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Suspended Particulate Matter in Elliott Bay

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NOTICE

CONTENTS

ABSTRACT

ABSTRACT. The distribution and transport of suspended particulate matter (SPM) in Elliott Bay, an embayment of Puget Sound, Washington, was compared for dry (August) and wet (February) seasons of 1979-1980. During both survey times, the SPM distribution throughout the bay consisted of 1) a thin (<5 m) surface layer of variable SPM concentration dominated by phytoplankton growth in summer and Duwamish River runoff in winter, 2) a uniform mid-depth minimum-SPM zone, and 3) a bottom nepheloid layer of concentrations and thickness highly variable in space and time. The total mass of SPM in Elliott Bay was about 20% higher in February (15.7×10^8 g) than in August (13.0×10^8 g). Scatter plots of salinity vs. SPM for both seasons indicate a strong negative correlation ($r = -.95$) in the surface water and a weaker positive correlation ($r = .52$) in the bottom waters. Vertical and horizontal transport of SPM was measured with sediment traps and current meter/transmissometers deployed at two stations. Accumulation of settled SPM 5 m above the bottom was 16%-30% higher in summer (~34.5 g/m^2/day) than in winter (26.8 g/m^2/day). Organic matter made up 6.9%-12.3% of the trapped sediment. Cross-spectral analysis between near-bottom velocity and SPM concentration showed significant coherency at tidal frequencies. Transport of the SPM was dominated by the mean flow; diffusion components had little influence. The high positive correlations between SPM and salinity concentrations and low negative correlations between SPM concentrations and current speed imply that advection plays a larger role than resuspension in maintaining the bottom nepheloid layer in Elliott Bay.

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1. INTRODUCTION

The research presented in this report concerns distribution and transport of suspended particulate matter (SPM) in Elliott Bay. This work is part of a general MESA task to characterize the physical transport processes and the physical fate of contaminants in various embayments around the margin of Puget Sound. The research program was undertaken in close cooperation with other investigators responsible for defining the hydrographic and current fields in Elliott Bay.

The research has four objectives:

(1) Describe the SPM distribution in Elliott Bay during typical summer (dry) and winter (wet) sampling periods.

(2) Estimate the total SPM loading in Elliott Bay at each sampling time.

(3) Characterize the SPM in Elliott Bay in terms of organic matter content, clay mineralogy, and particle size distribution.

(4) Measure the vertical and horizontal flux of SPM at specific mooring locations.

Elliott Bay, the study area, is a small embayment on the east side of Puget Sound (fig. 1) surrounded by residential and industrial sections of the city of Seattle. It has a surface area of ~20 km^2 (east of 122°25'W) with depths ranging to >185 m. The volume of water in the bay is ~2.05 x 10^{12} l. The bathymetry is dominated by a submarine canyon in the center of the bay which originates in two tributaries trending N-S and NW-SE and debouches onto the floor of the central basin of Puget Sound.

The principal source of freshwater is the Duwamish River, a lowland stream whose runoff is controlled by direct precipitation rather than snowmelt.

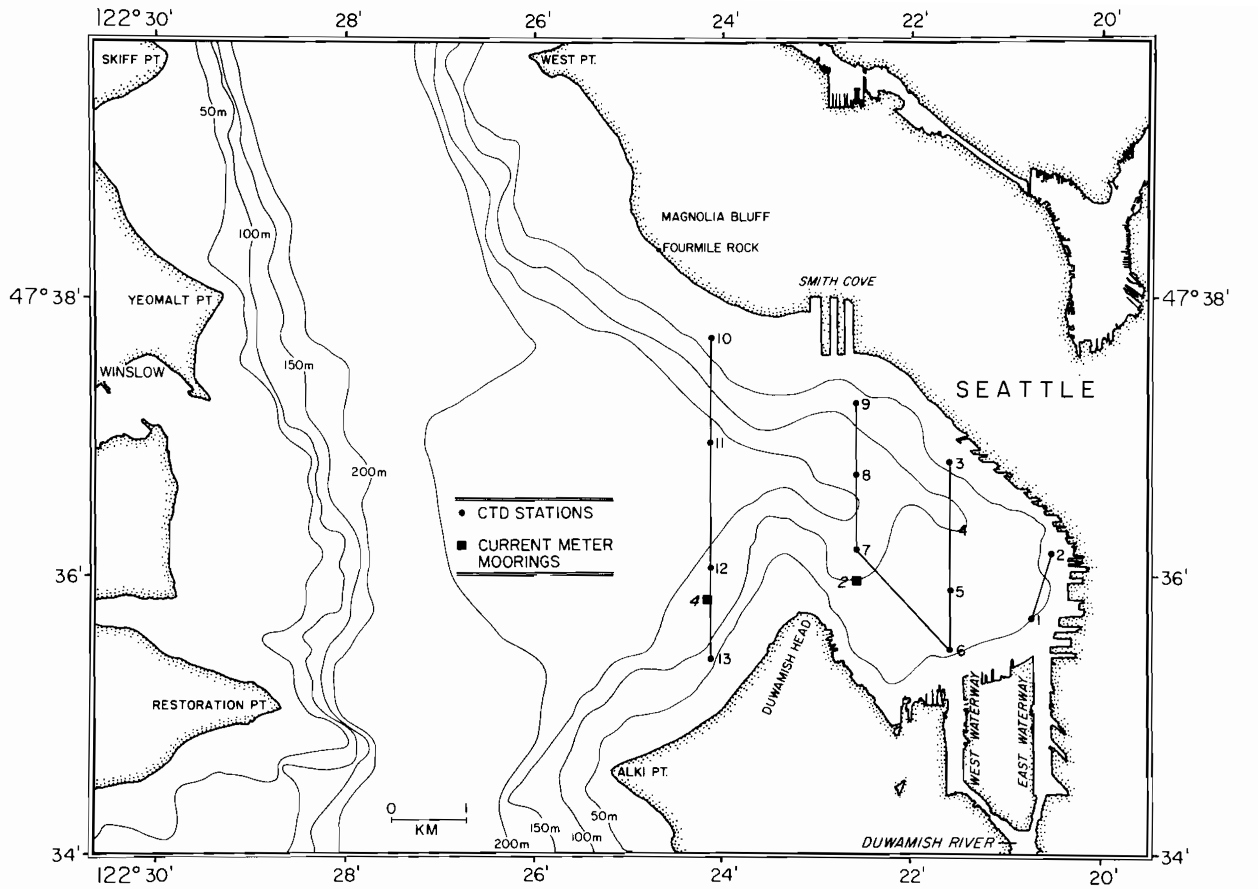


Figure 1.--Map of Elliott Bay showing bathymetry, station locations, mooring locations, and the mouth of the Duwamish River (West Waterway). Contour interval is 50 m.

2. METHODS

2.1 Field Methods

Sampling strategy consisted of 3-day areal surveys conducted once during the dry season (August 8-10, 1979) and once during the wet season (February 20-22, 1980) in order to gauge the effect of seasonal variations in freshwater runoff on the SPM distribution in Elliott Bay. The surveys were conducted as follows.

On the first and third day, stations 1-13 (fig. 1) were occupied sequentially in order to obtain a composite picture of the SPM distributions and hydrography throughout Elliott Bay. Occupation of these stations usually took ~10 hours and necessarily occurred across a broad segment of the tidal cycle. In August, these areal surveys covered the last half of the ebb tide and the beginning of the flood each day. In February, the surveys were started at the tail end of the flood tide and conducted mostly during the ebb. Figure 2 records the height of the tide at the time each station was occupied. In order to assess the effect of this tidal smearing on the data, the second day during each survey was devoted to a time series study of three stations--6, 7, and 12

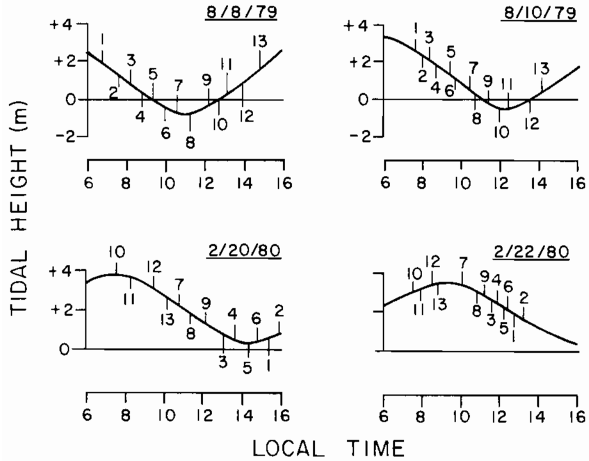


Figure 2.--Time of station sampling for each survey in relation to Elliott Bay tidal height.

in August and 6, 7, and 11 in February. These three stations were occupied as rapidly as possible for ~10 hours to observe changes that occurred during the day.

SPM vertical concentration profiles were constructed from light transmission data calibrated by gravimetric analysis of discrete water samples collected by Niskin bottles on a hydrowire. Water was filtered immediately after collection through preweighed 0.4-μm-pore Nuclepore polycarbonate filters in a closed system. Filters were rinsed three times with 10 ml of particle-free pH-8 distilled water, air dried, and returned to the laboratory for reweighing. Accuracy is about 1% of true sample concentrations.

The beam transmissometers used are newly developed devices suitable for either profiling or mooring work (Bartz et al., 1978). The light source is a light-emitting diode with a wavelength of 660 nm to eliminate attenuation resulting from dissolved humic acids ("yellow matter"). Accuracy and stability are sufficient to provide data with an error of <0.5% of the true light transmission. The path length is 0.25 m to provide excellent resolution in estuarine waters where SPM concentrations typically range from 0.5 mg/l to 20 mg/l.

For profiling work, the transmissometer readout was converted from the normal DC output to a frequency signal compatible with the CTD data flow. The transmission signal was then recorded on the CTD data tape along with temperature, salinity, and depth. A real-time strip chart record was also available to provide a guide for choosing appropriate depths for discrete water samples.

For mooring work, the transmissometers were directly coupled to the Aanderaa current meters moored by the Coastal Physics Group at PMEL. Transmission readings were recorded on the current meter data tape whenever a current velocity was recorded.

By correlating the absolute SPM concentrations from filter samples with the transmissometer reading from the same depth and location, transmissometer calibration curves were developed for both surveys. Light transmission values were first converted to the optical parameter of attenuation (α) using

$$\alpha = \frac{-\ln\ (T/100)}{R},$$

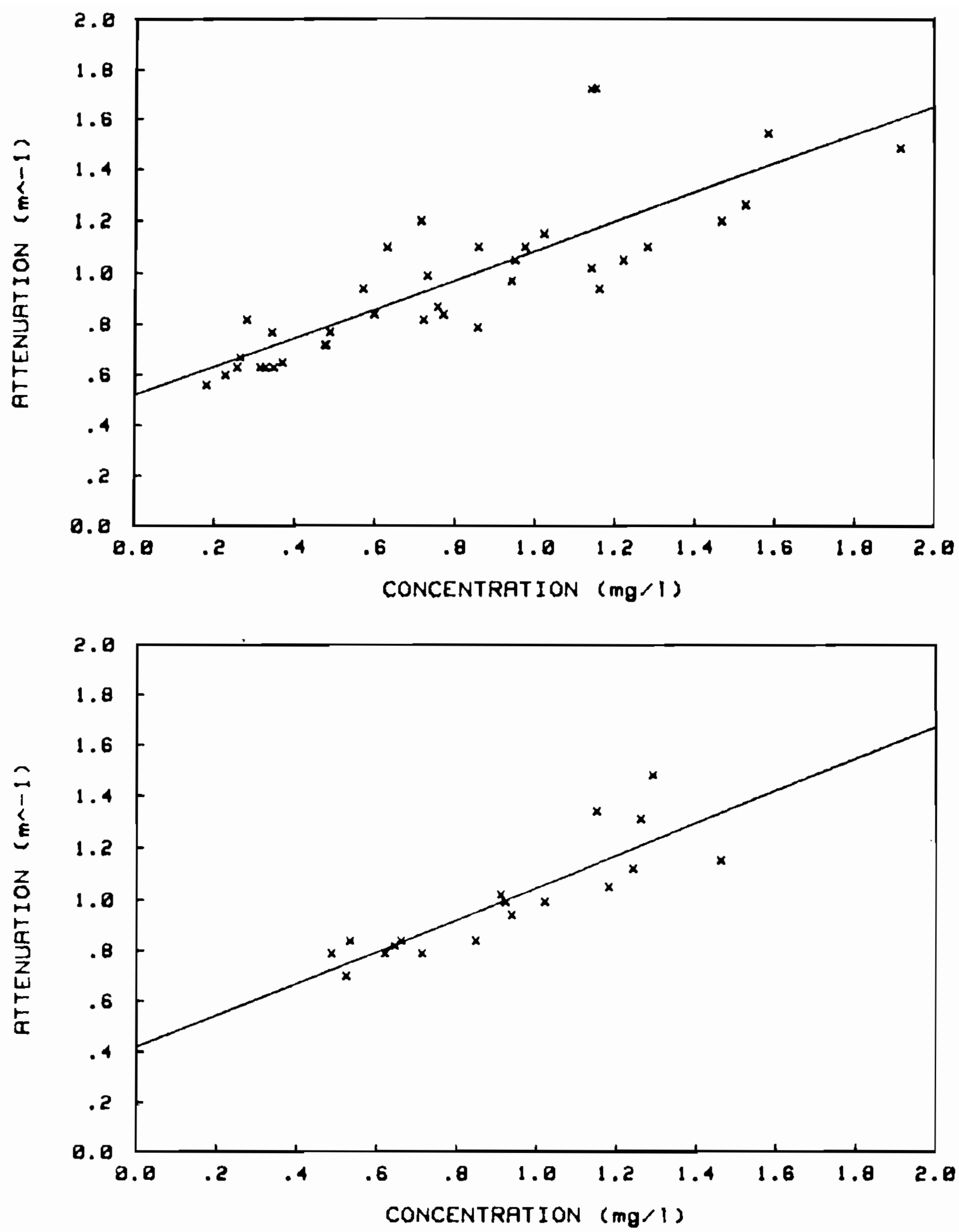


Figure 3.--Transmissometer calibration curves for (above) August 1979 and (below) February 1980 in Elliott Bay. The least-squares regression coefficients are listed in table 1.

where T = percent transmission and R = path length of the instrument (0.25 m). Plots of SPM concentration versus light attenuation are shown in fig. 3; statistical parameters of the least-squares regression are given in table 1. It is clear from the statistical data that the two curves are not significantly different at the 95% confidence level.

Scatter in the data can be attributed to two principal causes: sampling variability and inhomogeneity of the particle populations. Since the field equipment available required that transmissometer profiles and water samples be taken on successive casts rather than simultaneously, comparison of the two

Table 1.--Regression coefficients for scatter plots of attenuation (α) vs. suspended particulate matter (C)

	August 1979	February 1980
No. of samples	37	18
Least-squares regression	$\alpha = 0.56$ (C) + 0.52	$\alpha = 0.62$ (C) + 0.42
Correlation (r)	0.82	0.86
Standard error of estimate	0.18	0.11
95% confidence interval		
Slope	0.43-0.70	0.23-0.60
Intercept	0.40-0.64	0.43-0.82

measurements could be affected by ship drift, local SPM changes resulting from advection or diffusion, and wire angle, since the hydrocast had no in situ depth sensor. We attempted to minimize these problems by sampling depth horizons where no steep vertical SPM gradients were present.

Attenuation cannot be precisely explained by a single parameter such as mass concentration unless all other parameters--such as size, shape, number, and composition--are held constant. This assumption of particle population homogeneity is poorest in the surface layer where there is a pronounced dichotomy between organic and inorganic particles. Furthermore, organic particles are difficult to sample accurately on sievelike membrane filters because some of the protoplasm may be sucked through the filter pores.

A useful measure of the effectiveness of the transmissometer is a comparison of the value of α at the zero SPM intercept with that found in particle-free water. Tyler et al. (1974) present laboratory data showing that at 660 nm α lies between 0.34 and 0.43 m^{-1}. Both the February and August data are within or slightly above this range, indicating that the variation in particle concentration is indeed the primary influence affecting the transmissometer readings.

By using the calibration curves, the light attenuation profiles at each station were converted to SPM concentration profiles for areal and cross-section plotting purposes. The SPM loading at each station was also calculated by progressive summing of the SPM concentration at 1-m intervals from surface to bottom.

In addition to the survey work, transmissometers and sediment traps were deployed at two mooring locations (fig. 1) in Elliott Bay (EB2 and EB4). The sediment traps used were of standard cylindrical design with a butterfly closing lid to prevent sample washout (Larrance et al., 1979). Traps were paired at all depths to provide replicate samples.

The first deployment began on August 3, 1979, and was recovered on September 12, 1979. For this deployment, transmissometers were attached to the bottom current meters on EB2 (at 92 m, in water 112 m deep) and EB4 (at 132 m, in water 140 m deep). For the second deployment, February 6, 1980, to March 7, 1980, transmissometers were attached to two current meters on EB2 (at 30 m and 90 m, in water 104 m deep) and one on EB4 (at 130 m, in water 137 m deep). Sediment traps were deployed in conjunction with all transmissometers, and an additional pair of traps was moored at 30 m on EB4 during August 1979.

2.2 Laboratory Methods

2.2.1 Size analysis

The material collected in the sediment traps was analyzed for particle size distribution by sieving and pipette analysis. Material that was greater than 62-μm diameter (equal to 4ϕ according to the Wentworth graded size scale where $\phi = -\log_2$ [diameter in mm]) was separated from the rest of the material by pouring the sample through a 62-μm Nytex net sieve. Since much of the material larger than 4ϕ appeared to be associated with aggregates, the samples were sonicated for 5 minutes and then poured through the 62-μm Nytex again. The material remaining on the sieve was washed onto a preweighed 47-mm, 0.4-μm polycarbonate filter and weighed. The material previously associated with aggregates was collected on a preweighed 0.45-μm cellulose filter and weighed. A separate blank filter was used along with each cellulose filter.

Size distribution of the particles smaller than 62 μm (from the initial separation) was determined by pipette analysis which utilizes settling velocities of particles of various diameters (Krumbein and Pettijohn, 1938). Samples were diluted to 1 liter in glass settling cylinders with filtered Puget Sound seawater. Samples that represented a size range of whole phi units were obtained by removing 20-ml aliquots from the cylinders at appropriate time intervals after thorough shaking. The times for sampling were calculated according to Wadell's (1934) velocity formula, which differs from Stoke's equation by taking into account that natural particles are not perfectly spherical. The material was filtered onto 47-mm 0.4-μm polycarbonate filters, rinsed with particle-free distilled water, air dried, and weighed. Statistical parameters were calculated by summing the amounts of material in each size fraction and extrapolating for the whole sample.

