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DYNAMICS OF COMMENCEMENT BAY AND APPROACHES

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DISCLAIMER

CONTENTS

TABLES

FIGURES

DYNAMICS OF COMMENCEMENT BAY AND APPROACHES

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ABSTRACT. Oceanographic and hydraulic model data were examined to determine pathways of water and suspended particulate matter (SPM) in Commencement Bay, a small urban embayment adjoining Puget Sound's Main Basin and the City of Tacoma's waterways. The SPM enters the Bay with the Puyallup River plume as a thin surface layer, and some of the SPM moves into the waterways past industrial facilities. Because water flows into these waterways near both the surface and bottom, trapping of SPM and adsorbed materials may occur in the waterways. The circulatory pattern may be partially responsible for lower concentrations (eight-fold) of lead and PCB in the bottom sediments of Commencement Bay as compared to Elliott Bay adjacent to Seattle. There are counter-currents within the Bay that may change in velocity structure in response to long-term trends of currents observed in Puget Sound.

1. INTRODUCTION

Recent studies have documented increased levels of contaminant chemicals in the sediments of Commencement Bay, Washington, and its adjacent harbor waterways as compared to elsewhere in Puget Sound (Pavlou et al., 1973; Crecelius et al., 1975 and in-press; Riley et al., 1980, 1981; Dexter et al., 1981; and Hileman and Matta, 1983). Harmful effects upon the biota due to these chemicals have been documented in the waterways (Malins et al., 1980 and 1982; Riley et al., 1983; and Word and Day, 1985).

While the sources of these pollutants are generally believed to be the industrial facilities in the City of Tacoma located adjacent to the waterways, the physical and chemical processes that distribute these pollutants to the sediments are not well understood. Riley et al. (1980) reported elevated levels of chemical pollutants in suspended particulate matter (SPM) within Commencement Bay; however, neither the sources of the toxic substances nor their transport pathways to the sediments could be identified. Scavenging of trace metals by SPM, and subsequent advection, deposition, and resuspension of the SPM is believed to play a major role in the transport of chemical pollutants to final deposition in the sediments (Massoth et al., 1982; Pacific Marine Environmental Laboratory, 1982; Curl, 1982). This report discusses the circulation of water and SPM, as well as lead and PCB to a lesser extent, as a means of identifying transport pathways of chemical pollutants within Commencement Bay and its approaches.

1.1 Physical Setting

Commencement Bay lies at the southern end of Puget Sound's Main Basin, which connects through Admiralty Inlet and the Strait of Juan de Fuca to the Pacific Ocean near 48^0 North Latitude (Fig. 1.1). To the north of Commencement Bay, the southern portion of the Main Basin is divided into a number of channels by Vashon Island. To the east of this island lies East Passage, where depths near midchannel average 200 m (Fig. 1.2). West of Vashon Island lies Colvos Passage with depths averaging 110 m. Connecting the southern ends of East and Colvos Passages is Dalco Passage. Depths in this area shoal over a short distance from 165 m near the mouth of Commencement Bay to 44 m within The Narrows, a major sill zone of the Main Basin. Within Commencement Bay depths lessen gradually from the mouth toward the Bay's head, but shoal rapidly along the Bay's northern and southern sides. A number of waterways adjoin Commencement Bay at its head; these waterways are periodically dredged by the U.S. Army Corps of Engineers.

The topography surrounding Commencement Bay averages approximately 300 ft (100 m) in elevation and as a result winds near the water surface tend to be channeled along the major water passages. Wind records obtained at the Point Robinson Coast Guard lighthouse during 1970, 1971, and 1974-1975 indicate that the average wind speed from the south is typically 4-5 m/s in winter, contrasted with 2-3 m/s in summer (Fig. 1.3). Average wind speed from the north reaches 3 m/s during winter and is less than 2 m/s in other months. Average wind speed from all other directions seldom reaches 2 m/s. Hourly wind speeds are fairly equal throughout a day during winter, whereas winds occurring during daylight hours (10:00-20:00) are slightly stronger than those at night during summer months.

Commencement Bay contains approximately 3 km^3 of water at Mean Lower Low Water (MLLW); this volume is equivalent to approximately 4 percent of the Main Basin's volume (McLellan, 1954). A summary of the Bay's dimensions and volume is given in Table 1.1.

The tides in Commencement Bay are mixed in nature, having two unequal highs and lows during each tidal day lasting 24.84 hours. Sea level measurements recorded in Commencement Bay give a mean tidal range of 2.47 m and a diurnal range of 3.60 m (National Ocean Survey, 1977; data from March 10-December 28, 1977). The volume of water between Mean High Water and Mean Lower Low Water (MHW-MLLW, i.e., the tidal prism) is 0.10 km^3 (Table 1.1). Assuming each tide completely replaces an equivalent volume of water, the bulk residence time of water in the Bay is approximately 29 tidal cycles or approximately 15 days.

The Puyallup River is the main source of freshwater to Commencement Bay and discharges annually approximately 10% of Puget Sound's total runoff. The drainage area for the

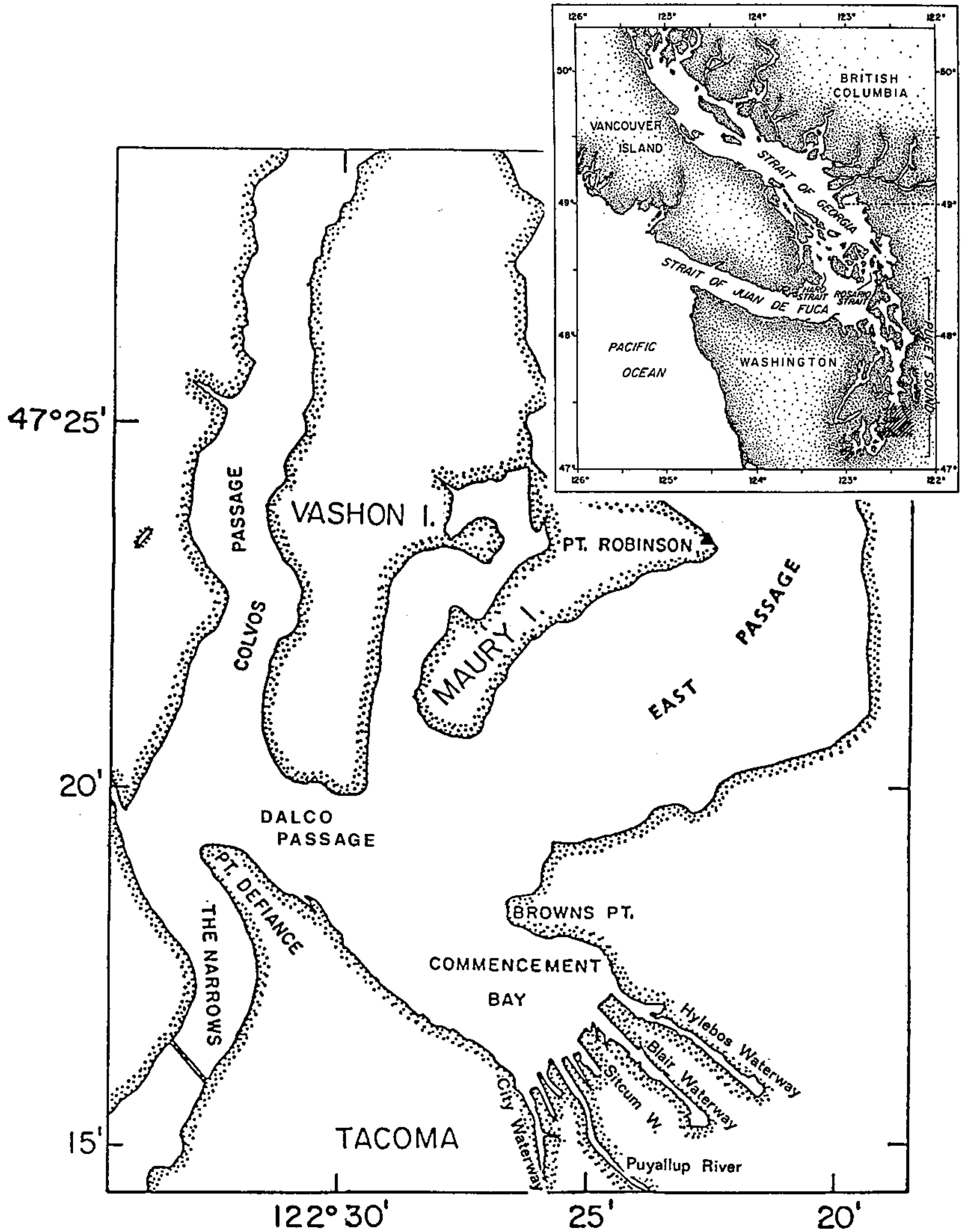


Figure 1.1. Commencement Bay and approaches. Inset shows the marine waterways of Washington and British Columbia; hatched area denotes study area in the map at upper right.

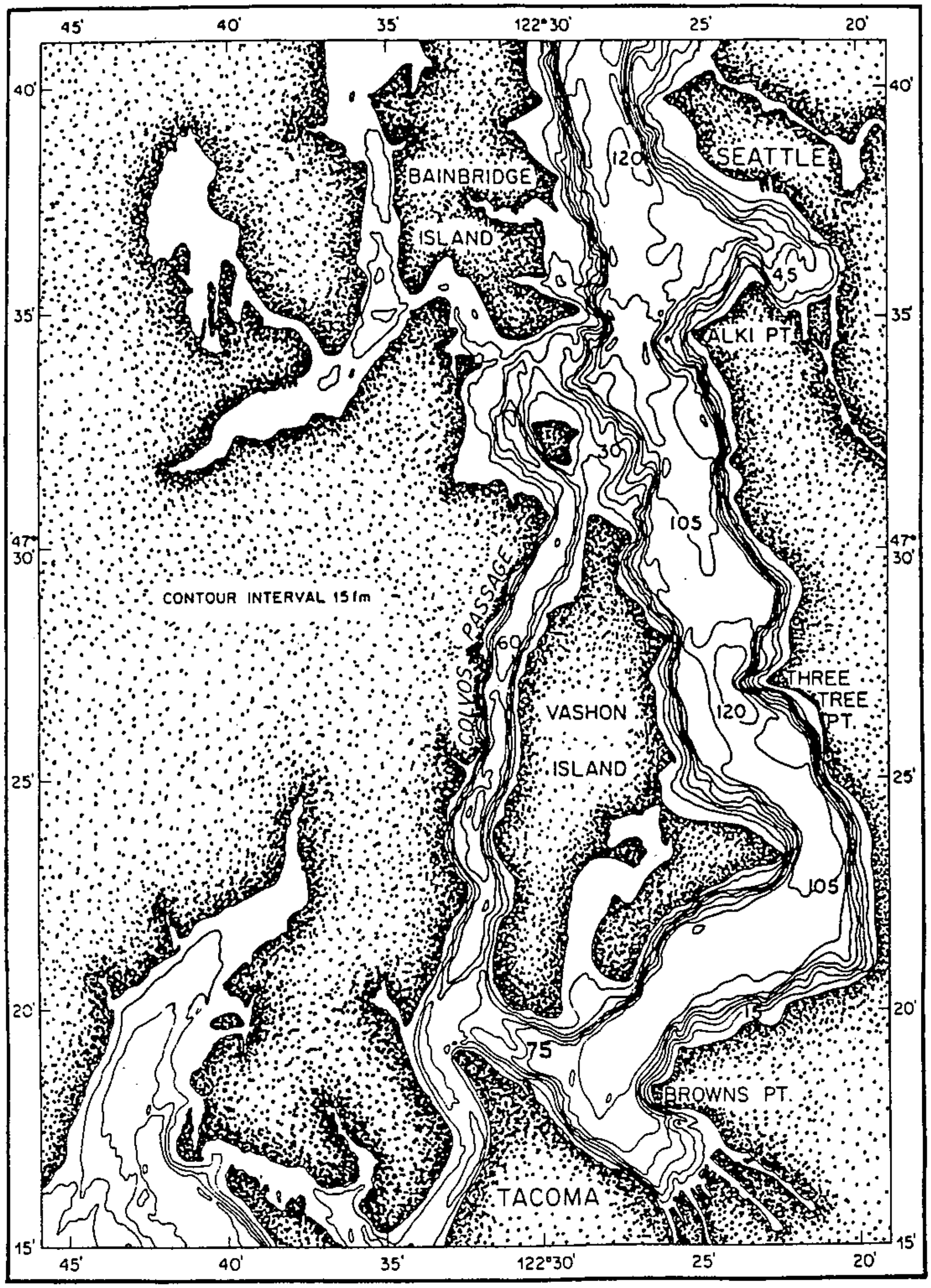


Figure 1.2. Bathymetry in Commencement Bay and approaches. Source, U.S. Navy, 1953. Contour interval is 15 fathoms.

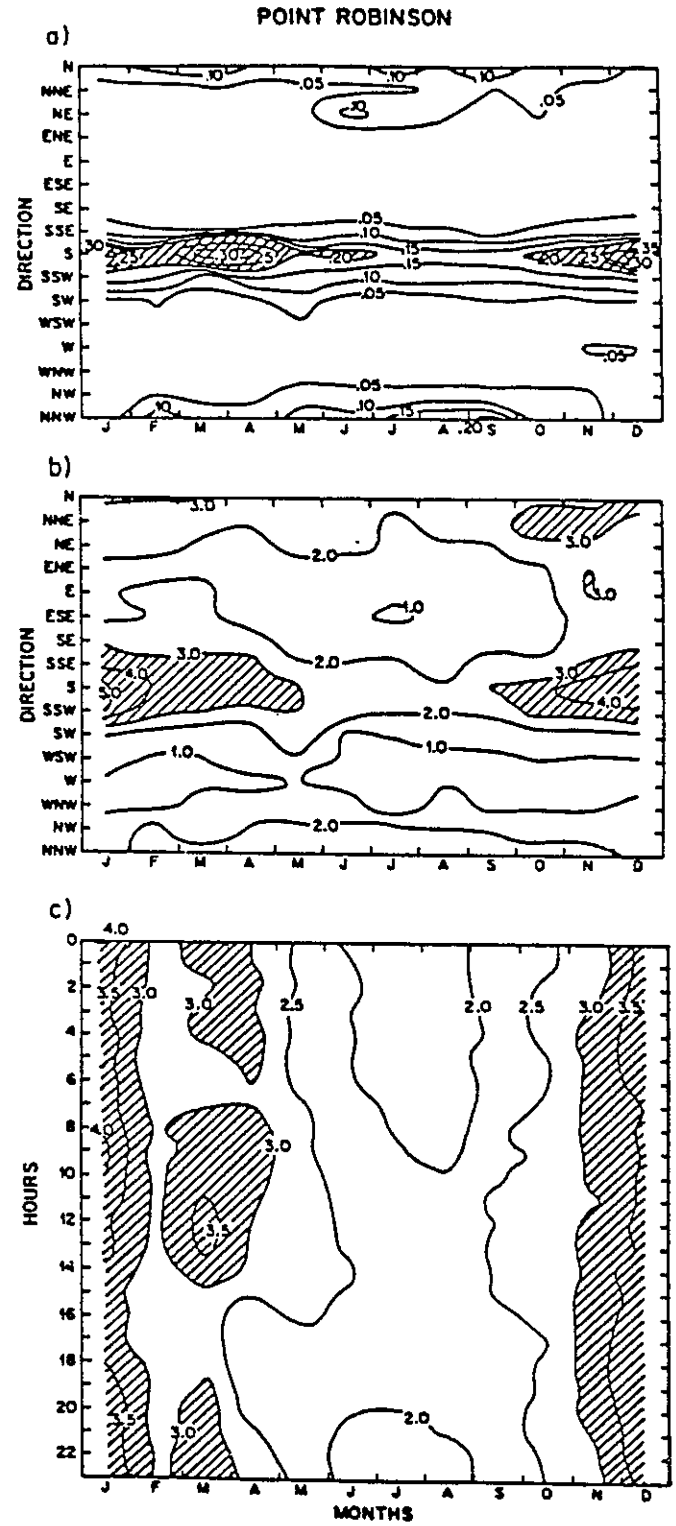


Figure 1.3. Monthly averages of winds observed at Point Robinson (see Fig. 1.1 for location). a) Frequency of winds by direction; b) Mean wind speed (m/s) by direction; c) Mean wind speed (m/s) versus time of day.

Table 1.1 Dimensions and ratios of Commencement Bay

	Amount	Units
Dimensions		
1. Volume MHW-MLLW	0.10	km^3
2. Volume below MLLW	2.86	km^3
3. Area at MLLW	29.4	km^2
4. Cross sectional area of the mouth of Commencement Bay	0.70	km^2
5. Length of Commencement Bay	4.59	km
6. Mean tide height	3.33	m
Ratios		
7. Bulk residence time =	28.6	Tidal cycle
or		
Volume (2)/Tidal prism (1)	14.8	days
8. Characteristic tidal speed = tidal prism (1)/ cross sectional area (4)/ quarter tidal day	0.64	cm/s

MHW = Mean high water
MLLW = Mean lower low water

Puyallup River watershed is approximately 2,455 square kilometers containing mountainous and lowland areas. The seasonal cycle of the Puyallup River runoff is shown in Figure 1.4.

2. METHODS

The sources of data and the analytical techniques used in this report are described below.

2.1 Bathymetry

Bathymetric charts were developed by the U.S. Navy in 1953, and have been recently reproduced by the Municipality of Metropolitan Seattle (METRO) at a scale consistent with topographic charts of the adjacent terrain by the U.S. Geological Survey (USGS). Figure 1.2 was drafted from these charts.

2.2 Wind

Observations of wind speed and direction have been made at Point Robinson (Fig. 1.1) at various intervals. During January 1970-December 1971 measurements were made hourly by the University of Washington (UW). Since January 1973 observations have been made by the U.S. Coast Guard at three-hour intervals. These measurements were obtained from the National Climatic Center in Ashville, North Carolina and the U.S. Weather Bureau in Seattle, Washington.

2.3 Tide

Water elevations have been recorded in Commencement Bay and at a number of locations along its approaches (Fig. 2.1; Table 2.1). Other measurements made in Puget Sound's Main Basin show that the phase and amplitude of the major tidal constituents change little between Seattle and Commencement Bay (Mofjeld and Larsen, 1984). Since the tides are routinely predicted for Seattle, those predictions have been used throughout this report.

2.4 Runoff

Daily averages of the discharge for the Puyallup River were obtained from the USGS for the period January 1931 through August 1979 and monthly averages were computed. In Figure 1.4 the seasonal progression of monthly average values is shown for periods prior to and following the construction of the Mud Mountain Dam in October 1944. The dam is located on the White River, a major tributary to the Puyallup River, and is used to dissipate flood waters. Nearly a decade of below average runoff accounts for the lower averages prior to the dam's construction.

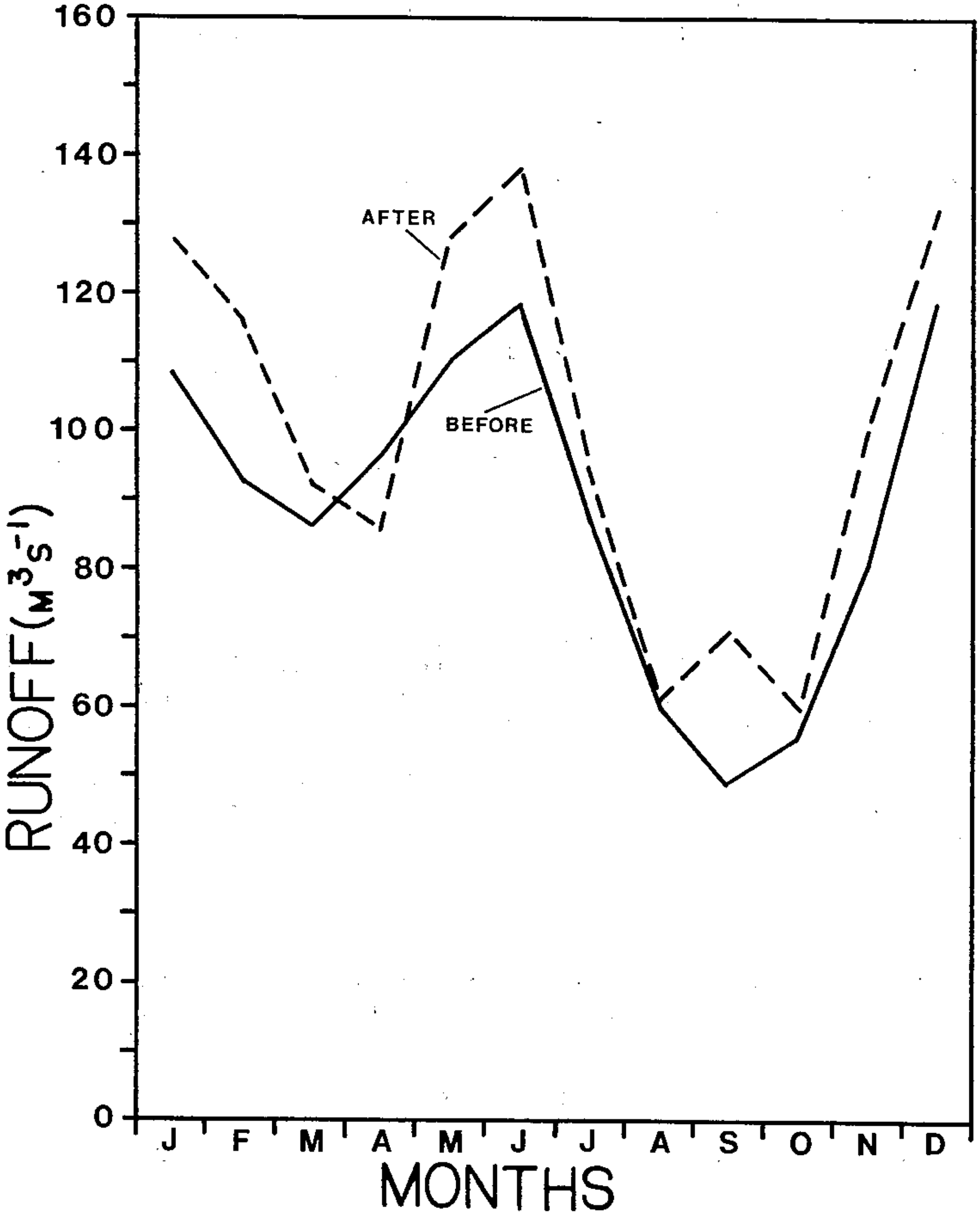


Figure 1.4. Monthly average discharge from the Puyallup River before (solid) and after (dashed) construction in October 1944 of the Mud Mountain Dam on the White River, a major tributary to the Puyallup River.

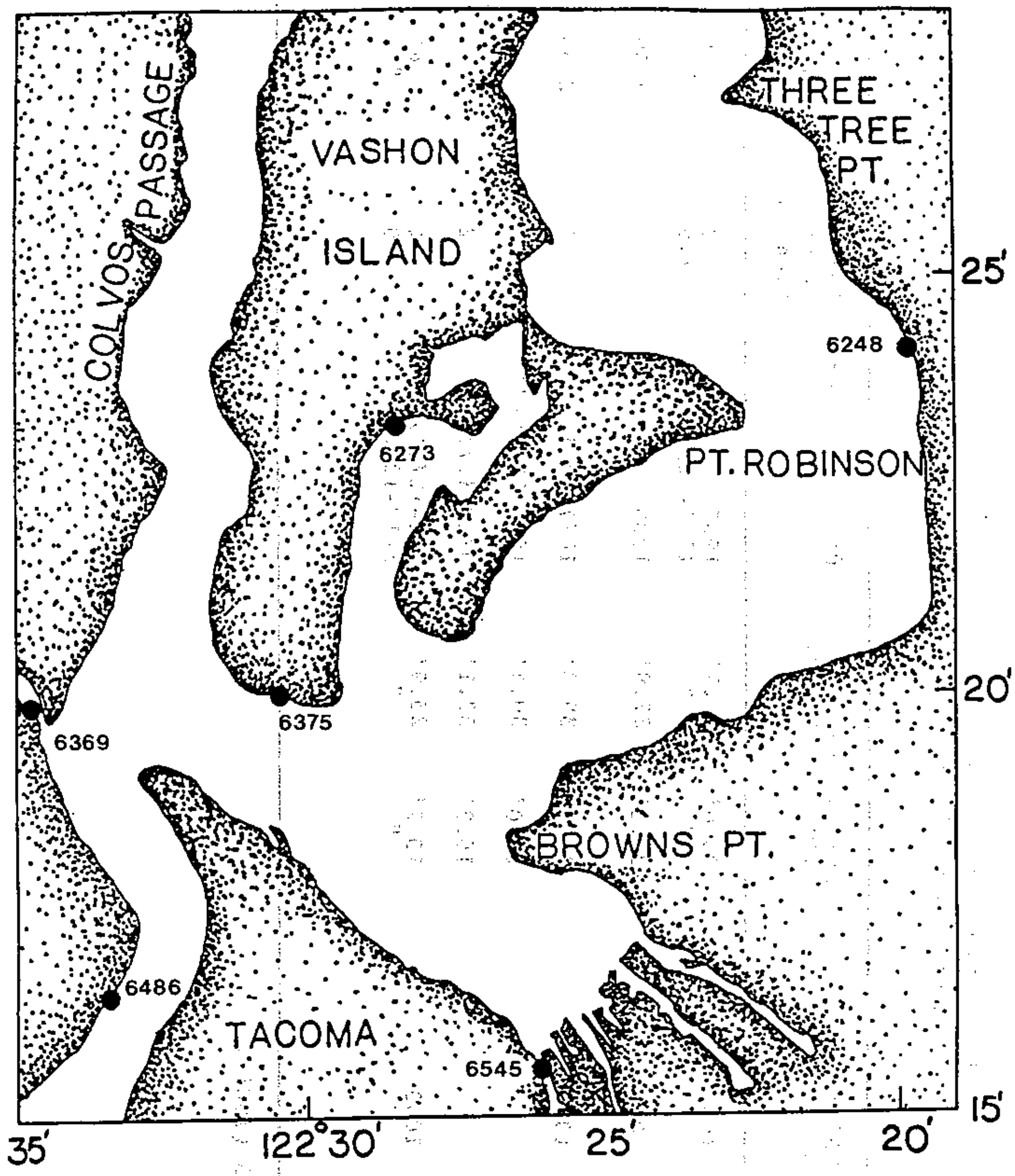


Figure 2.1. Locations (dots) of tidal observations. See Table 2.1 for description of the data which are indexed by the notation next to the dots.

