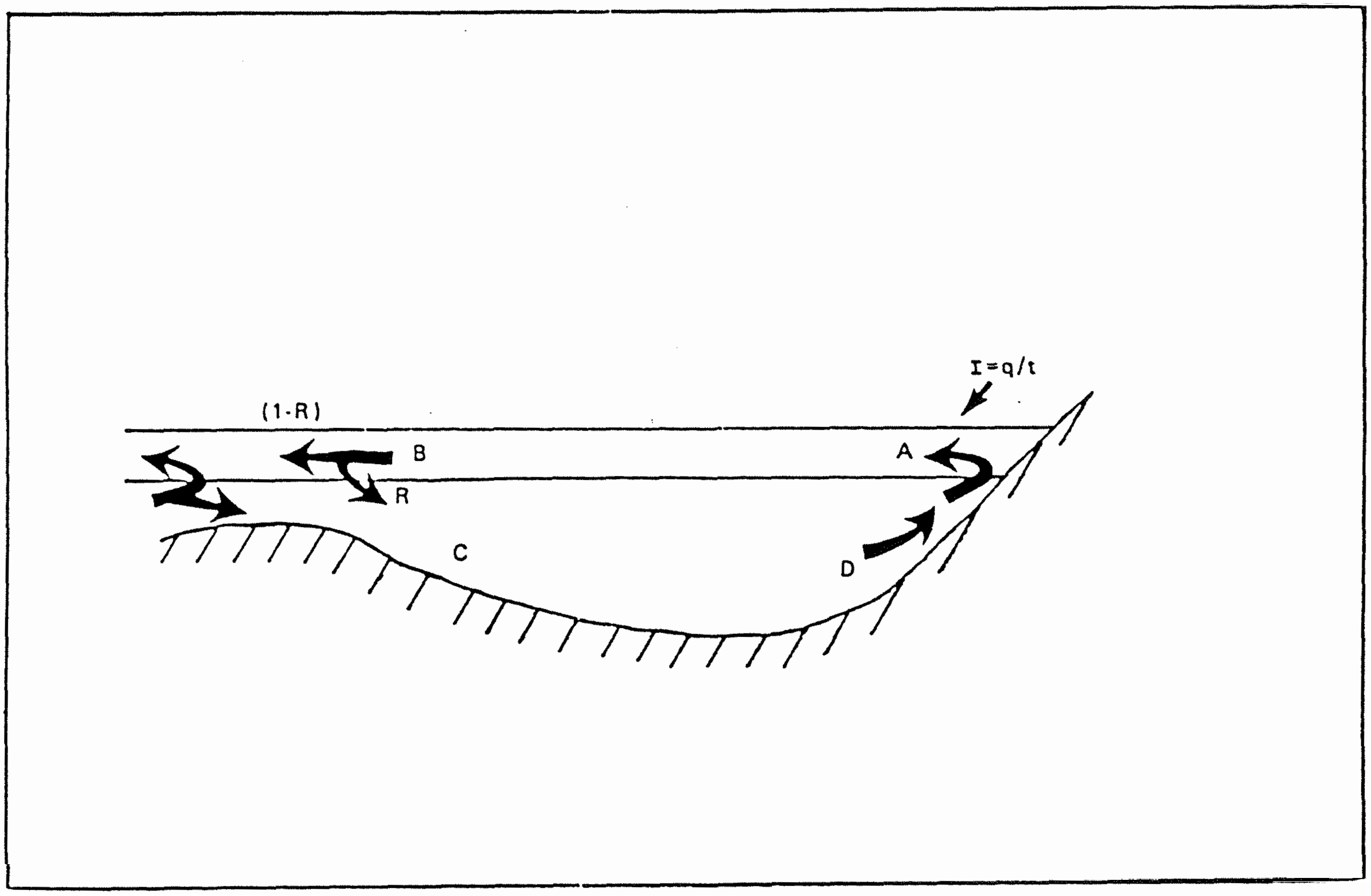


Figure 14. Model representation of a two-layer flow embayment. Locations A,B,C,D are referred to in the text.

non-conservative quantities, Table 9 could be revised to reflect actual times. Again, the final background concentration will remain unchanged for conservative substances.

Table 9. Amount of effluent in an embayment as it reaches equilibrium

Time	Amounts at: A	B	C	D
t	q			
2t	q	q		
3t	q	q	Rq	
4t	q	q	Rq	Rq
5t	(1+R)q	q	Rq	Rq
6t	(1+R)q	(1+R)q	Rq	Rq
7t	(1+R)q	(1+R)q	R(1+R)q	Rq
8t	(1+R)q	(1+R)q	R(1+R)q	R(1+R)q
9t	[1+R(1+R)]q	(1+R)q	R(1+R)q	R(1+R)q
13t	(1+R[1+R(1+R)]q	[1+R(1+R)]q	R[1+R(1+R)]q	R[1+R(1+R)]q

As shown in Table 9, the input is started and at time= t, one pulse of quantity q enters at point A. This material moves from point A to point B so that at time 2t a new pulse enters at A while the original pulse is at point B. During the next time step a portion (R) of the material at point B moves to point C, the material at point A moves to point B, and a new pulse enters at point A. In the next time step, the same movement occurs with the addition of the material at point C moving to point D. Now there is some effluent spread throughout the embayment. In the following time step, point A will receive a pulse from the source as well as some from point D. This new amount (1+R)q then cycles around until some of it reaches point D. On the next time step, the amount at point A will be the new pulse from the source plus the amount from point D or [1+R(1+R)]q. At 13t the amount at point A = (1+R[1+R(1+R)])q which is equivalent to $(1+R+R^2+R^3)q$.

This pattern will continue such that over a long period of time, the amount of material at point A will be:

(11) Amount at A = $(1+R+R^2+R^3 \ldots R^n)q$ or

(12) Amount at A = $q + q \sum_{n=1}^{\infty} R^n$

Of the total amount at point A, q is due to the new pulse of material from the source while $q \sum_{n=1}^{\infty} R^n$ is due to recycles material making up the background concentration. If we assume that the background material mixes completely in the upper layer while traveling from point A to point B, then the background concentration (BC) equals the amount of "old" effluent divided by the volume of the upper layer Vu or

$$(13)\quad BC = \frac{q \sum_{n=1}^{\infty} R^n}{Vu} = \frac{q\left[\frac{1}{(1-R)} - 1\right]}{Vu} = \frac{R}{(1-R)} \cdot \frac{q}{Vu}$$

This quantity does not include any contribution from the newly discharged effluent. It represents the background concentration of old effluent in the seawater being used to dilute newly discharged effluent.

Substituting Equation (10) into Equation (13) we get

$$(14)\quad BC = \frac{R}{(1-R)}\,\frac{tI}{Vu} = \frac{R}{(1-R)}\,\frac{I}{T_o}$$

where T_o = the transport out of the upper layer. Equation (14) defines the background concentration of conservative substances resulting from local inputs to the upper layer of the embayment. It assumes that water entering at point C from outside the embayment is uncontaminated. The model could be adjusted to account for this if necessary.

The background concentration, as used throughout this report, is proportional to the volume of recycled effluent contained in the volume of the upper layer and is therefore dimensionless. Often it is useful to determine the background concentration of specific elements in the effluent which would be expressed in units such as mg/l. This can easily be done for conservative quantities by multiplying the effluent discharge rate by the concentration of a substance in the effluent. For example, assume R=0.6, I=1 m^3/s, T_o = 1,000 m^3/s and the concentration of dissolved copper in the effluent was 10 ug/l, then

$$BC_{cu} = (1.5 \cdot 1m^3/s \cdot 10ug/l)/1000\ m^3/s$$

$= 1.5 \times 10^{-2}$ ug/l dissolved copper in the embayment. At the same time, the background concentration of effluent is:

$BC = (1.5 \cdot 1\ m^3/s)/1000\ m^3/s = 1.5 \times 10^{-3}$. Again, the latter formula, which relates to the background concentration of effluent, is used throughout this discussion.

Maximum Discharse Rate

The maximum discharge rate was defined in Equation (7) as $Imax=T_o(1-R)/D$. Knowing the transport out of an inlet, the reflux coefficient and the desired effective dilution, the maximum discharge rate can be determined. Imax is not directly dependent on the background concentration or the design dilution. However, to achieve the desired effective dilution these two factors must be considered. Expressions for the background concentration and design dilution corresponding to conditions of maximum discharge are given below.
Equation (14) becomes

$$(15)\quad BC = \frac{R}{(1-R)}\frac{Imax}{T_o} = \frac{R}{(1-R)}\frac{T_o(1-R)}{T_o} = \frac{R}{D} \text{ when } I = Imax.$$

Equation 9 can be solved for X to give

$$(16)\quad X = \frac{D-1}{1-D \cdot BC}$$

Substituting (15) into (16) we get

$$(17) \quad DD = X + 1 = \frac{D-1}{1-D\left(\frac{R}{D}\right)} + 1 = \frac{D-R}{1-R},$$ where DD = design dilution and

R and D are as previously defined.

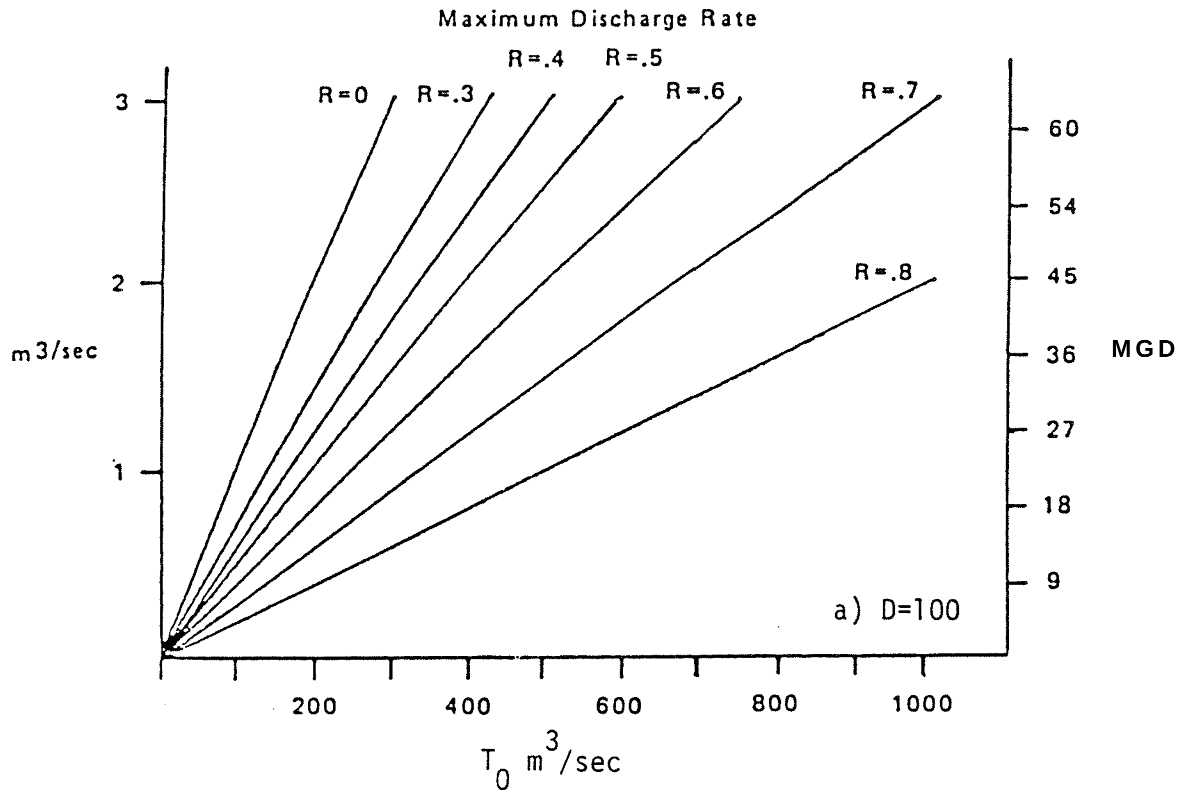
Table 10 presents values of R, Imax, BC, and DD corresponding to several values for refluxing and an effective dilution of 100. The maximum discharge rate is plotted versus transport for several values of R in Figure 15 (again (assuming D=100, and D=200)).

