July 1991

Field Studies of Nut Island Sewage Plumes and Background Water Properties in Boston Harbor: October-November 1990

Massachusetts Water
Resources Authority

Environmental Quality Department
Technical Report No. 91-7

FIELD STUDIES OF NUT ISLAND SEWAGE PLUMES AND BACKGROUND WATER PROPERTIES IN BOSTON HARBOR: OCTOBER-NOVEMBER 1990

by Scott McDowell
John Ryther, Jr.
Carl Albro

Prepared For:
Massachusetts Water Resources Authority
Harbor Studies Group
Charlestown Navy Yard
Boston, Massachusetts 02129

Environmental Quality Department Technical Report Series No. 91-7

Prepared By:
Battelle Ocean Sciences
397 Washington Street
Duxbury, Massachusetts 02332

July 1991

ACKNOWLEDGMENTS

This project was conducted with funding from the Massachusetts Water Resources Authority (MWRA) Harbor Studies Program through a contract with Battelle Ocean Sciences. Ms. Wendy Smith was the MWRA project manager for this project. We wish to thank Ms. Smith for her program assistance and technical input throughout the conduct of this project.

Dr. Scott McDowell was the project manager and chief scientist on this project. Mr. John Ryther, Jr., was responsible for the planning and conduct of the field activities and assisted in the preparation of the final report. Mr. Carl Albro developed the Mini-BOSS and conducted the majority of the data processing. Mr. Kevin King provided artistic rendering to many of the maps and data products. Mr. Tony Luksas fabricated the drifters and was responsible for the drifter tracking activities. Mr. Jack Bechtold and Mr. Kevin King provided technical support in the final development of the Mini-BOSS. Assistance from Ms. Heather Amoling for preparation of this report is greatly appreciated.

The survey vessels and vessel operators provided by TG&B Marine Services for the field activities contributed greatly to the success of this project. Special thanks are extended to Mr. Mark Avakian and Mr. Pete Sachs who operated the vessels.

CONTENTS

1.0 INTRODUCTION

2.0 DESCRIPTION OF MEASUREMENT PROGRAM

3.0 BACKGROUND WATER PROPERTIES THROUGHOUT THE HARBOR

4.0 STUDIES OF NUT ISLAND EFFLUENT PLUMES IN NANTASKET ROADS

CONTENTS (continued)

5.0 STUDIES OF NUT ISLAND SLUDGE PLUMES AT LONG ISLAND

6.0 DISCUSSION

7.0 REFERENCES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

1.0 INTRODUCTION

1.1 BACKGROUND

The Massachusetts Water Resources Authority (MWRA) is conducting studies to determine the present environmental conditions within Boston Harbor in order that improvements in the chemical and biological "health" of the Harbor can be detected when sewage discharge into the Harbor is terminated. A major component of this Harbor-wide pollution problem is the sewage plumes emanating from the various Deer Island and Nut Island sewage outfalls distributed throughout the Harbor (Figure 1-1). Three outfalls located within Nantasket Roads continually discharge sewage effluent generated by the Nut Island treatment plant. Two other outfalls are located in President Roads; one (located north of Long Island) discharges Nut Island sewage sludge on the ebb flow, the other (located near Deer Island) continually discharges sewage effluent generated at the Deer Island treatment plant. Although sewage plumes have been emanating from these outfalls for many decades, neither their regions of impact nor their chemical and biological effects upon the Harbor are well understood.

In June 1989, Battelle conducted a 2-day pilot study to track the Deer Island and Nut Island sewage plumes within President Roads. One of the results of this brief survey was that the Nut Island sludge plumes may not exit the Harbor during the ebb flow. In fact, they may remain near the outfall during the ebb, then move into the Harbor on the next incoming tide.

The results from the pilot study (Battelle, 1989) included recommendations for additional field measurements to confirm the preliminary conclusions from the pilot study. It was also recommended that a small version of the Battelle Ocean Sampling System (BOSS), the primary measurement tool used on the pilot study, be developed for use on small survey vessels that could maneuver in the shallow areas of the Harbor.

In the summer of 1990, Battelle developed the Mini-BOSS for high-resolution water-property surveys in Boston Harbor and other coastal areas. This measurement capability allowed Battelle to propose a detailed field survey of the various sewage plumes in Boston Harbor as preliminarily recommended in the report from the pilot study (Battelle, 1989). The scope of this field program was refined through collaboration with the MWRA; the specific objectives are given in the next section.

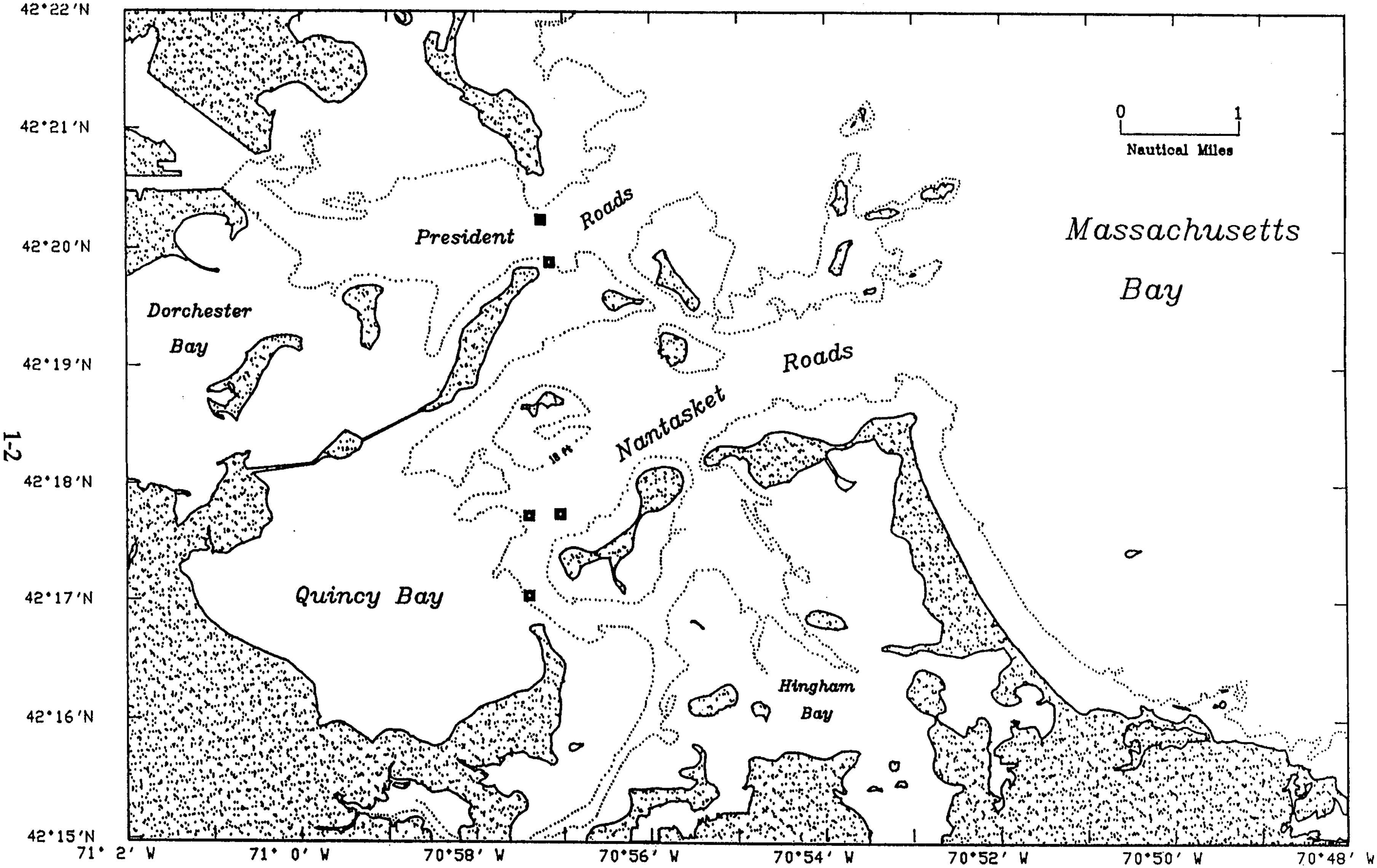

Figure 1-1. Chart of Boston Harbor Showing Locations of Sewage Outfalls in President Roads and Nantasket Roads.

1.2 STUDY OBJECTIVES

The field study conducted in Boston Harbor during October and November 1990 had four main measurement objectives, which are listed below. As demonstrated in the following Sections, a vast amount of high-resolution water-property data was acquired in achievement of these measurement objectives. To remain within the scope of the present study, it was necessary to formulate key questions that we would attempt to answer as part of the four main objectives. Questions posed within each of the four objectives are given below, and answered in Section 6: Discussion.

Objective 1. **Synoptically map the spatial variability of water properties within Boston Harbor at high water, then again at low water on the same day to determine the temporal variability over one tidal cycle**

Are the water properties within the northern part of the Harbor significantly different from those within the southern part of the Harbor during a synoptic high- or low-water survey?

Can specific water types within the Harbor be identified and uniquely associated with source regions (e.g., Dorchester Bay)?

Can a conceptual model of the circulation and mixing within the Harbor be developed from analysis of the water properties from a single, synoptic, high- or low-water survey?

Do water properties at specific locations within the Harbor vary significantly over one tidal cycle?

Can qualitative conclusions be drawn about flushing at specific locations in the Harbor from analysis of the temporal variability in water properties over one tidal cycle?

Objective 2. **Map the horizontal advection and dilution of the Nut Island sewage effluent plumes emanating from the three outfalls located in Nantasket Roads. Conduct synoptic surveys during the ebb flow on two consecutive days.**

Are the water-property characteristics of the sewage effluent sufficiently different from the receiving waters to allow tracking of the effluent plumes within Nantasket Roads?

Can the separate plumes from the three outfalls be tracked as they are advected eastward within Nantasket Roads?

Do significant concentrations of effluent enter Portuguese Cove on the west side of Peddocks Island as predicted by Signell's numerical model (Bothner *et al.*, 1990)?

Does relatively concentrated effluent reach Massachusetts Bay on a single ebb tide?

Objective 3. **Map the horizontal advection and dilution of the Nut Island sewage sludge plumes emanating from the outfall located north of Long Island in President Roads. Conduct synoptic surveys during the ebb flow on two consecutive days.**

Does the sludge remain as a concentrated plume that exits the Harbor on the ebb flow via South Channel?

Or, does the sludge remain in the vicinity of the outfall near Long Island throughout the ebb period, then get carried into the Harbor on the flood tide? If so, is the sludge carried westward past Long Island or does it enter the southern Harbor via Nubble Channel or through the Narrows?

Do the characteristics of the receiving water around the sludge outfall vary over the 6-h ebb?

Does the initial behavior of the sludge plume created on each ebb tide vary according to wind conditions and other effects?

Do high concentrations of sludge reach the seafloor in the vicinity of the outfall or neighboring regions?

Objective 4. **Monitor the eastward injection of Boston Harbor waters from Nantasket Roads into Massachusetts Bay, as time permits**

How far eastward do Boston Harbor waters penetrate into Massachusetts Bay during one ebb tide?

Is there a recognizable water-property front at the eastern boundary of the Boston Harbor plume that penetrates into Massachusetts Bay on the ebb tide?

A secondary objective of the study was to provide the field results to other Boston Harbor investigators at the MWRA, the United States Geological Survey (USGS) in Woods Hole, the University of Massachusetts at Boston (UMB), and the Massachusetts Institute of Technology (MIT). Collaboration with other investigators of Boston Harbor's physical, chemical, and biological systems will ensure the maximum use of the recent field results, as well as help to design future, optimum studies of the Harbor.

1.3 REPORT ORGANIZATION

This report (Volume I) presents the results of the recent field surveys of background water properties and Nut Island sewage plumes in Boston Harbor. To conduct the various oceanographic analyses of the field results, a large number of informative, graphic data products were generated, but only a subset of these products is included in this volume. To make the full breadth of field results available to the reader, appendices containing the complete set of data products resulting from the field surveys are provided in Volume II (under separate cover).

Within Volume I, Section 2.0 provides a description of the measurement program and the surveying techniques, vessels, and equipment utilized. Section 3.0 presents results from the November 1, 1990, survey of background water properties throughout the Harbor. Section 4.0 presents results from the October 16 and 17 surveys of Nut Island effluent plumes in Nantasket Roads. Section 5.0 presents results from the October 30 and 31 surveys of Nut Island sludge plumes in President Roads. A summary of the survey results, with recommendations for additional analyses and future studies, is presented in Section 6.0. References are given in Section 7.0.

2.0 DESCRIPTION OF MEASUREMENT PROGRAM

2.1 FIELD ACTIVITIES

The schedule for the October field studies of the Nut Island effluent and sludge plumes was planned to coincide with two early-morning ebb tide periods, one the week of October 15, the other 2 weeks later. Daily operations were scheduled to have the survey vessels at the outfalls at the time of high water to make measurements at the beginning of the ebb. This would allow drifter tracking and plume tracking surveys to be performed over the full 6-h ebb cycle during periods of sufficient daylight.

The sludge tracking surveys at the Nut Island sludge outfall (near Long Island) were originally scheduled for the week of October 15 and the effluent plume tracking in Nantasket Roads for the week of October 30. At the request of the MWRA, these dates were switched, with the result that the sludge study was delayed to the second week of operation to allow sufficient time for coordination between Battelle's monitoring program and the dye study being conducted by MIT.

During the week of October 8, field trials were successfully completed with the newly designed Mini-BOSS towfish and the new handling system on the survey vessel R/V *Surveysa*. On October 15 and 16, the vessels R/V *Surveysa* and R/V *Seaquest* were trailered from Duxbury and launched in Hingham, and mobilization activities were performed at the Hewitts Cove Marina.

Mobilization efforts were completed at 0930 h on October 16, and the two survey vessels departed Hingham for the Nut Island effluent outfalls within Nantasket Roads to begin surveying of the effluent plumes and drifter tracking. On October 17, a second day of effluent plume surveying and drifter tracking was performed in the vicinity of the Nut Island effluent outfalls.

On the morning of October 18, horizontal transects were conducted in the Weymouth Fore River and in Quincy Bay as part of a Harbor-wide survey to determine the spatial variability in background water properties throughout the Harbor. These operations were suspended at 1315 h EST as 30-kn winds and resulting 2- to 3-ft seas damaged the conductors in the Mini-BOSS tow cable. Drifter tracking continued throughout the day (see Volume II, Appendix A), but insufficient Mini-BOSS data were acquired for analysis of water-property variability. Beginning at 1800 h EST on October 17, the two survey vessels were hauled and trailered back to Duxbury. During the week of October 22, the tow cable was reterminated and the Mini-BOSS passed operational tests.

On the afternoon of October 29, the two survey vessels were relaunched in Hingham, and dockside checks of the Mini-BOSS were conducted. At 0700 h EST on October 30, the survey vessels departed Hingham enroute to President Roads to conduct sludge plume and dye tracking and drifter operations throughout the ebb tide. During the morning ebb tide on October 31, sludge tracking surveys (without dye injection) and drifter tracking were again conducted in President Roads. At the end of the day, the *Seaquest* was hauled and trailered back to Duxbury.

On November 1, the *Surveysa* was used to conduct a wide-area survey of background water properties throughout the Harbor. One near-synoptic survey was conducted during the morning high tide, and the survey was partially repeated during the afternoon low-water period. Survey operations were suspended by darkness and the *Surveysa* was hauled and trailered back to Duxbury.

2.2 SURVEY VESSELS

All surveying operations were conducted aboard the survey vessels *Seaquest* and *Surveysa,* operated by TG&B Marine Services of Falmouth, Massachusetts, under subcontract to Battelle. Both vessels are 25-ft Privateer workboats with enclosed Chesapeake cabins with full spray curtains providing protection for benches and racks of navigation and computer equipment. Both vessels are equipped with Loran C navigation systems, depth sounders, VHF radios, and radars. Both vessels are capable of 30-kn speeds, which permitted extensive coverage of the Harbor during the drifter exercises and Mini-BOSS background surveys. In addition, they are readily trailerable and were transported from Battelle in Duxbury to the Boston Harbor area for the two survey periods.

The *Surveysa* was equipped with a custom hydraulic A-frame that was used to launch and retrieve the Mini-BOSS during the plume tracking operations. A portable cellular telephone aboard this vessel permitted coordination of the survey operations with MWRA personnel and the Nut Island treatment plant.

2.3 NAVIGATION

Vessel positioning during the Mini-BOSS surveys and the drifter tracking operations was accomplished using Loran C. On the *Surveysa,* a RayNav 570 Loran C unit was interfaced to

Battelle's navigation display and recording system. With this system, the Boston Harbor coastline, including islands and channels, aids to navigation, and depth contours, was digitized and displayed on the navigation system's color monitor. Vessel position was continually updated at 4-s intervals, recorded on computer hard disk, and displayed on the color monitor. Specific positions, such as the edge of the plume, drifter locations, and navigation intercalibration points, were event-marked in the navigation data file throughout the survey so that the time and Loran position of each event could be easily identified. With the Battelle navigation software, map scales can also be readily changed, and navigation offsets or latitude/longitude corrections applied to the data. During the Mini-BOSS surveys, horizontal and vertical profiles were assigned unique computer data filenames to aid data management. At the end of each survey day, data were copied to duplicate computer diskettes and returned to Battelle's facility in Duxbury.

On the *Seaquest,* a Northstar 7000 Loran C unit was interfaced to a second Battelle navigation recording and display system for drogue tracking operations. Using this system, the drogue tracks were displayed on the navigation monitor, and the speed and direction of their trajectories calculated and displayed. Due to an electrical interference problem on the vessel, reliable Loran reception could not be obtained with the Northstar 7000. Despite repeated attempts to solve this electrical grounding problem, the Northstar 7000 and the navigation logging system could not be used for the drifter tracking operations. Instead, positions were obtained with the shipboard Micrologic Explorer Loran C and recorded manually on Drifter Logsheets or in the survey log book.

Calibration of the Loran units was performed at the Sunken Ledge Buoy #5 in the Weymouth Fore River and at Deer Island Light. A latitude/longitude correction was determined and entered into the onboard navigation systems. In addition, the offsets in Loran positions between the vessels were noted, and following the survey the *Seaquest* positions were corrected to match *Surveysa* positions at a known intercalibration location. It was imperative to perform this correction because both vessels were used to obtain positions during the drifter tracking operations, and inconsistencies were noted in the quality assurance check of the original, uncorrected drifter data obtained from the two survey vessels.

2.4 SURFACE DRIFTERS

Surface drifters were deployed and visually tracked during the surveys to obtain surface current information in conjunction with the Mini-BOSS surveys of the Nut Island effluent and sludge plumes. Fourteen low-cost, modified Davis drifters (Davis, 1985) were used during the study. This drifter design was developed at Scripps Institution of Oceanography and used successfully during the Coastal Dynamics Experiment (CODE) offshore Northern California. These drifters were designed to be (1) accurate current followers in the presence of winds and surface waves and (2) inexpensive so that a large number could be deployed to provide extensive coverage over survey regions. The original standard Davis drifters were equipped with radio transmitters and tracked by radio direction-finding by triangulation from mobile shore stations.

Figure 2-1 presents a drawing of the drifters fabricated for the present study. The vertical element of the drifters was constructed of 3-in.-dia PVC pipe. Fiberglass rods passed through the PVC pipe, arranged in a cruciform configuration to support sails that were fabricated of 50- × 90-cm sheets of lightweight nylon. Lobster pot toggle buoys were attached to the four corners of the drifter sails to provide buoyancy. A 100-cm fiberglass whip and 30- × 30-cm nylon flag replaced the radio beacon and whip antennae on the standard Davis drifter. The flags, which extended approximately 3 ft off the water, and the toggle buoys were fluorescent orange, red, and green to aid in relocation. In addition, the flags were labeled with a unique, 4-in.-high identification letter.

To obtain drifter positions, the survey vessels *Seaquest* and *Surveysa* would pass alongside the drifters, and the Loran position of the vessel (and adjacent drifter) would be obtained. The drifter identification letter, time, water depth, and Loran time delays were manually entered on the Drifter Logsheets.

2.5 MINI BATTELLE OCEAN SAMPLING SYSTEM (Mini-BOSS)

The Battelle Ocean Sampling System (BOSS) was developed by Battelle specifically for field programs requiring high-resolution *in situ* measurements of water properties *and* a means of collecting uncontaminated seawater samples. In June 1989, the BOSS was used aboard the EPA survey vessel *Anderson* during a 2-day pilot study of the Deer Island effluent plume and the Nut Island sludge plume in President Roads. During this survey, the BOSS successfully acquired conductivity/temperature/depth (CTD) and *in situ* turbidity data during vertical profiles and horizontal tows through the various plumes. However, one of the recommendations in the survey report was to develop a more portable BOSS designed for use in coastal areas such as Boston Harbor on shallow-draft vessels as small as 25 ft long.

Based on this requirement for a portable system, the Mini-BOSS was designed, fabricated, and tested by Battelle engineers in the fall of 1990 and was first used during the Boston Harbor surveys discussed in this report. During the two 3-day survey periods, the Mini-BOSS proved to be extremely reliable for acquisition and real-time display of high-resolution

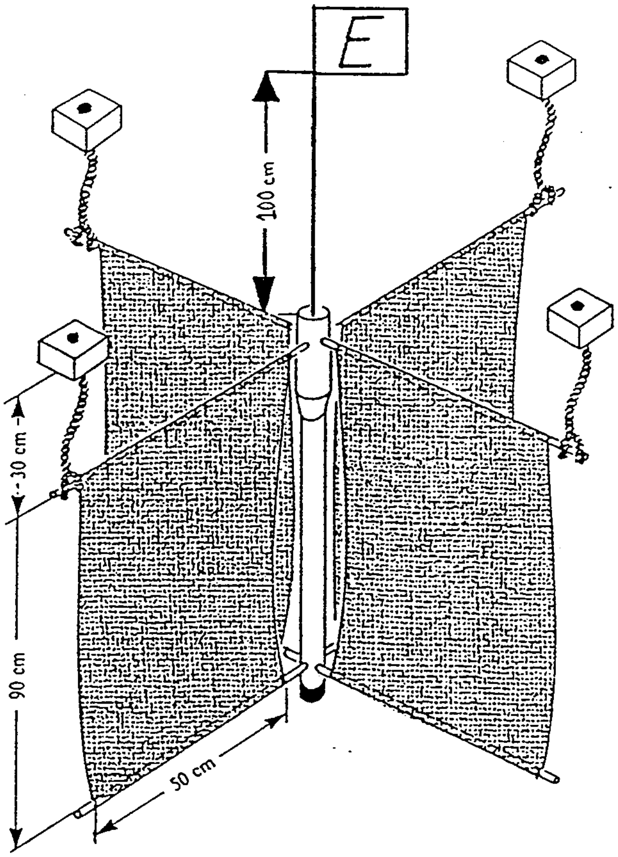

Figure 2-1. Drawing of Modified Davis Drifter Used during Boston Harbor Survey

salinity, temperature, depth, and turbidity data on station, or while towed at speeds up to 7 kn. The only problem experienced during the survey operations was a broken conductor in the termination of the tow cable, which was caused by excessive vessel heave during heavy sea conditions. On future surveys, a wave damping system will be used on the Mini-BOSS deployment system to reduce the risk of cable damage.

All Mini-BOSS components are housed in a custom-designed towfish that allows high towing speeds, open flow past the sensors and pump inlet, and sensor protection from submerged obstructions or bottom impact. Sensors are mounted in the towfish on a removable tray, permitting easy installation and field servicing. The major components of the Mini-BOSS system are illustrated in Figure 2-2 and described below.

CTD Profiling System

An Ocean Sensors OS100 high-resolution CTD profiling system is the central component of the Mini-BOSS sensor suite. The major parameters measured are seawater electrical conductivity, temperature, and pressure. These parameters are used in the computation of salinity, sensor depth, and seawater density. The measurements have a resolution better than 0.005% for pressure, 0.001°C for temperature, and 0.001 mS/cm for conductivity [equivalent to 0.001 ppt or practical salinity units (PSU)]. The OS100 CTD was factory-calibrated 2 months prior to the Boston Harbor Survey.

The lightweight, small-diameter, in-line sensor configuration makes the OS100 an ideal towed CTD system. Measurements from all the sensors were acquired at a 4.1-Hz rate, graphically displayed on the Mini-BOSS color monitor, stored on the computer disk drive, and copied onto diskettes at the end of each survey day.

In Situ Seawater Pump

A specialized seawater pump, developed at Battelle, was mounted in the Mini-BOSS towfish. The pump delivered seawater to the onboard laboratory at the rate of 10 L/min through a Teflon® tube enclosed in the electromechanical profiling cable. The pump was run continuously during towing operations, and water passed through two Turner model 10 fluorometers, one set up for chlorophyll fluorescence measurements and the other (provided by MIT) for Rhodamine WT® fluorescent dye measurements. On October 30, during the first day of survey operations at the Nut Island sludge outfall, Rhodamine WT dye was mixed with the sludge at the treatment plant, and dye levels were measured by the Mini-BOSS. Bottled-water sampling events were electronically flagged in the Mini-BOSS data file using an "event mark" so that a precise vessel position and the concurrent *in situ* water-column parameters (salinity, temperature, turbidity, and depth) could be linked with that particular bottle sample.

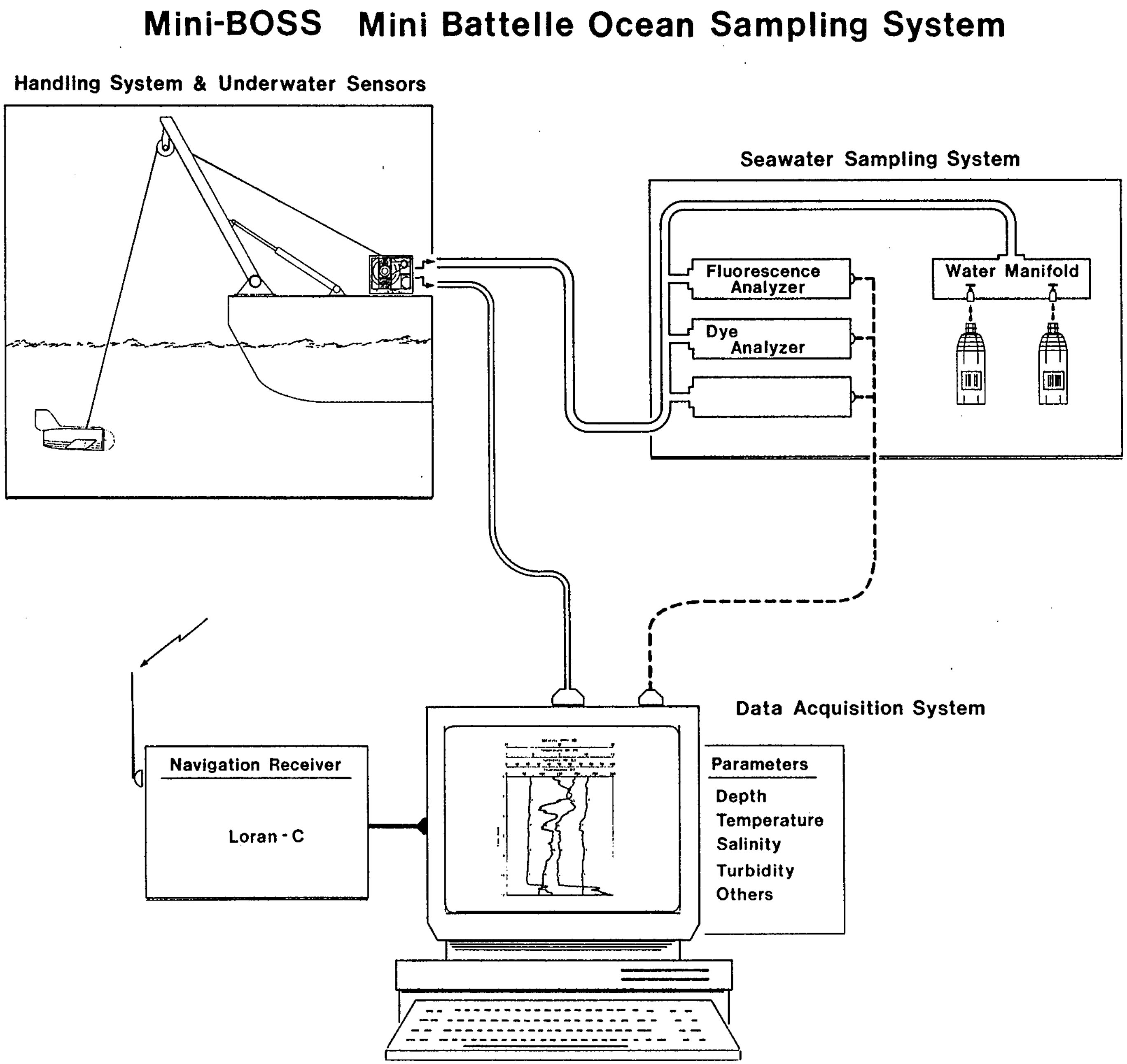

Figure 2-2. Schematic Drawing of Mini-BOSS Used during Boston Harbor Survey

Postsurvey data analyses were used to empirically determine the lag time for water flow between entry of the intake of the submerged towfish and the time at which the readings from the Turner fluorometers were acquired by the Mini-BOSS acquisition system. This time lag was determined to be 42 s and was subsequently used to adjust the timing of the on-deck Turner measurements to the coincident times of the *in situ* measurements.

Note that one of the Turner fluorometers was configured for flowthrough measurement of chlorophyll fluorescence, but in the absence of actual chlorophyll-*a* calibration from laboratory analysis of bottled water samples collected concurrently with the online measurements, the data represent only relative fluorescence levels, not actual chlorophyll-*a* concentrations. Therefore, the chlorophyll fluorescence data are presented without concentration units, and only relative units are used. Likewise, the dye data are presented in relative units.

In Situ Transmissometer

A 25-cm-pathlength SeaTech transmissometer was interfaced to the CTD and mounted in the Mini-BOSS towfish. The SeaTech unit has been designed to provide accurate, *in situ* measurements of optical beam transmission, which is directly related to the concentration of suspended matter in the water at the point of measurement. The sensitivity of the transmissometer is dependent on background water turbidity levels. In clear water, an increase of 0.004 mg/L in suspended mass can be detected with this transmissometer. During the October 1990 surveys, the transmissometer was able to detect very small changes in turbidity and proved to be an effective tool for mapping the boundaries of the sludge and effluent plumes.

Note that turbidity data presented in this report are given in percentages of light extinction. Thus, 100% turbidity represents total blockage of light along the light path of the transmissometer; 0% turbidity would represent totally clear water.

On-Deck Handling System

A portable, electrohydraulic winch and A-frame were designed for the Mini-BOSS and used to deploy and recover the underwater unit. A specially designed electromechanical profiling cable containing an internal Teflon tube was used for data transmission and delivery of seawater samples from the underwater unit to the surface.

Real-Time Acquisition Software

Specialized software routines developed by Battelle were used to display salinity, temperature, turbidity, and depth data, and relative concentrations of chlorophyll fluorescence and

Rhodamine dye in real-time on a color CRT monitor. Once the data are acquired, they are automatically written to a data file and logged concurrently with position data from the RayNav 570 Loran C unit.

3.0 BACKGROUND WATER PROPERTIES THROUGHOUT THE HARBOR

3.1 SURVEY OBJECTIVES AND MONITORING TECHNIQUES

As indicated in Section 1, one of the objectives of the monitoring study was to conduct rapid, synoptic field surveys of the Harbor to determine the spatial variability of water properties throughout the major bays and Harbor channels. Because the intense tidal flushing of the Harbor results in major displacements of water properties, interpretations of true spatial variability can be made only if temporal variability is eliminated or reduced. A truly synoptic survey of the Harbor would require numerous survey vessels operating simultaneously throughout the various regions of the Harbor, but this is impractical from both a cost and logistical perspective.

For this study, a single survey vessel was used to obtain spatial information on the variability of near-surface water properties throughout the Harbor on 1 day, November 1, 1990. The survey plan consisted of a near-synoptic survey conducted within roughly 3 h of the morning high tide, followed by a near-synoptic survey conducted within 1 to 2 h of low tide. With a single survey vessel towing the Mini-BOSS sensor package at speeds of roughly 4 kn, a finite number of horizontal transects and vertical profiles could be made during the two synoptic surveys. Limited daylight hours precluded extended surveying on November 1, and additional days of surveying could not be accommodated within the program budget.

The Harbor-wide surveys were conducted using the Mini-BOSS installed on the *Surveysa*. Data were acquired along the numerous transects with the underwater sensor package towed at a fixed depth of approximately 2 m and at speeds ranging from 3 to 5 kn. As discussed in Section 2, water properties were measured continuously at a rate of 4.1 scans per second, such that a measurement was made at horizontal intervals of approximately 1.6 ft along the transects. For the final processing, data were averaged to 1-s intervals so that each data point represents a horizontal distance of roughly 6 ft along the transects.

Throughout the survey, *in situ* measurements of temperature, salinity, turbidity, and instrument depth were recorded automatically by the Mini-BOSS computer. Also, water was continually pumped from the underwater unit to an on-deck Turner fluorometer for continuous, flowthrough measurement of chlorophyll fluorescence. Analog information from the fluorometer was digitized and archived by the Mini-BOSS computer system and merged with the simultaneous measurements from the *in situ* sensors. Continuous Loran C navigation data of vessel position were also acquired at a sampling interval of 4 s and merged with the water-property data.

Vertical profiles from the sea surface to the bottom were also made at selected locations while the survey vessel was stopped on station. No drifters were launched or tracked on November 1.

3.2 RESULTS FROM SURVEY AT HIGH WATER ON NOVEMBER 1, 1990

3.2.1 Sampling Activities

Fair weather with calm seas and winds less than 10 kn throughout the day on November 1 provided excellent operating conditions for rapid, spatial surveying. Wind directions were westerly in the morning, turning southeasterly in the afternoon. The morning high tide occurred at 0912 h EST with a range of 11.1 ft, nearing the maximum range of the spring tides for Boston Harbor. Low tide occurred at 1533 h EST.

As indicated in the previous Section, the objective of the background monitoring survey was to conduct one near-synoptic survey of Harbor water properties near high water, followed by a similar survey near low water. Figure 3-1 is a chart of the Harbor with superimposed transect lines and vertical profile stations that were surveyed using the Mini-BOSS during the morning survey on November 1. Transects are labeled 1-2, 3-4, etc., with the lower number indicating the starting position of each respective transect. Profile stations are labeled P1, P2, etc. The time and location of each transect and profile are given in Tables 3-1 and 3-2, respectively.

As illustrated in Figure 3-1, transects extended from the head of the major bays (Hingham, Quincy, Dorchester, etc.) to the eastward extension of the major Harbor channels: Nantasket Roads and President Roads (within North Channel). Transects 1-2 through 9-10 were made during the period from near high water to roughly 3 h into the ebb cycle. Transect 11-12 was made approximately 4 h into the ebb. For the purpose of this analysis, we will consider the results obtained from these transects as a synoptic data set representing the water properties at high water on November 1.

3.2.2 Results from Transects

With the rapid, underway sampling capability of the Mini-BOSS, high-resolution temperature, salinity, turbidity, and relative fluorescence measurements were acquired at a constant depth of roughly 2 m below the surface along each of the transects. Figure 3-2 presents the data

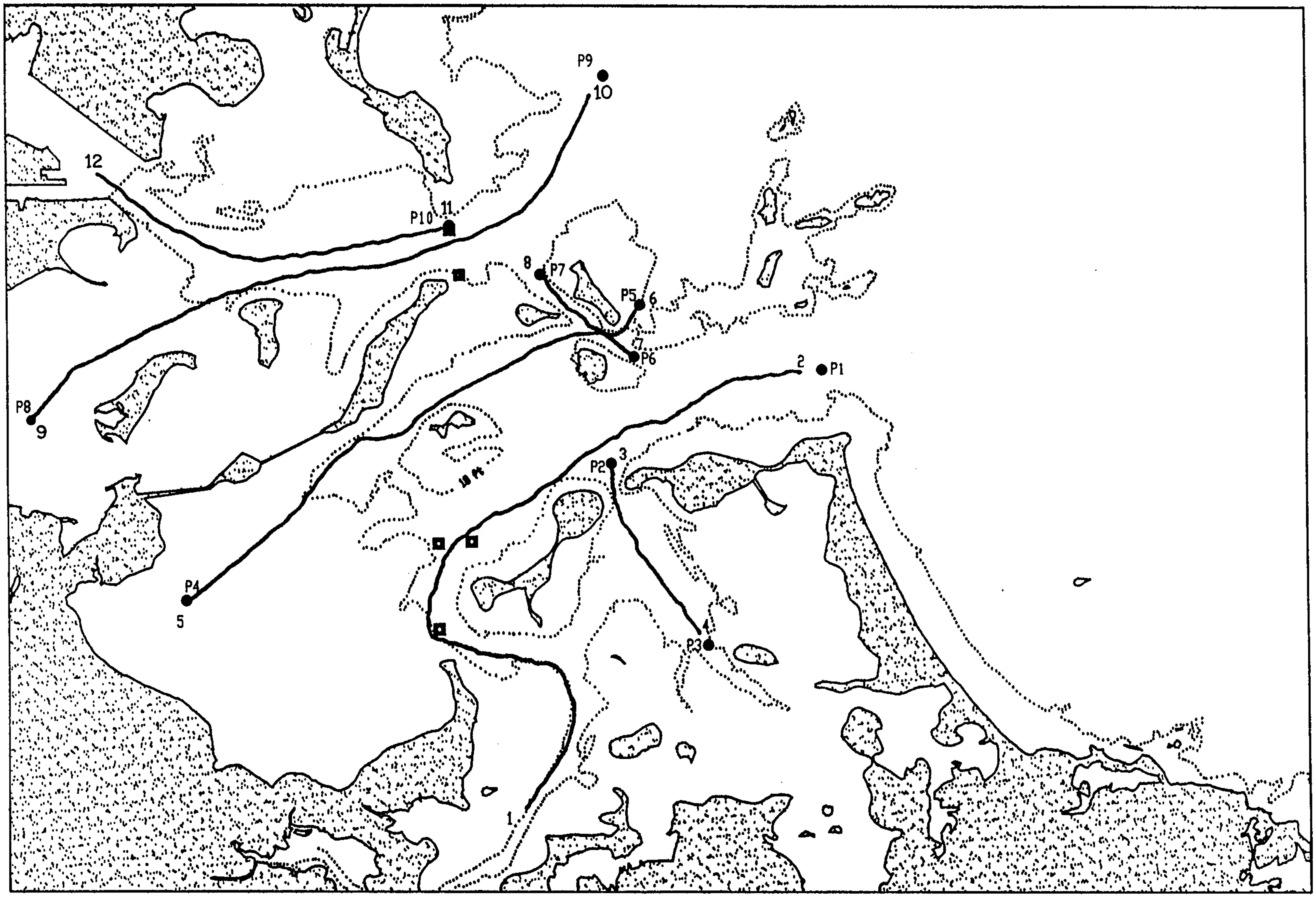

Figure 3-1. Location of Transects and Vertical Profile Stations (e.g., P1) Made near High Tide on the Morning of November 1, 1990

Table 3-1. Time and Location of Horizontal Transects Made on November 1, 1990

Transect Number	File Number	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Location	Start Position		End Position	
					Lat(N)	Long(W)	Lat(N)	Long(W)
1-2	MWRA6002	08:26:57	09:39:36	Weymouth - E Nantasket Roads	42°15.66′	70°56.44′	42°19.10′	70°53.42′
3-4	MWRA6007	09:56:16	10:15:28	Hull Gut - Hingham Bay	42°18.39′	70°55.52′	42°16.96′	70°54.52′
5-6	MWRA6011	10:34:44	11:17:48	Quincy Bay - Narrows	42°17.27′	71°00.08′	42°19.68′	70°55.16′
7-8	MWRA6017	11:26:18	11:38:38	Narrows	42°19.26′	70°55.26′	42°19.96′	70°56.35′
9-10	MWRA6021	11:57:26	12:45:42	Dorchester Bay - North Channel	42°18.72′	71°01.73′	42°21.36′	70°55.67′
11-12	MWRA6028	12:58:50	13:35:59	Deer Island - Inner Harbor	42°20.27′	70°57.26′	42°20.73′	71°01.11′
13-14	MWRA6033	14:21:08	15:16:11	Weymouth - E Nantasket Roads	42°15.85′	70°56.36′	42°19.50′	70°53.69′
15-16	MWRA6037	15:34:35	16:01:34	Narrows - Quincy Bay	42°19.30′	70°55.25′	42°18.42′	70°58.49′
17-18	MWRA6043	16:25:58	16:59:56	Dorchester Bay - Deer Island	42°19.32′	71°00.83′	42°20.40′	70°56.61′

Table 3-2. Time and Location of Vertical Profile Stations Made on November 1, 1990

Profile Number	File Number	Start Time (EST) (h:m:s)	Profile Depth (m)	Location	Position	
					Lat(N)	Long(W)
P1	MWRA6004	09:40:14	15	E Nantasket Roads	42°19.13′	70°53.27′
P2	MWRA6006	09:54:34	16	Hull Gut	42°18.35′	70°55.54′
P3	MWRA6008	10:16:02	11	Hingham Bay	42°16.94′	70°54.49′
P4	MWRA6010	10:32:46	5	NW Quincy Bay	42°17.28′	70°00.07′
P5	MWRA6013	11:18:03	13	Black Rock Channel	42°19.71′	70°55.12′
P6	MWRA6016	11:24:59	11	S Narrows	42°19.23′	70°55.29′
P7	MWRA6018	11:39:16	11	N Narrows	42°20.00′	71°56.35′
P8	MWRA6020	11:56:21	7	Dorchester Bay	42°18.71′	71°01.73′
P9	MWRA6024	12:46:44	13	North Channel	42°21.46′	70°55.59′
P10	MWRA6027	12:57:06	17	Deer Island	42°20.27′	70°57.30′
P11	MWRA6031	13:38:32	14	Inner Harbor Channel	42°20.87′	71°01.36′
P12	MWRA6041	16:15:26	3	N Quincy Bay	42°18.23′	70°58.97′
P13	MWRA6042	16:24:58	6	Dorchester Bay	42°19.32′	71°00.82′
P14	MWRA6045	17:00:46	20	Deer Island	42°20.41′	70°56.59′

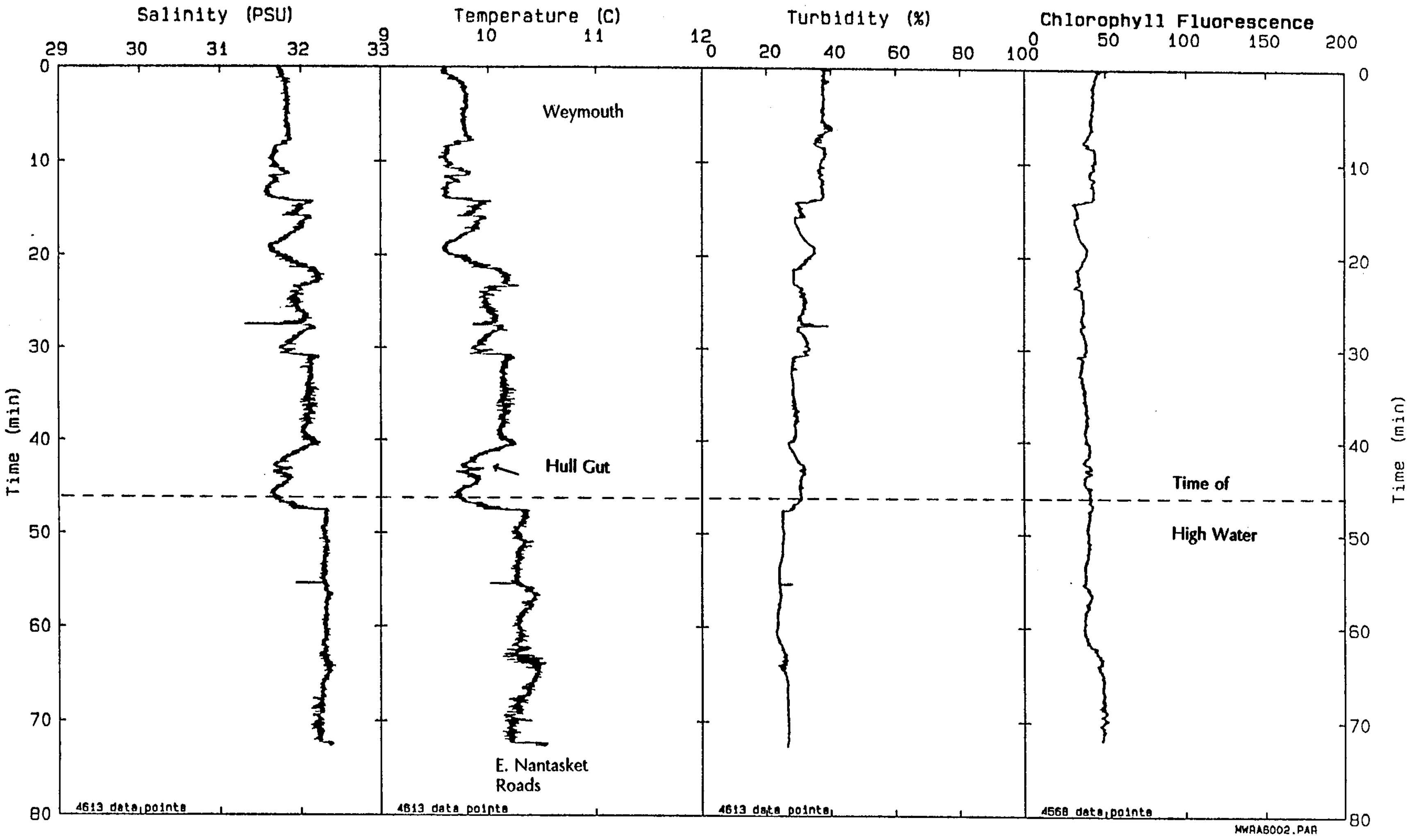

Figure 3-2. Time-Series Plot of Data Acquired along Transect 1-2 Made on November 1, 1990

acquired along transect 1-2 extending from Weymouth Fore River to East Nantasket Roads. Data have been processed to approximately 1-s averages, with the result that roughly 4600 data points are presented along this 73-min transect. From this presentation, it is apparent that there was considerable variability in water properties as the survey vessel steamed from Weymouth to the eastern end of Nantasket Roads. For example, as the vessel passed the northern end of Hull Gut heading northeastward along Nantasket Roads, relatively fresh, cool water of Hingham Bay origin was detected (at time ~45 min in Figure 3-2) flowing northward into Nantasket Roads. Careful inspection reveals that this Hingham Bay water had temperature/salinity (T/S) properties similar to those of the water encountered 10 min after the beginning of the transect in Weymouth Fore River.

Further analysis of the information presented in the time-series plot of Figure 3-2 is tedious, but bivariate scatter plots (e.g., T/S plots) are extremely useful for identifying specific water types by their individual water-property characteristics. For example, Figure 3-3 presents the data from transect 1-2 on each of three bivariate scatter plots: temperature/salinity (T/S), turbidity/salinity (Tu/S), and turbidity/chlorophyll fluorescence (Tu/Chl). Each 1-s-averaged data point on Figure 3-2 is plotted as an individual data point on each of the three scatter plots of Figure 3-3.

Using the concurrent navigation and water-property data acquired along the Mini-BOSS transects, it is possible to determine the location of each data point or cluster of points on the bivariate scatter plots. In Figure 3-3, labels have been added to indicate the specific water properties encountered at East Nantasket Roads, near Hull Gut, and within Weymouth Fore River. During this high-water survey, the eastern end of the transect was characterized by the relatively warm, saline water of Massachusetts Bay, whereas the waters from Weymouth and Hingham Bay (passing through Hull Gut) had the lowest salinity and temperature. From this T/S plot, it appears that the water within Nantasket Roads at high water is a relatively simple two-component mixture of saline offshore water with fresher waters from the Weymouth/ Hingham region.

From T/S properties alone, it is not possible to distinguish between the waters of Hingham Bay origin and those from the Weymouth Fore River system. Inspection of the Tu/S and Tu/Chl scatter plots in Figure 3-3 reveals, however, that the waters near the Weymouth Fore and Back Rivers have significantly higher turbidity than does the water of similar temperature and salinity characteristics from Hingham Bay. Although turbidity and chlorophyll-*a* (from relative fluorescence) are known to vary significantly over time scales of a tidal or diurnal cycle as a result of physical, chemical, and/or biological processes, the short period (approximately 1 h 13 min) over which transect 1-2 was made allows one to assume that the

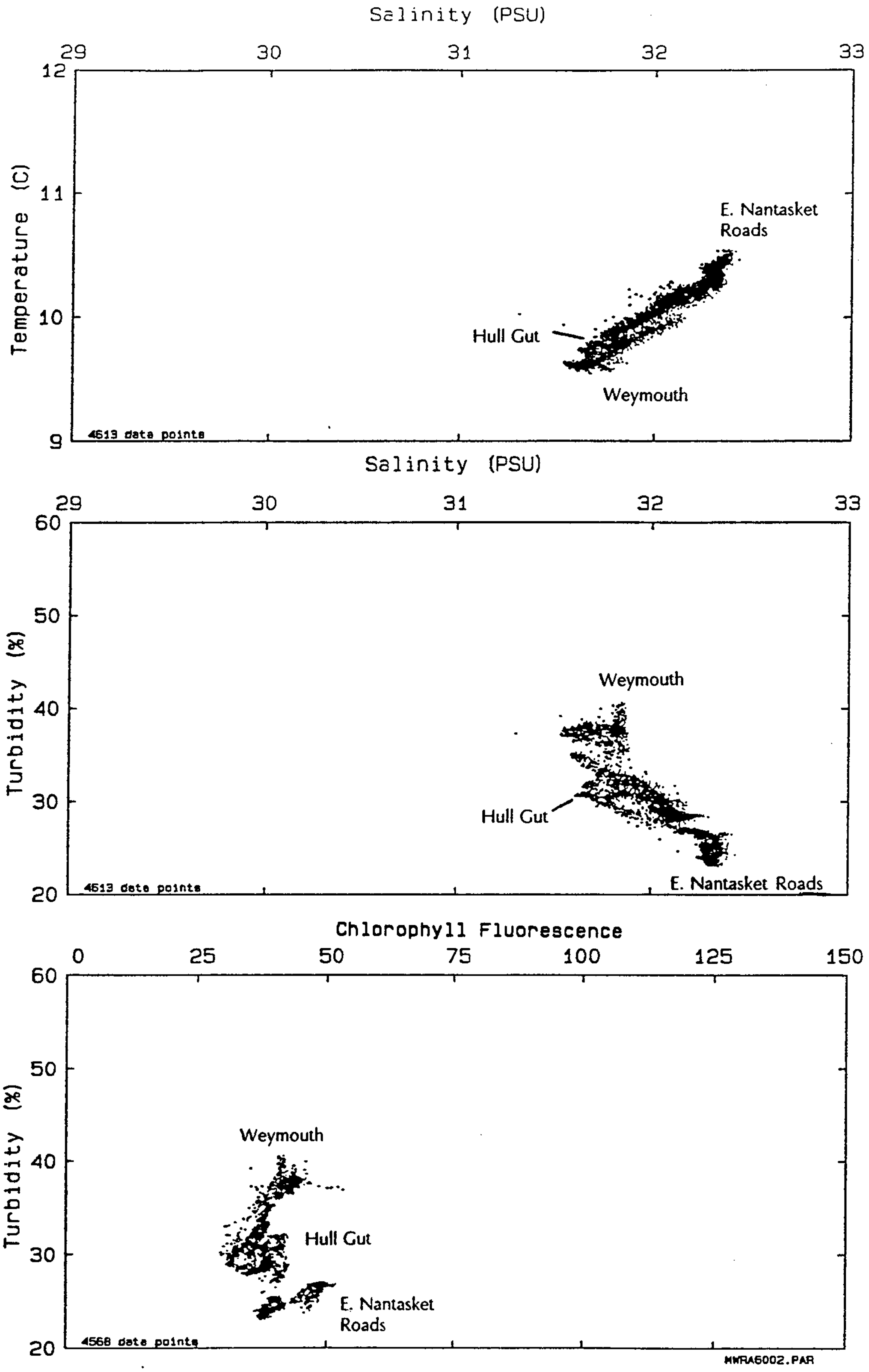

Figure 3-3. Scatter Plot of Data Acquired along Transect 1-2 Made on November 1, 1990

variability presented in Figure 3-3 is due strictly to spatial variations rather than to any temporal variability.

To illustrate the water-property variability along another transect made during the high-water survey on November 1, Figure 3-4 presents the data acquired along transect 9-10 extending from Dorchester Bay, eastward through President Roads, and into North Channel, located east of Deer Island. Approximately 20 min along the transect, relatively warm, low-salinity water was encountered north of Spectacle Island within President Roads. As will be demonstrated through analysis of additional transects, this water had originated from the Inner Harbor and was entering the President Roads channel from the northwest. The sharp property fluctuations encountered 30 min along the transect were associated with the plume from the sewage effluent outfall located at Deer Island Light.

The individual scatter plots in Figure 3-5 are extremely useful for interpretation of the large variability in water properties observed along transect 9-10. Analysis of the Mini-BOSS navigation and water-property data reveals that the most saline and turbid waters along the transect were found in North Channel. The high salinities within North Channel are associated with Massachusetts Bay water, but the high, near-surface turbidities are somewhat surprising because, during this post high-water transect, the waters within Dorchester Bay or emanating from the Inner Harbor were less turbid than the waters within North Channel.

From inspection of Figure 3-5, it is possible to distinguish between the T/S properties of Dorchester Bay water and water emanating from the Inner Harbor. Although their temperatures differ significantly, their turbidity, salinity, and chlorophyll fluorescence properties are relatively similar.

Figure 3-6 presents scatter plots of data acquired along transect 11-12 extending from Deer Island Light to the channel entering the Inner Harbor (see Figure 3-1). Both the T/S plot and the Tu/S plot illustrate that the waters along the central channel of President Roads are a mixture of relatively fresh, warm, low-turbidity water from the Inner Harbor and Deer Island water having similar characteristics to those observed in North Channel during the previous transect. There were no indications of Dorchester Bay water along this transect although it was situated only a small distance to the north of transect 9-10 within President Roads.

> **It is a significant result that, from high-resolution, synoptic data acquired along two transects within the northern portion of the Harbor, it is possible to distinguish between waters of Dorchester Bay origin and**

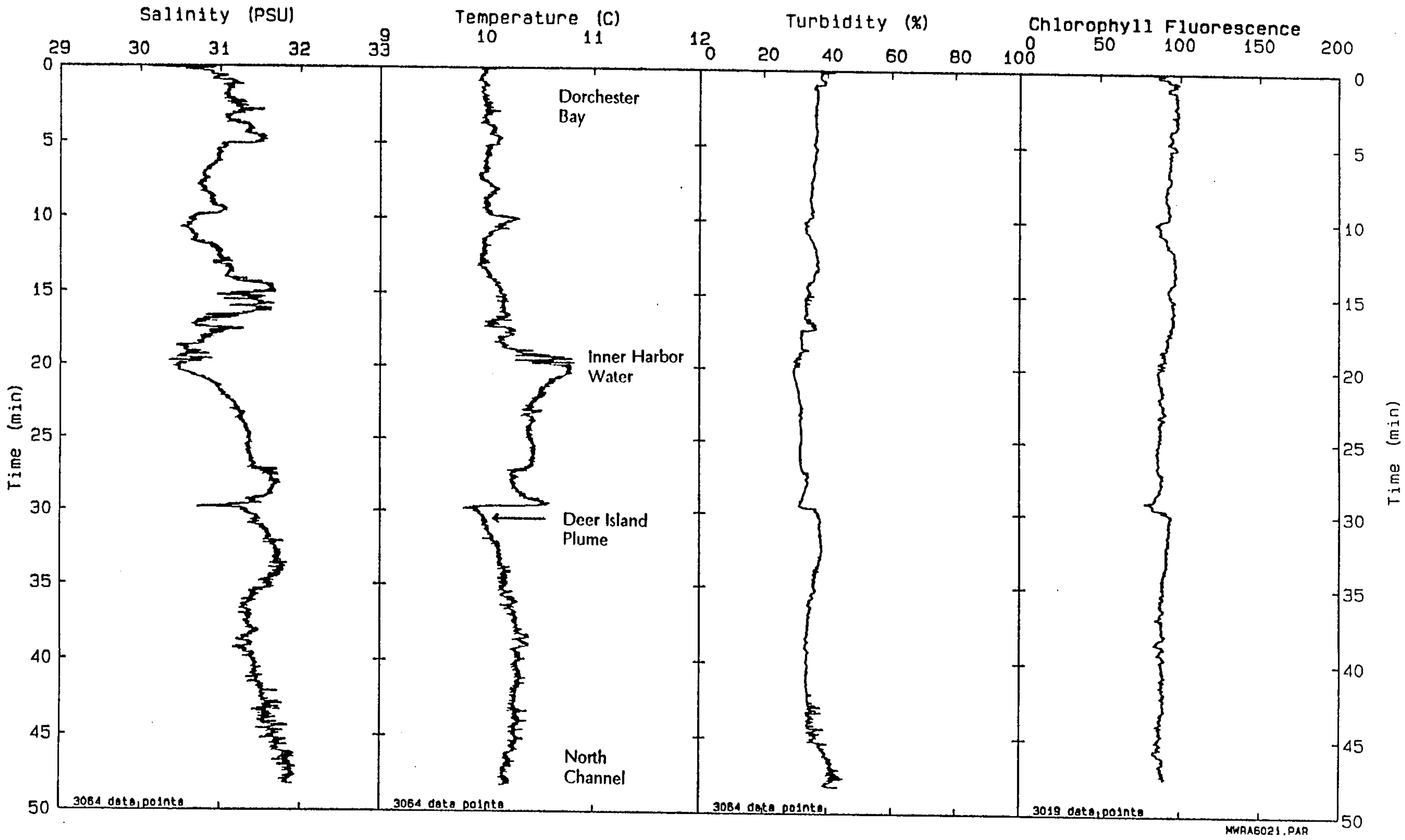

Figure 3-4. Time-Series Plot of Data Acquired along Transect 9-10 Made on November 1, 1990

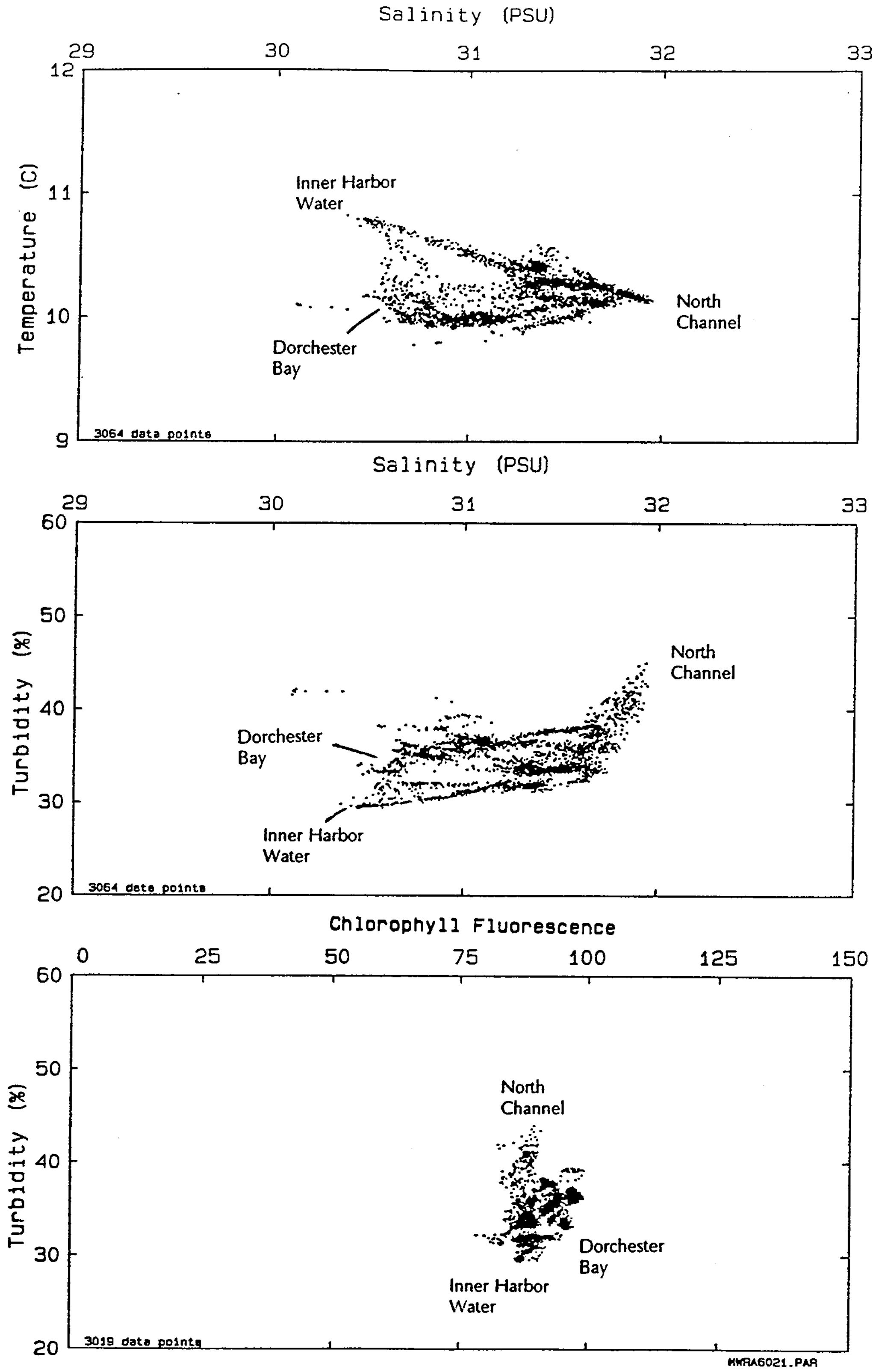

Figure 3-5. Scatter Plot of Data Acquired along Transect 9-10 Made on November 1, 1990

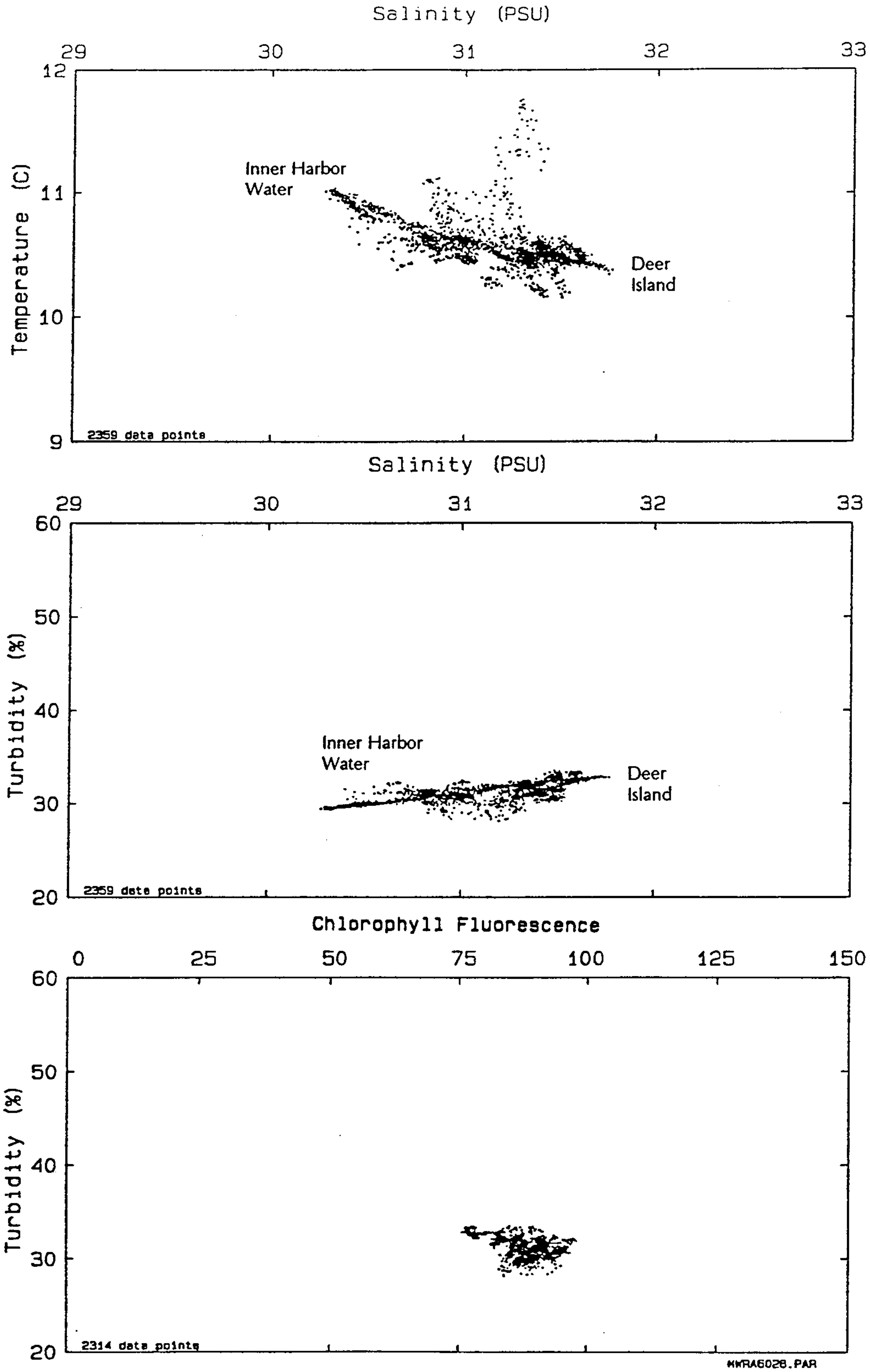

Figure 3-6. **Scatter Plot of Data Acquired along Transect 11-12 Made on November 1, 1990**

> **waters from the Inner Harbor using physical water properties alone. Sampling at a few positions along each transect and/or over a non-synoptic period (as during most water quality surveys) would result in a data set that suffers from spatial and temporal aliasing, to the extent that few, if any, of the above conclusions could have been developed. Although the high-resolution synoptic surveys provide an excellent view of the spatial variability throughout the Harbor, additional surveys will be required for investigation of the water-property variability caused by meteorological and seasonal forcing.**

Data acquired along transect 5-6 from northwest Quincy Bay to the Narrows reveals an interesting characteristic of the water exchange between the northern and southern basins of the Harbor. The T/S scatter plot in Figure 3-7 illustrates that the water from Quincy Bay is significantly cooler and less saline than are the waters that reside in the Narrows following high water, and that most of the T/S properties along this transect could be derived from various proportions of water from Quincy Bay and more saline waters at the eastern end of the transect. Also evident from the T/S plot is water having salinity of 31 PSU and temperature of 10 °C that was observed near the bridge extending from Moon Island to Long Island. Analysis of the water properties from transect 9-10 (Figure 3-5) confirms that this water originated from the vicinity of Dorchester Bay and that the ebb flow under the Moon Island bridge was from northwest to southeast.

Close inspection of the Tu/S and Tu/Chl scatter plots in Figure 3-7 reveals that the properties of the water from under the bridge (Dorchester Bay) and from northwest Quincy Bay are similar to each other, but are distinctly different from the properties of the waters within the Narrows and to the west (near Rainsford Island). The line labeled *Front* has been subjectively drawn on the scatter plots to indicate the water-property front between these two water-property groups. One hypothesis for this front is directly related to the ebb flow regime in this region. As discussed in Section 5.0, there is strong northward flow across Nubble Shoal (located east of the northern tip of Long Island) and through the Narrows during the ebb. Consequently, the eastern half of transect 5-6 is affected by waters from Nantasket Roads during the ebb; the lesser volume of water ebbing from northwest Quincy Bay may actually be partially blocked from flowing eastward due to the substantial northward flow from Nantasket Roads. This may result in decreased flushing within west Quincy Bay, but additional information from the flood stage is needed to validate this hypothesis.

Individual time-series plots and scatter plots of data acquired along each of the transects made during the high-water survey on November 1 are presented in Volume II, Appendix B.

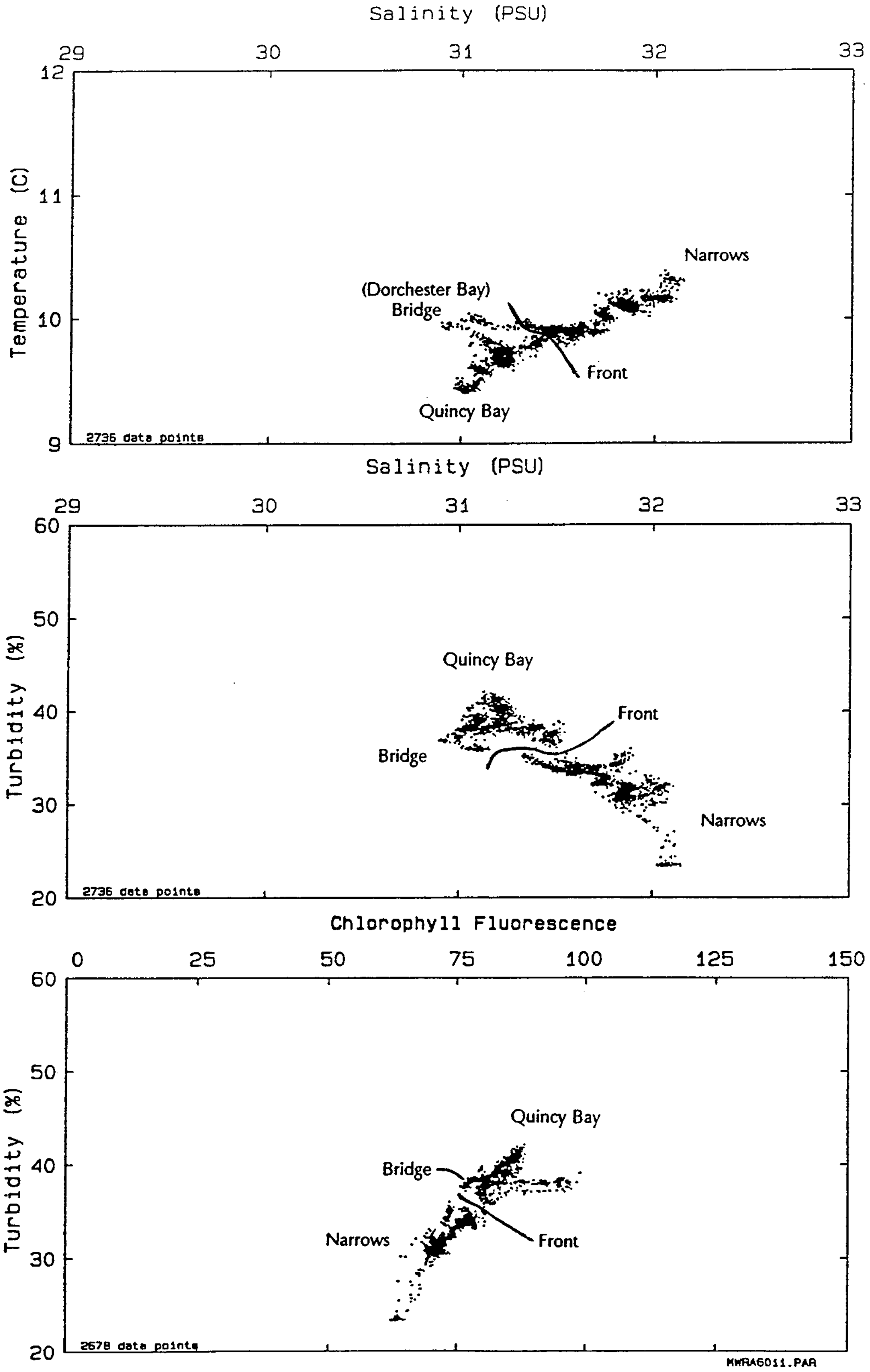

Figure 3-7. Scatter Plot of Data Acquired along Transect 5-6 Made on November 1, 1990

Figure 3-8 presents composite scatter plots of all data (transects and vertical profiles) acquired during the high-water survey. This presentation vividly demonstrates the extensive water-property variability throughout the various bays and Harbor channels during a single high-water period. Interpreting the Harbor circulation and mixing pathways from this plot alone would be impossible, but, as demonstrated above, analysis of data from individual transects does lead to a clear picture of transport pathways and accounts for the observed spatial variability of water properties.