Since no Coulter Counter system for SPM sizing was available during the Elliott Bay surveys, Coulter Counter size analyses were performed later on particles removed ultrasonically from sample filters. Although fragile particles such as aggregates are perturbed by this method, the majority of discrete particles are generally unaffected.

2.2.2 Organic content

Estimates of the percent organic matter associated with particles in Elliott Bay were determined by hydrogen peroxide treatment of material collected on polycarbonate filters. SPM filters collected during each of the cruises and filters representing the 4-, 6-, 8-, and 11-ϕ size ranges from the particle size analysis of sediment trap material were analyzed to determine how organic matter is distributed in Elliott Bay and the relationship between organic content and particle size in the settled material.

The filters were placed, unfolded, in small glass vials (20-ml capacity), and about 15 ml of 10% hydrogen peroxide was added. This amount was enough to cover the filters when the vials were placed on their sides. The filters were left in the H_2O_2 for 30 to 45 minutes, then sonicated for 1 minute in a Branson 50/60-Hz ultrasonic cleaner to remove all particles from the filter. The weights of some filters were checked to determine that most of the material was removed by this method. For typical filters with amounts of material in the 1- to 2-mg range, all but 3%-7% of the material was removed. After sonication, the filters were removed from the vials and rinsed with particle-free distilled water so that the rinse water was collected in the vials. The filters were replaced in their individual petri dishes, and the vials were placed in a 60°C oven for 24 hours. The contents of the vials were then poured back through the original filter, rinsed, air dried, and weighed. The difference of weights before and after treatment with hydrogen peroxide gives an estimate of the amount of organic matter in the sample.

3. RESULTS

3.1 Distributions of Suspended Particulate Matter-August 1979

3.1.1 SPM transects

The three-dimensional distribution of SPM in Elliott Bay will be described with reference to four N-S vertical cross sections contoured in units of mg/l. The cross sections are designated 1-2, 3-6, 6-9, and 10-13 (fig. 1). A separate set of cross sections is drawn up for each survey day. Slight variations in station location result in slight bathymetric differences between days.

Section 1-2. SPM concentrations are fairly uniform horizontally throughout the water column (fig. 4). Surface concentrations vary from day to day because of the proximity of the Duwamish River mouth.

Section 3-6. Typical Elliott Bay vertical SPM structure is apparent in these cross sections (fig. 5). The presence of the Duwamish River plume is apparent at station 6, with concentrations ~1.6 mg/l at the surface. Concentrations >1 mg/l are confined to the upper 3 m. A mid-depth minimum with concentrations between 0.2 and 0.4 mg/l is centered around the 30-m horizon. Bottom concentrations in the center of the bay are >1.2 mg/l.

Section 6-9. As in the previous section, river influence is restricted to station 6 (fig. 6). Significant surface increase can also be seen along the north shore at station 9 on both days. The mid-depth minimum is centered at about the same depth as Section 3-6. Bottom concentrations in the center of the bay (stations 7 and 8) are slightly higher (1.4-1.6 mg/l) than on Section 3-6 (stations and 5).

Section 10-13. Horizontal stratification and the mid-depth minimum are the dominant features as in other sections, but the mid-depth minimum is slightly more turbid here than in the inner bay (0.6 mg/l versus 0.4 mg/l) (fig. 7). As in the previous section, high surface values are seen along the north shore: surface water at stations 12 and 13 is the least turbid in the

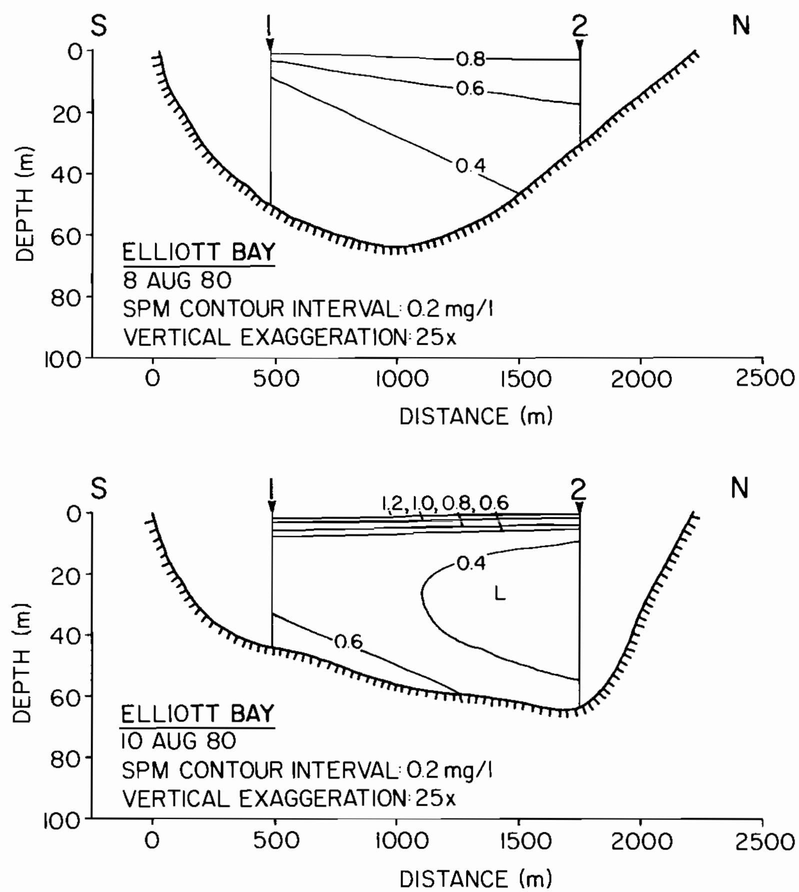


Figure 4.--SPM cross sections for stations 1-2, August 1979.

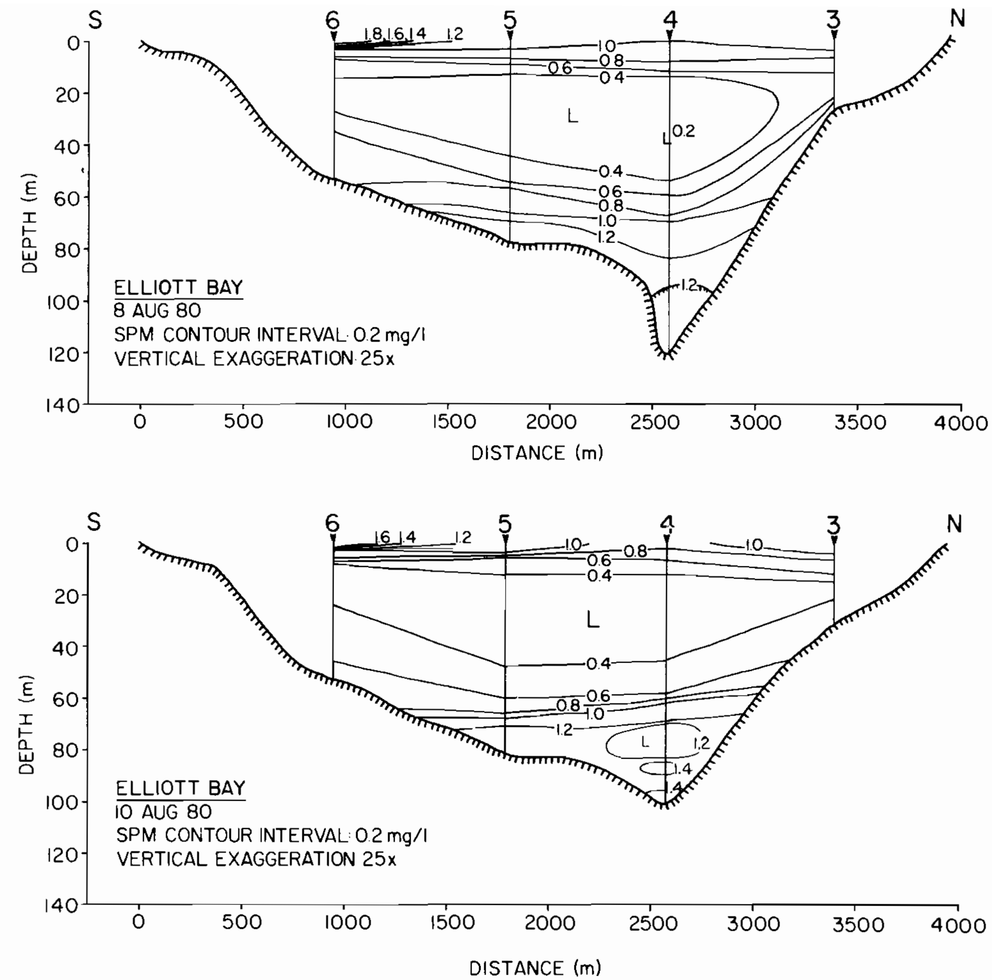


Figure 5.--SPM cross sections for stations 3-6, August 1979.

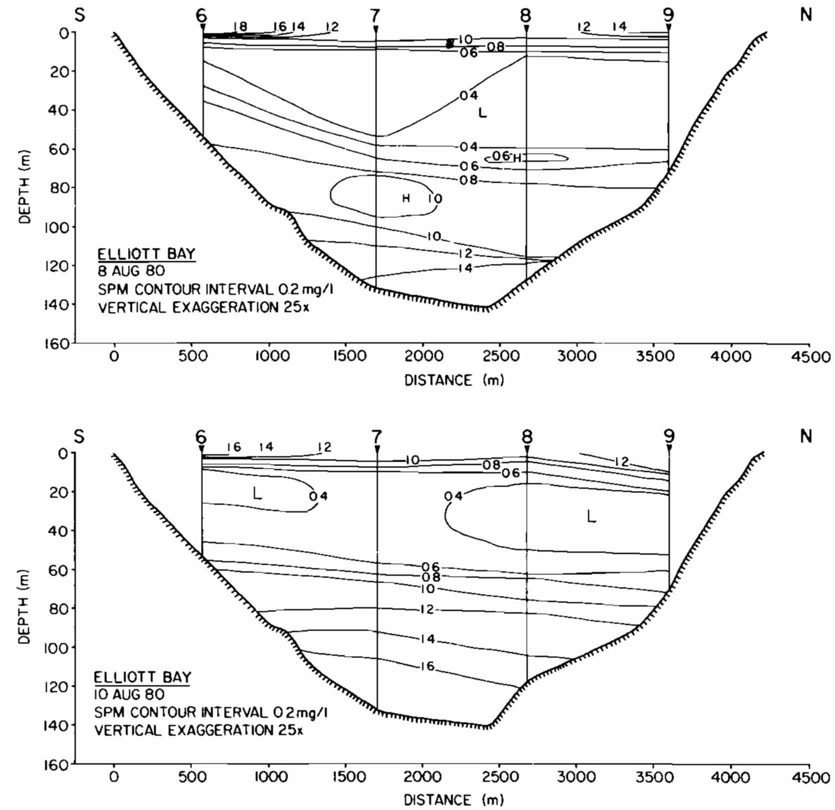


Figure 6.--SPM cross sections for stations 6-9, August 1979.

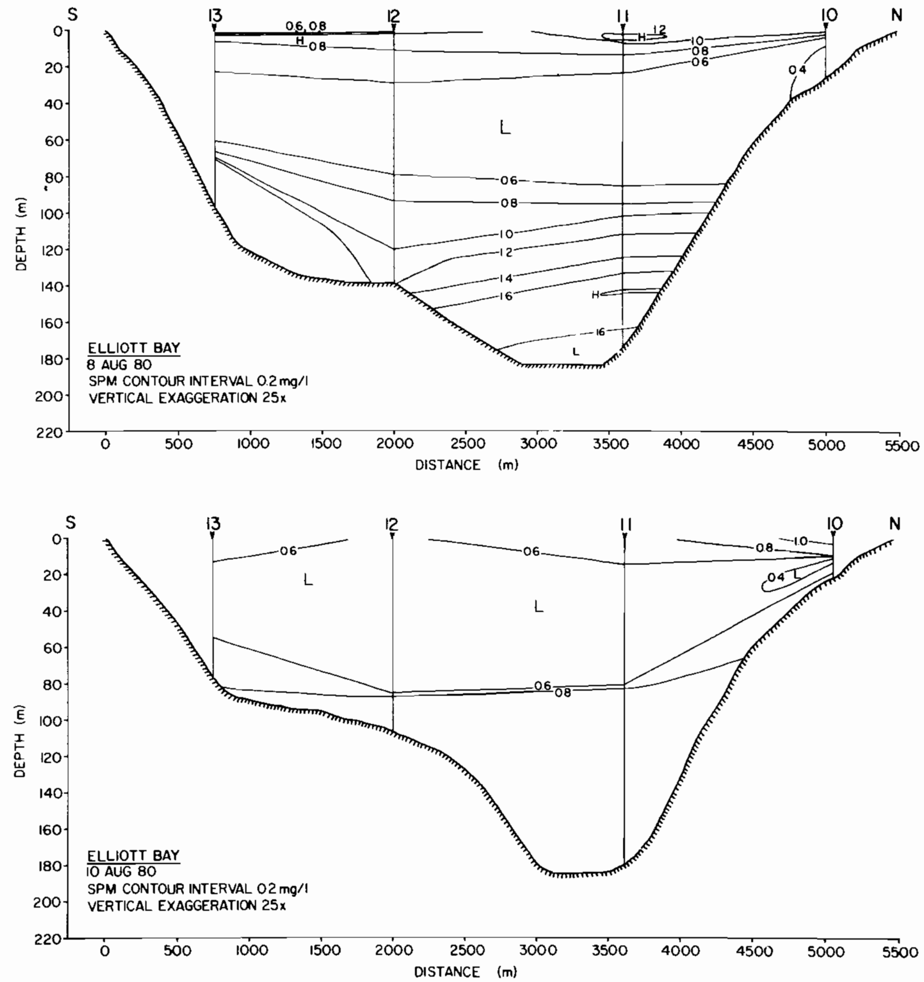


Figure 7.--SPM cross sections for stations 10-13, August 1979.

study area. Variability below 100 m is highest from day to day of any section, decreasing from >1.8 mg/l on August 8 to >1.0 mg/l on August 10.

The distribution of SPM in Elliott Bay during August 8-10, 1979, can be broadly described by three distinct features: 1) a thin (<5 m) surface layer of relatively high concentrations resulting from the Duwamish River plume. This layer is prominent near the river mouth and is found in steadily decreasing concentrations along the north shore; 2) a bay-wide, mid-depth minimum with concentrations in the range of 0.4-0.6 mg/l. This region thickens and deepens with increasing water depth; and 3) a bottom nepheloid layer (BNL) of concentrations highly variable in both space and time. Highest BNL concentrations were always found on the deepest stations of any transect.

3.1.2 Areal plots

It is clear from the foregoing discussion that the bulk of SPM in Elliott Bay is contained in the surface and bottom turbid layers. The geographic pattern of the SPM distribution, and its relation to the hydrographic field, can best be illustrated through the use of areal plots of SPM concentration and salinity.

Surface concentration maps from August 8 and 10 (fig. 8A) show high concentrations (1.6-1.8 mg/l) off the west waterway, rapidly decreasing to the north and west. Concentrations remained >1.2 mg/l along the northern shore as far as station 9 on August 10 but were patchier on August 9. Clearest water was always found in the southwest quadrant of the study area. Winds on both August 8 and 10 were typically from the west or northwest averaging about 10 km/h. This wind pattern and the weak discharge rate of the Duwamish River during the survey (7.8 m^3/s) combined to keep the plume against the eastern and northern shore of the bay.

Surface salinity maps (fig. 8B) follow a similar pattern. The salinity at station 6 was 27.04 °/₀₀ and 28.02 °/₀₀ on August 8 and 10, respectively, and showed a steep gradient to the west and a much gentler gradient around the east and north shore. Saltiest water both days was found at station 13 through 11, corresponding to the least turbid water.

Maps of SPM concentrations and salinity 5 m above bottom (figs. 9A and 9B) are substantially different than the surface distributions. There was a strong positive correlation between depth and concentration on both sampling days, but details of the distribution changed markedly between the two days. On August 8, the highest concentrations were found at the stations at the mouth of the submarine canyon and near the head of the western tributary. Concentrations decreased uniformly away from these stations. On August 10, however, the highest concentrations were found in the center of Elliott Bay; concentrations at the mouth of the submarine canyon had decreased by almost one half and concentrations in the eastern tributary canyon had risen about 30 percent. The distributions strongly suggest that either a discrete bolus of turbid water had been advected into the center of the bay via the submarine canyon, or that tidal current variations had produced differing patterns of resuspension each day. Since station 11 was occupied at roughly the same stage of the tide on both August 8 and 10 (fig. 2), however, tidal variations between the two sampling days were probably minimal.