Table 2.1 Positions and periods of observations for tide stations within Commencement Bay and approaches.

NOAA station code	Station name	NOS Tide station No.[a]	Latidude 47°N-	Longitude 122°W-	Dates of Record	Length of record (months)	Mean range (m)	Diurnal range (m)
944-6248	Des Moines	1037	24.0'	19.7'	1935	3	2.44	3.57
	"	"	"	"	10/1-11/13/77	1.5	"	"
944-6273	Burton (Quatermaster Harbor)	1039	23.2'	27.9'	1935		2.50	3.63
944-6369	Gig Harbor	1041	20.4'	35.3'	10/7/52-1/21/53	4	2.50	3.60
944-6375	Neill Point		20.0'	30.4'	10/4-11/15/77	1.5		
944-6486	Tacoma Narrows		16.3'	33.1'	9/28-11/16/77	2		
944-6545	Tacoma	1043	15.2'	25.9'	9/1-12/31/52	4	2.47	3.60
	"	"	"	"	3/10-12/28/77	9	"	"

[a]Station reference number from NOS (1984).

2.5 Currents

Currents have been measured at a number of sites in Commencement Bay and its approaches (Fig. 2.2). The methods by which these records were obtained have been previously described (Cox et al., 1984). These records were reexamined, edited, and computations of net speed, net direction and total variance were made based on an integer number of from 1 to 67 tidal days (Appendix A). Filters were not used in these computations although a few spurious points were deleted. These computations yielded usable data within Commencement Bay at three sites (Fig. 2.2; sites 182, 184, E,). Some observations were then smoothed using a 35-hour filter to suppress the tidal signal and then resampled every six hours to identify changes in net flow versus time.

2.6 Hydraulic Model Experiments

Several investigators have used the hydraulic model of Puget Sound to examine circulatory patterns. The model, built and operated by the University of Washington, has vertical and horizontal scales of 1:1152 and 1:40,000, respectively; a salinity scale approximating observed field conditions; a tide-generating machine having six constituents; and freshwater added proportionate to the discharge of major rivers (see Barnes et al., 1957; Lincoln, 1979). Operating characteristics of the model have compared favorably with selected field observations (Rattray and Lincoln, 1955). Discussions of circulation in Commencement Bay based upon experiments using the hydraulic model have been presented previously by Tsao (1954), Rogers (1955), and the City of Tacoma, Washington (1979).

For this report additional experiments were conducted. The first experiment involved measuring current speed and direction at particular sites within the study area (Fig. 2.3), and calculating net current over a tidal day at each of these sites. Net currents were determined for a spring tide with both high and low Puyallup River runoff. The experiment consisted of releasing spots of dye into the model once per second and photographing them at one-second intervals. From these photographs, the speed and direction of movement of each dye spot over the one-second interval was determined. The dye was released and photographed for two complete tidal cycles. An average of 76 current vectors taken during a tidal cycle were averaged to obtain the net current at each site during one tidal cycle. A comparison made of net currents computed during one versus two tidal cycles gave small differences; therefore, computed net currents are based on a single tidal cycle.

In the second model experiment, time exposures (streak photographs) were taken of the movement of bronze dust upon the model's water surface. During a four second interval one photograph was obtained (using an exposure time of two seconds),

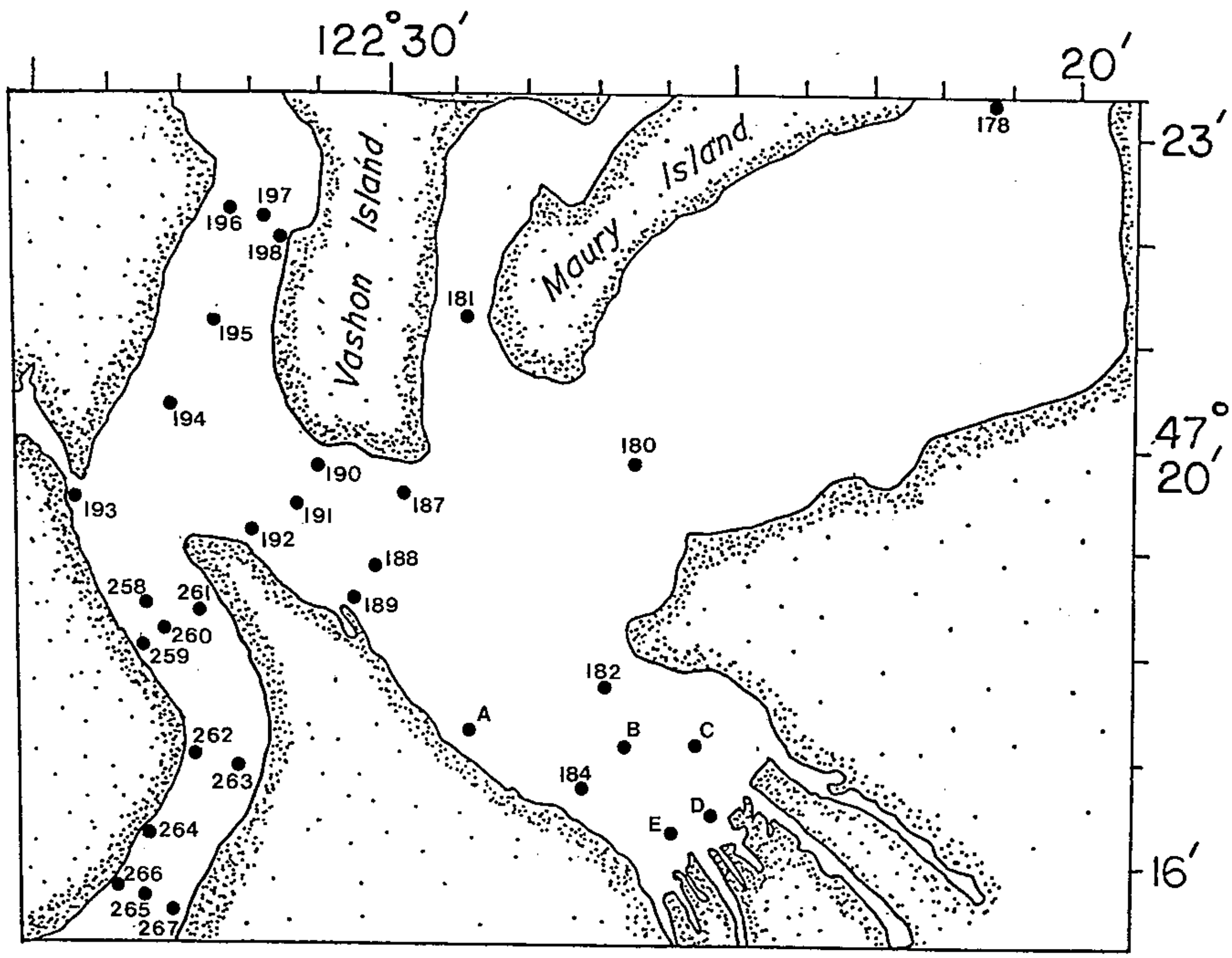


Figure 2.2. Location of current meter observations.
Numbers by dots indicate site numbers shown in Appendix A.

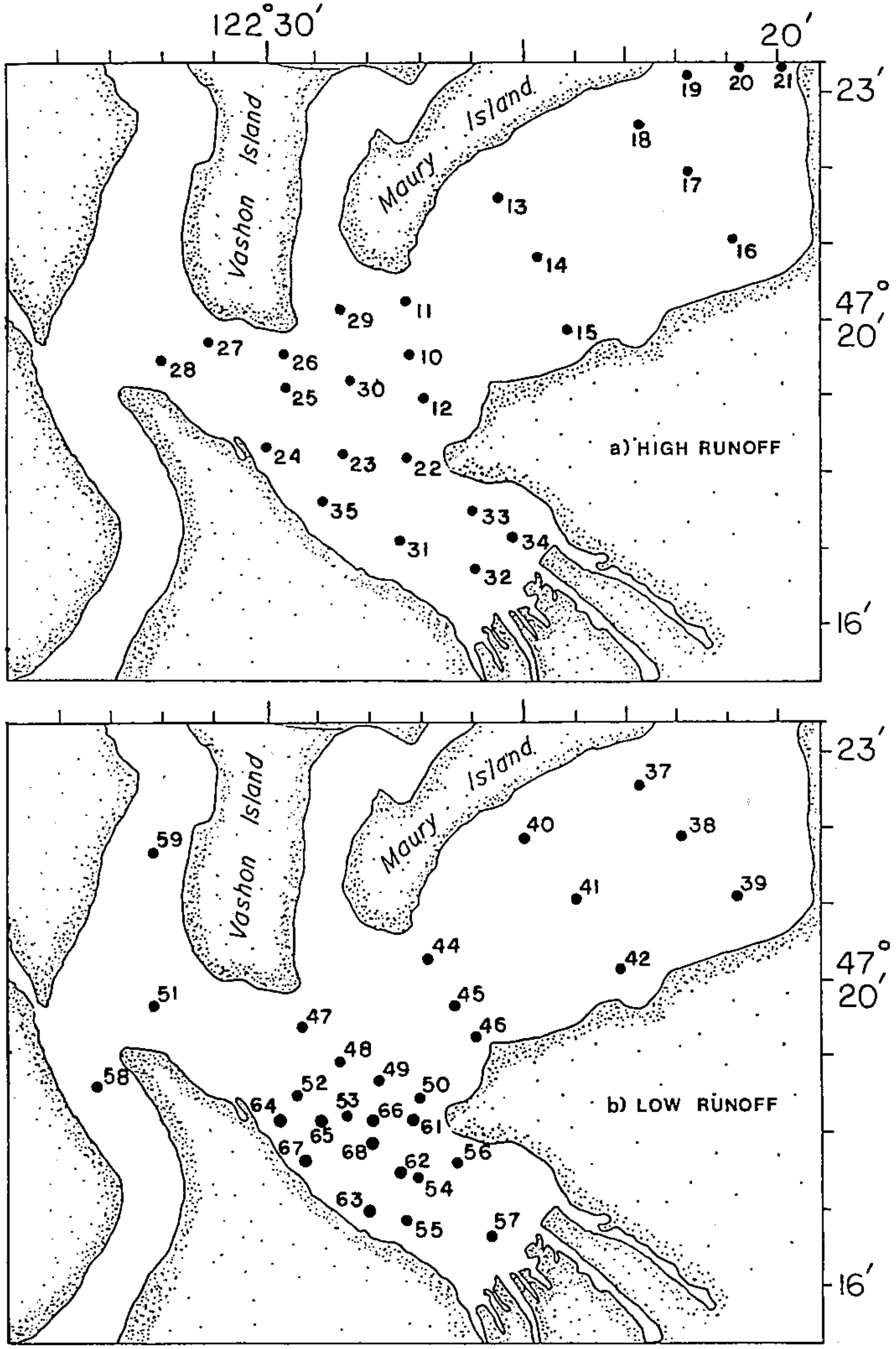


Figure 2.3. Locations of current measurements made in the UW hydraulic model during a) average January (high) runoff and b) average September (low) runoff as computed by Lincoln (1979). Numbers indicate site numbers.

so that 19 photographs were obtained during a tidal cycle. Streak photographs were made for three tide-runoff combinations: 1) spring tide with low runoff; 2) spring tide with high runoff; and 3) neap tide with low runoff. The tide machine was set so that artificial spring and neap tides repeated themselves each day, a technique previously used by McGary and Lincoln (1977). Average January (207 m^3/s) and September (62 m^3/s) runoff as calculated by Lincoln (1979) were used for high and low Puyallup River runoff conditions, respectively.

2.7 Water Properties

Water properties (temperature, salinity, dissolved oxygen) have been measured in Commencement Bay and its approaches by several investigators (Collias, 1970; Pacific Marine Environmental Laboratory, 1982; and Cannon and Grigsby, 1982; Table 2.2). The sites sampled are shown in Figure 2.4.

2.8 Aerial and Satellite Photographs

Photographs of Commencement Bay and approaches were taken from aircraft flying at various altitudes. The archives at the U.S. Geological Survey's Data Center in Sioux Falls, South Dakota, were searched for high-quality photographs having little cloud cover. Color, black and white, and infrared photographs were inspected for patterns of suspended sediment.

LANDSAT satellite photographs were obtained and processed to reveal patterns of suspended sediments. Three photographs have been rendered by an artist to provide a visual perception of the Puyallup River plume and are presented later in this report.

3. NET CIRCULATION

3.1 General Net Circulation

The circulation in Commencement Bay is primarily driven by tides and altered by local winds and runoff from the Puyallup River. The resulting net circulation is estuarine in nature. In the Commencement Bay area this estuarine flow can be subdivided into three regions: movement near the water surface where the effects of the river plume are pronounced; movement at depth where the effects of the Main Basin are strong; and movement in the waterways which receive discharges from man's facilities. Vertical profiles of salinity have shown that the Puyallup River plume in Commencement Bay occupies approximately the upper 2 meters of the water column (Cannon and Grigsby, 1982).

Within the Bay few measurements of the currents have been made from which to compute the net circulation. Recorded

Table 2.2 Hydrographic station locations.

Station[a] No.	Latitude (47°N)	Longitude (122°W)	Station[b] No.	Latitude (47°N)	Longitude (122°W)
320	26'30"	23'30"	4	28.0'	24.2'
321	23'00"	21'12"	25	28.7'	24.7'
322	19'12"	28'00"	26	28.8'	22.5'
323	18'54"	30'12"	27	26.3'	23.5'
324	19'54"	32'24"	28	19.2'	27.2'
352	24'42"	31'42"	29	19.2'	28.2'
353	21'06"	32'24"	30	19.4'	30.1'
375	16'18"	25'36"	31	19.0'	30.5'
376	16'42"	26'18"	32	18.7'	30.7'
377	17'00"	28'12"	33	19.7'	31.3'
378	17'48"	26'24"	34	21.2'	32.6'
379	16'42"	26'18"	35	22.4'	31.6'
380	17'30"	27'48"	36	19.2'	34.0'
381	18'06"	28'06"	37	18.9'	33.9'
401	19'00"	33'36"	38	17.8'	32.4'
402	17'18"	32'12"	39	16.6'	32.8'
403	14'54"	34'24"	40	16.1'	32.6'
			1	17.1'	24.8'
			2	16.8'	25.2'
			3	16.5'	25.7'
			4	16.2'	26.2'
			6	17.0'	26.3'
			8	17.5'	27.1'
			9	17.5'	28.6'
			10	18.3'	30.1'
			11	18.3'	28.3'
			12	18.1'	27.2'
			13	17.2'	28.2'

[a]Data from Collias,1978.
[b]Data from PMEL, 1982; Cannon and Grigsby, 1982.

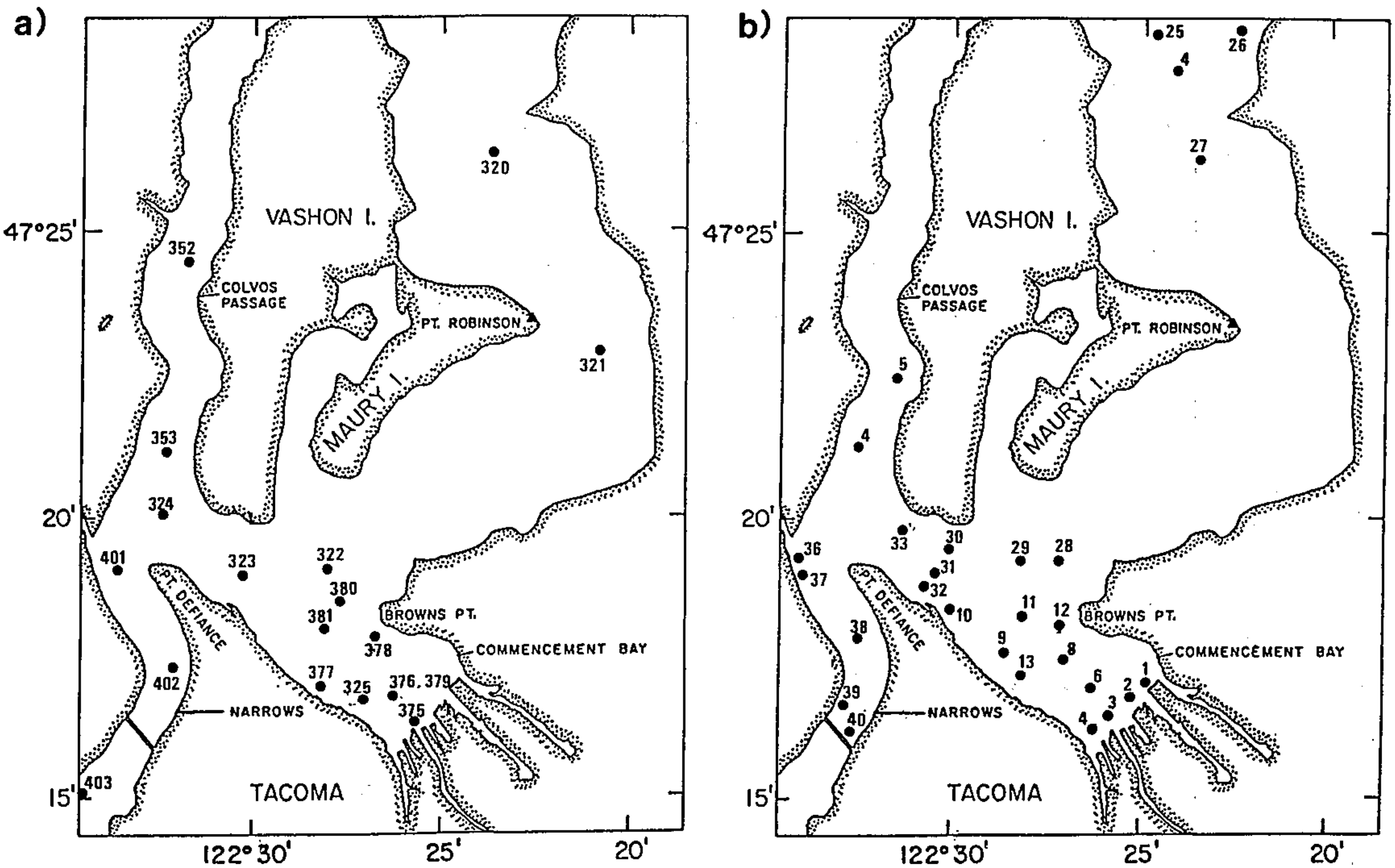


Figure 2.4. Locations of hydrographic observations taken by a) University of Washington (Collias, 1970); and b) Pacific Marine Environmental Laboratory (PMEL, 1982; Cannon and Grisby, 1982).

measurements spanning 14 days or longer have been made at only two sites (182, 184; see Fig. 2.2). Measurements lasting at least one tidal day have been taken at one additional site. None of the longer measurements were taken within the shallow river plume. The net currents computed for all measurements are presented in Figure 3.1 and Appendix A.

Near the surface within the river plume at a location in the Bay the City of Tacoma, Washington (1979) measured current speed and direction at depths of 1 ft and 5 ft over one tidal cycle. The observations were made at approximately hourly intervals; the net speeds and directions computed from these measurements over the tidal cycle are shown in Figure 3.1a. The striking result is that the velocity at 1 foot (14 cm/s) is several times faster than at 5 feet (5 cm/s), and that the directions at these two depths also differ. Based on these measurements the time required for a water parcel to travel from the mouth of the Puyallup River to the mouth of Commencement Bay at a depth of one foot is approximately a quarter of a tidal cycle. This suggests that water parcels in the Puyallup River plume may quickly exit the Bay.

To provide additional insight to the net circulation near surface, net currents were computed from dye spot movements at several sites in the hydraulic model (Table 3.1). These net currents, representing near-surface flow only, are presented in Figure 3.2. Spring tides with either high or low Puyallup River runoff conditions are shown.

The pattern of the net currents from model measurements was similar to that inferred from measurements made in the field. The pattern (Fig. 3.3) shows outflow from the Bay across its mouth with alongshore currents flowing westward toward Point Defiance and northward around Browns Point. The speed of the outflow in the model averaged 4 cm/s at an estimated depth of one meter. In contrast, the field observations indicate maximum speeds of 14 cm/s in the depth range of 0-5 ft. It appears that the model may substantially underestimate current speeds in the river plume.

The net current speed and direction at depth (5 m to bottom) within the Bay (Fig. 3.1) suggest counterflows across the mouth of the Bay. Previous investigators (Cannon and Grigsby, 1982; Baker and Walker, 1982) have suggested that these opposing net flows may be the result of eddy-like circulation. This apparent net eddy circulation also reverses between 75 m and 125 m depth. Attempts were made to confirm the existence and strength of these two net circulation eddy patterns within the hydraulic model using dye spots released at depth, however the technique proved unsatisfactory because the individual dye spots blended together in the slow currents.

The circulation in the waterways is also poorly known. Observations of the velocity and salinity structure within

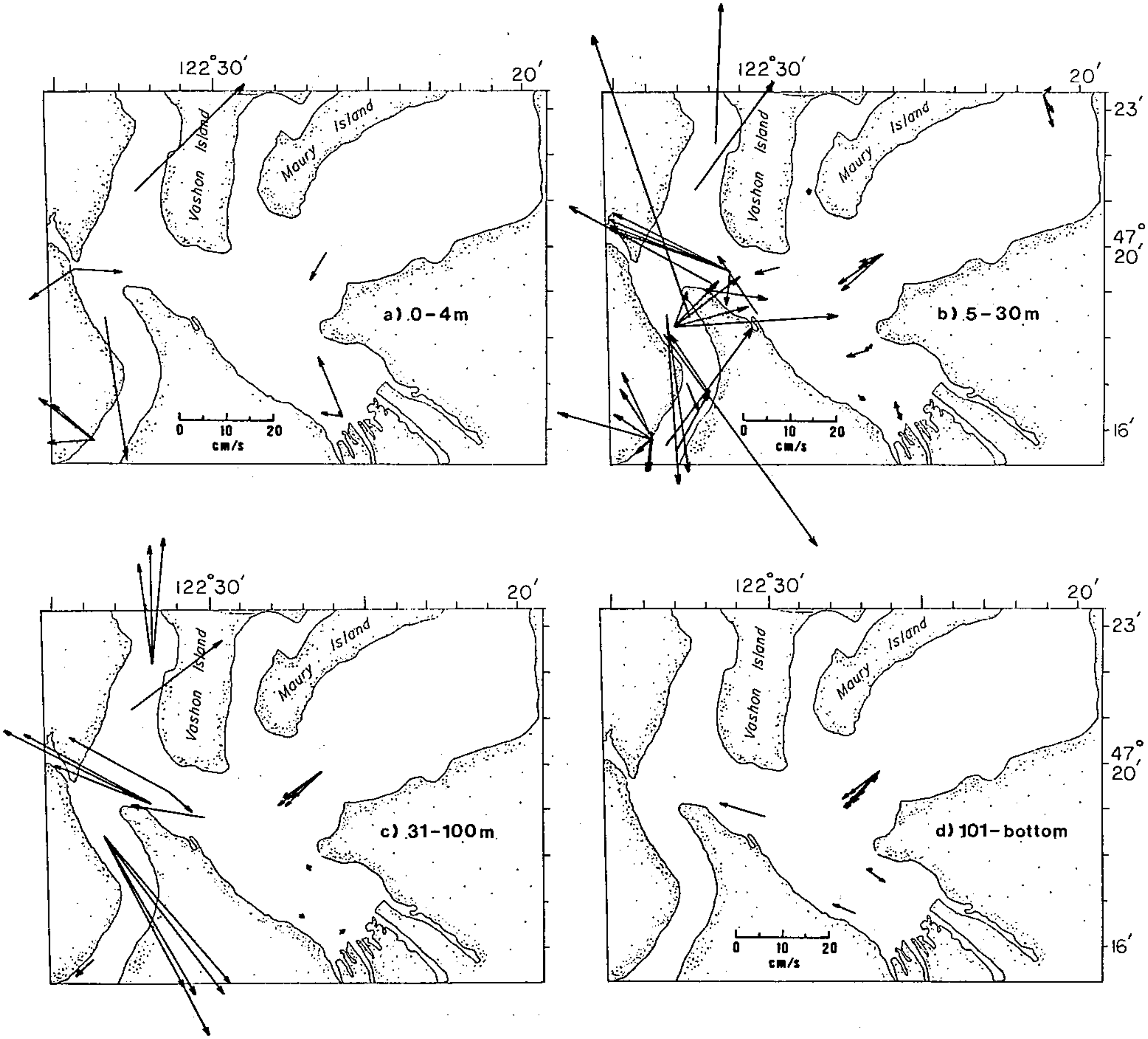


Figure 3.1. Net speed and direction computed from current meter records shown for four depth ranges: a) 0-4 m depth; b) 5-30 m; c) 31-100 m; and d) 101 m-bottom. Arrows indicate current direction and net speed in cm/s, and bases of arrows indicate locations of observations. See Appendix A for a tabulation of the observations.