Table 10. Maximum discharge rate and design dilution for various R values*

R	$\frac{R}{(1-R)}$	Imax	BC	DD** (X+1)
0.0	0.00	.010 T_o	.000	100
0.3	0.43	.007 T_o	.003	142
0.4	0.67	.006 T_o	.004	166
0.5	1.00	.005 T_o	.005	199
0.6	1.50	.004 T_o	.006	249
0.7	2.33	.003 T_o	.007	331
0.8	4.00	.002 T_o	.008	496

*Equations used are: Imax(7); BC(15); DD=X+1(17).
**Design dilution required to achieve an effective dilution of 100.

The model assumes that effluent is completely mixed in the upper layer. Discharging at the maximum discharge rate will result in the entire upper layer having the effective dilution D. Proper siting of individual discharges is important even if the maximum discharge rate is not exceeded. If diffusers are not properly sited in areas with good mixing, the required effective dilution will not be achieved.



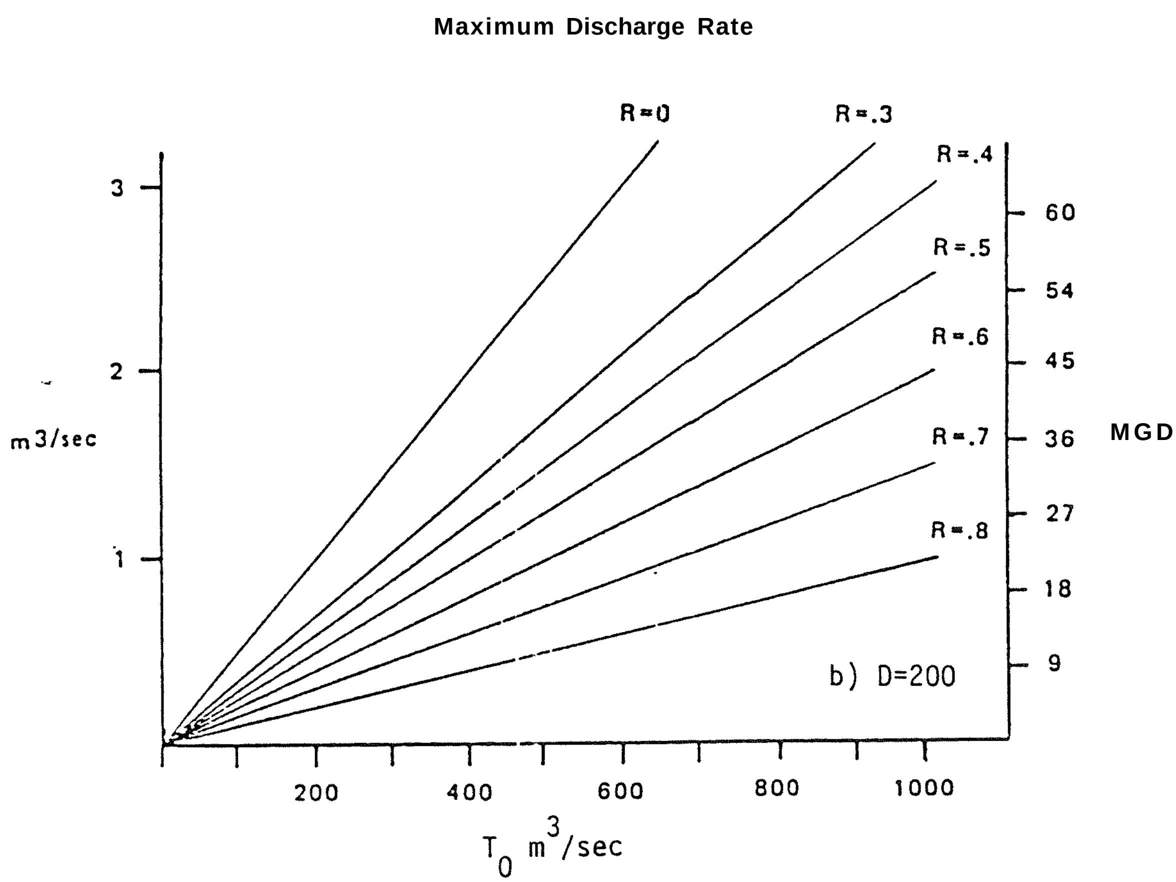


Figure 15. Maximum discharge rate versus transport for various R values. $Imax = T_0(1-R)/D$ a) D=100 ; b) D=200

Summary

Several important points which should be remembered while using this model are listed below:

- Background concentration generally refers to the concentration of old or recycled effluent and not specific chemical constituents.

- The embayment is modeled as a two-layer flow with water transferred between layers at the head and mouth of the inlet.

- Effluent mixes completely in the upper layer.

- The background concentrations result from recycling of local effluent inputs. Seawater coming from outside the inlet is assumed to be uncontaminated.

- The maximum discharge rate is set to achieve a specific effective dilution of effluent in the embayment. The volume of diluted effluent must be less than or equal to the transport out of the area.

- Proper siting of individual discharges is important to assure good initial dilution and subsequent dilution in the inlet.

The maximum discharge rate is dependent on three factors, the effective dilution, transport out of the embayment, and the reflux coefficient. The choice of the required effective dilution is a policy decision which would be made based on levels for substances in the effluent which affect water quality. An initial dilution of 100 is normally required for mixing within the zone of initial dilution (i.e. near the diffuser). This would indicate that an effective dilution of at least 100 would be required, and it is possible that a larger dilution would be required. The other two factors, T_o and R, are physical factors related to the circulation and flushing of individual inlets. These factors can not be measured directly but are determined from current measurements and water property data as previously discussed in this report.

Once D, T_o, and R are known, all other quantities can be determined. Effects of input rates above and below the maximum discharge rate can be examined. Some example cases are given in Appendix B.

MAXIMUM DISCHARGE RATES FOR THE SOUTHERN SOUND

Maximum discharge rates have been calculated for several areas of the Southern Sound using the model developed and the transport and refluxing estimates previously given. It should be remembered that there is considerable uncertainty in the transport and refluxing estimates. As more data become available, more accurate estimates can be made. However, by looking at the range of reasonable estimates, useful approximations of maximum discharge rates can be made.

Table 11 summarizes our best estimates for maximum discharge rates calculated for several areas of the Southern Sound based on average transport values. Table 12 presents ranges of maximum discharge rates considering a reasonable range of values for transport out of the inlet and for the reflux coefficient. Both tables present calculations for the case when D=100. Imax is directly proportional to 1/D, so if D=200 or 300, the Imax values would be 1/2 or 1/3 of the values presented.

These tables are not intended to establish policies on the maximum discharge rate allowable for a given area. However they could be useful in the decision making process. For example, Table 11 is based on average values of transport but transport during a low flow condition or the use of seasonal values may be more appropriate for setting policy. This report, and particularly Tables 5, 7, 10, 11 and 12, summarizes previous work and available data and outlines a methodology which could be used to define maximum discharge rates. Transport and reflux values will be better defined as we learn more about circulation processes and acquire more data.

In most areas of the Southern Sound, and particularly west of Dana Passage, water properties have not been collected with enough spatial or temporal coverage to provide an accurate annual average or to define seasonal variations.

The maximum discharge rate model could also be refined by adding a time element to account for degradation of chemical constituents within the effluent. However, this requires more detailed information of flow within each inlet. If calculations of this level of detail are desired for a specific inlet, other models are available which could provide more accurate results. Two such models were recently applied to Budd Inlet (URS, 1986).

The maximum discharge rate model as presently defined provides a means for comparing different areas of Southern Puget Sound. It also provides a simple means of relating transport, effluent discharge and average concentrations in an Inlet. It can be used to test various scenarios and provide guidance on acceptable limits:

Table 11. Maximum Discharge Rates for several areas of the Southern Sound to achieve an effective dilution of 100

Inlet	T_0 (10^3 m^3/s)	R	Imax (m^3/s)	Imax mgd
Budd	0.6	.6	2.2	50
Eld	0.6	.6	2.3	52
Totten	0.3	.6	1.0	23
Hammersley	0.3	.6	1.2	27
Henderson	0.1	.3	0.9	21
Case	1.7	.3	11.8	270
Carr	2.4	.6	9.5	220
South Sound west of:				
The Narrows	2.6	.3	18.2	415
Dana Passage	1.2	.6	4.8	109

Table 12. Ranges of values for maximum discharge rates to achieve an effective dilution of 100

Inlet	Method for T_o	$T_o (10^3 m^3/s)$	R	Imax (m^3/s)	mgd
Budd	Water Budget	0.1-1.1	0.6	0.3-4.3	6.8-98
	Duxbury (1972)	.2-3.0	0.6	0.9-12	21-270
	current Meas.	.5	0.6	2.1	48
		.6	0.3-0.8	4.0-1.1	91-25
Eld	Water Budget	0.1-0.7	0.6	0.3-2.8	6.8-64
		0.6	0.3-0.8	4.0-1.1	91-25
Totten	Water Budget	0.1-0.5	0.6	0.4-2.1	9.1-48
		0.3	0.3-0.8	1.8-0.5	41-11
Hammersley	Water Budget	0.2-0.6	0.6	0.7-2.3	16.-52
		0.3	0.3-0.8	2.1-0.6	48-14
Henderson	Water Budget	0.1-0.2	0.3	0.6-1.6	14-37
		0.1	0.2-0.4	1.1-0.8	25-18
Case	Water Budget	0.1-2.6	0.3	0.4-18	9.1-420
	Current Meas.	1.9	0.3	14	310
		1.4	0.2-0.4	11.5-8.6	260-200
Carr	Water Budget	1.0-4.0	0.6	4.2-16	96-360
		2.4	0.3-0.8	16.7-4.8	380-110
South Sound west of:					
Dana Passage	Current Meas.	1.2	0.6	4.9	110
			0.3-0.8	8.5-2.4	190-50
The Narrows	Current Meas.	2.6	0.3	18	410
			0.2-0.4	21-16	480-360

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APPENDIX A

SOUTH SOUND CURRENT METER CRUISE

INTRODUCTION

Three current meter arrays were deployed in Southern Puget Sound during April, 1985. The sites were selected to correspond with historical water property data (Collias, 1970). The three locations were Station 438 near Dougall Pt. in Pickering Passage, Station 450 on the old dredge spoil site, in Dana Passage, and Station 450 in Dana Passage north of Dover Pt. Table A1 lists information concerning these deployments.

Table A1. Information on current meter deployments made for this study

Array no.	Begin date	End date	Latitude	Longitude	Bottom depth (m)	Meter no.	Meter depth (m)
#438	4/16/85	6/24/85	47°17.92' N	122°51.92' W	28.0	7207	9
						7224	16
						7642	23
#450	4/16/85	6/24/85	47°10.96' N	122°50.50' W	43.3	7223	9
						7692	17
						7693	24
						7694	32
						7695	39
#452**	4/16/85	5/24/85	47°09.15' N	122°53.65' W	56.0	7221	15
						7685*	24
						7688	33
						7689	41
#452		6/25/85	47°09.06' N	122°54.00' W		7691	50

*Not Functioning
**Mooring Dragged - top portion recovered on 5/24/85. Data recorded through 5/23/85 were used in the analysis.

Thirteen Aanderaa models RCM4 and RCM5 current meters were used to measure current speed and direction, conductivity (salinity) and temperature. The meter nearest the water surface also recorded pressure. The number of Aanderaa current meters on each array varied with Station 452 and 450 having five each, and Station 438 having three meters. Each current meter was preset to measure data every 15 minutes, and record the observations on magnetic tape. All meters functioned properly with the exception of meter 7685 at Station 452, where no data were recorded. Data were collected at Station 452 until May 24th when the array was dragged approximately 300 meters to the west, before the cable parted. All of Station 452's meters were recovered. The current meter arrays were recovered during June 24-25th, 1985. All meters were in good condition except for the heavy growth of Balanus spp.(barnacles) on the meters.