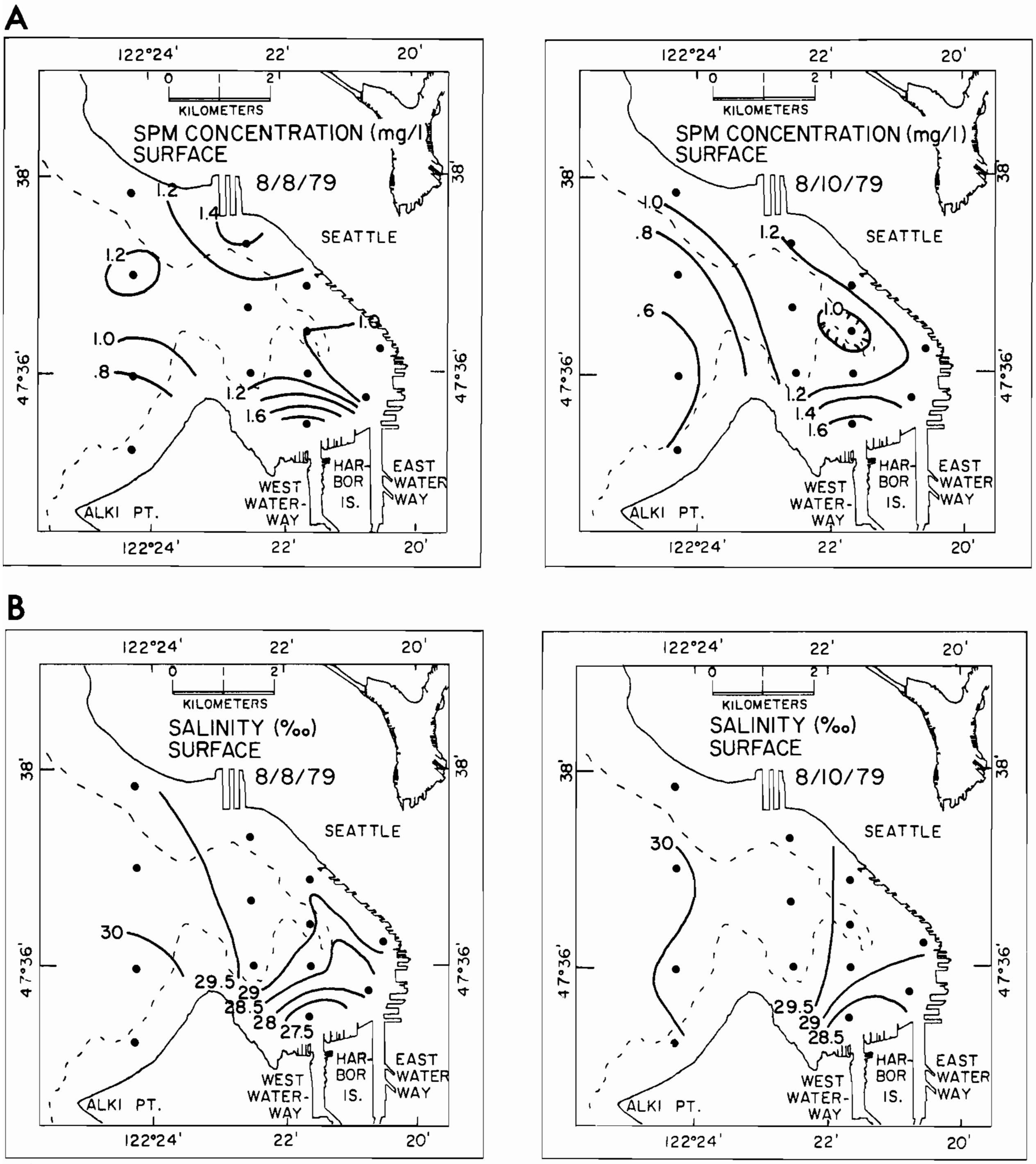


Figure 8.--Areal maps of surface (A) SPM concentration and (B) salinity at 1 m during the August surveys. Contour interval is 0.2 mg/l for SPM, 0.5°/oo for salinity. Dotted line is the 100-m isobath.

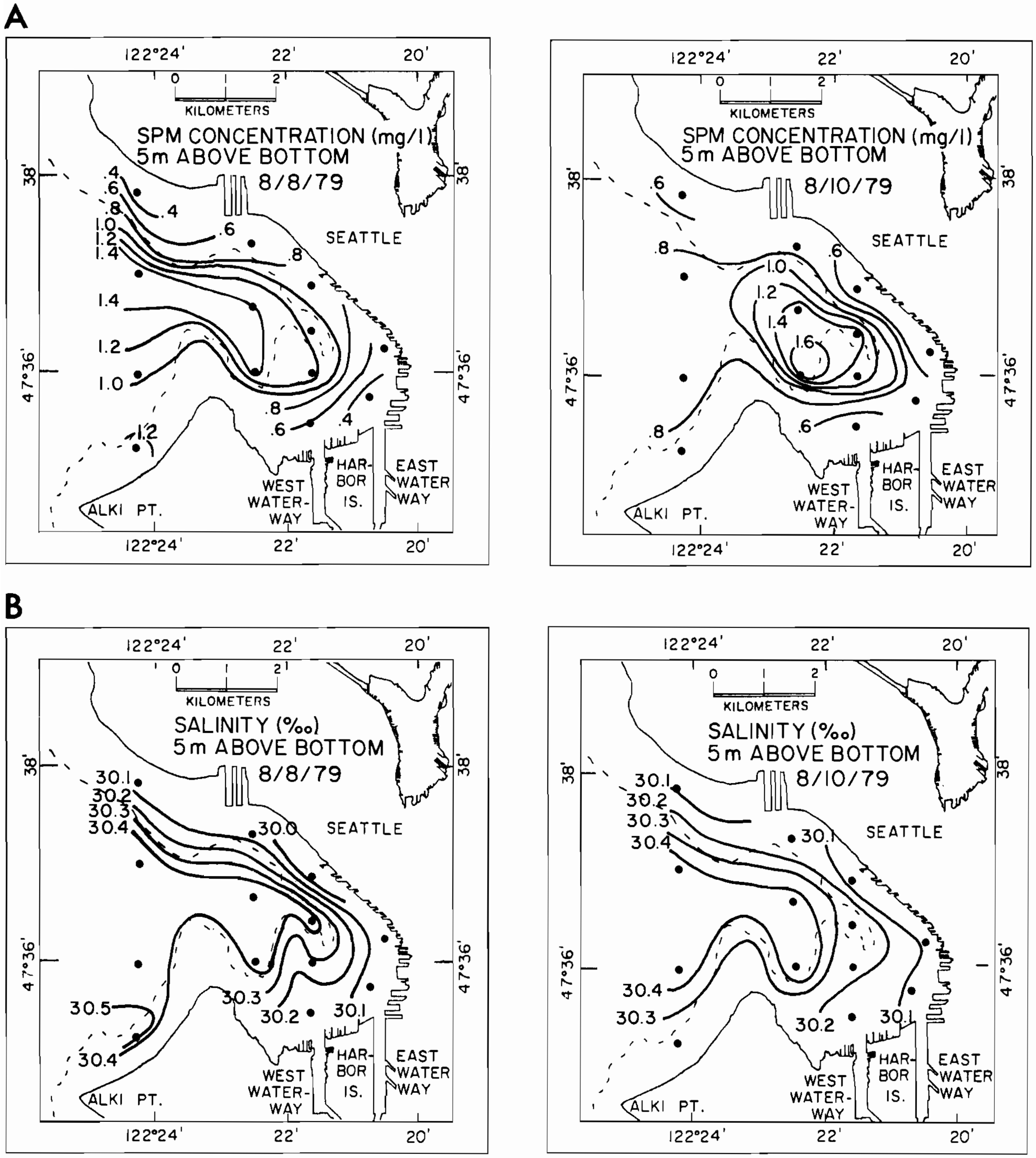


Figure 9.--Areal maps of bottom (A) SPM concentration and (B) salinity during the August surveys. Contour interval is 0.2 mg/l for SPM, 0.1°/oo for salinity. Dotted line is the 100-m isobath.

Maps of near-bottom salinity (fig. 9B) for August 8 and 10 show only slight variations. Higher salinity water intrudes farther up the east tributary canyon on August 8 than on August 10. Effects of this intrusion can also be seen at station 13, where the salinity reached 30.5 °/₀₀ on August 8. However, no evidence of an anomalous water mass in the center of the bay can be seen in the salinity data for August 10. Temperature data indicate that a general warming of 0.2°-0.4°C took place in the bottom water of most of the bay stations between August 8 and 10.

3.1.3 Time series data

Time series data were collected at three stations (6, 7, and 12) to assess the variability of the SPM distributions on an hourly scale. Knowledge of the short-term variability is necessary to interpret the integrated daily maps which span over half a tidal cycle. The stations chosen for the time series work were selected for their representativeness of the bay as a whole: station 6 monitored the river input, station 12 monitored the less variable outer bay (and was located adjacent to one of the transmissometer/sediment trap moorings), and station 7 was representative of the transition region between the inner and outer bay.

Station 6. Concentrations in the surface layer varied by more than a factor of 2 (1.0 to 2.2 mg/l) from about mid-ebb to low water (fig. 10). The highest concentration occurred at the time of low water. Concentrations in the mid-depth minimum (between 15 and 40 m) were relatively unchanged during the 8-h observation period, although the thickness of the minimum zone was diminished just before and after low water. This diminution resulted from the appearance of a strong BNL at approximately low tide (~1100 hours). The fact that the maximum BNL occurs just before low tide and the minimum during the rising tide suggests advection of turbid water in the canyon rather than local erosion and resuspension (see also sec. 4.3).

The salinity distribution (fig. 10) shows good agreement with the SPM distribution. Surface salinities vary by more than 2°/₀₀. The appearance of

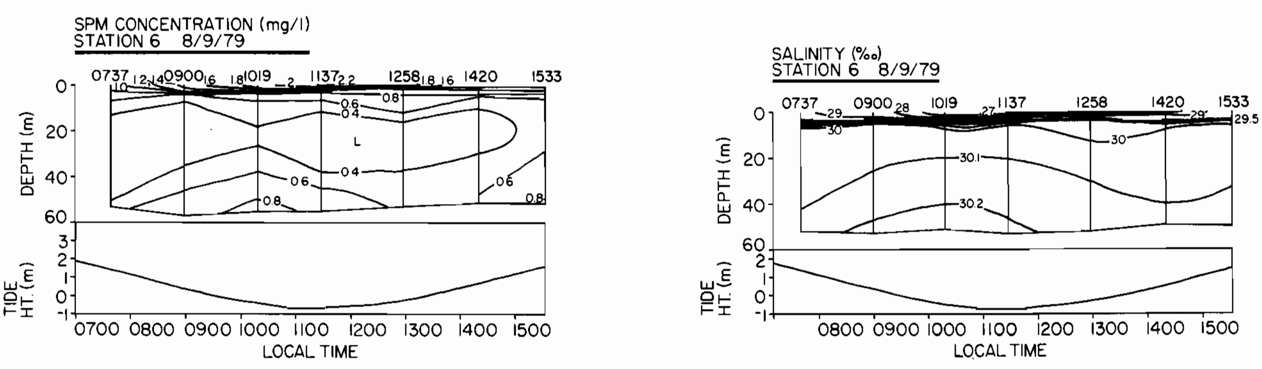


Figure 10.--Time series data for station 6. Station times are given in local time along the top of the profile. A time plot of the tide height is given at the bottom of each profile. Contour intervals are 0.2 mg/l for SPM; for salinity, contours vary from 1°/₀₀ to 0.1°/₀₀, depending on contour density.

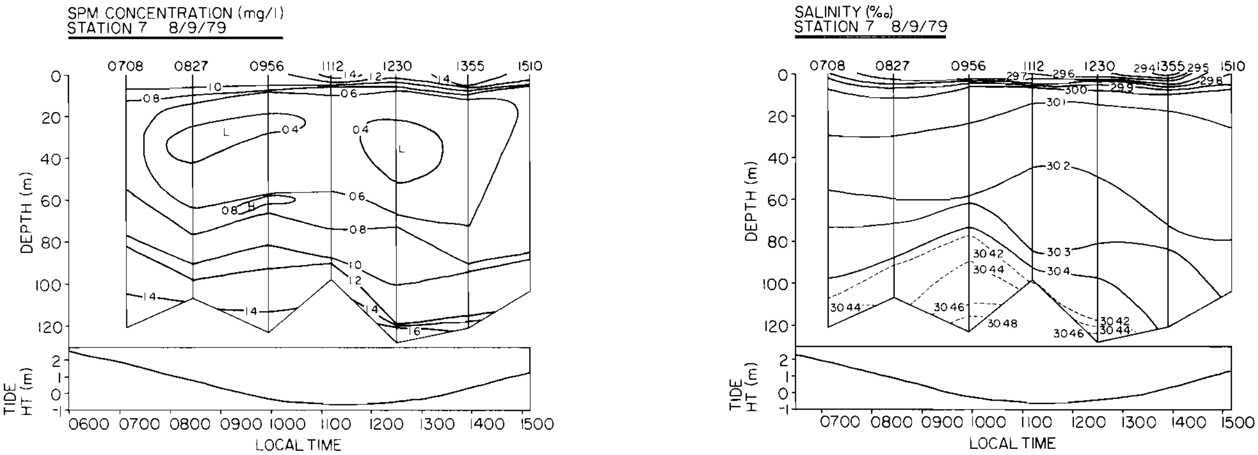


Figure 11.--Time series data for station 7. Station times are given in local time along the top of the profile. Contour intervals for SPM are 0.2 mg/l; for salinity, contours vary from 0.1°/oo for salinities <30.4°/oo to 0.02°/oo for salinities >30.4°/oo.

the BNL is closely associated with the appearance of 30.2°/oo water. The bottom of the mid-depth minimum follows a trend similar to that of the 30.1°/oo salinity contour.

Station 7. At station 7, the surface concentration maximum was less discrete and delayed from the time of low water (fig. 11). High concentrations were found both at 1112 and 1355 hours. This pattern is consistent with station 7's location in the central bay, especially since the areal maps suggest that most of the river plume hugs the north and east shore. The thickness and position of the mid-depth minimum was constant during the entire period, although slight changes were noted in the intensity of the layer. Changes in the bottom layer were difficult to quantify because ship drift and a steeply sloping bottom made accurate reoccupation of the position difficult. Concentrations at the bottom were generally between 1.4 and 1.6 mg/l; three shallow occupations showed lower concentrations, and one deeper occupation exceeded 1.6 mg/l.

The surface salinity pattern (fig. 11) showed a clear minimum about 2 hours after low tide. Near-bottom salinities also showed a strong cyclical pattern with a high value of 30.48°/oo at 0956 hours decreasing to ~30.27°/oo at 1510 hours. Variations in near-bottom salinities followed the SPM pattern, with the deeper casts showing higher values and the shallower casts lower values, suggesting that these variations were caused more by positioning than by actual changes in the bottom water conditions.

Station 12. Surface SPM concentrations show highs occurring between the times of high and low water (fig. 12), although the distance of station 12 from the river mouth and the shortness of the time series record make tidal inferences speculative. Surface variations are substantial, however, decreasing from a high of ~1.2 mg/l at 0630 hours to a low of ~0.5 mg/l at 0805 to 0924 hours. The mid-depth minimum was always present, but its intensity and thickness were significantly reduced by a thick BNL present when the survey

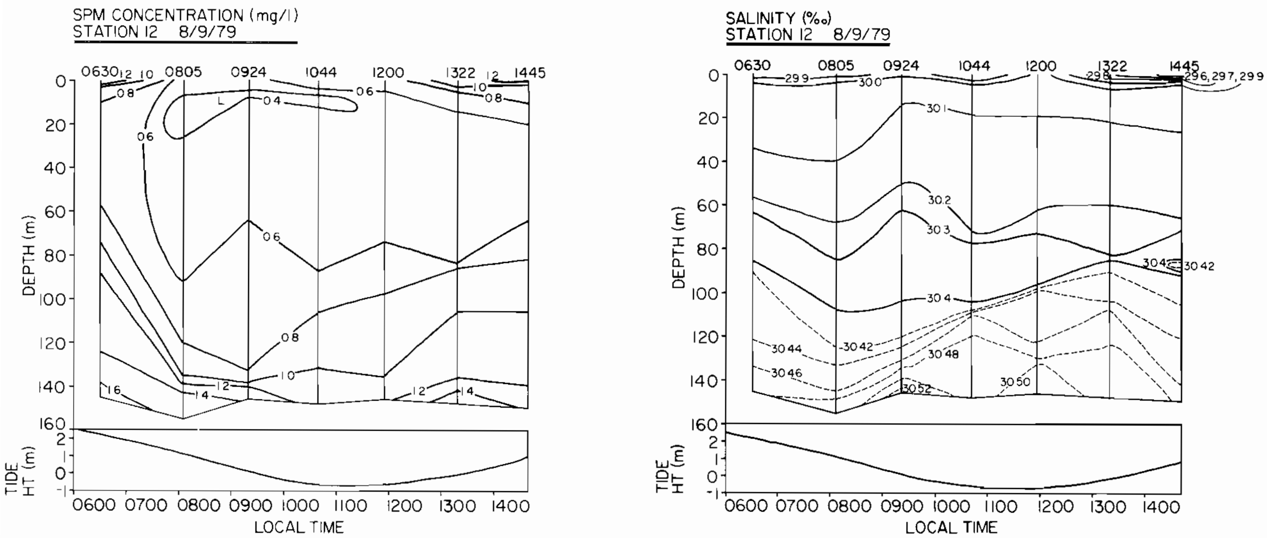


Figure 12.--Time series data for station 12. See legend of fig. 11.

began at 0630 hours. By 0924 hours the depth of the 0.8 mg/l contour had fallen from 55 m to 130 m and near-bottom concentrations had decreased from 1.7 to 1.3 mg/l. After 1044 hours, the BNL increased in both thickness and intensity.

As with the other stations, low surface salinity values were found with times of high SPM concentration (fig. 11). In the bottom waters, the position of the 30.42°/oo contour roughly followed the top of the BNL as defined by the 0.8 mg/l contour. The appearance of the saltiest water (>30.5°/oo), however, tended to coincide with times of the lowest bottom concentrations (0924 to 1200 hours). Analysis of the mooring data from this station (sec. 4.3), however, shows excellent agreement between peaks of salinity and turbidity over tidal-cycle time scales.

Results from the time series investigations can be summarized as follows: 1) the characteristic three-layer SPM stratification (surface high, mid-depth minimum, and BNL) was stable over the observational period, although the vertical gradients varied sharply over short time scales; 2) the surface SPM concentrations are strongly dependent on tide stage and distance from the river mouth; and 3) variations in the thickness and intensity of the BNL are at least broadly correlated with the salinity distribution in the bottom water.

