NOAA Technical Memorandum OMPA-26

SUSPENDED PARTICULATE MATTER IN COMMENCEMENT BAY

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UNITED STATES DEPARTMENT OF COMMERCE
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Office of Marine Pollution Assessment
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Contents

Abstract

The distribution and transport of suspended particulate matter (SPM) in Commencement Bay, an embayment of Puget Sound, was surveyed during September 9-11, 1980; November 12-14, 1980; and March 23-27, 1981. During each survey the SPM distribution consisted of: (1) a thin (<5 m) surface layer of variable SPM concentration; (2) a thick mid-depth low turbidity zone containing one or more high-turbidity layers extending seaward from the head of the Bay; and (3) a benthic turbidity layer of high variable concentration and thickness. The total mass of SPM in the Bay averaged 19.7 x 10^8g and varied by <10 percent between surveys. Scatter plots of salinity versus the SPM concentration in the surface water had the highest correlation during high runoff periods (r = -0.86 in March and November, -0.59 in September). Correlations of these parameters in the bottom waters were uniformly poor.

Horizontal transport of SPM was measured in the near-bottom waters at two stations with current meter/transmissometer combinations deployed from September 10 to November 13, 1980. Bottom-water flow was consistently clockwise with mean speeds ~5.4 cm/sec and mean attenuation values ~2.4/m. SPM transport averaged ~12.7 $\mu g/cm^2/sec$ at each station. Vertical particle flux, measured at the same stations from March 25 to May 4, 1981, averaged ~5.5 $g/m^2/day$ at 25 m and >80 $g/m^2/day$ in the bottom waters.

Transport of SPM in the surface layer was controlled by the Puyallup River plume and a weak counterclockwise circulation. Mid-depth turbidity layers extending seaward from the head of the Bay were common and appeared to be generated by bottom erosion near the river mouth. Transport in the bottom water was governed by daily erosion/deposition cycles which added suspended particles to a strong and steady clockwise circulation.

1. INTRODUCTION

1.1 Research Program

The research presented in this report is a companion study to a similar investigation of the distribution and transport of suspended particulate matter (SPM) in Elliott Bay (Baker, 1982), another Puget Sound embayment. The current study, as well as the previous Elliott Bay study, is part of a general effort of the Office of Marine Pollution Assessment of NOAA to characterize the physical transport processes and the 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 Commencement Bay (Cannon and Grigsby, 1982).

1.2 Research Objectives

The research objectives of this project are enumerated below:

1) Describe the SPM distribution in Commencement Bay during typical summer (dry) and winter (wet) sampling periods.
2) Estimate the total SPM loading in Commencement Bay at each sampling time.
3) Characterize the SPM in Commencement Bay in terms of organic matter content.
4) Measure the vertical and horizontal flux of SPM at specific mooring locations.

1.3 Study Area

Commencement Bay is a small embayment (about 23 km^2 area) at the southern end of the Main Basin of Puget Sound (Fig. 1). It is surrounded by residential and industrial sections of the city of Tacoma. No major bathymetric features are present. Bottom depths steadily increase away from the southeast side of the Bay and do not exceed 170 m. The principal source of freshwater is the Puyallup River which has a yearly average discharge rate of 96 m^3/sec at Puyallup, Washington (10.5 km upstream from Commencement Bay; average of 65 years data; U.S. Geological Survey Water-Data Report WA-79-1). The drainage area for the Puyallup River watershed is 2455 km^2 of both mountainous and lowland areas.

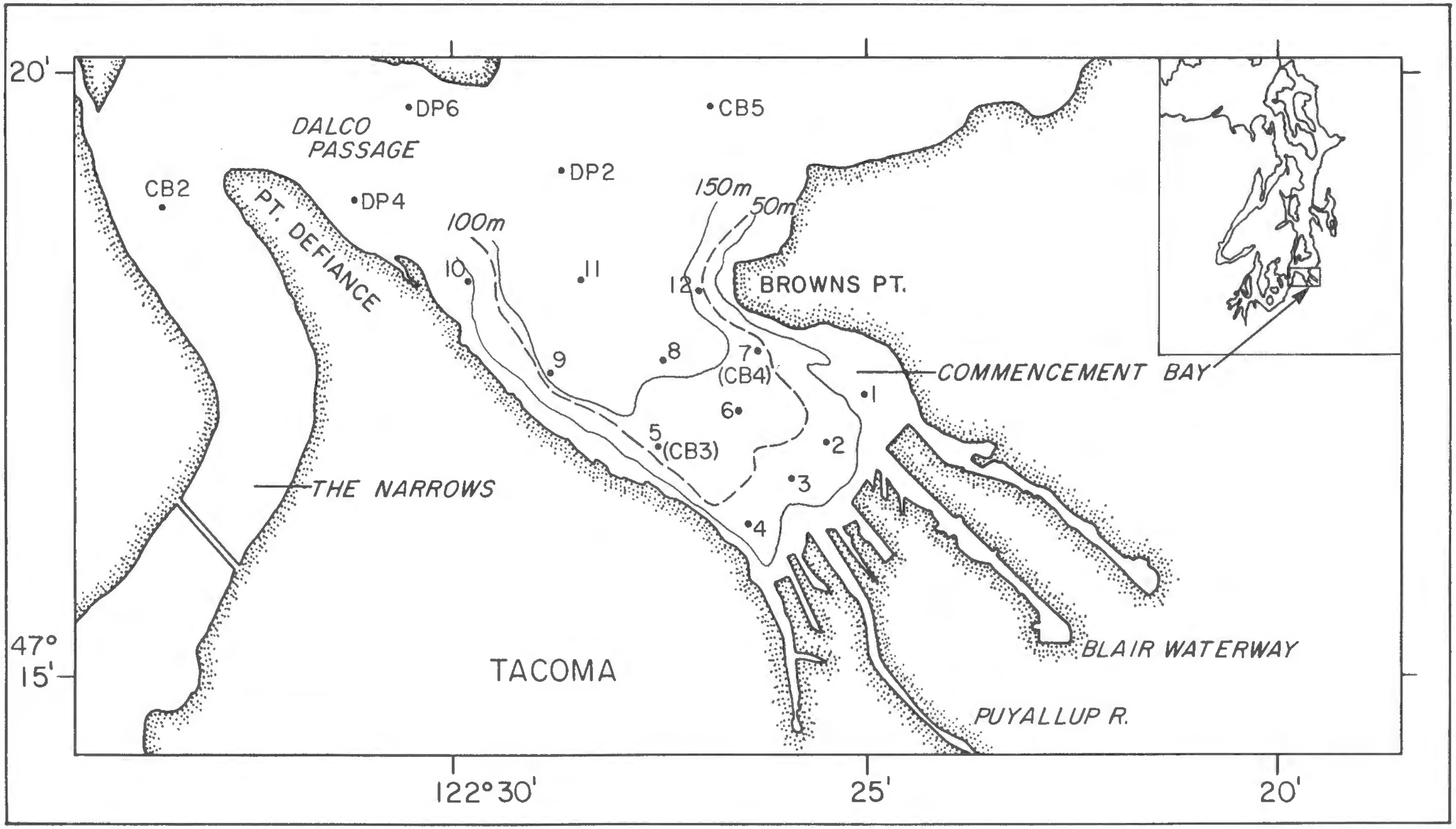


Figure 1. Map of Commencement Bay showing station locations, mooring locations, bathymetry and the mouth of the Puyallup River. Contour interval is 100 m.

1.4 Methods

1.4.1 Field Methods

The station grid for Commencement Bay (Fig. 1) was occupied on one day during each of three cruises: September 9-11, 1980; November 12-14, 1980; and March 23-27, 1981. The sampling at each station consisted of a CTD/transmissometer cast, followed by a hydrocast with bottles at the surface, the bottom, and one or two intermediate depths. The time of station occupation relative to phase of the tidal cycle is shown in Fig. 2. In addition to the station grid, a 25-hour anchored time series was obtained at the mouth of the Puyallup River in November and March to gauge the variability of river input of particles.

Gravimetric analysis was done on samples from selected stations and depths. Water samples were filtered through pre-weighed 0.4 μm polycarbonate membrane filters, rinsed with particle-free distilled water, air dried, and reweighed for use in comparing attenuation values to suspended matter concentration. The light transmission profiles from each station are the primary source of data used to determine suspended particulate matter (SPM) distributions and loading in Commencement Bay. The conversion from percent transmission values to concentration (mg/ℓ) is fully explained in a previous report from similar work in Elliott Bay (Baker, 1982), another Puget Sound embayment. Comparable curves relating light attenuation [-ln (light transmission)/transmissometer path length] for Commencement Bay are given in Fig. 3. Correlations were poor in this study compared to other areas of Puget Sound (Baker, 1982). Because of the sampling equipment available, samples of SPM could not be collected on the same casts as the CTD/transmissometer data. Steep spatial and temporal gradients in the SPM distributions made it very difficult to sample the same water parcel with both transmissometer and water bottle, thus creating a poor data set for determining the true correlation between optical and gravimetric estimates of SPM concentrations.

Transmissometers and sediment traps were moored at stations CB3 and CB4 on two sets of current meter arrays set out by the Coastal Physics Group of the Pacific Marine Environmental Laboratory. These locations correspond to station numbers 5 and 7, respectively, in the Commencement Bay grid (Fig. 1). The first set of moorings was deployed during the September cruise and was recovered during the November cruise. The second set of moorings was deployed during the cruise in March and was partially recovered on June 3, 1981. Unfortunately, the mooring at CB3 did not release properly and could not be recovered until late October, 1981. The mooring had been damaged and only the uppermost current meter/transmissometer and sediment trap were recovered.

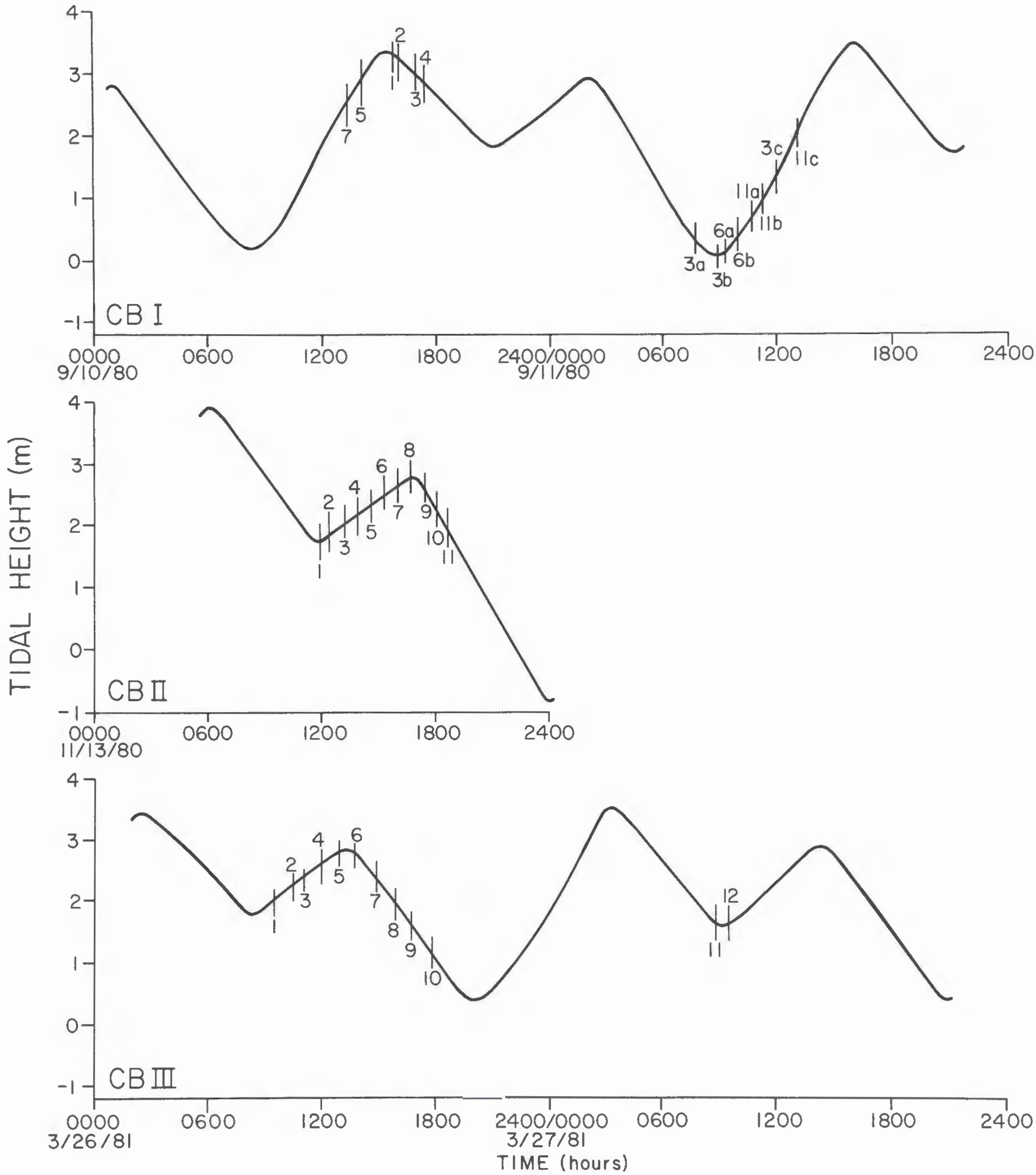


Figure 2. Local time of station sampling relative to Commencement Bay tidal height.

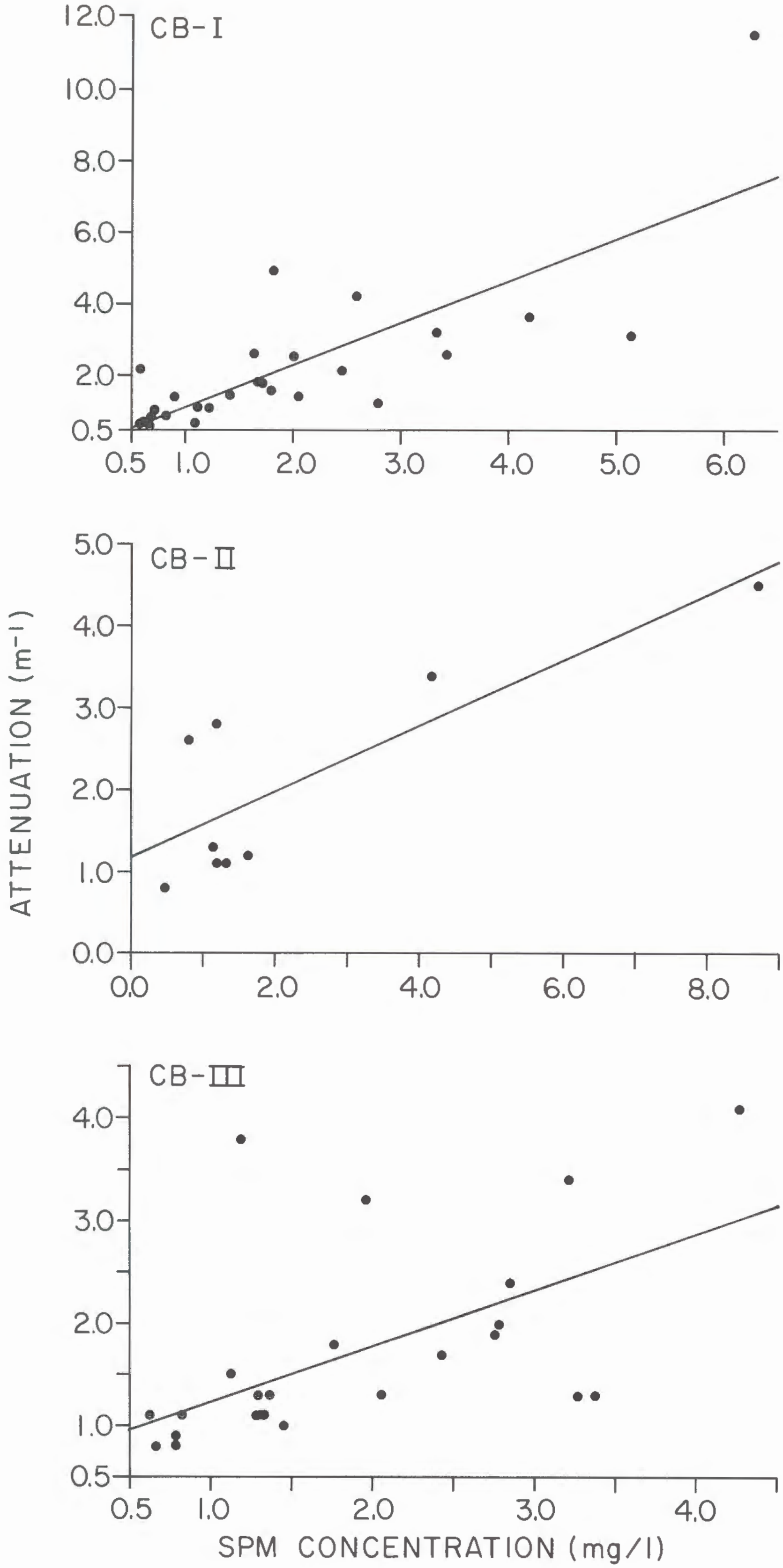


Figure 3. Transmissometer calibration curves for (top) September, 1980, (middle) November, 1980, and (bottom) March, 1981.

The transmissometers were directly coupled to the current meters so that transmission readings were recorded at the same time as current velocity, salinity, and temperature data. The sediment traps used on these moorings were sequentially sampling traps which have recently been designed and built by the Engineering Studies Group of PMEL. The traps have a rotating sample chamber which collects 10 separate samples during each deployment. The traps set out in the first mooring series failed to function properly. The traps that were recovered from the second set of arrays each yielded 10 consecutive 4-day samples.

1.4.2 Laboratory Methods

Sediment trap samples were split upon recovery into fractions for trace metal, organic compound, and particulate matter analysis. Ten milliliters of the particulate matter sample were taken for microscopic analysis. The remainder of the sample was then screened for organisms (>750 µm) and divided into a "major fraction" and a "minor fraction." All the material of the major fraction was collected onto 0.4 µm pore size polycarbonate filters, dried, and weighed to calculate total mass and average accumulation rates for each cylinder. Aliquots were taken from the "minor fraction" for pigment and particle size analysis.

The concentration of organic matter in the samples was determined by weight difference after treating each sample with a 10 percent solution of H_2O_2 at 60°C for 24 hours (Baker, 1982).

2. RESULTS

The pictorial representations of SPM distributions presented in Figures 4-14 must be interpreted with care. Although the figures purport to present synoptic data, that is clearly not the case. Areal distributions constructed of data collected over a wide portion of the tidal cycle properly represent only the conditions that existed at each station at the sampling time, although the pattern which evolves may well typify the regional distribution during the sampling period.