Figure 3-9 presents the scatter-plot data of Figure 3-8 with superimposed labels indicating the sources/locations of the individual water types near high water. The T/S plot indicates that the southern Harbor (the Nantasket Roads/Weymouth/Hingham Bay system) is significantly more saline than the northern Harbor (the North Channel/President Roads/Dorchester Bay/ Inner Harbor system). This is consistent with Signell's (Bothner *et al.,* 1990) hydrodynamic model of the Harbor circulation, which predicts much greater flushing in the southern Harbor than in the northern Harbor. The low salinities near Dorchester Bay and the Inner Harbor are due to the freshwater input from the Neponset and Charles Rivers, respectively. The freshwater effects of the Weymouth Fore and Back Rivers are small due to their small discharge and the high salinity influx through Nantasket Roads.

Because Quincy Bay does not have a large source of fresh water, it is suspected that its relatively low salinity (compared with waters from adjacent Nantasket Roads) is due to southwestward flowing waters from the northern Harbor passing under the Moon Island bridge during the flood tide. The relatively low temperature in Quincy Bay may be due to its large surface area-to-volume ratio, which would magnify the effects of radiational cooling in this shallow bay.

The Tu/S scatter plot in Figure 3-9 further supports the hypothesis that Quincy Bay communicates with the northern Harbor rather than with Nantasket Roads. The Nantasket Roads system of the southern Harbor is characterized by relatively clear (low turbidity), saline water, whereas the northern Harbor has somewhat higher turbidities on average. It is conceivable that Quincy Bay Tu/S properties are derived from President Roads/Dorchester Bay water that gains turbidity within Quincy Bay because of the shallow water and wave-induced suspension of fine sediments. Validation of this hypothesis would, however, require additional sampling in this region and calibration of the transmissometer to provide data on total suspended solids.

The Tu/Chl scatter plot in Figure 3-9 reveals that chlorophyll fluorescence levels within the Nantasket Roads system are much lower than within President Roads, Dorchester Bay, the

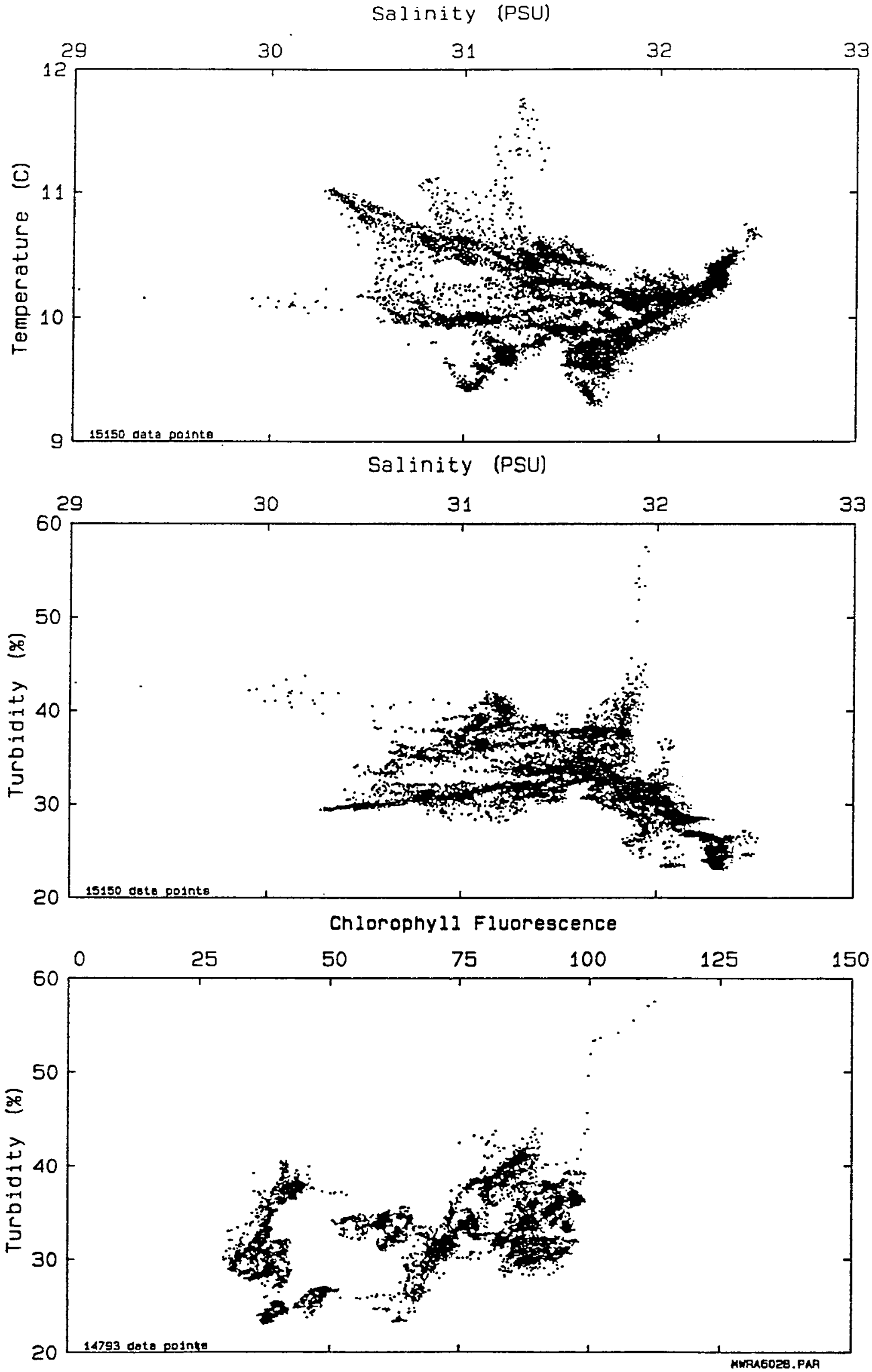

Figure 3-8. Composite Scatter Plot of All Data Acquired along Transects and at Vertical Profile Stations Made near High Water on November 1, 1990

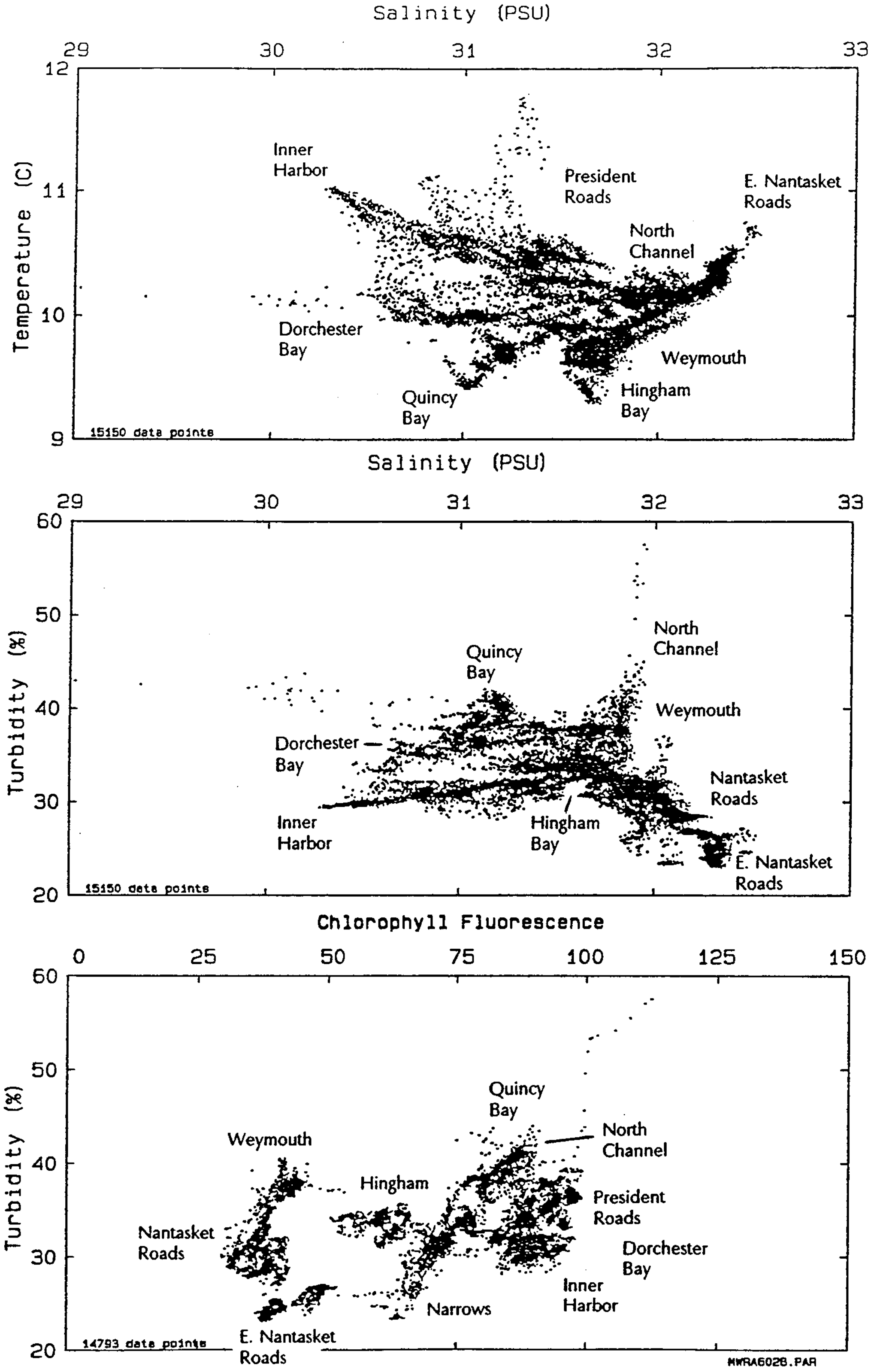

Figure 3-9. Identical Data Presentation as in Figure 3-8, with Labels Identifying Sources of Specific Water Types

Inner Harbor, or Quincy Bay. Again, this may be attributed to the southern Harbor's greater flushing, with the low-chlorophyll water coming from Massachusetts Bay in contrast to the inflow of chlorophyll-rich freshwaters from the Neponset and Charles Rivers into the northern Harbor.

In the Tu/Chl scatter plot of Figure 3-9, Hingham Bay water can be expected to mix with waters labeled Weymouth and Nantasket Roads. The relatively high chlorophyll fluorescence levels within Hingham Bay are attributed to local sources rather than to advection of high-chlorophyll water from other regions.

Figure 3-10 illustrates the conceptual mixing regimes that were developed from analysis of the scatter plot data presented in Figure 3-9. Shaded regions represent the specific water-property characteristics derived from the actual scatter-plot data: labeled IH for Inner Harbor; DB for Dorchester Bay; QB for Quincy Bay; HB for Hingham Bay; W for Weymouth; NAR for Narrows. For this high-water scheme, it is believed that the individual water types are affected by Massachusetts Bay water entering through one of the major Harbor channels (shown in boxes): labeled NC for North Channel and ENR for East Nantasket Roads.

As indicated in the T/S diagram of Figure 3-10, water from North Channel communicates with the Inner Harbor, Dorchester Bay, and Quincy Bay, whereas water from East Nantasket Roads affects Weymouth and Hingham Bay. The dashed line represents the hypothetical boundary between the waters of the northern and southern portions of the Harbor.

The Tu/S and Tu/Chl mixing diagrams presented in Figure 3-10 demonstrate the large differences in the properties of the waters within North Channel and East Nantasket Roads near high water. The hypothesized mixing lines and the expected water-property boundary (dashed line) between the northern and southern portions of the Harbor are well supported by the various and independent water-property types.

3.2.3 Results from Vertical Profiles

The previous Section presented water-property data acquired while the Mini-BOSS sensor package was towed horizontally at a depth of roughly 2 m below the surface. The results provide a synoptic picture of near-surface water properties throughout the Harbor, but one questions whether the surface properties were representative of the entire water column at the time of the observations. If there were substantial freshwater discharge from the Neponset

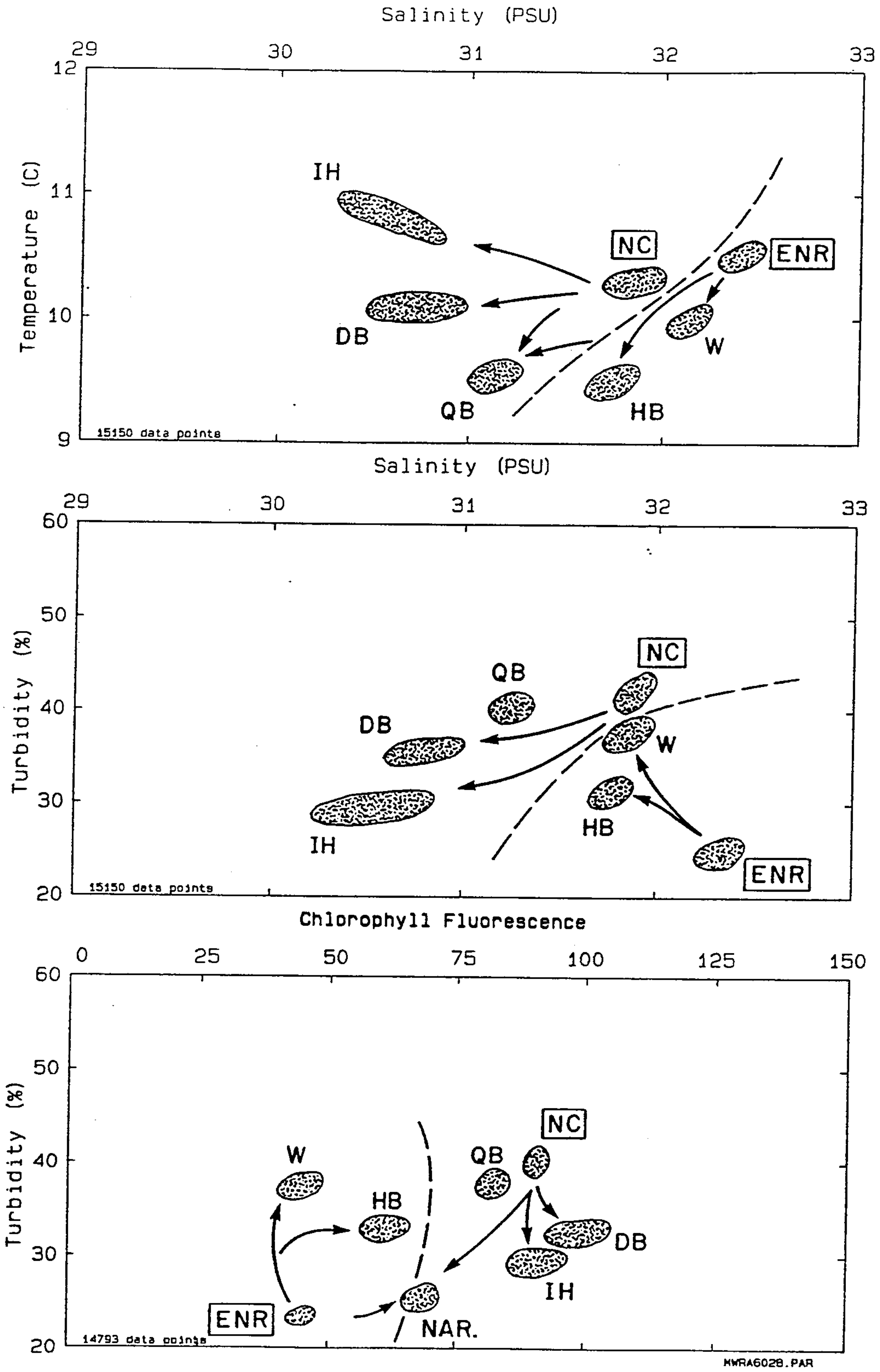

Figure 3-10. Simplified Presentation of Data from Figure 3-9, with Specific Water Types Shaded and Labeled According to Sources. Arrows Demonstrate Mixing on Flood Tide. Broken Line Represents Boundary between Northern and Southern Basins of the Harbor.

and Charles Rivers, this water would overlay the relatively dense, saline water entering the Harbor from Massachusetts Bay, creating a two-layer system readily distinguishable from the physical water properties. This occurs during spring periods of heavy rain, but in general river discharge is small, and the intense tidal mixing within the Harbor is sufficient to create a well-mixed water column. This is especially true in the fall when precipitation is moderate and solar radiation is near the annual minimum.

During the week prior to the November 1 survey, there was only minimal precipitation in the Boston area. For the reasons discussed above, the water column throughout most of the Harbor was well mixed from top to bottom, as demonstrated from 10 vertical profiles made during the high-water survey. Table 3-2 provides the time and location of each profile station (stations P1-P10).

Figure 3-11 presents the vertical profiles of salinity, temperature, turbidity, and chlorophyll fluorescence acquired from 2 m below the surface to the bottom (15 m) at profile station P1 located in East Nantasket Roads (see Figure 3-1). Similar well-mixed profiles were observed at all of the profile stations (P1 through P7) in the southern part of the Harbor (see Volume II, Appendix B-3 for all profiles).

In the northern part of the Harbor, the water column exhibited more vertical structure due to freshwater input from the rivers. Figure 3-12 presents the profile data from station P8 located in Dorchester Bay. The lower part of the water column at this 7-m-deep station was generally well mixed, but salinities less than 29 PSU were observed above 2 m, presumably because of freshwater discharge from the Neponset River. Water temperature, turbidity, and chlorophyll fluorescence were relatively constant over the profile.

A thin surface layer of relatively fresh water was also observed at profile station P10 located south of Deer Island in President Roads (Figure 3-13). This station was coincident with the beginning of transect 11-12, whose data revealed that the low, near-surface salinities were associated with water from the Inner Harbor (see Figure 3-6).

Although there may have been very thin (<2 m) layers of low-salinity water near the head of Dorchester Bay and within the Inner Harbor during the high-water survey, we believe that the results obtained from the ~2-m-deep horizontal tows along transects throughout the Harbor provide a good estimate of the spatial variations in water properties throughout the water column at each location.

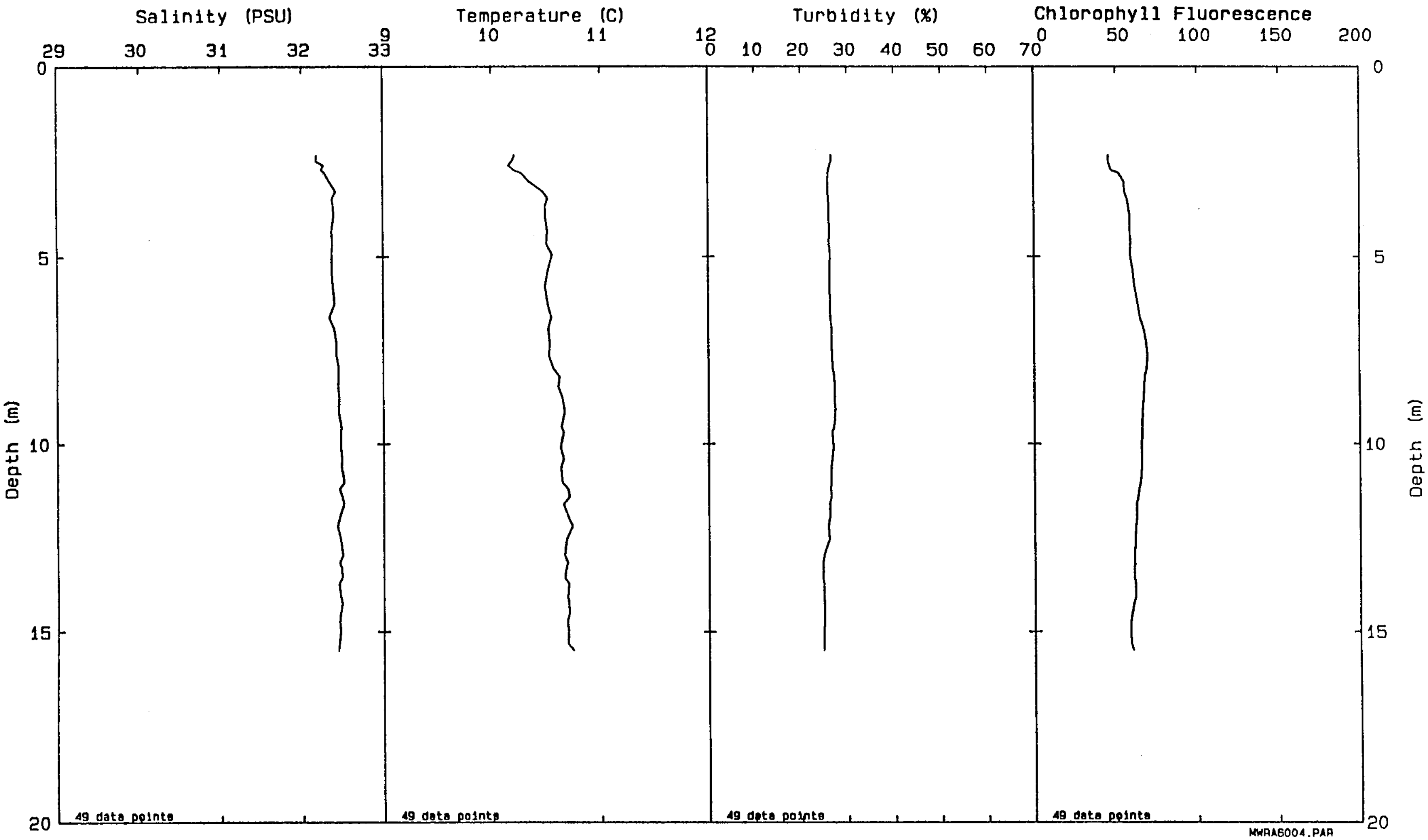

Figure 3-11. Vertical Profile Data Acquired at Station P1 Located in East Nantasket Roads near High Water on November 1, 1990

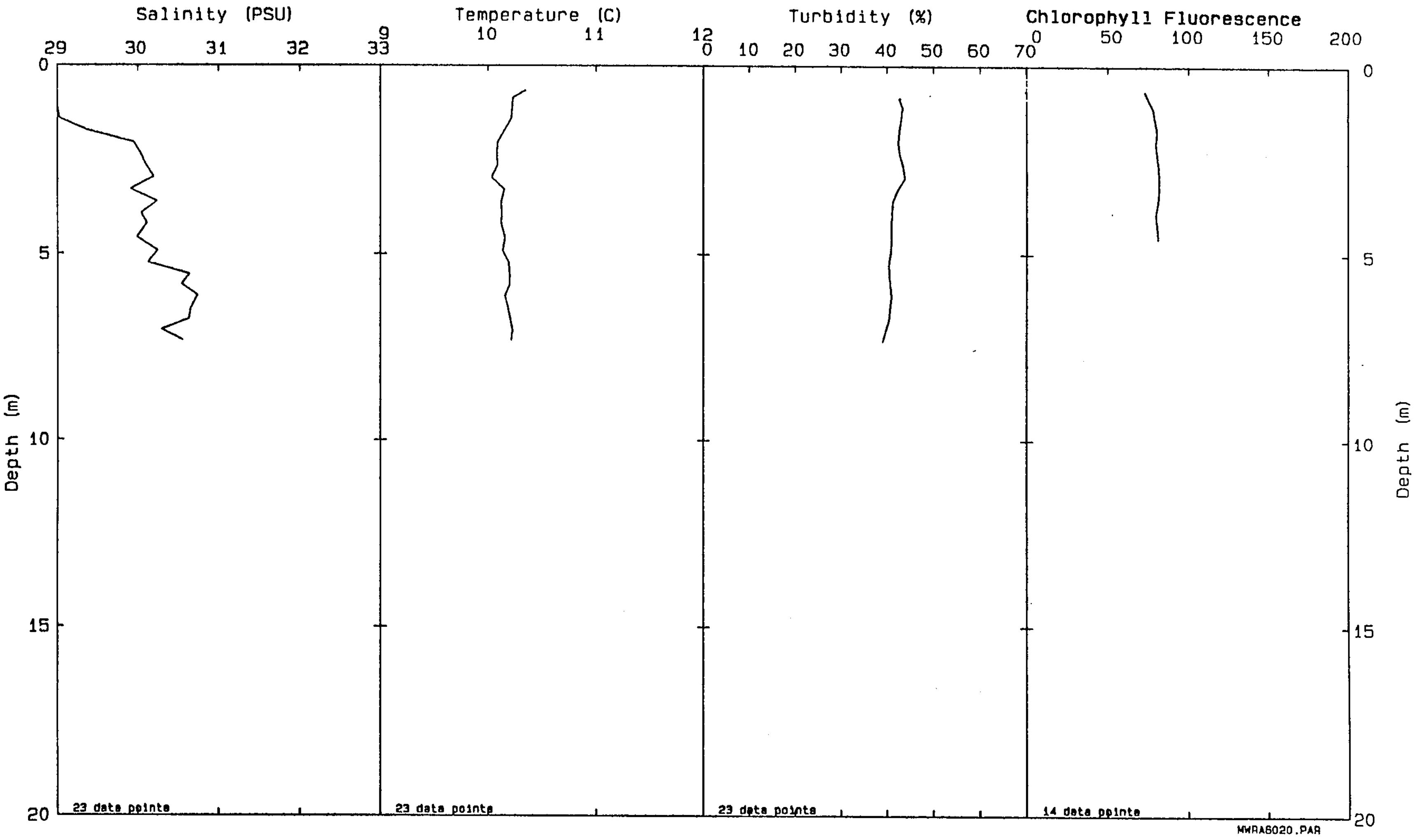

Figure 3-12. Vertical Profile Data Acquired at Station P8 Located in Dorchester Bay near High Water on November 1, 1990

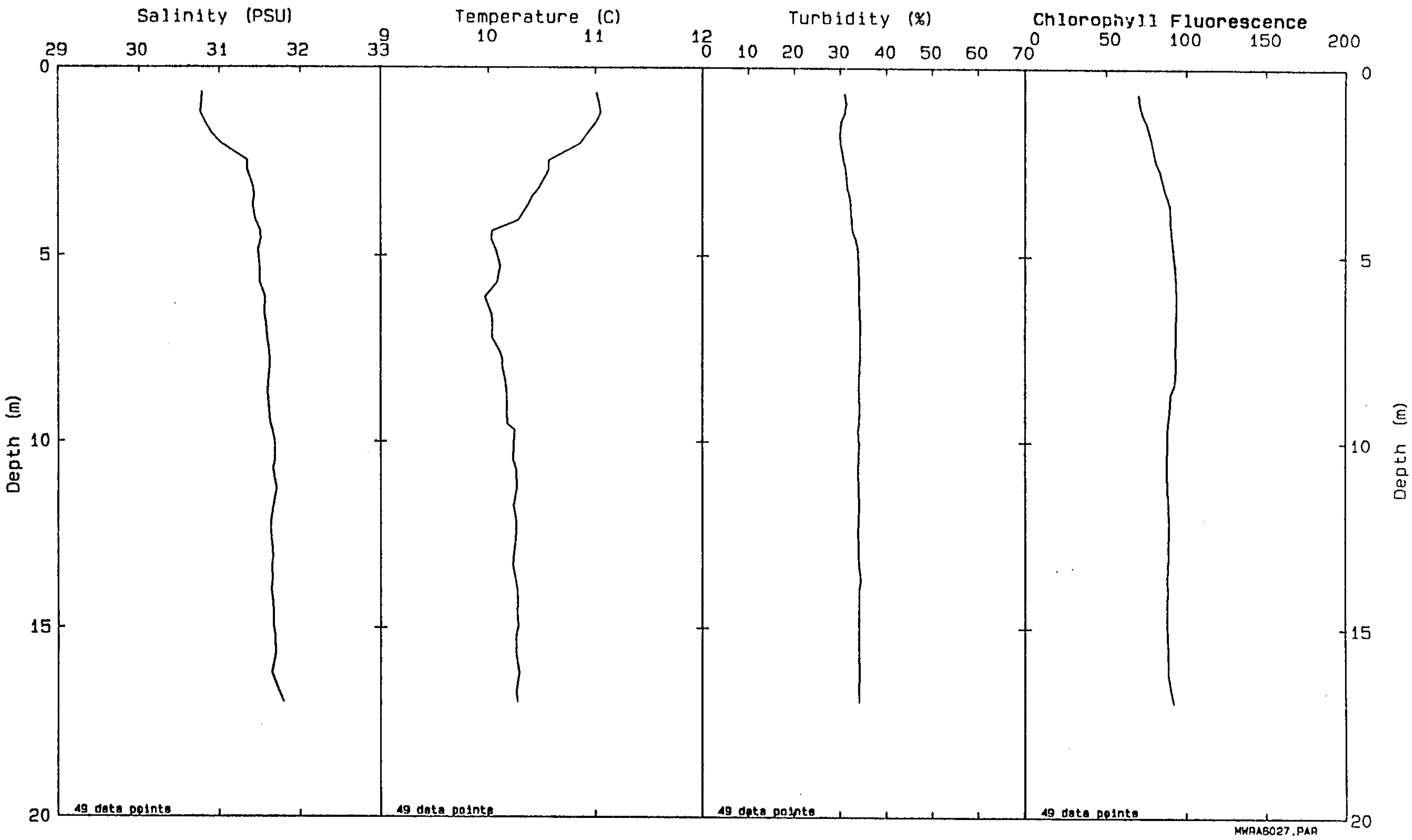

Figure 3-13. Vertical Profile Data Acquired at Station P10 Located in President Roads near High Water on November 1, 1990

3.3 RESULTS FROM SURVEY AT LOW WATER ON NOVEMBER 1, 1990

3.3.1 Sampling Activities

Figure 3-14 presents a chart of the Harbor, with superimposed transect lines and vertical profile stations that were surveyed during the afternoon of November 1. The survey operations began at profile station P11 in the Inner Harbor at 1338 h EST, followed by transects 13-14, 15-16, and 17-18, and the remaining vertical profiles (P12-P14), with sampling operations ending at 1700 h EST. The time and location of each transect and profile are given in Tables 3-1 and 3-2.

3.3.2 Results from Transects

The main objective of the afternoon, low-water survey was to reoccupy a subset of the morning high-water transects and profile stations to determine the temporal variability in water properties throughout the major Harbor channels. Note that Hingham Bay, Quincy Bay, and the entrance to the Inner Harbor were not sampled during the low-water survey. Because the three afternoon transects were made between 1 h before and 1.5 h after low water, we view these measurements as representative of low-water conditions in the Harbor.

Transect 13-14 was essentially a reoccupation of transect 1-2 from Weymouth Fore River to East Nantasket Roads made 6 h earlier at high water. The water-property results from the afternoon, low-water transect are presented in Figure 3-15. Again, we see the moderate range of salinities between the relatively fresh, cool waters of the Weymouth area and the warm, saline waters in East Nantasket Roads. Turbidity exhibited only minor variability along the low-water transect. Variations in chlorophyll fluorescence were small, with the highest values being observed in Weymouth.

Comparison with the T/S results from transect 1-2 (Figure 3-3) reveals that the inshore/offshore salinity range has remained relatively constant (~1 PSU) over the 6-h tidal period, but the entire transect is everywhere fresher at low water. Temperatures decreased a small amount from high to low water, presumably because of the relative contributions of warm water from Massachusetts Bay and cooler water from the Weymouth River system.

Curiously, turbidities in the Weymouth area decreased from high water to low water even though fresher water was observed at low tide. In contrast, turbidities at East Nantasket

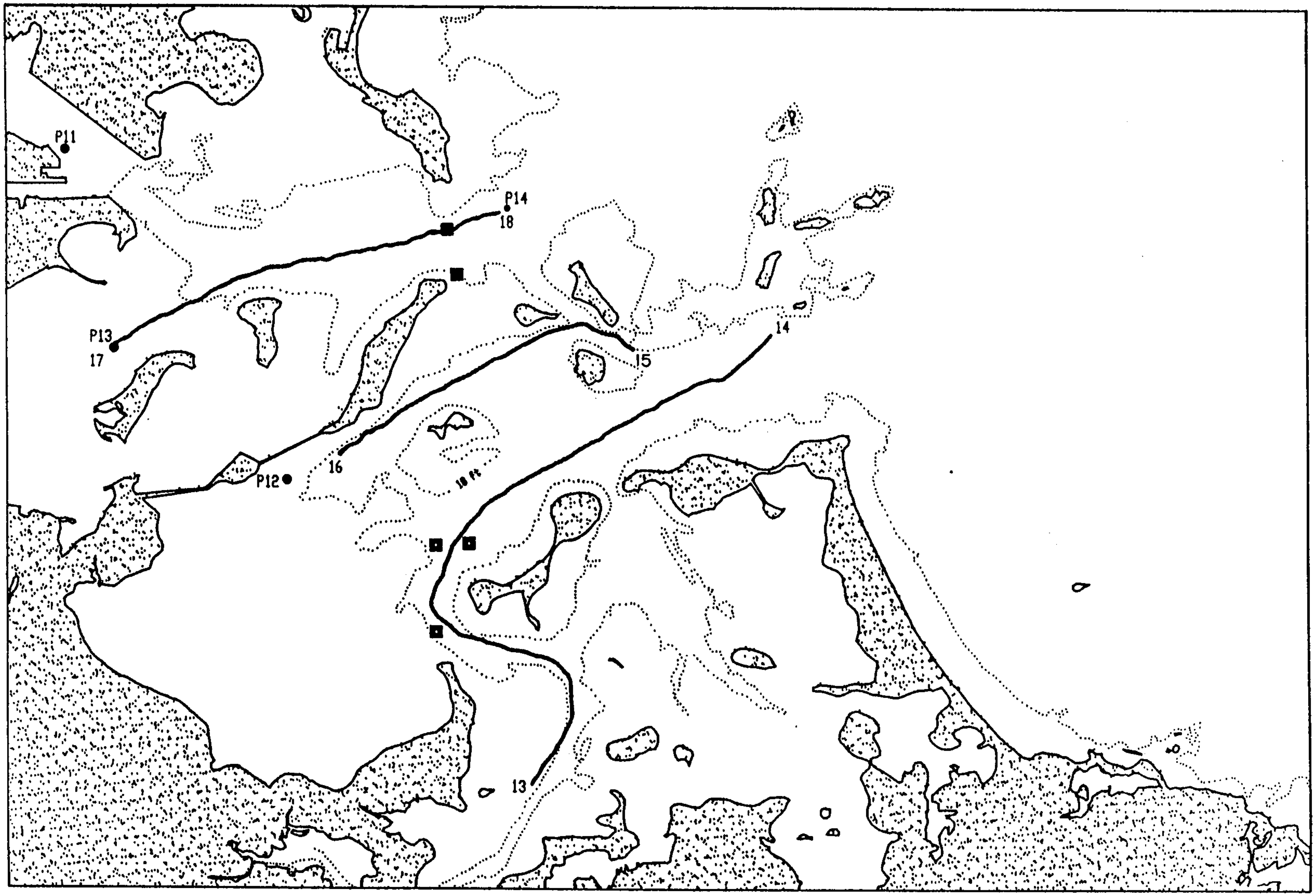

Figure 3-14. Location of Transects and Vertical Profile Stations (e.g., P11) Made near Low Tide on the Afternoon of November 1, 1990

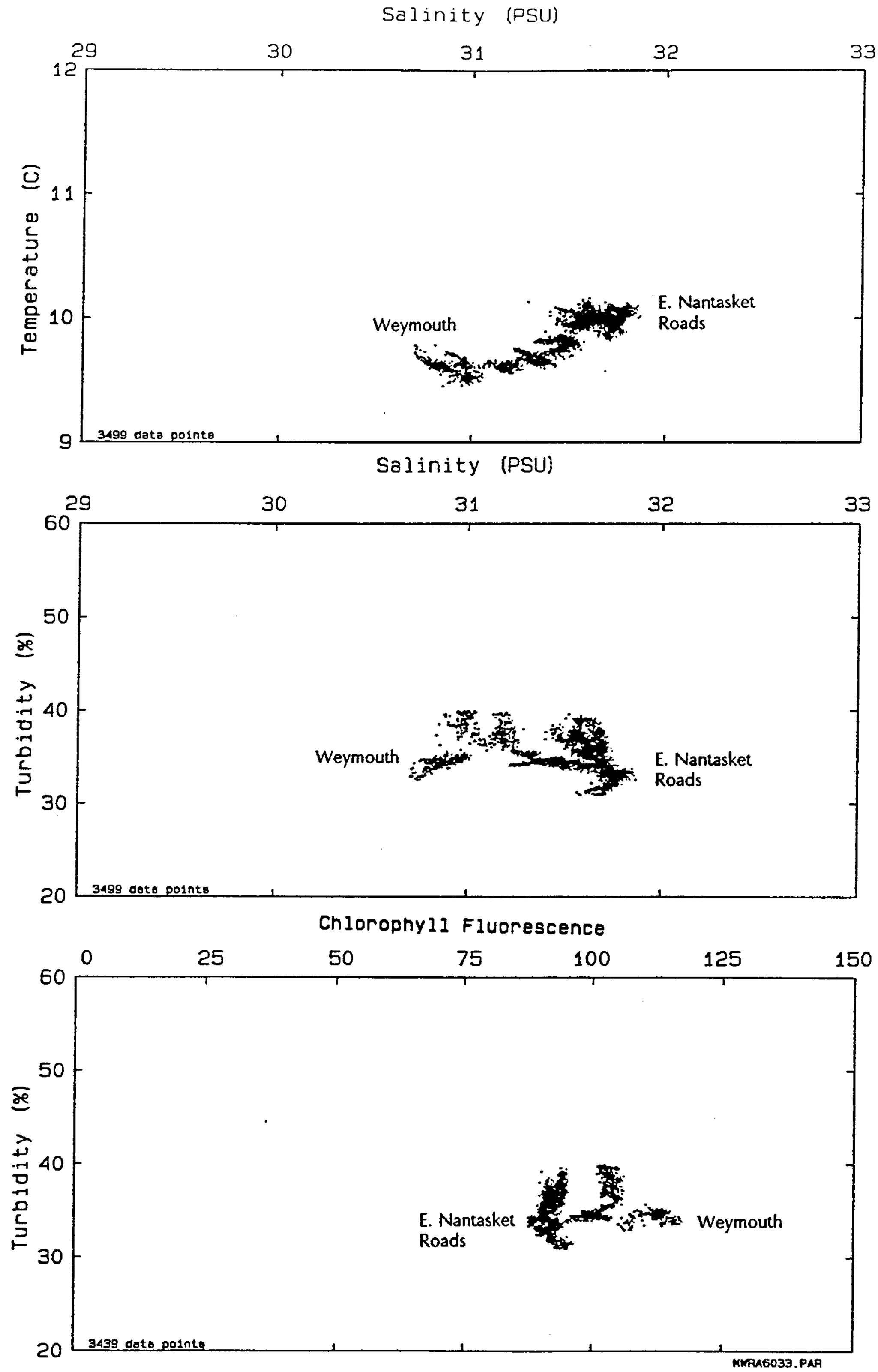

Figure 3-15. Scatter Plot of Data Acquired along Transect 13-14 Made on November 1, 1990

Roads increased from high to low water, apparently because of the eastward discharge of higher discharge of higher turbidity waters that resided in Nantasket Roads at high water.

Chlorophyll fluorescence values during the afternoon, low-water transect were nearly everywhere higher than during the morning, high-water transect. The highest chlorophyll fluorescence values were observed in Weymouth Fore River. Because chlorophyll-*a* levels are known to change appreciably on time scales of hours due to biological activity, we ***will not*** interpret the observed variability between the high- and low-water surveys as due to horizontal advection of a conservative water property.

Figure 3-16 presents the water-property data acquired along transect 17-18, which extends from Dorchester Bay to Deer Island (note that this transect is significantly shorter than transect 9-10, which started farther west and ended in North Channel). Transect 17-18 was made roughly 1 h after low water and 4.5 h after transect 9-10.

The T/S results in Figure 3-16 show relatively saline water within North Channel (at Deer Island) and fresher water at the eastern limit of Dorchester Bay (see Figure 3-14 for locations). North of Spectacle Island, traces of relatively warm Inner Harbor water were again detected in the channel. Turbidity values were relatively homogeneous along the low-water transect, but chlorophyll fluorescence values near Dorchester Bay were significantly higher than values within North Channel.

Individual time-series plots and scatter plots of data acquired along each of the transects made during the low-water survey on November 1 are presented in Volume II, Appendix B. Figure 3-17 presents composite scatter plots of all data (transects and vertical profiles) acquired during the low-water survey. Again, we can identify individual source-water characteristics from the T/S scatter plot, but the Tu/S and Tu/Chl data exhibit more homogeneity than was observed during the high-water survey (Figure 3-8). This lack of variability at low water is due to (1) no influx of saline, offshore water, (2) minimal fresh-water discharge from local rivers, and (3) the fact that the low-water transects did not extend to as many inshore source-water regions as did the more numerous high-water transects.

Figure 3-18 presents the scatter-plot data of Figure 3-17, with superimposed labels indicating the sources/locations of the individual water types at low water. The T/S plot indicates that similar water properties are encountered within East Nantasket Roads and North Channel (at Deer Island), but the water temperatures within the southern part of the Harbor are significantly cooler than within the northern Harbor. Salinities within Nantasket Roads and

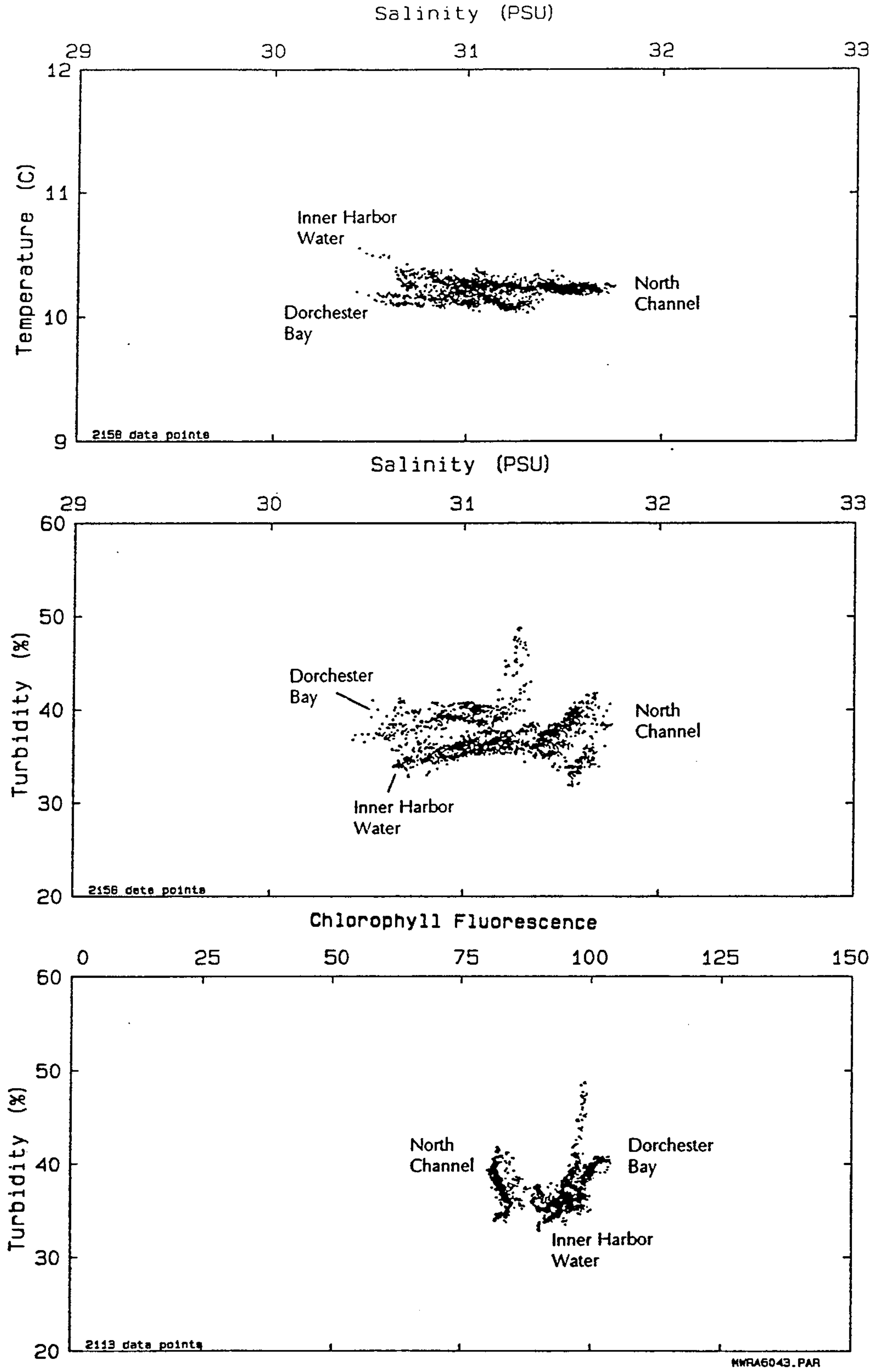

Figure 3-16. Scatter Plot of Data Acquired along Transect 17-18 Made on November 1, 1990

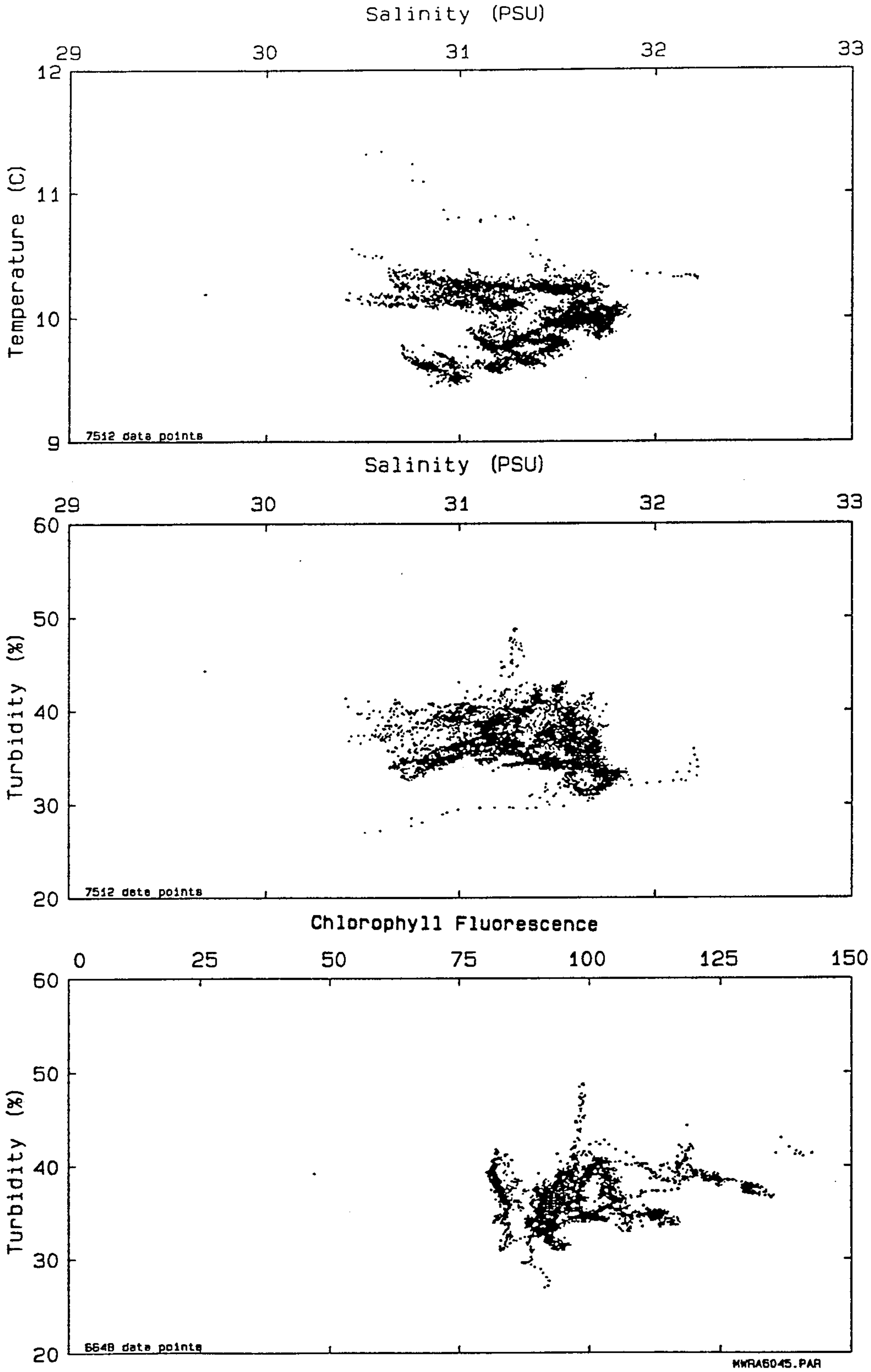

Figure 3-17. Composite Scatter Plot of All Data Acquired along Transects and at Vertical Profile Stations Made near Low Water on November 1, 1990

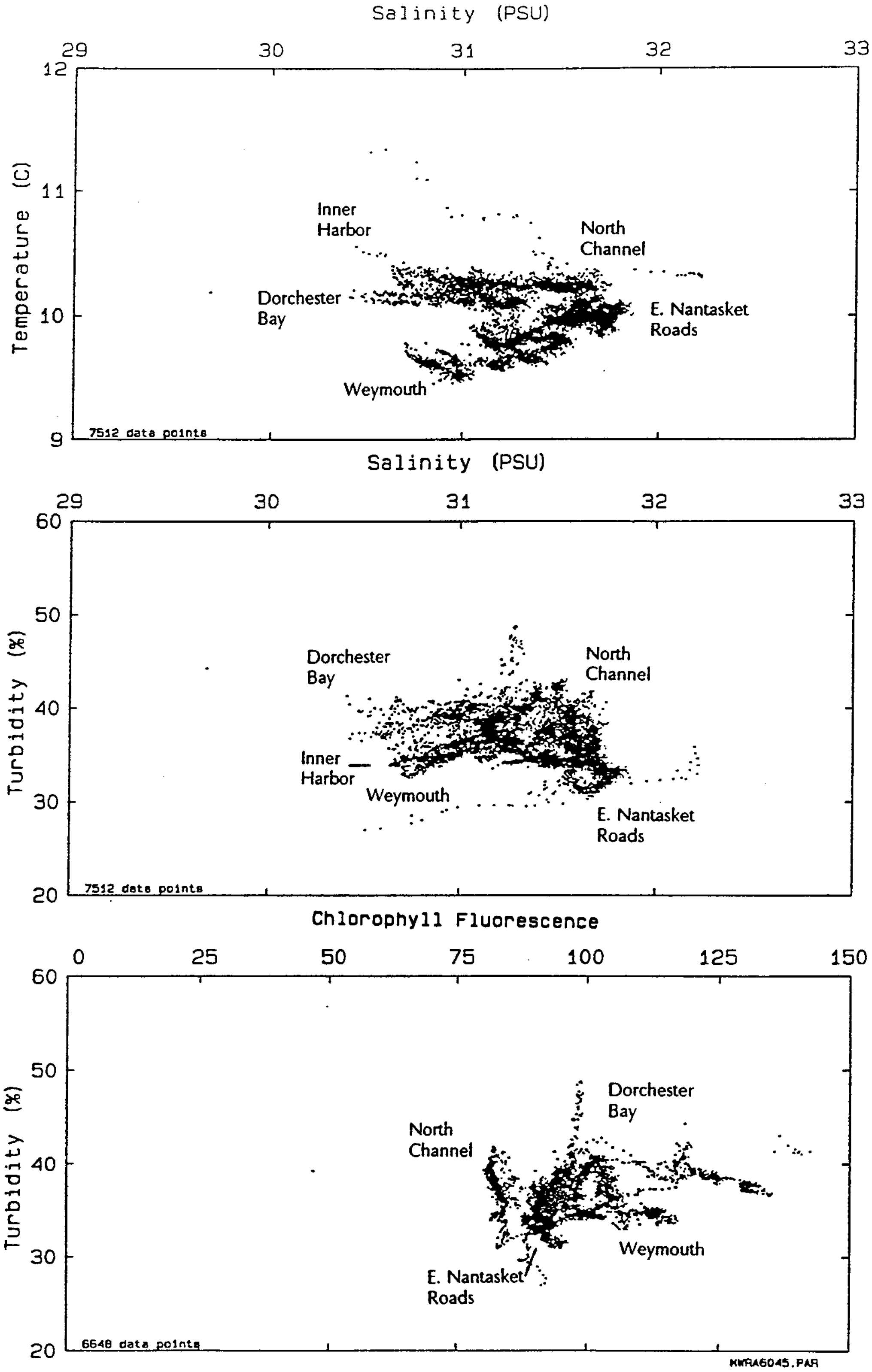

Figure 3-18. Identical Data Presentation as in Figure 3-17, with Labels Identifying Sources of Specific Water Types. Note that the Waters Labeled Inner Harbor were Sampled Well to the South of the Inner Harbor Entrance.

President Roads are similar. Note, that Figure 3-18 does not identify water properties in Hingham Bay or Quincy Bay because these areas were not sampled during the low-water survey. Also, note that the there was no low-water transect extending into the Inner Harbor; the characteristics labeled Inner Harbor on Figure 3-18 were observed along transect 17-18 in President Roads approximately 1 h after low water. Thus, the relatively low-salinity, high-temperature water from the Inner Harbor was not sampled adequately.

Figure 3-18 also illustrates that that turbidity levels throughout the northern and southern parts of the Harbor were similar, and that chlorophyll fluorescence levels were lower in the eastern channels than in the bays and headwaters.

Figure 3-19 illustrates the conceptual mixing regimes that were developed from analysis of the low-water scatter-plot data presented in Figure 3-18. As in Figure 3-10 for the high-water survey, the shaded regions represent the specific water-property characteristics derived from the actual scatter-plot data: labeled DB for Dorchester Bay; and W for Weymouth. Again note that the characteristics labeled IH (Inner Harbor) do not represent the true source-water characteristics as they were not sampled near the source. For this low-water scheme, it is believed that the individual water types within the the major Harbor channels (NC for North Channel; ENR for East Nantasket Roads) are affected by the waters from the adjacent bays and channels.

As suggested in the T/S plot of Figure 3-19, water from North Channel is affected by the Inner Harbor and Dorchester Bay, whereas water within East Nantasket Roads is affected by water from Weymouth River System (and also presumably Hingham Bay). The dashed line represents the hypothetical boundary between the waters of the northern and southern portions of the Harbor.

The Tu/S and Tu/Chl mixing diagrams presented in Figure 3-19 demonstrate the significant differences in the properties of the waters within North Channel and East Nantasket Roads near low water. The hypothesized mixing lines and the expected water-property boundary (dashed line) between the northern and southern portions of the Harbor are well supported by the various water-property types. Additional surveys will be required, however, to determine the extent to which seasonal changes in winds, water-column stratification, and river runoff will alter the water-property distribution and mixing characteristics within the Harbor.

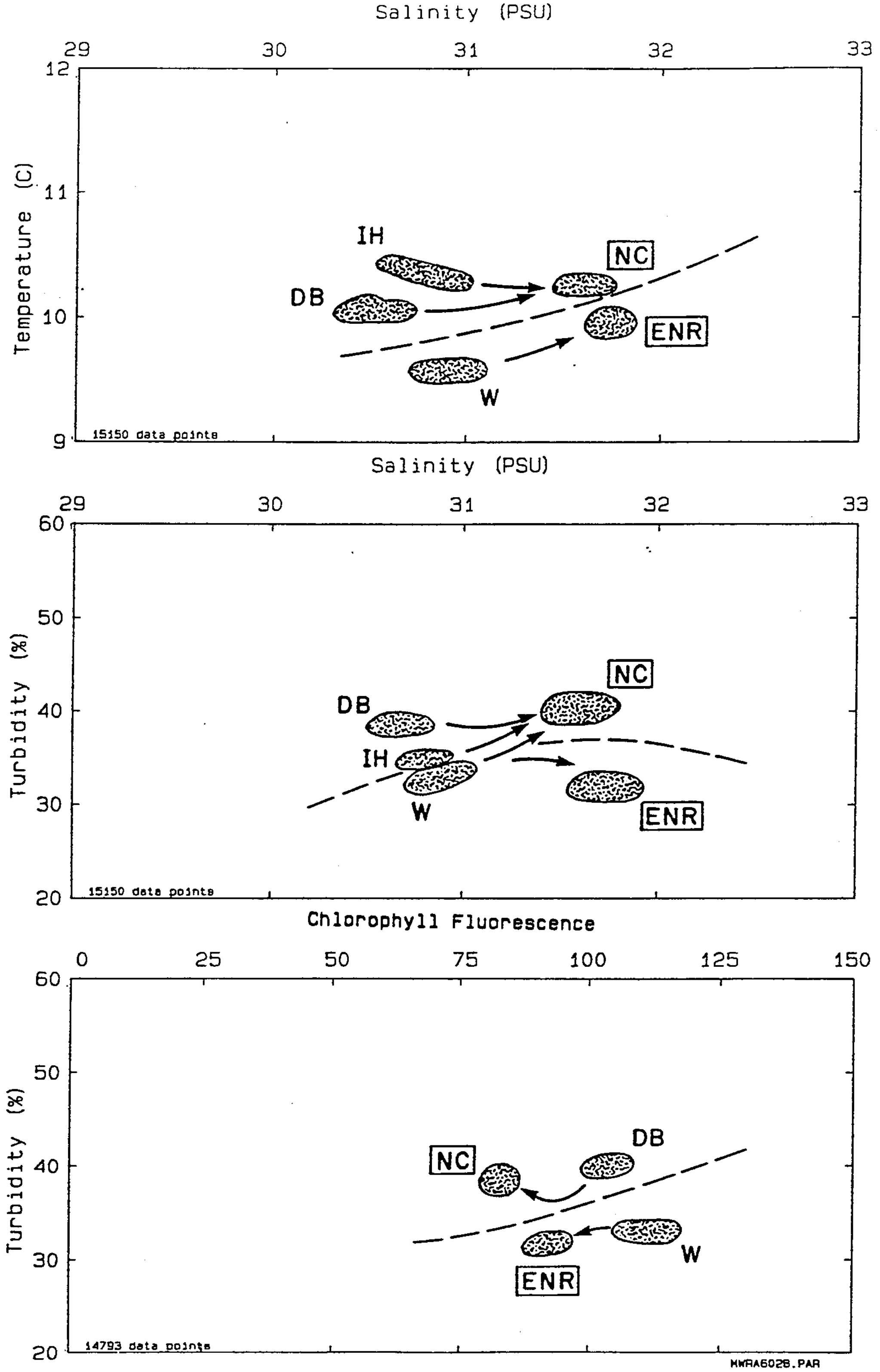

Figure 3-19. Simplified Presentation of Data from Figure 3-18, with Specific Water Types Shaded and Labeled According to Sources. Arrows Demonstrate Mixing on Ebb Tide. Broken Line Represents Boundary between Northern and Southern Basins of the Harbor.

3.3.3 Results from Vertical Profiles

The previous Section presented water-property data acquired during the low-water survey while the Mini-BOSS sensor package was towed horizontally at a depth of roughly 2 m below the surface. The results provide a synoptic picture of near-surface water properties throughout the Harbor, but there is still the question of whether the surface properties were representative of the entire water column at the time of the low-water survey.

During the low-water survey, four vertical profiles were made at various locations within the Harbor (see Figure 3-14). Table 3-2 provides the time and location of each profile station (stations P11-P14).

Figure 3-20 presents the vertical profiles of salinity, temperature, turbidity, and chlorophyll fluorescence acquired from 1 m below the surface to the bottom (14 m) at profile station P11 located in the channel entrance to the Inner Harbor. The lower part of the water column at this station was generally well mixed, but decreased salinities and increased temperatures were observed above a depth of roughly 6 m, presumably due to water ebbing from the Inner Harbor. Turbidity and chlorophyll fluorescence levels were relatively constant over the vertical profile.

At the remaining vertical-profile stations (P12-P14) made during the low-water survey (see Volume II, Appendix B-3 for plots of all profiles), water properties were generally well mixed throughout the water column. From these profile results, we believe that the results obtained from the ~2-m-deep horizontal tows along transects throughout the Harbor provide a good estimate of the spatial variations in water properties throughout the water column at each location.

3.4 COMPARISONS BETWEEN HIGH-WATER AND LOW-WATER SURVEYS

In addition to the spatial comparisons of water properties during either the synoptic low-water survey or the synoptic high-water survey, we can make temporal comparisons between the water properties observed at the two stages of the tide. Figure 3-21 attempts to portray this temporal and spatial comparison, based upon the scatter-plot results from Figure 3-10 (high water) and Figure 3-19 (low water). In Figure 3-21, a shaded region indicates the specific water-property characteristics observed at high water at one location (e.g., DB: Dorchester Bay), and the adjacent open region indicates the characteristics observed at low water at the same location. Note that data from Hingham Bay, Quincy Bay, and the entrance

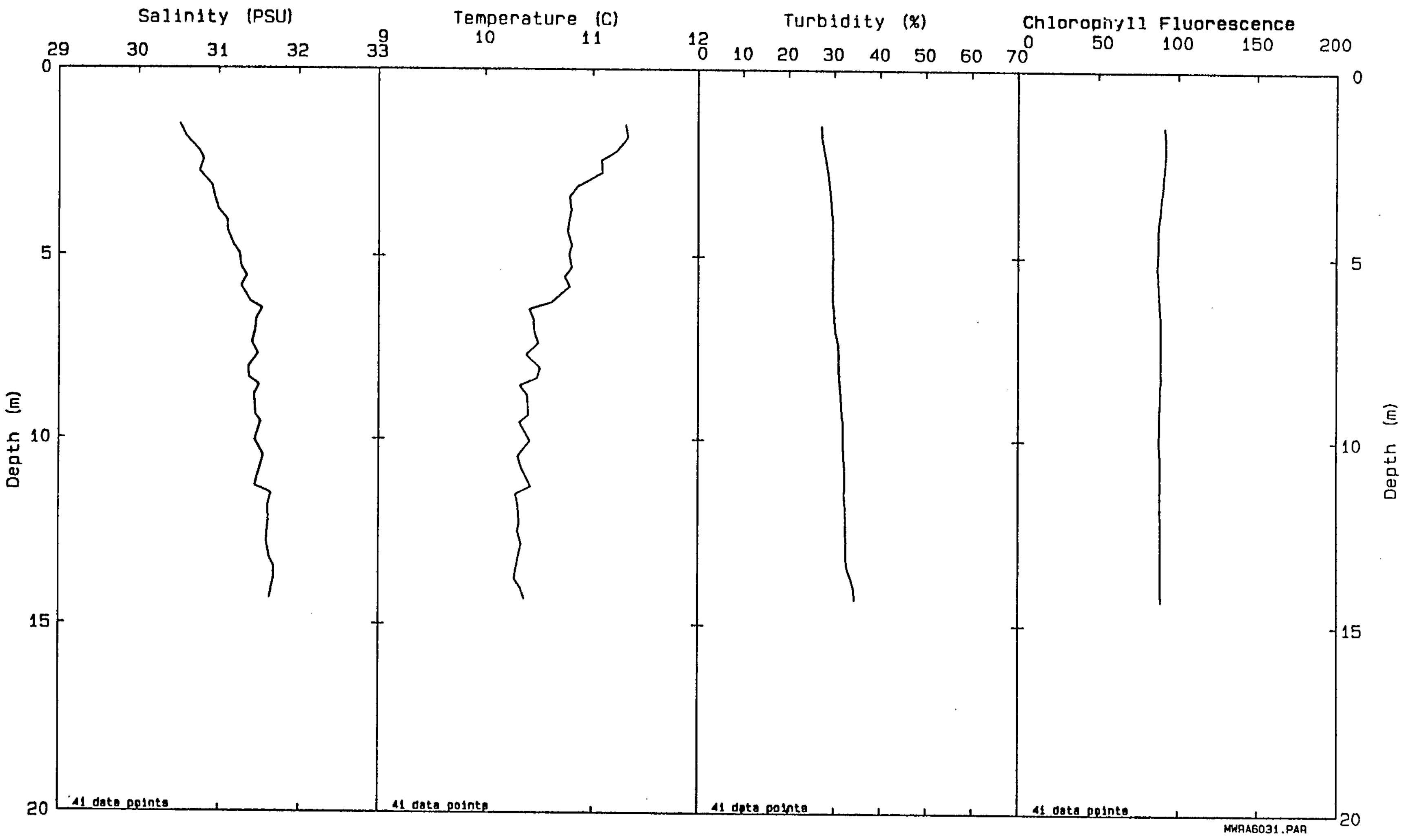

Figure 3-20. Vertical Profile Data Acquired at Station P11 Located in the Inner Harbor Channel near Low Water on November 1, 1990

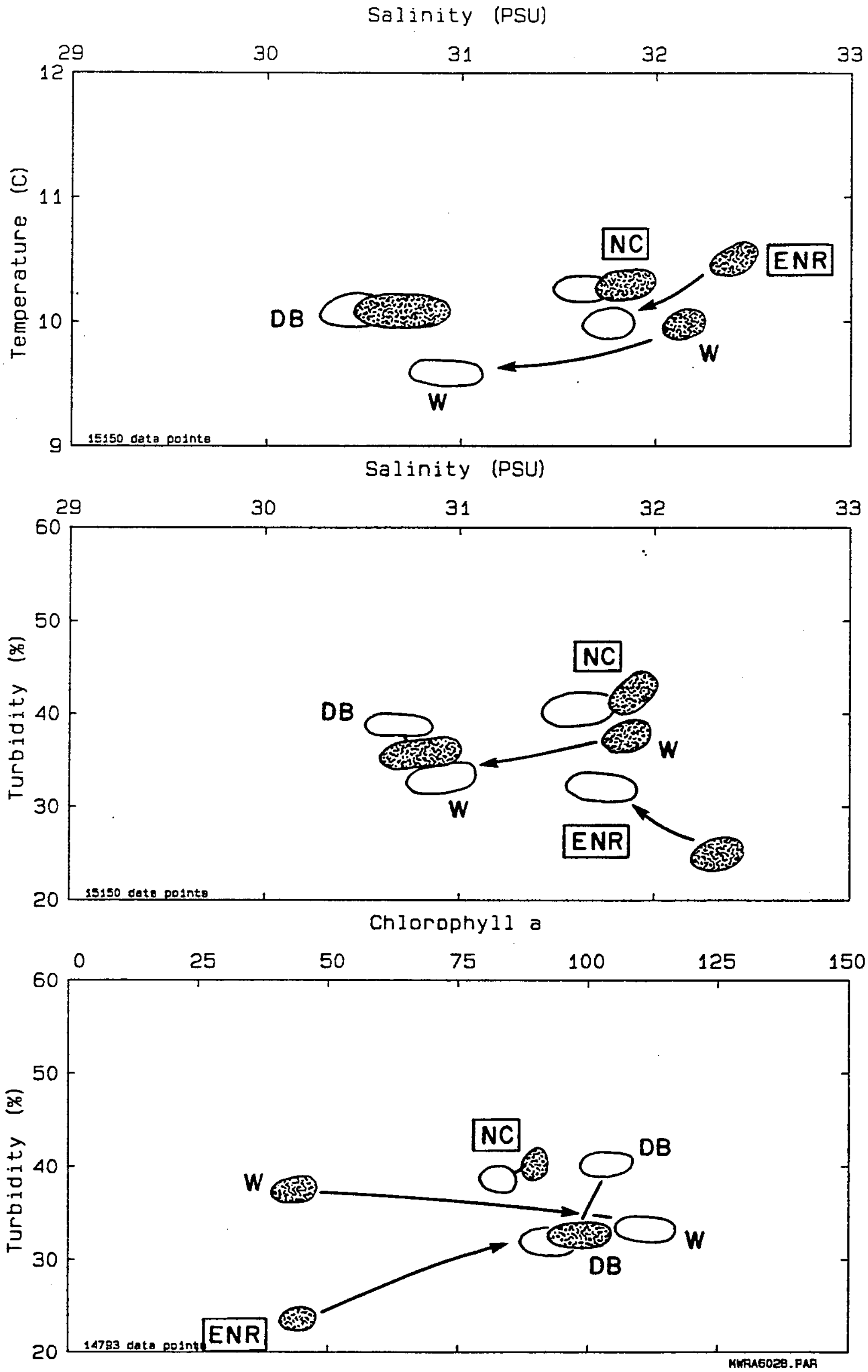

Figure 3-21. Schematic Presentation of Water Property Variations from High Water (Shaded Areas) to Low Water (Open Areas) for Specific Regions (e.g., DB: Dorchester Bay)

to the Inner Harbor are not shown because they were not adequately sampled during the afternoon, low-water survey.