3.1.4 SPM loading

After the SPM loading (expressed as mg/cm^2) was calculated for each station, the individual station results were extended to the entire study area by the following procedure. Elliott Bay was subdivided into 13 separate sub-areas (each sub-area centered around a station location) such that the boundaries between each sub-area primarily followed isobaths. The perimeter of the bay (depths <20 m) was not included. Depths below 20 m were divided into the following intervals: 20-50 m, 50-70 m, 70-90 m, 90-120 m, 150-180 m, and >180 m. The projected areal surface of each depth interval in each sub-area

Table 2.--SPM loading calculations by sub-area and depth interval for August 8, 1979

Sub-area	Depth interval (m)	Surface area ($\times 10^5$ m^2)	Sediment mass ($\times 10^5$ g)
1	20-50	4.22	50.6
2	20-50	3.62	89.3
3	20-50	5.95	161.6
4	20-50	0	0
	50-70	3.76	92.5
	70-90	14.26	616.0
	90-120	3.68	267.2
5	20-50	0	0
	50-70	14.3	414.7
6	20-50	4.15	77.8
7	20-50	4.50	92.2
	50-70	4.06	124.6
	70-90	9.80	443.9
	90-120	8.27	818.7
8	20-50	0	0
	50-70	1.80	47.2
	70-90	3.61	139.4
	90-120	8.44	506.4
	120-150	10.91	1047.1
9	20-50	5.76	106.0
10	20-50	9.98	131.0
11	20-50	0	0
	50-70	2.78	110.1
	70-90	2.98	146.5
	90-120	2.98	207.4
	120-150	4.41	471.9
	150-180	23.33	3732.8
	180	6.21	993.6
12	20-50	1.04	26.1
	50-70	.96	36.9
	70-90	1.68	82.3
	90-120	6.96	476.1
	120-150	12.39	1203.1
13	20-50	4.05	92.8
	50-70	2.23	80.7
	70-90	2.42	134.8
		194.98	13,200.8

Table 3.--SPM loading calculations by bay-wide depth intervals for August 8, 1979

Depth interval (m)	Total Elliott Bay surface area ($\times 10^5$ m^2)	Repre- sentative stations	Mean SPM accumulation (g/m^2)	Sediment mass ($\times 10^5$ g)
20-50	43.3	1,2,10	15.2	656.7
50-70	29.9	3,6	23.5	702.6
70-90	34.7	5,9	39.0	1353.3
90-120	30.3	4,13	81.0	2454.3
120-150	27.7	7,8,12	90.2	2493.9
150-180	29.5	11	150.3	4425.0
>180	6.21	11	160.1	994.2
				13080.0

was then calculated using a polar planimeter. Loadings for each sub-area were calculated by multiplying the accumulated SPM from the surface to the mid-point of each interval (or actual depth for the >180-m region) by the surface area covered by that interval. Summing each interval then gave the total loading for each sub-area.

There are two obvious sources of error in the approach given above. First, the SPM distribution may not be uniform over an entire sub-area. However, the cross sections indicate that horizontal changes between stations are gradual and features can be traced throughout the bay. Surface variability around the river mouth is probably most sensitive to this error. Second, this procedure assumes strong vertical stratification of the SPM. In sub-areas 4, 7, 8, 11, and 12, where there is a large depth range, it is implicitly assumed that the deep BNL does not continue up to shallower depths, i.e., that a transmissometer profile taken at a location in sub-area 7 where the water depth is only 70 m would be identical to the upper 70 m of a 120-m profile taken in the same sub-area. Although this assumption is imprecise, the strong horizontal stratification in the SPM cross sections makes it a reasonable approximation. Table 2 shows the calculation in detail for the survey of August 8, 1979.

An alternative calculation method was also tested as a secondary check. In this procedure, the projected surface area for each of the depth intervals listed above was calculated for the entire bay. Representative stations were then assigned to each depth interval and the average total accumulation at those stations was used as the average bay-wide accumulation over that depth interval. Finally, all the intervals were summed to arrive at a bay-wide total (table 3). This procedure assumes that profiles taken at a given water

Table 4.--SPM loadings for Elliott Bay

Date	Mass ($\times 10^8$ g)	% Inner bay (Stations 1-9)	% Outer bay (Stations 10-13)
August 8, 1979	13.2	41	59
August 10, 1979	12.7	44	56
February 20, 1980	15.3	40	60
February 22, 1980	16.1	40	60

depth anywhere in Elliott Bay will be similar. It also allows a BNL to be considered at every depth, although it must be uniform throughout the bay for a given depth interval. It can be seen from tables 2 and 3 that the two methods yield results less than 1% apart, implying that either method will yield a reasonably good estimate of the mass of SPM in the study area during the survey periods.

Table 4 details the results from the August 8 and 10 surveys. Total SPM in the study area on August 8 was approximately 13.2 x 10^8 g; 7.8 x 10^8 g was in the outer bay (stations 10 through 13) and 5.4 x 10^8 was in the inner bay. Loading on August 10 was about 12.7 x 10^8 g or 10% less than 2 days earlier. The outer stations lost about 10% of their load, and the inner stations increased their load by about 5%. At least part of this trend is due to the movement of near-bottom turbid water from the outer to the inner stations as seen in fig. 9A.

3.2 Distributions of Suspended Particulate Matter-February 1980

3.2.1 SPM transects

Section 1-2. The effects of the rainy season can be seen immediately in the February cross section of Section 1-2 (fig. 13) compared with that of August (fig. 4). Strong north-south surface plume gradients were seen on both survey days. A BNL was present at both stations each day, but an assortment of SPM maxima and minima were present in the BNL on February 22. The mid-depth minimum was again found, but the minimum value had increased 50% since August, from 0.4 to 0.6 mg/l.

Section 3-6. A strong influence from the Duwamish River was seen at stations 6 and 5 in this cross section also (fig. 14). The thickness of this riverine influence layer was no greater than in August. As in Section 1-2, SPM concentrations in the mid-depth minimum were significantly greater than in

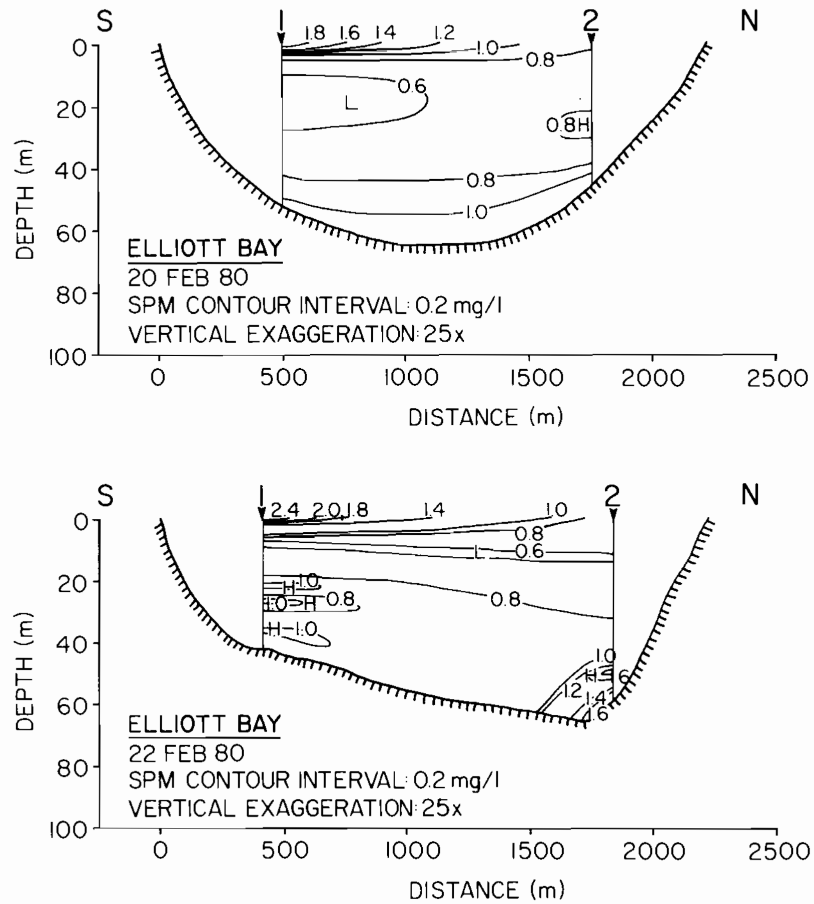


Figure 13.--SPM cross sections for stations 1-2, February 1980.

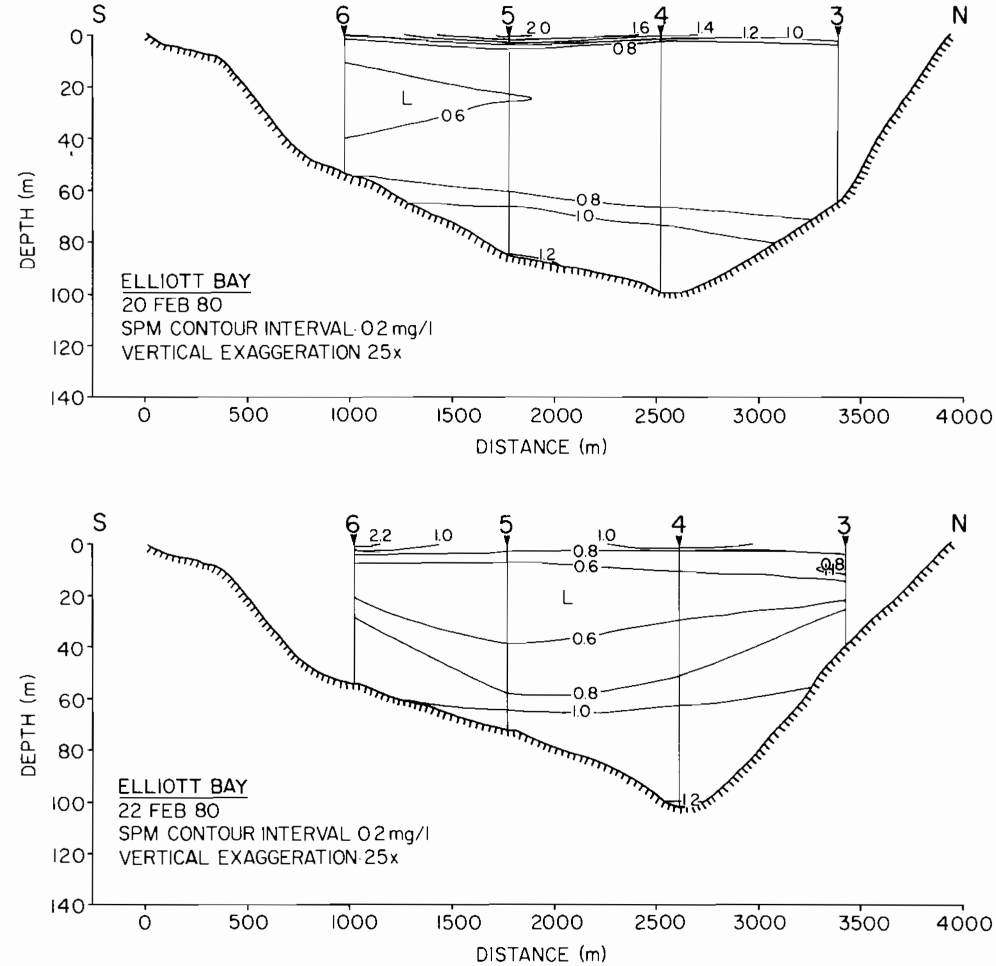


Figure 14.--SPM cross sections for stations 3-6, February 1980.

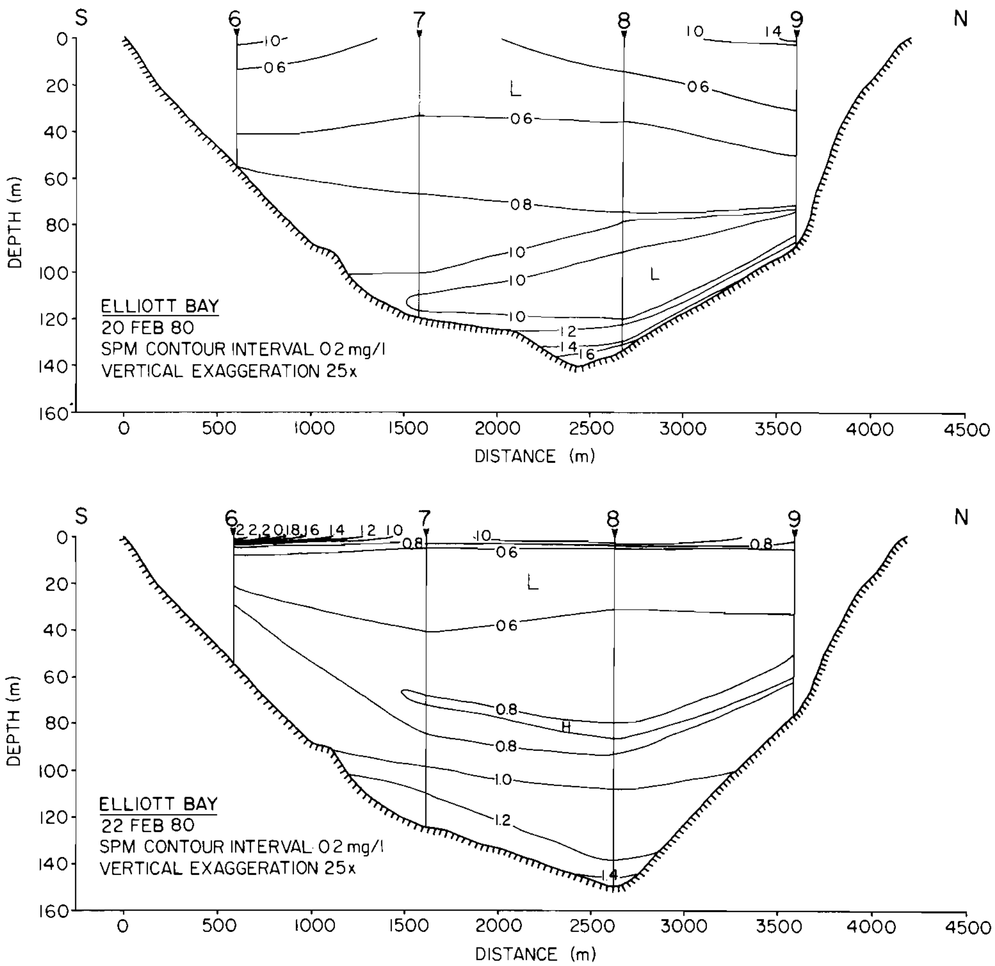


Figure 15.--SPM cross sections for stations 6-9, February 1980.

August. Compared with the August BNL, the February BNL was much weaker and somewhat thinner, with concentrations generally <1.2 mg/l.

Section 6-9. Surface concentrations varied significantly along this transect between the two surveys (fig. 15). A high concentration was found along the north shore at station 9 on February 20 but not on February 22. As with the other sections, concentrations in the mid-depth minimum were elevated above August levels. The highest concentrations found in the BNL (1.4 and 1.6 mg/l) were the same as in August, but the volume of this most turbid water was much less than in August; turbidity levels >1.4 mg/l occurred only at the deepest station and not more than 5 m above bottom.

Section 10-13. Surface values were relatively uniform all across the transect on both days (fig. 16). Values in the mid-depth minimum were the same as in the outer transects. Variability in the BNL in the submarine canyon (station 11), however, was extreme. On February 20 only a very weak BNL was present. Two days later, near-bottom values had more than doubled and

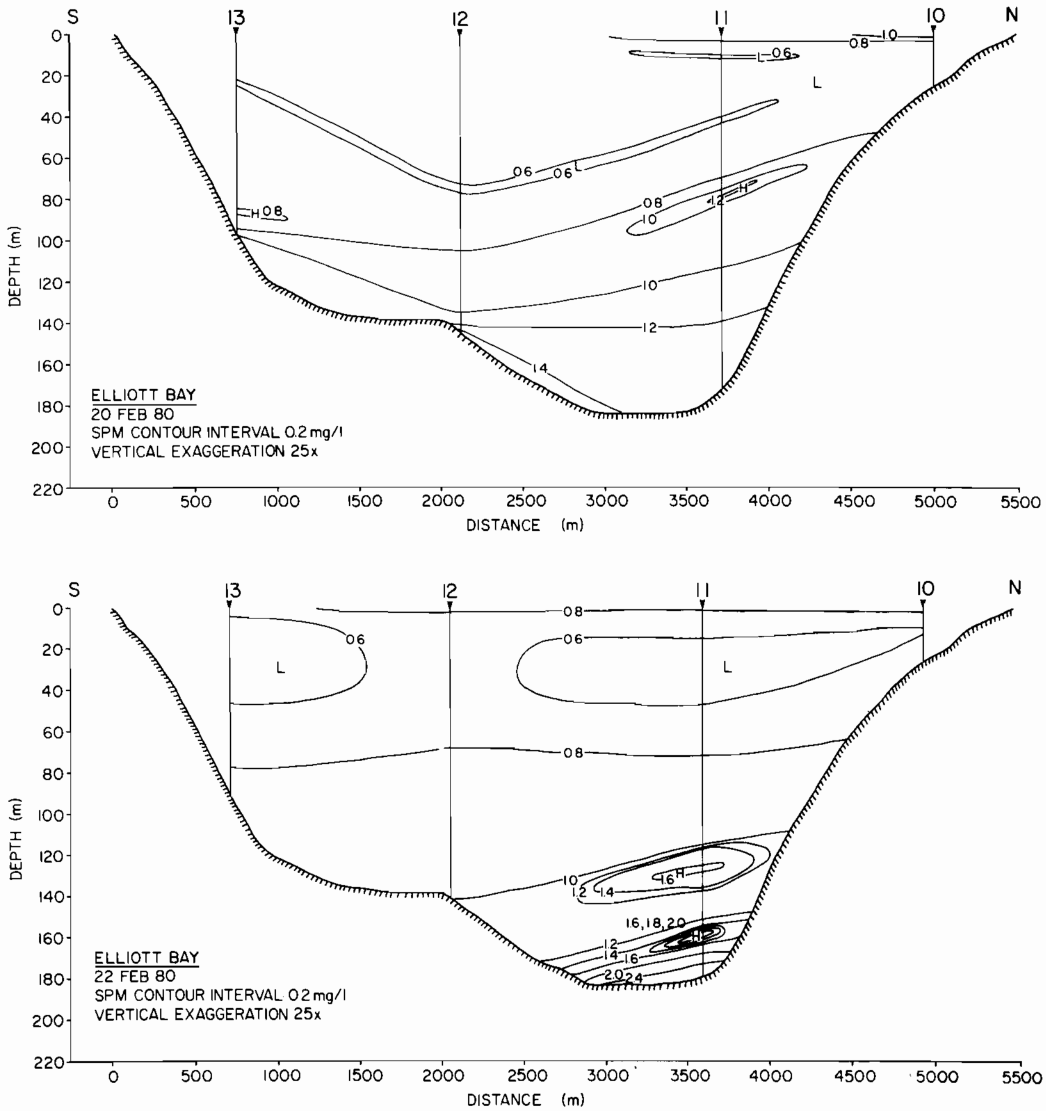


Figure 16.--SPM cross sections for stations 10-13, February 1980.

three major SPM maxima could be identified in the bottom 60 m. This change was similar to but more pronounced than the one that took place at the same station in August.

