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<u>Providence River Wet Weather Current Meter Study Data Report</u>

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Turner, Puckett, Isaji, Feng (ASA, Inc.)

Narragansett Bay Estuary Program

PROVIDENCE RIVER WET WEATHER CURRENT METER STUDY DATA REPORT

Prepared by:

A. Christian Turner
Suzanna Puckett
Tatsusaburo Isaji
Shih-shing Feng

Applied Science Associates, Inc.
70 Dean Knauss Drive
Narragansett, Rhode Island 02882

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FOREWORD

The United States Congress created the National Estuary Program in 1984, citing its concern for the "health and ecological integrity" of the nation's estuaries and estuarine resources. Narragansett Bay was selected for inclusion in the National Estuary Program in 1984 , and the Narragansett Bay Project (NBP) was established in 1985. Narragansett Bay was designated an "estuary of national significance" in 1988. Under the joint sponsorship of the U.S. Environmental Protection Agency and the Rhode Island Department of Environmental Management, the NBP's mandate is to direct a program of research and planning focussed on managing Narragansett Bay and its resources for future generations.

The NBP will develop a draft Comprehensive Conservation and Management Plan (CCMP) by December, 1991, which will recommend actions to improve and protect the Bay and its natural resources.

The NBP has established the following seven priority issues for Narragansett Bay:

- management of fisheries
- nutrients and potential for eutrophication
- impacts of toxic contaminants
- health and abundance of living resources
- health risk to consumers of contaminated seafood
- land-based impacts on water quality
- recreational uses

The NBP is taking an ecosystem/watershed approach to address these problems and has funded research that will help to improve our understanding of various aspects of these priority problems. The Project is also working to expand and coordinate existing programs among federal, state and local agencies, as well as with academic researchers, in order to apply research findings to the practical needs of managing the Bay and improving the environmental quality of its watershed.

This report represents the technical results of an investigation performed for the Narragansett Bay Project. The information in this document has been funded wholly or in part by the United States Environmental Protection Agency through Cooperative Agreement #CX812768 to the Rhode Island Department of Environmental Management. It has been subject to the Agency's and the Narragansett Bay Project's peer and administrative review and has been accepted for publication as a technical report by the Management Committee of the Narragansett Bay Project. The results and conclusions contained herein are those of the author(s), and do not necessarily represent the views or recommendations of the NBP.

This report is one component of a study coordinated by Dr. Raymond M. Wright: "Problem Assessment and Source Identification and Ranking of Wet Weather Discharges Entering the Providence and Seekonk Rivers". The interested reader is encouraged to investigate this reference for a comprehensive analysis of wet weather discharges from point and nonpoint sources of pollution in the Providence River drainage system.

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EXECUTIVE SUMMARY

A current and tide height measurement study was conducted as part of the Narragansett Bay Project Wet Weather program during the fall of 1988 and summer of 1989. The principal goal of the study was to provide continuous information on water motion and the behavior of the salinity field in the study area during three storms selected for the study. Current meter arrays consisting of near-surface and near-bottom meters were deployed at the edge of the shipping channel in the Gaspee Point-Bullock Point transect and at the south end of Fields Point in the Providence River. A fifth current meter was deployed near the bottom near Cold Spring Point in the lower Seekonk River. Tide heights were measured at the Port Edgewood Marine Facility, located just south of Fields Point and data were obtained from the National Ocean Survey Gauge at the State Pier north of Fields Point. Supplemental wind data were obtained from Green Airport in Warwick; USGS river flow data for the five tributary rivers to the area were obtained from other researchers.

The first instrument deployment was made between September 17 - November 7, 1988. Results were disappointing. The two Gaspee-Bullock Points transect meters were serviced on October 21, shortly before the first wet weather study and found to be malfunctioning. The tide gauge also failed to operate. The results of the second and third deployments were much more successful.

The three deployments produced nine current time series at four locations in the Providence River and three near-bottom current records from the lower Seekonk River, accompanied by tide height, wind and river flow data for the wet weather study periods.

A series of graphic products and time series were produced from the raw time series data, which included the speed and direction probability distributions for each record, progressive vector diagrams, raw and low pass filtered versions of the data, the extraction of tidal constituents from the data, and the calculation of coherence spectra to evaluate the coherence of current response to the forcing of local winds.

The data revealed that the influence of the first and third study (October 22-26, 1988 and June 13-16, 1989) storms on the circulation and salinity fields was noticeable, but small in relation to the typical tidal, wind and density-driven variations. The May 10-15, 1989 storm produced a strong down-estuary flow of low salinity water at the surface of the Providence River.

Examination of the data obtained by the study revealed the diversity in the character of the circulation in each area which was strongly influenced by the geometry in the area and upstream of the measurement station. These results suggest

that the characterization of the circulation in an area similar to the one studied may not be accomplished by a limited set of observations.

1. INTRODUCTION

1.1 Context of the Study

The present study is the current and tide height measurement element of a larger program of wet weather studies of the Providence River and Upper Narragansett Bay, funded by the Narragansett Bay Project during 1988-1989. The major objectives of the Wet Weather Study Program are to:

- Quantify the contributions of rivers and selected combined sewer overflows (CSO) as point sources of pollutants to the Providence River, based on measurements during and after three storms.

- Measure the characteristics of mass transport and pollutant behavior in the Providence River before, during and after the storms.

The information obtained from the combined wet weather program will serve to characterize pollutant levels in the area following rainstorms and as a data source for use in the development of time-dependent water quality models of the Providence River-Upper Bay system. The data will also provide planners and managers with information on the relative strengths of different sources.

The current and salinity measurement program presented in this report was conducted to provide information to resolve the circulation in the estuary during the wet weather studies. This information is important for two reasons. First, the distributions of pollutants in the study area are to a large extent controlled by the circulation. Knowledge of the circulation is therefore helpful in explaining pollutant behavior. Second, the data provide information which is necessary in the model calibration and verification process.

1.2 Description of the Study Area

The wet weather program study area, shown in Figures 1.1 and 1.2, lies at the head of the Narragansett Bay and is comprised of the Seekonk River, Providence River, and Upper Narragansett Bay. The area encompassed by the present study consists of the Providence and Seekonk Rivers. The Providence River is formed by the confluence of the Moshassuck and Woonasquatucket Rivers in the center of Providence. From its head, the river runs south approximately 2 km to the hurricane barrier at Fox Point. The river is generally quite shallow and narrow in this reach. At low tide, the river almost empties, becoming completely fresh as far south as the I-195 bridge. Below the bridge, the river widens to 100-150 m and deepens to 3-7 m. Just below the hurricane