Table 3.1 Currents near the water surface calculated from observations in the hydraulic model.

Site No.	Depth (m)	Mean Speed (cm/s)	Net Speed (cm/s)	Net Direction (^{0}T)	Variance (cm^2/s^2)
HIGH RUNOFF - SPRING TIDES					
10	1	12.78	4.47	270	183
11	1	15.26	6.22	250	269
12	1	12.93	2.52	343	206
13	1	7.92	2.31	344	74
14	1	9.64	3.98	325	95
15	1	8.89	7.99	271	100
16	1	6.46	3.69	236	45
17	1	8.59	5.60	246	57
18	1	10.78	7.36	37	127
19	1	26.94	10.02	95	771
20	1	14.18	4.64	83	252
21	1	12.87	5.19	169	200
22	1	8.03	2.21	274	67
23	1	8.88	4.01	258	90
24	1	14.66	7.20	318	244
25	1	26.41	7.92	267	913
26	1	35.08	10.95	275	1643
27	1	46.91	11.10	222	2719
28	1	41.43	28.89	237	1431
29	1	11.84	5.09	288	155
30	1	19.36	4.88	116	430
31	1	4.84	2.36	304	29
32	1	7.99	7.76	334	69
33	1	2.45	.57	293	9
34	1	insufficient data			
35	1	6.80	1.59	279	58
LOW RUNOFF - SPRING TIDES					
37	1	13.19	9.26	38	119
38	1	10.25	4.78	256	52
39	1	7.09	2.11	313	87
40	1	7.24	.46	214	68
41	1	7.61	1.23	262	75
42	1	7.16	.82	349	66
44	1	14.49	3.65	188	288
45	1	8.94	3.70	218	95
46	1	11.19	3.03	25	163
47	1	25.41	6.12	218	845
48	1	18.77	5.81	182	390
49	1	12.63	1.20	268	99
50	1	12.49	8.54	66	112
51	1	37.10	19.81	250	1694
52	1	17.02	3.80	172	369
53	1	8.31	4.60	140	86
54	1	3.57	3.05	319	4
55	1	insufficient data			
56	1	5.59	5.29	318	21
57	1	5.82	4.09	323	19
58	1	70.58	3.89	289	6769

Table 3.1 continued

Site No.	Depth (m)	Mean Speed (cm/s)	Net Speed (cm/s)	Net Direction (^{0}T)	Variance (cm^2/s^2)
LOW RUNOFF - SPRING TIDES (CONTD)					
59	1	35.36	35.96	45	793
61	1	7.05	3.02	235	78
	46	5.12	1.17	339	40
	91	7.54	1.77	204	80
	137	15.94	5.88	172	332
62	1	4.52	2.11	311	29
	46	3.31	2.03	241	17
	91	insufficient data			
	137	10.30	.65	100	135
63	1	4.98	3.86	309	37
	46	4.68	.65	276	25
	91	2.97	1.68	133	11
	137	3.42	.40	359	13
64	1	12.26	7.75	305	214
	46	insufficient data			
65	1	6.96	1.84	220	72
	46	insufficient data			
	91	7.33	4.33	214	70
66	1	10.15	.71	238	126
	46	9.15	5.90	225	117
	91	7.82	2.16	217	76
	137	12.48	1.79	3	198
67	1	5.41	4.10	308	55
68	1	6.20	5.87	308	62

See Figure 2.3 for locations of sites.

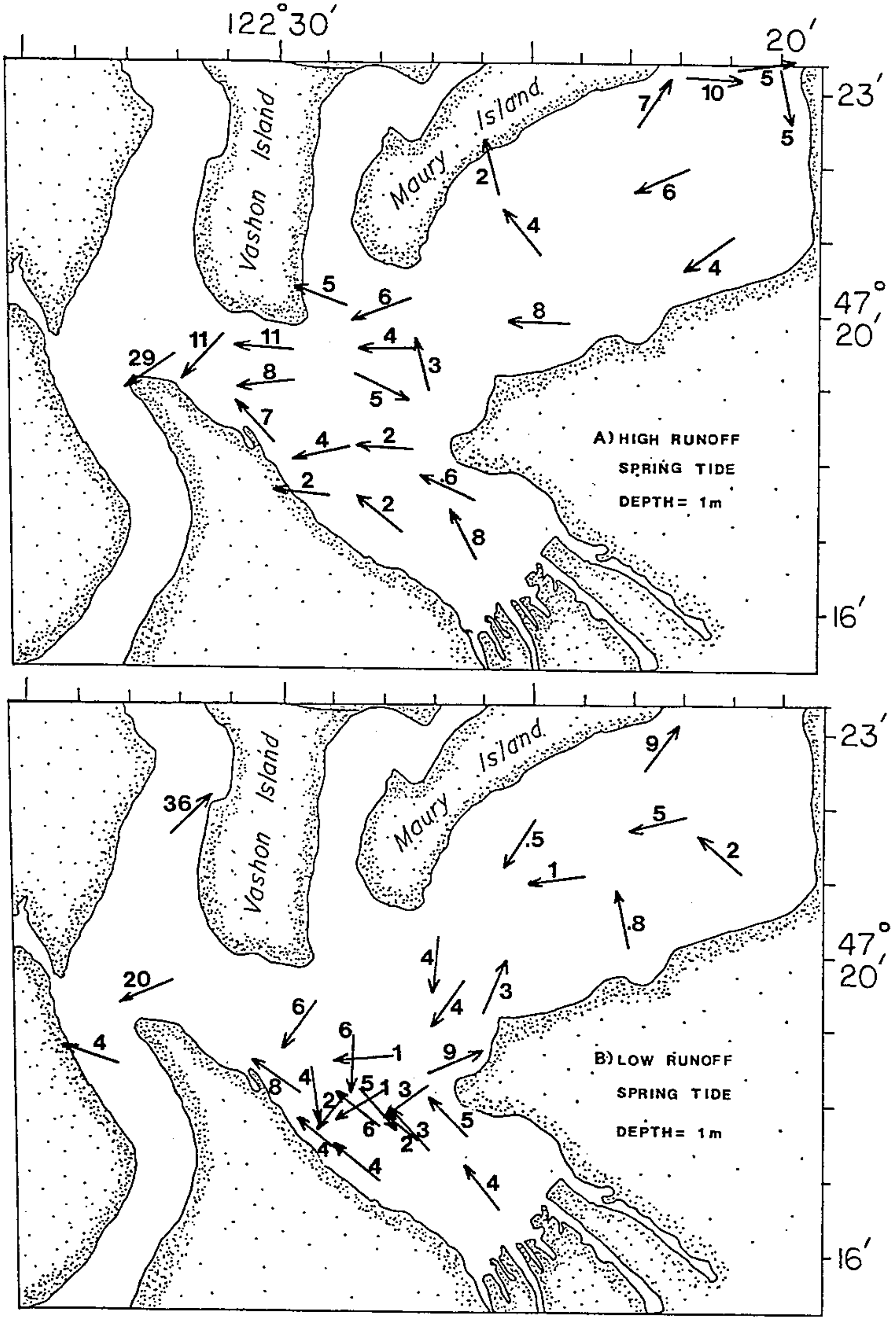


Figure 3.2. Net current speed and direction computed from observations near the surface in the UW hydraulic model: a) high runoff; b) low runoff. Arrows indicate current direction, numbers indicate net current speed in cm/s, and bases of arrows indicate locations of observations.

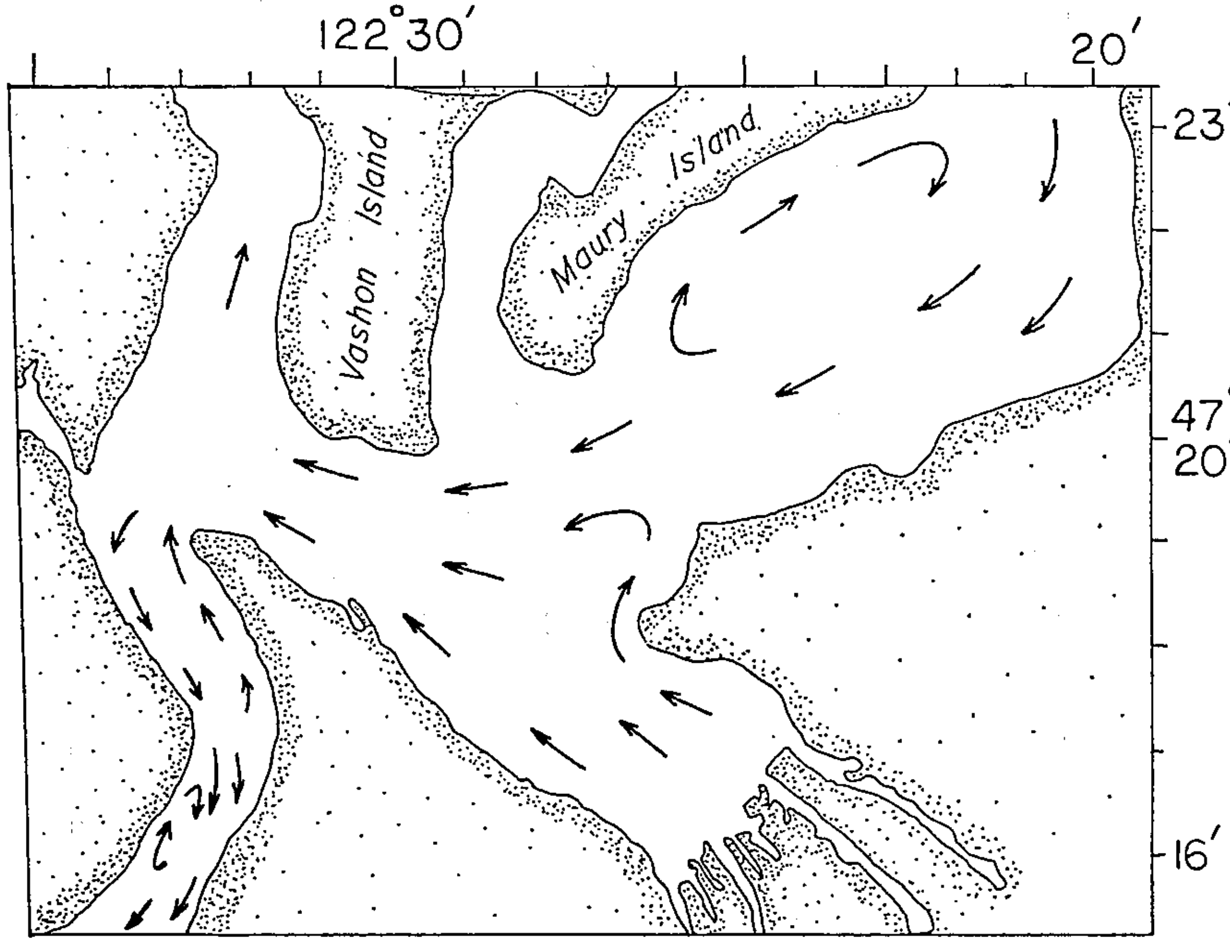


Figure 3.3. Mean circulation near the water surface inferred from observations made in the field and in the hydraulic model (c.f., Fig. 3.2).

Hylebos, Blair, and City Waterways have been reported by Loehr et al. (1981). They found net surface inflow from the Bay into some of the waterways, net outflow at mid-depth, and inflow near bottom (approximately 10 m depth). This circulatory pattern is comparable to other locales in which river runoff enters at the mouth of an estuary (e.g., Baltimore Harbor; Pritchard, 1967).

Understanding the circulation in Commencement Bay requires a diagnosis of the circulation in areas adjacent to the Bay. Portions of the net circulation in these areas have been described previously by other investigators (Barnes and Ebbesmeyer, 1978; Ebbesmeyer and Barnes, 1980; Ebbesmeyer et al., 1984). Herein we have added the results from hydraulic model experiments, and reviewed original records and results of previous studies.

The currents move predominantly in the horizontal direction within the Main Basin. Northward of Vashon Island, at mid-channel, the flow is two-layered with strong northward flow from the surface to a depth of approximately 58 m, and southward flow from below 58 m to the bottom, near 200 m. In the southern part of the Basin, the flow is separated horizontally into East and Colvos Passages. In Colvos Passage, the flow is northward from surface to bottom, whereas in East Passage the flow is generally southward.

In The Narrows there are strong residual currents produced by the interaction of tidal currents with the bathymetry (see Fig. 1.2). Hydraulic model experiments showed that on flood tides the flow in Dalco Passage from surface to bottom moved into The Narrows with little water escaping into Colvos Passage. On subsequent ebb tides, most of the water from The Narrows traveled into Colvos Passage with some flow escaping into Dalco Passage. To visualize the pattern of residual currents, net current speed and direction shown in Appendix A have been displayed in four depth ranges: 0-4 m; 5-30 m; 31-100 m; and 101 m-bottom (Fig. 3.1 a-d). It can be seen that the flow in Dalco Passage is westward over most of its width and depth, an observation that is based on nine estimates using the hydraulic model. The mean speed is 19 cm/s. In Dalco Passage there is a strong westward flow that is largely induced by the tides.

3.2 Variability of the Net Circulation

In Commencement Bay and the adjacent passages current measurements have not been taken at one site over a number of years. Only a few sites have had repeat measurements made, most of those were taken in 1980 and 1981. Consequently the steadiness of the net circulation over periods of years is unknown. However, an ongoing examination of the net circulation of Puget Sound's Main Basin has shown such fluctuations do occur and may have a substantial effect upon the net circulation of bays attached to the Main Basin.

For the Main Basin, Ebbesmeyer et al. (1985) examined several records which could be broken into 129 intervals each lasting 28 days. There is a substantial modulation of the tides at fortnightly intervals which was suppressed by averaging the current vectors over 28-day intervals. The result indicates long-term changes. Figure 3.4 shows the vertical distribution of the along-channel speeds for the 31 intervals in which two or more depths were sampled concurrently. The outstanding features of these current profiles are that the water column was consistently separated into an upper and lower layer; the depth of no-net-motion was fixed at 58 m; and current velocities in the lower depths (100-200 m) changed significantly over the last decade. The deepwater current was fastest near 100 m depth during 1972 to 1976, but changed to being fastest near 175-200 m from 1978 through 1984. Figure 3.5 shows a schematic of this change in the velocity profile. The change in the deepwater net current occurred during a broad climatic shift initiated in 1976. Ebbesmeyer et al. (1985) hypothesized that during pervasive climatic events occurring during 1976-1977, a shift to increased southerly winds along the Pacific Coast contributed to a change in the flow characteristics at the entrance sill zone which lowered the depth at which water masses entered the basin.

Because the Main Basin may be a major driving force for Commencement Bay, it is reasonable to expect that circulation within the Bay may also undergo long-term changes which in turn may impact dispersal patterns of waste products. Long-term fluctuations of priority pollutants and benthic animal populations have been observed in the vicinity of the Main Basin current meter moorings shown earlier (Crecelius and Bloom, 1984; Nichols, 1985), and although some changes may be associated with man's activities, strong long-term changes in the bottom current regime may be partially responsible for these fluctuations.

4. TIDAL CIRCULATION

Both the strength of the currents and the pattern of the circulation which occur throughout a tidal cycle influence the distribution and fate of suspended particulate matter (SPM) and associated contaminants in the Commencement Bay area. The strength of the currents influences the potential resuspension of bottom sediments as well as the distance which SPM will travel before settling to the sea floor. The patterns of the circulation during a tidal cycle direct the short term movement and distribution of SPM.

4.1 Strength of the Tidal Currents

A general idea of the strength of the currents which occur over tidal cycles can be obtained by examining the total variance of current meter records. In addition the total variance of currents measured in the model were computed for the sites shown

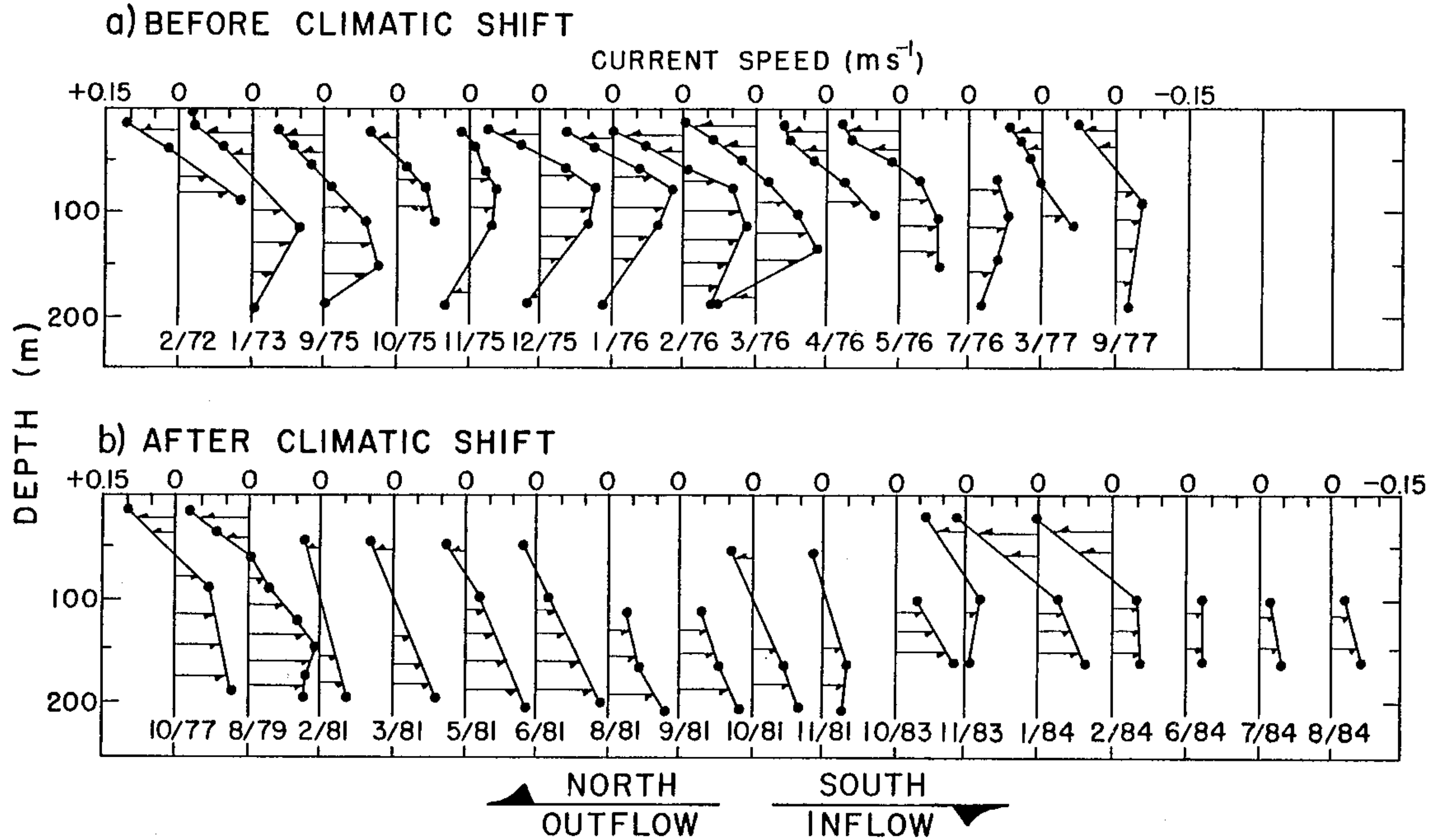


Figure 3.4. Profiles of 28-day average currents before (a) and after (b) the climatic shift. Arrows indicate outflow and inflow in the Main Basin, and the dates indicate the month/year of the center of the 28-day intervals.

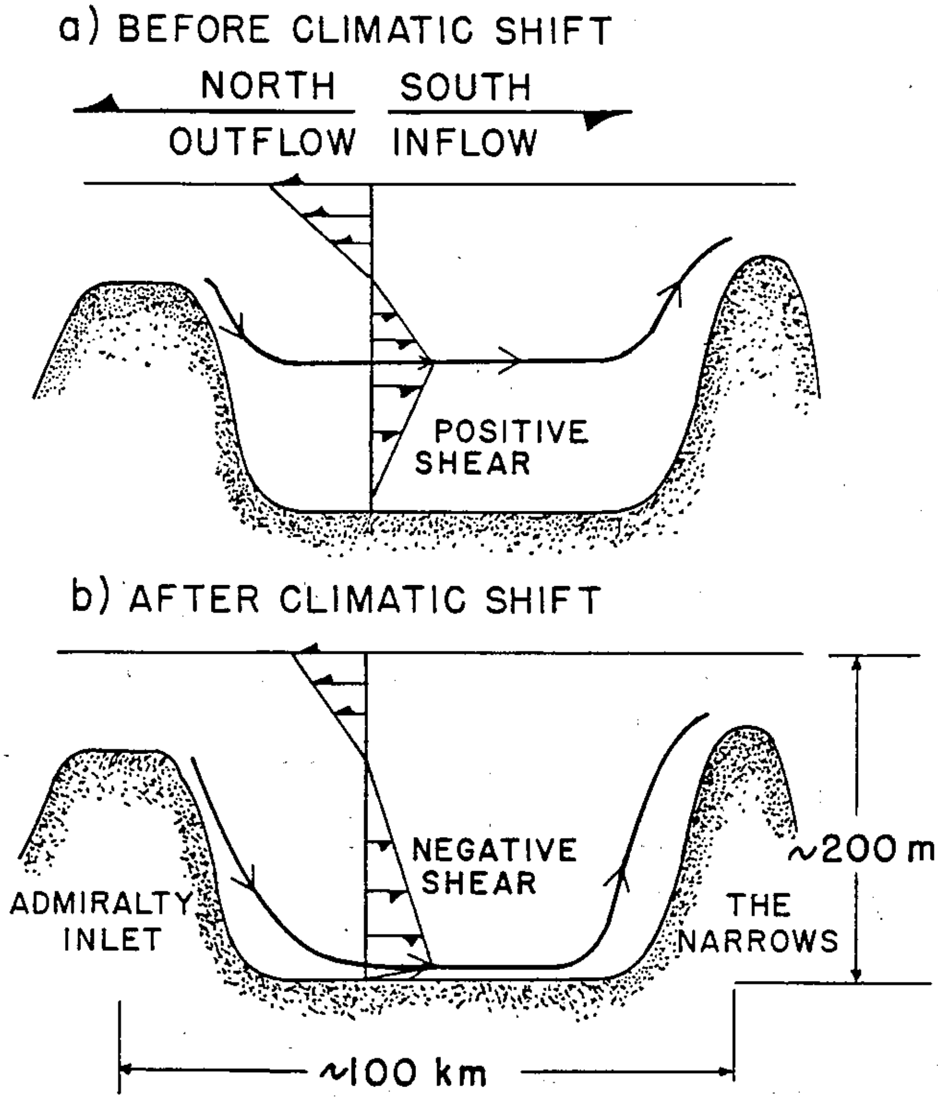


Figure 3.5. Schematic velocity profiles in Puget Sound's Main Basin before (a) and after (b) the climatic shift. The profiles have been superimposed on mid-channel depth between the basin's embracing sills. Before the climatic shift water travelled most rapidly at mid-depth, whereas afterward the fastest flow occurred near the bottom (see heavier lines). During the shift the velocity gradient, or shear in the lower half of the water column, reversed from positive (a) to negative (b).

in Figure 2.3. The variances computed from both the field and model observations are graphed in Figure 4.1 versus the distance from the head of Commencement Bay toward Point Defiance. Model data are surface measurements only; field data have been averaged vertically at each measurement site where more than one depth was sampled.

The data show that the variance within Commencement Bay averages approximately 50 cm^2/s^2, whereas between the mouth of the Bay and Point Defiance it increases rapidly. The strength of the gradient is equivalent to 330 cm^2/s^2 per nautical mile; the variance at Point Defiance reaches approximately 1000 cm^2/s^2, a twenty-fold increase over that in the Bay. For perspective, variance within the Main Basin off Seattle ranges from approximately 150-300 cm^2/s^2, within East Passage from 150-250 cm^2/s^2, within Colvos Passage from 500-700 cm^2/s^2, and within The Narrows from 3000-15,000 cm^2/s^2 (Cox et al., 1984). Other embayments adjoining the Main Basin's major passages such as Elliott and Seahurst Bays have variances of 10-40 cm^2/s^2 (unpublished data from the Municipality of Metropolitan Seattle). Commencement Bay thus has a low tidal current strength typical of other embayments adjoining the Main Basin. One important difference, however, is that it is situated adjacent to passages containing some of the strongest tidal currents within Puget Sound. The mean tidal current speeds without regard for direction associated with these variances have been calculated for only a few of the current meter records. Those that have been computed are given in Appendix A while mean speeds of the model observations are given in Table 3.1.