The overall distribution of SPM was generally similar to that found throughout the bay in August. River input of particulate matter was more pronounced, owing to the factor-of-5 increase in Duwamish River runoff between August (7.8 m^3/s) and February (42.5 m^3/s). The mid-depth minimum was again present but with concentrations increased by about 50% over August. Finally, the BNL was less well developed in the inner bay in February, but showed large variability in the outer bay. The transience of the BNL makes seasonal comparisons difficult if only the survey data are used. Moored transmissometer data, discussed in sec. 3.4, show there was little difference in the average near-bottom intensity of the BNL near station 7 between August and February.

3.2.2 Areal plots

Surface concentration maps from February 20 and 22 (fig. 17A) clearly show the Duwamish River plume spreading to the north and west. As in August, there was no indication of surface transport to the west along the southern shore. The difference in the shape of the plumes may be due to a marked difference in the wind pattern between February 20 and 22. The net wind direction and average speed for February 20 (SeaTac Airport) was 190° at 18.3 km/h; the wind was southerly, blowing the plume against the north shore. On February 22 the net wind was from 350° at 12.2 km/h; the wind was northerly and evidently opposed the discharge momentum and forced the plume into a narrow band in the center of the bay. It is interesting to note that the wind had been blowing fairly steadily out of the north since about midnight on February 20, and there was still no sign of the plume moving west past station 7 along the southern shoreline.

Salinity maps show an almost identical pattern (fig. 17B), implying that the particulate matter moves coherently with the freshwater river plume under varying meteorological conditions. The agreement between SPM and salinity patterns was much better than in August.

Maps of the SPM concentrations 5 m above bottom (fig. 18A) illustrate the dramatic daily variation found in the submarine canyon. Perimeter stations (except for station 2) varied only slightly from February 20 to 22. This episodic pattern agrees with that observed during August.

The only significant change in bottom-water salinities between the two surveys was the presence of water saltier than 29.8 ‰ at stations 12 and 8 on February 20 (fig. 18B). On February 22, no water saltier than 29.78 ‰ was found in the bay. No evidence of anomalous water related to the high turbidity at station 11 was seen in the temperature distribution either.

3.2.3 Time series data

Time series data were collected on February 21 at stations 6, 7, and 11. The outer station was changed from 12 in August to 11 in February because of its position in the submarine canyon and the presence of highly turbid water at that location. Unfortunately, the February time series study was severely curtailed by the thick fog in the morning, preventing boat operations until afternoon.

Station 6. The station taken at low tide (1454 hours) appears to have anomalously low SPM concentrations (fig. 19A), which may be a result of a positioning error by the ship. Concentrations in the BNL fell sharply from the beginning to the end of the survey.

Station 7. As in August, highest surface concentrations were seen sometime after low tide (fig. 19B). Concentrations in the BNL decreased with time.

Station 11. Surface concentrations were uniform throughout the survey (fig. 19C). BNL concentrations increased sharply with time, from about 1.4 mg/l at 1245 hours to >3.0 mg/l at 1640. Both temperature and salinity remained unchanged in the bottom water betweem 1410 hours and 1640 hours.

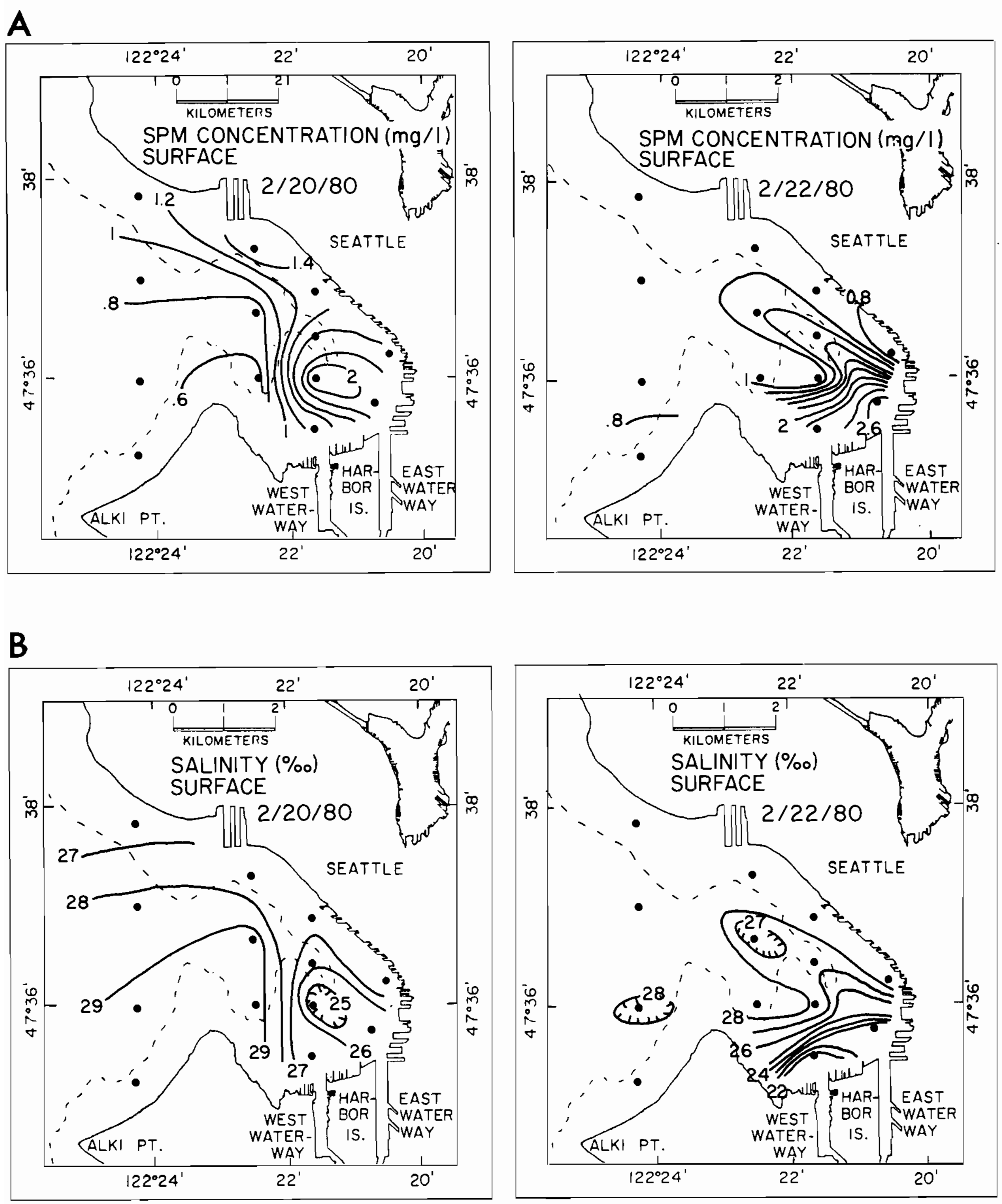


Figure 17.--Areal maps of surface (A) SPM concentration and (B) salinity at 1 m during the February surveys. Contour interval is 0.2 mg/l for SPM, 1°/oo for salinity. Dotted line is 100-m isobath.

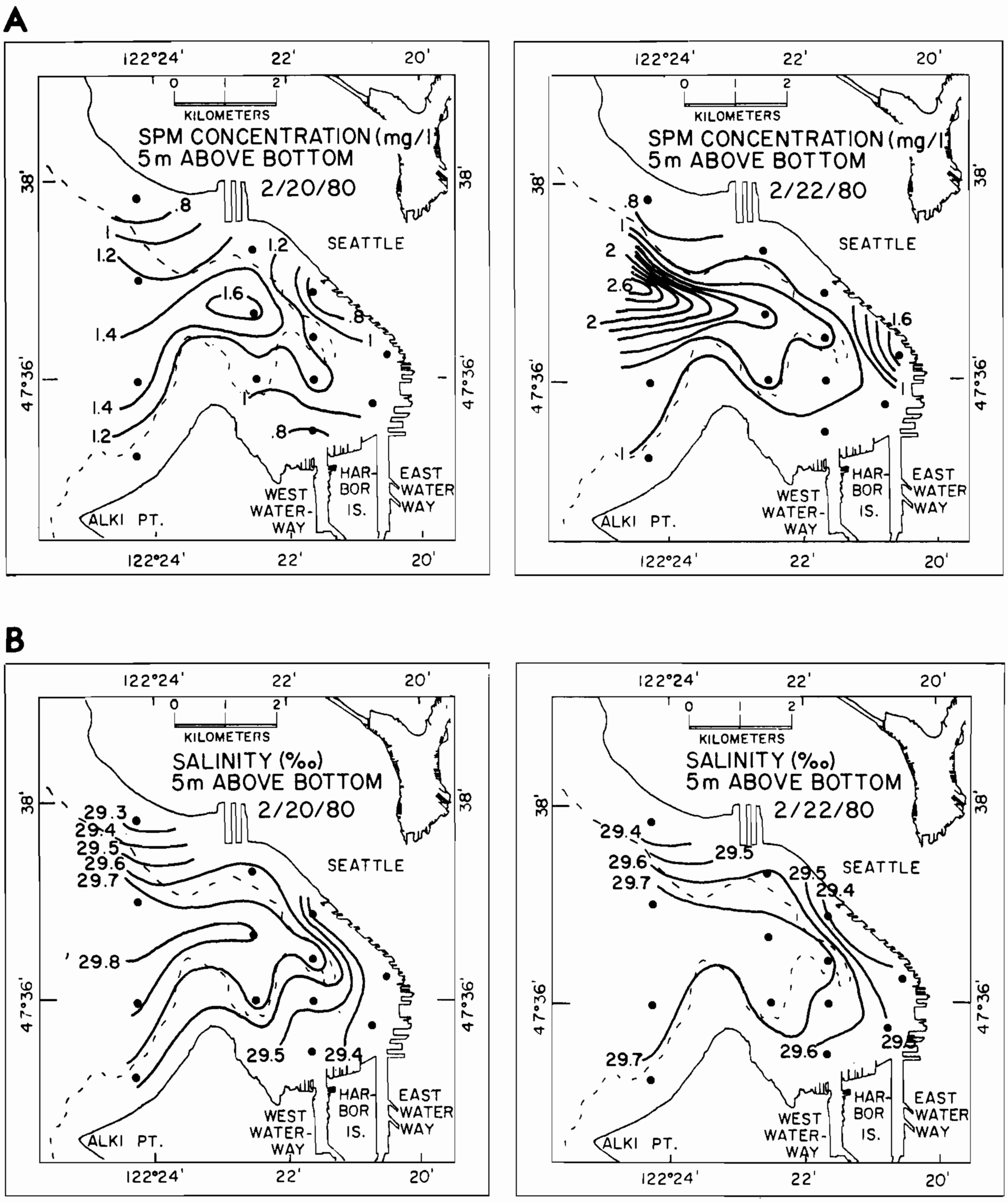


Figure 18.--Areal maps of bottom (A) SPM concentration and (B) salinity during the February surveys. Contour interval is 0.2 mg/l for SPM, 0.1°/oo for salinity. Dotted line is 100-m isobath.

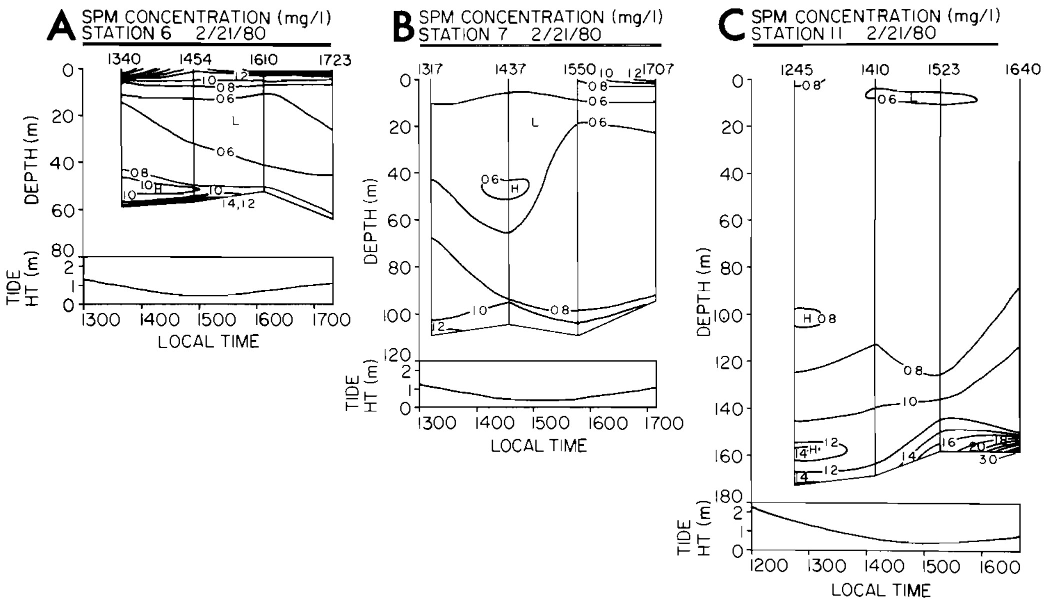


Figure 19.--Time series data for (A) station 6, (B) station 7, and (C) station 11. Station times are given in local time across the top of the profile. Contour interval is 0.2 mg/l. A time plot of the tide height is given at the bottom of the profile.

3.2.4 SPM loading

The amount of SPM in Elliott Bay was almost 20% higher in February than in August (table 4). Partitioning between the inner and outer regions of the bay was very similar to the August data, with 40% of the total in the inner bay on both February 20 and 22. The largest increases were seen in the inner bay near the Duwamish River--stations 1, 5, and 6 averaged a 58% increase from August to February. Increases elsewhere in the bay were more moderate, but all stations showed some increase, reflecting the bay-wide increase in SPM concentrations in the thick mid-depth minimum zone.

3.3 Characteristics of Suspended Particulate Matter

3.3.1 Organic content

The organic content of SPM in Elliott Bay was generally greater in August than in February. The surface values for August were about twice as great as those for February at all stations (averages of 41% and 18% organic matter for August and February, respectively); bottom values were about half again as high in August as in February. During both cruises, surface samples generally contained greater amounts of organic material than did deep samples. Stations 1 and 6, however, showed greater values at the bottom than at the surface during February and on one of the days in August (August 10).

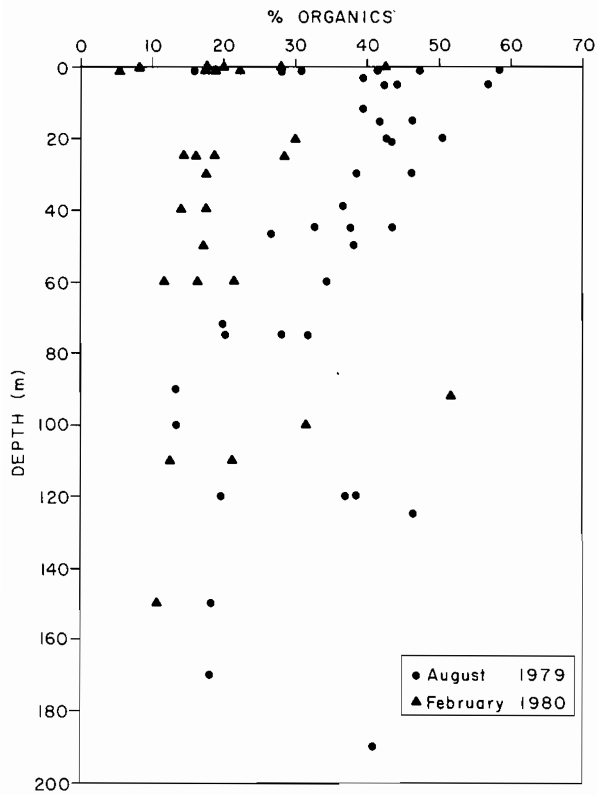


Figure 20.--Depth distribution of organic matter by percentage, for Elliott Bay surveys in August and February.

In August, higher percentages of organic matter in the surface layer tended to be at the outer stations, 11 and 12 (about 54%), and decreased towards stations 1 and 6 (about 35%) near the Duwamish River. The opposite was seen at the bottom, where decreasing organic content corresponded to increasing distance from the river (36% near the Duwamish River to about 20% in the outer bay).

Similar trends were observed in February. Surface values decreased from 20% in the outer bay to about 13% near the Duwamish River. At the bottom, values increased from 11% at station 11 to 19% at station 6.

Figure 20 summarizes the vertical profiles of organic matter for all stations during August and February. The August values for the upper 20 m show that about 40%-50% by weight of the particulates is organic in nature. This concentration steadily decreases to 20%-30% at 80 m and is somewhat variable below 80 m. In February, all surface values but one are below 30% organic matter, and other values are mostly within 10%-20% organic matter for the entire water column.

There does not appear to be a strong relationship between organic content and salinity, but the data suggest an inverse relationship between organic content and SPM concentration. This relationship may arise from the fact that the most concentrated SPM samples are either near-bottom, where the SPM is older and thus more refractory, or near a source of terrestrial runoff such as the Duwamish River.

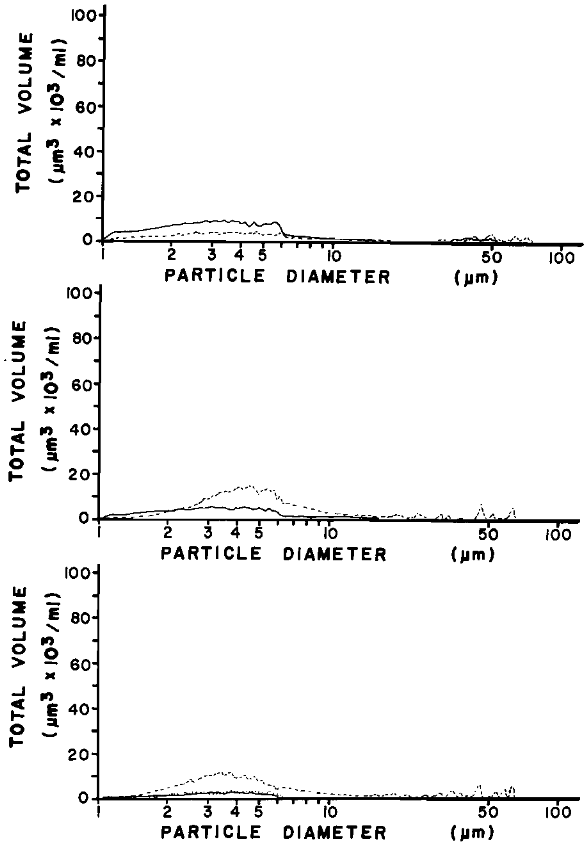


Figure 21.--Particle size distributions during the August survey. Solid line, surface; dashed line, 5 m above bottom; dotted line, mid-depth minimum. Spectra are from station 6 (top), station 7 (middle) and station 11 (bottom).