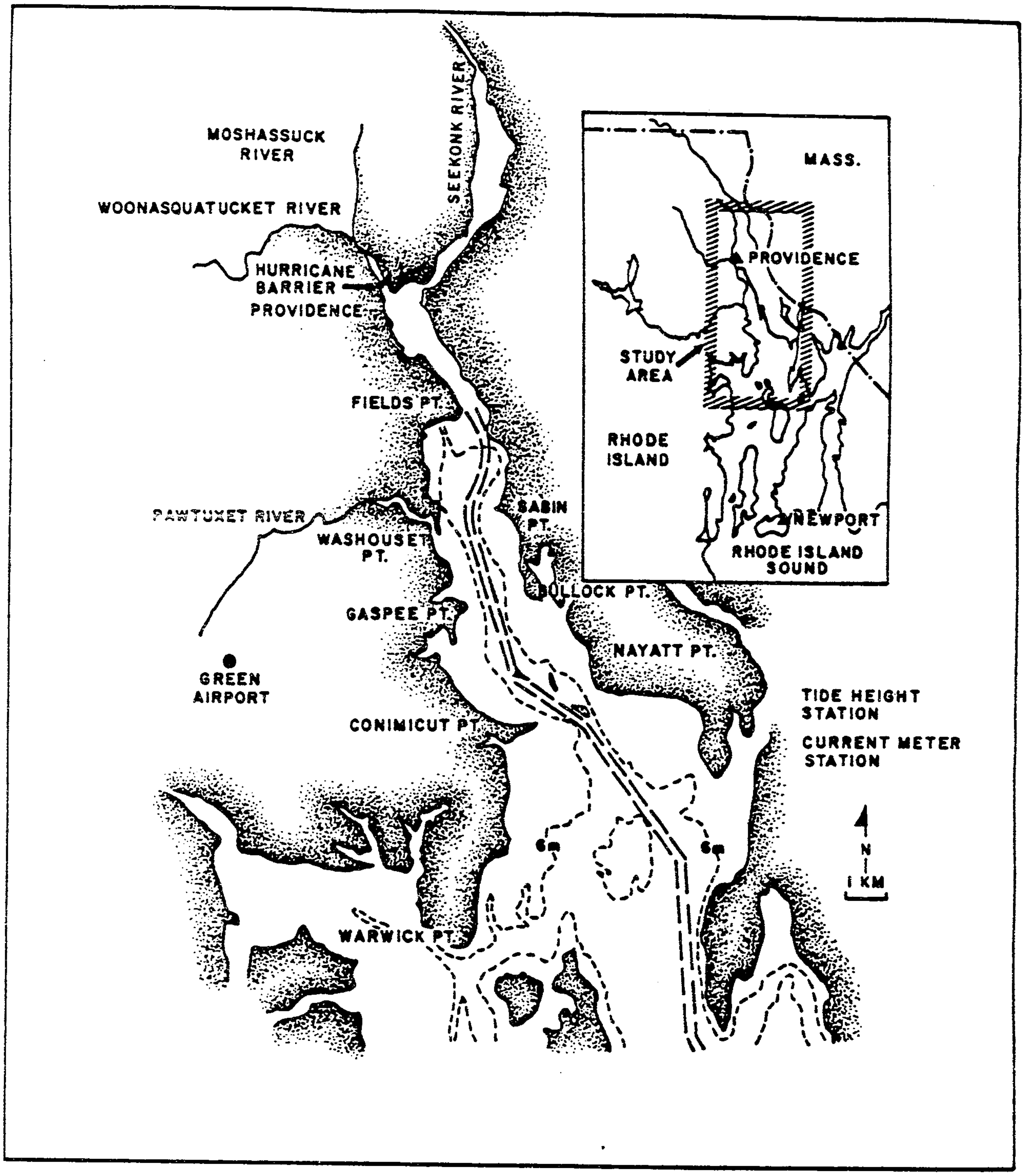

Figure 1.1 The Providence River and Upper Narragansett Bay

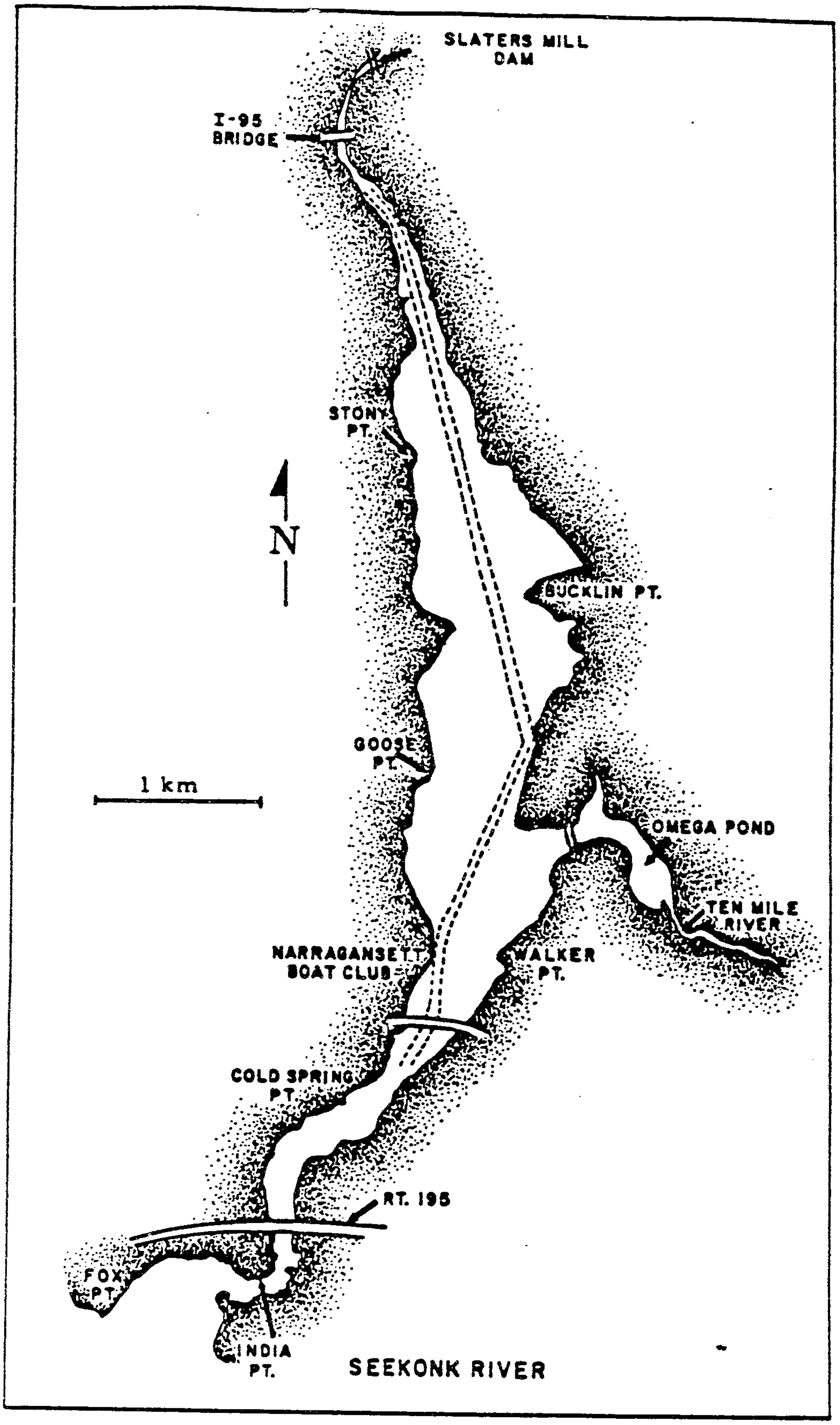

Figure 1.2 The Seekonk River

barrier at India Point, the Seekonk River joins the Providence River. Below this point, the Providence River is relatively wide (500 m). It expands to around 2 km below Fields Point and continues to widen to its mouth at Conimicut Point, 11.6 km south of Fox Point, where it becomes Upper Narragansett Bay.

A navigation channel runs from Upper Narragansett Bay to Fox Point (Figure 1.1). The channel depth is 12.2 m at MLW. It is typically 200 m wide below Fields Point and is flanked by wide shallow areas typically 1-2 m deep. Above Fields Point the 12.2 m deep dredged area widens to both banks of the river (500 m) to accommodate shipping traffic. At Mean Low Water (MLW), the surface area of the Providence River below India Point is 21.321 km^2, its volume is 8.51×10^7 m^3 and its mean depth is 4 m (Chinman and Nixon, 1985).

The Seekonk River (Figure 1.2) is an estuary which begins where the Blackstone River discharges over the Slaters Mill dam in downtown Pawtucket. It runs in a southerly direction for approximately 8 km from the dam at Pawtucket to the head of the Providence River at Fox Point. The river is generally quite narrow, ranging from 100 to 400 m in width over most of its length. The central section from Walker to Bishop Point, however, is much wider with a typical width of 650 m. The river is generally quite shallow with a major portion of the river bottom in the central region exposed at mean low tide. A relatively deep (5 m), narrow (45 m) dredged channel extends from Cold Spring Point to just below the dam. The MLW surface area of the Seekonk River is 2.81 km^2. Its volume is 3.63×10^6 m^3 and the mean MLW depth is 1.29 m (Chinman and Nixon, 1985).

The circulation in the Providence River is dominated by the tides. Based on an analysis of current data obtained at three locations in the river, Turner (1984) concluded that approximately 70-88% of current variance occurred at tidal frequencies. More than 50% of the variance in each record was present at the semidiurnal (12 hour) band. Similar results are reported by ASA (1985) from current observations made at Cold Spring Point in the Seekonk River. Currents in the Providence and Seekonk Rivers are dominated by the principal semidiurnal (M_2) constituent. The N_2 and S_2 constituents are one quarter the magnitude of the M_2 and produce a neap-spring variation in tidal range. Also significant are the M_4 (6.21 hr period) and M_6 (4.14 hr period) overtides. Their interaction with the semidiurnal tides, principally evident during periods of neap tide range, creates a double peak in current speed during the flood tide.

Free surface fluctuations are also strongly dominated by the tides, again the M_2 constituent. The phase relationship between free surface height and currents is characteristic of a standing wave system, with current phase leading free surface height phase by 70°-80°. Tidal motions are nearly uniform in phase throughout the Providence River. The tidal wave propagates across the Upper Bay and Providence River in 20 minutes, and takes an additional 26 minutes to travel between Fox Point and the head of the Seekonk River.

The circulation in the Providence and Seekonk Rivers is also influenced by the local wind field. Turner (1984) found a distinct response to wind events at 3 to 10 day periodicities in the Providence River. Current response to winds at the 3 m and 6 m depths was an upwind flow to replace water moving downwind at the surface. Net motion due to winds at a point in the Providence River was found to vary from nearly 0 km to nearly 20 km over a period of a week. A current response to wind events was also observed in the Seekonk River (ASA, 1985), however the response was significantly smaller.

The two-layered estuarine circulation has been found to dominate net circulation in both the Providence and Seekonk Rivers. Turner (1984) found mean current speeds in the Gaspee-Bullock Points transect to vary between 2.4-7.2 cm/s. At the 3 and 6 m depths, the mean current direction was upstream. This was attributed to the fact that at least 50% of the cross-sectional area in the transect was at depths less than 3 m. ASA (1985) observed a 2.3 cm/s down estuary mean flow 1.5 m below the MLW surface and a 5.3 cm/s up estuary mean flow 1.5 m above the bottom near Cold Spring Point in the Seekonk River.

The inflows of fresh water to the study area are dominated by the Blackstone River, which has a mean flow of 21.7 m^3/s, peak flows as high as 933 m^3/s and low flows of 4.6 m^3/s (Gadoury et al., 1988). Other tributaries to the Providence and Seekonk Rivers and their mean flows include the Ten Mile River, 2.9 m^3/s; the Moshassuck River, 1.2 m^3/s; the Woonasquatucket River, 2.1 m^3/s and the Pawtucket River, 9.7 m^3/s (Gadoury et al., 1988). Other point inflows of fresh water include the Fields Point (2.3 m^3/s), East Providence (0.09 m^3/s) and Blackstone Valley District Commission (1.0 m^3/s) Sewage Treatment Plants.

2. OBJECTIVES OF THE STUDY

The tide height and current measurement study was designed to aid in the interpretation of physical and chemical data collected during the wet weather study and to aid in the calibration and verification of a time-dependent water quality model of the area. Specific goals include:

Data Interpretation

- To quantify the advection of water quality parameters during the study.

- To provide detailed information on changes in the vertical salinity structure during wet weather as an aid in understanding vertical transport of water quality parameters.

Model Application

- To describe mean properties of the salinity and current fields during dry weather periods.

- To quantify the changes in the current and salinity fields caused by the fresh water surge from the storms.

- To quantify changes in water quality parameters during wet weather.

3. FIELD MEASUREMENT PROGRAM

3.1 Overview

The field measurement program consisted of the deployment of three current meter arrays and one tide gauge. Current meter arrays were deployed in the Gaspee Point-Bullock Point transect and at the south end of Fields Point in the Providence River, and near Cold Spring Point in the Seekonk River. The tide gauge was deployed at the Point Street Bridge in the Providence River for the first wet weather study, and at Port Edgewood Marine for the second and third studies. Locations are shown in Figure 3.1.

Supplemental data obtained for the study included wind speed and direction data, obtained from National Weather Service records at T.F. Green Airport in Warwick. Time histories of river flow from USGS gauges on the Blackstone River (Woonsocket), the Ten Mile River (East Providence), the Woonasquatucket River (Centerdale), the Moshassuck River (Providence), and the Pawtuxet River (Cranston) were obtained from the USGS via other researchers.

3.2 Current Meter and Tide Gauge Deployments

Two types of instruments were used for the current measurements: the InterOcean Model S4 and the Endeco Model 174. The S4 is a small spherical (~25 cm diameter) instrument which measures currents by setting up a magnetic field around the meter and sensing the voltage induced by the movement of the conductor, seawater, through the field. The orientation of the instrument relative to magnetic North is sensed by an internal flux-gate compass. From this information, microprocessor circuitry in the instrument then calculates the current vector components in the North-South and East-West (magnetic) reference frames. The S4 also measures conductivity and temperature, which are stored in non-volatile internal solid state memory. The current vector, temperature and conductivity are sensed at a rate of 2 Hz. For the deployments, the instrument was set to sample over a 5 minute period, calculate an average (or vector average) for the 5 min period, store the values in memory, then shut down for 10 minutes. The data stored therefore represent 5 minute average quantities determined at 15 minute intervals. After the instrument was recovered, it was downloaded to a personal computer through an RS-232 link. During the downloading process, coefficients determined from factory calibration of the instrument are applied to convert the data into engineering units.

The Endeco Model 174 is a tethered neutrally buoyant device which aligns itself with the local current field. Current speed is measured by a ducted impellor. Current direction is sensed by an internal compass. Compass corrections specific to the