EQUIPMENT

Figure A1 shows a typical current meter configuration used during this study.

Current Meters

The Aanderaa RCM4 current meter measures speed using a Savonius rotor which is magnetically linked to an internal rotation counter. Direction is measured by a compass needle clamped to a potentiometer ring. Temperature is acquired using a Fenwal thermistor. Conductivity measurements are made with an external inductive cell. The pressure measurements are made with a Bourdon tube connected to a potentiometer ring.

Release Mechanisms

Endeco model 900 acoustic releases were placed on the groundline release anchors of each array. The releases held VINY floats to 80 lb. groundline anchors. The acoustic releases were activated by a coded signal sent from a surface deck unit. The released VINY float carried a nylon line to the surface for subsequent use in groundline recovery.

Pinger

An ORE pinger was attached to each mooring cable to aid in the array recovery. The pinger signal was tracked by hydrophone input to a surface tracking unit. Pinger frequencies of 10 and 12 Khz were used.

Ancillary Equipment

Each array was held upright by 662 lbs of buoyancy provided by a 37 inch diameter steel buoy . Several 14 inch diameter VINY floats were located along the array, with each providing 44 lbs of buoyancy. The array was assembled using 1/4 inch galvanized cable. Copper Nicropress sleeves, galvanized shackles, and thimbles were used to connect the equipment. The groundline was 5/16 inch galvanized cable. The arrays were anchored with 1300 lbs. of 2 inch anchor chain strapped in clumps.. The groundline anchors were 80 lb. truckwheels.

Calibration

Each Aanderaa current meter was factory calibrated before shipment. The Aanderaa meters used in the Southern sound study were calibrated at the Northwest Calibration Center in Bellevue, Washington prior to the Southern Sound deployments.

DEPLOYMENT AND RETRIEVAL

Deployment

Each station was initially located by three point sextant fixes. The position was then marked using the Loran C. The water depth was taken at this time to verify that the arrays were cut to the correct length.

During deployment the arrays were assembled on deck and then strung over the side with the subsurface float deployed first. When the entire array was trailing off the stern ,the array was attached to the main anchor. The main anchor was secured to the stern by safety straps and a quick release clamp. The 1000 ft. of groundline was coiled in a barrel with one end attached to the truckwheel anchor and the other to the main anchor.

To deploy the array, the R/V Kittiwake motored to the station using Loran C coordinates. At the time of deployment the anchor was released allowing the array to free fall. The boat continued on a set course letting the groundline trail out of the barrel. With the groundline taut the truckwheel anchor was lowered to the bottom. When the deployment was complete the boat located the array on the fathometer to verify its position and deployed condition.

Recovery

Recovery was done by dragging gear because the acoustic releases on Stations 450 and 438 failed. During recovery the Kittiwake pulled the grapnel hooks across the truckwheel side of the groundline, using the Loran C and Radar to navigate. The time release on Station 452 functioned allowing for a simpler recovery. Once the ground1ine was recovered the main array was pulled on board using a hydraulic winch.

DATA ANALYSES

The current meter data tapes were converted to a compatable format after which calibration coefficients were then applied. The edited 9-track raw data tape was checked into the CDC computer at the University of Washington computer center. Current meter data was analyzed using the software package Rapid Retrieval Data Display (R2D2), developed by NOAA (Pearson, 1981). The raw data was run through a clean format program to produce a format compatable with the CDC computer. Two filter programs, 2.86 hour and 35 hour, were run to remove high frequency fluctuations and tidal effects. Current roses and speed histograms are presented in Figures A2 through A6. On a current rose display the current meter data is plotted on a compass sectioned into 16 directions. The length of each line is proportional to the mean speed of the observations in the direction of the line. The number at the end of the line is the percentage of time that currents flowed in the indicated direction for the time period analyzed. The speed histogram displays the frequency distribution of current speed regardless of direction. Standard statistics are also given with the histogram.

As indicated in figures A2 through A6, each meter is indentified by a header with the following information.

1. Station name and meter serial number, at which the meter was deployed.

2. The year, julian day, and time (0-24 hours) indicating the start and stop times of current meter data.

3. Station position expressed at latitude and longitude given in degrees, and minutes.

4. Type of filtering used, and the number of data points analyzed (N).

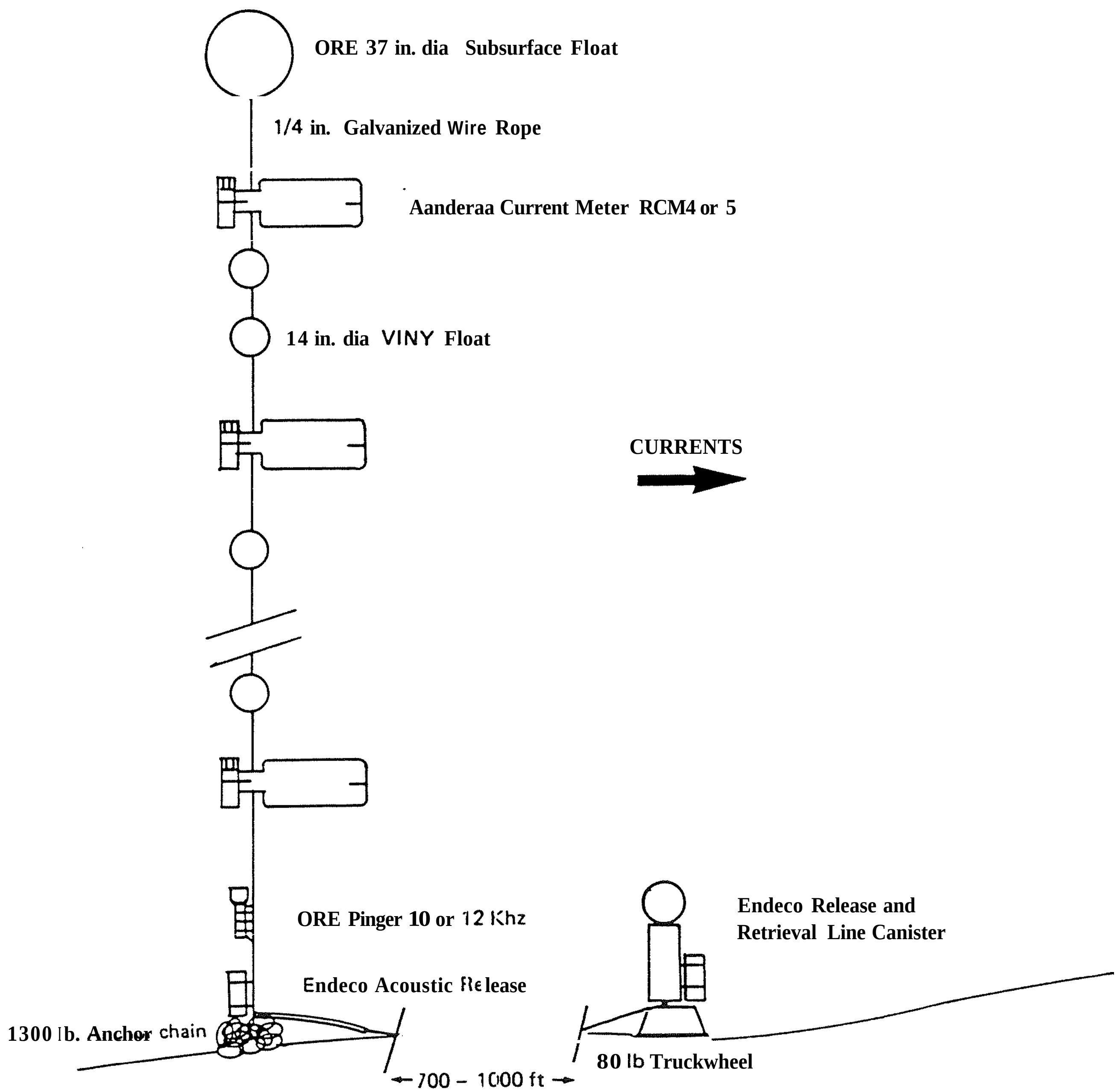


Figure A1. Typical current meter configuration used in this study.

FROM 851061700 TO 851431800
LRT 47.15N LON 122.89W
2.9 HR FILTER DATA N= 890

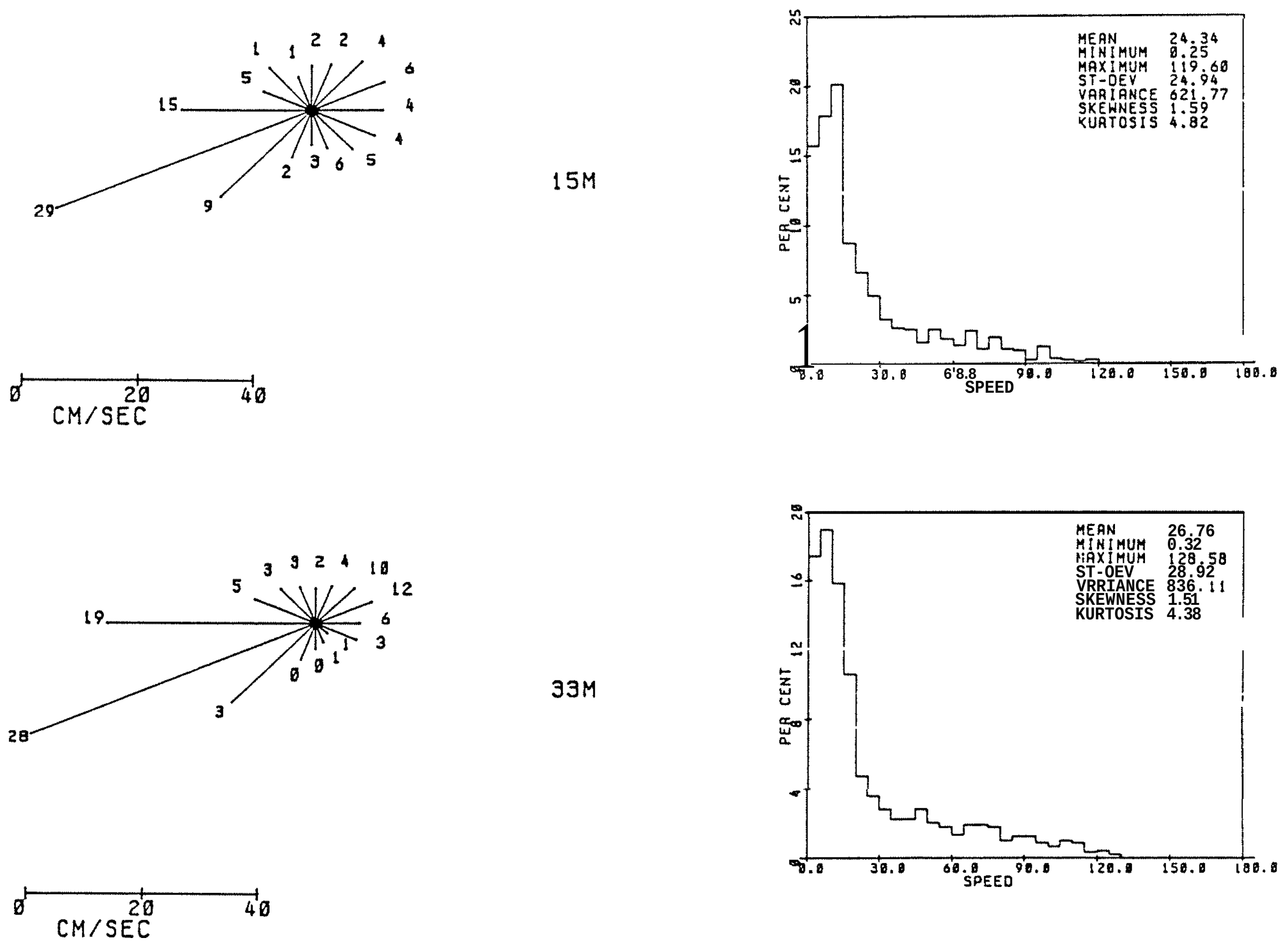
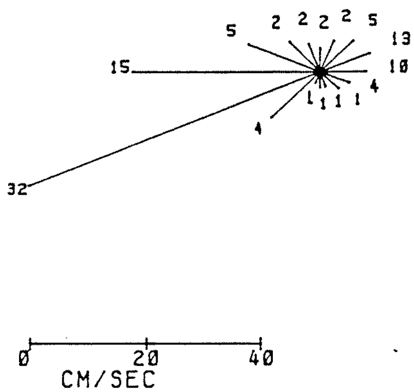
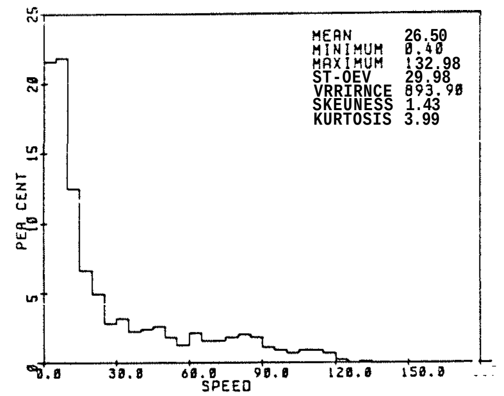