As indicated in the T/S plot of Figure 3-21, the North Channel (NC) T/S properties are very similar at high and low water; high- and low-water characteristics of turbidity and chlorophyll fluorescence are also relatively constant at the North Channel. In contrast, the water-property characteristics at East Nantasket Roads (ENR) vary greatly from high to low water. Over the 6-h ebb on November 1, the waters within East Nantasket Roads decreased in salinity and temperature and increased in turbidity and chlorophyll fluorescence. The characteristics at Weymouth (W) also changed greatly over the 6-h ebb: salinity, temperature, and turbidity decreased while chlorophyll fluorescence increased. The large temporal changes at Weymouth and East Nantasket Roads are consistent with the hypothesis that the deep parts of the southern Harbor are flushed appreciably during the tidal cycle; temporal variations in water properties at Dorchester Bay (DB) and North Channel (at Deer Island) were apparently much smaller, but the limited spatial coverage of the low-water survey precludes a well-supported conclusion.

4.0 STUDIES OF NUT ISLAND EFFLUENT PLUMES IN NANTASKET ROADS

4.1 SURVEY OBJECTIVES AND ACTIVITIES

Sewage effluent from the Nut Island sewage treatment plant is pumped to and continually discharged from three seabed outfalls located in the western arm of Nantasket Roads (Figure 4-1). The total effluent discharge flow from the Nut Island treatment plant is approximately 4.9 m^3/s (423,360 m^3/day). As indicated in Figure 4-1, one outfall is located off the northern tip of Nut Island, and two others are located northwest of the southern end of Peddocks Island. Throughout this report, the three effluent outfalls are referred to as the south, northeast, and northwest outfalls. The partition of effluent discharge from the three outfalls varies with the total flow rate and the tide (pressure head). The southern outfall is not open all the time; the two northern outfalls are used first, and any overflow is discharged through the southern outfall.

Intense tidal currents within Nantasket Roads are well documented in tidal-current charts and from direct observations. During the ebb flow, strong northward currents are found in the narrow channel between the northern tip of Nut Island and the southwestern tip of Peddocks Island. This flow then turns northeastward along the main channel of Nantasket Roads and continues into Massachusetts Bay. Therefore, in terms of the basic flow regime, it appears that the three effluent outfalls were placed in locations to maximize the eastward transport of the effluent during the ebb flow. Whether the effluent actually leaves the Harbor during the ebb has become a topic of concern as a result of the increased interest in the water quality of the Harbor. The fate of the effluent that is continuously discharged during the flood tide is also poorly understood, but not addressed by the present study.

Numerical hydrodynamic models can be used to predict the time-varying flow regimes within water bodies having variable topography, complex coastal morphology, water-column stratification, and multiple dynamic forcing mechanisms. In coastal embayments such as Boston Harbor, the tides and wind-driven flows are responsible for most of the circulation. Density-driven circulation caused by river discharge and influx of saline water from Massachusetts Bay are secondary effects, as are influences from solar radiation, evaporation, and precipitation. Recently, R. Signell at the USGS in Woods Hole developed a high-resolution numerical model of the tidal- and wind-driven circulation in Boston Harbor (Bothner *et al.,* 1990). High-resolution refers to the spatial resolution of the model elements and to the time steps used to resolve the time-dependent flow through the tidal cycle. This model of Boston Harbor is the first to offer the spatial resolution necessary to resolve the detailed flow around the numerous islands and complex bottom topography of the Harbor.

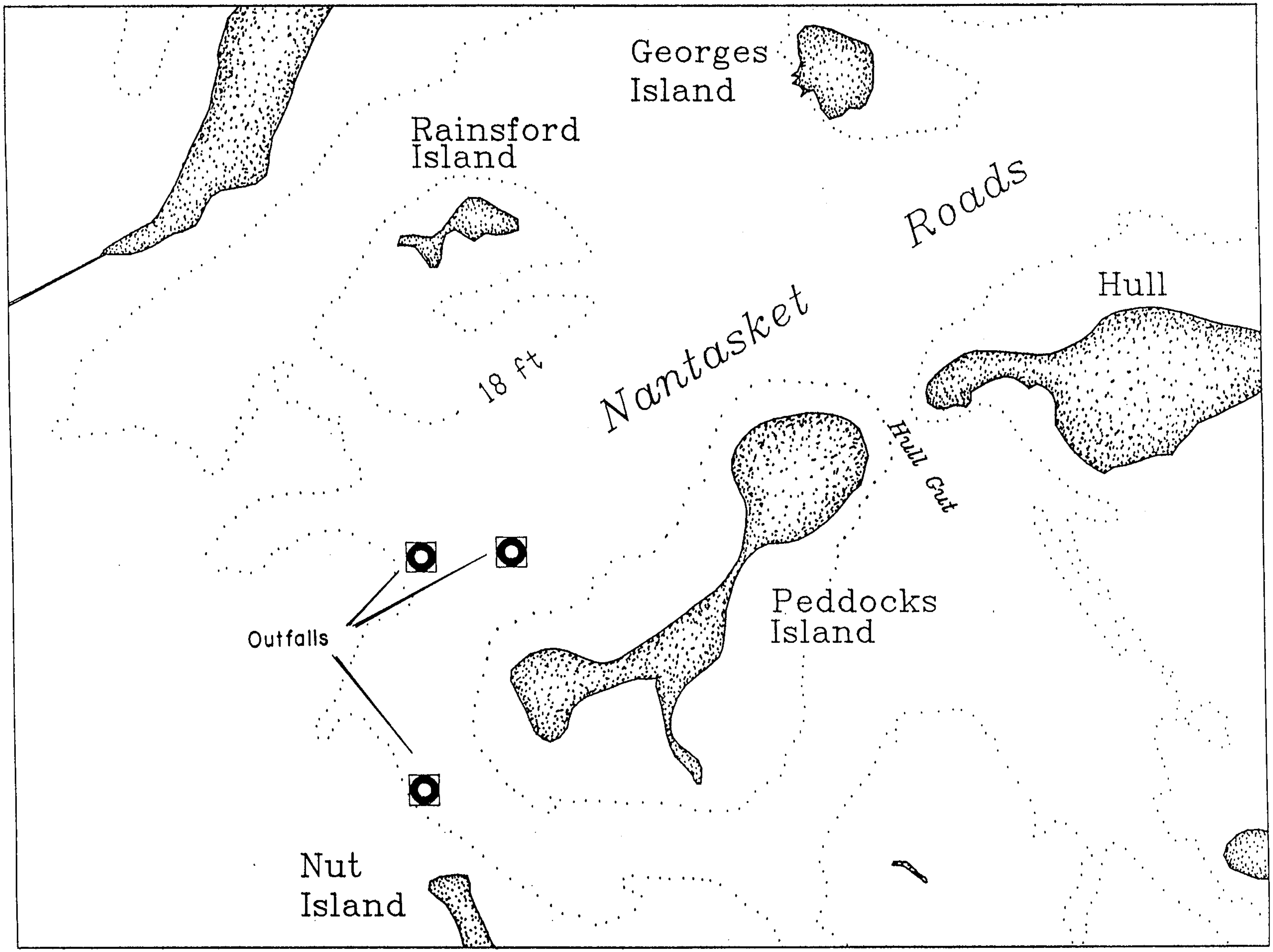

Figure 4-1. Map of Nantasket Roads Indicating the Location of Sewage Effluent Outfalls from the Nut Island Treatment Plant

Consequently, it is being used to predict the horizontal transport of particles released from the existing outfall locations within the Harbor.

Signell's preliminary model runs for prediction of the transport of effluent released from the Nut Island outfalls within Nantasket Roads suggest that the eventual fate of particles released during the ebb flow is highly sensitive to the time of release (in relation to the tidal phase) and to variations in the horizontal shear of currents within the main channel. Furthermore, Signell's model is based upon a vertically averaged water column; that is, it distributes the effects of wind stress and bottom friction over the entire water column and, in so doing, the model does not deal with water-column stratification. During November, the water column in the Harbor and especially within Nantasket Roads is well mixed so the physical assumptions of Signell's model are applicable if the wind stress, bottom friction, and horizontal current shear can be adequately represented.

As described in Section 1, one of the main objectives of the present study was to delineate and track the Nut Island effluent plumes within Nantasket Roads during the ebb flow regime. These results will provide valuable, direct observations of the effluent transport within the southern Harbor; the observations can also be used for design of water-quality monitoring studies in specific regions impacted by the effluent discharges. The information also represents valuable input to Signell's numerical model for verification of surface trajectories and current shears, because the individual plumes can be considered as tracers of the surface flow. Moreover, surface drifters deployed during the plume studies also provide valuable surface current observations for calibration of Signell's model.

In summary, the specific objectives associated with the field surveys of the Nut Island sewage effluent plume study were to

- Determine whether the water-quality sensors on the Mini-BOSS are adequate for real-time mapping of the effluent plumes emanating from the three Nut Island outfalls
- Use the Mini-BOSS to track the effluent plumes during the ebb flow period on two consecutive days
- Deploy and track surface drifters to obtain direct observations of the flow regime at the time of the plume measurements
- Use the field results to develop a conceptual model of the advection of the Nut Island effluent plumes during the ebb flow period

The field component of the Nut Island effluent plume surveys consisted of surveying during daylight hours on the ebb tidal cycle of October 16 and 17, 1990. The field monitoring consisted of two activities:

1. Vertical and horizontal profiling of water properties within and around the effluent plumes using the Mini-BOSS installed on the R/V *Surveysa*
2. Tracking of surface drifters released in the vicinity of the Nut Island outfalls using a second vessel, the R/V *Seaquest*

Details of the monitoring equipment and surveying techniques are given in Section 2. Note, that chlorophyll fluorescence measurements were not acquired with the Mini-BOSS system during these days. The results of the field surveys on October 16 and 17 are presented in Sections 4.2 and 4.3, respectively.

4.2 RESULTS FROM SURVEY ON OCTOBER 16, 1990

4.2.1 Drifter Results

Surface drifters of the configuration described in Section 2.4 were deployed at various times during the ebb tide on October 16 to obtain direct, Lagrangian current trajectories for the surface currents within Nantasket Roads. The drifters were released from the two survey vessels and tracked visually over the duration of the measurement period (roughly 1015 to 1630 h EST). The R/V *Seaquest* was dedicated to drifter tracking operations, whereas the R/V *Surveysa* was used primarily for Mini-BOSS surveying; the *Surveysa* assisted with drifter positioning when in close proximity to drifters during the conduct of the Mini-BOSS surveying. In Volume II, Appendix A, tables of time and position of each drifter fix are given for each drifter tracked; calculated drifter speed and distance between fixes are also provided.

Figure 4-2 presents data from four drifters that were released from the southern Nut Island effluent outfall at approximately 1015 h EST and two additional drifters released at approximately 1234 h EST within Nantasket Roads north of Hull Gut. Times in the Figure are presented in hours and minutes (hh:mm) after high water, which was at 0919 h EST. For each drifter cluster, the release time, recovery time, and drifter identification numbers are indicted. A1 represents the first release of drifter A; following recovery of drifter A, the second release would be labeled and the same convention is used for all drifters. The symbols in Figure 4-2 represent the positions where the survey vessel came alongside a drifter and obtained an accurate Loran C position. Note that drifter positions have been connected with straight lines to suggest a trajectory, but in many cases the actual drifter track between two positions may have been curvilinear in form. The data were insufficient to resolve the true trajectory form during that period.

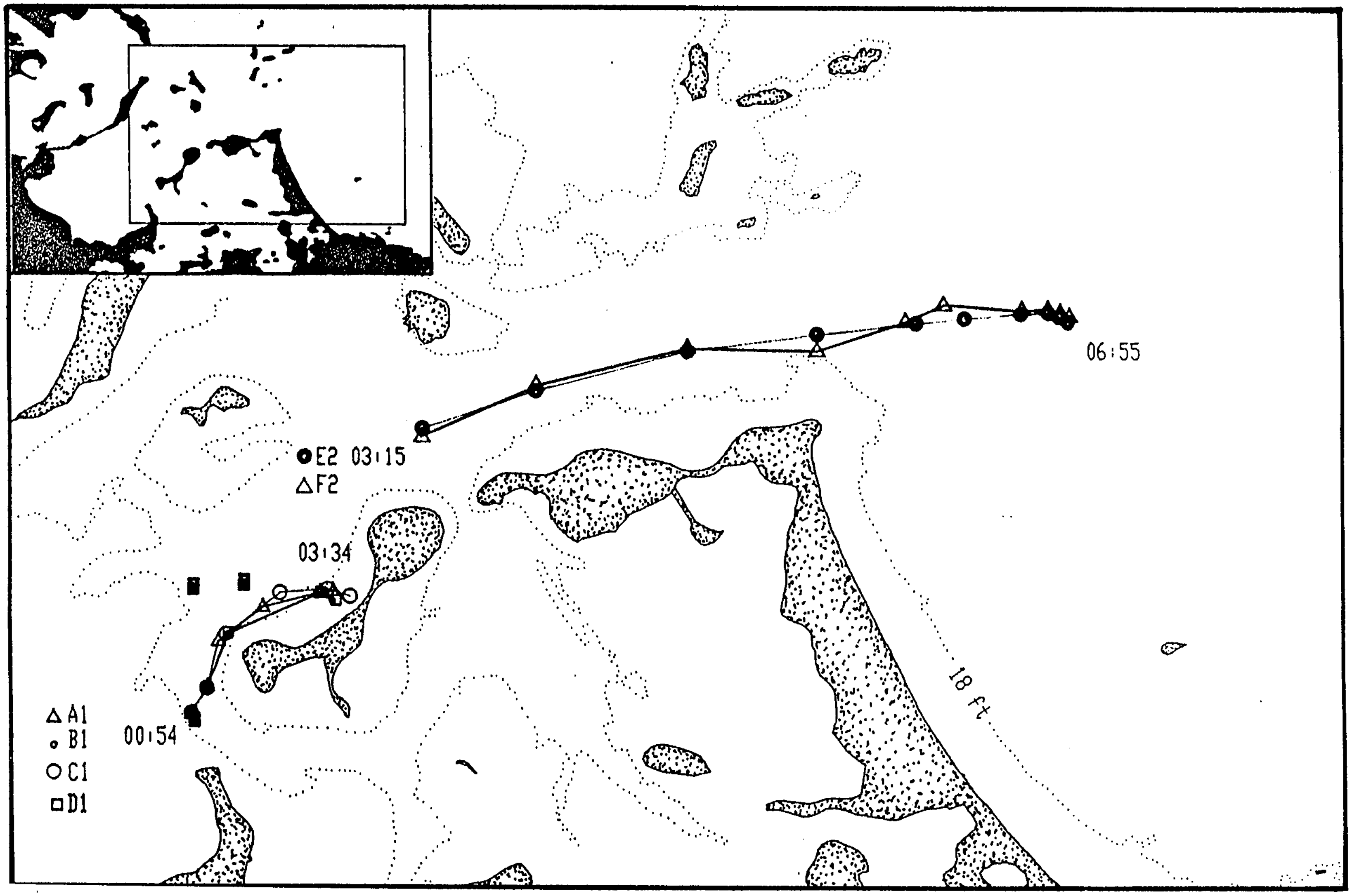

Figure 4-2. Trajectories of Six Drifters Released within Nantasket Roads on the Morning of October 16, 1990. Times of Deployment and Retrieval Are Indicated as Hours and Minutes after High Water (e.g., 03:15 = 3 h 15 min).

Drifters A1, B1, C1, and D1 were released at the southern outfall at the time when the ebb (northward) flow was observed to begin at that location. All four of these drifters remained remarkably close together as they moved northeastward, approaching the southern tip of Peddocks Island at a rate of roughly 15 to 35 cm/s. In less than 3 h, they all had entered Portuguese Cove on the west side on Peddocks Island and grounded in shallow water.

Figure 4-3 presents data from four drifters that were released from the northeast Nut Island effluent outfall at approximately 1 h after high water and two additional pairs of drifters released within Nantasket Roads north of Hull Gut at roughly 4 h after high water. Upon release, drifters E1, F1, G, and H remained together and moved eastward toward Peddocks Island at a speed of roughly 25 cm/s until they grounded in shallow water approximately 1.5 h after release.

As indicated in Figures 4-2 and 4-3, the eight drifters released from near the two effluent outfalls near the beginning of the ebb flow demonstrated that the surface flow in this localized region enters Portuguese Cove rather than following the channel of Nantasket Roads. The apparent eastward divergence of the drifters from the main flow direction within the channel is in direct agreement with the ~15-kn wind from the west that persisted throughout the day. It is expected that, very near the shore within Portuguese Cove, there was a northward current carrying the surface waters out of the Cove; the drifters grounded before reaching this hypothesized nearshore current. Comparisons between the trajectories of the drifters released from the outfalls and the direct observations of effluent plume advection on October 16 are presented in Section 4.2.3.

Following recovery of the grounded drifters from Portuguese Cove, drifters A though F were released again in Nantasket Roads, as indicated in Figures 4-2 and 4-3. As indicated in the Figures, the drifters within each pair remained together for the 3- to 4- h tracking period as the drifters moved eastward along Nantasket Roads at speeds of 40 to 95 cm/s during the remainder of the ebb. Near the time of low water (0600), drifters A2, B2, E2, and F2 slowed their eastward motion and essentially stalled at a distance of 1.5 nmi east of the Harbor channel. Drifters C2 and D2, which were launched on the northern side of the channel within Nantasket Roads, continued moving eastward at speeds of roughly 25 cm/s until they were recovered approximately 1 h after the beginning of the incoming tide. Additional comments about the eastward penetration of Boston Harbor water into Massachusetts Bay are provided in Section 4.2.4.

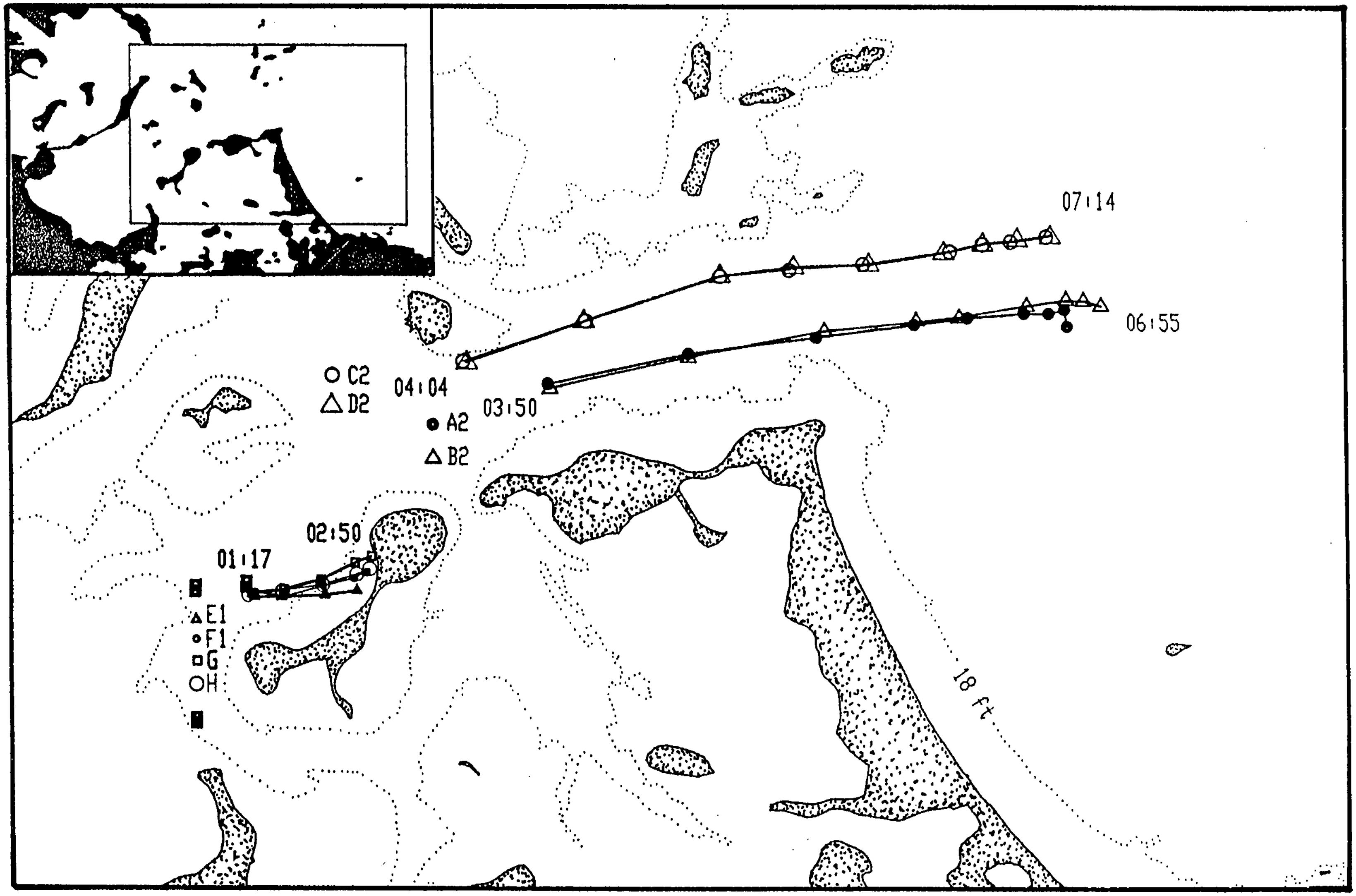

Figure 4-3. Trajectories of Eight Drifters Released within Nantasket Roads on the Morning of October 16, 1990

4.2.2 Plume Tracking Results

Water-quality surveying with the Mini-BOSS was initiated at roughly 0930 EST on October 16. Initial measurements were made in the vicinity of the southern Nut Island effluent outfall (see Figure 4-1), which was recognizable from a large surface "boil" caused by the buoyant effluent ascending to the surface. Although the predicted time of high tide in Boston Harbor was 0919 h EST, direct observations of the flow direction on this morning revealed that the ebb flow did not begin until roughly 1000 h EST in the vicinity of the southern Nut Island effluent outfall. This lag in the phase of the tide within the western arm of Nantasket Roads has been documented by other observers, as well as being reproduced in Signell's model (Bothner *et al.*, 1990).

Throughout the period from roughly 1030 to 1600 h EST on October 16, good-quality water-property measurements were made along 20 horizontal transects and at one vertical-profile station using the Mini-BOSS. Table 4-1 presents the time and location of each Mini-BOSS transect and the single vertical profile. Figure 4-4 presents a chart of Boston Harbor, with superimposed tracks representing the horizontal transects. As indicated, the majority of the transects were located in the vicinity of the northeast effluent outfall located to the northwest of Peddocks Island. Because the survey was conducted during the ebb flow, tracking of the effluent plume resulted in numerous transects across Nantasket Roads, progressing farther eastward during the later stages of the ebb flow regime.

The main survey objectives on October 16 were to locate the northwest outfall effluent plume and map the lateral progression of the effluent plume during the ebb tide. During the conduct of this survey, it was possible to obtain a limited amount of direct observations of the plumes emanating from the southern and northwestern effluent outfalls, but the significant distances between the individual plumes, combined with the rapid advection due to the tidal currents, prevented synoptic mapping of all three plumes with a single survey vessel.

Actual surveying operations consisted of near-continual towing of the Mini-BOSS sensor package at a depth of roughly 2 m below the surface. Selection of transect locations was made on a real-time basis by the scientist aboard the vessel, using the information from the real-time graphic display of water-property data and vessel position provided by the Mini-BOSS. The transects were situated to maximize the number of crossings of the effluent plume; the overall goal was to map the two-dimensional boundaries of the near-surface plume as it was advected by the tidal currents.

Table 4-1. Time and Location of Horizontal Transects (Tows) and Vertical Profiles Made on October 16, 1990

File Number	File Type	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Start Position		End Position	
				Lat(N)	Long(W)	Lat(N)	Long(W)
MWRA1004	Tow	10:30:46	10:39:28	42°17.76′	70°57.04′	42°17.87′	70°56.95′
MWRA1006	Tow	10:39:52	10:46:06	42°17.90′	70°56.94′	42°17.84′	70°57.25′
MWRA1007	Tow	10:46:10	10:53:44	42°17.82′	70°57.25′	42°17.65′	70°56.72′
MWRA1008	Tow	10:53:47	11:02:51	42°17.66′	70°56.70′	42°17.92′	70°57.07′
MWRA1009	Tow	11:02:54	11:08:26	42°17.93′	70°57.10′	42°18.01′	70°56.75′
MWRA1010	Tow	11:08:30	11:24:32	42°17.99′	70°56.74′	42°17.54′	70°57.17′
MWRA1011	Tow	11:24:36	11:28:13	42°17.54′	70°57.21′	42°17.59′	70°57.31′
MWRA1014	Tow	11:34:26	11:42:58	42°18.02′	70°57.00′	42°17.62′	70°56.63′
MWRA1016	Tow	11:48:31	12:00:52	42°18.06′	70°56.31′	42°18.30′	70°56.82′
MWRA1017	Tow	12:00:56	12:10:46	42°18.32′	70°56.84′	42°18.27′	70°56.02′
MWRA1018	Tow	12:10:50	12:15:23	42°18.27′	70°55.98′	42°18.43′	70°55.72′
MWRA1019	Tow	12:15:26	12:23:33	42°18.45′	70°55.70′	42°18.73′	70°55.98′
MWRA1020	Tow	12:23:38	12:32:01	42°18.76′	70°56.00′	42°18.37′	70°55.91′
MWRA1021	Tow	12:32:04	12:43:20	42°18.35′	70°55.89′	42°18.76′	70°55.86′
MWRA1024	Tow	12:56:26	13:06:34	42°18.34′	70°56.46′	42°17.91′	70°56.37′
MWRA1025	Tow	13:06:38	13:29:46	42°17.91′	70°56.41′	42°18.01′	70°57.64′
MWRA1028	Tow	14:02:06	14:07:19	42°18.81′	70°54.92′	42°18.63′	70°54.89′
MWRA1030	Tow	14:22:26	14:33:24	42°19.50′	70°53.34′	42°18.84′	70°53.36′
MWRA1031	Tow	14:46:35	15:53:05	42°19.13′	70°52.34′	42°19.73′	70°46.71′
MWRA1033	Tow	17:11:60	17:25:42	42°17.04′	70°57.36′	42°16.93′	70°57.04′
MWRAD001	Profile	15:59:54	16:01:39	42°19.65′	70°46.56′	42°19.64′	70°46.55′

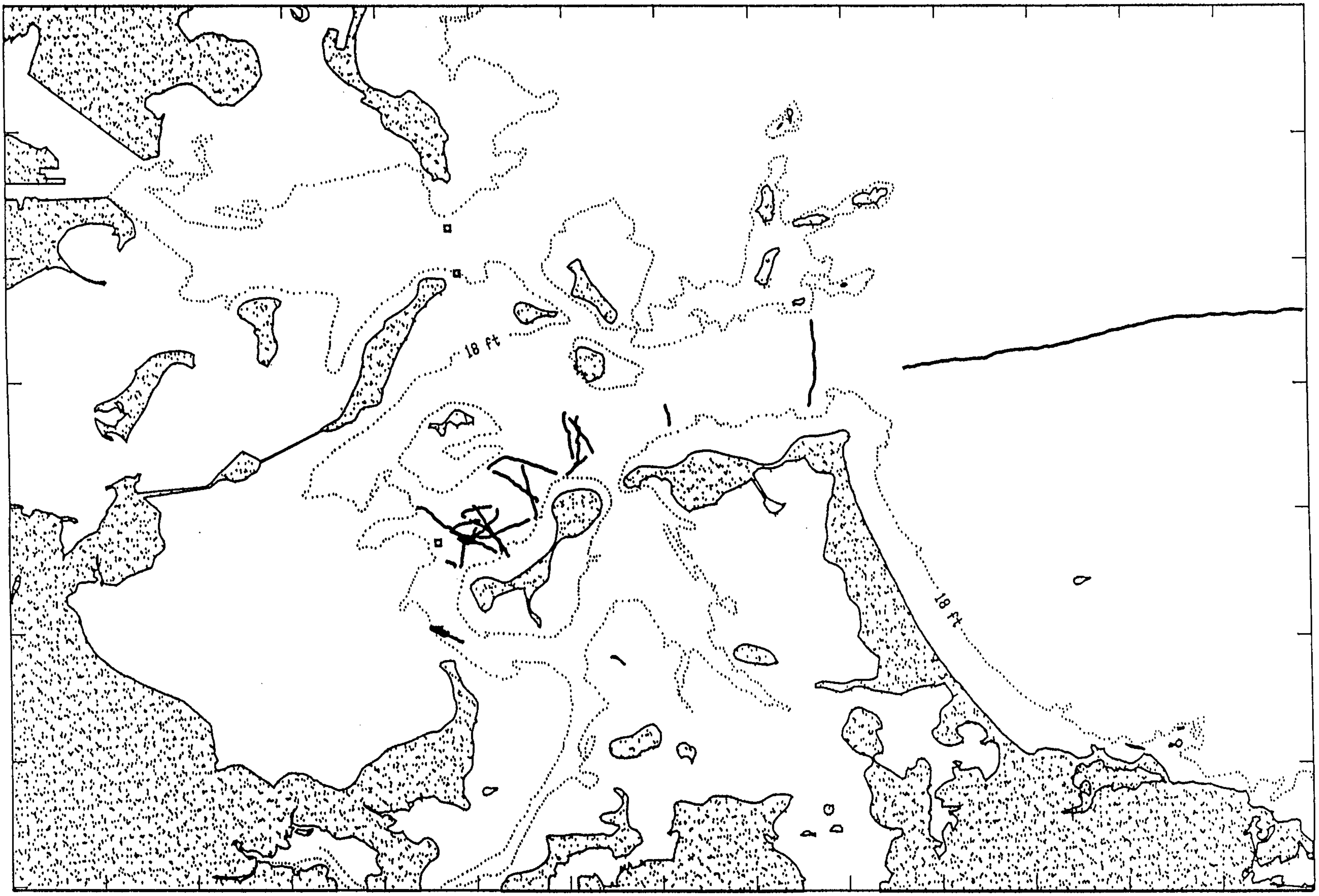

Figure 4-4. Location of Horizontal Transects Made on October 16, 1990

Figure 4-5 presents a detailed chart of the effluent outfall locations within Nantasket Roads, adjacent to Peddocks Island. Superimposed on this chart are the vessel tracks representing horizontal transects 7 and 10 (data files MWRA1007 and MWRA1010, respectively, in Table 4-1). Transect 7 began northeast of the northwest outfall, crossed over the northeast effluent outfall, and extended southeastward toward Portuguese Cove on the west side of Peddocks Island. Figure 4-6 presents the time series of salinity, temperature, and turbidity data acquired at a depth of roughly 2 m along transect 7. The crossing of the northeast outfall was clearly evident from the large decrease in salinity (due to the freshwater of the effluent) and the large increase in turbidity. Temperatures within the plume exhibited a small increase above the background temperatures on either side of the plume. Also evident from the high-resolution data acquired along the transect was small-scale variability in each measured parameter, in addition to large changes in the water properties, such as during the last ~2 min along the transect when the background water increased in turbidity and decreased in salinity.

Figure 4-7 presents temperature/salinity (T/S) and turbidity/salinity (Tu/S) scatter plots of the 1-s-averaged water-property data acquired along transect 7. From the Tu/S scatter plot, one can clearly distinguish between the relatively low salinities and high turbidities within the effluent plume from the northeast outfall versus the characteristics of the background water along this transect.

Transect 10 (data file MWRA1010) made at 1108 EST intersected the northeast outfall along a heading from northeast to southwest as illustrated in Figure 4-5. The time-series data acquired along this transect (Figure 4-8) clearly identified the northeast outfall roughly 9 min along the transect. The leading edge of the diffuse plume was encountered about 3 min after initiation of the transect, and the turbidity/salinity signature of the plume intensified approaching the outfall. Immediately to the southwest of the outfall, the background water properties were homogeneous until the leading edge of the effluent plume from the southern outfall was encountered.

The T/S and Tu/S scatter plots of data from transect 10 (Figure 4-9) are very useful for identifying the characteristics of the individual plumes. Basically, the plots illustrate differences between the temperature, salinity, and turbidity within the two plumes as well as in the background waters mixing with each plume. The T/S plot illustrates two features. First, the low salinity and high relative turbidity of the northeast effluent plume can be distinguished from the background water properties observed to the northeast of the plume.

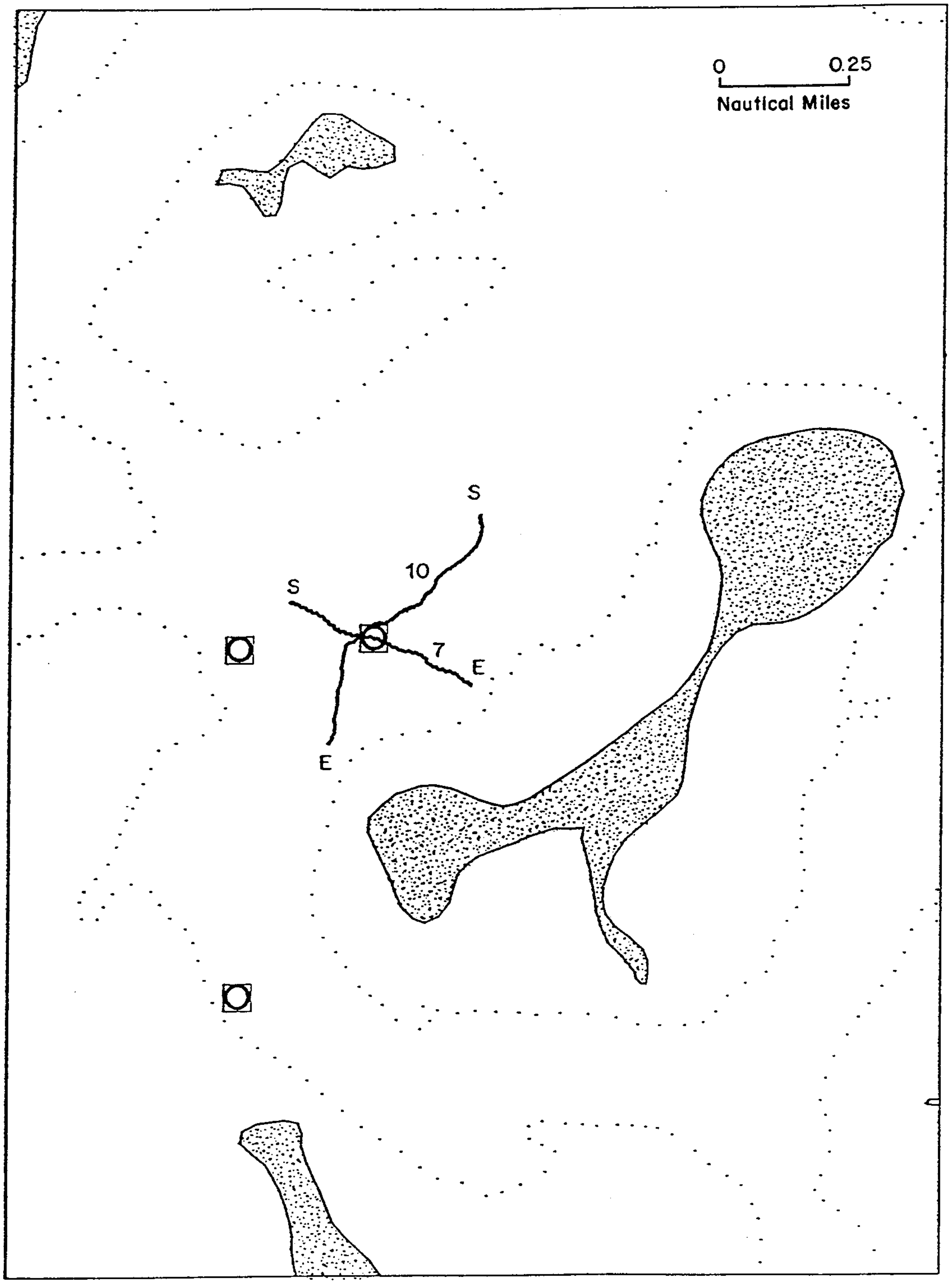

Figure 4-5. Expanded Map of Nantasket Roads (near Peddocks Island) Showing Location of Effluent Outfalls and Transects 7 and 10 on October 16, 1990. Start and End Positions of Transects Are Indicated by S and E, Respectively.

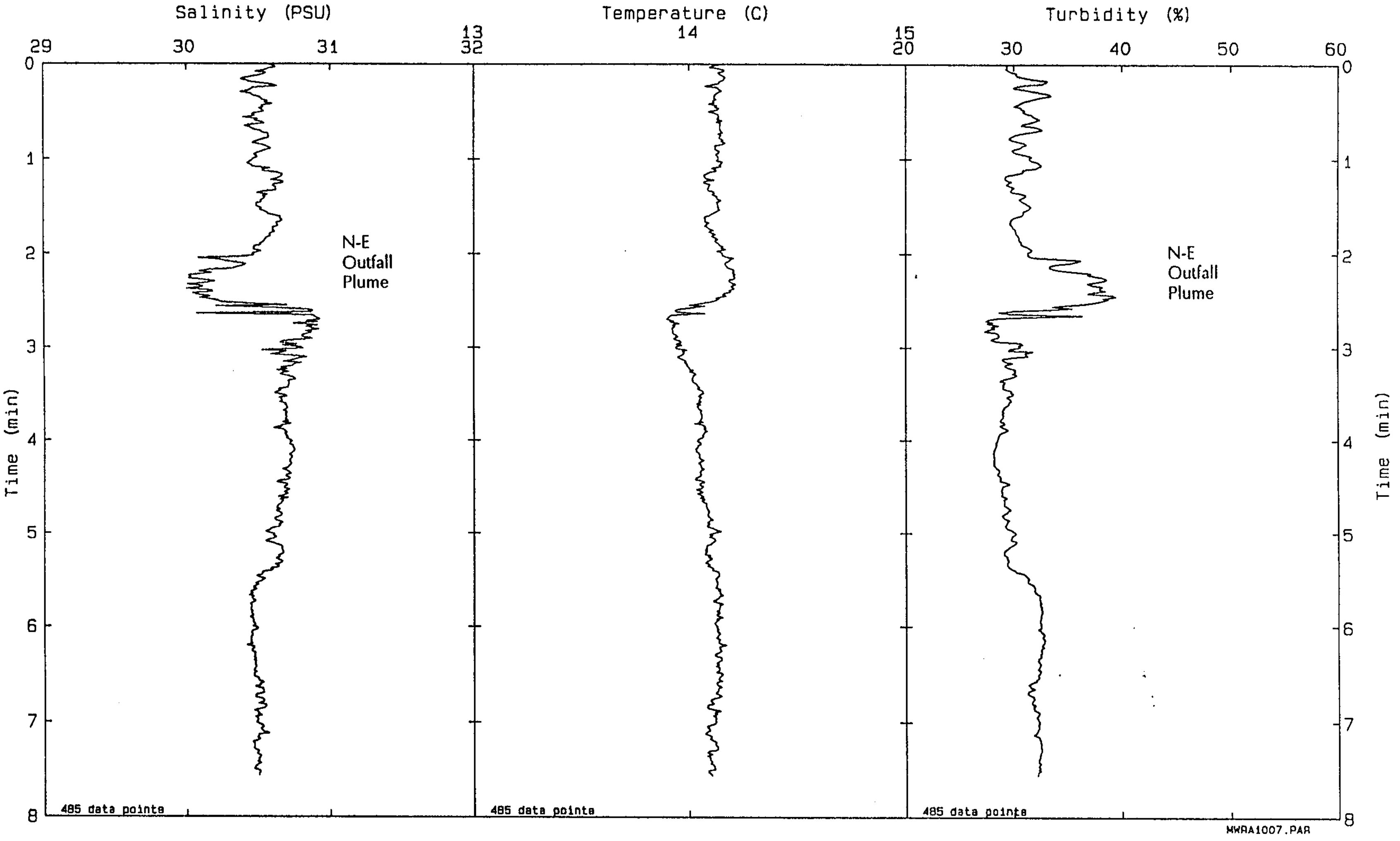

Figure 4-6. Time-Series Plot of Data Acquired along Transect 7 Made on October 16, 1990

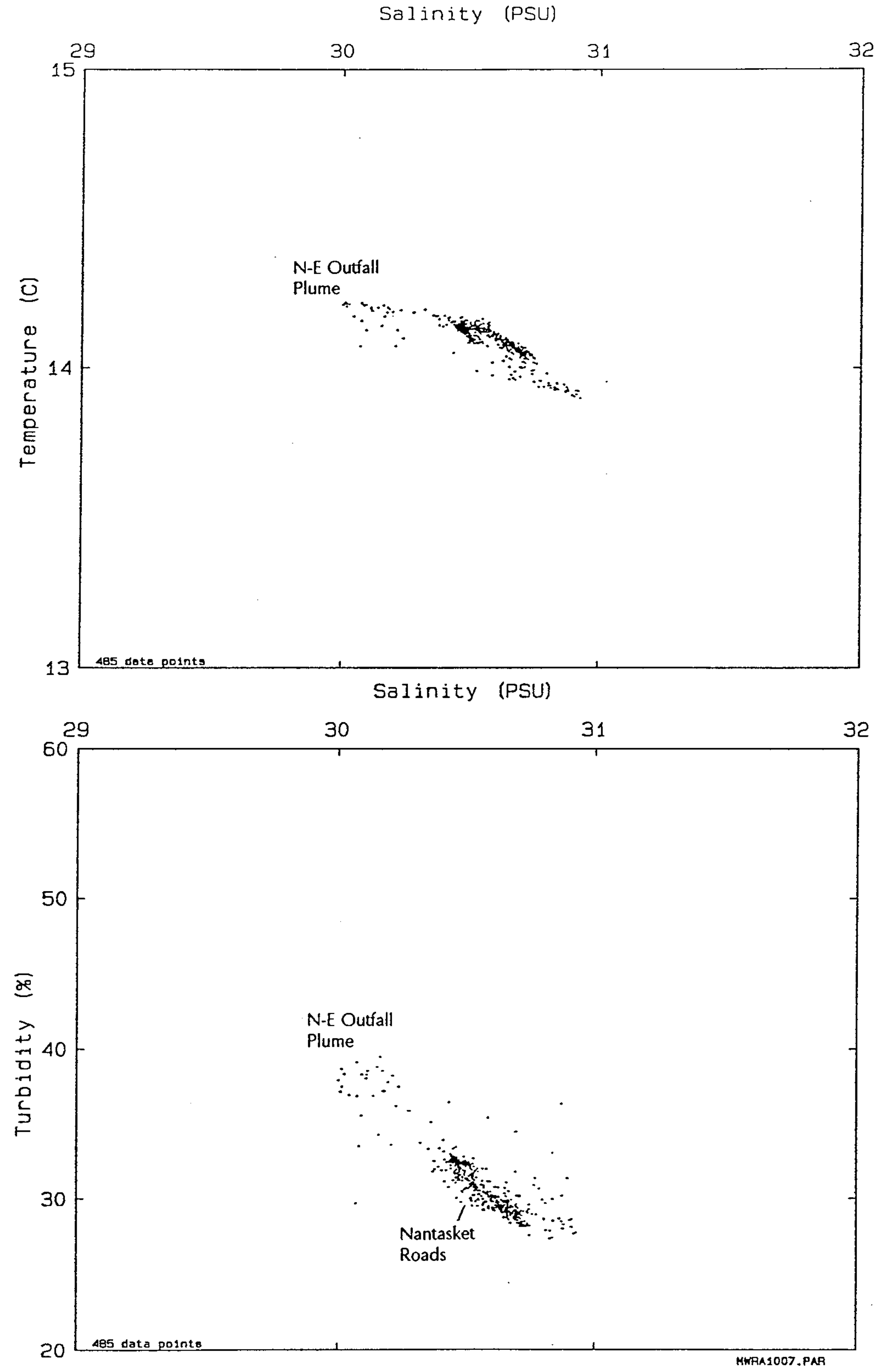

Figure 4-7. Scatter Plot of Data Acquired along Transect 7 Made on October 16, 1990

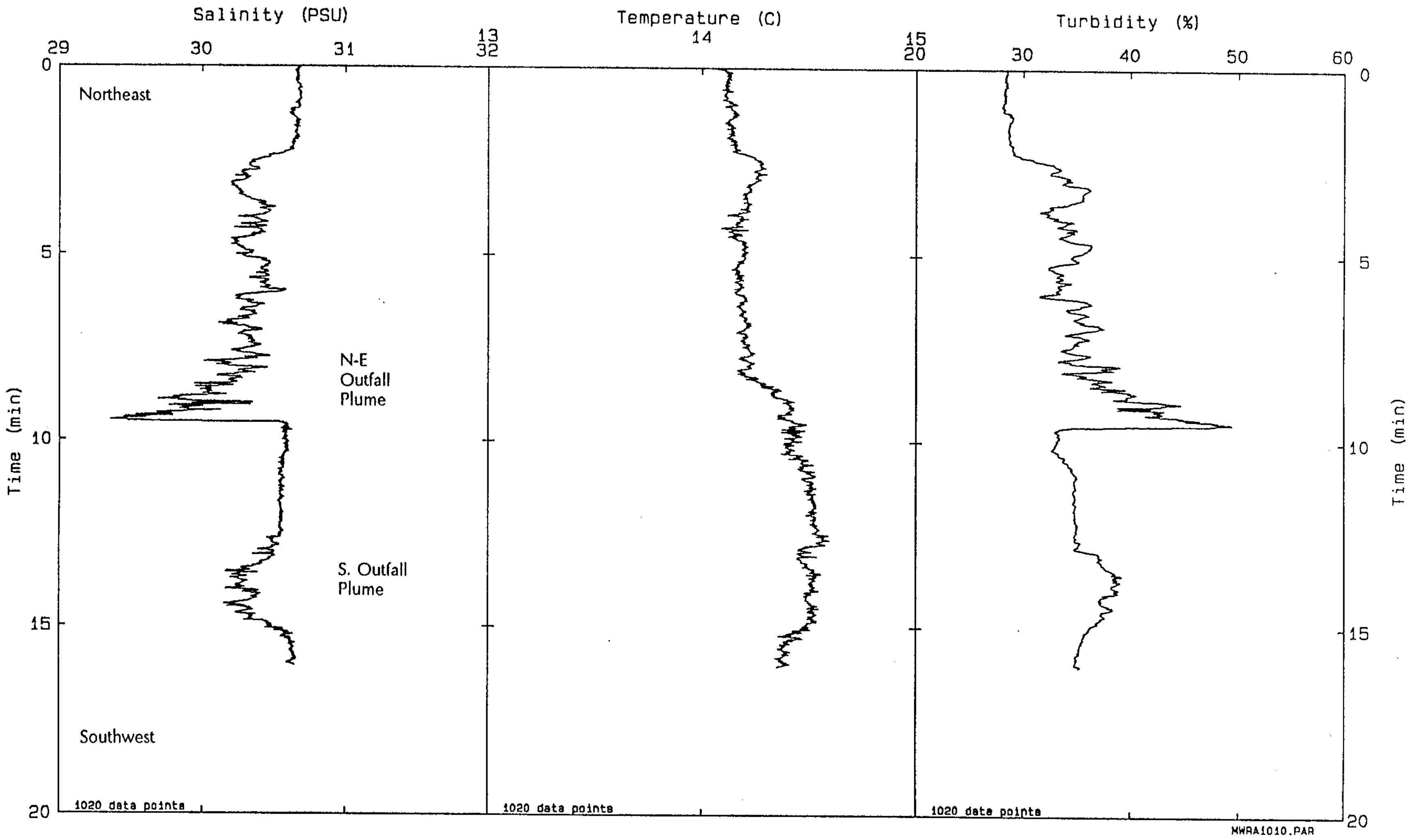

Figure 4-8. Time-Series Plot of Data Acquired along Transect 10 Made on October 16, 1990

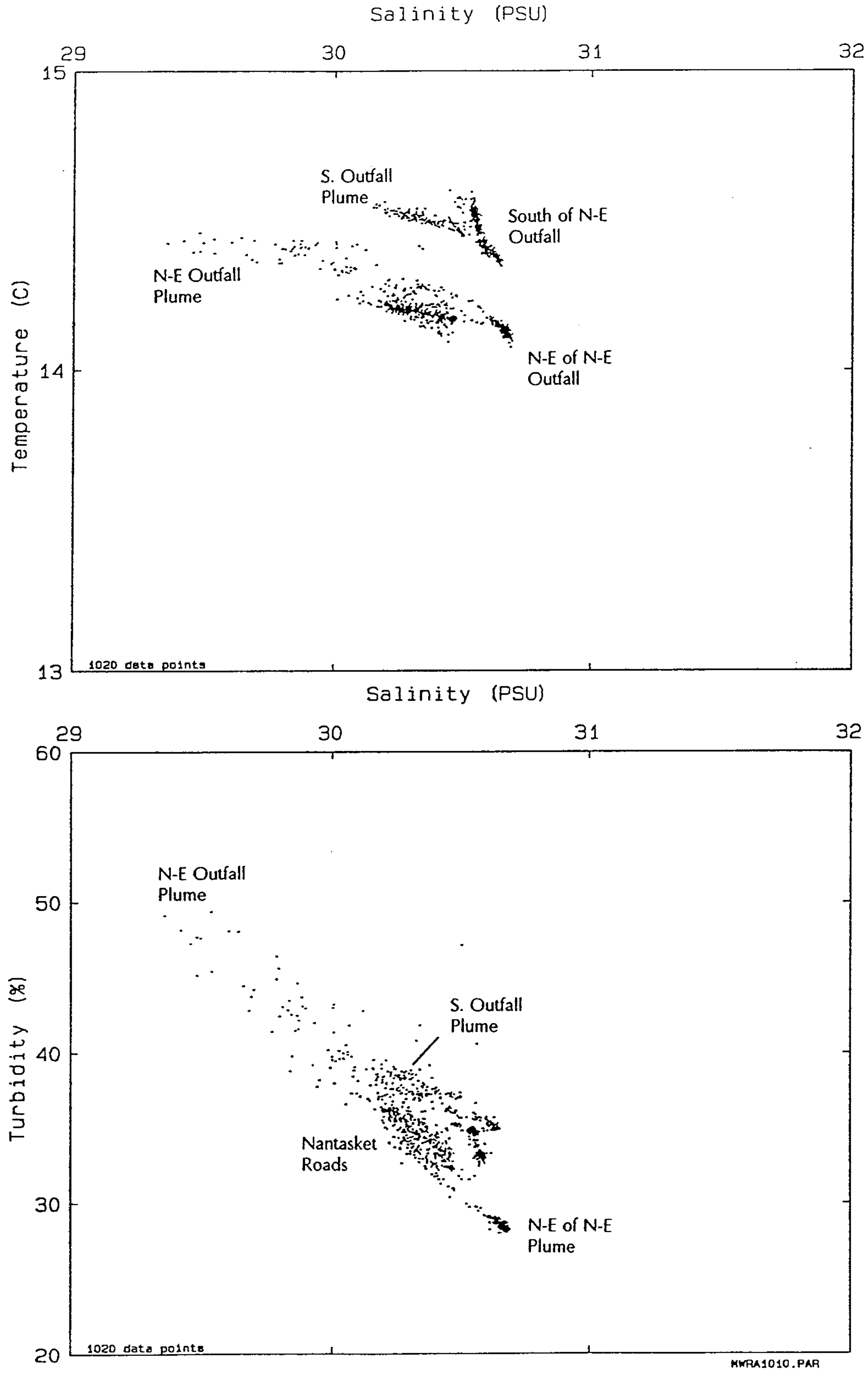

Figure 4-9. Scatter Plot of Data Acquired along Transect 10 Made on October 16, 1990

The scatter of points between the extreme characteristics of the northeast outfall plume and the high-salinity background water is a result of different mixing proportions of the two source-water types. Second, the leading edge of the plume from the southern outfall is mixing with water having much warmer background characteristics, in contrast to the background water observed to the northeast of the northeast outfall.

Significant differences in the background turbidity of the water on either side of the northeast outfall are also evident from the Tu/S scatter plot shown in Figure 4-9. However, the Tu/S properties within the plumes from the two outfalls are quite similar; the scatter of points is due to various mixing proportions with the background waters.

The water properties within the effluent plumes from the two different outfalls were expected to be similar since they originate from the same treatment plant. The large, observed differences in the background T/Tu/S properties at the two outfall locations were surprising since they are located close to each other, and the region is believed to be well mixed. These variations were certainly due to advection of waters having different properties, rather than to local alteration of properties. These variations in the background water properties did not pose a significant problem for mapping the effluent plumes during this study, but analysis of effluent outfall dilutions can be prone to large errors when the background properties of the receiving water are not well resolved at the specific time of the field measurements.

To further illustrate the variability in water properties observed within and adjacent to the effluent plume extending downstream from the northeast outfall, Figure 4-10 indicates the locations of transects 14 and 17 made at 1134 and 1200 h EST on October 16. The Tu/S data from transect 14 (Figure 4-11) show maximum turbidities of 40% within the effluent plume and background turbidities of roughly 31%. Two-component mixing between the northeast outfall plume and Portuguese Cove waters is suggested from the Tu/S scatter plot, but note that, as presented, turbidity is not on a linear scale proportional to total suspended solids.

Transect 17 in Figure 4-10 was situated downstream from the leading edge of the northeast plume at the time of the observations (1200 h EST). As illustrated in the Tu/S scatter plot from transect 17 (Figure 4-12), turbidities along this transect did not exceed 35%, and detailed analysis of the data confirm that no plume water was encountered during this transect. The Tu/S and T/S data from this transect clearly illustrate that there were, however, significant differences between the background water properties on the north and south sides of the Nantasket Roads channel. Furthermore, very clear water was found near the northern tip of Peddocks Island near Hull Gut.

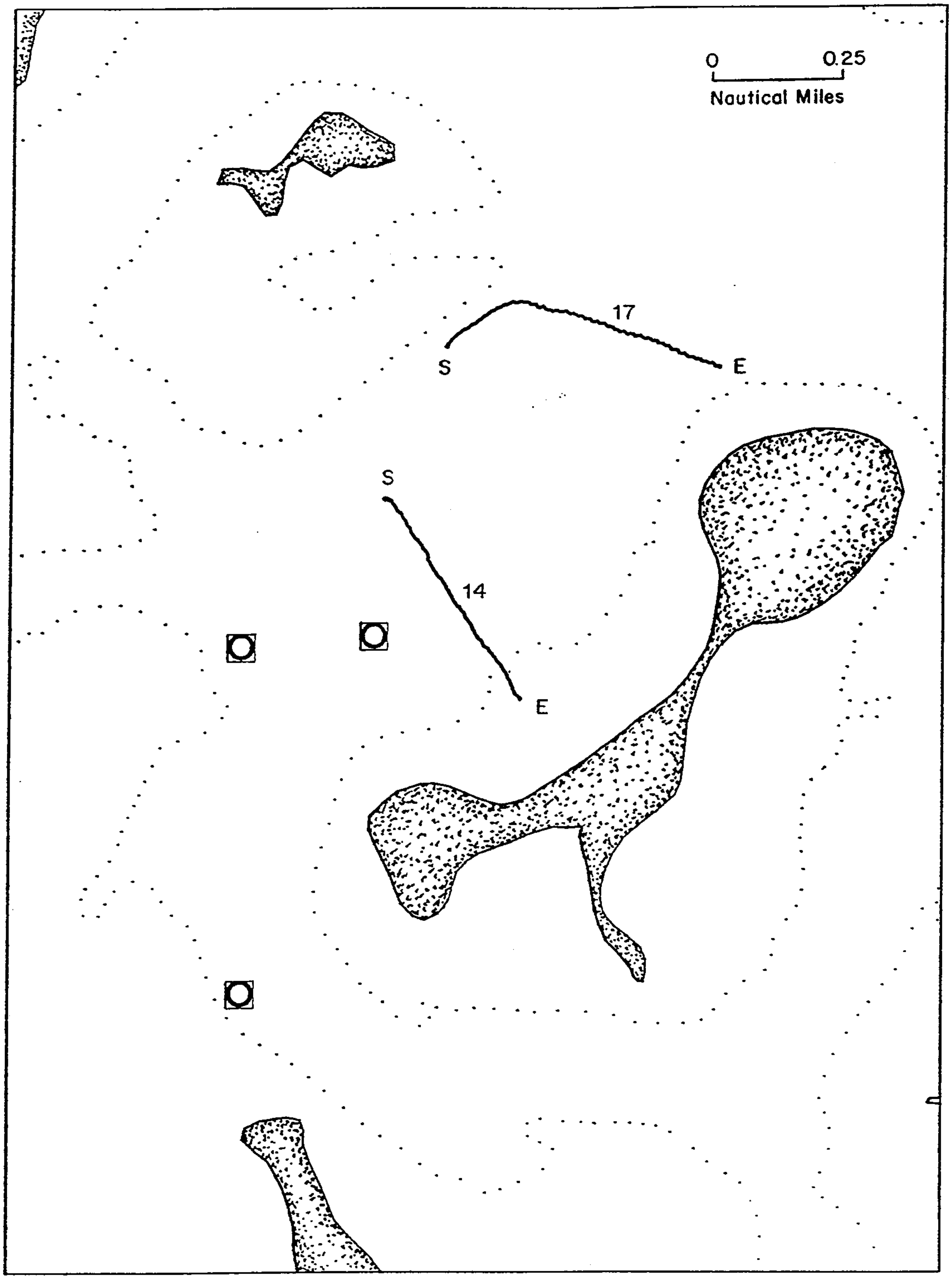

Figure 4-10. Expanded Map of Nantasket Roads Showing Location of Transects 14 and 17 on October 16, 1990

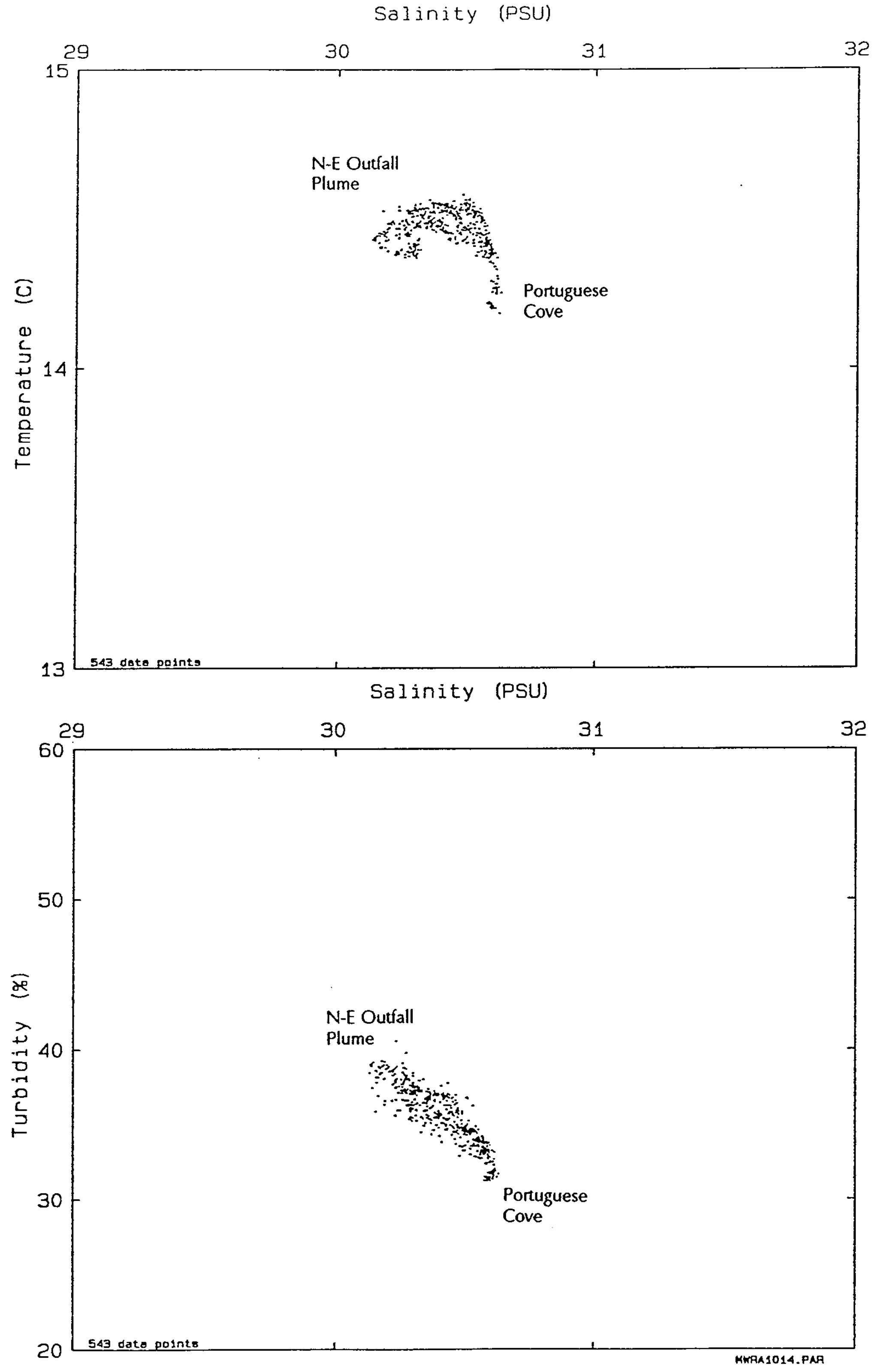

Figure 4-11. Scatter Plot of Data Acquired along Transect 14 Made on October 16, 1990

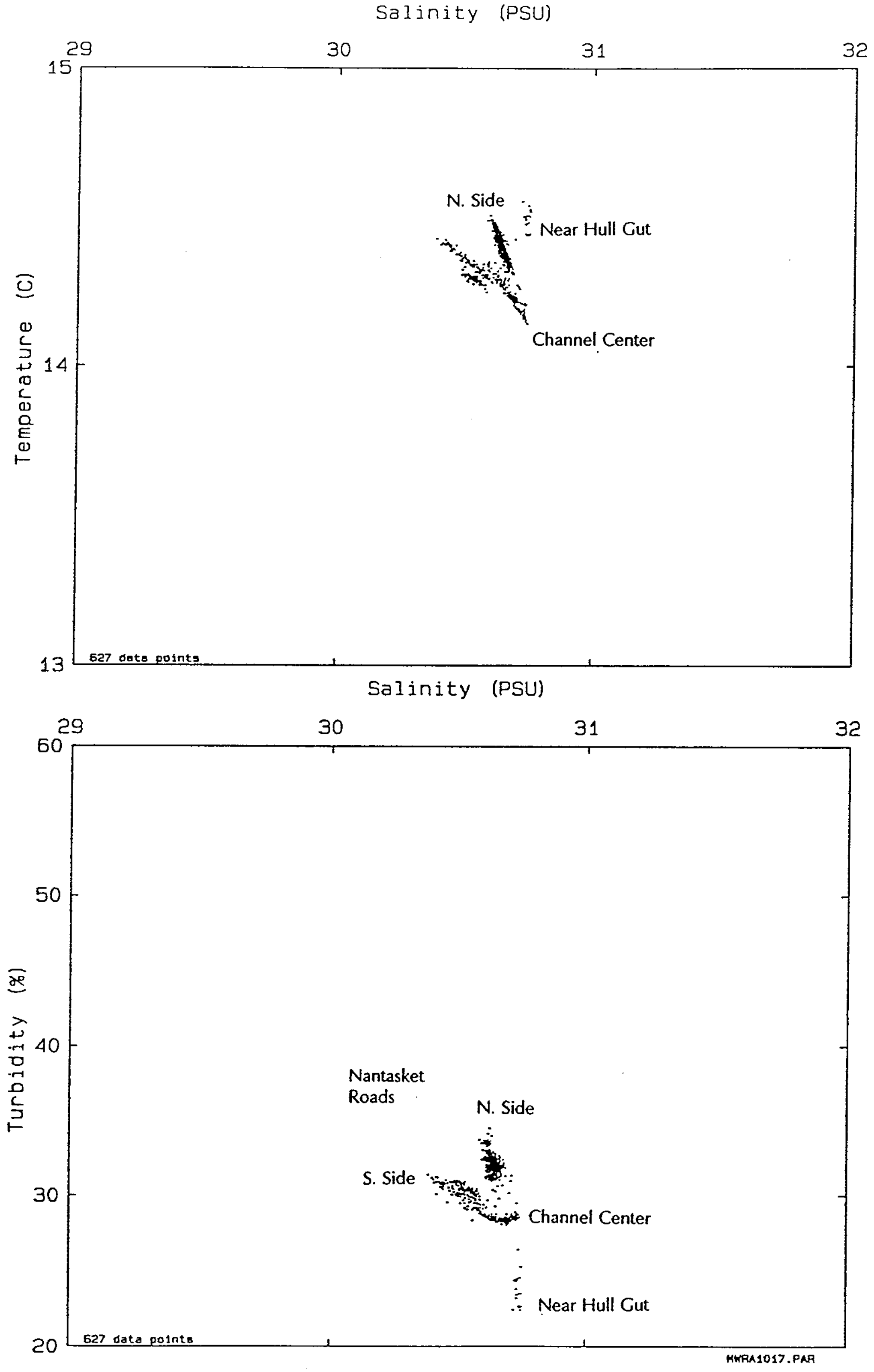

Figure 4-12. Scatter Plot of Data Acquired along Transect 17 Made on October 16, 1990

As final examples of the plume results from transects made later in the ebb, Figure 4-13 indicates the location of transects 24 and 25 made at 1256 and 1306 EST, respectively. The scatter plot results from transect 24, which are presented in Figure 4-14, confirm that the plume from the northeast outfall was northwest of the northern end of Peddocks Island roughly 3.5 h into the ebb period. The most concentrated effluent within the plume was found near the northern end of transect 24, whereas near Peddocks Island, relatively low-turbidity/high salinity background water indicated no appreciable effluent concentrations. The drifter results presented in Figure 4-3 indicated that drifters grounded in the northern portion of Portuguese Cove at 2 h 50 min after high water. We believe that these drifters did represent the trajectory of the effluent plume, part of which was blown into Portuguese Cove by the moderate northwesterly wind. At the time of transect 24, the easternmost plume had not been advected northward out of Portuguese Cove, thus the effluent-free water at the southern end of transect 24. A short time later when the northward flow increased, all of the effluent-free surface waters near Peddocks Island were displaced toward the north along Nantasket Roads.

The data acquired along transect 25 (Figure 4-15) reveal crossings of both the northeast and northwest plumes. As indicated by the scatter-plot results from this transect (Figure 4-16), the T/S results allow distinction between the two plumes, and the background water properties were very homogeneous along the transect.

4.2.3 Summary of Effluent Plume Behavior

The previous Section demonstrated that high-resolution, near-surface measurements of temperature, salinity, and turbidity along horizontal transects can be used to distinguish between effluent plume water and the background receiving water whose characteristics vary considerably with time and location relative to each outfall. To illustrate this variability in the characteristics of the background water, Figure 4-17 presents composite T/S and Tu/S scatter plots, including all data acquired during the plume surveying activities (data files MWRA1004 through MWRA1030 in Table 4-1) on October 16, 1990. In the T/S plot, individual plume crossings are represented by points having low salinity that are connected though implied mixing lines to relatively homogeneous (albeit short-lived) background-water characteristics. The dense clusters of data points are associated with the background characteristics, which clearly vary over the course of the 4-h field study. This variability in background characteristics is also evident in the Tu/S scatter plot of Figure 4-17.