Vertical cross-sections are constructed of the actual attenuation profiles recorded at each station. The vertical line marking the station position also represents an attenuation value of 1.5/m on each profile; scale marks at 1 and 2/m are given at the top of each profile. Selected isopycnals are also plotted on each cross-section to illustrate the coherence between certain particle maxima and density surfaces.

2.1 Suspended Particulate Matter Distributions - September, 1980

Surface attenuation values for Commencement Bay during September were mostly greater than 2.0/m (Fig. 4). The highest concentration of SPM was found in the area surrounding stations 1-3 with the greatest attenuation value at station 3, off the mouth of the Puyallup River (5.7/m). On the day that the station grid was sampled, the higher SPM concentrations appeared to be confined to the north-easterly corner of the bay, not extending as far as the line of stations at mid-bay. Surface salinity values increased with distance from the mouth of the Puyallup River (Fig. 4).

Bottom attenuation values (Fig. 5) were generally lower than surface values, mostly falling within 1.0-1.6/m. The highest values were seen at station 2 rather than station 3 as at the surface, and at station 5 with an exceptionally high value of 3.5/m. Attenuation decreased to below 1.0/m near Pt. Defiance. Bottom salinity values ranged between 30.2 °/₀₀ and 30.6 °/₀₀ (Fig. 5). The lowest salinity water was at stations 1-4.

The vertical distribution of SPM during CBI (Fig. 6) showed several characteristic features. The high inner bay surface concentrations extended no deeper than the top two or three meters of the water column. Vertical profiles along the transect between stations 1 and 4 were highly variable. Deeper stations (5, 6, 7, and 11) were more uniform, commonly showing a prominent mid-depth turbidity maximum as well as a bottom nepheloid layer (BNL) of varying thickness and intensity. (Note that in the mid-bay cross-section, station 6 was occupied on September 11, whereas stations 5 and 7 were occupied on September 10.) An along-Bay transect from September 11 suggests that the mid-depth turbidity layer originates at the head of the Bay and moves seaward between the 23.0 and 23.2 σ_t isopycnals. It is interesting to note that no comparable mid-water features were observed in a similar study of Elliott Bay (Baker, 1982).

2.2 Suspended Particulate Matter Distributions - November, 1980

Surface attenuation values for November were generally lower than those in September with most of the values falling in the range of 1.0-2.0/m (Fig. 7). Values were highest at stations 2 and 3 (4.5/m and 3.9/m, respectively) and decreased to below 2.0/m before reaching the line of stations at mid-bay. The lowest values were along the south shore towards Pt. Defiance as in September. The region of high SPM concentration was centered more along the axis of the bay in November than in September. Surface salinity followed a similar pattern (Fig. 7). A lens of water with high attenuation and low salinity was observed at station 8.

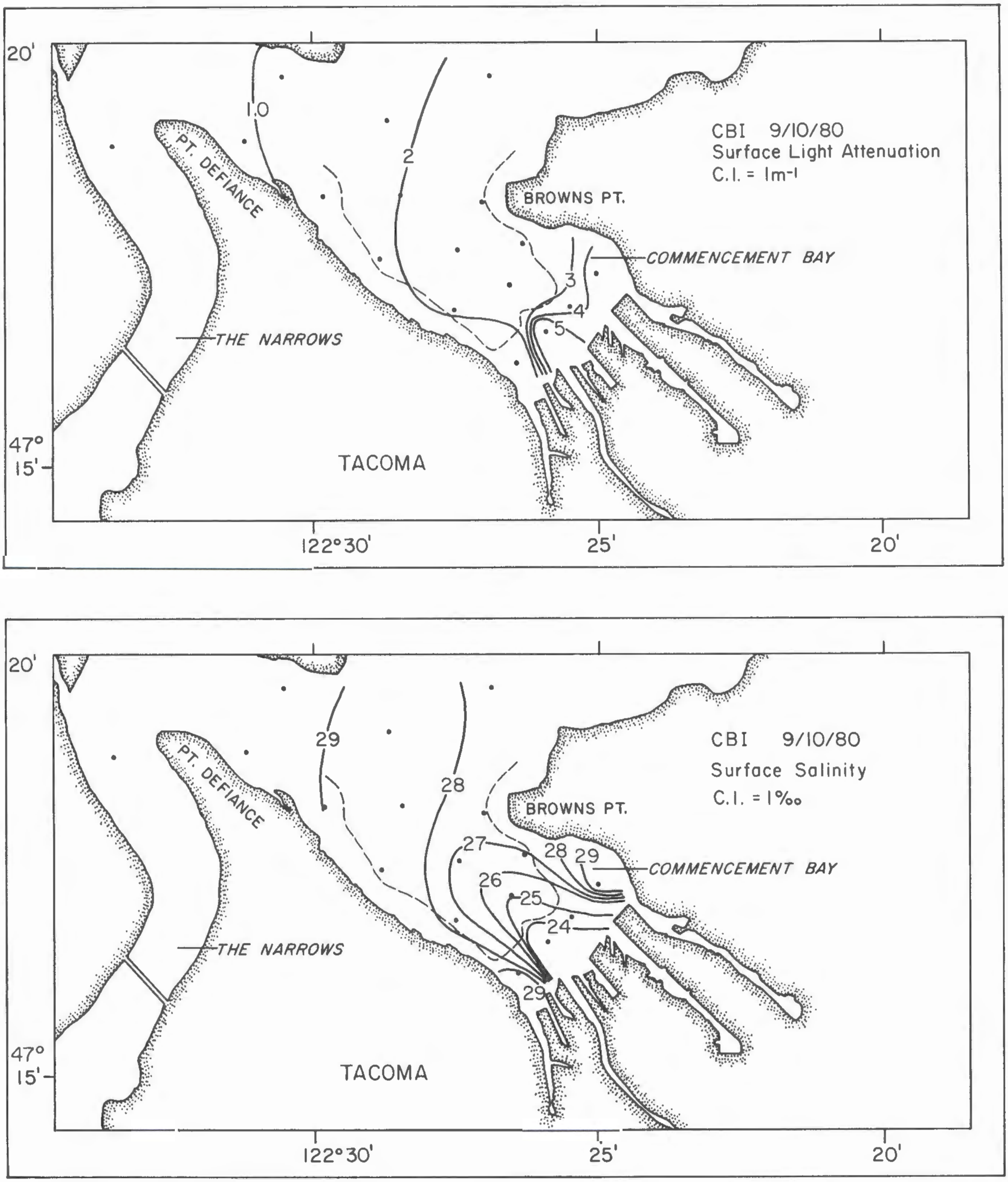


Figure 4. Areal maps of light attenuation and salinity at the surface during September, 1980. Contour interval is 1.0/m for attenuation, and 1.0 ‰ for salinity.

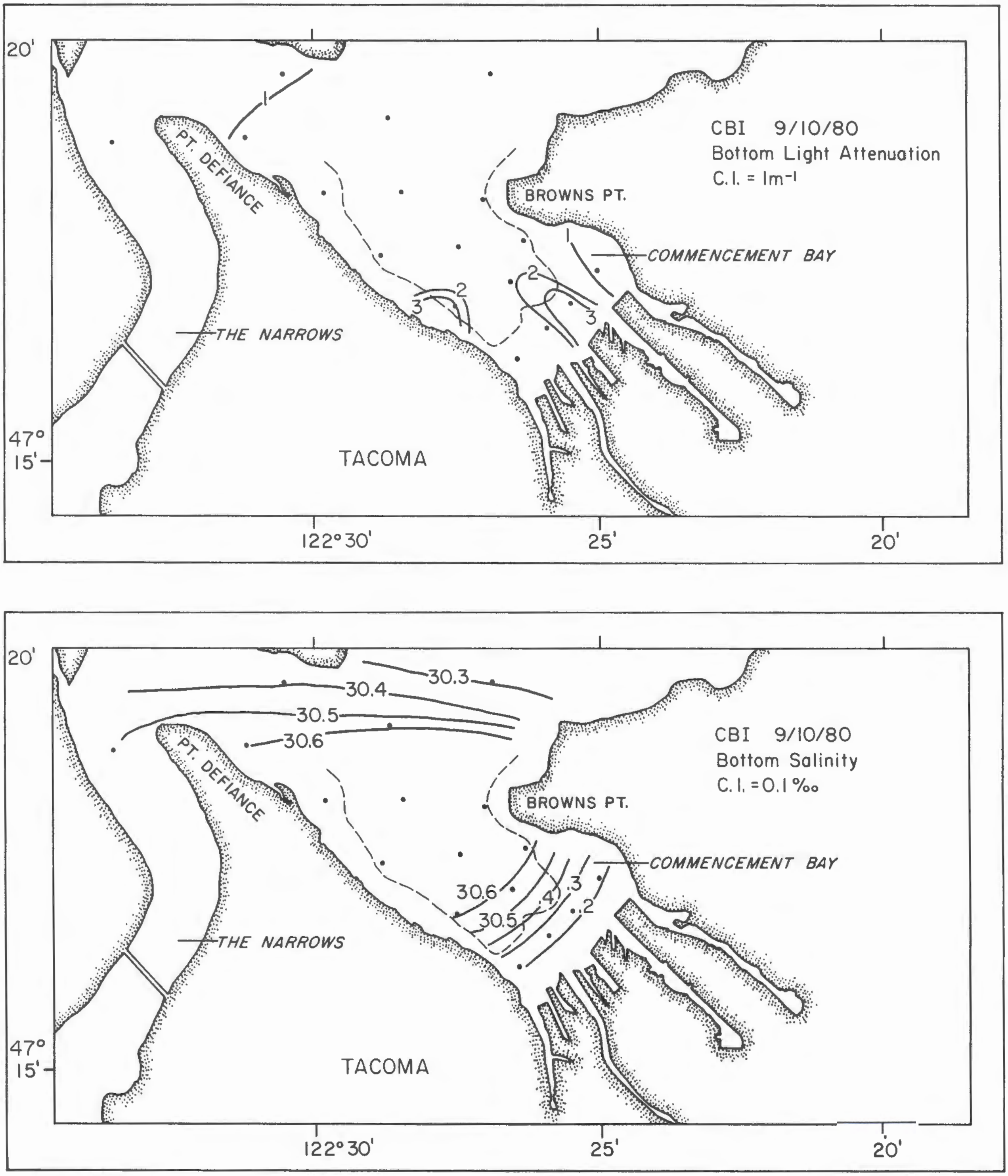


Figure 5. Areal maps of light attenuation and salinity 5 m above bottom during September, 1980. Contour interval is 1.0/m for attenuation, and 0.1 °/oo for salinity.

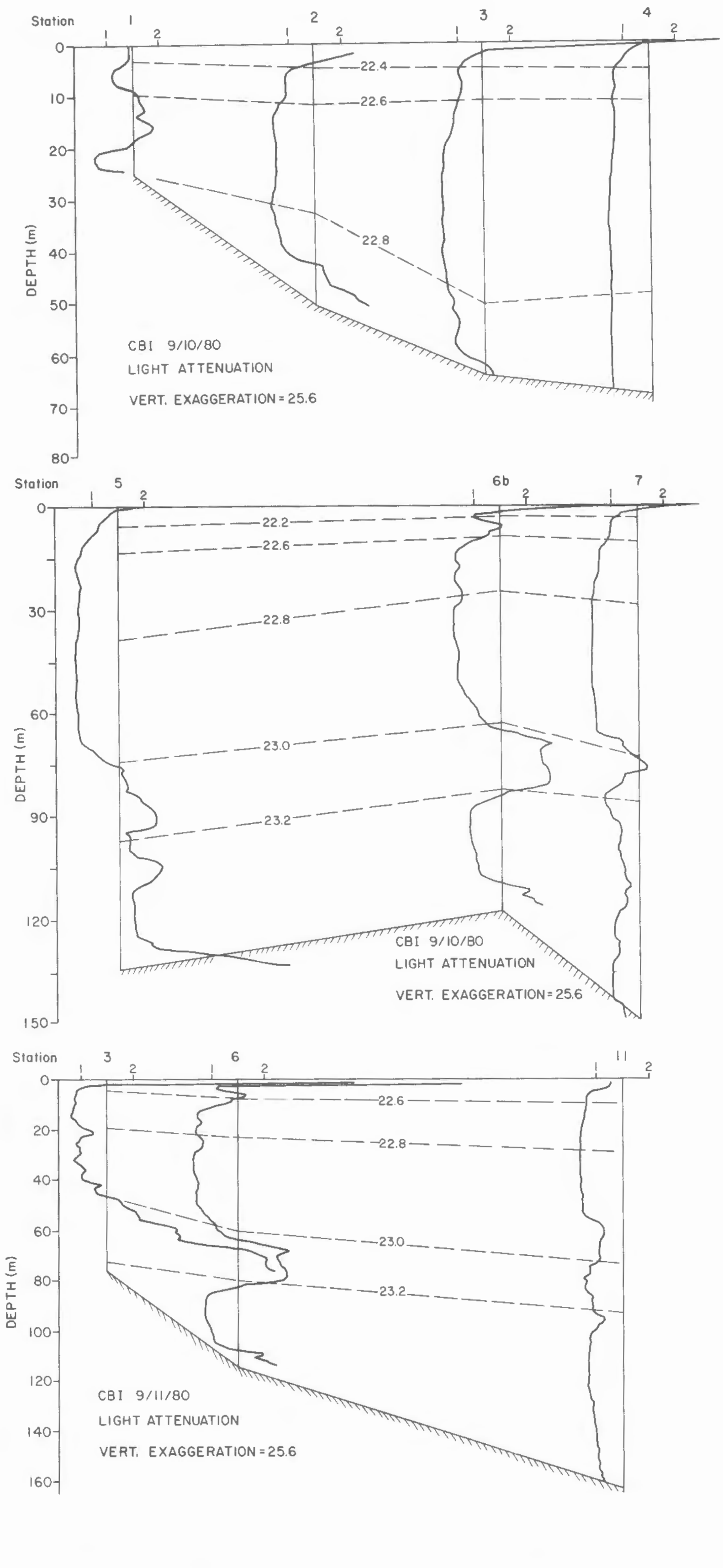
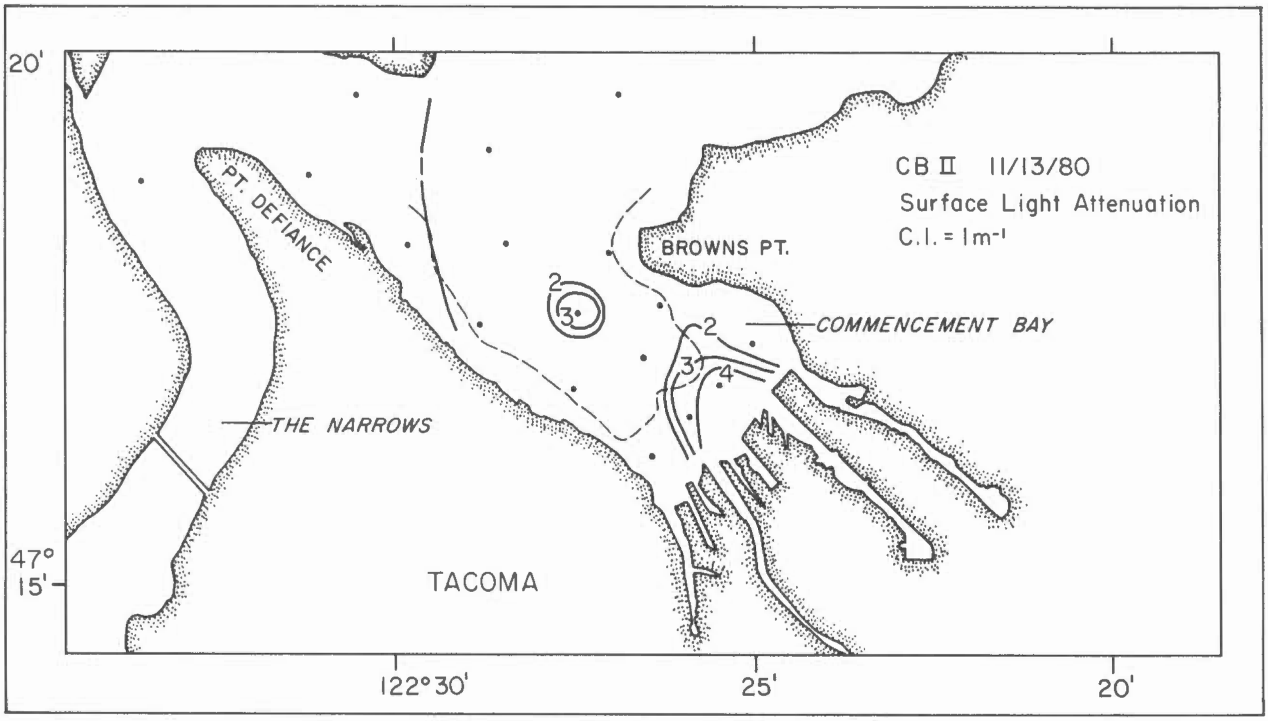


Figure 6. Light attenuation profiles from station transects during cruise CBI, September, 1980.



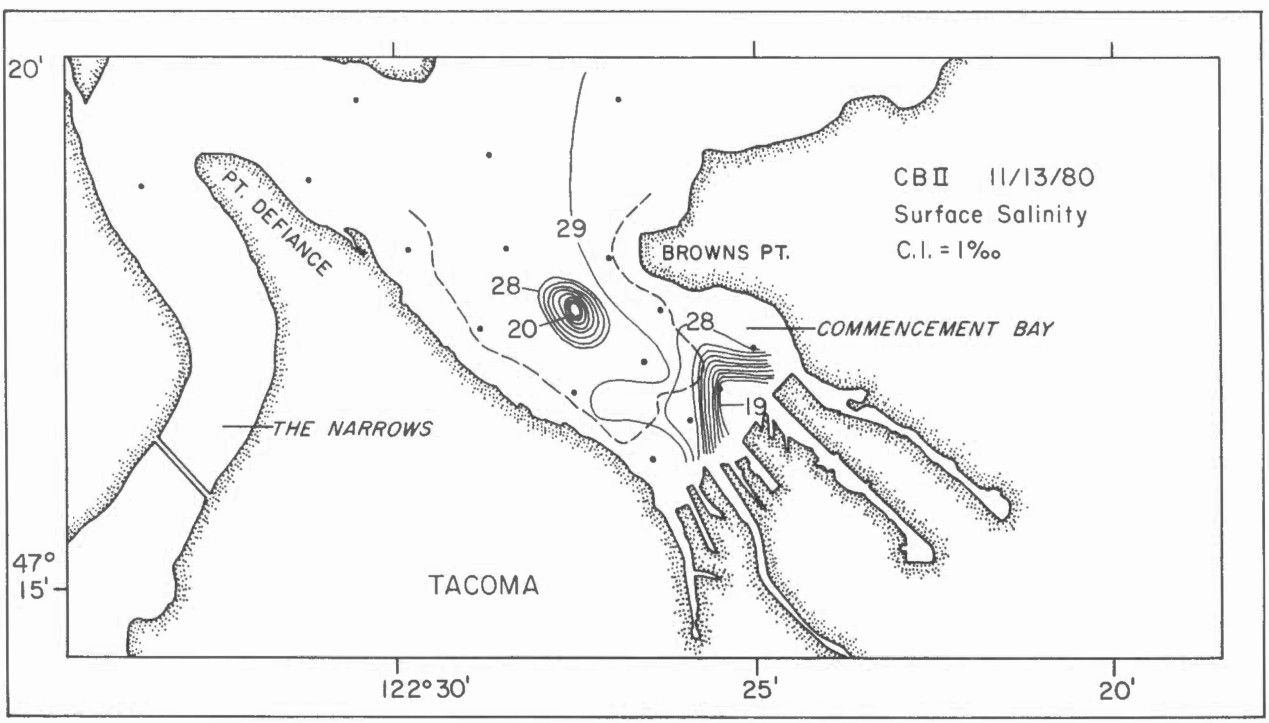


Figure 7. Areal maps of light attenuation and salinity at the surface during November, 1980. Contour interval is 1.0/m for attenuation, and 1.0 °/₀₀ for salinity.