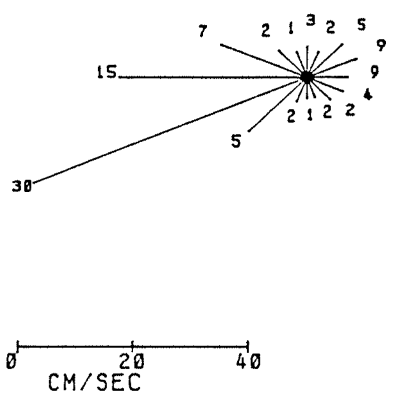
Figure A2. Current roses and speed histograms for data collected at station 452, 15m and 33m.

FROM 851061700 TO 851431800
LAT 47.15N LON 122.89W
2.9 HR FILTER DATA N= 890



41M





50M

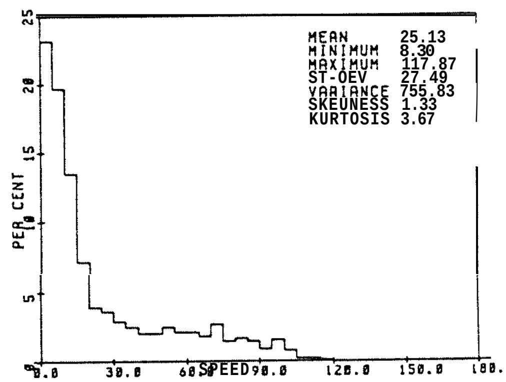


Figure A3. Current roses and speed histograms for data collected at at station 452, 41m and 50m.

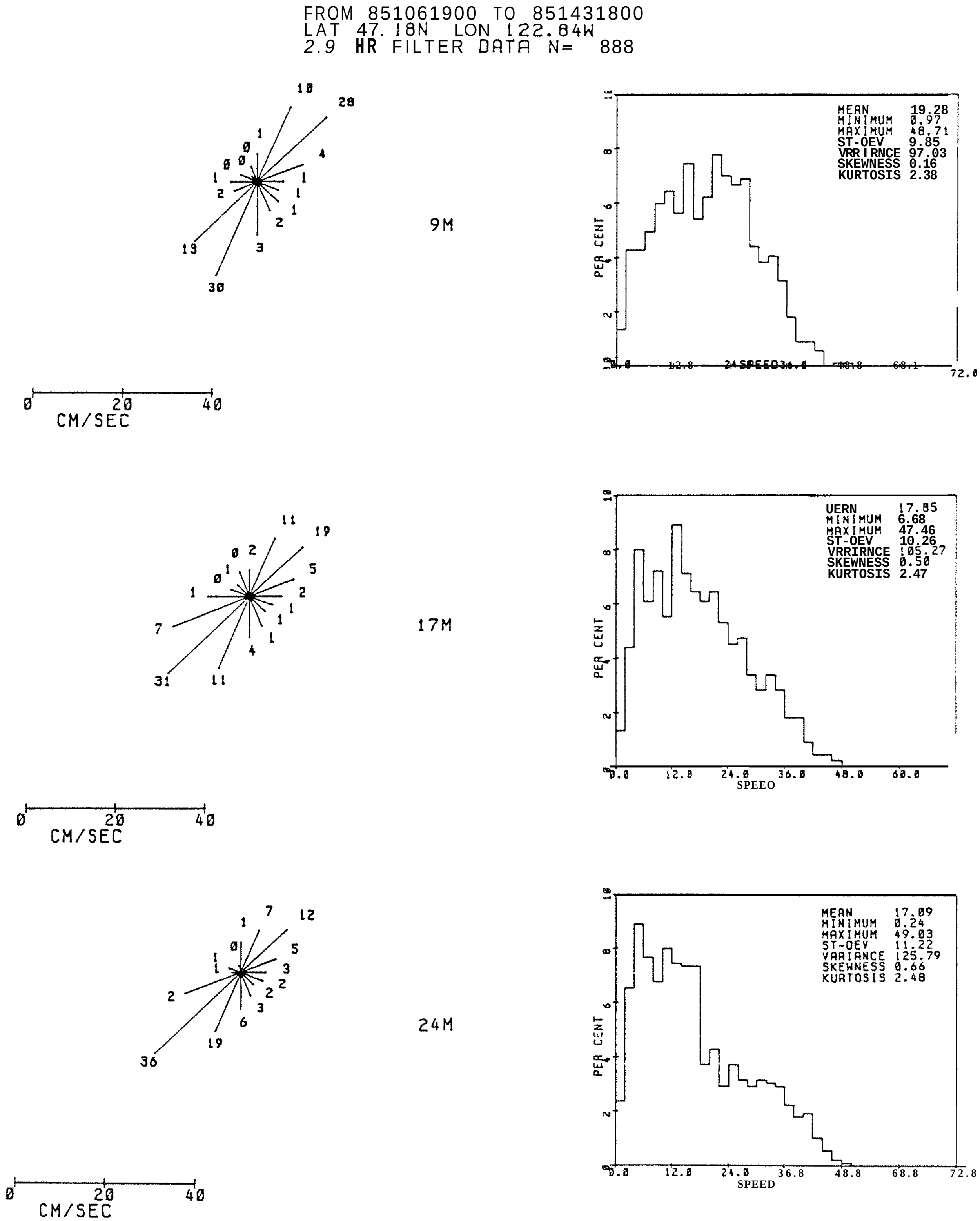


Figure **A4.** Current roses and speed histograms for data collected at station 450, 9m, 17m and 24m.

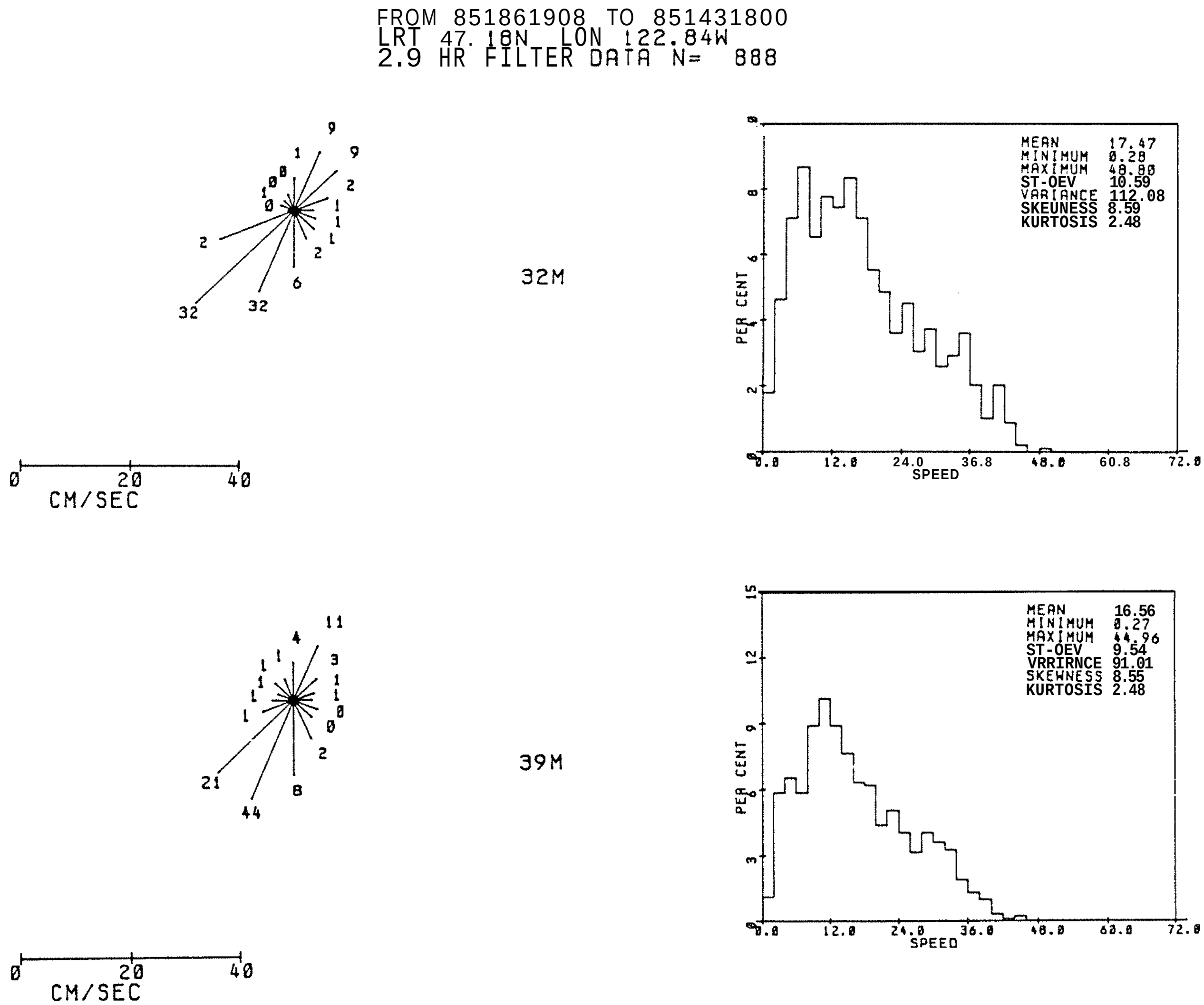
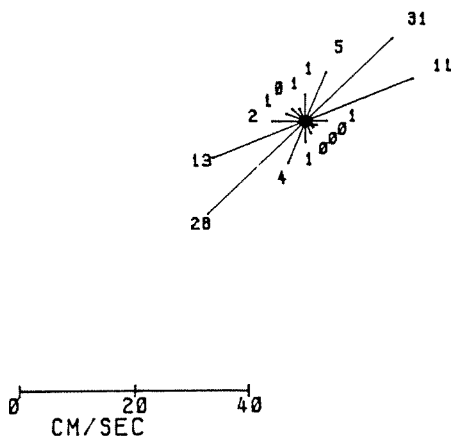
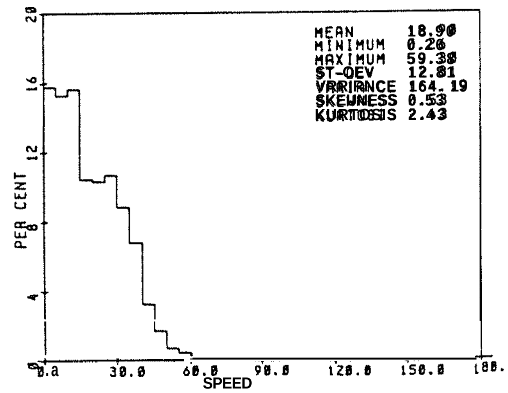


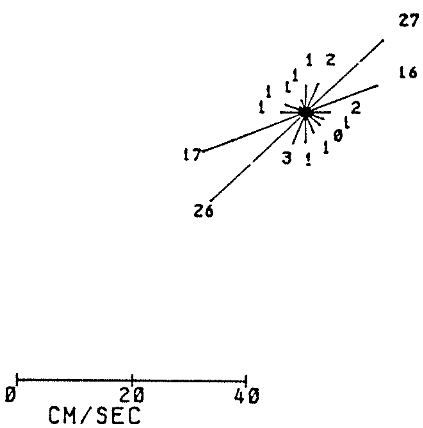
Figure A5. Current roses and speed histograms for data collected at station 450, 32m and 39m.