4.2 Patterns of Tidal Currents

4.2.1 Commencement Bay

To visualize tidal currents in Commencement Bay, streak photographs were examined (Appendix B). Streak photographs capture the movement of the surface water in the model. Inspection of the model photographs shows that within the Bay the direction of water movement at many tidal stages is difficult to ascertain.

A number of aerial photographs have been made of the Bay at various tidal phases which show patterns of suspended sediment. These photographs are useful in interpreting tidal currents. To interpret the aerial photographs, it is necessary to know the vertical scale of the suspended sediment. The photographs often show sediment flowing from the mouth of the Puyallup River as a jet (Fig. 4.2a). This sediment is contained within the Puyallup River plume which is the dominant source of freshwater to the Bay. As the plume enters the Bay it overrides the more saline Puget Sound water forming a thin surface layer. The thickness of this layer can be judged from vertical profiles of salinity and

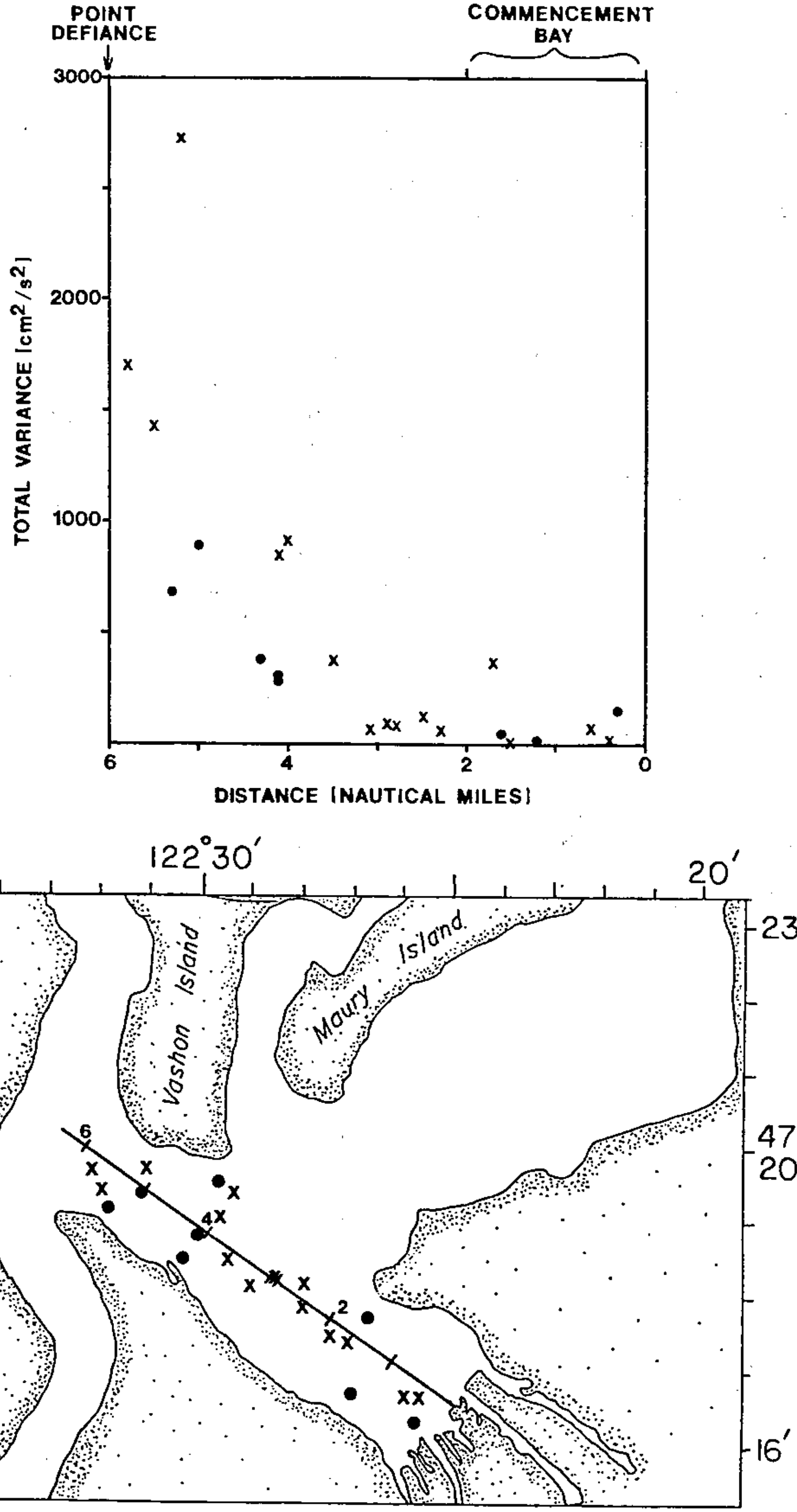


Figure 4.1. Total variance from current measurements versus distance from the head of Commencement Bay (a). Dots (●) indicate field data and X's indicate model data. Figure (b) shows the observation sites and the scale indicates distance in nautical miles from the head of Commencement Bay.

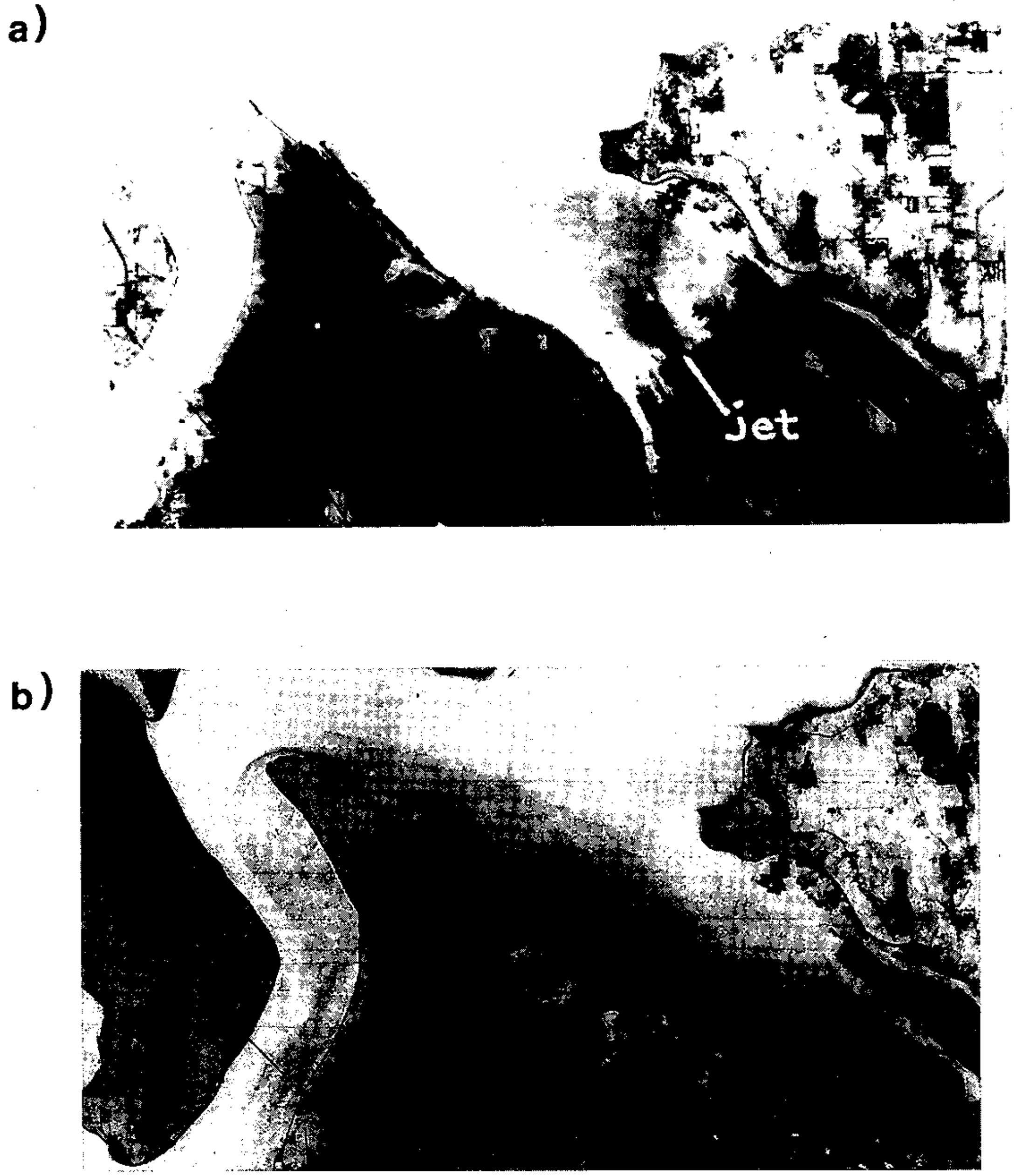


Figure 4.2. Aerial photographs showing suspended sediment exiting the Puyallup River. Photo (a) shows the plume exiting the river as a "jet"; photo (b) shows the plume entering the Bay and adjacent waterways at the head of the Bay.

light attenuation (Cannon and Grigsby, 1982; Baker and Walker, 1982). The presence of sediment can also be verified visually from aircraft, or by watching a small boat travel through the river plume which results in contrasting water colors. The wake of the boat fractures the plume, and the color of Puget Sound water is evident in summer as a green color which shows through the lighter brown color of the sediment. Vertical profiles and aerial photographs indicate that the river plume and suspended sediment are largely contained in a surface layer approximately two meters thick.

The aerial photographs show that the river plume can be distributed over most of the Bay's surface (Fig. 4.3). The photographs also show that river water enters Blair, Hylebos, and City Waterways at the surface (Fig. 4.2b). These waterways are approximately 5-10 meters deep and receive a small amount of freshwater compared with the total discharge from the Puyallup River. Consequently, Puyallup River water is the dominant freshwater source for these waterways causing a net movement of water near the surface into the waterways. This movement apparently induces a three-layer flow pattern with outflow at mid-depth and inflow near the bottom in the waterways (Loehr et al., 1981). This circulatory pattern may have important consequences for the fate of toxicants released within the Bay as discussed later.

The aerial photographs also show that suspended sediment is drawn out of the Bay at various tidal stages. Superposition of Figures 4.3 a-c shows that the river plume can be present at any position in the near approaches to Commencement Bay embraced by The Narrows on the west and Poverty Bay on the east.

4.2.2 The Narrows and Approaches

The pattern of tidal currents at the water surface in The Narrows and approaches has been previously presented based upon observations in the hydraulic model and in the field (McGary and Lincoln, 1977; NOS Tidal Current Charts, 1973). The progression of these patterns through a tidal day is shown in Appendix C. To more accurately interpret the behavior of the tidal currents, similar patterns taken at more closely spaced time intervals were required. For this purpose, streak photographs were obtained of this area within the hydraulic model (Appendix D). The photographs were taken at approximately one hour intervals during the tidal cycle used by McGary and Lincoln (1977).

The streak photographs show that the tidal current patterns change significantly between the hourly photos. As the tide begins to ebb in The Narrows, an eddy begins to form immediately north of Point Defiance (Appendix D, m-r). As the ebb tide progresses, the eddy grows in size until its diameter spans Dalco Passage. In the later stage of the ebb cycle, the eddy shifts to the mouth of Colvos Passage and the flood waters progress from Dalco Passage into The Narrows. This sequence occurs twice per

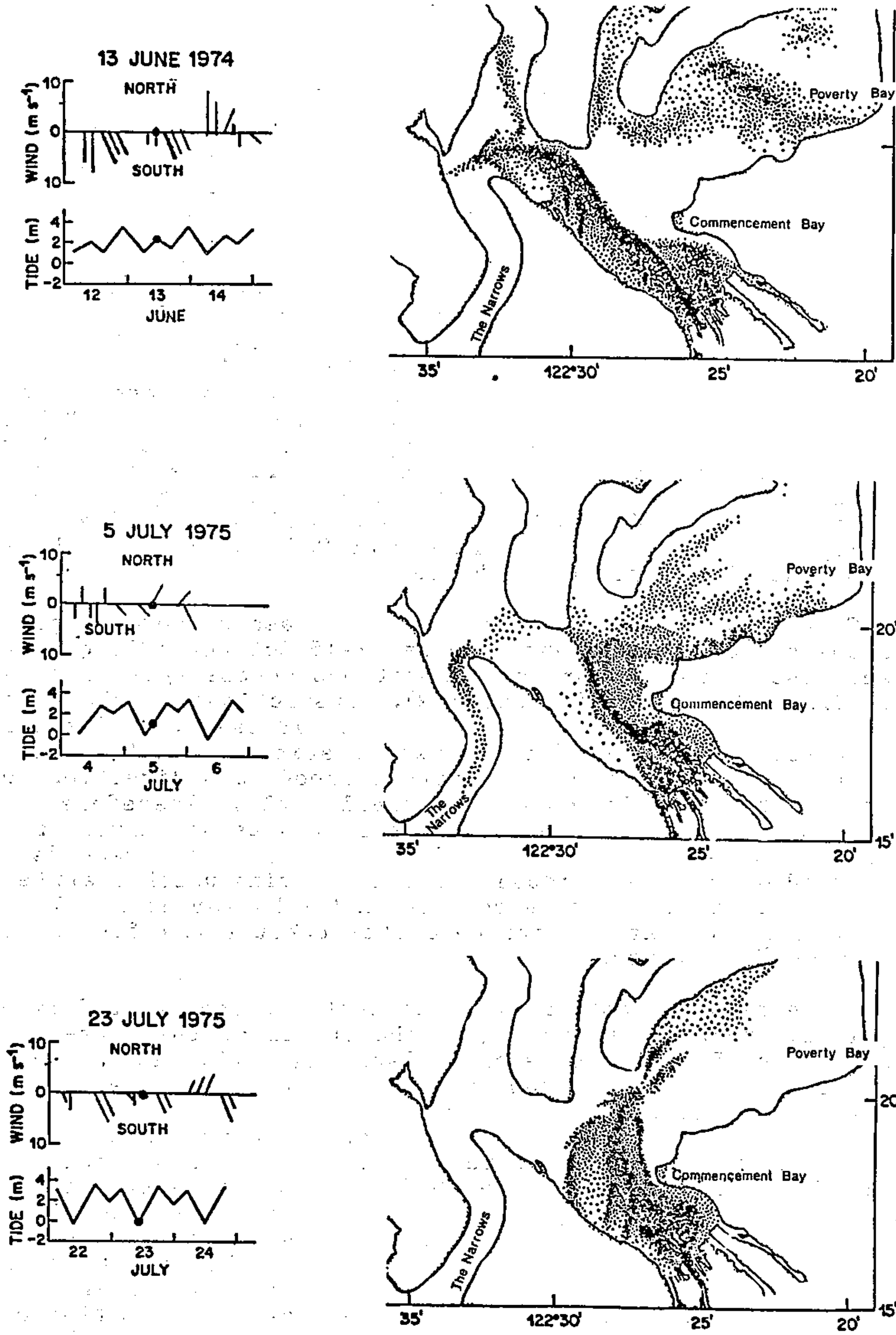


Figure 4.3. Artist's rendition of LANDSAT photographs of Commencement Bay and approaches taken on 13 June 1974, 5 July 1975, and 23 July 1975, showing suspended sediment patterns. The graphs to the left of each drawing show the wind condition and tidal phase at the time (●) the photograph was taken.

day in association with the daily occurrence of two flood and two ebb tides.

Because this eddy partially regulates the flow of water from Dalco Passage and also Commencement Bay, a closer inspection was made of the eddy's characteristics, and a description of the eddy was made with reference to Seattle tides. The life of the eddy during an ebb tide is approximately as follows: initially as water begins to ebb from The Narrows, the streak lines are parallel to the shoreline. After approximately 10% of the ebb interval has elapsed, a small vortex is evident immediately north of Point Defiance. By the time approximately 40% of the ebb interval has elapsed, the eddy has grown and its diameter spans approximately half the width of Dalco Passage. After 70% has elapsed, the eddy has grown to occupy the width of Dalco Passage. After 90% has elapsed the eddy occupies nearly the entire area bounded by Point Defiance, Vashon Island, and the shoreline immediately westward. As water begins to flood into The Narrows the eddy moves into the southern end of Colvos Passage, where it is subsequently advected northward.

Current meter measurements in Dalco Passage were compared with the streak photographs. During 7-15 October 1952 current measurements were made at three locations across Dalco Passage (Fig. 2.2; sites 190, 191, and 192). Inspections of the records showed that the data were incomplete at mid-channel. Furthermore, correlations made for the two locations on either side of Dalco Passage showed that the current speeds and directions were uniform with depth throughout the tidal cycle. Therefore, current speed and direction were contrasted using current meter records at mid-depth from sites 190 and 192. These records were contrasted over an individual tidal day during which Seattle tides were comparable to those used in the hydraulic model (Fig. 4.4a). Current vectors were then constructed for the two locations (Fig. 4.4b).

These records contain evidence that the eddy does form on ebb tides. Near the beginning of the ebb tide, the currents on both sides of Dalco Passage are relatively weak. As the ebb progresses the currents grow in strength but are opposite in direction and aligned with the shore. As the eddy grows it increasingly affects both locations causing currents to grow in strength. Immediately after the ebb ends, the flood tide begins causing the currents near Point Defiance to grow even stronger, reaching their fastest speed at about midway through the flood tide. Concurrently, along the Vashon Island shoreline the currents reverse early in the flood tide and flow parallel to shore. Because of the eddy, the currents along the Point Defiance shoreline within Dalco Passage nearly always flow westward. A direct comparison of the current vectors with the streak photographs is shown in Appendix E.

To gain additional confidence that the streak photographs are representative of the environment, comparisons were made with

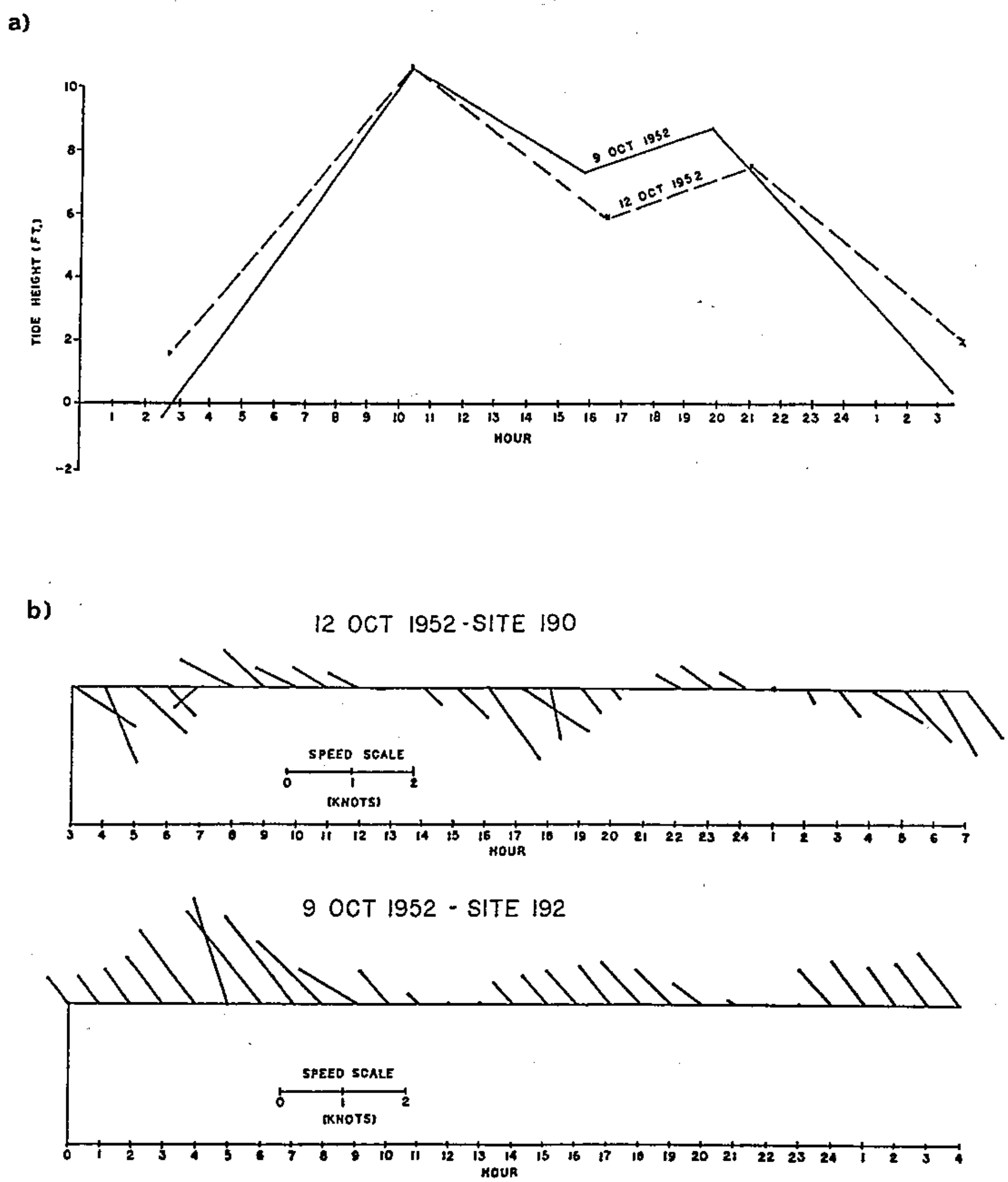


Figure 4.4. Seattle tide stages (a) compared with current speeds and directions (b) in Dalco Passage (see Fig. 2.2 for site locations). The time scales for the current records have been shifted so that the times of lower low water are coincident.

aerial photographs showing patterns of suspended sediment (Figs. 4.5-4.7). The Puyallup River contains a sizeable load of suspended sediment, and portions of the sediment-laden plume are visible between the mouth of the Puyallup River and The Narrows. Photographs were compared at two flood tide stages (Fig. 4.8). On 20 July 1972 a photograph was made after approximately 50% of a larger flood tide had elapsed. On 11 July 1973 two photographs were made after approximately 25% of a larger flood tide had elapsed.

The comparisons may be summarized as follows. On 20 July 1972 there are two lines of sediment in Dalco Passage which parallel streak lines in the model. On 11 July 1973 sediment from the Puyallup River can be seen flowing around Point Defiance into The Narrows. The edge of the sediment-laden water parallels streak lines in the model. The second aerial photograph of 11 July 1973 was made such that reflections from the water revealed tidal current patterns. At the bottom of both photographs the convergence of water from Dalco and Colovos Passages is visible. This convergence, which is prominent in the streak photographs, begins as a stagnation point at the southern end of Vashon Island and extends westward as a darker streak. Although data is limited, we conclude there is general agreement between the model results and the movement of the plume on flood tides.

Additional comparisons can be made with other experiments conducted in the hydraulic model. In those experiments blue dye was released throughout the water column in Dalco Passage on several flood tides. Subsequently, the dye was followed as it moved westward through Dalco Passage. On each flood tide all of the dyed water flowed from Dalco Passage into The Narrows with none entering Colvos Passage. The path followed by the dye paralleled the streak lines from the water surface to near the bottom. When the dye entered The Narrows it was mixed top to bottom with the result that on the ensuing ebb the eddy was not clearly evident in the cloud of mixed dye that emerged from The Narrows. We suspect that because of the intense mixing the eddy is not evident in aerial photographs of suspended sediment.

5. SUSPENDED PARTICULATE MATTER

The fate of contaminants in our nation's water systems, especially in close proximity to concentrated urbanization, is a growing concern. The distribution of suspended particulate matter has been found to be sensitive to transport characteristics of a given environment (Baker et al., 1983).

5.1 Processes

Some observations of SPM have been made in Commencement Bay by Baker and Walker (1982), who found that transport of SPM in the upper portion of the water column was controlled by the a]

b]

Figure 4.5. Comparison of : a) patterns of suspended sediment in Dalco Passage with b) streak lines in the hydraulic model after half a tidal phase has elapsed on 20 July 1972 (see Fig. 4.8 for tidal phases).

a)

b)

Figure 4.6. Comparison of : a) patterns of suspended sediment in Dalco Passage and The Narrows with b) streak lines in the hydraulic model after 25% of a tidal phase has elapsed on 11 July 1973 (see Fig. 4.8 for tidal phases).