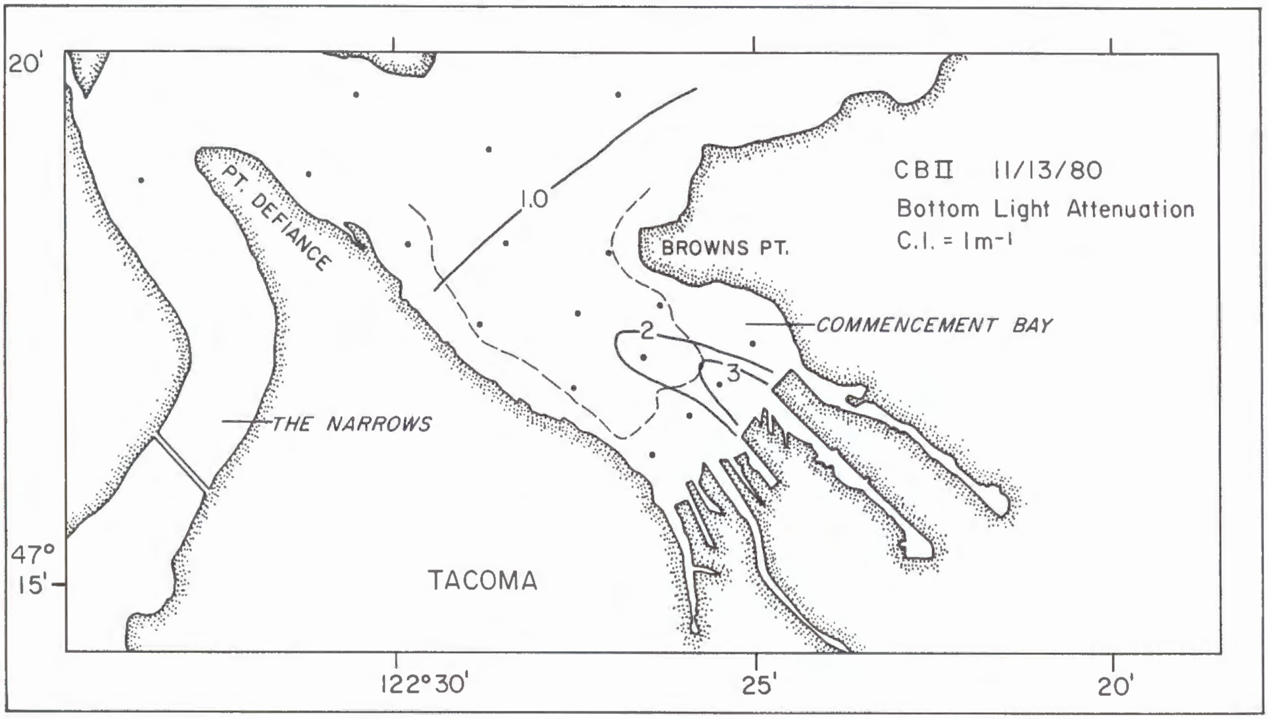
Bottom attenuation values were similar in distribution and intensity to those seen in September (Fig. 8). High attenuation values (>2.0/m) were seen at stations 2 and 6, but not at station 5. Low values (<1.0/m) were observed much closer to the mouth of the Bay than in September and at station CB5 in the main basin to the north of Commencement Bay. Bottom salinity values were nearly uniform with a mean of 30.7 $^o/_{oo}$ (Fig. 8).

The vertical distribution of SPM was somewhat different along the station 1-4 transect (Fig. 9) in November from what had been observed in September. The surface layer, with high attenuation values, was again very shallow and confined to the area around stations 2 and 3, but the wide mid-depth minimum layer seen in September was divided into an upper and lower portion by an intermediate layer of higher SPM concentrations. This intermediate maximum may have been associated with the BNL at station 1. The lower SPM minimum zone had the lowest values at station 2. Station 2 also had the thickest and most intense BNL, beginning ~20 m above the bottom and reaching a value of 3.4/m.

Surface values were relatively uniform across the mid-bay line of stations (Fig. 9) on the day of sampling. The mid-depth minimum was centered at about 25 m, somewhat deeper than along the inshore line. Assorted maxima and minima occurred at each of these stations below about 50 m. Three fairly intense peaks (2.2/m, 2.8/m, and 1.8/m) and the most turbid BNL of the transect (3.0/m) were seen at station 6. The highest concentration of SPM at station 5 was about 20 m above the bottom with attenuation values greater than 2.2/m.

The transect along the axis of the bay, stations 3, 6, 8, and 11, showed surface concentrations of SPM to be greatest at stations 3 and 8. The mid-water maximums were most intense at station 6. Similar features of less intensity and complexity were also observed at stations 3, 8, and 11. The upper and lower minimums were wider and more distinct at station 8. Station 11, near the mouth of the Bay, showed relatively clear water throughout the water column. Both the surface and mid-depth features in this transect strongly suggest the action of tidal processes that create pulses of turbid water in the nearshore zone and send these turbid water parcels seaward through the Bay along particular isopycnal surfaces.

Surface attenuation values were variable with time ranging from a low of 1.2/m to a high of 14.1/m over the 25-hour time series at the mouth of the Puyallup River (Fig. 10). The flood tides were characterized by attenuation values <1.0/m throughout the water column below ~5 m. Ebb tides were characterized by a BNL with attenuation values >1.5/m, as well as isolated patches of turbid water (>1.5/m) in the water column. The tidal periodicity



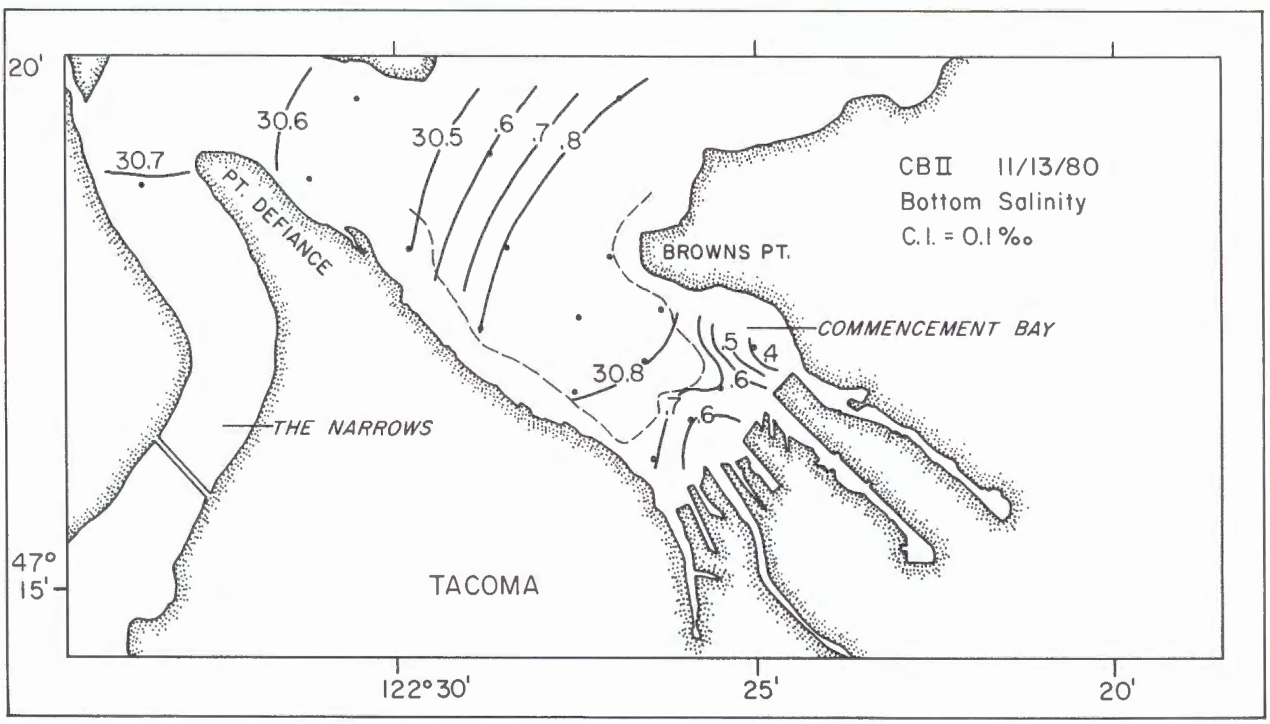


Figure 8. Areal maps of light attenuation and salinity 5 m above bottom during November, 1980. Contour interval is 1.0/m for attenuation, and 0.1 $^{o}/_{oo}$ for salinity.

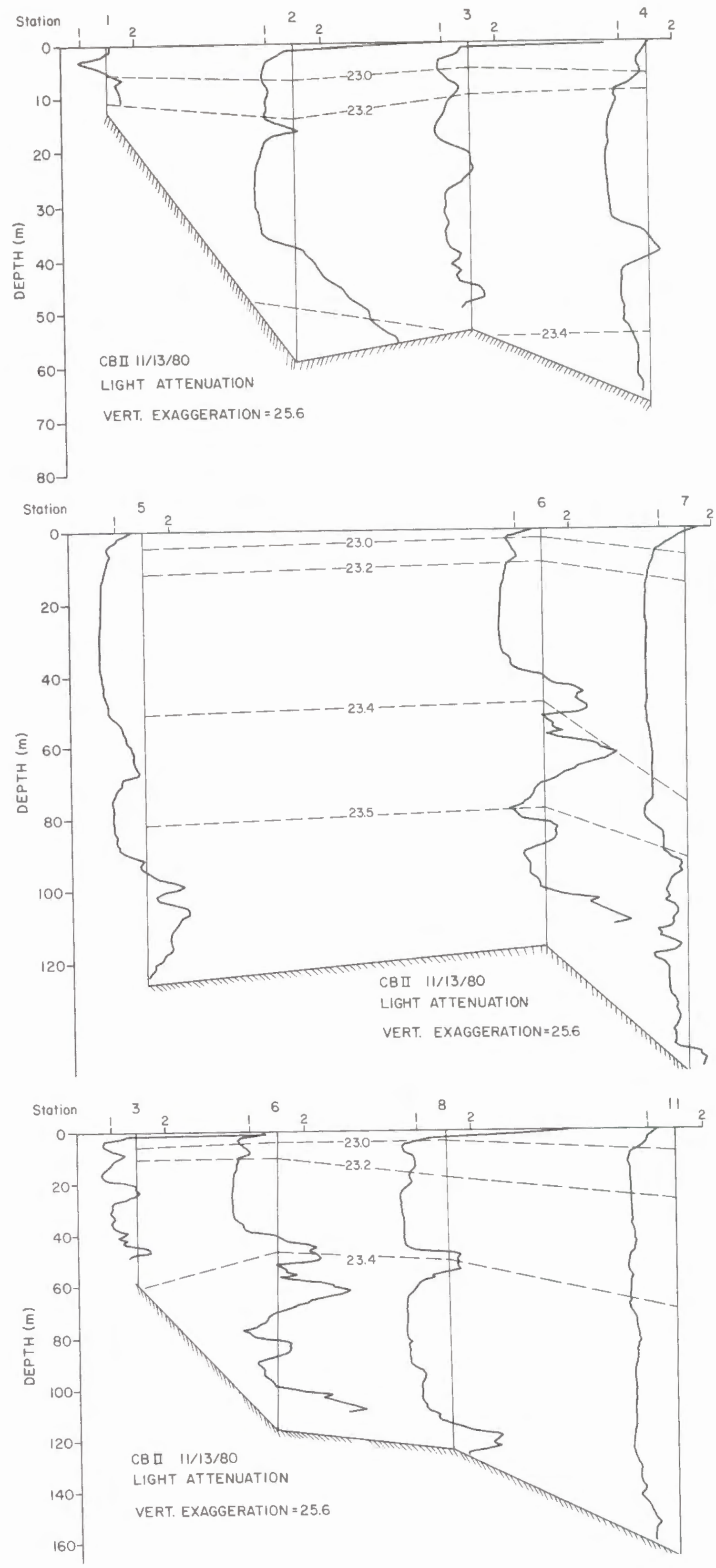


Figure 9. Light attenuation profiles from station transects during cruise CBII, November, 1980. Scale in 1/m is given at the top of each profile.

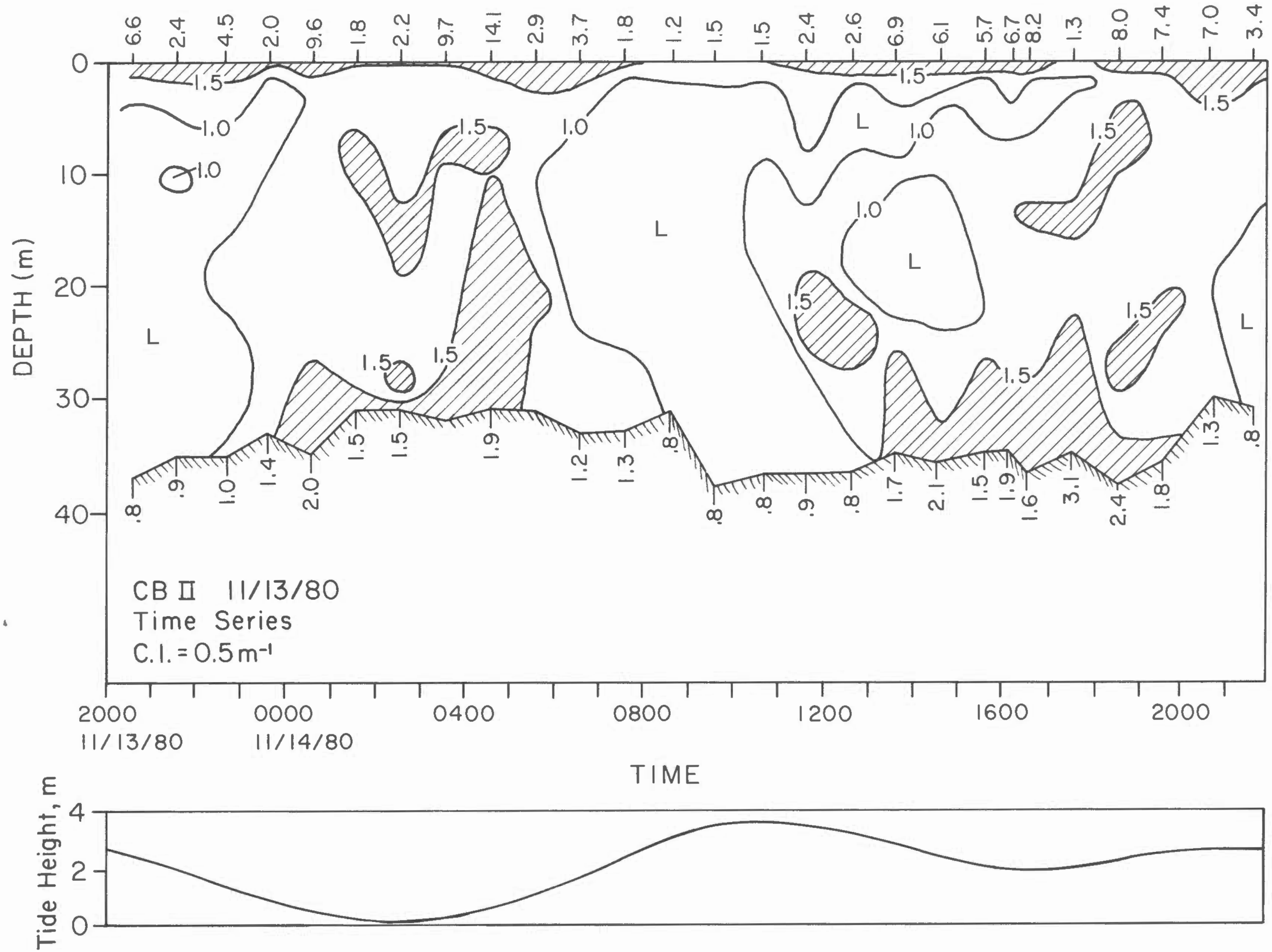


Figure 10. Puyallup River time series light attenuation data, November, 1980. Attenuation values >1.5 are shaded. Values at the surface and bottom of each cast are also shown.

of the BNL at the head of the Bay may be related to the mid-depth turbid layers seen elsewhere in the Bay (Figs. 6, 9).

2.3 Suspended Particulate Matter Distributions - March, 1981

Surface attenuation values observed in March (Fig. 11) were very similar to those seen in November. High values were observed at stations 2 and 3 decreasing to below 2.0/m by the mid-bay line of stations. A patch of high attenuation, low salinity surface water similar to the one seen at station 8 in November was observed near station 7 at this time. Attenuation values varied little from the previous cruise. Salinity values, however, were slightly lower than they had been in November (Fig. 7).

The bottom SPM distribution (Fig. 12) found in March was very similar to what was seen during each of the two previous cruises. The highest attenuation value was again at station 2 (3.2/m). Stations 4 and 8 were isolated high spots where the measured attenuation was greater than 2.0/m. Low values occurred towards Dalco Passage, as in September. The bottom salinity was nearly uniform again but averaged about 1-1.5‰ lower than in November, as at the surface.

The region of high surface SPM concentration along the station 1-4 transect (Fig. 13) was not significantly different in width or depth from the previous cruises. Compared to September, the region of minimum concentration along this transect was similar at station 1, occurring near the bottom, but somewhat narrower and shallower at stations 2, 3, and 4. The BNL was absent at station 1, strongest at stations 2 and 4, and somewhat weaker at station 3.

The subsurface maxima and minima observed along the station 5-7 transect were much less intense than in either September or November. The minimum layer just below the surface layer was narrower and shallower at mid-bay than it was at the innermost stations. There was only one broad maximum (~1.2/m) between 45-85 m, and BNL concentrations did not rise above 1.6/m.