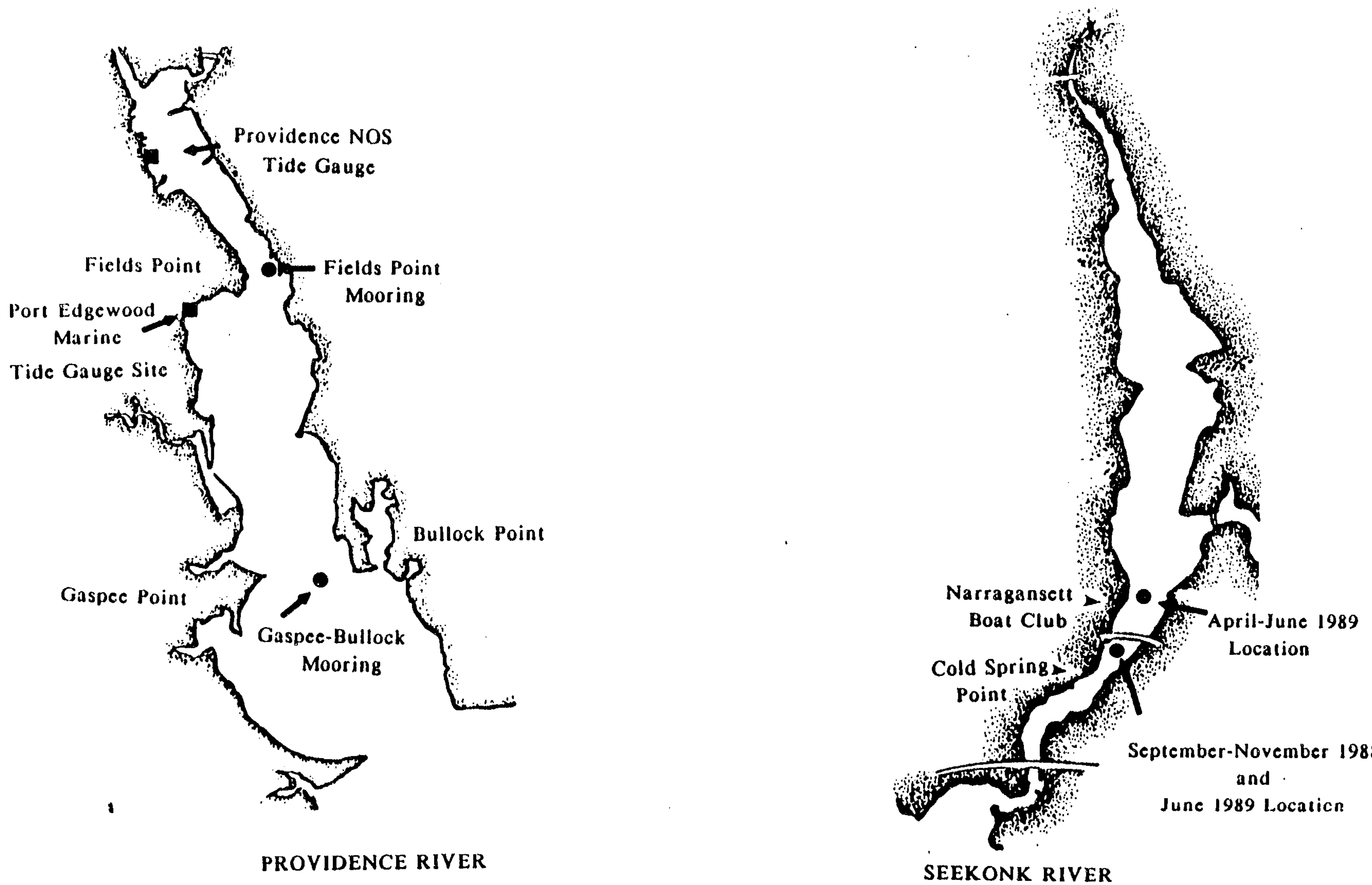

Figure 3.1 Current meter mooring and tide gauge deployment locations

instrument, determined by a recent calibration of the unit, are contained in a 32-point table which is programmed into the instrument. Current speed and direction are measured at a 1 Hz rate, compass corrections applied, then vector summed over a 15 minute averaging period. Conductivity and temperature are sensed and averaged in a similar manner. The data are then stored in solid state memory. At the end of the deployment, the current speed, direction, temperature and conductivity series are downloaded to a personal computer. Corrections for local magnetic variation are applied to the direction data during the downloading process. The temperature and conductivity are used to calculate salinity during post-processing using a procedure given in Kjerve (1979).

Tide height measurements were made with an Endeco Model 1029 tide gauge. The instrument senses the pressure exerted by the water column across a submerged ceramic differential pressure sensor. One side of the sensor is exposed to atmospheric pressure via a vent tube, while the other side is exposed to ambient pressure. Pressure readings are stored on a solid state memory cartridge (EPROM) at 15 minute intervals. After recovery, the cartridge is downloaded to a computer. The download software converts the pressure data to water height using an estimate of mean local salinity.

The locations of the three current meter moorings are shown in Figure 3.1. The mooring configurations in each transect are shown in Figure 3.2 and 3.3 and listed in Table 3.1. The moorings at Fields Point and Gaspee Point were designed to permit measurements to be made as close as possible to the surface. The current meters were therefore attached to a floating surface buoy consisting of a PVC shell filled with closed cell foam. This arrangement allowed the S4 current meter to be placed at a constant depth of 1 m. A flat 100 lb depressor weight was placed on the array below the current meters to keep its orientation vertical. The depressor was in turn attached by a chain to a bottom clump anchor. The slack in the chain was sufficient to allow surface buoy to float at high tide, while allowing a minimum of horizon excursion, 9 m. When the current reversed at low tide, this 9 m excursion could account for a maximum error of 1.0 cm/s in the current record due to movement of the array. The Seekonk River mooring consisted of a submerged taut moored buoy connected to a bottom anchor with wire cable. The current meter was attached to this cable by a swivel as shown in Figure 3.3.

The study began on September 17, 1988 with the deployment of the current meters and tide gauge. The Gaspee Point meters were serviced on October 21, shortly before the start of the first wet weather study. On recovery, computer communications could not be established with one instrument (#029). Data obtained from the second

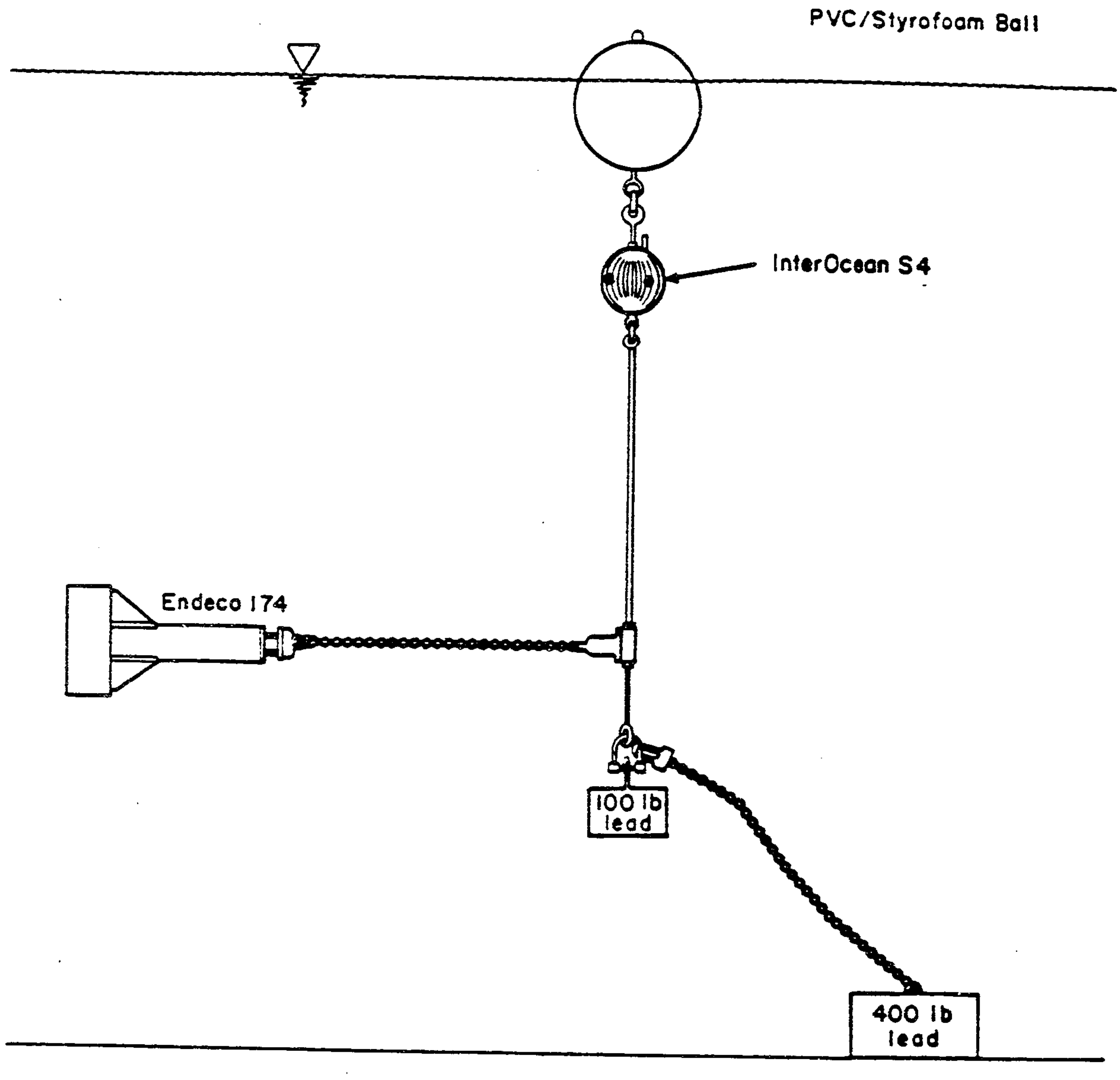

Figure 3.2 Current meter configurations for the Fields Point and Gaspee-Bullock transect sites

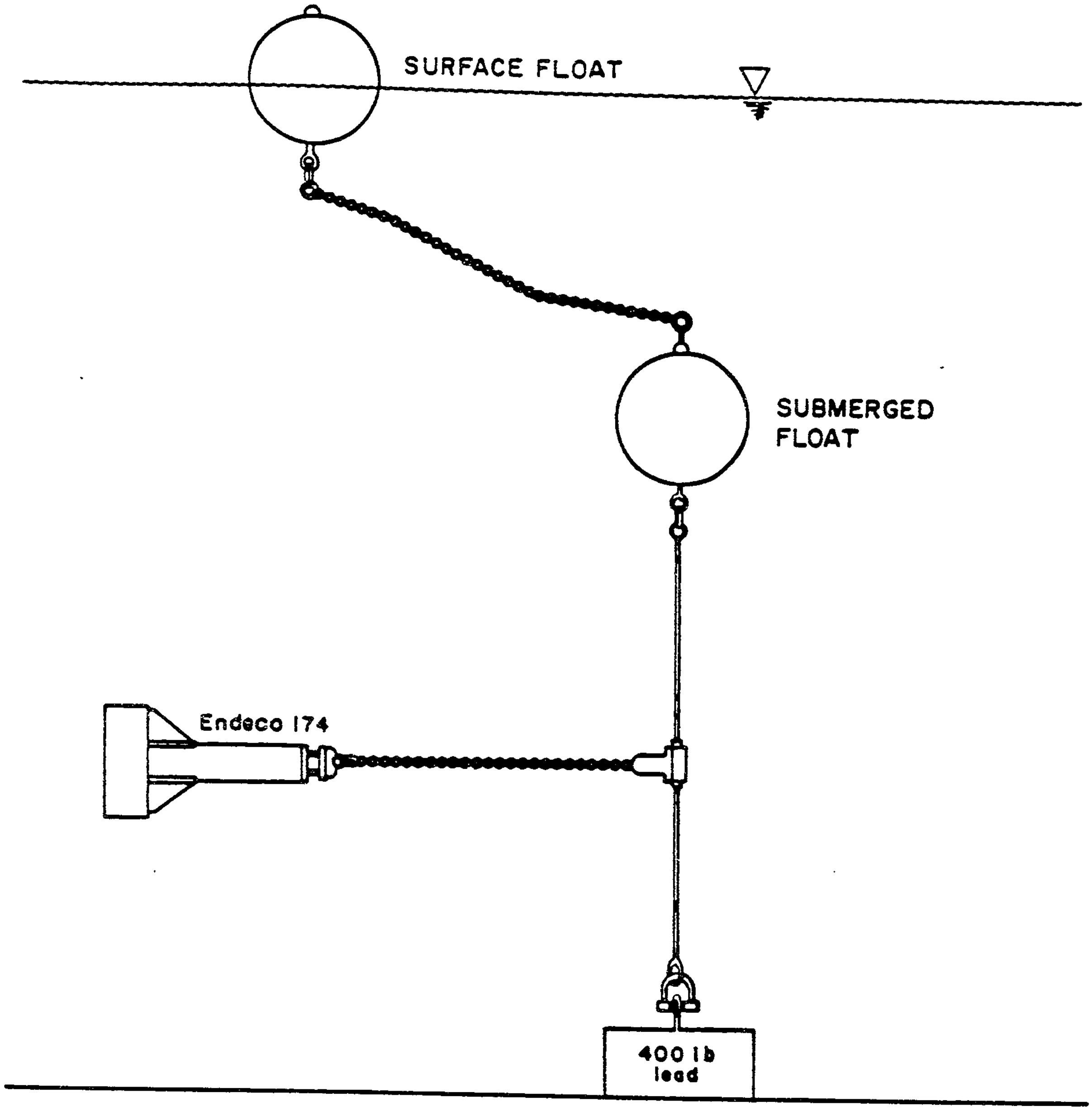

Figure 3.3 Current meter configurations for the Seekonk River site

Table 3.1 Current Meter Deployment Locations.