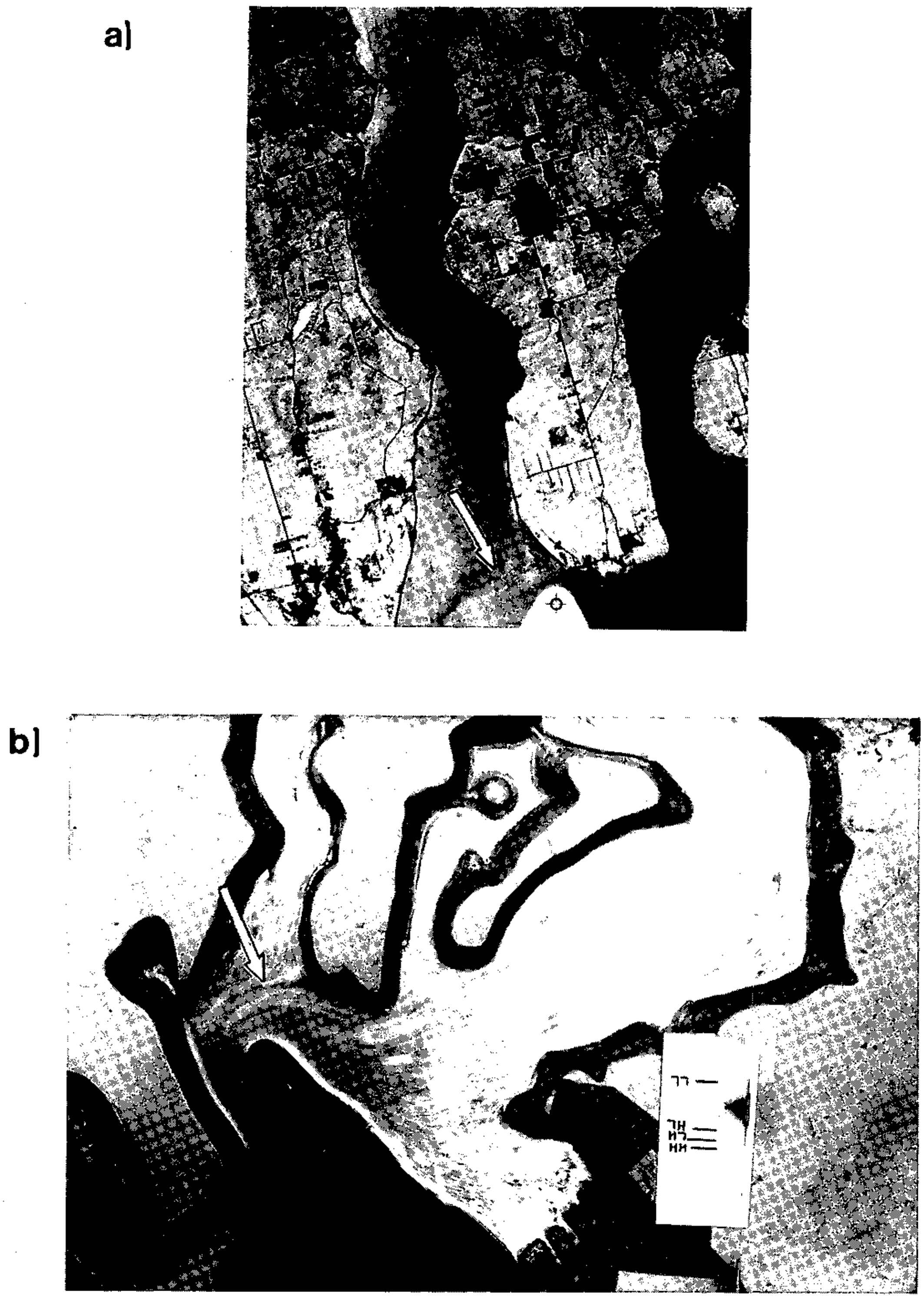


Figure 4.7. Comparison of: a) aerial photograph with b) the convergence line (see arrow) observed in the hydraulic model after 25% of the major flood tide has elapsed on 11 July 1973 (see Fig. 4.8 for tidal phases).

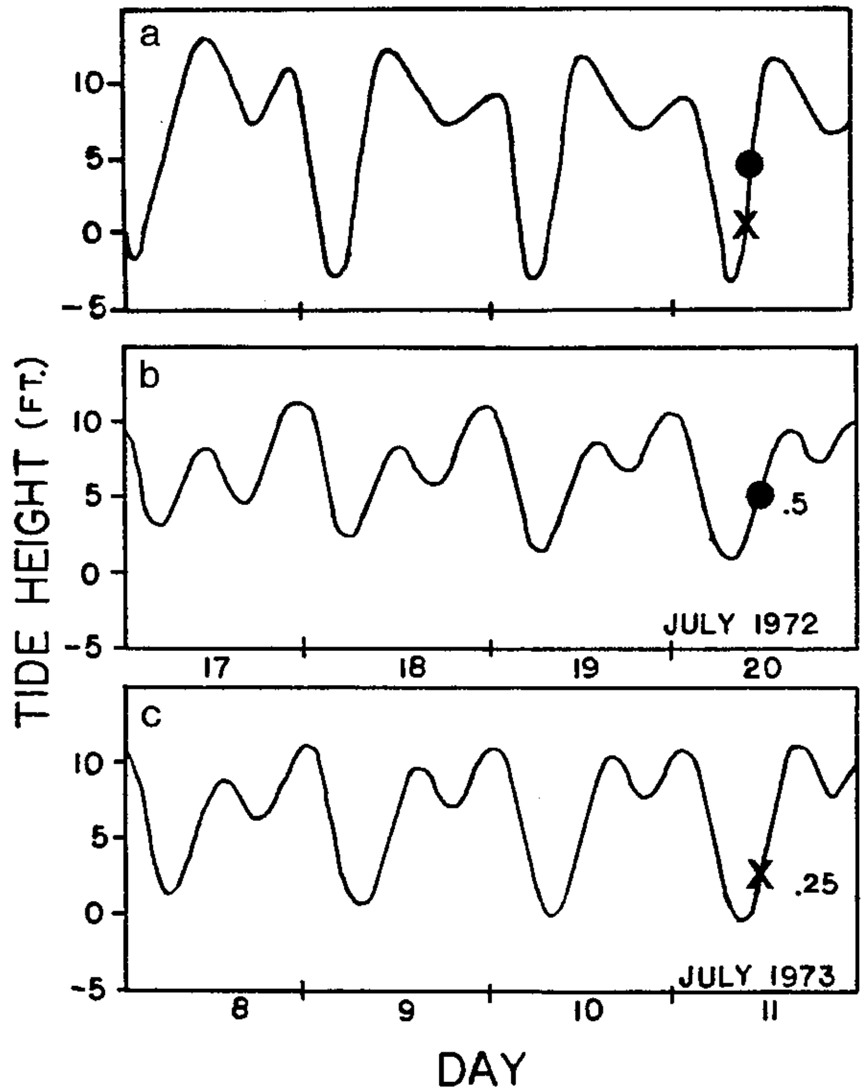


Figure 4.8. Tides in the hydraulic model (a) compared with Seattle tides on 20 July 1972 (b) and 11 July 1973 (c). The symbols in (a) indicate the times of the model photographs shown in Fig. 4.5 (dots) and Figs. 4.6 and 4.7 (x). The dot in (b) indicates 50% of a major flood tide had elapsed at the time of the aerial photograph of Fig. 4.5a. The x in (c) indicates 25% of a major flood tide had elapsed at the time of the aerial photograph shown in Figs. 4.6a and 4.7a.

Puyallup River plume. They also found that throughout most of Commencement Bay, SPM appears 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 et al. (1983) 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. As we saw earlier, speed measured near the surface over a tidal day was several times larger than measurements made at a few meters depth. In Section 4, we noted that SPM is transported into the waterways where some settling must occur. It is doubtful that the advection and diffusion of SPM in Commencement Bay can be understood without more comprehensive measurements of SPM and currents very near the water surface where the largest transport of SPM most likely occurs. The available data are insufficient to adequately explore the fate of SPM in the river plume, however losses of SPM from the Bay are thought to occur by advection out of the Bay towards Dalco Passage and also into the waterways, as well as some settling within the Bay.

There is some evidence for resuspension below the river plume derived from a comparison of the vertical flux measured by a bottom sediment trap at site 182 (see Fig. 2.2) and sedimentation rates estimated from sediment cores. Schell et al. (1977) dated a gravity core and estimated an accumulation rate of 0.67 cm per year. Assuming a dry sediment density of 2.6 g/cm^3 and a porosity of 80%, a mass accumulation rate of 9.5 $g/m^2/day$ is calculated for this core, which is equivalent to approximately 12% of the average flux collected by the bottom sediment trap (82 $g/m^2/day$). This imbalance implies that substantial recycling of bottom sediments by resuspension occurs in order to produce the large apparent sedimentation rate in the sediment trap. Moreover, sediment traps farther up in the water column collected less than 10% as much as the sediment trap near the bottom indicating that settling from farther up in the water column was not a major contributor to the flux observed near the bottom.

The conditions near the bottom in Commencement Bay contrast with those in Elliott Bay. The influence of resuspension was judged to be smaller in Elliott Bay because the near bottom vertical flux in the sediment traps was only approximately 31 g/m /day, or less than twice the net accumulation rate calculated by Schell et al. (1977) from dated sediment cores. From these and other data Baker et al. (1983) concluded that the bottom nepheloid layer was primarily maintained by an influx of turbid, salty water from the Main Basin rather than by local resuspension. Sedimentation in Elliott Bay was judged to be the result of a substantial drop in current speed as this water flowed through the Bay.

Elliott Bay appears to be a passive acceptor of sediments supplied by the benthic nepheloid layer of Puget Sound's Main Basin. In contrast, the concentration and transport of SPM in the bottom waters of Commencement Bay are apparently controlled by local resuspension processes rather than by variations in the flushing rate by deep water from the Main Basin. These conclusions are based on data collected during 1980 when bottom currents in the Main Basin were quite strong. We speculate that the balance of processes affecting SPM near the bottom may change in other years when the bottom currents are weaker (compare 1975 versus 1981; Fig. 3.4).

5.2 Distributions of Lead and PCB

We have seen that the physical processes of circulation and SPM transport in Commencement Bay are different from those in Elliott Bay. Because a number of chemicals and metals are known to attach to SPM, one might expect that the distributions of the concentrations of certain toxicants might also differ between the two bays. To test this hypothesis we contrasted the distributions of lead and polychlorinated biphenyls (PCB).

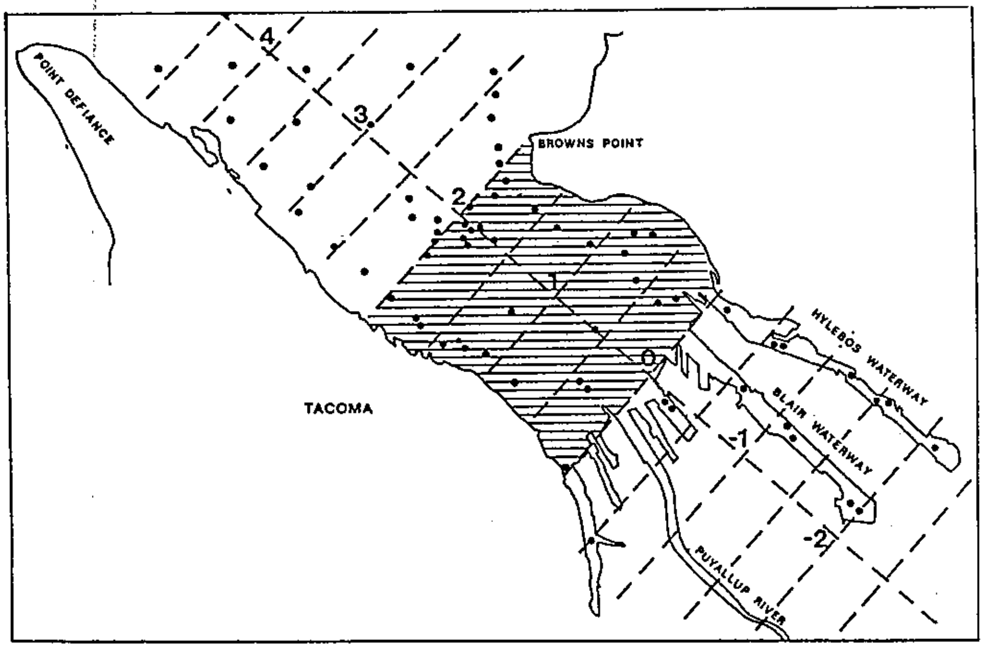
A number of measurements have been made of the concentration of lead and PCB in the sediments in Elliott and Commencement Bays and their approaches (Quinlan et al., 1984). These observations were grouped within bands 0.5 nautical mile long and stretching approximately the width of the Bays (Figs. 5.1 and 5.2). Within each interval the observations were averaged and graphed versus distance along the axis of each bay (Fig. 5.3).

The concentrations of lead and PCB are generally much higher in Elliott Bay than in Commencement Bay, the one exception is the higher concentration of PCB in the waterways of Commencement Bay than the waterways of Elliott Bay. The average concentrations of lead and PCBs are nearly seven and eight times higher, respectively, in Elliott Bay than in Commencement Bay (Table 5.1; hatched portion of Figure 5.3). These differences in concentrations are significant with 95% confidence based on the t-statistic.

Another difference between the two bays is the distribution of the sediment concentrations. As one proceeds away from the mouths of the waterways of Commencement Bay the sediment concentrations abruptly decrease to nearly the same value as found outside of the Bay. In contrast, in Elliott Bay there is a more gradual transition between the values found in the waterways and the lowest values found outside of the Bay. The differences may be attributed in part to the locations the lead and PCBs enter each water system.

Elliott Bay's waterways are actually part of the Duwamish River, the major source of freshwater and suspended sediment to Elliott Bay. Lead, PCBs, and many other metals and chemicals are known to adsorb onto suspended particulate matter. Several industrial sources are located on the Duwamish River, and it appears the discharged substances adhere to the river

a) LEAD



b) PCB

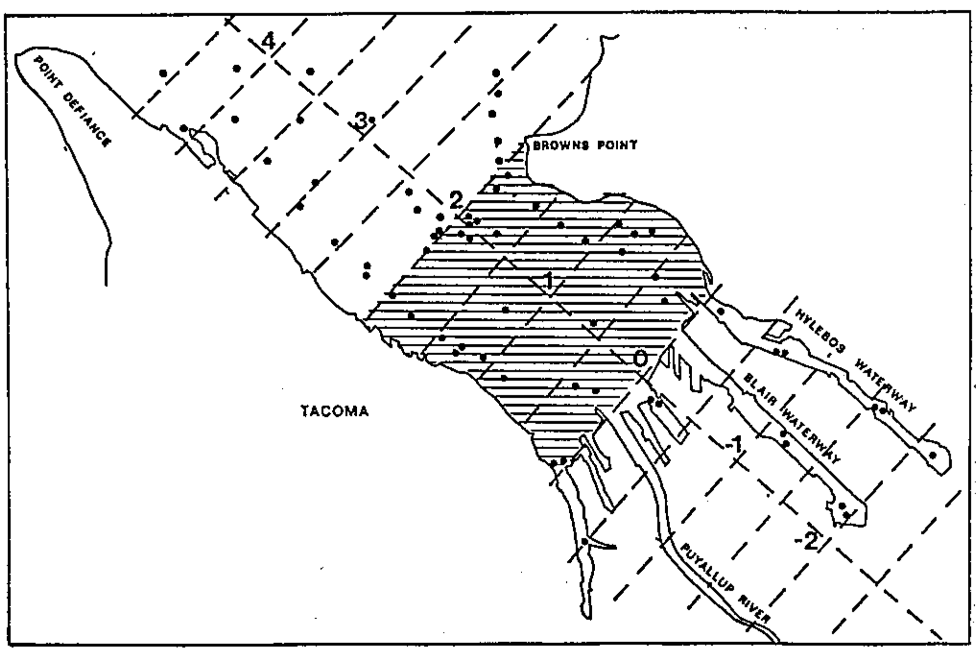


Figure 5.1. Locations of the observations (dots) of lead (a) and total PCB (b) concentrations in Commencement Bay and approaches. Dashed lines indicate the grid used to group the observations. The axial line is marked at one nautical mile increments where the origin is taken at the mouth of the waterways, positive numbers between 0 and 2 (hatched) occur in Commencement Bay, numbers greater than 2 occur in the Main Basin, and negative numbers occur in the waterways.

a) LEAD

b) PCB

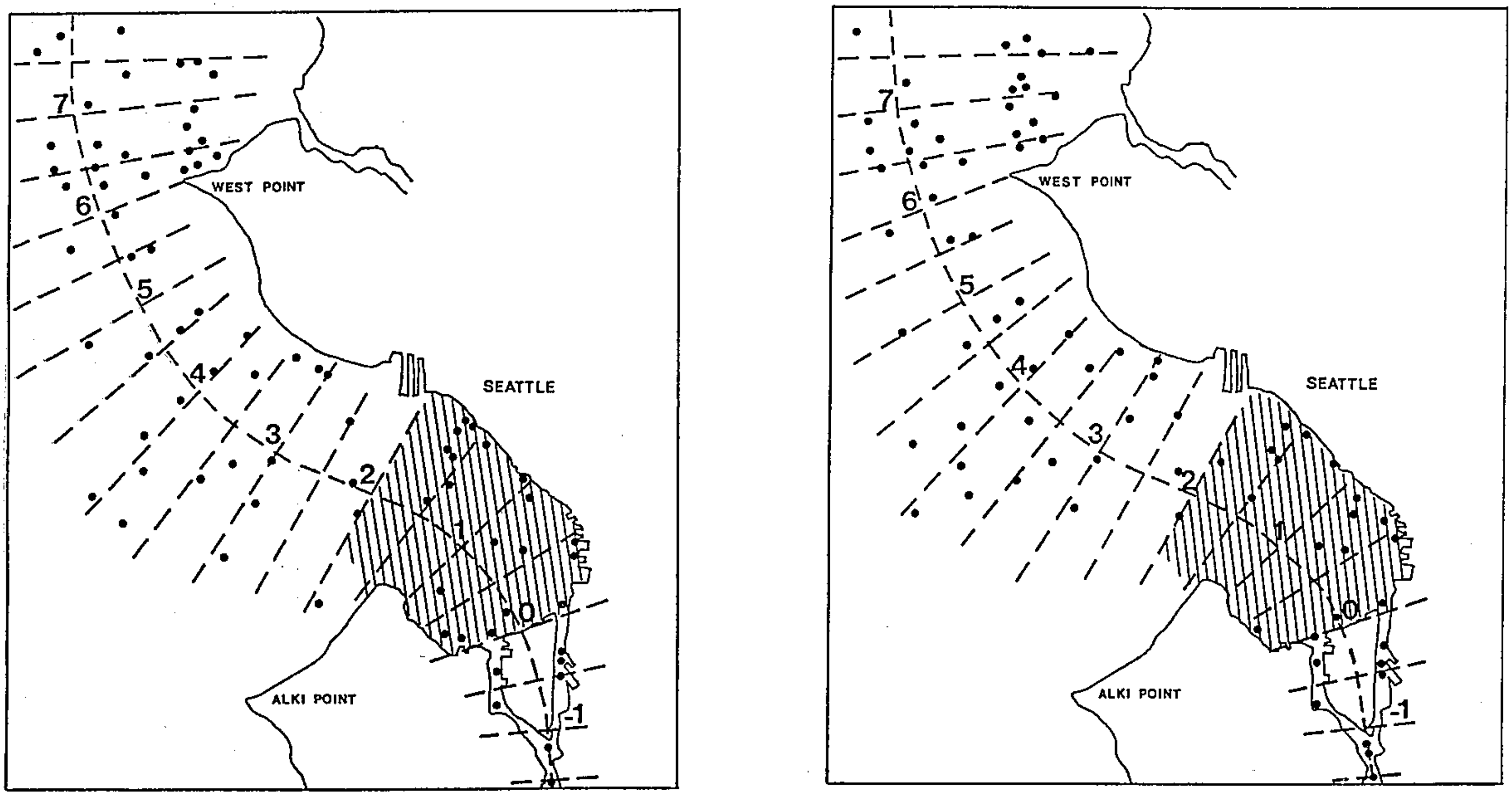


Figure 5.2. Locations of the observations (dots) of lead (a) and total PCB (b) concentrations in Elliott Bay and approaches. Dashed lines indicate the grid used to group the observations. The axial line is marked at one nautical mile increments where the origin is taken at the mouth of the waterways, positive number between 0 and 2 (hatched) occur in Elliott Bay, numbers greater than 2 occur in the Main Basin, and negative numbers occur in the waterways.

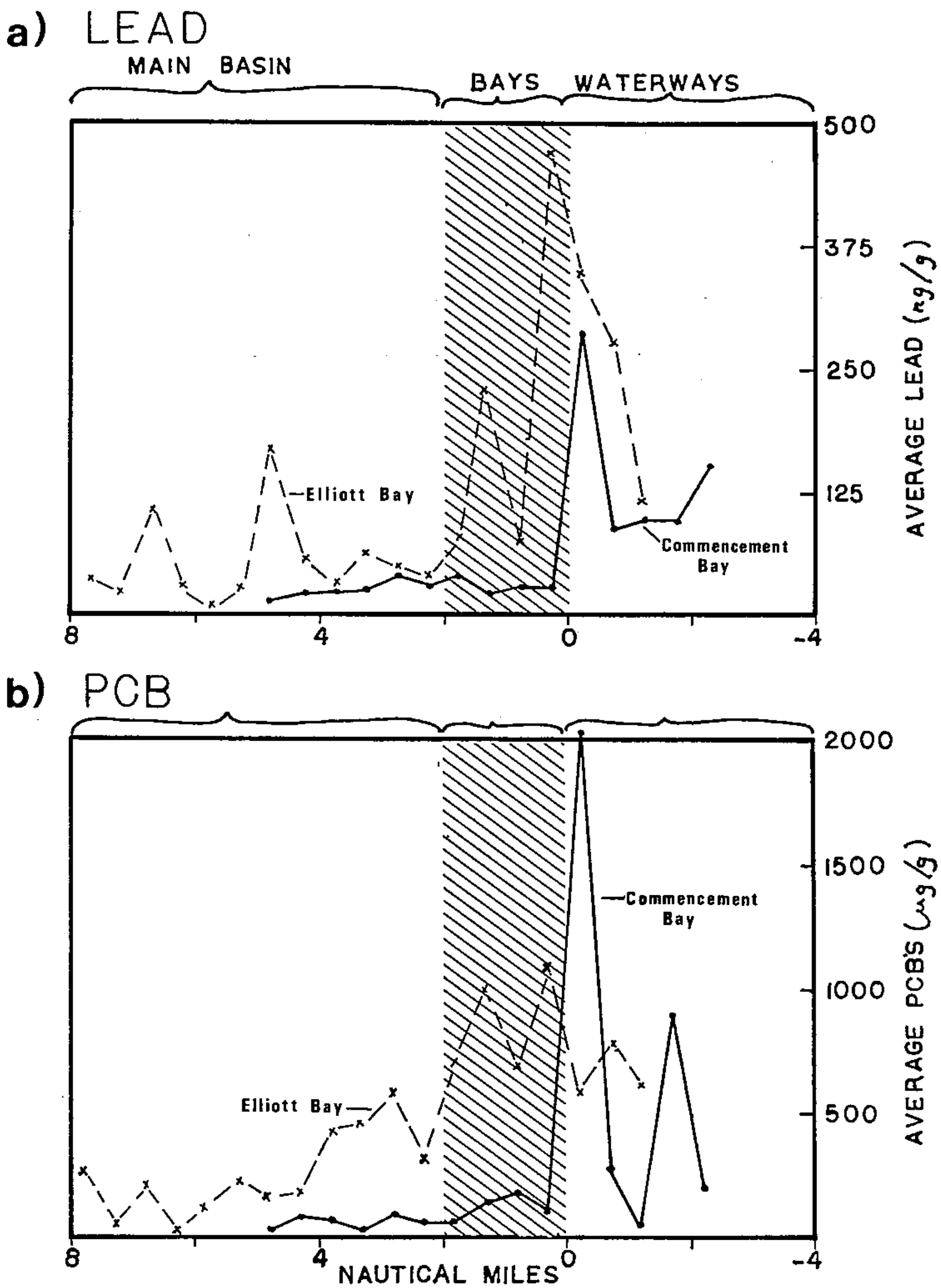


Figure 5.3. Mean concentration of lead (a) and PCB (b) versus distance in Commencement Bay (solid line) and Elliott Bay (dashed line) and approaches. See Figures 5.1 and 5.2 for distance coordinates and data locations. Hatching indicates the data that is considered to be within the two bays and that was averaged to obtain values for Table 5.1.

Table 5.1. Means, standard deviations, and sample size of sediment concentrations in Commencement and Elliott Bays. See Figures 5.1 and 5.2 for station locations and Quinlan et al. (1984) for data.

	Commencement Bay	Elliott Bay
1. Total PCB (Ng/g)		
sample size	29	22
mean	98	823
standard deviation	152	800
2. Lead (µg/g)		
sample size	30	22
mean	30	215
standard deviation	28	408

particulates in the waterways. Subsequently, the suspended sediments together with lead and PCB flow through Elliott Bay in the Duwamish River plume. As the plume moves through the Bay some of the particles settle to the bottom causing elevated concentrations of lead and PCB. Industries located along the shoreline of the Bay also contribute pollutants to the sediment concentrations. The high concentration of lead in Elliott Bay four to five miles from the mouth of Duwamish River may be due to the Four Mile Rock dredge disposal site.

In contrast, the industrial sources in Commencement Bay for the most part are located in waterways adjacent to the Puyallup River and are not fed with substantial freshwater. Nearly all of the suspended sediment enters Commencement Bay via the Puyallup River, and the SPM exiting the river is probably fairly clean since it is not exposed to industrial pollutants.

The circulatory patterns in Commencement Bay's waterways may also explain the lower concentrations of lead and PCB found in the Bay. Measurements of currents made in the Hylebos, Blair, Sitcum, Milwaukee, and City Waterways (Loehr et al., 1981), indicated that the net circulation was contained in three layers.

