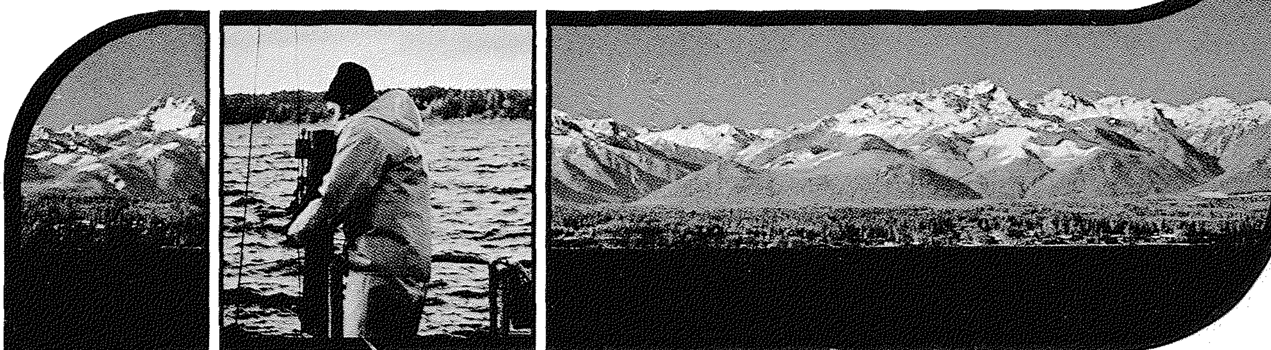
PUGET SOUND INTERIM STUDIES



A STUDY OF THE NUTRIENTS IN THE MAIN BASIN OF PUGET SOUND

DEPARTMENT OF OCEANOGRAPHY
UNIVERSITY OF WASHINGTON

FEBRUARY, 1977

FINAL REPORT

MUNICIPALITY OF METROPOLITAN SEATTLE

UNIVERSITY OF WASHINGTON
DEPARTMENT OF OCEANOGRAPHY
SEATTLE, WASHINGTON 98195

A STUDY OF THE NUTRIENTS IN THE MAIN BASIN OF PUGET SOUND

by

Eugene E. Collias and John H. Lincoln

for the

MUNICIPALITY OF METROPOLITAN SEATTLE
AS AUTHORIZED BY COUNCIL RESOLUTION NO. 2203

Approved by:

Eugene E. Collias, Principal Oceanographer and Co-principal Investigator

Francis A. Richards, Professor, Principal Investigator, and Associate Chairman for Research

REF: M77-2
February 1977

ABSTRACT

In 1973, the council of the Municipality of Metropolitan Seattle (METRO) implemented a program of environmental planning, pilot plant studies, Puget Sound water research projects, etc. One of the tasks proposed was to determine what effects on water properties within the main basin of Puget Sound are attributable to discharge from METRO's sewers. This study compared recent and historical data to determine the presence of any significant changes in nutrient and oxygen concentrations subsequent to METRO discharge, examined seasonal cycles in water properties, and examined the flux of nutrients within the study area. The study area included those waters south of Whidbey Island and north of The Narrows including Colvos Passage but excluding the Port Orchard system.

Observations of water properties were made during 22 cruises beginning 5 November 1974 and ending 19 November 1975. Water properties observed at three week intervals included salinity, dissolved inorganic orthophosphate, nitrate, nitrite, ammonia, silicate, and dissolved oxygen. Two time studies were made at the end of the West Point sewer. Samples for the uptake of ^{15}N-labeled compounds were made at selected locations and times.

A comparison of the new data (1974-75) with the historical data (1932-1963) indicated about a 10% increase in phosphate and no measureable change in the dissolved oxygen. This increase in phosphate was well within the normal variability observed in the historical data. Long-term changes in both dissolved oxygen and phosphate have been observed that are related to changes in upwelling off the Washington coast.

Ammonia originating at a sewer may be used as a tracer of the effluent very close to an outfall, but concentrations generally decrease rapidly to the usual low background level in a short distance and time. Uptake of nitrate and ammonia by phytoplankton showed a definite seasonal trend and were high in comparison to open ocean values.

Observations made in the physical model of Puget Sound indicated that the effluent plume from the West Point outfall were filamentous, fractured, and generally of low concentrations outside of the "near field". This was confirmed by limited field observations.

Transport calculations for the main basin showed an average flux of 60,000 m^3sec^{-1} into or out of the basin. In comparison, the average combined discharge of all sewers entering Puget Sound was 225 m^3sec^{-1}. Calculations of the flux of phosphate (as phosphate ion) showed an average transfer of 1,210 metric ton per day while the average phosphate contribution from sewers was only 12.6 tons per day. Also at any given time the amount of phosphate in the main basin is about 18,400 tons.

From these data, it was concluded that the sewage entering the main basin of Puget Sound from the sewers of METRO and other sewage systems has had no measurable effect upon either the nutrient concentrations or the dissolved oxygen content of the water.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

This study of the nutrient distribution in the main basin of Puget Sound was made possible by a contract with the *Municipality of Metropolitan Seattle* under Council Resolution Number 2203.

The authors wish to thank the many students and members of the professional staff who contributed to the success of this study. A list of personnel participating in each cruise is given in the data report for this study (Collias, 1976). Mssrs. Lincoln C. Loehr and Joseph Glasscock are extended a special thanks for the diligent performance of duties both in the field program and in the office. They were responsible for obtaining and reducing much of the data used in this study. Ms. Rachel Ozretich cared for and operated the Autoanalyzer® aboardship and was responsible for the excellent suite of nutrient data obtained during this survey. Dr. Terry Whitledge was responsible for the nitrogen uptake studies and prepared the portions of this report on that subject. The drawings were prepared by Noel McGary and photographed by Richard Cromoga.

A STUDY OF THE NUTRIENTS IN THE MAIN BASIN OF PUGET SOUND

1. INTRODUCTION

1.1 *Background and objectives*

In July 1973, the Council of *The Municipality of Metropolitan Seattle* (METRO) adopted Resolution No. 1910 to establish a *best practicable treatment* (BPT) policy for sewage and authorized the Executive Director to prepare for implementation of this policy. The implementation was to include developing a program of environmental planning, pilot plant studies, Puget Sound water research projects, etc. Under the BPT policy, a comprehensive study program encompassing water chemistry, biological fauna, and hydrography entitled *"Puget Sound Interim Studies"* was approved by the Council in Resolution No. 2106. One of the tasks proposed in the *Interim Studies* was to identify what effect, if any, the effluent from METRO's sewers have upon the waters of the main basin of Puget Sound as related to concentration of nutrients associated with sewerage. Another task was to identify any possible biological response to these nutrients. These two tasks were combined into a single contract and awarded to the University of Washington Department of Oceanography on 3 October 1974 under METRO Council resolution No. 2203.

For practical purposes, the work performed under this contract was divided into the two basic components: nutrient studies and biological studies. This report describes the distribution and variations in nutrient distribution and the factors influencing the changes within the main basin of Puget Sound. The objectives of this nutrient study were to: (1) compare recent and historical data to determine if any significant changes in nutrient concentrations have ocurred that can be attributed to METRO's sewers, (2) define the seasonal cycles in water characteristics, and (3) estimate the amount of nutrients entering and leaving the study area. Results of the biological studies will be presented in a separate report by Campbell, et al., (1977).

1.2 *Description of the Study Area*

1.2.1 *Geography:* The study area encompassed the main basin of Puget Sound which in turn is a small part of the Strait of Juan de Fuca-Georgia Strait-Puget Sound system (see Fig. 1-1). The main basin extends from the south end of Admiralty Inlet to the north end of The Narrows, a distance of 80 km (43 nautical

miles)[1] and is presented in Figure 1-2. The main basin is separated from Possession Sound by a line extending eastsoutheast from Possession Point to the mainland. Several sub-divisions are found in the main basin and include Elliott Bay, Commencement Bay, Colvos Passage, Quartermaster Harbor, and the Port Orchard system on the west side of Bainbridge Island. The water properties in each of these sub-divisions are closely related to those in the main basin but with slight differences due to the nature of the source seawater, the amount of freshwater entering the sub-division, and tidal mixing at the entrance of the subdivision.

The shoreline of the main basin is characterized by a narrow beach adjacent to bluffs about 100 meters (300 feet) high. Very little of the land on the east side is in its original state because of the intense urban and suburban growth from Everett to Olympia. The shore from Mukilteo to Meadow Point has been stabilized by riprap placed by the Burlington Northern Railroad in the construction of their right-of-way. Meadow Point is a public beach and is in a more or less natural state. The shoreline in Shilshole Bay has been stabilized for a marina, private residences, and commercial uses. Riprap has been placed around West Point to protect the light house. Elliott Bay has been extensively modified since the founding of Seattle including the making of Harbor Island. Alki Beach is a public beach but has been protected by a major seawall. From Alki Point to Tacoma, many bulkheads have been built by residents to prevent errosion of their property. On the west side, the population growth has been less, but the area has been logged and second growth timber is found along much of this side. The main population center on the west side is the City of Bremerton. But with the introduction of the Trident Nuclear Submarine base at Bangor, population pressure on the Great (or Kitsap) Peninsula is beginning to increase.

The main basin has an average width of 7.2 km (4 nmi), an average depth of 108m (64 fathoms) and a length of 80km. The surface area at mean high water level in Seattle (3.26m above MLLW[2]) is 743 km^2 (217 nmi^2) and the volume at high water is 80.57 km^3 (12.7 nmi^3). The deepest part of the basin is located west of Richmond Beach and has a depth of over 284m (155 fath.). Another de-

- - - - - - - - - - -

1. The metric system of units will be used throughout this report but English equivalents will frequently be specified.

2. MLLW stands for mean lower low water, the reference level for tides in Puget Sound and in fact, for the entire Pacific Coast of North America.

pression of comparable depth is located off West Point. Near Point Robinson, the basin begins gradually to shoal toward the south with a depth of 172m off Brown Point. In Dalco Passage, the basin shoals rapidly to 54m north of Point Defiance. The tidal prism[3] for the main basin is 2.39 km^3.

1.2.2 *Summary of existing oceanographic data:* Beginning in 1932 and continuing to the present, oceanographic data have been obtained from many locations in Puget Sound and adjacent waters. From 1932 to early 1942, data were collected by personnel from the Oceanographic Laboratories[4] under the direction of Dr. Thomas G. Thompson using the research vessel *Catalyst*. During this period, no systematic survey was made of the entire Puget Sound system, but several stations in the main basin were occupied at about monthly intervals. From 1942 to late 1946, the Oceanographic Laboratories were closed by World War II and then reopened by Dr. Thompson. Sampling of Puget Sound waters was resumed at irregular intervals using the *RV Onchorhynchus*. From September 1952 through November 1954, an intensive systematic survey of Puget Sound and the adjacent waters was made on a monthly basis using the *RV Brown Bear*. From 1954 to date, sampling for specific projects has continued. In 1970 and 1971, many stations were occupied in the main basin of Puget Sound for a study conducted for the City of Seattle, Department of Lighting (Collias, Lincoln, and Barnes, 1973).

At each station, observations of meteorological conditions, water temperature, salinity, and dissolved oxygen were routinely observed. Orthophosphate, silicate, nitrate, and other parameters were measured at selected stations. A summary of oceanographic data collected in Puget Sound and adjacent waters has been prepared by Collias (1970), and an atlas of physical and chemical properties, based upon these data, has been prepared to present this data in a graphical form (Collias, McGary, and Barnes, 1974).

1.2.3 *Climatology:* Local and regional weather conditions have a definite effect upon the oceanographic characteristics of the main basin of Puget Sound. Local winds affect the transport of water in the main basin while regional winds

- - - - - - - - - -

3. The tidal prism is the volume of water contained in a given geographic area between high water and low water stands for a specified tide.

4. The Oceanographic Laboratories were a branch of the Graduate School and included faculty from many disciplines. In 1951, the Department of Oceanography was established under the College of Arts and Sciences with Dr. Richard H. Fleming as Chairman. He was succeeded in 1968 by Dr. Maurice Rattray, jr, the present chairman.

influence the type of water being transported through the Strait of Juan de Fuca. Regional barometric pressure differentials affect water levels and thereby influence to some extent both tidal heights and currents. Meteorological conditions affect precipitation and runoff, contributing to the fresh water inflow from rivers. This fresh water inflow in turn affects the surface water salinity which is later reflected in the salinity of the deeper waters.

The climate of the Puget Sound region is predominately a temperate, marine type. Summers are cool and relatively dry, whereas the winters are mild with considerable cloudiness and rain. Daily and annual ranges of air temperatures are small. Some factors influencing the climate are terrain, distance and direction from the ocean, location within the belt of prevailing westerly winds, and the position and intensity of the semi-permanent high and low pressure cells over the north Pacific Ocean.

During summer, the surface winds along the Washington coast are, for the most part, attributable to the circulation around the semi-permanent high pressure cell that dominates the eastern Pacific Ocean. This anticyclone causes a prevailing northwesterly wind along the Pacific Coast. In autumn, the Pacific high begins to retreat southward and weaken. Simultaneously, the semi-permanent low pressure center, usually centered near the Aleutian Islands, begins to intensify and deepen. By mid-winter, these changing pressure systems have shifted so that the prevailing wind along the coast is southwesterly.

In winter, the coastal area lies directly in the path of the migratory storms that follow the Polar Front. As a result of these storms, much of the Pacific Coast is subjected to strong winds varying in direction from southeast to northnorthwest, even though the prevailing flow is well defined as south to southwest.

The prevailing surface winds over the main basin of Puget Sound from October through March are usually from the south with an average speed of about 30 km hr^{-1} (15 mph). Storm winds in fall and winter sometimes exceed 100 km hr^{-1} with extreme storms in excess of 120 km hr^{-1} having been observed on occasion. Winter winds may be from the north accompanied by very cold air and frequently snow. In April and May, the winds become more variable but southerly winds of about 20 km hr^{-1} are frequent. In summer, the prevailing winds are northerly with an average speed of under 20 km hr^{-1}. Air temperatures during the observation period varied from a high of 32.2°C (90°F) to a low of -6.1°C (21°F) with an average of 10.4°C (50.8°F).

1.2.4 *Freshwater Sources:* Freshwater sources entering directly into the main basin of Puget Sound include two rivers, the Lake Washington Ship Canal, many small creeks, ground water, and direct precipitation. A major portion of the freshwater inflow into the total Puget Sound system occurs in the Whidbey basin but only a portion of this freshwater finds its way into the main basin through Possession Sound. The Duwamish River discharges into Elliott Bay, the Puyallup into Commencement Bay, and the Ship Canal into Shilshole Bay. The flow of these two rivers is controlled to some extent for power purposes and flood control, but the water is returned to the rivers upstream from their mouths. The Puyallup River exhibits two periods of high runoff during the year. The winter peak is the result of direct precipitation or quickly melting snow on the low lands, whereas the early summer peak results from snow melting in the Cascade Mountains. On the other hand, the Duwamish River exhibits a single extended peak in winter because there is no portion of the watershed extending into the mountains. The flow from the Ship Canal is highly regulated by the US Army Corps of Engineers at the Chittenden Locks. One high runoff period occurs during winter. But during summer, the spillway discharge is greatly reduced or stopped to compensate for lower inflow into Lake Washington and increased lockage requirements while maintaining the required lake level.

Direct precipitation on the drainage basin supplying fresh water to the main basin varies with geographic location. For the 13 month study period, the highest recorded rainfall was 173 cm (68.2 in) at Bremerton and the lowest was 59.4 cm (23.4 in) at Port Townsend. The rainfall at Seattle during this period was 121 cm (47.8 in) which is equivalent to an average flow of 28.5 $m^3 sec^{-1}$, or 1,006 cfs, directly on the water surface of the main basin. The contribution by ground water and artesian flow is unknown. Evaporation from the water surface has been estimated to be about 64 cm per year (Friebertshauser and Duxbury, 1972).

1.2.5 *Seawater Sources:* Admiralty Inlet supplies about 98% of all seawater entering the Puget Sound system with the remaining 2% coming into Deception Pass at the north end of Whidbey Basin. Hence, what happens in Admiralty Inlet strongly influences the water characteristics of the entire Puget Sound system. Water in Admiralty Inlet is a mixture of fresher surface water leaving Puget Sound and deeper saltier water entering from the eastern end of the Strait of Juan de Fuca. In turn, the waters in the Strait are a mixture of

surface water leaving Puget Sound and Georgia Strait and deeper oceanic water entering from the Pacific Ocean off Cape Flattery. The nature of this deeper oceanic water is dependent upon the offshore winds. During summer when northerly winds are dominant along the Washington coast, a considerable amount of upwelling occurs along the coast that brings water from 100m or deeper into the Strait. This water is cooler, more saline, lower in oxygen content and higher in nutrients than water usually present during the remainder of the year. The oceanic water moves landward and by August begins to mix with water in Admiralty Inlet. As a result, the average salinity of the waters of all Puget Sound exhibit a salinity maximum in September and October accompanied by a depression in dissolved oxygen and an elevation in nutrient concentrations. This phenomenon occurs each year with the maximum effect depending upon the long-term meteorological cycles of the north Pacific Ocean.

Water properties in the main basin of Puget Sound are strongly influenced by interchange of seawater with Admiralty Inlet and with Whidbey Basin through Possession Sound. The tidal pumping action of The Narrows influences the water in the southern portion of the main basin. The effect of Whidbey Basin upon the main basin is most evident when Port Susan flushes in early winter. This flushing action sometimes causes a tongue of low oxygen content water to enter the main basin at about 50m depth and may be observed as far south as Apple Cove Point. Also, when the Skagit River is in flood stage, the fresh water layer may be observed several kilometers south of Possession Point. Observations suggest that there is a net flow of about 500 m^3 sec^{-1} from the main basin into Whidbey Basin, but the amount varies with season and wind conditions (Collias, et al., 1973).

The Narrows is the only connection between southern Puget Sound and the main basin. As a result, the tidal currents in The Narrows are strong and the turbulence high. For an average tide of 3.9 m (13 ft), the tidal exchange is 1.64 km^3. The volumes exchanged on flood and ebb are nearly equal because the contribution of fresh water from rivers and land drainage south of The Narrows is very small in comparison with the total tidal exchange. On a flood tide, water is drawn from Dalco Passage at the south end of Vashon Island and, to a much lesser extent, from Colvos Passage. On an ebb tide, water from The Narrows is discharged mostly into Colvos Passage. This flow also appears to aspirate water from Dalco Passage, thereby increasing the northerly flow through Colvos Passage during large ebbs. This mechanism produces a significantly greater net transport in the main basin than otherwise would exist (Ebbesmeyer and Barnes,

1976).

1.2.6 *Tides:* Astronomical tides are the principal driving force for the oscillating water movement within the Puget Sound system. Throughout Puget Sound, the tides are of the mixed type having two highs and two lows each tidal day[5]. However, the tides become nearly diurnal[6] once a month in the eastern end of the Strait of Juan de Fuca as evidenced by the tidal curve at both Port Townsend and Victoria.

A major characteristic of the Puget Sound tides is the large diurnal inequality (i.e., the difference in heights of successive high and low waters) with the largest inequality being the heights of low waters. Astronomical tides may be computed with considerable accuracy for any given locality and are published annually by the National Ocean Survey. Predictions for Seattle may be found in the series titled *Tide Tables West Coast of North and South America*. But,these calculations cannot take into account the effects of the unpredictable meteorological forces and variations in river discharge. The difference between actual and predicted tide height may be as much as 1 meter on a high tide when strong winds accompany a low barometric pressure cell over Puget Sound. The major effect is upon currents and tidal exchange within a local area, but damage to improperly located shoreline installations may result.

Tides are primarily a wave phenomenon; thus the change in water level with time varies throughout the entire Puget Sound system and is strongly influenced by the geomorphology of the basin. Because of the morphological character of the main basin, the tide wave progresses rapidly from Point No Point to The Narrows with less than 15 minutes travel time. Hence, the predicted tides at Seattle are representative of the entire main basin. Seattle is a primary tide station with a continuously operating water-level recorder maintained by the National Ocean Survey at the Washington State Ferry Terminal in Elliott Bay. Records at Seattle date back to January 1898.

1.2.7 *Sewer discharges:* Thirty-two sewers discharge into the main basin of Puget Sound and three discharge into Possession Sound. The locations of the

- - - - - - - - -

5. A tidal day is 24.84 hours in length principally in response to the effect of the moon.

6. A diurnal tide has only one high and one low per day. The higher low and lower high become either nearly or exactly equal so that the water level remains almost constant for a period of from three to six hours.

outfalls are shown in Figure 1-3 and a brief description of each, except for five very small ones, is given in Table 1-1. Data for this table were obtained from the Department of Ecology and from local sewer districts. The combined average flow of these sewers for the period from 1 November 1974 through 30 November 1975 was 10.1 m^3sec^{-1} (231 MGD or 356 cfs). Of this total, the five sewers of METRO contributed 70%. In comparison, the fresh water flow from rivers into the central basin for the same period averaged 195 m^3sec^{-1} (6,882 cfs).

The effluent from most sewers is a combination of domestic and industrial wastes plus storm water. During the rainy season or periods of high rainfall, the flow from the sewage treatment plants will be high and storm water will be a major fraction of the discharge. On the other hand, during periods of low rainfall and especially during the late summer months, the quantity of effluent will be most representative of the steady-state contributions from domestic and industrial sources. On an average, about 70% of the discharge is from domestic and industrial sources but, during heavy rain storms, the storm water may be 3 to 4 times that of the steady state discharge of the pure poop.

Analyses of the chemical composition of the sewerage has been made on a systematic basis only at the West Point and Renton METRO plants. Some of the results from West Point are presented in Table 1-2 and in Table 1-3 for the Renton plant.

TABLE 1-1

SEWERS DISCHARGING INTO OR NEAR THE MAIN BASIN OF PUGET SOUND

SEWER	*DISCHARGE in MGD*[1]		
	Average	*Maximum*	*Minimum*
Alderwood Mannor	0.345	0.835	0.178
Alki Point (METRO)	8.142	24.6	5.3
Annapolis	0.519	1.033	0.203
Bremerton 1	2.622	4.76	1.17
Bremerton 2	3.235	6.03	2.07
Carkeek (METRO)	3.374	17.2	1.60
Des Moines	2.869	6.101	2.047
Edmonds	4.702	8.75	3.24
Everett[2]	10.644	41.95	4.59
Lakota	1.004	1.951	0.679
Lynnwood[3]	2.193	3.075	1.080
Manchester[4]	0.031	0.094	0.009
Miller Creek[5]	2.124		
Mukilteo	0.116	0.580	0.025
Olympic Terrace[6]	0.357		
Point Defiance (Tacoma)	1.952	3.00	0.98
Port Orchard[7]	0.428	1.877	0.090
Redondo	1.310	2.044	0.675
Renton (METRO)	28.079	54.84	19.66
Richmond Beach (METRO)	1.754	3.57	0.99
Salmon Creek[5]	2.717		
Silverdale	0.348	0.859	0.124
Suquamish[8]	0.023		
Tacoma, Central	25.254	52.9	9.50
Tacoma, North	5.293	18.991	1.10
Vashon	0.065	0.409	0.017
West Point (METRO)	120.934	277.	67.4
Winslow[9]	0.100		

- - - - - - - - - - - - - - - -

1. Based upon 13 months record from 1 November 1974 through 30 November 1975.
2. Discharges into Everett Harbor, 46 km north of West Point.
3. Incomplete records - only 7.2 months available.
4. Based upon 12 months records.
5. Only weekly rates recorded.
6. Only monthly accumulated amounts recorded.
7. Monthly rates only but with maximum and minimum daily flows recorded.
8. Five months data - July through November 1975.
9. Four months data - August through November 1975

TABLE 1-2

NUTRIENT DATA FROM THE WEST POINT PLANT
(all values in parts per million)

Year	Month	Day	Ammonia	Phosphate	Total Nitrogen	Flow MGD
1974	11	14	35.1	5.3	83.6	71.5
		18	21.9	3.3	62.9	141.9
		26	26.6	4.6	26.5	95.6
1974	12	04	28.3	4.7	28.0	175.6
		11	27.8	4.5	62.3	118.9
		18	28.5	4.2	51.0	165.6
1975	01	01		4.75		128.0
		09	10.3		22.2	
		14	8.1	3.4	11.3	202.2
		19	8.9	4.0	17.5	119.5
		27		5.3		114.6
1975	02	02		5.25		94.9
		06	14.5		24.9	97.9
		10	12.1	6.10	22.3	111.1
		17		6.13		110.9
		18	12.2		20.8	118.6
		24	9.9	4.88	19.9	147.2
1975	03	03	8.3	3.7	17.9	168.3
		10	12.8	4.8	25.2	114.3
		18	10.0	3.3	20.9	202.0
		24	11.3	4.5	20.5	113.0
		27		4.4		101.8
		31	11.6	4.9	24.7	109.7
1975	04	07	14.7	5.25	28.5	106.7
		14	12.5	5.13	38.4	104.0
		22	16.4	4.90	45.2	93.8
		28	18.2	5.26	36.9	96.5
1975	05	05	15.5			99.3
		12	11.3	3.2	24.5	108.6
		19	14.3	4.6	24.7	90.9
		26	17.6	4.3	29.7	74.5
1975	06	03	19.6	6.5	38.4	85.0
		09	21.1	5.0	44.2	82.5
		16	16.0	6.0	34.2	82.9
		23	20.4	6.9	37.5	80.6
		30	16.3	5.7	30.9	89.4

TABLE 1-2 (continued)

Year	Month	Day	Ammonia	Phosphate	Total Nitrogen	Flow MGD
1975	07	07	15.5	6.2		86.2
		14		5.8		85.7
		21	12.8	6.5		85.7
		28	12.0	8.3		90.8
1975	08	06	11.6	5.8	21.6	101.7
		11	11.2	6.2	36.5	99.1
		20	12.7	5.8	21.4	108.2
		25	14.6	6.7	23.6	99.5
1975	09	03	15.4	6.7	26.2	105.7
		09	17.4	6.0	27.3	102.3
		16	17.1	6.0	27.9	104.8
		17	16.4	6.2	30.6	108.8
		22	16.1	4.7	25.3	100.2
		29	18.9	4.8	29.3	96.7
1975	10	06	15.8	3.3	28.2	108.1
		14		3.0		116.7
		16	8.8		19.2	150.7
		21	5.6	3.1	14.2	216.9
		28	5.8	3.6	14.5	194.3
1975	11	04	7.1	4.6	16.2	124.1
		10	9.9	5.1	19.1	128.1
		17	6.1	3.4	14.4	179.5
		24	9.8	4.6	19.0	141.0
1975	12	01	9.0	3.9	23.1	127.0
		10	7.8	3.7	18.6	142.8
		15	9.0	4.3	18.2	157.3
		22	11.5	4.5	20.1	129.1
		30	13.4	3.8	22.0	149.1

NOTE - Missing values in body of table indicate that no analyses were recorded for that parameter on that particular day.

TABLE 1-3

EFFLUENT CHARACTERISTICS OF THE RENTON TREATMENT PLANT
(Monthly averages)

Year	Month	Phosphate	Nitrate	Ammonia	Organic Nitrogen	Flow MGD
1974	11	5.3	0.525	9.2	7.2	25.28
	12	3.8	2.975	4.6	3.5	28.74
1975	01	2.27	2.941	5.4	2.7	33.73
	02	4.0	1.350	8.1	2.6	32.31
	03	3.4	0.38	9.3	4.2	30.74
	04	5.0	0.167	14.5	3.9	27.20
	05	4.8	0.035	15.9	3.4	25.75
	06		0.13	18.5	0.6	24.47
	07	4.8	0.006	14.6	5.2	23.86
	08	4.1	0.003	17.7	5.0	25.41
	09	5.75	0.007	20.5	5.4	24.95
	10	4.6	0.006	15.8	5.64	28.97
	11	3.4	0.035	11.4	3.9	33.75

Values of nutrients in parts per million

(Data obtained from Mr. R. E. Finger of the Renton Treatment Plant staff.)

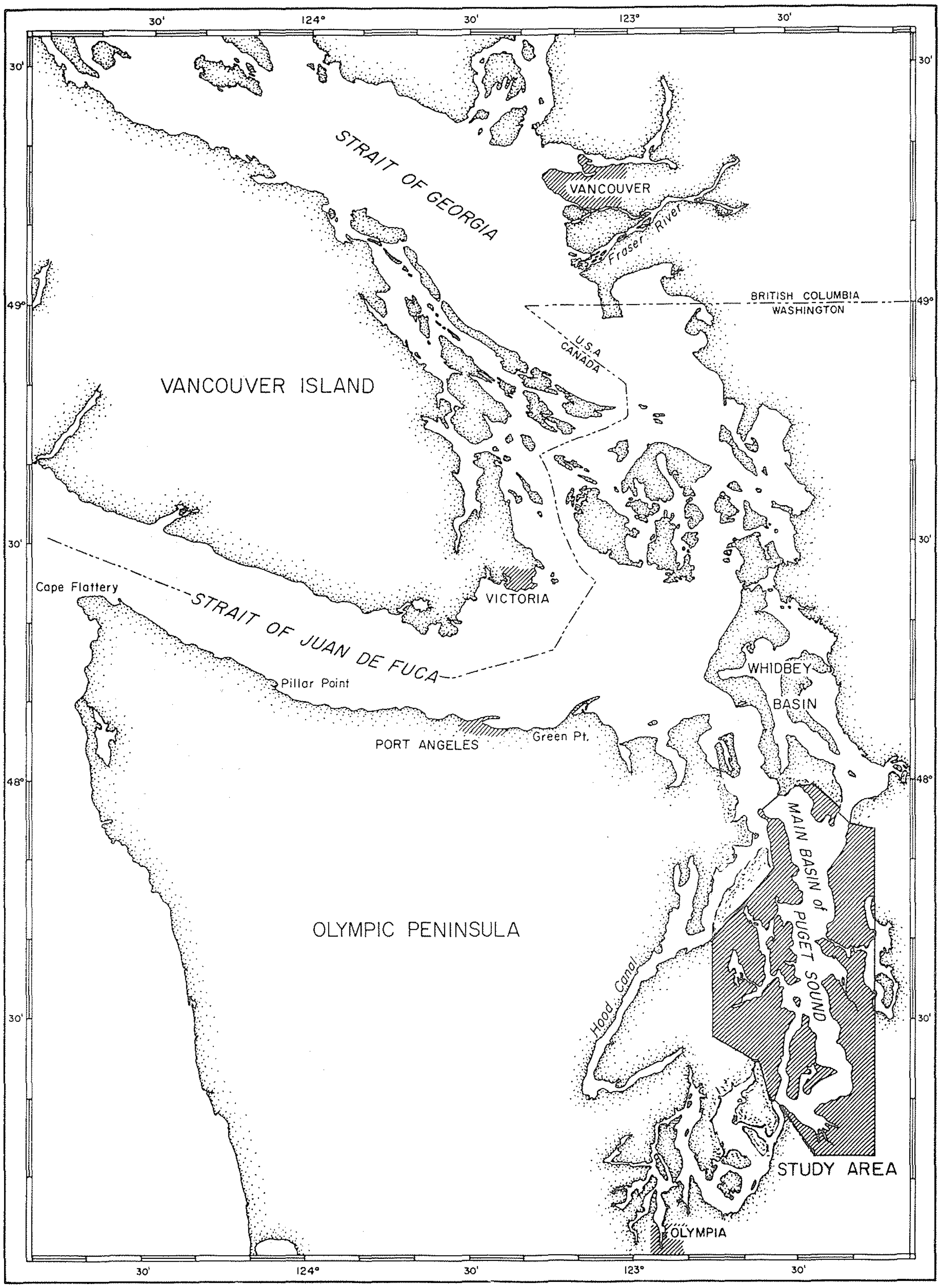


Figure 1-1 The Strait of Juan de Fuca-Georgia Strait-Puget Sound System. The study area is shaded.

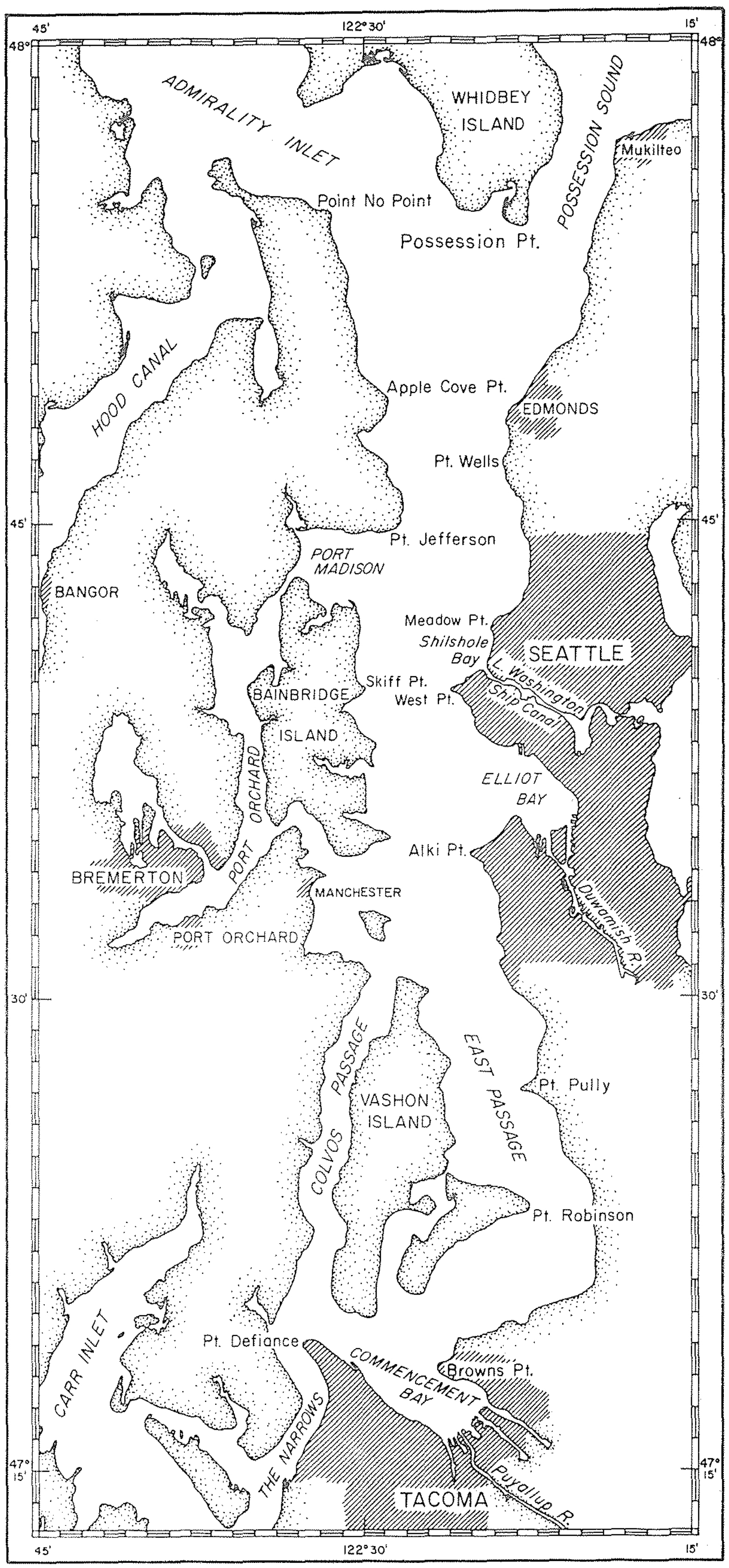


Figure 1-2 The main basin of Puget Sound.

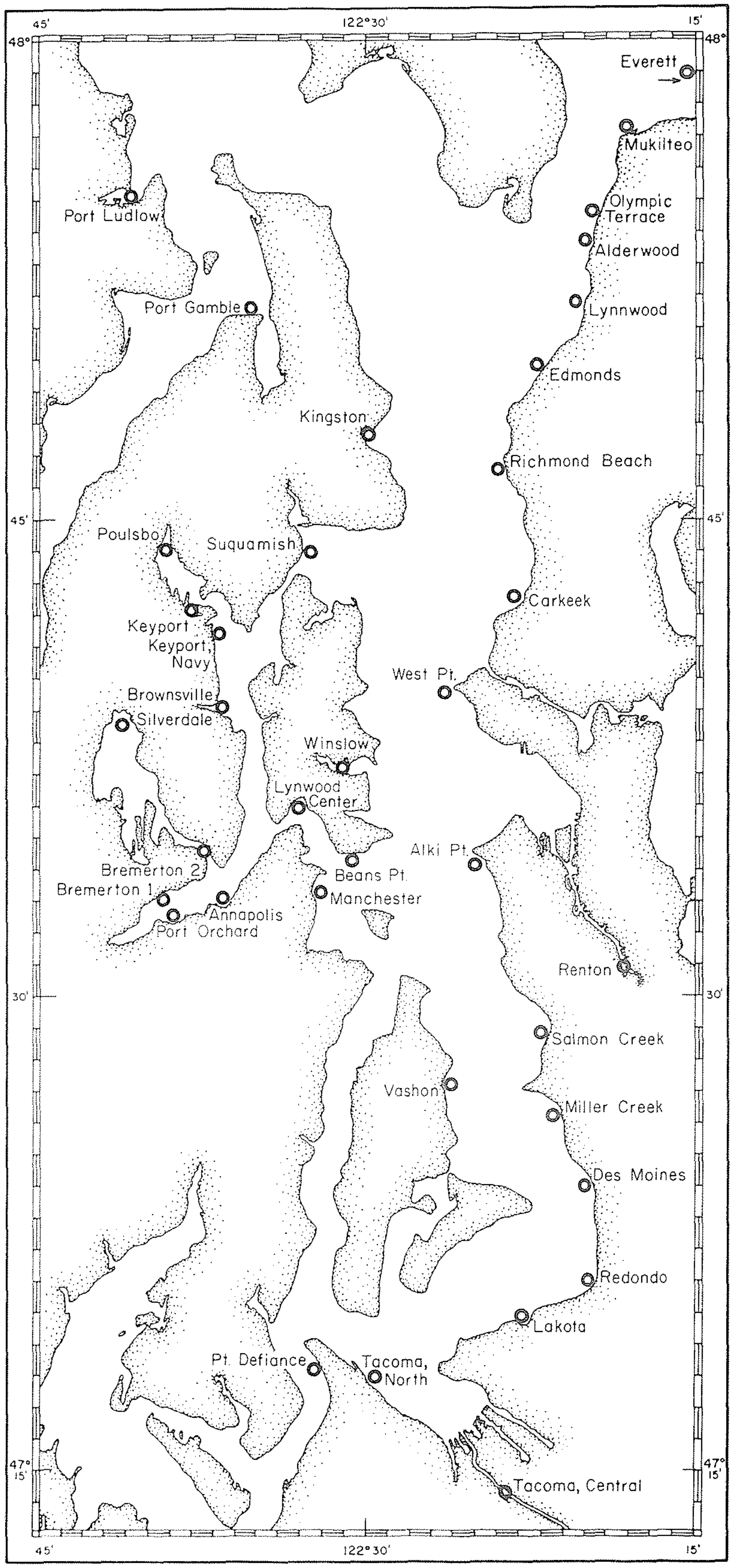


Figure 1-3 Location of sewer outfalls entering the main basin of Puget Sound.

2.0 OBSERVATIONS AND METHODS

2.1 *Field observations*

2.1.1 *Water characteristics:* Observations of water properties in the study area were made on 22 cruises during the thirteen month study period beginning 5 November 1974 and continuing through 19 November 1975. Water characteristics were observed at tri-weekly intervals on 19 cruises with a total of 31 stations being occupied at locations shown in Figure 2-1. However, each station was not necessarily occupied on each tri-weekly cruise. Time studies at the seaward end of the West Point sewer were made in May and September 1975. Also one cruise (MET-07) was in support of the heavy-metals program of the *Interim Studies* (Schell, et al., 1977). A summary of these cruises is presented in Table 2-1.

Each tri-weekly cruise required from two to three days for completion. Scheduling of the cruises did not permit sampling of the major stations (see Fig. 3-1) on the same stage of the tide. Because of tidal variability at each station, a variable is introduced into the data that must be considered when comparing water properties at different locations on the same cruise or when examining variability at a given location over any extended period of time.

Water samples were obtained at selected depths using non-metallic Scott-Richards sampling bottles equipped with protected deep-sea reversing thermometers. Upon retrieval, the thermometers were read and samples of the trapped water drawn for analyses of salinity, dissolved oxygen, and nutrients (i.e., phosphate, silicate, nitrate, nitrite, and ammonia). Salinity was determined by electrical conductivity using the University of Washington salinity bridge (Paquette, 1956). The average error in salinity determination was less than 0.006 $^{o}/oo$ (parts per thousand) and the average error in temperature less than 0.04^{o}C. Densities as *sigma-t*[7] were computed from the *in situ* temperatures and salinities using the equations of Knudsen (Knudsen, et al., 1901 and Cox, et al., 1970). Dissolved oxygen was determined by the modified Winkler method (Thompson, 1939) with an average error of less than 5%. Nutrients were analysed on board ship so that the analyses were commenced within 10 minutes after obtaining the samples. A Technicon® autoanalyser was used for nutrient determin-

- - - - - - - - - -

7. *Sigma-t* is an expression for density of seawater, at atmospheric pressure and its *in situ* temperature and salinity, as defined by the equation:

$$Sigma\text{-}t = (density - 1) \times 1000$$

TABLE 2-1

SUMMARY OF METRO CRUISES

METRO SERIES NUMBER	SHIP'S CRUISE*	DATES	PURPOSE (REMARKS)
01	K7-033	05-07 Nov 1974	First tri-weekly cruise
02	K7-034	25-27 Nov	Second tri-weekly cruise
03	K7-035	16-18 Dec	Third tri-weekly cruise
04	K7-036	07-09 Jan 1975	Fourth tri-weekly cruise (Incomplete because of mechanical failures)
05	K7-037	28-30 Jan	Fifth tri-weekly cruise
06	OA-637	19-21 Feb	Sixth tri-weekly cruise and nitrogen uptake study
07	K7-039	27-28 Feb	Heavy metals sampling
08	K7-040	10-11 March	Seventh tri-weekly cruise and dredge spoils study
09	K7-041	01, 03 April	Eighth tri-weekly cruise
10	K7-034	22-24 April	Ninth tri-weekly cruise
11	K7-045	07-09 May	Time study at West Point
12	K7-046	14-16 May	Tenth tri-weekly cruise
13	OH-959	03-05 June	Eleventh tri-weekly cruise
14	K7-049	25-27 June	Twelfth tri-weekly cruise
15	K7-050	15-17 July	Thirteenth tri-weekly cruise
16	K7-052	04-08 Aug	Fourteenth tri-weekly cruise
17	K7-053	25-27 Aug	Fifteenth tri-weekly cruise
18	K7-054	02-03 Sept	Time study at West Point
19	K7-056	16-17 Sept	Sixteenth tri-weekly cruise
20	K7-058	07-08 Oct	Seventeenth tri-weekly cruise
21	K7-059	28-30 Oct	Eighteenth tri-weekly cruise
22	K7-061	17-19 Nov	Nineteenth tri-weekly cruise and nitrogen uptake study

\- - - - - - - -

* The first two digits indicate the vessel used and the last three digits indicate the cruise number for that ship.

K7 = *RV Kestrel*　　OH = *RV Hoh*
OA = *RV Onar*

ation according to the methods of Armstrong (1967) and Koroleff (1970). Values of oxygen saturation were computed using the equations of Weiss (1970). All data on water characteristics were processed by machine methods and are reported in a separate volume (Collias, 1976).

2.1.2 *Nitrogen uptake:* Nitrogen uptake experiments utilizing ^{15}N-labeled compounds were made in February, April, May, August, September and November 1975. In all, 20 stations were sampled, 82 samples analyzed for uptake of ^{15}N-labeled nitrate, 74 for ammonia, and 19 for urea. Initial and final particulate matter, assumed to be from phytoplankton, were determined on each sample.

Field samples were collected using 5-liter non-metalic Niskin water sampling bottles at depths corresponding to light intensities of 100, 50, 30, 25, and 1 percent of the *incident* radiation. Samples were drawn into 2-liter Pyrex bottles masked with metal screens of varying porosity to reduce the internal light levels to approximately the same intensity as was found at the original sampling depth. Immediately after the bottles were filled, a measured quantity of ^{15}N in the form of either nitrate ions, ammonium ions, or urea was introduced. The bottles were tightly stoppered, the necks covered with aluminum foil, and placed in a Plexiglas® tank exposed to daylight and cooled with continuously flowing surface seawater. The water remaining in the Niskin bottles was filtered through glass fiber filters for later determination of the initial amount of particulate nitrogen. After a six-hour incubation period, the labeled samples were filtered through glass filters, dried at about 55°C, and stored in a dessicator until analysis by a mass spectrometer.

In the laboratory, the isotope ratios and particulate nitrogen content were determined using a combined nitrogen analyzer and mass spectrometer (Pavlou, et al., 1974). Briefly this method consisted of using the Dumas procedure to pyrolyze the sample, a liquid nitrogen trap to eliminate any carbon dioxide, a Toepler pump to collect the resulting nitrogen gas, and a gas burette to measure the volume of gas. The nitrogen was then introduced into an AEI Model MS-10 symmetrical single focusing mass spectrometer by means of a variable leak valve and the ^{14}N to ^{15}N ratios determined. The uptake ratios and rates were calculated using the period of incubation, amount of ^{15}N originally added, the enrichment by the phytoplankton, and the original nitrogen content of the plankton.

2.2 *Model studies*

Studies of the currents near West Point and the dispersion of effluent from the West Point outfall were made using the oceanographic model of Puget Sound located at the University of Washington. The model is of relatively small scale[8] and wind effects cannot be simulated. These factors along with other modeling artifacts must be considered in interpreting results obtained from the model. However, good agreement has been obtained between field and model observations at many places in Puget Sound so that model results may be reported with a high level of confidence. The model was filled with salt water (sodium chloride only) and the salinity in the ocean tank was maintained at 16.00 $^{o}/oo \pm 0.02\ ^{o}/oo$. Fresh water was introduced at 11 sites corresponding to the mouths of the major rivers. Individual river flows were precisely controlled during a given experiment. Tides were generated by a six-component Kelvin tide prediction machine that can readily be set for any time period between 1850 and 2000 AD.

Current velocities[9] were determined by measuring the horizontal displacement between two successive small diameter (0.5 - 1.0 mm) dye vortecies injected into the water at precisely one-second intervals and at the exact location and depth of the West Point outfall[10]. Dispersion characteristics of the plume were studied by continuous injection of dye at the same location using a precise motor-driven syringe pump set at a rate corresponding to a sewer flow of 86 MGD (the actual dye flow was 8.7 ml per hour). In both cases, the dye used had a density near to but not greater than that of the receiving waters. This was to provide a slight positive buoyancy and thus better simulate the action of the plume.

Movement of the dye was recorded photographically using a 16 mm movie camera operated by an intervalometer at two-frames per second. Black and white reversal film (Kodak Plus-X) was used to record the current measurements while color film (Kodak ECO 449 Ektachrome Commercial) was used for the dispersion studies.

- - - - - - - - - - - - -

8. The horizontal scale of the model is 1:40,000, the vertical scale is 1:1,152, and the time scale is 3.055 seconds per hour.
9. Velocity is a vector quantity so that both speed and direction must be determined.
10. The diffuser of the West Point outfall is situated in 67 m (220 ft) of water at latitude 47^{o} 39' 39.16"N and longitude 122^{o} 26' 45.57"W.

Two time periods were studied: 7-10 May 1975 and 2-5 September 1975. These corresponded to the field studies made at the terminus of the West Point outfall. The tides and river flows set into the model corresponded to these dates. The exact details are given in Tables 2-2 and 2-3. Each combination of dates and river flows was photographed on three separate runs to provide replicate measurements. The agreement between runs of the same combination was very good.

TABLE 2-2

TIDES FOR SEATTLE USED DURING STUDY PERIODS

MAY 1975			SEPTEMBER 1975		
Date	Time	Height	Date	Time	Height
7	0154	10.4	2	0016	9.6
	0841	1.8		0736	-0.2
	1517	9.1		1455	10.7
	2032	4.9		2023	6.0
8	0220	10.4	3	0125	9.9
	0913	0.9		0825	-0.4
	1606	9.8		1530	11.2
	2115	5.3		2109	4.9
9	0246	10.3	4	0228	10.3
	0943	0.1		0915	-0.4
	1648	10.3		1602	11.6
	2157	5.7		2154	3.7
10	0311	10.4	5	0327	10.8
	1015	-0.7		0959	-0.1
	1723	10.8		1632	11.9
	2239	6.1		2236	2.4

TABLE 2-3

RIVER DISCHARGE RATES

	DISCHARGE (cfs)	
RIVER	MAY	SEPTEMBER
Skagit	25,000	12,000
Snohomish	15,000	3,100
Stillaguamish	5,400	1,600
Puyallup	4,300	1,700
Lake Washington	4,300	900
Duwamish	2,700	500
Nisqually	2,000	900
Skokomish	2,000	550
Hamma Hamma	700	100
Dosewallips	1,110	250
Duckabush	750	250

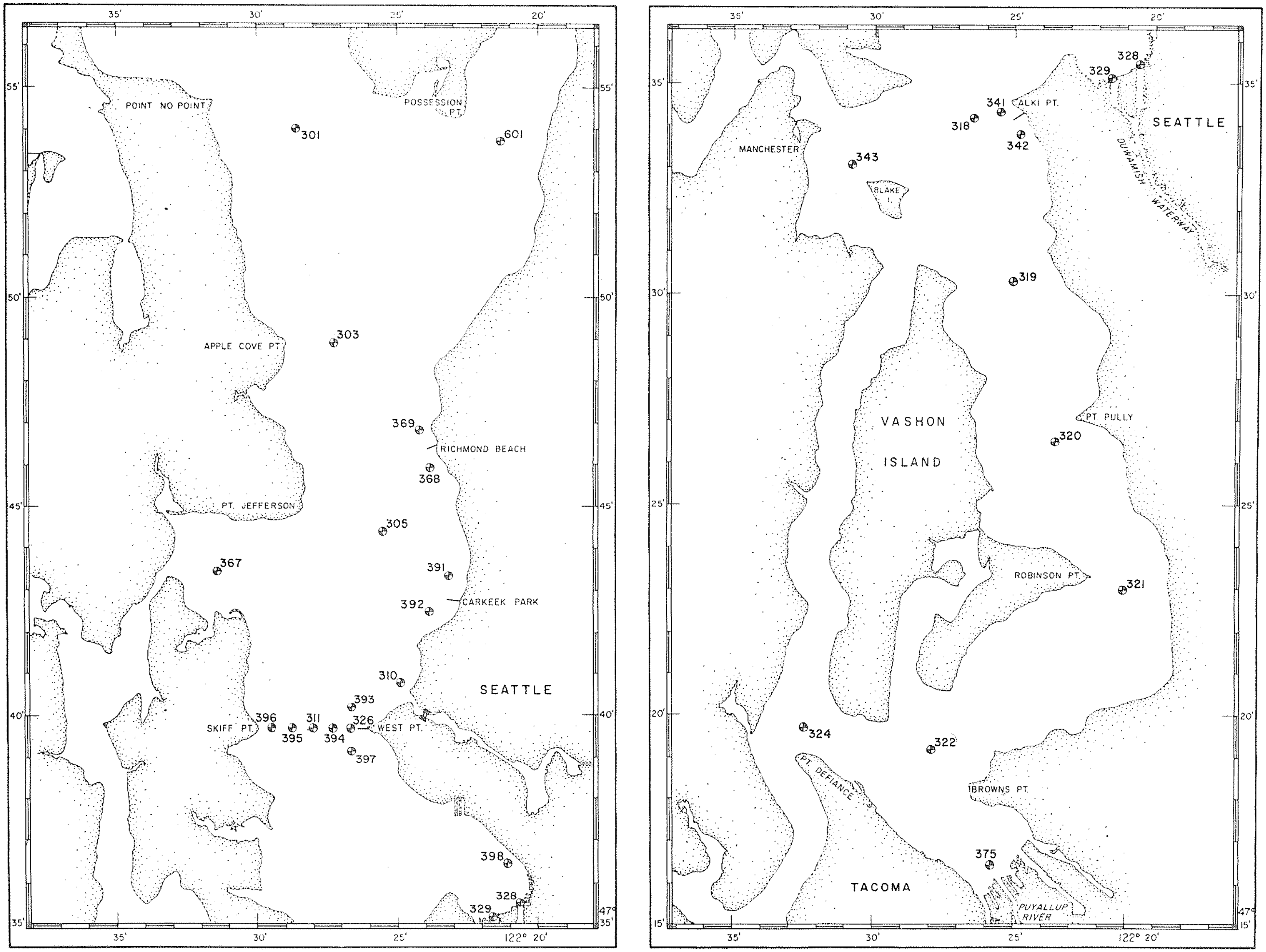


Figure 2-1

Location of stations occupied during the Metro Survey

3.0 PRESENTATION OF OBSERVED DATA

3.1 *Water charactersitics*

Vertical profiles of water characteristics along a mid-channel line beginning at Point No Point and terminating west of Tacoma at Point Defiance (see Fig. 3-1 for routing) are presented in Figures 3-2 through 3-21. Properties presented include temperature, salinity, density as *sigma-t*, dissolved oxygen, percent oxygen saturation, phosphate, silicate, nitrate, nitrite, and ammonia. Annual cycles of these properties at selected stations are presented in Figures 3-22 through 3-41. Vertical profiles of properties along a lateral section from West Point on the east to Skiff Point on the west are shown in Figures 3-42 through 3-45.