The SPM distribution along the axis of the Bay was similar to what was seen in September. High surface concentrations did not extend as far as station 6. An intermediate maximum extended through stations 6 and 8 at about the level of the BNL at station 3. The intensity of this layer was much less than it had been in September (1.2/m in March compared to 2.4/m in September). The BNL was the strongest around station 8.

Surface values during the 25-hour time series varied much less in March than in November (Fig. 14). The highest value for

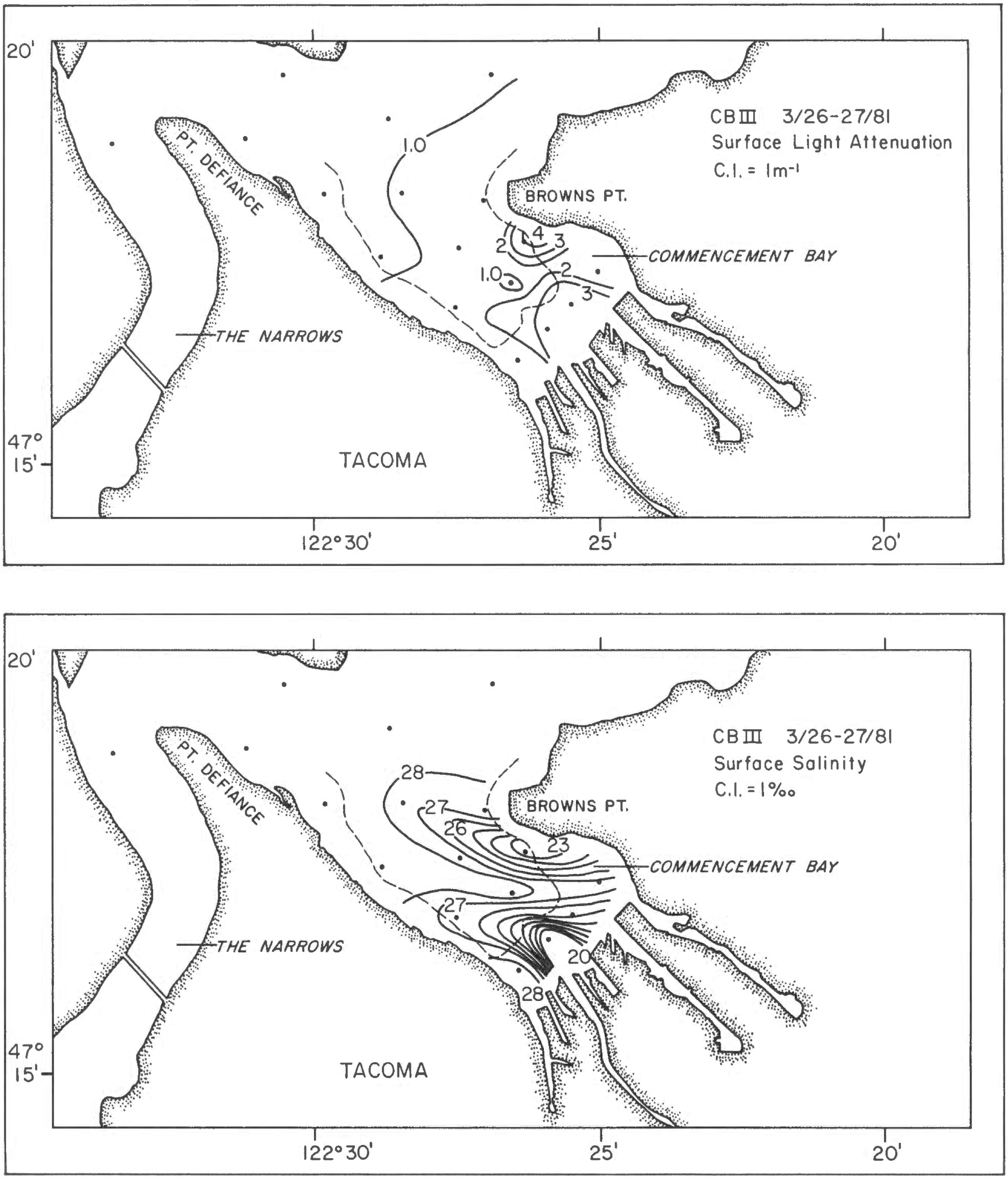
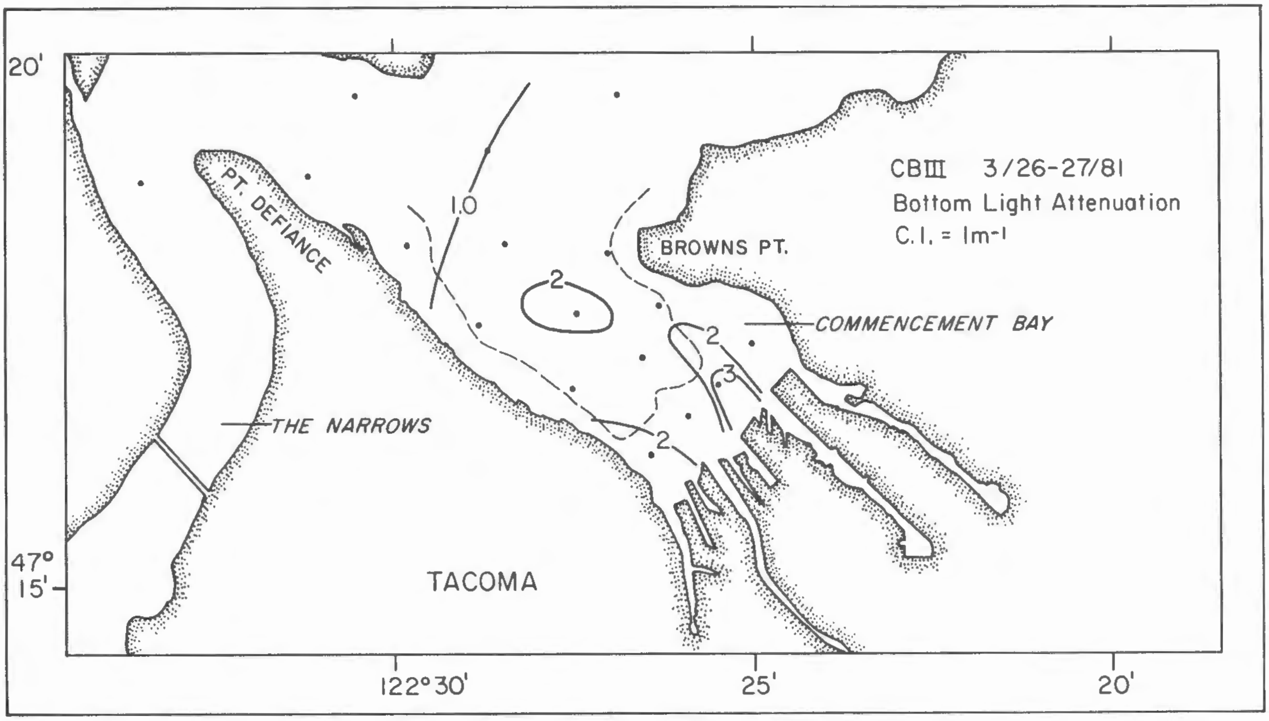


Figure 11. Areal maps of light attenuation and salinity at the surface during March, 1981. Contour interval is 1.0/m for attenuation, and 1.0 ‰ for salinity.



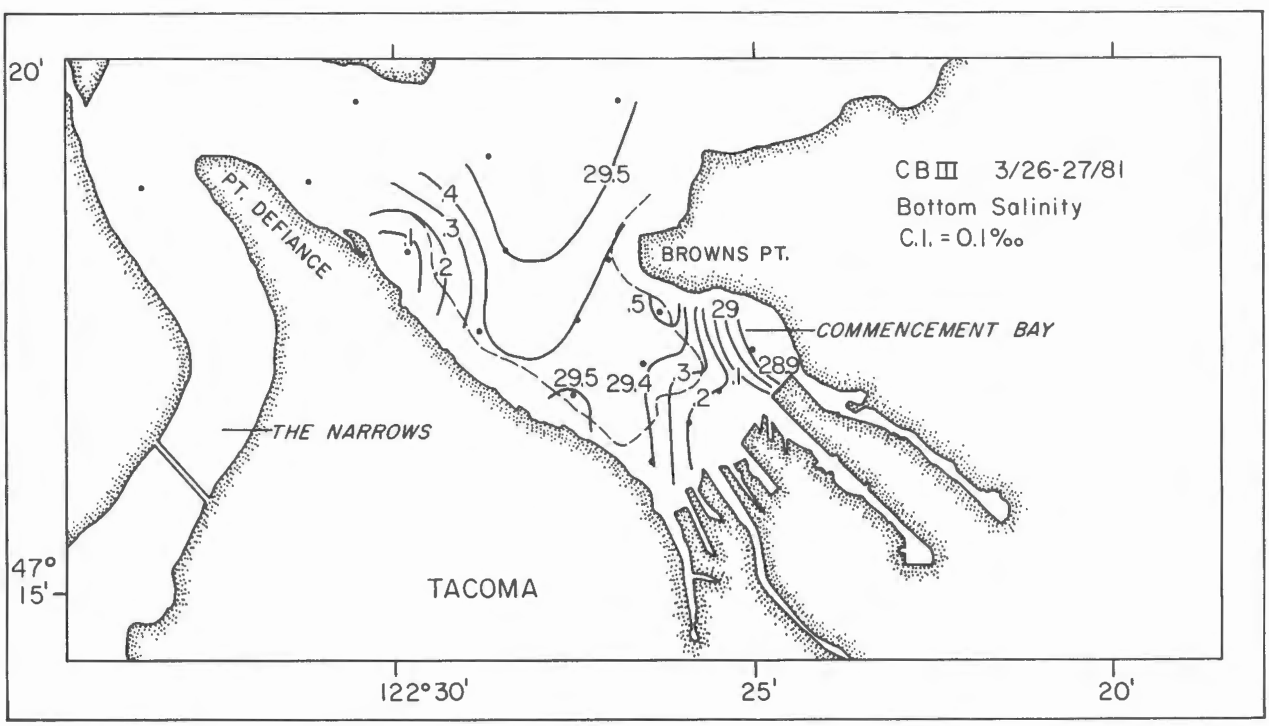


Figure 12. Areal maps of light attenuation and salinity at the bottom during March, 1981. Contour interval is 1.0/m for attenuation, and 0.1 °/oo for salinity.

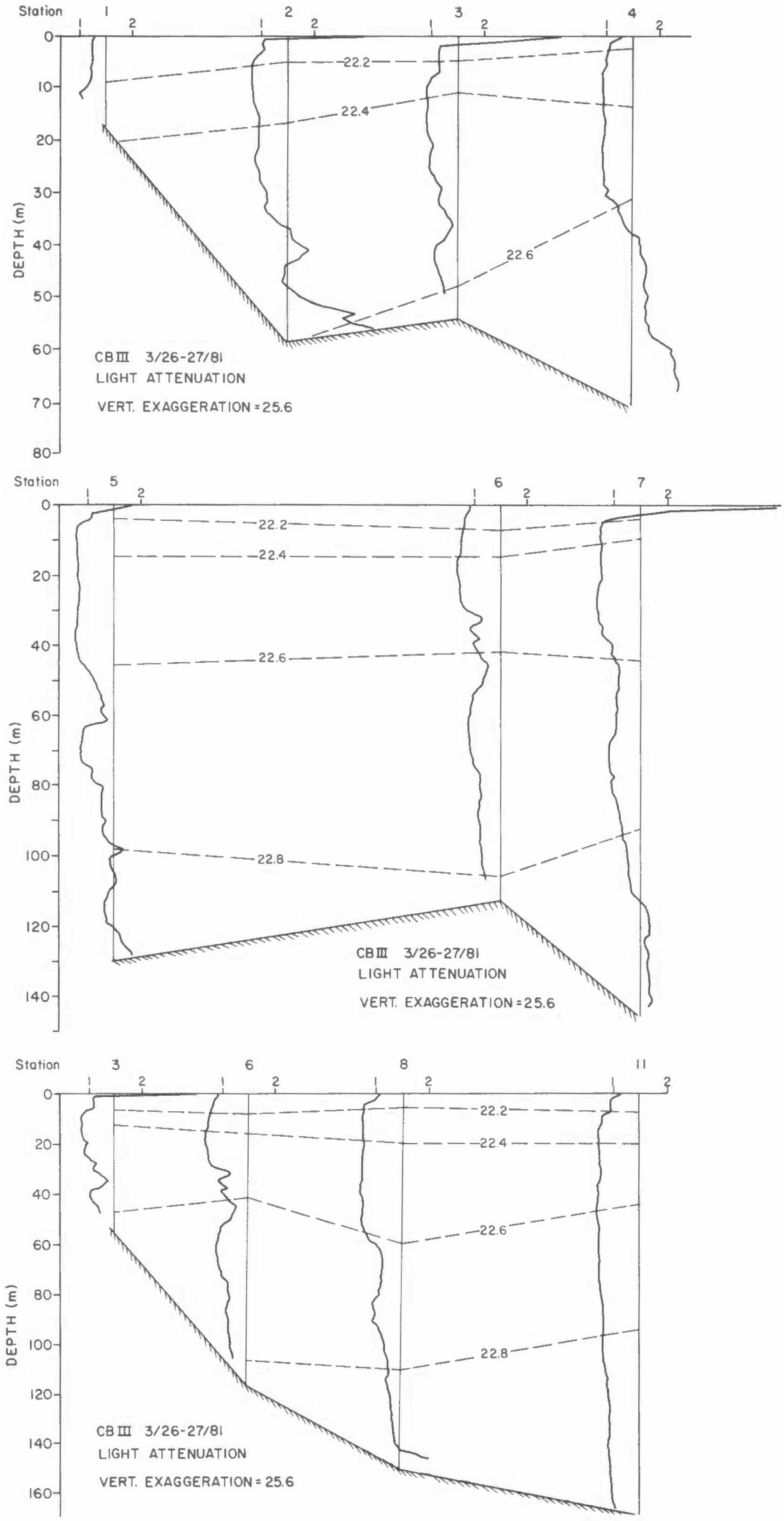


Figure 13. Light attenuation profiles from station transects during cruise CBIII, March, 1981. Scale in 1/m is given at the top of each profile.

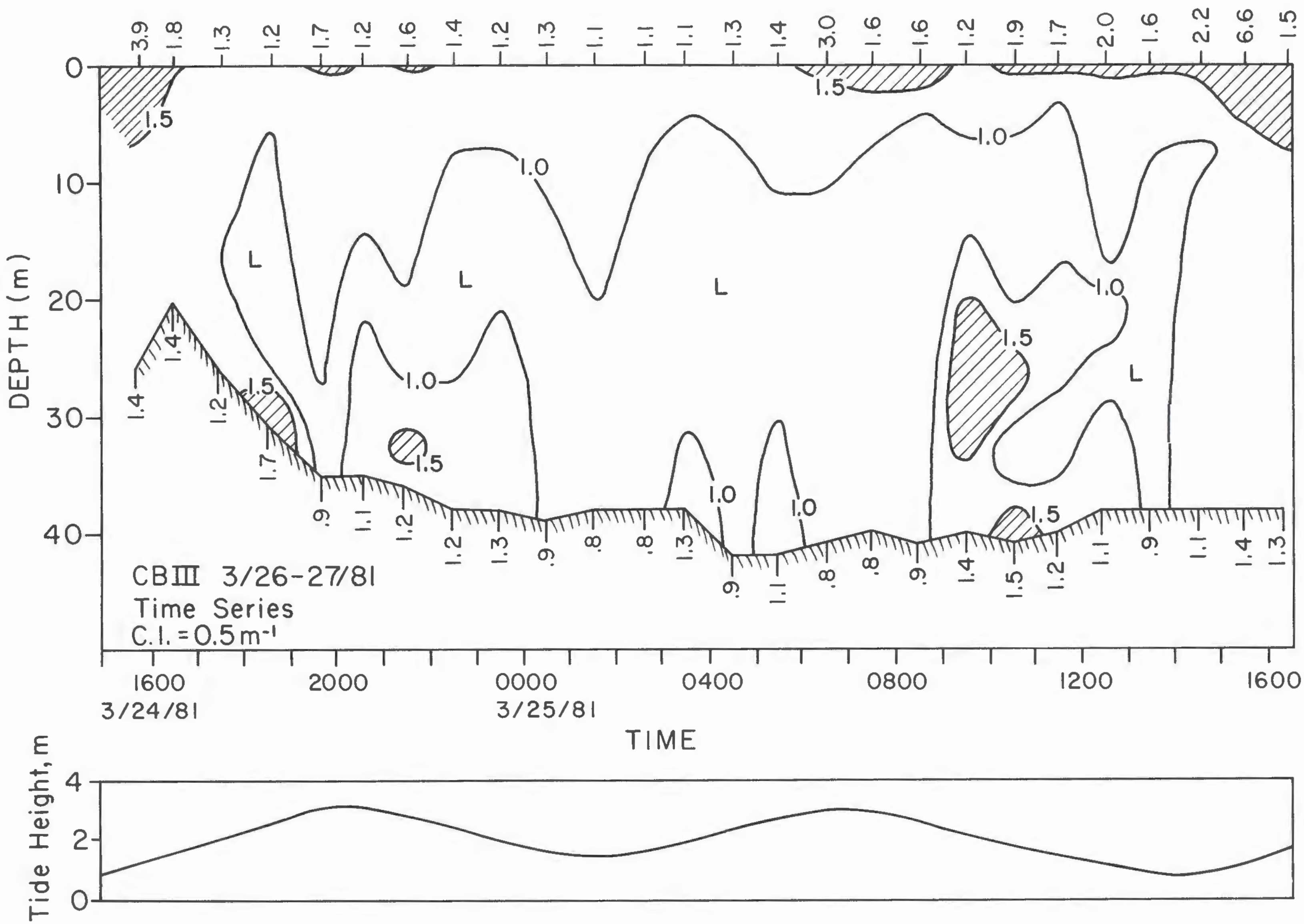


Figure 14. Puyallup river time series light attenuation data, March, 1981. Attenuation values >1.5 are shaded. Values at the surface and bottom of each cast are also shown.

March was 6.6/m, and the lowest was 1.1/m. Water with attenuation of less than 1.0/m was present at mid-depths most of the time, and bottom attenuation values seldom rose above 1.5/m. High bottom and mid-depth values were generally seen shortly after high water during the ebb tide. The surface layer became somewhat thicker around low tide.