Wet Weather Study Number	Location Description	Surface/ Bottom	Latitude (Deg./Min. (North)	Longitude (Deg./Min. (West)	Instrument Model	Serial Number	Deployment Date Start (M/D/Y)	Deployment Date End (M/D/Y)	Water Depth (MLW, m)	Instrument Depth	Instrument Depth Reference (S/B)
1	Gaspee-Bullock Transect	S	41° 44.57'	71° 22.03'	Endeco 174	027	No Data		6.3	1.0	B
1		B	41° 44.57'	71° 22.03'	Endeco 174	029	No Data		6.3	1.0	B
2		B	41° 44.42'	71° 21.23'	Endeco 174	011	04/23/89	06/1/89	6.3	1.8	S
2		S	41° 44.42'	71° 21.23'	Interocean S4	1148	04/23/89	05/22/89	6.3	5.3	S
3		B	41° 44.42'	71° 21.23'	Endeco 174	011	06/08/89	06/16/89	6.3	4.5	S
3		S	41° 44.42'	71° 21.23'	Interocean S4	1148	06/08/89	06/16/89	6.3	1.0	S
1	Fields Point Transect	B	41° 47.17'	71° 22.34'	Endeco 174	011	09/17/88	11/07/88	8.0	5.8	S
1		S	41° 47.17'	71° 22.34'	Interocean S4	1148	09/17/88	11/06/88	8.0	1.0	S
2		B	41° 47.17'	71° 22.34'	Endeco 174	027	04/23/89	05/31/89	8.0	6.2	S
2		S	41° 47.17'	71° 22.34'	Interocean S4	1149	04/23/89	06/01/89	8.0	6.2	S
3		S	41° 47.17'	71° 22.34'	Interocean S4	1149	06/08/89	06/16/89	8.0	1.0	S
3		B	41° 47.17'	71° 22.34'	Endeco 174	027	No Data		8.0	6.2	S
1	Seekonk River	B	41° 45.77'	71° 22.65'	Endeco 174	092	09/17/88	11/07/88	3.6	1.0	B
2		B	41° 50.17'	71° 22.67'	Endeco 174	029	04/23/89	06/01/89	3.6	2.1	B
3		B	41° 45.77'	71° 22.65'	Endeco 174	027	06/08/89	06/16/89	3.6	2.1	B

instrument (#027) were unusable, indicating that the instrument had malfunctioned. Both instruments were removed and returned to the manufacturer for repair.

Three current meters were therefore in the water for the first wet weather study: two instruments at Fields Point (surface and bottom), and one instrument near the bottom in the Seekonk River.

These instruments were recovered on November 7, 1988 and downloaded. The Fields Point array was recovered without incident. The surface buoy above the current meter on the Seekonk mooring had been removed. In addition the Seekonk River subsurface buoy had been struck by a boat propeller. Because the buoy had closed cell foam inside the shell, however, it remained buoyant. The decision was therefore made to relocate the mooring and the tide gauge to a wider area of the river for the subsequent studies, so that interference with boating traffic would be minimized along with the tide gauge. Evaluation of the data revealed that the tide gauge had failed. The cause of the failure was determined to be the flooding of the air equalizing line. Tide height data for this report were therefore obtained from the National Ocean Survey gauge in Providence. In addition, the thermistor on the InterOcean Model S4 surface meter (#1148) at Fields Point failed as a result of corrosion failure of a weld at its base. As a result, no temperature data were obtained from this instrument.

During the winter of 1988-1989, each of the instruments to be used during the subsequent surveys was returned to the manufacturer for servicing. Each instrument was also subjected to test deployments during the spring of 1989 to ensure proper operation.

Preparations for the second wet weather survey commenced with the deployment of the tide gauge on April 21, 1989 at Port Edgewood Marine. The current meter arrays were deployed two days later on April 23. The Seekonk mooring was moved to a site north of the Narragansett Boat Club.

The second wet weather study was conducted during May 10-15, 1989; the current meters and the tide gauge were serviced on May 22 and June 1, 1989. The Seekonk River mooring was again vandalized: shackles attaching both surface buoys to the array had been removed and the surface buoys were lost. The array was successfully located, however, by dragging a wire through the area between two boats, and the instrument was recovered. Data were recovered from all instruments for this deployment. No current speed information was obtained from the bottom meter (#011) at Gaspee Point; however, complete time series of current direction, temperature and conductivity were obtained.

The meters were re-deployed on June 8, 1989. The Seekonk mooring was moved south to its original location near Cold Spring Point, and NICOPRESS fittings and wire cable were used to attach the surface buoys to the mooring. The third wet weather study followed shortly thereafter, over the period June 13-16, 1989. Following the end of the wet weather study on June 16, the current meter moorings and instruments were recovered. The tide gauge was recovered on July 14, 1989. Complete data sets were recovered from the tide gauge and four of the five current meters. Endeco #029 was found to have flooded, with subsequent loss of data after corrosion of the thermistor resulted in a leak of seawater into the instrument package.

3.3 Environmental Data

Wind data for the current meter deployment periods were obtained from the National Weather Service office in Warwick. Tide height data from the Providence tide gauge were obtained for September and October, 1988 from the National Ocean Survey, Rockville, Maryland. The data were entered manually into computer files for subsequent processing. Flow data for the Blackstone, Ten Mile, Moshassuck, Woonasquatucket and Pawtuxet Rivers were obtained in magnetic form from researchers at the University of Rhode Island.

4. PROCESSING OF THE FIELD DATA

4.1 Overview of Results

The field program produced nine current time series at four locations in the Providence River and three current time series at one location in the lower Seekonk River. The current data were accompanied by two sets of tide height and wind observations, and river inflow data for the wet weather study periods.

A series of procedures was performed on the above data to provide information describing the behavior of the estuary during a (typical) dry weather period and during each of the three storms. Summary time series of the data for each deployment are presented in Appendix A. Also included in this appendix are the observations covering the period of each wet weather study which show the behavior of each parameter in greater detail. Summaries of the speed and direction distributions of currents at each location are shown in Appendix B. These summaries are produced by sorting the current speed and direction observations in each record by speed (2 cm/s increments) and direction (22.5 degree increments). Numbered boxes in each figure indicate the percentage of observations which occurred within a specified speed and direction range. For example Figure B.1 shows that the current flowed toward the Northeast at a speed of 12-14 cm/s during 3% of the observations. Boxes marked with a '+' indicate a frequency of occurrence between 0-1%. Empty boxes indicate that no observations occurred at the applicable speed and direction combination. A histogram of the directional probability distribution of the record are presented by a solid bars along the left axis of each figure. The directional probability scale (in %) is presented at the top of the figure. Speed probability distributions are presented in tabular form across the bottom of each figure.

The next procedure was a low pass filtering operation. The low pass filter removes short-period oscillations, revealing long term trends in the data. A Butterworth squared filter with a half-power response at the 30 hour period was used for the analysis. Low passed filtered time series are presented in Appendix C. As in Appendix A, the time series are presented as stacked time series plots. The time series are also windowed to illustrate the trends in each parameter during the wet weather studies.

Progressive vector plots calculated from the current time series are presented in Appendix D. The lines in each figure represent the net excursion of water past the measurement location with data indicated as open circles. The progressive vector series from longitudinally separated current meters can be used in conjunction with salinity and dye data, and cross-sectional areas to infer water mass movements down river during the wet weather experiments.

The relationship between local wind field and circulation can be examined using the multiple coherence function (Bendat and Piersol, 1980). The multiple coherence function establishes the percentage of variance of the current variance in each frequency band which is attributable to the local wind. The coherence spectra calculated from each current series and winds at Green Airport are presented in Appendix E.

4.2 Circulation Dynamics

Means and standard deviations of the current time series are presented in Table 4.1, along with temperature and salinity statistics. Table 4.2 presents the tidal constituent data for currents at each deployment site, obtained from a harmonic analysis of the data. Tide height constituents are presented in Table 4.3 from a harmonic analysis of the NOS Providence tide data and the tide gauge data from Port Edgewood Marine.

The time series displays and analyses reveal a wide diversity in the character of circulation at different locations in the estuary. Currents at Gaspee Point are generally rectilinear and uniform in phase and direction at the surface and bottom. The principal forcing mechanism is the tides. Table 4.2 shows that the M_2 current amplitude is 15.672 cm/s at the surface. The aspect ratio of the current ellipse is 29.6:1, with the major axis directed toward 353.8°T. The orientation of the 18 ft contour outside the edge of the channel is 357°T (NOS Chart #13224), reflecting a strong steering by the bathymetry. The principal contrast between the surface and bottom currents appears to be caused by the estuarine circulation. The surface current has a strong down-estuary mean component between 2.2 cm/s and 4.5 cm/s on which the tidal oscillations are superimposed. The mean appears to significantly bias the tidal currents, with the result that flood currents are noticeably weaker than ebb currents. Up-estuary flood currents are nearly absent on some flood tides, particularly during neap tidal periods. The multiple coherence spectra at Gaspee Point reflect a distinct relationship between the wind and surface currents. This relationship is apparent as a down-wind current response to wind events. The apparent influence of the wind in affecting net transport on the monthly time scale is evidently small. For example, Figure D.10 shows that weekly variations in net movement at the surface are large, for example between 7-14 May and 14-21 May. Examination of Figure A.8 reveals nothing in the wind record which could account for these variations.

The circulation at Fields Point is different from that near Gaspee Point. Tidal currents are distinctly smaller in magnitude. The M_2 current amplitude varies between

Table 4.1 Means and standard deviations of current meter and wind data.

Current Meter Location	Surface /Bottom	Start and End Dates	Current (cm/s) East/West Mean	Current (cm/s) East/West S.D.	Current (cm/s) North/South Mean	Current (cm/s) North/South S.D.	Temperature (°C) Mean	Temperature (°C) S.D.	Salinity (ppt) Mean	Salinity (ppt) S.D.
Seekonk River	B	9/17/88-11/07/88	2.98	16.66	1.41	12.80	15.11	3.17	25.27	3.06
Fields Point	S	9/17/88-11/06/88	1.52	4.91	-2.97	9.32	----	----	----	----
Fields Point	B	9/17/88-11/07/88	-0.71	2.12	0.99	7.83	14.69	3.09	26.20	3.21
Seekonk River	B	4/23/89-06/01/89	-1.71	7.09	-3.12	12.01	11.44	2.82	20.85	7.25
Fields Point	S	4/23/89-06/01/89	0.98	5.45	-1.76	10.44	12.88	3.21	20.69	5.48
Fields Point	B	4/23/89-06/01/89	-0.86	3.86	1.04	7.44	9.90	2.44	28.37	1.94
Gaspee-Bullock	S	4/23/89-05/22/89	1.69	4.41	-3.29	12.81	11.60	2.55	23.30	2.73
Gaspee-Bullock	B	4/23/89-06/01/89	----	----	----	----	11.33	3.20	27.46	2.20
Seekonk River	B	6/08/89-06/16/89	2.19	11.08	2.00	12.83	15.45	0.77	24.87	5.41
Fields Point	S	6/08/89-06/16/89	1.23	4.50	-1.33	8.86	16.53	0.85	24.70	2.71
Gaspee-Bullock	S	6/08/89-06/16/89	2.04	3.66	-0.60	11.09	16.63	0.72	25.31	1.49
Gaspee-Bullock	B	6/08/89-06/16/89	1.68	3.02	2.88	10.68	15.24	0.66	29.39	1.09

Green Airport Wind (m/sec)

Time	East/West Mean	East/West S.D.	North/South Mean	North/South S.D.
09/13/88 - 10/31/88	1.79	3.12	0.08	3.65
04/17/89 - 06/16/89	0.70	3.23	0.25	3.77

Table 4.2 Tidal Current Constituents Calculated from the Current Meter Data.