A portion of the SPM exiting the river does enter the waterways at their mouths. Some of the lead and PCB become adsorbed as the SPM moves toward the heads of the waterways in the upper layer, and a certain amount of settling out occurrs in the quiet circulation. The SPM which does exit these waterways and enter Commencement Bay contains only a small fraction of the contaminants which reside in the waterways. In effect the circulation of the waterways appears to be trapping the majority of the pollutants discharged to them.

We speculate that the order of magnitude difference between lead and PCB concentrations in the bottom of Commencement Bay and Elliott Bay is due in part to the differences in the circulatory patterns in the waterways that feed the two bays. Other factors also may contribute to this difference including resuspension, the amount of SPM which enters the two bays, and the magnitude of the pollutant loading. It is beyond the scope of this report to fully investigate the factors which cause the different concentrations in the bays.

6. CONCLUSIONS

The field and model data for Commencement Bay and the surrounding areas provide insight concerning the processes that affect the circulation of the water and transport of suspended particulate matter. The patterns of tidal currents in the streak photographs of the hydraulic model and aerial photographs are in reasonable agreement with the field observations of currents.

The thin surface layer in Commencement Bay has a net westward flow toward Dalco Passage and is caused by interaction of the tides with bathymetry near The Narrows. Current measurements below the surface river plume indicate that substantial counter-currents exist; however these patterns may change because of the long-term trends observed in the Main Basin's current structure.

The suspended particulate matter introduced by the Puyallup River plume is evident in a thin layer near the water's surface in Commencement Bay. The SPM contained within this layer can quickly exit Commencement Bay or can be transported into the adjacent waterways. The sediments at the bottom of Commencement Bay undergo resuspension caused by tidal currents. The resuspension is sensitive to current speed, and because the bottom current speeds may change over long periods of time, the resuspension activity may also undergo long-term changes.

Concentrations of lead and PCB in the bottom sediments are an order of magnitude smaller in Commencement Bay than in Elliott Bay. This difference in concentration may be associated with the pathway of SPM from the Puyallup River, through the surface layer in the Bay, then into the waterways, and eventually back into Commencement Bay. There may be trapping of pollutants by settling of SPM in the waterways.

The available historical data indicate some of the pathways of SPM through the Bay and its waterways. However, the observations make it clear that SPM and currents need to be measured at the same time in locations that have not previously been examined. These areas include the waterways and the river plume, especially very near the water surface. These measurements should be conducted concurrently with observations made at mid-depth and near the bottom.

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Appendix A. Summary of current measurements observed over one tidal day or longer in Commencement Bay and approaches.

General Locations	Site No.	Depth (m)	Net Speed (cm/s)	Flow Direction (°T)	Total Variance (cm^2/s^2)	Observation Date	Tidal Days	Longitude 48 N- (minutes)	Latitude 122 W- (minutes)
Commencement Bay	182	5	5.09	256	31	2/8-10/44	1	17.7	26.4
		25	0.76	27	38	9/9-11/12/80	64	17.6	26.5
		75	0.76	331	26	"	64	"	"
		125	5.29	127	23	"	64	"	"
		27	0.39	354	45	3/24-5/13/81	48	17.6	26.8
		127	0.72	99	132	4/2-6/3/81	60	"	"
	184	24	1.67	126	16	9/9-11/12/80	64	16.7	27.5
		74	1.06	133	30	"	64	"	"
		125	5.19	290	65	"	64	"	"
	A	12.5	Record averages not yet available.			7/1-15/83		17.25	28.98
		19.5				7/1-8/29/83		17.25	28.98
		21.5				"		"	"
		37.5				"		"	"
	B	29	(See City of Tacoma, Washington, 1983)			8/11-29/83		17.16	26.68
		39				"		"	"
		59				"		"	"
		84				"		"	"
		109				"		"	"
	C	27				8/11-29/83		17.14	25.47
		37				"		"	"
		47				"		"	"
		57				"		"	"
	D	11				8/11-29/83		16.60	25.38
		21				"		"	"
		31				"		"	"
		41				"		"	"
	E	.3	13.60	340	397	7/30-31/79	1	16.3	25.8
		1.5	4.65	278	205	"	1	"	"
		3	1.38	335	148	"	1	"	"
		6	2.77	348	66	"	1	"	"
		18	0.89	153	53	"	1	"	"
		27	0.39	94	30	"	1	"	"

Appendix A. continued

General Locations	Site No.	Depth (m)	Net Speed (cm/s)	Flow Direction (^{0}T)	Total Variance (cm^2/s^2)	Observation Date	Tidal Days	Longitude 48° N- (minutes)	Latitude 122° W- (minutes)
Southern East Passage	178	5	2.22	32	290	3/15-23/43	4	23.3	21.2
		5	3.96	154	300	9/12-28/77	15	23.4	21.4
		21	7.42	162	305	"	15	"	"
	180	5				2/1-7/44		19.9	26.5
		5	5.24	249	131	3/10-15/47	3	19.9	26.4
		29	12.21	237	140	2/24-3/29/77	32	20.0	26.1
		57	12.46	233	151	"	32	"	"
		71	10.29	233	153	"	32	"	"
		111	8.32	232	193	"	32	"	"
		144	2.99	211	145	2/24-26/77	1	"	"
		176	6.66	220	136	2/24-3/29/77	32	"	"
		16	5.77	238	76	9/15-11/11/77	49	20.0	26.2
		55	9.92	235	151	9/15-11/16/77	61	"	"
		176	8.69	225	243	"	61	"	"
		15	11.70	231	125	9/8-11/12/80	62	19.9	26.6
		40	10.60	228	117	"	62	"	"
		74	8.02	229	174	"	62	"	"
		125	10.31	233	227	"	62	"	"
		170	10.93	224	218	"	62	"	"
		4	6.90	211	1679	3/24-6/3/81	67	19.8	26.8
		125	10.94	222	215	"	67	"	"
		170	8.97	220	169	"	67	"	"
	181	5	1.39	170	246	2/12-16/44	1	21.2	28.8
Dalco Passage	187	5	5.63	253	382	3/10-15/47	3	19.6	29.8
	188	15	13.99	277	282	2/24-3/28/77	32	18.9	30.2
		43	15.56	280	223	"	32	"	"
		92	unable to locate data			"	32	"	"
		147	10.14	286	405	"	32	"	"
	189	5	14.54	324	304	3/10-15/47	4	18.6	30.4

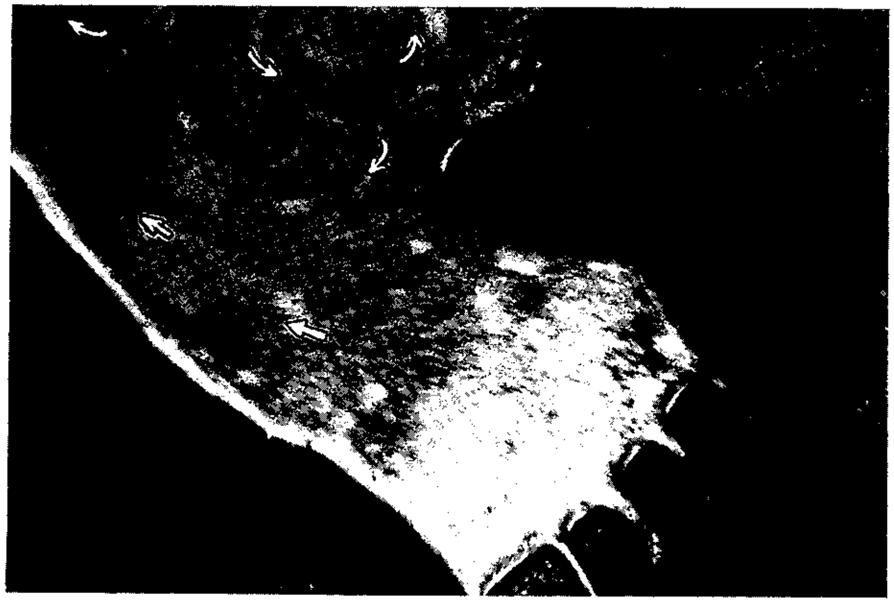
Appendix A. continued

General Locations	Site No.	Depth (m)	Net Speed (cm/s)	Flow Direction (°T)	Total Variance (cm^2/s^2)	Observation Date	Tidal Days	Longitude 48° N- (minutes)	Latitude 122° W- (minutes)
	191	5	28.53	294	551	10/17-11/1/77	14	19.3	31.2
		21	28.34	291	465	"	14	"	"
		5	27.93	298	664	11/1-16/77	14	"	"
		21	28.09	292	574	"	14	"	"
		68	24.14	300	715	10/17-11/16/77	30	"	"
		15	7.37	186	2203	3/24-6/2/81	68	19.8	31.1
		90	6.86	136	1500	"	67	"	"
	192	19	35.25	295	683	2/23-3/28/77	31	19.4	31.8
		39	33.28	297	691	"	32	"	"
		72	30.98	299	806	"	32	"	"
		97	21.80	292	595	"	32	"	"
Southern Colvos Passage	195	4	33.09	46	1137	10/17-11/2/77	9	22.2	32.3
		21	29.44	39	874	"	15	"	"
		79	25.37	48	360	"	15	"	"
	197	27	31.46	3	615	2/25-3/25/77	27	22.3	31.7
		59	27.53	5	701	"	27	"	"
		74	25.60	359	728	"	27	"	"
		88	21.88	353	611	"	27	"	"
The Narrows	193	3	12.24	238	1246	2/11-13/44	1	19.6	34.5
		3	9.84	95	1621	2/12-16/45	1	19.6	34.4
	258	43	48.62	153	5086	2/23-3/28/77	32	18.4	33.4
		67	43.19	144	3409	"	32	"	"
		68	41.56	141	3160	"	32	"	"
		6	37.13	176	7472	10/17-11/1/77	14	18.5	33.4
		62	38.97	151	7775	"	30	"	"
		6	34.98	172	7491	11/1-17/77	14	"	"
		4	31.44	172	7305	3/8-4/10/78	22	18.6	33.4
		61	36.92	153	6421	"	32	"	"
	259	5	56.56	145	6180	2/28-3/4/46	1	18.2	33.4

Appendix A. continued

General Locations	Site No.	Depth (m)	Net Speed (cm/s)	Flow Direction (^{0}T)	Total Variance (cm^2/s^2)	Observation Date	Tidal Days	Longitude 48^0 N- (minutes)	Latitude 122^0 W- (minutes)
	260	5	17.94	53	13760	3/18-24/43	4	18.3	33.0
		5	16.72	76	6542	1/19-2/18/44	1	"	"
		5	14.13	46	12941	"	3*	"	"
		5	36.10	87	13746	"	3*	"	"
		5	7.65	21	6173	"	1*	"	"
	261	5	65.21	343	5862	2/27-3/4/46	4	18.5	32.5
	262	5	7.49	159	22196	2/27-3/3/46	4	17.1	32.6
	263	5	15.14	327	7985	2/28-3/4/46	4	17.1	32.0
	265	5	30.58	36	7640	2/28-3/4/46	3	15.7	33.8
	266	2	10.16	267	15923	8/29-9/28/52	29	15.7	33.1
		12	7.12	187	15542	"	29	"	"
		23	6.80	188	16015	"	29	"	"
		2	11.98	312	16022	9/17-21/52	1	15.7	33.6
		2	14.82	309	14700	"	3*	"	"
		12	9.72	305	14904	"	1	"	"
		12	15.45	337	13923	"	3*	"	"
		23	13.18	329	15859	"	1	"	"
		23	20.71	287	17202	"	2*	"	"
		45	4.74	228	17530	2/23-3/15/77	16	15.6	33.5
		5	1.02	346	18914	3/9-30/78	19	15.7	33.4
		22	4.74	228	17530	"	19	"	"
	267	5	14.62	28	14481	2/27-3/4/46	4	15.5	33.1

* Records which contain gaps greater than one hour. These have been divided into subrecords and statistics have been computed for each subrecord.



Appendix B. Streak photographs of Commencement Bay in the UW hydraulic model. Arrows indicate flow pattern but not speed. Inset shows the phase of the tide.

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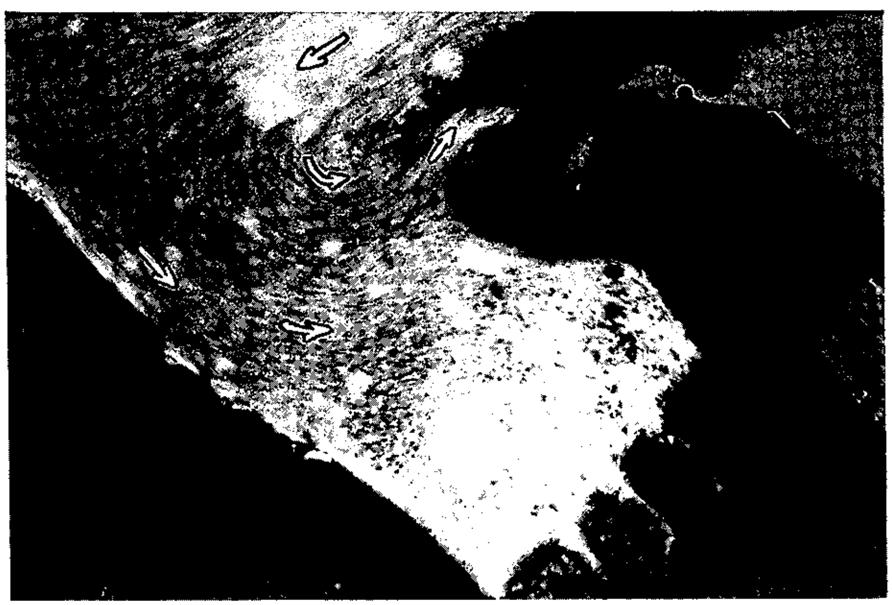

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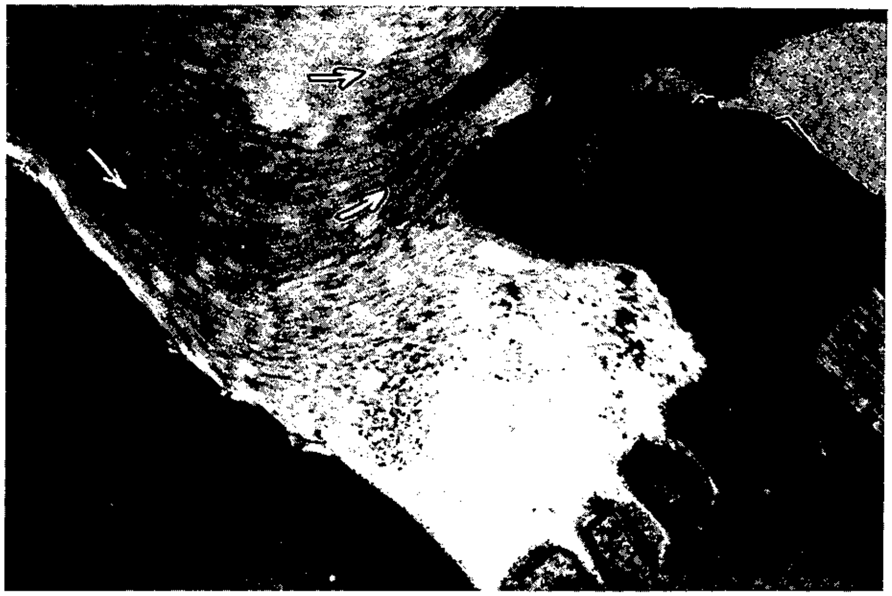

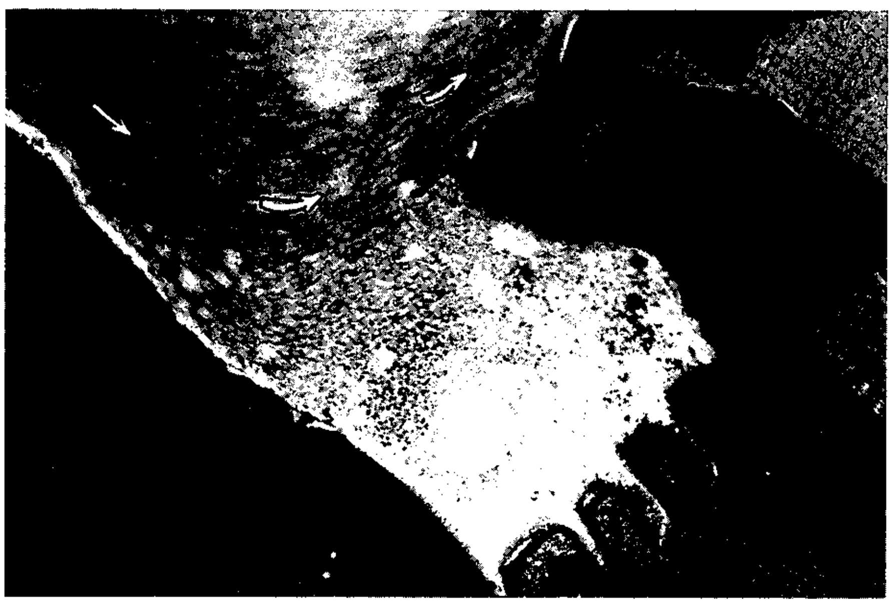

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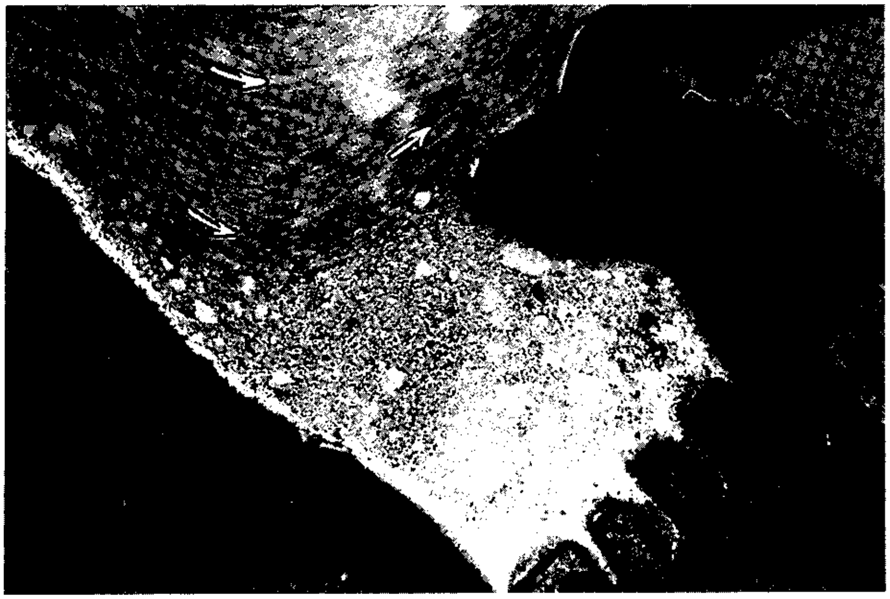

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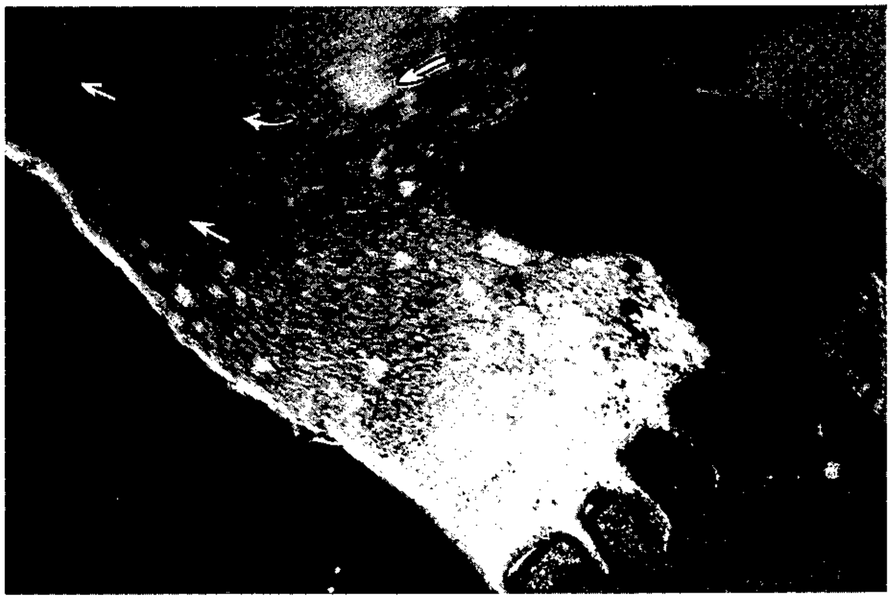

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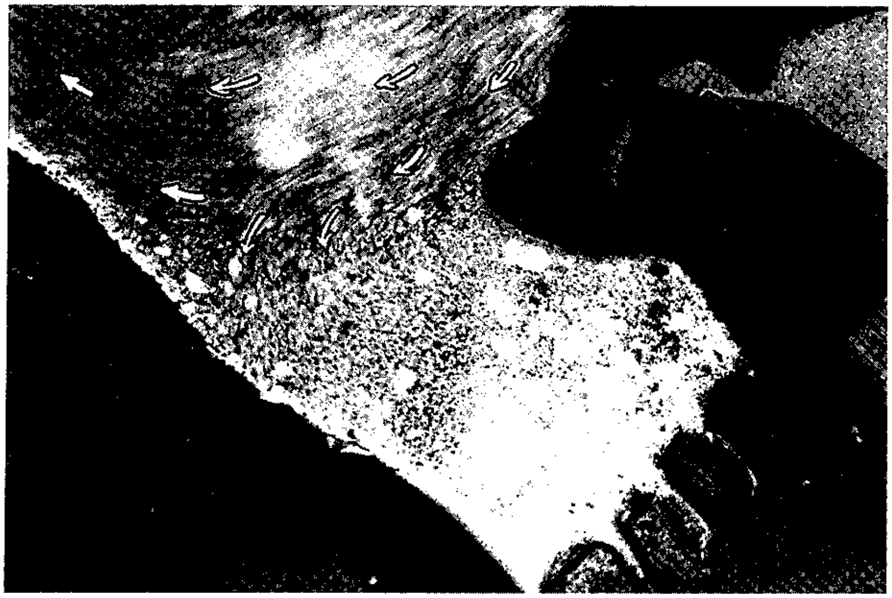

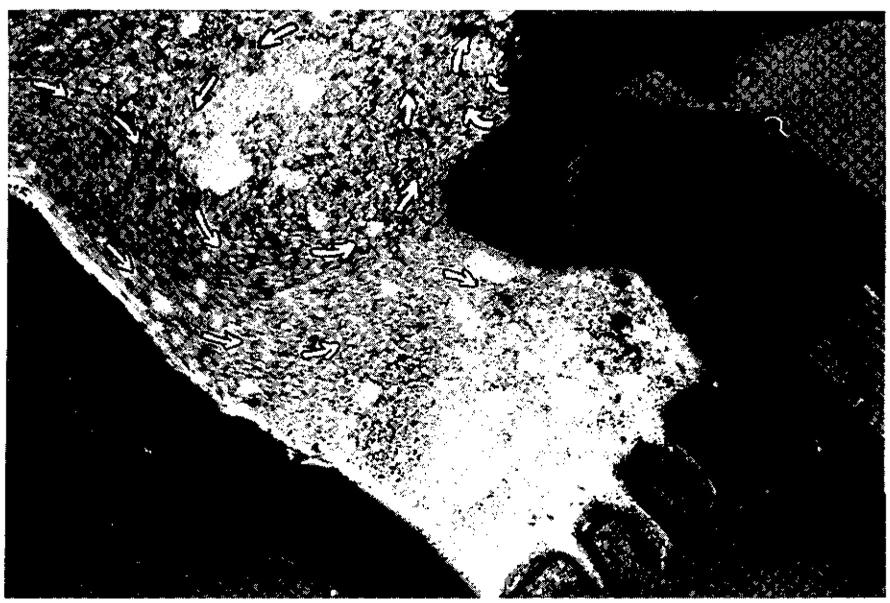

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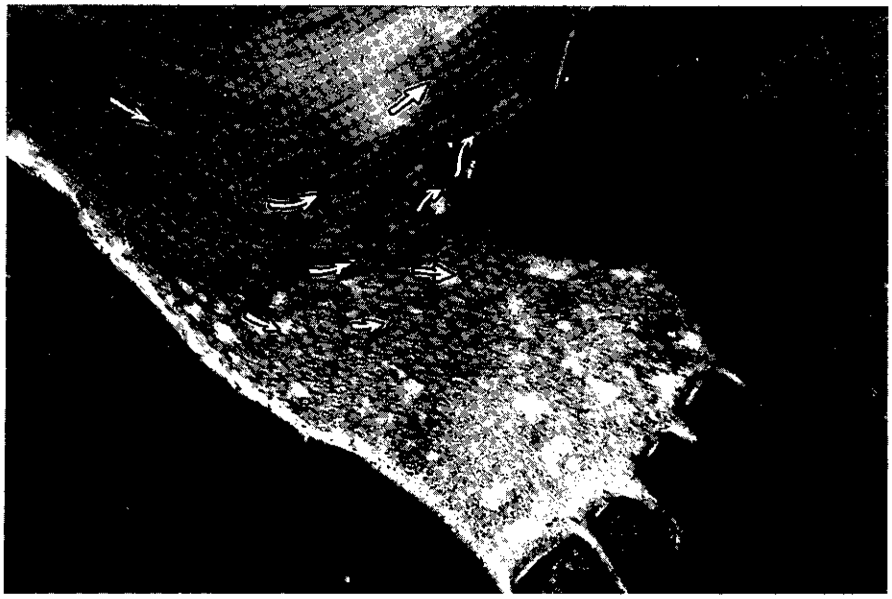