2.4 Suspended Particulate Matter Loadings

Estimates of the mass of suspended particles in the Bay during each cruise were made from the transmissometer casts at each station. First, the surface area of the Bay south of Brown's Point was divided into regions representing four different depth zones (Table 1). Each depth zone contained 2-4 representative stations as determined by the bottom depth of each station. (Zone assignments for a particular station sometimes changed between cruises as a result of slight differences in positioning and the resultant bottom depth.) Next, the average SPM concentration determined from the representative stations was used as the average Bay-wide concentration for that depth zone. The total mass of SPM in each region was calculated as the product of this average concentration, average depth, and total surface area of the region. Finally, all the regions were summed to arrive at a Bay-wide total for each cruise. Details and validity of this procedure were discussed by Baker (1982).

Total loadings for each cruise varied by <10 percent, indicating that sharp changes in surface turbidity caused by changes in the Puyallup River outflow have very little impact on the total particle concentration in the Bay. The average particle concentration in the Bay, calculated as the quotient of the average loading and the total volume (2.86 km^3), is 0.70 mg/ℓ (~1.1/m). This figure agrees with observed concentrations away from the surface and bottom boundaries of the Bay.

2.5 Organic Matter Concentrations

Organic matter in the SPM varied between 63 and 10 percent with distinct seasonal and depth trends. Average values from the surface water varied from a low of 26.8 percent during the November survey to over 40 percent in September and March (Table 2). Average values in the BNL (~5 m above bottom) were always lower than the surface averages. Least-square linear regressions were computed between SPM concentrations and percent organic matter from the surface and near-bottom waters of each cruise (Fig. 15). Samples from the BNL were always negatively correlated with an average correlation coefficient of -0.78 (σ = 0.11) and an average slope of -5.0 (σ = 0.33). This uniformity implies that higher turbidity values in the BNL are derived from sediment sources relatively low in organic matter, such as resuspended sediments.

Table 1. Suspended particulate matter loadings in Commencement Bay

Depth Zone (m)	Representative Stations	Average Conc. (g/m^3)	Area ($x10^6 m^2$)	SPM Mass ($x10^8 g$)
Cruise CBI				
$0<z<55$	1,2	0.95	7.44	1.94
$55<z\leq 110$	3,4	0.89	6.31	9.37
$110<z\leq 150$	5,6	0.99	5.08	6.44
$z\geq 150$	7,11	0.53	9.02	7.57
				20.32
Cruise CBII				
$0<z<55$	1,3,10	0.84	7.40	1.72
$55<z\leq 110$	2,4	1.08	6.31	5.29
$110<z\leq 150$	5,6,8	0.95	5.08	6.18
$z\geq 150$	7,9,11	0.43	9.02	6.14
				19.33
Cruise CBIII				
$0<z<55$	1,3,10	0.67	7.44	1.38
$55<z\leq 110$	2,4,6	0.97	6.31	9.75
$110<z\leq 150$	5,7	0.88	5.08	5.72
$z\geq 150$	8,9,11,12	0.53	9.02	7.58
				19.43
				$\bar{x}$ = 19.69
				σ = 0.55

Table 2. Average percent organic matter of surface and near-bottom samples in Commencement Bay

Cruise		Surface 0-2 m	Near-bottom 1-6 m above bottom
CBI:	September, 1980	44.1	34.3
CBII:	November, 1980	26.8	22.9
CBIII:	March, 1981	40.9	15.0

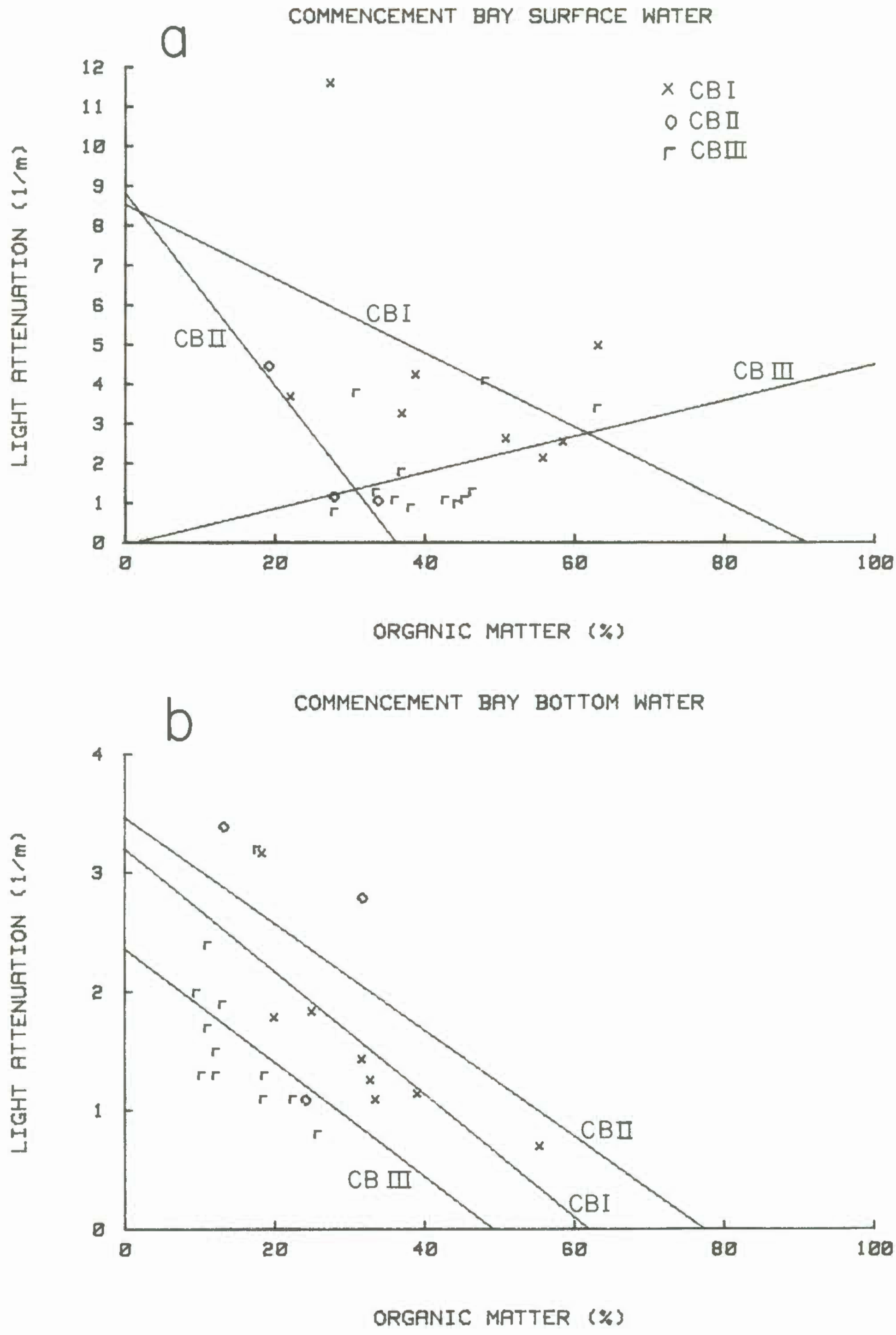


Figure 15. Light attenuation vs. percent organic matter for Commencement Bay (a) surface water and (b) near-bottom water for September, 1980 (x, CBI) November, 1980 (o, CBII) and March, 1981 (r, CBIII).

Surface samples from September and November, when production in Puget Sound is low (Ebbesmeyer and Helseth, 1977), show trends similar to the BNL samples and are probably the result of the addition of high turbidity, low-organic-matter-content runoff from the Puyallup River. Organic matter content in the surface samples decreased away from the river mouth during September and November. During March, however, organic matter percentage and SPM concentration were positively correlated. The reason for this reverse is unknown, but could have been the result of somewhat unusual meteorological conditions during the survey period. Skies were sunny for ~83 percent of the daylight hours during the 10-day period just before and during the survey period, perhaps triggering an early spring phytoplankton bloom in the shallow surface mixed layer created by the river plume.

2.6 Suspended Particulate Matter Transport

2.6.1 Current Meter/Transmissometer Time Series Records

Current velocities, temperature, salinity, and attenuation were measured and recorded at hourly intervals for 63 days in September-November, 1980, and 70 days in March-June 1981. Details of the circulation characteristics are reported by Cannon and Grigsby (1982). Seasonal comparisons cannot be made here because data from the second deployment were not available for analysis at the time of this writing.

Subtidal (35 hr. average) vector stick diagrams from current meters at 25 and 125 m on CB3 and CB4 illustrate the general circulation pattern in Commencement Bay during the first deployment (Figs. 16 and 17). Flow at 25 m sugests a counterclockwise pattern while near-bottom flow was clockwise. Subtidal surface vectors suggest a strong and relatively regular inflow at CB3 and a weaker and more variable outflow at CB4. Inflow at 25 m may thus be concentrated along the southwest side of the Bay, while outflow may be dissipated over a much broader area. Subtidal near-bottom flow was remarkably steady at both locations: net flow was 5.22 cm/sec along 290° at CB3 and 5.57 cm/sec along 127° at CB4. Mean speeds were somewhat higher at CB3 (7.36 cm/sec) than at CB4 (5.71 cm/sec). Net flow at 25 m was much greater at CB3 (7.44 cm/sec along 135°) than at CB4 (0.89 cm/sec along 19°); mean speeds were also correspondingly greater (17.75 vs. 5.16 cm/sec).

Mean values of the light attenuation at 125 m paralleled the speed differences. Average attenuation at CB3 was 2.60/m ± 0.62 (1σ). At CB4 this value fell to 2.16/m ± 0.57, about a 20 percent decrease. Interpretation of this difference is complicated by the fact that the transmissometer was 17 m above the seafloor at CB4, but only 6 m above at CB3.

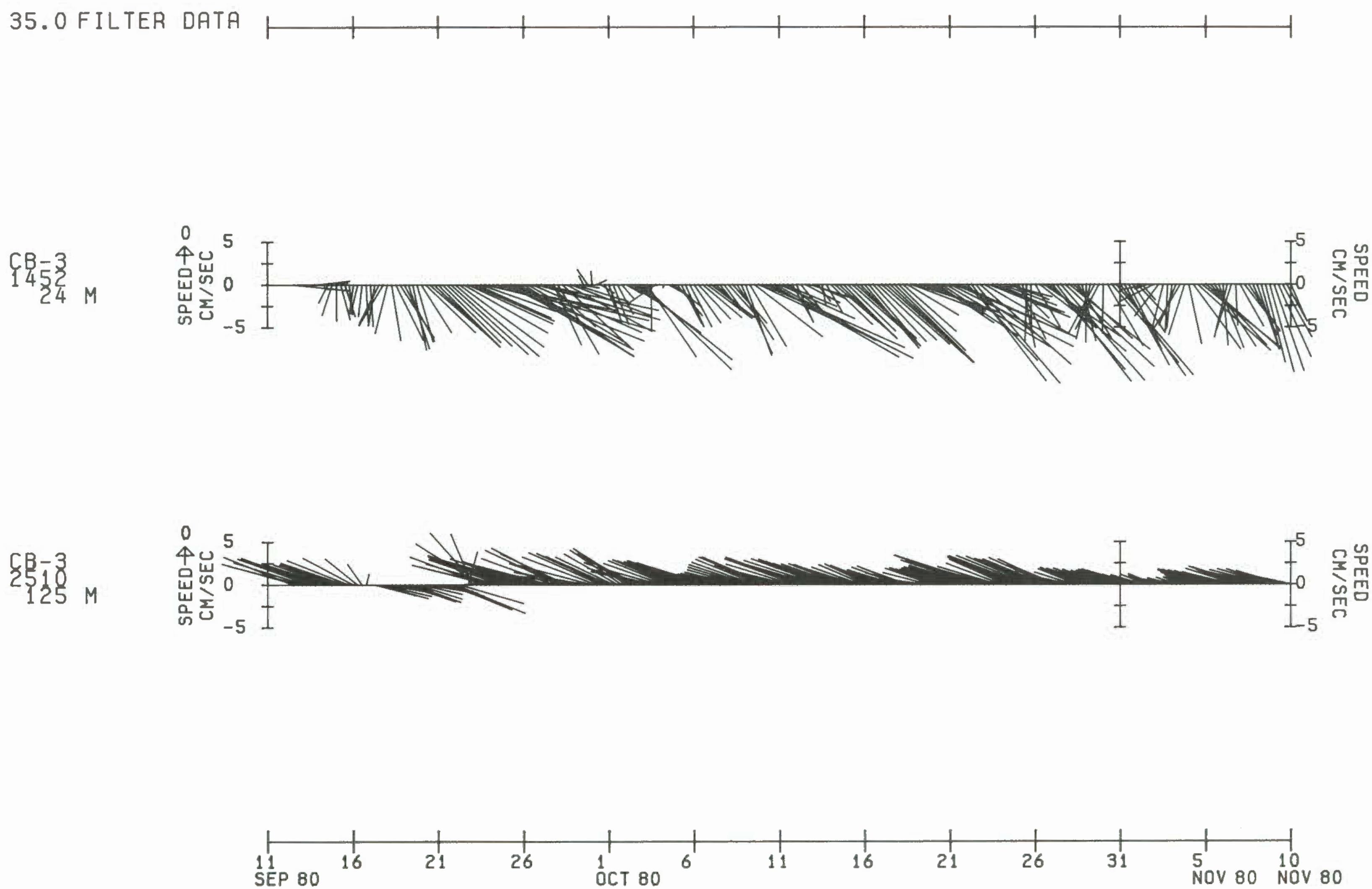


Figure 16. Subtidal (35-hr average) flow at mooring CB3, September-November, 1980.

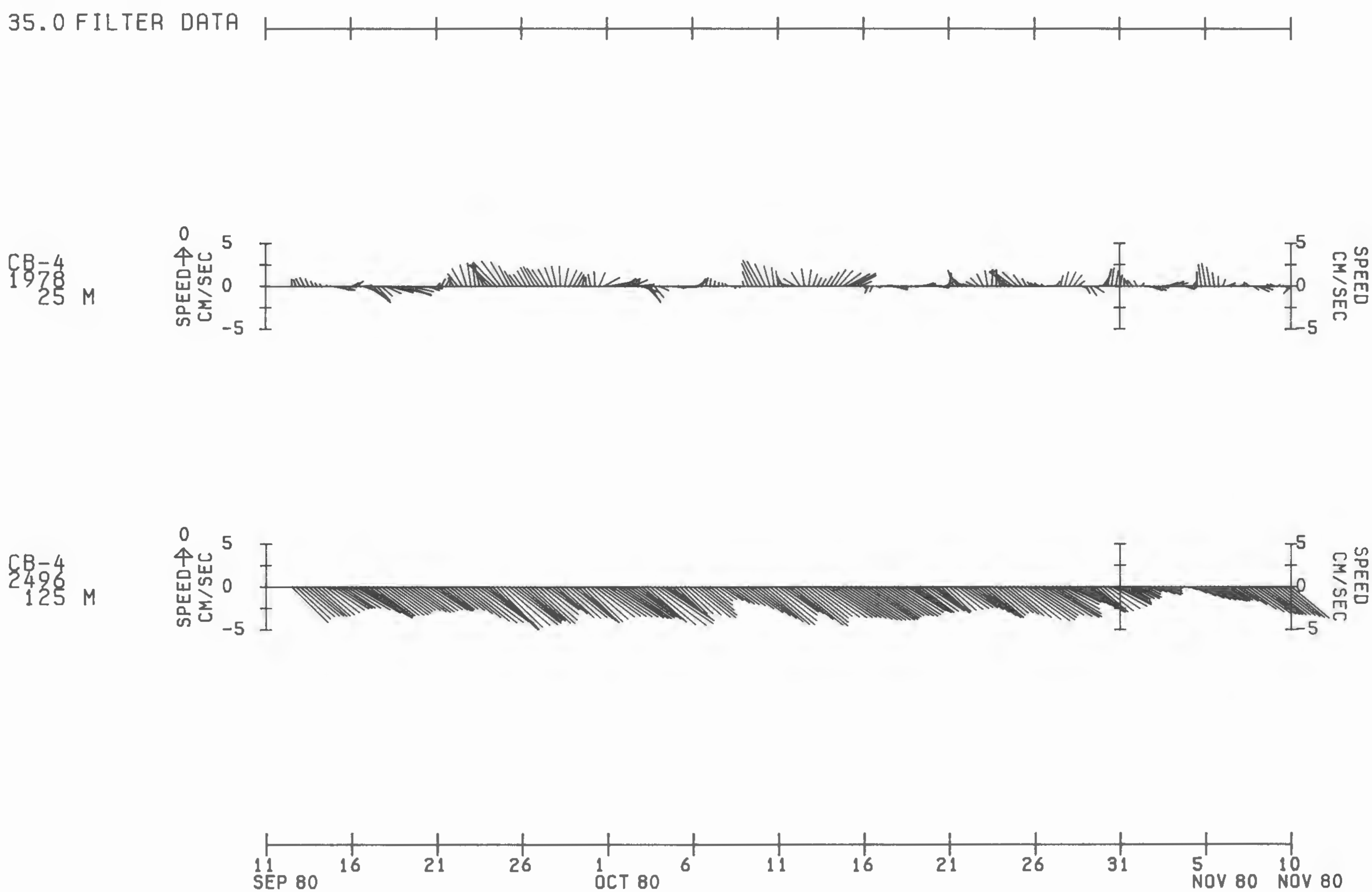


Figure 17. Subtidal (35-hr average) flow at mooring CB4, September-November, 1980.

Spectral analysis of attenuation records from both meters show strong attenuation peaks at periods of 1.01, 0.520, 0.350, and 0.257 days. For both records, variance was greatest at a period of 0.52 days, corresponding to the semidiurnal tidal signal. Cross spectral analysis between attenuation and salinity likewise shows the greatest coherency (coherence squared) at a period of ~0.52 days (coherency = 0.798 for CB3, 0.802 for CB4). A similar analysis between attenuation and speed along the direction of net flow showed coherencies to be greatest at shorter periods: 0.24 days at CB3 (0.764) and 0.350 days at CB4 (0.863).

The variability of near-bottom SPM concentrations was thus dominated by events occurring at tidal frequencies, at least for observations on the scale of a few months. These changes were correlated with both semidiurnal changes in water mass characteristics (as evidenced by salinity changes) and the more frequent changes in bottom water tidal velocities.

2.6.2 Horizontal Particle Flux

Magnitude and direction of net transport of suspended matter 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:

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

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 SPM concentrations. Transport direction relative to the component axes is given by:

$$\theta = \tan^{-1}\left(\frac{\bar{u}\,\bar{s} + \frac{1}{n}\Sigma\, u's'}{\bar{v}\,\bar{s} + \frac{1}{n}\Sigma\, v's'}\right).$$

The fluctuating component of the flux was always <10 percent of the mean flux. A summary of the transport results is given in Table 3. At a depth of 125 m, particles move into Commencement Bay past CB4 and out of the bay along the southern shore by CB3. The direction of transport corresponds to the net clockwise flow of water at this depth. About 13 percent more material is transported past CB3 than past CB4, but the present sampling density is not sufficient to ascertain whether this increase is indicative of a net removal of suspended particles from the Bay by the clockwise circulation.