Temperatures (Figs. 3-2, 3-3, 3-22, and 3-32) through the main basin of Puget Sound decreased from the first cruise in November 1974 to an overall minimum of about 7.5°C in April 1975. The temperatures at all depths then began to increase with the surface increasing at a faster rate than those at depth. Maximum surface temperature off Seattle was over 15°C in July but at depth the maximum of over 11°C was delayed until early October 1975. Warming of the deeper waters was slightly slower in East Passage because of reduced circulation at depth. In October, the temperatures at all depths began to decrease. Usually, the waters at Point No Point were about one degree cooler than those off Browns Point.

The salinity distribution (Figs. 3-4, 3-5, 3-23, and 3-33) in the main basin reflected the character of the source seawater and the fresh water input. Frequently a surface layer of somewhat lower salinity developed depending upon runoff. Following a heavy rainfall between 18 and 22 November 1974, a surface layer was evident at both ends of the main basin. Increased rainfall in January and March 1975 produced a strong surface layer. In June 1975, when the rainfall was lessening but river runoff was up due to high snowmelt, a pronounced surface layer was evident over the entire main basin. At depth, the salinity maximum occurred in November 1974 followed by a steady decrease to March 1975. A gradual increase followed until June when another decrease occurred reflecting the decrease of source water salinity in Admiralty Inlet. This decrease was caused by an increase in the Fraser River flow which in turn diluted the water in the eastern end of the Strait of Juan de Fuca. This secondary low was followed by a steady increase in salinity at all depths until another

high was observed in October 1975. Because Puget Sound is a small portion of the Strait of Juan de Fuca-Georgia Strait-Puget Sound system, any major change occurring in the other two parts is eventually reflected in the deeper waters of Puget Sound.

The density of the water in Puget Sound is controlled primarilly by salinity and only slightly modified by temperature. Thus, the density distribution (Figs. 3-6, 3-7, 3-24, and 3-34) is very similar to that of salinity. Maximum densities were observed in November and the minimum in March. The effect of increased fall and winter runoff and temperature increase in June was quite evident from the presence of a more stable upper layer with a depth of about 20m. At any given time, the difference in density over the entire main basin was usually less than 3 *sigma-t* units except near the mouth of rivers or streams.

Upwelling along the Washington coast, resulting from summer northerly winds, brings oxygen-deficient nutrient-rich deep oceanic type water into the Strait of Juan de Fuca. This water eventually is carried into Puget Sound causing a drop in the oxygen content of the waters of the entire Puget Sound system. In the main basin, this oxygen minimum was observed in late October or early November. At this time the oxygen content of the deeper waters reached a minimum of 0.31 mg-at/1[11] and that of the surface less than 0.40 mg-at/1 (see Figs. 3-8, 3-9, 3-25, and 3-35). A slow increase in oxygen content began in late November 1974 with higher values at depth in the northern end than in East Passage. This was caused by the slower transport of oxygen-deficient water to the south at depth. Oxygen concentrations remained near 0.5 mg-at/1 from January to April. Then the effect of photosyntheticly generated oxygen by phytoplankton in the surface layer became evident in May and continued to be large until late August. Also, the oxygen in the upper layer increased from north to south, especially during plankton blooms. At depth the oxygen content began to decrease in late June until the seasonal minimum was again observed in

- - - - - - - - - - - -

11. Dissolved oxygen concentrations may be expressed as (1) milligram-atoms per liter (mg-at/1), (2) milliliters per liter (ml/1), and (3) parts per million (ppm). The first two are related precisely and have a fixed relation to the third for a given density of sea water. For Puget Sound waters having a mean density of 1.023 gm cm^{-3}, we have

1 ml/1	=	0.0893 mg-at/1	=	1.397 ppm
1 mg-at/1	=	11.20 ml/1	=	15.64 ppm .

November 1975.

Oxygen production by phytoplankton was best observed in values of oxygen saturation[12]. Saturation values in excess of 100% indicated that phytoplankton productivity was high. This is a near-surface phenomenon confined to the euphotic zone and rarely goes deeper than 20m (see Figs. 3-10, 3-11, 3-26, and 3-36). Values in excess of 140% were observed in May indicating that the spring phytoplankton bloom began at about the usual time in mid-spring. Another pronounced bloom was observed in August 1975 when saturation values exceeded 150% off Seattle. At depth, the maximum oxygen saturation was observed in April 1975. Then a steady decline occurred to the annual low in October 1975.

The distribution of dissolved orthophosphate (Figs. 3-12, 3-13, 3-27 and 3-37) was similar to that observed in the past (Collias, McGary, and Barnes, 1974). Highest concentrations of phosphate observed during the present study occurred in late fall when the maximum intrusion of oceanic type seawater was evident and when degradation of plankton was highest. When plankton are subjected to degradation, bound nutrients are returned to the seawater in simple form. At depth, phosphate values varied from 2.1 μg-at/l [13] to a high of 3.2 μg-at/l. With increased phytoplankton production in May through August, phosphate depletion in the euphotic layer was evident.

Silicate (Figs. 3-14, 3-15, 3-28, and 3-38) showed a trend similar to phosphate. Maximum values occurred in late fall 1974 followed by a decrease with the introduction of new source water from Admiralty Inlet. This utilization of silicate by phytoplankton was evident by decreasing values in the surface during spring and summer.

Compounds containing nitrogen in the forms of nitrate, nitrite, and ammonia also undergo seasonal variations. Features of the seasonal curves of the various

- - - - - - - - - - -

12. Oxygen saturation is the amount of oxygen actually present in a given sample of seawater compared to what it could contain at the same salinity and temperature and under normal atmospheric gases at standard pressure (760 mm of mercury). Saturation decreases with an increase in either salinity or temperature. These base values are compiled in convenient tables, graphs, or nomograms. At present the most valid equation for oxygen saturation is that derived by Weiss (1970).

13. μg-at/l is microgram atoms per liter. All nutrient concentrations in this report are given in μg-at/l. These values may be converted to parts per billion (ppb) by multiplication of the formula weight of the ion or element. To get phosphate-phosphorous, the multiplier is 30.975 and for nitrogen compounds the multiplier is 14.008.

nitrogen constituents were not precisely coincident because in addition to changes associated with biological uptake and degradation, nitrogen compounds are affected by non-biological changes. Ammonia is oxidized to nitrite and nitrite eventually to nitrate. Biological activity tends to maintain a nearly fixed ratio between the number of phosphorus and nitrogen atoms. As productivity in the euphotic layer increases, phosphate and nitrate are removed. When productivity ceases in the fall, organic detritus sinks and decomposes, and the nutrients are returned to the water in about the same proportion as originally utilized. Thus, the seasonal patterns of phosphate and nitrate tend to follow each other. Data for nitrate and phosphate obtained during this study confirm this relationship. Maximum nitrate (see Figs. 3-16, 3-17, 3-29, and 3-39) was observed in January 1975 with the minimum occuring in early August 1975. Depletion of nitrate in the surface layer by phytoplankton was quite evident from May through August.

Seasonal variations of nitrite concentrations within the study area were appreciably different from those observed for nitrates. From November 1974 through May 1975, nitrite (Figs. 3-18, 3-19, 3-30, and 3-40) followed an approximate inverse relationship to nitrates. In February 1975, the nitrite maximum occured at about the same time as did the nitrate maximum. Nitrites increased until June when both nitrates and nitrites decreased to a minimum in August. But at this time, nitrites were not as low as those observed in February 1975. Nitrites again increased until October and reached a maximum average amount of 0.65 μg-at/l in the upper 20m.

Observations showed that ammonia (Figs. 3-20, 3-21, 3-31 and 3-41) also followed a seasonal trend that was more erratic than the other nitrogen components. Minimum amounts of ammonia were observed from early January through March. From mid-March to May, ammonia gradually increased. During summer, concentrations were generally highest but were also the most variable. In the northern part of the main basin from Point No Point to Point Jefferson, peak values observed in the upper layer tended to coincide with peaks at depth. But from West Point south to Browns Point, coincidence of the variations in the upper and lower layers was poor although the seasonal trend was evident.

Water properties along the lateral section from West Point to Skiff Point (Figs. 3-42 to 3-45) were measured during four cruises. In general, there was little cross channel variations in all properties. But there was evidence of

the plume from the West Point sewer discharge producing localized changes near West Point. Localized areas of high concentrations were also observed in Elliott Bay near the mouths of the East and West Waterways. Anomalies were also observed at the mouth of the Puyallup River and occasionally near Manchester and in Port Madison. These anomalies were particularly evident in concentrations of ammonia.

The two time studies at West Point (Figs. 3-46 and 3-47) indicated considerable short term variability. The most prominent feature was the pockets of high ammonia concentration that occurred with tidal periodicity. These pockets are associated with the upward movement of the plume, density differences, and the horizontal movement associated with tidal currents, which may at times limit dilution. Observations in the model showed a similar behavior of dye released at the discharge site.

3.2 *Oceanographic Model Studies*

3.2.1 *Tidal current velocities:* Hourly tidal current velocities were determined for each of three replicate runs. The values obtained were averaged and are tabulated in Table 3-1 for the May series and in Table 3-2 for the September run. The mean deviation in the replicate current speed measurements was ±0.049 knot for the May observations and ±0.051 knot for the September series. This agrees well with the reading precision of ±0.05 knot.

A comparison of model and field observations showed good agreement. Model observations appear to be smoother than the field measurements because of reduced small-scale turbulence in the model and a much longer integration time compared with field observations. Field observations made at half-hourly intervals were integrated over a period of about 10 seconds while the model measurements were integrated over a period equivalent to 20 minutes. Thus the field measurements indicated nearly instantaneous velocities that were affected by passage of small eddies of a size below that generated in the model or were undetected by the technique used to measure the model currents. For example, on 3 September 1975, successive field measurements showed a variation of as much as 0.5 knot in a 30-minute interval, but the maximum change between the successive model measurements was about 0.4 knot.

An additional source of the differences between field and model measurements is the result of techniques used. Field observations were Eularian, measuring the flow past a fixed point in space, whereas the model measurements

TABLE 3-1

AVERAGE TIDAL CURRENTS FOR THE PERIOD 7-10 MAY 1975
AS MEASURED IN THE PUGET SOUND MODEL.

Hour	May 7 Speed Kt.	May 7 Dir °T	May 8 Speed Kt.	May 8 Dir °T	May 9 Speed Kt.	May 9 Dir °T	May 10 Speed Kt.	May 10 Dir °T
00	0.38	186	0.50	180	0.58	177	0.52	173
01	0.20	197	0.33	187	0.48	182	0.60	177
02	0.15	347	0.18	210	0.25	189	0.44	183
03	0.40	003	0.15	000	0.00		0.13	196
04	0.67	007	0.58	007	0.38	002	0.22	001
05	0.72	008	0.80	008	0.78	008	0.58	006
06	0.58	005	0.78	007	0.85	005	0.90	008
07	0.40	000	0.60	003	0.68	005	0.85	008
08	0.20	000	0.40	000	0.58	002	0.78	003
09	0.07	186	0.18	357	0.35	000	0.63	000
10	0.35	176	0.18	180	0.00		0.23	350
11	0.58	175	0.48	176	0.40	175	0.25	183
12	0.67	176	0.70	174	0.83	171	0.65	170
13	0.53	182	0.72	179	0.98	171	0.92	168
14	0.32	192	0.67	180	0.95	176	1.12	171
15	0.12	250	0.42	189	0.75	178	0.97	178
16	0.20	001	0.00		0.40	190	0.72	181
17	0.45	003	0.35	002	0.18	304	0.32	198
18	0.57	002	0.53	005	0.40	004	0.23	349
19	0.43	004	0.68	004	0.68	002	0.48	004
20	0.18	005	0.43	006	0.72	006	0.78	003
21	0.00		0.07	003	0.38	006	0.75	005
22	0.33	179	0.22	180	0.17	001	0.33	003
23	0.57	178	0.42	176	0.30	182	0.00	

TABLE 3-2

AVERAGE TIDAL CURRENTS FOR THE PERIOD 2-5 SEPTEMBER 1975
AS MEASURED IN THE PUGET SOUND MODEL

Hour	Sept 2 Speed Kt.	Sept 2 Dir °T	Sept 3 Speed Kt.	Sept 3 Dir °T	Sept 4 Speed Kt.	Sept 4 Dir °T	Sept 5 Speed Kt.	Sept 5 Dir °T
00	0.15	190	0.50	177	0.62	174	0.38	183
01	0.10	000	0.30	184	0.68	179	0.72	173
02	0.44	006	0.10	000	0.38	180	0.78	177
03	0.70	009	0.43	000	0.00		0.38	182
04	0.78	010	0.77	007	0.47	003	0.08	196
05	0.70	005	0.80	007	0.90	008	0.58	003
06	0.60	003	0.78	005	0.88	008	0.98	005
07	0.35	359	0.67	000	0.80	004	0.93	008
08	0.10	348	0.38	357	0.63	001	0.68	000
09	0.35	177	0.07	260	0.32	354	0.60	002
10	0.73	178	0.40	183	0.10	190	0.30	359
11	1.00	175	0.90	181	0.51	176	0.12	190
12	0.92	180	1.08	176	1.02	172	0.58	179
13	0.73	182	0.90	180	1.10	175	0.98	174
14	0.40	192	0.70	183	0.97	179	1.03	175
15	0.00		0.32	193	0.65	183	0.88	177
16	0.35	000	0.17	340	0.15	197	0.47	189
17	0.50	000	0.52	003	0.36	357	0.12	312
18	0.73	005	0.85	004	0.65	002	0.58	005
19	0.53	004	0.80	007	1.02	009	1.10	005
20	0.25	004	0.47	002	0.75	006	0.92	009
21	0.00		0.18	356	0.40	000	0.67	006
22	0.30	185	0.10	200	0.10	000	0.37	002
23	0.53	175	0.40	177	0.10	180	0.11	352

were Lagrangian in which a given water parcel is tracked over a specified time interval. The model measurements thus provided a velocity averaged over both time and distance and would be more similar to field observations made with drifting objects such as drogues (Ebbesmeyer and Helseth, 1975). Also, because of the complex bathymetry near West Point, flow does not follow a straight path but curves around the point. Thus directions measured in the field at a given point will be different than those observed at another nearby point. These directions also will be somewhat different than the average direction of the 20 minute path measured in the model. Field measurements are also sensitive to rapid direction variations caused by small-scale turbulence.

The differences between velocity measured in the field and in the model do not invalidate the model representation of dispersal characteristics. Field observations show the flow in the immediate vicinity of the outfall (i.e., near-field flow), whereas the model shows a larger area of the dispersing plume. Local dispersion rates are expected to be somewhat slower in the model than in nature because of viscosity effects. Thus the streaks and filaments of dye observed in the model are considered to be representative of the areal distribution of the effluent in the receiving waters. But the boundaries of the actual effluent plume and its filaments may be more diffuse.

Current speeds measured in the model during the 7-10 May 1975 time period are shown in Figure 3-48. Field observations obtained during the same time have been included for comparison. Because of the uniformity of directions observed in the model, where there was little evidence of rotary direction change except very close to times of slack water, the current directions are shown as either ebb or flood without regard to their precise direction. Current vectors observed in the model for the same period are shown in Figure 3-49. Difficulty experienced with the current meter used in the field resulted in unreliable directions; hence the field data are not included. But because of the similarity of current directions obtained in the model for both May and September observations, it may be assumed that the direction of the actual currents in May near West Point were similar to those observed in September.

Current speeds obtained from model and field observations for the 2-5 September 1975 period are shown in Figure 3-50. During this period, the field observations showed a greater variation than in May. Also, observations made during the flood were more variable than those made during the ebb. A vector diagram for both model and field observations is shown in Figure 3-51. Field

measurements showed a general westerly trend of the ebb currents (about 315°) while in the model ebb currents were northerly (about 005°). Flood currents were much closer in agreement between model and field, being about 175°T. The difference in ebb direction between model and field is due to the different methods of measurement - i.e., Eularian vs. Lagrangian.

3.2.2 *Relation between tidal current speed and tidal range:* A comparison between maximum current speed and tidal range indicated that a non-linear relationship existed. Speeds observed during small ranges were greater in proportion to those for larger ranges. The mean current speed ($\overline{V}$) for successive flood and ebb tides was determined and the ratio of speed to tide range (ΔH) calculated. These data have been plotted in Figure 3-52. The equation for the curve, as determined by linear regression, is

$$\log \overline{V} = (\Delta H - 15.0) / 22.6 \qquad (3.1)$$

From this equation, it is evident that the average tidal current at the West Point outfall is less sensitive to large tide ranges and that a minimum current of about 0.2 knot will be present even during the smallest tide range.

3.2.3 *Dispersion of effluent:* Model studies indicated that the principal dispersion area of effluent discharged at West Point extended from about four miles south of West Point to about five miles north. North of this area, dye was dispersed to just-barely visible concentrations and could be followed only with difficulty. Higher concentrations of dye occurred within the eastern half of the main basin, although lesser and more diffuse concentrations were observed near Bainbridge Island. The dye distribution at the end of each successive ebb and flood tide for May are shown in Figure 3-53 (A - L) and for the September period in Figure 3-54 (A - L). Each figure was prepared by tracing the outlines of the plume from a projected image of the appropriate frame from the photographic record.

Tidal currents and circulation patterns appeared to be consistent with respect to their general character, although variability related to the large-scale turbulence produced noticable differences in the effluent distribution with each successive tide. Flood tides tended to disperse the effluent more toward mid-channel south of West Point, with the average direction being about 155°T. Flood flows past West Point usually produced a weak counterclockwise eddy south of the point during the latter part of the tide. In the model, this

eddy was observed to cause the entrained dye to spiral upward to shallower depths, but it did not appear to reach the surface. Such an eddy was observed by Ebbesmeyer and Helseth (1975) on the south side of West Point during a flood tide.

When the tide reversed to ebb, dye entrained in the southern eddy moved back toward West Point and flowed around it to the north. As the ebb continued, the discharged dye tended to move in a direction of about 030°T, swinging to the east in the vicinity of Shilshole Bay, then toward mid-channel near Meadow Point. Again an eddy developed on the lee side of West Point that also exhibited a spiralling behavior.

The dispersion and transport observed during both May and September were quite similar even though there was considerable difference in river discharge rates.

A much better understanding of the dispersion processes was possible by viewing the photographic record as a motion picture. The resulting motion dramatically showed the dynamic character of the dye flow. Also, faint clouds and filaments of dye were far more visible than when examining single frames. This method of analysis also more clearly showed the northerly net transport, particularly during the May series when the river flow was high. Faint clouds and filaments of dye could be seen moving north beyond President Point, the northern limit of the photographic coverage. Ebb movement was greater than flood in this area, thus plainly showing the northerly transport. Dispersal of the dye had distributed the small clouds quite uniformily across the channel north of Meadow Point. After reaching this location, no dye was returned to West Point and successive ebbs carried the dye further north. Transport during September appeared to be much slower. This slower progress apparently allowed more time for mixing and dispersion because small clouds and filaments near Meadow Point were appreciably less evident although some could be seen.

3.3 *Nitrogen uptake*

The results of the nitrogen uptake experiments are presented in Appendix A. Data include station position, date, time, experimental conditions, and the observed results. The nutrient concentration in the incubation bottle at time of inoculation is the sum of the initial amount of nutrient plus the amount of ^{15}N-labeled substrate added. Initial particulate nitrogen values represent the amount of particulate matter retained on a 0.45 micron Millipore® filter

from an aliquot obtained just prior to inoculation. The final particulate nitrogen value less the initial particulate value represents the growth of the phytoplankton during incubation. Specific uptake rates of the various nitrogen compounds ($V\text{-}NO_3$, $V\text{-}NH_3$, and V-UREA) are a measure of substrate nitrogen (N_s) utilized per unit of particulate nitrogen (N_p) per unit time, expressed as μg-at N_s/μg-at N_p/hour which reduces to $hour^{-1}$ (Dugdale and Goering, 1967).

Nutrient uptake rates (ρ) are the amount of nutrients utilized by the phytoplankton in a given sample. The nitrogen uptake rates were obtained by multiplying the quantity of particulate nitrogen by the specific uptake rate and are expressed for both hourly and daily rates. The daily uptake rates for nitrate and urea are estimated by multiplying the hourly rates by 12 and for ammonia by 18. These factors are the hours per day during which the uptake of the specific nutrient is assumed to occur (J. Dugdale, personal communications).

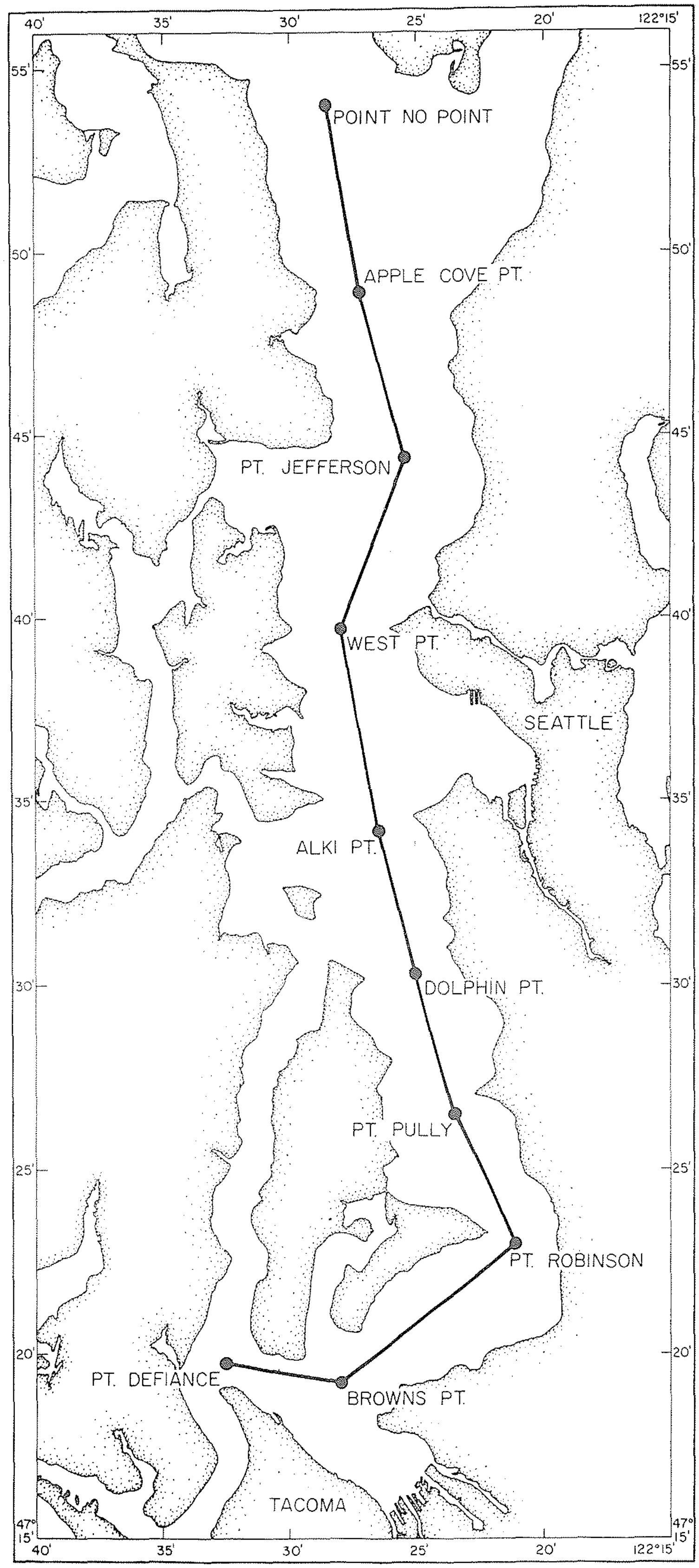


Figure 3-1

Location of stations used to prepare the vertical distributions of properties in the main basin of Puget Sound

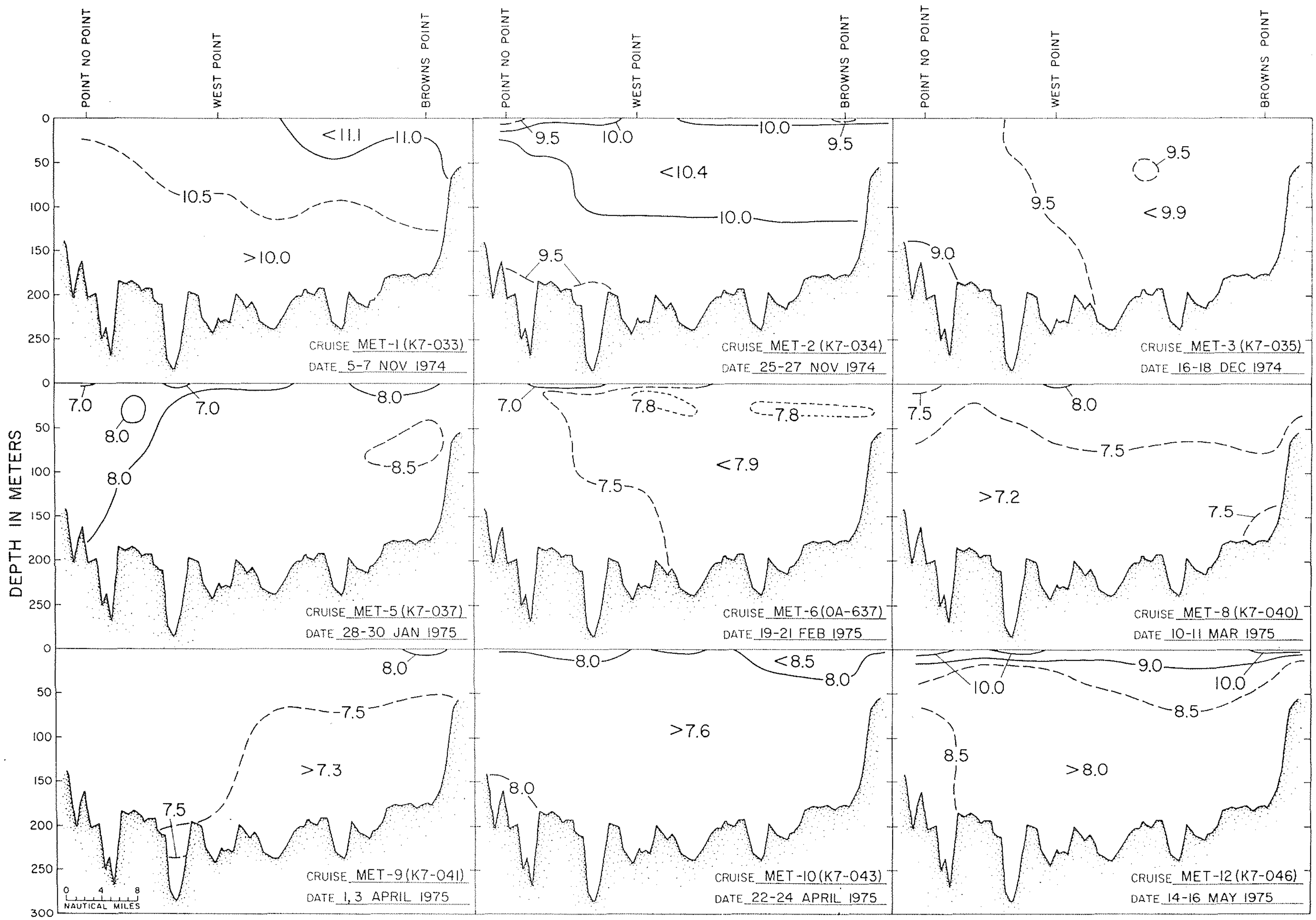


Figure 3-2

Vertical distribution of temperature in the Main Basin of Puget Sound

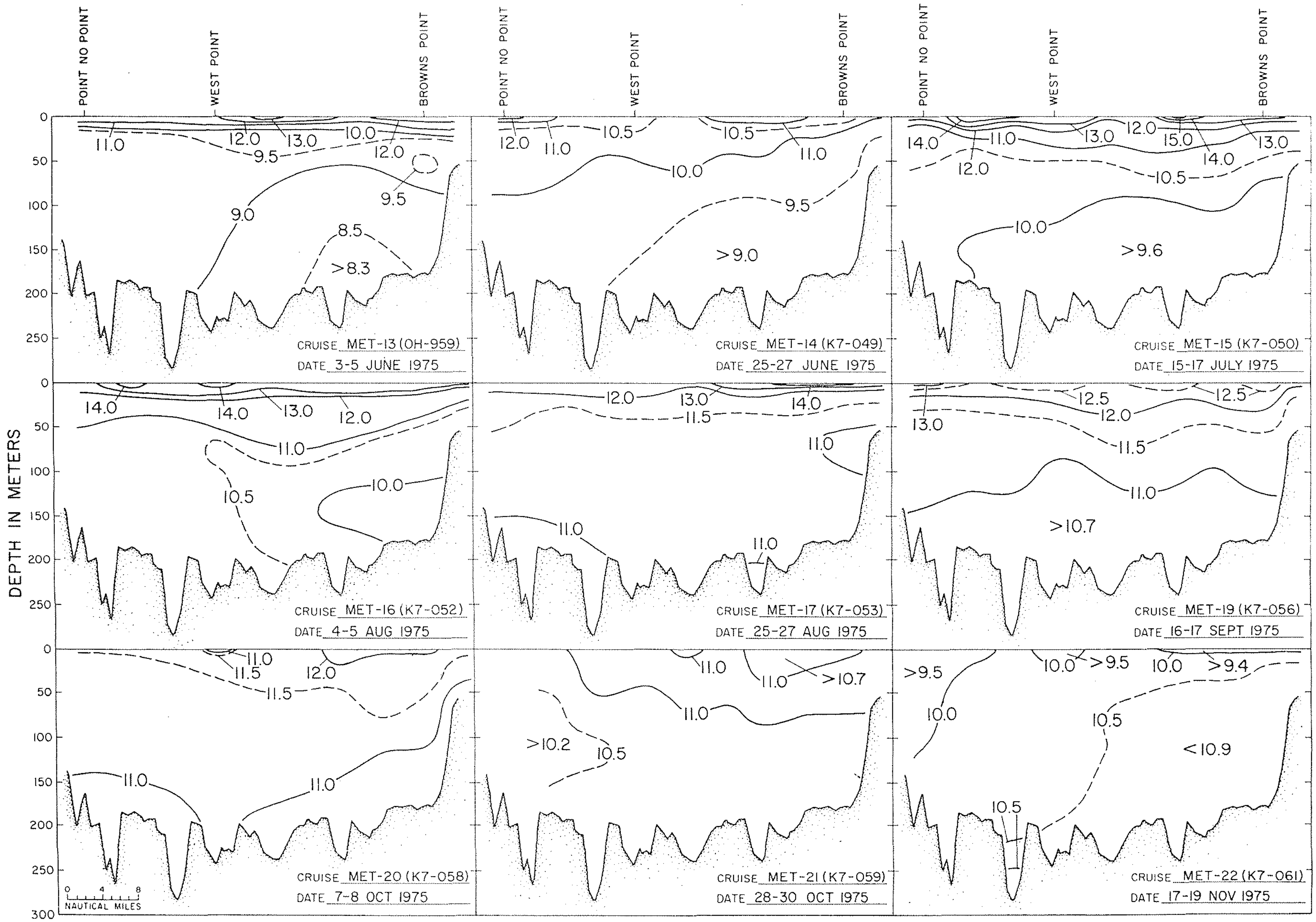


Figure 3-3

Vertical distribution of temperature in the Main Basin of Puget Sound (continued)

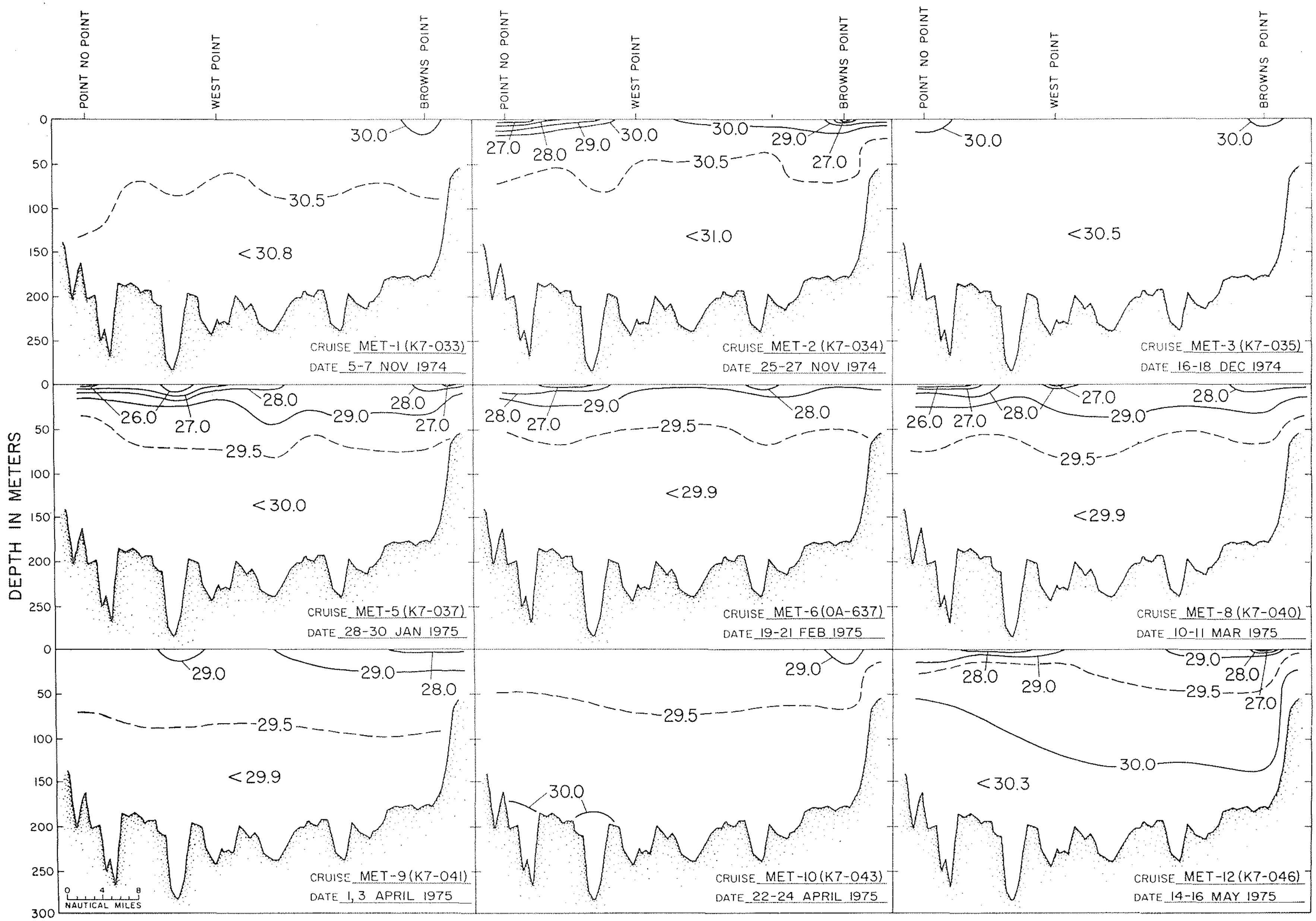


Figure 3-4

Vertical distribution of salinity in the Main Basin of Puget Sound

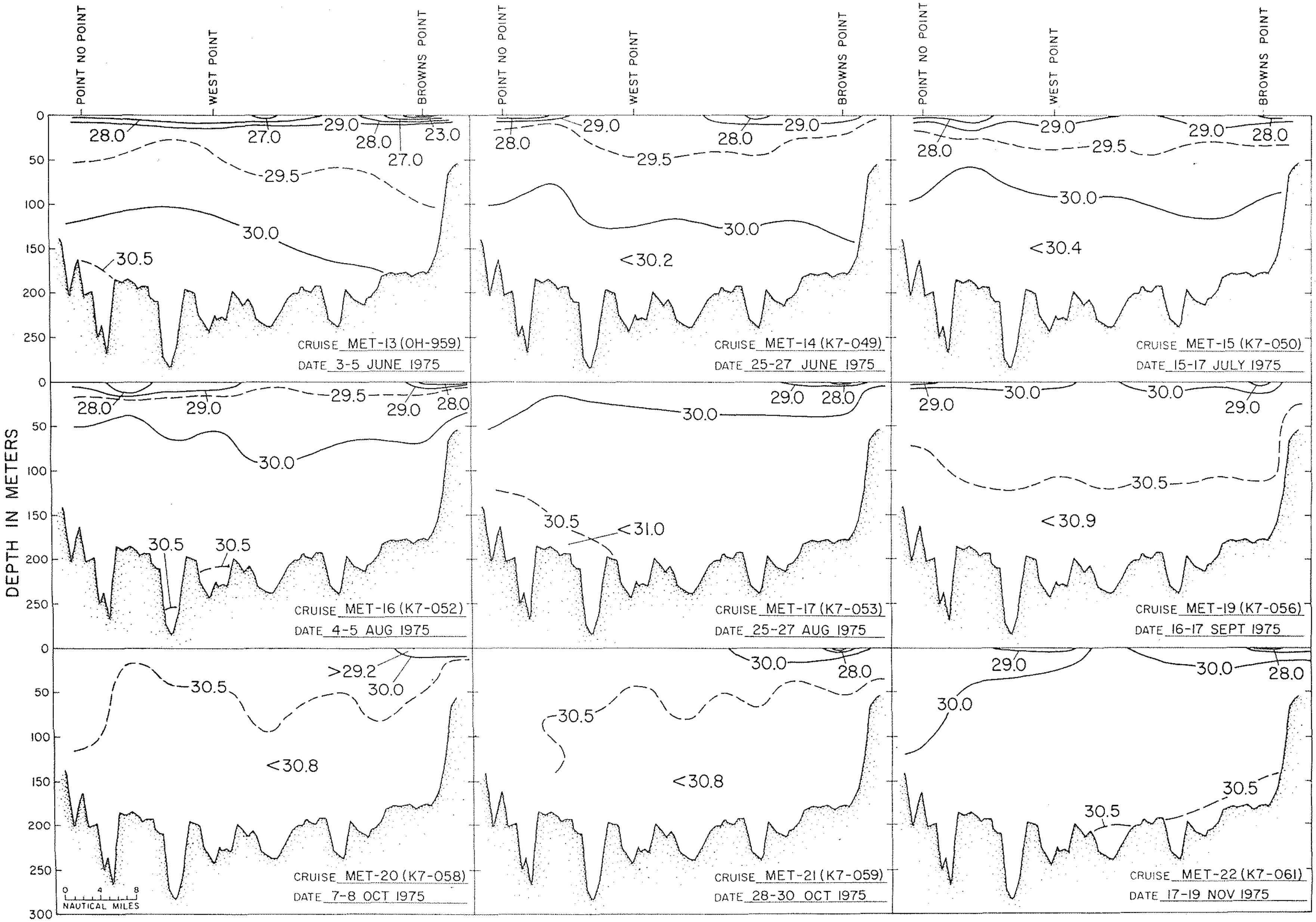


Figure 3-5

Vertical distribution of salinity in the Main Basin of Puget Sound (continued)

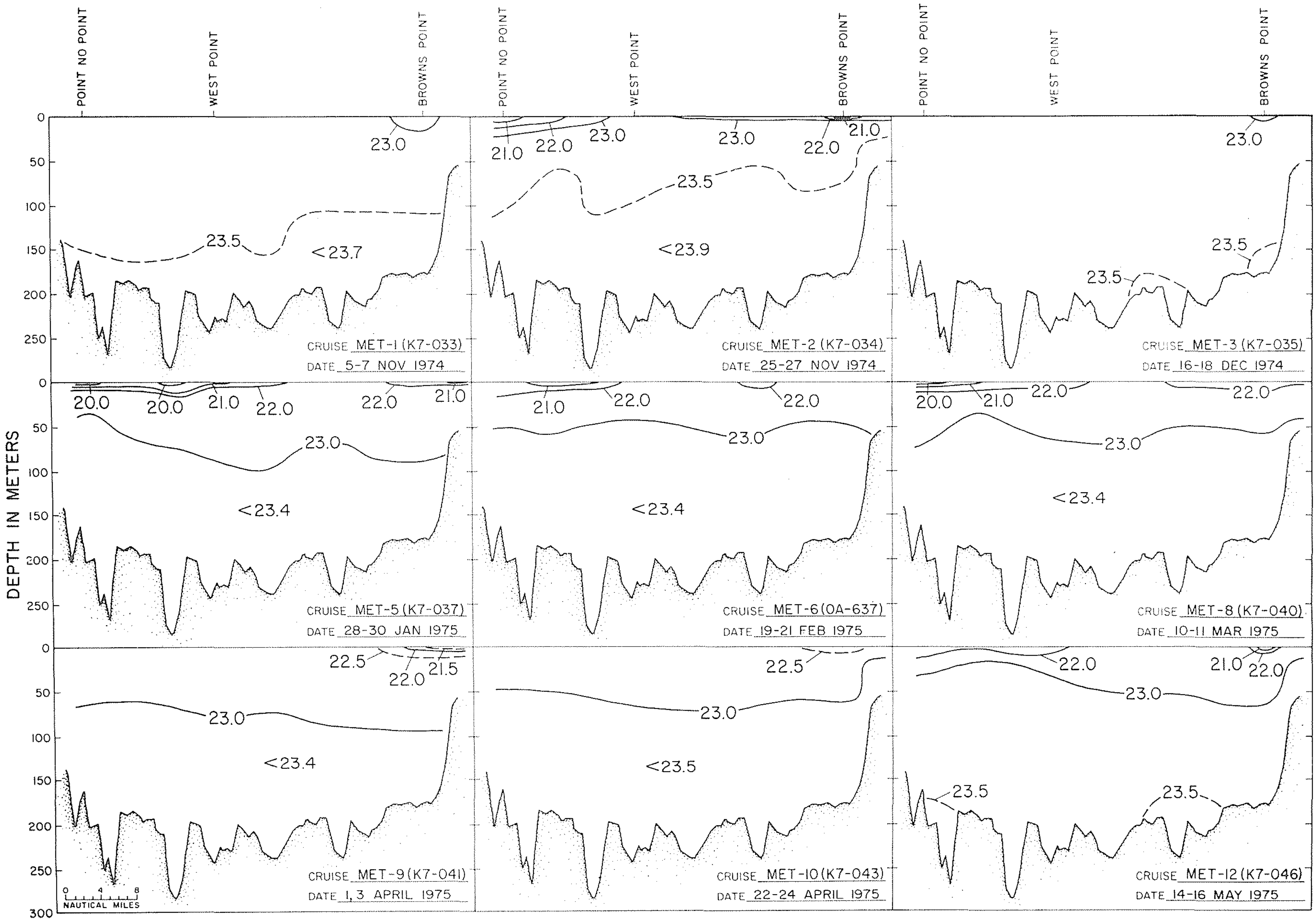


Figure 3-6

Vertical distribution of density (as Sigma-t) in the Main Basin of Puget Sound

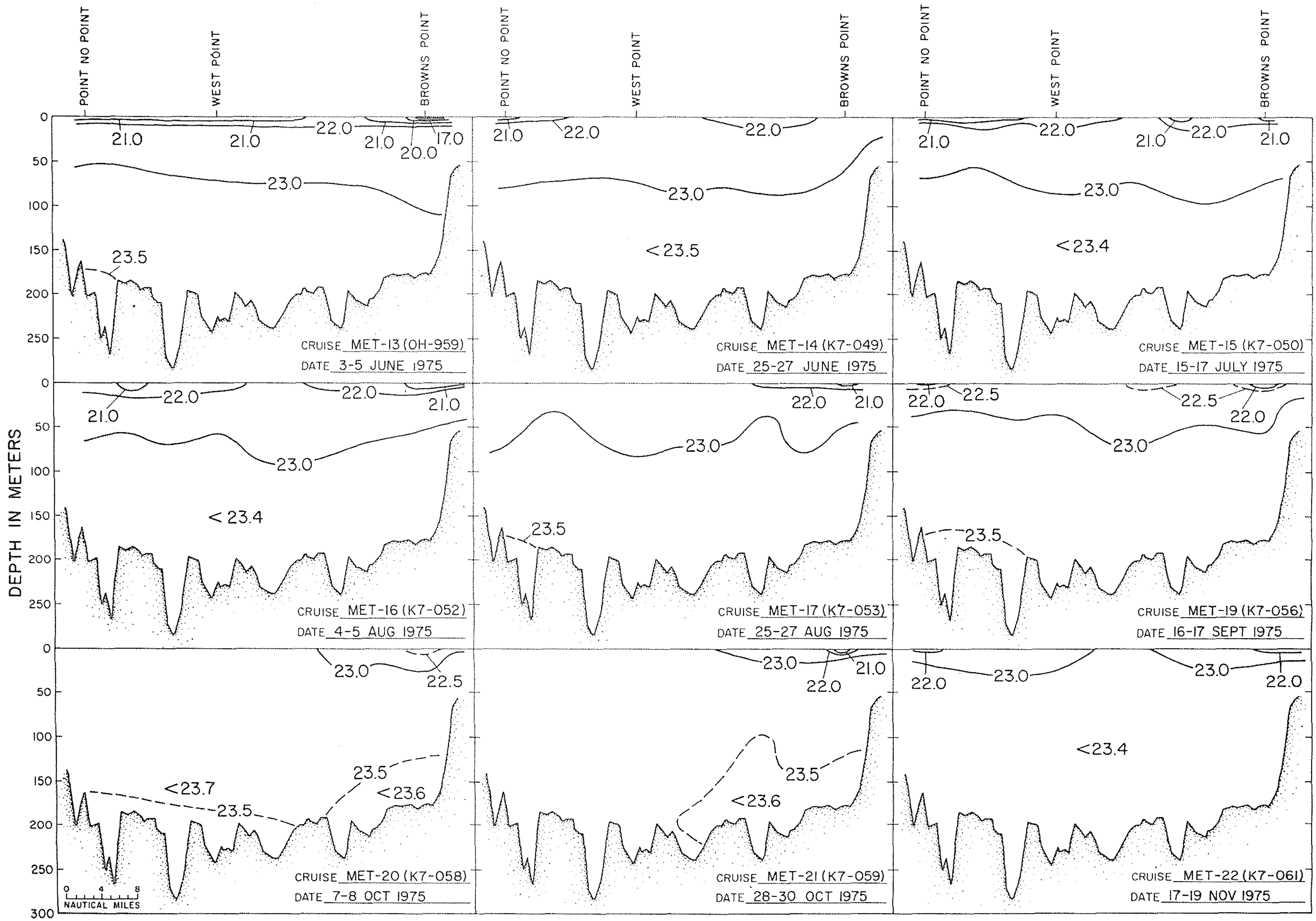


Figure 3-7

Vertical distribution of density (as Sigma-t) in the Main Basin of Puget Sound

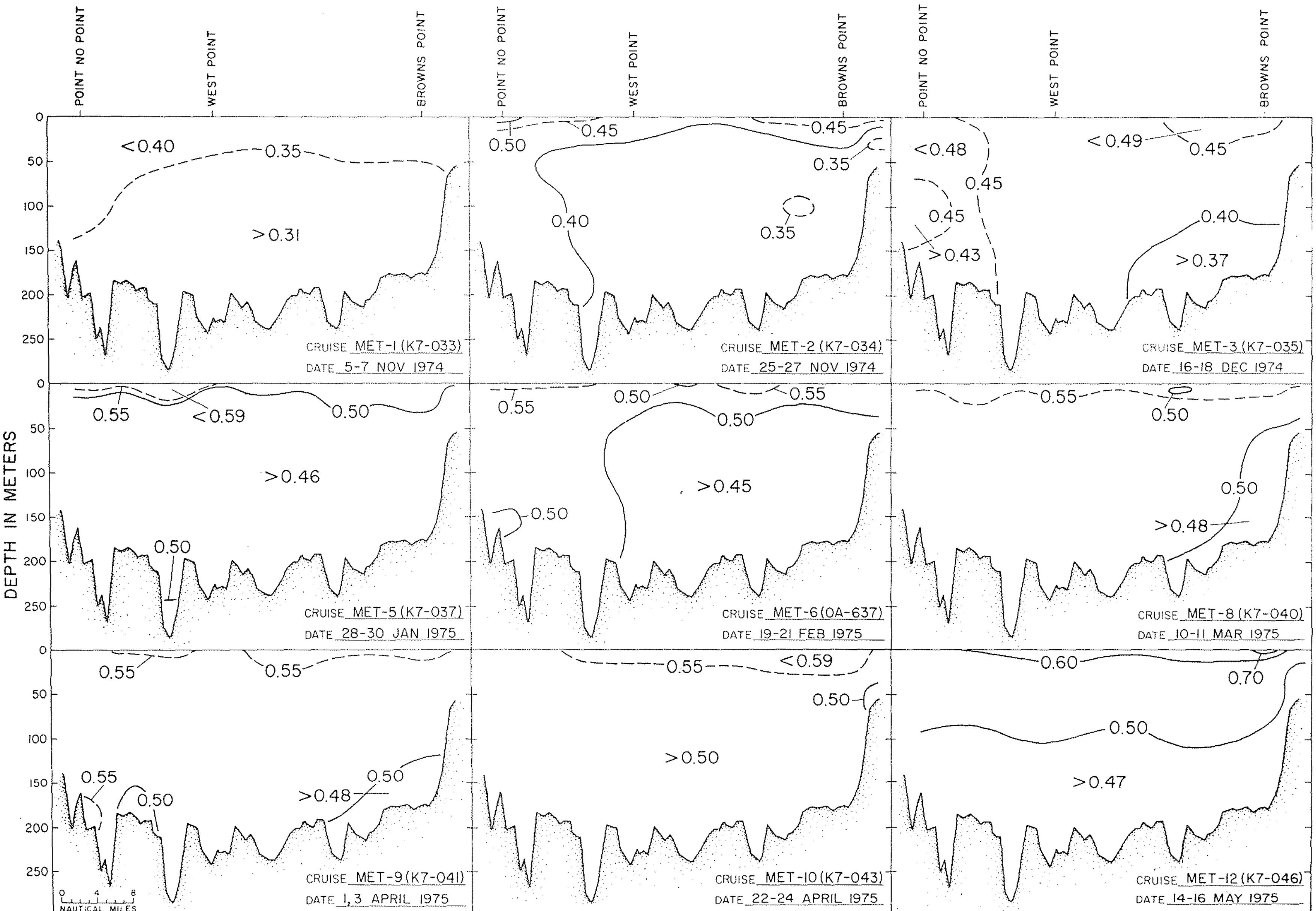


Figure 3-8

Vertical distribution of dissolved oxygen in the Main Basin of Puget Sound

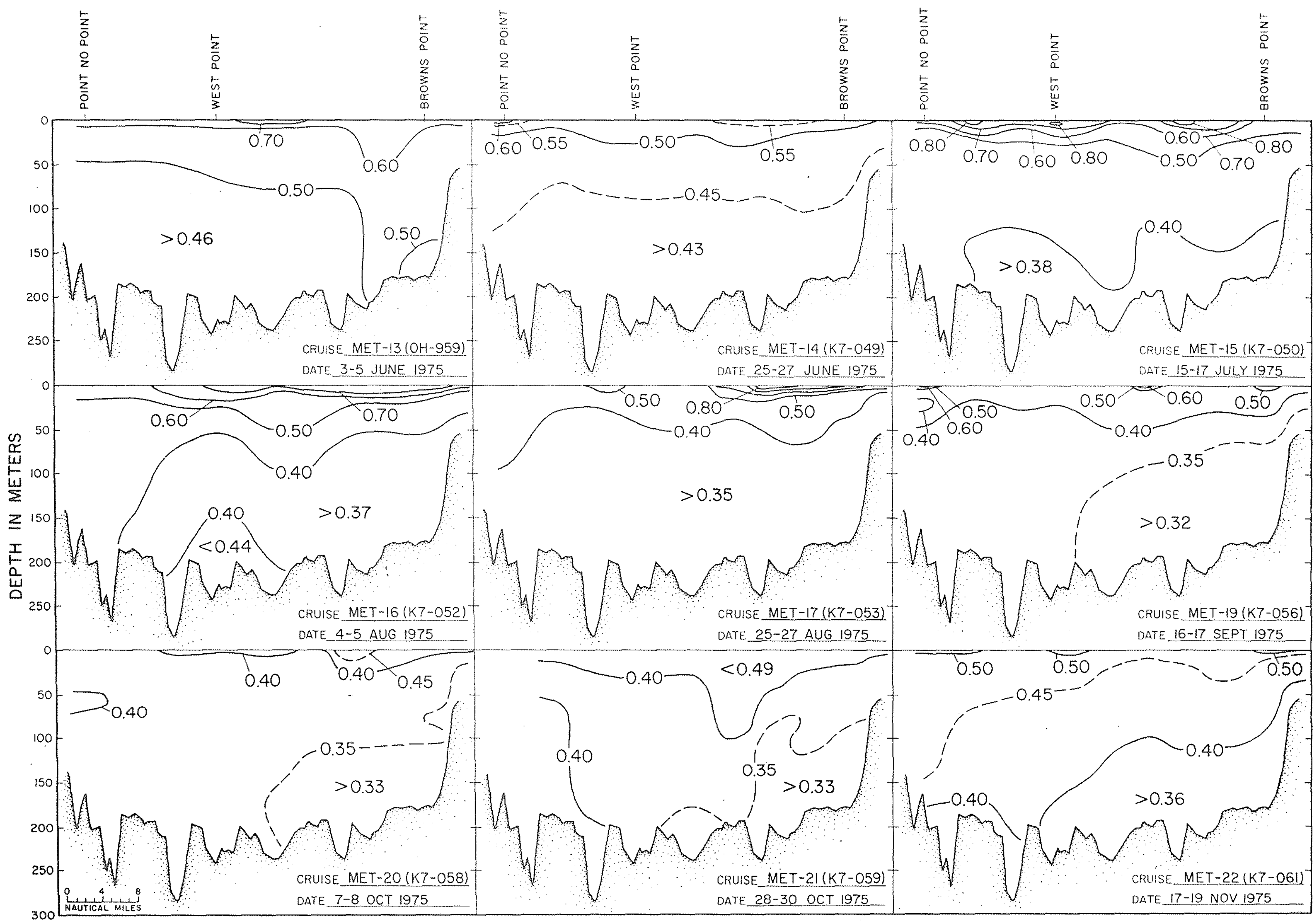


Figure 3-9
Vertical distribution of dissolved oxygen in the Main Basin of Puget Sound (continued)