FROM 851062100 TO 851410400
LAT 47.30N LON 122.87W
2.9 HR **FILTER DATA N= 824**

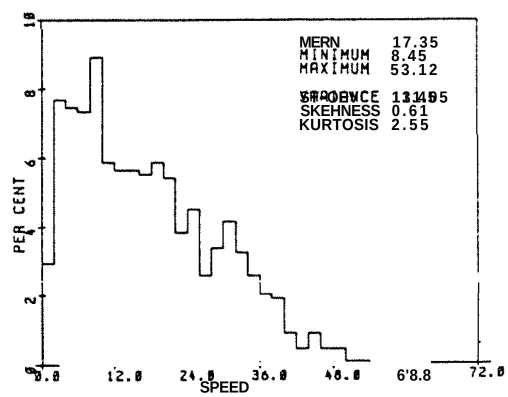


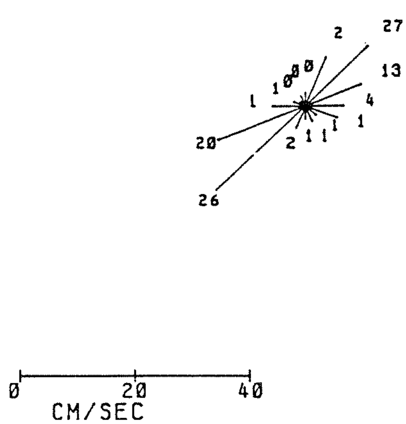
9M





16M





23M

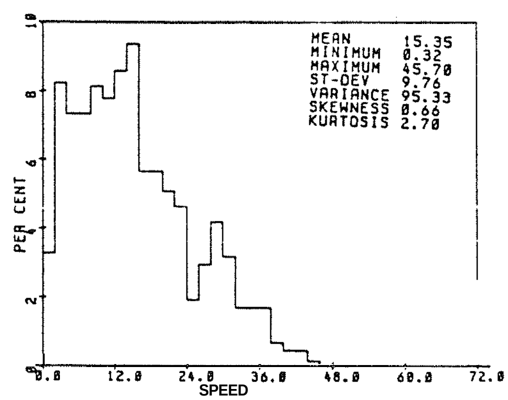


Figure A6. Current roses and speed histograms for data collected at station 438, 9m, 16m and 23m.

APPENDIX B

SUPPORTING DATA FOR TRANSPORT CALCULATIONS

This appendix contains supporting data used in the transport calculations presented in this report. Figures B.l through B.7 contain vertical profiles of current measurements. These data were used in conjunction with cross-sectional areas to estimate transport through several areas of the Southern Sound. Tables B.l through B.7 present the salinity and runoff data used in the transport calculations using the water budget method. Calculations of interim steps are also presented in these tables.

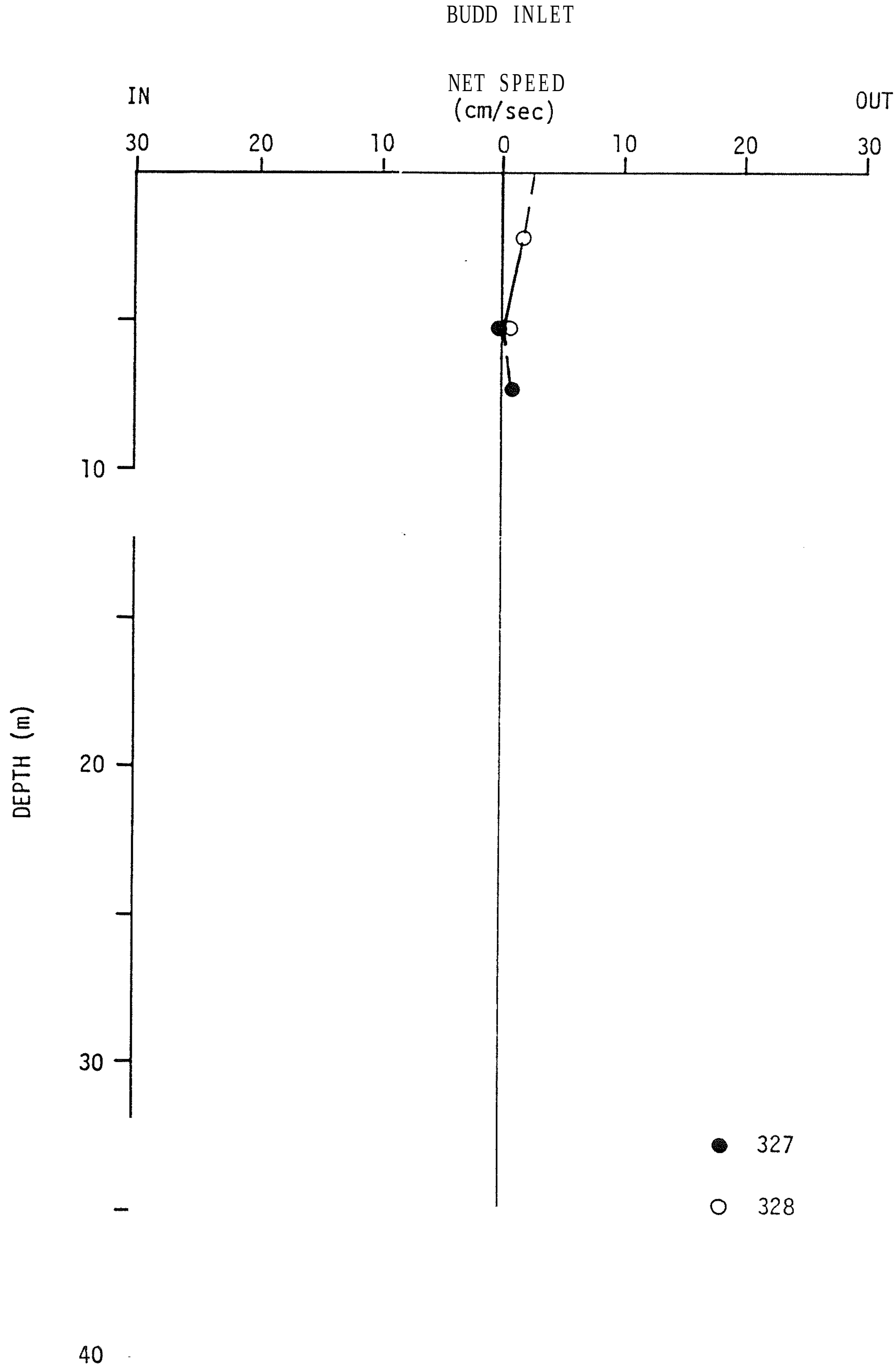


Figure B1. Vertical current profile for Budd Inlet used in transport calculations.

NORTH PICKERING PASSAGE

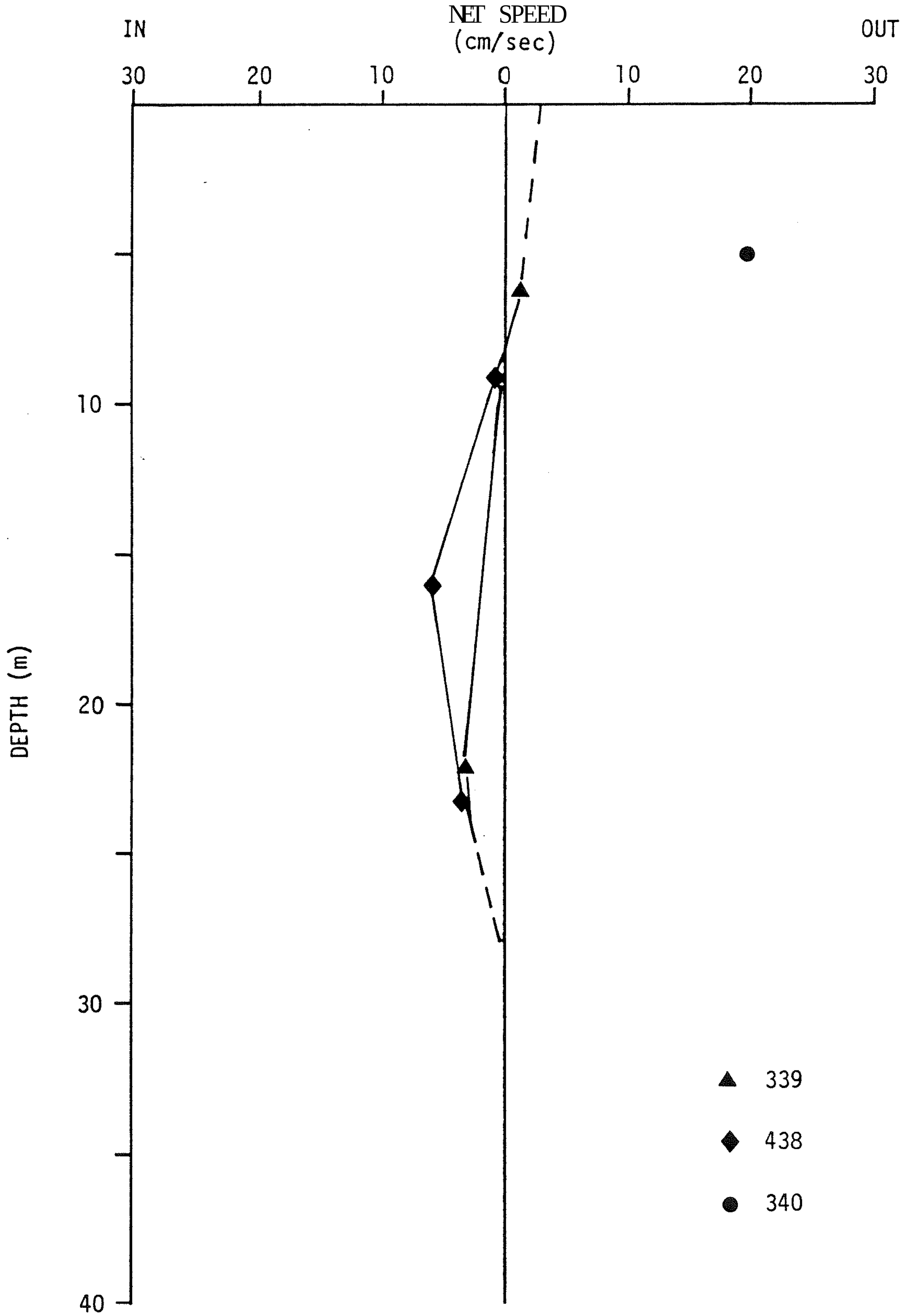


Figure B2. Vertical current profile for North Pickering Passage used in transport calculations.