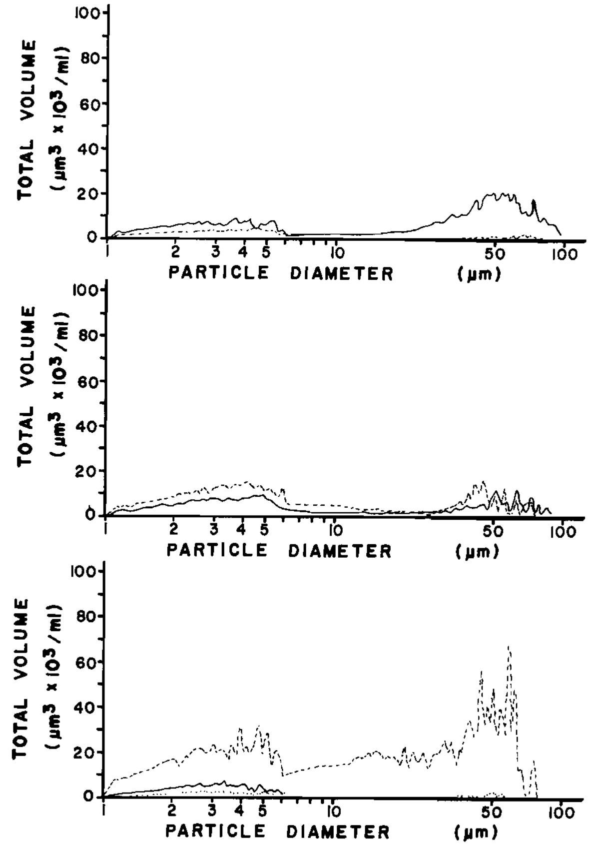


Figure 22.--Particle size distributions during the February survey. Solid line, surface; dashed line, 5 m above bottom; dotted line, mid-depth minimum. Spectra are from station 6 (top), station 7 (middle) and station 11 (bottom).

3.3.2 Particle size distribution

Particle size distributions from surface, bottom, and mid-depth of three stations on the axis of Elliott Bay (6, 7, and 11) are presented as representative of the bay as a whole (figs. 21 and 22). Station 6 samples from both August and February were collected within an hour of low tide; SPM concentrations were ≈0.8 mg/l during both surveys, but surface concentrations were higher in August (1.8 mg/l) than in February (1.2 mg/l). Station 7 samples were collected at low tide in August and at high tide in February; both surface and bottom SPM concentrations were higher in August than in February. Station 11 samples were collected on a rising tide in August and at high tide in February; the bottom concentration in August was higher (1.6 mg/l) than in February (1.2 mg/l).

Size distributions on a volume basis are similar for all August surface samples (fig. 21) for diameters less than ~6 μm, showing a broad, nonpeaked spectrum of miscellaneous particles (Kranck, 1980). The volume concentrations in the <6-μm region decreases with increasing distance from the Duwamish River. In addition to this fine-grained region, significant volume concentrations occur in the 25-to 70-μm range only at station 6, closest to the Duwamish River.

Near-bottom spectra show an entirely different pattern. For station 6, the near-bottom spectrum has a similar shape but only about half the total volume of the surface sample. Distribution at the coarse end of the spectrum is similar to that at the surface. Near-bottom samples from stations 7 and 11 show marked peaks and a substantial increase in volume concentration over the surface samples. The mode at the fine end of the spectrum is slightly coarser (~4.5 μm vs. 3.5 μm) at station 7 than at station 11. Both stations show a high percentage of total volume in the coarse-fraction part of the spectra. The mid-depth spectrum at station 11 (75 m) is almost identical to the surface spectrum.

Samples from these same stations and depths during February were dramatically different (fig. 22). The fine-particle population spectra at stations 7 and 11 in the surface were similar to, although of higher concentration than, the summer spectra. The increased outflow of the Duwamish during the winter resulted in a very high particle volume concentration at diameters >10 μm at station 6 even though the bulk concentration was lower than in August. These large particles were still abundant at station 7 but had settled out of the surface water between station 7 and station 11.

This energy gradient is reversed in the bottom waters, where station 11 shows very large volume concentrations at all particle sizes. In contrast to the summer data, the fine-particle mode was coarser at station 11 (~4.5 μm) than at station 7 (~4 μm). Large numbers of particles with diameters >50 μm were also found in the near-bottom water at station 11. Note that these samples were collected on February 20 and that the maximum BNL concentrations at station 11 were found on February 22 (fig. 18). Large particles are rare at station 6, which had less volume than during the summer. The particle distribution at mid-depth at station 11 changed very little between summer and winter.

3.4 Transport of Suspended Particulate Matter

3.4.1 Current meter/transmissometer time series records

Outer Elliott Bay – mooring EB4

Edited data plots of current speed, temperature, attenuation, and salinity approximately 5 m above bottom at site EB4 were obtained for 38 days in August/September 1979 (fig. 23) and 29 days in February/March, 1980 (fig. 24). Bottom conditions in the summer were warmer, saltier, and slightly less turbid than in the winter (mean attenuation of 1.04 ± 0.028 in August/September vs. 1.16 ± 0.032 in February/March). Mean speed of the bottom currents was almost twice as high in the summer (5.37 cm/s vs. 2.89 cm/s). A similar difference was also found in the maximum speeds achieved during each period (26.35 cm/s in August/September vs. 14.4 cm/s in February/March).

Progressive vector diagrams (35-h filter data) for each deployment period are similar--dominant flow was to the north or northeast, suggesting bottom

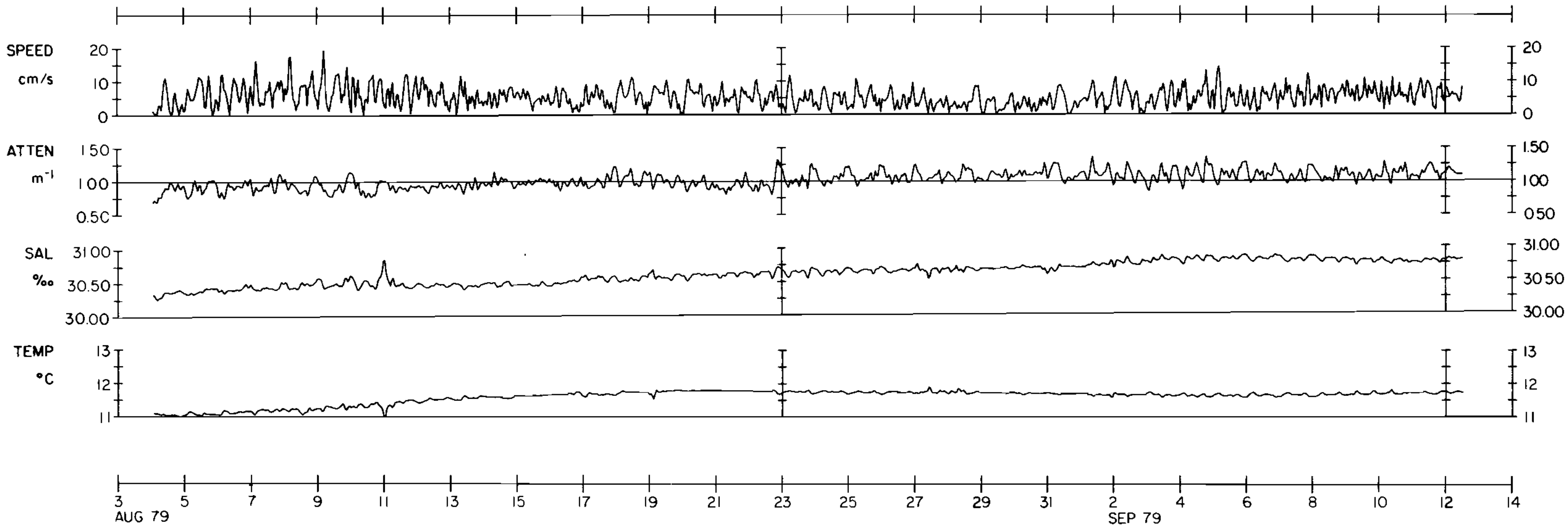


Figure 23.--Mooring data from EB4, 132-m depth, from the summer deployment.

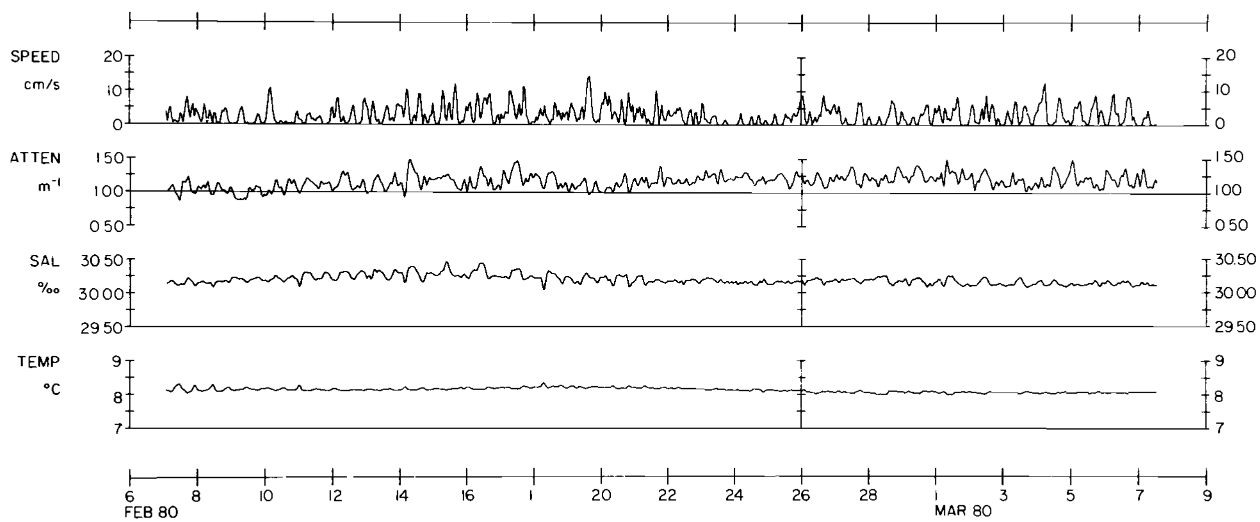


Figure 24.--Mooring data from EB4, 130-m depth, from the winter deployment.

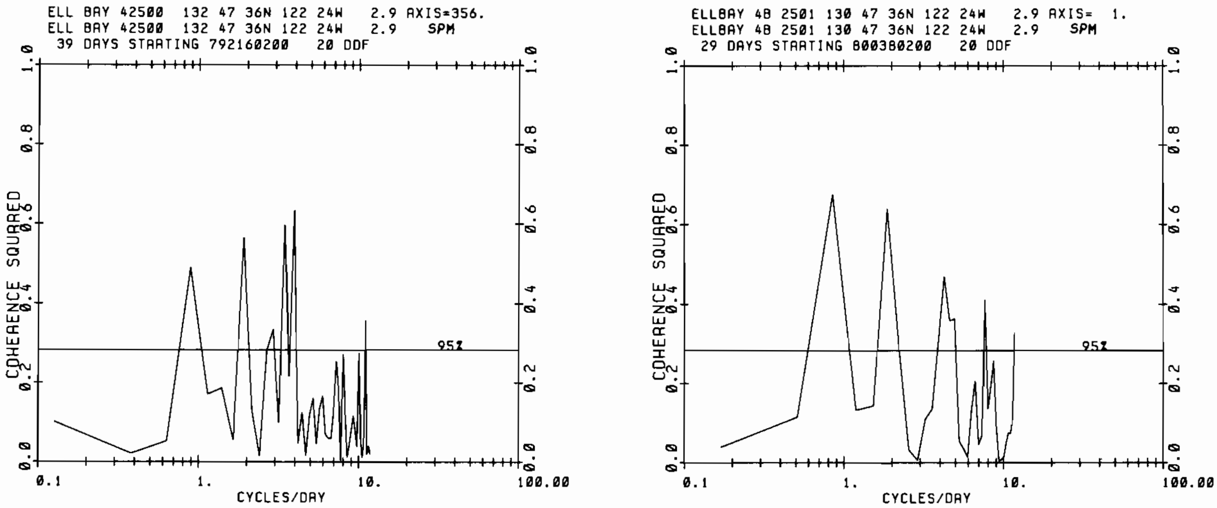


Figure 25.--Spectral coherence squared between velocity along the principal tidal axis and the SPM concentration at mooring EB4 in the summer (left) and winter (right).

water moving into Elliott Bay around Duwamish Head. Net flow in the summer was 2.98 cm/s at 56°, while winter net flow was reduced to 1.45 cm/s at 17°.

In order to evaluate the relationship between the energy spectra of the bottom currents and the SPM concentration, coherence spectra were plotted (fig. 25). At EB4, significant coherence along the principal (M2) tidal axis was present at diurnal (T ≅ 1.04 days) and semidiurnal (T ≅ 0.51 days) periods for both summer and winter. Coherence at higher frequencies was also present, but the period varied with the season. Coherence at both the diurnal and semidiurnal periods was greater in the winter than in the summer.

Inner Elliott Bay – mooring EB2

Edited data plots for EB2 analogous to those for EB4 are shown in figs. 26-28. Attenuation in the canyon bottom was similar for both seasons (1.03 ± 0.030 for August/September vs. 1.15 ± 0.037 for February/March) even though the bottom water was much fresher and colder in the winter than in the summer. Unlike that at EB4, the mean current speed at EB2 was ~65% higher in the winter (4.95 cm/s vs. 3.01 cm/s), although the maximum speeds measured varied only slightly between the seasons (19.6 cm/s in August/September vs. 21.9 cm/s in February/March).

Progressive vector diagrams were significantly different for summer and winter. During summer, net flow was weak (0.48 cm/s) and consistently down-canyon (~298°). During winter, flow was along 290° for ~5 days, then reversed to a steady 110° for the remainder of the deployment. The resultant net flow was 2.41 cm/s at 110°.

Coherence spectra (fig. 29) show very strong coherence at semidiurnal tidal periods (~0.52 days) and low or nonsignificant coherence at diurnal periods (~1 day). Examination of the edited data plots (figs. 26 and 27) clearly shows this strong semidiurnal frequency in attenuation, temperature, and salinity.

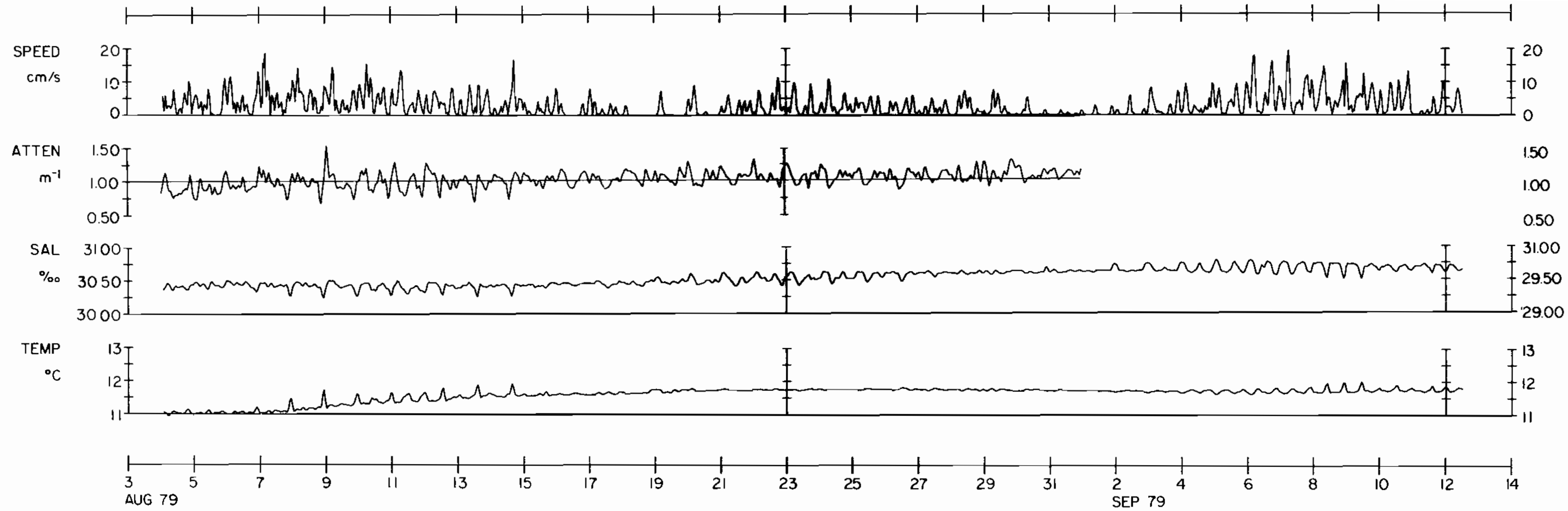


Figure 26.--Mooring data from EB2, 92-m depth, from the summer deployment. Data acquired after the flooding of the transmissometer near September 1 were not used in subsequent analyses.

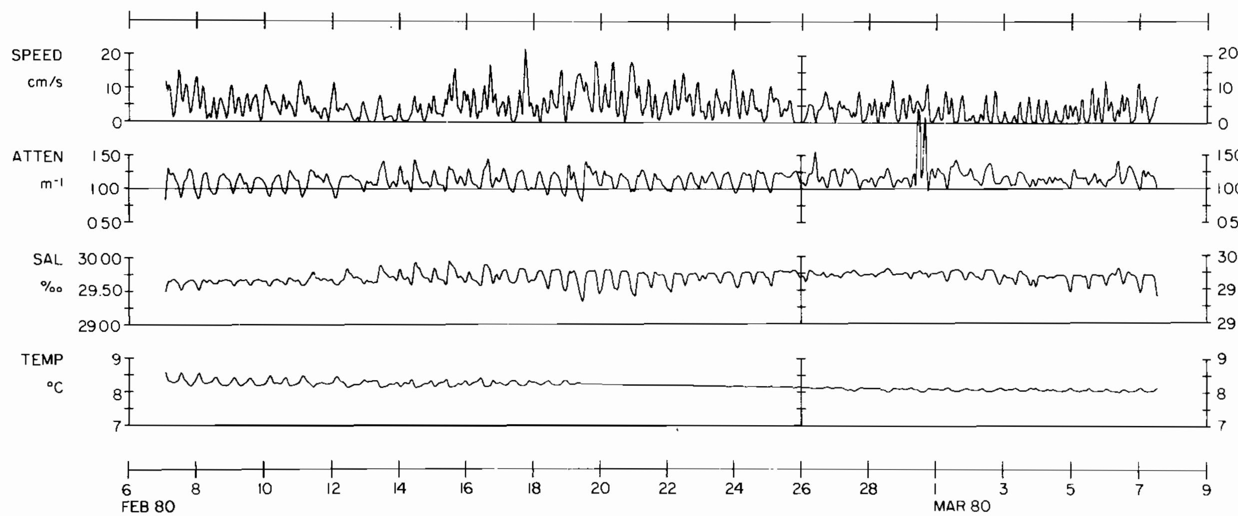


Figure 27.--Mooring data from EB2, 90-m depth, from the winter deployment.