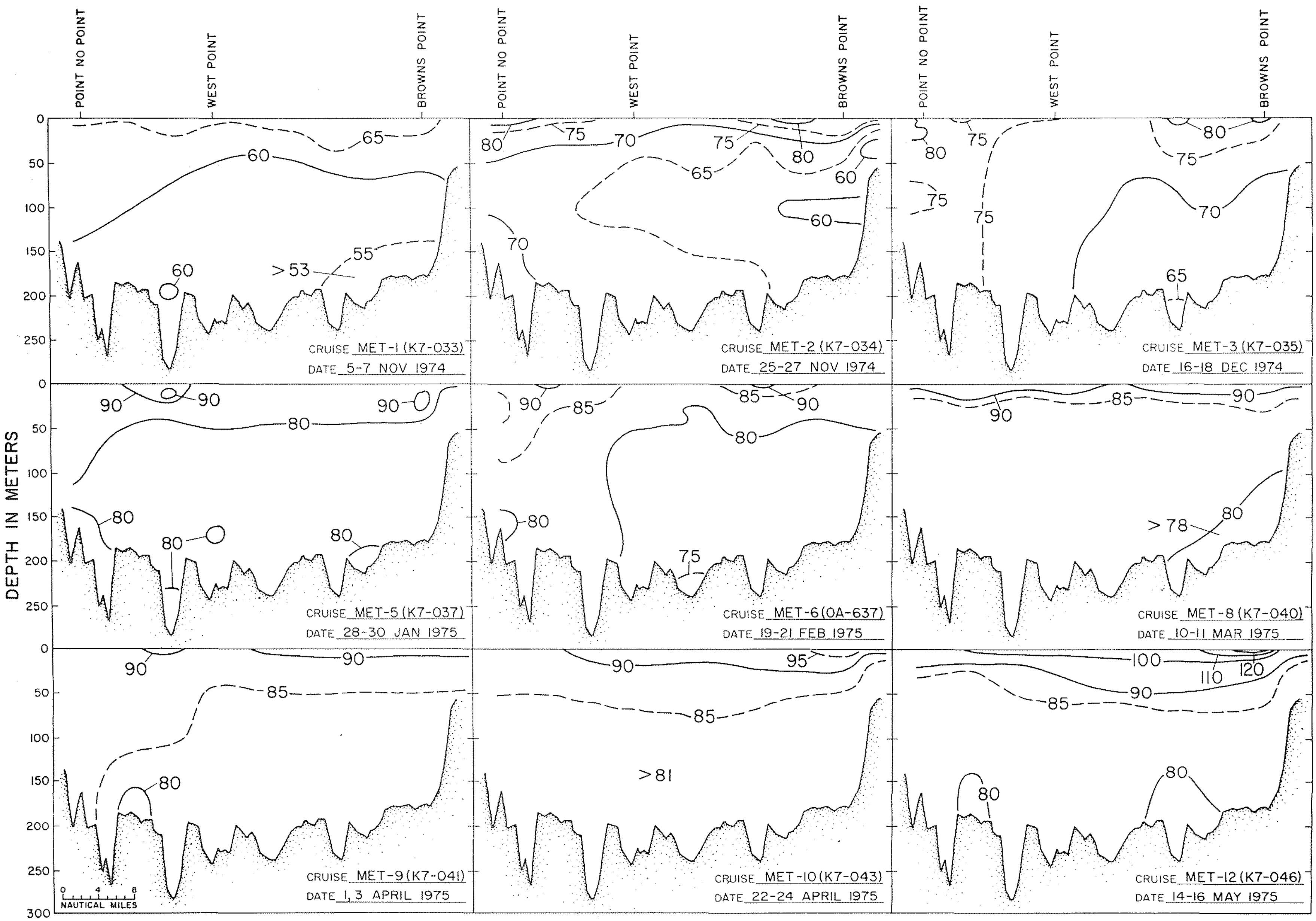


Figure 3-10
Vertical distribution of oxygen saturation in the Main Basin of Puget Sound

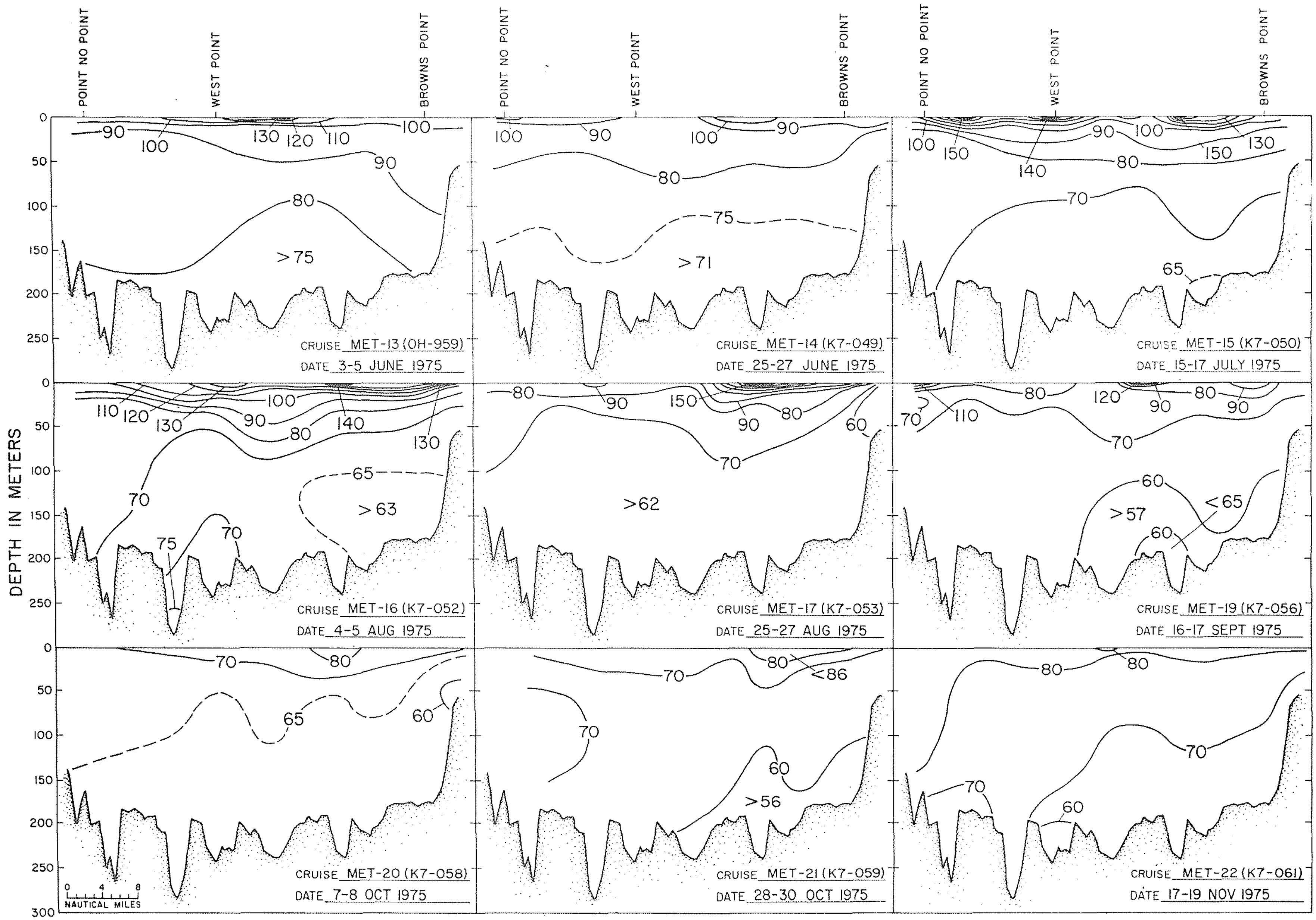


Figure 3-11

Vertical distribution of oxygen saturation in the Main Basin of Puget Sound (continued)

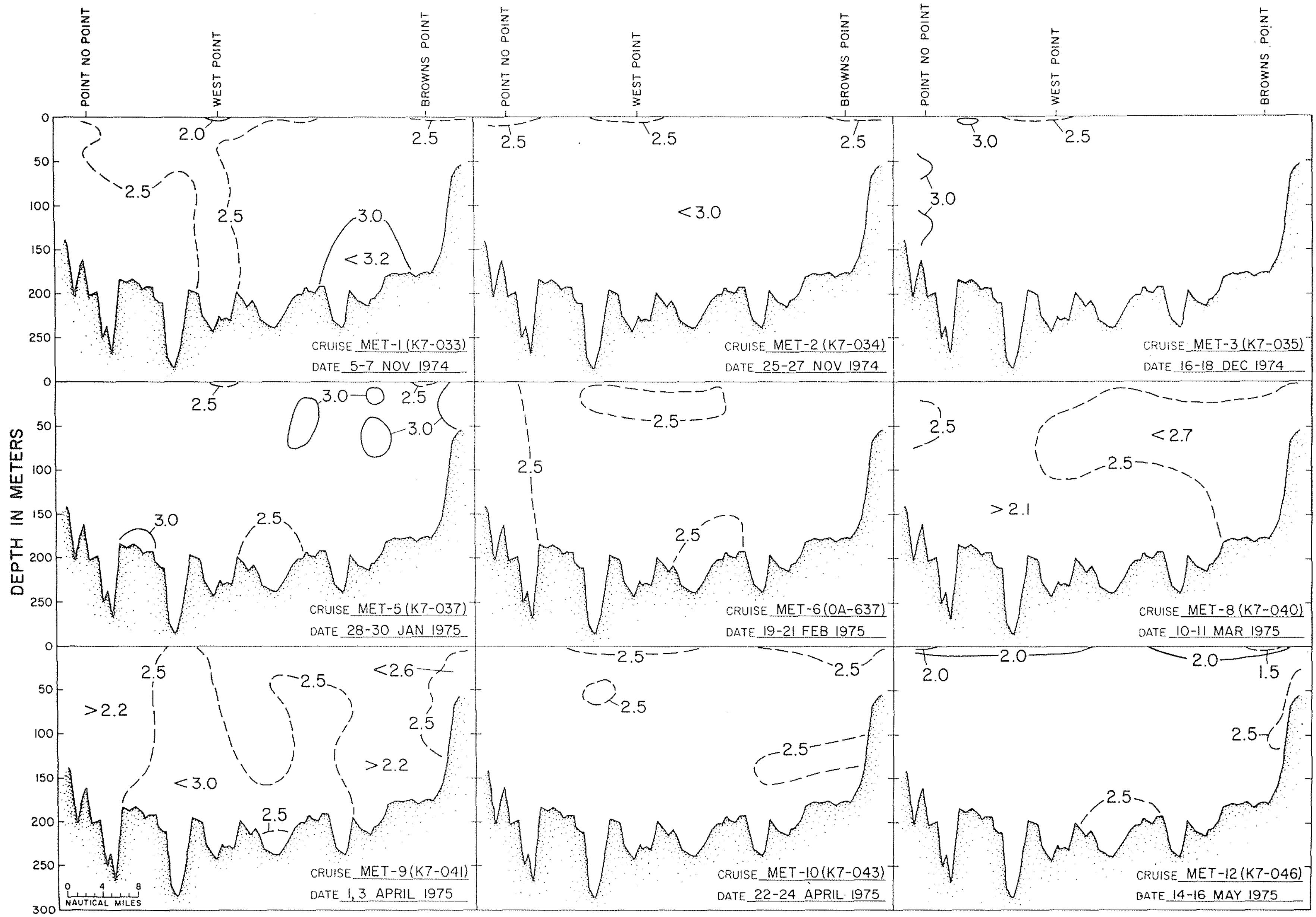


Figure 3-12

Vertical distribution of phosphate in the Main Basin of Puget Sound

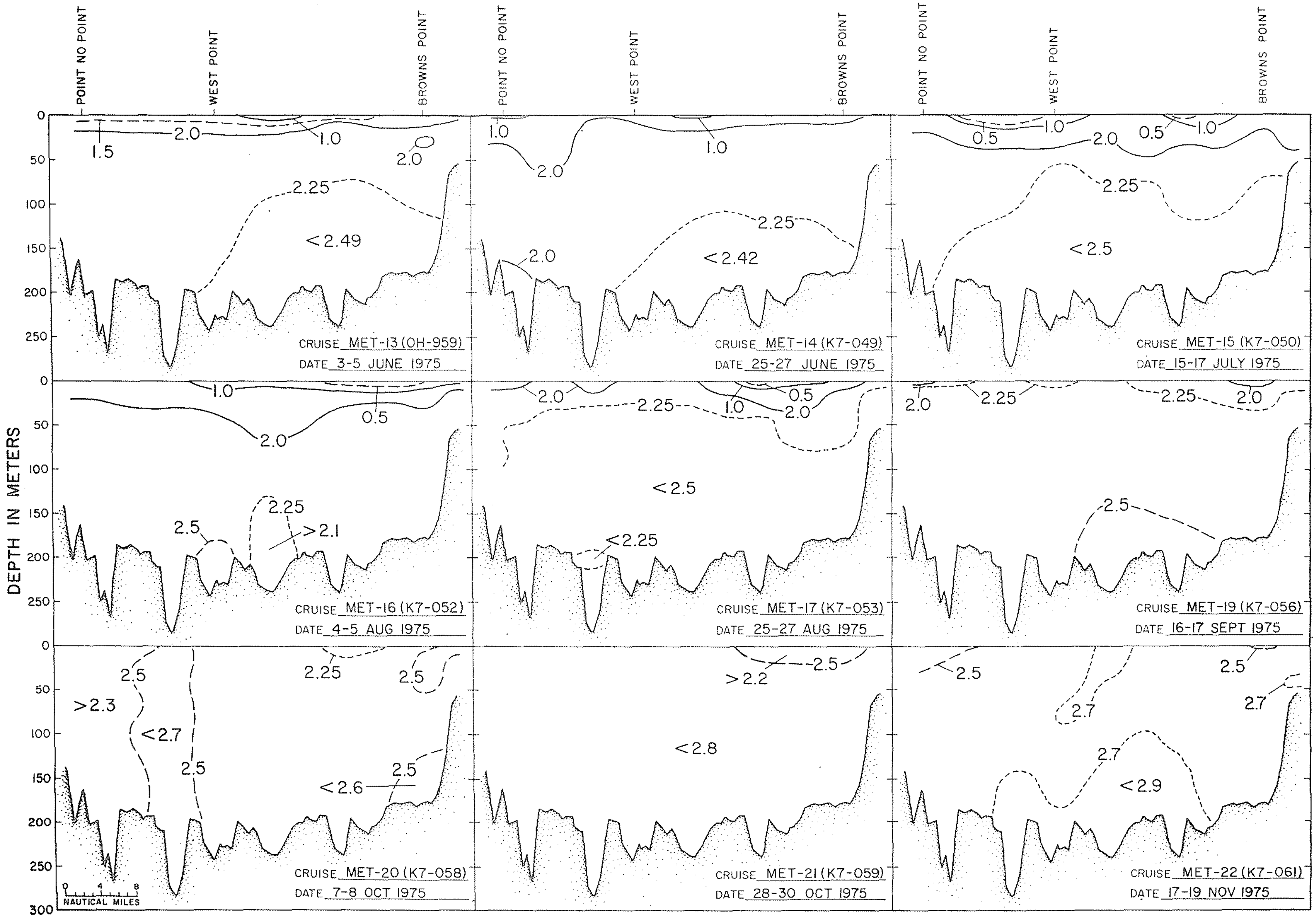


Figure 3-13

Vertical distribution of phosphate in the Main Basin of Puget Sound (continued)

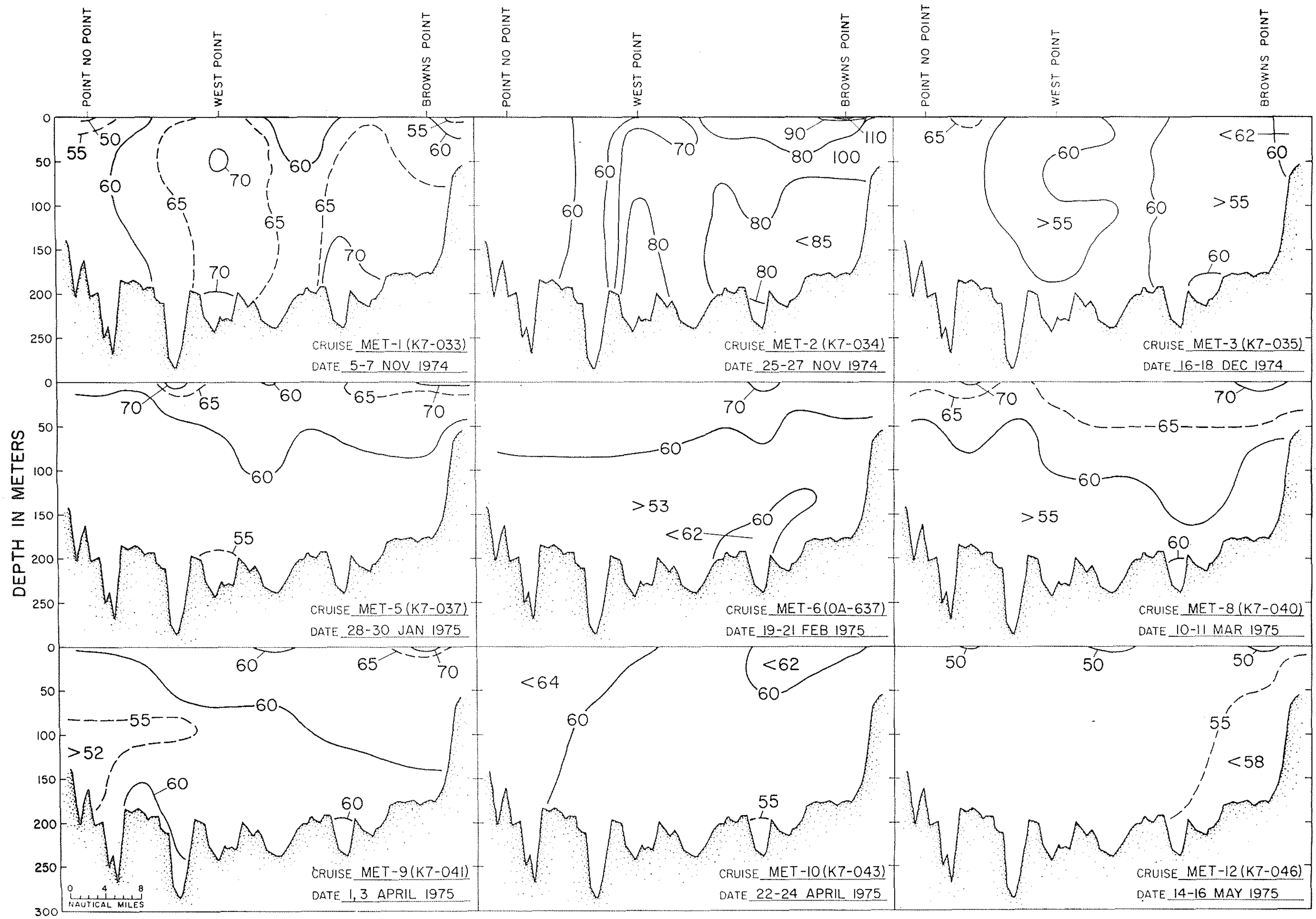


Figure 3-14

Vertical distribution of silicate in the Main Basin of Puget Sound

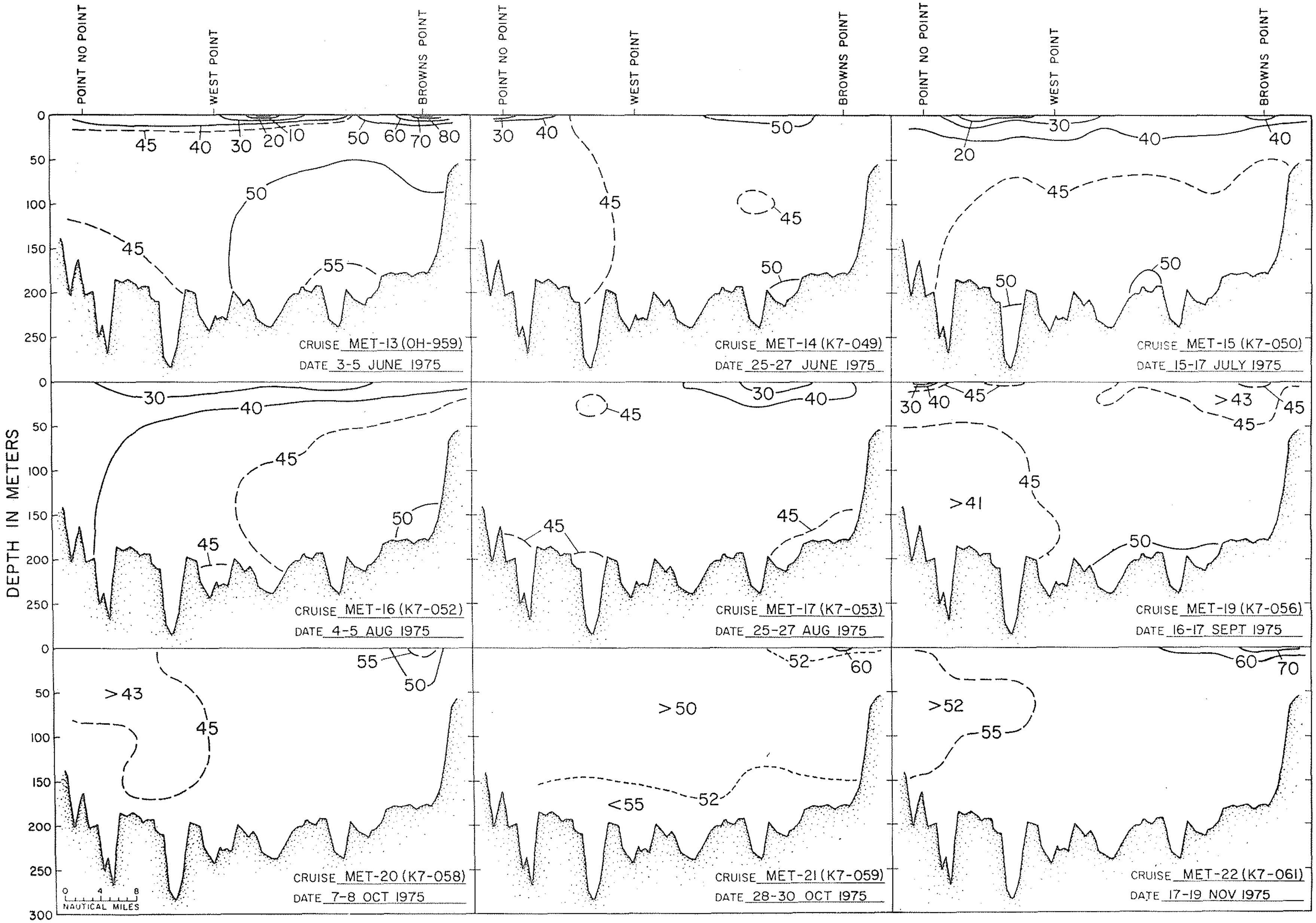


Figure 3-15

Vertical distribution of silicate in the Main Basin of Puget Sound (continued)

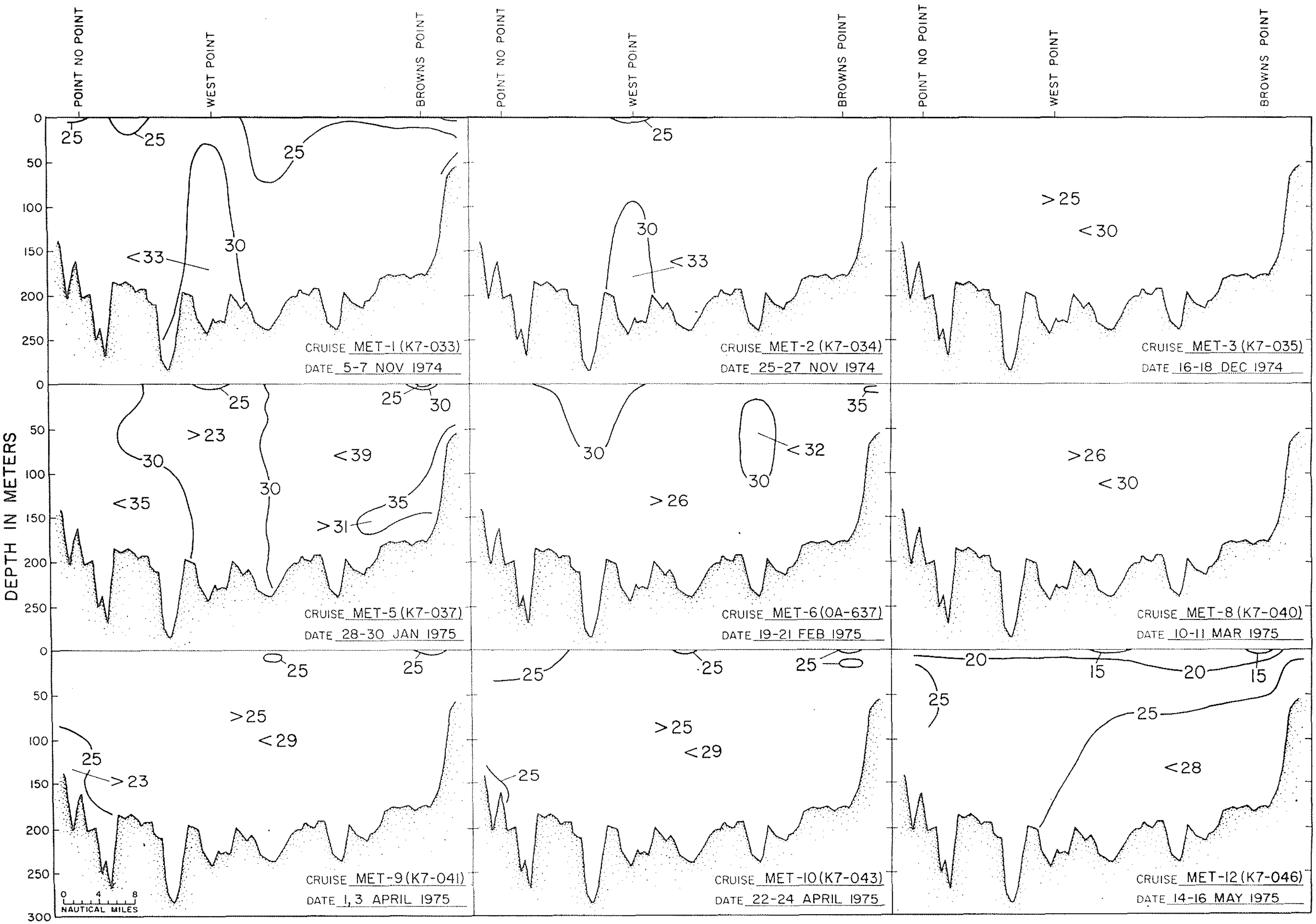


Figure 3-16

Vertical distribution of nitrate in the Main Basin of Puget Sound

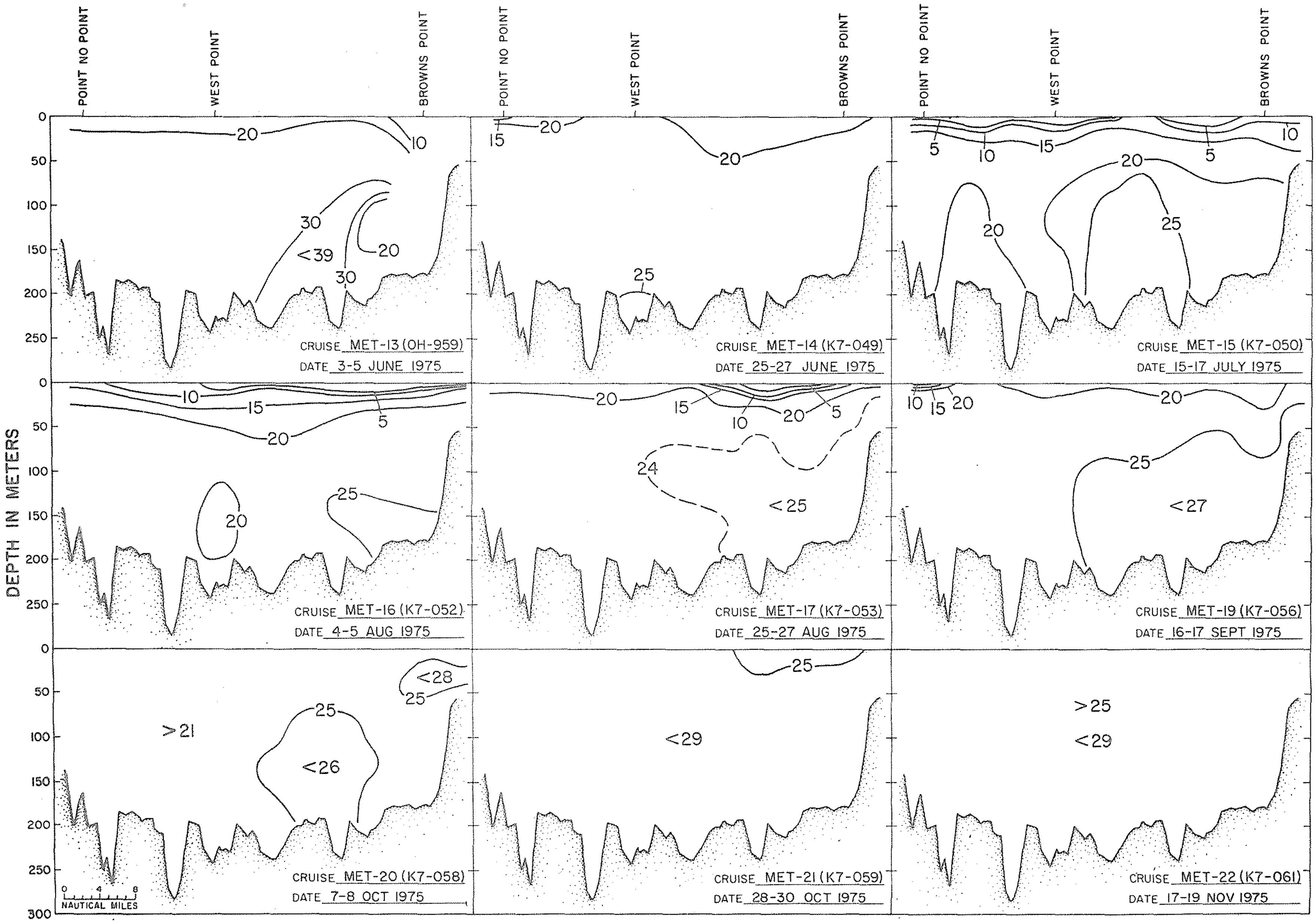


Figure 3-17

Vertical distribution of nitrate in the Main Basin of Puget Sound (continued)

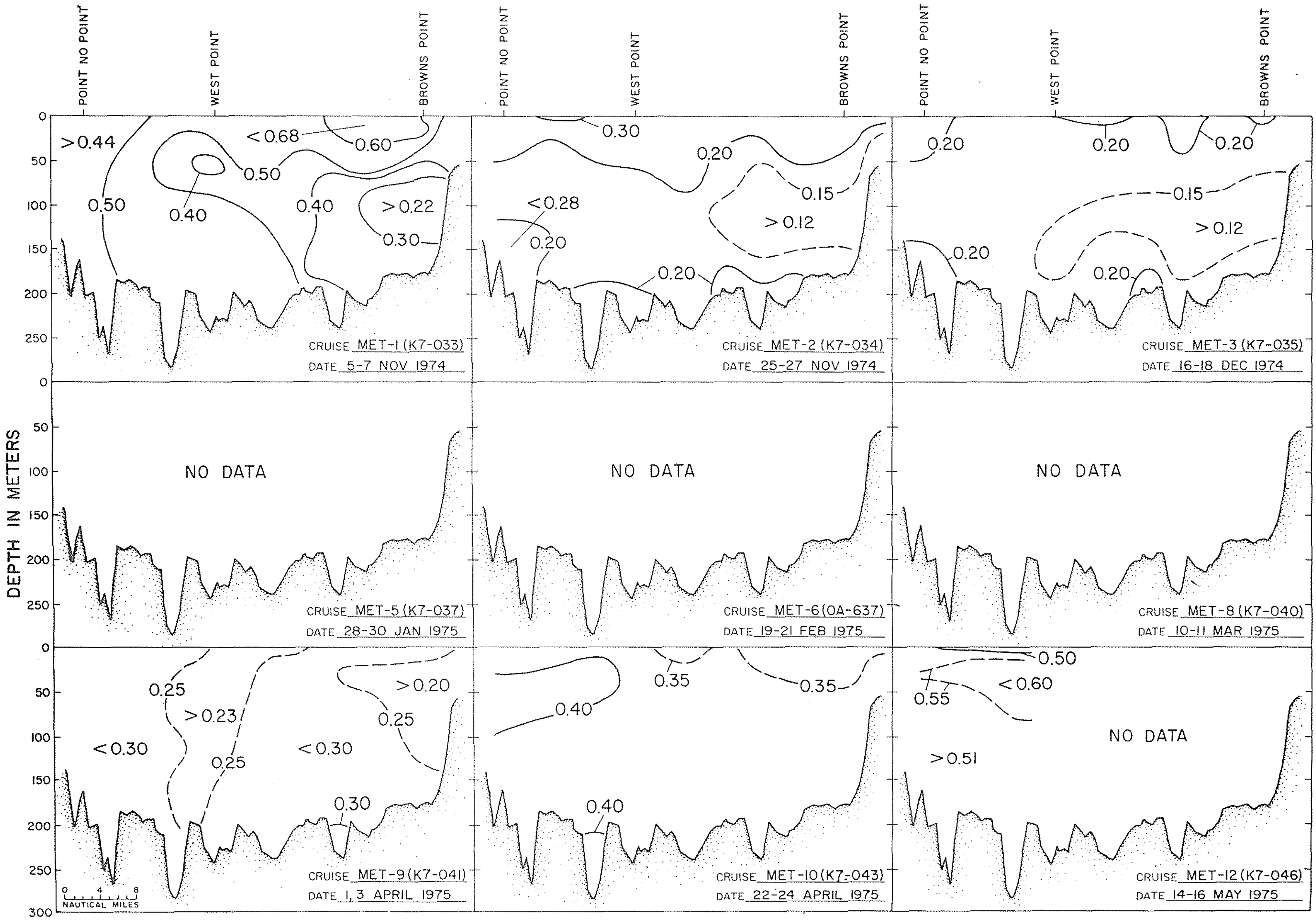


Figure 3-18

Vertical distribution of nitrite in the Main Basin of Puget Sound

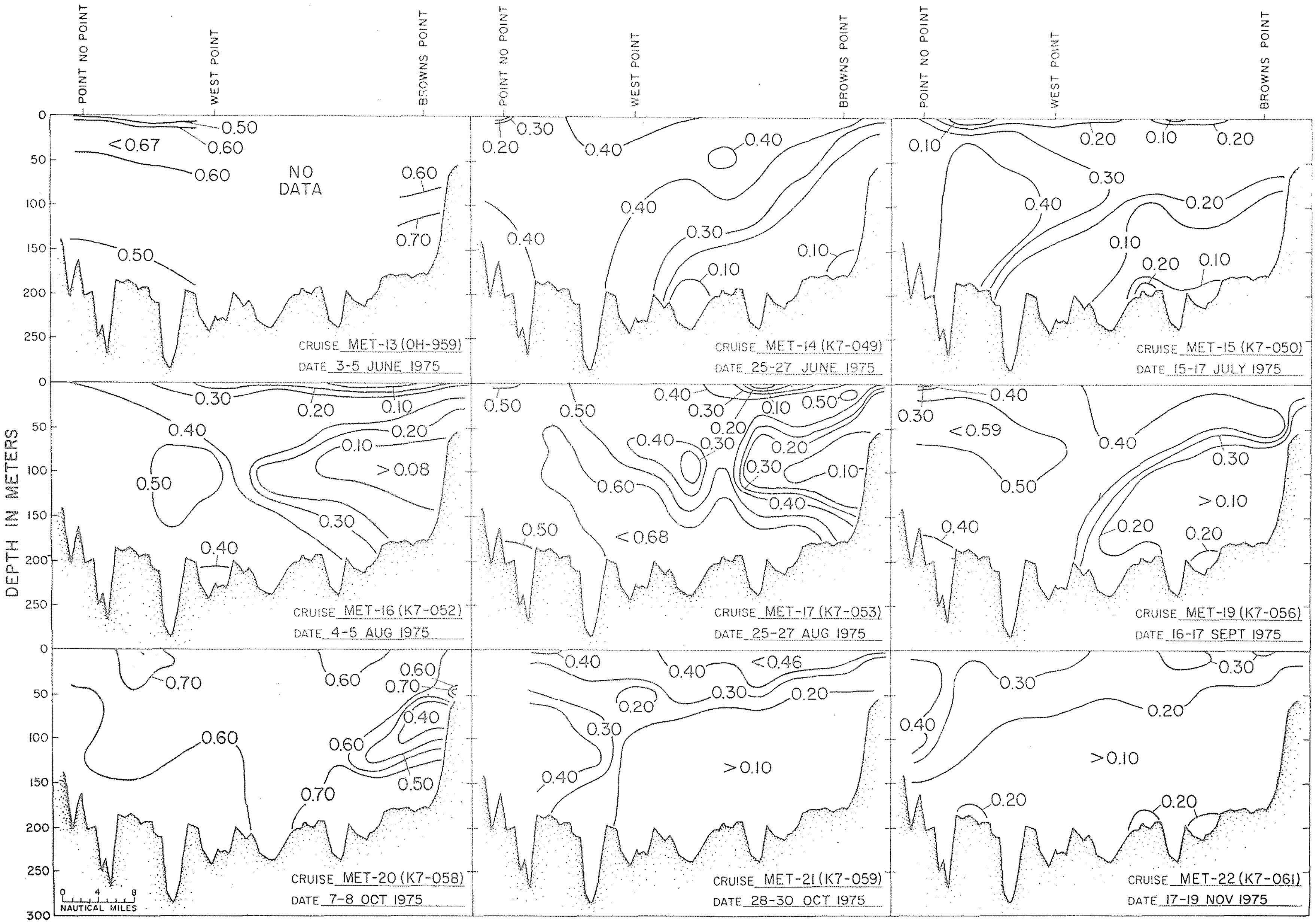


Figure 3-20

Vertical distribution of nitrite in the Main Basin of Puget Sound (continued)

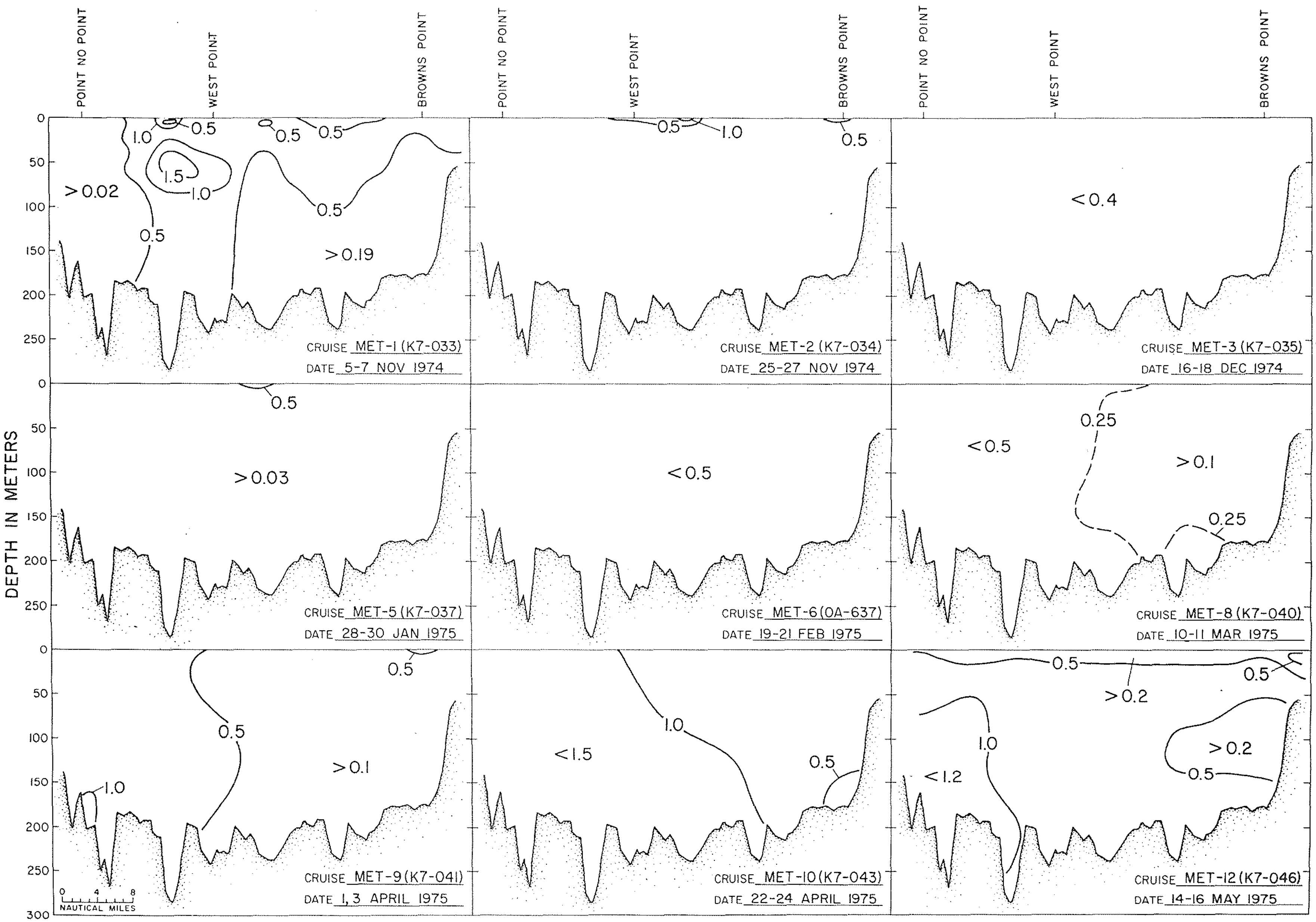


Figure 3-19
Vertical distribution of ammonia in the Main Basin of Puget Sound

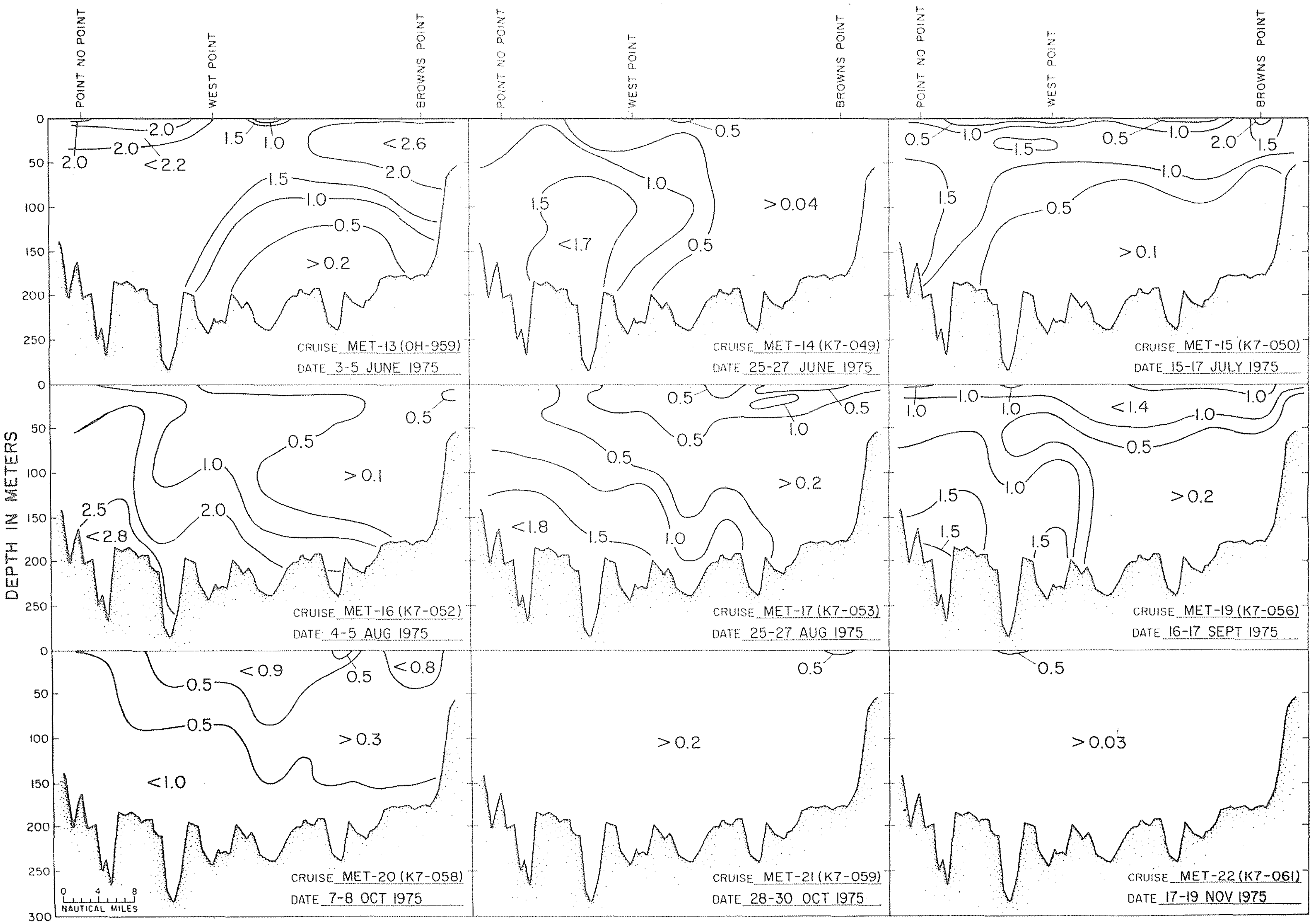


Figure 3-21

Vertical distribution of ammonia in the Main Basin of Puget Sound (continued)

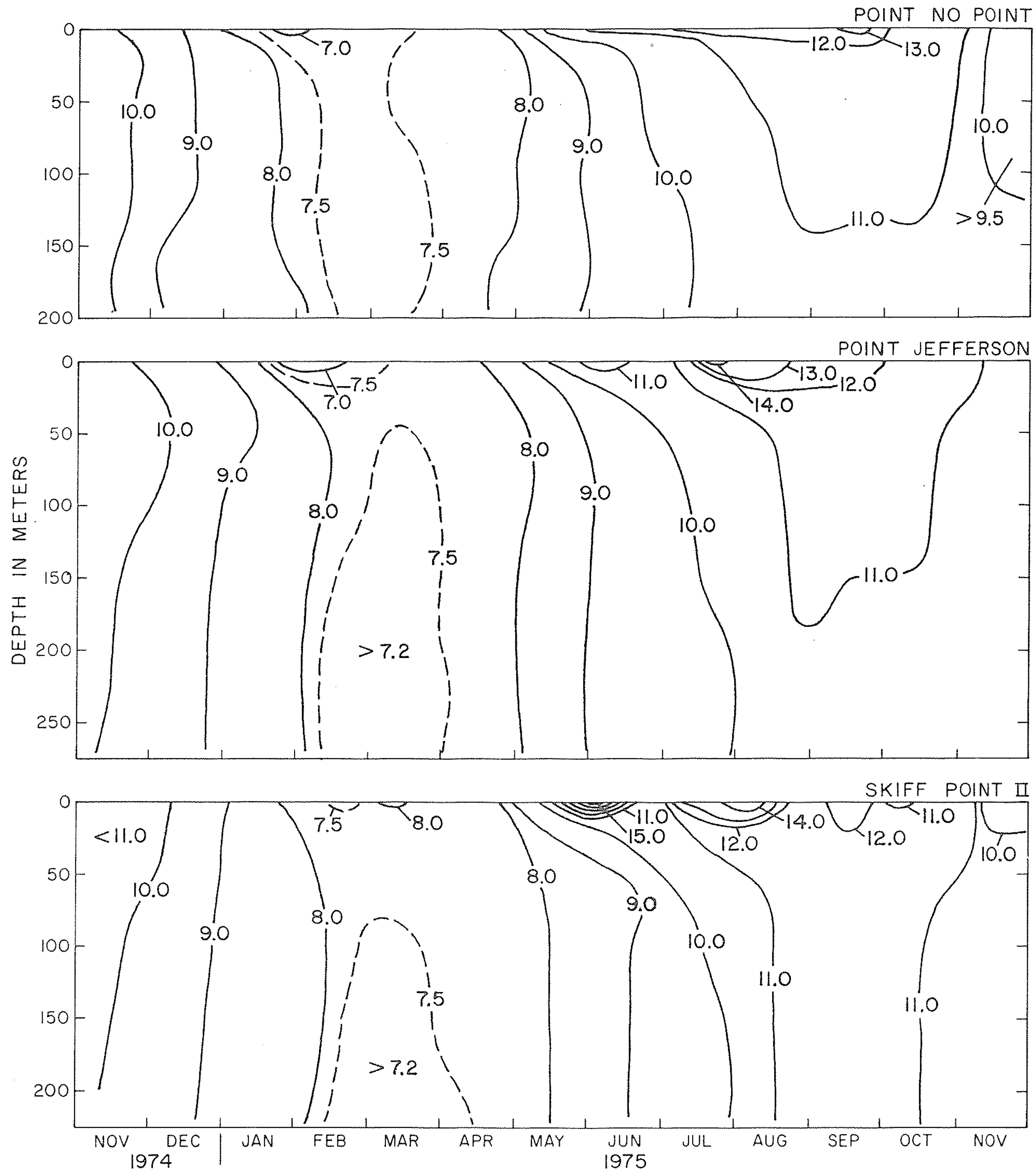


Figure 3-22

Seasonal variations in temperature at Point No Point, Point Jefferson, and Skiff Point II