CENTER OF DANA PASSAGE

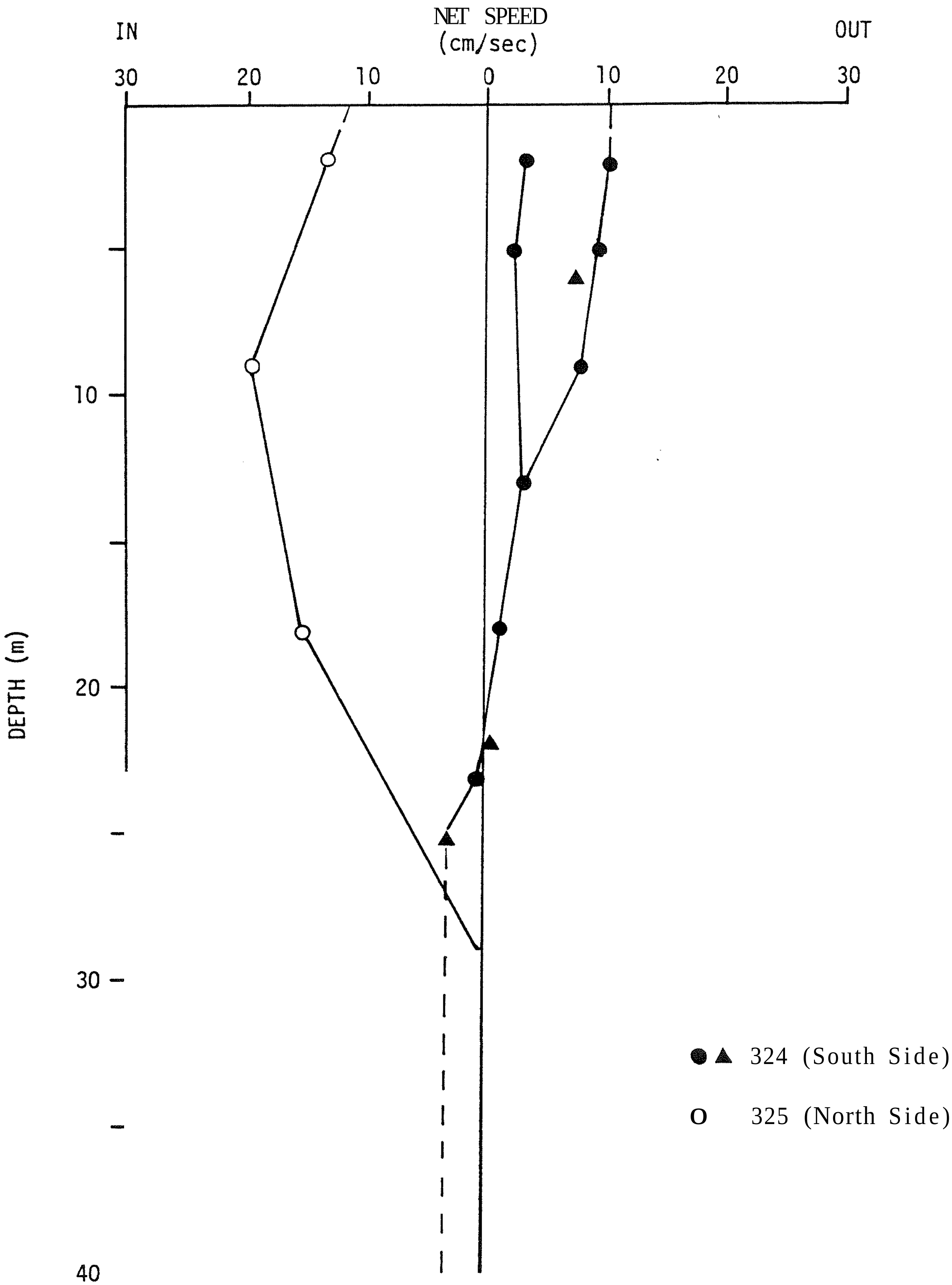


Figure B3. Vertical current profile for the center of Dana Passage used in transport calculations.

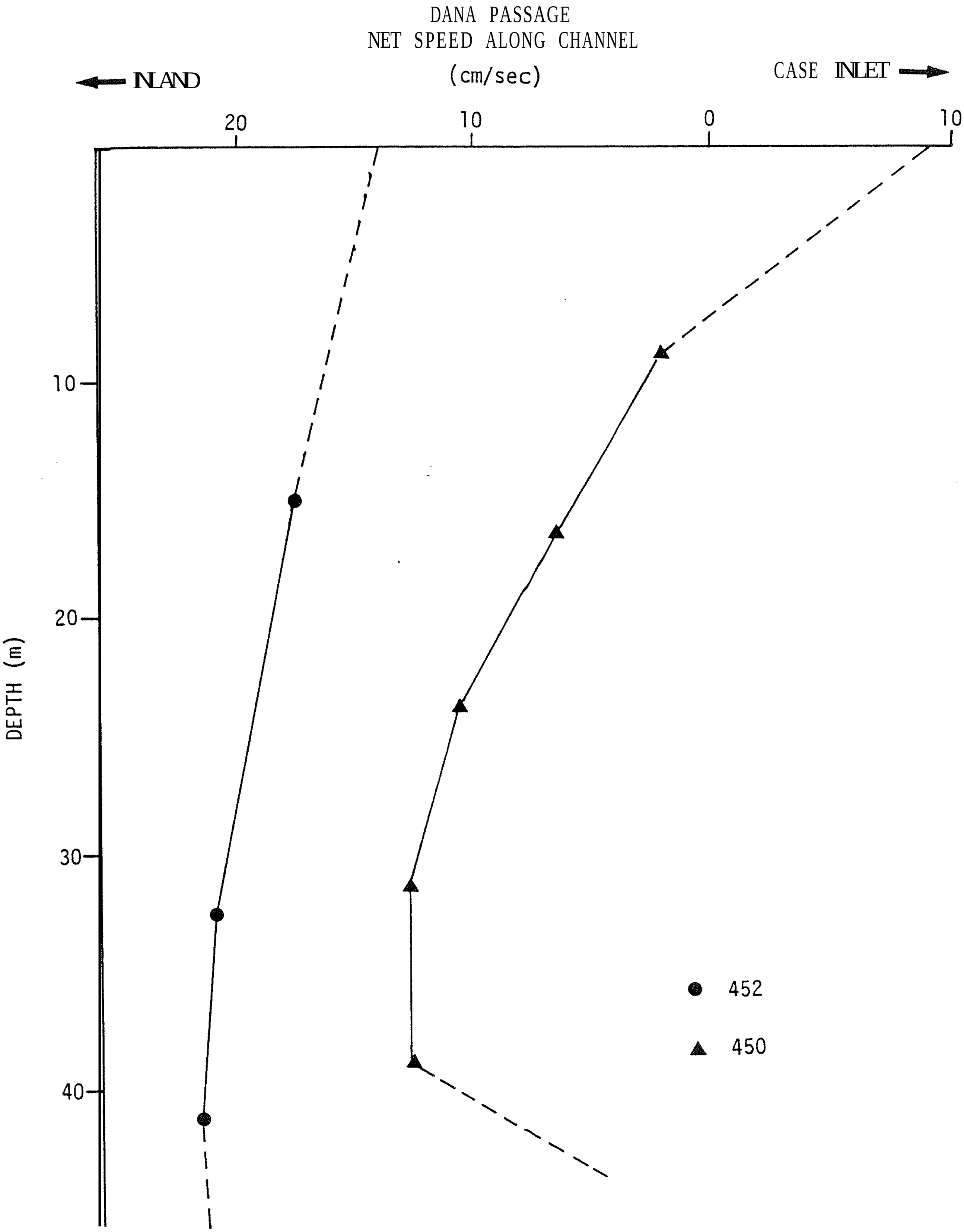


Figure B4. Vertical current profile for the east-west side of Dana Passage used in transport calculations.

CASE INLET

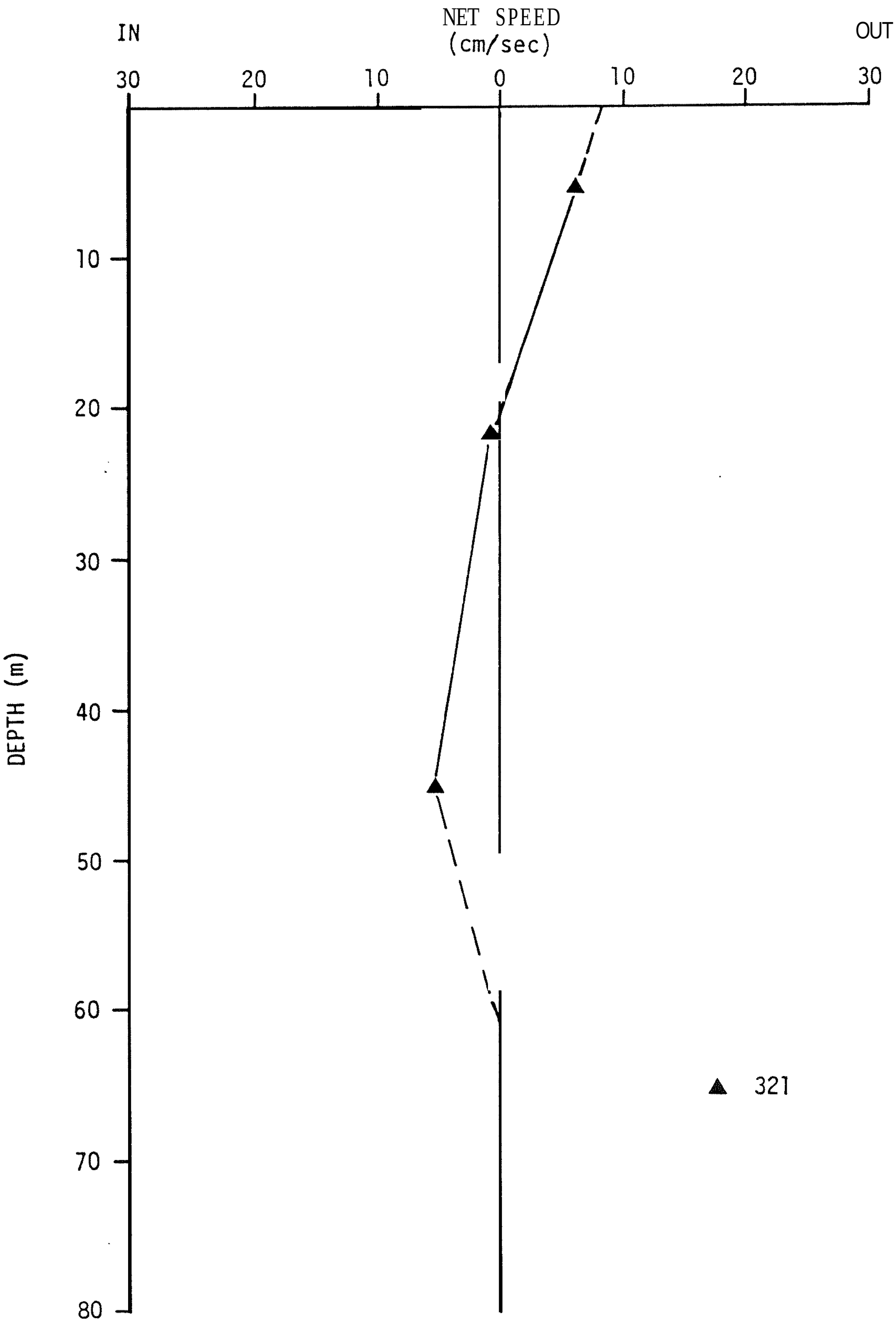


Figure B5. Vertical current profile for Case Inlet used in transport calculations.