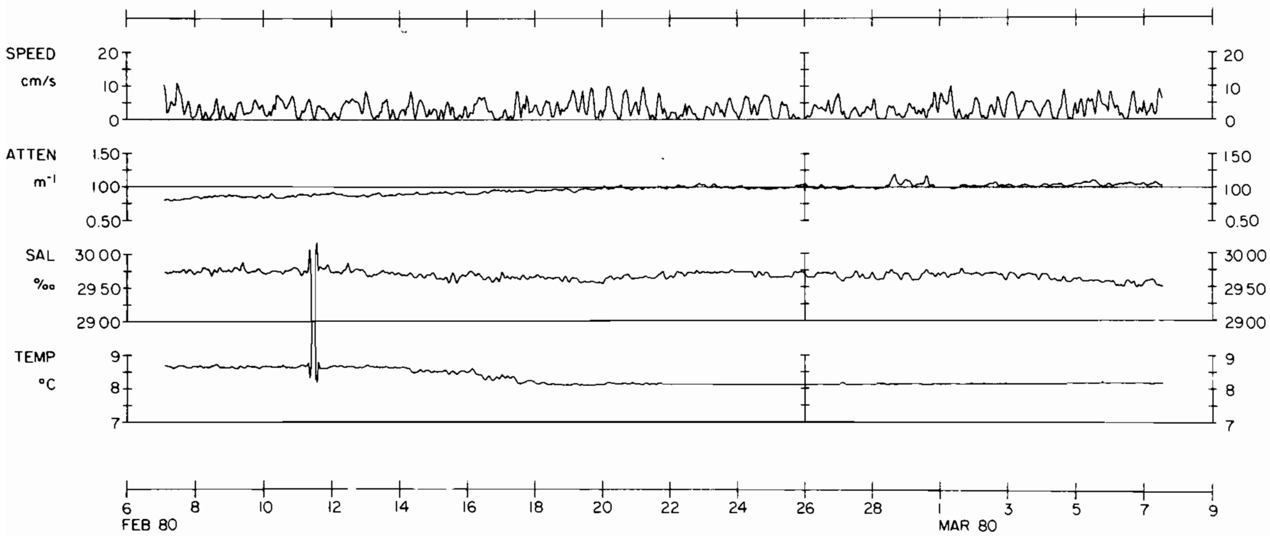
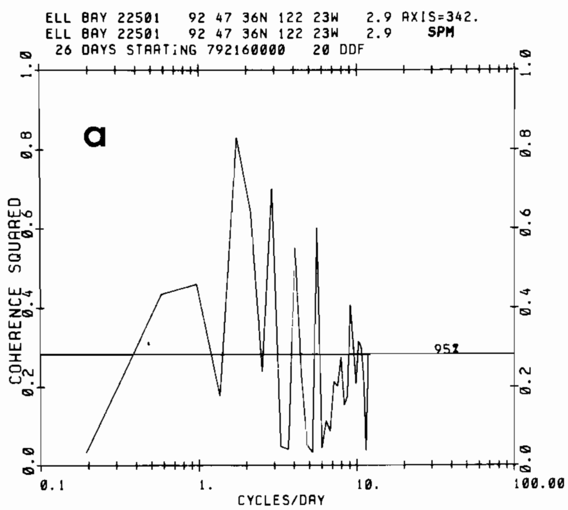
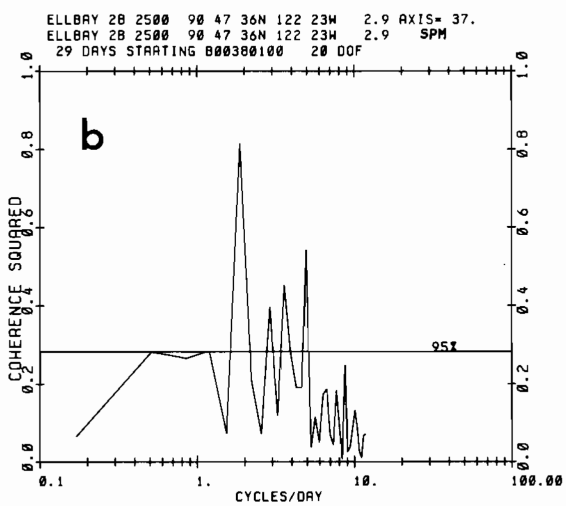


Figure 28.--Mooring data from EB2, 30-m depth, from the winter deployment.





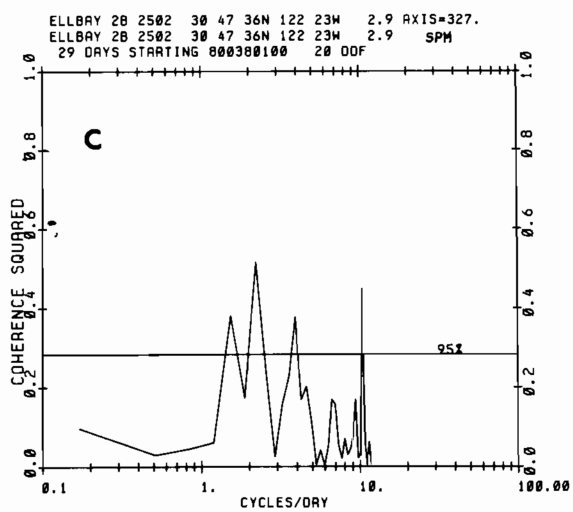


Figure 29.--Spectral coherence squared between velocity along the principal tidal axis and the SPM concentration at mooring EB2 in the summer at 92-m depth (a), in the winter at 90-m depth (b), and in the winter at 30-m depth (c).

The 30-m record at EB4 (fig. 28) was substantially different in all respects from the near-bottom record. The attenuation values were low and very stable (0.96 ± 0.018) on a tidal scale, showing a gradual decrease with time. These characteristics can be considered typical of conditions in the mid-depth minimum zone of Elliott Bay. Coherence spectra (fig. 29) showed only weak coherence near semidiurnal and quarter-diurnal frequencies. Net flow was 1.63 cm/s at 347°.

3.4.2 Horizontal transport of SPM and salt in Elliott Bay

Magnitude and direction of net transport of suspended matter and salt were calculated for each current meter/transmissometer deployment. Transport fluxes were obtained by vector addition of the mean and variable portions of the flow along two component axes:

$$\text{Flux} = \left[(\bar{u}\ \bar{s}) + \frac{1}{n}\ \Sigma\ u's')^2 + (\bar{v}\ \bar{s}\ + \frac{1}{n}\ \Sigma\ v's')^2\right]^{1/2} ,$$

where $\bar{u}$, u' and $\bar{v}$, v' = the mean and fluctuating components of the flow along the east-west and north-south axes, respectively, and $\bar{s}$ and s' = the mean and fluctuating components of the SPM or salt concentrations. Transport direction is given by

$$\theta = \tan^{-1} \frac{\bar{u}\ \bar{s} + \frac{1}{n} \sum u's'}{\bar{v}\ \bar{s} + \frac{1}{n} \sum v's'}) .$$

SPM and salt were compared to see if the characteristics of transport for particulate and dissolved phases in the water column were significantly different. A summary of the transport results is given in table 5.

Table 5.--Flux measurements of suspended particulate matter and salt

Mooring	Depth (m)	SPM flux ($\mu g/cm^2/s$)	Salt flux ($mg/cm^2/s$)	Dir. (°)	Mean speed (cm/s)
2A	92	0.35	11.60	347	3.01
2B	30	1.58	48.5	346	3.32
2B	90	2.85	71.5	113	4.95
4A	132	3.02	75.9	56	5.37
4B	130	1.61	43.8	17	2.89

At mooring EB4 in outer Elliott Bay the transport of both salt and SPM was ~45% larger in the summer than in the winter, the same as the increase in mean current speed between seasons. Transport of both salt and SPM was to the northeast at EB4, suggesting that dissolved and particulate phases are being transported into Elliott Bay from the main basin at this depth. A corresponding net flow out of Elliott Bay was found at a mooring just north of station 11 (Sillcox et al., 1981).

Mooring EB2, in the southern canyon of Elliott Bay, was more seasonally variable than EB4. During the summer deployment, transport was to the northwest, or downcanyon, at the bottom. In the winter, although mean speed increased by a factor of only ~1.7, net transport of both salt and SPM increased by factors of 6.0 and 7.8, respectively. These transport increases correspond to the increase in net speed at this location from 0.48 cm/s downcanyon in the summer to 2.41 cm/s upcanyon in the winter (Sillcox et al., 1981). Transport at 30 m at EB2 in the winter was out of Elliott Bay to the northeast at about half the rate of the bottom flux. The full vertical profile of flux is, of course, unknown. Nevertheless, the canyon bottom flow reversal from summer to winter does suggest an estuarine-type flow regime driven by increased outflow of the Duwamish River during the winter (5-10 times higher in February 1980 than August 1979). Unfortunately, the lack of instrumentation above 30-m depth prohibits an accurate assessment of near-surface flow since the river plume is restricted to the upper 5-10 m.

3.4.3 Vertical transport of SPM in Elliott Bay

A summary of the vertical flux measurements made in Elliott Bay is given in table 6. Each trap location had dual traps for replicate observations. At EB4, measured flux at the bottom decreased by about 17% from the summer deployment to the winter. A similar decrease was seen in both the organic matter content (22% less) and in the >4ϕ fraction (19% less) of the trapped material, suggesting that at least a portion of the decrease was a result of lowering of zooplankton activity (i.e., fewer fecal pellets from summer to winter). Mean size of the material increased slightly in the winter, although the modal size was unchanged at 7ϕ.

The trap at 30 m at EB4 during summer sampled considerably different conditions than the bottom traps. Flux was only about 2% of that found near the bottom and the percentage of organic matter was about double. There was also a striking increase in the >4ϕ fraction, and, for an unknown reason, a substantial difference in this fraction between the replicate traps. The large difference between surface and bottom fluxes implies substantial near-bottom addition of material from either lateral advection or local resuspension, in agreement with observations of a persistent BNL in Elliott Bay, or a large contribution of fecal material from zooplankton migrating below 30 m depth.

Conditions at EB2 were generally similar to EB4 (table 6). Near-bottom flux in summer averaged 31.6 g/m^2/day and decreased by 29% in the winter, identical to the decrease in organic matter concentration. Unlike EB4, however, the percentage of >4ϕ fraction increased in the winter, and the percentage of aggregates in this fraction dropped by more than 20%, implying that more large, discrete grains were entering the bottom trap in winter than in summer. This finding agrees with information from the bottom current meter/

Table 6.-- Characteristics of the trapped material in Elliott Bay

Trap/Depth	Flux ($g/m^2/day$)	Organic matter (%)	Size Distribution: Mean ϕ	Modal ϕ	>4ϕ (%)	Aggregate in >4ϕ fraction (%)
EB4						
Summer/30 m	0.66	23.0	5.3*	>4	44.8	92.7
	0.75	17.7	6.3	7	18.1	85.4
Summer/132 m	37.9	12.8	6.6	7	5.2	97.1
	37.0	10.9	6.8	7	7.1	75.3
Winter/130 m	32.7	9.6	6.0	7	4.8	81.9
	30.0	8.9	6.3	7	5.2	85.1
EB2						
Summer/92 m	30.1	8.6	6.7	7	5.3	88.7
	33.1	12.3	7.0	8	4.3	87.9
Winter/30 m	6.7	11.3	5.9	7	13.4	79.0
	6.6	9.1	6.5	7	10.9	79.8
Winter/90 m	22.1	7.9	6.0	7	6.2	66.5
	22.3	6.9	5.9	7	8.6	71.0

* Median, not mean, for this trap

transmissometer unit which showed more energetic flow during the winter. The mean size was almost a whole ϕ-size coarser in the winter, also reflecting a higher energy environment.

Flux at the 30-m level at EB2 in winter was an order of magnitude higher than at EB4 in summer, presumably because of increased fallout from the Duwamish River plume. The percentage of large aggregates at EB2, however, was significantly less than at EB4, implying that much of this increased fallout was not from "biological packing" (fecal matter), or that the fecal matter was so loosely bound as to be unmeasurable.

Detailed examinations of the organic matter content of various size classes showed similar results for all traps--an increase in percentage of organic matter with decreasing particle size (fig. 30). The percentage of organic matter associated with the 11ϕ material (0.25-0.5 µm) was twice that associated with the 4ϕ (31-62 µm) material collected in the summer. The trend for the winter is similar, although the increase was only about 20%. These results coincide with the view that less than ~62 µm organic matter exists largely as surface coatings and is thus proportional to the surface area/mass ratio.

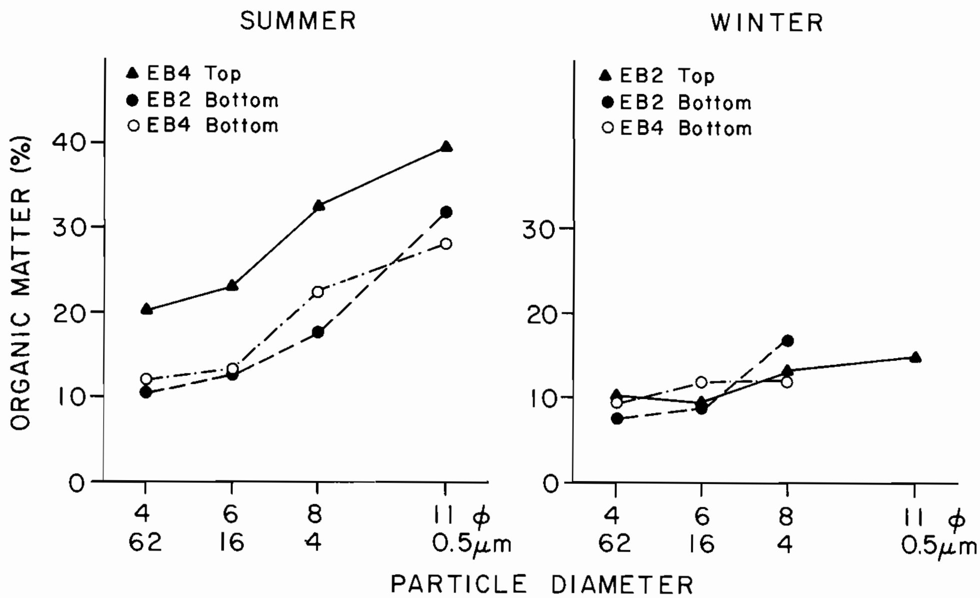


Figure 30.--Scatter plots of particle size vs. percentage of organic matter for sediment trap deployments.

4. DISCUSSION

4.1 Relationship Between SPM and Salinity in Elliott Bay

Since the features of the salinity distribution in an estuarine system are generally better known than that of the particulate matter, it is useful to examine the interrelationships between these two phases. Their relationships can be described by the use of a salinity-vs.-concentration (attenuation) scatter plot analogous to the mixing diagrams used to trace the loss or addition of dissolved constituents in an estuary (Liss, 1976).

4.1.1 Surface waters

Attenuation-salinity plots for the surface layer of Elliott Bay had approximately the same slope for both summer and winter data (fig. 31). This similarity suggests that during both seasons the SPM distribution is controlled by the Duwamish River plume, either as a particle source or as a regulator of primary productivity. That summer SPM levels are increased relative to salinity suggests that the loss of SPM input from a lowering of river input in the summer is closely balanced by an increase resulting from phytoplankton growth. Also, the character of the Duwamish River particulates may change in the summer to particles capable of a longer residence time in the surface waters.

Inclusion of the data from the Duwamish River itself (salinity, <20 ppt) shows seasonal differences (fig. 32). In winter, the river data were on the

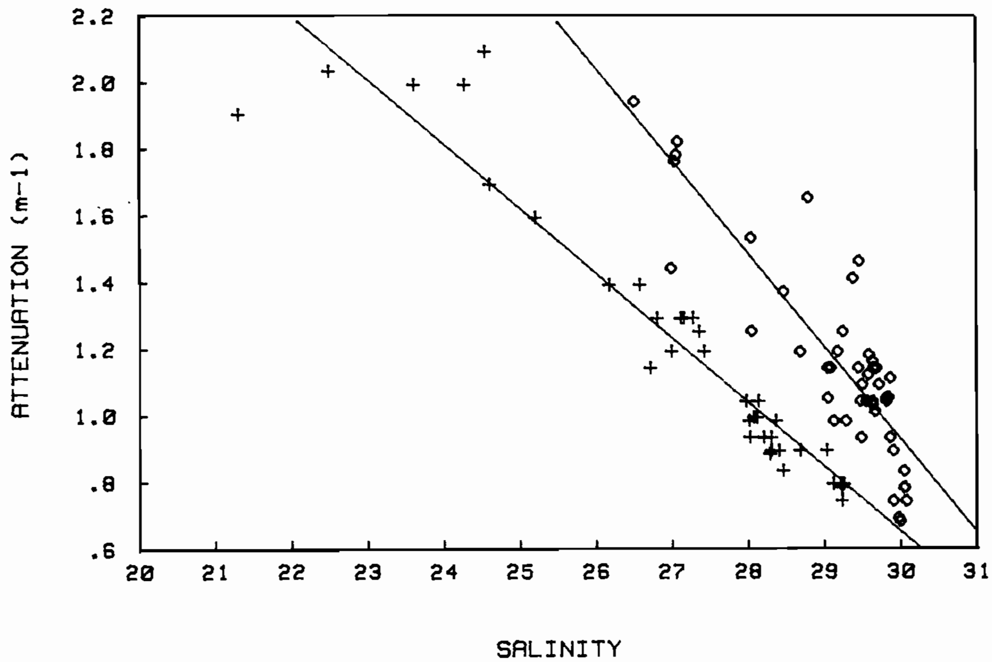


Figure 31.--Scatter plots of salinity vs. attenuation for Elliott Bay samples in August (o) and February (+). Correlation coefficient (r) and standard error of estimate for August were -0.86 and 0.15, respectively. In February, these statistics improved to -0.95 and 0.12.