Table 3. Suspended particulate matter horizontal flux

Mooring	Depth (m)	SPM Flux ($\mu g/cm^2/sec$)	Direction (°)	Mean Speed (cm/sec)
CB3	125	13.6	290	7.36
CB4	125	12.0	126	5.71

2.6.3 Vertical Particle Flux

The vertical flux of particles from the surface waters (0-25 m) of Commencement Bay ranged from 0.20 to 13.54 $g/m^2/day$ during 10 4-day intervals between March 25 and May 4, 1981 (Table 4, Fig. 18; this range does not include one questionable value of 24.06 $g/m^2/day$ at CB3). Both surface traps showed a marked decline in flux with time. This pattern may be real, or may be partially the result of bio-fouling on the baffles over the trap mouth which inhibited accurate particle collection towards the end of the deployment. The anomalous flux value during the ninth interval of the CB3 trap (Fig. 18) may thus have been the result of deposition of material previously accumulated on the upper trap surfaces. Surface sedimentation rates throughout the deployment period were about twice as great at CB4 than at CB3, a difference which is consistent with SPM and salinity distributions, as well as current meter records, which all suggest the Puyallup River plume is carried counterclockwise around the perimeter of the Bay.

Table 4. Average vertical flux values at moorings CB3 and CB4

Mooring	Depth (m)	Total Accumulation Rate ($g/m^2/day$)	Chlorophyll-a Accumulation Rate ($mg/m^2/day$)	Percent Organic Matter
CB3	25m	5.08	1.80	----
CB4	23m	5.91	4.21	15.0
CB4	123m	81.93	10.62	6.5

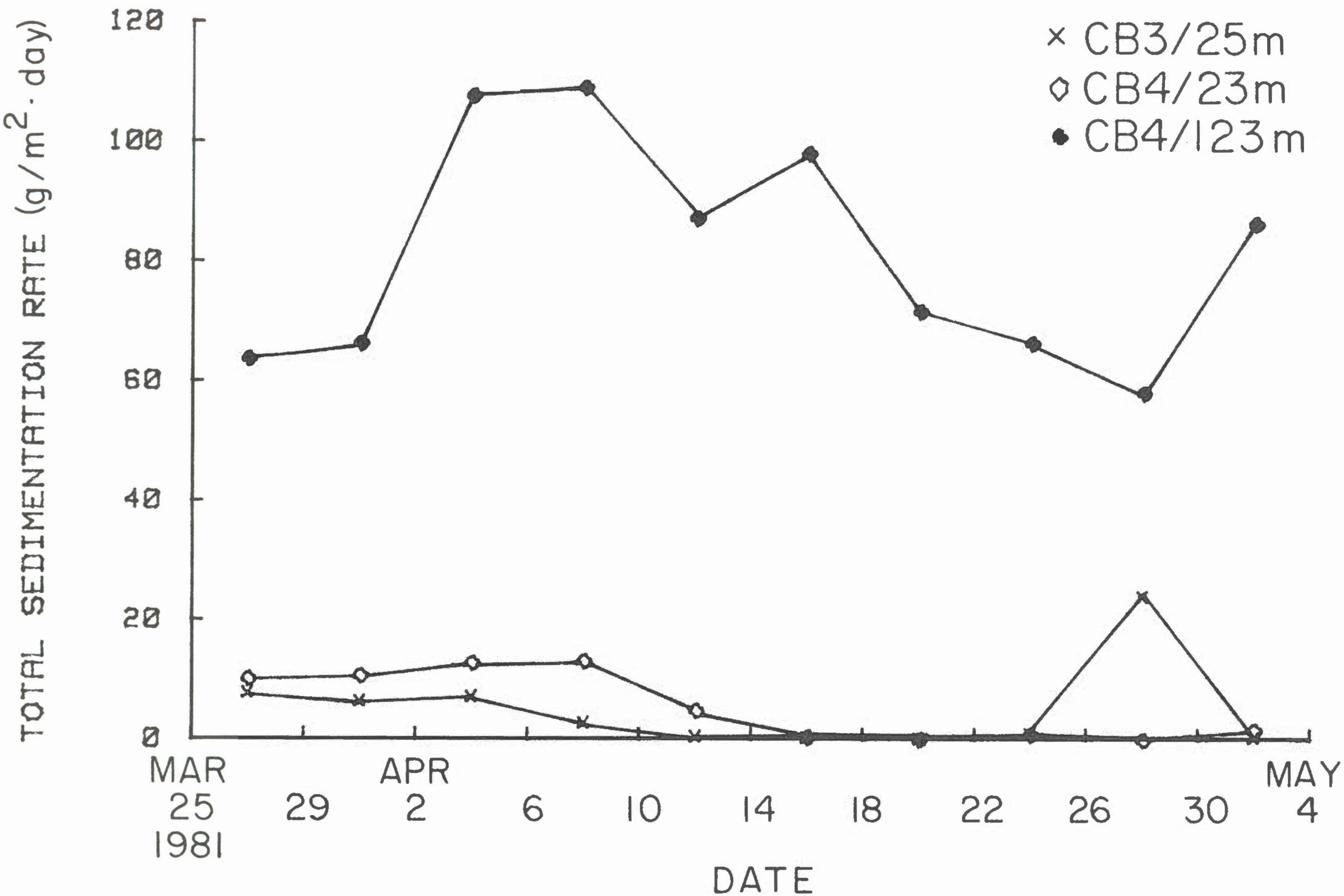


Figure 18. Total sedimentation rates at moorings CB3 and CB4, March-May, 1981.

Near-bottom accumulation rates are only available from CB4; average near-bottom flux was almost 14 times greater than the surface flux (Table 4, Fig. 18). This imbalance indicates that material in the near-bottom trap is not supplied solely by fallout from waters shallower than ~25 m.

The trend of phytoplankton pigment sedimentation into the traps yields some information on primary production in Commencement Bay (Fig. 19). The pigment flux is expressed in terms of chlorophyll-a equivalents, or the sum of the chlorophyll a flux plus 1.52 times the phaeopigment flux (Shuman and Lorenzen, 1975). Phaeopigments are the degradation products of chorophyll-a and undergo a weight loss of 66 percent (i.e., 1/1.52) during degradation. Pigment flux in the surface water at CB4 is up to 5 times greater than at CB3, suggesting that riverine influences (such as nutrient supply or increased stability of the surface mixed layer) demonstrably affect primary production in Commencement Bay. Conditions were evidently right for a plankton bloom in the early part of the deployment; pigment flux peaked during the period April 1-April 6 at both stations. Evidence of the bloom was also clearly seen in the deep water at CB4 where high pigment flux was sampled during both the third and fourth intervals. The higher pigment flux rates found in the near-bottom trap compared to the 23-m trap could occur through at least three mechanisms: 1) pigment flux in the form of fecal pellets by-passing the 23-m trap by means of zooplankton vertical migration; 2) local resuspension and particle recycling of the surface-originating flux, resulting in a higher apparent sedimentation rate in the bottom trap; and 3) horizontal advection of pigment particles from other areas in the Bay to the CB4 site by means of the BNL.

Organic matter content of the CB4 traps averaged 15.0 percent (σ = 7.9) at 23 m and 6.5 percent (σ = 1.0) at 123 m. These values are roughly half of mean values of percent organic matter of the SPM from the surface water (40.9 percent, σ = 9.4) and deep water (15.0 percent, σ = 5.3) samples collected during the March survey.

3. DISCUSSION

3.1 Relationships Between Suspended Particulate Matter and Salinity

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 parameters. Their relationships can be described by the use of a salinity vs. concentration (i.e., light attenuation) scatter plot analogous to the mixing diagrams used to trace the loss or addition of dissolved constituents in an estuary (Liss, 1976).

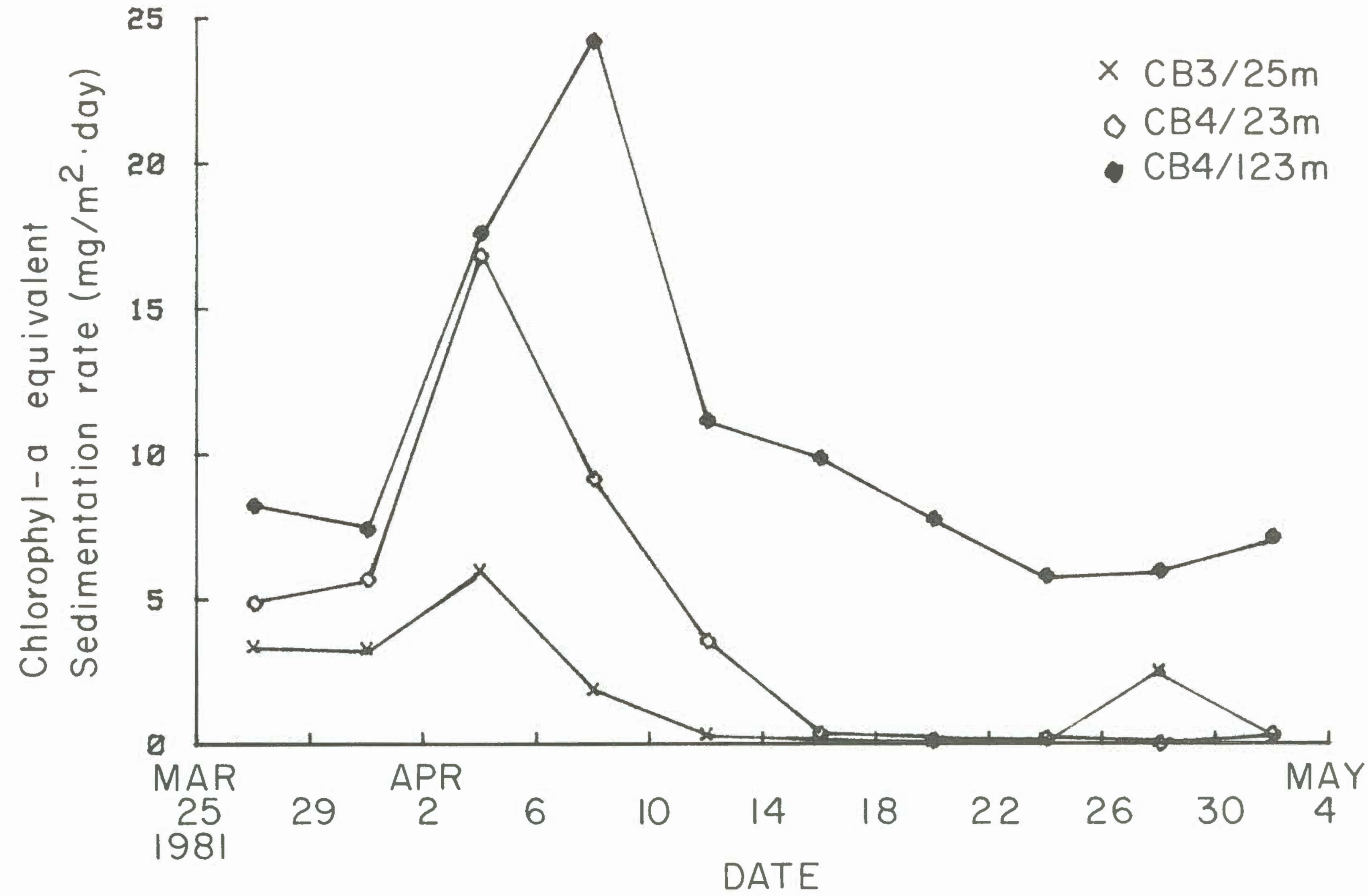


Figure 19. Chlorophyll-a equivalent sedimentation rates at moorings CB3 and CB4, March-May, 1981.

3.1.1 Surface Waters

Attenuation-salinity plots for the surface layer of Commencement Bay had similar slopes (-0.30 to -0.37) for each survey period (Fig. 20). Highest correlation coefficients (r = -0.86) were found for the November and March survey period; the corresponding value during September was -0.59. Higher correlation values in winter and spring are presumably the result of increased runoff during those times. Mean runoff in November and March was 98 m^3/sec and 76 m^3/sec, respectively, compared to only 30 m^3/sec in September.

In addition to the three Bay-wide surveys, two 25-hour time series stations were occupied between stations 3 and 4 off the mouth of the Puyallup River. Attenuation-salinity plots from these two observation periods are shown in Fig. 21. River flow during the November time series was ~62 m^3/sec; during the March time series flow was only ~43 m^3/sec. This difference is apparent in the increased range of salinity and attenuation values found during November. The slope of the November time series regression (-0.29) agrees quite well with that found during the November (-0.30), March, and September Bay-wide surveys. The March slope was much steeper (-0.61), although the significance of this difference is questionable since all but two of the data points for March occupy a very limited range.

The similarity of the attenuation-salinity relationships indicates that the Puyallup River plume controls the surface concentration of SPM in Commencement Bay, at least during those parts of the seasonal cycle represented by the sampling periods. Examination of the regression plots (Figs. 20 and 21) reveals that this coherence was poorest at the low-salinity stations nearest the river mouth, and improved substantially at salinity values >~27 $^{o}/_{oo}$. This partitioning is probably the result of two mechanisms: 1) at high turbidity levels (>~3.0/m) the scale of both spatial and temporal variability becomes smaller and a single measurement may not be representative of a large water parcel; and 2) SPM probably does not behave conservatively just at the mouth of the river. Throughout most of the Bay, however, SPM does appear to behave at least quasi-conservatively, implying that particle losses from the surface plume are governed by mixing and dilution rather than particle settling. A similar conclusion was reached by Baker (1982) in analyzing the Duwamish River plume in Elliott Bay; by Syvitski and Murray (1981) in Howe Sound, a Canadian fjord; and by Zaneveld and Pak (1979) in the Columbia River plume.

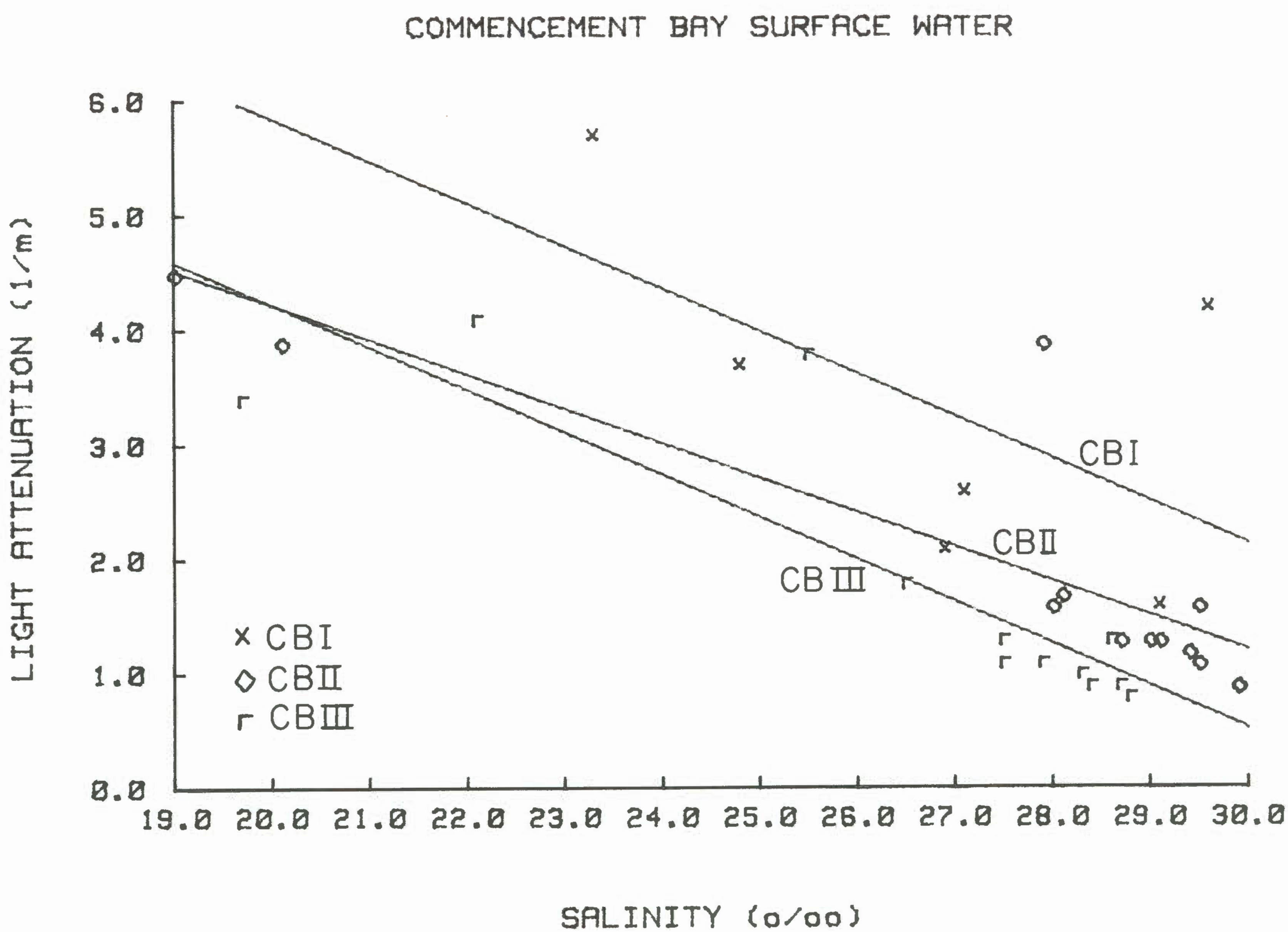


Figure 20. Light attenuation vs. salinity for Commencement Bay surface water for September, 1980 (x, CBI), November, 1980 (o, CBII), and March, 1981 (r, CBIII).