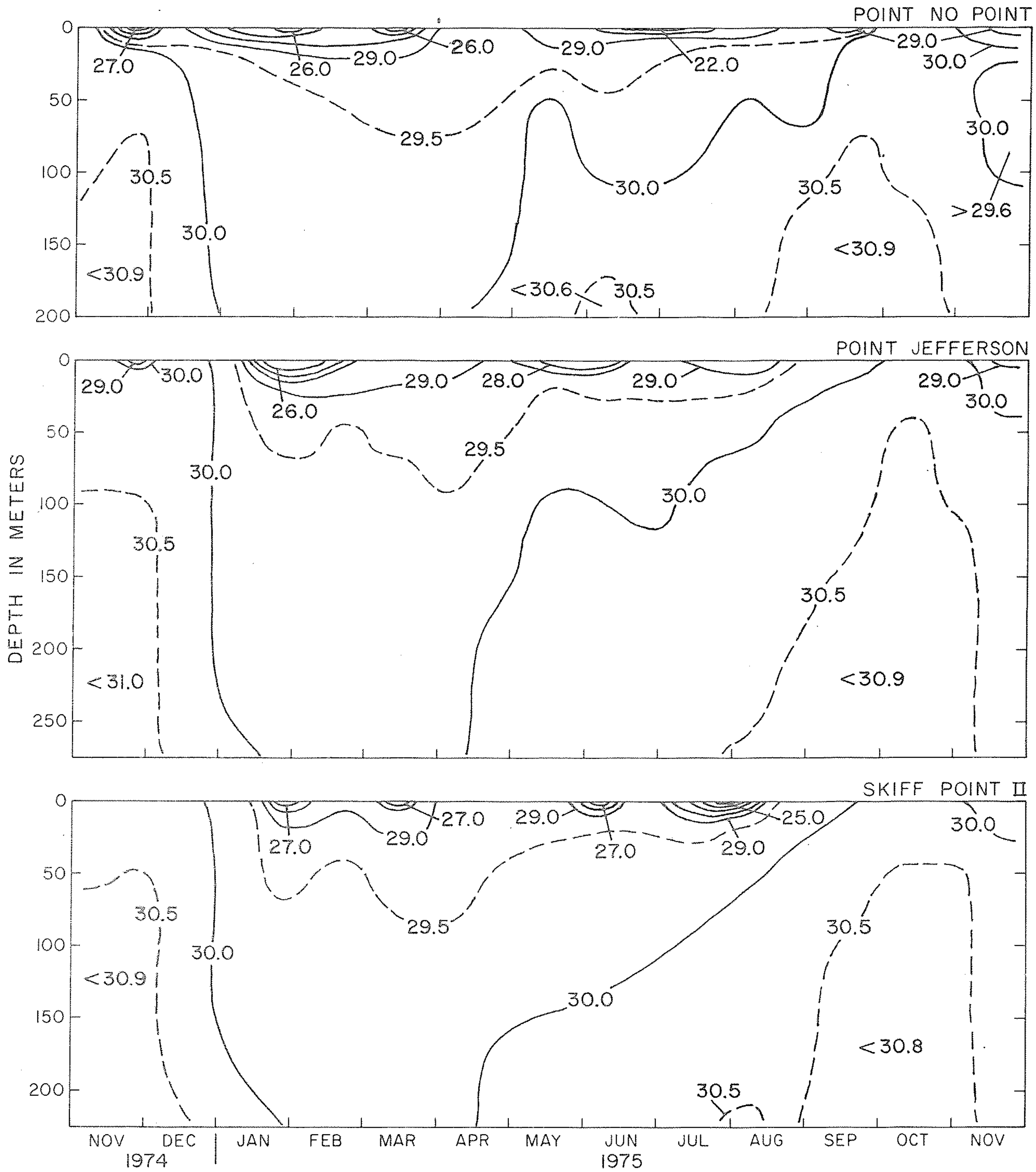


Figure 3-23

Seasonal variations in salinity at Point No Point, Point Jefferson, and Skiff Point II

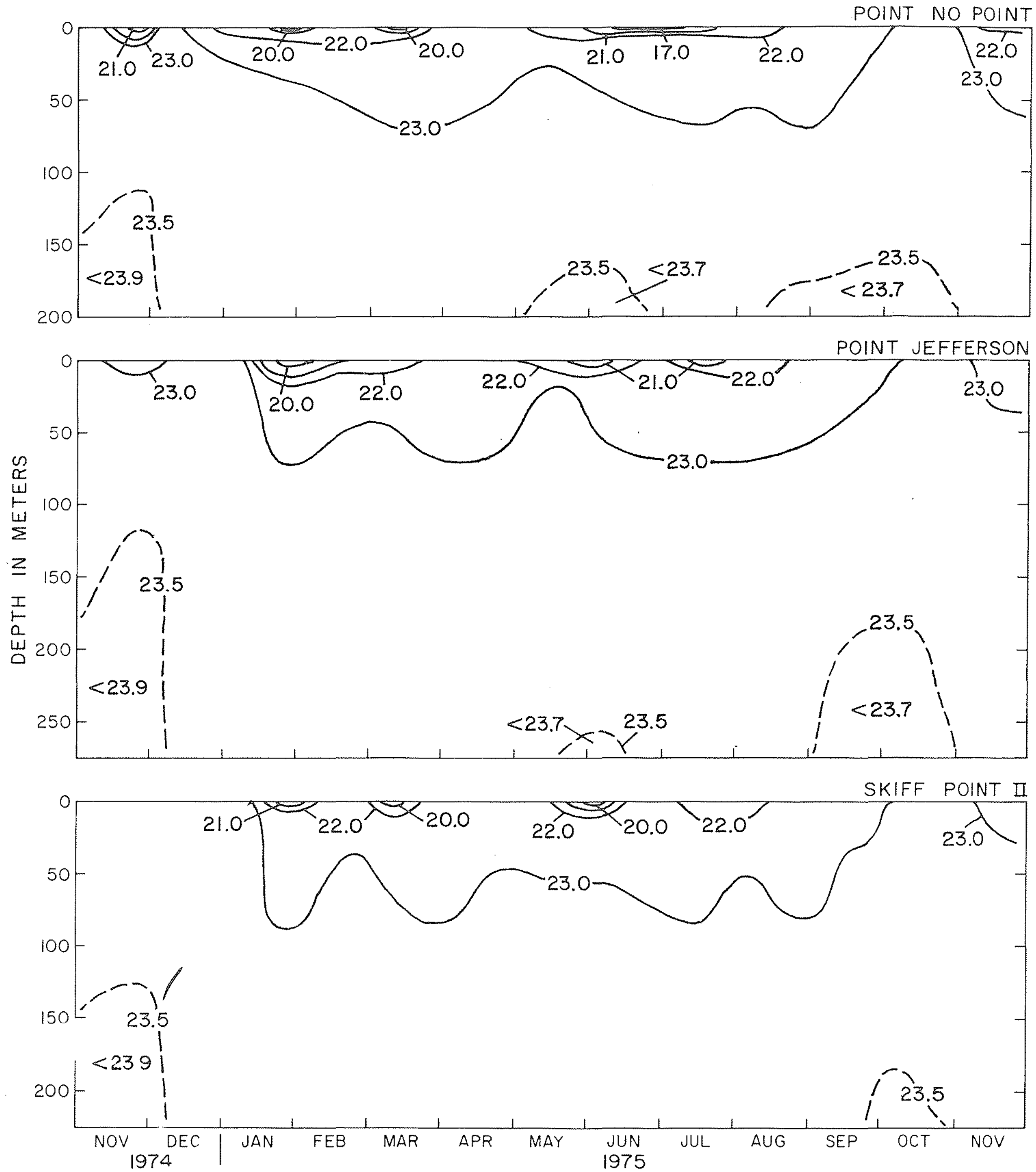


Figure 3-24

Seasonal variations in density (as σ_t) at Point No Point, Point Jefferson, and Skiff Point II

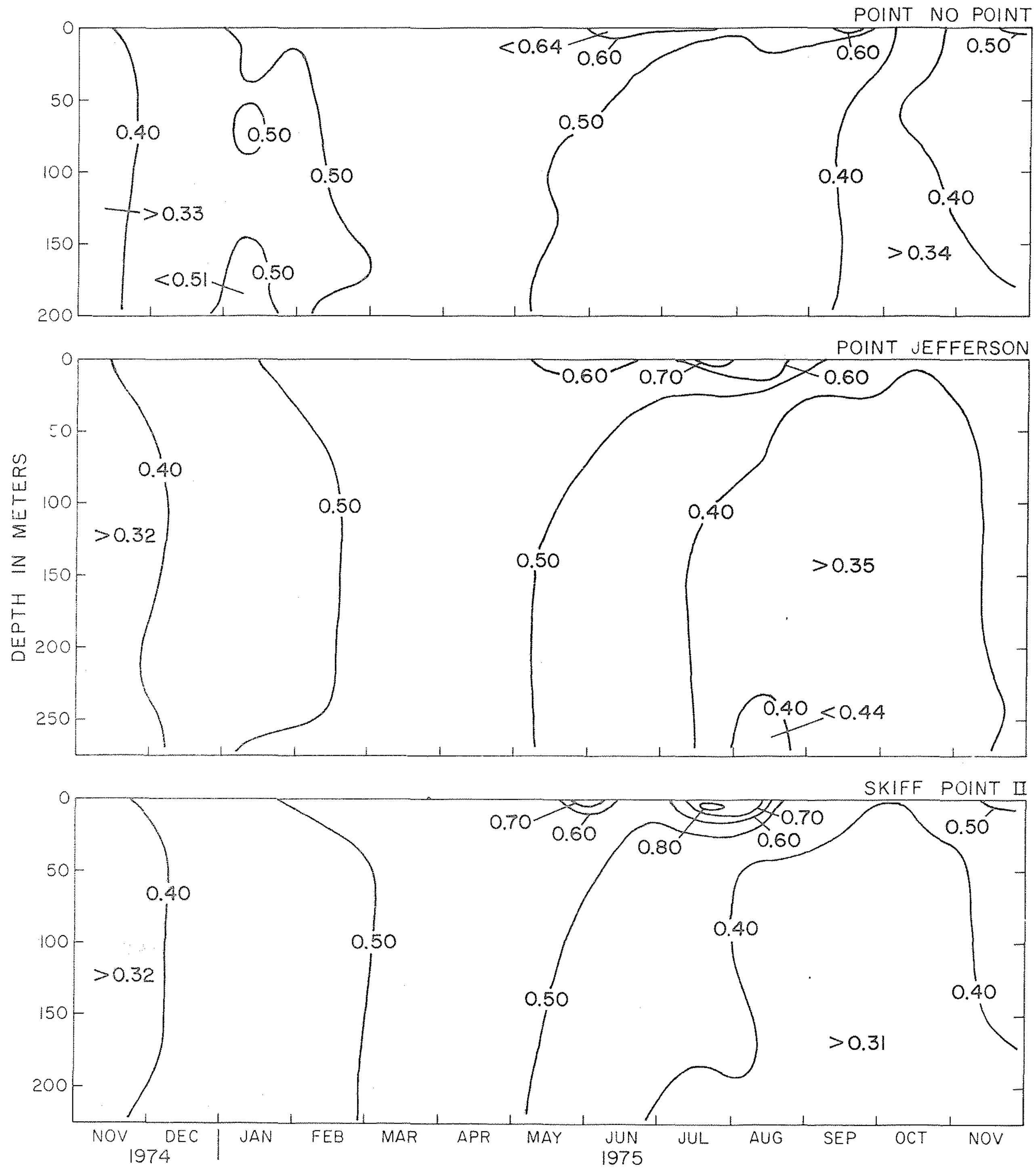


Figure 3-25

Seasonal variations in dissolved oxygen at Point No Point, Point Jefferson, and Skiff Point II

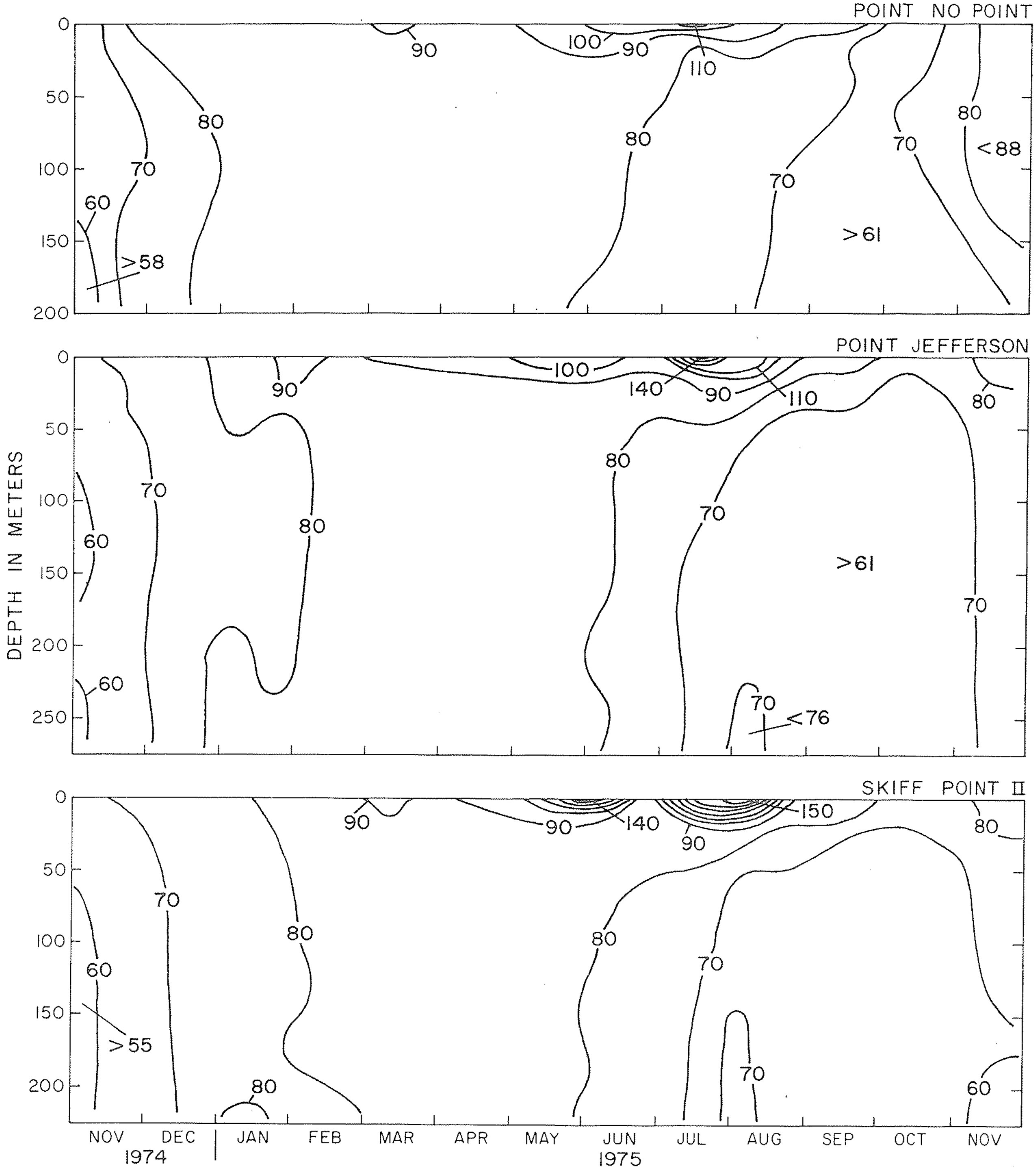


Figure 3-26

Seasonal variations in % oxygen saturation at Point No Point, Point Jefferson, and Skiff Point II

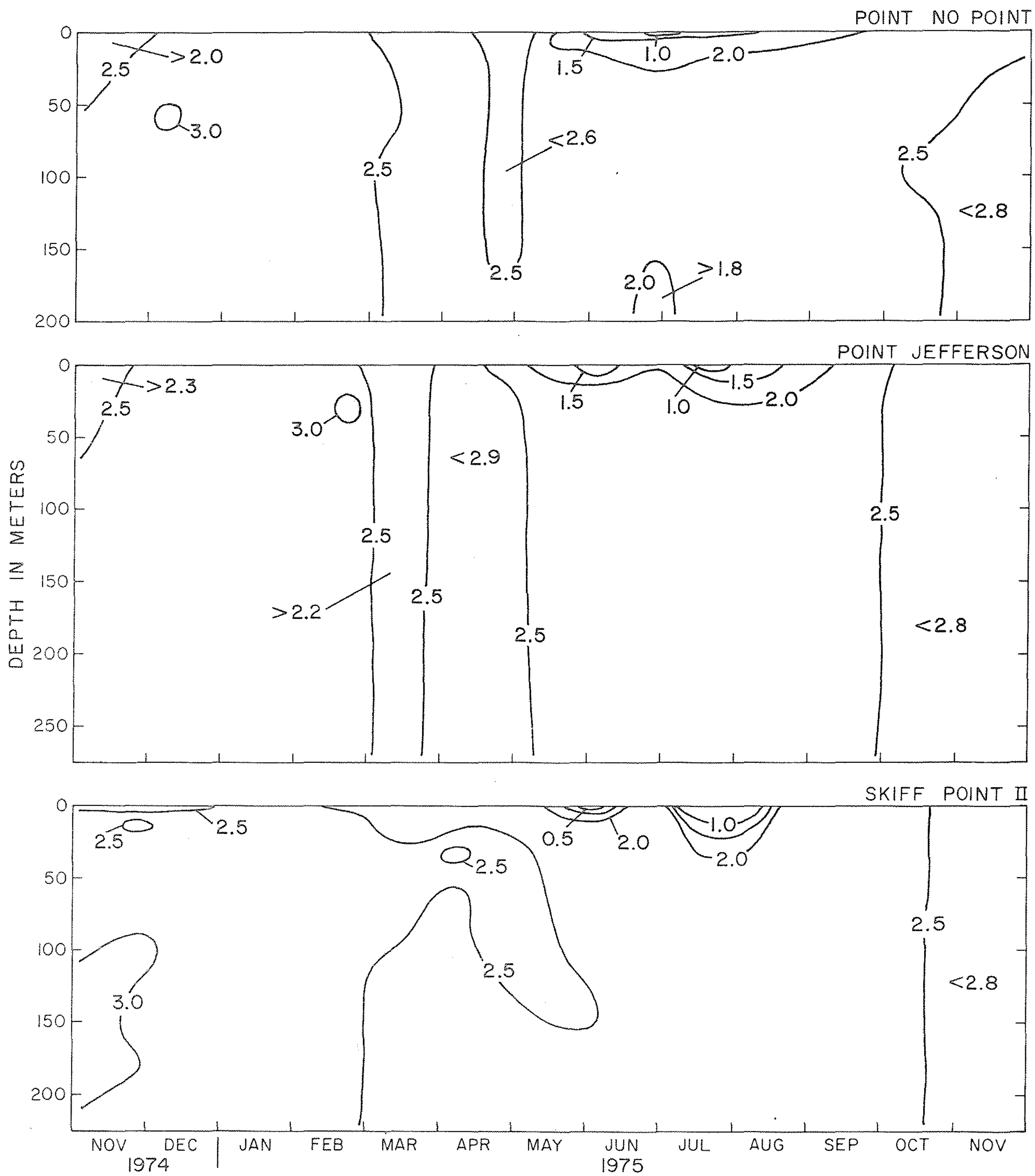


Figure 3-27

Seasonal variations in phosphate at Point No Point, Point Jefferson, and Skiff Point II

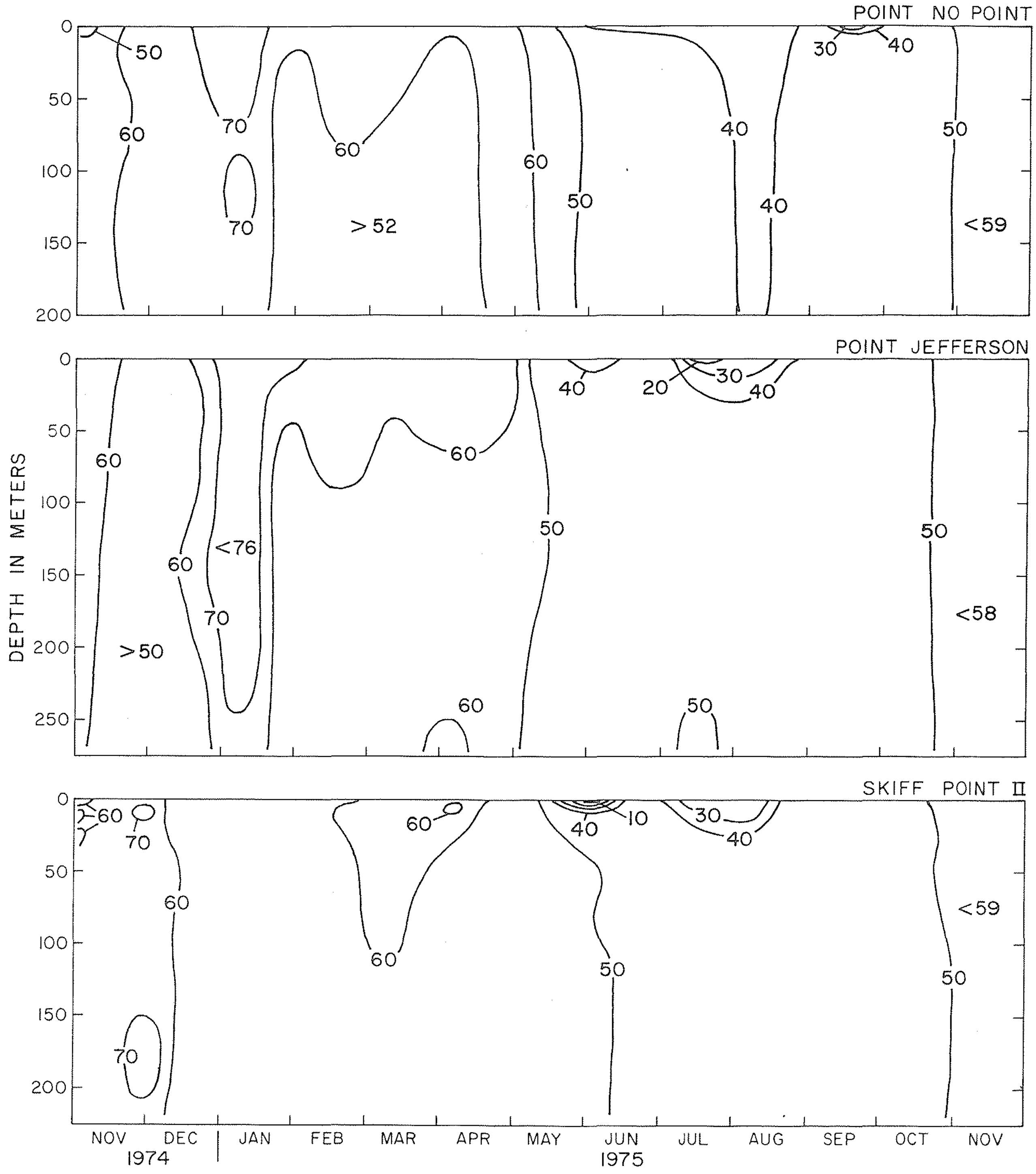


Figure 3-28

Seasonal variations in silicate at Point No Point, Point Jefferson, and Skiff Point II

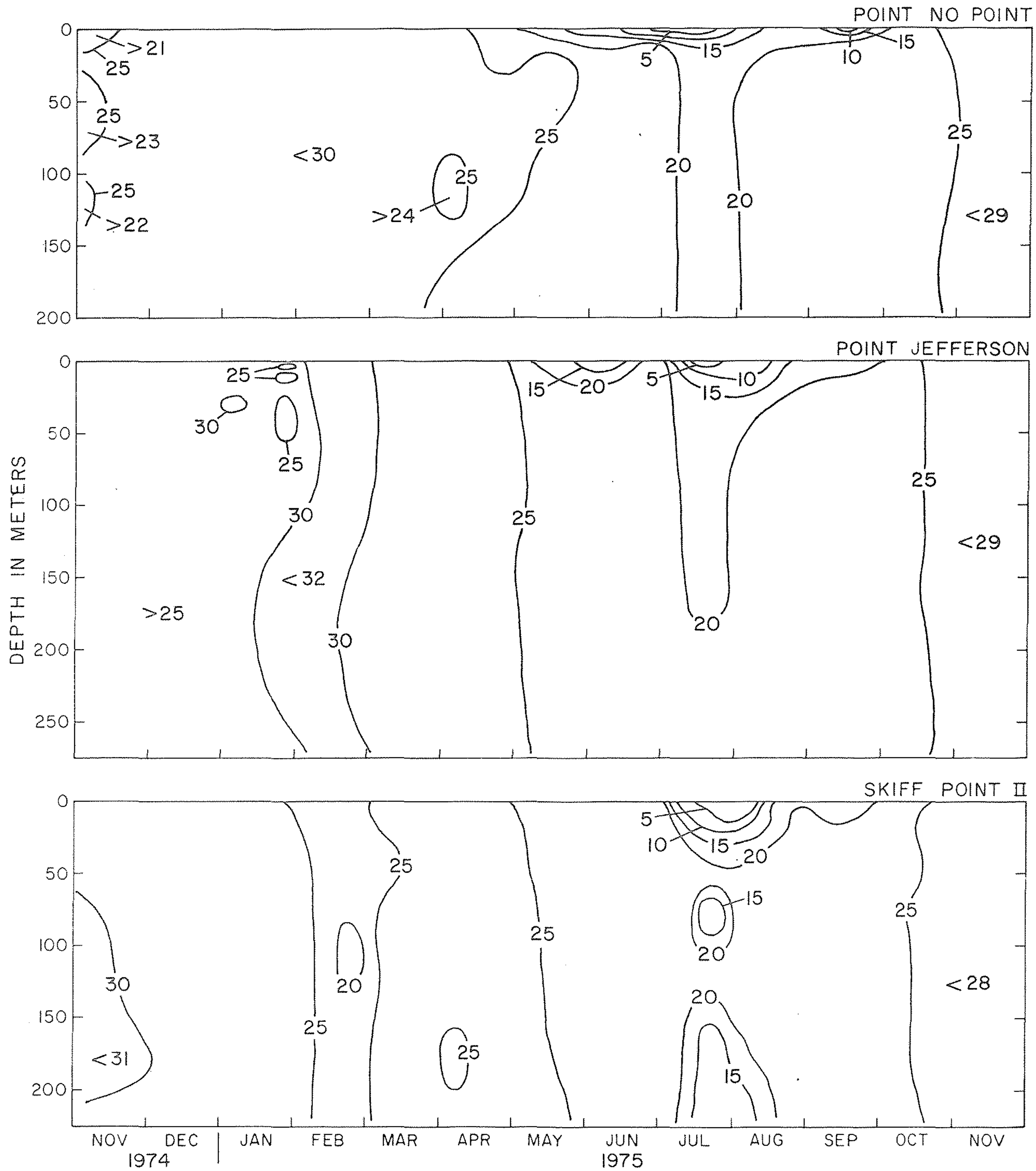


Figure 3-29

Seasonal variations in nitrate at Point No Point, Point Jefferson, and Skiff Point II

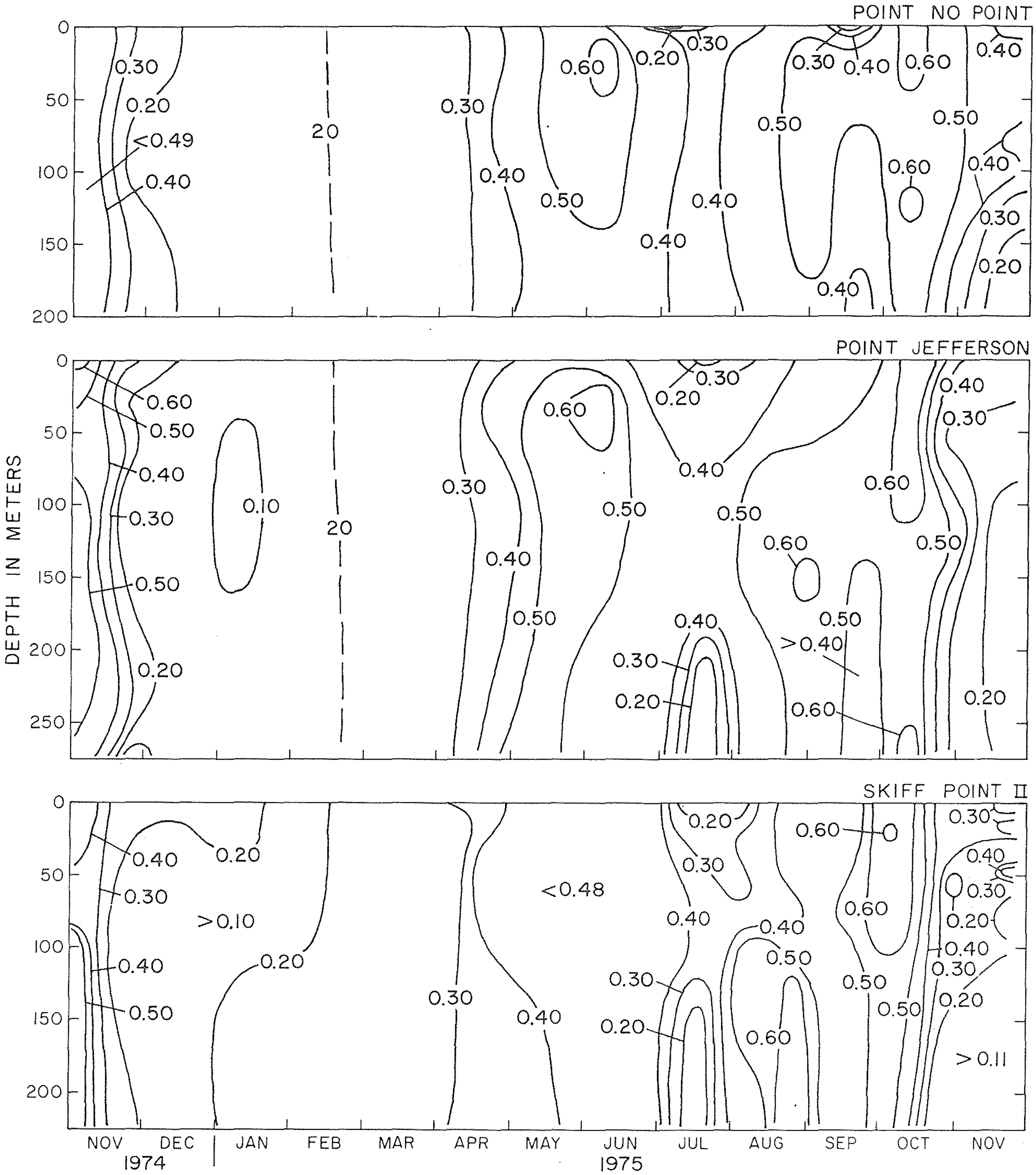


Figure 3-30

Seasonal variations in nitrite at Point No Point, Point Jefferson, and Skiff Point II

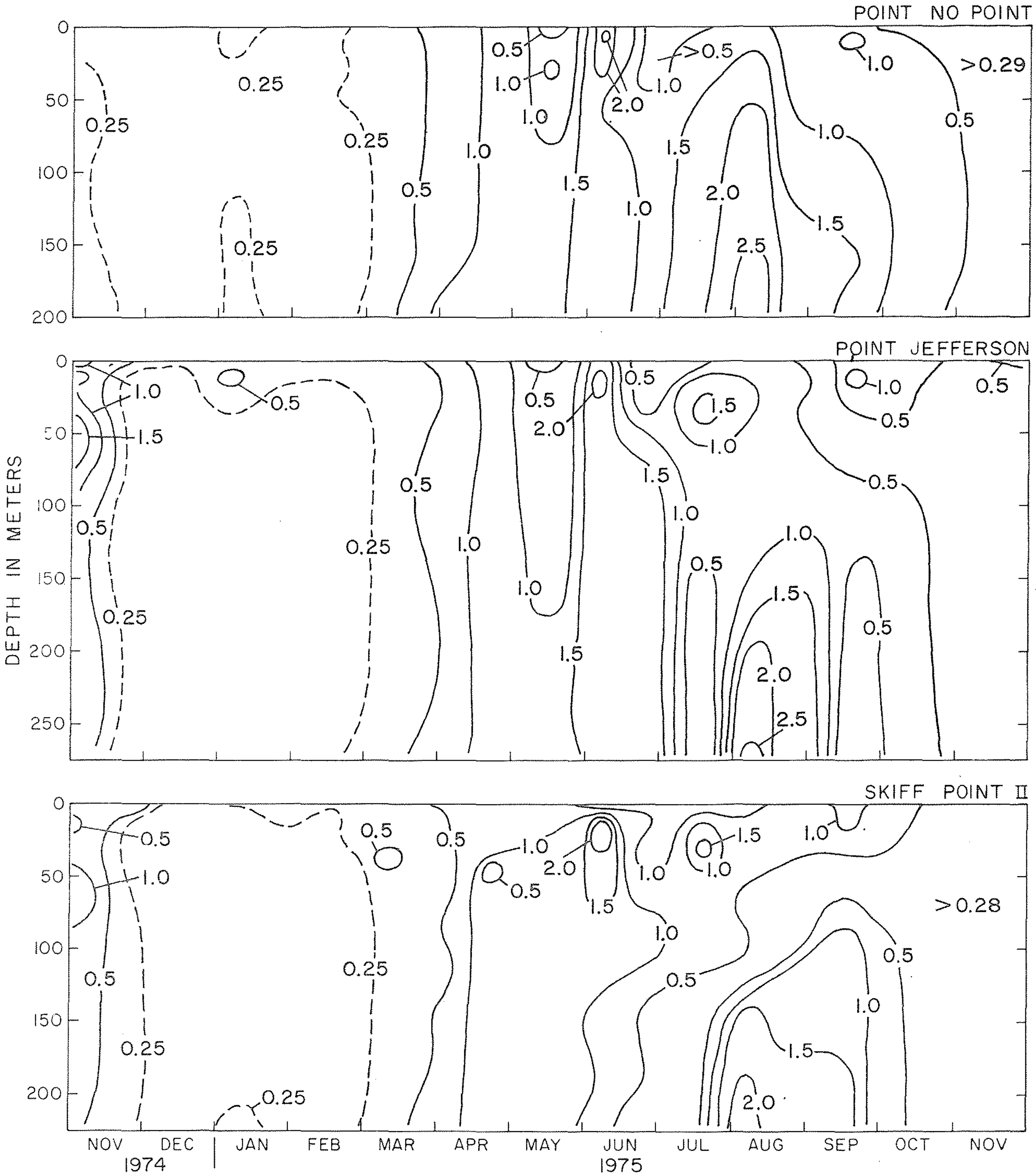


Figure 3-31

Seasonal variations in ammonia at Point No Point, Point Jefferson, and Skiff Point II

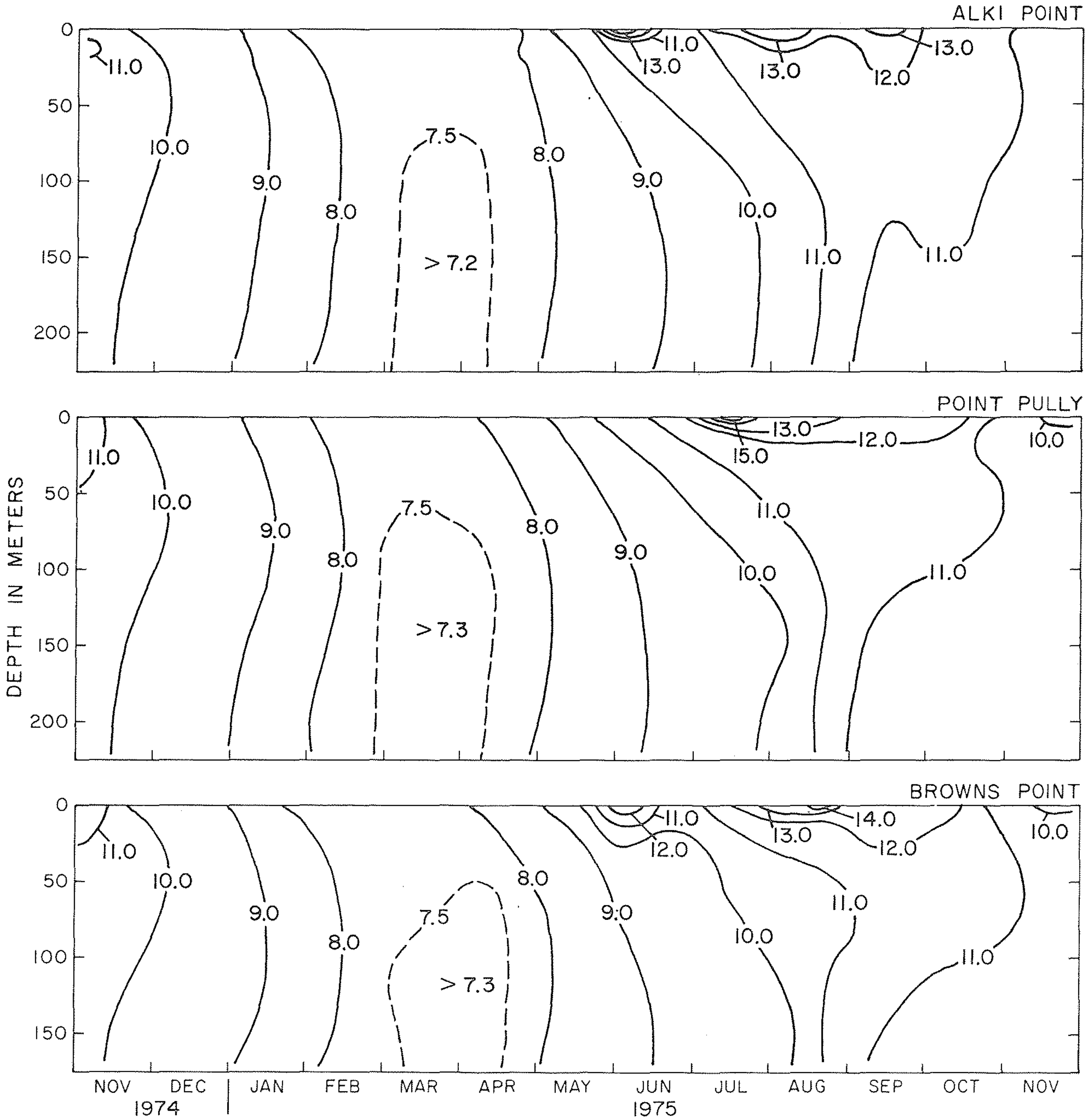


Figure 3-32

Seasonal variations in temperature at Alki Point, Point Pully, and Browns Point

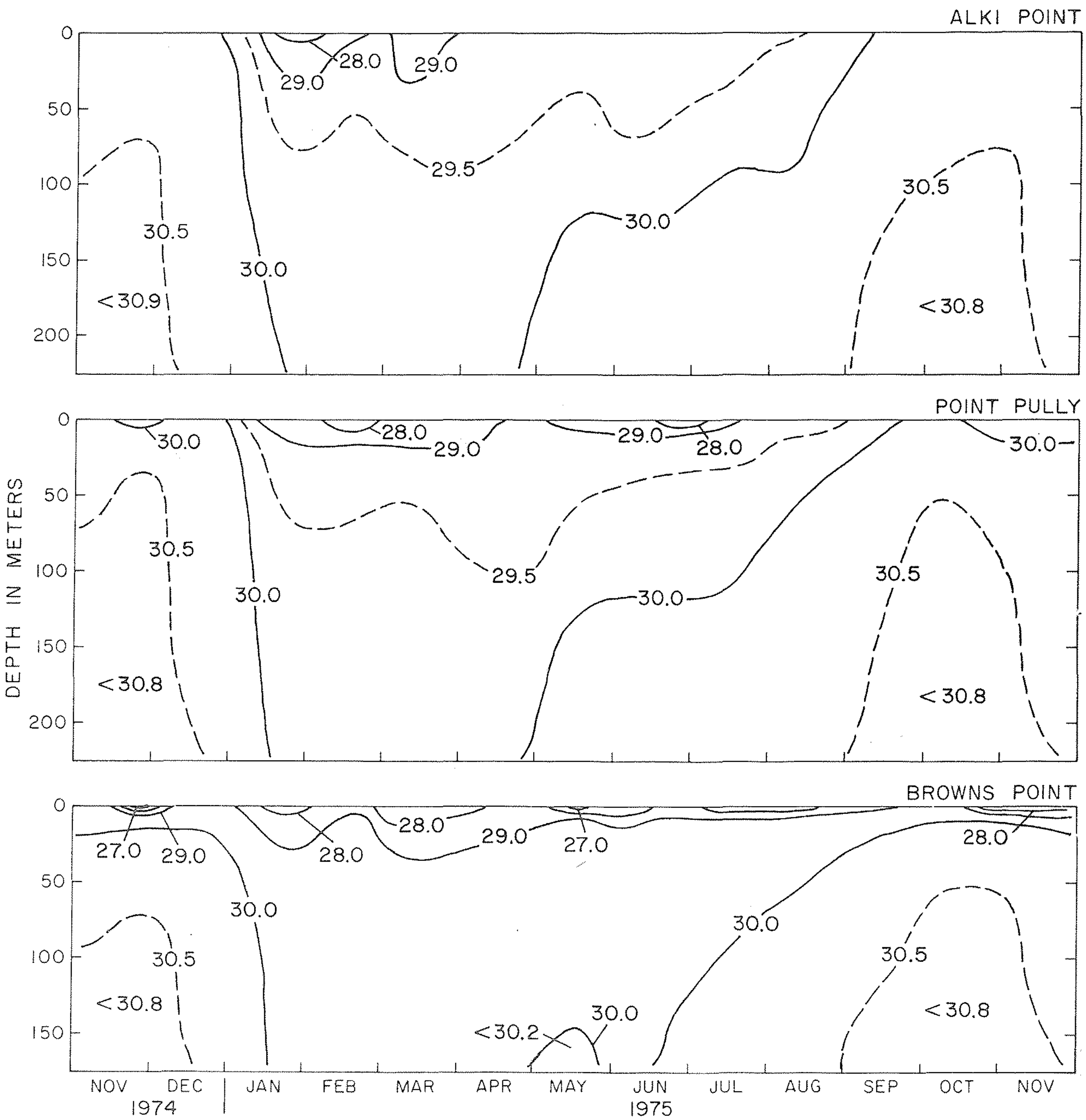


Figure 3-33

Seasonal variations in salinity at Alki Point, Point Pully, and Browns Point

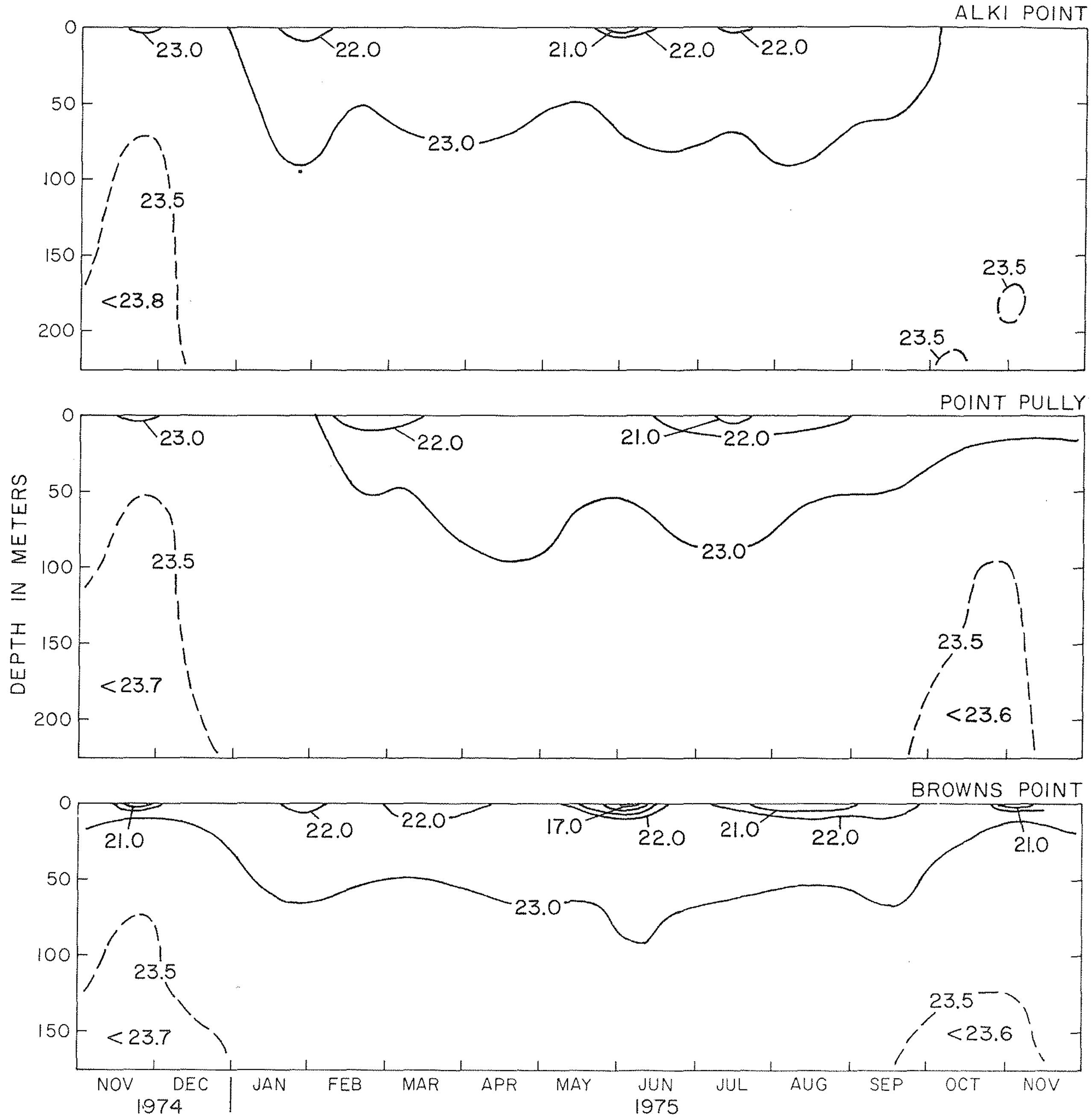


Figure 3-34

Seasonal variations in density (as σ_t) at Alki Point, Point Pully, and Browns Point

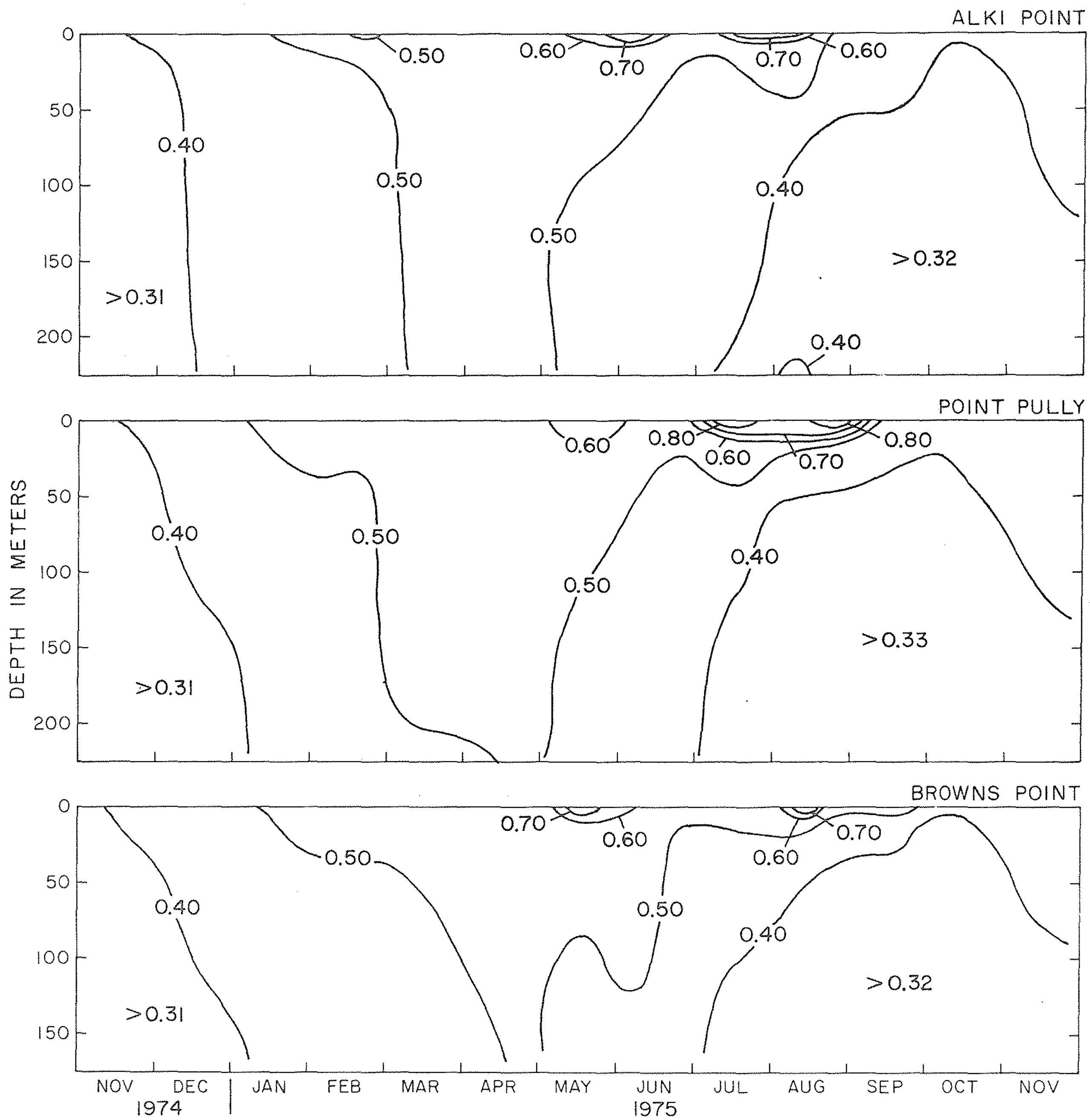


Figure 3-35

Seasonal variations in dissolved oxygen at Alki Point, Point Pully, and Browns Point