Location: Gaspee Point Surface

Constituent	Period	Ellipse Major Axis (cm/s)	Minor Axis (cm/s)	Phase (deg)	Orientation of Major Axis (°T)
M2	04/23/89-05/22/89	15.672	0.529	142.7	353.8
N2		11.758	-0.469	163.0	350.6
S2		4.973	-0.223	9.2	349.7
O1		0.662	-0.323	57.1	023.2
K1		0.463	-0.270	113.5	062.2
M4		4.547	-1.987	63.1	353.9
M6		3.052	0.028	117.9	008.6

Location: Fields Point Surface

Constituent	Period	Ellipse Major Axis (cm/s)	Minor Axis (cm/s)	Phase (deg)	Orientation of Major Axis (°T)
M2	09/17/89-11/06/89	6.975	0.240	165.8	339.6
	04/23/89-06/01/89	11.797	-0.094	146.1	336.2
N2	09/17/89-11/06/89	2.358	0.013	169.7	334.1
	04/23/89-06/01/89	4.990	0.237	127.6	334.6
S2	09/17/89-11/06/89	2.880	0.101	163.3	338.6
	04/23/89-06/01/89	2.236	-0.063	173.5	345.3
O1	09/17/89-11/06/89	0.619	-0.020	55.7	341.2
	04/23/89-06/01/89	1.536	0.118	158.8	340.6
K1	09/17/89-11/06/89	1.411	0.074	32.5	337.6
	04/23/89-06/01/89	1.605	0.279	158.5	344.7
M4	09/17/89-11/06/89	4.443	0.057	105.1	336.5
	04/23/89-06/01/89	3.151	0.314	41.7	335.2
M6	09/17/89-11/06/89	1.632	0.043	70.5	334.8
	04/23/89-06/01/89	1.794	-0.372	94.8	342.6

Table 4.2 (Continued)

Location: Fields Point Bottom

Constituent	Period	Ellipse Major Axis (cm/s)	Ellipse Minor Axis (cm/s)	Ellipse Phase (deg)	Ellipse Orientation of Major Axis (°T)
M2	09/17/88-11/07/88	9.398	-0.395	124.0	349.1
	04/23/88-06/01/89	9.994	0.232	141.3	335.1
N2	09/17/88-11/07/88	1.230	-0.210	90.8	344.0
	04/23/88-06/01/89	3.543	0.198	118.9	331.4
S2	09/17/88-11/07/88	2.743	-0.200	151.2	348.9
	04/23/88-06/01/89	2.343	0.206	25.9	331.2
O1	09/17/88-11/07/88	0.205	-0.017	172.9	312.4
	04/23/88-06/01/89	0.649	-0.034	93.9	328.9
K1	09/17/88-11/07/88	0.796	-0.079	165.5	345.8
	04/23/88-06/01/89	0.520	0.032	83.4	338.8
M4	09/17/88-11/07/88	4.319	-0.169	40.5	349.1
	04/23/88-06/01/89	5.852	-0.033	79.6	334.1
M6	09/17/88-11/07/88	0.995	0.045	153.6	337.4
	04/23/88-06/01/89	2.072	-0.023	42.7	332.0

Table 4.2 (Continued)

Location: Seekonk River

Constituent	Period	Major Axis (cm/s)	Minor Axis (cm/s)	Phase (deg)	Orientation of Major Axis (°T)
		Ellipse			
M2	09/17/88-11/07/88	22.775	0.059	111.4	52.8
	04/23/88-06/01/89	5.696	0.603	160.7	30.8
N2	09/17/88-11/07/88	5.298	0.139	108.7	54.8
	04/23/88-06/01/89	2.502	0.282	96.7	34.6
S2	09/17/88-11/07/88	6.765	0.133	125.6	53.8
	04/23/88-06/01/89	2.613	0.211	15.8	30.3
O1	09/17/88-11/07/88	0.932	-0.026	37.1	46.1
	04/23/88-06/01/89	0.717	-0.004	81.9	17.4
K1	09/17/88-11/07/88	1.603	0.461	170.8	51.3
	04/23/88-06/01/89	1.048	-0.196	129.7	20.0
M4	09/17/88-11/07/88	5.351	0.824	2.1	54.1
	04/23/88-06/01/89	4.566	-0.393	131.1	29.1
M6	09/17/88-11/07/88	7.312	-0.470	64.9	55.5
	04/23/88-06/01/89	3.787	0.127	60.5	25.5

Table 4.3 Tidal Elevation Constitutents Calculated from the Tide Height Data.

Location: Providence State Pier (NOS)

Period: 9/15/88-10/31/88

Constituent	Amplitude (cm)	Modified Epoch Phase (Deg)
M(2)	59.19	223.82
N(2)	14.37	210.06
S(2)	13.02	237.09
O(2)	07.86	134.34
K(1)	07.39	101.66
M(4)	10.75	128.65
M(6)	02.83	218.05

Location: Port Edgewood Marine

Period: 4/21/89-7/14/89

Constituent	Amplitude (cm)	Modified Epoch Phase (Deg)
M(2)	85.48	222.22
N(2)	17.93	205.69
S(2)	17.87	239.43
O(1)	07.14	134.92
K(1)	09.37	90.39
M(4)	15.21	131.80
M(6)	04.06	231.27

67.975 - 11.797 cm/s at the surface, and is 9.7 cm/s at the bottom station. The orientation of the ellipse is 340° at the surface and 349° near the bottom. The local 18 ft depth contour is 337°.

Both the Gaspee-Bullock Points and Fields Point stations are located close to the edge of the dredged channel. No obstructions are present either up or down estuary from the moorings. The difference in tidal current strengths at these two stations is probably attributable to the geometry of the area. Although the Gaspee-Bullock transect is much wider than the Fields Point transect, the Fields Point transect is approximately twice as deep. A cross-sectional area calculated from bathymetric data on NOS Chart #13224 produced an estimated cross-sectional area of 4700 m^2. The cross-sectional area of the Gaspee-Bullock transect is around 9300m^2 (Turner, 1984), which is about two times greater than Fields Point. The upstream tidal prism volume of the Gaspee-Bullock transect is much greater, however, than at Fields Point. Chinman and Nixon (1985) report a surface area of 14.34 km^2 upstream of the Gaspee-Bullock transect, while the area upstream of Fields Point is only 5.81 km^2. The disparity in the surface area to cross-sectional area ratios at the two points indicates that currents in the Gaspee-Bullock transect will be 25% stronger. The strength and direction of the tidal currents in relationship to other current forcing processes therefore reflect the strong influence of geometry.

The strength of the down-estuary mean surface current (1.8 - 3.3 cm/s) relative to the tidal current is higher than at Gaspee Point, with the result that flood currents are very weak. In Figure B.2, for example, the most probable flood current speed is between 4-6 cm/s (to the North and Northwest). Ebb currents, to the South and Southeast, on the other hand are frequently higher than 18 cm/s. The response of currents to wind forcing at Fields Point is also significant, as evidenced by Figures E.3-E.5. The coherence spectra show a strong current response at the 1 day and 3 to 5 day period time scales. The September-November 1988 surface and bottom records reflect the influence of wind events in Figure C.2. The low passed surface current vector mirrors the wind vector, while the bottom record shows a weak counterflow response. The significance of this relationship to the net circulation is small, however. Figures D.2 and D.3 clearly show the dominance of the estuarine circulation in driving the circulation on the long term.

The predominant factor driving currents in the Seekonk River is again tidal forcing. The strength of the M_2 current constituent at Cold Spring Point is 22.775 cm/s. Upstream of the Narragansett Boat Club, the M_2 current is 5.695 cm/s, owing to the fact that the river is wider. The predominance of the tides in forcing currents through the Seekonk River may again be inferred from its geometry. The cross-sectional area of the Cold Spring transect is smaller than at Fields Point by a factor of 4.9 (960 m^2 versus 4700 m^2 at Fields Point). The upstream tidal prism area only drops by a factor of two, to 2.807 km^2 versus 5.806 km^2 at Fields Point. The change in the ratio of tidal prism to cross-sectional area suggests a 2.37-fold increase in tidal current strength at the Cold Spring Point relative to Fields Point, which agrees fairly well with the 1.93 to 3.27-fold increase calculated from the M_2 current constituent data. Because the meter was located near the bottom for the three deployments, the strength of the mean surface current is not known. The direction and magnitude of bottom currents vary between the two mooring locations. The mean current vector is directed up-estuary at the Cold Spring Point site during the September-November 1988 and June 1989 deployments and down-estuary for the April-June 1989 deployment. The change in the mean flow direction apparently results because a greater percentage of the cross-sectional area of the estuary lay below the meter during the April 23-June 1 deployment. As noted by ASA (1985) a significant correlation does exist between the wind and currents in the Seekonk River. The coherence spectra in Figures E.1 and E.2 indicate a close coupling of the response at the 1 day period and at greater than 10 day periods. The influence of the wind is not apparent in the low frequency currents, however as shown by Figures C.1 and C.5. The low frequency response is dominated by the estuarine circulation and net riverflows in both the September-November 1988 and April-June 1989 deployments.

The current time series at each site during the three studies are shown in Figures A.3, A.4, A.9-A.11, and A.13-A.15 along with the concurrent winds, tide height, temperature and salinity. The time series indicate that the influence of the wind and freshwater inflows was relatively minor during the October 22-26, 1988 and June 13-16, 1989 studies. This conclusion is further supported by an examination of the low pass filtered time series in Appendix C and the progressive vector series in Appendix D.

The response to the May 10-15, 1989 storm was quite different, however, with the greatest impacts apparent at the two near-surface stations. Surface currents at Fields Point (Figure A.10) flow almost entirely seaward during and after the storm. The surface current at Gaspee Point behaves in a similar fashion, although the seaward component is not as strong. The trend is even more apparent in the low frequency component of the current series, shown in Figure C.6 and C.9 for Fields Point and Figures C.7 and C.10 for Gaspee Point. The cause for the different response during this period lies with the fact that the total rainfall was significantly higher during the May 10-15, 1989 study: 2.47 inches as opposed to 0.72 inches for October 22-26, 1988 and 0.58 inches for June 13-16, 1989. The surface current records therefore reflect the massive down-estuary flow of runoff following the storm.

4.3 Salinity and Temperature Field Characteristics

The mean and standard deviation of the temperature and salinity time series recorded by the current meters are presented with the current statistics in Table 4.1. Results from the September-November 1988 Fields Point surface station are not reported, since the instrument's thermistor failed. Since salinity is calculated as a function of temperature, the salinity is correspondingly absent.

The means and standard deviations show clear trends along the length of the estuary. Mean salinity increases seaward at both the surface and bottom. The change between the Seekonk River site and Fields Point varies from a low value of 0.93 ppt in the September-November 1988 deployment to a high value of 7.52 ppt in the April-June 1989 deployments. Interestingly, this increase in the salinity gradient does not appear to be accompanied by increases in mean surface current speed. The variability of the salinity field decreases in the seaward direction. This result may be attributed to the fact that stratification increases toward the head of the river. As the stratification of the water column increases, the degree of change seen by a meter located at a fixed point in the water column will also increase, particularly if the meter is located near the halocline. The salinity change observed by the meter is then a result of the vertical movement of the halocline on the rising and falling tide, and not necessarily by temporal changes in salinity resulting from the horizontal translation of a salinity gradient. This is particularly true when step changes in salinity occur, as in Figure A.9, from the Seekonk River. In this figure, each step decrease is accompanied by a step rise in temperature. This further confirms that the halocline has dropped, exposing the meter to warmer, less saline surface water.