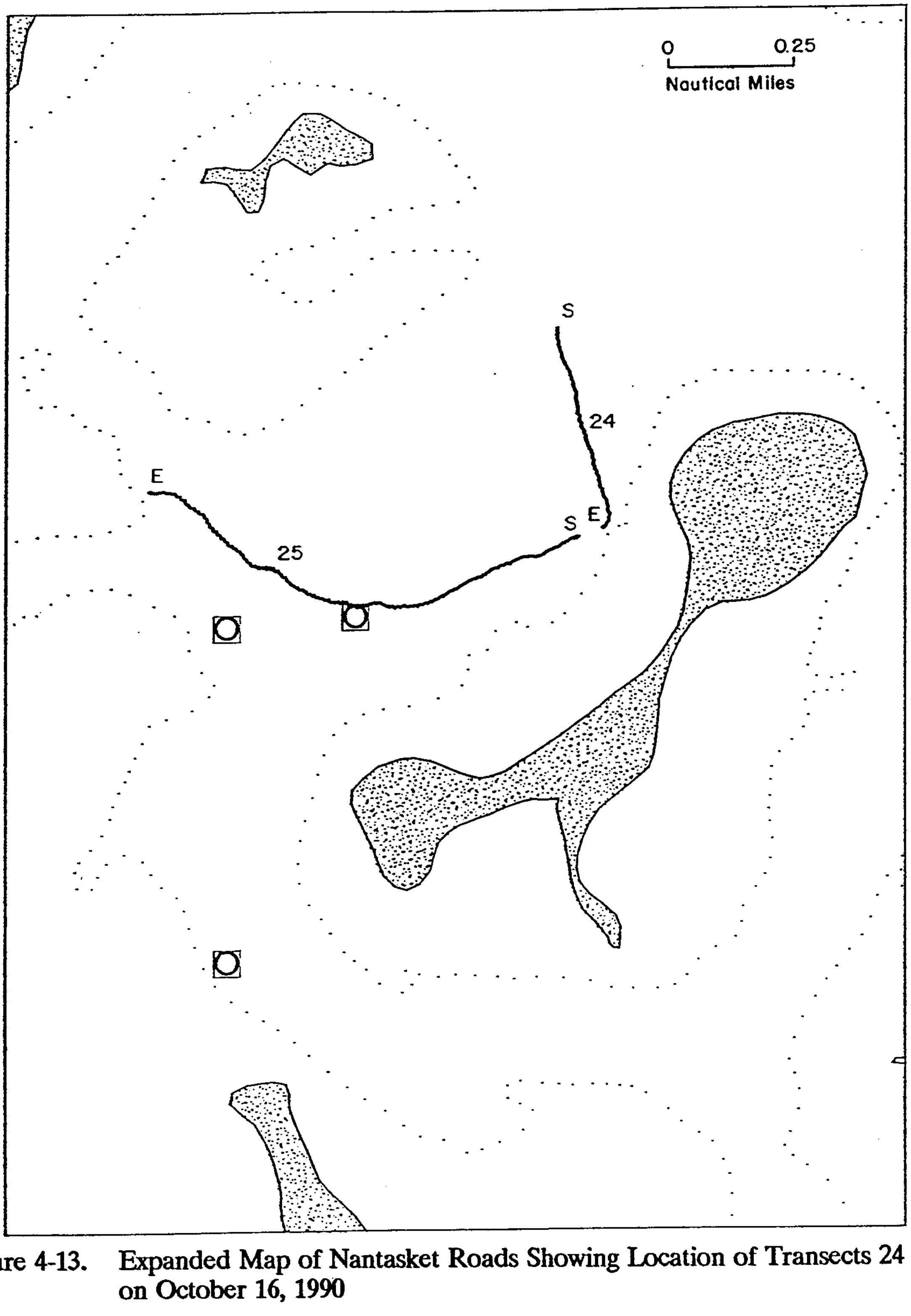

Figure 4-13. Expanded Map of Nantasket Roads Showing Location of Transects 24 and 25 on October 16, 1990

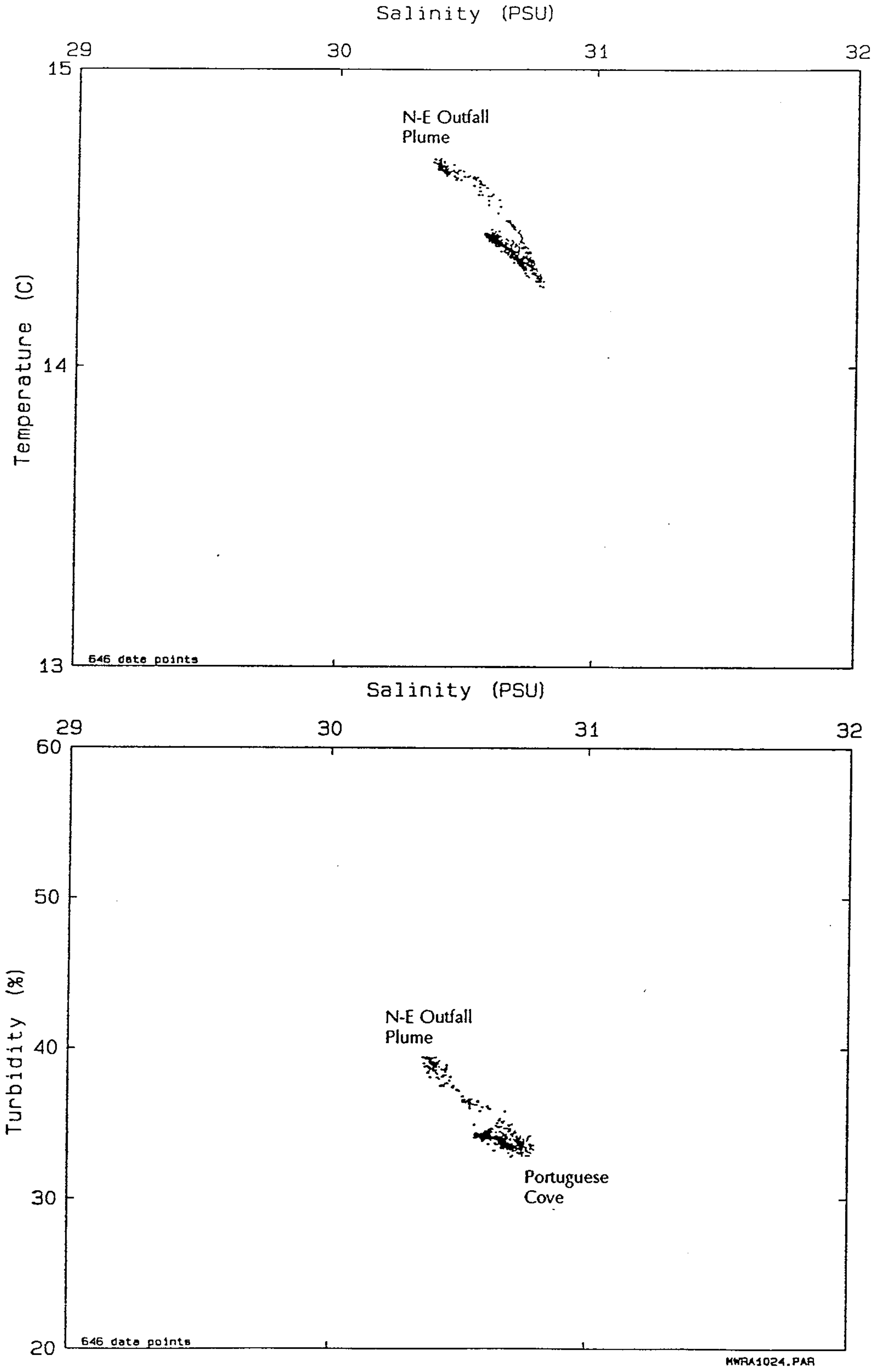

Figure 4-14. Scatter Plot of Data Acquired along Transect 24 Made on October 16, 1990

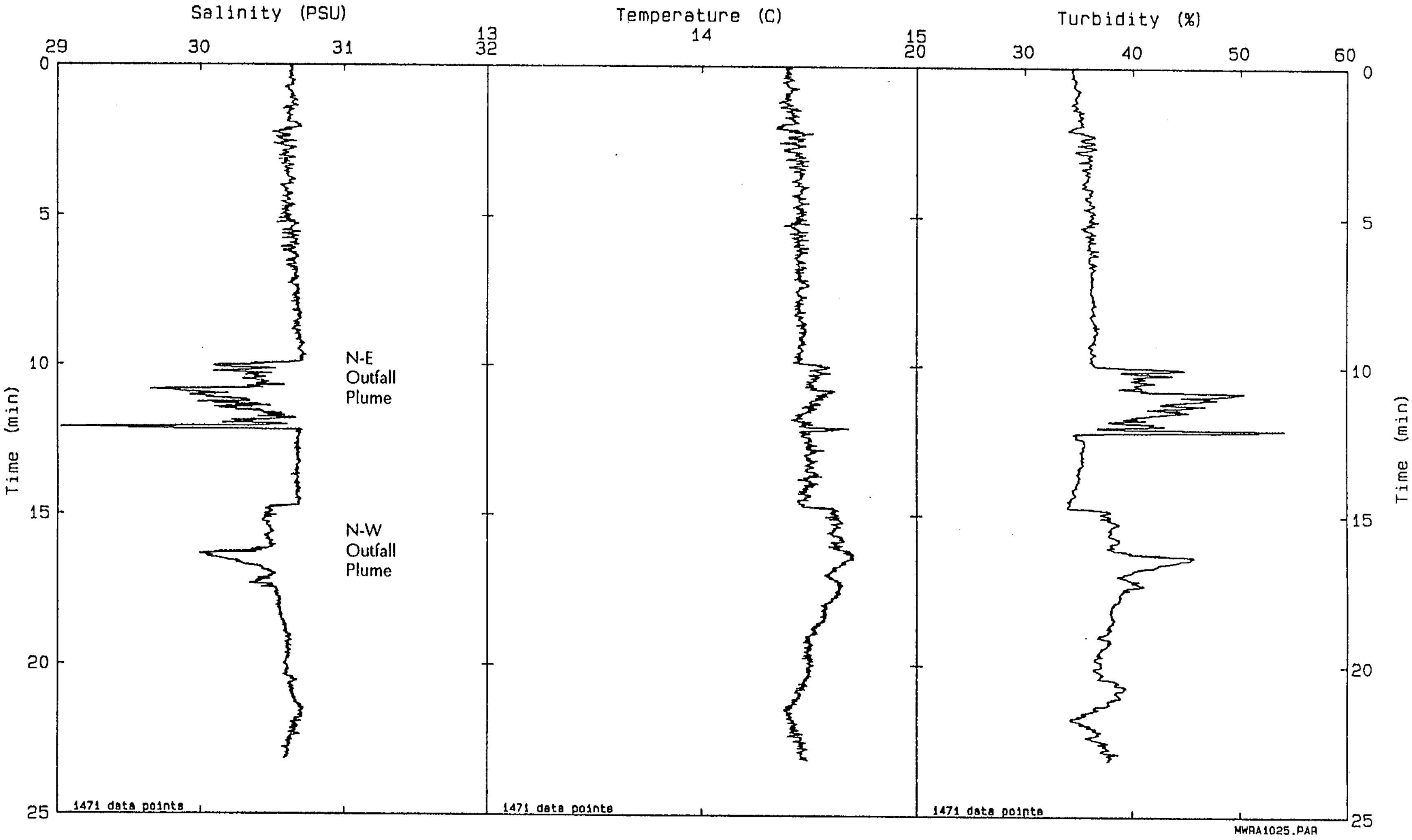

Figure 4-15. Time-Series Plot of Data Acquired along Transect 25 Made on October 16, 1990

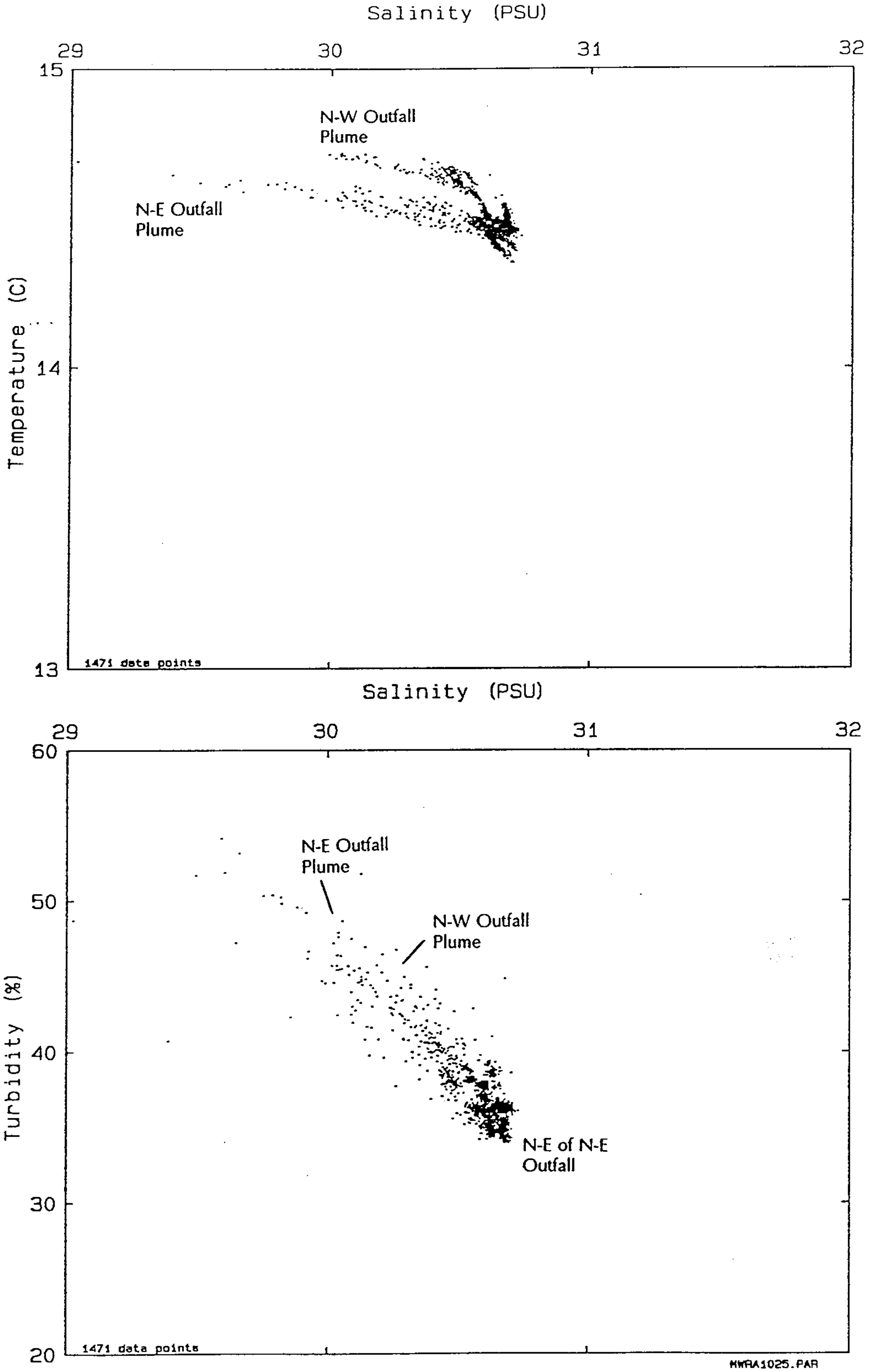

Figure 4-16. Scatter Plot of Data Acquired along Transect 25 Made on October 16, 1990

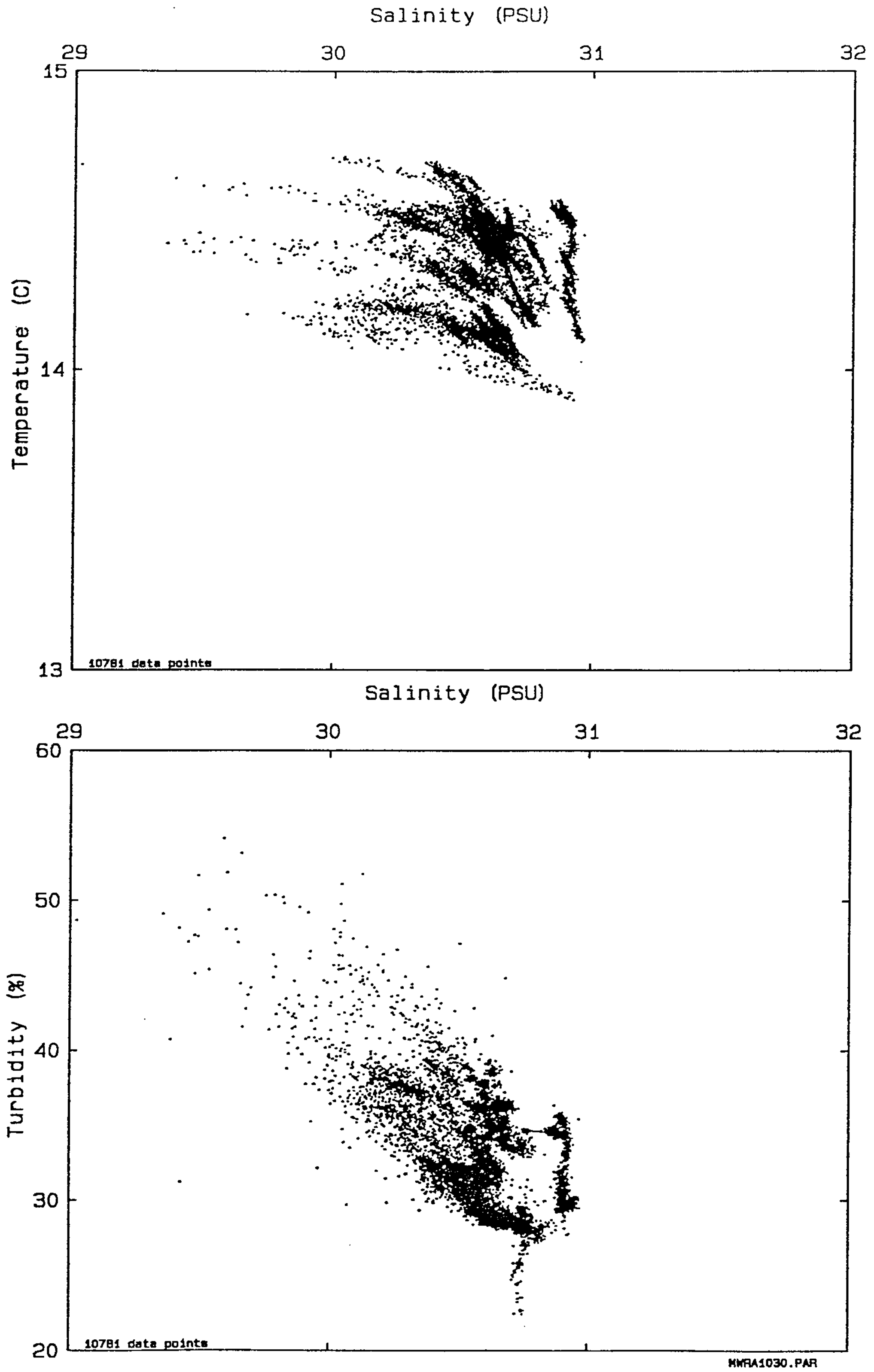

Figure 4-17. Composite Scatter Plot of All Data Acquired along Transects and at Vertical Profile Stations Made on October 16, 1990

> **Consequently, it was absolutely critical in the analysis of these data that identification of the effluent plumes be derived from analyses of the background-water characteristics on each transect, rather than assuming that the background water had relatively constant water properties during the ebb tide.**

As stated above, from analysis of the water properties along each transect, it is possible to determine whether waters from any of the three effluent outfalls were present along any of the transects surveyed on October 16. Therefore, using the water-property data combined with the navigation information from the survey tracks, one can effectively map the location of individual plumes. Because of the rapid advection of the plumes as a result of the tidal currents, it was necessary to use a set of consecutive transects (which are closely grouped in time) to generate a near-synoptic map of plume locations. An independent map can then be made from the next group of near-synoptic transects, and so on. For example, Figure 4-18 is a map of the study area within Nantasket Roads with shading that represents the spatial extent of the near-surface effluent plume emanating from the northeast outfall. This plume map was derived from analysis of all transects made over the period from 1.1 to 1.7 h after high water on October 16; the dotted line indicates the areal coverage of the transects made during the specified period. From the limited spatial extent of the northeast plume, it is clear that strong, northeastward ebb flow had not yet begun. This substantial time lag for the beginning of the ebb flow at this location is discussed at the beginning of Section 4.2.2.

Figure 4-19 presents a diagram of the spatial extent of the effluent plumes derived from transects made during the period from 2.0 to 2.5 h after high water. The spatial coverage provided by the transects during this period is delineated by two regions: one near the northern end of Peddocks Island and the other farther to the south in the vicinity of the northeast outfall. Transects within the northern survey area revealed that the leading edge of the effluent plume had just reached this location. In contrast, water characteristics within the southern survey area were nearly everywhere affected by plume water. The dark shading in Figure 4-19 represents high concentrations of effluent, whereas light shading represents a more-diluted plume. Only in the extreme northern corner of the southern survey area were plume effects not observed. As indicated by the dark shading, concentrated plumes from the southern and northeast outfalls were spreading toward the northeast within Nantasket Roads. The southern plume was quite broad and had actually reached the northern outfall locations, causing a broad mixture of plumes from the three outfalls. It is apparent from these results that effluent from the southern outfall enters Portuguese Cove during the early stages of the ebb flow. This is consistent with the trajectories of the drifters that entered Portuguese Cove early in the ebb cycle (see Section 4.2.1). Although the synoptic data over this period do not

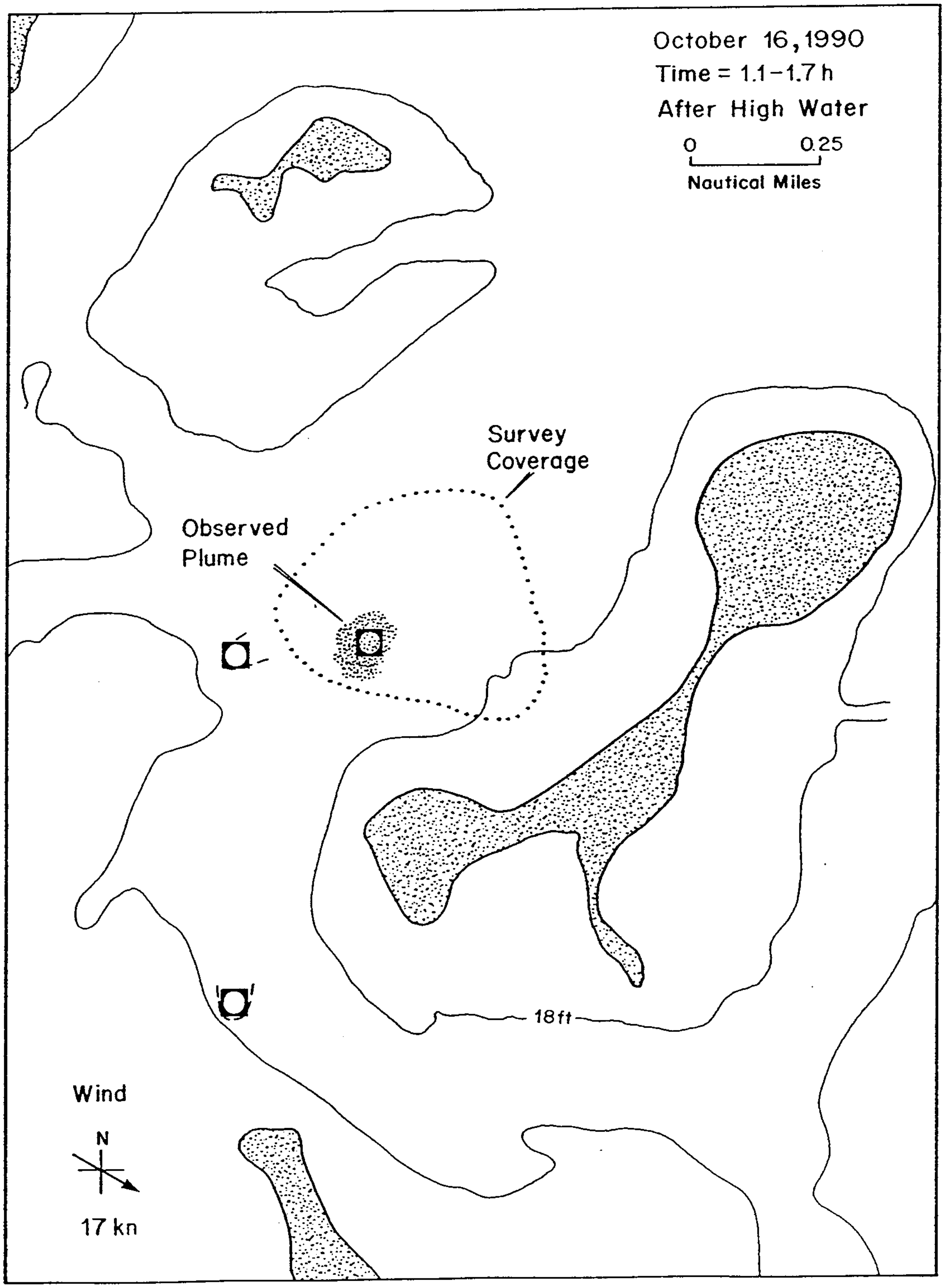

Figure 4-18. Map of Nantasket Roads Showing Plume Location 1.1 to 1.7 h after High Water on October 16, 1990. Arrows Represent Flow Direction; Dotted Line Indicates Survey Coverage.

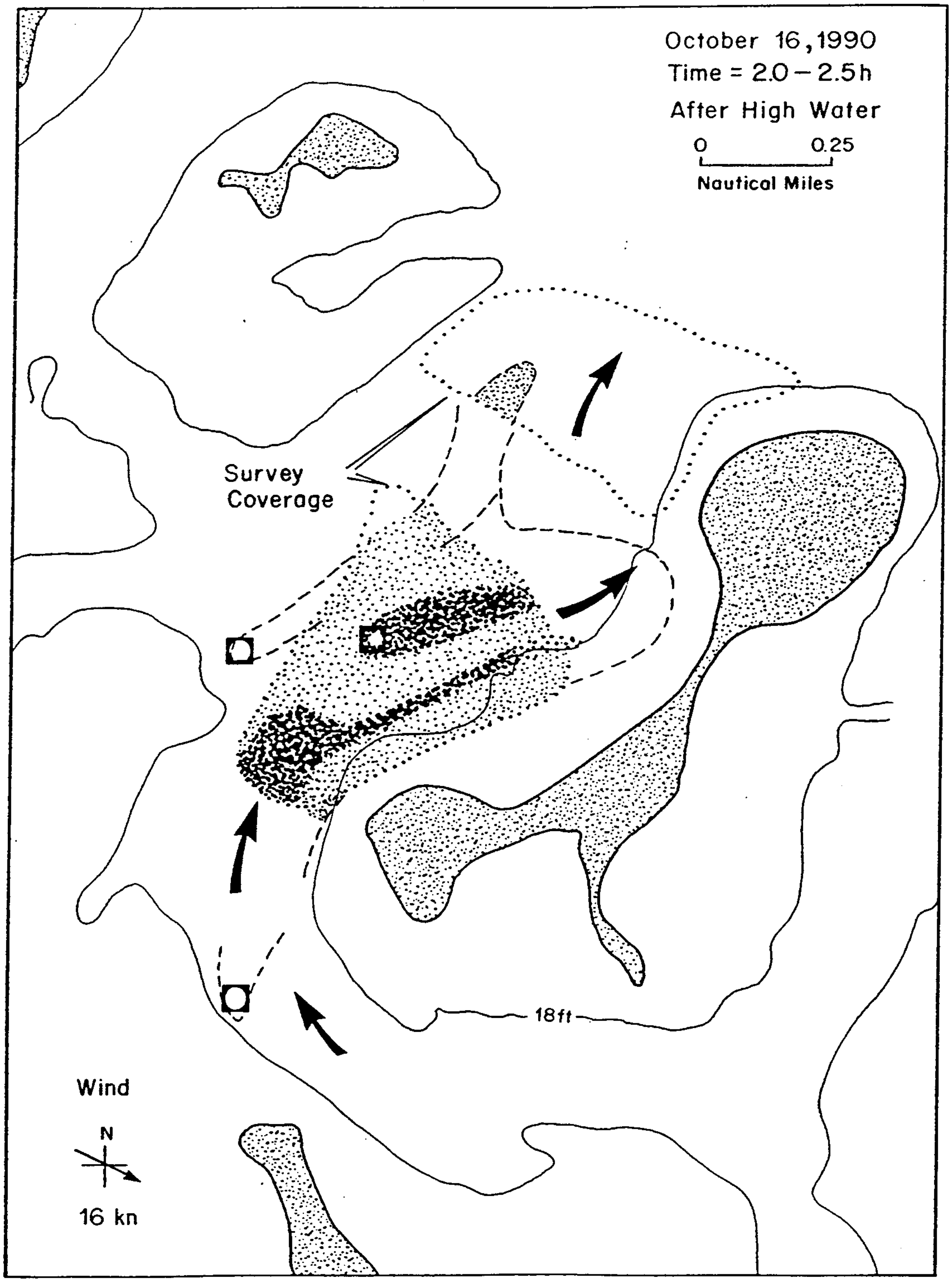

Figure 4-19. Map of Nantasket Roads Showing Plume Locations 2.0 to 2.5 h after High Water on October 16, 1990. Dashed Line Represents Hypothetical Plume Boundaries.

cover the full extent of Nantasket Roads and Portuguese Cove, dashed lines in Figure 4-19 have been included to represent an estimate of the expected boundaries of the plumes from the three outfalls.

Figure 4-20 presents a diagram of the spatial extent of the two northern effluent plumes derived from transects made during the period from 3.6 to 4.2 h after high water. The dark shading illustrates that concentrated effluent from both outfalls is being advected along the general direction of Nantasket Roads channel, whereas earlier in the ebb, when the flow may have been weaker, the plumes had a more easterly component of advection. Concentrated effluent from the northeast outfall was passing the northern end of Peddocks Island, in contrast with the previous Figure, where plume advection had not progressed as far to the northeast.

The results from Figures 4-19 and 4-20 suggest that during early in the ebb, the currents were moderate but the strong northwesterly winds caused eastward displacement of effluent into Portuguese Cove. Later in the ebb, the winds had decreased and become more westerly, and the northeastward currents within Nantasket Roads had intensified, causing plume trajectories to align with Nantasket Roads.

4.2.4 Mini-BOSS Measurements in Massachusetts Bay

As a secondary objective of the field activities on October 16, the Mini-BOSS was used to acquire near-surface temperature, salinity, and turbidity data along a 4-nmi-long transect extending from the eastern end of Nantasket Roads into Massachusetts Bay (Figure 4-21). The purpose of this transect was to attempt to locate the offshore front between the Harbor waters discharged from Nantasket Roads and the more saline waters of Massachusetts Bay. Figure 4-22 illustrates the variability in temperature, salinity, and turbidity that was detected along the >1-h transect. In general, salinity increased and turbidity decreased with distance offshore. Temperature, on the other hand, generally decreased during the first two-thirds of the transect; a strong temperature gradient (front) was then encountered at roughly 50 min along the transect, along with a moderate salinity increase corresponding with the temperature increase.

Figure 4-23 presents the data acquired along the Massachusetts Bay transect plotted on the same T/S and Tu/S axes as had been used for the analyses of the effluent plumes. On the T/S plot, the data labeled *Inshore* represent the characteristics of the water at the eastern end of Nantasket Roads, whereas the *Offshore* characteristics represent the warm, saline, low-turbidity

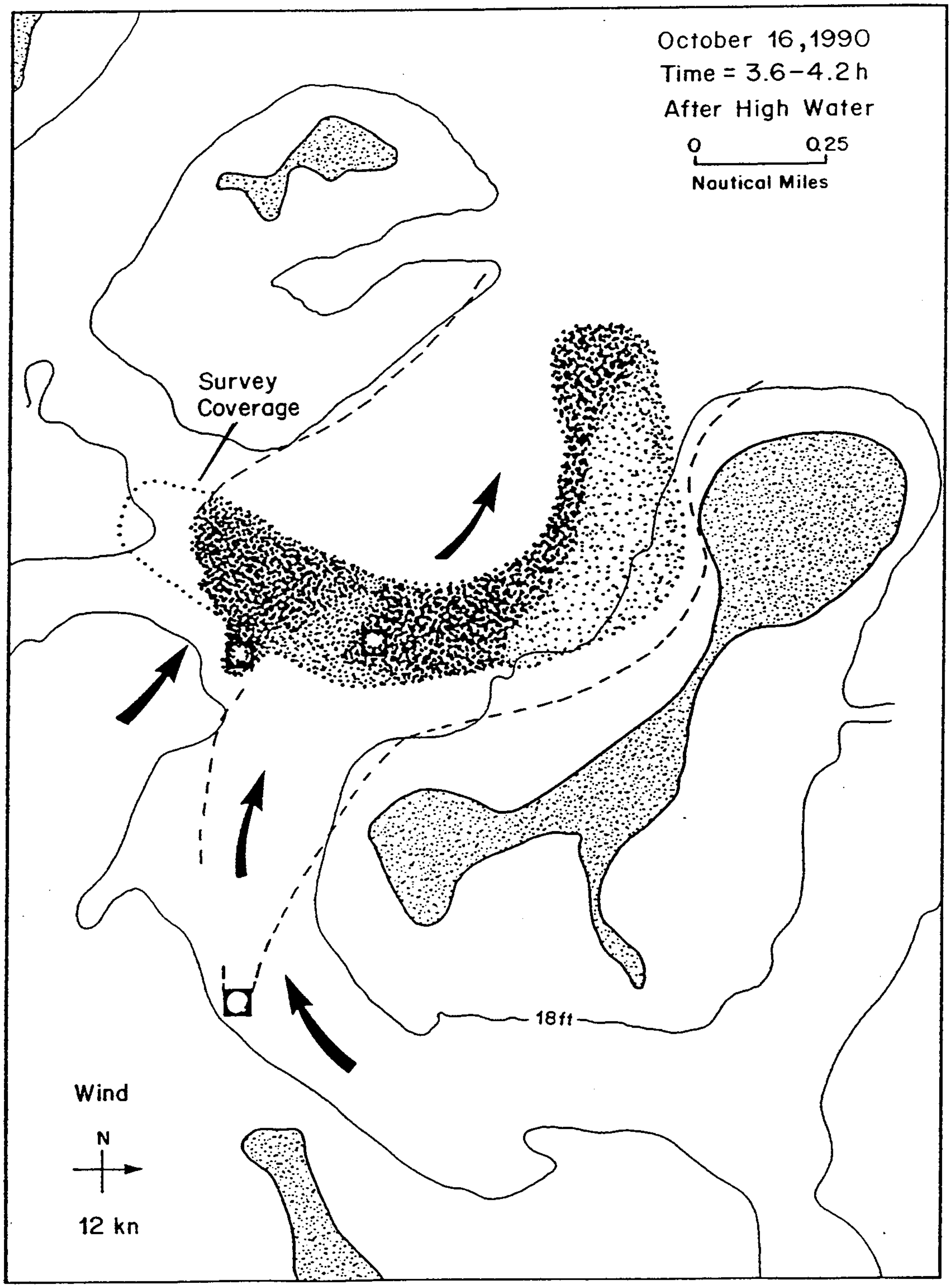

Figure 4-20. Map of Nantasket Roads Showing Plume Locations 3.6 to 4.2 h after High Water on October 16, 1990

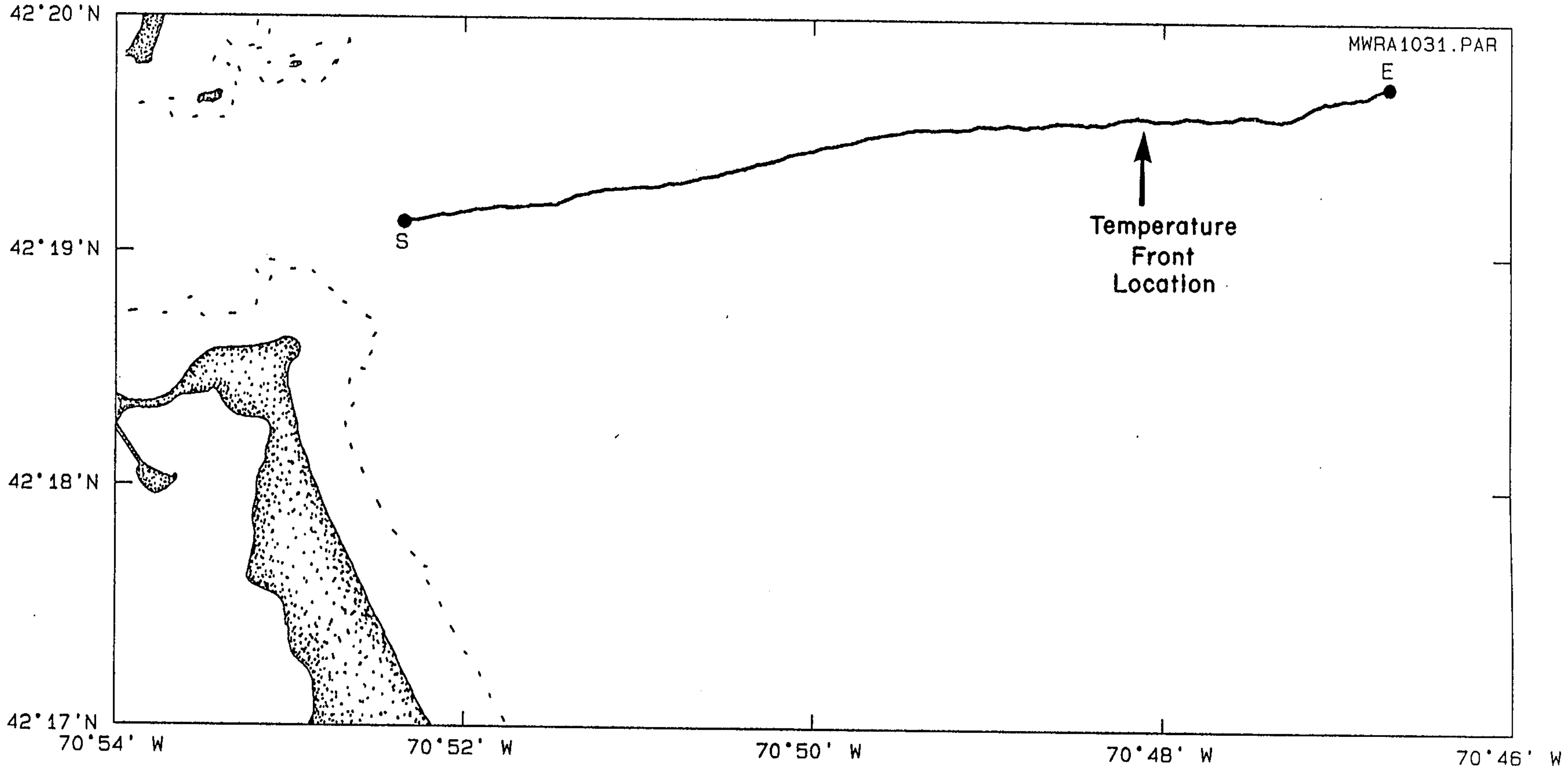

Figure 4-21. Map of Eastern Nantasket Roads and Hull Showing Location of Horizontal Transect Made on October 16, 1990, Which Extends into Massachusetts Bay

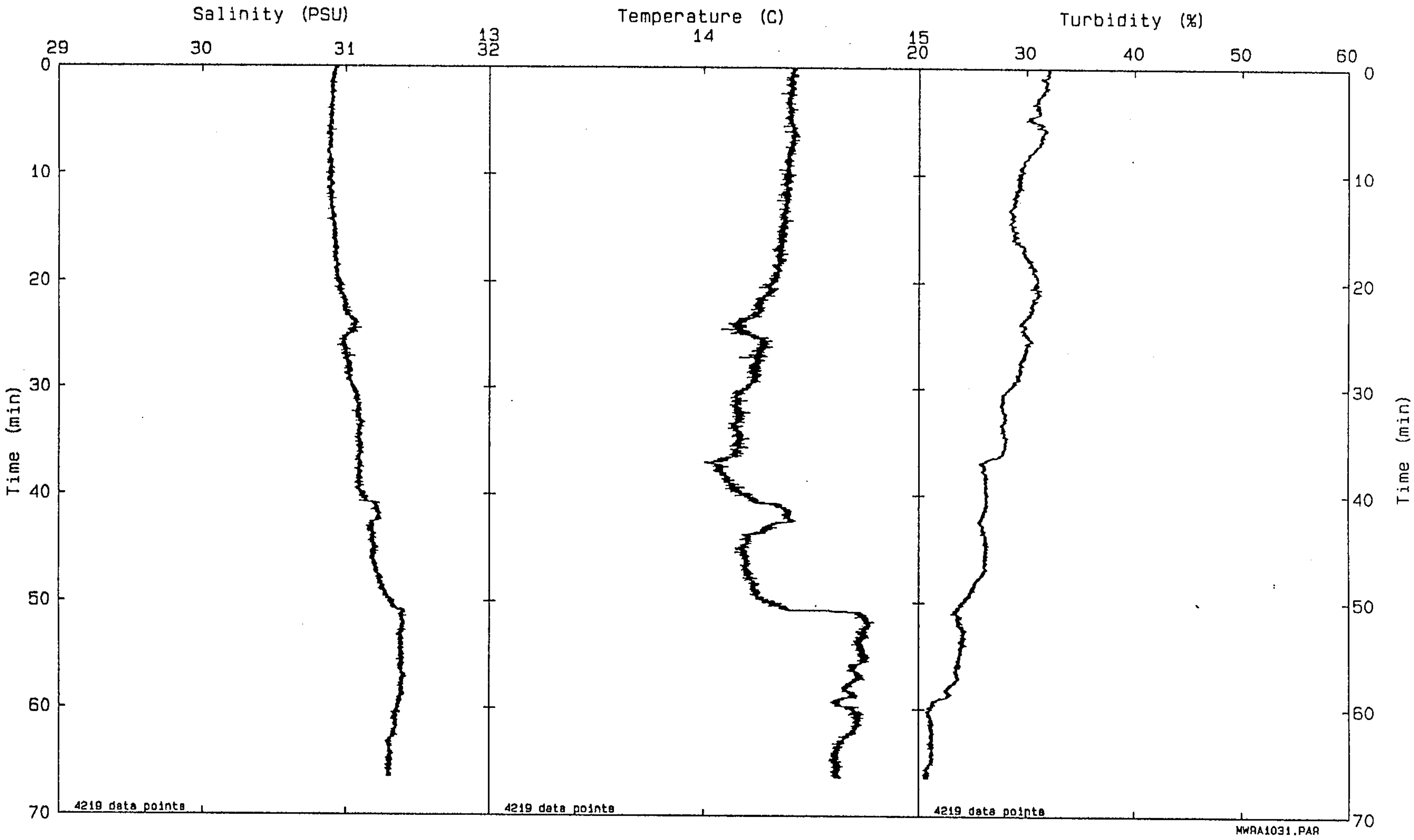

Figure 4-22. Time-Series Plot of Data Acquired along Transect Extending from Nantasket Roads into Massachusetts Bay Made on October 16, 1990

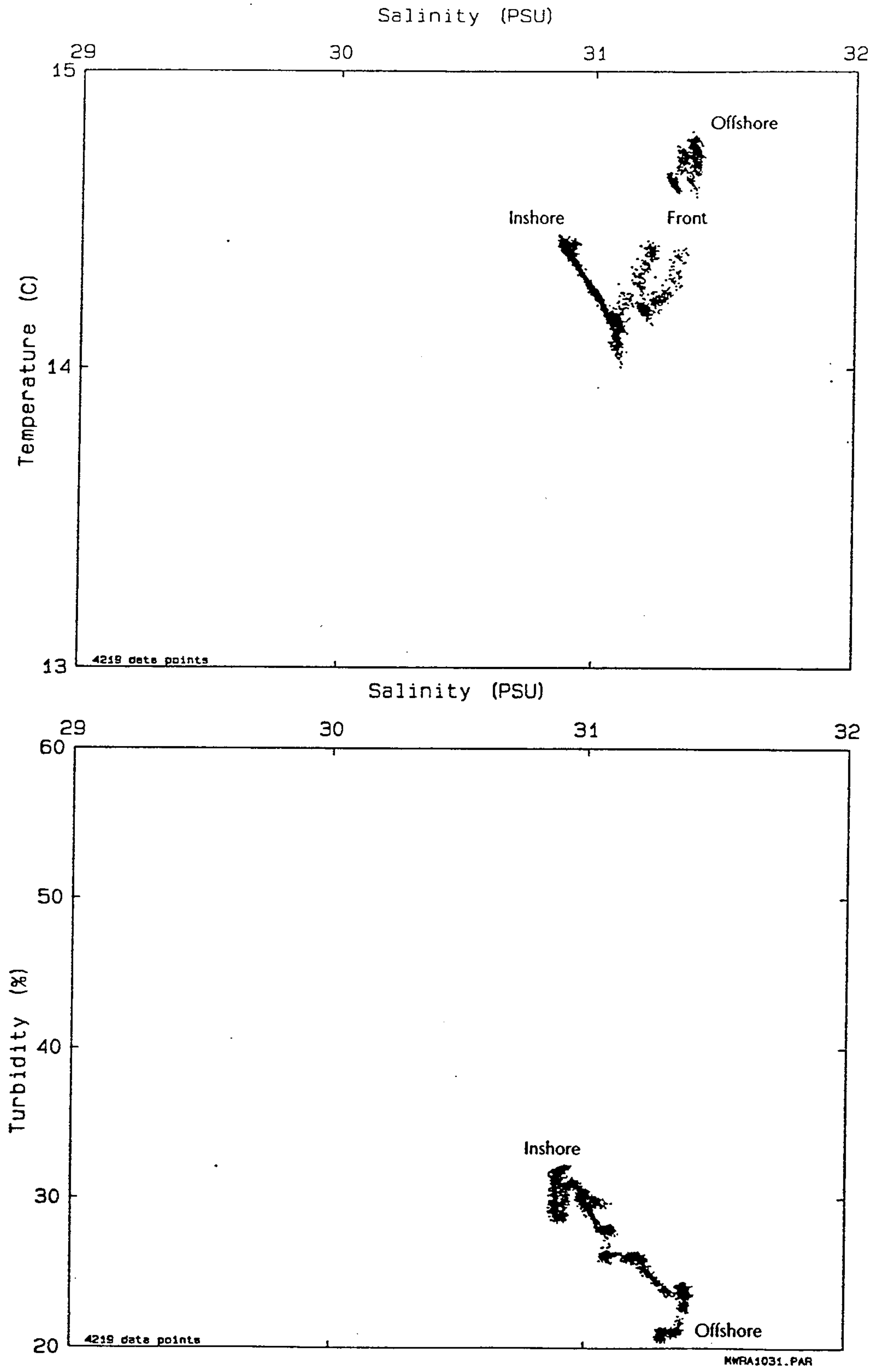

Figure 4-23. Scatter Plot of Data Acquired along Transect Extending from Nantasket Roads into Massachusetts Bay Made on October 16, 1990

characteristics of the Massachusetts Bay water. The sharp temperature front has been labeled on the T/S plot, but it is not evident in the Tu/S scatter plot.

From inspection of the T/S plot in Figure 4-23, it appears that the observed T/S characteristics are derived from three-component mixing of three specific water types: inshore, offshore, and a relatively cool water mass having a salinity of roughly 31.1 PSU. Neither the source of this third water mass nor its origin or horizontal extent can be resolved from the data acquired along this single transect. Nevertheless, the resolution of these data appears adequate for identifying the front between the inshore (and presumably Harbor-derived) water masses and the Massachusetts Bay water. Had additional daylight allowed continued surveying on October 16, additional northward or southward transects could have been made to delineate the spatial boundaries of this front. A single vertical profile made from the surface to the bottom at the offshore end of the long transect (Figure 4-24) shows that the characteristics of the offshore water extend from the surface to a depth of roughly 7 m, below which temperatures decrease continually.

Analysis of the drifters released at 3 to 4 h into the ebb flow at locations near Hull Gut within Nantasket Roads (Figures 4-2 and 4-3) indicate that they traveled roughly 1.5 nmi east of Pt. Allerton before the ebb tide ceased. If they had been released from the vicinity of Pt. Allerton within Nantasket Roads at the beginning of the ebb, it is conceivable that they could have migrated the 3.6-nmi eastward distance where the T/S front was encountered along the Mini-BOSS transect. For this reason, we believe that it is technically feasible to design a small field study that uses surface drifters and Mini-BOSS profiling along horizontal transects to delineate the boundaries of the Harbor water as it emerges into Massachusetts Bay on the ebb tide. Such data would be extremely valuable for validation of Signell's model (Bothner *et al.*, 1990), which predicts "blobs" of Harbor water being injected into Massachusetts Bay on each ebb tide.

4.3 RESULTS FROM SURVEY ON OCTOBER 17, 1990

4.3.1 Drifter Results

Surface drifters were deployed at various times during the ebb tide on October 17 to obtain additional information on the surface currents within Nantasket Roads. Drifters were released from the two survey vessels and tracked visually over the duration of the measurement period (roughly 1030 to 1600 h EST) as described in Section 4.2.1. In Volume II, Appendix A, tables of time and position of each drifter fix are given for each

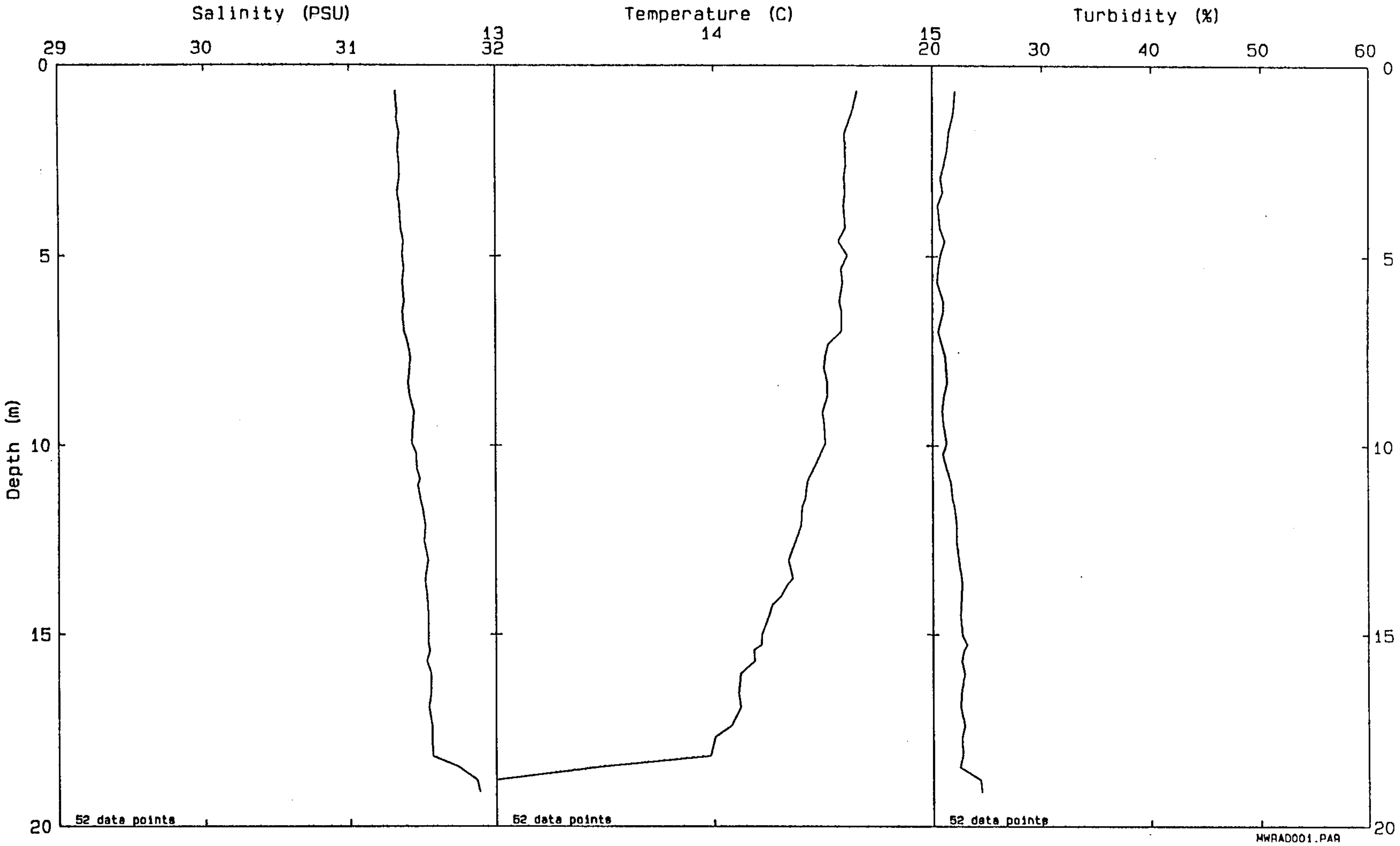

Figure 4-24. Vertical Profile Data Acquired on October 16, 1990, at Eastern End of Transect Shown in Figure 4-21. Total Water Depth at Station was 35 m.

drifter tracked; calculated drifter speed and distance between fixes are also provided.

On October 17, a total of 11 drifters were released at four sites within Nantasket Roads during the period from 37 to 57 min after predicted high water. Two additional drifter releases were made in the same area later during the ebb. The direction of the wind was relatively steady from 210° (south-southwest) with speeds increasing from 15 to 25 kn during the 6-h survey operations. Predicted high tide was at 1001 h EST.

Figure 4-25 presents data from two drifters that were released from the southern Nut Island effluent outfall at 31 min after predicted high water. Initially, these drifters remained within a few meters of each other as they moved northeastward past Peddocks Island at average speeds of roughly 40 cm/s. Near the northern tip of Peddocks Island, drifter I became trapped in a stagnant-flow region roughly 4 h after high water and remained there until the incoming tide carried it into Hull Gut. Drifter M did not get trapped near the island, and was consequently advected to the northeast at a speed of roughly 150 cm/s due to the intense northward flow from Hull Gut. This drifter reached the northern side of Nantasket Roads channel and continued northeastward at speeds that decreased to approximately 40 cm/s as it entered Massachusetts Bay.

Figure 4-26 presents data from three drifters that were released from the northeast Nut Island effluent outfall at 36 min after the predicted time of high water. As illustrated in the Figure, the three drifters remained together as they moved toward Portuguese Cove and then toward the northward tip of Peddocks Island at speeds of approximately 30 cm/s. At roughly 3 h after high water, drifters C and F1 became trapped in the same stagnant-flow region as drifter I, which was released from the southern outfall (see Figure 4-25). Drifter F1 remained there and became grounded, whereas drifter C eventually escaped near the end of the ebb cycle and began to move northeastward due to the northward flow from Hull Gut.

Drifter D (the third drifter released from the northeast outfall) did not get trapped near the tip of Peddocks Island and consequently remained within the ~40-cm/s northeastward flow of Nantasket Roads until is was recovered 0.75 nmi east of Boston Light (Figure 4-26). Note, however, that the speed of drifter D reached 149 cm/s, when it was entrained within the strong northeastward flow emanating from Hull Gut.

Figures 4-27 and 4-28 present data from three drifter clusters that were released at two additional sites within the eastern portion of Nantasket Roads. These drifters were released shortly after the drifter releases from the two outfalls to gain synoptic information on the entire Nantasket Roads flow system. From inspection of the data from the six drifters, it is

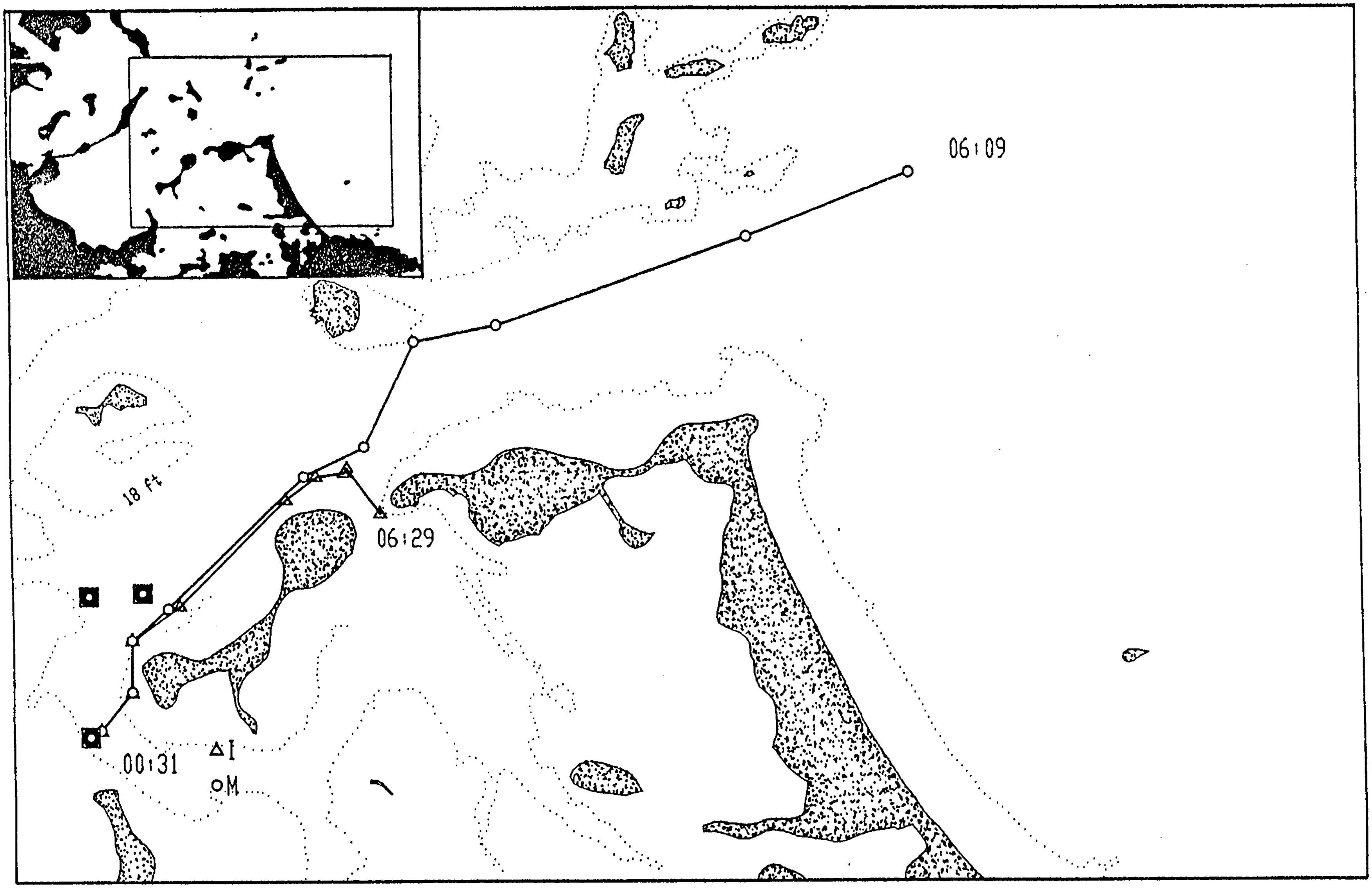

Figure 4-25. Trajectories of Two Drifters Released within Nantasket Roads on the Morning of October 17, 1990

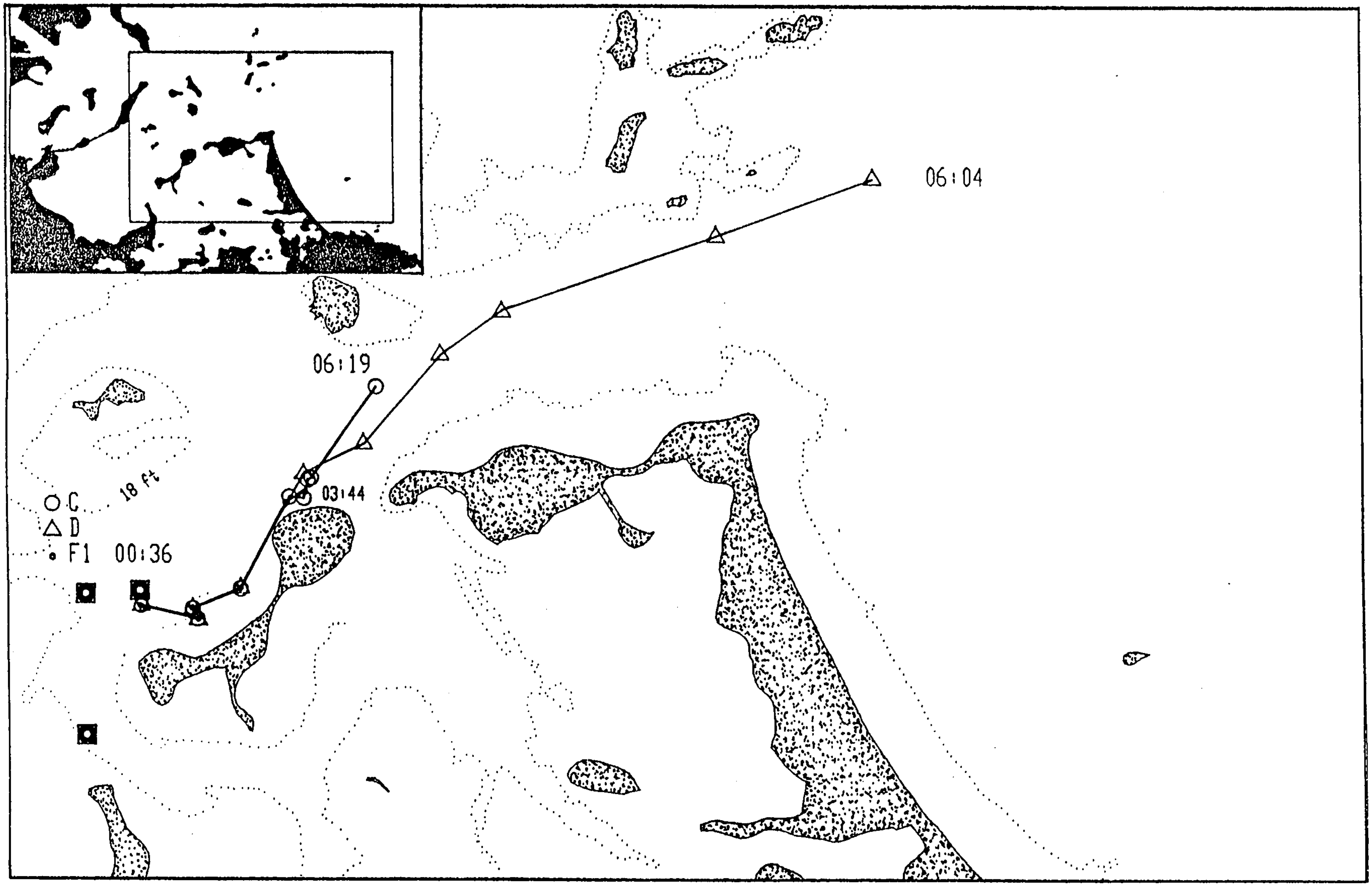

Figure 4-26. Trajectories of Three Drifters Released within Nantasket Roads on the Morning of October 17, 1990

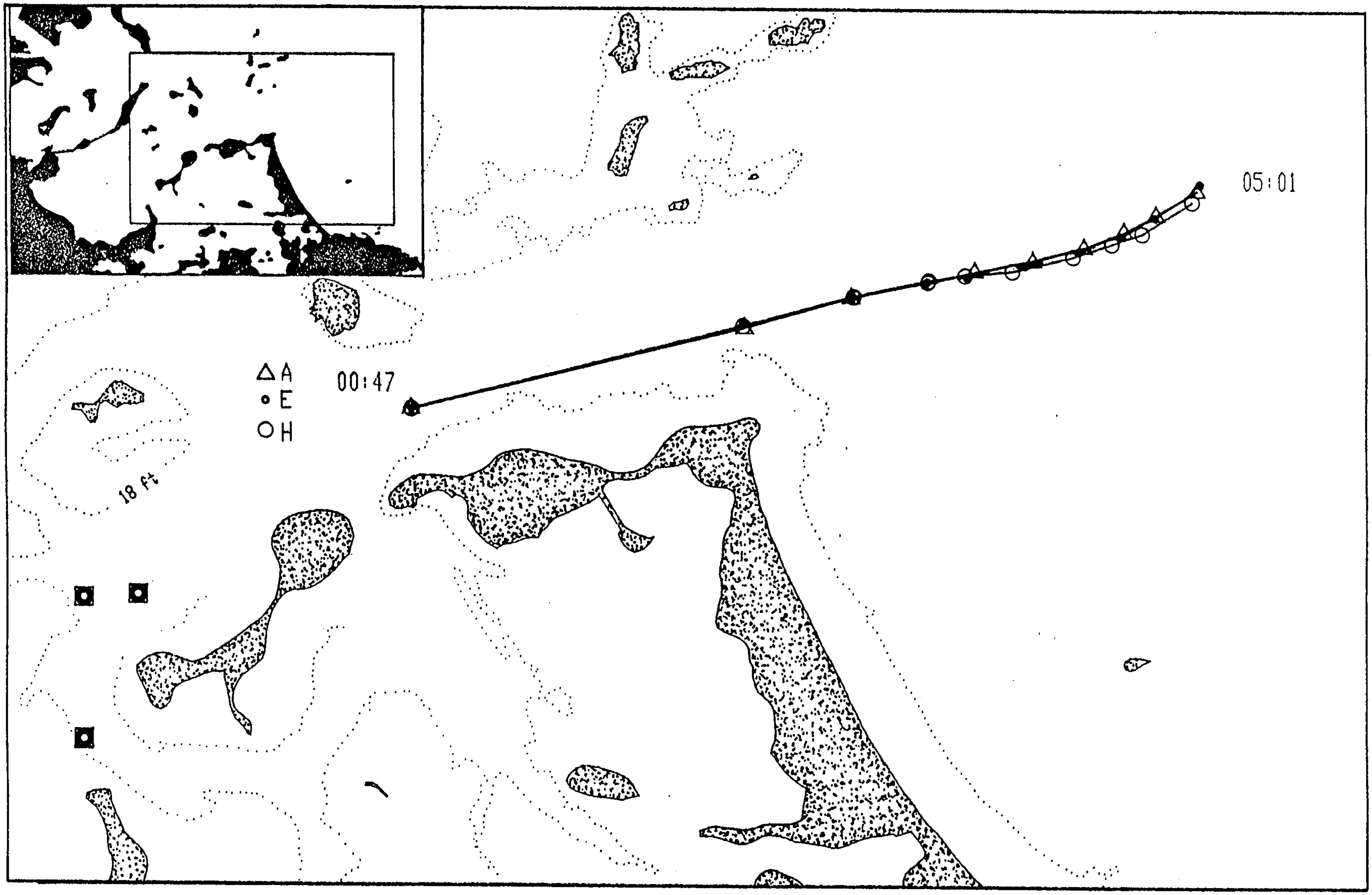

Figure 4-27. Trajectories of Three Drifters Released within Nantasket Roads on the Morning of October 17, 1990

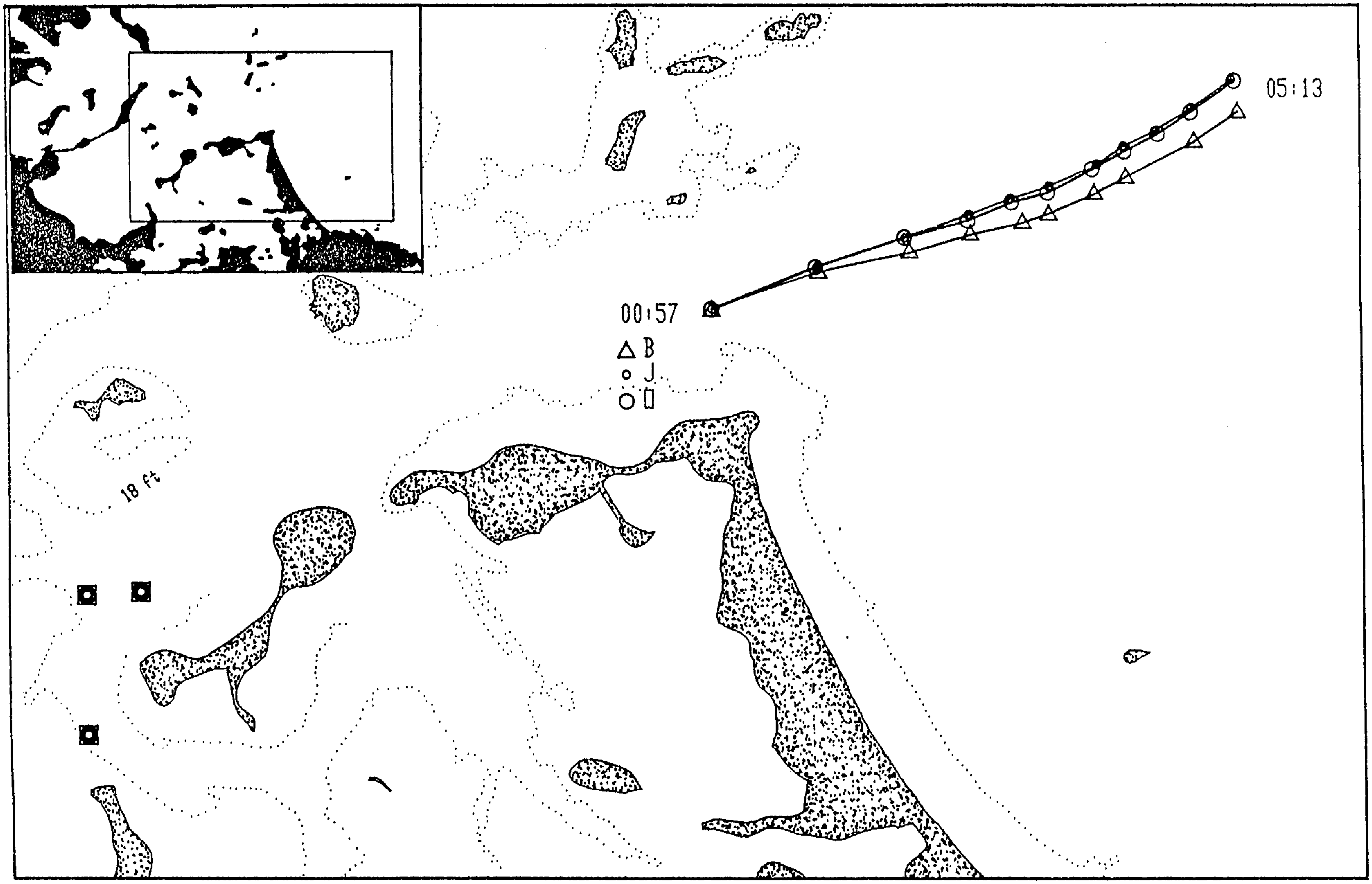

Figure 4-28. Trajectories of Three Drifters Released within Nantasket Roads on the Morning of October 17, 1990

apparent that (1) each cluster remained remarkably close together (suggesting minimal small-scale horizontal dispersion), (2) the trajectories were very linear with speeds ranging from ~55 cm/s within Nantasket Roads channel to ~35 to 40 cm/s as the drifters moved east-northeast into Massachusetts Bay, and (3) the final positions of the six drifters were quite close to each other when all were recovered roughly 5 h after high water. All drifters were recovered approximately 2.5 nmi east of Boston Light.

Data from the two additional drifters released later in the ebb cycle during October 17 are provided in Volume II, Appendix A. **Overall, the 13 drifter trajectories obtained on October 17 show that effluent released from the outfalls within western Nantasket Roads can reach Massachusetts Bay during a single ebb cycle.** Comparisons between the trajectories of the drifters and the direct observations of effluent plume advection on October 17 are presented in Section 4.3.3.

4.3.2 Plume Tracking Results

Water-quality surveying with the Mini-BOSS was initiated at roughly 1030 h EST on October 17. As during the previous day, the initial measurements were made in the vicinity of the southern Nut Island effluent outfall. Although the predicted time of high tide in Boston Harbor was 1001 h EST, the ebb flow at this site did not begin until approximately 1045 h EST (a time lag similar to that observed on the previous day).

Throughout the period from roughly 1030 to 1540 h EST on October 17, water-property measurements were made along 19 horizontal transects and at two vertical-profile stations, using the Mini-BOSS. Table 4-2 presents the time and location of each Mini-BOSS transect and of each vertical-profile station. Figure 4-29 presents a chart of Boston Harbor, with superimposed tracks representing the horizontal transects. As indicated, the transects were located in the vicinity and to the northeast of the three Nut Island effluent outfalls within Nantasket Roads.