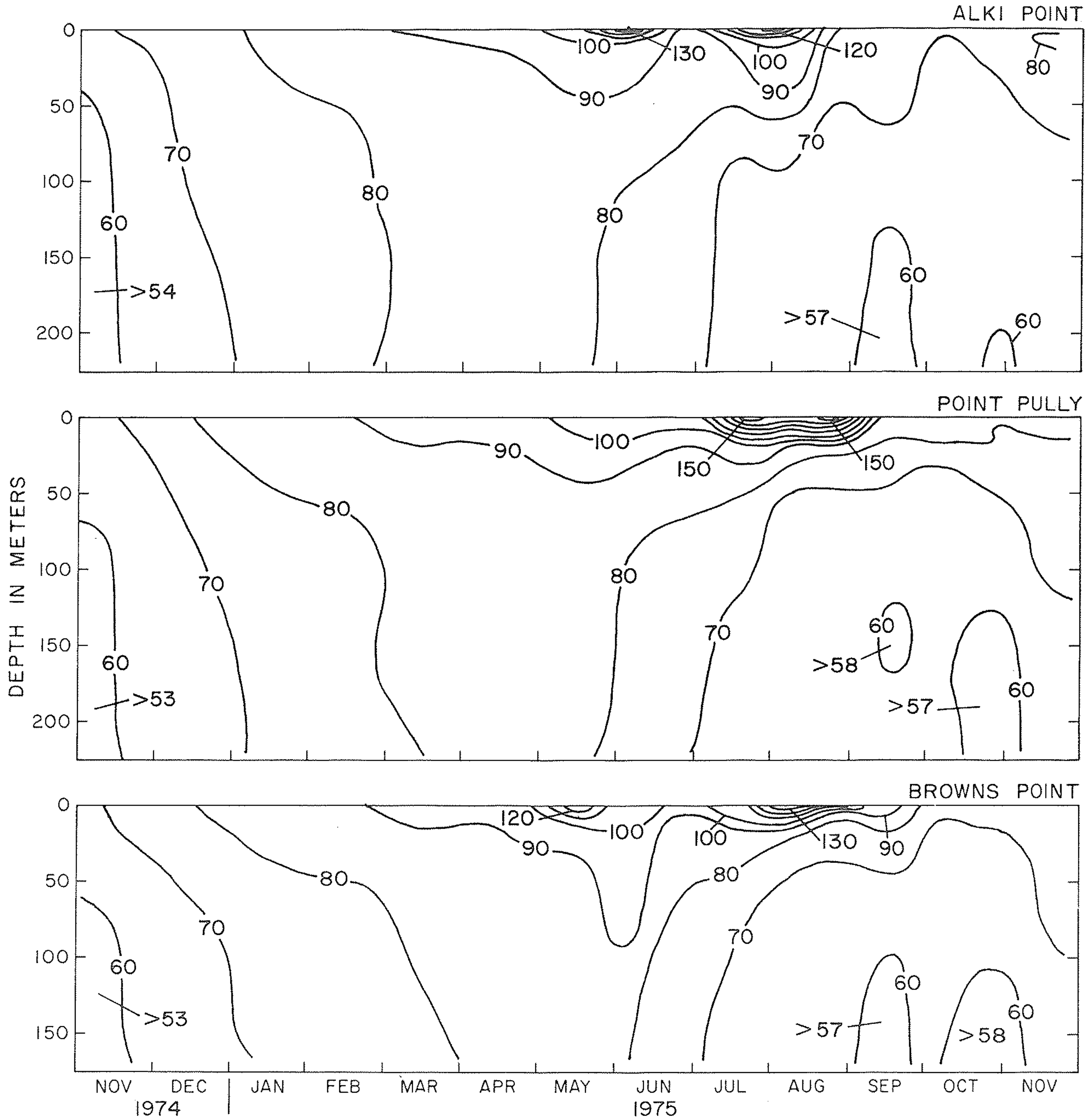


Figure 3-36

Seasonal variations in % oxygen saturation at Alki Point, Point Pully, and Browns Point

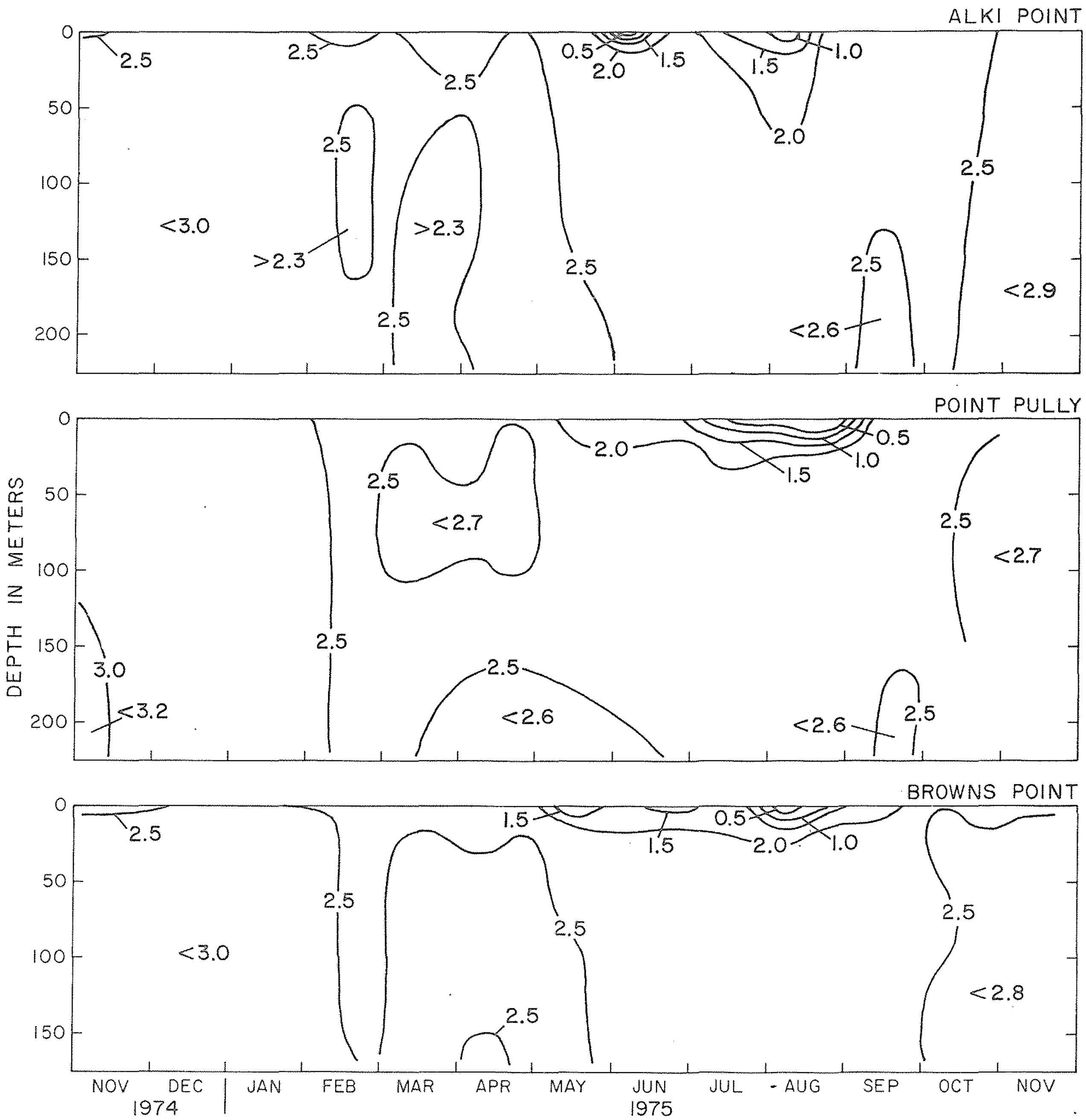


Figure 3-37

Seasonal variations in phosphate at Alki Point, Point Pully, and Browns Point

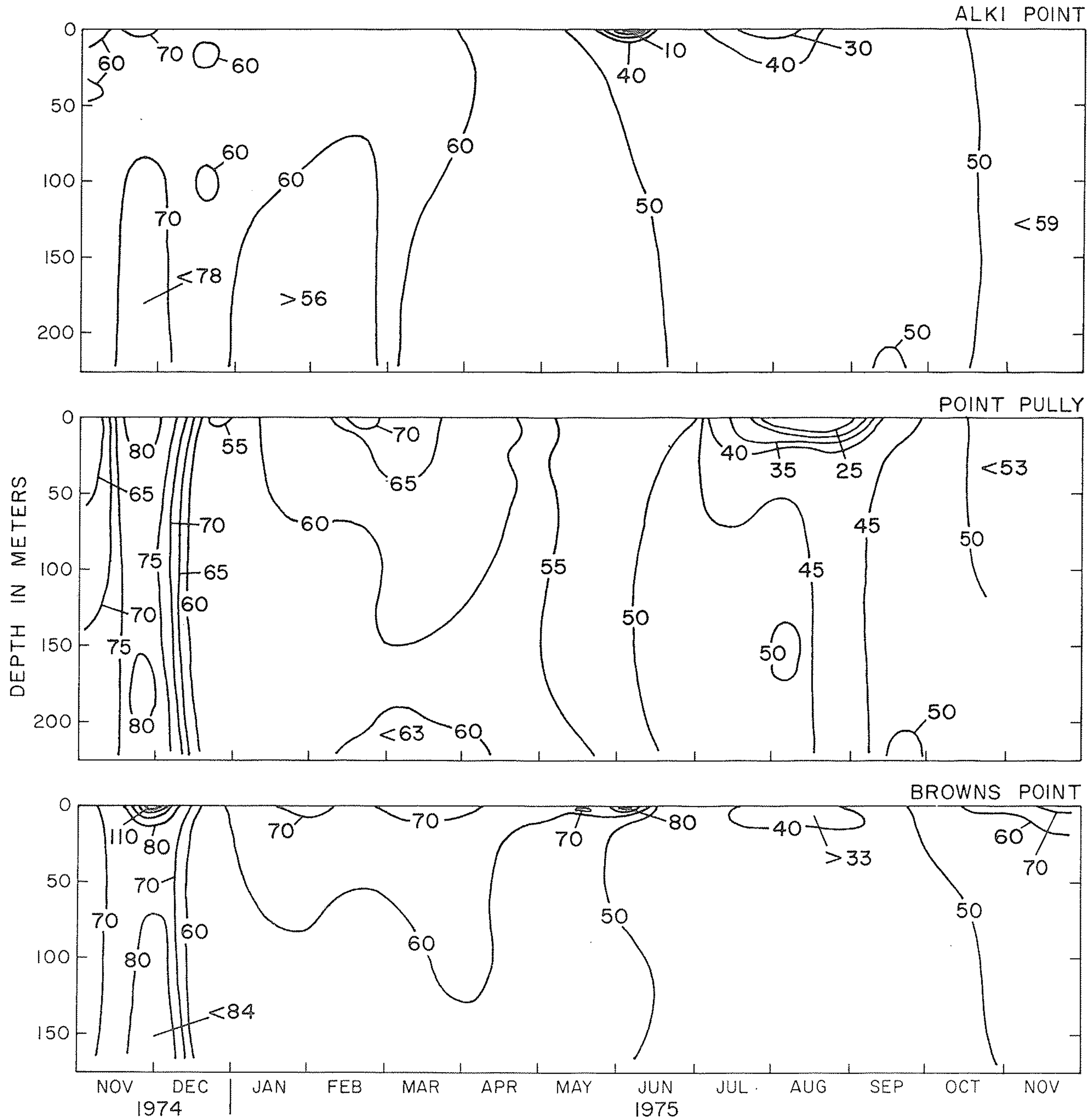


Figure 3-38

Seasonal variations in silicate at Alki Point, Point Pully, and Browns Point

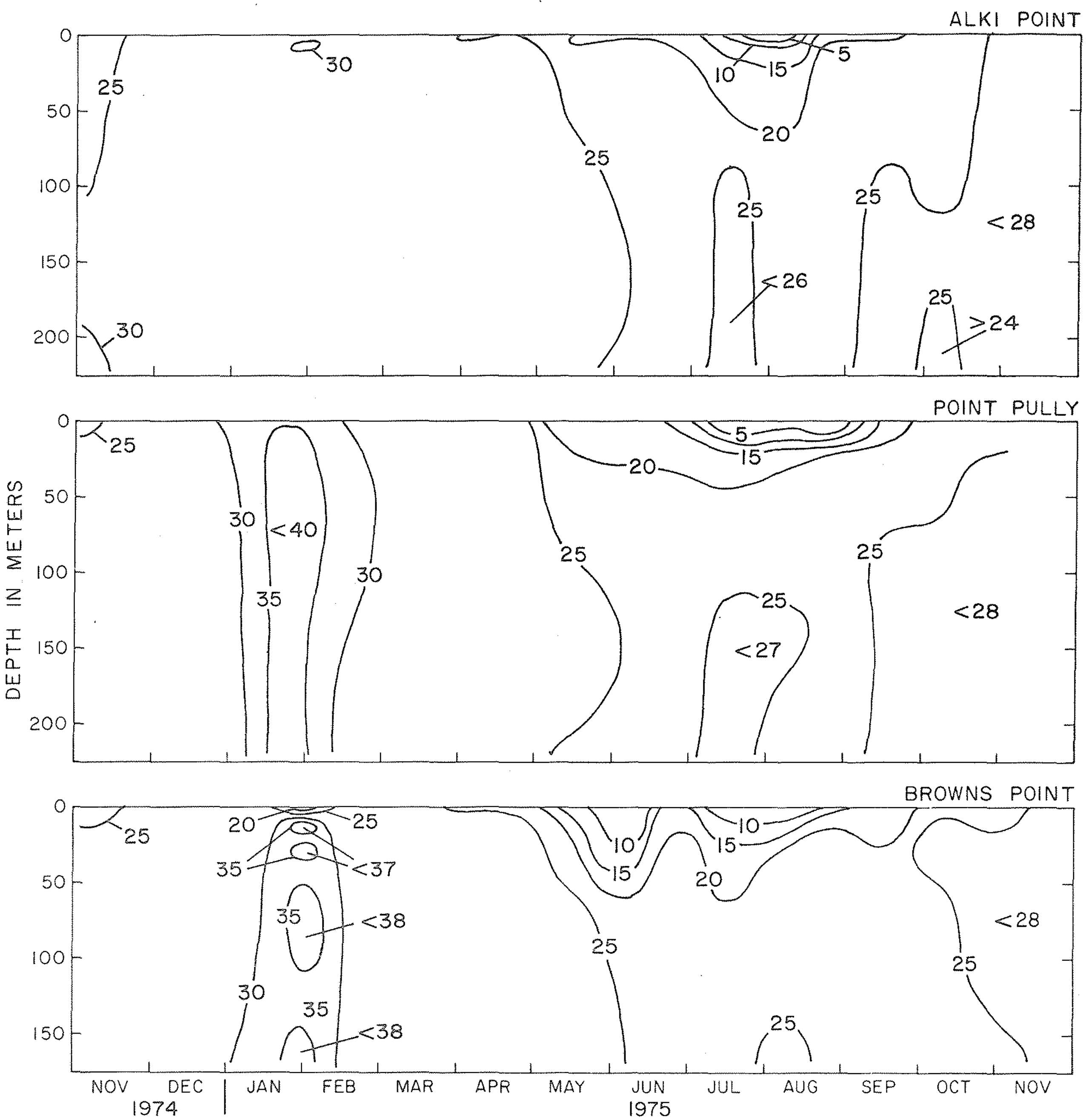


Figure 3-39

Seasonal variations in nitrate at Alki Point, Point Pully, and Browns Point

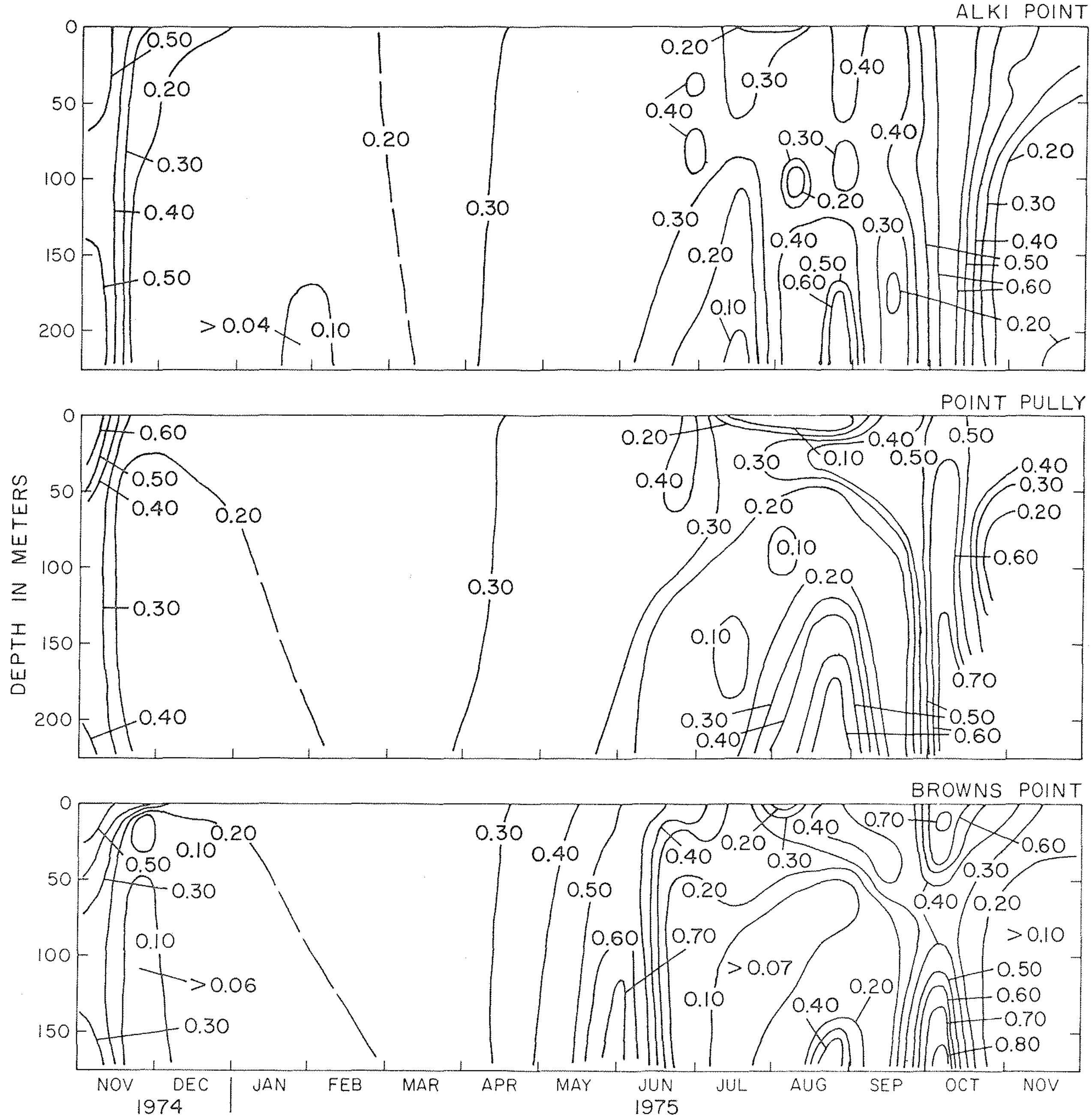


Figure 3-40

Seasonal variations in nitrite at Alki Point, Point Pully, and Browns Point

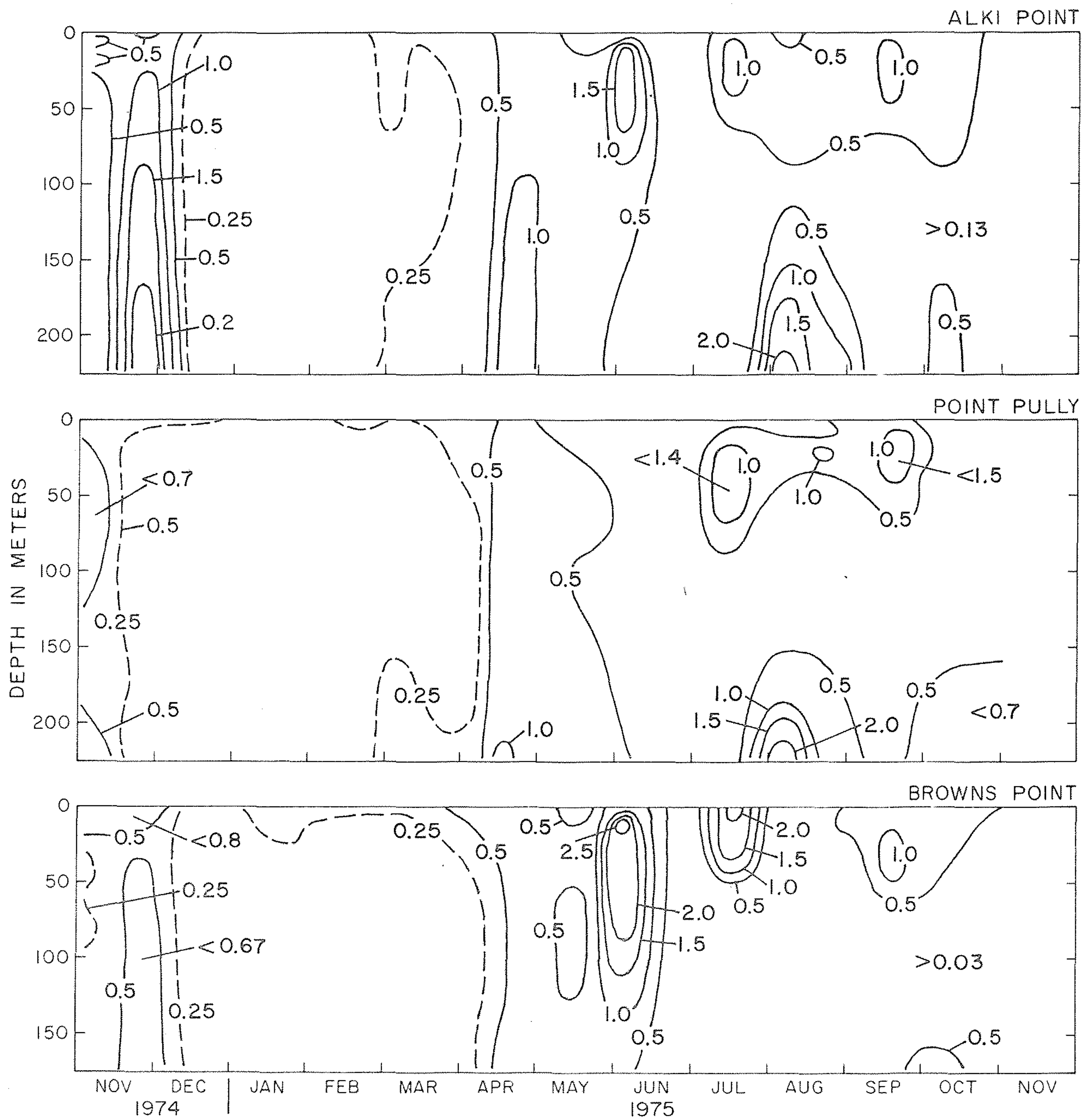


Figure 3-41

Seasonal variations in ammonia at Alki Point, Point Pully, and Browns Point

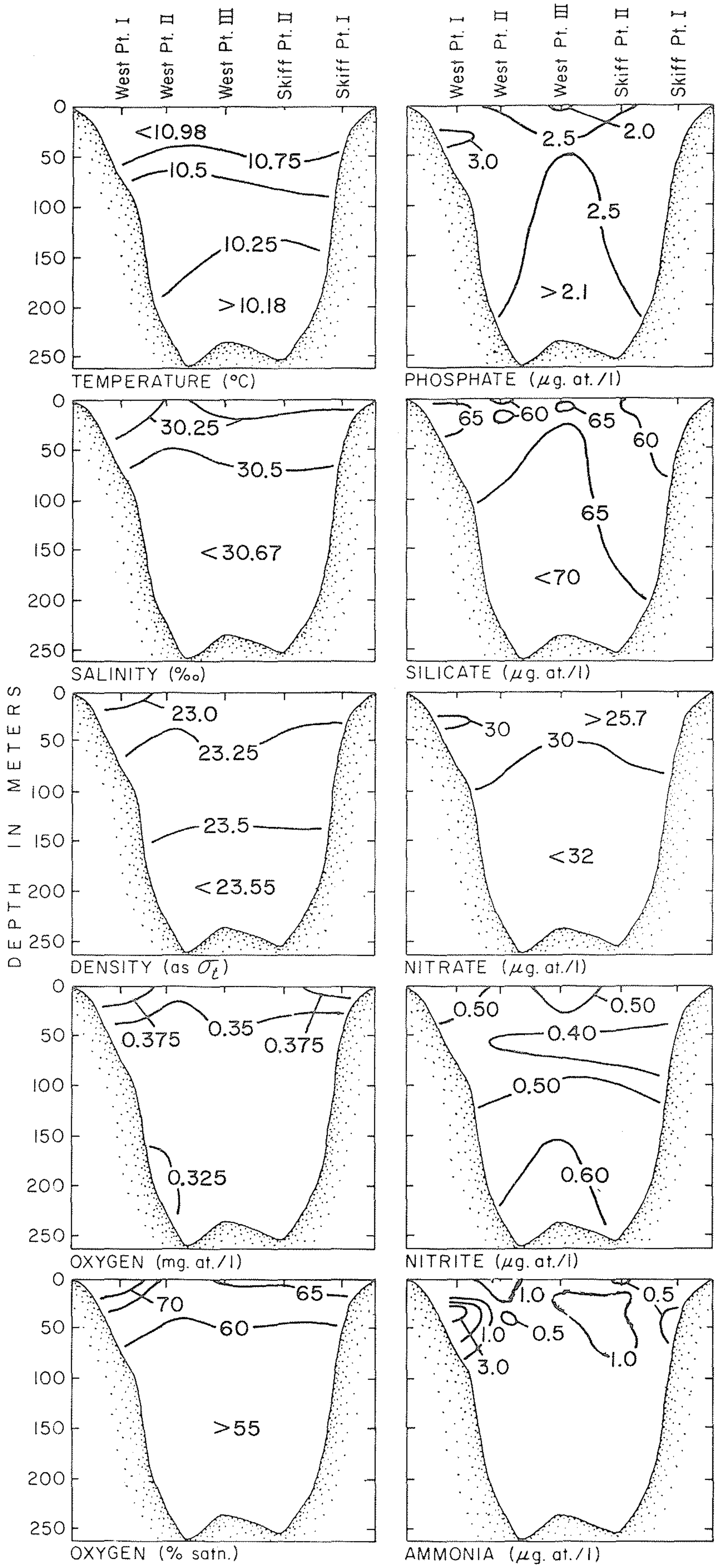


Figure 3-42
Vertical distribution of properties from West Point to Skiff Point for cruise MET-01, 7 November 1974.

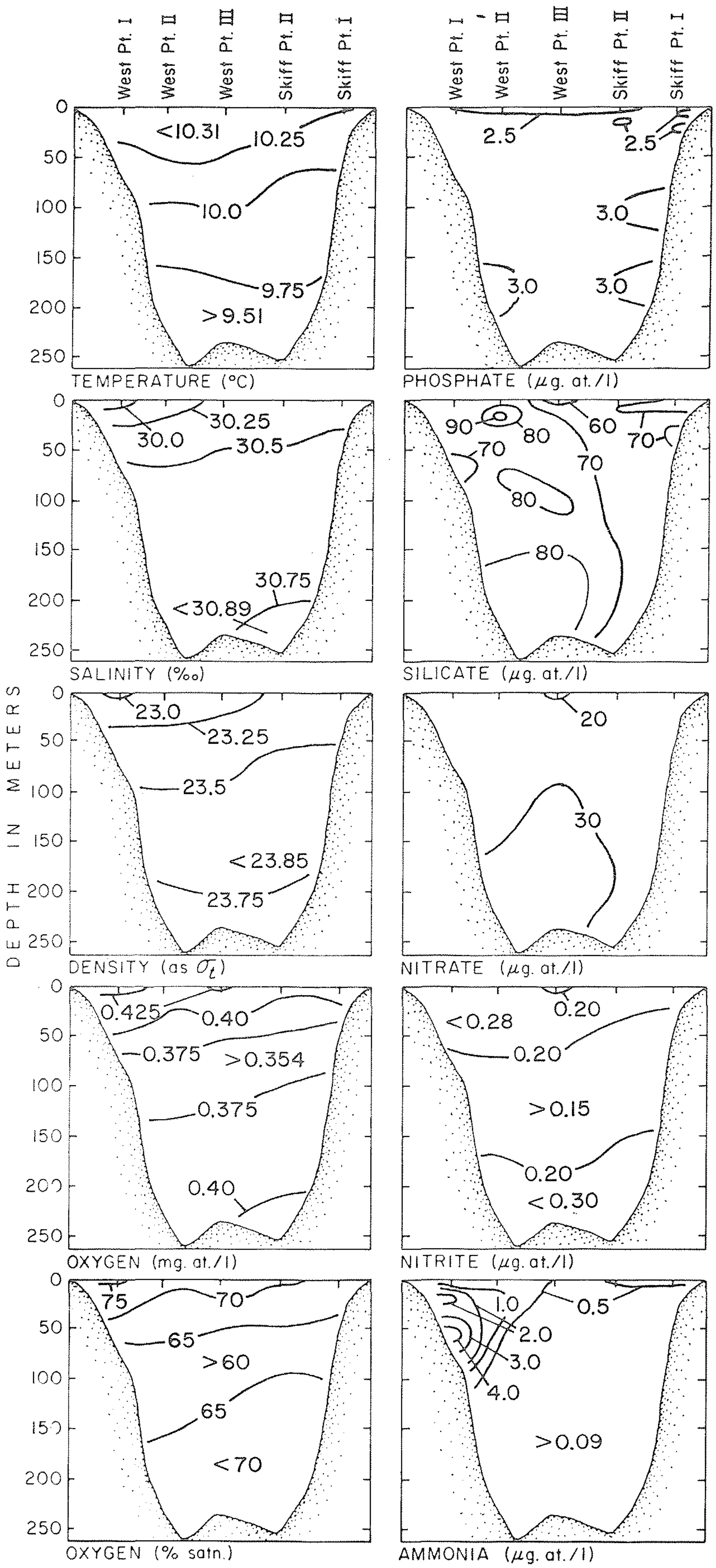


Figure 3-43
Vertical distribution of properties from West Point to Skiff Point for cruise MET-02, 25 November 1974.

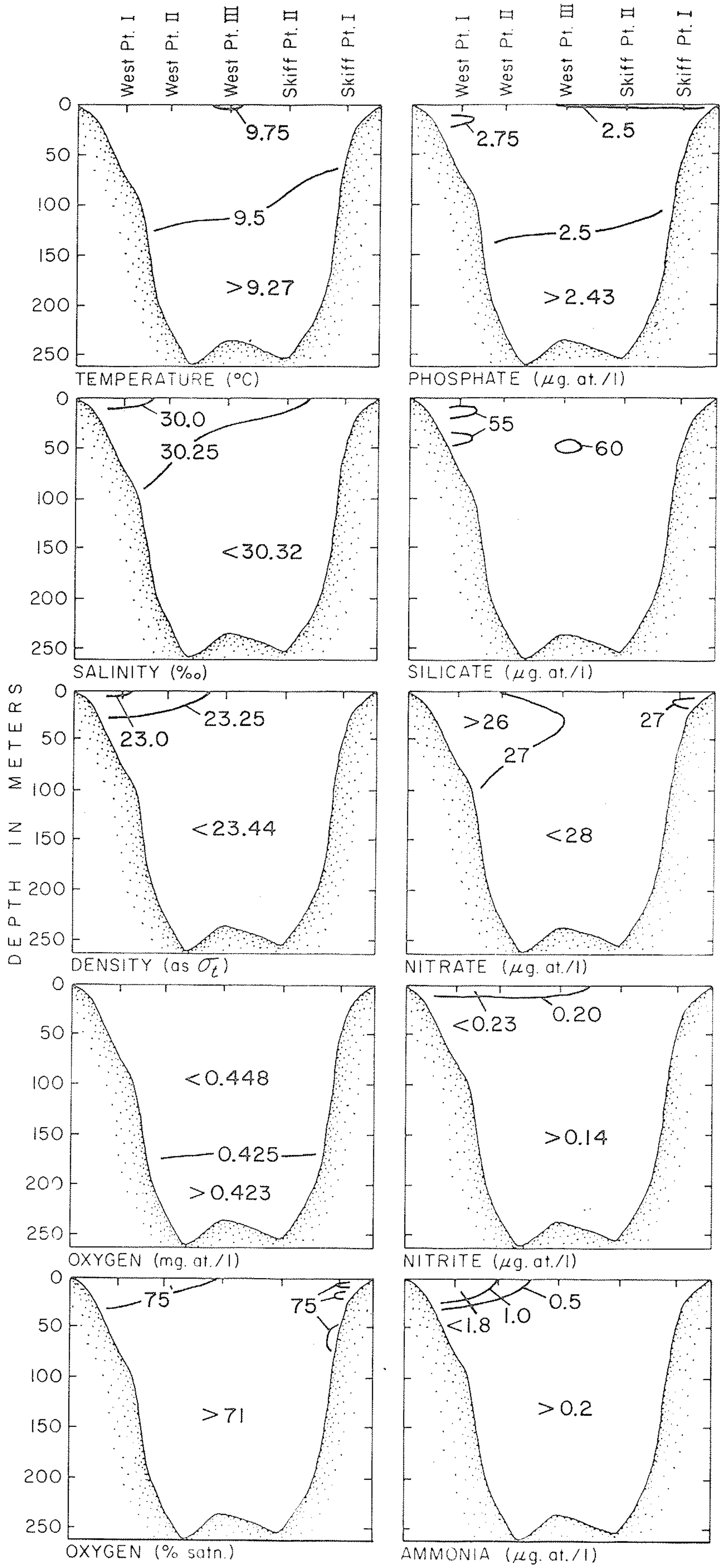


Figure 3-44
Vertical distribution of properties from West Point to Skiff Point for cruise MET-03, 18 December 1974.

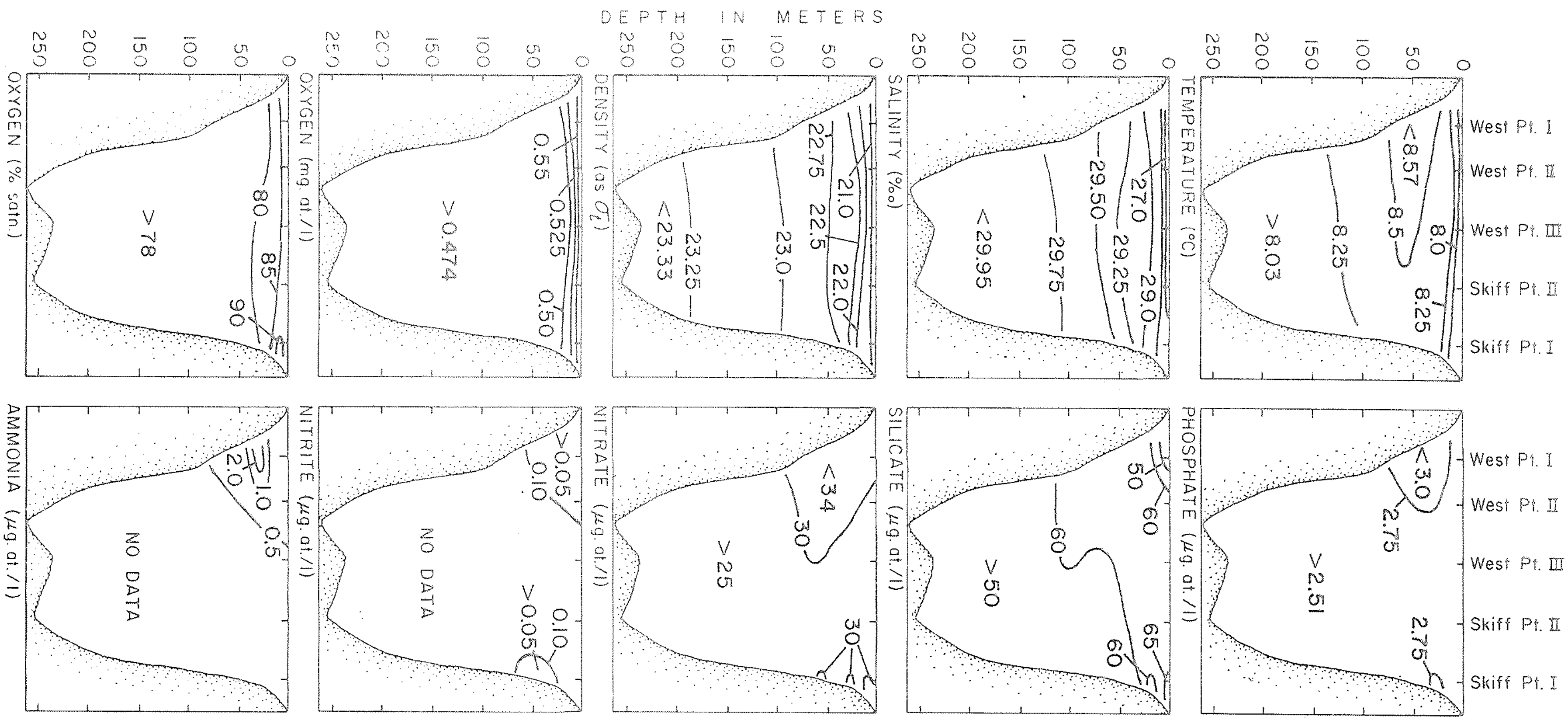


Figure 3-45

Vertical distribution of properties from West Point to Skiff Point for cruise MET-05, 29 January 1975.

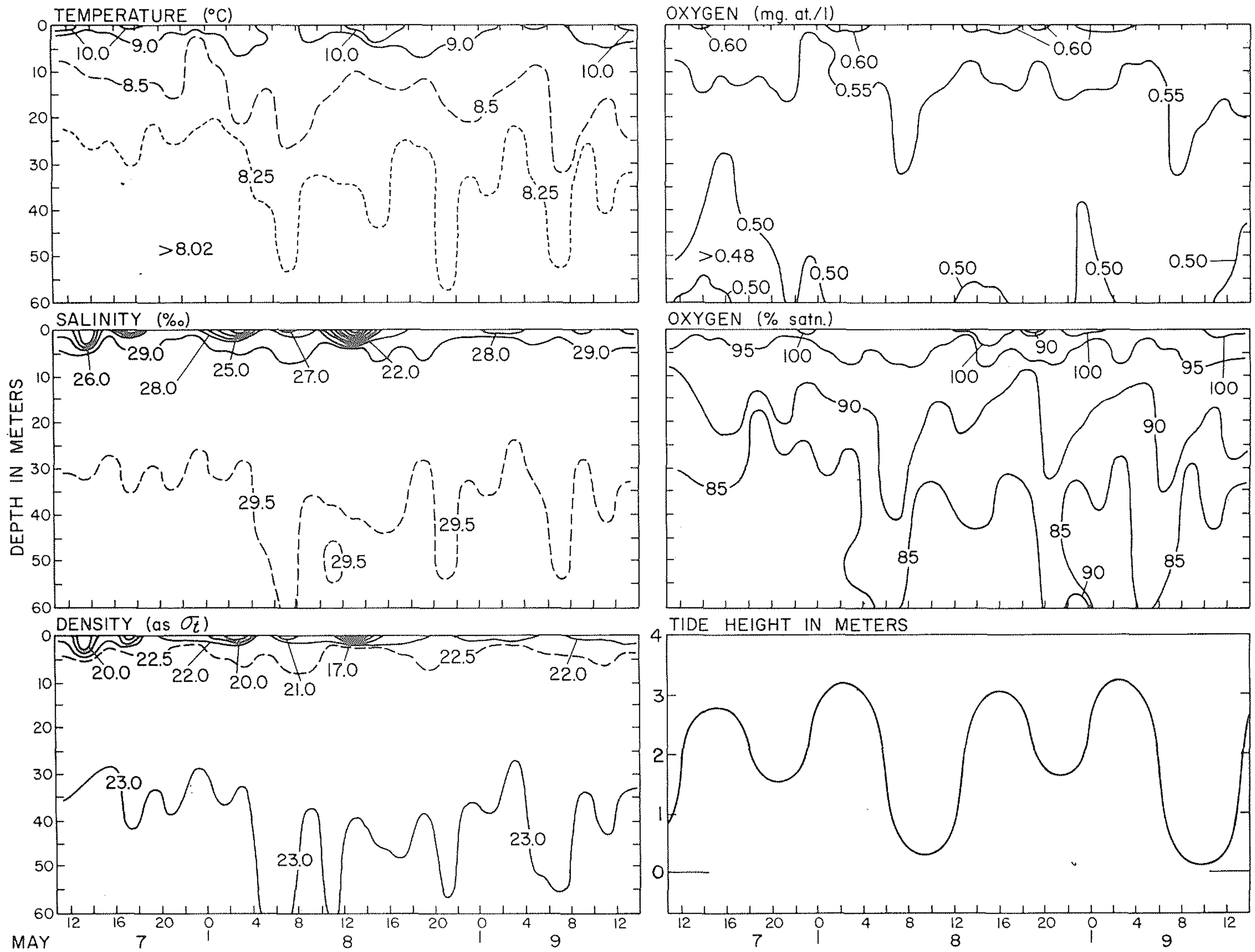


Figure 3-46

Time series of water characteristics of a station over the diffuser of the West Point outfall.
May 7-9, 1975

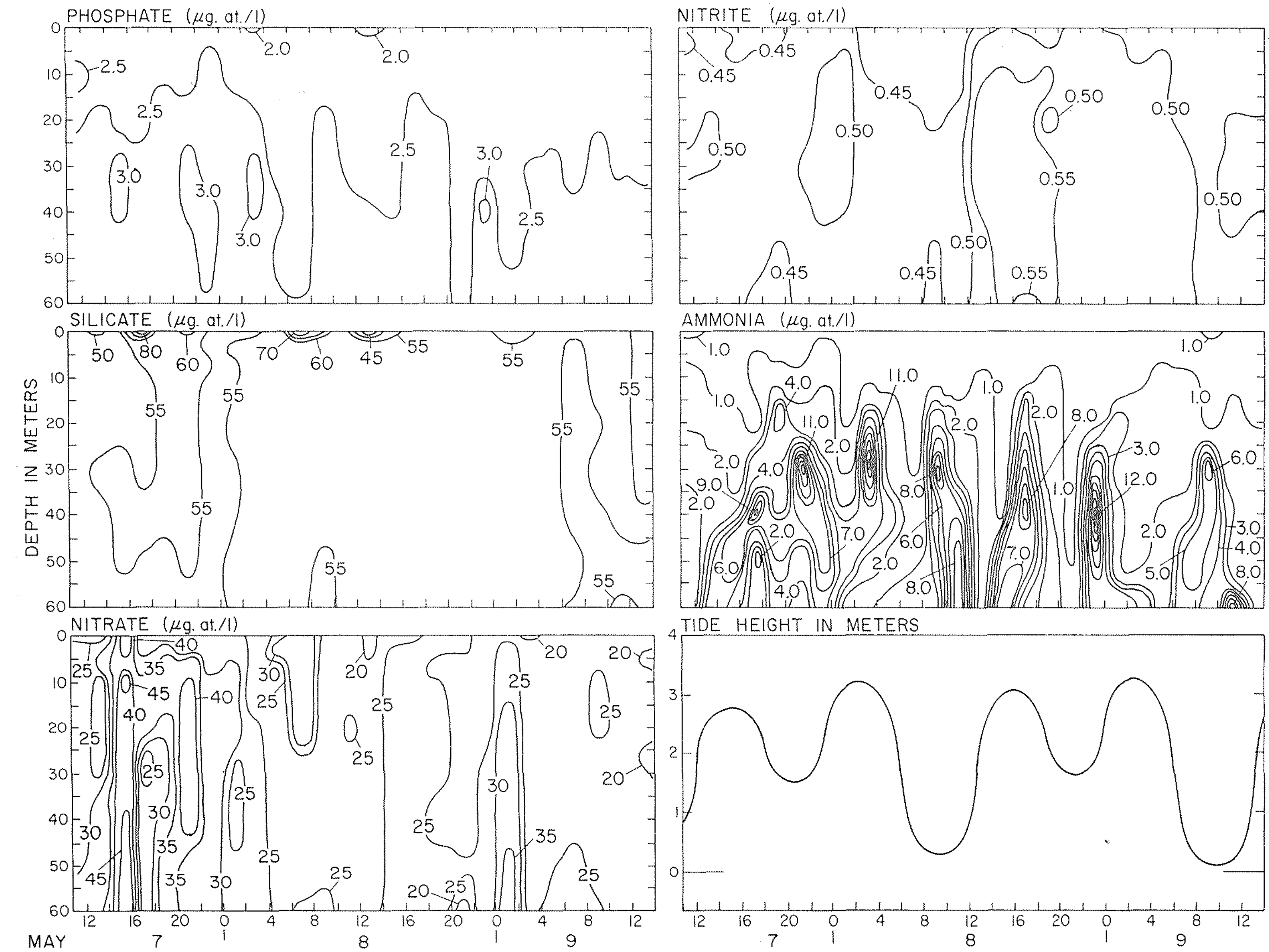


Figure 3-46 (Continued)

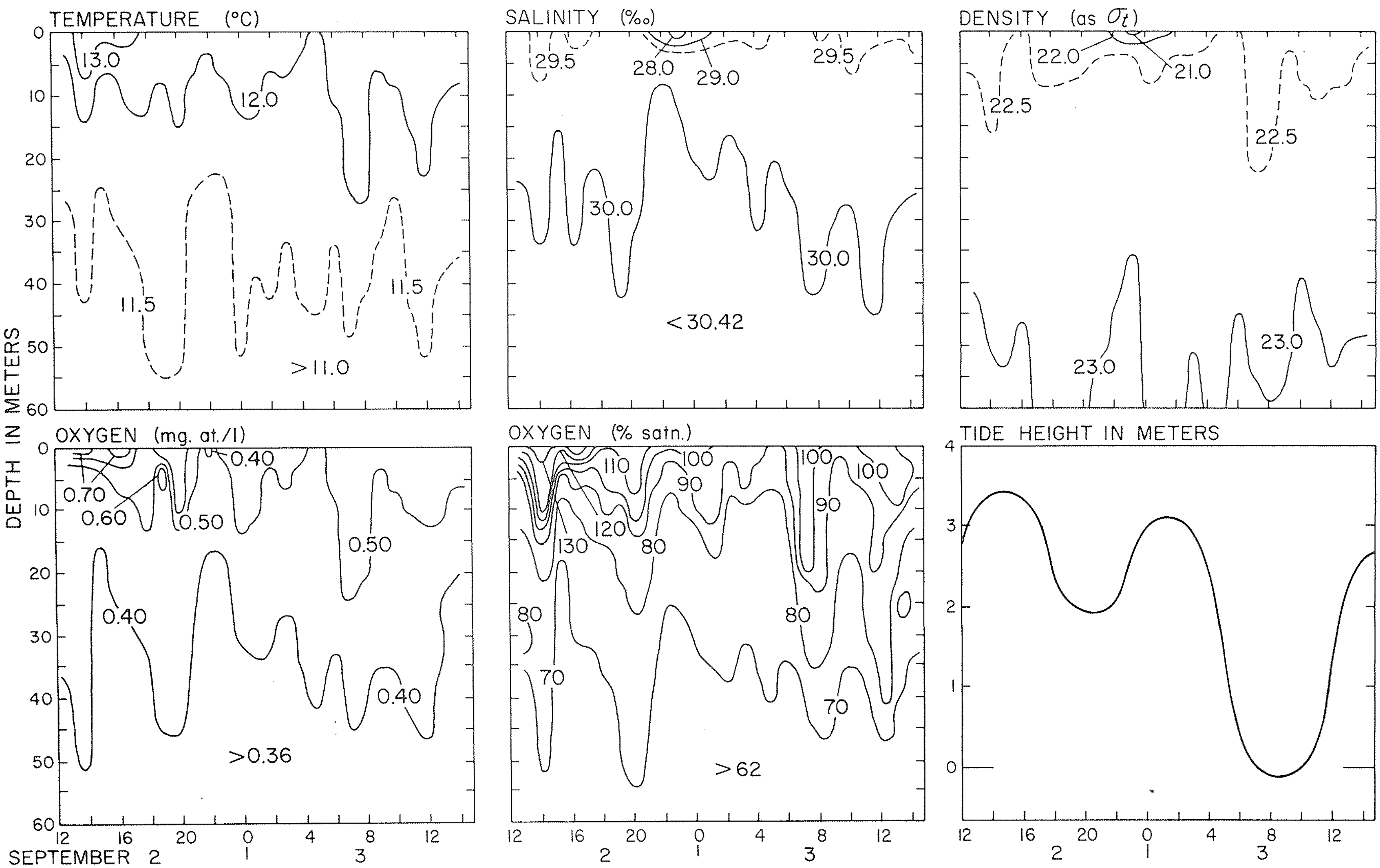


Figure 3-47

Time series of water characteristics of a station over the diffuser of the West Point outfall.
September 2-3, 1975

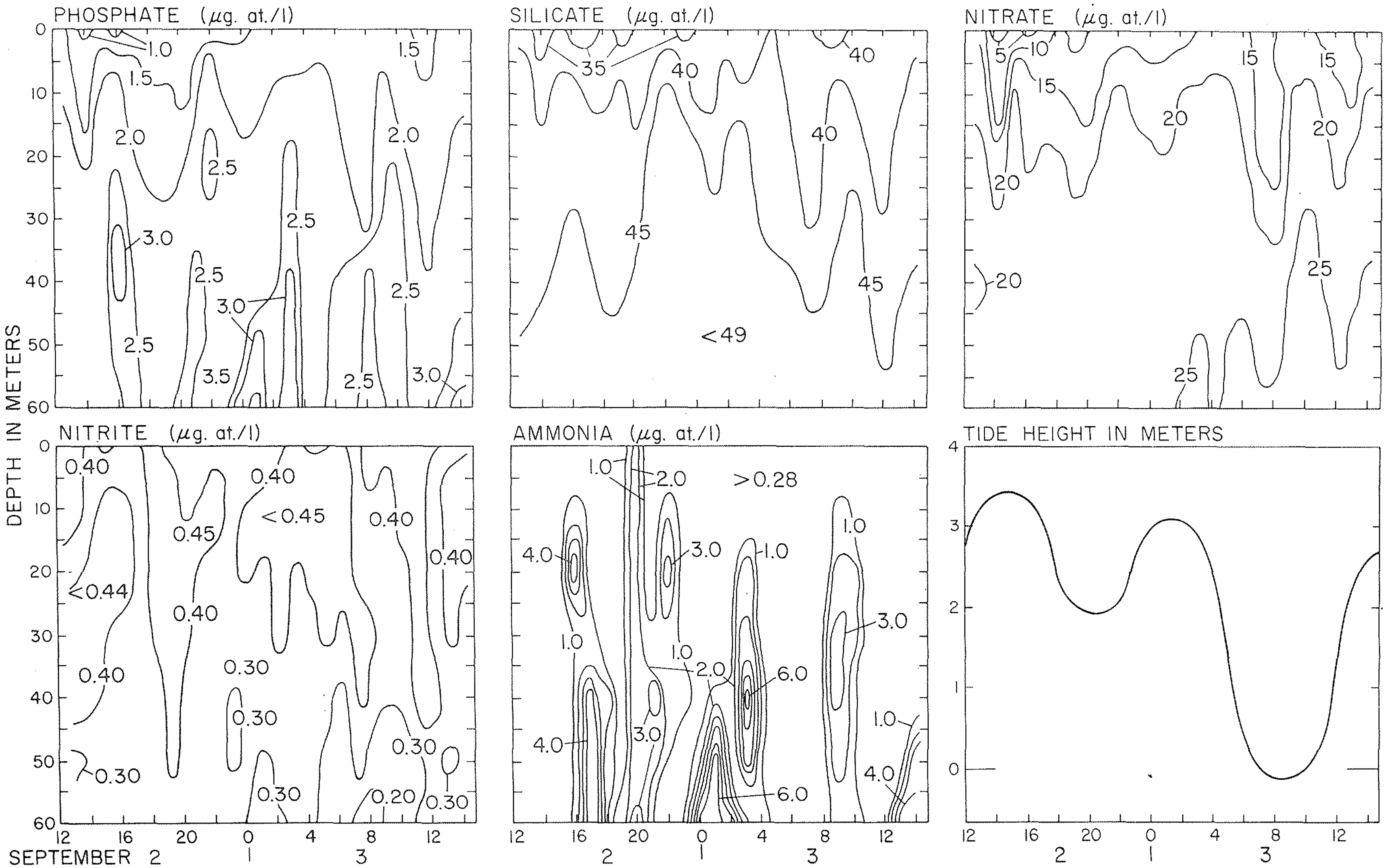


Figure 3-47 (Continued)