The data show a varied degree of response of the temperature and salinity fields to rainfall between each of the studies. The response is most dramatic to the storm of May 10-12, 1989, when a total of 2.47 inches of rain fell. Bottom salinities throughout the study area appear to remain fairly constant. While low tide salinities drop to near zero at the Seekonk site, high tide salinities are relatively stable. Little change in bottom salinity is evident at Fields Point and near Gaspee Point. Surface salinities drop dramatically at all three stations, and do not recover to their pre-storm weather levels until May 17, nearly five days after the end of the rain. The effect of the October 22, 1988 and June 13, 1989 rain storms on the salinity records is not noticeable at the Fields Point and Gaspee Point sites. The tidal step changes in salinity discussed above are evident during the June 13-16 study, Figure A.13. These step changes are smaller than those observed during June 10-13, prior to the start of the third study. The effects of the two smaller storms on the density structure of the river was minor. Since no salinity response was observed at the two surface meter locations, the conclusion must be made that either the net fresh water inflow was small, or that the storm runoff was confined to a layer within 1 m of the water surface north of Gaspee Point.

5. CONCLUSIONS

A current and tide height measurement study funded by the Narragansett Bay Project was conducted for three wet weather events. They successfully produced continuous information on current speeds and tide heights and on the degree to which the storms affected circulation in the study area.

Examination of the data revealed that the influence of the October 22-26, 1988 and June 13-16, 1989 storms on circulation and salinity fields in the study area was noticeable, but small. The May 10-15, 1989 storm produced significantly more rainfall than the other two storms. Consequently, it did significantly change circulation and salinities, particularly near the surface. The lack of a noticeable change in surface salinity during the first and third studies suggests that the fresh water runoff from tributaries and sewage treatment plants was confined to a shallow layer lying within 1 m of the surface.

The current data retrieved during the study were obtained over a wide area of the estuary. The data were subjected to a series of analyses designed to quantify the circulation response to tides, winds and density forcing. The analysis results suggest that the degree of circulation response to each forcing process is strongly influenced by the geometry of the system. For example, specific controlling factors affecting the tidal current response were found to be:

- The upstream tidal prism surface area/volume.
- The cross-sectional area of the transect in which the measurements are made.

These results suggest that the characterization of circulation in an estuary having the varying geometric features of the Providence and Seekonk Rivers may not be accomplished by a limited set of observations.

6. REFERENCES

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APPENDIX A: TIME SERIES DATA

Study #1

A.1 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.

A.2 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.

A.3 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.

A.4 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.

A.5 Flows for the Blackstone Ten Mile, Moshassuck, Woonasquatucket and Pawtuxet Rivers during wet weather study #1, October 22 - October 26, 1988.

Studies #2 and #3

A.6 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23, - June 16, 1989.

A.7 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989

A.8 Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989.

A.9 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000, May 10 - 1700 May 14, 1989

A.10 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000, May 10 - 0000 May 14, 1989.

A.11 Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000, May 10 - 0000 May 14, 1989.

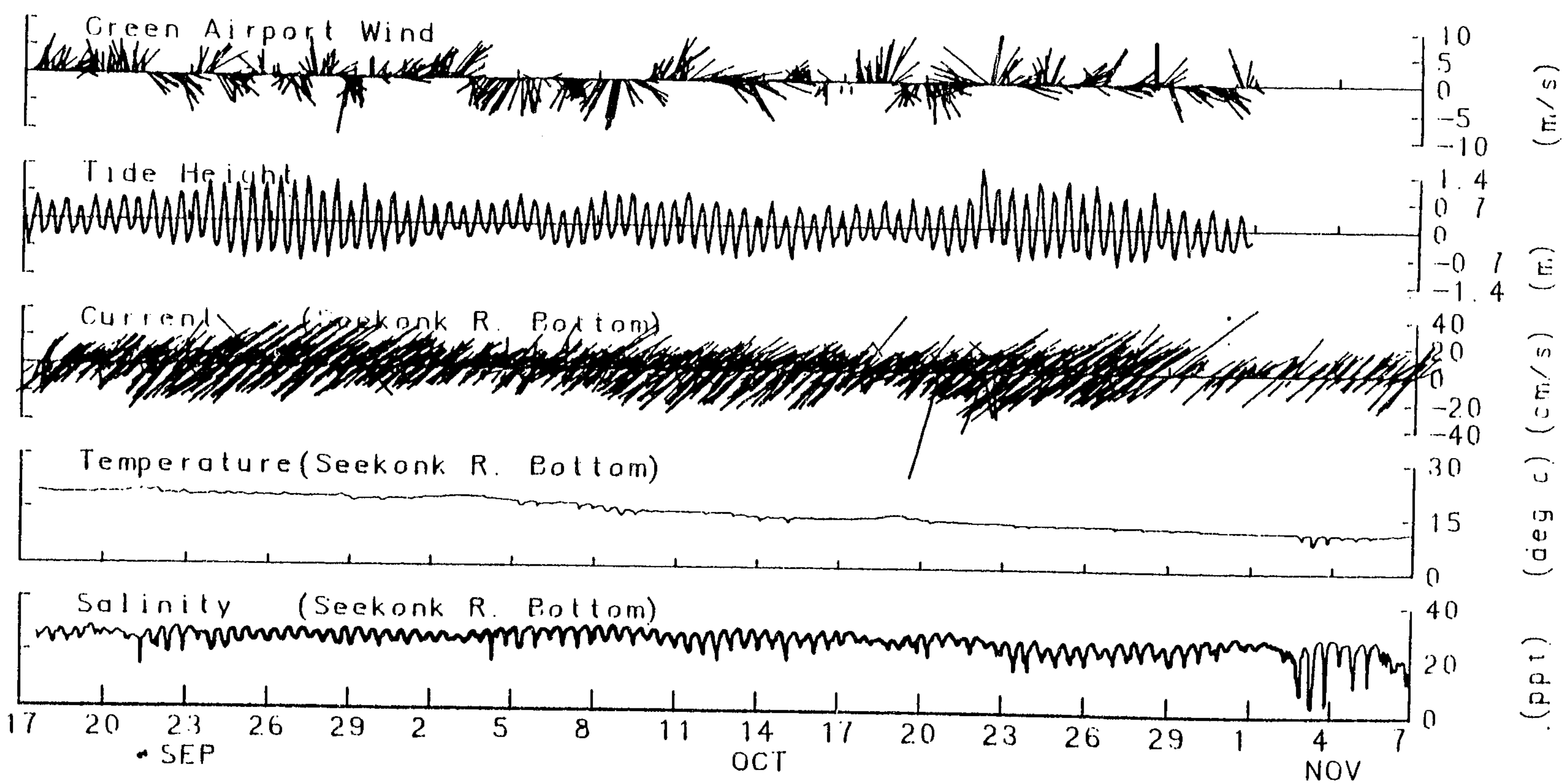
A.12 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 June 13 - 0000 June 17, 1989.

A.13 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 June 13, - 0000 June 17, 1989.

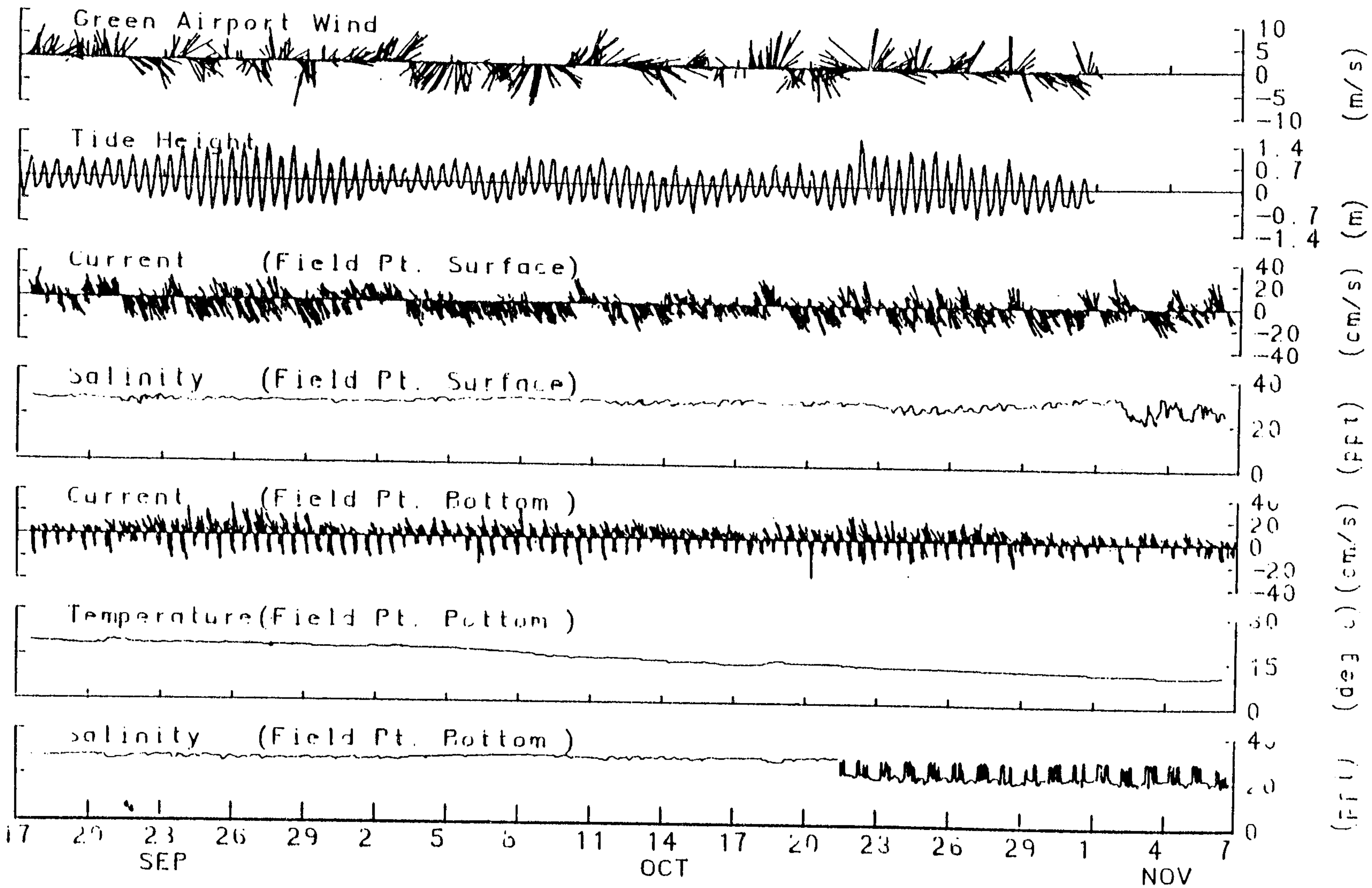
A.14 Gaspee-Bullock Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 June 13 - 0000 June 17, 1989.

A.15 Flows for the Blackstone Ten Mile, Moshassuck, Woonasquatucket and Pawtuxet Rivers during wet weather study #2, May 10 - May 15, 1989.