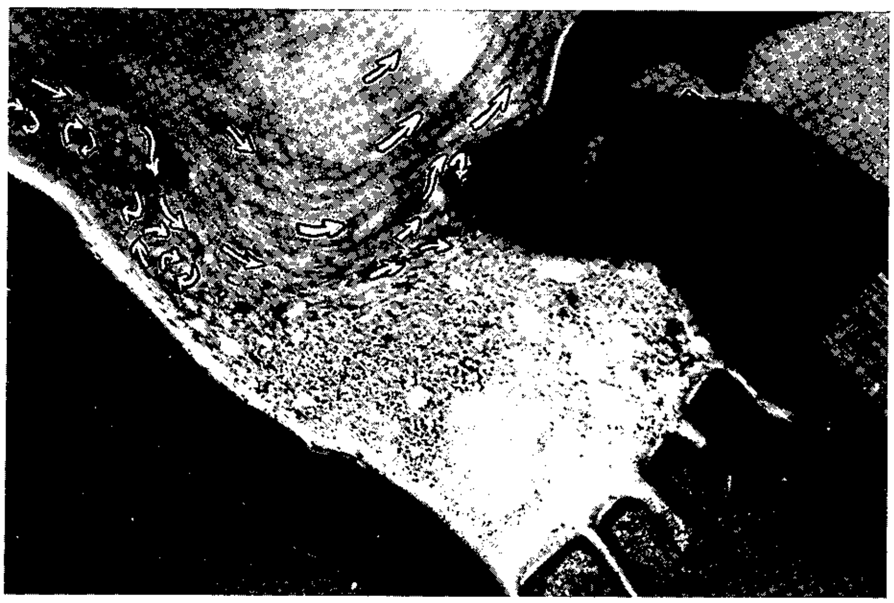

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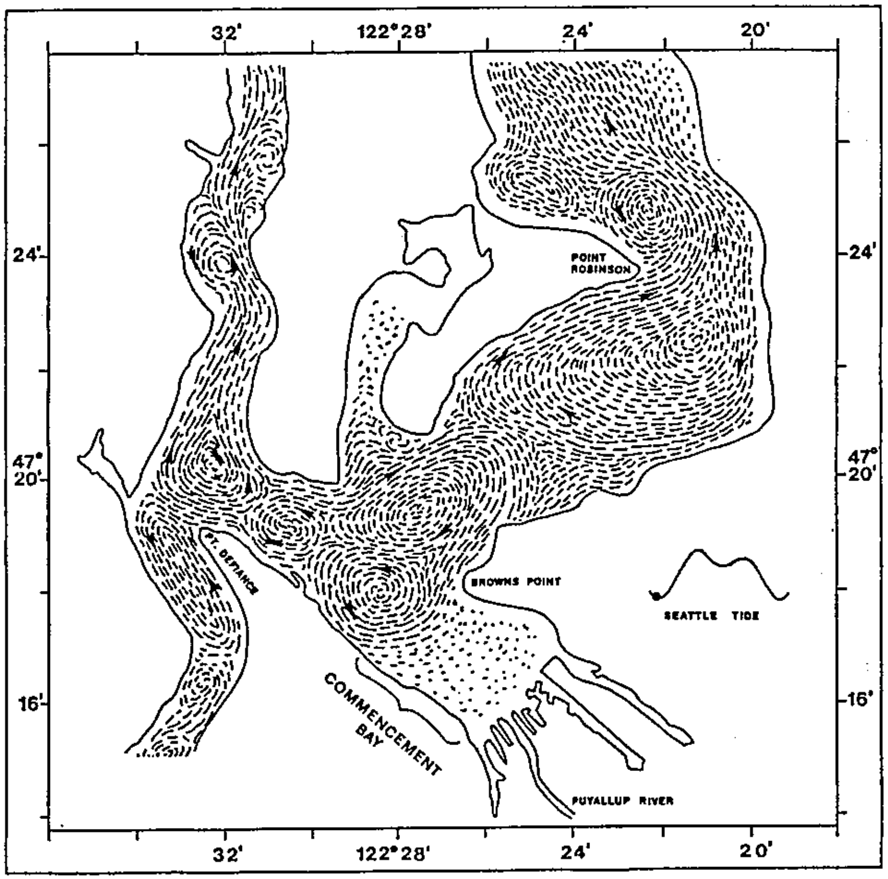
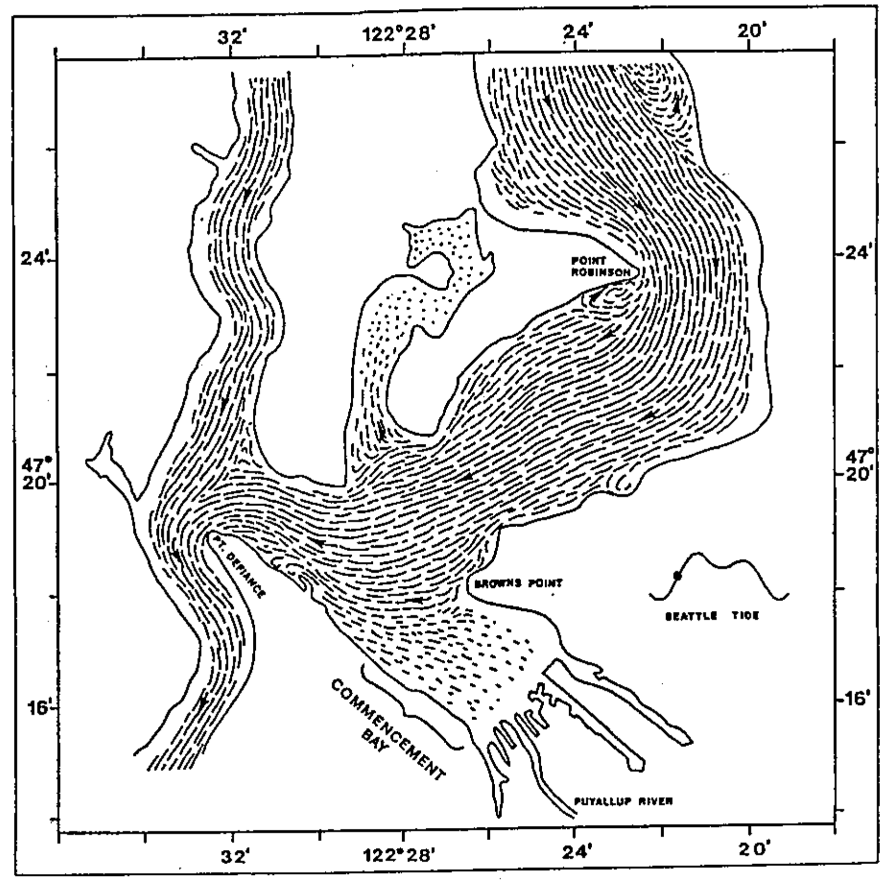
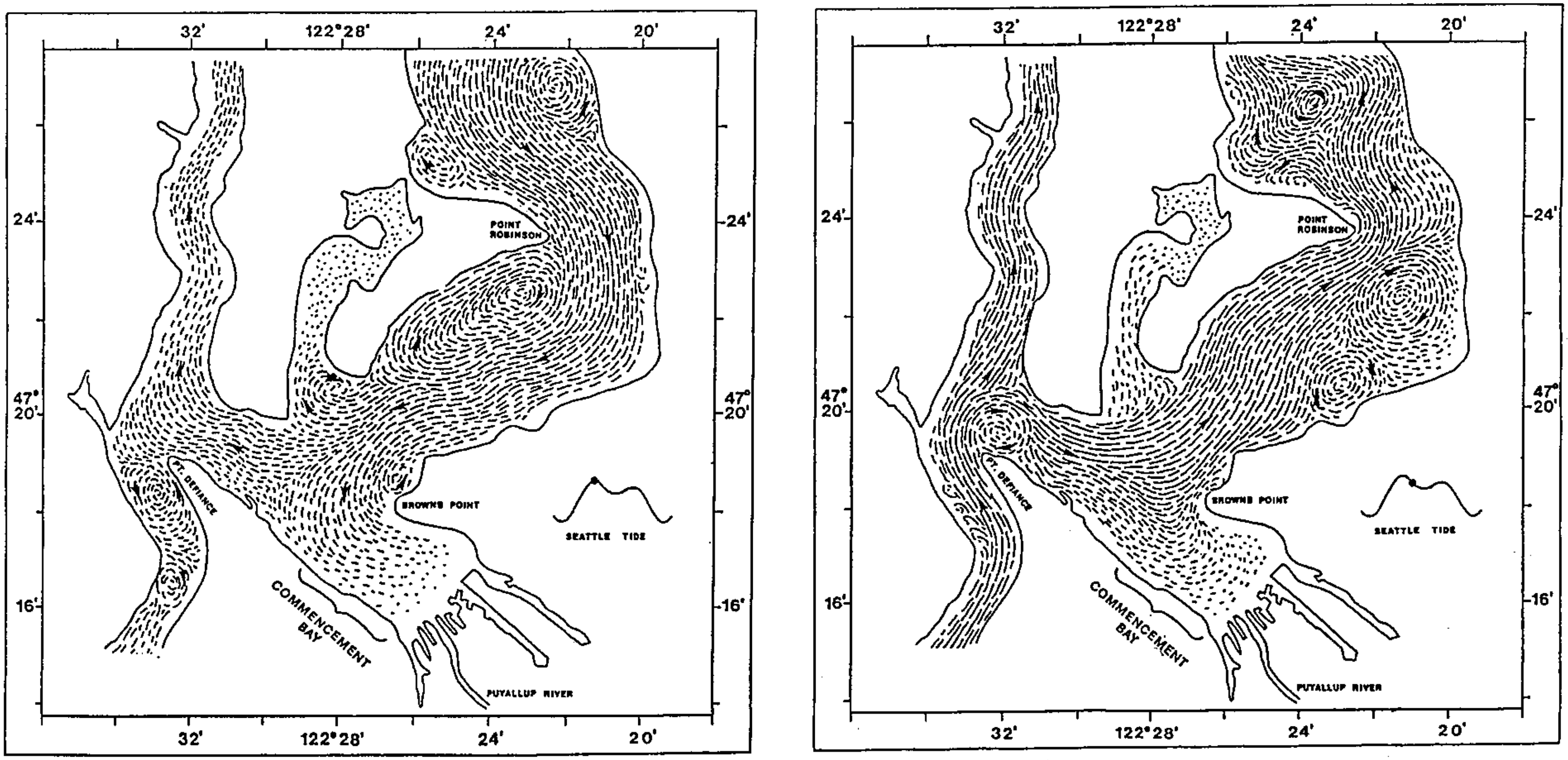
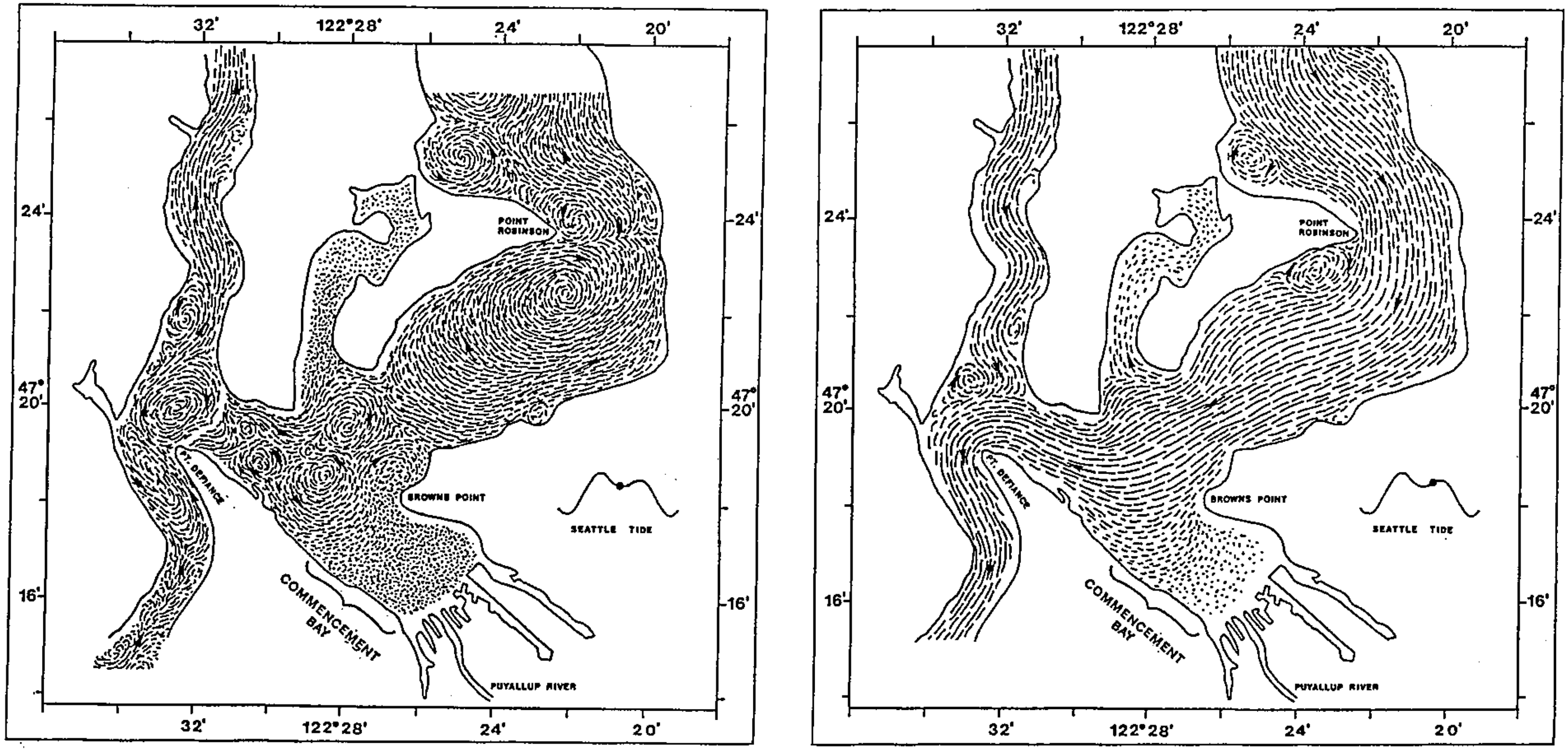




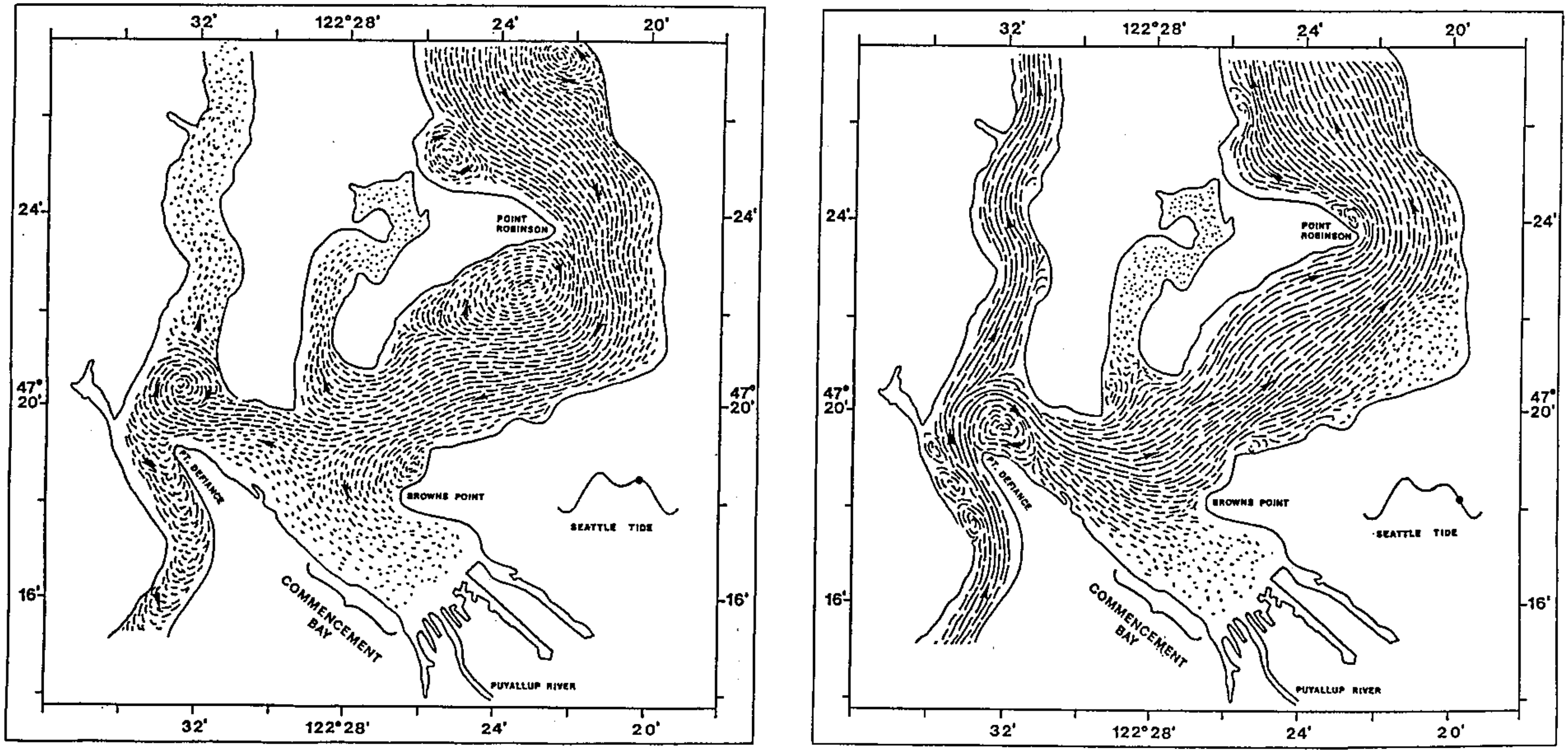
Appendix C. Patterns of tidal currents from McGary and Lincoln (1977). Arrows indicate current direction but not speed. Inset shows the phase of the tide at Seattle.



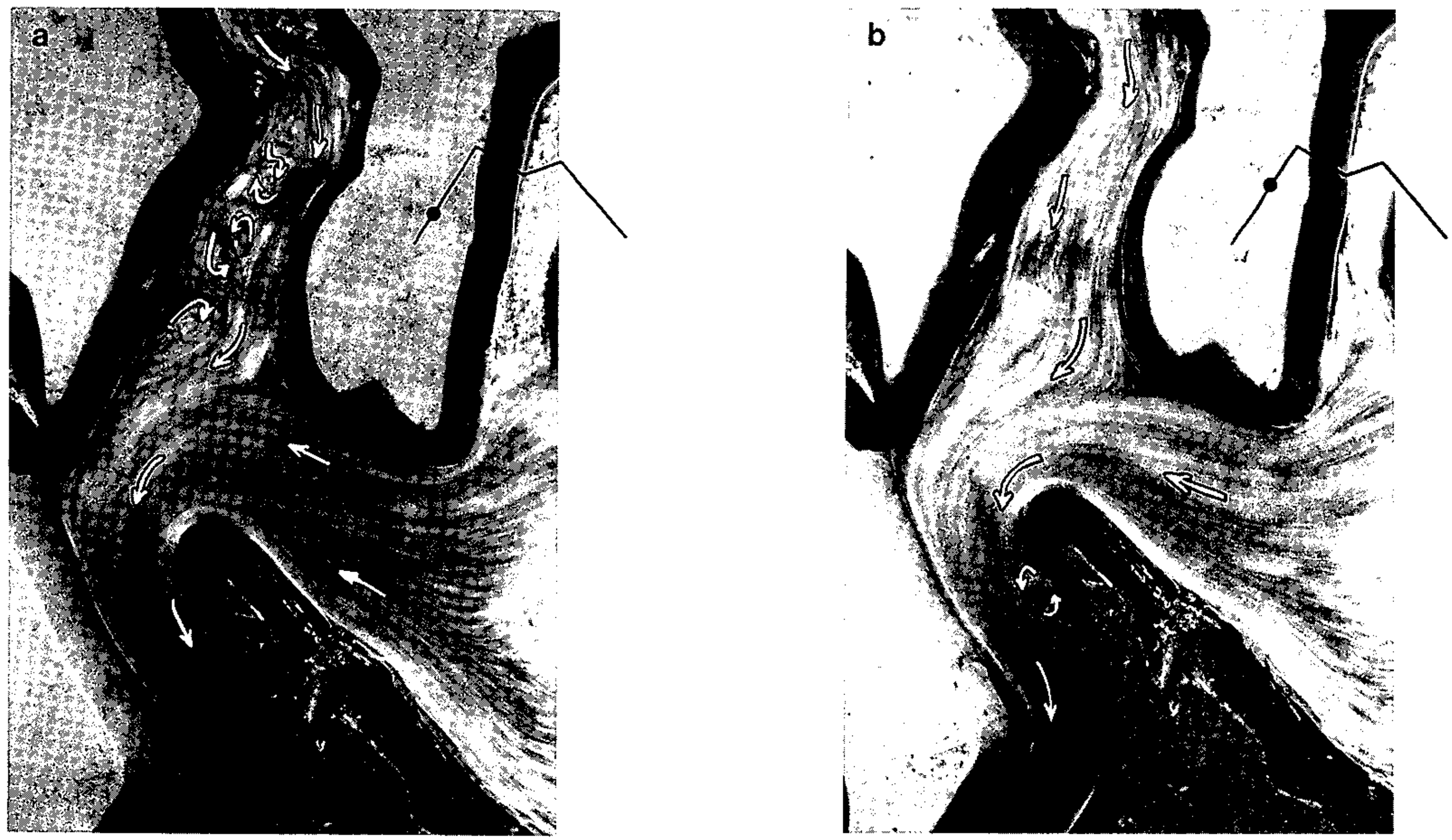
Appendix C. Patterns of tidal currents from McGary and Lincoln (1977). Arrows indicate current direction but not speed. Inset shows the phase of the tide at Seattle.



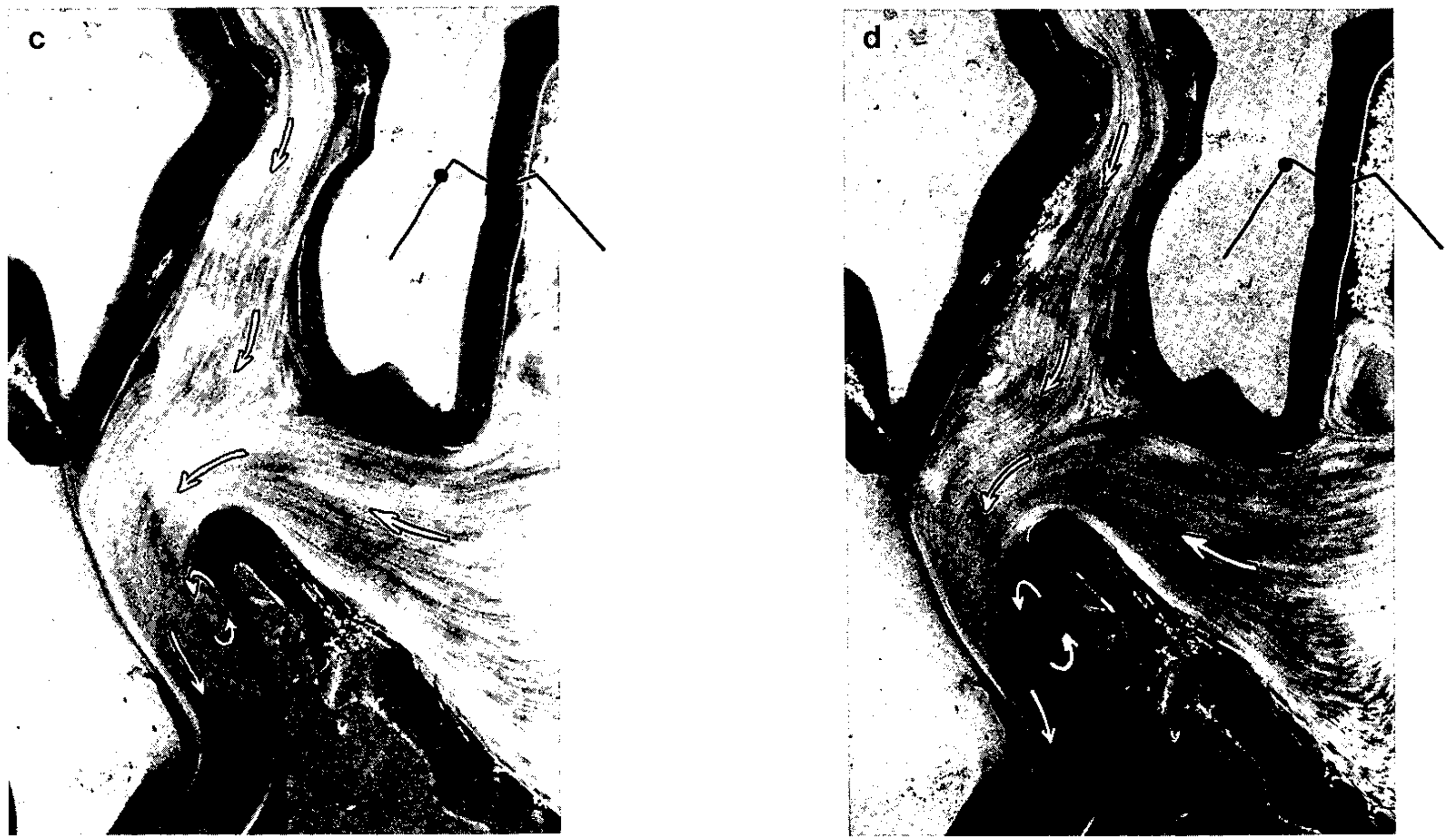
Appendix C. Patterns of tidal currents from McGary and Lincoln (1977). Arrows indicate current direction but not speed. Inset shows the phase of the tide at Seattle.