The survey objective was to obtain information on the lateral spreading and advection of the three Nut Island effluent plumes, with primary emphasis on the plumes emanating from the southern and northeastern outfalls. As during the previous day, surveying operations consisted of near-continual towing of the Mini-BOSS sensor package at a near-constant depth of roughly 2 m below the surface. Selection of transect locations was made on a real-time basis by the scientist aboard the vessel, using the information from the real-time graphic display of water-property data and vessel position provided by the Mini-BOSS.

Table 4-2. Time and Location of Horizontal Transects (Tows) and Vertical Profiles Made on October 17, 1990

File Number	File Type	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Start Position		End Position	
				Lat(N)	Long(W)	Lat(N)	Long(W)
MWRA1037	Profile	10:31:40	10:32:32	42°17.20′	70°57.33′	42°17.20′	70°57.33′
MWRA1039	Tow	10:34:24	10:42:39	42°17.30′	70°57.31′	42°17.08′	70°57.44′
MWRA1040	Tow	10:42:42	10:48:10	42°17.11′	70°57.44′	42°17.33′	70°57.34′
MWRA1041	Tow	10:48:13	10:51:13	42°17.33′	70°57.30′	42°17.21′	70°57.35′
MWRA1042	Tow	10:51:17	10:56:04	42°17.19′	70°57.34′	42°17.35′	70°57.14′
MWRA1043	Tow	10:56:08	10:58:21	42°17.37′	70°57.13′	42°17.31′	70°57.06′
MWRA1044	Tow	10:58:24	11:03:51	42°17.30′	70°57.06′	42°17.39′	70°57.39′
MWRA1045	Tow	11:03:54	11:10:12	42°17.42′	70°57.41′	42°17.30′	70°57.13′
MWRA1046	Tow	11:10:16	11:15:42	42°17.30′	70°57.10′	42°17.60′	70°57.08′
MWRA1047	Tow	11:15:45	11:22:14	42°17.73′	70°57.30′	42°17.84′	70°57.49′
MWRA1048	Tow	11:22:17	11:34:08	42°17.86′	70°57.48′	42°17.68′	70°56.86′
MWRA1049	Tow	11:34:12	11:40:43	42°17.68′	70°56.88′	42°17.50′	70°57.13′
MWRA1050	Tow	11:40:48	11:47:17	42°17.50′	70°57.15′	42°17.85′	70°57.45′
MWRA1052	Tow	12:02:18	12:12:48	42°17.93′	70°56.26′	42°18.37′	70°56.73′
MWRA1054	Tow	12:17:56	12:29:13	42°18.19′	70°57.18′	42°17.70′	70°56.56′
MWRA1056	Tow	12:31:30	12:42:05	42°17.62′	70°56.70′	42°18.09′	70°57.41′
MWRA1057	Tow	12:42:08	12:55:27	42°18.10′	70°57.45′	42°17.59′	70°56.80′
MWRA1059	Tow	13:13:48	13:27:28	42°18.10′	70°56.40′	42°18.61′	70°56.95′
MWRA1062	Tow	14:25:37	14:37:20	42°18.00′	70°56.30′	42°18.47′	70°56.83′
MWRA1064	Profile	14:44:36	14:45:38	42°18.35′	70°55.86′	42°18.35′	70°55.86′
MWRA1066	Tow	15:28:41	15:40:25	42°18.84′	70°54.11′	42°19.57′	70°53.84′

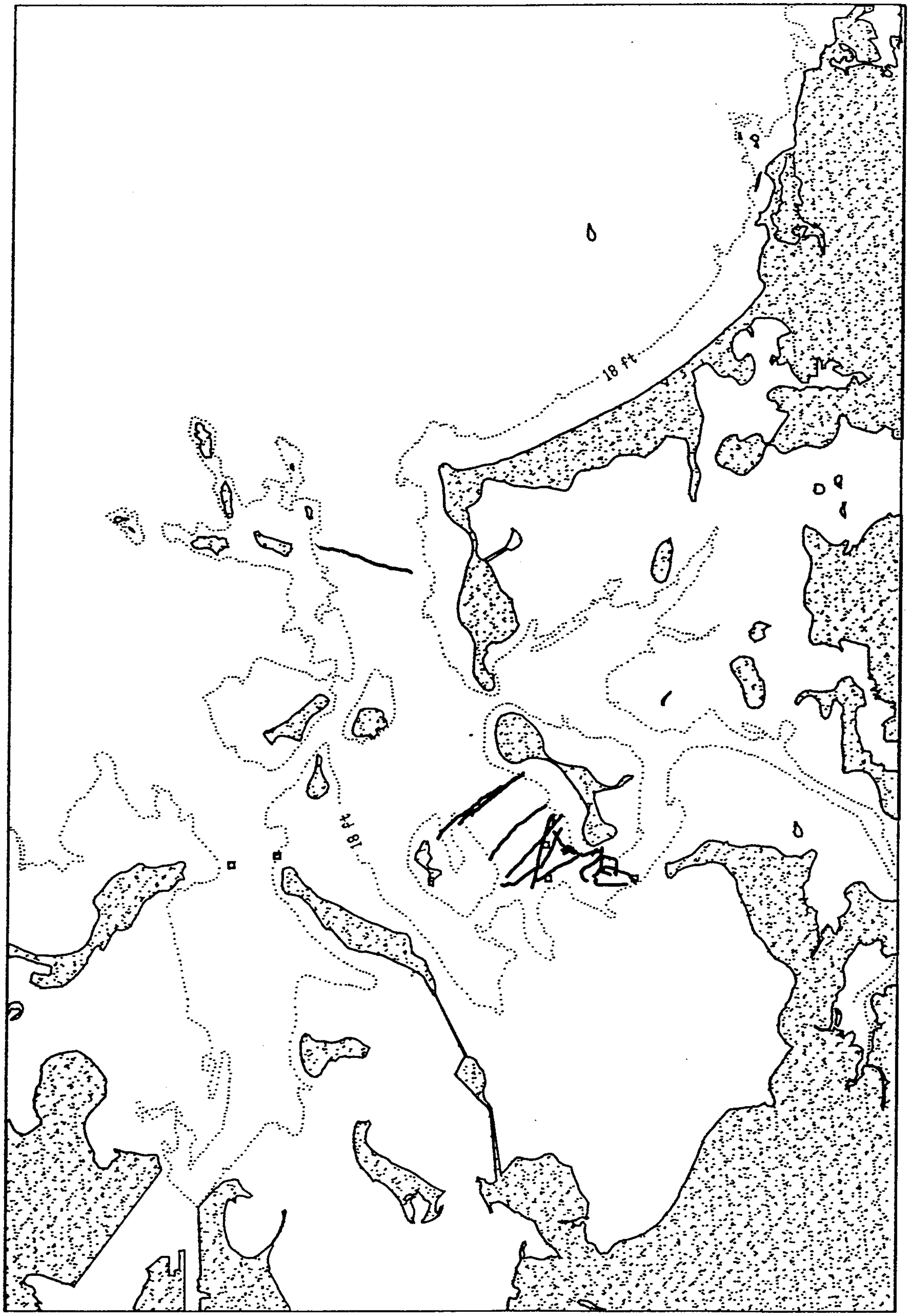

Figure 4-29. Location of Horizontal Transects Made on October 17, 1990

Figure 4-30 presents a detailed chart of the effluent outfall locations within Nantasket Roads with superimposed vessel tracks representing horizontal transects 40, 44, 45, and 46 (data files MWRA1040, MWRA1044, etc.). Transect 40, made at 1042 h EST, began within the effluent plume at the southern outfall and ended a short distance to the north, beyond the northern boundary of the plume. Figure 4-31 presents T/S and Tu/S scatter plots of the data acquired along transect 40, plotted on the same scales as used to present the results from October 16. The data illustrate that, although the vessel was located in the effluent plume close to its source, turbidities did not exceed 40%. The plume was, however, distinguishable from the relatively clear, more saline background waters located to the north of the effluent plume.

Data from transect 46 (Figure 4-32), obtained at 1110 h EST, illustrate the characteristics of the southern effluent plume as it progresses northward past the southwestern tip of Peddocks Island. The characteristics of the water lying to the northeast of plume are again readily distinguishable from the plume characteristics when analyzed from the Tu/S scatter plot.

Figure 4-33 presents the locations of five additional transects made in Nantasket Roads from 1140 and 1313 h EST. To illustrate the variability in water properties observed within and adjacent to the plumes emanating from the three effluent outfalls located in Nantasket Roads, Figures 4-34 to 4-37 present data acquired on transects 56, 57, and 59.

Transect 56, which extended from Portuguese Cove at Peddocks Island toward the northwest across Nantasket Roads, intersected the plumes from all three outfalls. The characteristics of the three outfall plumes and the relatively clear, saline water residing within Portuguese Cove have been labeled on the Tu/S plot of Figure 4-34. **(Note that the actual identity of these characteristics was determined through careful analysis of numerous, independent transects taken during October 17.)** The characteristics of the northeast and northwest outfall plumes were very similar, but the turbidities within the plume from the more distant southern outfall were much lower, presumably due to increased mixing with the lower turbidity and higher salinity background waters en route to transect 56.

Time-series data acquired along transect 57, located upstream from the northeast outfall but downstream from both the south and northwest outfalls, are presented in Figure 4-35. In this Figure, the high turbidity and low salinity of the northwest outfall are clearly evident; the small increase in turbidities prior to reaching Portuguese Cove are remnants of the dilute plume from the southern outfall. Figure 4-36 also presents the data from transect 57, but in terms of T/S and Tu/S scatter plots. From this display, it is simple to distinguish between the relatively high-turbidity and low-salinity water of the northwest outfall and the more dilute plume from the southern outfall, which blends into the background water properties.

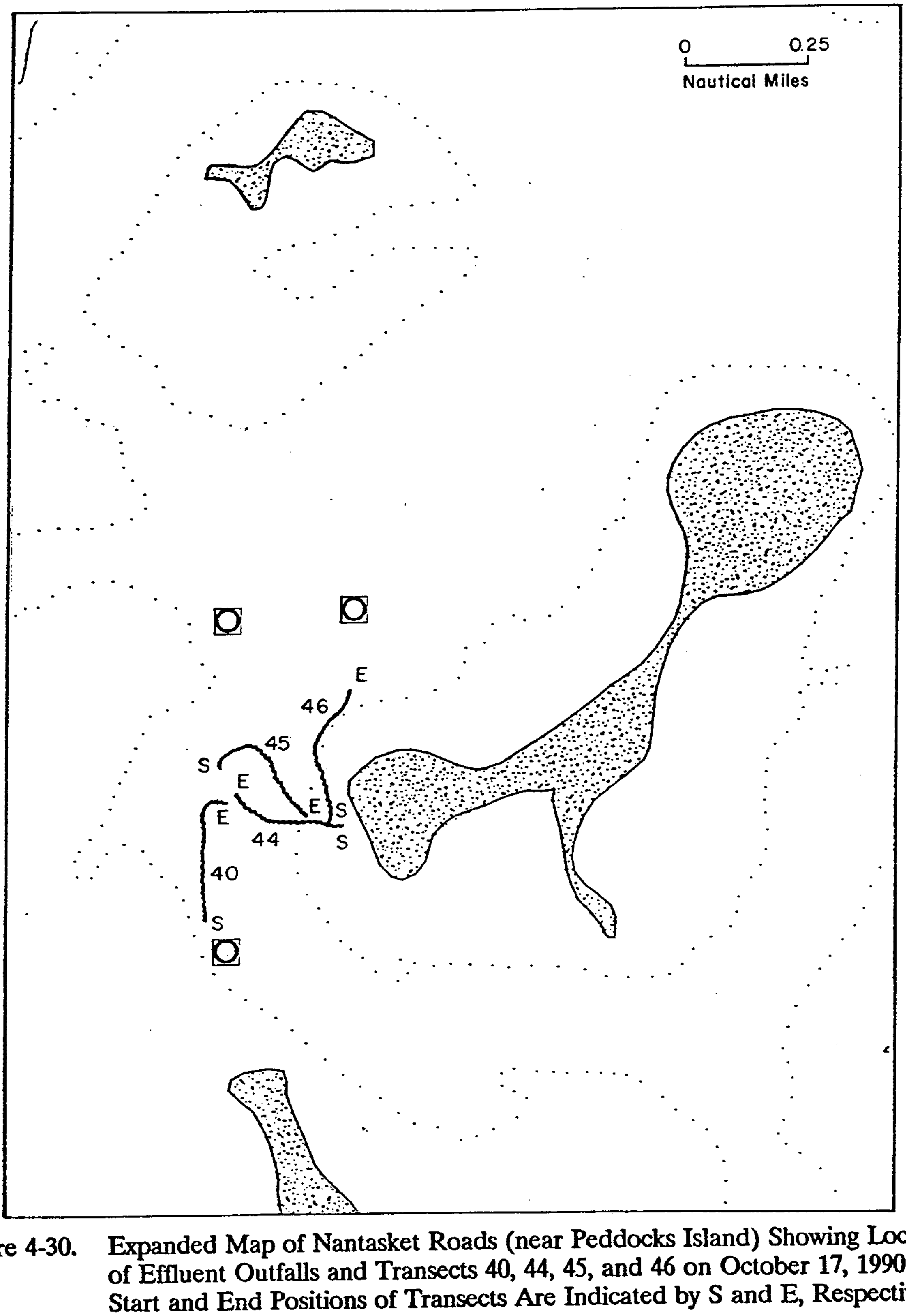

Figure 4-30. Expanded Map of Nantasket Roads (near Peddocks Island) Showing Location of Effluent Outfalls and Transects 40, 44, 45, and 46 on October 17, 1990. Start and End Positions of Transects Are Indicated by S and E, Respectively.

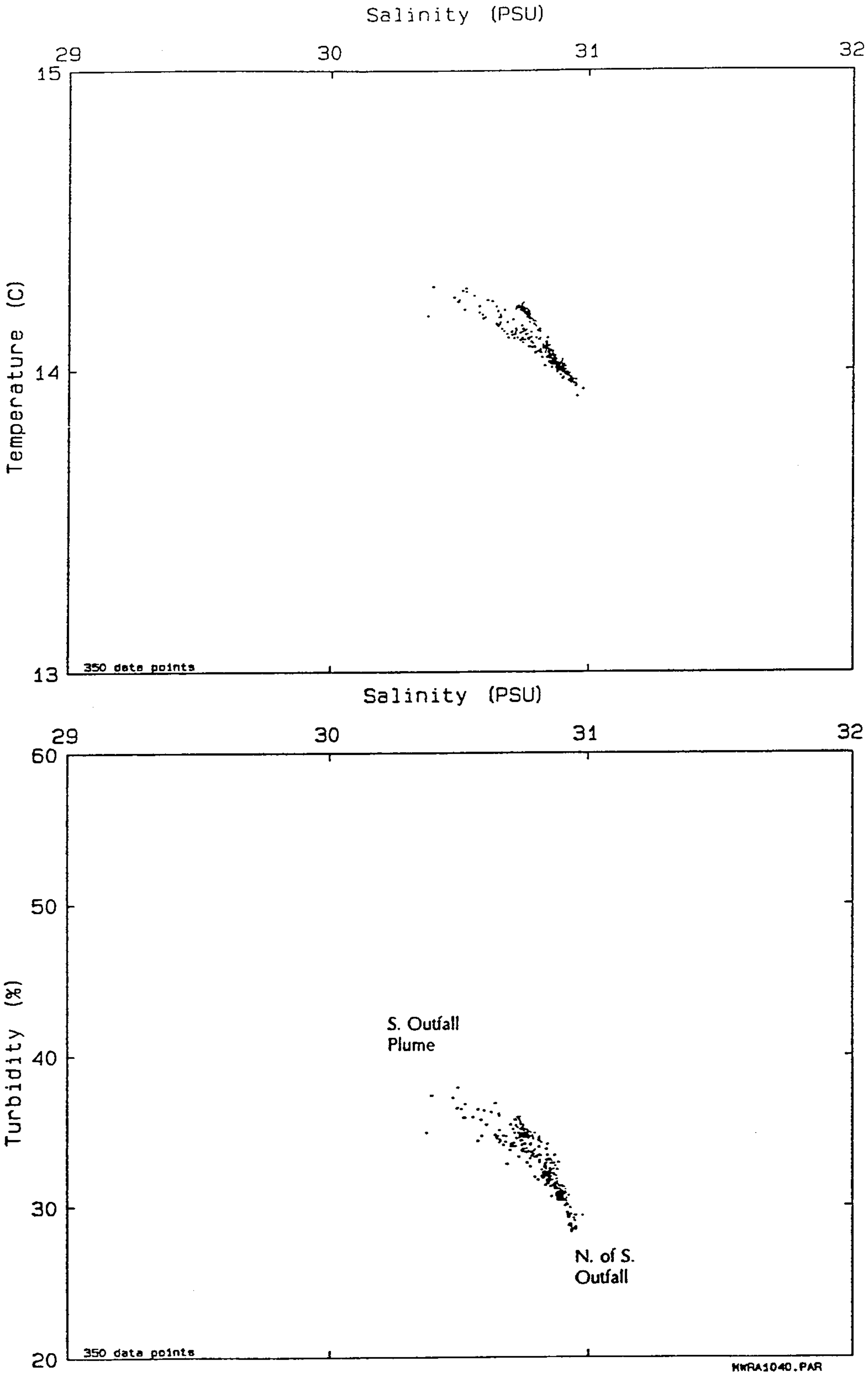

Figure 4-31. Scatter Plot of Data Acquired along Transect 40 Made on October 17, 1990

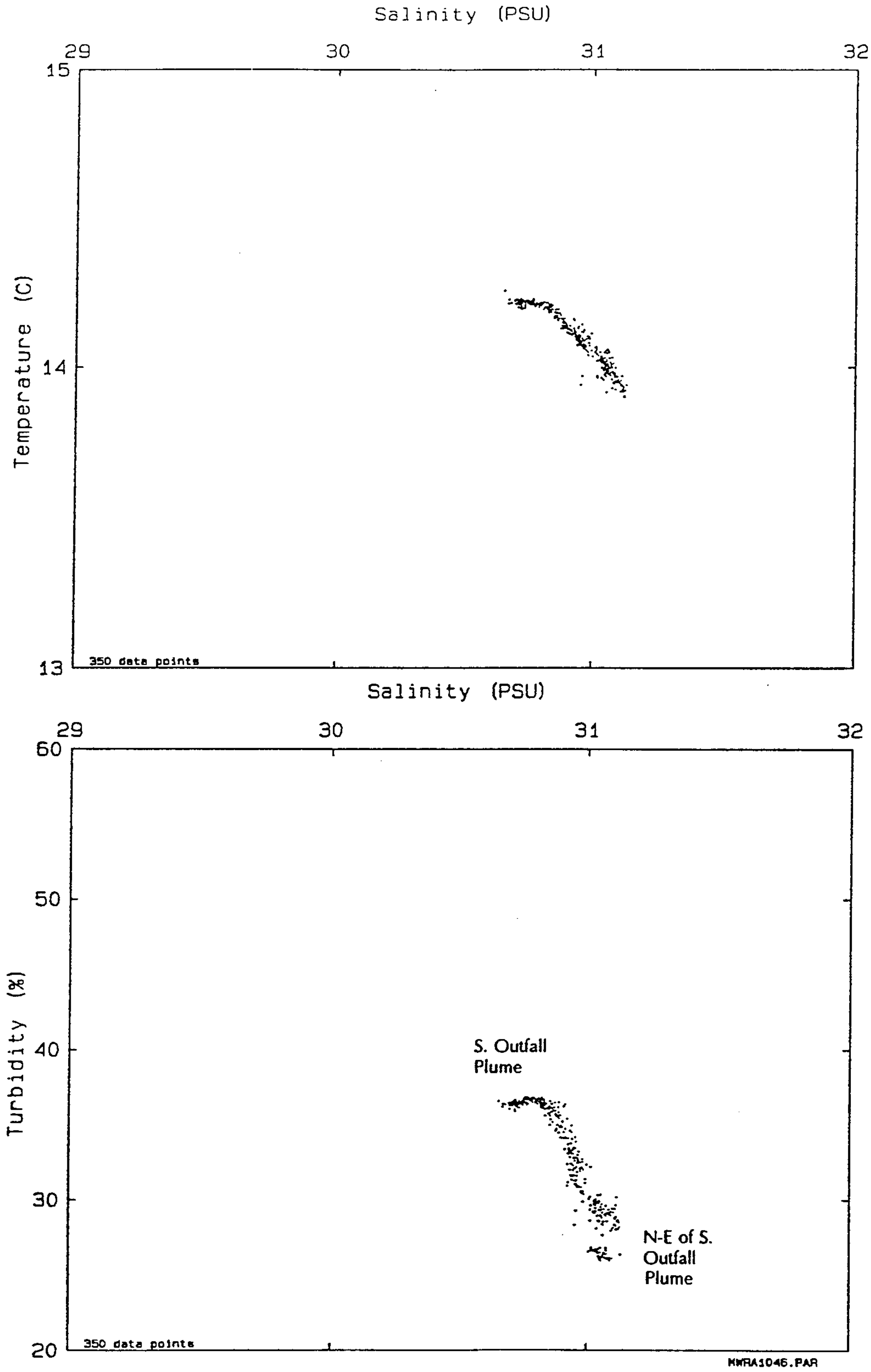

Figure 4-32. Scatter Plot of Data Acquired along Transect 46 Made on October 17, 1990

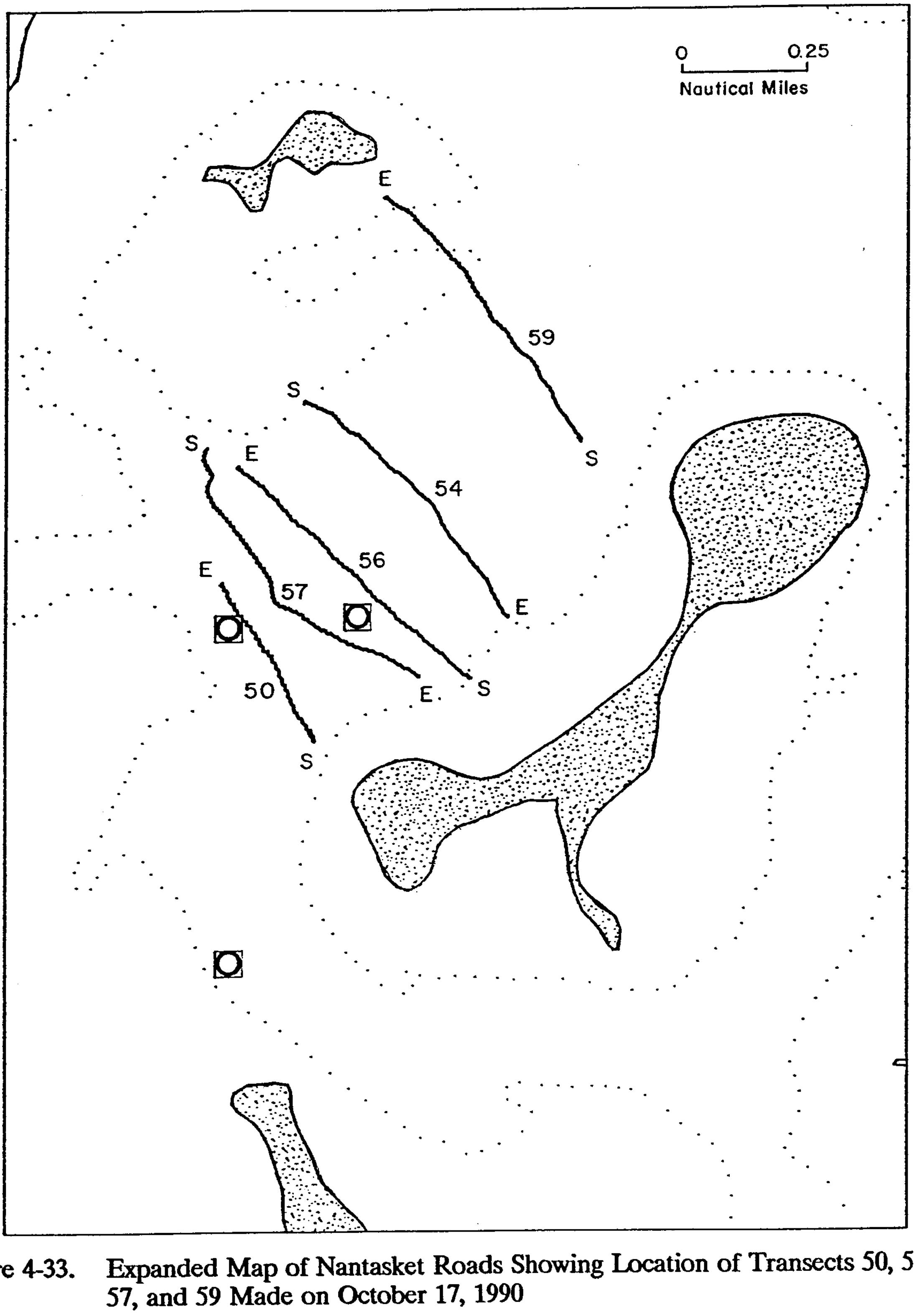

Figure 4-33. Expanded Map of Nantasket Roads Showing Location of Transects 50, 54, 56, 57, and 59 Made on October 17, 1990

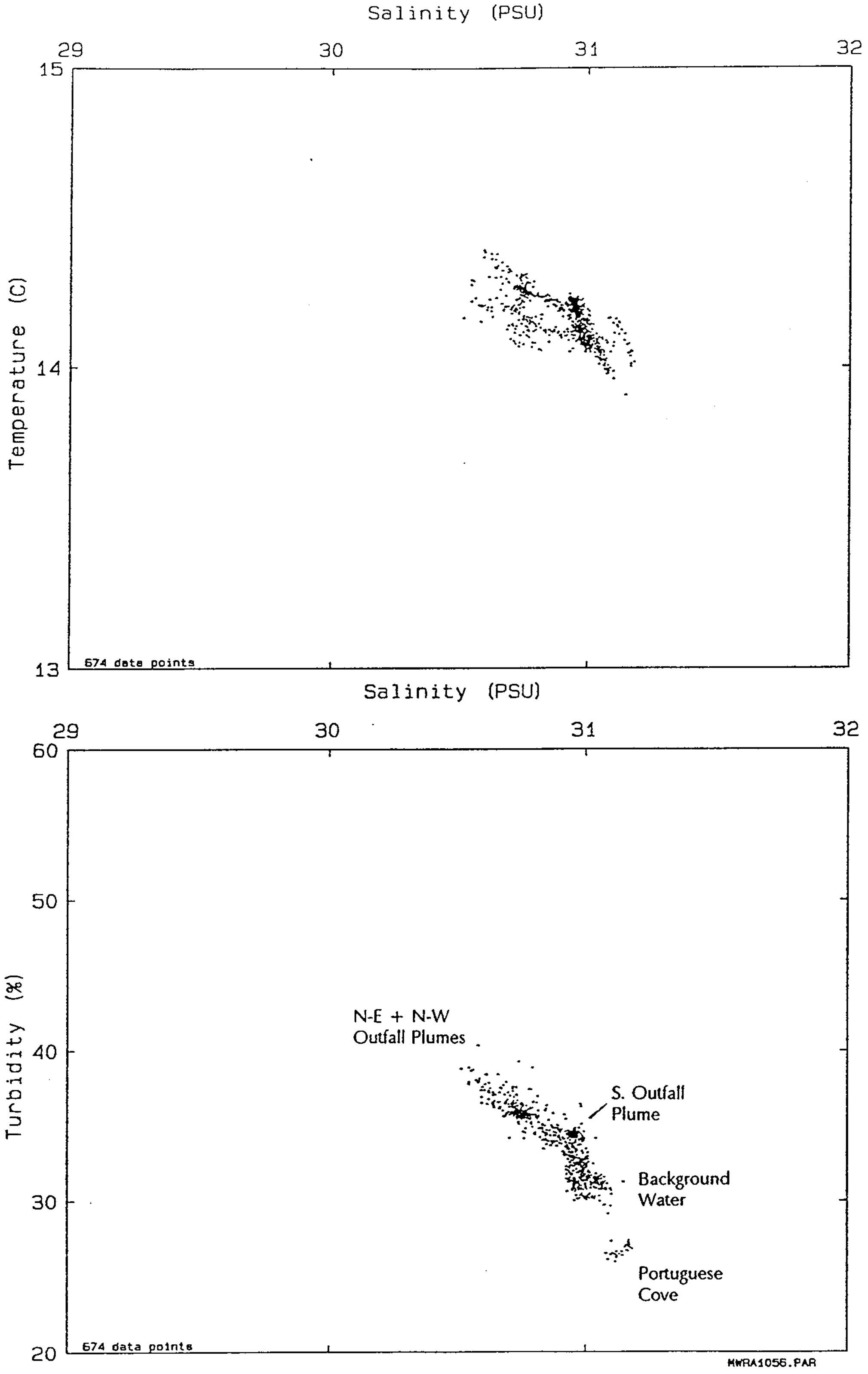

Figure 4-34. Scatter Plot of Data Acquired along Transect 56 Made on October 17, 1990

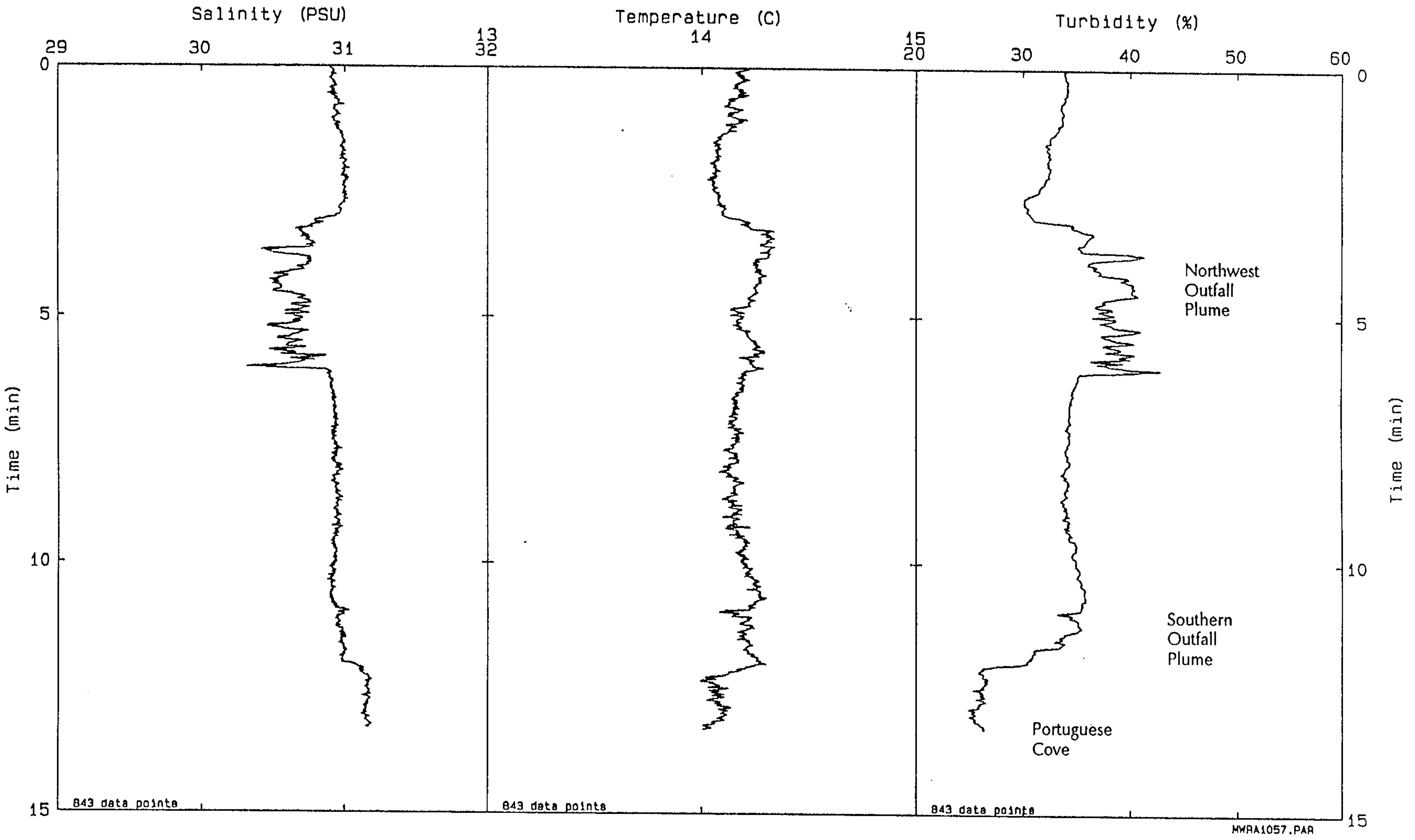

Figure 4-35. Time-Series Plot of Data Acquired along Transect 57 Made on October 17, 1990

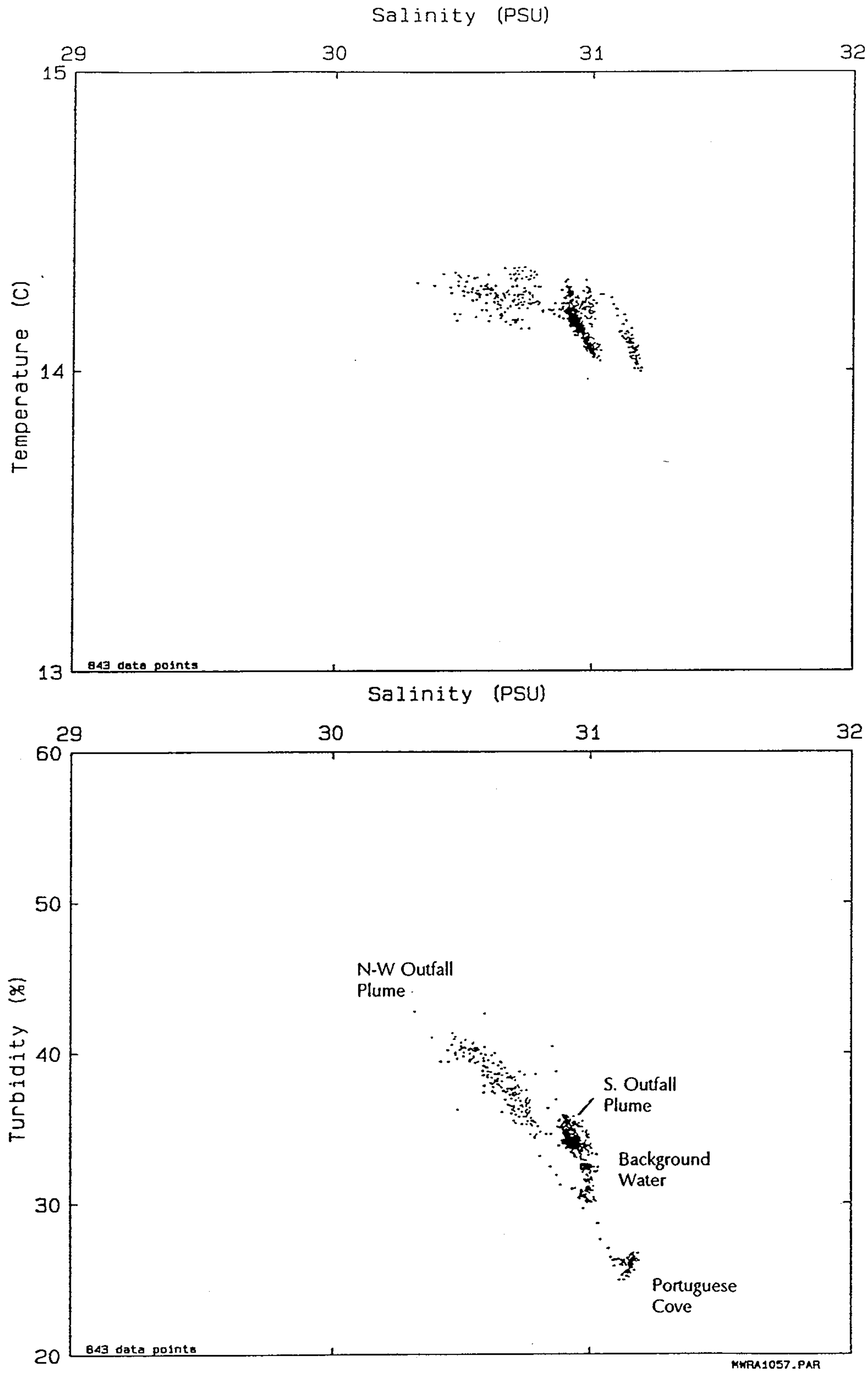

Figure 4-36. Scatter Plot of Data Acquired along Transect 57 Made on October 17, 1990

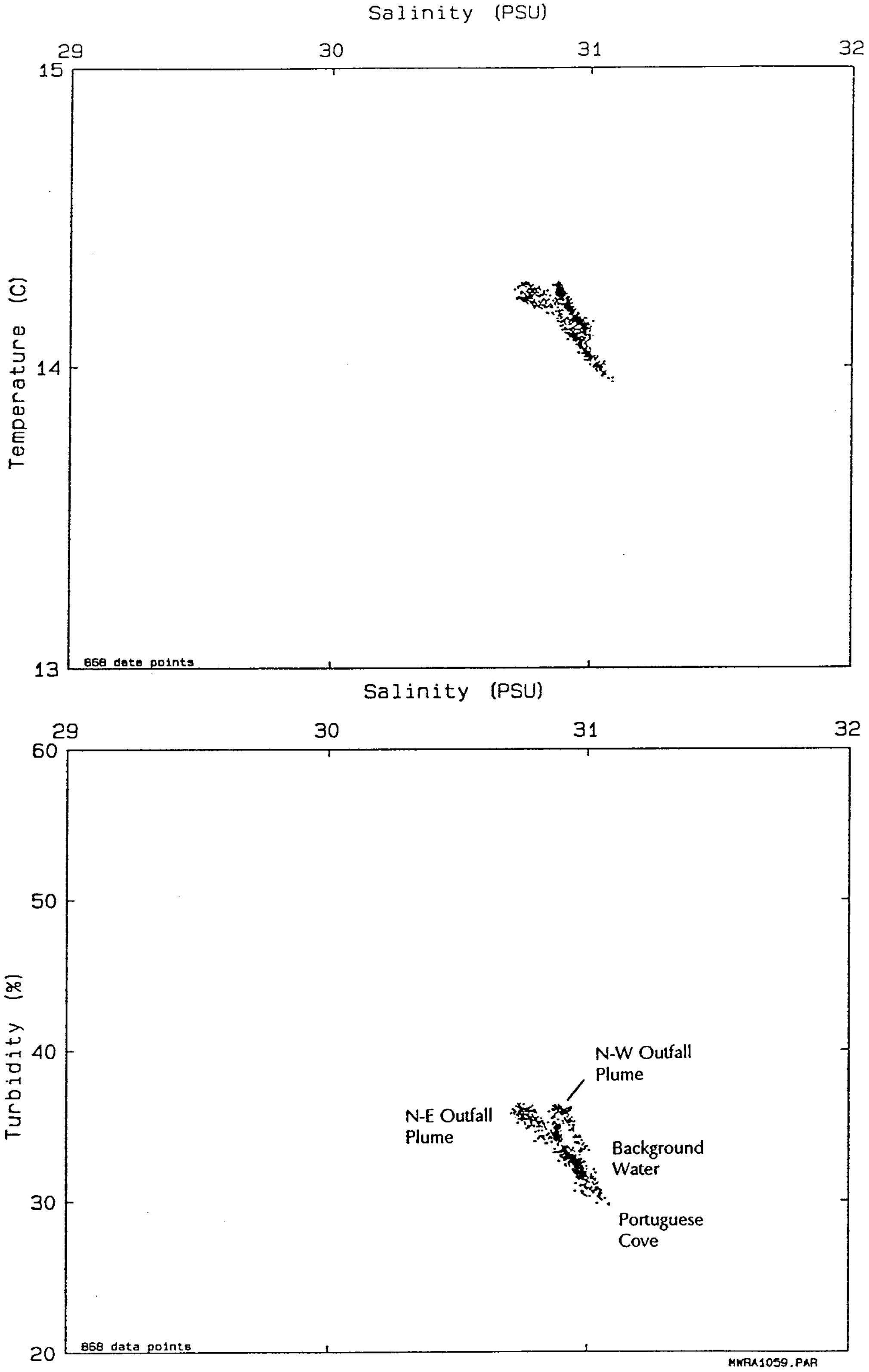

Figure 4-37. Scatter Plot of Data Acquired along Transect 59 Made on October 17, 1990

Farther downstream along transect 59, the northeast and northwest plumes have diluted significantly such that maximum turbidities are <40% and barely distinguishable from the more clear and saline background waters within Nantasket Roads and Portuguese Cove (Figure 4-37).

4.3.3 Summary of Effluent Plume Behavior

As for the previous day of survey operations, the high-resolution, near-surface measurements of temperature, salinity, and turbidity along the horizontal transects were useful for distinguishing between the effluent plume water and the relatively less-turbid and more-saline background waters within Nantasket Roads. Figure 4-38 presents composite T/S and Tu/S scatter plots, including all data acquired during the plume surveying activities on October 17, 1990. From comparison with the composite data from October 16 (Figure 4-19), it is apparent that (1) the background water properties exhibited much less variability on October 17 and (2) the plumes were much more dilute on October 17, as evidenced from the significantly lower turbidities and higher salinities within the plumes as compared with the background waters of the same day. This increased dilution may have been due to reduced effluent discharge on October 17, compared with the previous day, but discharge records from the Nut Island Treatment Plant were not available for this study. It is unlikely that the increased dilution on October 17 was associated with increased near-surface mixing due to wind waves because winds were generally less than 17 kn during most of the surveying operations on both October 16 and 17.

As demonstrated in Section 4.2.3, analysis of the water properties along each transect and the concurrent navigation information allow one to effectively map the location of individual effluent plumes within Nantasket Roads. Figure 4-39 presents a map of the study area within Nantasket Roads with shading that represents the spatial extent of the near-surface effluent plume emanating from the southern outfall. This plume map was derived from analysis of transects made approximately 1 h after the time of predicted high water on October 17; the dotted line indicates the areal coverage of the transects used to generate this near-synoptic map. This map illustrates that at the beginning of the ebb flow the leading edge of the plume emanating from the outfall had progressed approximately 0.25 nmi to the north in the direction of the flow within the west arm of Nantasket Roads. Near the southwest tip of Peddocks Island, a plume of effluent water was detected near shore, progressing northward. From analysis of the T/S and Tu/S data, we suspect that this plume was associated with the plume created during the incoming tide from the same southern outfall. Because these outfalls discharge effluent throughout the tidal cycle, it is not surprising that the trailing edge of the plume created during the flood cycle is detectable as it moves out on the ebb. As

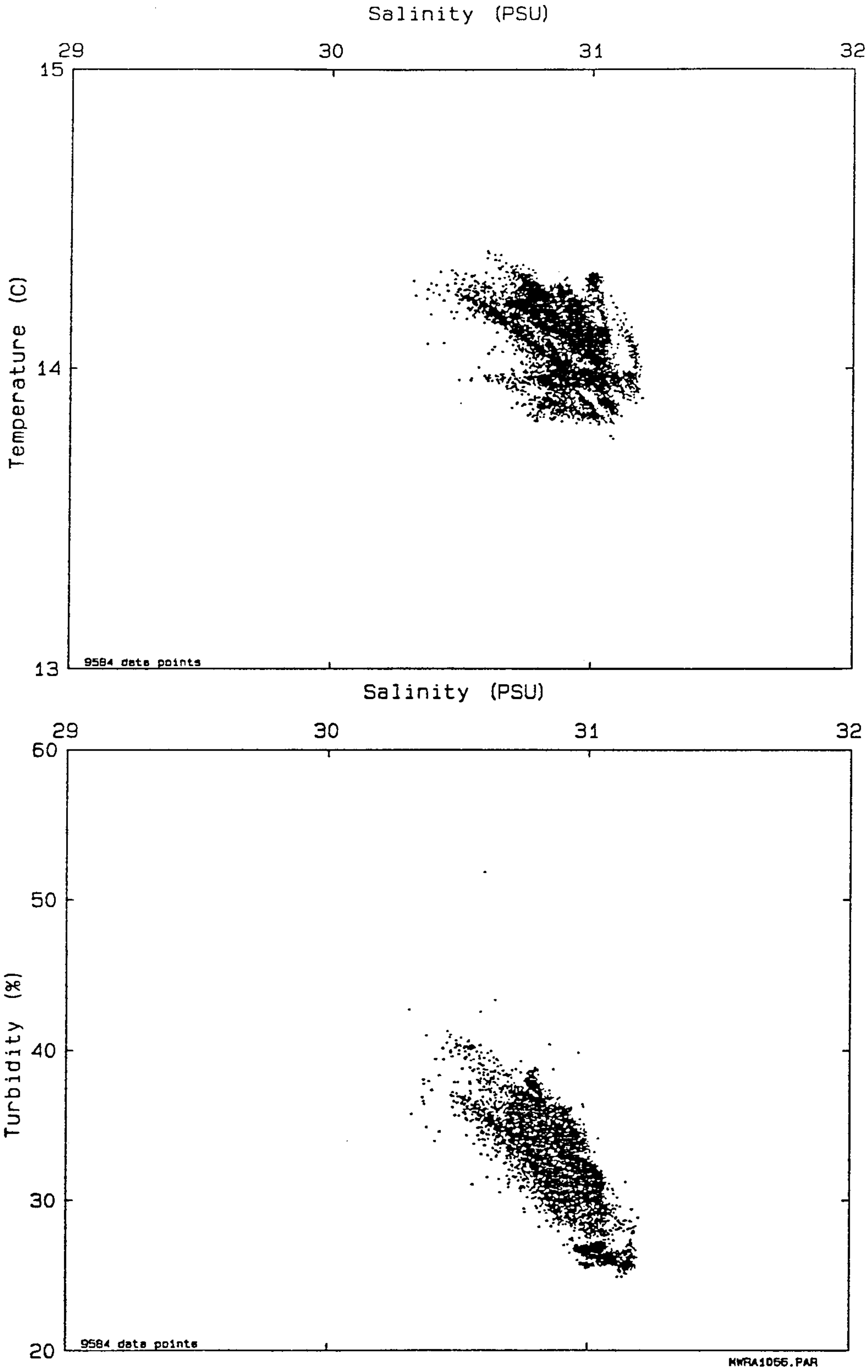

Figure 4-38. Composite Scatter Plot of All Data Acquired along Transects and at Vertical Profile Stations Made on October 17, 1990

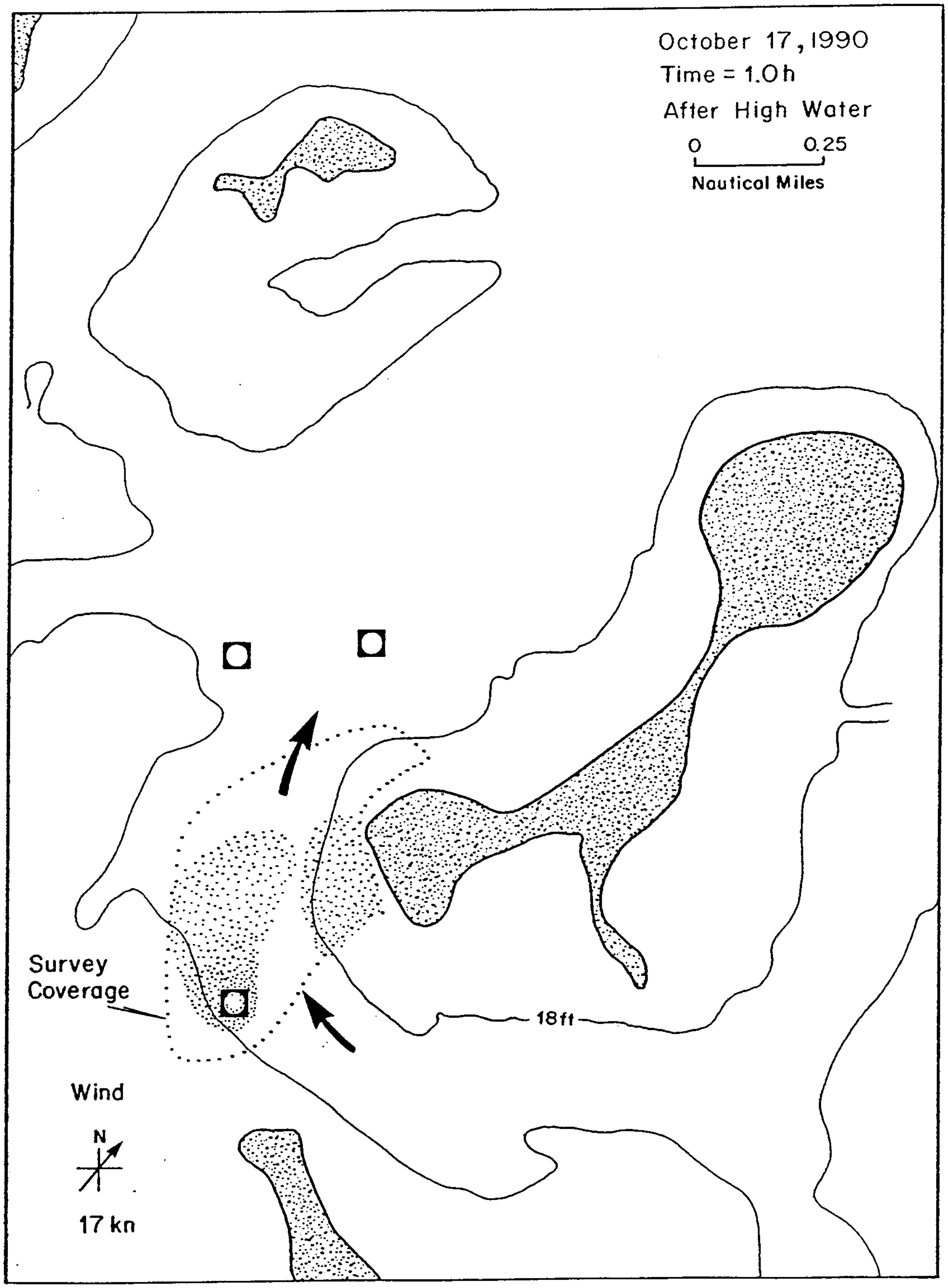

Figure 4-39. Map of Nantasket Roads Showing Location of Southern Plume 1.0 h after High Water on October 17, 1990. Arrows Represent Flow Direction; Dotted Line Indicates Survey Coverage. Dashed Line Represents Hypothetical Plume Boundaries.

indicated in Figure 4-40, which presents a synoptic map from data acquired at roughly 1.7 h after predicted high water, the plume from the southern outfall had not yet reached the northeast outfall; the plume from the northwest outfall was also readily distinguishable from the background waters.

Figure 4-41 presents a diagram of the spatial extent of the effluent plumes derived from transects made during the period from 2.5 to 3.5 h after predicted high water. The spatial coverage provided by the transects during this period is delineated by two regions: one near the northern end of Peddocks Island and the other farther to the south in the vicinity of the two northern outfalls. Transects within the northern survey area revealed that the leading edge of the effluent plume(s) had reached this location, but it was somewhat difficult to distinguish between the properties of the two plume sources. These data also illustrate that the plume(s) were confined to the northern side of Nantasket Roads channel, probably due to the effects of the southwesterly wind. Note that, on the previous day when the wind was from the west, the plume extended to the south side of the channel, approaching Peddocks Island (see Figure 4-20). Furthermore, with the westerly wind on October 16, the plumes from the southern and northeastern outfalls entered Portuguese Cove, but they did not impact the west side of Peddocks Island when the wind was from the southwest on October 17.

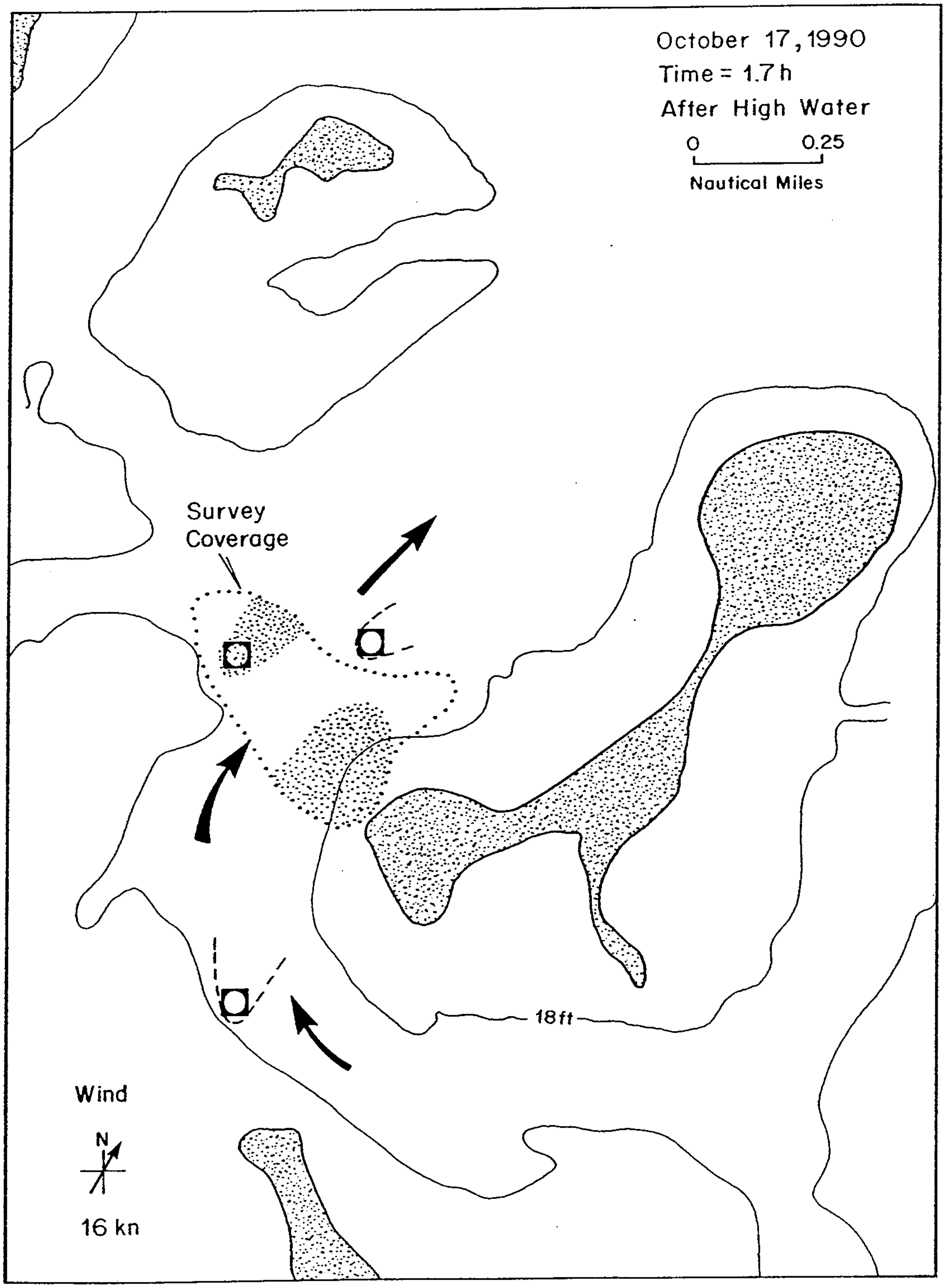

Figure 4-40. Map of Nantasket Roads Showing Plume Locations 1.7 h after High Water on October 17, 1990

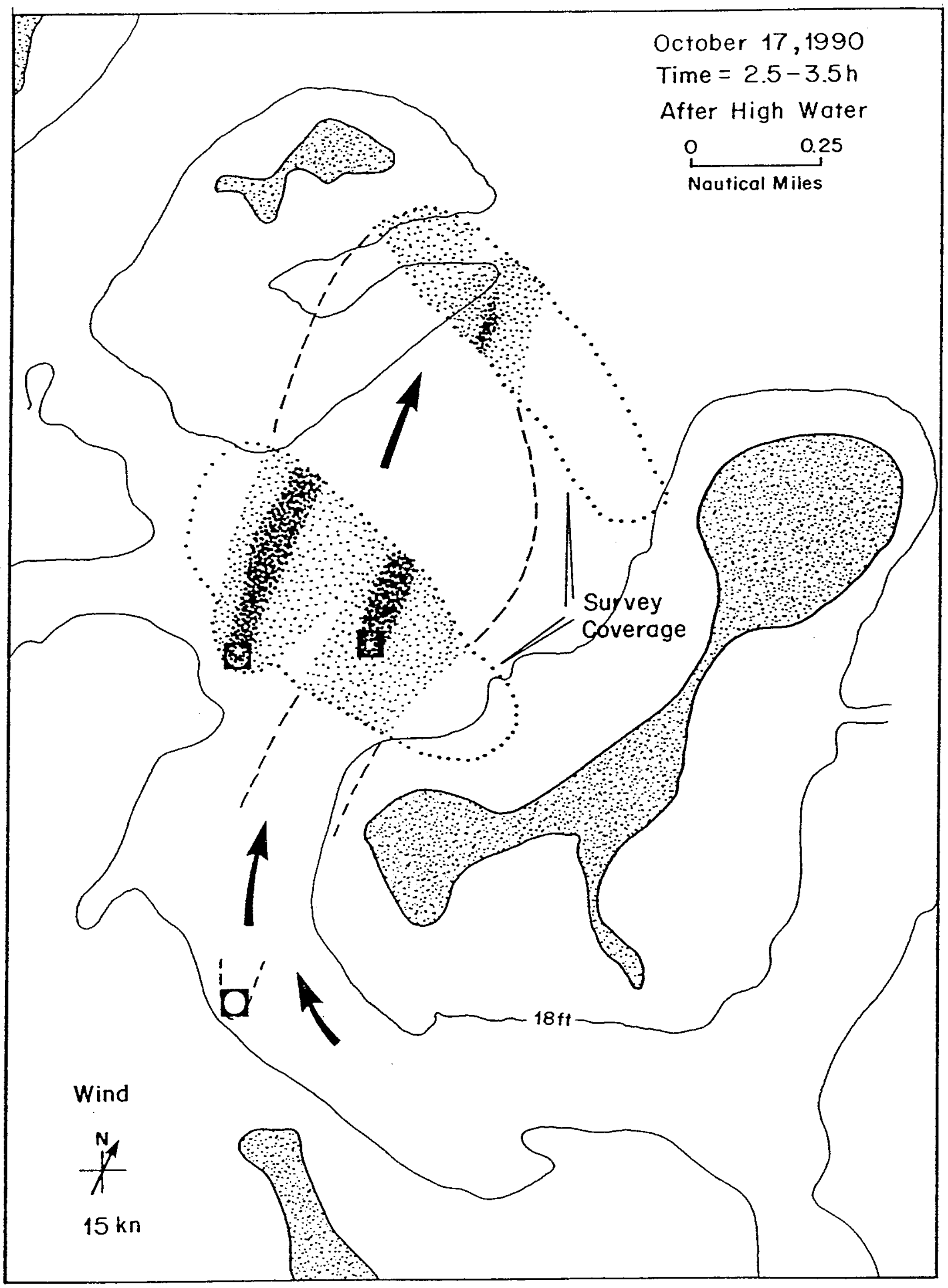

Figure 4-41. Map of Nantasket Roads Showing Plume Locations 2.5 to 3.5 h after High Water on October 17, 1990

5.0 STUDIES OF NUT ISLAND SLUDGE PLUMES AT LONG ISLAND

5.1 SURVEY OBJECTIVES AND ACTIVITIES

Sewage sludge from the Nut Island sewage treatment plant is discharged from a single outfall located off the northern tip of Long Island within President Roads (Figure 5-1). This discharge is released during the ebb flow period twice per day. The discharge rate has been estimated at 2 ft^3/s (0.0566 m^3/s) for a period of roughly 4 h on each ebb (~815 m^3/ebb) (Dr. E. Adams, MIT; personal communication). Considering that there are roughly two ebb flow periods each day, the sludge discharge can be estimated at 1630 m^3/day. This discharge is added to the 4905 m^3/day of Nut Island effluent that is discharged continuously from the same outfall. Thus, the daily discharge of effluent is three times greater than the daily discharge of sludge. Furthermore, the effluent discharged from the three outfalls within Nantasket Roads is roughly 260 times greater than the daily sludge discharge at Long Island.

Significant variations in the time of the initial sludge discharge (relative to the beginning of the ebb) and the duration of the discharge (and, hence, the volume of sludge) are known to occur. For instance on October 30, the discharge began roughly 0.5 h after high water and continued for roughly 4 h. On October 31, the discharge began 1.25 h after high water and from field observations it appeared that the discharge of sludge (mixed with effluent) continued for roughly 5.25 h such that the last 0.5 h of the discharge was made during the incoming (flood) tide when the local flow was to the west. This suggests that sludge may occasionally be discharged on the incoming tide and carried into the Harbor in significant concentrations.

As described in Section 1, one of the main objectives of the present study was to track the Nut Island sludge plume within President Roads during the ebb cycle and longer, if the plume remains detectable. Tidal current charts predict strong eastward flow within President Roads and strong northward flow within the Narrows during the ebb tide, but information on small-scale flow variations in the vicinity of the sludge outfall and nearby shoals is lacking. Signell's model (Bothner *et al.,* 1990) provides good spatial and temporal resolution in this general vicinity, to the extent that variations in the intensity of northward flow of water across Nubble Shoal can be resolved. Resolving the detailed flow patterns around Nixes Mate Shoal may be beyond the capabilities of the model. For this reason, it was decided that additional direct observations of sludge plume advection and mixing were required to understand its effect upon the water quality of the Harbor. This Section presents results obtained from surveys conducted on October 30 and 31, 1990.

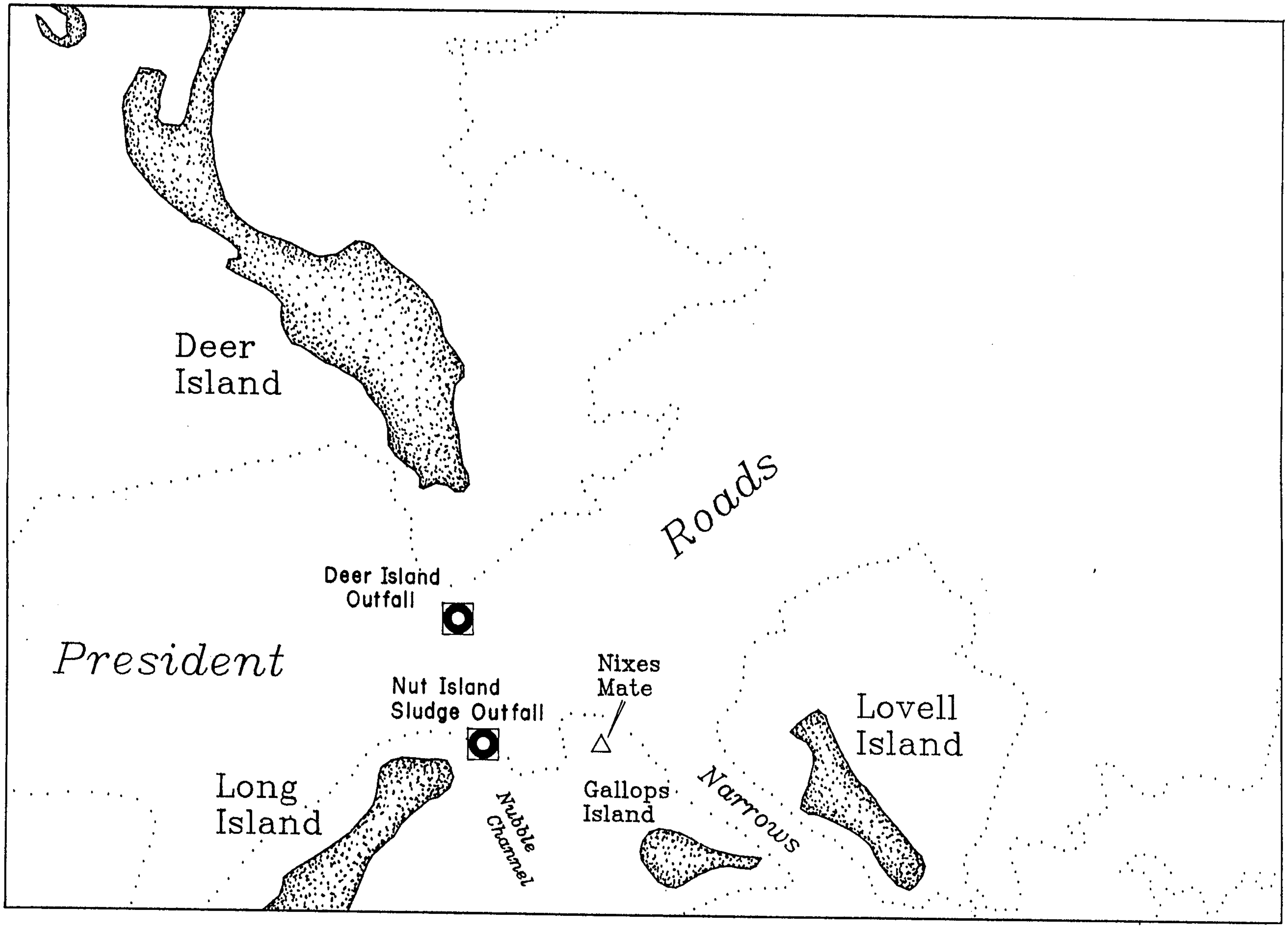

Figure 5-1. Map of President Roads, Showing the Location of the Deer Island Effluent Outfall and the Nut Island Sludge Outfall near Long Island

The field component of the Nut Island sludge plume surveys on both days consisted of the following surveying activities during daylight hours on the ebb tidal cycle.

1. Vertical and horizontal profiling of water properties within and around the sludge plume using the Mini-BOSS installed on the R/V *Surveysa*
2. Tracking of surface drifters released in the vicinity of the Nut Island sludge outfall using a second vessel, the R/V *Seaquest*

Details of the monitoring equipment and surveying techniques are given in Section 2. Note that chlorophyll fluorescence measurements were acquired with the Mini-BOSS during these two survey days.

On October 30, concurrent with field measurements of the sludge plume presented in this report, MWRA, MIT, and UMB conducted a dye study of the Nut Island sludge discharge. MIT was responsible for injecting Rhodamine dye into the sludge waste stream at the Nut Island treatment plant. UMB provided a technician aboard the R/V *Surveysa* for collection of water samples from within the sludge plume during the Mini-BOSS sampling operations. MIT and UMB were responsible for postsurvey analysis of dye concentration, total suspended solids, and dissolved and particulate metals concentrations within the water samples.

For the dye component of the field study, MIT provided a Turner fluorometer to measure the appropriate wavelength for Rhodamine WT dye fluorescence. Continuous, analog measurements of relative dye concentration were acquired in parallel with the standard Mini-BOSS sensors. The dye results in this report are uncalibrated as the intercomparison between onboard (Mini-BOSS) dye measurements and absolute dye concentrations determined analytically after the survey have yet to be conducted.

In summary, the specific objectives of the field surveys of the Nut Island sludge plume study were to

- Use the Mini-BOSS to track the effluent plumes during the ebb flow period on two consecutive days
- Deploy and track surface drifters to obtain direct observations of the flow regime at the time of the plume measurements
- On October 30 only, obtain continuous dye measurements with the Mini-BOSS and collect water samples for postsurvey analysis by MIT and UMB
- Use the field results to develop a conceptual model of the advection of the Nut Island sludge plume during the ebb flow period.

The results of the field surveys on October 30 and 31 are presented in Sections 5.2 and 5.3, respectively.

5.2 RESULTS FROM SURVEY ON OCTOBER 30, 1990

5.2.1 Drifter Results

Surface drifters of the configuration described in Section 2.4 were deployed at various times during the ebb tide on October 30 to obtain direct, Lagrangian current trajectory information for the surface currents in the vicinity of the Nut Island sludge outfall located at the northern tip of Long Island. The drifters were released from the two survey vessels near the outfall and tracked visually over the duration of the measurement period (roughly 0800 to 1600 h EST). The R/V *Seaquest* was dedicated to drifter tracking operations, whereas the R/V *Surveysa* was used primarily for Mini-BOSS surveying; the *Surveysa* assisted with drifter positioning when in close proximity to drifters during the conduct of the Mini-BOSS surveying. In Volume II, Appendix A, tables of time and position for each drifter fix are given for each drifter tracked; calculated drifter speed and distance between fixes are also provided.

Winds on October 30 were mild, ranging from 8 to 12 kn, with directions changing from northwesterly in the morning to southwesterly in the afternoon. The time of the predicted high tide was 0739 h EST.

Figure 5-2 presents the trajectories of two drifters released at the Nut Island outfall 13 min after high water on October 30. Both drifters moved eastward at a speed of roughly 25 cm/s until they reached the vicinity of the shoal at Nixes Mate, where they both remained for the duration of the ebb cycle (a period of over 5 h). Drifter P was eventually lost in the breakers, but, at the beginning of the incoming tide, drifter I moved southward within the Narrows at speeds of 10 to 25 cm/s until it was recovered at roughly 1.5 h after low water.

Figures 5-3 through 5-5 present trajectories of three-drifter clusters that were released at the Nut Island outfall at 0 h 41 min, 1 h 41 min, and 2 h 42 min after high water, respectively. All of these drifters initially moved eastward to Nixes Mate shoal at speeds of 20 to 30 cm/s. The majority (seven of nine) of these drifters continued eastward across the Narrows and remained in the vicinity of the shoals around Lovell Island until the beginning of the incoming tide.

Overall, the trajectories of the 11 drifters presented in Figures 5-2 through 5-5 reveal that

- The drifters released from the Nut Island sludge outfall during the first 3 h of the ebb neither entered South Channel nor exited the Harbor during the period of observations.