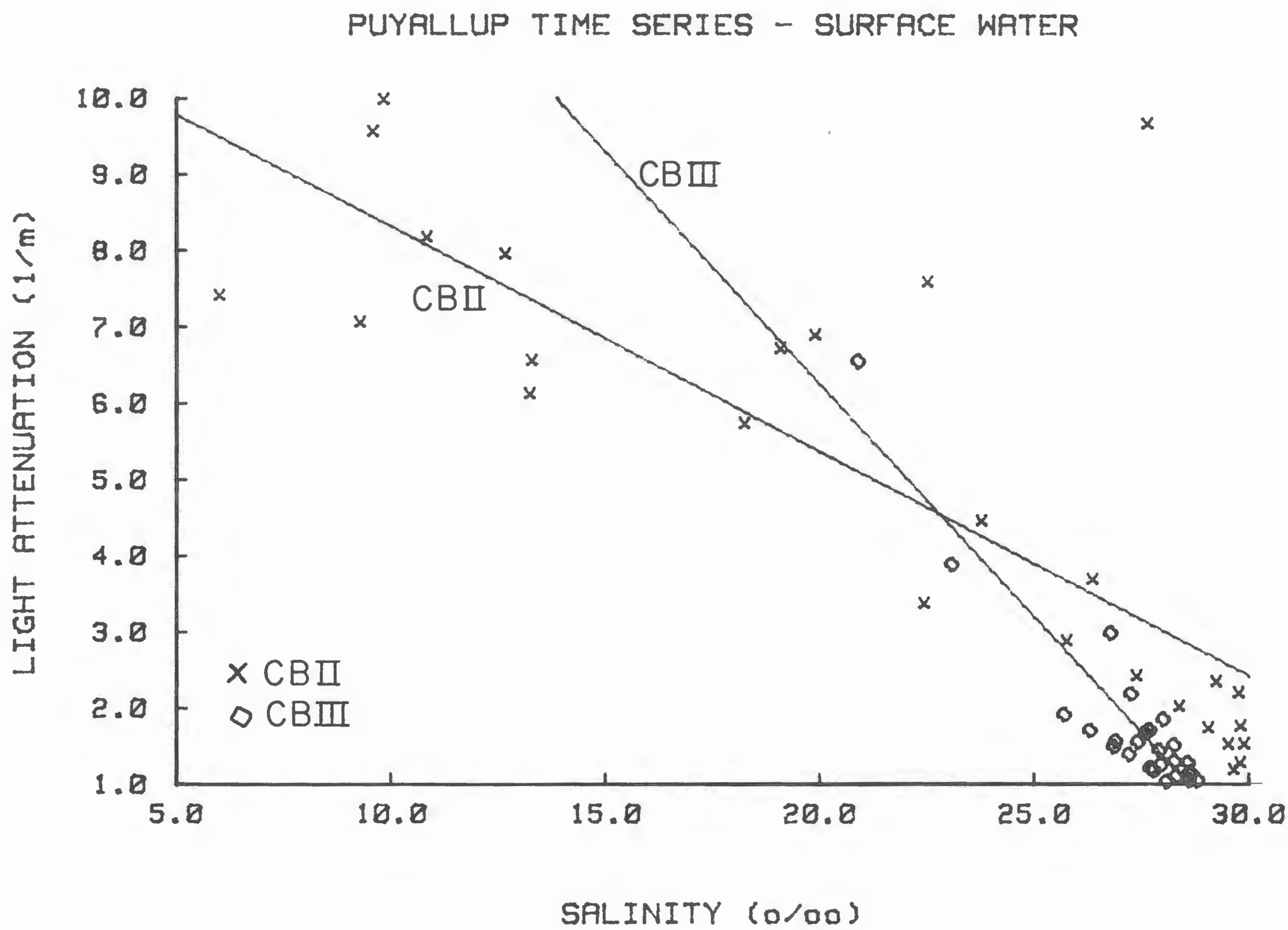


Figure 21. Light attenuation vs. salinity in the surface water during the Puyallup River time series; November, 1980 (x, CBII) and March, 1981, (o, CBIII).

3.1.2 Bottom Waters

Unlike the surface waters, no correlation was found between attenuation and salinity 5 m above the bottom throughout Commencement Bay. Correlation coefficients (r) were -0.72 (CBI), 0.13 (CBII), and 0.16 (CBIII) (Fig. 22). The anomalous value for CBI was caused by a single data point at station 5; without this low salinity, high attenuation value the correlation coefficient would have equalled 0.27 with a slope similar to CBII and CBIII. Furthermore, the period of maximum mean salinity (November) did not correspond to the period of either maximum (September) or minimum (March) mean attenuation.

Correlations between salinity and attenuation in the BNL can also be examined from the point of view of the mooring data, which give a detailed comparison of these parameters at a single location over a long period of time. Regressions between salinity and attenuation at CB3 and CB4 (Fig. 23) showed no significant correlation over the length of the deployments. Correlation coefficients were -0.012 for CB3 and 0.069 for CB4. These data thus imply, as do those from the CTD casts, that SPM in the BNL is not conservative even in a gross sense. Variations in the SPM concentration depend on local processes (such as resuspension) and do not simply reflect differences related to changes in the hydrographic and particle characteristics of deep water entering Commencement Bay from the Main Basin of Puget Sound. In this sense, the salinity-attenuation relationship in the BNL is quite different than that found in the surface waters of the Bay, or in either the surface or bottom waters of Elliott Bay, another Puget Sound embayment of similar depth and dimensions (Baker, 1982).

3.2 Relationships Between Suspended Particulate Matter and Current Flow

Data from the moorings and station work reveal at least three distinct avenues of SPM transport within Commencement Bay. In the surface layer, transport is dominated by the Puyallup River. Areal plots of light attenuation during each cruise show a persistent high off the river mouth and a tendency for this material to be carried out of the Bay along the northern shore. Stations offshore of Pt. Defiance consistently showed the lowest light attenuation levels. This pattern strongly suggests a counterclockwise circulation pattern in the surface water, a conclusion supported by the current meter results at 25 m (Figs. 16 and 17) and the position of the surface plume observed by the authors in Landsat images. The consistently higher 25-m accumulation rates at CB4 compared to CB3 are apparently the result of this preferential position of the surface plume. Linear relationships between salinity and light attenuation in the surface layer suggest that the suspended particles in the river plume are removed largely by mixing and that settling has little effect on particle loss within Commencement Bay.

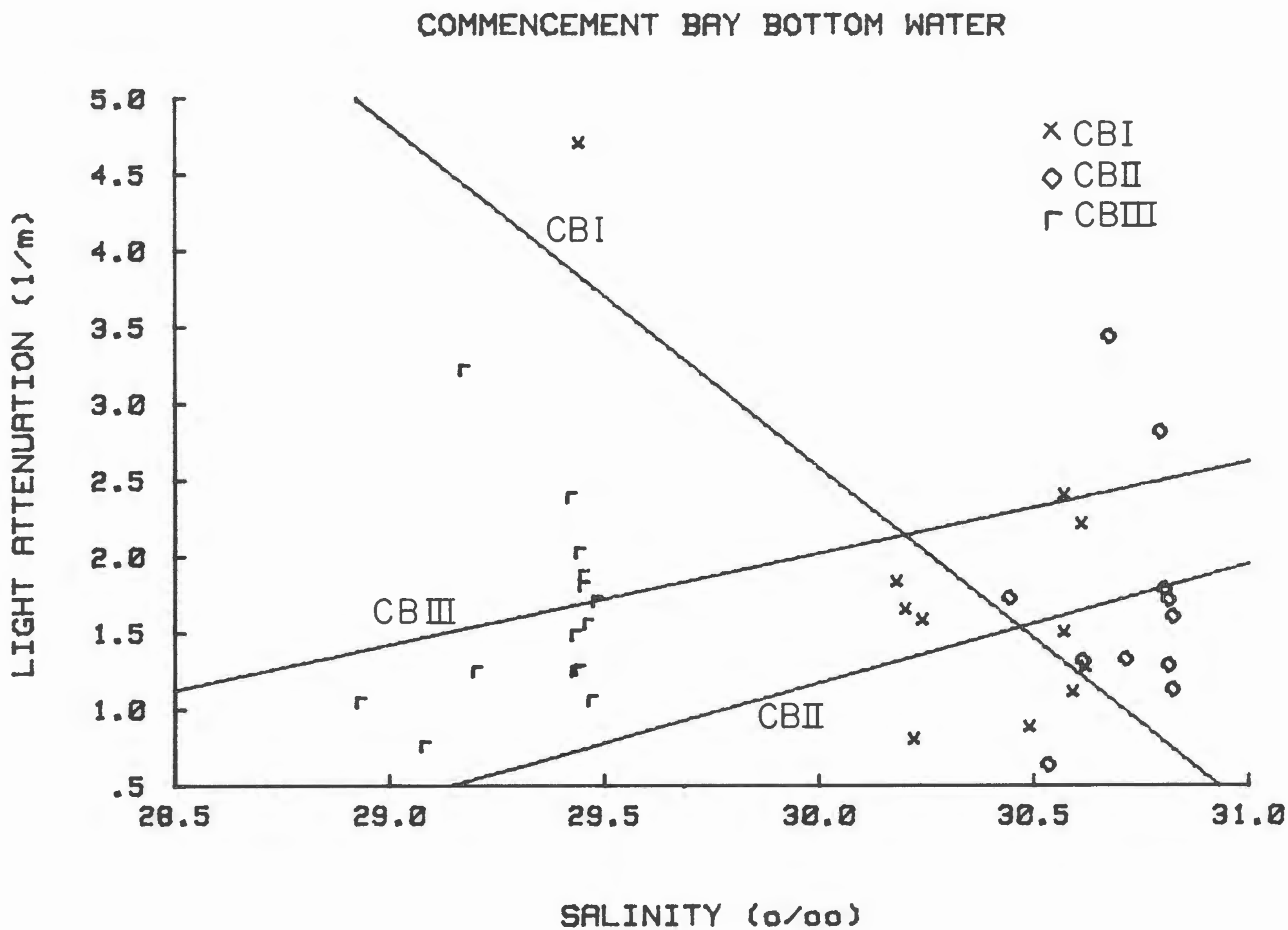


Figure 22. Light attenuation vs. salinity for Commencement Bay bottom water for September, 1980 (x, CBI), November, 1980 (o, CBII), and March, 1981 (r, CBIII).

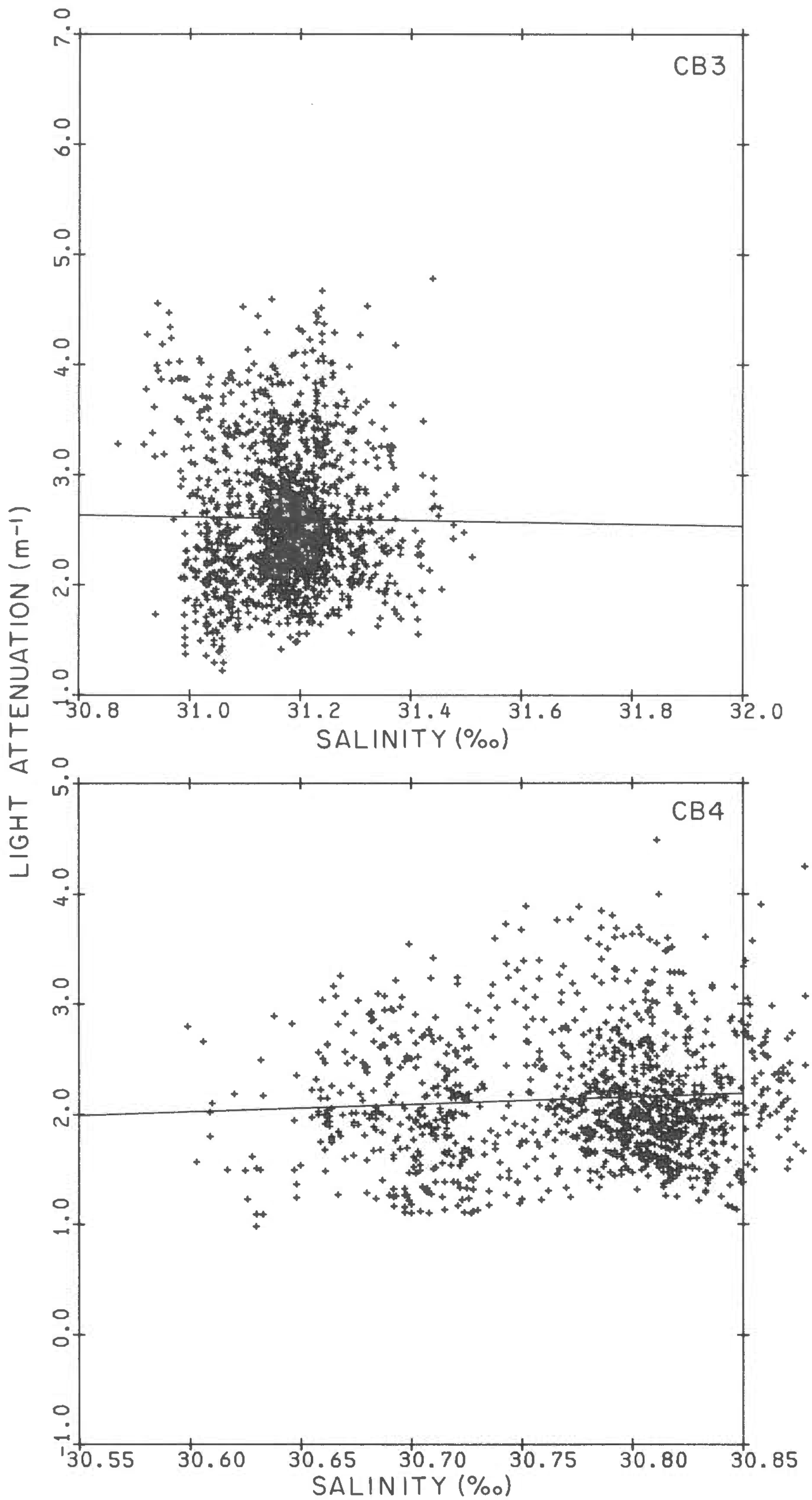


Figure 23. Scatter plots of light attenuation vs. salinity for near-bottom time series records at moorings CB3 and CB4, September-November, 1980.

In addition to this surface plume, transmissometer casts revealed a prominent mid-depth turbidity plume in the outer Bay, especially during the September and November cruises. The plume appeared to originate in the shallow waters at the head of the Bay and extend seaward at a depth of 50 to 70 m (Figs. 6, 9, and 13). Light attenuation values were often greater than in the surface plume at a comparable distance from shore. This feature, which was often thicker and more turbid than the surface plume, thus represented a substantial particle redistribution process in Commencement Bay. Also unlike the surface plume, concentrations in the mid-depth maximum were not correlated with salinity. These facts, along with the rapid diminishment of SPM concentrations away from the apparent source at the head of the Bay, suggest that the particles in this plume are lost by settling to the deeper waters and bottom sediments of the Bay.

The source of the particles in this feature is unknown. A likely possibility is resuspension of the shallow sediments at the head of the Bay by tidal currents. The time series observations off the Puyallup during the November and March cruises (Figs. 10 and 14) indicate that BNL values increase on the ebb tide. Some of this material may then be advected seaward along the density surface which corresponds to the density at the resuspension point at the head of the Bay. During CBII, for example, the plume was centered around a σ_t surface of ~23.44, the same value as occurred just above the bottom at station 2, where the plume appeared to originate.

The third prominent zone of SPM transport is the BNL. One principal question of interest is the origin of the material in the BNL - is it primarily local, derived from resuspension of Commencement Bay bottom sediments or fallout from turbid sources such as the Puyallup River, or is it brought into the Bay from the Main Basin by circulation processes which renew the Bay's deep water?

Examination of attenuation-salinity scatter plots from CTD and mooring data (Figs. 22 and 23) indicated that there was no significant correlation between the salinity and the SPM concentration of the BNL during this study period. Areal plots of salinity and attenuation (Figs. 5, 8, and 12) consistently show a freshening of the bottom water throughout the head of the Bay but a maximum in light attenuation only off Blair Waterway and extending in a narrow band down the center of the Bay. This configuration is probably related to the origin of the mid-depth turbidity plume discussed above.

The fact that the concentrations of salt and particles in the BNL are not related does not mean that changes in the concentrations of each are unrelated. To illustrate this point, we examined in detail a 12-day period in the mooring deployment from both CB3 and CB4 (Figs. 24 and 25). Several relationships among the various parameters are clear from these records. At mooring

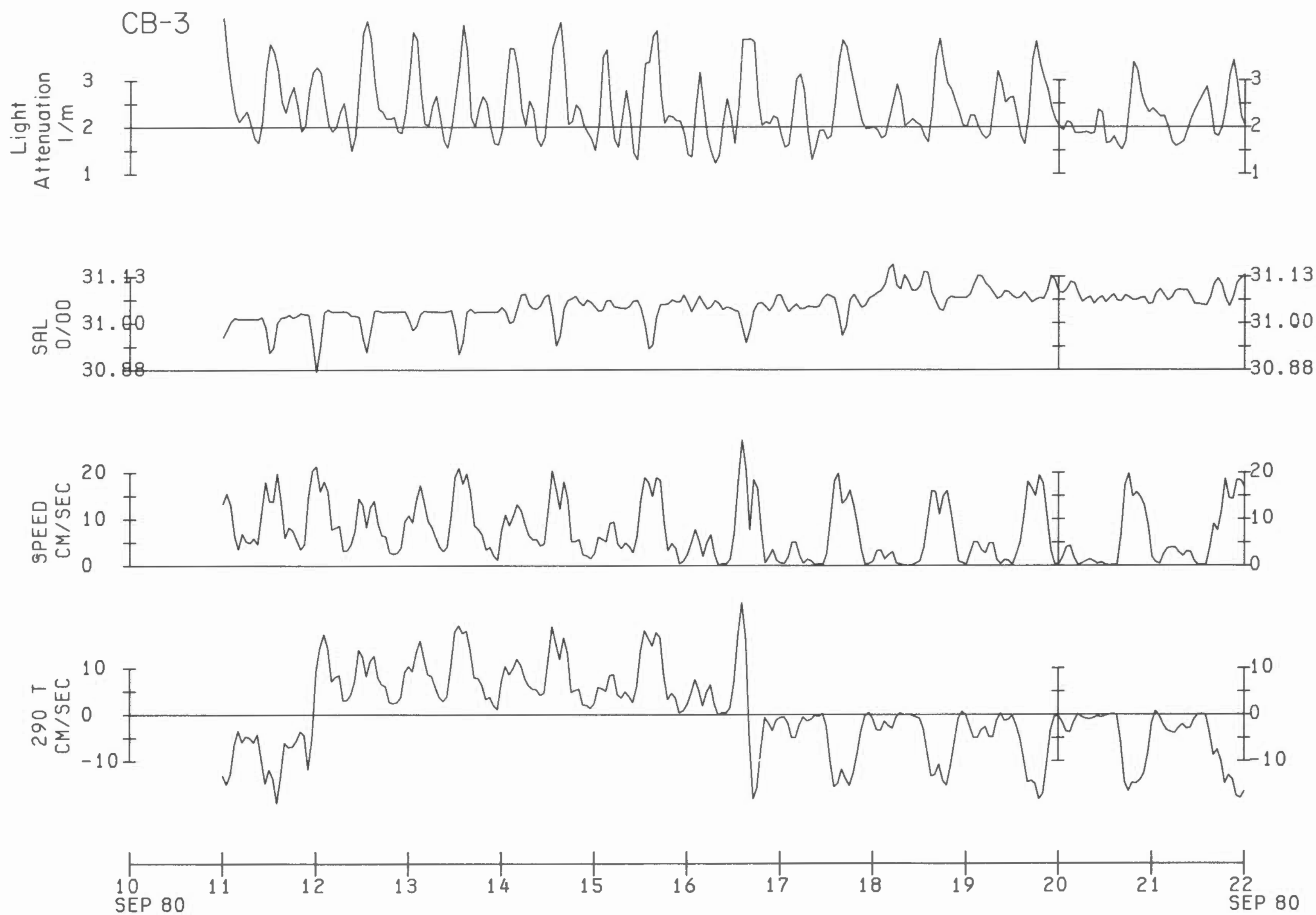


Figure 24. Mooring data from CB3, 125 m, September 10-22, 1980.