NISQUALLY - DANA BASIN

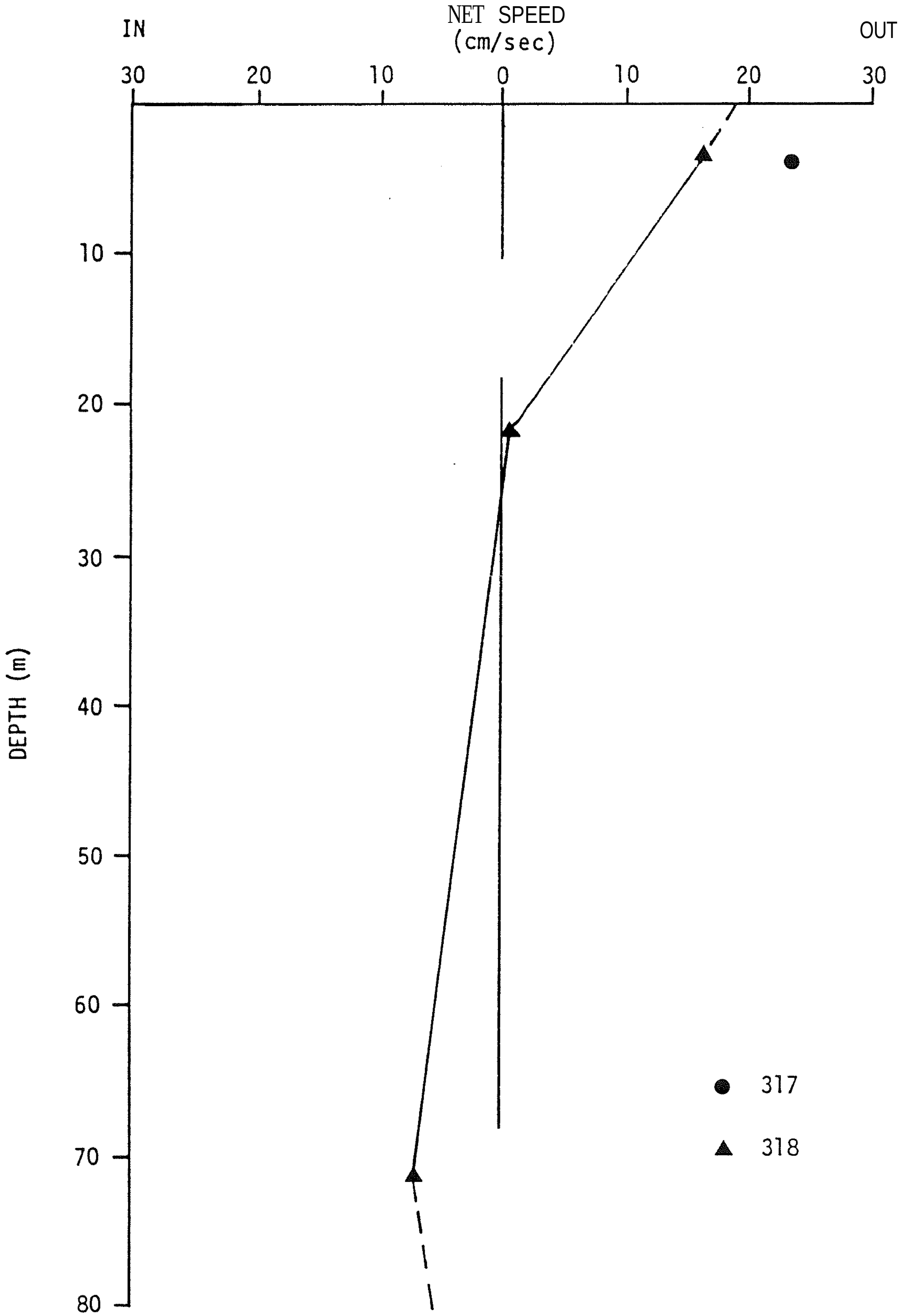


Figure B6. Vertical current profile for Nisqually-Dana Basin used in transport calculations.

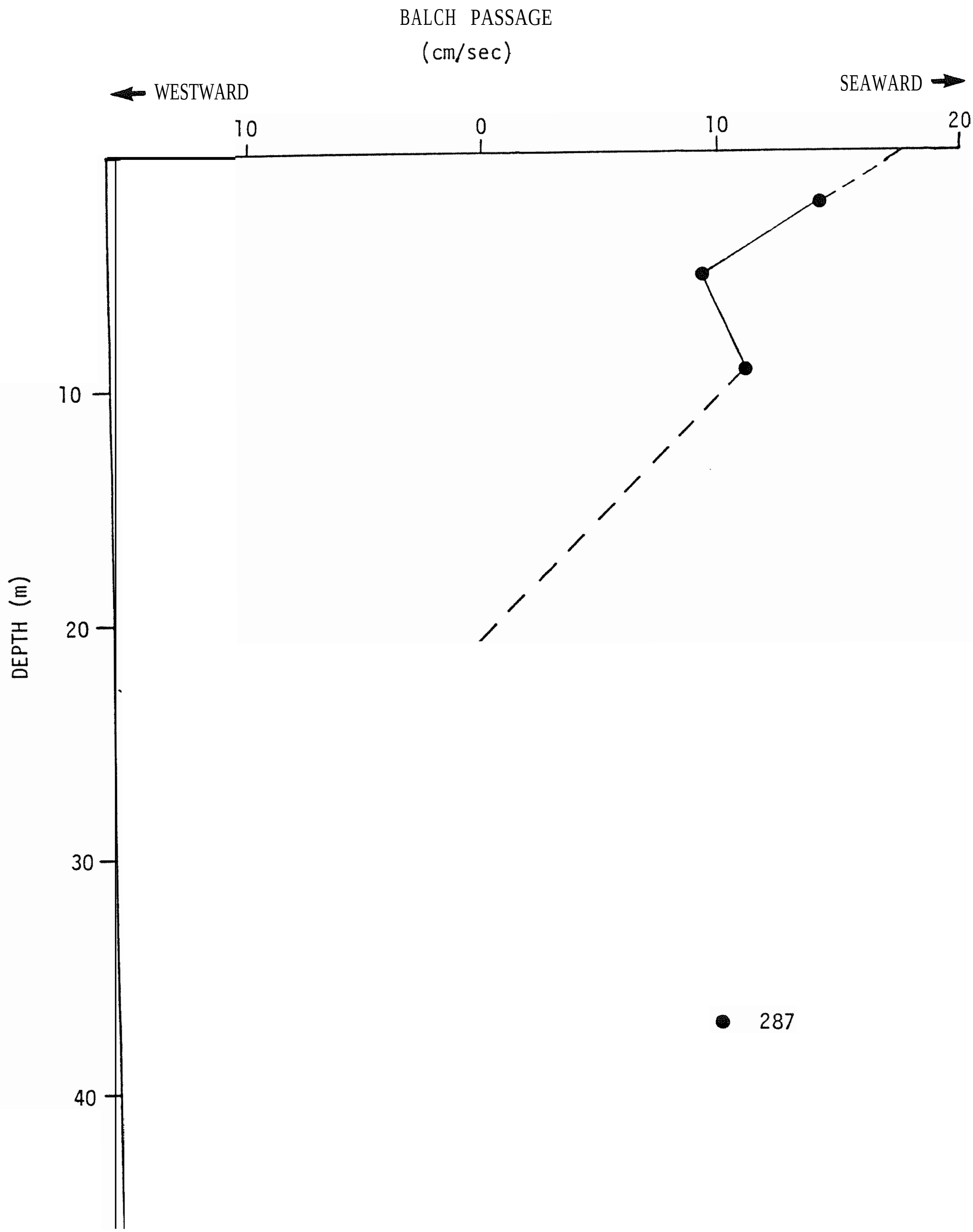


Figure B7. Vertical current profile for Balch Passage used in transport calculations.

Table B1. Data and calculations used to estimate transport in Henderson Inlet

100% Olympia

Date		S_p (o/oo)	Precip (inches)	S_o (o/oo)	S_i (o/oo)	$\frac{S_o}{S_i - S_o}$	$\frac{S_b}{S_i - S_o}$	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^6 m^3/s$)	F (m^3/s)	R (m^3/s)
4-5-58	22	28.023	6.75	28.017	28.586	49.239	59.402	0.09	0.09	9.30	0.270	2.1
4-26-58	29	27.704	.59	28.188	28.721	52.885	63.415	0.09	0.09	9.82	-0.235	1.4
5-24-58	24	28.069	1.63	28.427	28.656	124.135	147.598	0.18	0.18	9.23	-0.196	1.2
6-16-58	23	28.321	.97	28.585	28.860	103.945	122.908	0.12	0.12	8.82	-0.203	0.9
7-8-58	24	28.571	.00	28.859	29.159	96.196	112.666	0.12	0.12	8.42	-0.357	0.7
7-31-58	20	29.030	.09	29.156	29.323	174.587	202.395	0.15	0.15	7.68	-0.211	0.6
8-19-58	22	29.256	.58	29.365	29.529	179.055	206.098	0.08	0.09	7.32	0.109	0.6
9-9-58	33	29.127	2.81	29.527	29.659	223.689	256.061	0.23	0.23	7.53	-0.294	0.7
10-11-58		29.648								6.69		
							AVERAGE	0.13	0.13			

Total Volume to MHW (nm^3) = 0.00857

Table B2. Data and calculations used to estimate transport in Budd Inlet

100% Olympia

Date		S_p (o/oo)	Precip (inches)	S_o (o/oo)	S_i (o/oo)	$\frac{S_o}{Si-So}$	$\frac{S_b}{Si-So}$	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^7 m^3/s$)	F (m^3/s)	R (m^3/s)
8-2-57	18	27.932	.86	28.694								4.9
8-19-57	17	28.142	.01	28.850								3.8
9-4-57	35	28.529	1.95	29.158								3.9
10-8-57	26	28.509	3.45	29.250								5.9
11-2-57	22	28.669	3.21	29.095								10.2
11-23-57		28.707										
3-8-58	50	26.855	5.77	27.789	28.361	48.582	59.091	0.72	0.74	5.17	1.807	17.1
4-26-58	29	25.806	.59	28.130	28.460	85.242	102.424	1.06	1.07	5.95	-2.011	10.0
5-24-58	24	26.483	1.63	28.320	28.613	96.655	115.358	0.73	0.73	5.45	-0.596	6.8
6-16-58	23	26.649	.97	28.121	28.777	42.867	51.524	0.30	0.31	5.32	-1.461	5.3
7-8-58	24	27.039	0.00	28.436	28.992	51.144	60.791	0.48	0.48	5.03	-4.587	3.9
7-31-58	20	28.317	.019	28.971	29.243	106.511	124.265	0.47	0.47	4.08	-0.870	3.4
8-19-58	22	28.519	.58	29.132	29.478	84.196	97.688	0.07	0.07	3.93	2.052	3.2
9-9-58	33	27.995	2.81	29.401	29.678	106.141	122.021	0.69	0.70	4.32	-3.250	2.8
10-11-58		29.240								3.39		
							AVERAGE	0.57	0.57			

Total Volume to MHW (nm^3) = 0.0396

Table B3. Data and calculations used to estimate transport in Eld Inlet

Date		S_p (o/oo)	Precip (inches) 33% Shelton 67% Olympia	S_o (o/oo)	S_i (o/oo)	S_n / Si-So	S_b / Si-So	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^7 m^3/s$)	F (m^3/s)	R (m^3/s)
8-3-57	18	28.896	1.15	29.081								0.4
8-20-57	17	29.067	.04	29.287								0.2
9-5-57	35	29.288	1.59	29.562								0.3
10-9-57	26	29.530	4.26	29.706								1.1
11-3-57	22	29.538	3.67	29.581								2.5
11-24-57	34	29.286	10.05	28.649	29.386	38.872	45.862	0.19	0.20	2.13	1.490	6.7
12-27-57	31	28.358	8.17	27.952	28.981	27.164	32.847	0.21	0.22	2.57	1.539	9.5
1-26-58	18	27.484	4.73	27.962	28.776	34.351	41.523	0.24	0.25	2.98	1.635	9.0
2-12-58	26	26.945	6.25	27.769	28.460	40.187	48.915	0.39	0.40	3.23	-0.901	8.7
3-9-58	29	27.374	2.07	27.864	28.202	82.438	100.000	0.34	0.34	3.03	-0.691	3.3
4-6-58	22	27.741	5.05	27.622	28.258	43.431	53.145	0.19	0.20	2.86	1.400	6.2
4-27-58	29	27.177	.58	27.612	28.460	32.561	39.859	0.12	0.12	3.12	-1.644	1.6
5-25-58	24	28.050	1.52	28.227	28.613	73.127	87.564	0.10	0.10	2.71	-0.512	0.8
6-17-58	23	28.275	.95	28.541	28.777	120.936	143.220	0.20	0.20	2.61	-0.957	0.5
7-9-58	24	28.678	.00	28.868	28.992	232.805	272.579	0.25	0.25	2.42	-0.751	0.2
8-1-58	20	29.008	.09	29.164	29.243	369.162	427.846	0.24	0.24	2.26	-0.470	0.1
8-20-58	22	29.180	.67	29.259	29.478	133.603	154.338	0.07	0.07	2.18	-0.283	0.2
9-10-58	33	29.294	3.86	29.484	29.678	151.979	174.227	0.18	0.18	2.13	-.438	0.7
10-12-58		29.559								2.00		
							AVERAGE	0.21	0.21			