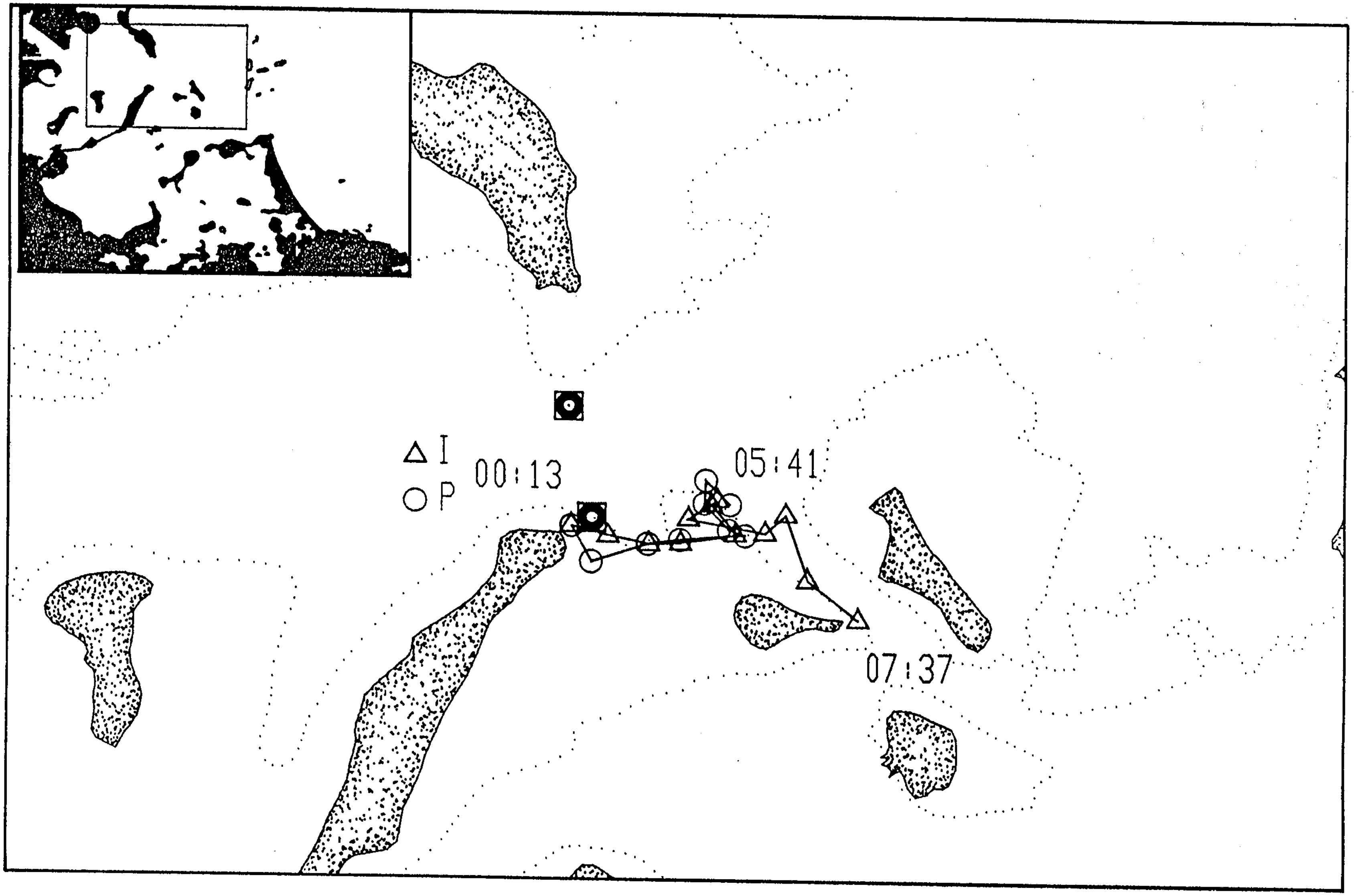

Figure 5-2. Trajectories of Two Drifters Released within President Roads in the Morning of October 30, 1990

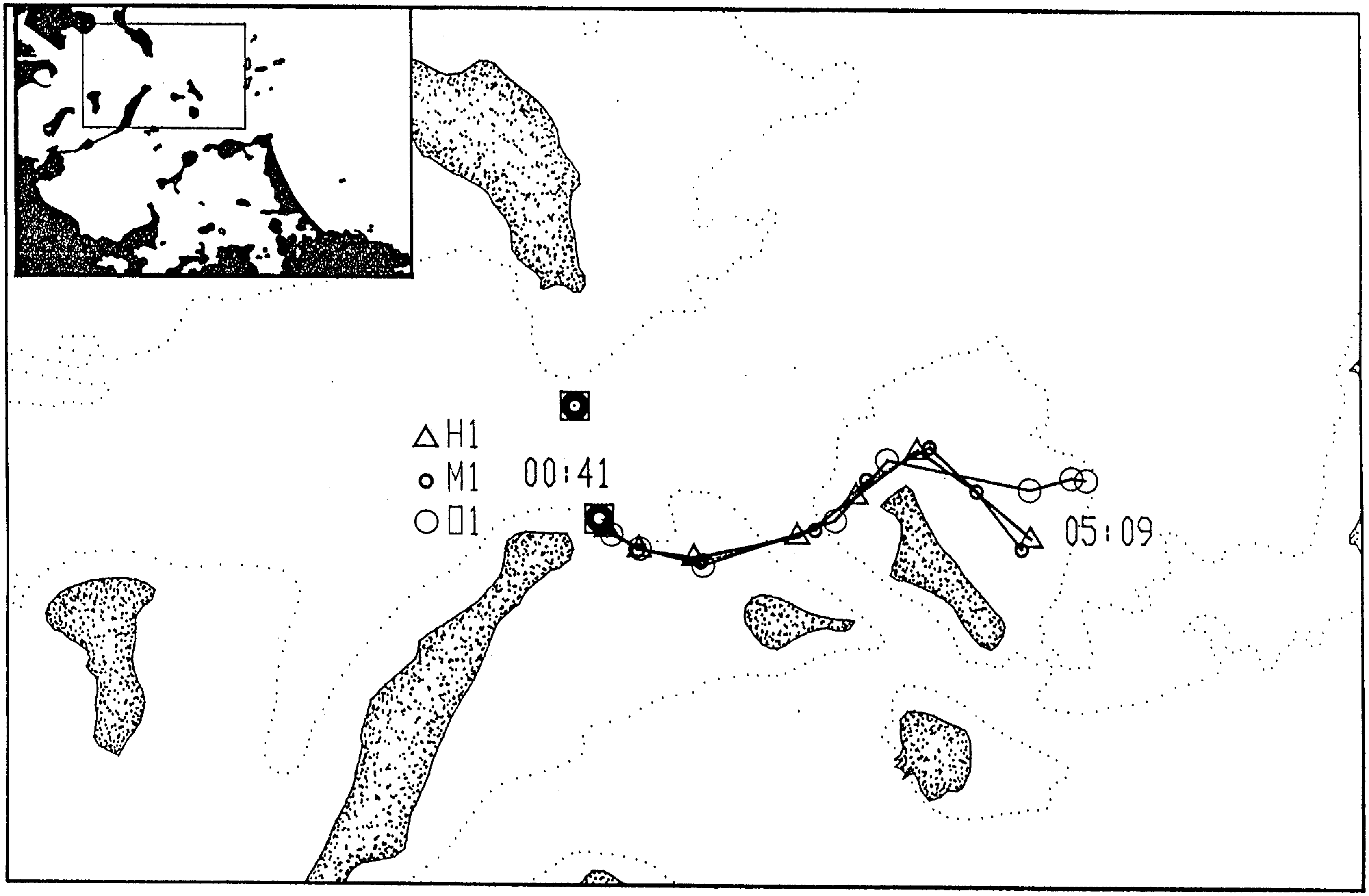

Figure 5-3. Trajectories of Three Drifters Released within President Roads in the Morning of October 30, 1990

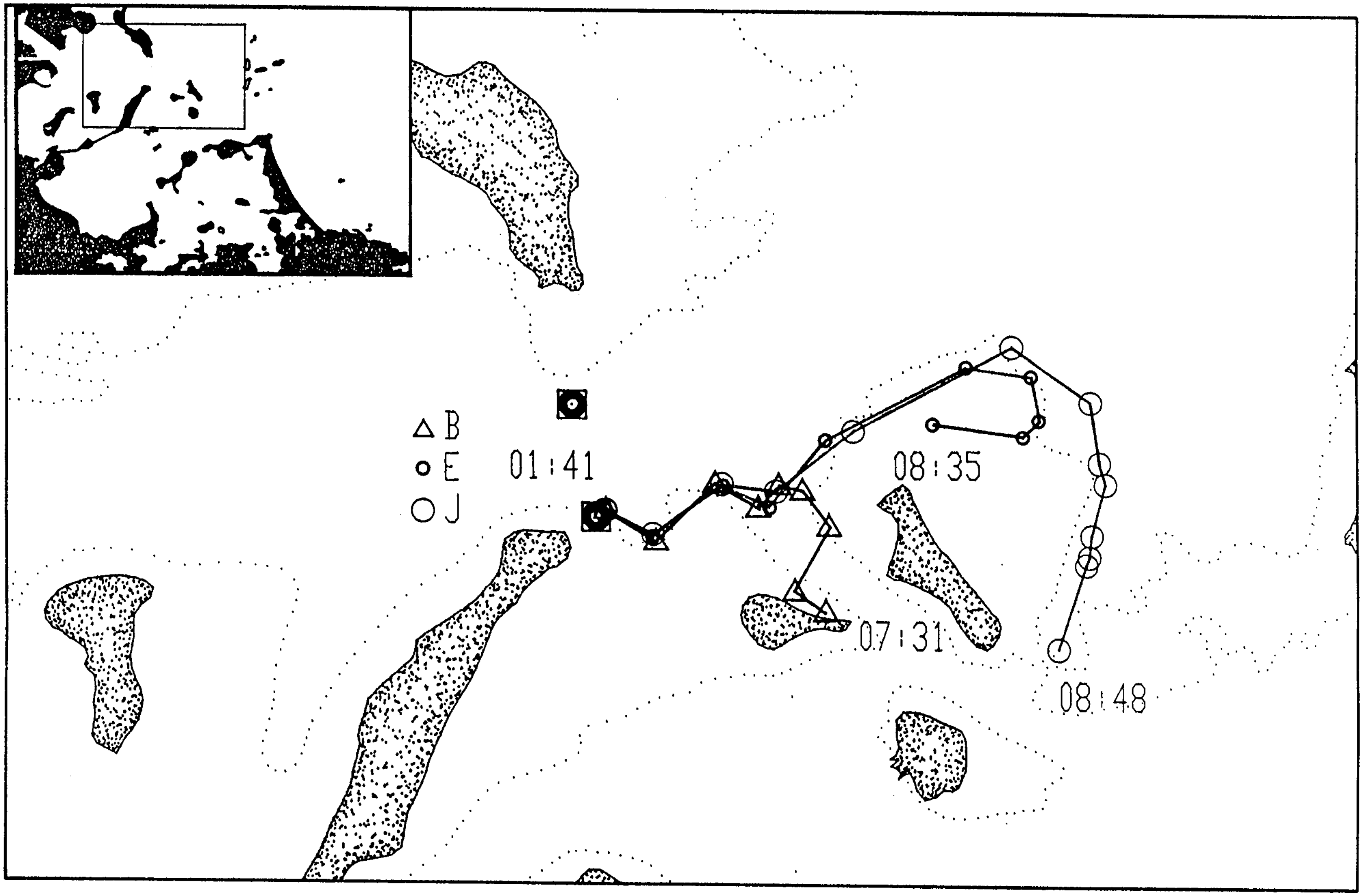

Figure 5-4. Trajectories of Three Drifters Released within President Roads in the Morning of October 30, 1990

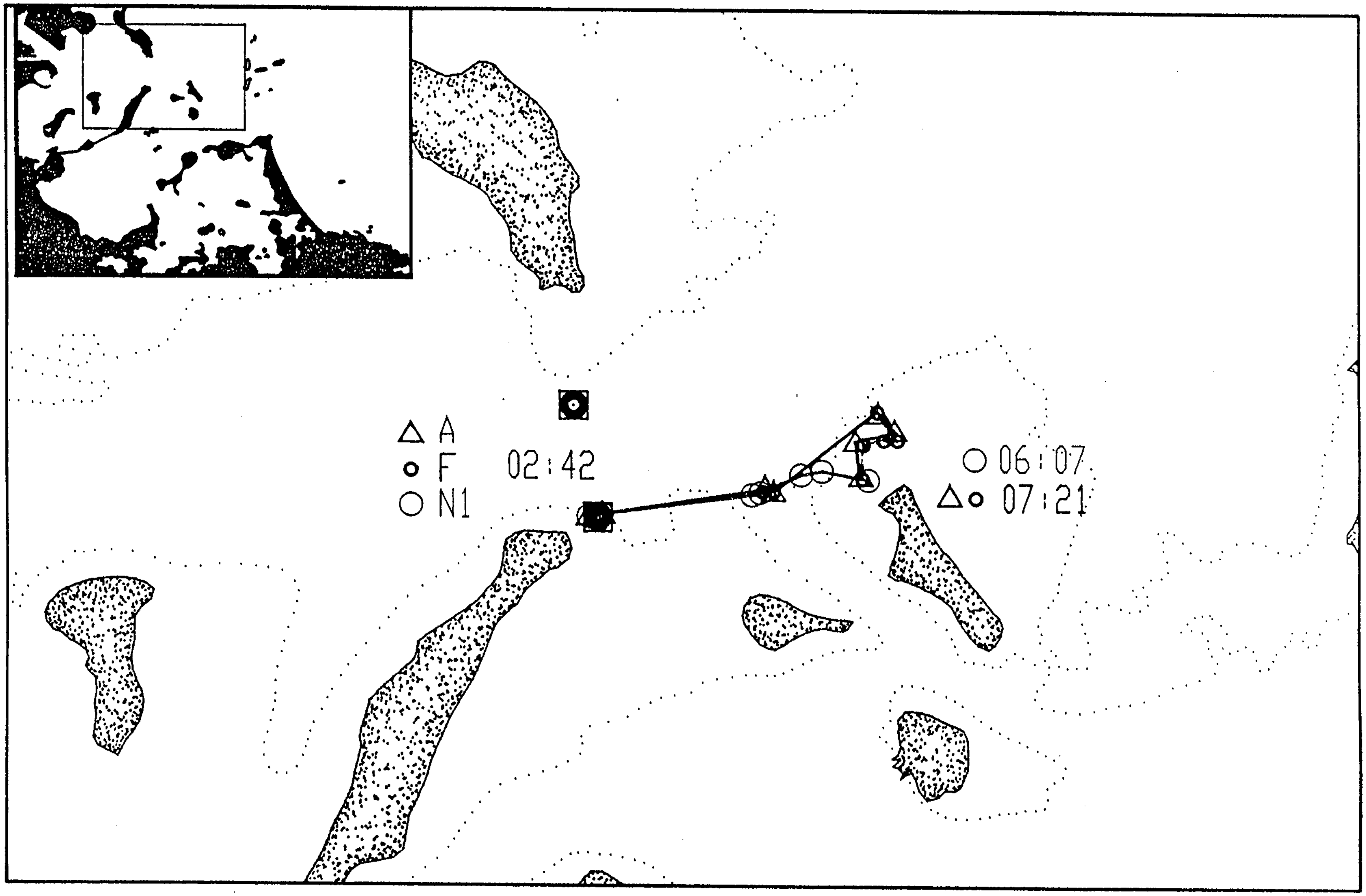

Figure 5-5. Trajectories of Three Drifters Released within President Roads in the Morning of October 30, 1990

- Three of the 11 drifters became trapped in a stagnant-flow region on the east side of Nixes Mate for the duration of the ebb period.
- The remaining eight drifters remained on the shoals around Lovell Island until the beginning of the flood period, when they were advected to the west or south.

Trajectories from five additional drifters that were released in this same general vicinity during the flood tide on October 16, 1990, are presented in Volume II, Appendix A; tables giving the time, position, and calculated speed and direction for each drifter fix are also presented in Appendix A. The drifters released on the west side of Nixes Mate during the flood tide demonstrate that this localized region is relatively stagnant, although the southward flow through the Narrows was quite strong.

5.2.2 Plume Tracking Results

As discussed in Section 5.1, the primary survey objective on October 30 was to obtain information on the lateral spreading and advection of the Nut Island sludge plume emanating from the outfall located at the northern tip of Long Island. Survey operations were similar to those on October 16 and 17, with near-continual towing of the Mini-BOSS sensor package at a depth of roughly 2 m below the surface. Selection of transect locations was made on a real-time basis by the scientist aboard the vessel, using the information from the real-time graphic display of water-property data and vessel position provided by the Mini-BOSS. Vertical profiles were also made to determine the vertical structure of water properties from the surface to the seafloor.

During the period from roughly 0800 to 1420 h EST on October 17, water-property measurements were made along 26 horizontal transects and at nine vertical-profile stations, using the Mini-BOSS. Table 5-1 presents the time and location of each of the Mini-BOSS transects and the vertical-profile stations. Figure 5-6 presents a detailed chart of the study area within President Roads, with superimposed tracks representing the horizontal transects. As indicated, the majority of the transects were located in the vicinity of the Nut Island sludge outfall north of Long Island and in President Roads near the northern end of the Narrows. The Deer Island effluent outfall is also indicated in Figure 5-6, on the north side of President Roads.

Figure 5-7 presents a detailed chart of President Roads with the locations of survey vessel tracks representing horizontal transects 3 and 7 (data files MWRA2003 and MWRA2007) made on October 30. Transect 3, made at 0807 h EST, began northeast of the Deer Island outfall and extended southward to the Nut Island sludge outfall. Figure 5-8 presents a time-series plot of water-property data acquired along transect 3. Near the beginning of this tran-

Table 5-1. Time and Location of Horizontal Transects (Tows) and Vertical Profiles Made on October 30, 1990

File Number	File Type	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Start Position		End Position	
				Lat(N)	Long(W)	Lat(N)	Long(W)
MWRA2003	Tow	08:07:17	08:19:44	42°20.35′	70°57.07′	42°19.91′	70°57.19′
MWRA2004	Profile	08:19:59	08:21:09	42°19.92′	70°57.18′	42°19.91′	70°57.18′
MWRA2005	Tow	08:23:03	08:37:10	42°19.91′	70°57.11′	42°19.89′	70°57.17′
MWRA2007	Tow	08:39:57	08:44:34	42°19.92′	70°57.24′	42°19.78′	70°56.96′
MWRA2008	Tow	08:44:38	08:47:34	42°19.75′	70°56.94′	42°19.90′	70°56.79′
MWRA2010	Tow	08:51:32	08:54:32	42°19.77′	70°57.03′	42°19.93′	70°57.01′
MWRA2011	Tow	08:54:37	08:57:20	42°19.96′	70°57.04′	42°19.91′	70°57.19′
MWRA2012	Tow	08:57:25	09:05:53	42°19.92′	70°57.20′	42°19.91′	70°57.14′
MWRA2013	Profile	09:06:12	09:07:13	42°19.91′	70°57.11′	42°19.91′	70°57.11′
MWRA2015	Tow	09:11:43	09:15:44	42°19.98′	70°56.96′	42°19.87′	70°57.10′
MWRA2017	Tow	09:19:46	09:21:52	42°19.90′	70°56.90′	42°19.97′	70°56.87′
MWRA2018	Tow	09:21:57	09:27:08	42°19.99′	70°56.89′	42°19.88′	70°57.09′
MWRA2019	Tow	09:27:13	09:29:57	42°19.86′	70°57.13′	42°19.93′	70°57.18′
MWRA2025	Profile	09:57:15	09:58:24	42°19.97′	70°57.04′	42°19.96′	70°57.04′
MWRA2026	Tow	09:58:55	10:01:15	42°19.97′	70°57.05′	42°19.93′	70°56.94′
MWRA2027	Profile	10:01:47	10:03:19	42°19.95′	70°56.96′	42°19.95′	70°56.96′
MWRA2028	Profile	10:04:10	10:05:37	42°19.94′	70°56.93′	42°19.94′	70°56.94′
MWRA2030	Tow	10:10:20	10:15:17	42°19.97′	70°56.94′	42°20.09′	70°56.73′
MWRA2031	Tow	10:15:21	10:18:18	42°20.10′	70°56.69′	42°19.99′	70°56.60′
MWRA2032	Tow	10:18:21	10:23:36	42°19.97′	70°56.59′	42°19.98′	70°56.28′
MWRA2033	Tow	10:23:41	10:28:36	42°19.98′	70°56.24′	42°20.17′	70°56.30′
MWRA2034	Tow	10:28:41	10:37:58	42°20.18′	70°56.29′	42°19.98′	70°56.60′
MWRA2036	Tow	10:39:25	10:47:16	42°19.99′	70°56.52′	42°20.33′	70°56.50′
MWRA2037	Profile	10:47:30	10:49:20	42°20.34′	70°56.49′	42°20.34′	70°56.50′
MWRA2039	Tow	10:52:25	11:01:18	42°20.33′	70°56.49′	42°20.19′	70°56.41′
MWRA2041	Tow	11:08:47	11:22:46	42°20.18′	70°56.29′	42°20.09′	70°56.13′
MWRA2042	Tow	11:22:49	11:45:32	42°20.07′	70°56.13′	42°20.97′	70°56.60′
MWRA2044	Tow	12:16:49	12:29:52	42°20.38′	70°55.33′	42°20.81′	70°55.52′
MWRA2045	Tow	12:29:57	12:46:12	42°20.82′	70°55.54′	42°20.30′	70°55.86′

Table 5-1. Time and Location of Horizontal Transects (Tows) and Vertical Profiles Made on October 30, 1990 (continued)

File Number	File Type	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Start Position		End Position	
				Lat(N)	Long(W)	Lat(N)	Long(W)
MWRA2046	Tow	12:46:17	13:08:06	42°20.31′	70°55.87′	42°20.00′	70°56.62′
MWRA2057	Tow	13:52:21	14:04:36	42°19.99′	70°56.56′	42°19.93′	70°57.12′
MWRA2058	Profile	14:04:58	14:06:18	42°19.93′	70°57.16′	42°19.94′	70°57.14′
MWRA2060	Profile	14:09:24	14:10:36	42°19.88′	70°57.08′	42°19.87′	70°57.09′
MWRA2061	Tow	14:11:28	14:15:01	42°19.87′	70°57.06′	42°19.86′	70°56.91′
MWRA2062	Profile	14:15:06	14:16:19	42°19.87′	70°56.89′	42°19.87′	70°56.88′

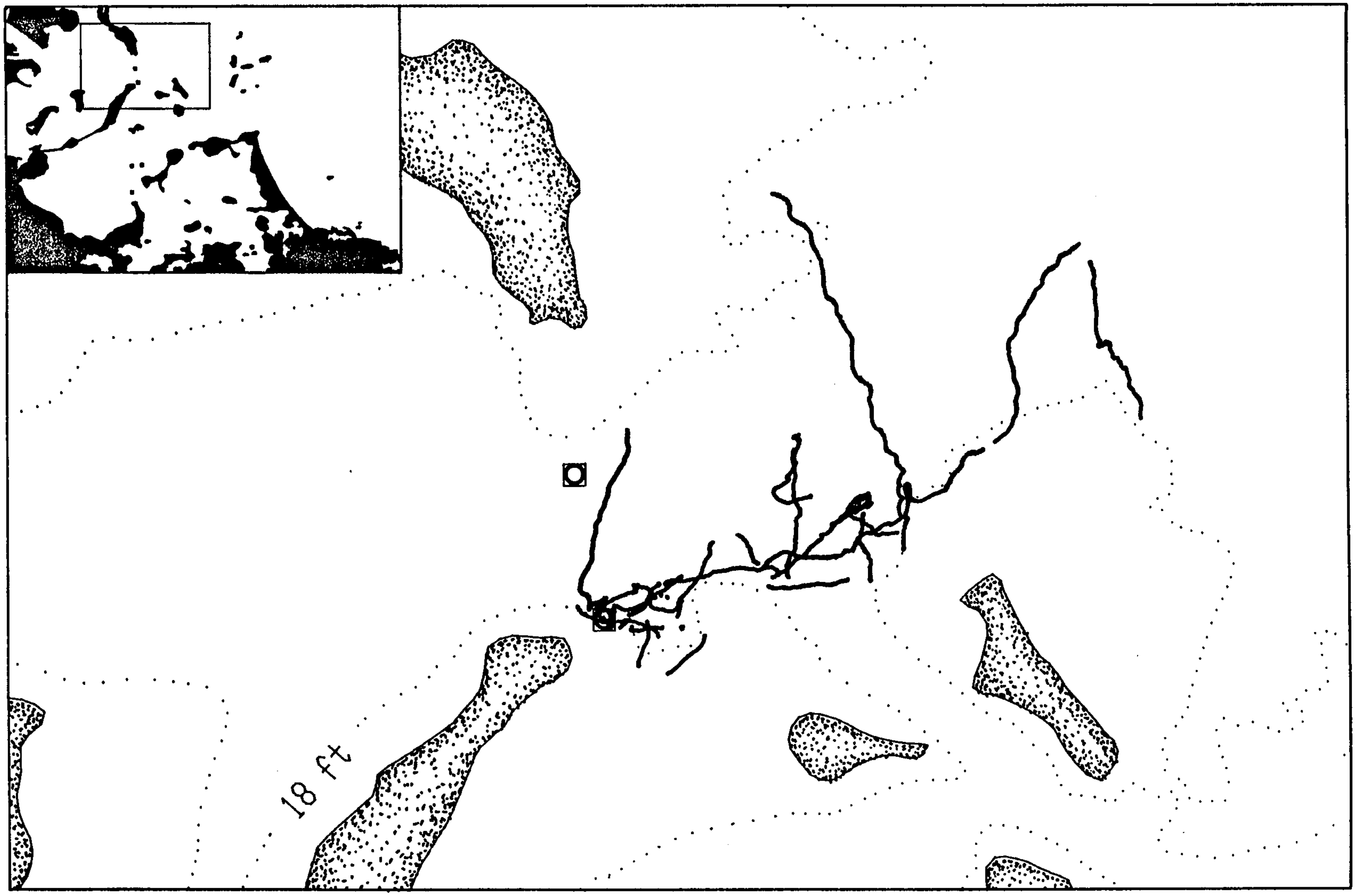

Figure 5-6. Location of Horizontal Transects Made on October 30, 1990

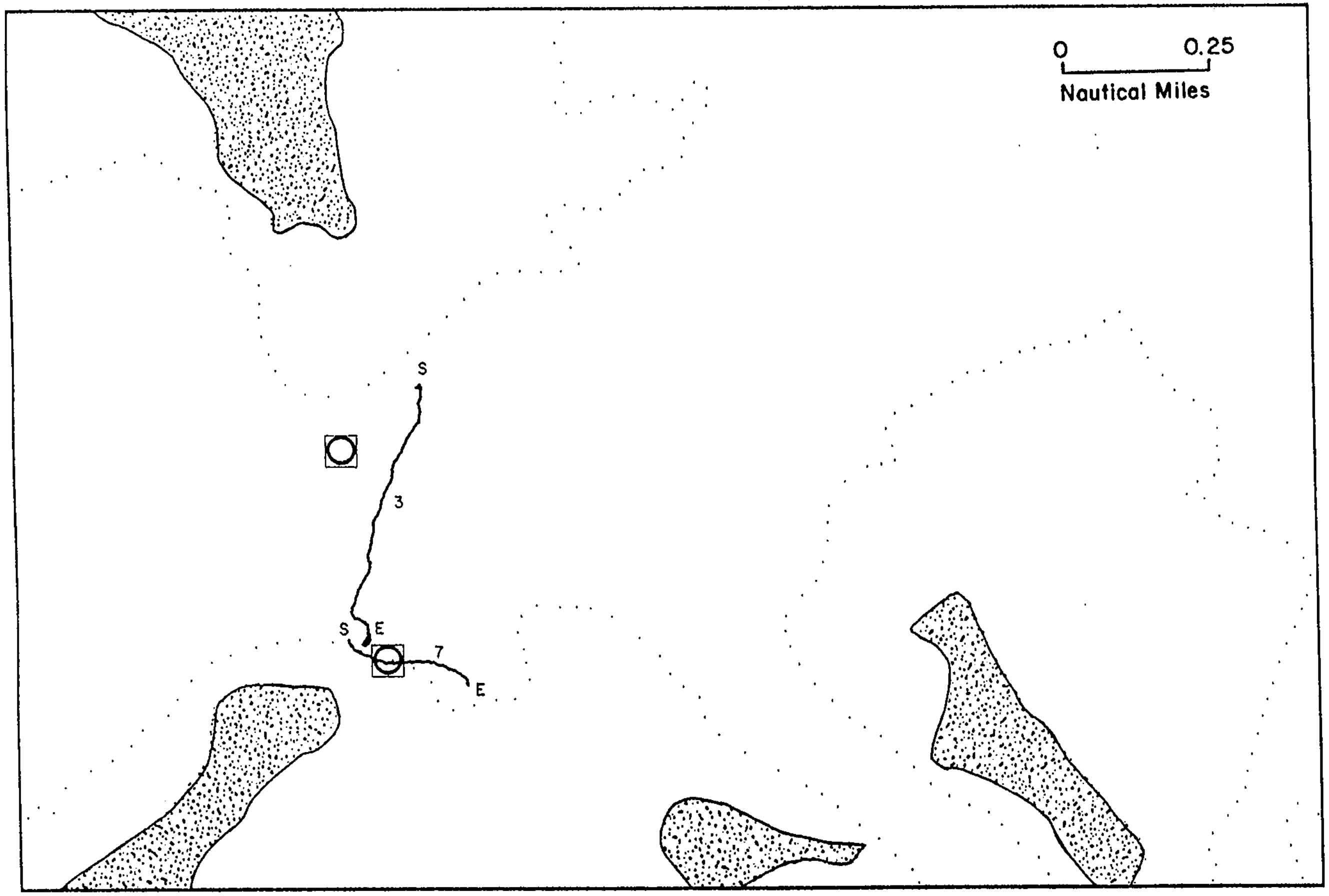

Figure 5-7. Expanded Map of President Roads (near Long Island) Showing Location of Deer Island and Nut Island Outfalls and Transects 3 and 7 Made on October 30, 1990. Start and End Positions of Transects Are Indicated by S and E, Respectively.

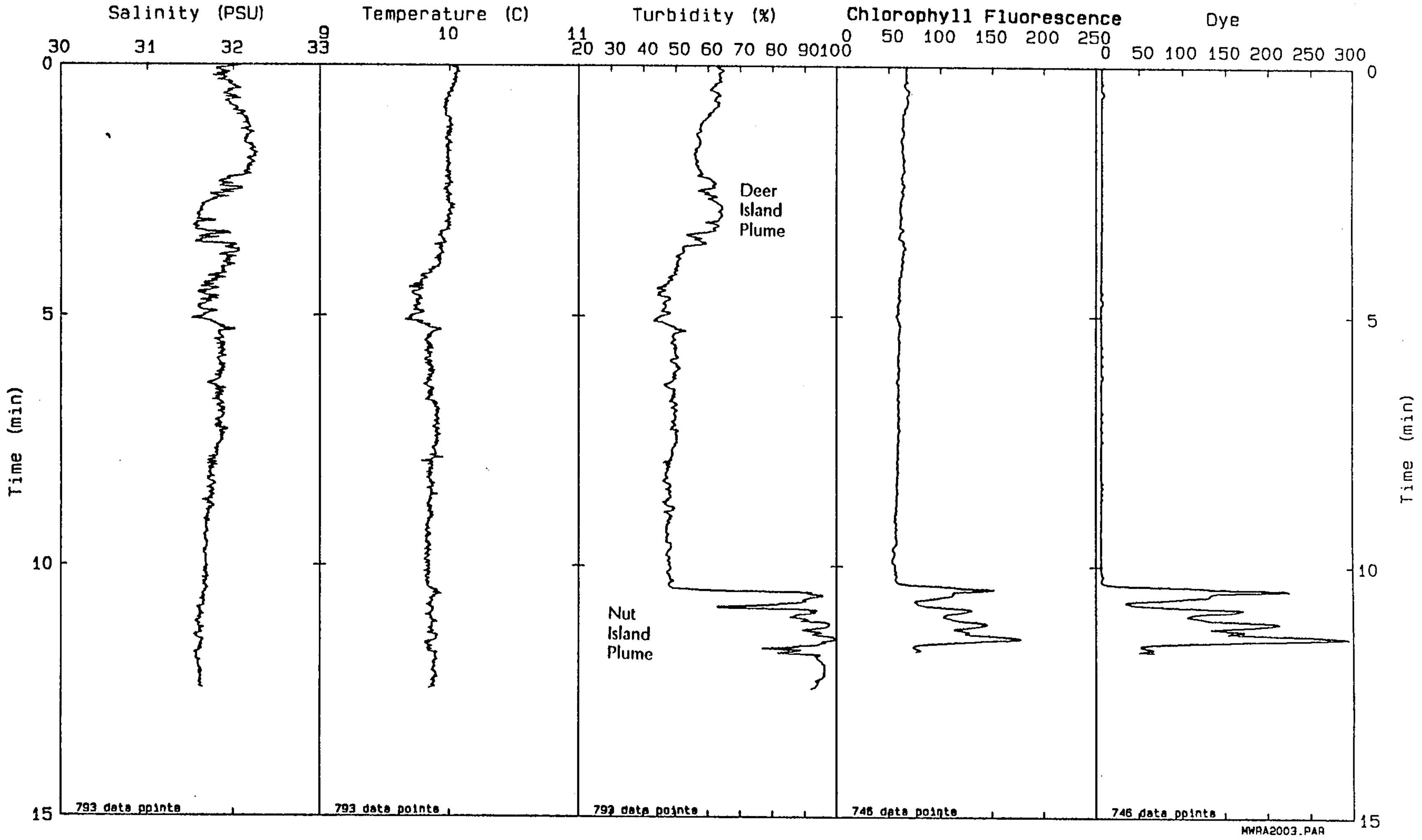

Figure 5-8. Time-Series Plot of Data Acquired along Transect 3 Made on October 30, 1990

sect, relatively high turbidities corresponding to reduced salinities were due to the Deer Island effluent plume. At the end of the transect, the vessel entered the Nut Island sludge plume, which exhibited high values of turbidity, fluorescence, and dye (injected by MIT at the Nut Island treatment plant). Due to the relatively small discharge rates of the Nut Island sludge outfall, there was no apparent decrease in near-surface salinities associated with the sludge plume.

Figure 5-9 presents temperature/salinity (T/S), turbidity/salinity (Tu/S), and turbidity/chlorophyll fluorescence (Tu/Chl) scatter plots of the data acquired along transect 3. Note that these plots are similar to those used in Section 3 for presentation of the Boston Harbor background water properties monitored on November 1. From the Tu/S scatter plot in Figure 5-9, it is easy to distinguish the high turbidity (>80% light extinction) of the Nut Island sludge plume from the other water types encountered along this transect. The Deer Island effluent plume and the high-salinity Massachusetts Bay-derived waters have intermediate (~60% to 65%) turbidities, whereas the waters within President Roads channel had the lowest turbidities along the transect. The T/S properties within the individual plumes were not significantly different from the adjacent water types.

The Tu/Chl scatter plot presented in Figure 5-9 illustrates that, within the Nut Island sludge plume, chlorophyll fluorescence values were high and extremely variable. Determining the correlation, if any, between the observed chlorophyll fluorescence and turbidity levels within the Nut Island sludge plume is beyond the scope of the present study, but it may warrant further investigation.

Figure 5-10 presents a time-series plot of water-property data acquired along transect 7 (see Figure 5-7 for location). This relatively linear transect passed over the Nut Island sludge outfall (at roughly 2 min along the transect) and one edge of the plume located farther to the east (note that clear water was situated between the outfall and the portion of the plume detected). Where the Nut Island sludge was evident from elevated levels of turbidity, chlorophyll fluorescence, and dye, there was no large effect evidenced by the local temperature or salinity. One would expect the continual discharge of effluent from the outfall to freshen the surface waters in close proximity to the outfall, but inspection of the salinity data from transects 3 and 7 shows fairly consistent background salinities within the southern portion of President Roads and near Long Island. Hence, the lack of a large salinity deficit at the outfall suggests high dilutions of the sludge and effluent. For example, for the observed salinity deficit of <0.1 PSU, the effluent and sludge would have been diluted with background waters by the ratio of at least 300:1.

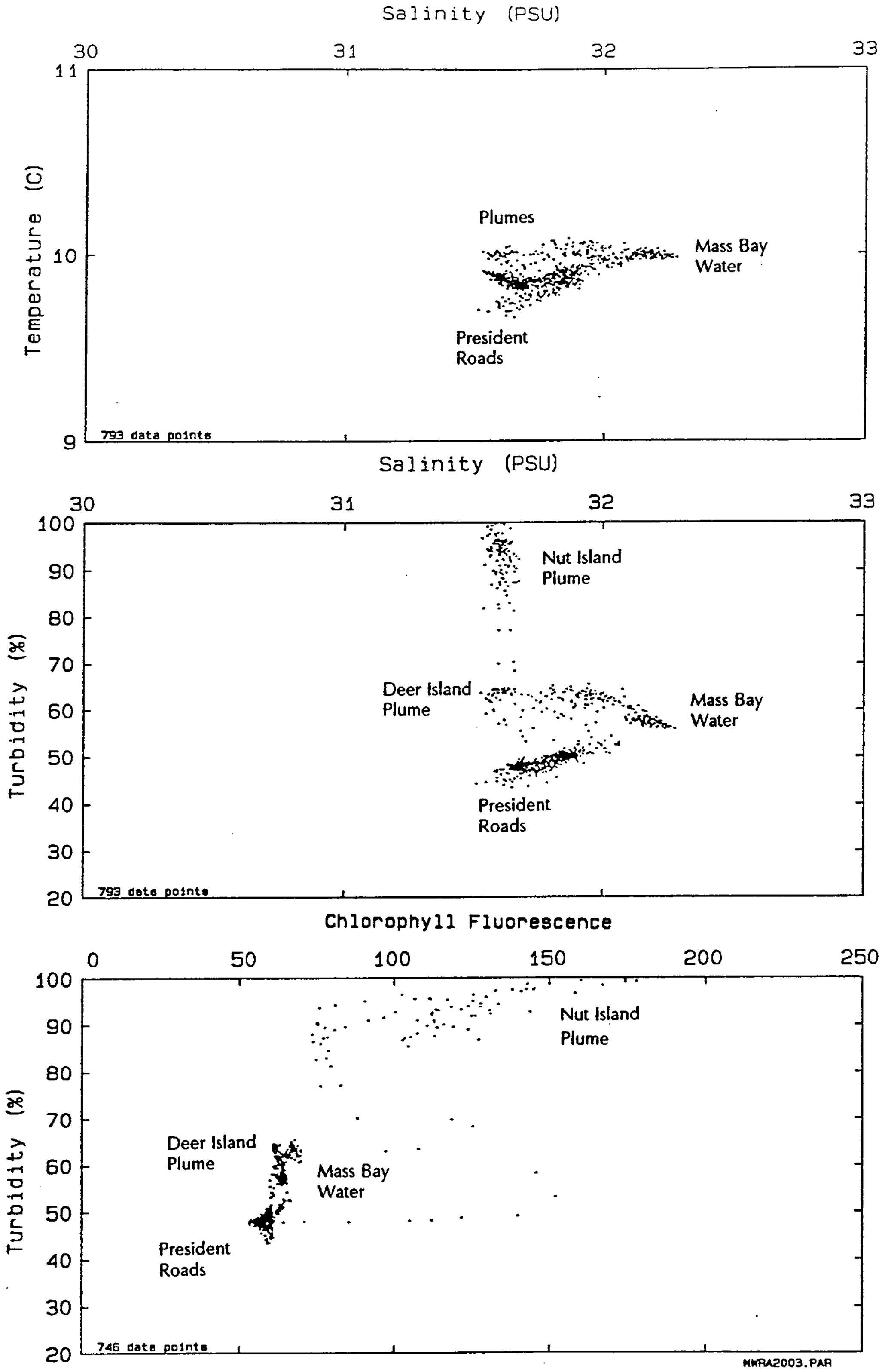

Figure 5-9. Scatter Plot of Data Acquired along Transect 3 Made on October 30, 1990

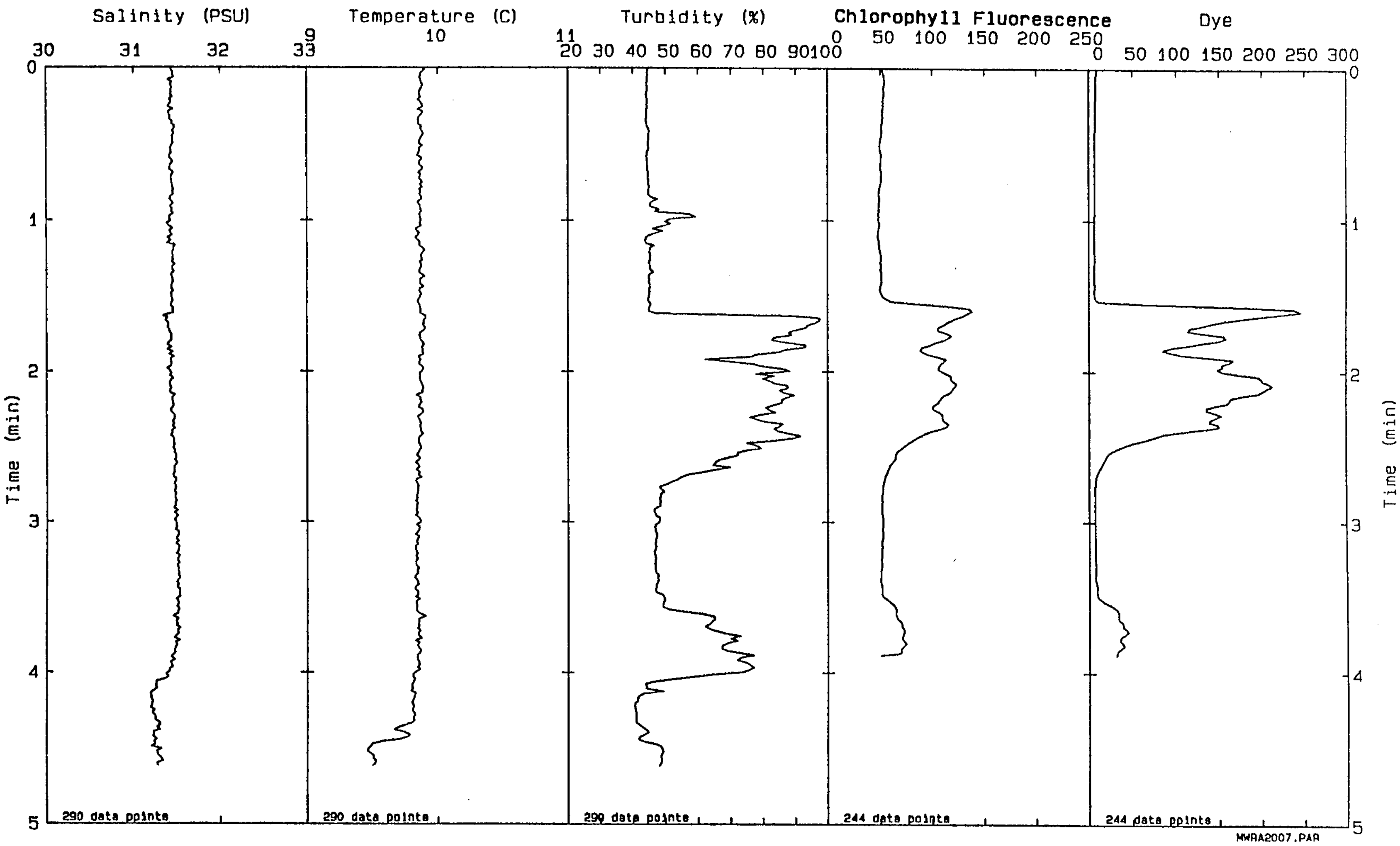

Figure 5-10. Time-Series Plot of Data Acquired along Transect 7 Made on October 30, 1990

The Tu/S scatter plot of data from transect 7 (Figure 5-11) provides clear delineation between the sludge plume, and the relatively low turbidity of the water within President Roads. Again, the high chlorophyll fluorescence values were roughly correlated with the high turbidities within the plume.

Figure 5-12 presents a chart of President Roads with the location of transect 18 (data file MWRA2018) made at 0921 h EST on October 30 (roughly 1 h 14 min after transect 3). This short transect, extending from northeast to southwest, crossed two portions of the Nut Island sludge plume, as illustrated in the time-series plot of Figure 5-13. Turbidity levels on these two crossings were still high and reasonably well correlated with chlorophyll fluorescence, as illustrated in the Tu/Chl scatter plot shown in Figure 5-14.

Further analysis of the water-property data from the numerous transects and profiles made on October 30 leads to a conceptual picture of the behavior of the Nut Island sludge plume during the ebb flow. As discussed in Section 5.2.3, the sludge plume did not remain as a continuous, linear plume that extended eastward past the Narrows and into South Channel to eventually leave the Harbor on the ebb flow. In fact, the data suggest that the plume was dispersed locally by strong flows from multiple directions. This conclusion was based upon monitoring both the nearfield behavior of the plume (in the vicinity of the outfall) and the farfield water properties (and/or evidence of sludge) at the northern end of the Narrows and within the western end of South Channel.

Figure 5-15 indicates the location of transects 42 and 46, which were part of the farfield transects made over a broad portion of the study area. Transect 42, which extended from the shoal north of Lovell Island to the shoals east of Deer Island, was made to detect any Nut Island sludge entering South Channel, but the highest turbidities along the transect (Figure 5-16) were associated with the Deer Island effluent plume at the northern end of the transect. Careful analysis of the Tu/S scatter plot data from transect 42 (Figure 5-17) reveals only a very small, dilute remnant of the Nut Island sludge plume; other water types from the Narrows, the Deer Island effluent plume, and President Roads are uniquely identified in the Tu/S plot. A tight correlation between chlorophyll fluorescence and turbidity within the Deer Island effluent plume is also evident in Figure 5-17. Note that the high chlorophyll fluorescence values could have been caused by apparent fluorescence of the particulate matter in the effluent rather than by fluorescence of biological material.

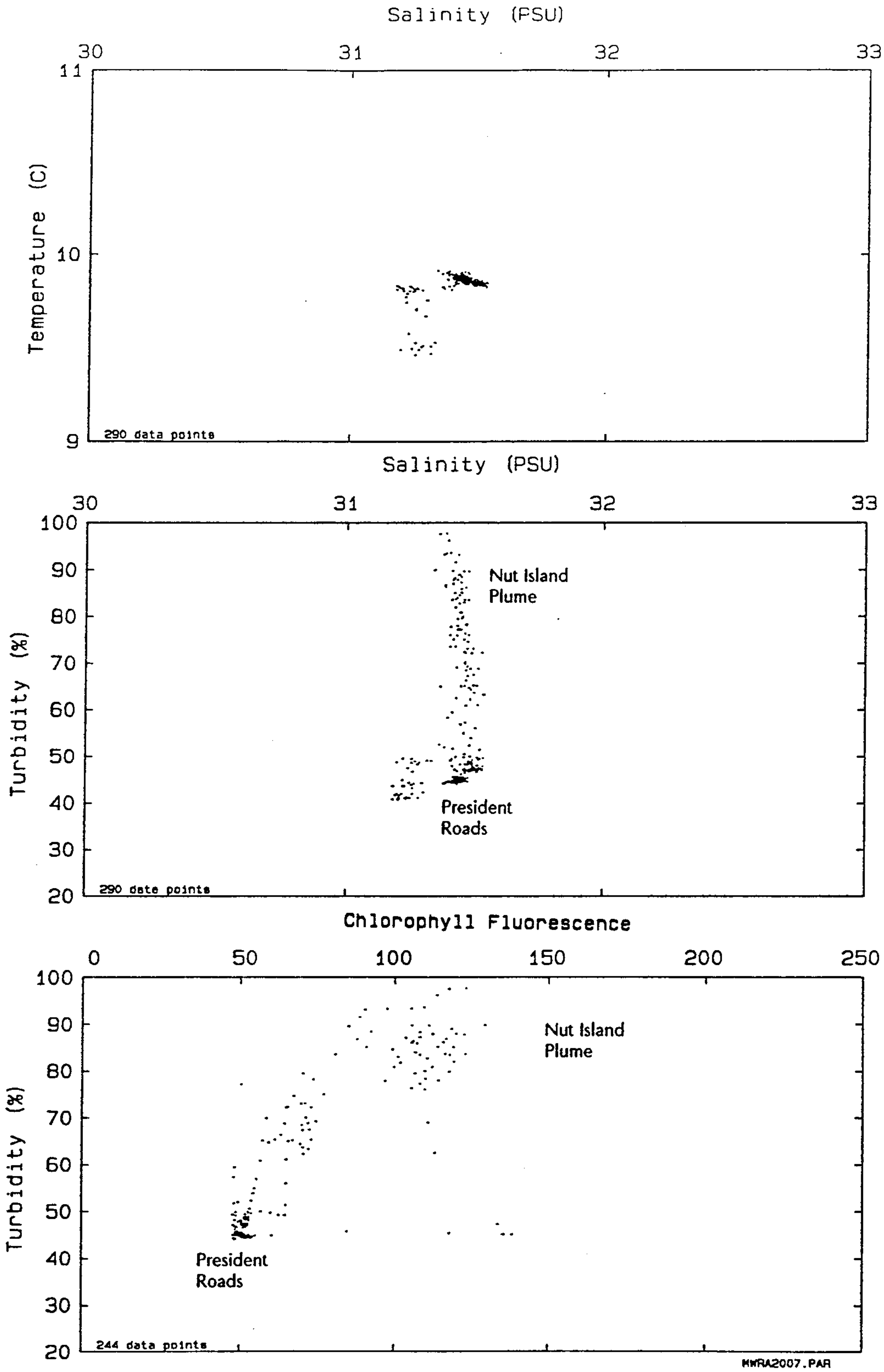

Figure 5-11. Scatter Plot of Data Acquired along Transect 7 Made on October 30, 1990

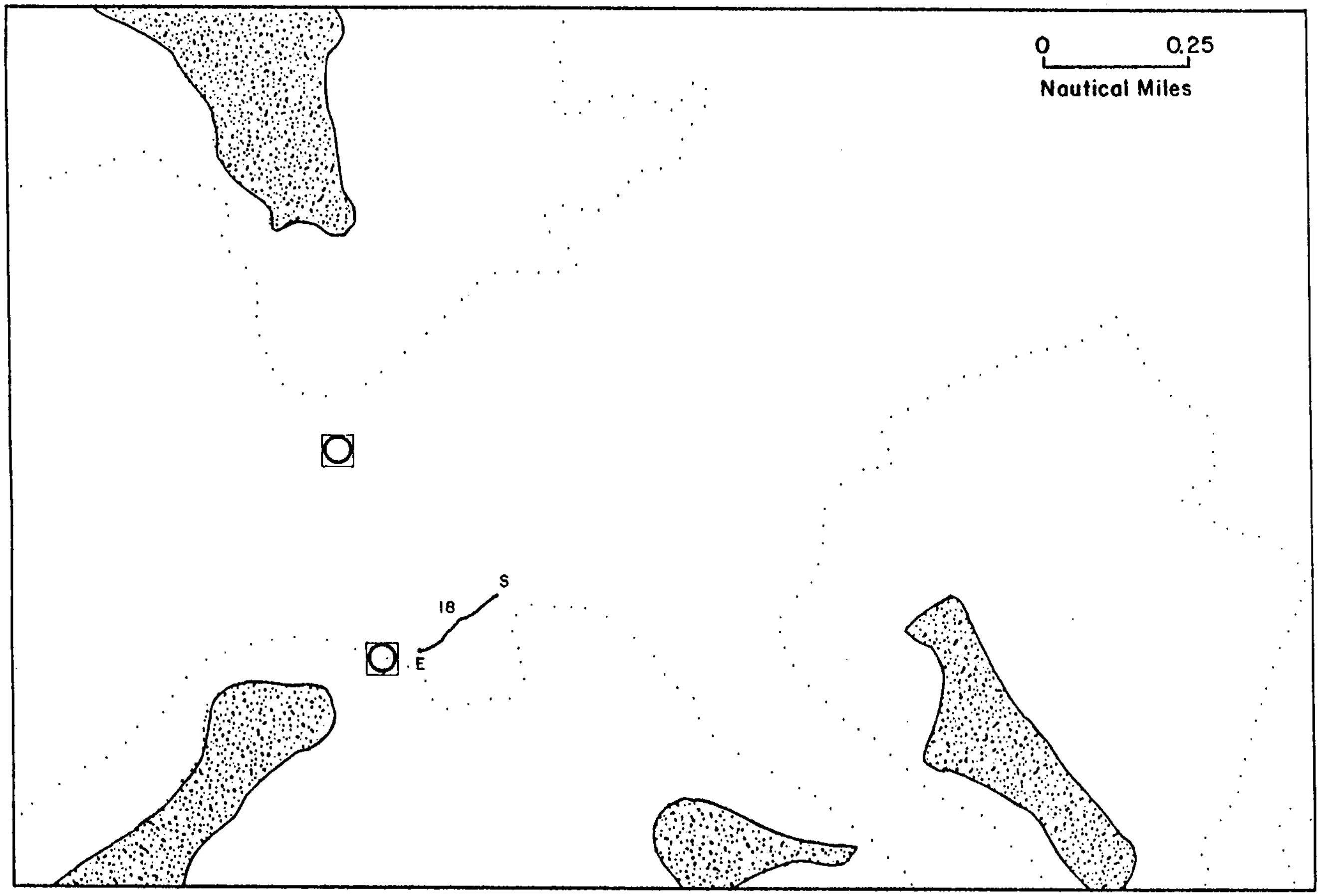

Figure 5-12. Expanded Map of President Roads Showing Location of Transect 18 on October 30, 1990

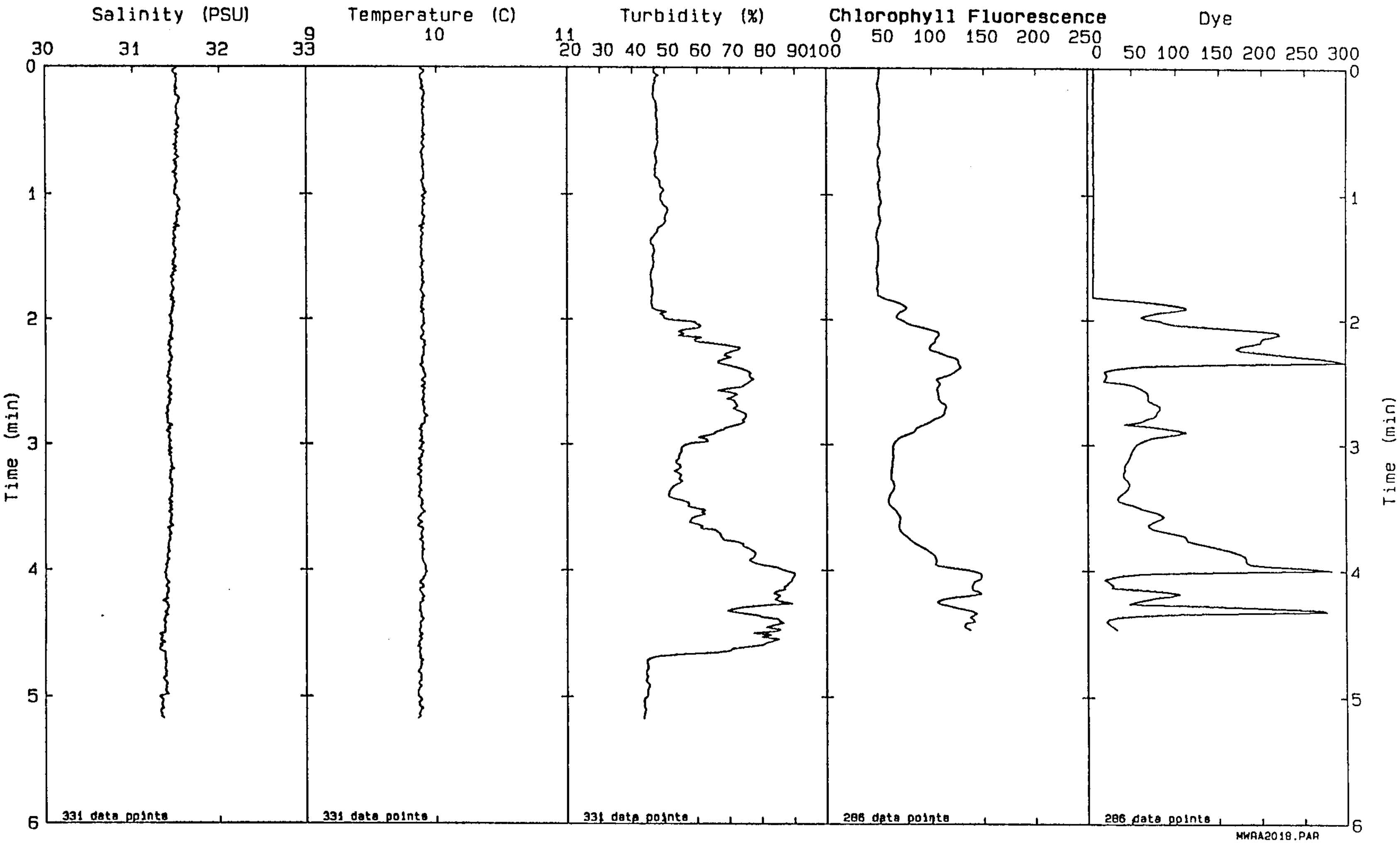

Figure 5-13. Time-Series Plot of Data Acquired along Transect 18 Made on October 30, 1990

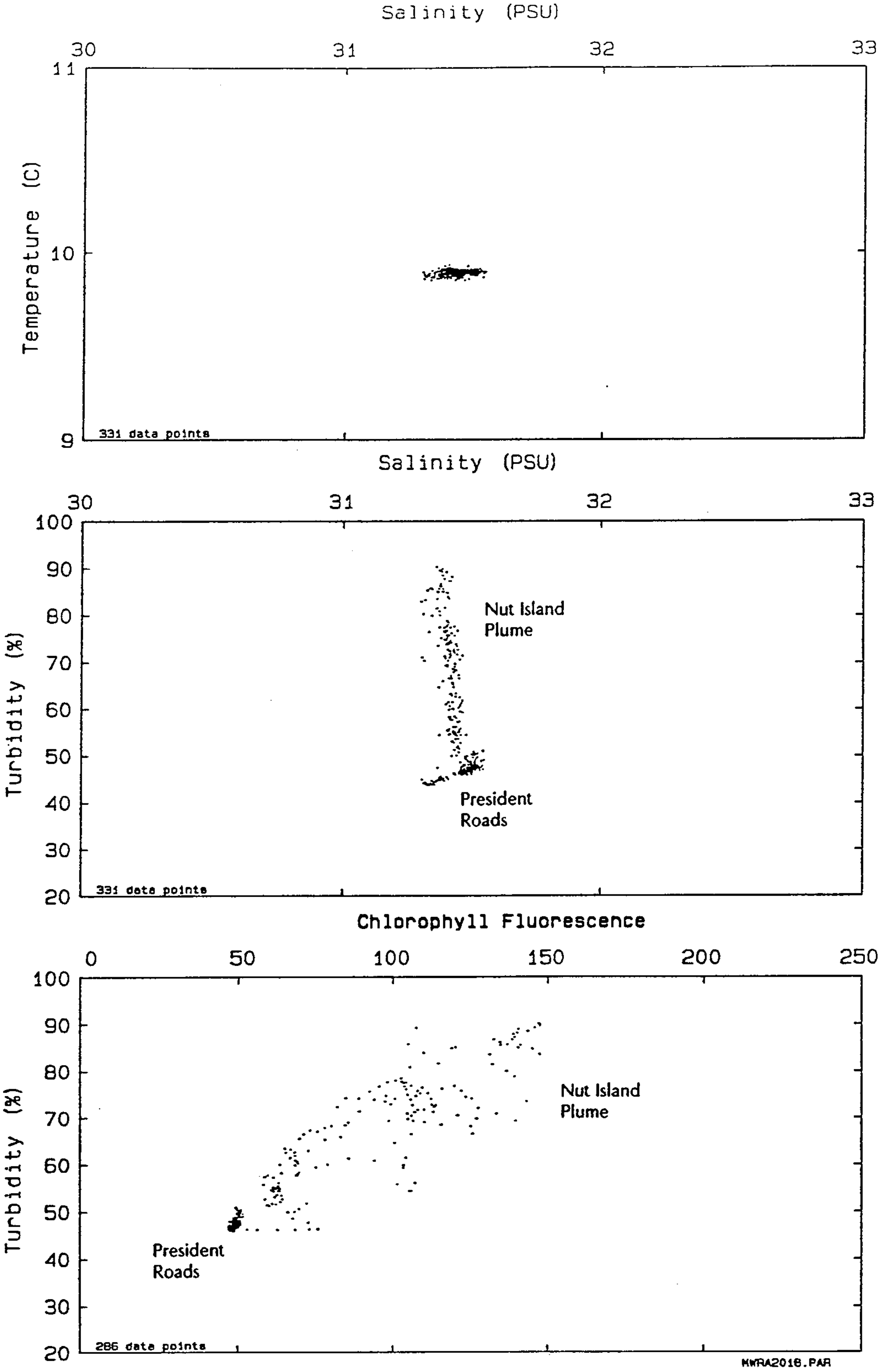

Figure 5-14. Scatter Plot of Data Acquired along Transect 18 Made on October 30, 1990

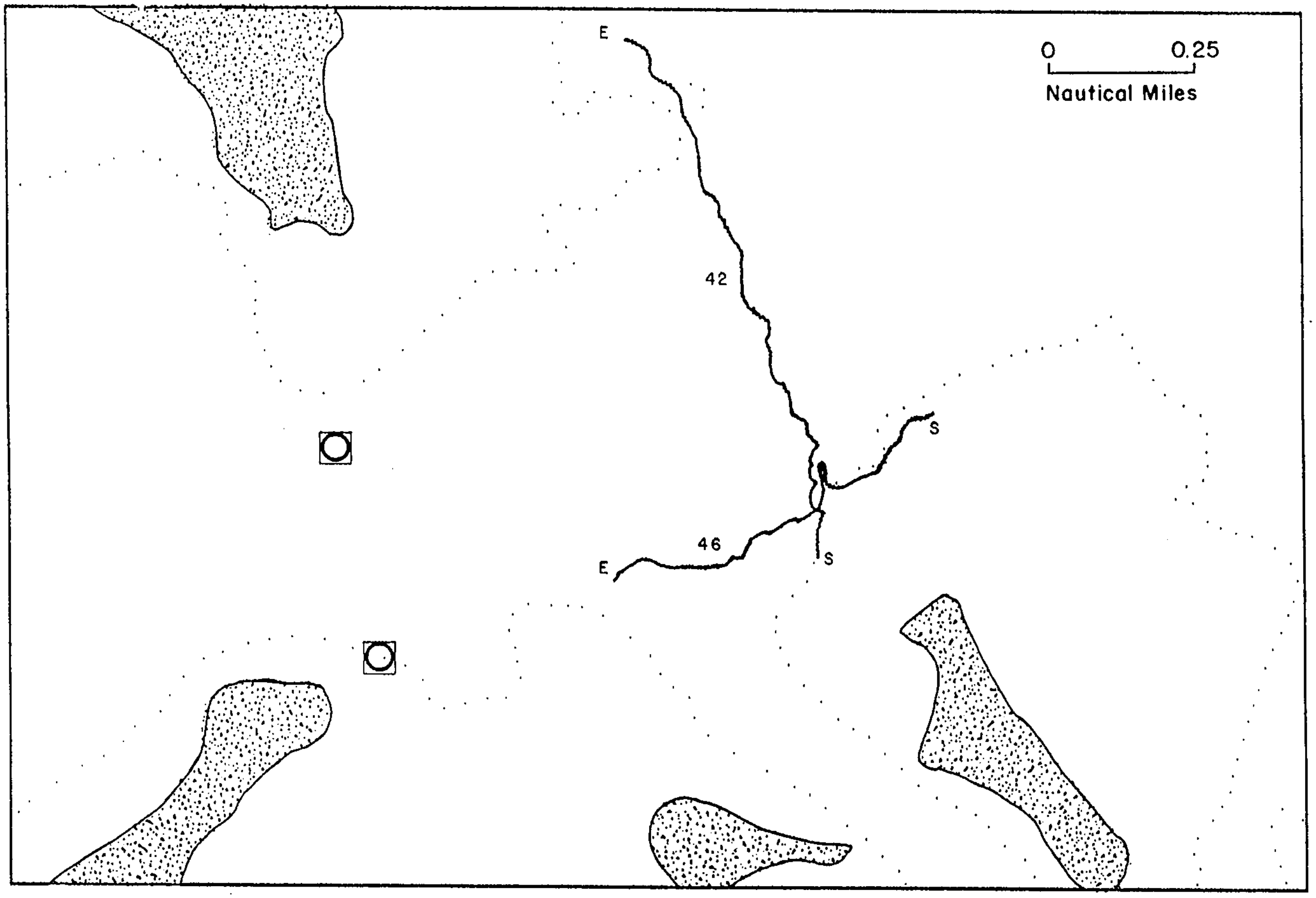

Figure 5-15. Expanded Map of President Roads Showing Location of Transects 42 and 46 on October 30, 1990

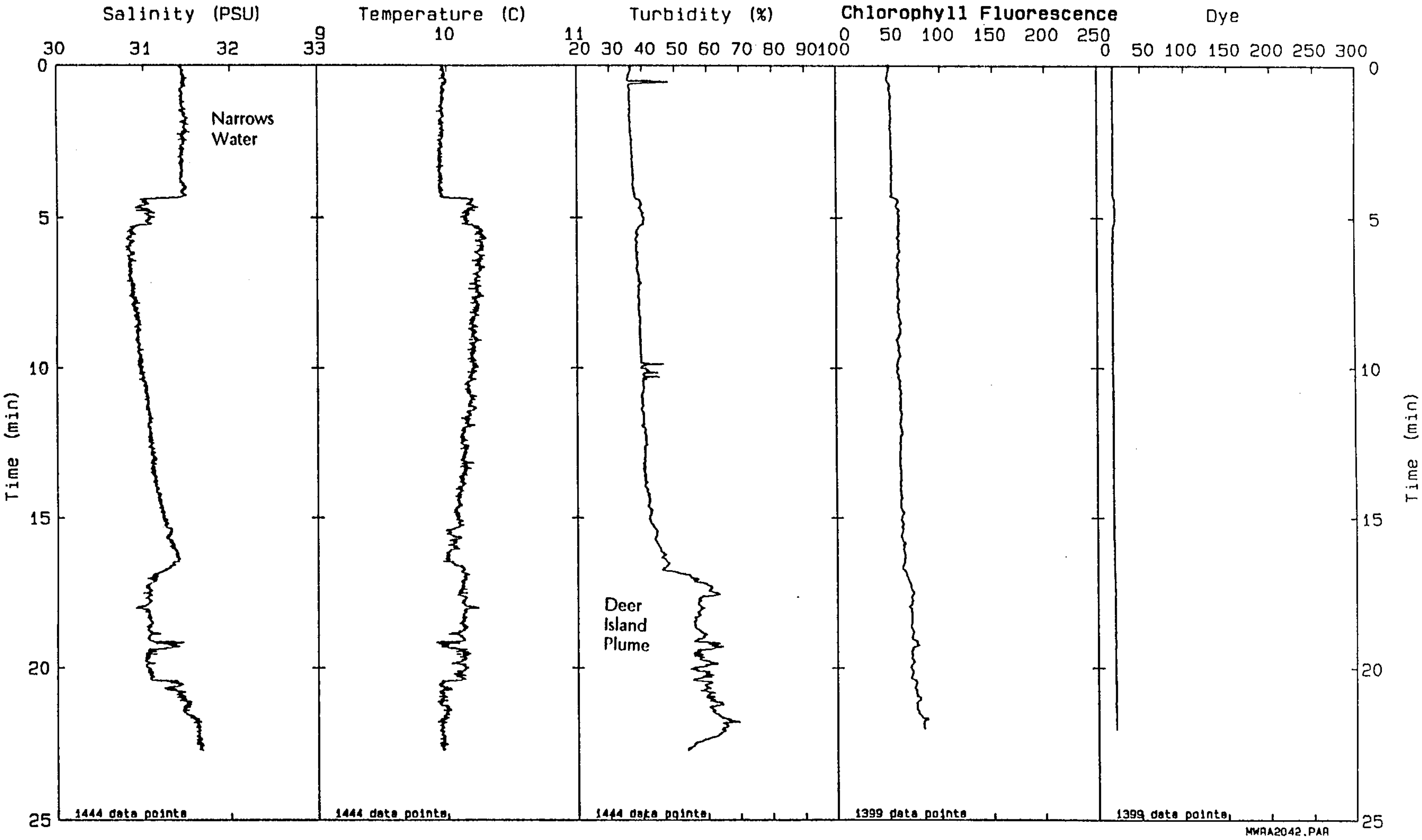

Figure 5-16. Time-Series Plot of Data Acquired along Transect 42 Made on October 30, 1990

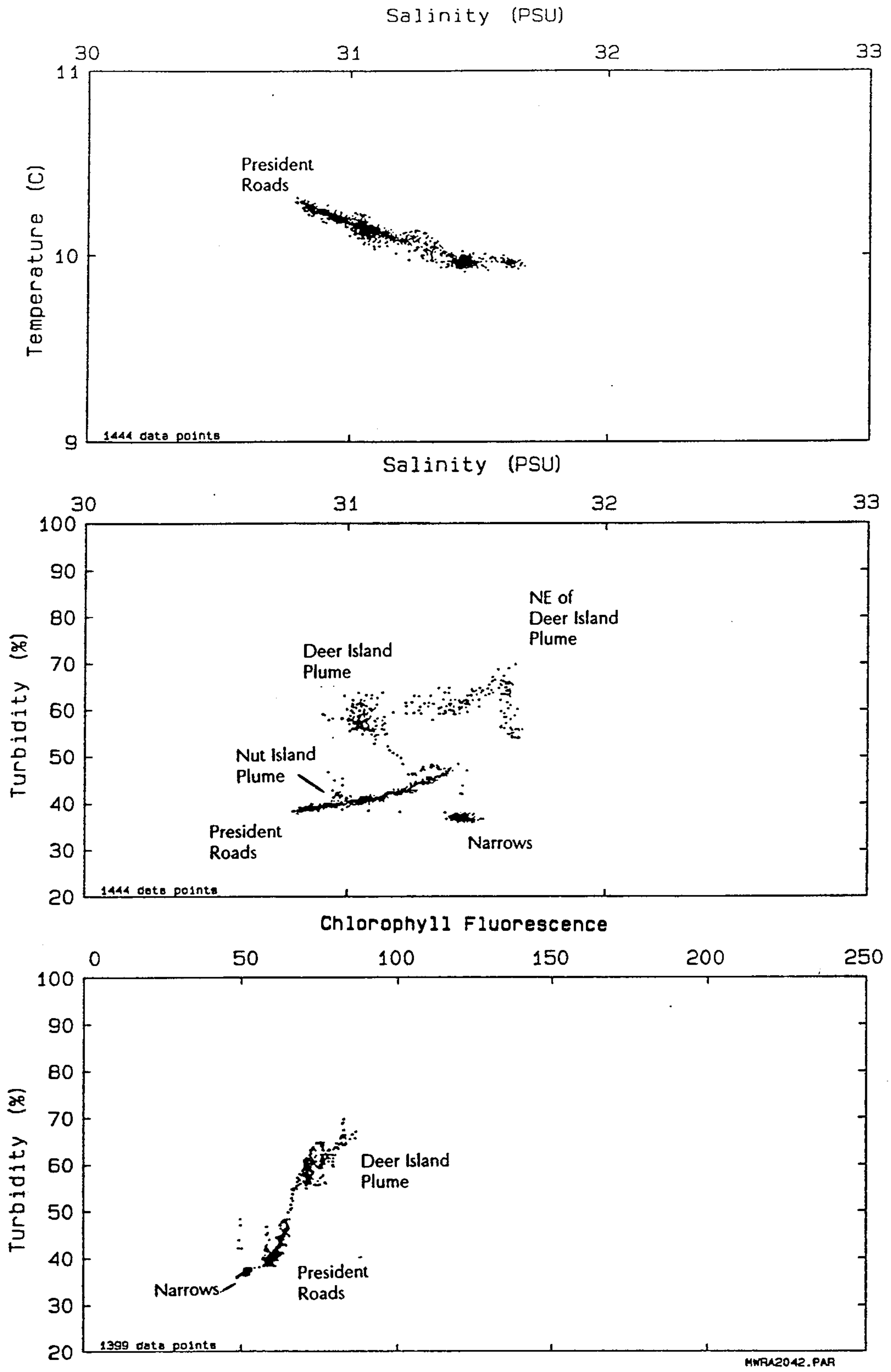

Figure 5-17. Scatter Plot of Data Acquired along Transect 42 Made on October 30, 1990

Background water properties along transect 46 (oriented westerly across the northern entrance to the Narrows) were highly variable due to the convergence of relatively high-salinity water flowing northward in the Narrows, with fresher waters flowing eastward within President Roads. Inspection of the time-series data along this transect (Figure 5-18) also reveals isolated parcels of relatively high-turbidity water that have much smaller-length scales (proportional to time along the transect) than the scales of the T/S fluctuations. The Tu/S scatter plot of Figure 5-19 reveals that these high-turbidity parcels may be remnants of the Nut Island sludge that has mixed extensively with background waters from the Narrows or President Roads.