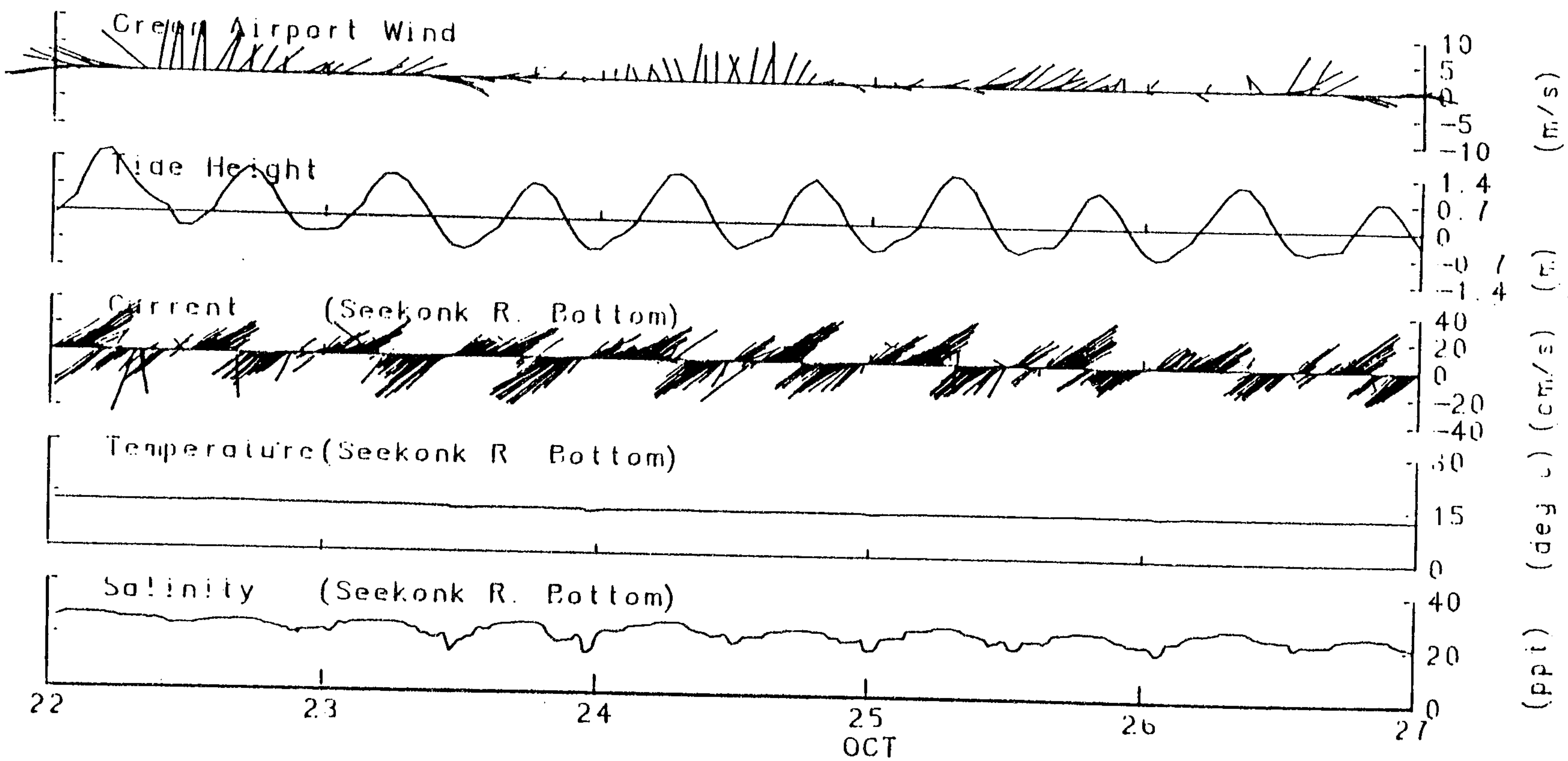
A.16 Flows for the Blackstone Ten Mile, Moshassuck, and Pawtuxet Rivers during wet weather study #3, June 13 - June 16, 1989. Data for the Woonasquatucket River were not available for this period.



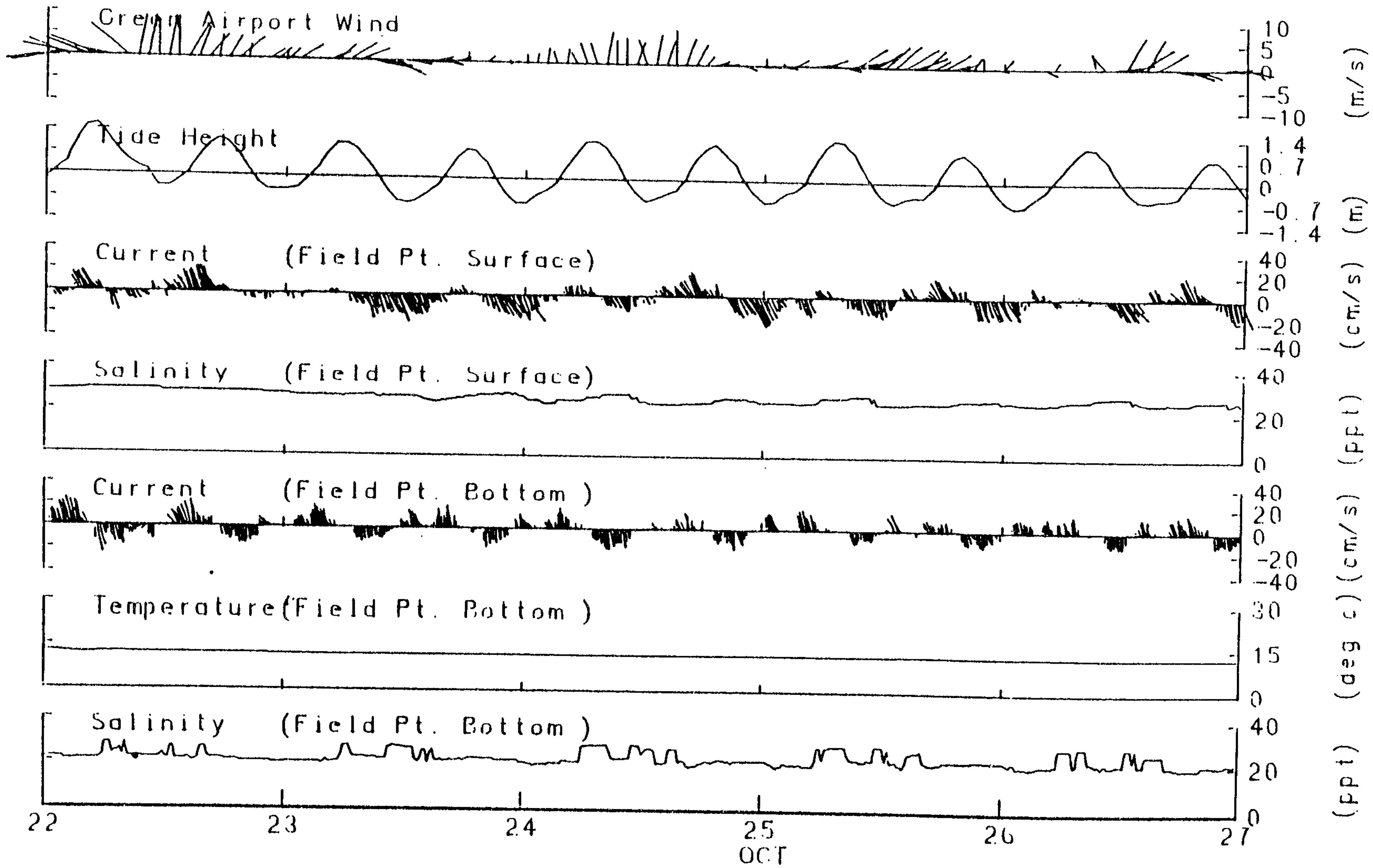
A.1 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.



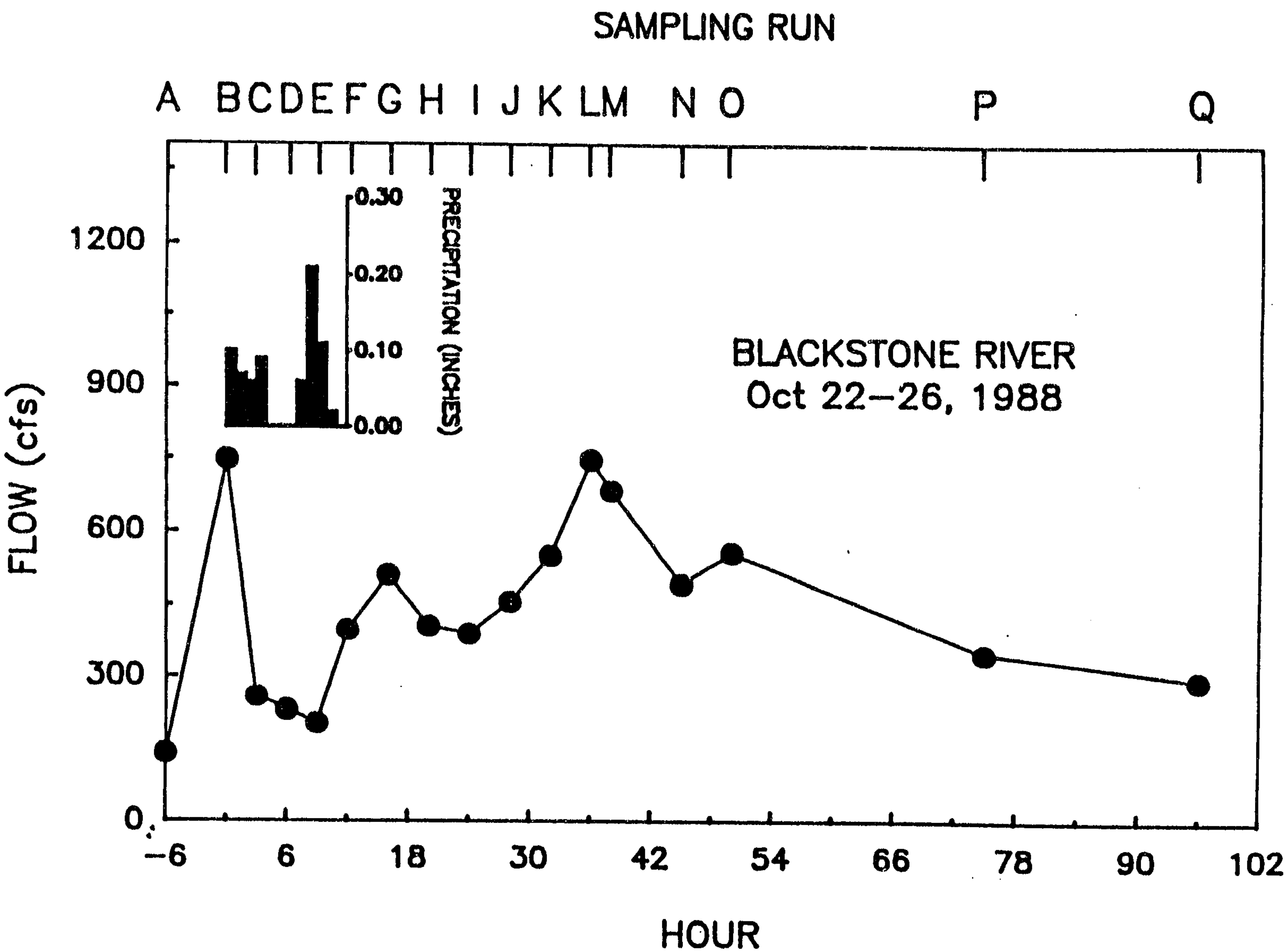
A.2 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.