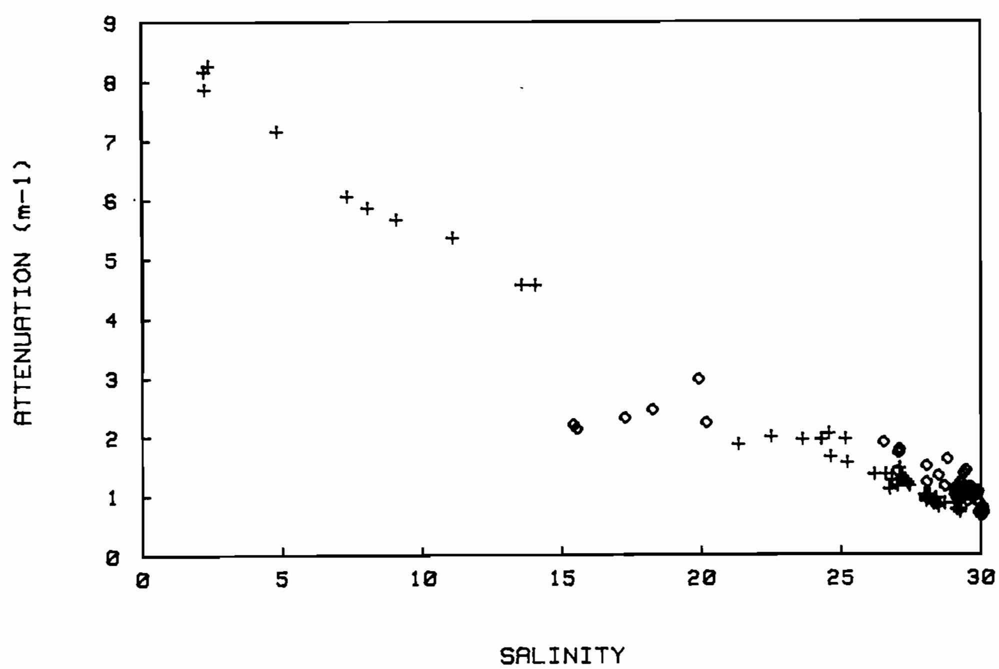


Figure 32.--Scatter plots of salinity vs. attenuation for combined Elliott Bay and Duwamish River samples for August (o) and February (+). Note summer-vs.-winter difference in the river samples (salinity values <20 ppt).

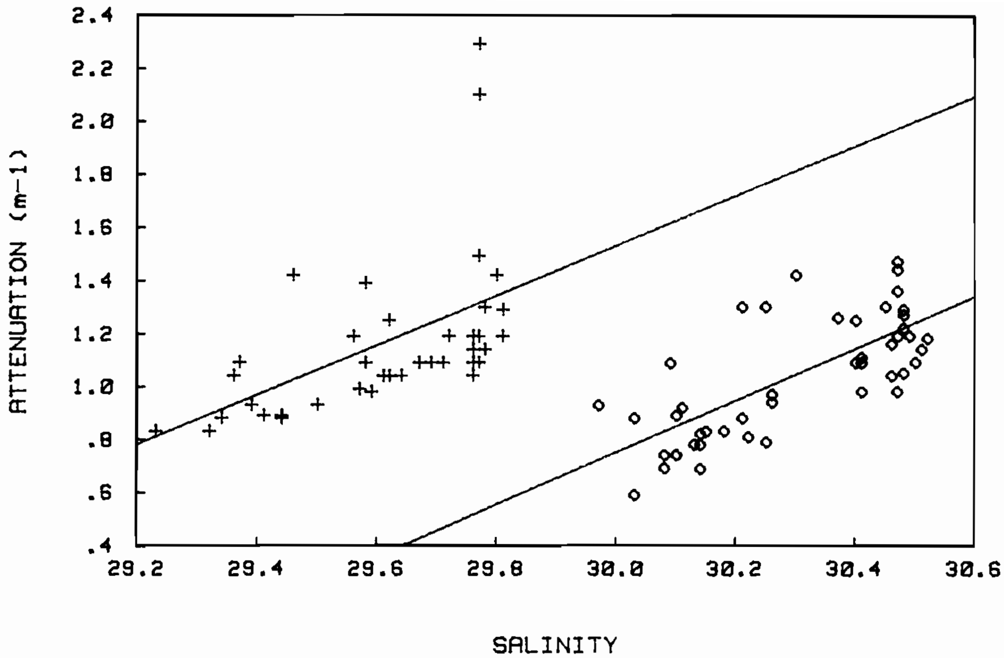


Figure 33.--Scatter plots of salinity vs. attenuation for bottom water samples in August (o) and February (+). Note the similar slopes for both seasons.

same regression line as the Elliott Bay data, indicating the dominance of plume water in the Bay and conservative mixing of the SPM. In summer, the river samples fell substantially below the Elliott Bay line, showing the expected river situation of lower SPM concentration per unit volume of freshwater resulting from the lower energy of the river (low flow and lower hydraulic competency) and a lessened supply of SPM as a result of lower rainfall.

4.1.2 Bottom waters

SPM-salinity relationships within the BNL were the inverse of the surface water relationship (fig. 33). SPM-salinity bottom-water regression lines have correlation values lower than those for the surface water data. Both seasons showed the same direct relationship between SPM and salinity: the slope was the same for each season, and the mean attenuation was slightly higher in February (1.17 m^{-1}) than in August (1.04 m^{-1}). All salinity values were higher in August than in February, however, because the densest bottom water is found in Puget Sound during the summer (Cannon et al., 1979).

These relationships strongly imply a source of SPM into Elliott Bay from the deep waters of the main basin of Puget Sound via the central submarine canyon. Other concurrent studies by the author have identified a thick (>50 m) BNL in the main basin which could be contiguous with the BNL observed in the deepest portions of Elliott Bay. Future mooring work in Elliott Bay should include instrumentation of the canyon mouth to examine SPM and water transport from the main basin into Elliott Bay.

4.2 Characteristics of the Duwamish River Plume in Elliott Bay

The Duwamish River plume, as expressed in both SPM and salinity, was always found on the north and east sides of Elliott Bay during the four surveys of this study (figs. 8 and 17). On the basis of dye studies with the Puget Sound hydraulic model, Winter (1977) postulated that for all combinations of tide and river flow, material entering Elliott Bay from the West Waterway would be swept past Duwamish Head. Under spring tides and low river flow (the August survey conditions) water from the East Waterway and the Seattle waterfront also moved clockwise around the bay's perimeter in the model. Although our data are severely limited in time, none of the surveys found evidence of SPM transport past Duwamish Head. Stations 7, 12, and 13 had generally the lowest SPM surface concentrations in the Bay. National Weather Service data show that winds during the August survey (measured at SeaTac Airport) were from the north or northwest. Winds were from the south on February 20, and from the north on February 22, when the plume moved away from the northern shore and into the center of the bay. During both days maximum concentrations were found in the east central portion of the bay.

Duwamish River flow and SPM concentration, along with the surface plume concentration, can be used to make some very rough estimates of the contribution of river SPM to the surface layer of inner (east of 122° 23'W) Elliott Bay during the summer and winter. On the basis of the SPM loading data, the mass of SPM in the upper 5 m of inner Elliott Bay in mid-August was $\sim 573 \times 10^5$ g. Subtracting the average mass of a 5-m layer in the SPM minimum zone yields a net SPM excess in the upper 5 m of $\sim 298 \times 10^5$ g resulting from phytoplankton production and river input. Phytoplankton contribution to this total can be roughly estimated at $\sim 84 \times 10^5$ g on the basis of a typical surface standing crop of 2 mg chlorophyll *a*/m^3 in August for Elliott Bay (Ebbesmeyer and Helseth, 1977), a factor of 30 for the ratio of carbon to chlorophyll *a* (Strickland, 1960), and a factor of 2.3 for the ratio of dry plankton to carbon (Sverdrup et al., 1942).

Sampling in the Duwamish River about 2 km upstream of the mouth gave an SPM concentration value of ~2.5 mg/l; the variability of this figure is unknown but is probably less than a factor of 2 (1.2-5 mg/l). Stream gages on the Duwamish gave an average flow of 8.24 m^3/s for the two weeks preceding the sampling, yielding an average SPM input of 20.6 g/s. At this rate, it would take approximately 12 days for the Duwamish to supply the 214×10^5 g of estimated river-derived SPM in the upper 5 m of inner Elliott Bay. Other runoff sources were not considered in this analysis.

Similar calculations for the February conditions reveal a substantially different situation. Net SPM in the upper 5 m was actually lower (110×10^5 g) because of lower concentrations outside the river plume and a higher average concentration in the SPM minimum zone. Standing crops of phytoplankton for March are typically <25% of the August value in Elliott Bay (Ebbesmeyer and Helseth, 1977) and February values are estimated to be similar. Phytoplankton contribution to surface SPM loadings is probably 20×10^5 g, leaving a net river contribution of $\sim 90 \times 10^5$ g for inner Elliott Bay.

River concentrations of SPM at the same location in the summer were much higher (7.4 mg/l), and river flow for the 2 weeks preceding sampling was

44 m^3/s, yielding an input rate of 325.4 g/s. At this rate, the river could supply the excess surface SPM in only 0.32 days, about 36 times quicker than in the summer.

Conclusions from this kind of sketchy data are tenuous, but it seems clear that the Duwamish River plume is the controlling factor of surface SPM distributions during the winter months. In situ biological production, which is 10 times higher in August than March in Elliott Bay (Ebbesmeyer, and Helseth, 1977), is much more influential during the summer. This conclusion is supported qualitatively by the areal plots (figs. 8 and 17) which show only minimal plume definition in August and a well-defined plume with steep areal gradients in February.

4.3 SPM Transport

Data from both moorings and station work suggest that there is significant exchange of SPM between the bottom waters of the Main Basin and Elliott Bay. The highest BNL concentrations in the bottom water were found at the mouth of the submarine canyon in Elliott Bay. SPM was added to the deep waters of Elliott Bay during both seasons by the net northeastward flow recorded at EB4, although an absence of SPM measurements at the north end of the bay make it impossible to determine whether there was a net gain or loss of SPM within Elliott Bay from this mechanism. The close association of SPM and salt flux at all mooring locations, however, strongly suggests SPM transport out of Elliott Bay at the northwest mooring site.

Transport in the inner bay varied dramatically between seasons. In summer, net transport at EB2 was downcanyon so addition of particulate material from the lower to the upper levels of the bay was probably minimal at this time. In winter, however, the pronounced upcanyon SPM transport suggests an active recycling of deep SPM, perhaps supplied from the Main Basin, to the upper levels of Elliott Bay via the axial submarine canyon. This transport may be a partial explanation of the increased SPM concentrations in the mid-depth minimum zone during the winter.

An important question bearing on the cycling of SPM within Elliott Bay is the balance between advective input and local resuspension as a source of particulate matter for the BNL. Although more sophisticated instrumentation would be required to answer this question conclusively, the available data seriously undermine support for local resuspension as a dominant contributor to the BNL.

The time series plots (figs. 23, 24, 25, and 27) indicate that salinity and attenuation variations are positively correlated in the bottom waters. On the other hand, little or no coherence can be seen between speed and attenuation variations in any of the records. Increases in salinity are nearly always associated with increases in attenuation, the same correspondence as that found in the CTD records (fig. 33). A section of the EB2 winter mooring record has been expanded to illustrate the coherence of the salinity and attenuation profiles (fig. 34). The record extends from February 9 through February 16 and encompasses the point in the record where the subtidal flow (35-h filter) changed from steady downcanyon (~298°) to steady upcanyon (~110°) on February 12. During the downcanyon flow, salinity values showed

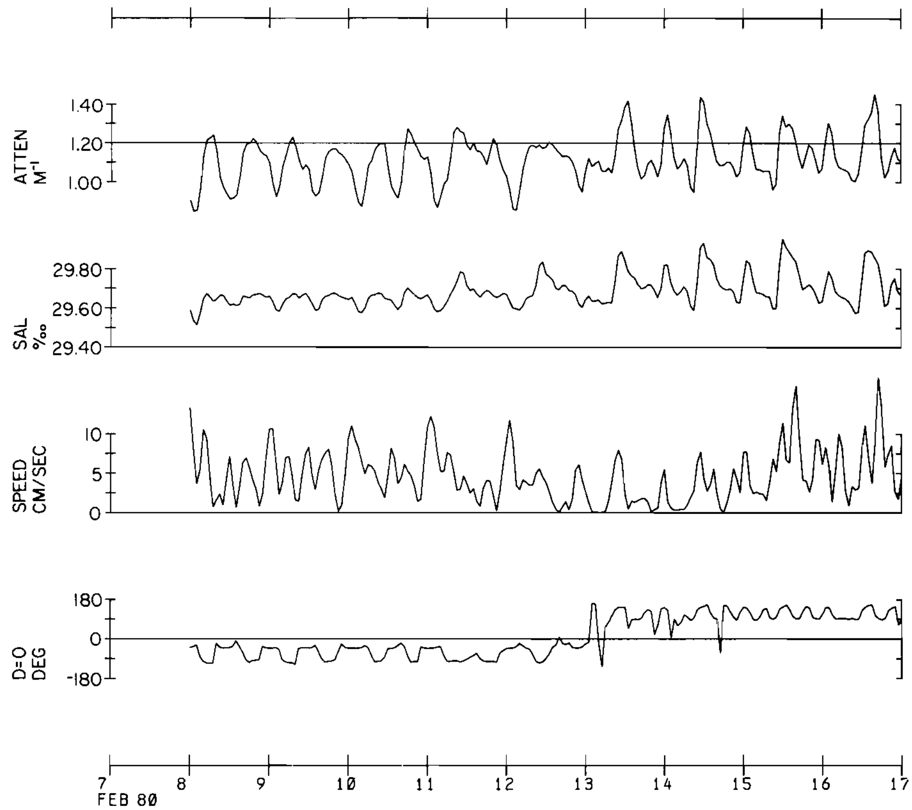


Figure 34.--Expanded record for EB2, 90-m depth, winter deployment. Note the close correspondence between salinity and attenuation variability.

small regular semidiurnal variations between 29.59°/₀₀ and 29.67°/₀₀. Attenuation varied similarly between 0.9 m^{-1} and ~1.25 m^{-1}, with minima and maxima occurring exactly at the time of salinity minima and maxima. After February 12, however, both the salinity and attenuation records became more peaked and exhibited two distinct and unequal cycles each day. Salinity maxima increased to more than 29.9°/₀₀ and attenuation maxima to more than 1.4 m^{-1}. Coherence between the two records is remarkable, extending even to small features on the scale of a few hours. This coherence is typical of the entire 29-day record.

Coherence between the accompanying speed record and the salinity and attenuation records is less straightforward. The greatest peak speed each day prior to February 13 occurs about 2 hours before the daily salinity/attenuation minimum and indicates downcanyon (298°) advection of relatively clear, low salinity water. After February 13, peak speeds occur with salinity/attenuation maximums, suggesting upcanyon (110°) advection of more turbid, high-salinity water from the deeper portions of Elliott Bay.

Although the winter EB2 mooring provides the best example, all the moorings exhibited higher correlations between attenuation and salinity than between attenuation and speed (table 7). In fact, all four moorings showed a negative correlation between speed and attenuation, casting serious doubt on the importance of resuspension in Elliott Bay areas typical of the mooring locations. Note particularly, however, that no mooring data were taken at the

Table 7.--Comparison of salinity-vs.-attenuation and speed-vs.-attenuation correlation coefficients

Mooring/Season	Coefficient of salinity vs. attenuation (r)	Coefficient of speed vs. attenuation (r)
EB2, 92-m depth/summer	0.638	-0.073
EB2, 90-m depth/summer	0.633	-0.122
EB4, 132-m depth/summer	0.687	-0.115
EB2, 130-m depth/winter	0.217	-0.131

mouth of the Elliott Bay Canyon (approximately station 11) where both the most turbid and most variable bottom water were found.

The lack of significant positive correlation between current speed and turbidity is not surprising when the range of observed speeds is considered. Speeds greater than 23.5 cm/s were never recorded at either EB2 or EB4, and typical daily peak speeds were generally ~15 cm/s (figs. 23, 24, 25, and 27). Lonsdale and Southard (1974), for example, found that even for Pacific red-clay material with a water content of 84% and the bed roughened with manganese nodules, a speed of ~12 cm/s, 1 m above the bed, was required to initiate erosion. All measurements in Elliott Bay were $\geq$10 m above the bed, implying that observed current speeds at the mooring sites were only rarely capable of significant erosion.

Vertical flux rates measured by near-bottom sediment traps averaged 31 g/m^2/day. Assuming an average sediment density of 0.6 g/cm^3, this mass flux translates to ~18.8 mm/yr deposition rate, similar to the values of 10.3 and 8.1 mm/yr calculated by Schell et al. (1977) from ^{210}Pb measurements on two cores from outer Elliott Bay. If these samples are typical of the yearly cycle, it implies that only minimal recycling of the bottom sediment takes place through resuspension, since repeated resuspension would result in the apparent sedimentation rate observed by the sediment traps being several times greater than the net accumulation rate measured in the bottom sediments. Thus the BNL must be a reasonably persistant feature throughout Elliott Bay, and variations must stem more from lateral water movements than from local resuspension. These conclusions are in agreement with the long-term picture from the moored transmissometers, which almost never showed variations of more than a factor of 2 in near-bottom attenuation values.

Flux rates at 30 m were only 2% to 21% of those observed at depth. These figures indicate that the majority of the vertical flux originated below 30 m, particularly in the outer bay in the summer. Typical Elliott Bay August productivity is ~1 g C/m^2/day (Ebbesmeyer and Helseth, 1977), which amounts to ~2.3 g dry weight/m^2/day. The August 30 flux at EB4 was ~0.7 g/m^2/day and is apparently a good estimate of the amount of material that escapes the surface layer in the outer bay during summer. Most of the bottom sedimentation occurring at EB2 and EB4, and by extension in most of Elliott Bay, must thus be a result of steady fallout from within the BNL. The BNL may have many sediment sources, but this study suggests that a dominant one is the deep water of the Main Basin, where bottom resuspension is active (Baker, 1982).

5. ACKNOWLEDGMENTS

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