Another interesting result from the numerous transects made during the ebb flow on October 30 is that the salinity of the background water within President Roads decreased significantly during the 6-h survey operations. Comparison of the Tu/S scatter plots from transects 18 and 46 (Figures 5-14 and 5-19, respectively) illustrates that background salinities near Nixes Mate within President Roads decreased from roughly 31.5 to 30.5 PSU during the ~3.5-h period between the transects. As seen in Figure 5-19, this 1 PSU range in salinities can also be encountered along a single, relatively short, synoptic transect such as transect 46.

> **This exemplifies that physical, chemical, or biological analyses of water samples collected from plumes or other pollutant sources can be compared with background characteristics *only if* the local background characteristics are well determined at the same time and place of the sample collection. Thus, analyses of temporal or spatial variations in pollutant concentrations in a dynamic water body such as Boston Harbor can be totally misleading if these factors are not addressed properly.**

5.2.3 Vertical Profile Results

The previous Section presented water-property data acquired while the Mini-BOSS sensor package was towed horizontally at a depth of roughly 2 m below the surface along various horizontal transects. To determine whether this towing depth was appropriate for mapping the horizontal extent of the Nut Island sludge plume, vertical profiles were made to determine the vertical structure of water properties within the plume at various times and locations during the ebb cycle on October 30.

Figure 5-20 presents vertical profiles of salinity, temperature, turbidity, chlorophyll fluorescence, and dye acquired from the surface to the bottom (5 m) at the Nut Island sludge outfall at 0819 h EST on October 30. This profile illustrates that turbidities were extremely

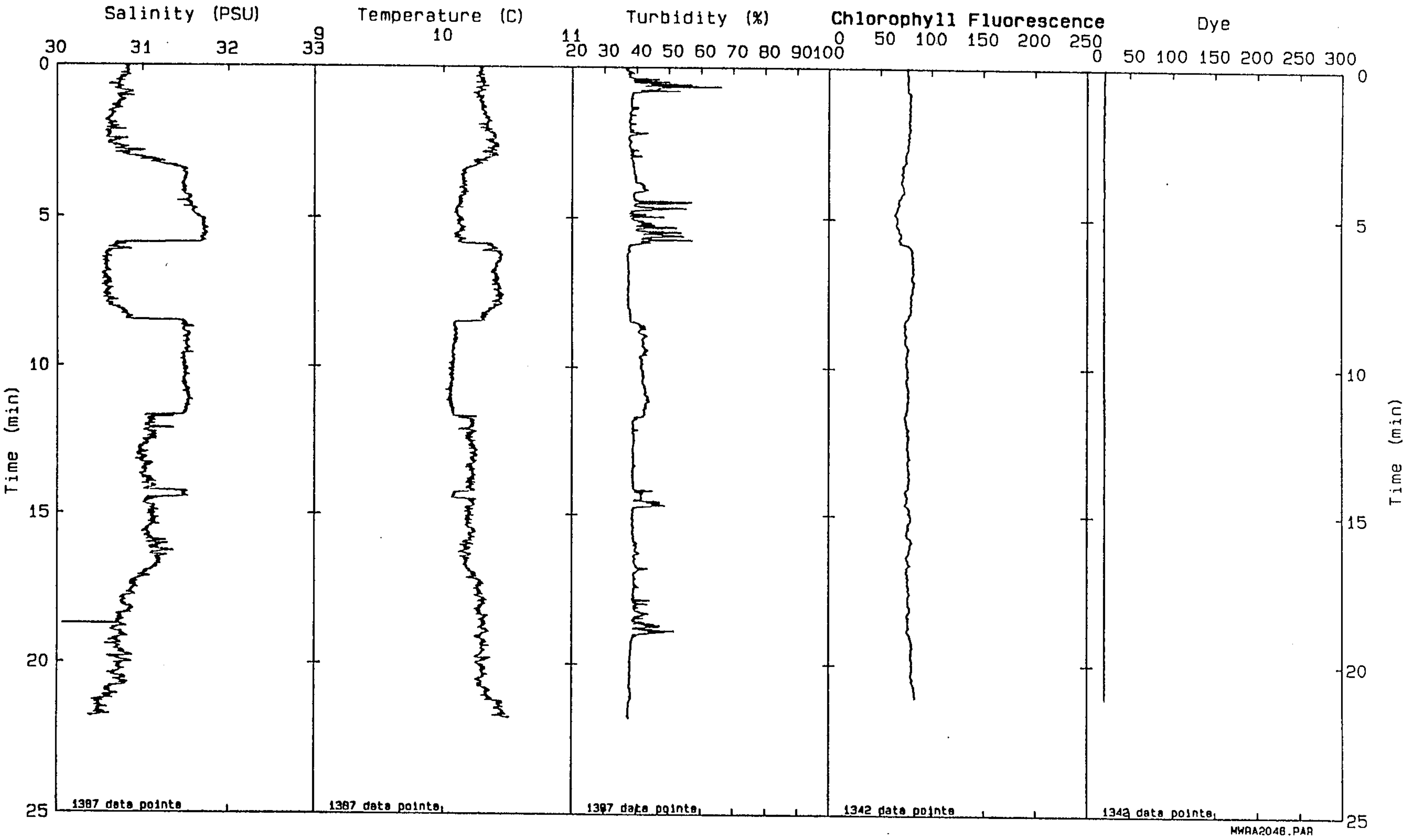

Figure 5-18. Time-Series Plot of Data Acquired along Transect 46 Made on October 30, 1990

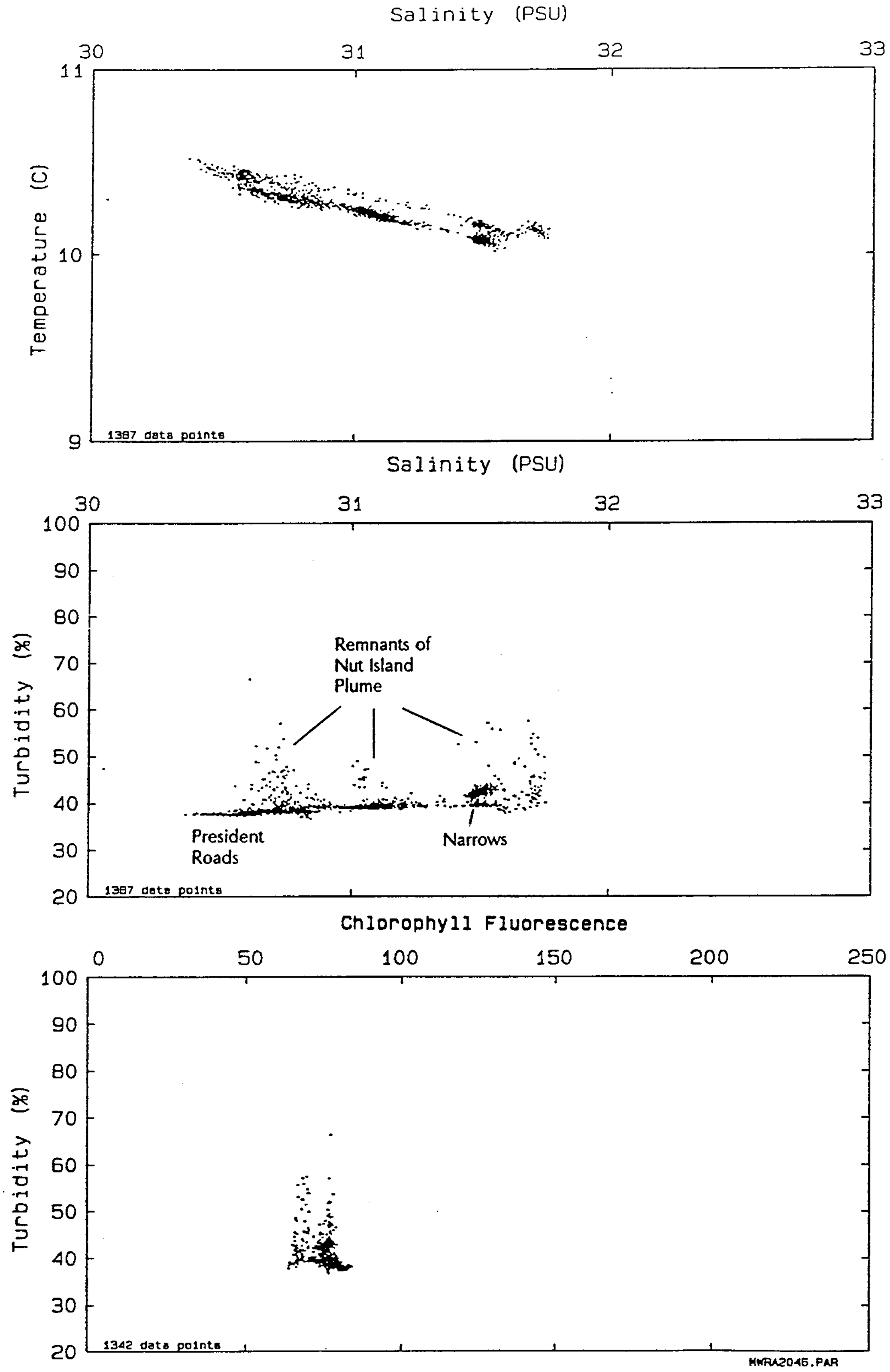

Figure 5-19. Scatter Plot of Data Acquired along Transect 46 Made on October 30, 1990

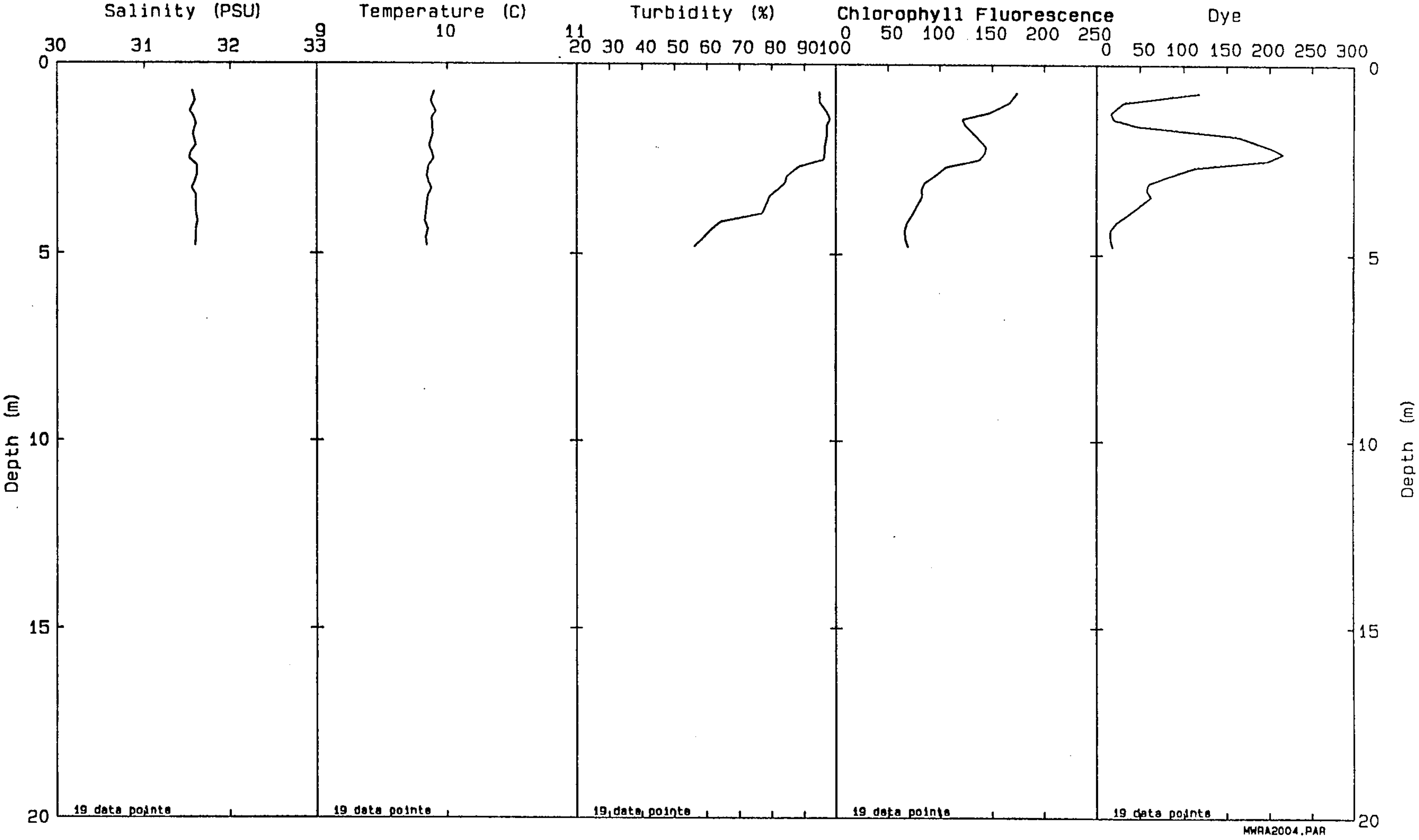

Figure 5-20. Vertical Profile Data Acquired near Sludge Outfall at 0819 h EST on October 30, 1990

high (>80%) over the upper 3 m of the water column, with minimal values of ~55% observed near the bottom. Chlorophyll fluorescence values were also highest in the upper 3 m of the water column. The dye profile exhibits a subsurface maximum near 2 m, but the vertical structure of dye concentration is significantly more complex than that of turbidity and chlorophyll fluorescence.

Figure 5-21 presents another vertical profile of water properties made at 1001 h EST within the sludge plume located a short distance east of the outfall. The turbidity profile again demonstrates that the highest concentrations of sludge were situated within the upper 3 m of the water column. Elevated levels of chlorophyll fluorescence and dye also reveal a relatively thin, near-surface plume.

Additional vertical profiles made during the ebb study confirmed that, if sludge could be detected, it was situated within the upper few meters of the water column. These profiles are included in Volume II, Appendix A.

5.2.4 Summary of Sludge Plume Behavior

The previous Section demonstrated that high-resolution, near-surface measurements of temperature, salinity, turbidity, chlorophyll fluorescence, and dye along horizontal transects can be used to distinguish between Nut Island sludge plume water and the background receiving water, whose characteristics vary considerably with time and location relative to the outfall. To illustrate this variability in the characteristics of the background water, Figure 5-22 presents composite T/S, Tu/S, and Tu/Chl scatter plots, including all data acquired during the plume surveying activities on October 30 (see Table 5-1). The T/S scatter plot vividly illustrates the broad range in background water properties encountered in one relatively small area over the period of a single ebb tide. The densest cluster of points at roughly 31.5 PSU and 10 °C represents the characteristics of water within President Roads near the beginning of the ebb.

Later in the ebb, when the waters from the western portion of the Harbor were flowing past the tip of Long Island, the background properties became less saline and warmer. From comparison with the results of the background measurements taken during the ebb flow on November 1 (Figure 3-9), one can deduce that the low-salinity waters in Figure 5-22 were associated with the outflow from the Inner Harbor. If this water had originated in the vicinity of Dorchester Bay, the data from November 1 suggest that it would have been significantly cooler than the water from the Inner Harbor over the same salinity range. More synoptic

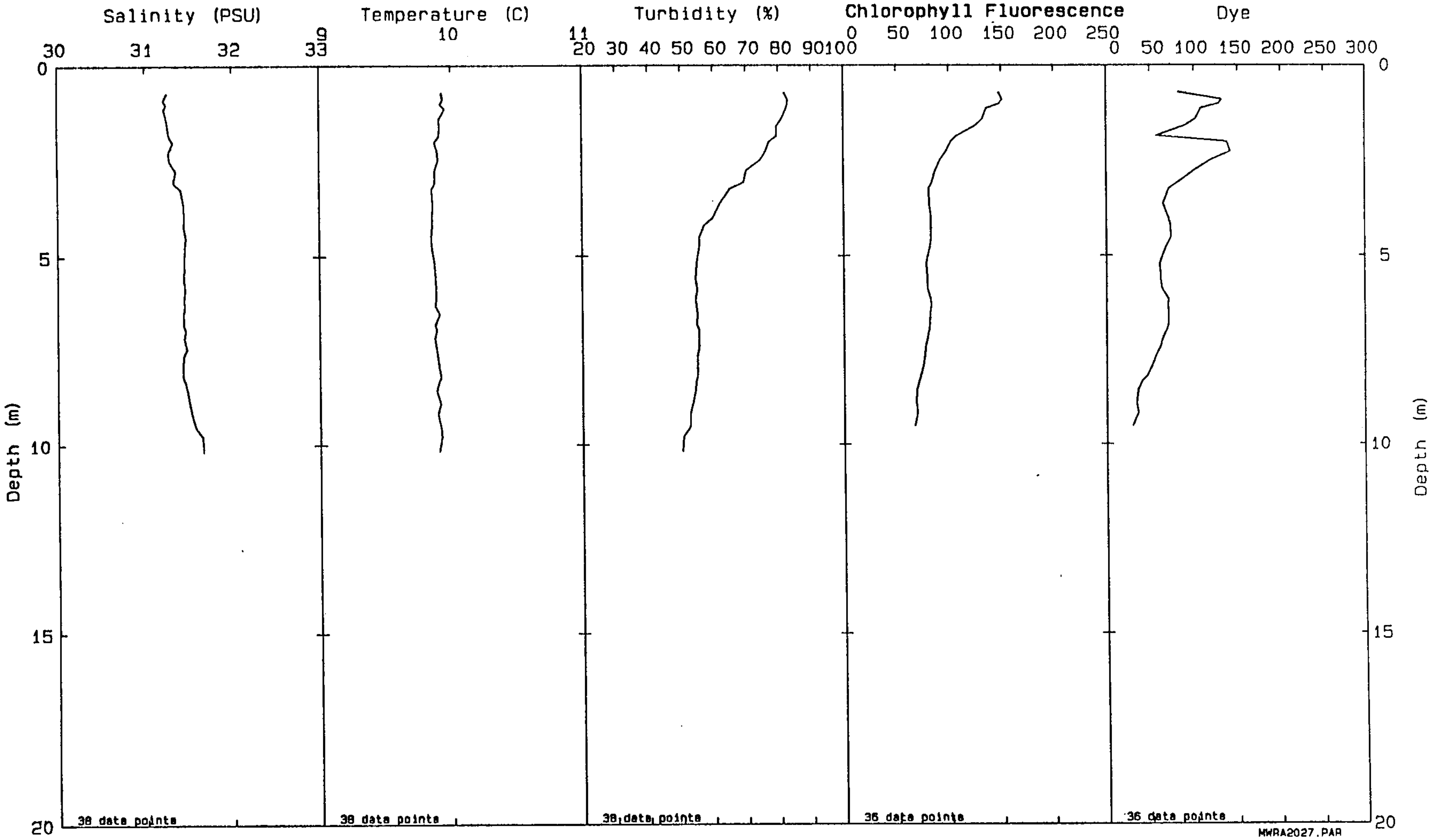

Figure 5-21. Vertical Profile Data Acquired near Sludge Outfall at 1001 h EST on October 30, 1990

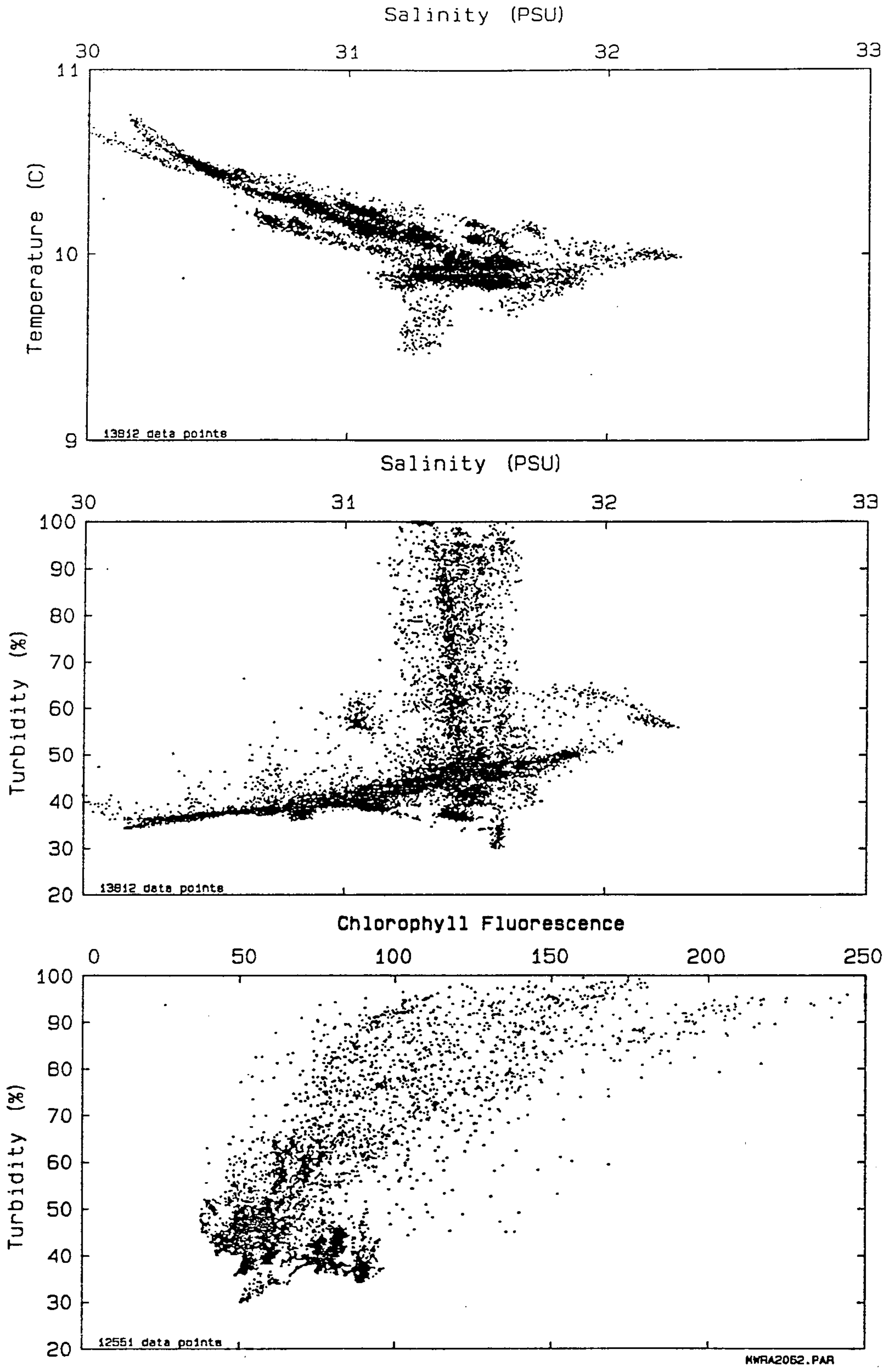

Figure 5-22. Composite Scatter Plot of All Data Acquired along Transects and at Vertical Profile Stations Made on October 30, 1990

spatial data from broad regions of the Harbor would, however, be required to verify this hypothesis concerning flow regimes within President Roads.

The composite Tu/S scatter plot in Figure 5-22 illustrates that the high-turbidity Nut Island sludge plume was easily recognizable from the background water properties. Furthermore, the high turbidities associated with the sludge plume were observed within a relatively narrow salinity range, or, in other words, the plume essentially mixed with only one “flavor” of background water. Later in the ebb, when fresher waters were passing the outfall, no sludge was being discharged.

The composite Tu/Chl scatter plot in Figure 5-22 illustrates that turbidity/chlorophyll fluorescence levels were fairly consistent within the background waters, but within the high-turbidity plumes, chlorophyll fluorescence increased with increasing turbidity. Because turbidity, as presented, is a nonlinear function of total suspended solids, it is possible that the correlation between these two measured parameters is nonlinear, but this level of analysis is beyond the scope of the present study.

As demonstrated in Sections 4.2.3 an 4.3.3, the high-resolution measurements of near-surface water properties along horizontal transects can be used to identify plume boundaries, and, hence, to map its spatial distribution during the ebb flow. Because some of the survey time on October 30 was dedicated to vertical profiling and collection of water samples for MIT and UMB, detailed synoptic coverage across President Roads and in the vicinity of the Narrows was difficult to accomplish with the single survey vessel. Nevertheless, the acquired data were sufficient to develop two maps of the Nut Island sludge plume location during the ebb flow on October 30.

Figure 5-23 presents a map of the study area within President Roads with shading that represents the spatial extent of the near-surface sludge plume emanating from the outfall off Long Island. This plume map was derived from analysis of all transects made over the period from 0.5 to 1.5 h after high water on October 30. The arrows in this Figure represent strong eastward flow on the north side of President Roads and weaker flow near Long Island. Weak northward flow was also observed in Nubble Channel (east of Long Island) and along the eastern side of the Narrows.

During the first hour of the ebb, there is no appreciable flow across Nubble Channel, such that the sludge plume is able to move southeastward within the small cove east of Long Island. However, later in the ebb when the northward flow in Nubble Channel increases, the sludge plume is displaced northward as it moves to the east. This is portrayed in Figure 5-24,

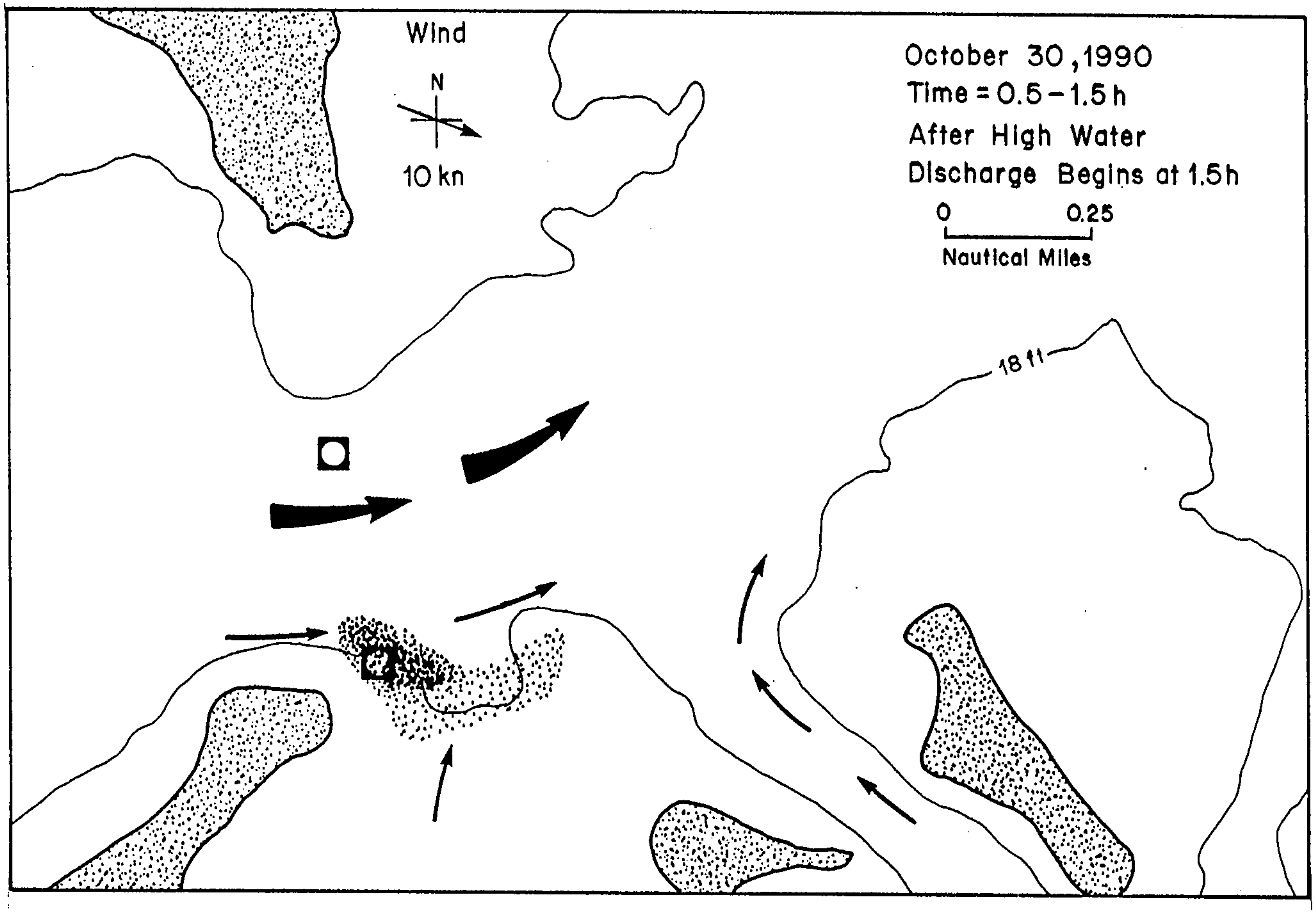

Figure 5-23. Map of President Roads Showing Plume Location 0.5 to 1.5 h after High Water on October 30, 1990. Arrows Represent Flow Direction.

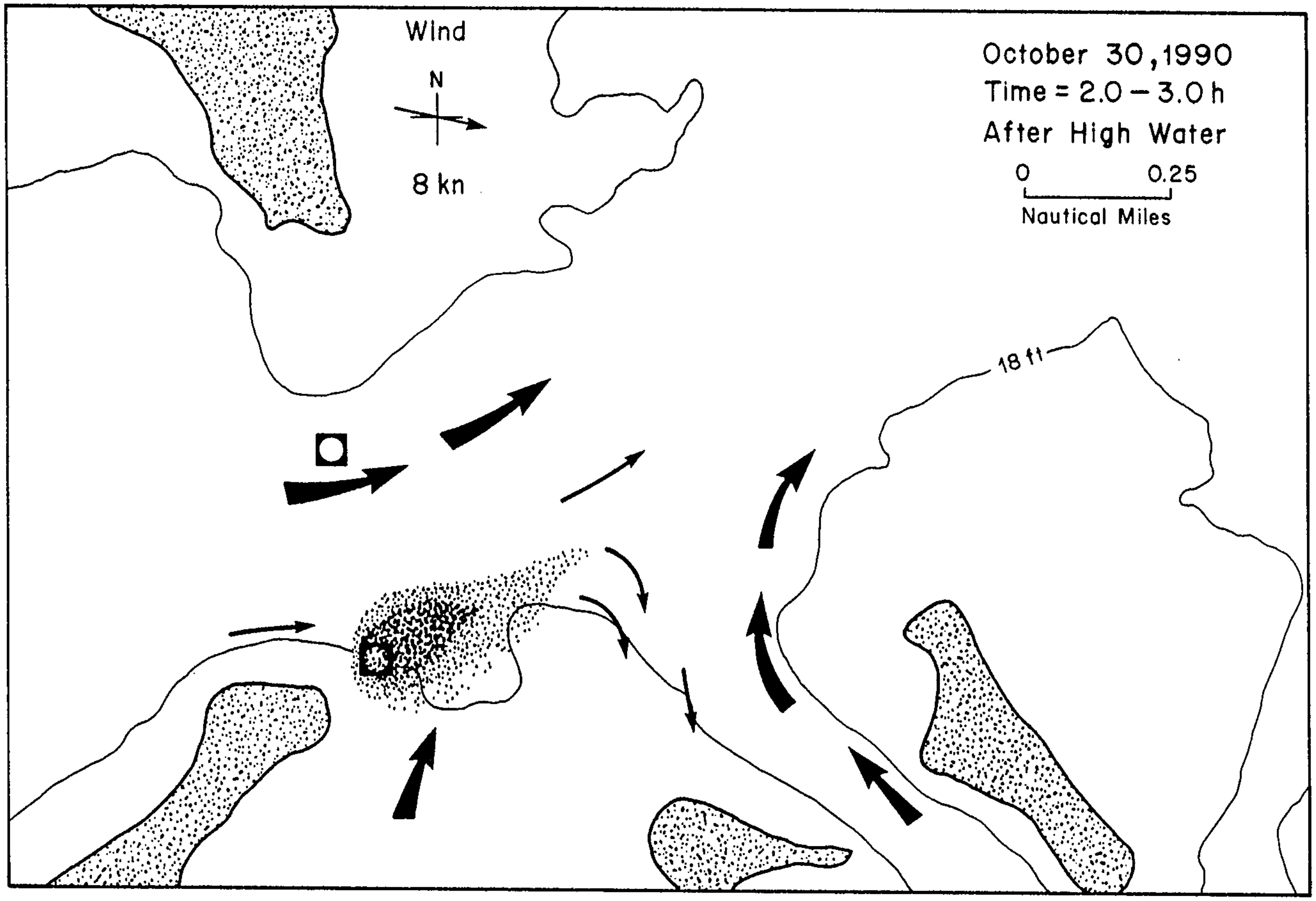

Figure 5-24. Map of President Roads Showing Plume Locations 2.0 to 3.0 h after High Water on October 30, 1990

which illustrates the general location of the plume obtained from surveying during the period from 2.0 to 3.0 h after high water. At this time, the plume had elongated toward the northeast as a result of relatively strong northward flow across Nubble Channel. The strong flow from Nubble Channel actually had two effects on the plume: (1) northward displacement and (2) intense mixing along the southern edge of the plume. Consequently, as the plume reached Nixes Mate Shoal, it was very narrow and quite dilute.

The drifter data presented in Section 5.2.1 revealed a stagnant-flow region on the northeast side of Nixes Mate Shoal. It is believed that a major fraction of the sludge plume entered this region and became actively mixed with the relatively clear waters moving northward across Nubble Shoal and within the Narrows. Moderate wave action on Nixes Mate Shoal would further accelerate this mixing process. A small proportion of the sludge plume may continue eastward past Nixes Mate Shoal toward South Channel, but additional mixing from the strong flow emanating from the Narrows would greatly reduce the sludge concentrations. This was confirmed by numerous transects taken in the vicinity of the Narrows and South Channel, which showed only dilute traces of sludge northeast of the Narrows. Figure 5-25 presents a schematic diagram of the flow regime near the end of the ebb cycle. The exact time when sludge discharge from the outfall ended is not known, but transects made during the last hour of the ebb in the vicinity of the outfall showed no traces of sludge.

5.3 RESULTS FROM SURVEY ON OCTOBER 31, 1990

5.3.1 Drifter Results

Surface drifters were deployed at various times during the ebb tide on October 31 to obtain additional information on the surface currents within President Roads. Drifters were released from the two survey vessels and tracked visually over the duration of the measurement period (roughly 0900 to 1600 h EST), as described in Section 5.2.1. The time of predicted high water was 0827 h EST. In Volume II, Appendix A, tables of time and position of each drifter fix are given for each drifter tracked; calculated drifter speed and distance between fixes are also provided.

On October 31, pairs of drifters were released in the vicinity of the Nut Island sludge outfall at four times during the ebb period; the releases were roughly 1.5 h apart, starting 42 min after predicted high water. Winds were from the north-northwest at speeds of 11 to 23 kn throughout the drifter operations. Figure 5-26 presents trajectories of the two drifters released to the northwest of the Nut Island sludge outfall at 42 min after high water. The

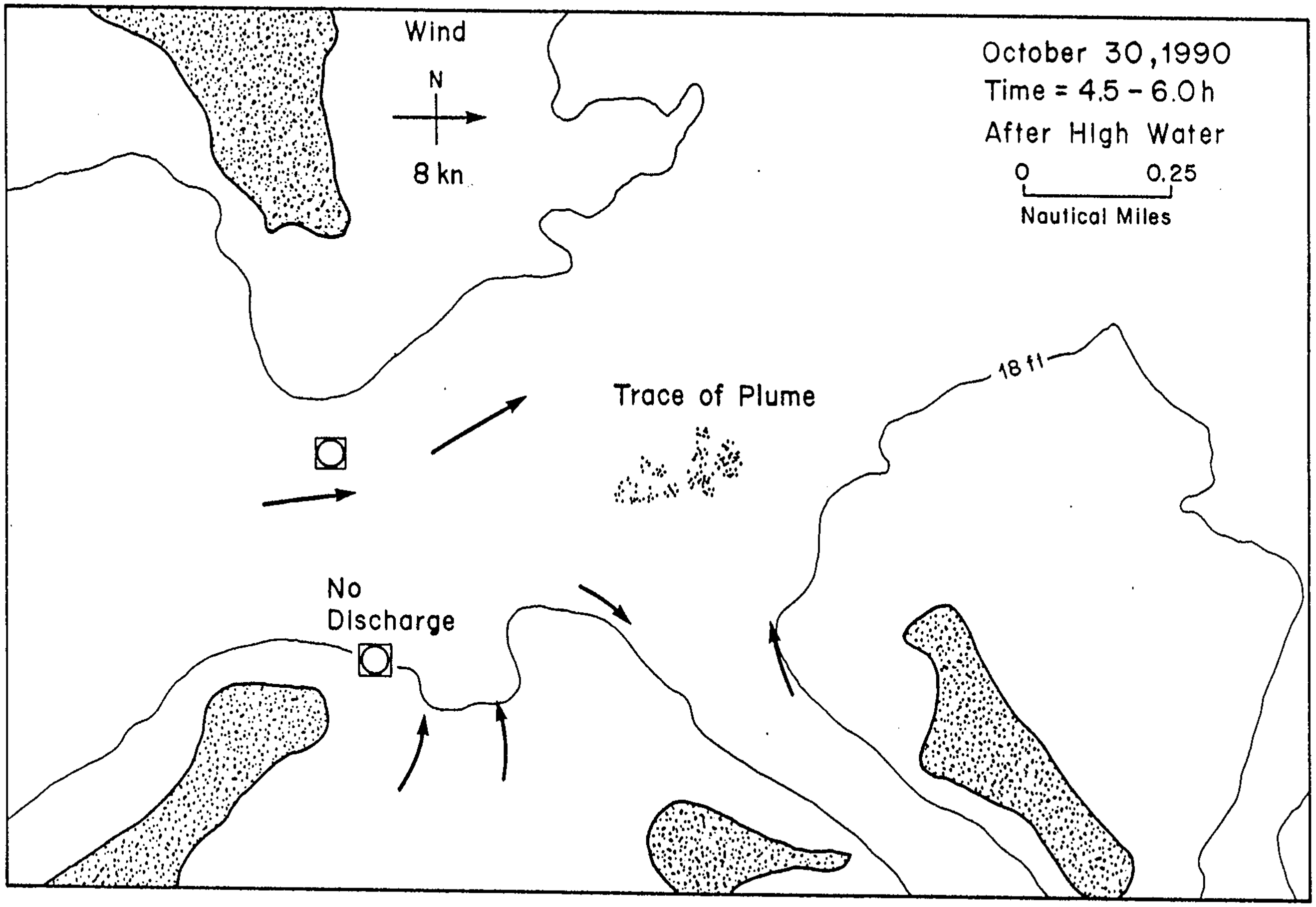

Figure 5-25. **Map of President Roads Showing Plume Locations 4.5 to 6.0 h after High Water on October 30, 1990**

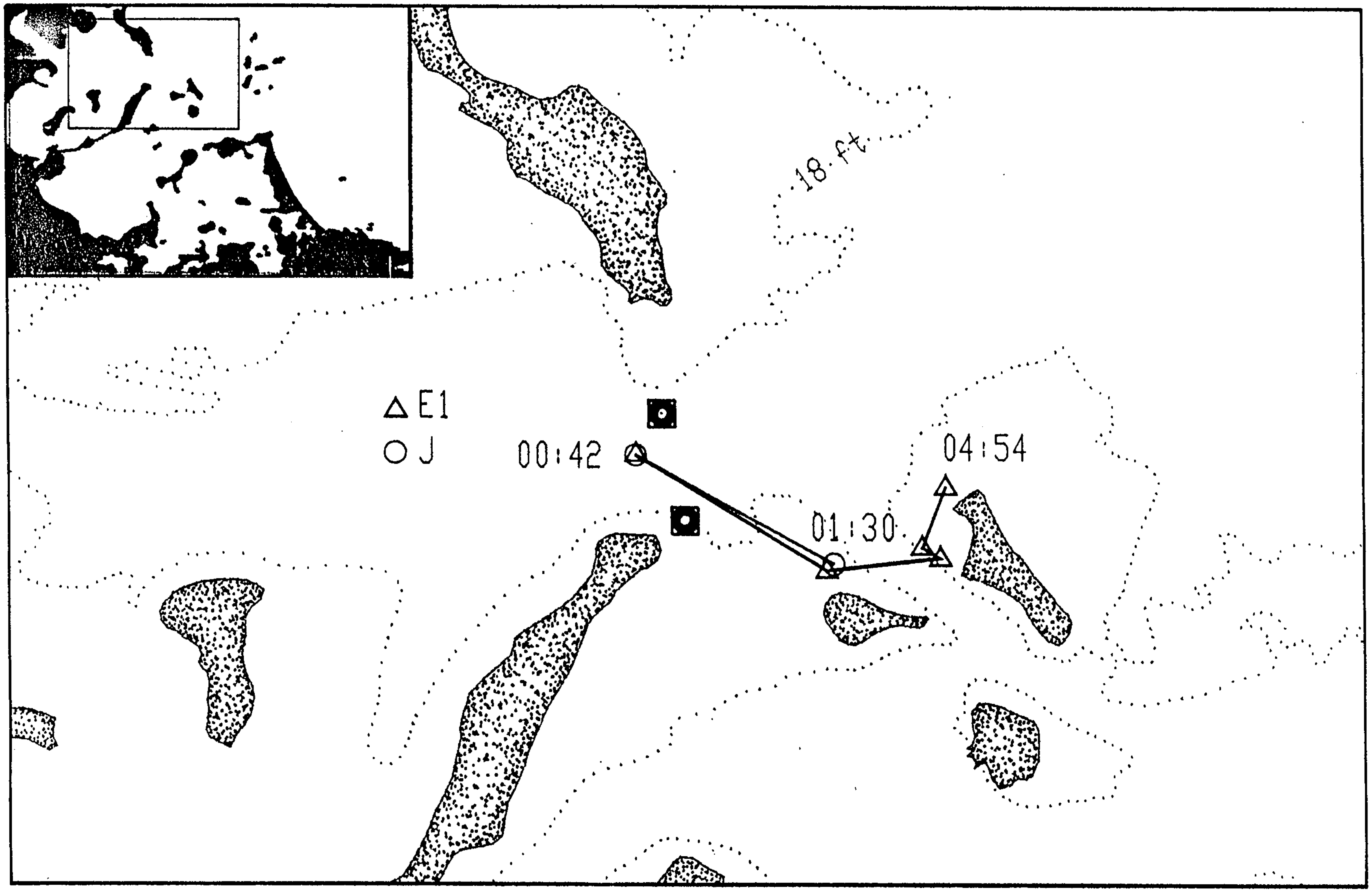

Figure 5-26. Trajectories of Two Drifters Released within President Roads in the Morning of October 31, 1990

drifters remained together as they moved southeastward at roughly 50 cm/s until they reached the shoals north of Gallops Island. One of the drifters became grounded on the shoals, whereas the other continued eastward across the Narrows (at roughly 2 h after high water), apparently before the strong northward flow had developed within the Narrows. That drifter (E1 in Figure 5-26) remained on the shoals northwest of Lovell Island until it was lost at nearly 5 h after high water.

Figures 5-27 and 5-28 present trajectories of drifter pairs released from the Nut Island sludge outfall at 2 h 5 min and 3 h 33 min after high water on October 31. Winds were strong (15 to 23 kn) from the northwest during this period. As indicated in the two Figures, all four of these drifters moved eastward toward Nixes Mate Shoal, then became stalled (but not grounded) on the shoals east of Nixes Mate and north of Gallops Island, and remained there until roughly the time of low water, when the flow in the Narrows turned southward. Thus, these four drifters illustrated that

- Although the winds were strong from the northwest, these drifters moved eastward at roughly right angles to the wind, thereby demonstrating their capability of following the near-surface current.
- The eastward flow at the Nut Island sludge outfall between 2 and 4 h after high water is partially a result of strong northward flow across Nubble Shoal during this period of the ebb.
- None of these drifters continued eastward past Lovell Island or exited the Harbor via South Channel.
- All four of the drifters remained on the shoals adjacent to the northern end of the Narrows until the tide turned and carried them southward within the Narrows.

These results are quite similar to those obtained from drifters released during the ebb on October 30 when the winds were less strong and oriented from the west (see Section 5.2.1), especially since none of the drifters exited the Harbor during the ebb. Comparing the results from the 2 days, we see that there was a greater tendency for drifter trapping on the shoal east of Nixes Mate when the winds were strong from the north-northwest (on October 31); mild westerly winds (on October 30) resulted in the drifters being able to cross the Narrows and remain on the shoals around Lovell Island. It is suspected that the wind-driven flow within the Narrows was significantly different on these 2 days.

The trajectories of two additional drifters (shown in Volume II, Appendix A) released in President Roads northwest of the Nut Island sludge outfall showed that, at the beginning of the flood tide, the flow across Nubble Channel is toward the southwest. This is in agreement with (1) drifter results from the previous day of this study, (2) drifter results from an earlier Boston Harbor field study (EG&G, 1984), and (3) flow predictions from Signell's high-resolu-

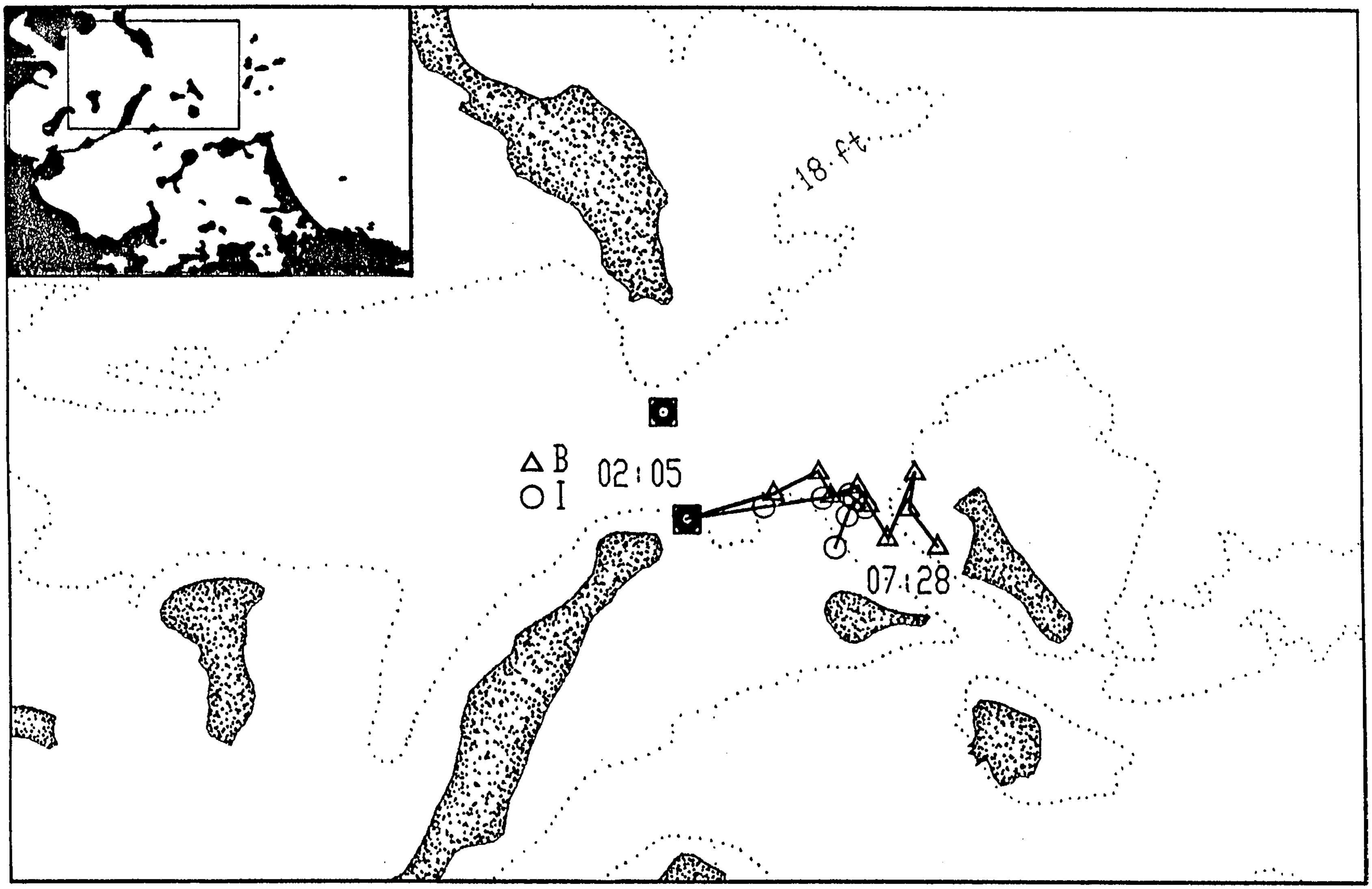

Figure 5-27. Trajectories of Two Drifters Released within President Roads in the Morning of October 31, 1990

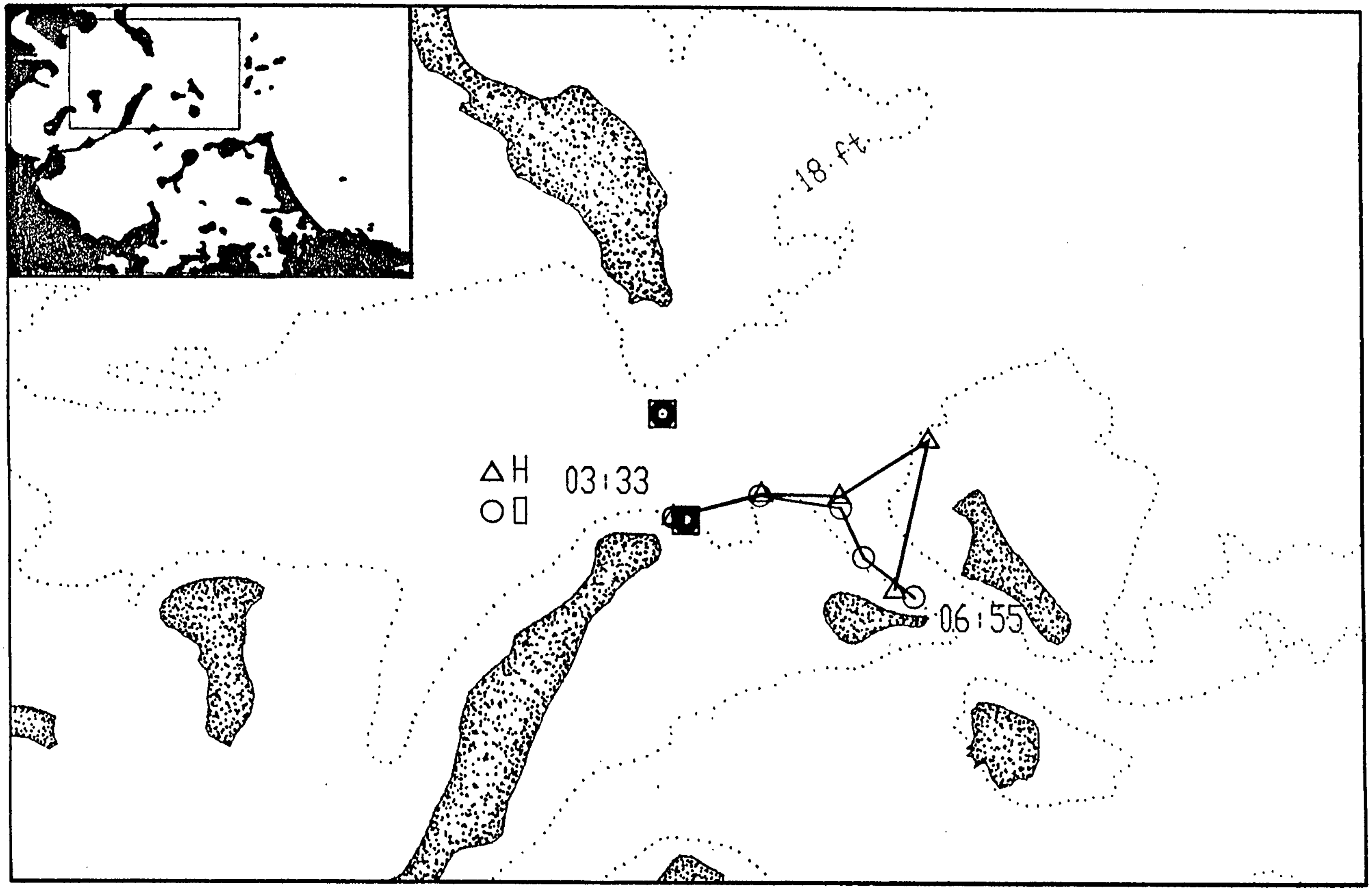

Figure 5-28. Trajectories of Two Drifters Released within President Roads in the Morning of October 31, 1990

tion numerical circulation model (Bothner *et al.,* 1990). These results suggest the following scenarios for transport of Nut Island sludge at the beginning of the incoming tide:

- If a Nut Island sludge plume were situated a short distance east of the outfall when the incoming tide began, it would be carried southward across Nubble Channel then southwestward along Long Island.
- If remnants of Nut Island sludge were located in the stagnant region on the east side of Nixes Mate when the incoming tide began, it would be carried southeastward within the Narrows.
- If sludge were being discharged during the incoming tide, it would most likely be carried westward past the northern tip of Long Island.

Further discussion of the probable pathways of sludge transport is presented in Section 5.3.3.

5.3.2 Plume Tracking Results

Water quality surveying with the Mini-BOSS was conducted during the period from roughly 0910 to 1610 h EST on October 31. As during the previous day, the survey transects and vertical profiles were made in the vicinity of the Nut Island sludge outfall off the northern tip of Long Island in President Roads. Table 5-2 presents the time and location of each of the 31 horizontal transects and one vertical profile made on October 31. Figure 5-29 is a chart of President Roads with superimposed tracks representing the horizontal transects.

The survey objective was to obtain additional information on the advection and mixing of the Nut Island sludge plumes during the ebb flow period. Because the winds on October 31 were strong (11 to 23 kn) from the north-northwest as compared to the mild westerly winds of the prior survey day, comparison between the flow regime on the 2 days can also be made. As for October 30, surveying operations consisted of near-continual towing of the Mini-BOSS sensor package at a near-constant depth of roughly 2 m below the surface. Selection of transect locations was made on a real-time basis by the scientist aboard the vessel, using the information from the real-time graphic display of water-property data and vessel position provided by the Mini-BOSS.

Figure 5-30 is a detailed chart of President Roads in the vicinity of Long Island with superimposed vessel tracks representing horizontal transects 7E and 10E (data files MWRA407E and MWRA410E, respectively). Transect 7E, made at 1009 h EST, was oriented from west to east and situated a short distance to the north of the sludge outfall. As illustrated in Figure 5-31, high-turbidity water associated with the Nut Island sludge plume was encountered about 0.5 min along this transect. Elevated chlorophyll fluorescence levels

Table 5-2. Time and Location of Horizontal Transects (Tows) and Vertical Profiles Made on October 31, 1990

File Number	File Type	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Start Position		End Position	
				Lat(N)	Long(W)	Lat(N)	Long(W)
MWRA4003	Tow	09:10:49	09:16:21	42°20.25′	70°57.37′	42°19.95′	70°57.32′
MWRA4006	Tow	09:57:06	09:59:53	42°19.92′	70°57.28′	42°19.94′	70°57.13′
MWRA407C	Tow	10:03:34	10:07:24	42°19.97′	70°57.19′	42°19.98′	70°57.06′
MWRA407E	Tow	10:09:46	10:13:19	42°19.95′	70°57.24′	42°19.99′	70°56.98′
MWRA407G	Tow	10:16:39	10:18:38	42°19.93′	70°57.17′	42°19.96′	70°57.23′
MWRA407H	Tow	10:18:38	10:23:09	42°19.95′	70°57.27′	42°19.98′	70°56.95′
MWRA407I	Tow	10:23:09	10:26:07	42°19.97′	70°56.98′	42°19.93′	70°57.14′
MWRA407K	Tow	10:28:05	10:31:37	42°19.92′	70°57.20′	42°19.97′	70°56.94′
MWRA4008	Tow	10:37:09	10:40:41	42°19.93′	70°57.05′	42°19.96′	70°57.23′
MWRA4009	Tow	10:40:44	10:55:31	42°19.91′	70°57.23′	42°19.86′	70°56.96′
MWRA410A	Tow	10:55:36	10:59:08	42°19.85′	70°56.94′	42°19.97′	70°57.03′
MWRA410B	Tow	10:59:08	11:01:18	42°19.96′	70°57.05′	42°19.86′	70°57.18′
MWRA410C	Tow	11:01:18	11:05:02	42°19.87′	70°57.17′	42°19.92′	70°56.86′
MWRA410E	Tow	11:10:45	11:15:17	42°20.06′	70°56.83′	42°19.85′	70°57.08′
MWRA410F	Tow	11:15:17	11:19:01	42°19.85′	70°57.10′	42°19.98′	70°57.20′
MWRA410G	Tow	11:19:01	11:23:09	42°19.98′	70°57.21′	42°19.92′	70°56.91′
MWRA410I	Tow	11:28:16	11:32:45	42°20.07′	70°56.67′	42°20.32′	70°56.59′
MWRA4011	Tow	11:32:48	11:40:38	42°20.34′	70°56.60′	42°20.16′	70°56.18′
MWRA4012	Tow	11:40:42	11:59:60	42°20.15′	70°56.15′	42°19.77′	70°57.09′
MWRA4018	Tow	13:55:59	14:05:59	42°19.98′	70°57.21′	42°19.96′	70°57.41′
MWRA4019	Tow	14:06:03	14:12:12	42°19.97′	70°57.44′	42°19.89′	70°57.10′
MWRA4020	Tow	14:12:15	14:23:54	42°19.89′	70°57.10′	42°19.91′	70°57.04′
MWRA421A	Tow	14:23:59	14:27:02	42°19.91′	70°57.05′	42°19.90′	70°57.23′
MWRA421C	Tow	14:30:40	14:34:01	42°19.93′	70°57.44′	42°19.91′	70°57.22′
MWRA421F	Tow	14:41:06	14:46:53	42°19.90′	70°57.06′	42°19.92′	70°57.37′
MWRA4022	Tow	14:46:57	15:03:14	42°19.93′	70°57.38′	42°19.93′	70°57.46′
MWRA4023	Tow	15:03:17	15:17:16	42°19.94′	70°57.42′	42°19.95′	70°57.29′
MWRA4025	Profile	15:18:51	15:19:29	42°19.94′	70°57.32′	42°19.93′	70°57.33′
MWRA4026	Tow	15:19:51	15:35:20	42°19.93′	70°57.29′	42°19.44′	70°56.78′

Table 5-2. Time and Location of Horizontal Transects (Tows) and Vertical Profiles Made on October 31, 1990 (continued)

File Number	File Type	Start Time (EST) (h:m:s)	End Time (EST) (h:m:s)	Start Position		End Position	
				Lat(N)	Long(W)	Lat(N)	Long(W)
MWRA4027	Tow	15:35:24	15:40:24	42°19.44′	70°56.75′	42°19.36′	70°57.07′
MWRA4029	Tow	15:43:31	16:02:13	42°19.66′	70°57.14′	42°19.96′	70°57.54′
MWRA4030	Tow	16:02:17	16:10:20	42°19.96′	70°57.56′	42°19.83′	70°57.11′

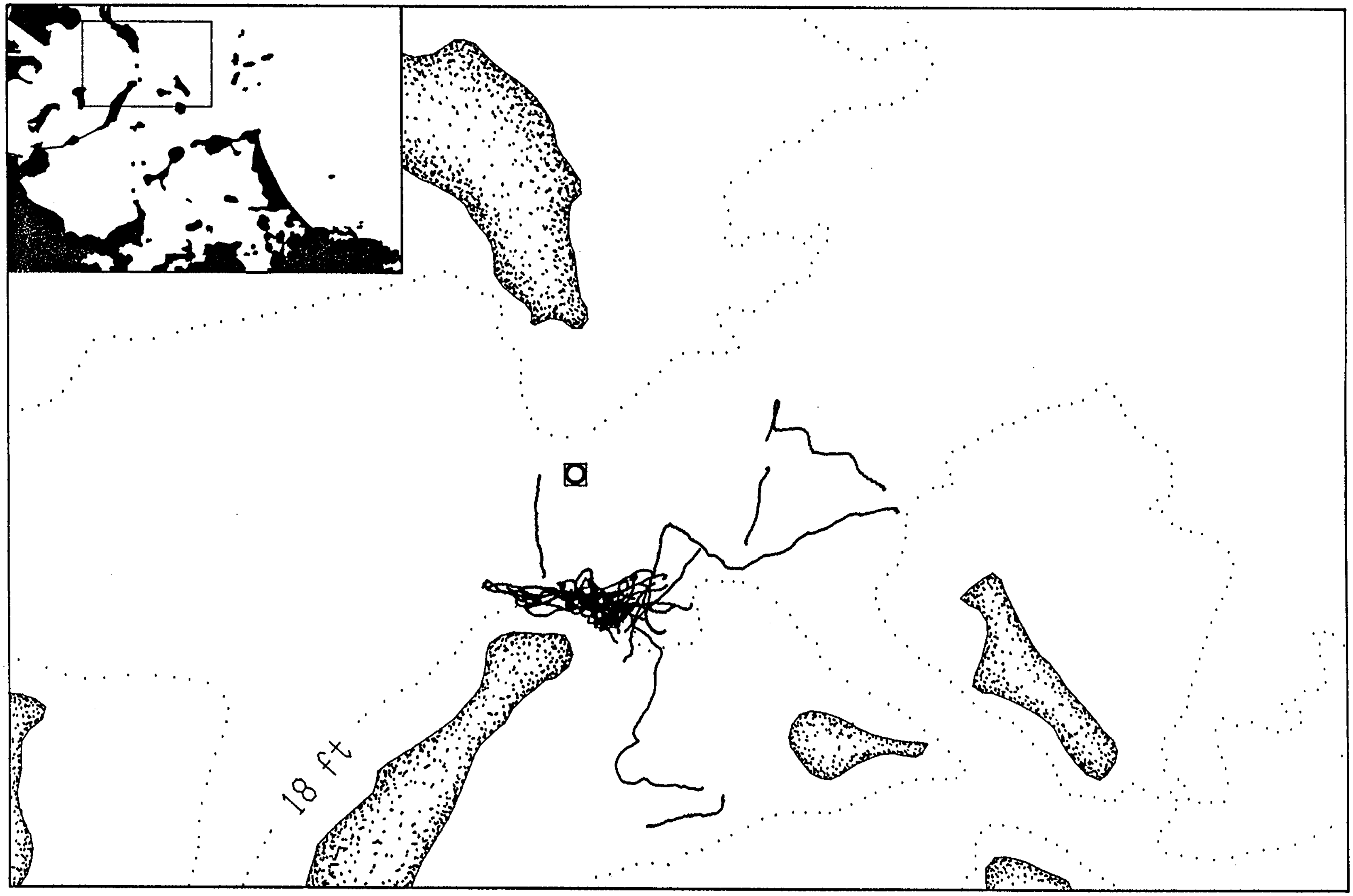

Figure 5-29. Location of Horizontal Transects Made on October 31, 1990

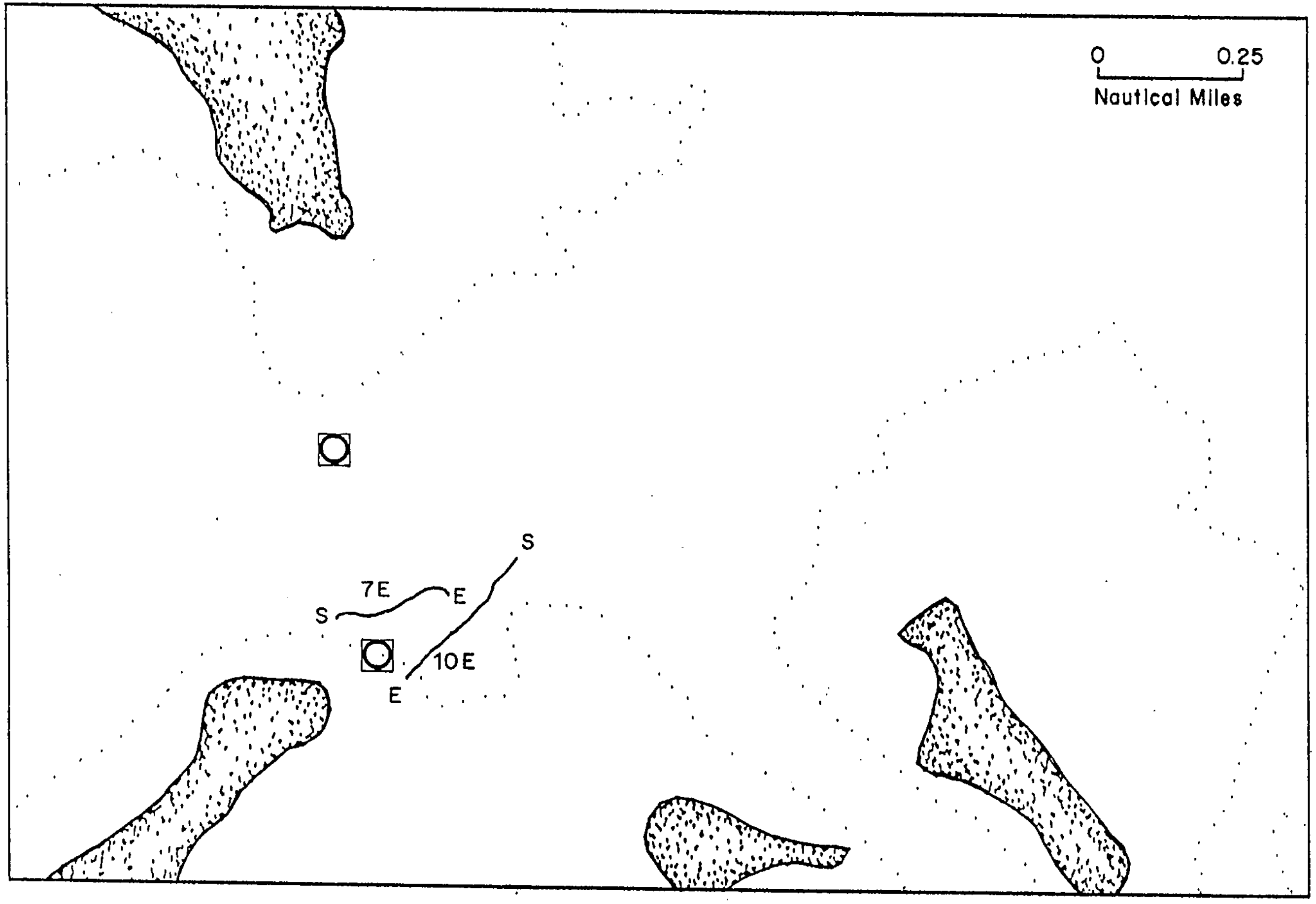

Figure 5-30. Expanded Map of President Roads (near Long Island) Showing Location of Transects 7E and 10E on October 31, 1990. Start and End Positions of Transects Are Indicated by S and E, Respectively.