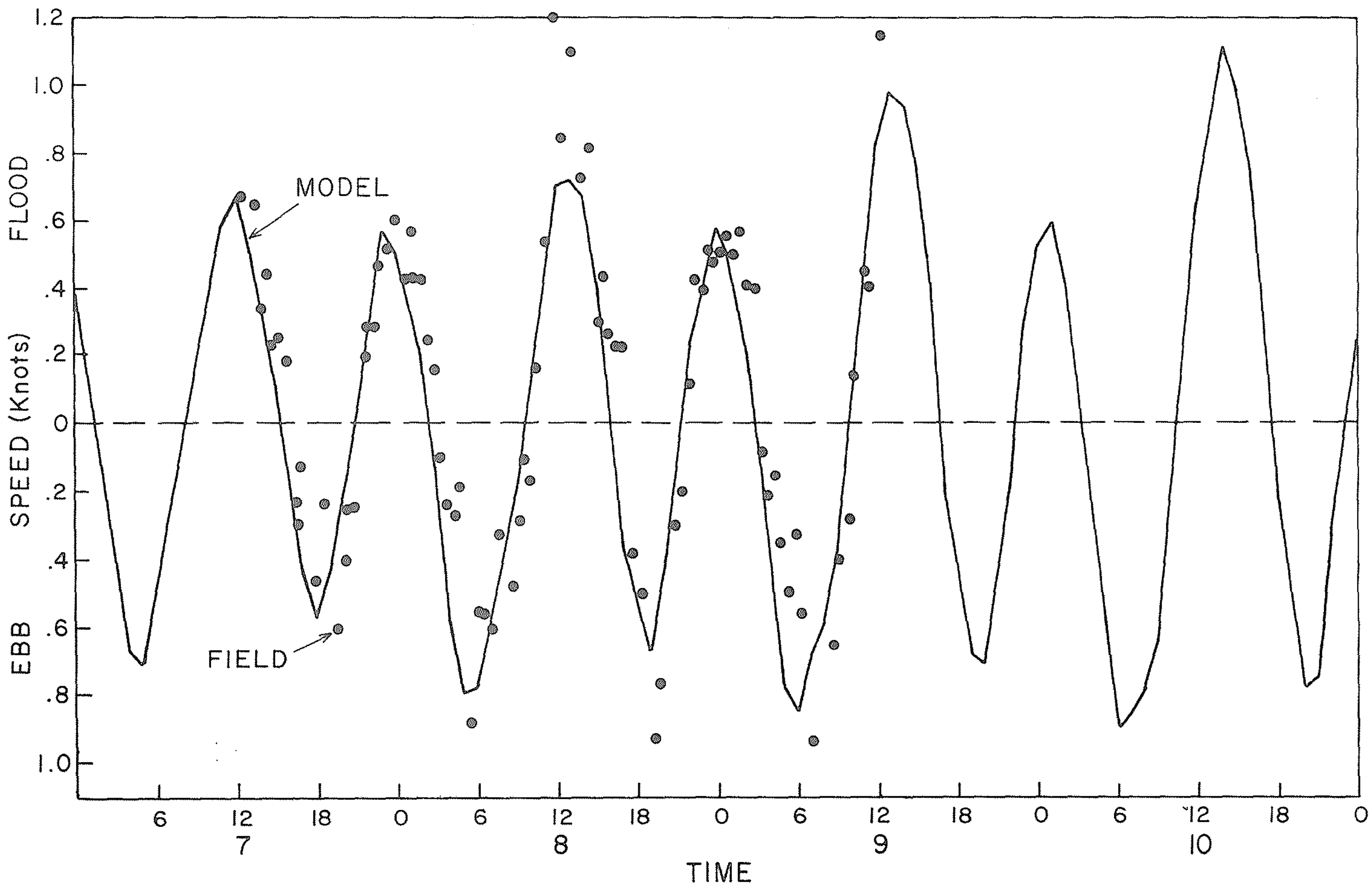


Figure 3-48

Tidal currents at the West Point outfall site from model and field measurements.
May 7-10, 1975

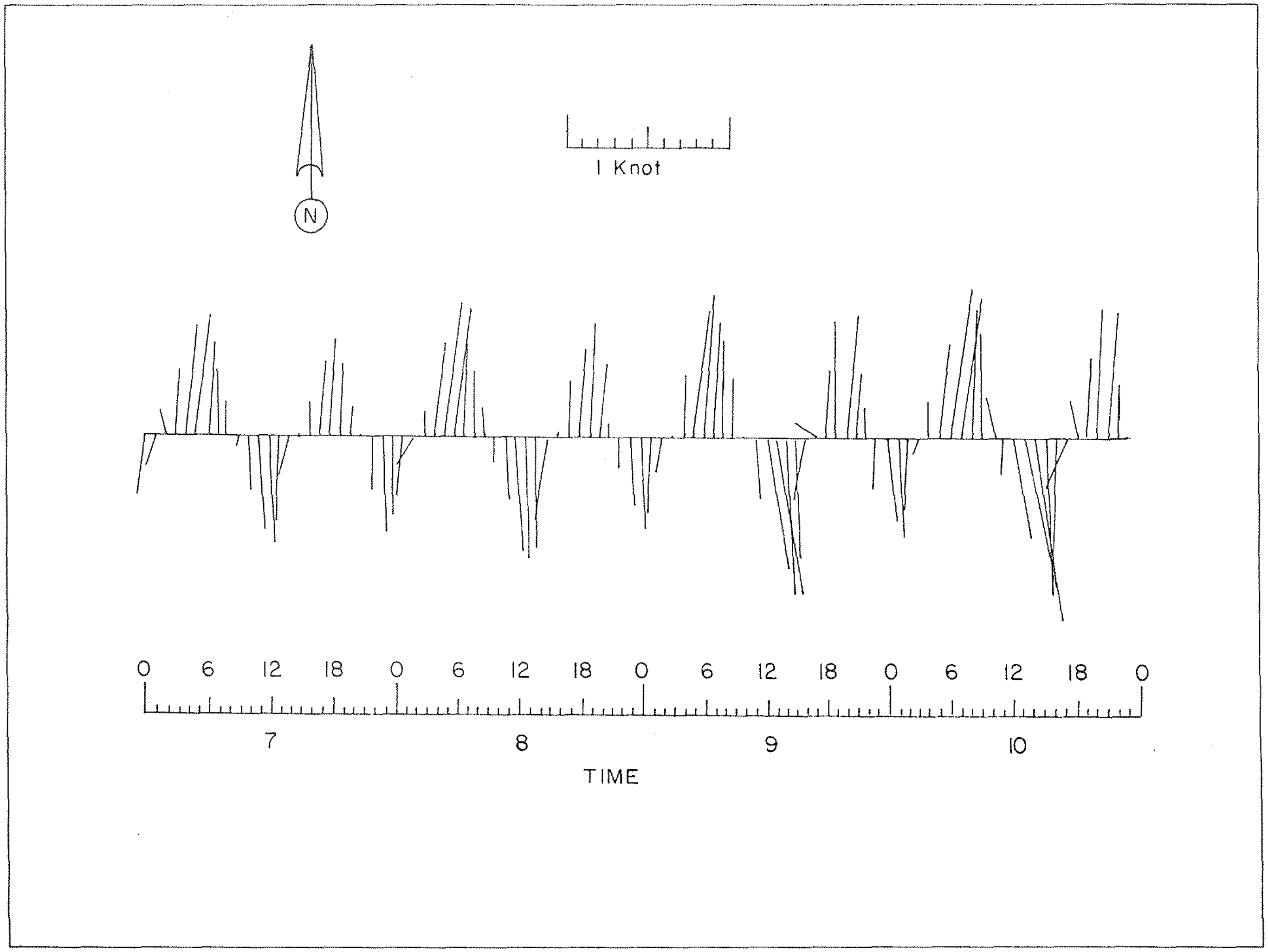


Figure 3-49

Tidal current vectors at the West Point outfall site from model measurements. May 7-9, 1975

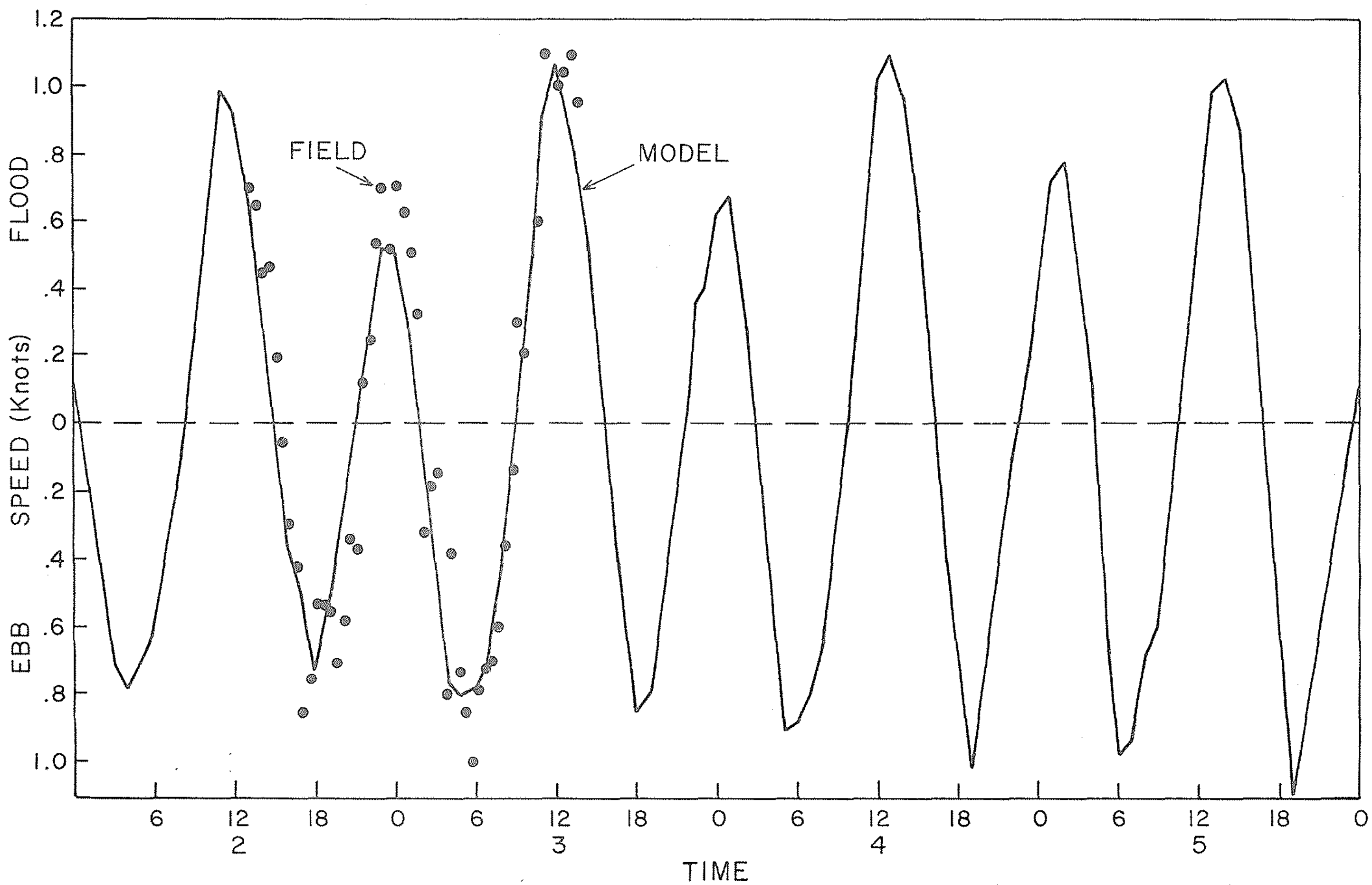


Figure 3-50

Tidal currents at the West Point outfall site from model and field measurements.
September 2-5, 1975

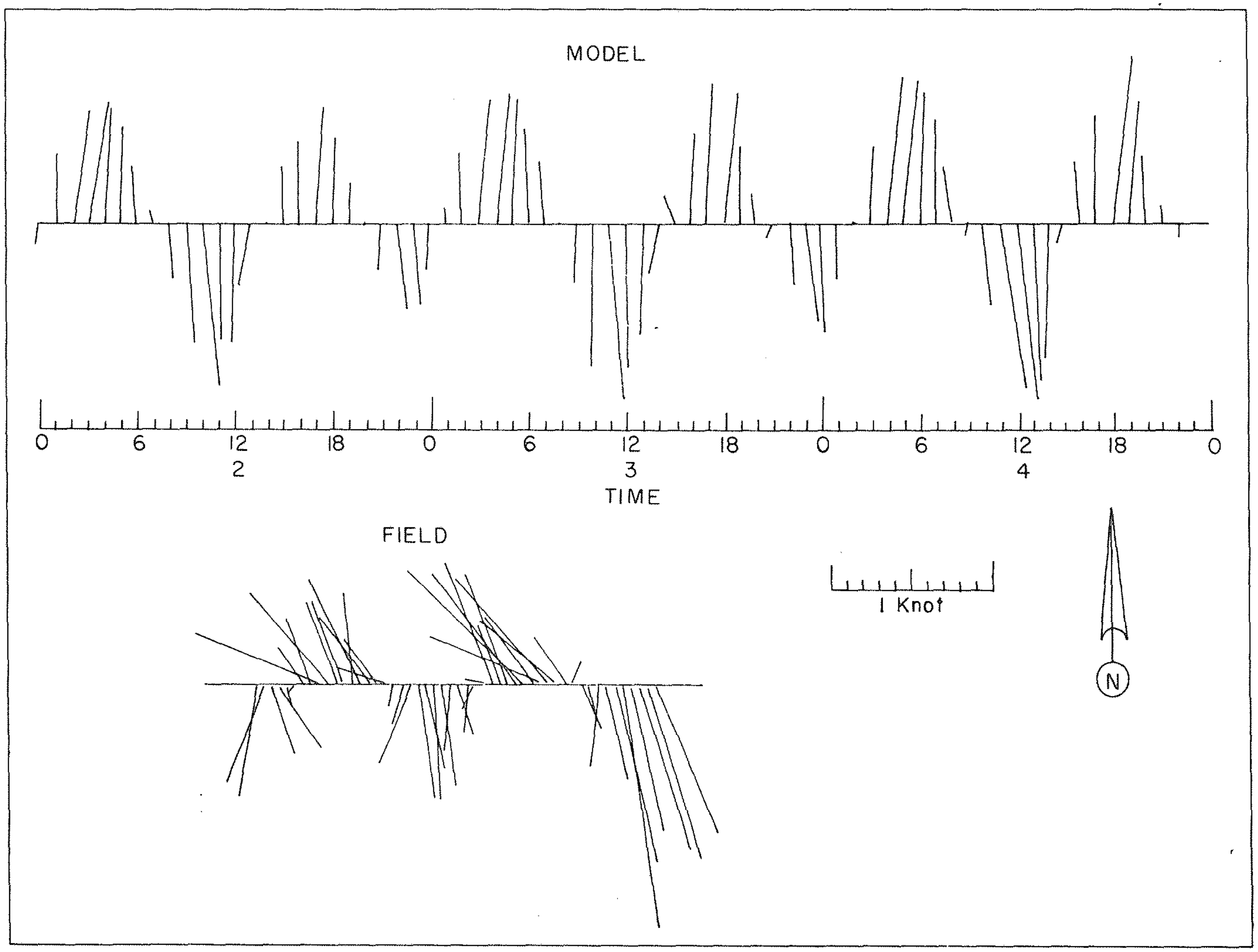


Figure 3-51

Tidal current vectors at the West Point outfall site from model and field measurements. September 2-4, 1975

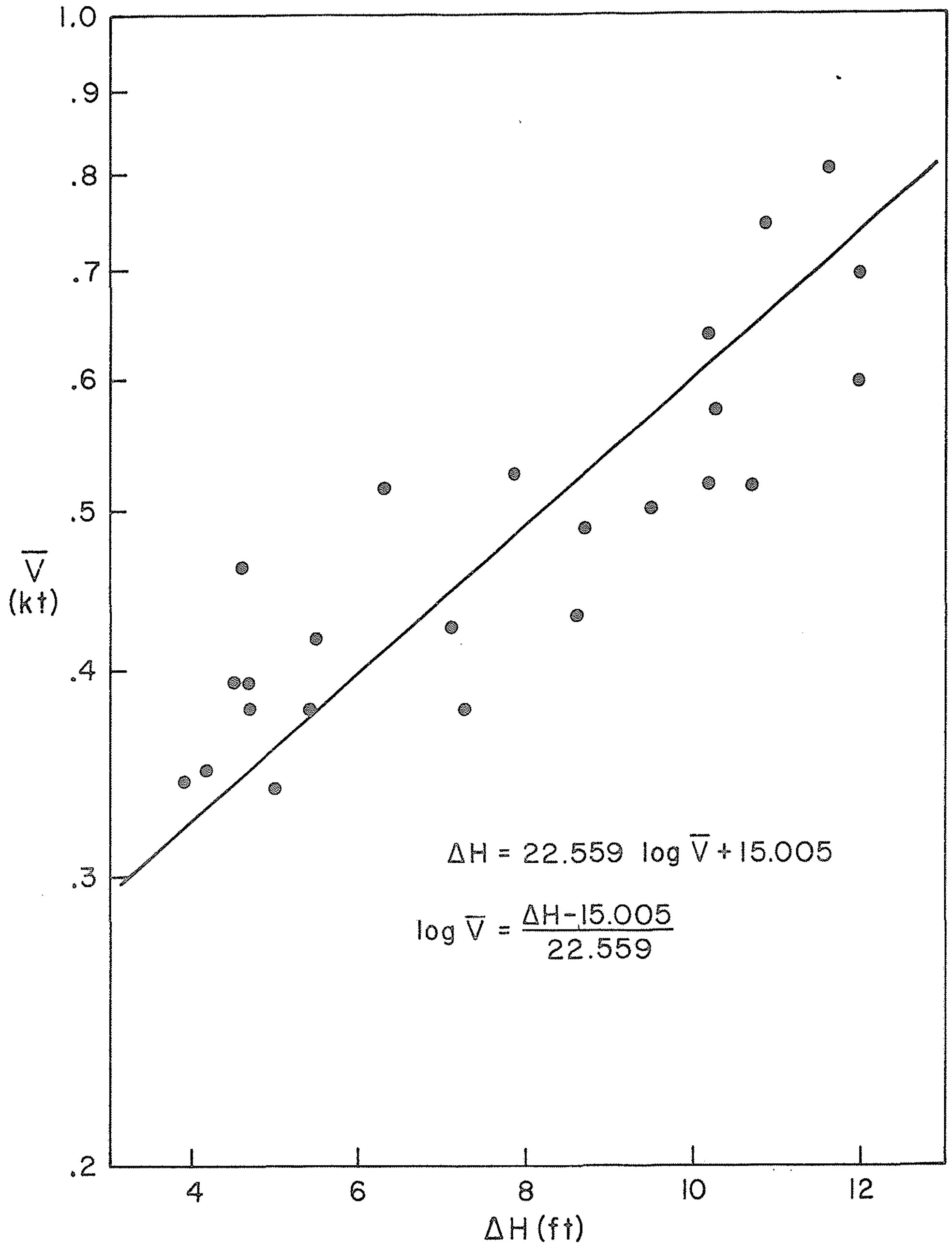


Figure 3-52

Mean current speed in knots vs. tide range in feet at West Point outfall site.

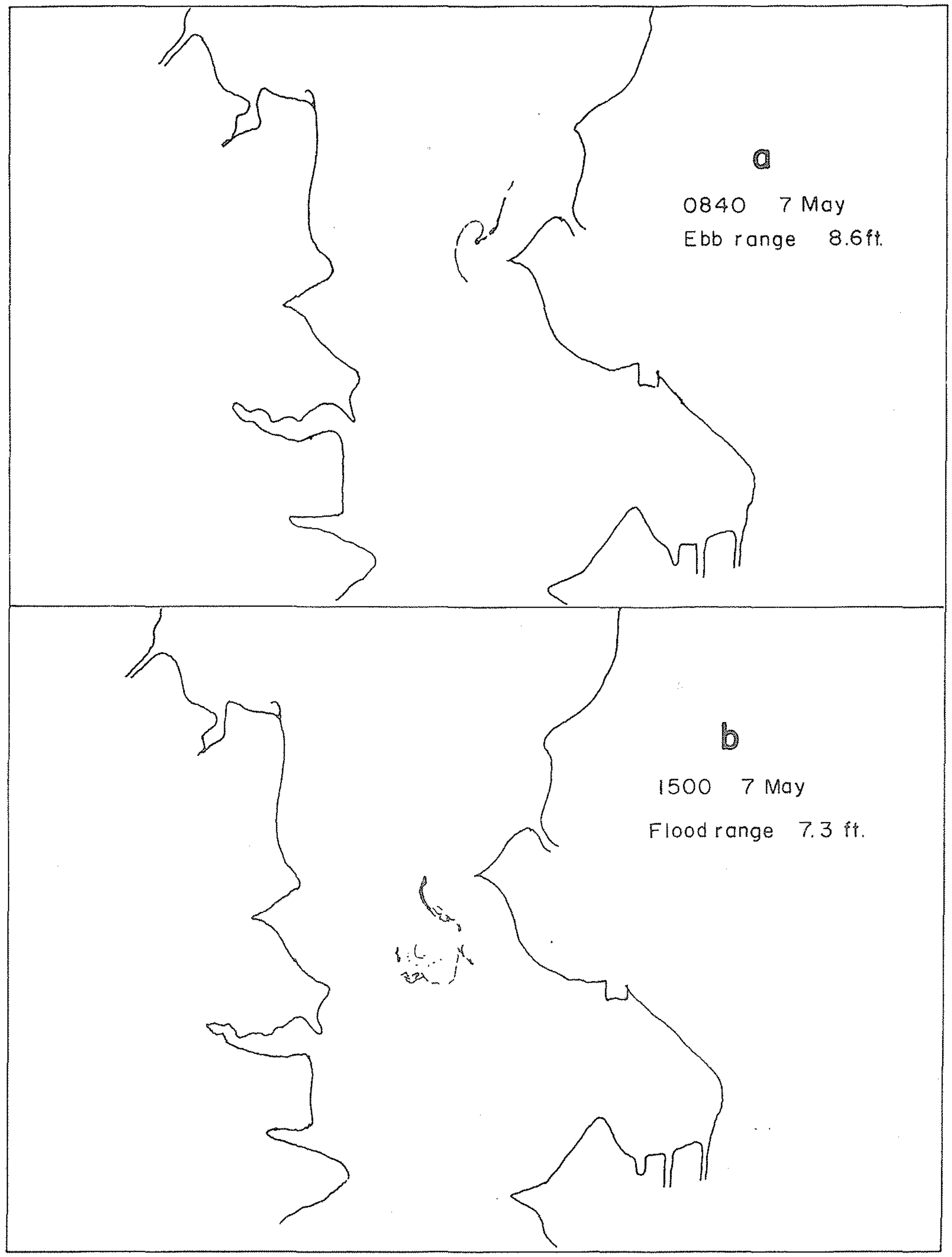


Figure 3-53

Dispersal behavior of effluent plume from West Point outfall. May 7-10, 1975

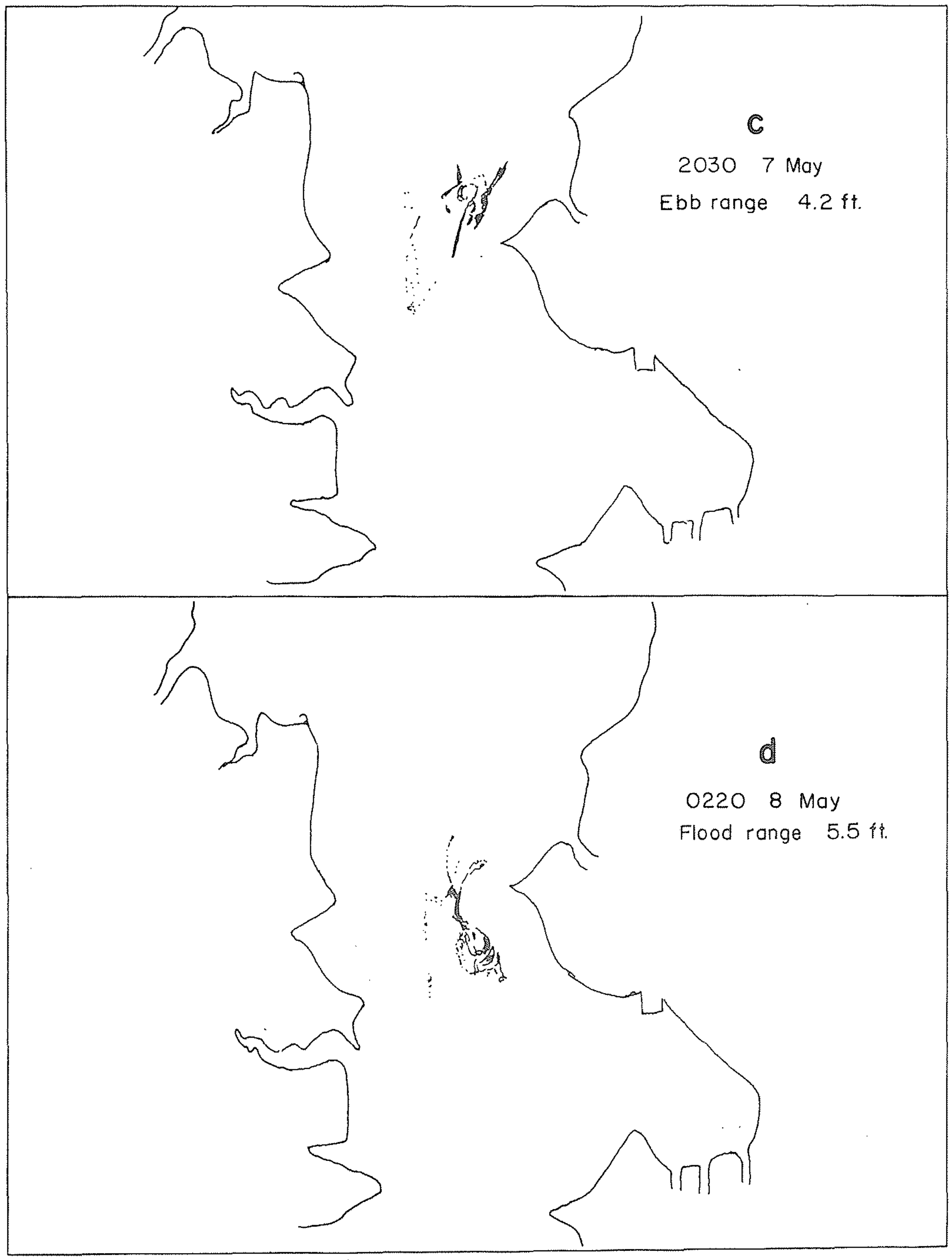


Figure 3-53 (Continued)

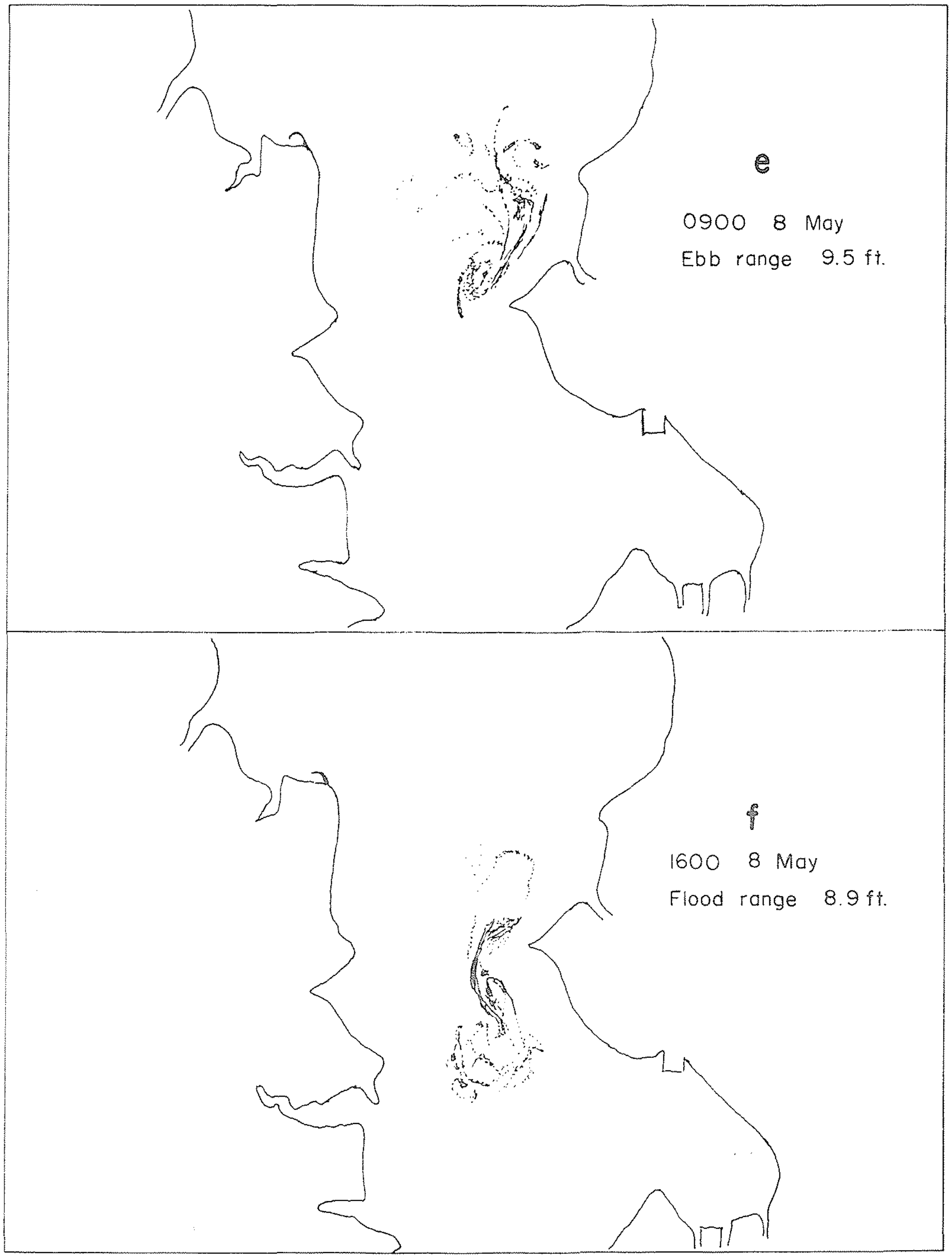


Figure 3-53 (Continued)

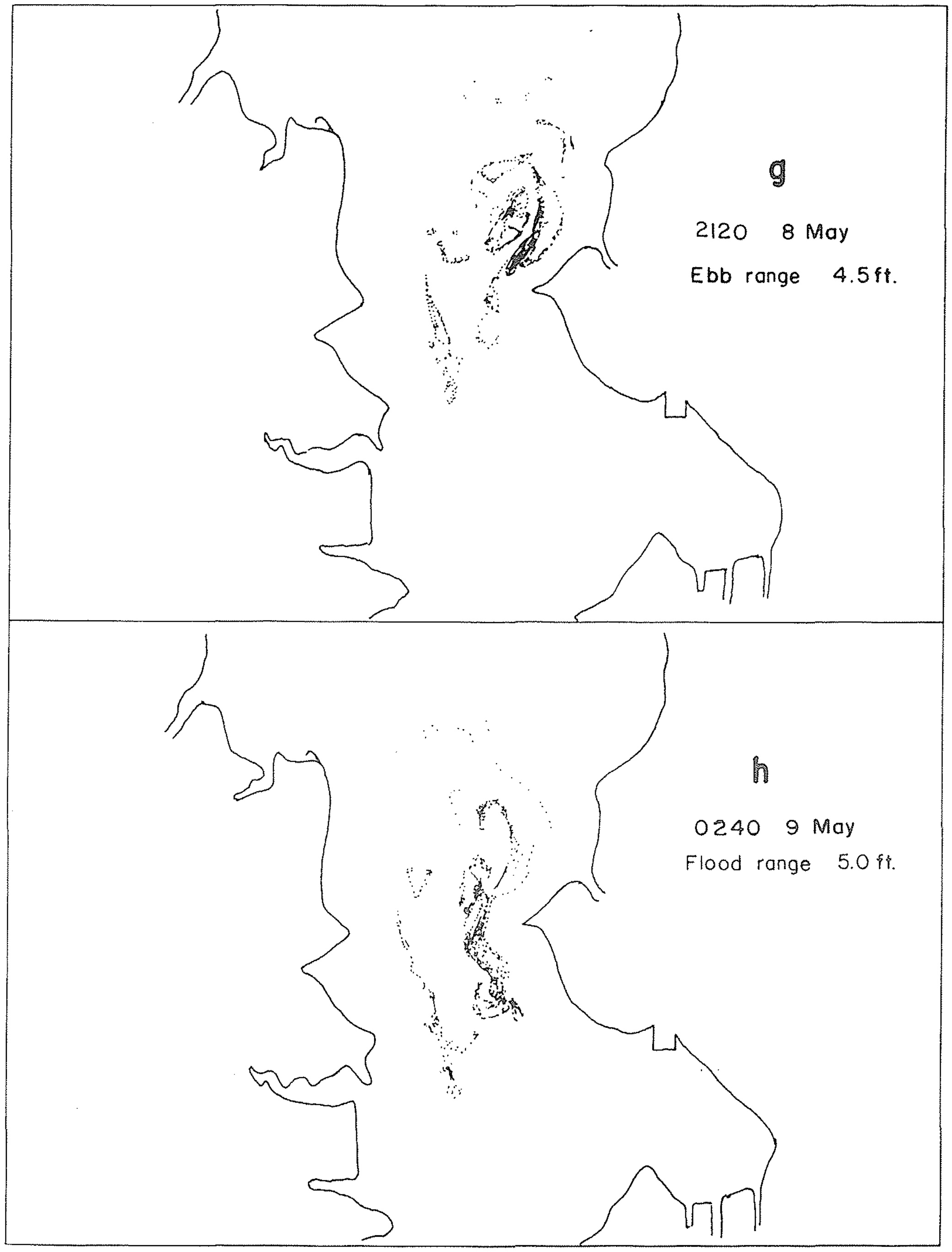


Figure 3-53 (Continued)

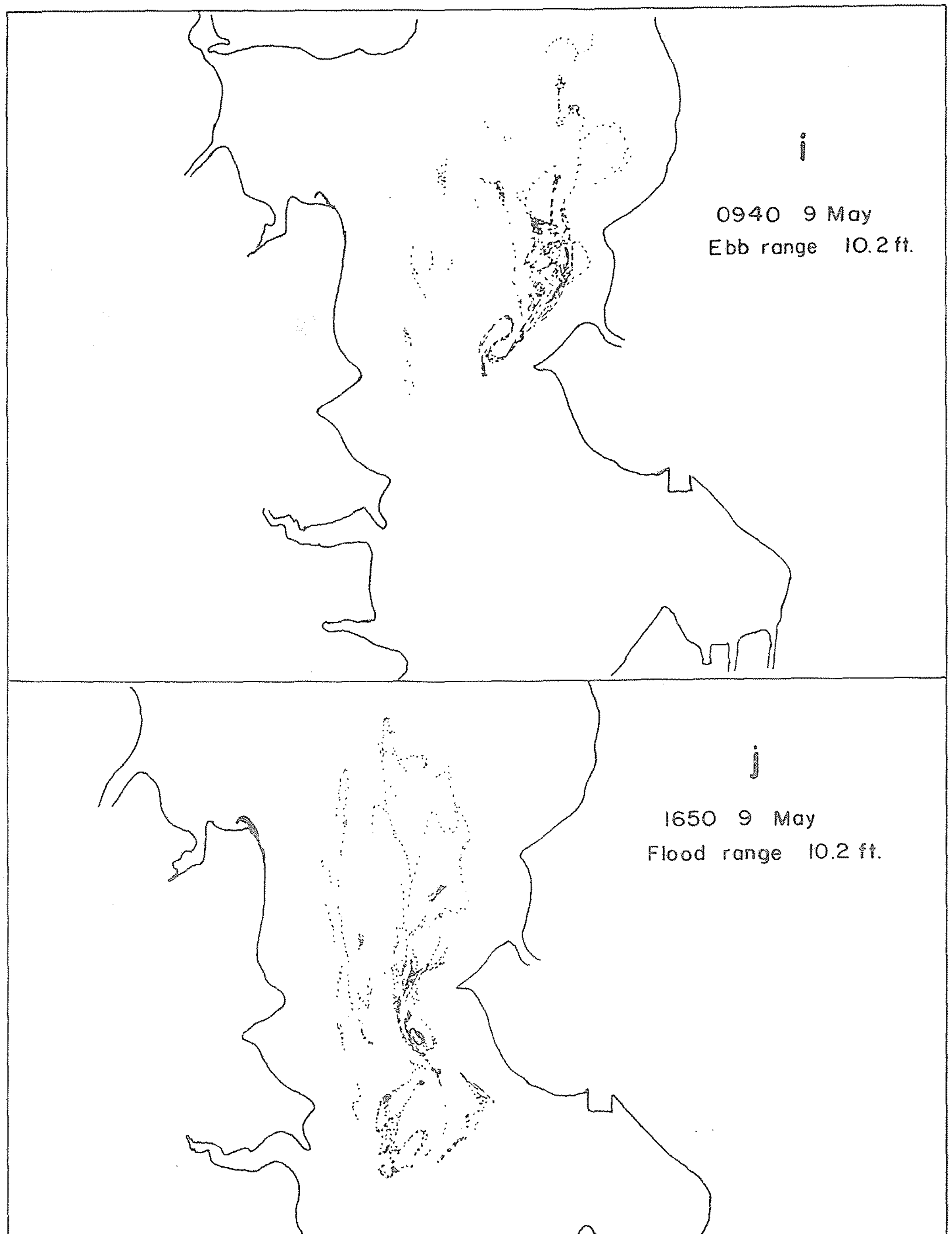


Figure 3-53 (Continued)

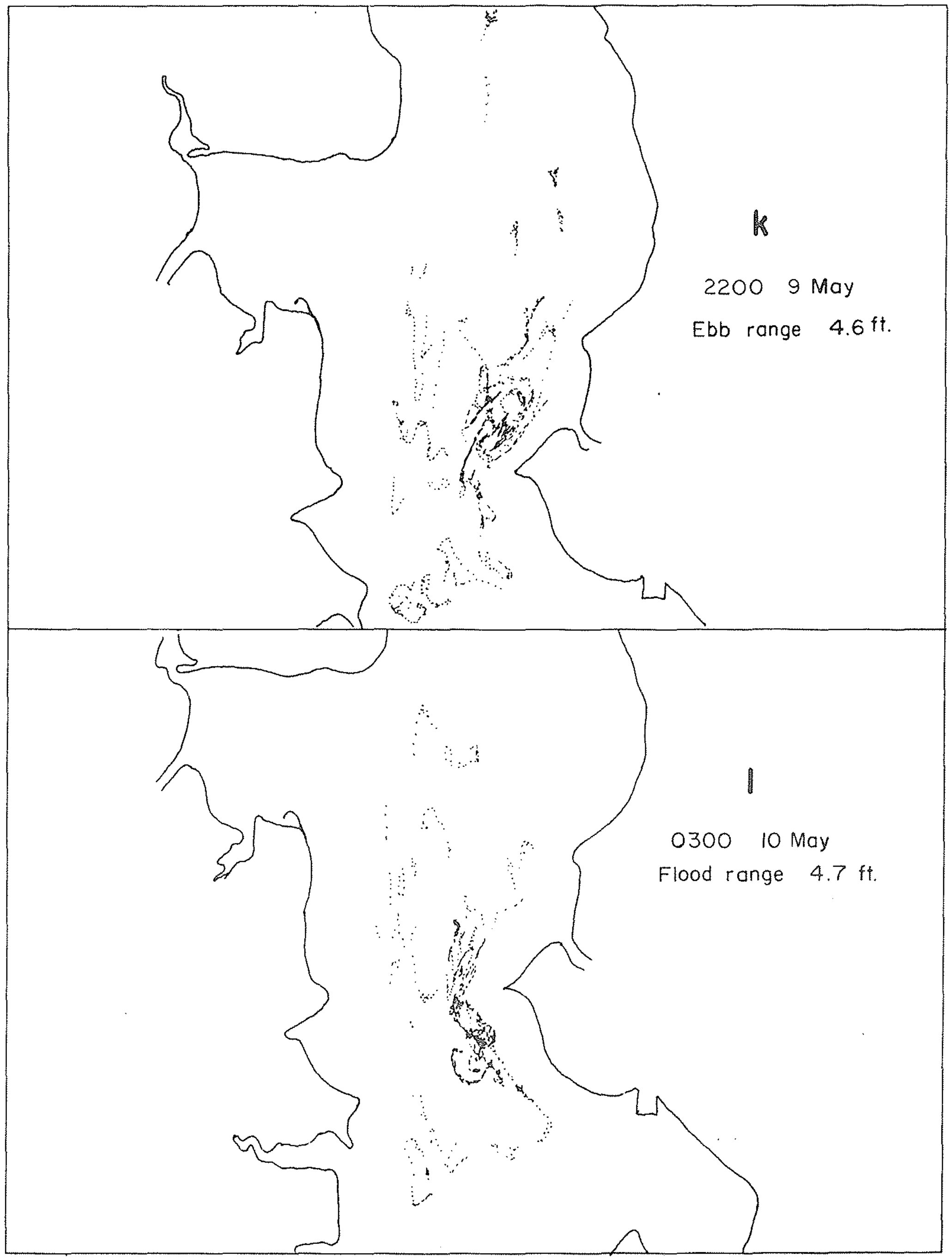


Figure 3-53 (Continued)

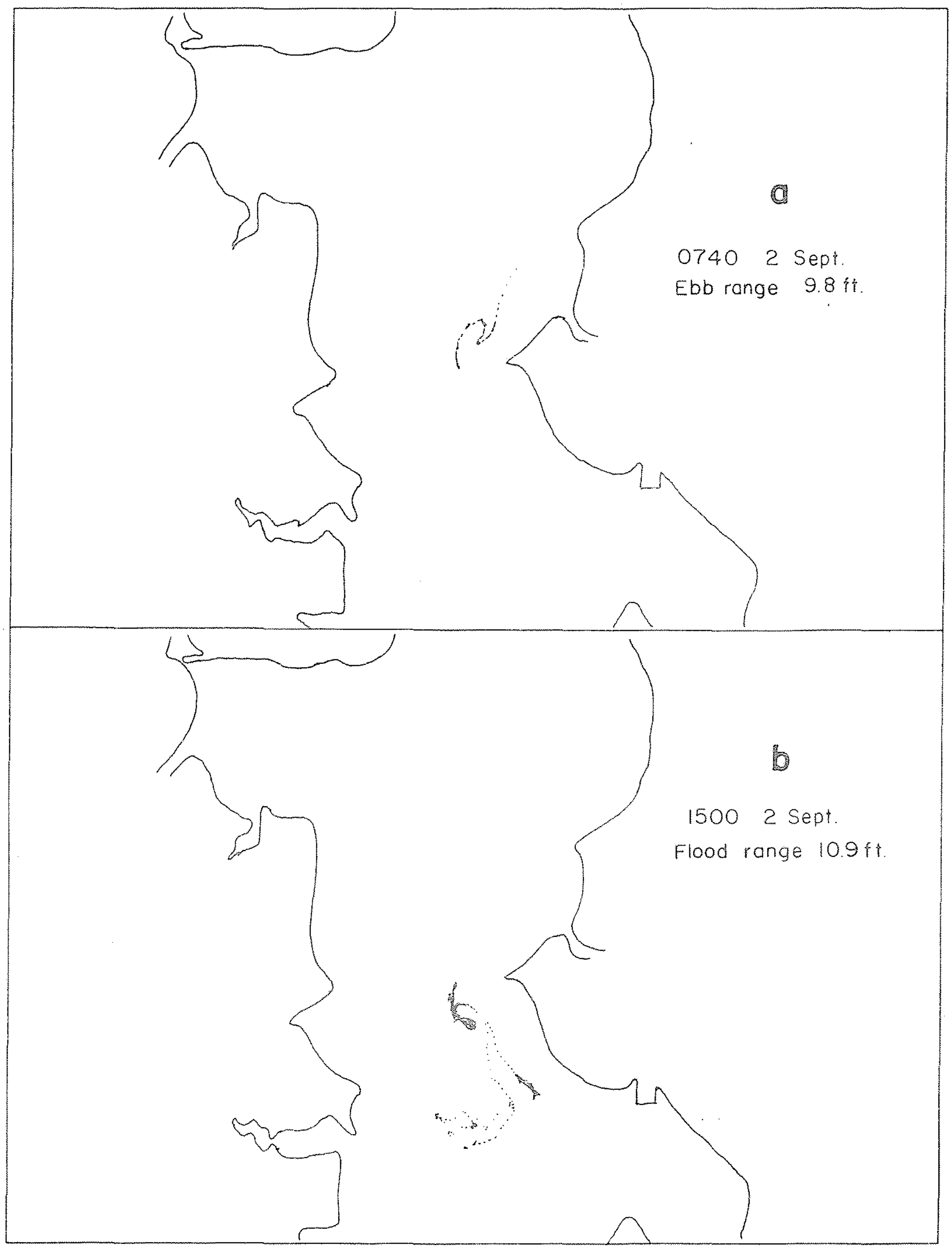


Figure 3-54

Dispersal behavior of effluent plume from West Point outfall. September 2-5, 1975

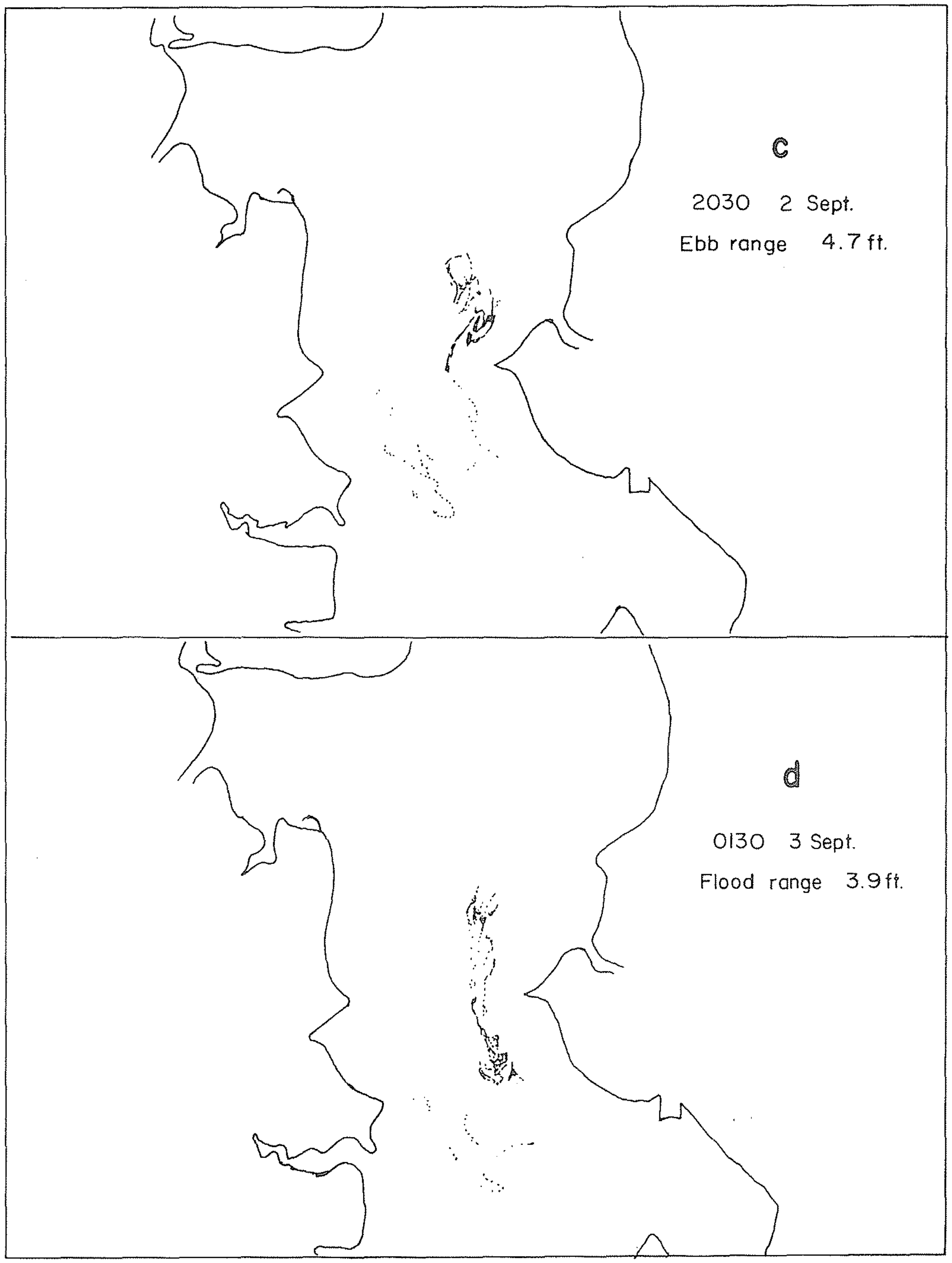


Figure 3-54 (Continued)

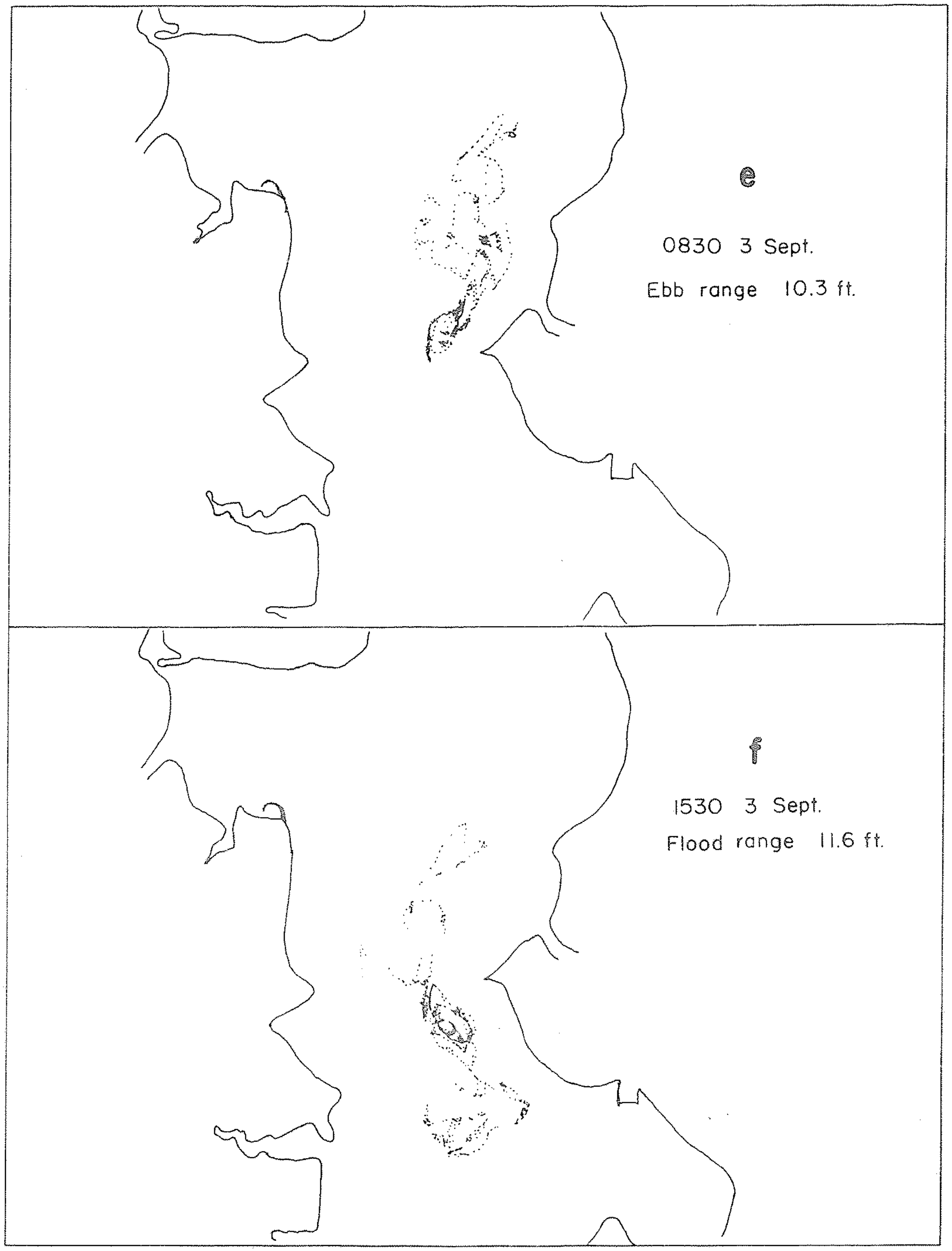


Figure 3-54 (Continued)