Appendix C. Patterns of tidal currents from McGary and Lincoln (1977). Arrows indicate current direction but not speed. Inset shows the phase of the tide at Seattle.



Appendix D. Streak photographs of the Narrows and approaches. Arrows indicate flow patterns but not speed. Inset shows the phase of the tide.



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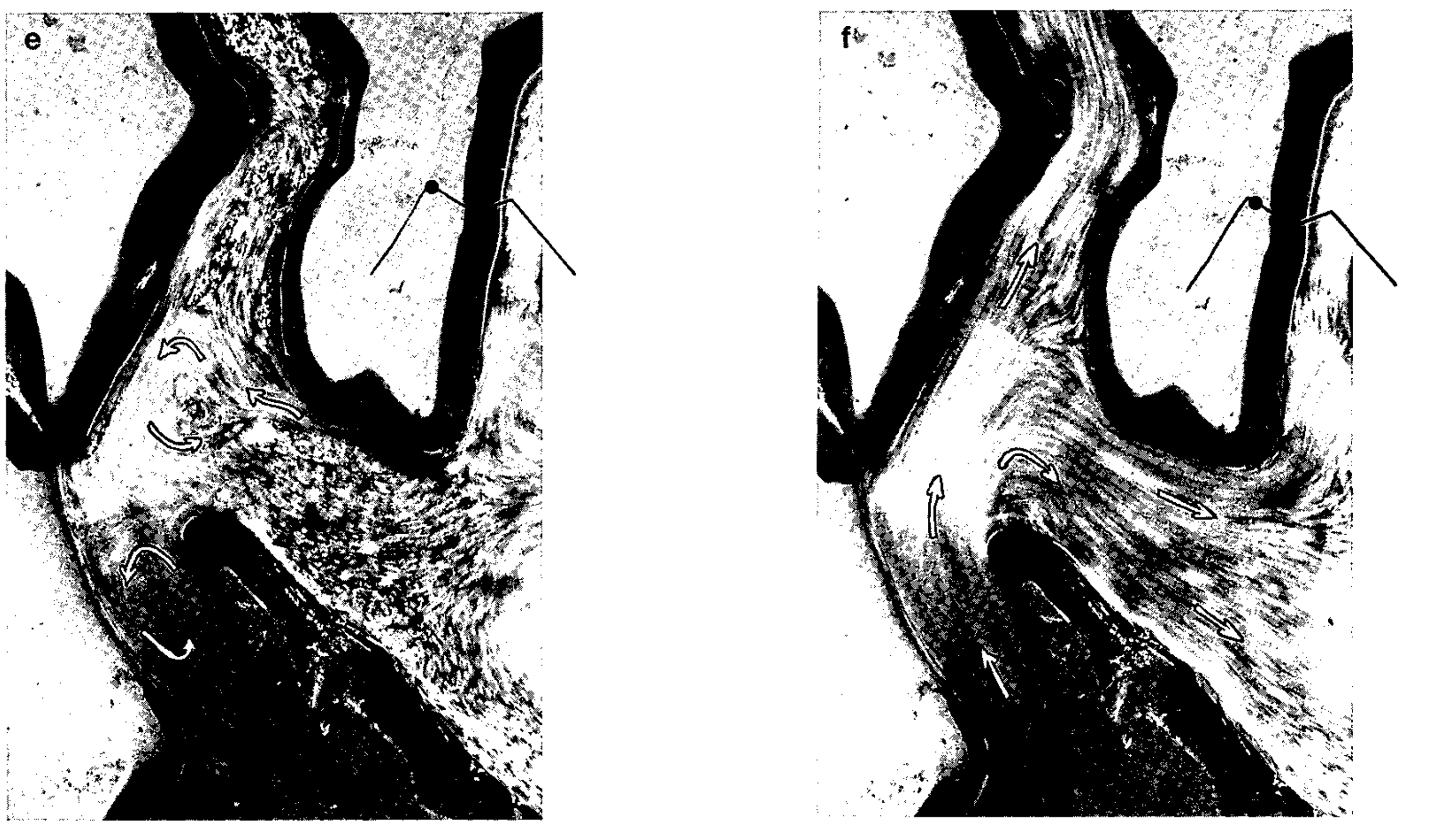

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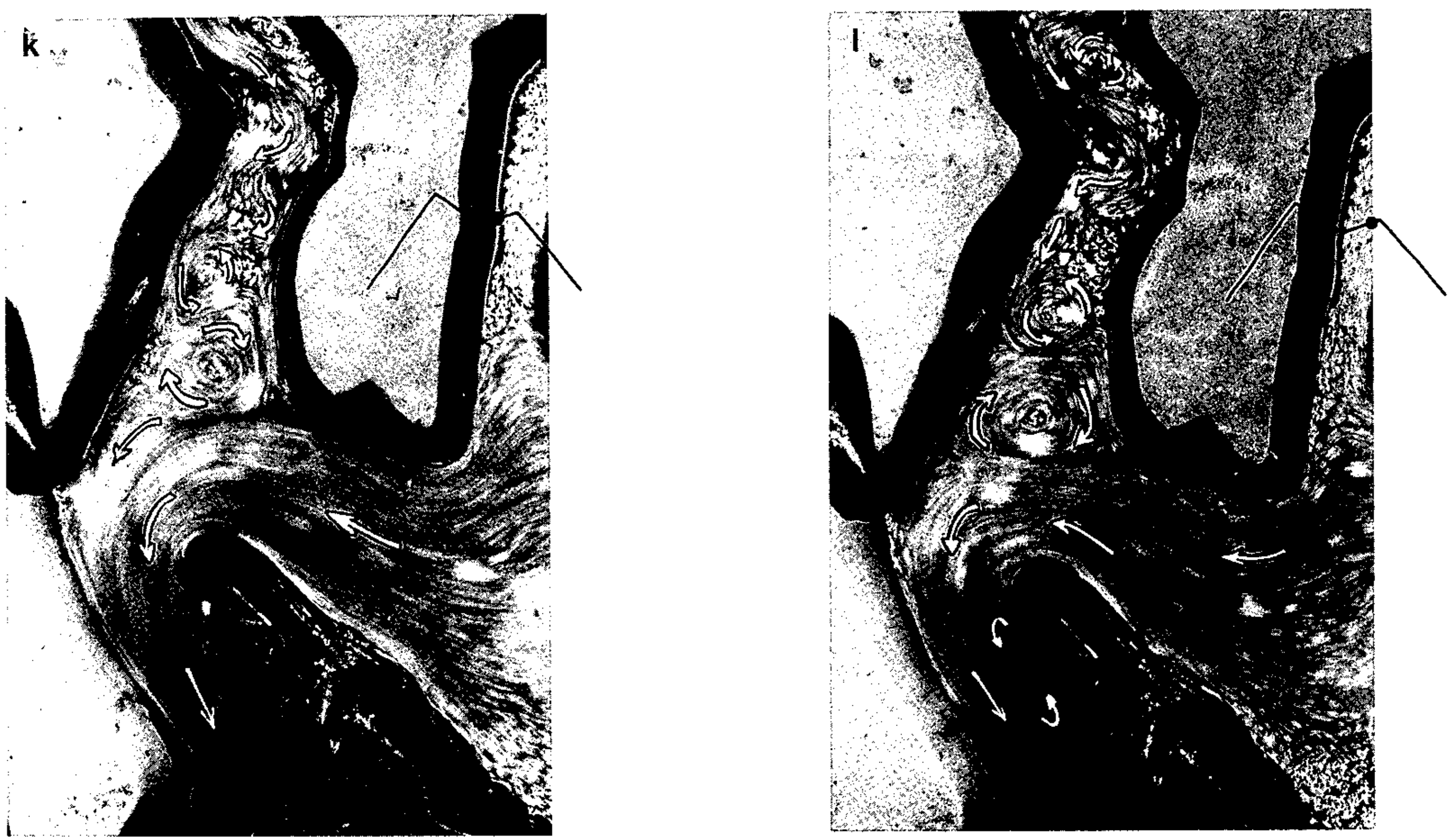

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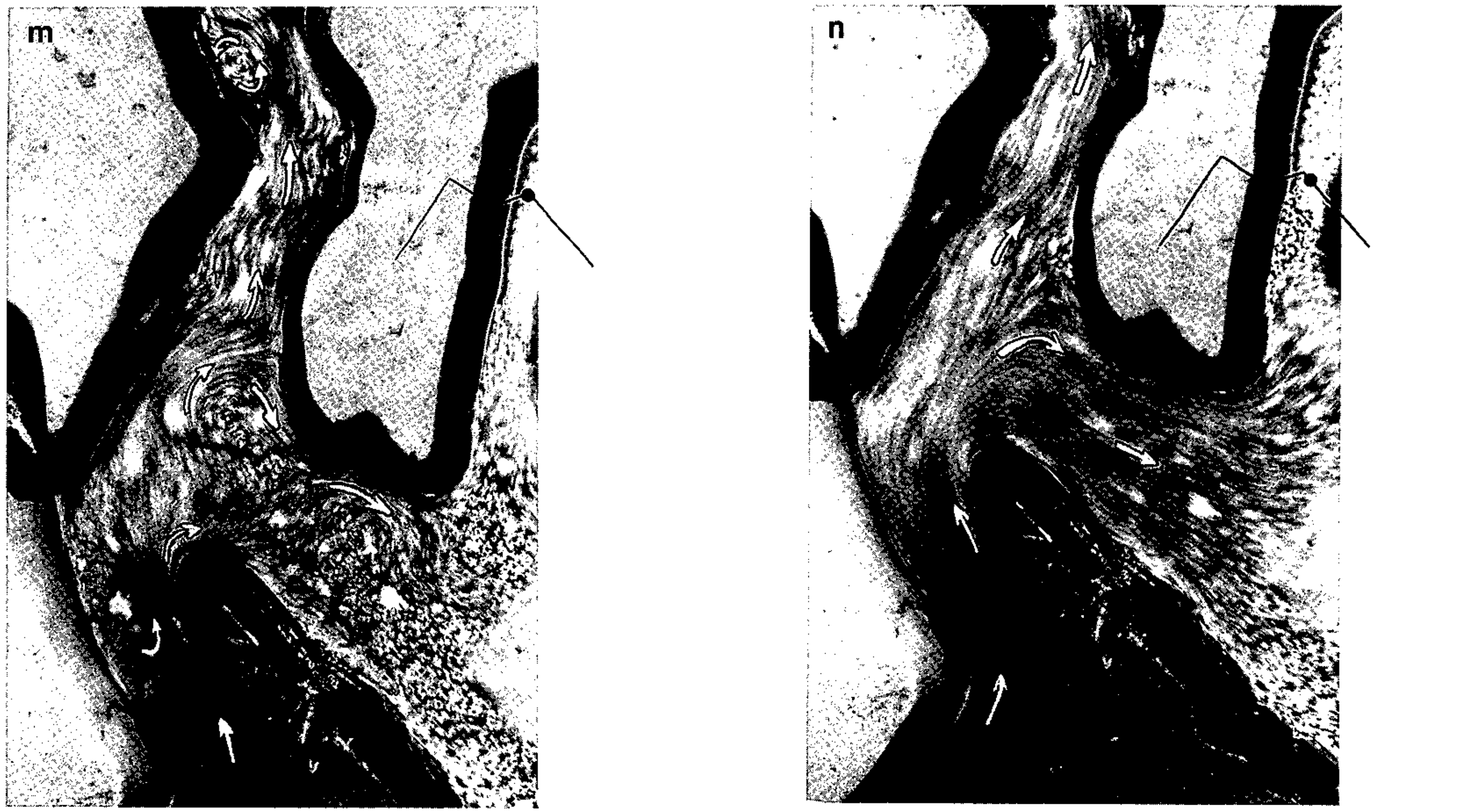

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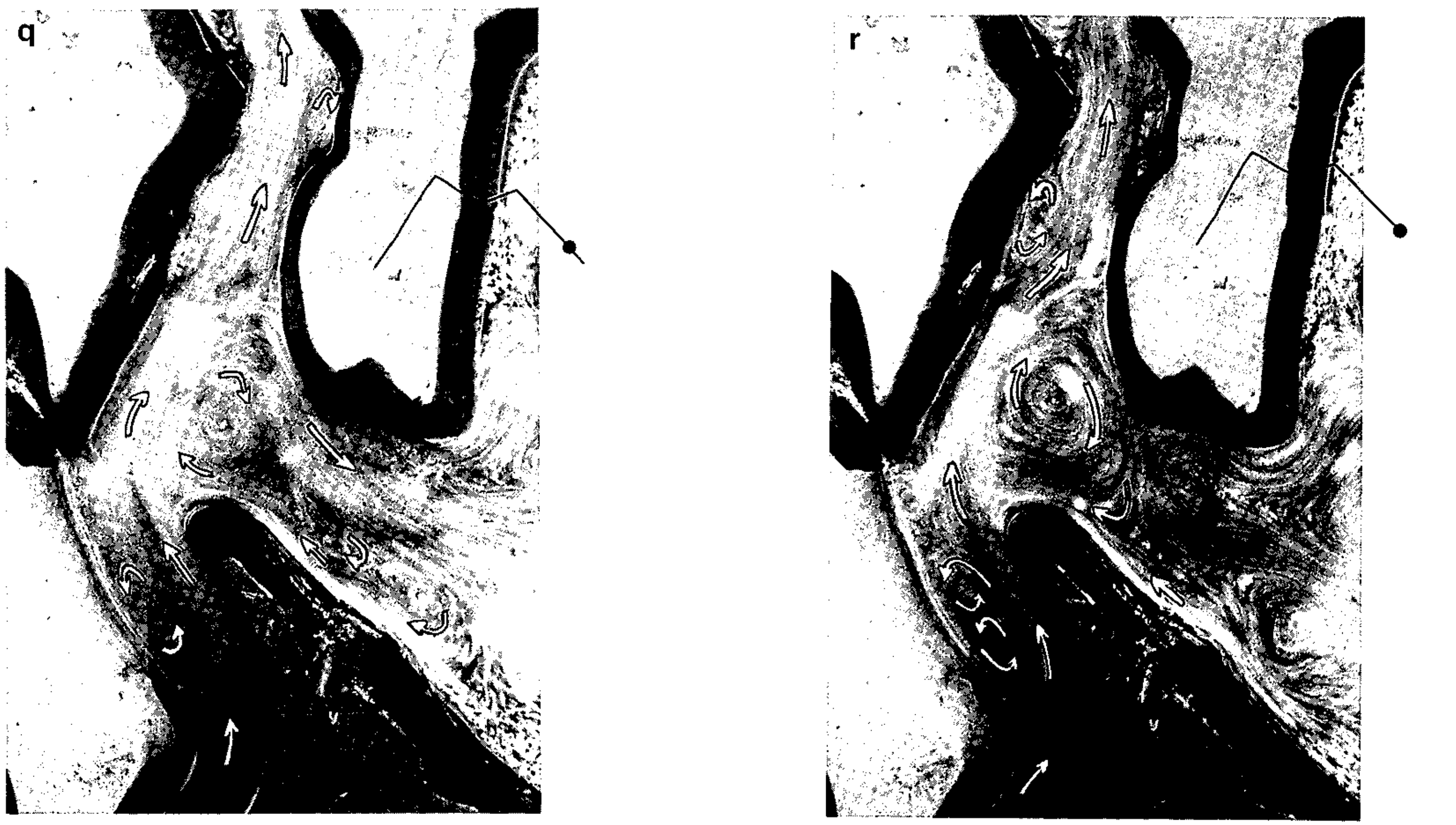

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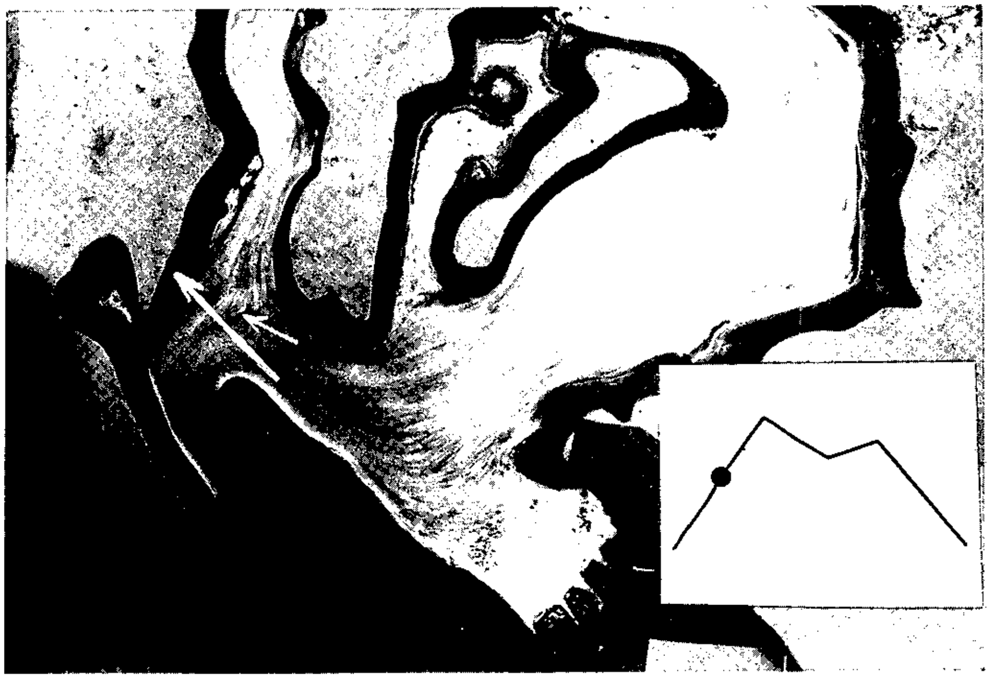
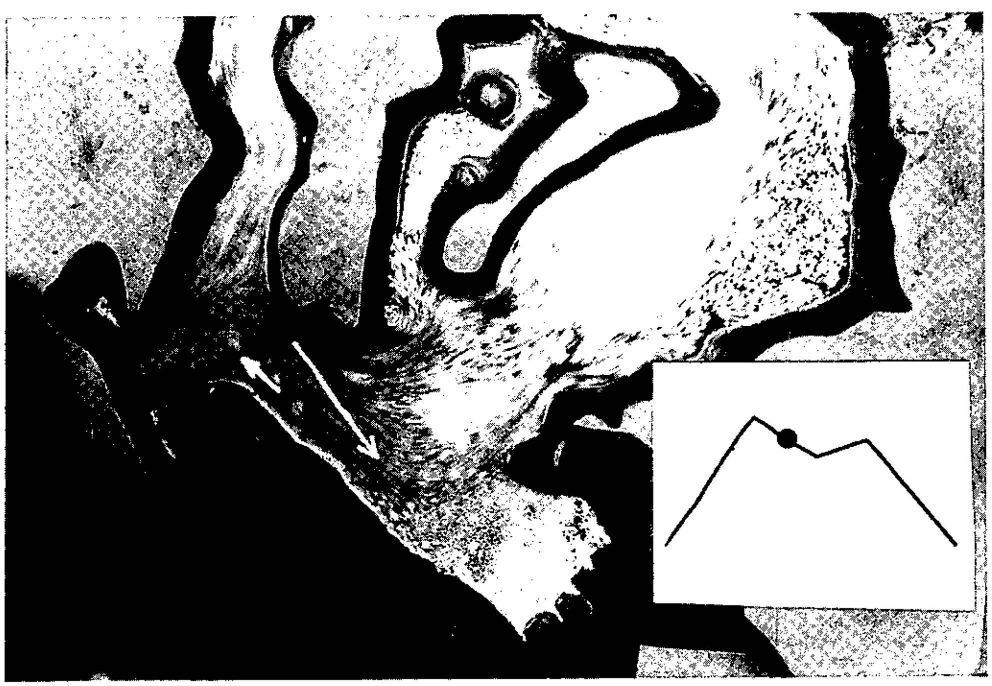
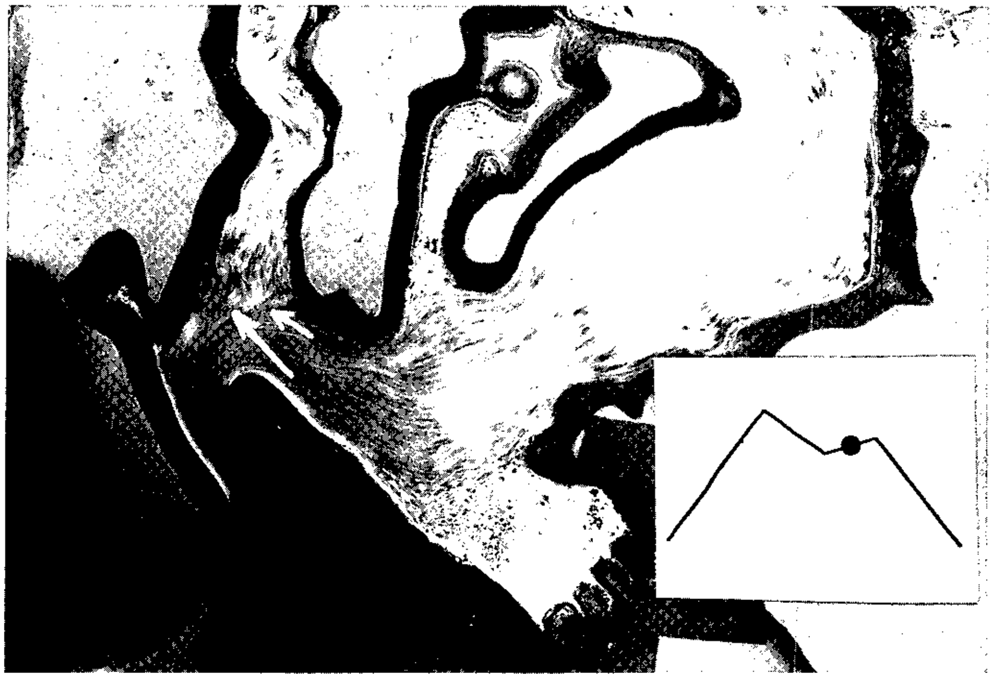
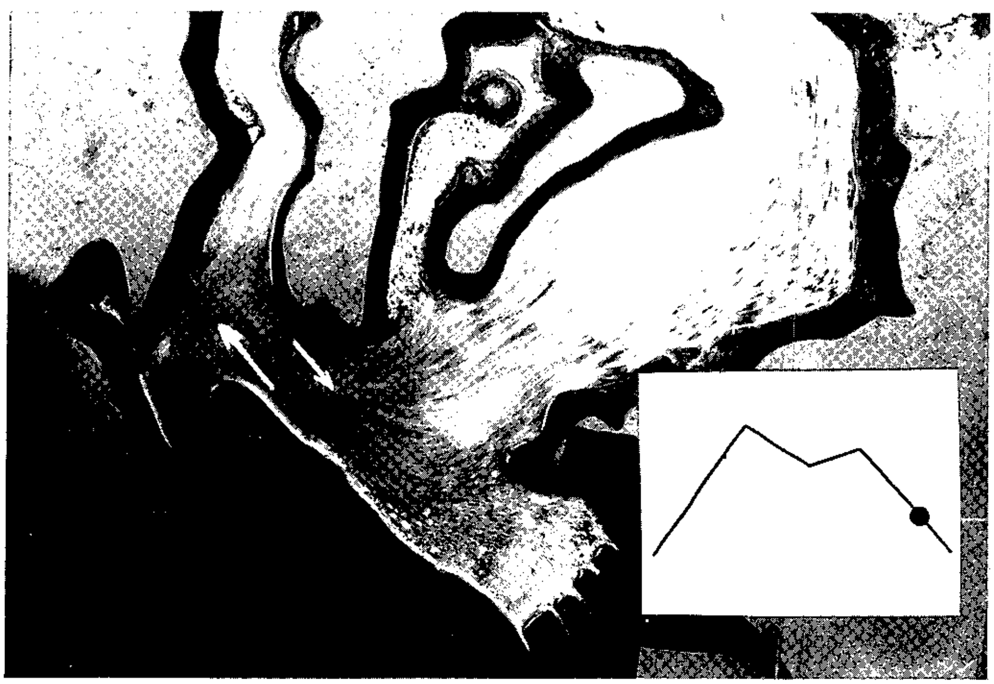




Appendix E. Streak photographs of the model superimposed with current vectors observed in Dalco Passage. Inset shows the phase of the tide.





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