Total Volume to MHW (nm^3) = 0.0251

Table B4. Data and calculations used to estimate transport in Totten Inlet

60% Shelton
40% Olympia

Date		S_P (o/oo)	Precip (inches)	S_o (o/oo)	S_i (o/oo)	$\frac{S_o}{Si-So}$	$\frac{S_b}{Si-So}$	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^7 m^3/s$)	F (m^3/s)	R (m^3/s)
8-3-57	18	28.703	.91	28.870	29.203	86.697	101.502	0.13	0.13	3.22	-0.706	0.7
8-20-57	17	28.877	.04	29.010	29.394	75.547	88.021	0.12	0.11	3.11	-0.890	0.4
9-5-57		29.084								2.98		
11-3-57	22	29.126	4.04	29.239	29.656	70.118	81.055	0.31	0.31	2.95	1.043	5.6
11-24-57		28.812								3.15		
1-26-58	17	26.760	5.03	27.021	28.154	23.849	29.832	0.40	0.43	4.45	3.577	21.4
2-11-58	26	25.928	7.15	26.678	27.814	23.484	29.754	0.51	0.53	4.97	-0.885	20.7
3-8-58		26.243								4.77		
5-24-58	24	27.467	1.43	27.927	28.537	45.782	55.410	0.18	0.18	4.00	-1.885	1.6
6-16-58	23	28.076	.93	28.405	28.634	124.039	147.598	0.31	0.31	3.61	-1.265	1.0
7-8-58	24	28.474	.01	28.738	29.125	74.259	87.339	0.12	0.12	3.36	-1.020	0.4
7-31-58	20	28.809	.08	28.977	29.225	116.842	136.290	0.15	0.15	3.15	-0.877	0.3
8-19-58	22	29.049	.62	29.168	29.379	138.237	160.189	0.15	0.15	3.00	-0.615	0.4
9-9-58	33	29.234	3.64	29.400	29.493	316.128	363.439	0.36	0.36	2.88	-0.024	1.1
10-11-58		29.245								2.88		
						Average		0.25	0.25			

Total Volume to MHW (nm^3) = 0.0336

Table B5. Data and calculations used to estimate transport in Oakland/Hammersly Inlet

100% Shelton

Date		S_p (o/oo)	Precip (inches)	S_o (o/oo)	S_i (o/oo)	S_o / Si-So	S_h / Si-So	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^8 m^3/s$)	F (m^3/s)	R (m^3/s)
8-19-57	17	27.552	.05	28.611	29.045	65.924	77.880	0.33	0.33	1.36	-1.129	3.6
9-4-57	35	28.313	.86	29.127						1.20		3.6
10-8-57	27	28.837	5.92	28.680								6.8
11-3-57	21	27.152	4.48	27.885	29.102	22.913	27.773	0.31	0.32	1.45	-0.078	13.3
11-23-57	35	27.217	12.01	25.744	28.147	10.713	14.066	0.19	0.22	1.44	4.297	23.6
12-27-57	30	21.256	10.92	22.949	26.910	5.794	8.533	0.22	0.26	2.73	0.911	39.0
1-25-58	30	20.173	6.67	22.850	27.174	5.284	7.817	0.21	0.25	2.97	-1.910	37.8
2-12-58	19	21.611								2.66		
4-5-58	22	24.029	6.38	23.689	26.785	7.651	10.917	0.14	0.17	2.13	3.481	23.8
4-26-58	29	20.994	.94	24.460	27.133	9.151	12.645	0.15	0.17	2.79	-4.127	11.2
5-24-58	24	25.737	1.29	27.191	27.866	40.283	50.074	0.36	0.36	1.76	-1.515	7.0
6-16-58	23	27.178	.91	27.771	28.199	64.886	78.972	0.32	0.32	1.44	0.168	5.1
7-8-58	24	27.025	.01	28.093	28.568	59.143	71.158	0.31	0.31	1.48	-1.276	3.7
7-31-58	20	28.239	.08	28.625	28.890	108.019	127.547	0.36	0.36	1.21	-0.016	3.3
8-19-58	22	28.252	.64	28.798	29.150	81.813	96.023	0.28	0.28	1.21	-0.154	3.2
9-9-58	33	28.386	4.19	29.051	29.267	134.486	156.482	0.57	0.58	1.18	-0.051	4.2
10-11-58		28.453								1.17		
							Average	0.29	0.30			

Total Volume to MHW (nm^3) = 0.0116

Table B6. Data and calculations used to estimate transport in Case Inlet

Date		S_p (o/oo)	Sta#431 @5m S_o (o/oo)	Sta#431 @50m S_i (o/oo)	$\frac{S_o}{S_i-S_o}$	$\frac{S_o}{S_i-S_o}$	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^8 m^3$)	F (m^3/s)	R (m^3/s)
11-23-57	36	29.756	29.619	29.942	91.700	104.644	-1.2	-1.22	2.85	24.811	14.9
12-28-57	29	28.661	29.142	29.655	56.807	65.887	0.04	0.06	3.62	15.582	18.8
1-25-58	18	28.107	28.725	29.284	51.386	60.465	1.90	1.92	4.01	-15.770	18.5
2-11-58	26	28.455	28.508	28.960	63.071	74.779	0.27	0.29	3.77	12.078	18.6
3-8-58	29	28.070	28.465	28.675	135.548	160.953	1.08	1.08	4.04	-0.197	7.7
4-5-58	22	28.077	28.538	28.672	212.969	252.237	2.10	2.11	4.03	3.003	13.4
4-26-58	29	27.996	28.583	28.756	165.219	195.375	2.62	2.62	4.09	-9.929	4.1
5-24-58	24	28.349	28.553	28.781	125.232	148.245	1.04	1.05	3.84	-4.418	3.1
6-16-58	23	28.479	28.785	28.966	159.033	186.741	2.65	2.65	3.75	-12.129	2.4
7-8-58	24	28.821	29.032	29.193	180.322	209.936	1.01	1.01	3.51	-3.875	1.1
7-31-58	20	28.935	29.228	29.424	149.123	172.450	2.34	2.35	3.43	-12.643	1.1
8-19-58	22	29.245	29.455	29.660	143.683	164.878	16.71	1.61	3.21	-8.342	1.6
9-9-58	33	29.470	29.522	29.775	116.688	133.597	0.98	0.99	3.05	-3.955	3.9
10-11-58	42	29.630	29.538	29.831	100.813	115.359	0.63	0.64	2.94	6.448	13.6
11-21-58		29.298							3.17		
						Average	1.22	1.23			
							1.41	1.41	(without first value)		

Total Volume to MHW (nm^3) = 0.375

Table B7. Data and calculations used to estimate transport in Carr Inlet

Date		S_p (o/oo)	Sta#411 @5m* S_o (o/oo)	Sta#411 @50m* S_i (o/oo)	$\frac{S_o}{S_i - S_o}$	$\frac{S_o}{S_i - S_o}$	T_i ($10^3 m^3/s$)	T_o ($10^3 m^3/s$)	F ($10^8 m^3$)	F (m^3/s)	R (m^3/s)
2-15-54	36	28.219	28.170	28.330	176.063	211.250	1.06	1.07	7.64	6.73	14.1
3-22-54	33	28.066	28.140	28.300	175.875	211.250	3.16	3.16	7.85	-8.78	7.4
4-23-54	21	28.249	28.140	28.495	79.267	95.211	1.65	1.66	7.59	-14.63	3.3
5-13-54	42	28.443	28.465	28.785	88.953	105.625	1.89	1.89	7.33	-14.78	3.7
6-23-54	18	28.835	28.840	29.005	174.789	204.850	1.04	1.05	6.79	-2.02	3.6
7-10-54	32	28.858	28.935	29.075	206.677	241.426	2.39	2.39	6.76	-8.26	1.9
8-10-54	51	29.025	29.320	29.425	279.239	321.906	6.43	6.43	6.53	-17.11	3.3
9-29-54	26	29.576	29.660	29.755	312.213	355.792	3.98	3.98	5.78	-9.07	2.4
10-19-54	28	29.725	29.775	29.845	425.359	482.859	3.84	3.84	5.58	-2.66	6.0
11-15-54	29	29.772	29.635	29.645	2963.432	3379.923	-45.65	-45.64	5.51	23.59	11.5
12-13-54	36	29.340	29.245	29.270	1169.818	1352.021	-9.10	-9.09	6.10	14.43	8.9
1-17-55	24	29.012	28.985	29.045	483.088	563.338	-0.90	-0.89	6.55	9.83	9.6
2-9-55	24	28.863							6.75		

*Cannot accurately (in comparison to the other Inlets) determine the crossover point from historical current meter data. Best estimate is 5m for S_o and 50m for S_i - both taken from hydrographic station #411 (Gibson Point).

Total Volume to MHW (nm^3) = 0.375

APPENDIX C

SAMPLE CALCULATIONS FOR MAXIMUM DISCHARGE RATE, DILUTION, AND BACKGROUND CONCENTRATION

The main body of this report includes equations for calculating the maximum discharge rate (Imax), background concentration (BC), design dilution (DD) and effective dilution (D). These equations use measured or derived values of effluent input (I), transport (T_o) and the reflux coefficient (R). This appendix contains three examples to demonstrate how these equations can be used.

Example 1

Assume T_o = 500 m^3/s, R = 0.4, DD = 130 and determine BC and D for I = 0.7 m^3/s and 4 m^3/s.

I = 0.7 m^3/s

$$BC = \frac{R}{(1-R)} \frac{I}{T_o} = \frac{0.667 \times 0.7}{500} = .0009 \qquad \text{(Equation 14)}$$

$$D = \frac{X+1}{X \cdot BC+1} = \frac{130}{130(.0009)+1} = 116 \qquad \text{(Equation 9)}$$

I = 4 m^3/s

BC = .0053

D = 77

In this case when I = 3 m^3/s, the effective dilution of 100 cannot be achieved. With I = 4 m^3/s, the effective dilution will be 77. By increasing the design dilution to 166, the effective dilution could be raised to 88. Further increases in the design dilution would require larger volume transports of water, i.e., further increases cannot be accomplished by the natural transport characteristics of the inlet.

Example 2

Assume R = 0.6, D = 100, and determine the transport and design dilutions required in an embayment to allow discharges of 0.5 and 3 m^3/s.

$I = 0.5\ m^3/s.$

$$Imax = \frac{T_o(1-R)}{D} \text{ or} \qquad \text{(Equation 7)}$$

$$T_o = \frac{(Imax)(D)}{1-R} = \frac{0.5 \times 100}{1-0.6} = 125\ m3/s$$

$$DD(@Imax) = \frac{D-R}{1-R} = 249 \qquad \text{(Equation 17)}$$

$I = 2\ m^3/s$

$T_o = 750\ m^3/s$
DD = 249

The design dilution for these two cases is the same. When discharging at the maximum rate the input and transport factors cancel each other such that the design dilution is dependent only on the refluxing and the effective dilution.

Example 3

Assume T_o = 400 m^3/s, R = 0.5, D = 100, and determine the design dilution required for inputs not exceeding Imax when I = 0.3, 1, 2.5 m^3/s.

Determine Imax.

$$Imax = \frac{T_o(1-R)}{D} = \frac{400 \times 0.5}{100} = 2\ m^3/s \qquad \text{(Equation 7)}$$

Therefore, it will not be possible to achieve D=100 if I = 2.5 m^3/s.

I = 0.3

$$BC = \frac{R}{(1-R)} \frac{I}{T_o} = \frac{0.5 \times 0.3}{0.5 \times 400} = .0008 \qquad \text{(Equation 14)}$$

$$DD = X+1 = \frac{D-1}{1-D'BC} + 1 = 109 \qquad \text{(From Equation 16)}$$

I = 1

BC = .001
DD = 111

Equations 15 and 17 can not be used here to calculate BC and DD since they apply only to times when I = Imax.