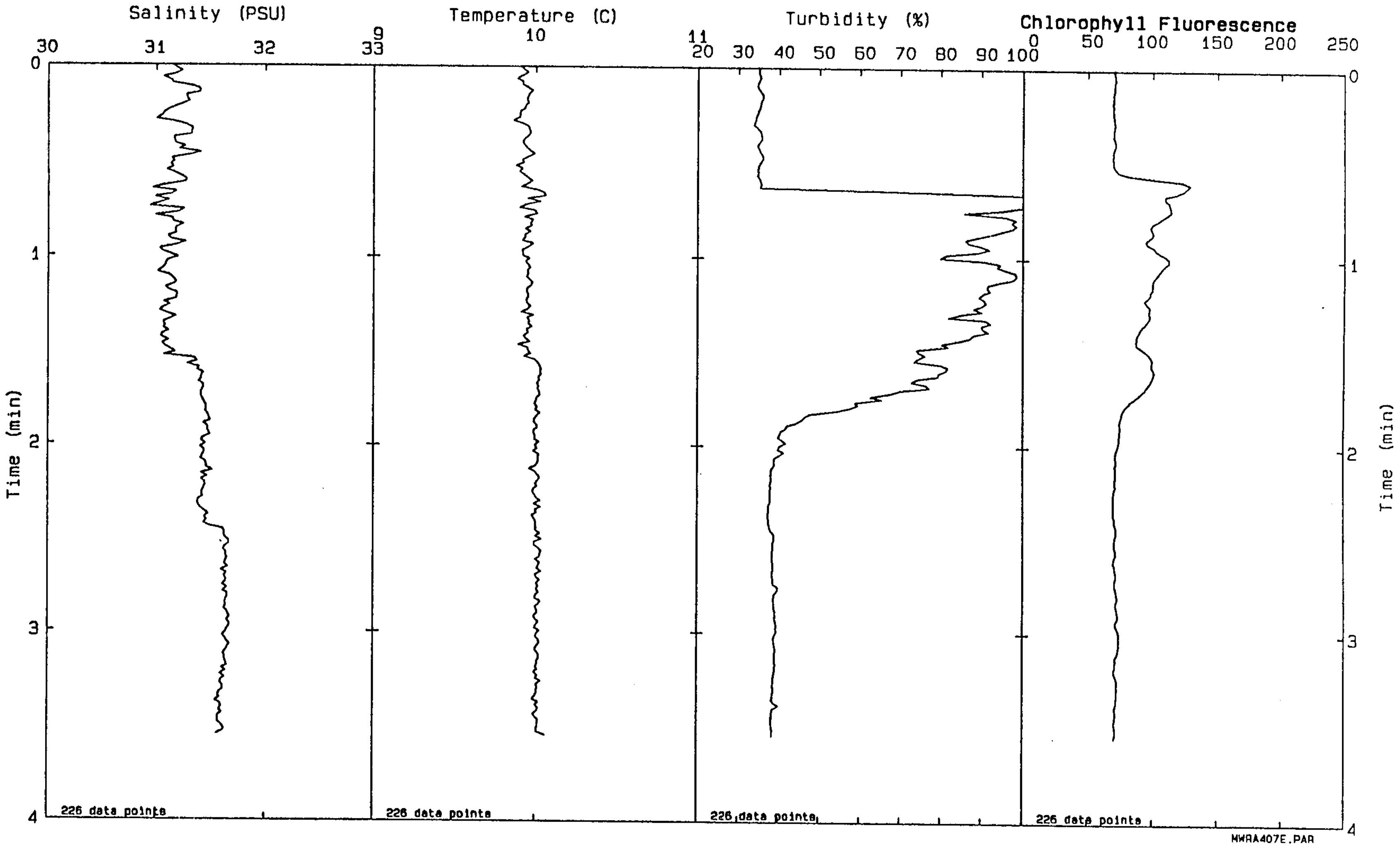

Figure 5-31 Time-Series Plot of Data Acquired along Transect 7E Made on October 31, 1990

corresponded with the high turbidities within the plume, but salinity and temperature were uncorrelated with turbidity.

Figure 5-32 presents T/S, Tu/S, and Tu/Chl scatter plots of the data acquired along transect 7E, plotted on the same scales as used to present the results from October 30. The high-turbidity characteristics are clearly related to the Nut Island sludge plume. The Tu/S scatter plot also indicates that the low-turbidity receiving water adjacent to the outfall has a relatively broad (~0.6 PSU) salinity range. From analysis of the numerous transects made during this ebb-flow survey, it was determined that the highest salinity background water in Figure 5-32 was associated with water flowing northward across Nubble Channel. The less-saline background water was typical of waters found within President Roads at the time of these observations.

Careful inspection of Figure 5-31 and the Tu/S scatter plot in Figure 5-32 reveals that the high-turbidity western edge of the sludge plume had significantly lower salinities than did the more dilute eastern edge of the plume. Presumably, the highest turbidities and lowest salinities were obtained by discharging sludge into President Roads water. On the eastern edge of the plume, intense mixing with more-saline waters flowing northward from Nubble Channel was causing rapid dilution of the plume.

Figure 5-33 presents a time-series plot of the water-property data acquired along transect 10E made roughly 1 h after transect 7E (see Figure 5-30 for location). This transect produced a crossing of a more-dilute portion of the sludge plume with maximum turbidities reaching about 70%. Turbidities to the northeast of the plume (0 to 2 min along transect in Figure 5-33) were quite erratic, possibly due to small parcels of dilute sludge, whereas near the end of the transect low-turbidity waters having an origin within the Harbor were encountered. The scatter plots of data from transect 10E (Figure 5-34) illustrate that the Nut Island sludge plume can be readily distinguished from the two types of background water by its turbidity, salinity, and chlorophyll fluorescence characteristics.

The discharge of sludge from the Nut Island outfall ended at approximately 1455 h EST on October 31 – 5 h 15 min after the discharge began and 6 h 28 min after predicted high water. Near the end of this discharge period, the turbidity levels of the discharge water were considerably lower, with maximum values near 60% turbidity as compared with earlier values of 100% turbidity. Figure 5-35 demonstrates the characteristics of the water being discharged from the outfall at 1441 h EST acquired along transect 21F, which crossed over the outfall. Visual observations at the outfall indicated that there was still a significant volume discharge

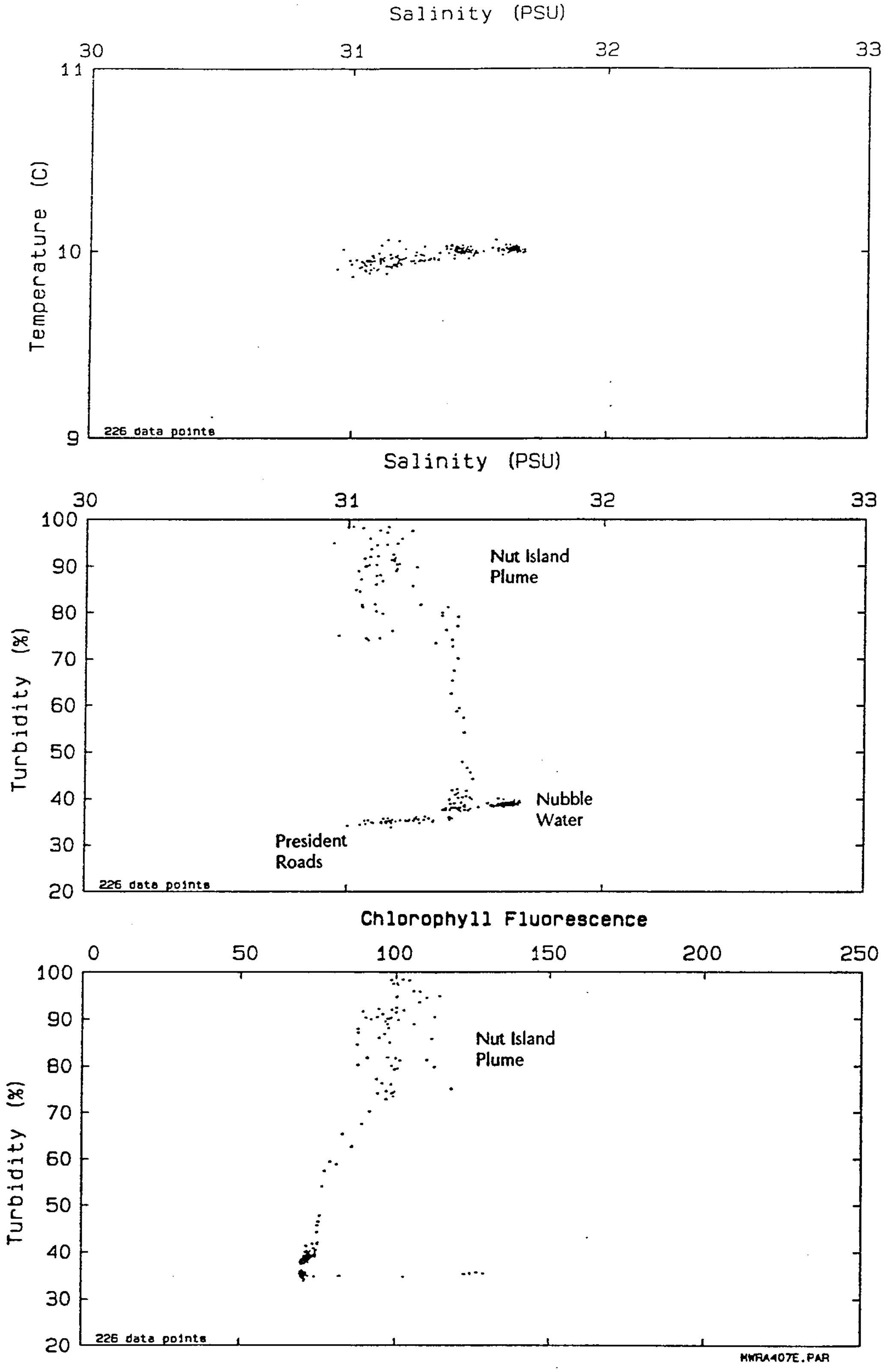

Figure 5-32. Scatter Plot of Data Acquired along Transect 7E Made on October 31, 1990

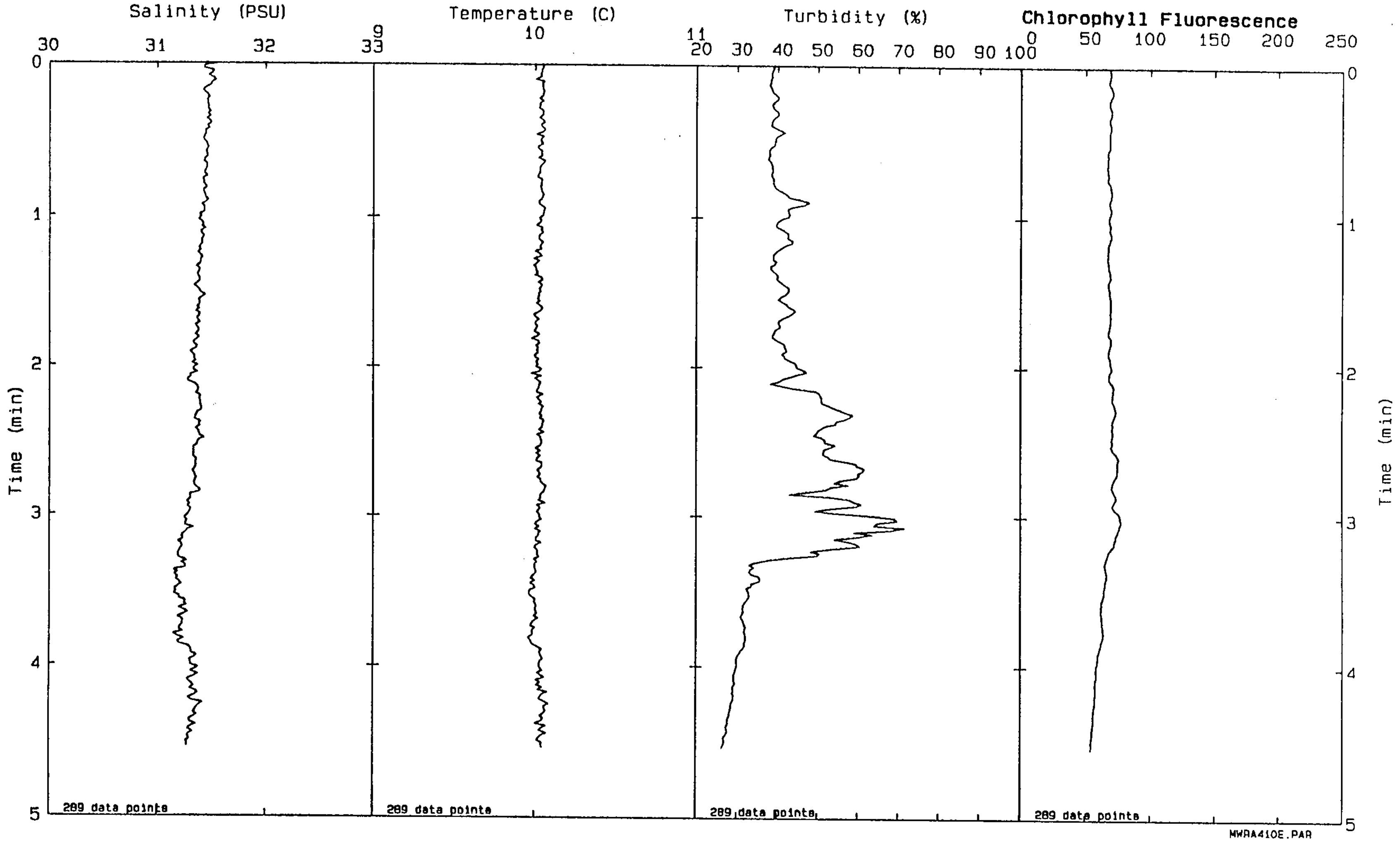

Figure 5-33. Time-Series Plot of Data Acquired along Transect 10E Made on October 31, 1990

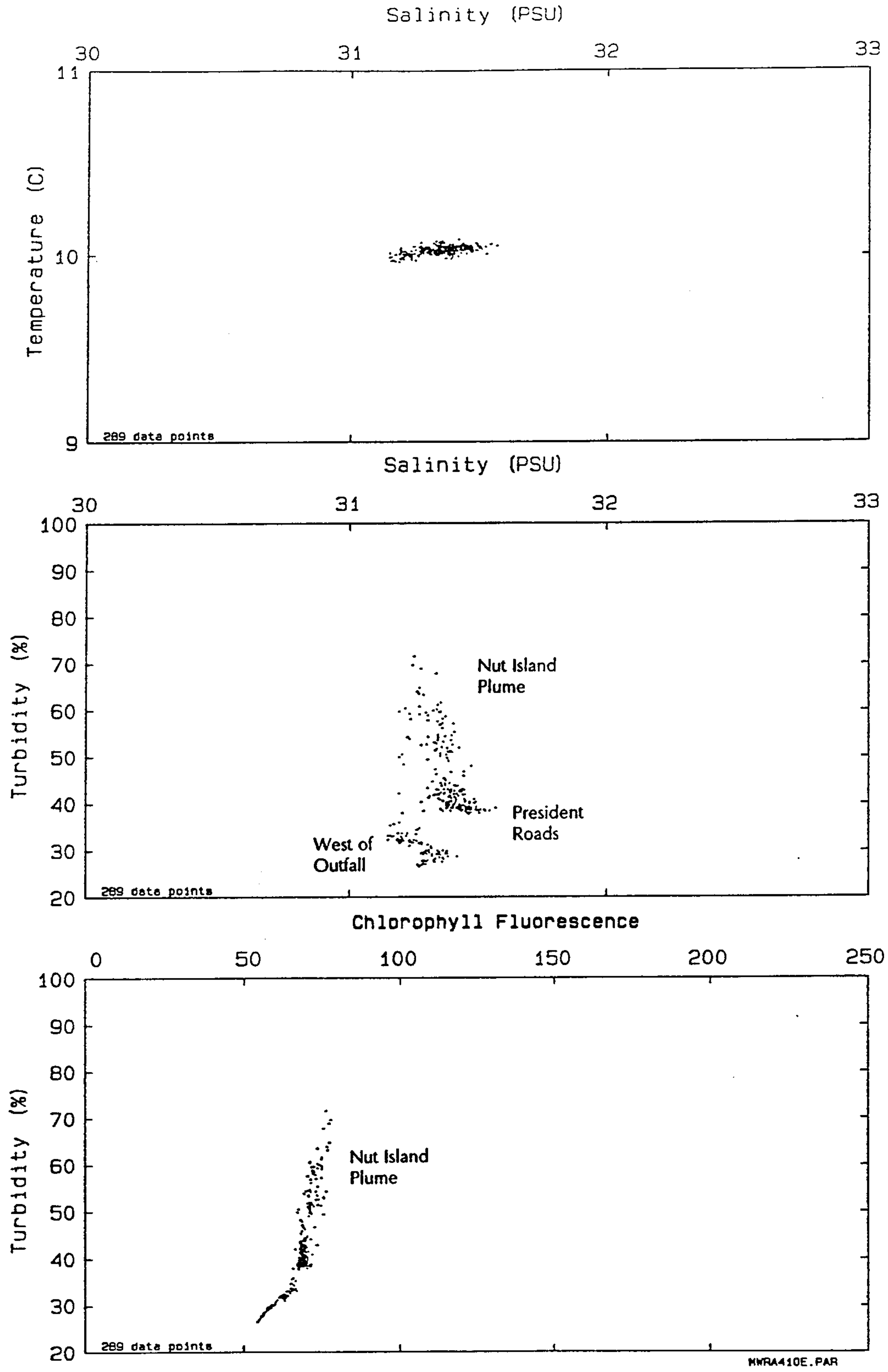

Figure 5-34. Scatter Plot of Data Acquired along Transect 10E Made on October 31, 1990

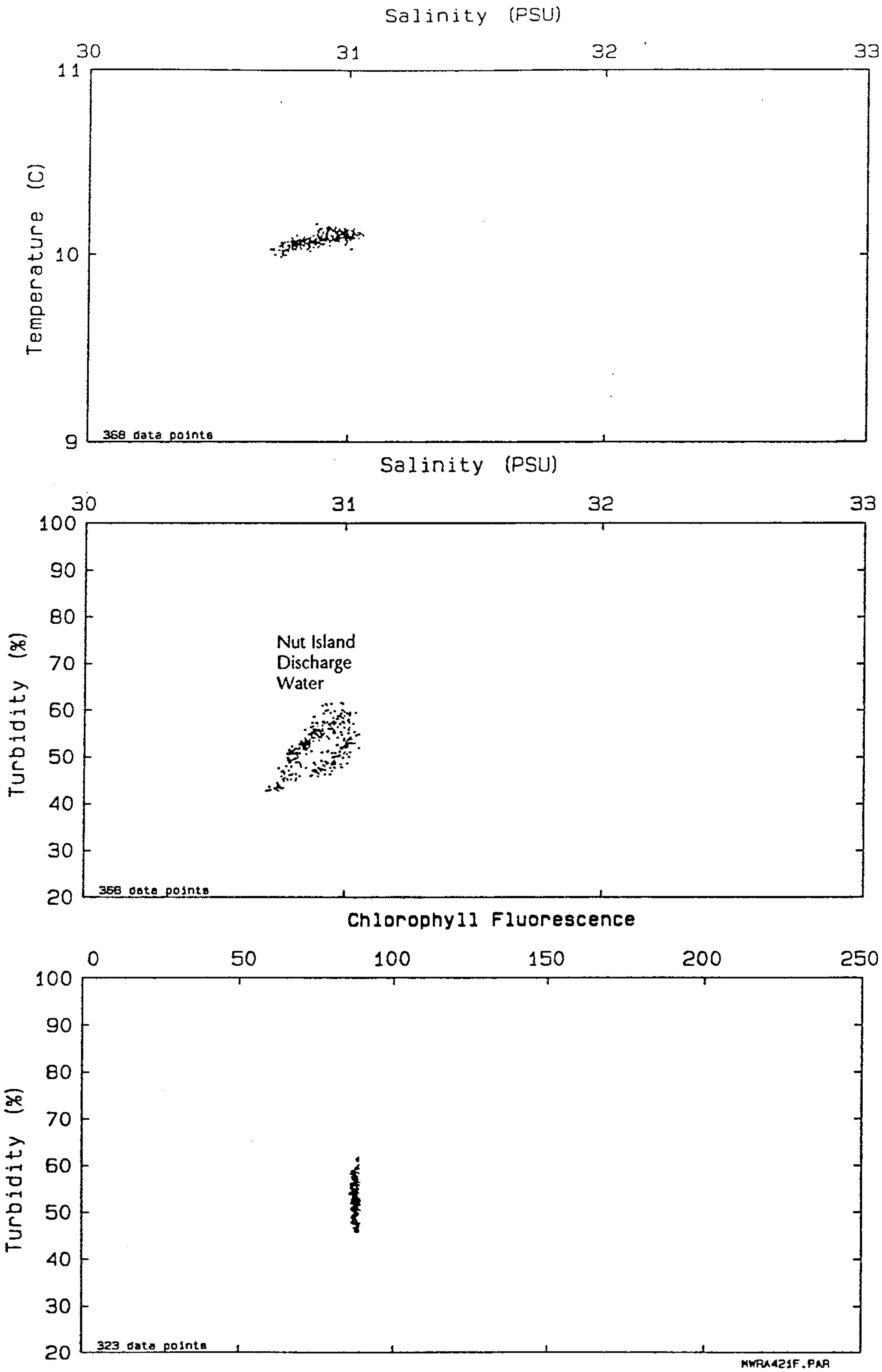

Figure 5-35. Scatter Plot of Data Acquired along Transect 21F Made on October 31, 1990

from the outfall, but that the sludge (suspended solids) concentrations had decreased significantly.

Shortly after the end of the discharge from the Nut Island outfall, there were only traces of sludge in the vicinity of the outfall. Figure 5-36 presents the location of transects 26 and 30 made at 1519 and 1602 h EST in the vicinity of the outfall. At the western end of transect 26, remnants of the Nut Island plume were recognizable from the consistent Tu/S properties (Figure 5-37) of the waters that resided in Nubble Cove (near the outfall). Salinities were consistently higher near the southern end of transect 26. At the time of transect 30 (1 h 35 min after low water), there were no traces of Nut Island sludge in the vicinity of the outfall; Tu/S properties were consistent along the transect (Figure 5-38).

5.3.3 Summary of Sludge Plume Behavior

As for the previous day of survey operations, the high-resolution, near-surface measurements of temperature, salinity, and turbidity along the horizontal transects were useful for distinguishing between the Nut Island sludge plumes and the less-turbid background waters within President Roads. Figure 5-39 presents composite T/S, Tu/S, and Tu/Chl scatter plots including all data acquired during the plume surveying activities on October 31, 1990. From comparison with the composite data from October 30 (Figure 5-22), it is apparent that the background water properties in the vicinity of the outfall had changed significantly between the two surveys. The low-salinity (<30.5 PSU) water associated with the Inner Harbor, which was detected on October 30, was absent on October 31. The Tu/S scatter plot in Figure 5-39 reveals that the high turbidity sludge was mixing with background waters that ranged in salinities from approximately 30.9 to 31.4 PSU, whereas on the previous day the range of salinities within the plume was considerably more narrow (Figure 5-22).

Background turbidity levels on October 31 were generally in the range from 30% to 45%, although the Tu/S data presented in Figure 5-39 suggest that much of the background water had turbidities in the range from 40% to 60% and salinities from 30.7 to 30.9 PSU. The large cluster of points having these characteristics was not, in fact, background water; these characteristics were actually associated with the effluent being discharged from the outfall. Because many of the October 31 transects were made near low water and at the beginning of the flood tide, many of the observations around the outfall were made after the sludge discharge had ceased, but the effluent discharge was appreciable.

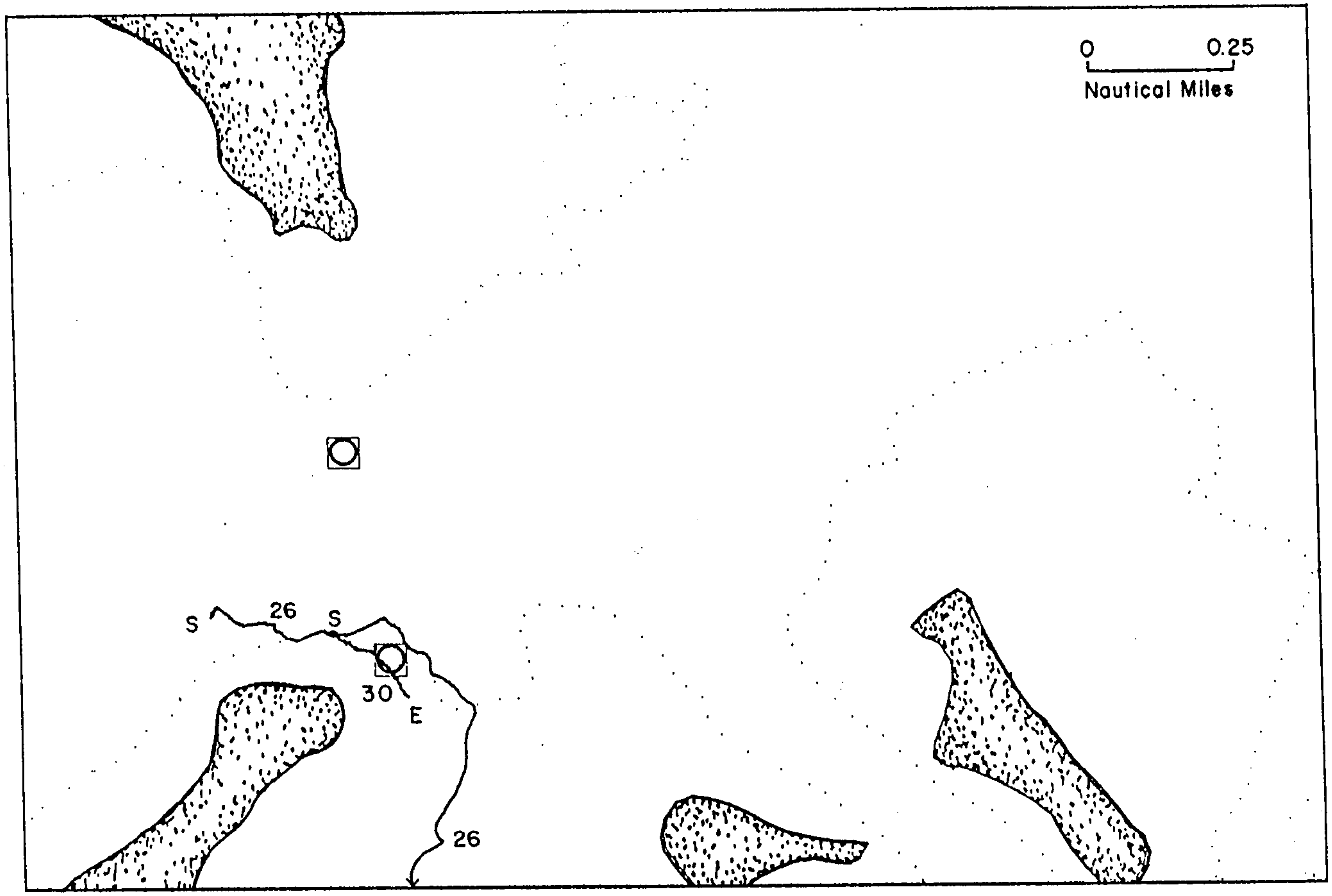

Figure 5-36. Expanded Map of President Roads Showing Location of Transects 26 and 30 on October 31, 1990

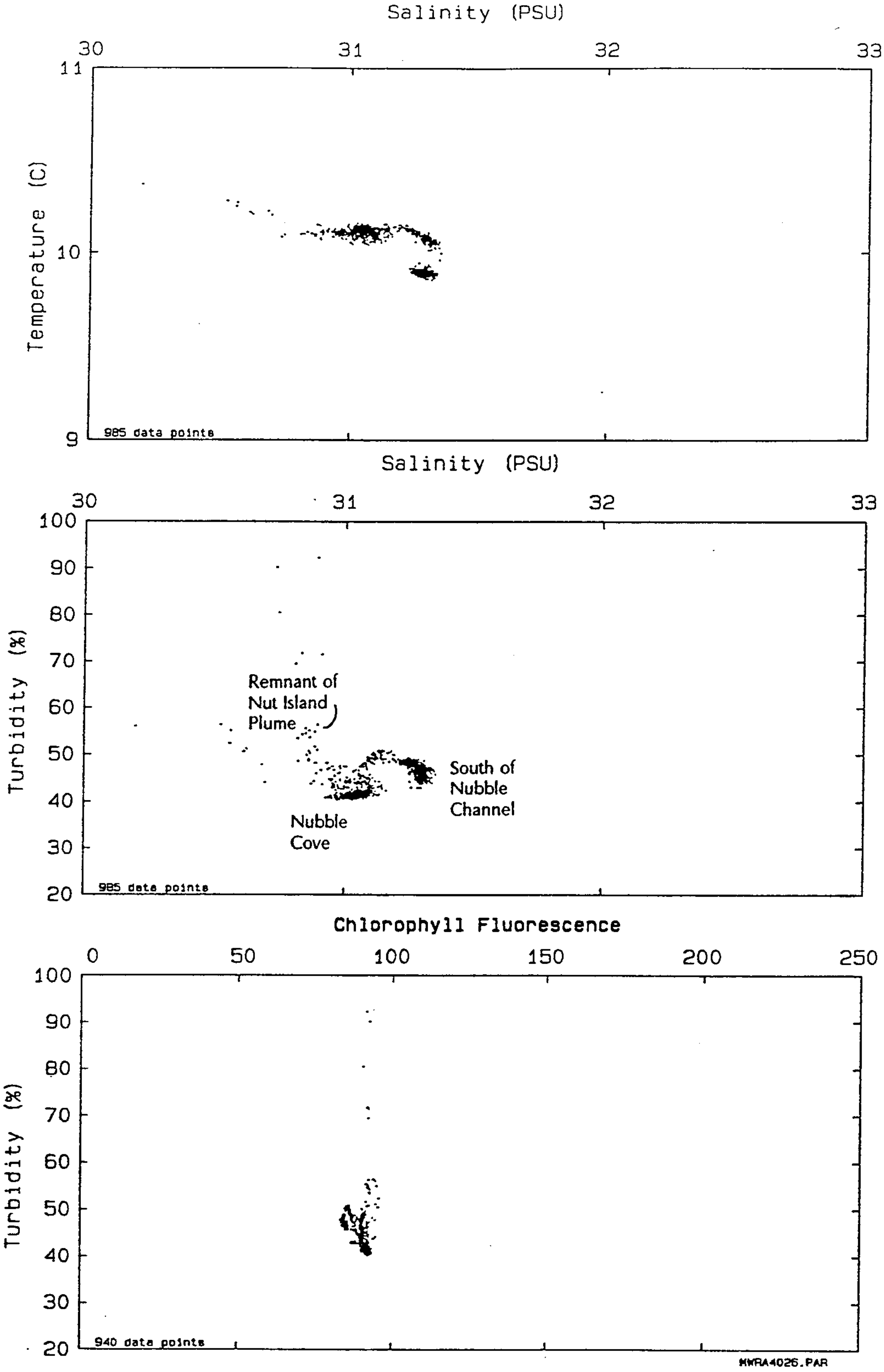

Figure 5-37. Scatter Plot of Data Acquired along Transect 26 Made on October 31, 1990

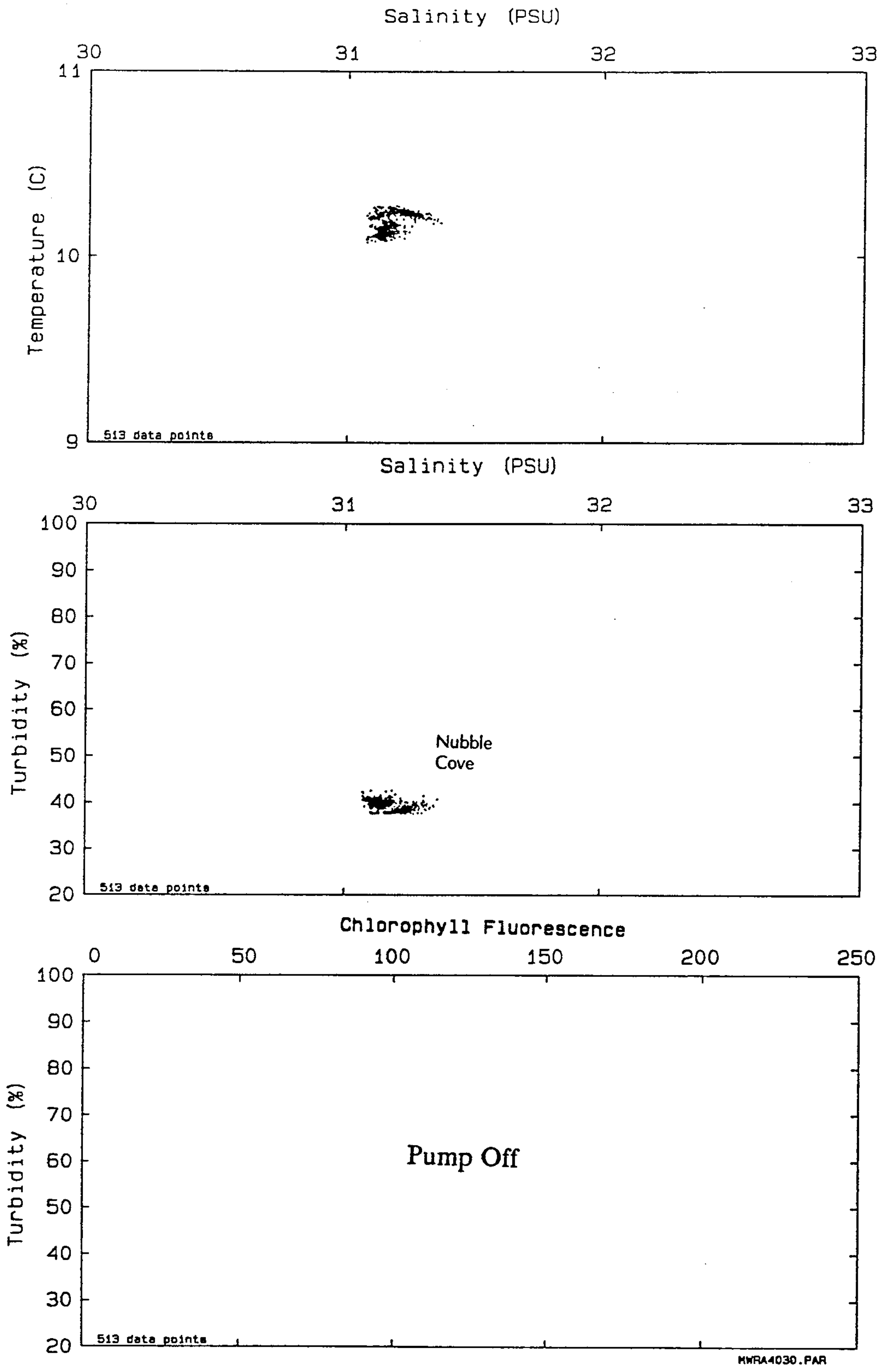

Figure 5-38. Scatter Plot of Data Acquired along Transect 30 Made on October 31, 1990

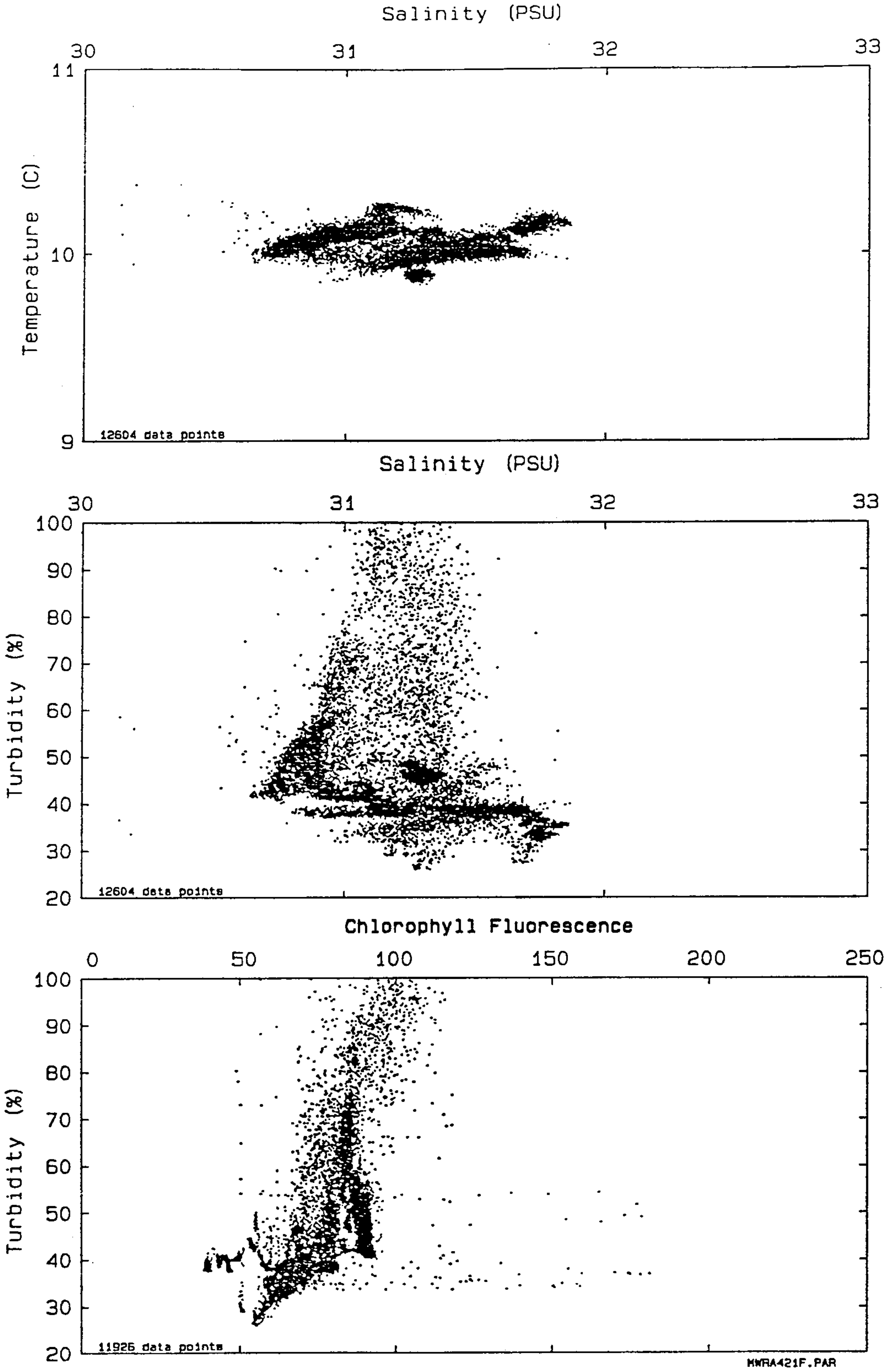

Figure 5-39. Composite Scatter Plot of All Data Acquired along Transects and at Vertical Profile Stations Made on October 31, 1990

Another interesting difference between the results from the two survey days is the substantially lower chlorophyll fluorescence values within the high-turbidity sludge plume on October 31 (Figure 5-39) compared with October 30 (Figure 5-22). Future studies would be required to determine the cause of this apparent variability.

As demonstrated in Section 5.2.3, analysis of the water properties along each transect and the concurrent navigation information allow one to effectively map the location of the Nut Island sludge plume within President Roads. Figure 5-40 presents a map of the study area within President Roads with shading that represents the spatial extent of the near-surface sludge plume emanating from the outfall. This plume map was derived from analysis of transects made between approximately 1.5 and 2.0 h after the time of predicted high water on October 31. This map illustrates that the plume was confined to a relatively small area near the outfall.

Over the next hour (Figure 5-41), the sludge plume remained very close to the outfall even though strong northward flow was observed in Nubble Channel. This flow of relatively low-turbidity, high-salinity water from the southern regions of the Harbor resulted in intense mixing (dilution) of the plume along its southern edge. Because this northward flow encountered increasing water depths in the vicinity of the plume, significant deceleration of the northward flow could also be expected in this region.

The results of the plume observations during the first 3 h of the ebb on October 31 illustrate that, **although the winds were strong from the north-northwest, the sludge plume did not move eastward to Nixes Mate as had been observed under less-intense wind conditions on October 30. In fact, the plume remained relatively stationary for the duration of the ebb flow period.** It should not, however, be interpreted that none of the water in this local area moves eastward; eastward flow is indicated by the drifter trajectories in Section 5.3.1. We suspect that the sludge plume was intensely diluted, near the outfall, by the strong northward flow from Nubble Channel. This highly diluted water actually moves eastward toward Nixes Mate Shoal (in agreement with the drifter tracks), but its sludge concentration is extremely low.

In conclusion, the strong north-northwest winds on October 31 caused (1) intensified northward flow across Nubble Channel, (2) intense, local dilution of the sludge plume near the outfall, and (3) reduced eastward advection as compared with the flow condition observed on October 30.

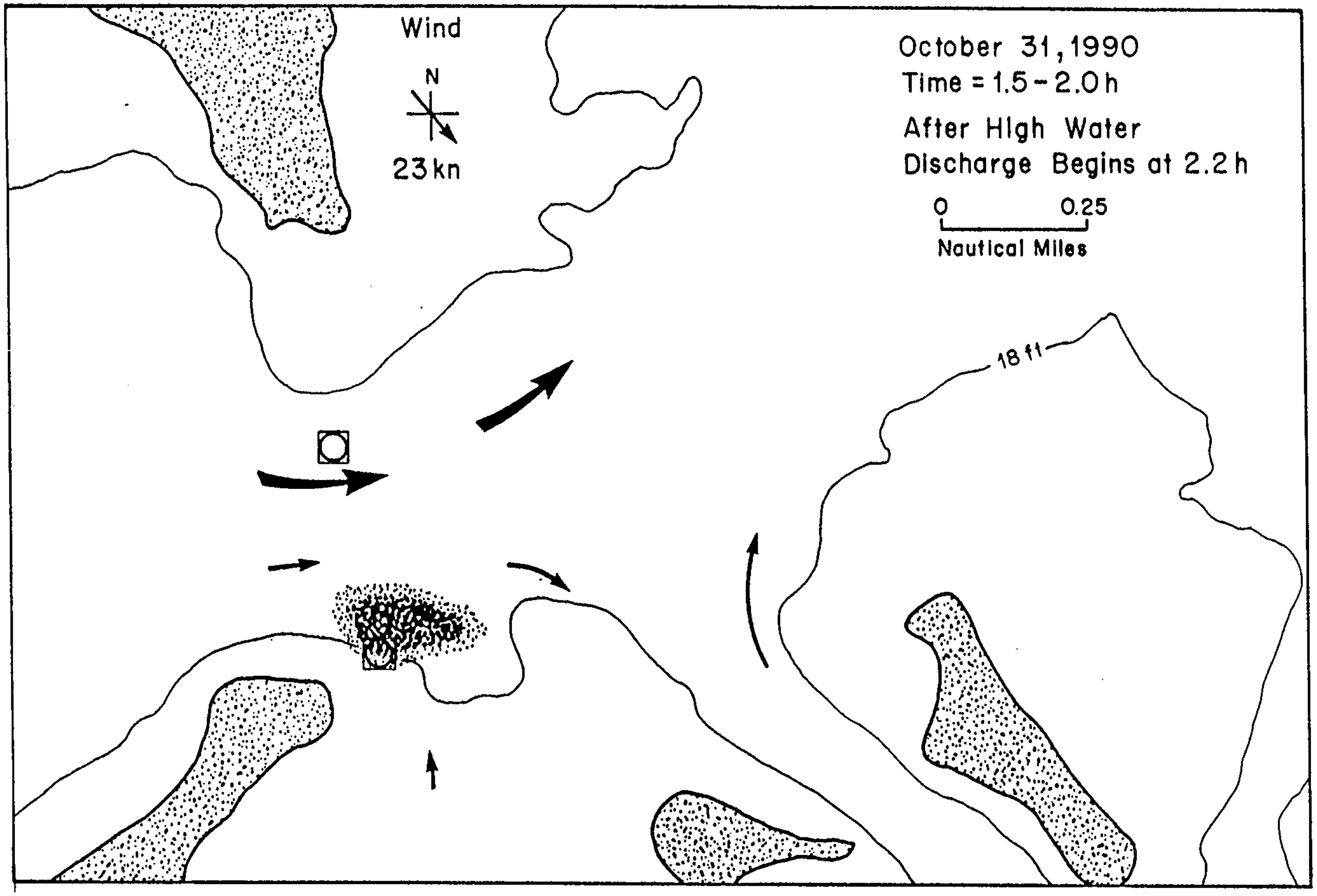

Figure 5-40. Map of President Roads Showing Plume Locations 1.5 to 2.0 h after High Water on October 31, 1990. Arrows Represent Flow Direction.

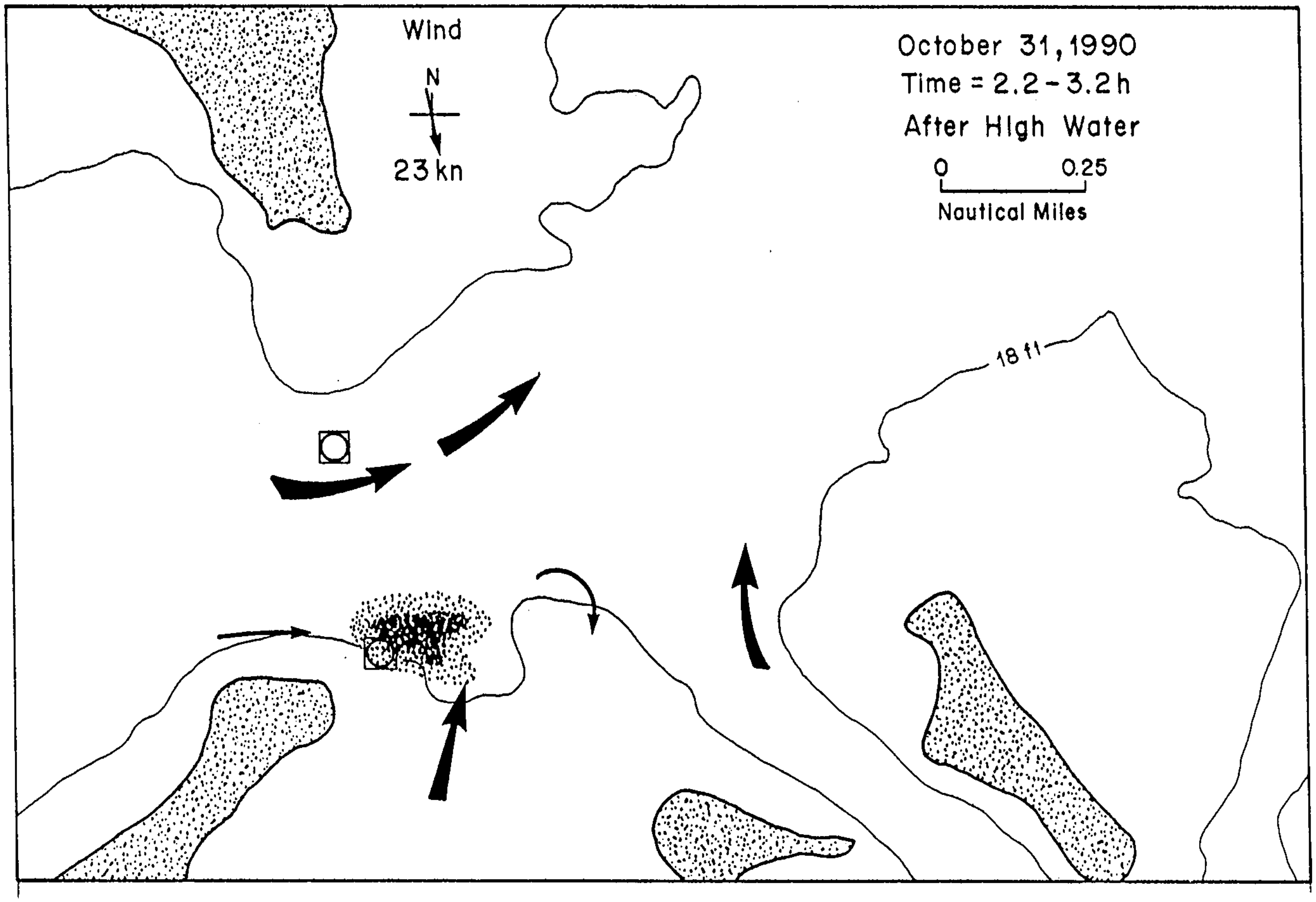

Figure 5-41. Map of President Roads Showing Plume Locations 2.2 to 3.2 h after High Water on October 31, 1990

As described previously, the sludge discharge from the outfall appeared to continue until approximately 28 min after the beginning of the incoming tide. Figure 5-42 illustrates the location of the plume and the general flow regime during the period from approximately 6.0 to 6.4 h after high water. Although the turbidity values within the plume (and in the discharge water) were lower than earlier in the ebb period, the plume could be unmistakably delineated from the background waters as it was advected westward past the northern tip of Long Island.

Later in the flood cycle, and presumably after the sludge discharge had ceased (Figure 5-43), the plume of dilute sludge and effluent could be detected in the near-shore waters along Long Island. Surveying operations were suspended following the acquisition of these results.

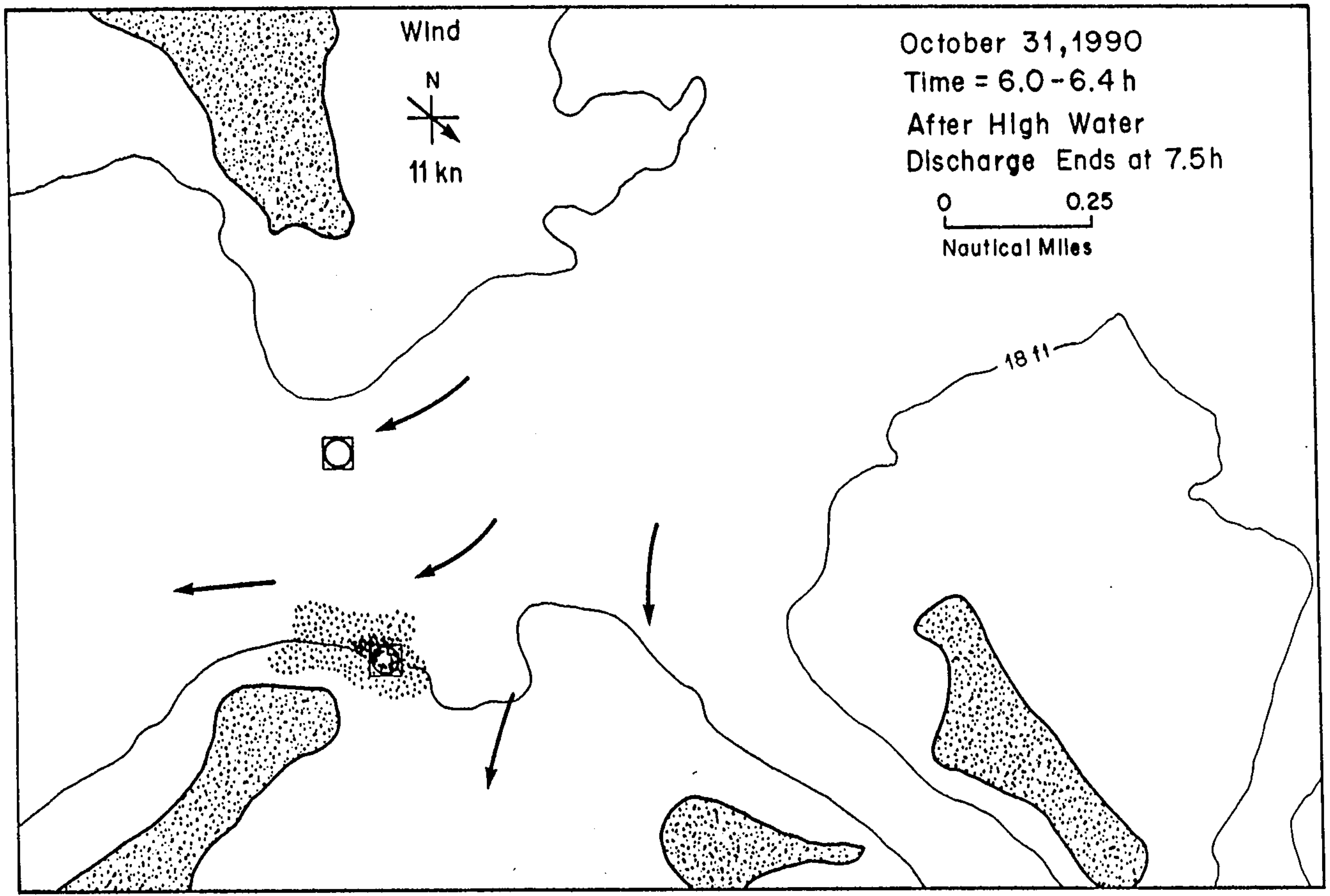

Figure 5-42. Map of President Roads Showing Plume Locations 6.0 to 6.4 h after High Water on October 31, 1990

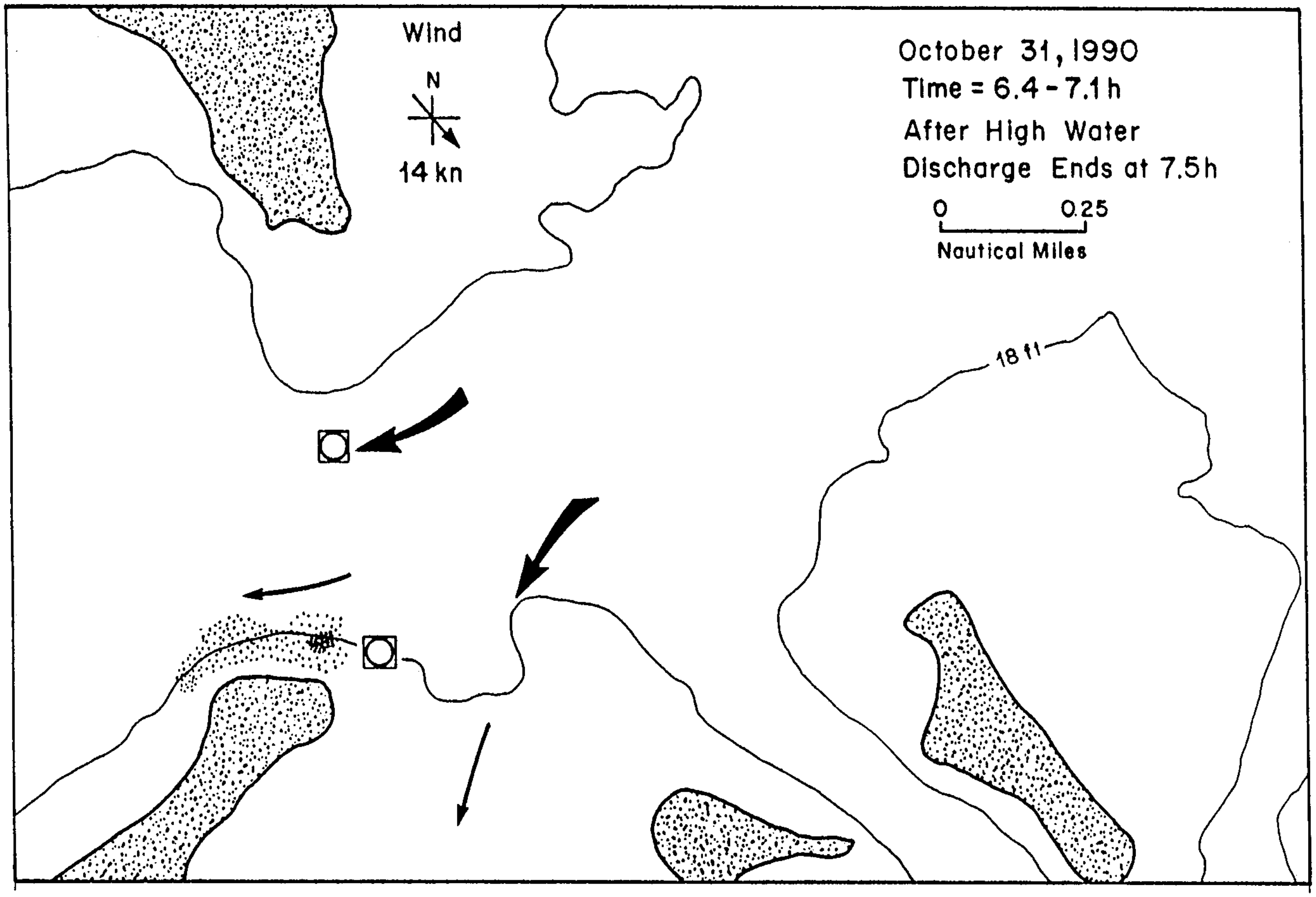

Figure 5-43. Map of President Roads Showing Plume Locations 6.4 to 7.1 h after High Water on October 31, 1990

6.0 DISCUSSION

6.1 BACKGROUND WATER PROPERTIES THROUGHOUT THE HARBOR

As indicated in Section 1.2, Objective 1 of the study was met by synoptic mapping of the spatial variability of water properties within Boston Harbor near high water, then again near low water on the same day to determine the temporal variability over one tidal cycle. Answers are given below for the specific questions associated with Objective 1. Supporting results are given in Section 3.0.

1. Are the water properties within the northern part of the Harbor significantly different from those within the southern part of the Harbor during a synoptic high- or low-water survey?

   Yes. The temperature, salinity, turbidity, and chlorophyll fluorescence concentrations differ significantly between the northern and southern parts of the Harbor during a single, synoptic survey at either high or low water.

2. Can specific water types within the Harbor be identified and uniquely associated with source regions (e.g., Dorchester Bay)?

   Yes. Each of the bays within the northern and southern parts of the Harbor have specific water properties that can be used to distinguish the origin of waters that are horizontally advected within the Harbor.

3. Can a conceptual model of the circulation and mixing within the Harbor be developed from analysis of the water properties from a single, synoptic, high- or low-water survey?

   Yes. From the spatial water-property data acquired during the synoptic, high-water survey, one can develop a model of the transport pathways of waters from the various "sources." Furthermore, mixing schemes can be developed to identify bays and channels that exchange water and those that do not. The results from the low-water survey can be used to develop an independent model of water transport and mixing within the Harbor at low water.

4. Do water properties at specific locations within the Harbor vary significantly over one tidal cycle?

   Yes. At most locations within the Harbor, water properties change significantly over the tidal cycle because of horizontal advection of waters from varying sources.

5. Can qualitative conclusions be drawn about flushing at specific locations in the Harbor from analysis of the temporal variability in water properties over one tidal cycle?

Yes. Over a tidal cycle, water properties varied greatly in Nantasket Roads and other areas in the southern Harbor because of strong tidal flushing. The exception was in Quincy Bay, where flushing is apparently limited. In the northern Harbor, water property variations were less than in the southern Harbor because of relatively less flushing. These results are consistent with numerical models of circulation and mixing within the Harbor.

6.2 NUT ISLAND EFFLUENT PLUMES

Objective 2 was met by mapping the horizontal advection and dilution of the Nut Island sewage effluent plumes emanating from the three outfalls located in Nantasket Roads. Synoptic surveys were conducted during the ebb flow on two consecutive days. Answers are given below for the specific questions associated with Objective 2. Supporting results are given in Section 4.0.

1. Are the water-property characteristics of the sewage effluent significantly different from the receiving waters to allow tracking of the effluent plumes within Nantasket Roads?

   Yes. Although the turbidity levels within the effluent plumes were only moderately elevated over the turbidity of the background waters, the turbidity/salinity characteristics of the effluent plume could be used to differentiate between the dilute effluent and the background waters.

2. Can the separate plumes from the three outfalls be tracked as they are advected eastward within Nantasket Roads?

   Yes. The plumes originating from the three outfalls could each be tracked as they were advected generally eastward within Nantasket Roads. However, in regions where the plumes intersected, it was difficult to differentiate among them because they all had the same characteristics, having originated from the same source at Nut Island.

3. Do significant concentrations of effluent enter Portuguese Cove on the west side of Peddocks Island as predicted by Signell's numerical model (Bothner *et al.*, 1990)?

   On October 16 when the wind was from the west, effluent discharged from the southern and northeastern outfalls moved directly into Portuguese Cove. Portuguese Cove was not affected by effluent on October 17 when the winds were from the southwest.

4. Does relatively concentrated effluent reach Massachusetts Bay on a single ebb tide?

   Probably not, because the mixing within the eastern portion of Nantasket Roads is relatively active, especially on the south side of the channel, which is influenced by the strong flow from Hull Gut. The field study did not provide definitive results because the majority of the water-property transects were made within a few miles of the outfalls.

   Drifters released from the outfalls at the beginning of the ebb did show that water parcels can reach Massachusetts Bay during a single ebb period, but near-surface mixing enroute is believed to be strong enough to dilute the effluent beyond recognition by the Mini-BOSS sensors.

6.3 NUT ISLAND SLUDGE PLUMES

Objective 3 was met by mapping the horizontal advection and dilution of the Nut Island sewage sludge plumes emanating from the outfall located north of Long Island in President Roads. Synoptic surveys were conducted during the ebb flow on two consecutive days. Answers are given below for the specific questions associated with Objective 3. Supporting results are given in Section 5.0.

1. Does the sludge remain as a concentrated plume that exits the Harbor on the ebb flow via South Channel?

   No. The sludge plumes observed on the two survey days were actively mixed and diluted in the vicinity of the outfall and on the shoals around Nixes Mate. There were no indications that concentrated sludge exits the Harbor via South Channel.

2. Or, does the sludge remain in the vicinity of the outfall near Long Island throughout the ebb period, then get carried into the Harbor on the flood tide? If so, is the sludge carried westward past Long Island or does it enter the southern Harbor via Nubble Channel or through the Narrows?

   Yes. Sludge released during the early stages of the ebb will be extensively diluted by northward-flowing waters from Nubble Channel and waters from President Roads. The dilute sludge may remain in the vicinity of Nixes Mate until the incoming tide carries it southwestward across Nubble Channel and into the southern Harbor.

   Sludge released near low tide will experience limited dilution while it remains near the outfall. With the incoming tide, it will be carried westward past the tip of Long Island.

3. Did the characteristics of the receiving water around the sludge outfall vary over the 6-h ebb?

   Yes. The turbidity, salinity, and chlorophyll fluorescence characteristics of the receiving water changed significantly during the 6-h ebb on both survey days. Major temporal differences in these water properties were also observed between the 2 days.

4. Does the initial behavior of the sludge plume created on each ebb tide vary according to wind conditions and other effects?

   Yes. With mild winds from the west on October 30, the plume was quickly advected eastward to Nixes Mate Shoal, whereas on October 31, when the winds were strong from the north-northwest, the plume remained near the outfall. These differences may be due to major variations in the intensity of the flow across Nubble Channel from variations in the wind.

5. Do high concentrations of sludge reach the seafloor in the vicinity of the outfall or neighboring regions?

   Sludge may settle in the immediate vicinity of the outfall due to the relatively weak local currents, but the plume is confined primarily to the upper few meters of the water column. On the ebb, sludge does impact the shallow regions near Nixes Mate. On the flood tide, concentrated sludge that is discharged near the time of low water intersects the shoreline at the north and west side of Long Island. Moderately dilute sludge may also enter Nubble Channel on the incoming tide.

   In regard to this question, we note that the MIT-UNB Field Study conducted in conjunction with the mini-BOSS sampling will address this question in additional detail.

6.4 BOSTON HARBOR DISCHARGE INTO MASSACHUSETTS BAY

Objective 4 was met by monitoring the eastward injection of Boston Harbor waters from Nantasket Roads into Massachusetts Bay, as time permitted. Answers are given below for the specific questions associated with Objective 4. Supporting results are given in Section 4.2.4.

1. How far eastward do Boston Harbor waters penetrate into Massachusetts Bay during one ebb tide?

   Combined results from drifter trajectories and a single, eastward Mini-BOSS transect suggest that waters leaving Nantasket Roads on the ebb flow may reach approximately 3.5 nmi east of Boston Light before they change direction with the incoming tide. Additional field measurements are needed to validate this result.

2. Is there a recognizable water-property front at the eastern boundary of the Boston Harbor plume that penetrates into Massachusetts Bay on the ebb tide?

   A single transect was made from Nantasket Roads into Massachusetts Bay during the ebb on October 16. This transect revealed a water-property front that may have marked the boundary between Harbor waters and Massachusetts Bay water, but additional field measurements are needed to substantiate this result.

6.5 ASSESSMENT OF SURVEY TECHNIQUES

Survey Vessels

The R/V *Surveysa* and the *Seaquest,* both chartered from TG&B Marine Services, Inc., proved to be excellent, reliable vessels for Mini-BOSS surveying and drifter tracking in Boston Harbor. Their shallow draft allowed profiling and drifter recoveries in shallow, nearshore areas. The vessel operators provided by TG&B were also highly experienced in navigation within the Harbor.

Navigation

Loran C positioning proved adequate for the Mini-BOSS surveying and drifter tracking, although neither the absolute accuracy nor the spatial resolution of the Loran C data were comparable to those which could have been provided by a microwave navigation or GPS system. The Loran C data acquired during the survey had to be geographically adjusted by using offsets determined from field measurements at selected calibration sites. Significant time averaging was also necessary to eliminate the large variability from fix to fix.

With the high-resolution capabilities of a microwave system, it would have been possible to construct a predetermined grid of survey lines that could be followed by the vessel operator, with the result of better overall survey coverage, especially in small survey regions such as near the Nut Island sludge outfall.

Mini-BOSS Profiling System

The Mini-BOSS proved to be an excellent system for acquiring high-resolution water-property data along horizontal transects or at vertical-profile stations. The integrated Loran C positioning capability and the water-sample delivery system to the flowthrough Turner fluorometers proved extremely useful.

Although most of the horizontal transects were conducted at towing speeds of 4 kn, the system was capable of towing at up to 7 kn.

The only problem encountered with the Mini-BOSS was associated with damage to the electrical conductors within the electromechanical termination immediately above the towfish. This occurred on October 18, when seas of roughly 3 ft caused extensive shock loading and strain on the profiling cable. Modifications to the design of the Mini-BOSS handling system and profiling cable are being considered to eliminate this mechanical problem.

Drifter Tracking

The modified Davis drifters proved to be excellent followers of the surface currents during the field study. Even under strong wind conditions, the drifters exhibited minimal effects from the wind. Furthermore, drifters released in clusters generally remained in tight clusters for periods of many hours, demonstrating that individual drifter tracks were representative of the surface flow.

Visual tracking and Loran C positioning of the drifters proved acceptable for this field study. The dedicated drifter-tracking vessel was capable of obtaining fixes at intervals of once or twice per hour for nearly all of the drifters released. A small number of drifters were lost during 5 days of tracking operations, but some of these were found and returned to Battelle during the weeks following the field survey.

6.6 RECOMMENDATIONS FOR FUTURE STUDIES

Based upon the results from the recent surveys in Boston Harbor, we present the following recommendations for additional analyses of the survey data, as well as additional surveys aimed at specific water-quality issues.

Background Water Properties within Boston Harbor

- Further analyze the water-property data acquired on November 1, including comparisons with existing data acquired by UMB and the NEA. Evaluating the appropriateness of the sampling stations of the NEA Ten-Year Boston Harbor Monitoring Program may be of interest.

- Develop a conceptual circulation/mixing model of the Harbor based upon the water-property data acquired on November 1. Comparisons could be made with numerical models developed at MIT and USGS.

- Design and implement another synoptic field survey of water properties throughout the Harbor, with focus on the mixing of waters from the Inner Harbor and the Neponset River within President Roads. Determining the source of waters that reside in the shallow, western regions of Quincy Bay is also an interesting measurement topic because it is not clear whether local pollution is due to Nut Island sludge and effluent and/or local sewer overflows, contamination of storm drains, or failing septic systems.

Nut Island Effluent Plumes in Nantasket Roads

- Provide the drifter data acquired on October 16 and 17 to R. Signell at USGS for the purpose of calibration of the numerical model of the circulation in the southern Harbor. The effluent plume trajectory data can also be compared with trajectories predicted by the model. The trajectories of drifters entering Massachusetts Bay are also useful for validation of Signell's model prediction of injection of Nantasket Roads water into Massachusetts Bay.

- Conduct a survey for tracking the Nut Island effluent plumes on the incoming tide to identify inshore regions that are highly impacted by the effluent. Direct observations will indicate whether significant quantities of effluent are transported into Quincy Bay, Hingham Bay, or the Weymouth area.

Nut Island Sludge Plumes in President Roads

- Collaborate with UMB on calibration of the Mini-BOSS transmissometry data using TSS results from discrete water samples analyzed by UMB.

- Collaborate with MIT on calibration of the Mini-BOSS dye fluorescence data using dye results from discrete water samples analyzed by MIT.

- Use the calibrated TSS and dye results from October 30 to determine dilutions versus time within the sludge plume.

- Provide the drifter data acquired on October 30 and 31 to R. Signell at USGS for the purpose of calibration of the numerical model of the circulation in the northern

Harbor. The sludge plume trajectory data can also be compared with trajectories predicted by the model.

- Conduct a survey for tracking the Nut Island sludge plume on the incoming tide to determine whether detectable levels of sludge are transported into the Harbor along Long Island and possibly into Dorchester and Quincy Bays.

Water Properties in Massachusetts Bay

- Design and implement a synoptic survey of water properties offshore of Nantasket Roads over an ebb tidal cycle and the early stages of the flood tide. The purpose would be to identify the spatial boundaries of the Harbor water that is injected into Massachusetts Bay and compare the results with Signell's model (Bothner *et al.,* 1990).

- Design and implement high-resolution Mini-BOSS surveys of water properties in western Massachusetts Bay to obtain continuous chlorophyll fluorescence, turbidity, and CTD data along transects and at selected vertical-profile stations. Water samples can be collected at distinct water-property boundaries for postsurvey laboratory analysis of chlorophyll-*a* and nutrient concentrations. The purpose of these surveys would be to identify synoptic, small-scale variations in physical, chemical, and biological water properties in the vicinity of the proposed outfall in Massachusetts Bay. Accurate, seasonal studies of the background water properties prior to sewage discharge will be extremely useful for predictions and later field studies of the effects of the offshore sewage discharge.

7.0 REFERENCES

Battelle 1989. A Pilot Study of the Deer Island and Nut Island Sewage Outfalls within Boston Harbor: June 8-9, 1989. Report submitted to the Massachusetts Water Resources Authority, Boston, MA.

Bothner, M.H., C.M. Parmenter, A.B. Brown, and R.P. Signell. 1990. Studies of Circulation and Pollutant Transport in Massachusetts Coastal Water. USGA Open File Rep. 90-328. February 1990.

EG&G 1984. Oceanographic Study of Various Outfall Siting Options for the Deer Island Treatment Plant. Report submitted to Havens & Emerson/Parsons-Brinkerhoff.

The Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Charlestown, MA 02129
(617) 242-6000