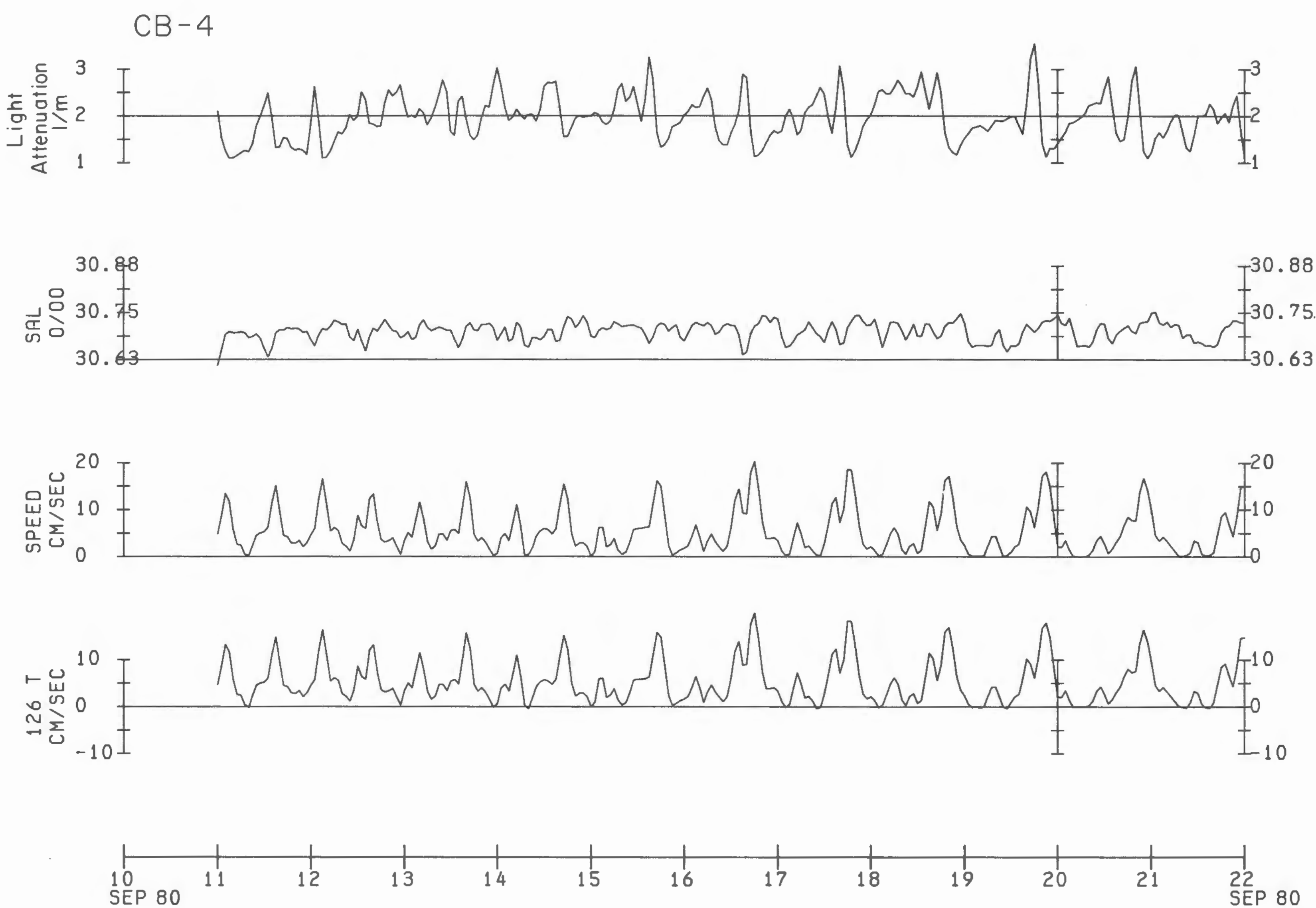


Figure 25. Mooring data from CB4, 125 m, September 10-22, 1980.

CB3, for example, twice daily peaks in light attenuation were associated with sharp decreases in the background salinity and increases in the scalar speed (speeds at both moorings were directed almost exclusively along the alongshore component; onshore-offshore motion was insignificant). Although increased attenuation, decreased salinity, and increased speed were generally correlated ($r = -0.52$ for salinity, 0.60 for speed; see Fig. 26), the details of these correlations are complex. The daily current peak was commonly interrupted by a short and sharp drop of current speed; it was precisely at this minimum that the salinity minimum and the attenuation maximum occurred. This agreement held for flow either in or out of the Bay, although during flow into the Bay the periodic salinity decreases were much subdued.

Flow at CB4 during this period was always into the head of the Bay; no flow reversal was seen as at CB3. Although CB4 also showed a tendency for peak speeds to correlate with salinity decreases, this trend was not consistent. Attenuation was poorly and negatively correlated with both salinity ($r = -0.29$) and speed ($r = -0.24$) during this period (Fig. 27). The picture is further complicated by the fact that the current meter/transmissometer was 6 m above bottom at CB3 but 17 m above bottom at CB4.

Only tentative conclusions can be drawn from the limited data set available. Although the salt and SPM concentrations in the BNL are sometimes correlated, they do not appear to share the same origins. At CB3, for instance, salinity decreases were prominent during flow out of the Bay (presumably as a result of freshwater input at the head of the Bay) but were only minor during flow into the Bay (September 17-22, Fig. 26). Attenuation peaks, however, were of about equal magnitude during both flow conditions. This lack of change in the attenuation signal with such a profound change in the current pattern is strong evidence for local erosion causing changes in the attenuation at the mooring site. Unfortunately, the situation is more complex at CB4, where attenuation was negatively correlated with speed during the September 10-22 interval. The large distance between the meter and the seafloor at this location may make correlations between speed and erosion-produced SPM difficult to identify.

Probably the most compelling evidence for a high level of resuspension activity in Commencement Bay is the comparison between the vertical flux measured by the bottom sediment trap at CB4 and sedimentation estimate from sediment cores. Schell et al. (1977) dated (using ^{210}Pb) a gravity core collected near station 11 and calculated an accumulation rate of 0.67 cm/yr. Assuming a dry sediment density of 2.6 g/cm^3 and a porosity of 80 percent, a mass accumulation rate of 9.5 $g/m^2/day$ is calculated for this core, or about 12 percent of the average flux (82 $g/m^2/day$)

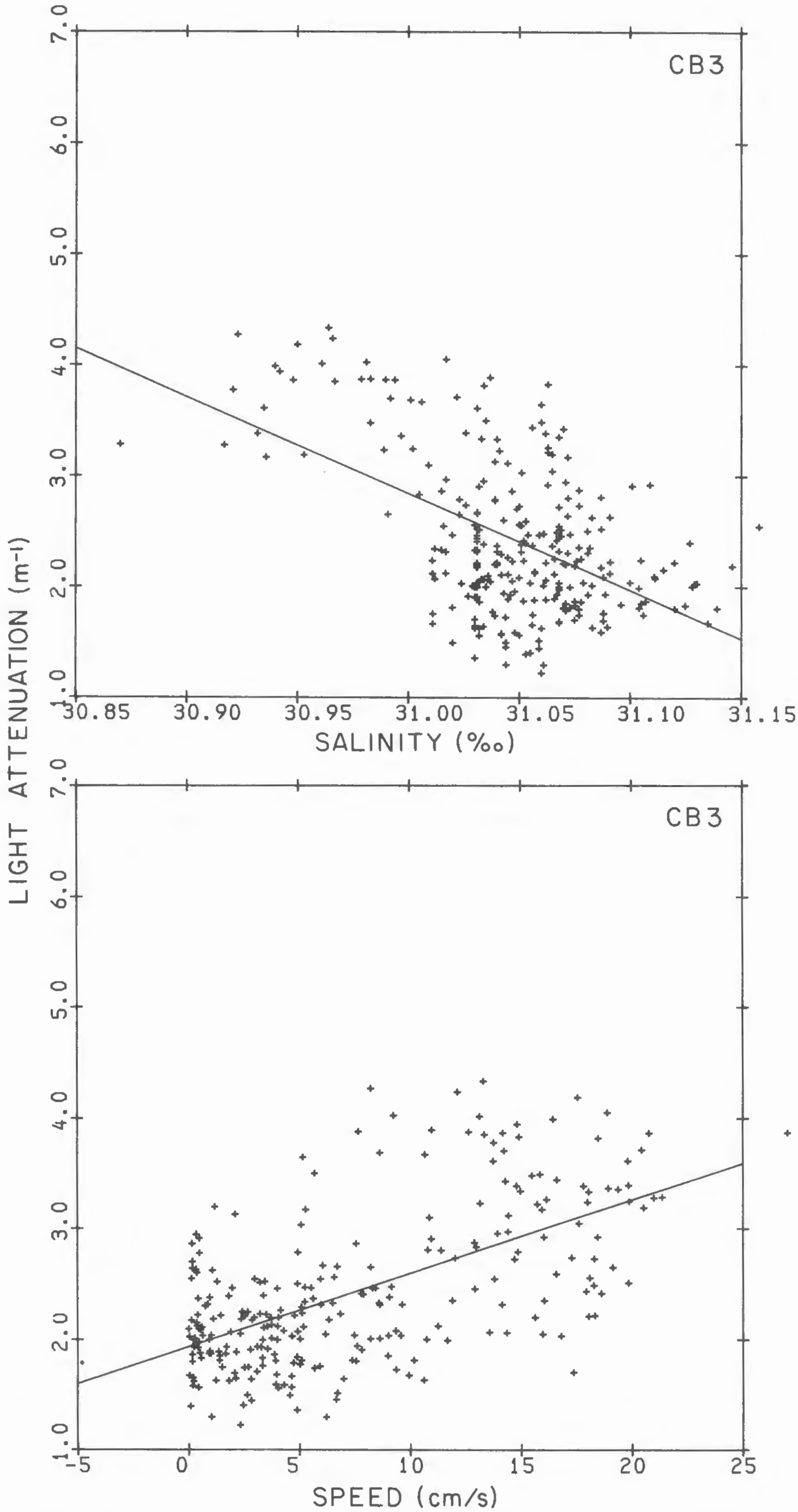


Figure 26. Scatter plots for light attenuation vs. salinity and light attenuation vs. speed at mooring CB3, September 10-22, 1980. Least-squares regression line is plotted.

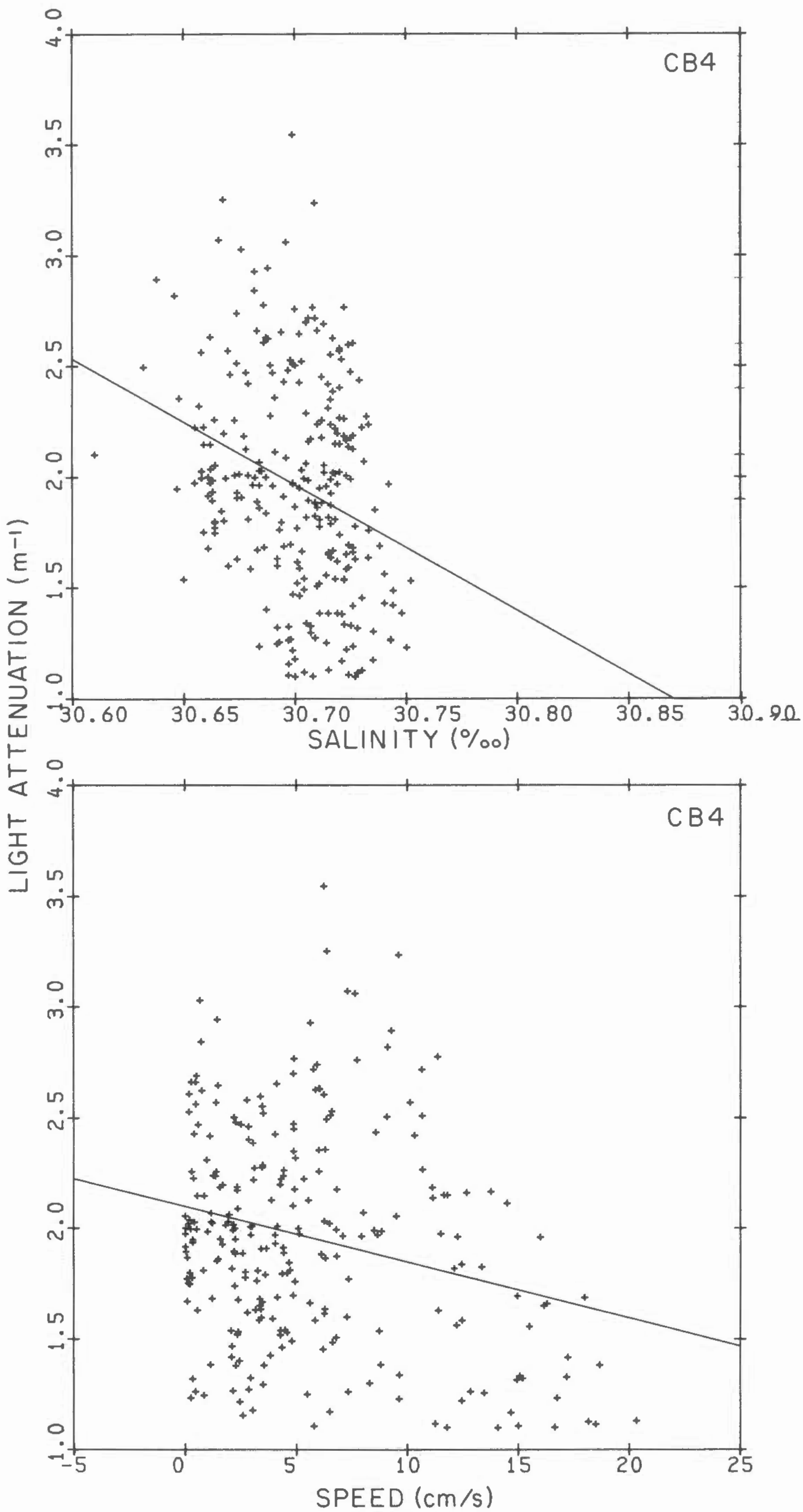


Figure 27. Scatter plots for light attenuation vs. salinity and light attenuation vs. speed at mooring CB4, 125 m, September 10-22, 1980. Least-squares regression line is plotted.

collected by the bottom sediment trap. This imbalance implies that substantial recycling of bottom sediments by resuspension must occur in order to produce the large apparent sedimentation rate in the sediment trap. Note also that the surface traps collected less than 10 percent as much as the bottom trap and so could not contribute a major amount to the observed flux in the bottom trap. The influence of the mid-depth plume is unknown, but the cross-sections show that it was always much more concentrated in the center of the Bay than towards the perimeter where the sediment trap was located.

3.3 Comparisons Between Elliott Bay and Commencement Bay

Commencement Bay and Elliott Bay are both relatively small, urbanized embayments on the Main Basin of Puget Sound. SPM distribution and transport in Elliott Bay were examined in an earlier MESA-sponsored research project (Baker, 1982).

Both bays are characterized by a three layer SPM distribution - a thin surface layer in which turbidity decreases away from the river mouth, a broad mid-depth zone of normally low and uniform SPM concentrations, and a BNL of variable thickness and turbidity throughout the Bay. The SPM concentration in the surface layer of each bay was highly and negatively correlated with the observation that the surface plume is readily identifiable from the head to the mouth of each bay on the basis of both turbidity and salinity, suggests that most of the river-supplied particles are removed from the bays by advection of the riverine plume into the Main Basin. Losses from the surface plume occur principally by mixing, not by particle settling. Although observations of the vertical particle flux in the upper 25 m are few, results from each bay are comparable. Flux at the 30 m level of Elliott Bay in February/March of 1980 averaged 6.6 g/m^2/day over 29 days; the flux from two traps at 25 m at comparable locations in Commencement Bay averaged 4.3 g/m^2/day over 40 days from March to May.

The mid-depth minimum zone in Elliott Bay was always found to be a region of low and uniform (both horizontally and vertically) SPM concentrations. In Commencement Bay, one or more prominent turbidity layers was always present in this zone. These layers appeared to originate from resuspension processes at the head of the Bay, and disappeared or were greatly diminished before reaching the mouth of the Bay. No similar feature was ever seen in Elliott Bay.

Although each bay has a prominent BNL, the transport processes and origin of the particles in each BNL appear to be substantially different. In Elliott Bay, SPM concentrations were highly and positively correlated with salinity. The influence of resuspension on maintaining the BNL was considered minimal because daily peak current speeds near the bottom were commonly <10 cm/sec, and because the near-bottom vertical flux in the sediment traps was only ~31 $g/m^2/day$, or less than twice the net accumulation rate calculated by Schell et al. (1977) from ^{210}Pb dated sediment cores. This sluggish bottom current field resulted in a mean light attenuation near the bottom of only ~1.1/m at two mooring locations, and an average lateral transport of ~2.0 $\mu g/cm^2/sec$. From these and other data, Baker (1982) concluded that the BNL in Elliott Bay was primarily maintained by an influx of turbid, salty water from the Main Basin rather than local resuspension. Sedimentation in the Bay was the result of a substantial drop in current speed as this water flowed through Elliott Bay.

Conditions are quite different in the BNL of Commencement Bay. Although light attenuation peaks often occurred simultaneously with sharp decreases in salinity, there was no significant correlation between the concentration of salt and particles in the bottom water over the entire duration of the moorings. Daily peak speeds commonly were in excess of 20 cm/sec, but the times of maximum speed did not always correlate with the times of maximum light attenuation. The apparently more vigorous bottom circulation in Commencement Bay resulted in a substantially higher mean attenuation (~2.4/m) and lateral transport rate (~12.8 $\mu g/cm^2/sec$) than in Elliott Bay. Because of this the near-bottom sediment trap flux was ~12 times greater than the net bottom accumulation rate.

Elliott Bay appears to be a somewhat passive acceptor of sediments supplied by the BNL of the Main Basin of Puget Sound. There is no evidence for substantial redistribution of bottom sediments within Elliott Bay. Sediment redistribution processes in Commencement Bay, however, are vigorous, at least at the two mooring sites. Consequently, the concentration and transport of SPM in the bottom waters of Commencement Bay are controlled by local processes rather than by variations in the flushing rate of these waters by deep water from the Main Basin. More explicit descriptions of the circulation and particle transport processes in this region will require data coverage of the study area on a more extensive scale than provided for in the present study.

4. ACKNOWLEDGMENTS

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