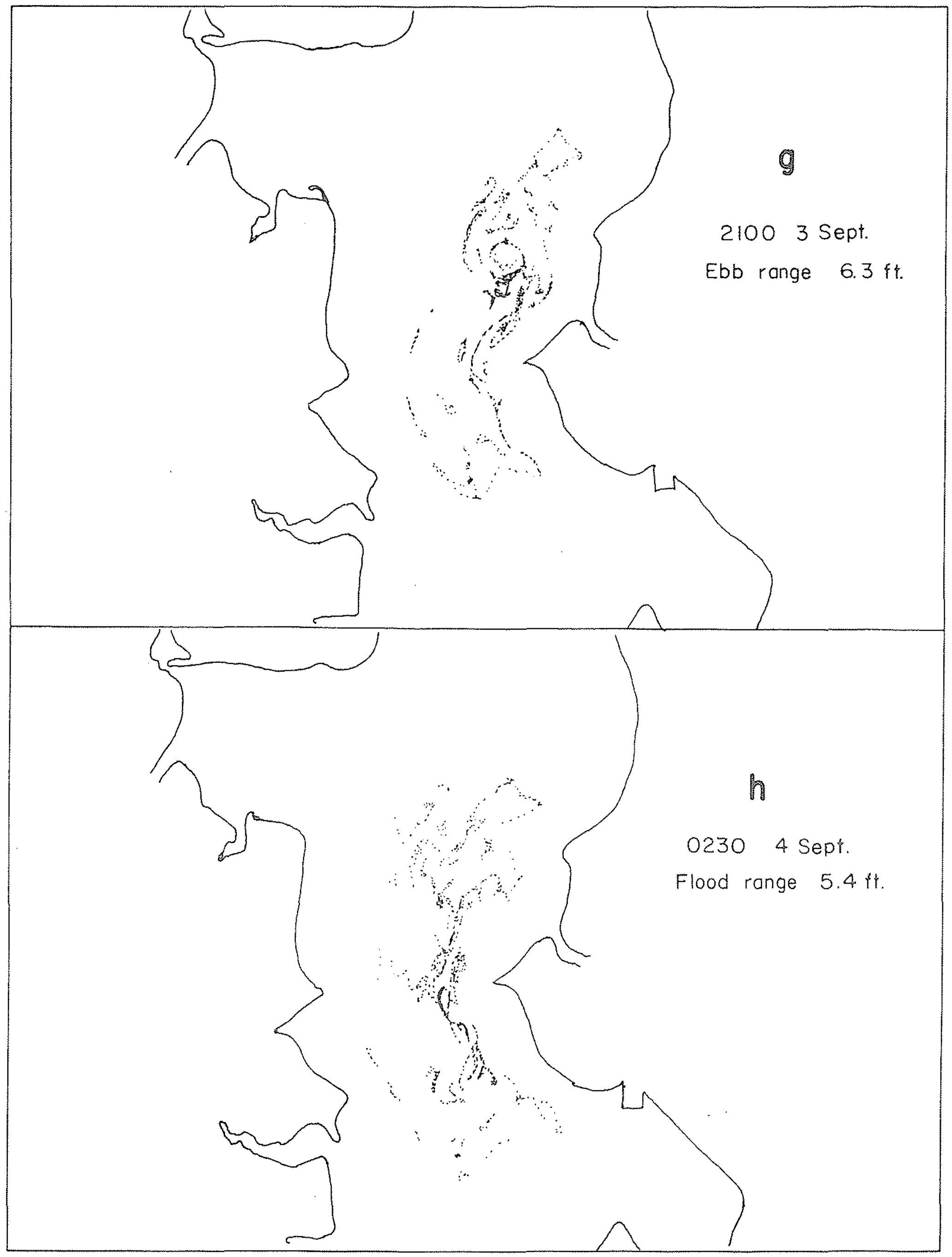


Figure 3-54 (Continued)

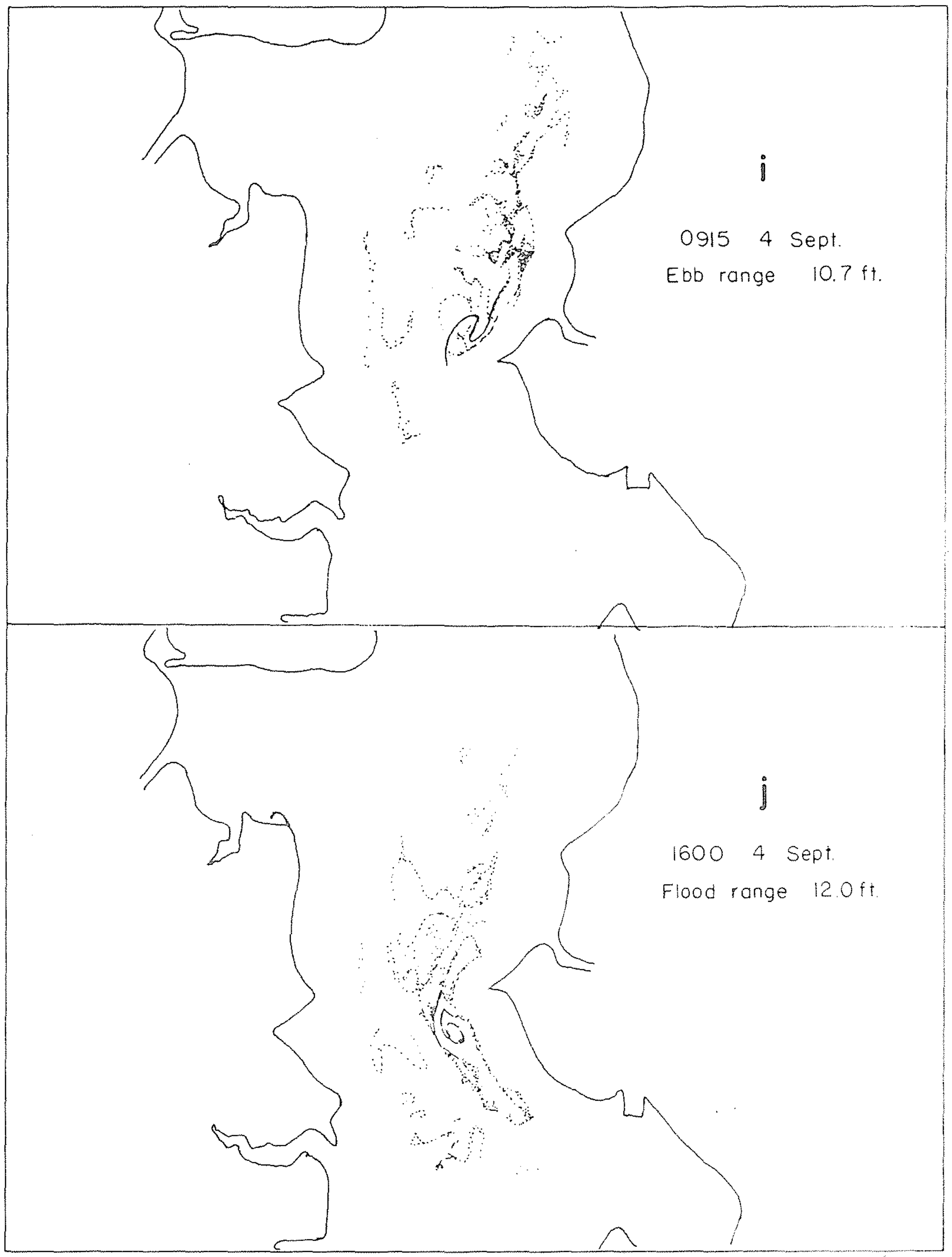


Figure 3-54 (Continued)

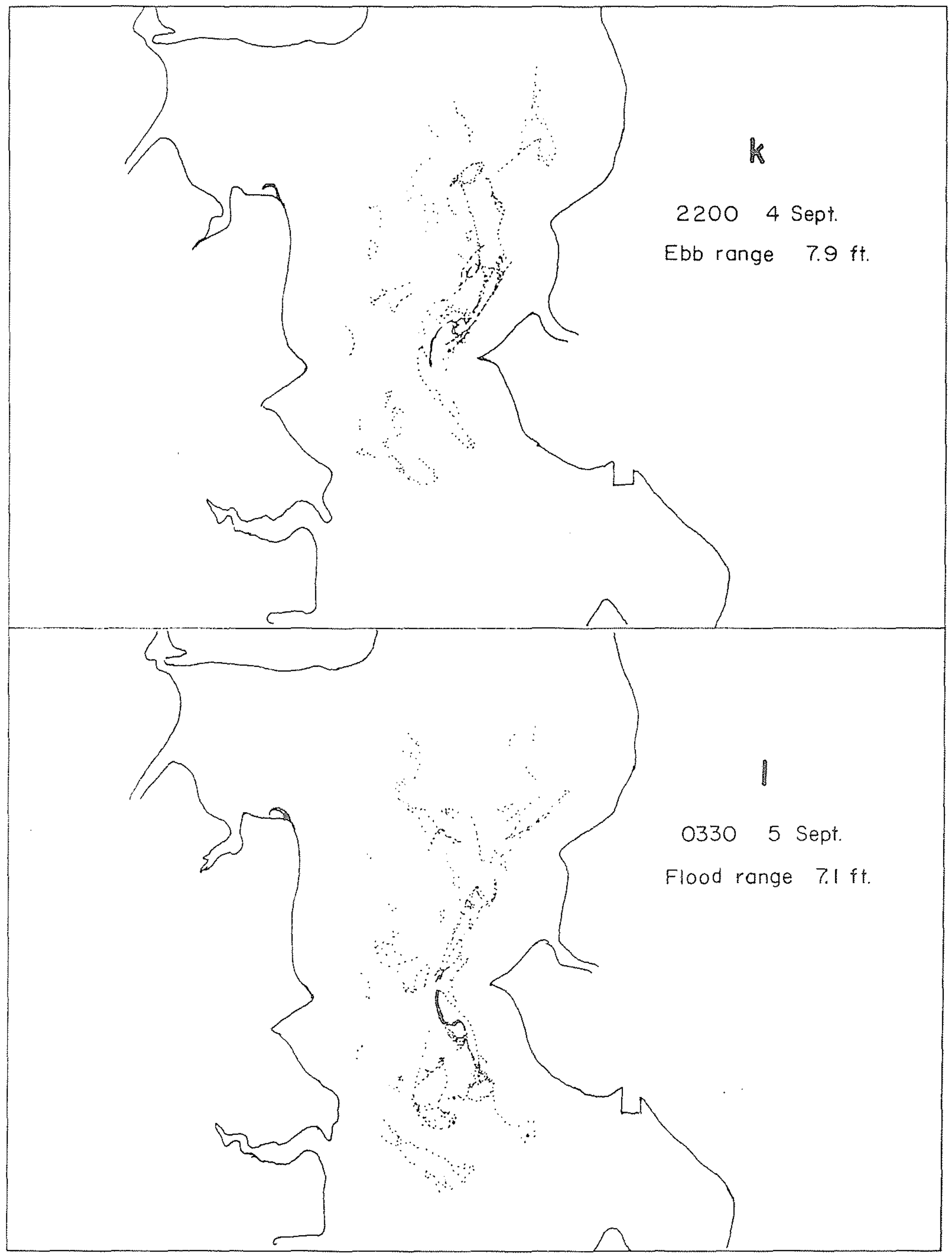


Figure 3-54 (Continued)

4.0 ANALYSIS OF THE DATA

4.1 *General considerations*

The *Strait of Juan de Fuca-Georgia Strait-Puget Sound* system as shown in Figure 1-1 may be characterized as a series of deep basins interconnected by narrow shallow channels and/or sills which act as mixing zones. Proceeding from Cape Flattery through the main basin of Puget Sound to Olympia, the principal mixing zones encountered are the Victoria-Green Point sill[14], the eastern end of the Strait of Juan de Fuca, Admiralty Inlet, and The Narrows. In a simplified manner, the waters contained within each basin form a two-layer system consisting of a surface layer of lower salinity water flowing seaward and overriding a deeper layer of more saline water flowing landward. The surface layer is a mixture of seawater and freshwater (see Section 1.2.4). The deeper layer has its origin in the Pacific Ocean and flows landward in response to pressure forces associated with the density differences between fresh- and sea-water, and to tide related forces. The *boundary* between the two layers, or *depth of no-net motion*, is usually at a depth from 40 to 60 m and is not distinct or well defined except near the mouth of a river or close to a constriction such as Admiralty Inlet. For the main basin, the most significant dilution of oceanic type water occurs in Admiralty Inlet where the fresher surface layer from Puget Sound mixes with the more saline waters from the eastern end of the Strait of Juan de Fuca.

The deeper waters in the Strait of Juan de Fuca undergo seasonal cycles that are dependent upon the coastal winds. In July and August, strong northerly winds along the Washington coast cause upwelling. This upwelled water enters the Strait at depth, usually below 100m. It is cooler (about $7^{o}C$), more saline (up to nearly 34 $^{o}/oo$), relatively low in dissolved oxygen ($<$ 0.25 mg-at/l), and higher in nutrients (over 3 µg-at/l of phosphate) than the water entering the Strait at other times of the year. As this water moves landward, it influences the mixed water being supplied to the various basins by producing a salinity maximum, a depression in dissolved oxygen, and an increase in nutrient concentration at any given location. The time required for the oceanic-type water, even though considerabley modified, to reach the various extremities

---

14. The Victoria-Green Point sill is 18km east of Port Angeles. The sill has an effective depth of 120m near mid-channel. But for the most part the water depths are less than 100m.

of Puget Sound takes from two to three months. By the time the maximum upwelling off Cape Flattery has passed, the rainy season has begun, and the source oceanic water has become less saline, warmer, higher in dissolved oxygen, and lower in nutrients. Thus the major cycles of water characteristics in any given basin of Puget Sound are strongly influenced by factors external to the basin.

Water characteristics within the main basin of Puget Sound vary in response to seasonal changes in source-water properties, river discharge, and biological processes as well as to short-term effects related to dynamic processes associated with tides and meteorological parameters. Within the system, variations that follow seasonal trends occur with respect to both location and depth. Spatial variations result from advective processes produced by tidal action and associated circulation patterns. Superimposed on these processes are localized effects of the introduction of fresh water and nutrients at sewer outfalls and river mouths. The magnitude and extent of these latter effects are strongly dependent upon discharge rates and the character of the dynamic processes within the localized area. Thus, a freshwater source often results in a marked localized surface effect upon salinity and density structure. But this effect becomes less prominent with increasing distance from the source. The effect of seawater dilution is controlled by slower transport and exchange with oceanic water. On the other hand, nutrients, being non-conservative[15], are affected by both dynamic and non-dynamic processes.

Tidal flow introduces short-period variability throughout the main basin. This variability is most evident where strong gradients (both vertical and horizontal) occur. Depending upon location and tidal character, a single ebb or flood tide may carry a parcel of water several kilometers from that location. If appreciable non-homogenieties are present within the water mass upstream from the location, transient changes may be observed at the given location.

---

15. Non-conservative properties are affected by biological and chemical processes. These properties include dissolved oxygen, nutrients, chlorophyl-a, etc. Conservative properties are affected only by physical processes such as mixing and advection. These include temperature, salinity, electrical conductivity, etc.

4.2 *Comparison of new data with historical data*

4.2.1 *Introduction:* The most frequently reported properties in the historical data were temperature, salinity, dissolved oxygen, and orthophosphate. Only limited data were available on other nutrients because methods for rapid shipboard analyses of nutrients were not fully developed until the late 1960's. Hence comparisons in the following discussion will be limited to dissolved oxygen and orthophosphate. Five stations were selected for comparison of the historical data with data obtained during this study; namely, Point No Point, Point Jefferson, Alki Point, Pully Point, and Browns Point. Figure 4-1 shows the locations of these stations and the number of times each station was occupied from 1932 through 1963.

Most of the variability of water properties observed in Puget Sound occurred in the upper 20m where dynamic processes are most effective. Also, both the historical and recent observations were collected without regard to tide stage or meteorological conditions. To reduce the effect of both short-term and year-to-year variations, the depth integrated average concentrations of oxygen and phosphate in the upper 20m were computed as follows:

$$\overline{P} = \frac{\sum \{ (P_i + P_{i+1}) / 2\} \{\Delta Z\}}{Z_m} \qquad (4.1)$$

where $\overline{P}$ is the depth-integrated average concentration for the specified property P, P_i is the value of P at depth Z_i, P_{i+1} is the value at depth Z_{i+1}, ΔZ is the depth interval between Z_i and Z_{i+1}, and Z_m is the maximum depth used or in this case, 20m.

The results of the calculations for dissolved oxygen at the five selected stations are presented in Table 4-1 and for orthophosphate in Table 4-2. The 1932-63 time frame was selected as being a *baseline* period because this period represents the water conditions in the study area prior to the installation of the METRO sewage system and the creation of the West Point sewage treatment plant. Although the *baseline* data represent observations over a 31-year period, the number of times a given station was occupied during a particular month varied from 2 to 22 times. Data from Point No Point and Point Jefferson were the most complete.

Any observable change evident from a comparison of the *baseline* data with data obtained during this study must be assessed not only as being the result of METRO's discharges, but also as a result of the large population increase in

TABLE 4-1

INTEGRATED VALUES OF DISSOLVED OXYGEN IN THE UPPER 20M
FOR THE PERIOD 1932 - 1963

	Point No Point		Pt. Jefferson		Alki Point		Point Pully		Browns Point		Main Basin	
Month	Avg.	StDev	Avg.	StDev	Avg.	StDev	Avg.	StDev	Avg.	StDev	Avg.	StDev
January	0.506	0.027	0.509	0.019	0.504	0.020	0.508	0.023	0.482	0.039	0.506	0.025
February	0.531	0.039	0.517	0.021	0.513	0.050	0.514	0.032	0.522	0.029	0.522	0.032
March	0.521	0.057	0.553	0.048	0.548	0.038	0.573	0.062	0.549	0.029	0.538	0.077
April	0.558	0.065	0.561	0.049	0.556	0.079	0.534	0.062	0.524	0.056	0.553	0.059
May	0.613	0.075	0.619	0.074	0.612	0.075	0.626	0.076	0.606	0.075	0.616	0.072
June	0.563	0.068	0.608	0.053	0.608	0.084	0.601	0.026	0.581	0.047	0.587	0.063
July	0.537	0.050	0.533	0.042	0.494	0.086	0.545	0.068	0.540	0.098	0.531	0.065
August	0.478	0.083	0.497	0.098	0.551	0.015	0.519	0.055	0.506	0.030	0.498	0.081
September	0.438	0.050	0.428	0.034	0.415	0.019	0.495	-----	0.500	0.023	0.442	0.045
October	0.394	0.044	0.407	0.021	0.398	0.007	0.434	0.047	0.407	0.006	0.404	0.032
November	0.395	0.049	0.416	0.023	0.398	0.014	0.434	0.021	0.421	0.012	0.408	0.036
December	0.447	0.049	0.451	0.025	0.442	0.015	0.465	0.025	0.450	0.016	0.451	0.032

TABLE 4- 2

INTEGRATED VALUES OF INORGANIC PHOSPHATE IN THE UPPER 20M

FOR THE PERIOD 1932 - 1963

	Point No Point		Pt. Jefferson		Alki Point		Point Pully		Browns Point		Main Basin	
Month	Avg.	StDev	Avg.	StDev	Avg.	StDev	Avg.	StDev	Avg.	StDev	Avg.	StDev
January	2.22	0.37	2.53	0.24	2.50	0.20	2.54	0.17	2.55	0.14	2.39	0.29
February	2.26	0.31	2.49	0.28	2.43	0.22	2.40	0.35	2.41	0.34	2.38	0.30
March	1.98	0.32	2.23	0.53	2.06	0.62	2.11	0.64	2.39	0.25	2.14	0.47
April	1.89	0.70	1.93	0.37	1.86	0.64	2.29	0.63	2.29	0.66	2.00	0.55
May	1.42	0.54	1.75	0.54	1.69	0.49	1.89	0.40	2.01	0.30	1.63	0.53
June	1.27	0.52	1.48	0.33	1.63	0.51	1.42	0.34	1.60	0.49	1.42	0.41
July	1.26	0.39	1.59	0.32	1.37	0.27	1.20	0.32	1.41	0.30	1.35	0.34
August	1.44	0.27	1.50	0.38	1.48	0.29	1.59	0.19	1.59	0.22	1.50	0.29
September	1.88	0.24	2.05	0.20	2.22	0.06	1.82	0.32	1.83	0.19	1.96	0.25
October	2.17	0.42	2.14	0.27	2.47	0.20	2.40	0.24	2.44	0.22	2.25	0.33
November	2.22	0.25	2.31	0.24	2.39	0.25	2.36	0.30	2.55	0.16	2.30	0.25
December	2.38	0.33	2.40	0.28	2.73	0.15	2.64	0.24	2.62	0.33	2.51	0.31

the Puget Sound area (see Table 4-3) and associated industrialization, commerce, and recreational uses to which the waters of the Puget Sound system have been and are being subjected. Also, variations associated with long-term natural processes must be considered. For example, the water temperatures on the east side of the Pacific Ocean in 1958 were abnormally warm while the waters off Japan at the same time were abnormally cool (Isaac and Sette, 1958). This warming was reflected in water properties observed in Puget Sound in late 1958.

4.2.2 *Dissolved oxygen:* Seasonal cycles of dissolved oxygen for both the *baseline* and new data at the five stations are apparent in Figure 4-2. This figure presents the integrated mean values of dissolved oxygen at each station as reported in Table 4-1 together with an envelope generated by plotting the mean values plus or minus one standard deviation. The probability that a given data point will fall inside this envelope is 67%. All five stations showed similar seasonal trends. At the beginning of the year, oxygen concentrations were about 0.5 mg-at/l. A steady increase occurred until May followed by a decline to the minimum in October. This minimum resulted from the combined effects of intrusion of low-oxygen content oceanic-type water into the central basin, a reduction of plankton productivity associated with declining insolation, and the degradation of planktonic detritus. The newer data usually fell within the *baseline* envelope with maximum deviations occurring in summer when short-period variations were largest. (See Table 4-4 for the recent data.)

In general, the main basin of Puget Sound behaves predominately as a single unit with regard to water properties. Thus, the *baseline* data from the five stations were combined into a single monthly average and the standard deviation recomputed. A similar process was used on the new data. Then the envelopes with a width of plus and minus one standard deviation were plotted for both sets and are also presented in Figure 4-2. Both envelopes are nearly the same, but in July and August, the period of maximum variability, the upper limit of the new data was slightly higher than the *baseline* data. The lower limit fell slightly below the *baseline* envelope on only three occasions. When averaged for the entire year, the *baseline* concentration was 0.508 mg-at/l and for the new data 0.513 mg-at/l.

It is evident from this data that the oxygen concentration within the main basin of Puget Sound has not changed from the pre-1963 level, although the population within the region has increased about 75% from the 1946 (mid-*baseline* period) population.

TABLE 4-3

POPULATION OF COUNTIES BORDERING PUGET SOUND

County	1930	1940	1950	1960	1970	1973#
Island	5,369	6,098	11,079	19,638	29,011	30,400
Jefferson	8,346	8,918	11,618	9,639	10,661	10,900
King	463,517	504,980	732,992	935,014	1,156,633	1,128,300
Kitsap	30,776	44,387	75,724	84,176	101,732	102,700
Mason	10,060	11,603	15,022	16,251	20,918	21,600
Pierce	163,842	182,081	275,876	321,590	411,027	401,200
Skagit	35,142	37,650	44,273	51,350	52,381	52,800
Snohomish	78,861	88,754	111,580	172,199	265,236	256,600
Thurston	31,351	37,285	44,884	55,049	76,894	84,000
TOTAL	827,264	921,756	1,323,048	1,664,905	2,124,493	2,088,500

Most recent estimate by the U.S. Bureau of the Census.

4.2.3 *Phosphate:* Data for orthophosphate have been treated in a manner similar to that for oxygen. The results are presented in Tables 4-2 and 4-5 and Figure 4-3. At Point No Point, the 1974-75 values were consistently higher than the average *baseline* mean. But from Point Jefferson and south, the newer data was closer to the *baseline* means though still somewhat higher. This becomes more evident by examination of Table 4-6 which is a listing, by station, of the difference between the newer and *baseline* means. As in the case of oxygen, the data for all five stations were combined and are also presented in Figure 4-3. For the main basin of Puget Sound as a whole, the newer data were generally higher but usually were within one standard deviation (67%) of the older data. Those points that did fall outside of the upper limit of the *baseline* curve were still well within the 95% confidence limit.

The apparent increase in orthophosphate of the recent data, about 11% above the *baseline* means, may result from many factors other than the contributions from sewage introduced by METRO. During 1975, the plankton bloom was delayed from April to late May and the summer bloom was earlier. This reduced the overall utilization of phosphate by phytoplankton and would cause the average phosphate concentration to be higher. Increased fertilization of farm areas may possibly result in increased phosphate in river water especially during the rainy season but no substantiating data are available. Also long-term changes in the source seawater will introduce changes into the *normal* phosphate levels. Such changes that may have occured in recent years or that may be occurring cannot be defined or evaluated because there is no ongoing systematic monitoring program for the waters of Puget Sound and its approaches.

4.3 *Subdivisions of the main basin*

Even though the main basin of Puget Sound responds for the most part as a single unit, the geomorphology and various dynamic processes roughly delineate four subdivisions (see Fig. 4-4) as follows:

(1) the northern part from Point No Point to Point Wells;

(2) the central portion from Point Wells to Alki Point;

(3) East Passage from Alki Point to Browns Point; and

(4) the southern end from Browns Point to Point Defiance plus all of Colvos Passage.

The northern portion is strongly influenced by processes occurring in both Admiralty Inlet and Whidbey Basin. Ninety-eight percent of the entire tidal prism of Puget Sound must pass through Admiralty Inlet and most of this water,

TABLE 4-4

INTEGRATED VALUES OF DISSOLVED OXYGEN IN THE UPPER 20M FOR THE METRO CRUISES (1974-75) - (units in mg-at/l)

METRO Cruise	Point No Point	Point Jefferson	Alki Point	Pully Point	Browns Point	Main Basin# Avg.	Main Basin# StDev
1	0.368	0.375	0.369	0.385	0.384	0.372	0.012
2	0.461	0.415	0.398	0.422	0.450	0.426	0.024
3	0.472	0.437	0.431	0.463	0.458	0.449	0.018
5	0.523	0.563	0.511	0.509	0.540	0.524	0.023
6	0.545	0.551	0.511	0.544	0.512	0.530	0.018
8	0.552	0.548	0.545	0.560	0.564	0.549	0.015
9	0.544	0.550	0.555	0.552	0.556	0.553	0.006
10	0.541	0.552	0.554	0.568	0.577	0.558	0.013
12	0.563	0.578	0.585	0.626	0.624	0.591	0.027
13	0.554	0.580	0.605	0.577	0.585	0.592	0.032
14	0.519	0.516	0.505	0.540	0.553	0.524	0.018
15	0.505	0.605	0.664	0.674	0.535	0.598	0.068
16	0.496	0.592	0.594	0.628	0.589	0.591	0.052
17	0.452	0.471	0.430	0.659	0.484	0.491	0.083
19	0.427	0.444	0.422	0.441	0.461	0.440	0.014
20	0.376	0.392	0.389	0.450	0.396	0.397	0.027
21	-----	0.411	0.416	0.454	0.419	0.422	0.019
22	0.494	0.470	0.461	0.467	0.441	0.470	0.019

These data include the West Point III station.

TABLE 4-5

INTEGRATED VALUES OF INORGANIC PHOSPHATE IN THE UPPER 20M FOR THE METRO CRUISES (1974-75) - (Concentrations in μg-at/l)

METRO Cruise	Point No Point	Point Jefferson	Alki Point	Pully Point	Browns Point	Main Basin# Avg.	StDev
1	2.43	2.39	2.68	2.80	2.64	2.59	0.015
2	2.55	2.90	2.76	2.76	2.66	2.77	0.015
3	2.88	2.54	2.64	2.65	2.61	2.64	0.013
5	no data	no data	2.66	2.94	2.67	2.72	0.015
6	2.75	2.91	2.51	2.34	2.42	2.59	0.021
8	2.39	2.37	2.50	2.46	2.45	2.42	0.052
9	2.41	2.55	2.43	2.46	2.42	2.45	0.051
10	2.54	2.51	2.56	2.53	2.45	2.51	0.042
12	2.06	2.07	2.11	1.87	1.85	2.01	0.116
13	1.80	1.70	1.61	1.93	1.91	1.78	0.123
14	1.80	2.03	2.08	1.91	2.00	1.99	0.113
15	1.81	1.44	1.20	1.09	1.88	1.47	0.318
16	1.84	1.30	1.28	1.01	1.20	1.30	0.285
17	2.04	1.96	2.14	1.05	1.86	1.86	0.410
19	2.29	2.32	2.29	2.17	2.08	2.24	0.094
20	2.44	2.56	2.44	2.25	2.66	2.46	0.136
21	no data	2.56	2.58	2.49	2.44	2.53	0.070
22	2.47	2.74	2.77	2.64	2.59	2.65	0.109

These data include the West Point III station.

TABLE 4-6

DIFFERENCES BETWEEN 1974-75 AND PRE-1963 PHOSPHATE VALUES

(Concentrations in μg-at/l)

Observation Date	Point No Point	Point Jefferson	Alki Point	Pully Point	Browns Point
29 Jan 75	no data	no data	0.19	0.45	0.17
20 Feb 75	0.53	0.46	0.15	-0.04	0.01
10 Mar 75	0.35	0.10	0.38	0.25	0.06
2 Apr 75	0.48	0.49	0.49	0.29	0.08
22 Apr 75	0.76	0.62	0.74	0.30	0.24
14 May 75	0.62	0.31	0.42	0.06	-0.09
4 Jun 75	0.48	0.13	-0.03	0.36	0.18
27 Jun 75	0.54	0.51	0.56	0.58	0.48
16 Jly 75	0.55	-0.14	-0.17	-0.14	0.46
6 Aug 75	0.46	-0.22	-0.16	-0.45	-0.33
26 Aug 75	0.44	0.26	0.39	-0.59	0.22
16 Spt 75	0.40	0.26	0.06	0.39	0.30
7 Oct 75	0.35	0.44	0.03	0.16	0.55
29 Oct 75	no data	0.34	0.15	0.10	-0.20
6 Nov 74	0.23	0.13	0.26	0.43	0.14
18 Nov 75	0.24	0.42	0.35	0.27	0.04
26 Nov 74	0.27	0.56	0.25	0.41	0.08
17 Dec 75	0.48	0.14	-0.10	0.00	-0.02
MEAN	0.449	0.283	0.220	0.157	0.142
1 Standard Deviation	0.141	0.237	0.255	0.311	0.216

except for the Hood Canal tidal prism, must pass through the northern part of the main basin. This large volume of water (about 8.08 10^9 m^3 for an average tide of 3.2m at Seattle) plus the restricted size of Admiraly Inlet (minimum cross-sectional area of 3.74 10^6 m^2) create strong currents and mixing in the Inlet especially on larger tides. Also most of the fresh water entering the main basin comes from Whidbey Basin through Possession Sound. The major rivers discharging into Whidbey Basin are the Skagit, Stillaguamish, and Snohomish. These three rivers account for over 70% of the total annual river discharge. Of this quantity, about 75% enters the main basin in the surface layer. During June when the rivers are in flood stage, the surface layer may move as far south as Point Jefferson. On occasion, deeper water from Possession Sound has been observed to enter the main basin off Possession Sound at a depth of about 50m. This deeper water is characterized by lower oxygen content and higher nutrient content.

Variations in water properties suggest that the central area is a transition zone between the northern area and East Passage. In this portion, circulation patterns resulting from tidal flow are quite intricate. Large-scale eddies, forming in the vicinity of West Point and Alki Point, and the outflow from Colvos Passage on ebb tide strongly influence flow behavior and promote cross-channel dispersion.

East Passage is characterized by slower tidal currents, shorter tidal excursions, less turbulent flow, and less mixing. In this area, the net transport of both surface and deeper water is toward the south as a result of the pumping action of The Narrows-Colvos Passage system. Reduced transport is also evident by distinguishable pockets of water at depth near Browns Point as is evident in Figures 3-2, 3-3, 3-8, and 3-9. The effect of the Colvos Passage jet, plus the large-scale eddies associated with the flow past Pully Point, Point Robinson, and Browns Point result in the formation of parcels having properties distinguishable from the general water mass in East Passage.

Although the landward tansport of the deeper layer in Puget Sound is usually attributed to longitudinal density gradients, it is not the only mechanism of transport within the main basin of Puget Sound. The behavior of The Narrows-Colvos Passage system causes a relatively rapid southerly transport of deeper water in East Passage. In brief, the mechanism as derived from model studies and limited field observations is as follows: During flood tide, surface water

including Puyallup River discharge together with bottom water upwelled in Dalco Passage is carried toward and into The Narrows. Strong turbulence within The Narrows effectively mixes these waters. On the following ebb, the outflow from The Narrows creates strong turbulence between Point Defiance and the southern end of Vashon Island. As the ebb continues, and the inertia of the water in Colvos Passage is overcome, the water is driven northward in that channel by the outflow from The Narrows. After transiting Colvos Passage, the deeper water, deflected to the west by the Blake-Vashon Island sill, flows around the west side of Blake Island and then north in the main basin near Bainbridge Island. Because of the physical characteristics of the channels, the major portion of the Colvos Passage flow passes over the Blake-Vashon Island sill and moves across the main basin toward Alki Point. This constriction accentuates the jet-like character of the flow. A minor portion of the jet flow is deflected into East Passage and makes another circuit around Vashon Island. This behavior creates a pump-like action that not only markedly increases the net southerly transport of the deeper layer in East Passage but increases the net seaward transport of the upper layer north of Alki Point. Another result is a southerly net transport of the upper layer in East Passage and a strong net northerly flow in Colvos Passage. Because of this mechanism, flushing within the main basin of Puget Sound is far more rapid than occurs within Whidbey Basin although the fresh water inflow from the rivers into Whidbey Basin exceeds that of the combined river flow into the main basin and into Southern Puget Sound by a factor of about 8.

4.4 *Nitrogen compunds*

4.4.1 *Nitrates:* As mentioned in Section 3.1, biological activity tends to maintain a nearly fixed ratio of phosphate to nitrate. To evaluate the relationship between phosphate and nitrate for the study period, a linear correlation was calculated for all of the 20m integrated means for six stations from Point No Point to Browns Point. The results are as follows:

Point No Point	$N = 12.14\ P - 4.96$	(4.2)
Point Jefferson	$N = 11.38\ P - 4.16$	(4.3)
West Point	$N = 12.48\ P - 6.35$	(4.4)
Alki Point	$N = 13.35\ P - 8.40$	(4.5)
Pully Point	$N = 13.36\ P - 6.92$	(4.6)
Browns Point	$N = 13.84\ P - 8.50$	(4.7)
Entire Main Basin	$N = 12.83\ P - 6.78$	(4.8)

In these equations, N is the concentration of nitrate expressed in μg-at/l and P is the phosphate concentration in the same units. The correlation coefficient for all of these equations averaged 0.9 or better. It is evident from these equations that in general the ratio increased from north to south along the main basin.

A comparison was made between observed and calculated concentrations of nitrate. In the northern portion of the main basin, there appeared to be a general trend in the differences in which observed nitrate concentrations were from 2 to 4 μg-at/l higher than the calculated values during the period from March to July. The maximum difference at West Point appeared simultaneously with that observed to the north,but the duration was shorter. In February 1975 at Pully Point, the observed nitrate concentration was 4.8 μg-at/l higher than the calculated value. But in general, the calculated and observed nitrate values agreed within 15%. Variations between calculated and observed concentrations are most likely associated with the dynamics of biological uptake and degradation and by the physical characteristics of the water that occur in the euphotic layer.

4.4.2 *Nitrites:* Nitrite concentrations observed during this study exhibited two peaks, one in early June and another in early October (see Figs. 3-31 and 3-40). The latter peak was coincident with the oxygen minimum and salinity maximum associated with the intrusion of upwelled oceanic water into the main basin. A comparison of nitrites along the length of the main basin (Figs. 3-18 and 3-19)showed considerable changes with location and depth, with a general decrease from north to south. It appeared that both phytoplankton productivity and dynamic processes related to tidal flow were important in creating this distribution. A tongue of nitrite-deficient water developed south of Point Robinson suggesting that dynamic processes of circulation in East Passage are indeed important. At Point No Point, strong mixing within Admiralty Inlet maintained much closer agreement between the surface and deeper layers. Toward the south, in the deeper basin, smaller scale turbulence became less important and the larger scale circulation patterns became dominant. In general, nitrite is an intermediate product and may not be of great importance in limiting phytoplankton growth.

4.4.3 *Ammonia:* The normal range of ammonia in sea water varied from almost zero to about 0.6 μg-at/l, although near-surface values of up to 1.5 μg-at/l have occurred on the Washington coast (Sverdrup, et al., 1946). Because ammonia responds rapidly to biochemical changes, concentrations are irregular, with higher concentrations occurring during and after periods of high plankton development. Ammonia is produced by the decomposition of organic matter and is affected not only by plankton productivity and subsequent decomposition but also by the introduction of exotic organic matter. Thus localized high concentrations are frequently associated with plumes from sewers that discharge directly into Puget Sound or from rivers having sewer outfalls upstream from the mouths. Both types of plumes were observed within the study area. Even though biochemical processes, dilution, and mixing, rapidly modify the ammonia concentrations, high levels are useful as an indicator of sewage, especially when they can be traced to their origin.

Localized areas of high ammonia concentrations were observed throughout the study period. In most cases, ammonia was low except near a sewer outfall or river discharge. Transient localized concentrations exceeding 12 μg-at/l were observed at the West Point sewer outfall. Elevated nitrate, phosphate and silicate concentrations near West Point were also evident (Figs. 3-42, 3-43, 3-45, 3-46, and 3-47). On 5 November 1974 (Fig. 3-42), a lens-shaped cloud of low ammonia was observed in the upper 10m near West Point while at depth the ammonia values increased to over 3.0 μg-at/l. To the west, a second cloud having concentrations up to 1.5 μg-at/l was present. This pattern was consistent with observations made in the model that showed the effluent plume from West Point being broken into clouds and filaments which produced a spotty and irregular distribution.

High concentrations were also observed in Elliot Bay near the East and West Waterways and near Pier 60. These high concentrations of ammonia were associated with the discharge from the Duwamish River that carries effluent from the Renton METRO treatment plant and possible discharge from the industrial area of Seattle,although no specific industrial source in this area has been identified. High concentrations of ammonia were also associated with the discharge from the Puyallup River which carried effluent from the large treatment plant and from other towns located upstream. Additional loads of nutrients may have originated from the farmlands in the Puyallup Valley when fertilizer added to the land was washed into the river by local rains.

4.5 *Nitrogen uptake*

4.5.1 *Nitrate:* A definite seasonal trend in the uptake of nitrate by phytoplankton was evident from the data presented in Figure 4-5. In February, the uptake rates were low except near Pier 60 and one sample in the boil at the end of the Alki sewer. The increased uptake rate at Pier 60 may be due to the increased stability[16] of the upper layer in Elliott Bay because of the fresh water from the Duwamish River. The other stations sampled in February were located in areas of relatively low stability.

In spring, nitrate uptake, measured at weekly intervals at Point Jefferson, showed an increase with each sampling until values were 4 to 5 times higher than the average winter values. By late summer, nitrate uptake rates at the surface had reached a maximum of 2.15 µg-at/l. Five of the six stations sampled exhibited uptake rates greater than 1 µg-at/l in the surface layer. But at depth the uptake was only slightly higher than in spring. The highest uptake was measured at Point Jefferson and the lowest at Pier 60. There is no obvious reason for the low fall rate at Pier 60, although high levels of ammonia were observed at this time suggesting some influence from the Duwamish River or local discharge that could inhibit phytoplankton growth. By November, the nitrate uptake was at its annual minimum.

4.5.2 *Ammonia:* Ammonia uptake rates were measured at most stations concurrently with nitrate. The observed winter rates were low and almost equal to the nitrate uptake rate. A single sample at 9m in the Alki sewer boil showed elevated rates for both ammonia and nitrate (each averaging 1.47 µg-at/l) that reflect a local stimulation of the phytoplankton by the sewer effluent. This effect was local in nature and not observed outside the immediate area of the boil. Figure 4-6 presents the ammonia uptake rates.

In spring the ammonia uptake rates increased weekly and were about four times the winter rates at all depths. Ammonia uptake showed considerable dependence upon light with maximum uptake rates being observed in the surface while near the bottom of the euphotic zone, the uptake was very low.

4.5.3 *Urea:* Due to limitations of available equipment, only a limited number of urea uptake experiments were performed. The uptake of urea was high-

---

16. Stability is the resistance to overturning or mixing of the water column because of the presence of strong positive density gradients. Fresh water from a river will produce strong surface gradients.

est in summer (0.42 μg-at/l/day) at Point Jefferson where the highest nitrate and ammonia uptake rates also were measured. In spring, the urea uptake rate was less than nitrate or ammonia and showed very little light dependence. By fall, the urea uptake rates were similar to both those for nitrate and ammonia.

4.6 *Fluxes of water and matter*

4.6.1 *Water budgets:* No direct measurement of transports of fresh and salt water were made during this study because of budgetary constraints. Field observations were planned to provide sufficient data to permit estimates of water budgets using the method of Friebertshauser and Duxbury (1972), which in turn was patterned after the method of Waldichuk (1957). Their method used the salinity structure of the water at various locations in the entire Puget Sound system, but for this report, only the main basin of Puget Sound has been considered. The equations used to calculate the budgets of total water, fresh water, and sea water are as follows:

$$T_i + R - T_o - \Delta W = 0 \tag{4.9}$$

$$\Delta F = R + T_i\,(S_b - S_i)/S_b \;-\; T_o(S_b - S_o)/S_o \tag{4.10}$$

$$\Delta P = \Delta W - \Delta F \tag{4.11}$$

$$= T_i\{1 - (S_b - S_i)/S_b\} \;-\; T_o\{1 - (S_b - S_o)/S_o\} \tag{4.12}$$

where T_i is the average rate (volume per unit time) of inflow of water from the sea to the main basin, T_o is the average rate of outflow of water from the main basin to the sea, R is the total fresh water input into the main basin, ΔW is the change in water volume due to change in mean sea level, ΔF is the change in fresh water content of the basin, ΔP is the change in seawater content of the basin, S_i is the average salinity of the inflowing seawater (T_i water type), S_o is the average salinity of the outflowing water (T_o water type), and S_b is a selected base salinity. Values associated with R, ΔW, ΔF, and ΔP were computed for the period of time between surveys. Combining equations (4.9) to (4.12) we obtain

$$T_i = (R - \Delta W)\{S_o/(S_i - S_o)\} + \{\Delta W - \Delta P\}\{S_b/(S_i - S_o)\} \tag{4.13}$$

and

$$T_o = T_i + R - \Delta W\;. \tag{4.14}$$

In order to use these equations it is necessary to evaluate each variable from the data obtained during the study period.

The runoff (R) contribution to the main basin was determined by evaluating the flow from 20 gaged rivers and streams entering the main basin, southern Puget Sound, and Whidbey Basin (US Geological Survey, 1974 and 1975). The relationship between gaged and ungaged drainage areas tributary to these bodies provided the basis for calculating the total freshwater inflow. Then the inflow into each basin during the interval between sampling periods was computed and the total used for R. It has also been assumed, for these calculations, that all freshwater entering southern Puget Sound appears as a runoff at The Narrows and that the runoff entering Whidbey Basin, except for that discharging through the North Fork of the Skagit River, appears as a runoff at Possession Point. Because Hood Canal enters into Admiralty Inlet, north of the study area, runoff into the Hood Canal basin has not been included in these calculations.

The mean sea level in Puget Sound changes throughout the year because of sea level changes in the northeast Pacific Ocean. Unpublished data for water levels at Seattle for the years 1974 and 1975 were obtained from the local office of the National Ocean Survey. From these data, the change in water level (Δh) between sampling periods was determined. The volume change (ΔW) was assummed to be Δh times the surface area of the main basin which is about 740 km^2 at an average tide height of 3.2m at Seattle.

The fresh water storage (F) in the main basin at the time of each survey was evaluated as

$$F = V_b \; (S_b - S_p)/S_b \qquad (4.15)$$

where V_b is the volume of the basin corrected for mean sea level and S_p is the average salinity of the entire water volume in question. To obtain S_o, the main basin was divided into small sections associated with each station indicated in Figure 3-1. The total salt within selected depth increments of each section was calculated from the observed salinities. Then the amount of salt per depth increment was summed for the entire main basin and the result divided by the total volume to obtain the average integrated salinity (S_p). To obtain S_i and S_o, it was assumed that the average integrated salinity of the water below 50m was representative of S_i and those above 50m for S_o. The 50m level was selected as being near the level of *no net-motion* for most of Puget

Sound (Ebbesmeyer and Barnes, 1976).

A value for the base salinity (S_b) of 33.8^o/oo was selected by Waldichuk as being typical of the salinity of the deeper oceanic type water entering the Strait of Juan de Fuca. Throughout the year, the salinity of this deeper water varies from 33.3^o/oo to 33.9^o/oo but is usually on the high side. This selection of 33.8^o/oo was arbitrary, but a change in S_b will have only a small effect on computations of T_i and T_o.

Values of T_i and T_o were calculated from equations (4.13) and (4.14) from data given in Table 4-7 using the IBM 1130 computer to perform the large number of calculations involved in this type of analysis. The results of these computations are listed in Table 4-8 along with other data. During the 315-day period presented in Table 4-8, the mean values of T_i and T_o were 59,600 and 60,800 m^3sec^{-1} respectively. These values compare favorably with those calculated by Ebbesmeyer and Barnes (1976) who obtained a value of 43,000 m^3sec^{-1} at a station about two miles northwest of West Point.

4.6.2 *Nutrient flux:* The integrated concentrations of nutrients in the upper and lower layers were calculated at the same time as the integrated values of salinity. From the results of the transport calculations (T_i and T_o) and the integrated nutrient concentrations, the flux of phosphate and nitrate into and out of the main basin was computed using the 50m depth as the boundary between layers. These data are also presented in Table 4-8 along with the amount of phosphate being discharged into the main basin from sewers discharging into the main basin (see Section 1.2.7)

During the period presented in Table 4-8, the average flux of phosphate into the main basin was 1,223 metric tons per day and the flux out was 1,200 tons per day. For nitrate, the values were 8,631 ton into and 8,406 tons out of the system. The average flux in and flux out for both of these nutrients was within 3% which is very good considering the assumptions made in this type of mathematical analysis. Also, long-term changes in nutrient concentrations associated with long-term climatic changes have some effect on the average concentrations (Duxbury, 1974). Further, the difference between flux in and out of a given nutrient for any specified short period may vary considerably because of biological activity. But over a long period of time, the amount of nutrients coming into and leaving the main basin will be nearly constant.

TABLE 4-7

SUMMARY OF VARIABLES USED TO COMPUTE TRANSPORT OF WATER INTO AND OUT OF THE MAIN BASIN

Period	From	To	No. of Days	Runoff $10^6 m^3$	Sewers@ $10^6 m^3$	Δh cm	ΔW $10^6 m^3$	ΔF $10^6 m^3$	Salinity# in	Salinity# out
1	5 Nov 74	25 Nov 74	21	2,030	13.0	2.4	18.0	-345	30.576	30.167
2	25 Nov 74	16 Dec 74	23	2,116	18.3	-1.8	-13.5	625	30.455	30.093
3	16 Dec 74	28 Jan 75	45	8,042	46.3	-7.6	-56.4	2,034	29.979	29.413
4	28 Jan 75	19 Feb 75	23	2,419	21.1	4.3	31.6	-239	29.676	29.836
5	19 Feb 75	10 Mar 75	20	2,546	21.6	-8.5	-63.2	577	29.642	28.832
6	10 Mar 75	1 Apr 75	23	1,845	21.6	-8.2	-60.9	-317	29.561	28.894
7	1 Apr 75	22 Apr 75	22	1,278	16.9	-3.4	-24.8	-430	29.634	29.197
8	22 Apr 75	14 May 75	23	2,150	17.7	0.9	6.8	-479	29.863	29.329
9	14 May 75	3 Jun 75	21	2,561	13.5	0.03	2.3	402	29.951	29.225
10	3 Jun 75	25 Jun 75	23	2,508	14.4	3.7	27.1	-838	29.933	29.237
11	25 Jun 75	15 Jly 75	21	2,178	13.3	-0.04	-2.3	482	29.994	29.349
12	15 Jly 75	4 Aug 75	21	1,100	12.5	-1.2	-9.0	-410	30.099	29.408
13	4 Aug 75	25 Aug 75	22	941	26.0	-1.8	-13.5	-523	30.244	29.713
14	25 Aug 75	16 Spt 75	23	1,061	16.7	-7.0	-51.9	-424	30.404	30.021

NOTES @ This is the sum of all the sewers discharging into Puget Sound as presented in Table 1-1.

This is the average salinity between the two dates at the 50m integrated depth level.

TABLE 4-8

RESULTS OF TRANSPORT CALCULATIONS

PERIOD	TRANSPORTS (M^3 m sec^{-1}) IN	TRANSPORTS (M^3 m sec^{-1}) OUT	PHOSPHATE# (10^3 kg day^{-1}) INFLOW	PHOSPHATE# (10^3 kg day^{-1}) OUTFLOW	PHOSPHATE# (10^3 kg day^{-1}) SEWERS	NITRATE* (10^3 kg day^{-1}) INFLOW	NITRATE* (10^3 kg day^{-1}) OUTFLOW
1	99,290	100,400	2,232	2,173	8.34	14,499	14,046
2	59,750	60,840	1,329	1,401	11.27	8,872	8,858
3	76,530	78,620	1,707	1,776	13.68	12,233	23,329
4	47,100	48,310	1,019	1,066	16.08	7,320	7,481
5	39,110	40,650	803	838	16.22	5,665	5,999
6	48,540	49,510	989	1,005	12.66	10,923	11,257
7	62,800	63,570	1,295	1,304	11.97	8,909	9,024
8	75,130	75,220	1,519	1,476	10.52	10,335	9,903
9	46,750	48,170	886	814	9.19	4,802	5,419
10	73,880	75,130	1,323	1,223	11.75	9,733	9,117
11	41,070	43,280	741	664	11.98	4,694	3,834
12	37,130	37,740	684	548	12.12	4,117	2,967
13	45,660	46,170	731	853	13.16	5,596	5,701
14	61,020	61,590	1,180	1,115	14.19	8,772	6,928
Integrated Average	*59,600*	*60,800*	*1,223*	*1,200*	*12.58*	*8,641*	*8,406*

\- - - - - - - - - - - - -

To obtain amount of phosphorus multiply by 0.3262.

* To obtain amount of nitrogen multiply by 0.2259.

4.6.3 *Contributions from sewers:* Based upon analyses of the effluent from the West Point sewage treatment plant and from the total amount of effluent being discharged into the main basin during the study period (see Table 1-1), the addition of phosphate from sewage was only 12.58 metric tons per day or 4,592 tons per calendar year. During the study period, the average concentration of phosphate in the main basin was 2.416 μg-at/l which amounted to 18,400 tons of phosphate at average tide level (2.8m). By comparison, the contributions from the sewers is a very small fraction of either the total amount of phosphate in the main basin at any given time and also is very small in comparison to the average flux into or out of the main basin of 1,200 tons per day. A similar analysis for nitrate could not be accomplished because the contribution of nitrate in the sewage effluent was not documented.

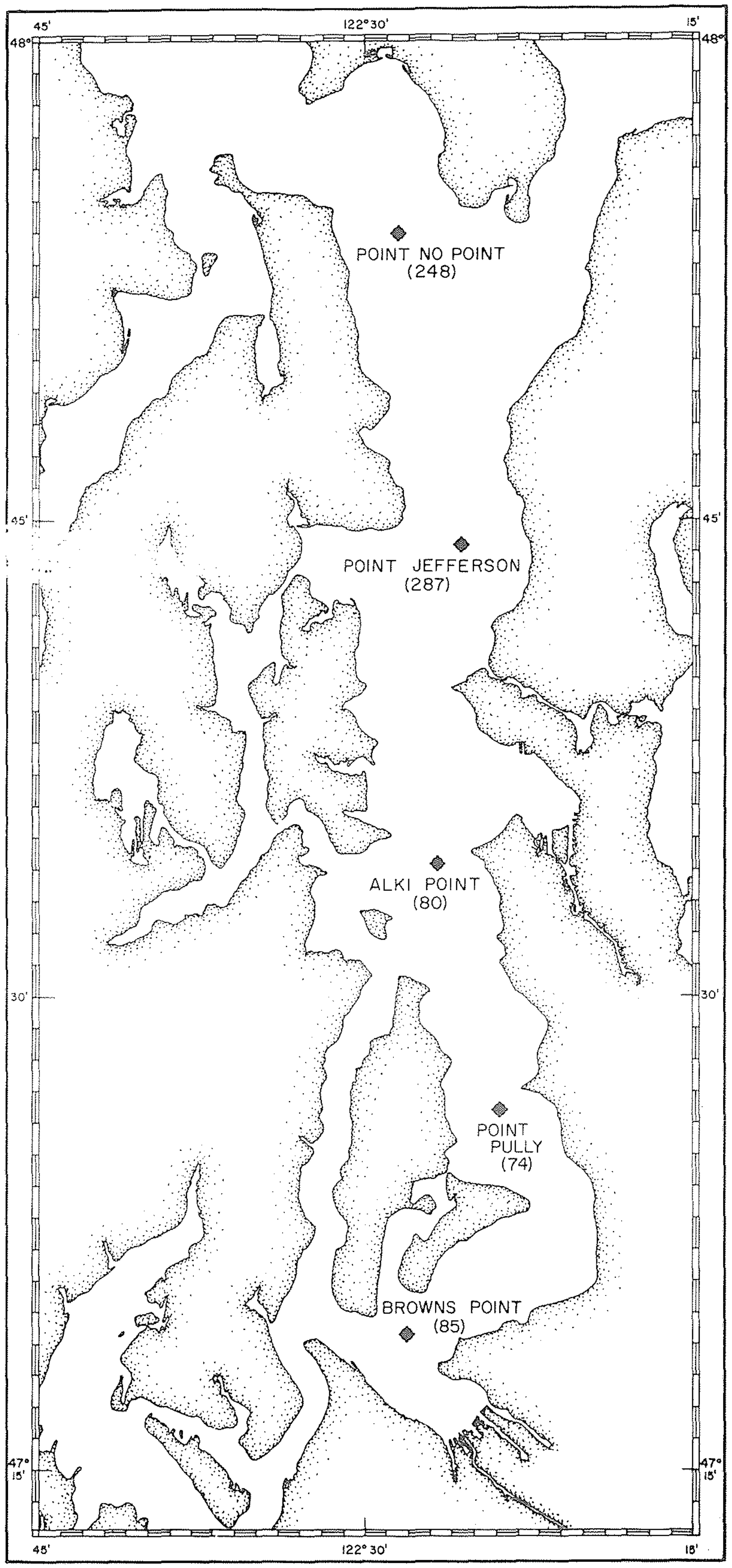


Figure 4-1

Location of stations used for comparison of historic data.

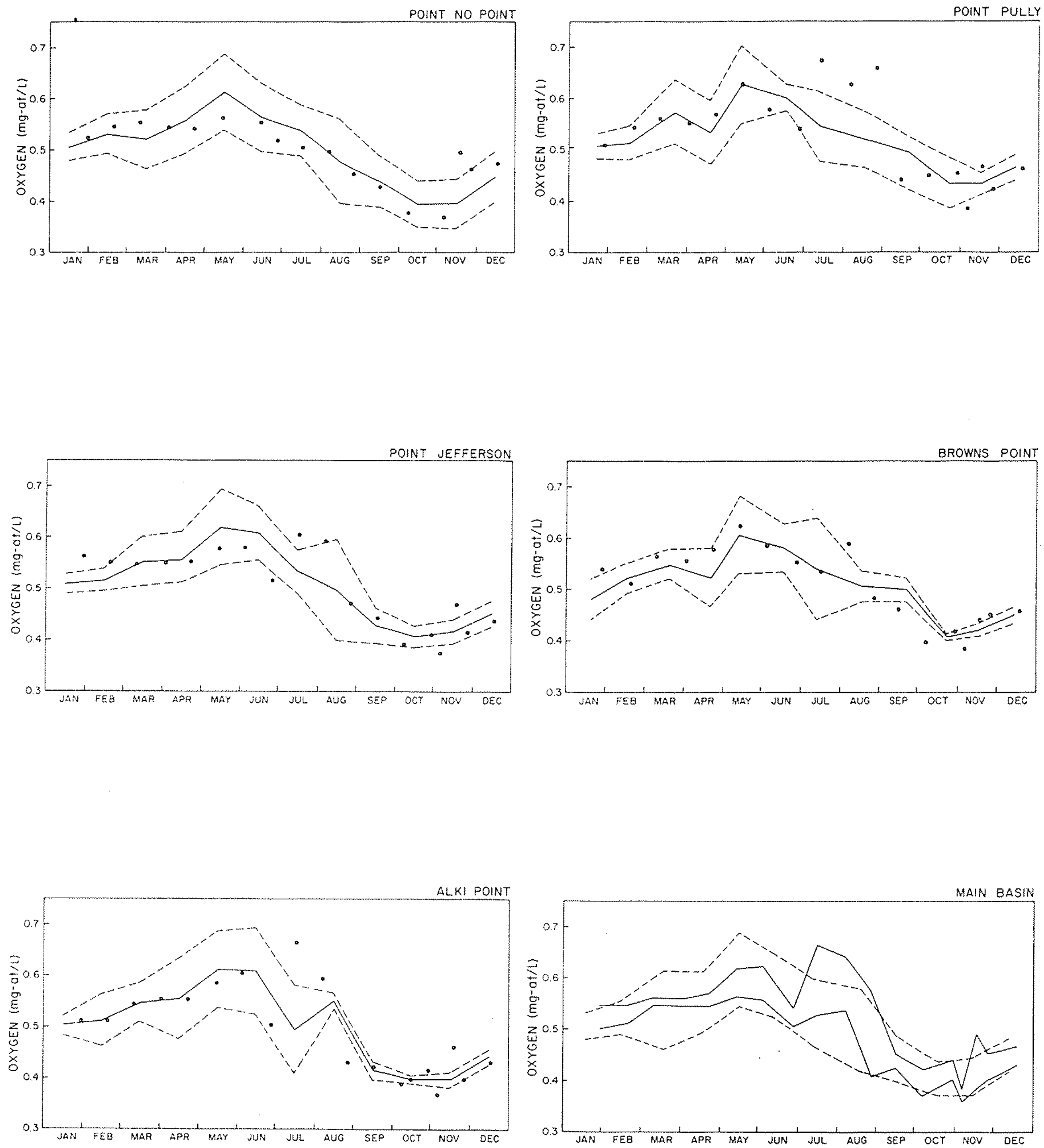


Figure 4-2

Average dissolved oxygen concentrations at selected stations for the period 1932-1963 with present data superimposed. (Solid line is the long term average, dashed line ±1 standard deviation, and dots are data obtained from the study.)

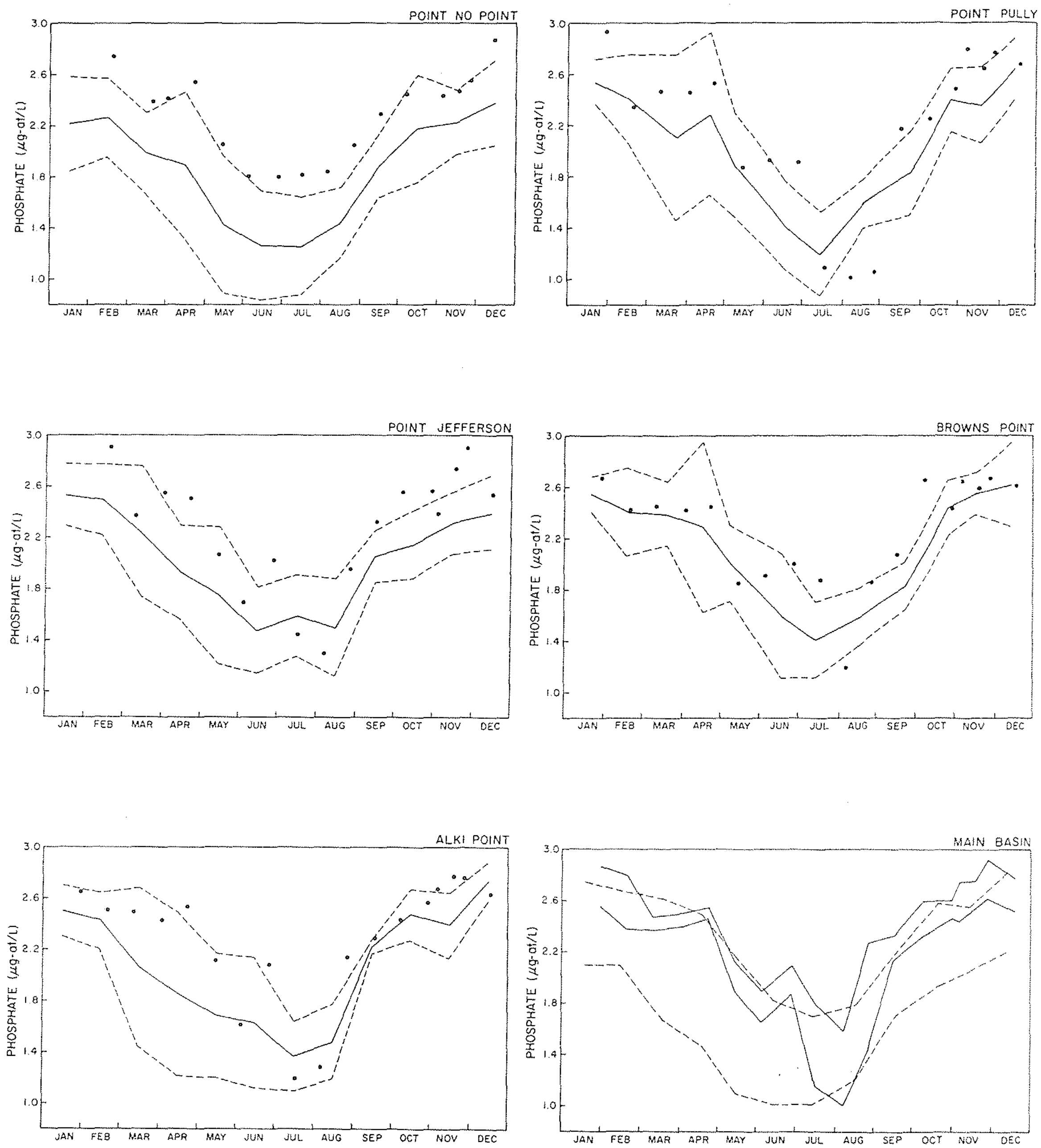


Figure 4-3

Average dissolved orthophosphate concentrations at selected stations for the period 1932-1963 with present data superimposed. (Solid line is the long term average, dashed line ±1 standard deviation, and dots are data obtained from the study.)

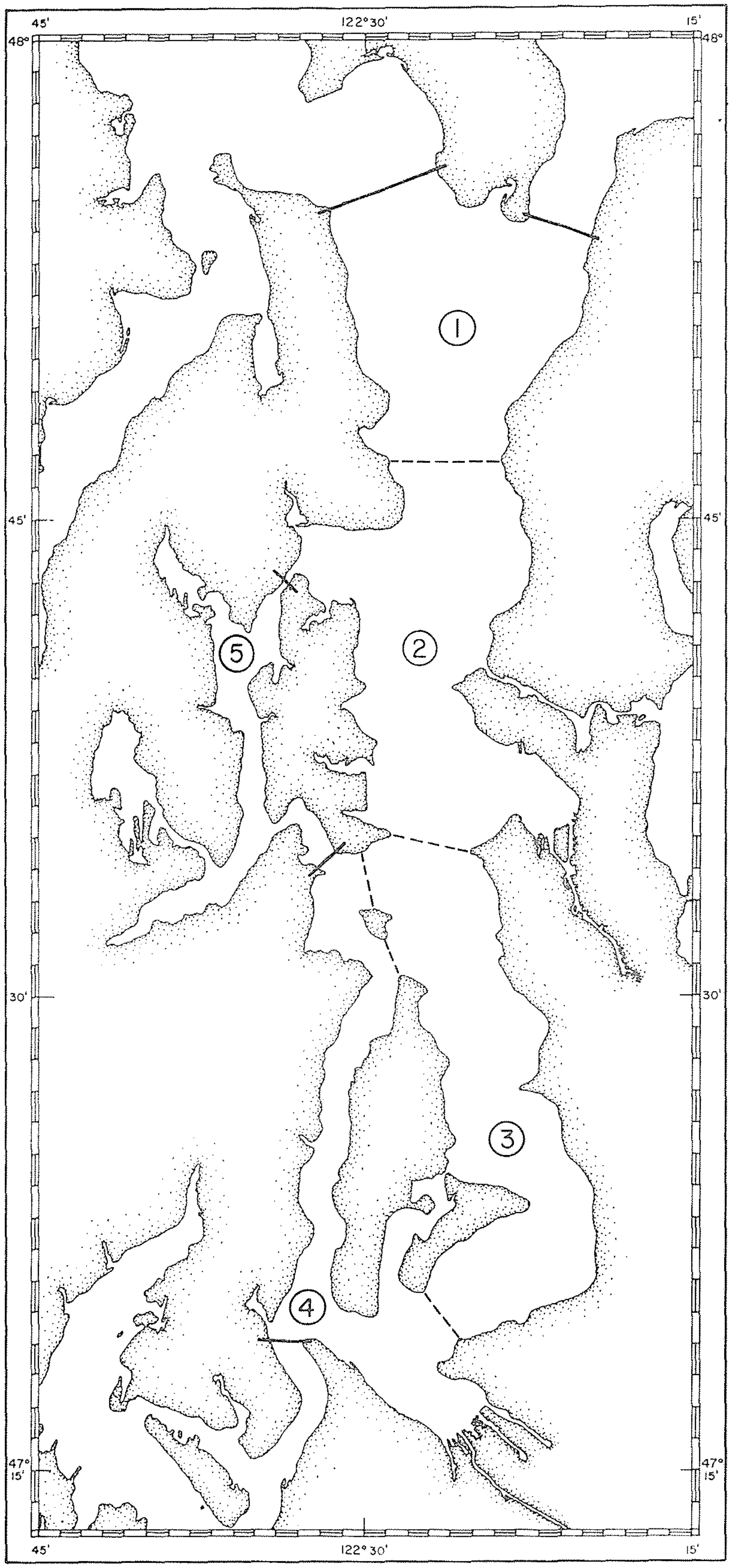


Figure 4-4

Oceanographic subdivisions of Puget Sound main basin.

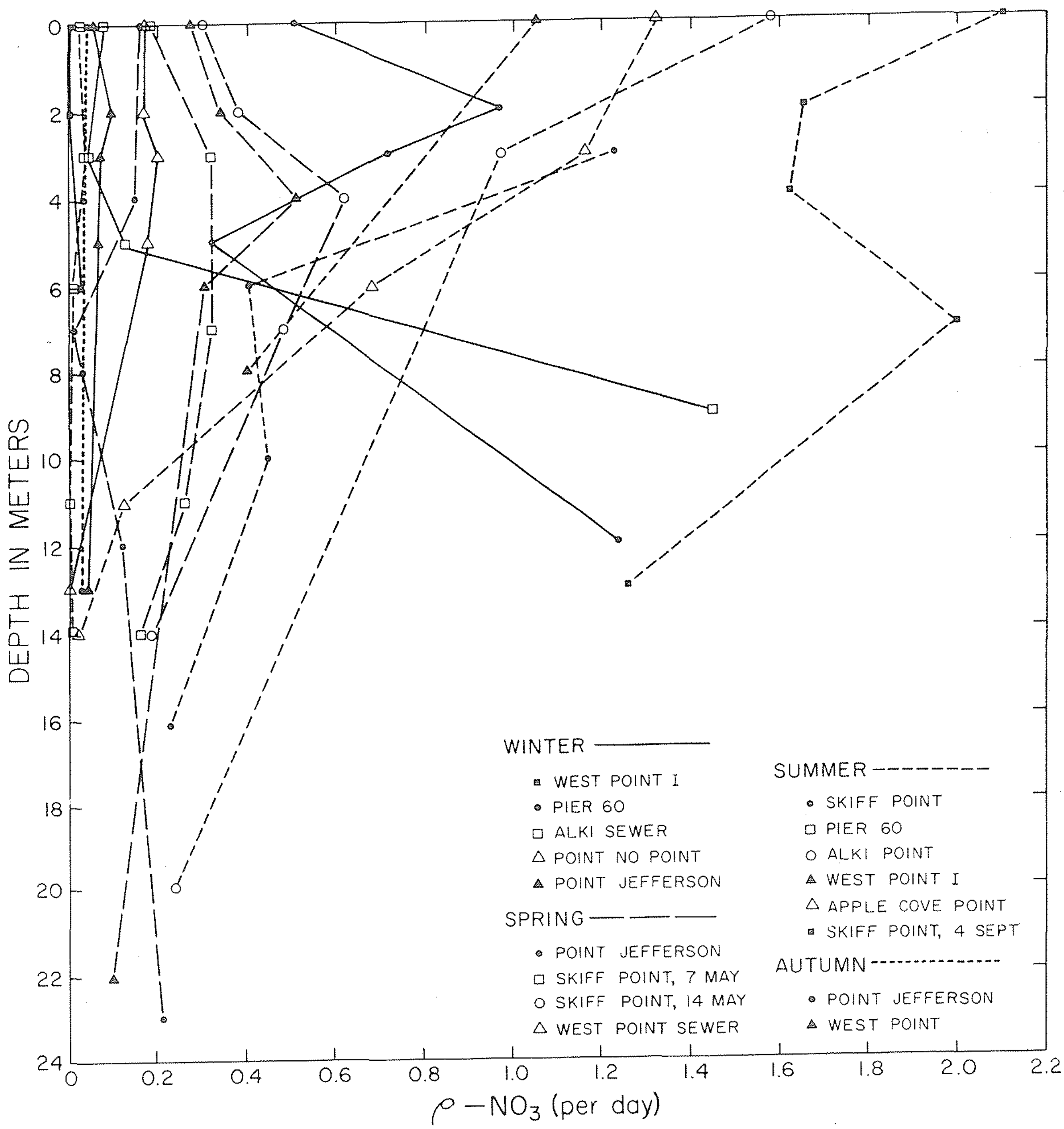


Figure 4-5

Uptake rates of ^{15}N-labeled nitrate vs. depth at selected stations and times.

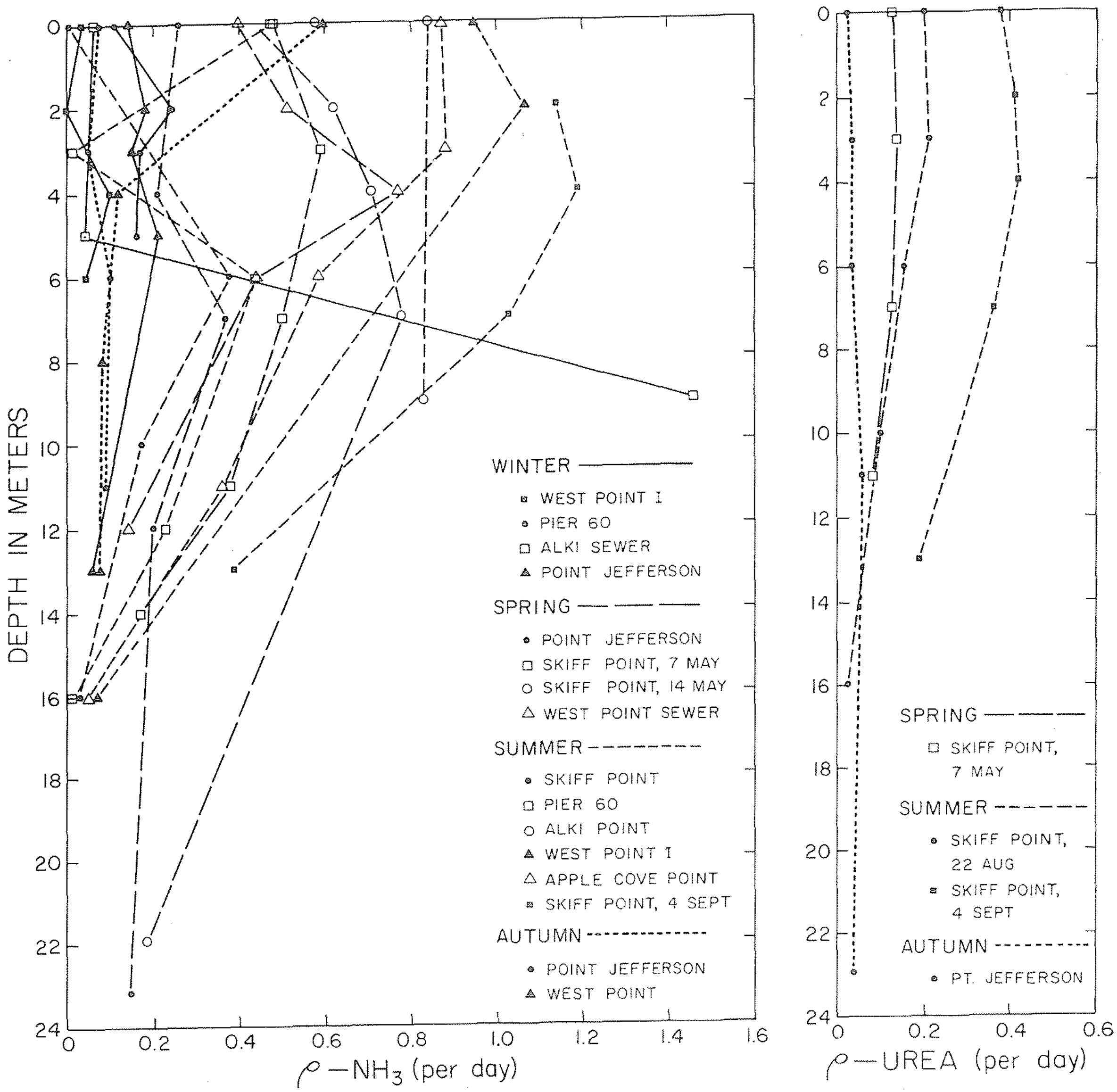


Figure 4-6

Uptake rates of ^{15}N-labeled ammonia and urea vs. depth at selected stations and times.

5.0 SUMMARY AND CONCLUSION

Compared to the long-term average from historical water characteristic data obtained from 1932 to 1963, the integrated mean concentration of phosphate in the upper 20m in the main basin of Puget Sound for the present period (1974-75) was about 10% higher. However, this increase was well within the normal variability observed in the historical data and, with few exceptions, the recent data fell within one standard deviation (the 67% confidence level) envelope of the earlier data (see Fig. 4-3). Water properties observed along the longitudinal axis of the main basin (see Figs. 3-2 through 3-21) show no significant departure from similar data obtained from 1952 through 1954 (Collias, McGary, and Barnes, 1974). Major changes in the climatic patterns of the northeast Pacific Ocean affect the amount of upwelling along the Washington coast and hence the nature of the deeper oceanic type water entering the Strait of Juan de Fuca and Puget Sound. Long-term changes in both dissolved oxygen and phosphate concentrations off Point Jefferson have been documented by Duxbury (1974).

The average daily contribution of phosphate (as $PO_4^{\equiv}$ ion) from the total sewage discharge into the main basin (Section 1.2.7) is only 12.58 metric tons. In comparison, the average daily flux of phosphate into or out of the main basin is 1,210 tons while the average amount of phosphate in the main basin at any given time is over 18,400 tons. Thus, the contribution by the sewers is a minor fraction of these amounts. Lack of complete data precluded similar analysis for nitrate. Since phosphate and nitrate tend to be utilized in a nearly constant ratio (see Section 4.4.1), it can be assumed with considerable confidence that the two nutrients behave similarly.

A comparison of the present oxygen data with the historical data indicated that no measurable change had occurred(Fig. 4-2),even though the population surrounding the main basin had increased 2.5 times from 1930 to 1973. Slower changes in dissolved oxygen content are closely related to long-term climatic changes in a manner similar to nutrients. The seasonal low oxygen in autumn reflects the intrusion of the deep oceanic type water that was originally upwelled off Cape Flattery in summer.

The contribution of ammonia from a sewer may be used as a "near-field" tracer of effluent,but the ammonia decreased to near background within about 1.5 km and in a short period of time. Observations about 2km either side of the West Point outfall failed to show elevated ammonia concentrations.

The uptake rates of nitrate and ammonia by phytoplankton showed a definite seasonal trend and were high in comparison to open ocean values as would be expected from the natural highly productive area of the main basin of Puget Sound.

Model observations and limited field observations indicated that the effluent plume from the West Point outfall was filamentous, fractured, and generally of low concentration outside the "near field". The eddy structure and turbulence developed in the vicinity of West Point from tidal action, dispersed effluent filaments across the main basin as well as in the north-south direction. The southern excursion of the effluent was less than 7km from West Point while the net movement was to the north and out of the system.

From these data, both new and old, it is concluded that the sewage entering the main basin of Puget Sound from the sewers of METRO and other sewage systems has had no measurable effect upon either the nutrient concentrations or the dissolved oxygen content except in the "near field" at an outfall. The "near field" effect is very localized and has no impact upon the entire system.

6. LITERATURE CITED

Armstrong, F. A. J., C. R. Sterns, and J. D. H. Strickland
1967 The measurement of upwelling and subsequent biological processes by means of the Technicon AutoAnalyzer and associated equipment. *Deep-Sea research.* Vol. 14, No. 3, pages 381 - 389.

Campbell, Serena, Willis K. Peterson, and James Postel
1977 Phytoplankton production and standing stock in the main basin of Puget Sound. METRO (In press)

Collias, Eugene E.
1976 Physical and chemical oceanographic data from the main basin of Puget Sound, November 1974 - November 1975. METRO (In press).

Collias, Eugene E., John H. Lincoln, and Clifford A. Barnes
1973 Skagit Bay Study, Dynamical Oceanography, Final Report. University of Washington, Department of Oceanography, Reference No. M73-73, 197 pages.

Collias, Eugene E., Noel McGary, and Clifford A. Barnes
1974 Atlas of Physical and Chemical Properties of Puget Sound and Approaches. University of Washington Press, Seattle and London.

Cox, Ronald A., M. M. McCartney, and F. Calkin
1970 The specific gravity/salinity/temperature relationship in natural sea water. *Deep-Sea Research,* Vol. 17, No. 4, pages 679 - 690.

Dugdale, Richard C. and J. J. Goering
1967 Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnology and Oceanography.* Vol. 18, pages 196 - 206.

Duxbury, Alyn C.
1974 Orthosphosphate and dissolved oxygen in Puget Sound. *Limnology and Oceanography.* Vol. 17, No. 2, pages 270 - 274.

Ebbesmeyer, Curtis C. and Clifford A. Barnes
1976 Some aspects of Puget Sound's circulation and water properties. *Proceedings of the Seventh Baruch Symposium on Estuarine Transport Processes, 19-22 May 1976, Georgetown, S.C.* (In press)

Ebbesneyer, Curtis C. and Jonathan M. Helseth
1975 A study of current properties and mixing using drogue movement observed during summer and winter in central Puget Sound, Washington. METRO, 81 pages.

Friebertshauser, Mark A. and Alyn C. Duxbury
1972 A water budget study of Puget Sound and its subregions. *Limnology and Oceanography.* Vol. 17, No. 2, pages 237 - 247.

Isaacs, John D. and Oscar E. Sette
1959 Unusual Conditions in the Pacific. *Science.* 3 March 1959.

Knudsen, Martin (Editor)
1901 Hydrographical Tables. G. E. C. Gad, Copenhagen, 63 pages.

Koroleff, F.
1970 Revised version of "Direct determination of ammonia in natural waters as indephenol blue". International Council for the Exploration of the Sea, C.M. 1969/C:9. ICES, Information on Techniques and Methods for Sea Water Analysis, Interlaboratory Report No. 3, pages 19-22.

Paquette, Robert G.
1958 A modification of the Wenner-Smith-Soule salinity bridge for the determination of salinity of sea water. University of Washington Department of Oceanography. Technical Report No. 61, 62 pages.

Pavlou, Spyros P., G. E. Friederich, J. J. Mac Isaac, and R. C. Dugdale
1974 A modified tracer technique for the determination of nitrogen uptake by marine phytoplankton. *Tethys.* Vol. 6, No. 1-2, pages 171 - 178.

Schell, William and others
1977 Heavy metals near the West Point outfall and in the main basin of Puget Sound. METRO (In press)

Sverdrup, H. U., Martin W. Johnson, and Richard H. Fleming
1946 The Oceans: their physics, chemistry, and general biology. Prentice-Hall, Inc., New York.

Thompson, Thomas G. and Rex J. Robinson
1939 Notes on the determination of dissolved oxygen in sea water. *Sears Journal of Marine Research.* Vol. 2, No. 1, pages 1 - 8.

U.S. Geological Survey
1974 Water Resources Data for WAshington, Part 1. Surface water records for the water year 1974. U. S. Geological Survey, Water Resources Division, Tacoma, Washington.

U.S. Geological Survey
1975 Water Resources Data for Washington, Water Year 1975. U. S. Geological Survey, Water Resources Division, Tacoma, Wash.

Waldichuk, Michael
1957 Physical Oceanography of the Strait of Georgia, British Columbia. *Journal of the Fisheries Research Board of Canada.* Vol. 14, No. 3, pages 321 - 486.

Weiss, R. F.
1970 The solubility of nitrogen, oxygen, and argon in water and sea water. *Deep-Sea Research.* Vol. 17, No. 4, pages 721-736.

APPENDIX A

RESULTS OF UPTAKE RATES USING ^{15}N-LABELED COMPOUNDS CONTAINING NITRATE AND AMMONIUM IONS AND ^{15}N-LABELED UREA

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-06 (OA-637)

STATION - 1 at West Point Sewer End DATE - 19 February 1975 TIME - 0912 (08)

LAT. 47° 39.7'N LONG. 122° 26.7'W SECCHI DISK - 6m

NITRATE UPTAKE

Amount of nitrate added = 2.21 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	32.4	1.09	4.25	------	------	------
2	50	32.5	2.15	4.74	------	------	------
6	15	34.3	2.13	3.26	0.0090	0.0024	0.0292
15	1	33.6	1.99	2.75	0.0147	0.0035	0.0418

AMMONIA UPTAKE

Amount of ammonia added = 0.44 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	3.81	1.09	3.84	0.00080	0.0020	0.0356
2	50	4.12	2.15	3.96	0.00000	0.0000	0.0000
4	30	2.31	2.07	4.08	0.00193	0.0059	0.1070
6	15	3.53	2.13	3.91	0.0082	0.0025	0.0446

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-06 (OA-637)

STATION - 2 at Pier 60 DATE - 19 February 1975 TIME - 1142 (08)

LAT. 47° 36.4'N LONG. 122° 20.8'W SECCHI DISK - 4.5m

NITRATE UPTAKE

Amount of nitrate added = 2.21 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	31.8	2.65	2.53	0.01613	0.0418	0.5013
2	50	30.4	1.12	3.07	0.03839	0.0806	0.9674
3	30	30.7	0.54	1.13	0.07101	0.0596	0.7158
5	15	31.4	0.70	1.00	0.03094	0.0263	0.3156
12	1	39.2	0.44	0.95	0.14718	0.1030	1.2363

AMMONIA UPTAKE

Amount of ammonia added = 0.44 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	3.53	2.65	3.11	0.00221	0.0064	0.1146
2	50	3.49	1.12	2.16	0.00862	0.0141	0.2545
3	30	0.67	0.54	1.41	0.00963	0.0094	0.1699
5	15	1.19	0.70	1.33	0.00876	0.0089	0.1608
12	1	0.01	0.44	0.64	--	--	--

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-06 (OA-637)

STATION - 6 at Alkai Sewer DATE - 19 February 1975 TIME - 1518 (08)

LAT. 47° 34.3'N LONG. 122° 25.2 SECCHI DISK - 5m

NITRATE UPTAKE

Amount of nitrate added = 2.21 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)		$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$)	
			Initial	Final		(μg-at/l /hour)	(μg-at/l /day)
0	100	26.0	0.45	0.94	0.20845	0.1459	1.7510

AMMONIA UPTAKE

Amount of ammonia added = 0.49 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen		$V-NH_3$	Ammonia uptake ($\rho-NH_3$)	
			Initial	Final		(per hour)	(per day)
0	100	0.03	0.45	0.99	0.04499	0.0324	0.5831

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-06 (OA-637)

STATION - 8 at Alkai Sewer DATE - 20 February 1975 TIME - 0942 (08)

LAT. 47^{o} 34.2'N LONG. 122^{o} 26.5'W SECCHI DISK - 8m

NITRATE UPTAKE

Amount of nitrate added = 2.21 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	23.5	1.02	1.80	0.00460	0.0065	0.0778
3	50	28.0	1.93	3.24	0.00135	0.0035	0.0420
5	30	23.0	1.04	1.65	0.00773	0.0104	0.1252
9	15	20.0	0.53	0.81	0.18472	0.1238	1.4851
21	1	19.9	0.29	0.71	--	--	--

AMMONIA UPTAKE

Amount of ammonia added = 0.44 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	4.32	1.02	2.16	0.00242	0.0038	0.0693
3	50	> 8.80	1.93	3.53	--	--	--
5	30	4.38	1.04	2.18	0.00245	0.0025	0.0445
9	15	0.01	0.53	0.80	0.12112	0.0812	1.4607
21	1	0.00	0.29	0.80	--	--	--

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-06 (OA-637)

STATION - 16 at Point Jefferson DATE - 21 February 1975 TIME - 0730 (08)

LAT. 47° 44.4'N LONG. 122° 25.5'W SECCHI DISK - 5m

NITRATE UPTAKE

Amount of nitrate added = 2.21 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	18.2	0.83	1.57	0.00359	0.0043	0.0517
2	50	19.0	0.74	1.13	0.00861	0.0081	0.0971
3	30	18.8	0.93	1.37	0.00467	0.0054	0.0644
5	15	18.4	0.76	1.41	0.00458	0.0050	0.0599
13	1	17.5	0.87	1.33	0.00313	0.0034	0.0413

AMMONIA UPTAKE

Amount of ammonia added = 0.44 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	0.29	0.83	1.32	0.00726	0.0078	0.1400
2	50	0.33	0.74	1.52	0.00867	0.0098	0.1763
3	30	0.31	0.93	1.58	0.00687	0.0087	0.1558
5	15	0.32	0.76	1.21	0.01213	0.0120	0.2162
13	1	0.27	0.87	1.18	0.00349	0.0036	0.0647

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-Anderson Cruise-09 (OA-659)

STATION - 1 DATE - 28 April 1975 TIME - 1018 (+07)

LAT. 47° 40.7'N LONG. 122° 27.7'W SECCHI DISK - 9m

NITRATE UPTAKE

Amount of nitrate added = 4.59 µg-at/l

Depth (m)	Light (%)	Initial Nitrate (µg-at/l)	Particulate Nitrogen (µg-at/l) Initial	Final	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (µg-at/l /hour)	(µg-at/l /day)
0	100	25.2	0.55	1.47	0.01338	0.0135	0.1622
4	50	25.3	0.99	1.31	0.01103	0.0127	0.1522
7	30	25.4	0.49	5.59	0.00022	0.0007	0.0080
12	15	25.5	0.48	1.59	0.00978	0.0102	0.1221
23	1	25.5	0.45	1.17	0.02254	0.0183	0.2191

AMMONIA UPTAKE

Amount of ammonia added = 0.92 µg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	0.59	0.55	1.19	0.01656	0.0144	0.2593
4	50	0.59	0.99	1.03	0.01168	0.0118	0.2123
7	30	0.71	0.49	1.03	0.02718	0.0207	0.3718
12	15	1.08	0.48	1.01	0.01061	0.0111	0.2005
23	1	0.67	0.45	1.23	0.00876	0.0074	0.1325

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-06 (OA-637)

STATION - 17 Point No Point DATE - 21 February 1975 TIME - 1030 (08)

LAT. 47° 54.0'N LONG. 122° 28.0'W SECCHI DISK - 5m

NITRATE UPTAKE

Amount of nitrate added = 2.21 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	27.1	0.80	1.26	0.01354	0.0139	0.1674
2	50	26.2	0.79	1.19	0.01402	0.0139	0.1666
3	30	26.7	1.15	1.32	0.01329	0.0165	0.1978
5	15	26.1	0.94	1.06	0.01461	0.0146	0.1753
13	1	27.0	0.47	0.75	--	--	--

AMMONIA UPTAKE

Amount of ammonia added = 0.44 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	--	0.80	1.30	--	--	--
2	50	0.27	0.79	1.24	--	--	--
3	30	0.25	1.15	1.37	--	--	--
5	15	0.21	0.94	2.12	--	--	--
13	1	0.11	0.47	0.86	0.05604	0.0375	0.6758

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-Anderson Cruise-18 (OA-659)

STATION - 1 Skiff Point DATE - 7 May 1975 TIME - 1130 (+07)

LAT. 47° 40.7'N LONG. 122° 27.7'W SECCHI DISK - 8.5m

NITRATE UPTAKE

Amount of nitrate added = 4.59 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	22.7	1.32	2.13	0.00851	0.0147	0.1767
3	50	22.9	1.90	2.49	0.01245	0.0274	0.3287
7	30	23.3	1.44	2.72	0.01284	0.0267	0.3205
11	15	23.9	1.03	1.72	0.01615	0.0223	0.2674
22	1	24.1	0.76	1.11	0.01488	0.0140	0.1678

AMMONIA UPTAKE

Amount of ammonia added = 0.92 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	0.75	1.32	2.75	0.01302	0.0266	0.4781
3	50	0.55	1.90	2.44	0.01511	0.0328	0.5902
7	30	0.55	1.44	2.24	0.01505	0.0277	0.4985
11	15	0.62	1.03	1.91	0.01437	0.0211	0.3802
22	1	0.81	0.76	1.11	0.00928	0.0087	0.1570

UREA UPTAKE

Amount of urea added = 3.67 μg-at/l

Depth	Light	Initial Urea	Particulate Nitrogen Initial	Final	V-UREA	Urea uptake (ρ-Urea) (per hour)	(per day)
0	100	0.89	1.32	2.76	0.00485	0.0099	0.1187
3	50	0.78	1.90	2.48	0.00515	0.0108	0.1292
7	30	0.82	1.44	1.98	0.00602	0.0103	0.1235
11	15	0.86	1.03	1.49	0.00585	0.0074	0.0885
22	1	0.85	0.76	0.51	--	--	--

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-Anderson Cruise-25 (OA-659)

STATION - 1 Skiff Point DATE - 14 May 1975 TIME - 1142 (+07)

LAT. 47° 40.7'N LONG. 122° 27.7'W SECCHI DISK - 5.5m

NITRATE UPTAKE

Amount of nitrate added = 4.59 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/1)	Particulate Nitrogen (μg-at/1) Initial	Final	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/1 /hour)	(μg-at/1 /day)
0	100	19.0	5.66	4.79	0.00475	0.0248	0.2981
2	50	19.4	2.74	5.09	0.00809	0.0317	0.3806
4	30	17.7	4.11	4.94	0.01145	0.0519	0.6224
7	15	14.2	3.98	4.03	0.01011	0.0405	0.4865
14	1	21.3	1.33	1.80	0.01019	0.0160	0.1920

AMMONIA UPTAKE

Amount of ammonia added = 0.92 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	1.21	5.66	4.32	0.00496	0.0248	0.4455
2	50	1.02	2.74	4.02	0.01027	0.0347	0.6248
4	30	0.67	4.11	4.32	0.00933	0.0394	0.7087
7	15	0.50	3.98	3.26	0.01196	0.0433	0.7793
14	1	0.92	1.33	1.64	0.00648	0.0097	0.1738

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-Anderson Cruise-25 (OA-659)

STATION - West Point Sewer DATE - 14 May 1975 TIME - 1200 (+7)

LAT. 47° 40.7'N LONG. 122° 27.8'W SECCHI DISK - 4.5m

NITRATE UPTAKE

Amount of nitrate added = 4.59 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l) Initial	Final	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	12.5	2.32	3.16	0.00812	0.0222	0.2670
2	50	12.4	2.97	3.44	0.00892	0.0286	0.3436
4	30	17.1	4.31	3.70	0.01072	0.0430	0.5158
6	15	19.5	2.98	3.25	0.00792	0.0247	0.2965
12	1	22.2	2.68	1.56	0.00372	0.0079	0.0946

AMMONIA UPTAKE

Amount of ammonia added = 0.92 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen Initial	Final	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	0.42	2.32	4.64	0.01175	0.0222	0.4005
2	50	0.41	2.97	3.98	0.01287	0.0286	0.5154
4	30	0.38	4.31	4.47	0.01087	0.0430	0.7738
6	15	0.44	2.98	3.21	0.01338	0.0247	0.4448
12	1	0.79	2.68	1.83	0.00440	0.0079	0.1420

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MT-109 (OA-672)

STATION - 1 off Skiff Point DATE - 22 August 1975 TIME - 0948 (+07)

LAT. 47° 40.7'N LONG. 122° 27.7'W SECCHI DISK - 7m

NITRATE UPTAKE

Amount of nitrate added = 2.41 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	15.3	3.82	--	--	--
3	50	15.6	4.80	0.02141	0.10278	1.2333
6	25	15.5	3.20	0.01019	0.03263	0.3916
10	10	15.4	4.94	0.00775	0.03833	0.4599
16	1	16.1	3.70	0.00511	0.01893	0.2272

AMMONIA UPTAKE

Amount of ammonia added = 0.71 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	0.15	2.88	0.00014	0.00042	0.00754
6	25	0.13	5.24	0.00403	0.02114	0.38047
10	10	0.12	3.69	0.00260	0.00960	0.17287
16	1	0.17	3.47	0.00049	0.00173	0.03103

UREA UPTAKE

Amount of urea added = 3.70 μg-at/l

Depth	Light	Initial Urea	Particulate Nitrogen	V-UREA	Urea uptake (ρ-Urea) (per hour)	(per day)
0	100	0.17	5.15	0.00221	0.01139	0.20507
3	50	0.76	4.80	0.00243	0.01168	0.21015
6	25	0.34	4.67	0.00180	0.00841	0.15138
10	10	0.29	4.64	0.00108	0.00505	0.09086
16	1	0.24	3.04	0.00043	0.00132	0.02374

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-17 (K7-053)

STATION - 17 at Pier 60 DATE - 25 August 1976 TIME - 0930 (+07)

LAT. 47° 36.4'N LONG. 122° 20.8'W SECCHI DISK - 8m

NITRATE UPTAKE

Amount of nitrate added = 5.25 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	21.6	2.42	0.00097	0.002363	0.02836
3	50	21.0	1.98	0.00162	0.003214	0.03857
6	25	20.6	2.00	0.00018	0.000376	0.00451
11	10	21.6	1.50	0.00017	0.000264	0.00317
22	1	22.4	1.37	0.00136	0.001863	0.02236

AMMONIA UPTAKE

Amount of ammonia added = 1.04 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	5.37	4.65	0.00571	0.026575	0.47835
3	50	2.19	1.98	0.00041	0.000815	0.01467
6	25	1.62	2.25	0.01090	0.024529	0.44152
12	10	0.73	1.27	0.01024	0.013007	0.23413
24	1	0.42	1.26	0.00259	0.003267	0.05881

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-17 (K7-053)

STATION - 20 at Alkai Point DATE - 25 August 1975 TIME - 1200 (+07)

LAT. 47° 34.2'N LONG. 122° 26.5'W SECCHI DISK - 7m

NITRATE UPTAKE

Amount of nitrate added = 5.26 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	18.6	4.32	0.03062	0.13230	1.5876
3	50	20.0	3.31	0.02450	0.08111	0.9733
20	1	21.3	1.17	0.00168	0.00197	0.0236

AMMONIA UPTAKE

Amount of ammonia added = 1.04 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	0.70	4.57	0.01020	0.04665	0.8397
9	10	0.63	3.89	0.01183	0.04604	0.8288

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-17 (K7-053)

STATION - 27 at West Point I   DATE - 27 August 1976   TIME - 0742 (+07)

LAT. 47° 39.7'N   LONG. 122° 26.7'W   SECCHI DISK - 6m

NITRATE UPTAKE

Amount of nitrate added = 5.26 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	9.5	5.42	0.01619	0.08775	1.0530
8	10	10.6	5.99	0.00565	0.03389	0.4067

AMMONIA UPTAKE

Amount of ammonia added = 1.04 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V\text{-}NH_3$	Ammonia uptake (ρNH_3) (per hour)	(per day)
0	100	0.68	5.93	0.00891	0.05285	0.9513
2	50	0.54	5.40	0.01104	0.05963	1.0733
16	1	0.48	2.95	0.00162	0.00480	0.0864

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-17 (K7-053)

STATION - 28 at Apple Cove Point DATE - 27 August 1975 TIME - 0912 (+07)

LAT. 47° 49.0'N LONG. 122° 27.5'W SECCHI DISK - 8m

NITRATE UPTAKE

Amount of nitrate added = 5.26 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	19.4	5.58	0.01990	0.11108	1.3230
3	50	19.3	5.03	0.01921	0.09664	1.1596
6	25	19.2	4.28	0.01336	0.05721	0.6865
11	10	19.3	3.41	0.00262	0.00893	0.1072
22	1	21.7	2.66	0.00044	0.00120	0.0143

AMMONIA UPTAKE

Amount of ammonia added = 1.04 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	0.47	5.28	0.00925	0.04885	0.8793
3	50	0.50	5.23	0.00935	0.04891	0.8804
6	25	0.50	7.27	0.00446	0.03249	0.5848
11	10	0.50	3.24	0.00620	0.02011	0.3619
22	1	0.68	2.34	0.00163	0.00383	0.0690

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MT-122 (OA-672)

STATION - 1 off Skiff Point DATE - 4 September 1975 TIME - 1640 (08)

LAT. 47° 41.0'N LONG. 122° 27.7'W SECCHI DISK - 5m

NITRATE UPTAKE

Amount of nitrate added = 4.80 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	8.58	6.10	0.02932	0.17886	2.1463
2	50	8.52	5.96	0.02318	0.13820	1.6584
4	25	7.81	5.72	0.02366	0.13537	1.6244
7	10	10.23	6.10	0.02729	0.16648	1.9978
13	1	11.09	5.27	0.00425	0.02243	1.2692

AMMONIA UPTAKE

Amount of ammonia added = 1.91 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
2	50	0.33	5.91	0.01073	0.063457	1.14223
4	25	0.40	5.76	0.01149	0.066185	1.19133
7	10	0.46	5.46	0.01157	0.063203	1.13765
13	1	0.39	5.24	0.00413	0.021650	0.38970

UREA UPTAKE

Amount of urea added = 3.70 μg-at/l

Depth	Light	Initial Urea	Particulate Nitrogen	V-UREA	Urea uptake (ρ-Urea) (per hour)	(per day)
0	100	0.48	6.24	0.00341	0.021338	0.38408
2	50	0.64	6.16	0.00366	0.022599	0.40678
4	25	1.04	6.00	0.00394	0.023646	0.42563
7	10	1.14	5.57	0.00363	0.020245	0.36441
13	1	0.65	5.19	0.00206	0.010729	0.19312

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-22 (K7-061)

STATION - 1 at Point Jefferson DATE - 17 November 1976 TIME - 1218 (08)
LAT. 47^{o} 44.4'N LONG. 122^{o} 25.5'W SECCHI DISK - 8m

NITRATE UPTAKE

Amount of nitrate added = 4.82 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V-NO_3$ (/hour)	Nitrate uptake ($\rho-NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	27.3	2.02	0.00074	0.00151	0.01806
3	50	27.6	1.70	0.00090	0.00153	0.01841
6	25	27.5	2.02	0.00104	0.00212	0.02544
11	10	27.7	1.40	0.00135	0.00190	0.02278
22	1	28.2	1.28	0.00122	0.00157	0.01882

AMMONIA UPTAKE

Amount of ammonia added = 1.91 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V-NH_3$	Ammonia uptake ($\rho-NH_3$) (per hour)	(per day)
0	100	0.52	2.18	0.00163	0.003573	0.06431
3	50	0.43	1.70	0.00171	0.002914	0.05234
6	25	0.40	1.84	0.00313	0.005763	0.10373
11	10	0.40	1.98	0.00262	0.005201	0.09362
22	1	0.40	1.99	0.00149	0.002965	0.05337

UREA UPTAKE

Amount of urea added = 2.77 μg-at/l

Depth	Light	Initial Urea	Particulate Nitrogen	V-UREA	Urea uptake (ρ-Urea) (per hour)	(per day)
0	100	0.76	1.95	0.00061	0.001201	0.02164
3	50	0.84	2.04	0.00097	0.001984	0.03571
6	25	0.58	2.00	0.00092	0.001841	0.03314
11	10	1.05	2.35	0.00131	0.003082	0.05548
22	1	0.73	1.98	0.00096	0.001904	0.03427

NITROGEN UPTAKE EXPERIMENTS
FOR CRUISE MET-22 (K7-061)

STATION - 14 at West Point I   DATE - 19 November 1975   TIME - 0743 (08)

LAT. 47° 39.7'N   LONG. 122° 20.7'W   SECCHI DISK - 10m

NITRATE UPTAKE

Amount of nitrate added = 4.82 μg-at/l

Depth (m)	Light (%)	Initial Nitrate (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V\text{-}NO_3$ (/hour)	Nitrate uptake ($\rho\text{-}NO_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	25.4	2.44	0.00144	0.003524	0.04229
4	50	26.8	1.77	0.00132	0.002336	0.02803
8	25	26.3	1.45	0.00185	0.002695	0.03234
13	10	25.7	1.74	0.00136	0.002379	0.02855
27	1	26.0	1.97	0.00092	0.001813	0.02176

AMMONIA UPTAKE

Amount of ammonia added = 2.39 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	2.60	1.77	0.00647	0.011467	0.60641
4	50	0.30	3.71	0.00167	0.006231	0.11216
8	25	0.38	1.33	0.00347	0.004621	0.08318
13	10	0.89	1.52	0.00262	0.003988	0.07178
27	1	1.08	1.90	0.00076	0.001458	0.02624

NITROGEN UPTAKE EXPERIMENTS

FOR CRUISE MET-22 (K7-061)

STATION - 15 at Alkai Point Sewer DATE - 19 November 1976 TIME - 0848 (08)

LAT. 47° 34.3'N LONG. 122° 25.2'W SECCHI DISK - 9m

AMMONIA UPTAKE

Amount of ammonia added = 2.39 μg-at/l

Depth (m)	Light (%)	Initial Ammonia (μg-at/l)	Particulate Nitrogen (μg-at/l)	$V\text{-}NH_3$ (/hour)	Ammonia uptake ($\rho\text{-}NH_3$) (μg-at/l /hour)	(μg-at/l /day)
0	100	0.36	1.50	0.00236	0.003550	0.06390
3	50	0.36	1.63	0.00196	0.003194	0.05749
6	25	0.59	1.35	0.00272	0.003678	0.06620
10	10	0.33	1.32	0.00235	0.003114	0.05673
20	1	0.25	1.17	0.00094	0.001100	0.01980

STATION - 19 at Pier 60 DATE - 19 November 1976 TIME - 1336

LAT. 47° 36.4'N LONG. 122° 20.8'W

AMMONIA UPTAKE (Surface sample only)

Amount of ammonia added = 2.39 μg-at/l

Depth	Light	Initial Ammonia	Particulate Nitrogen	$V\text{-}NH_3$	Ammonia uptake ($\rho\text{-}NH_3$) (per hour)	(per day)
0	100	2.93	3.15	0.00314	0.009916	0.017849