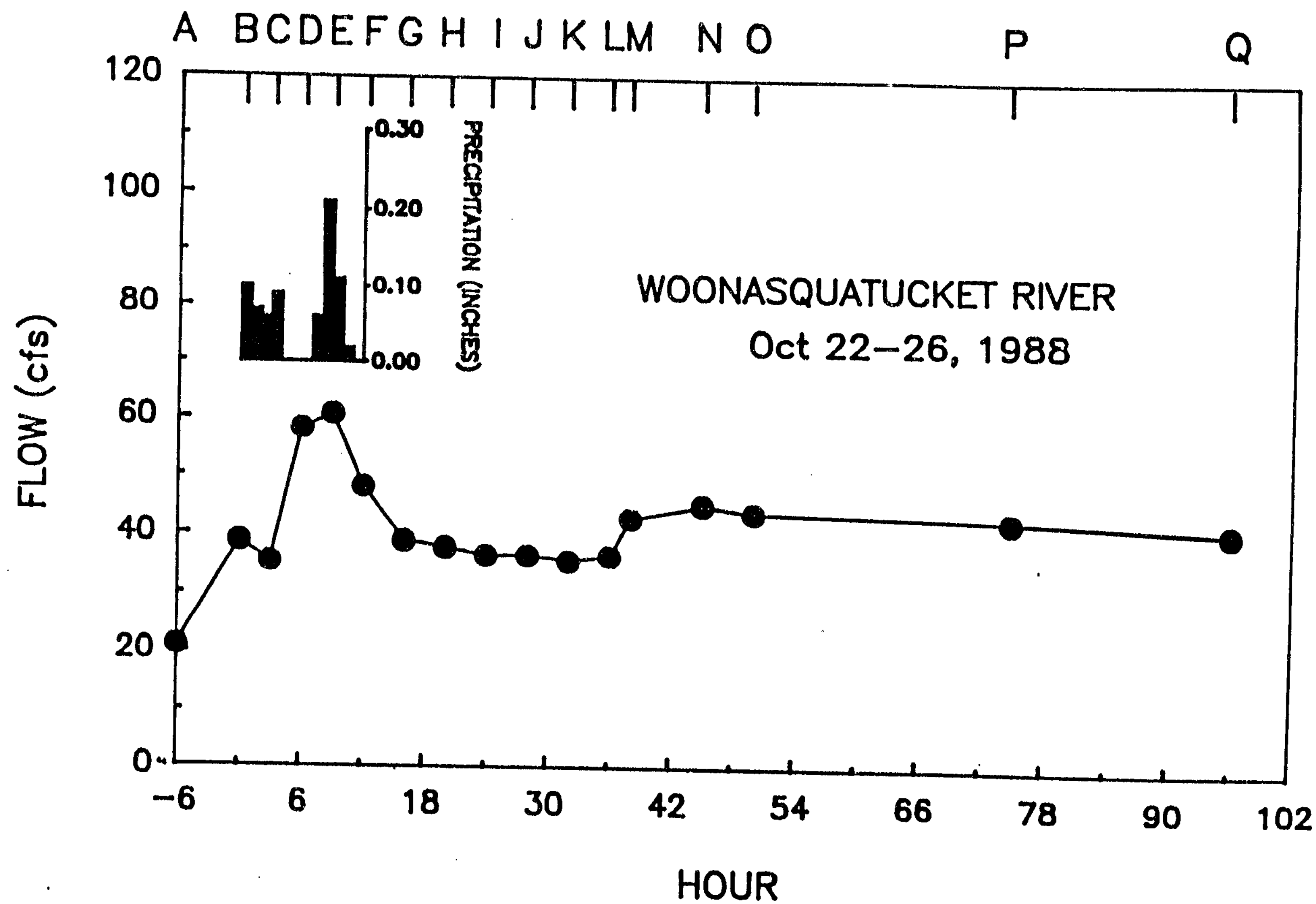
A.3 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.



A.4 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.



A.5 Flows for the Blackstone Ten Mile, Moshassuck, Woonasquatucket and Pawtuxet Rivers during wet weather study #1, October 22 - October 26, 1988.



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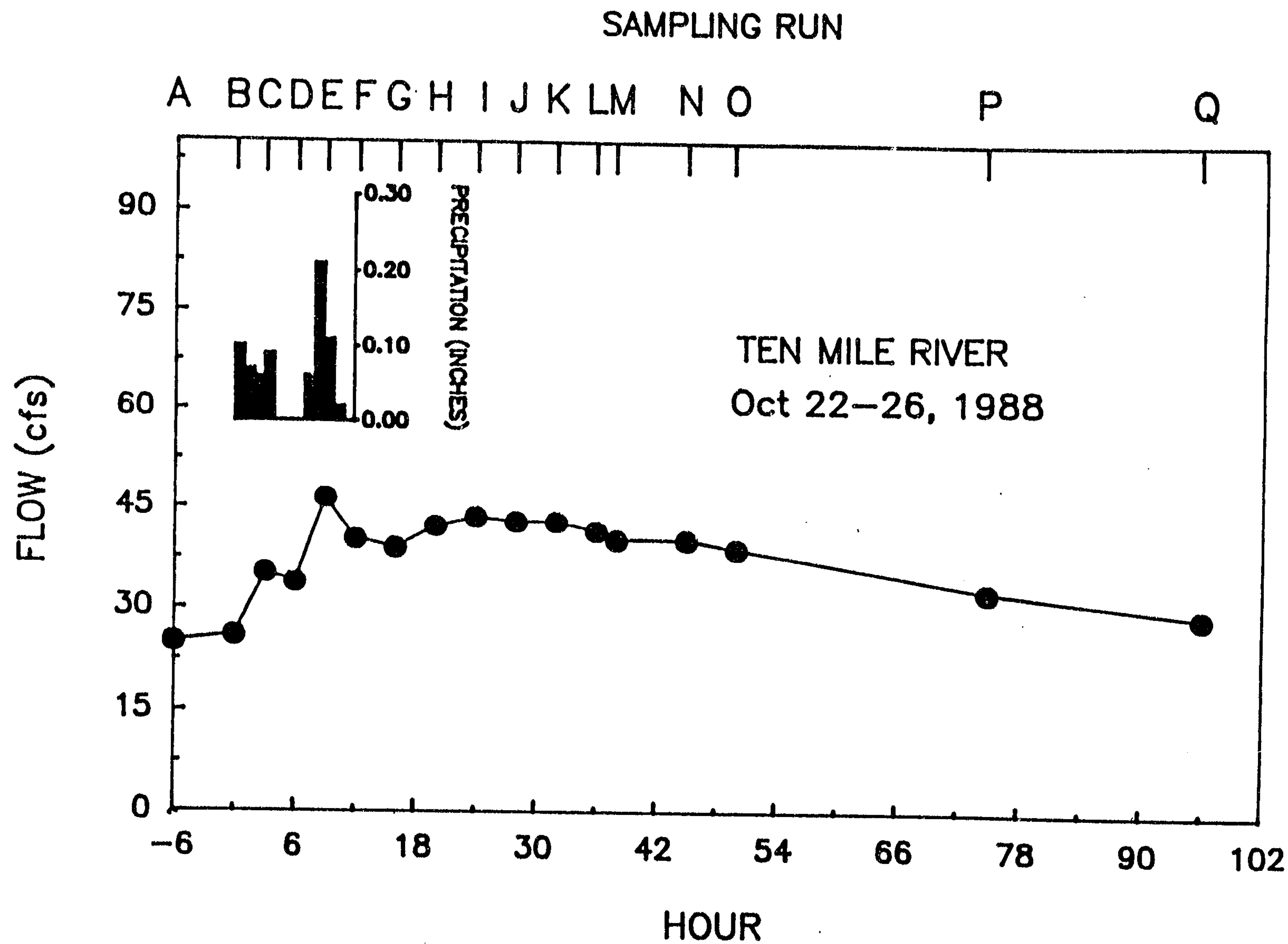

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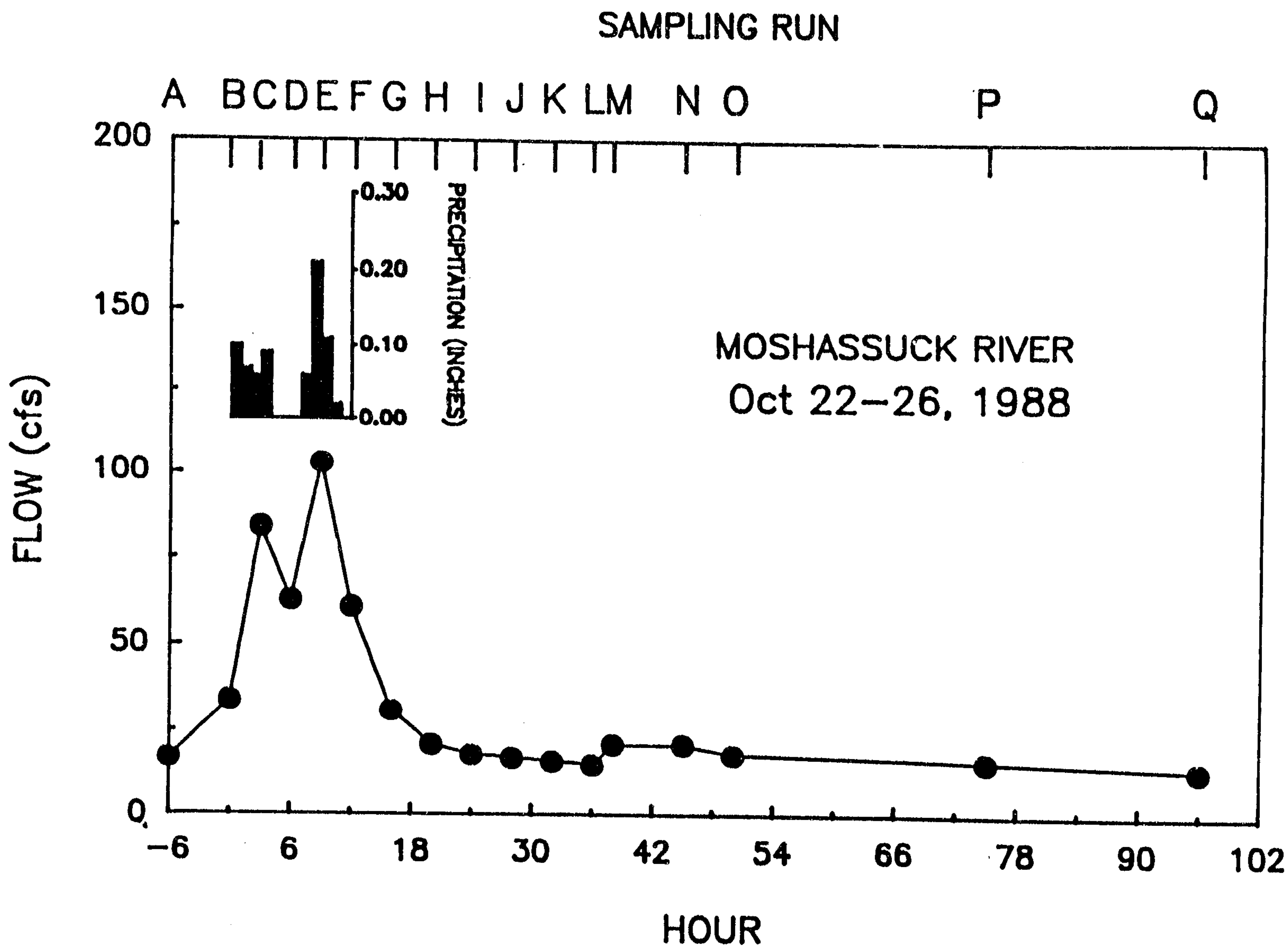

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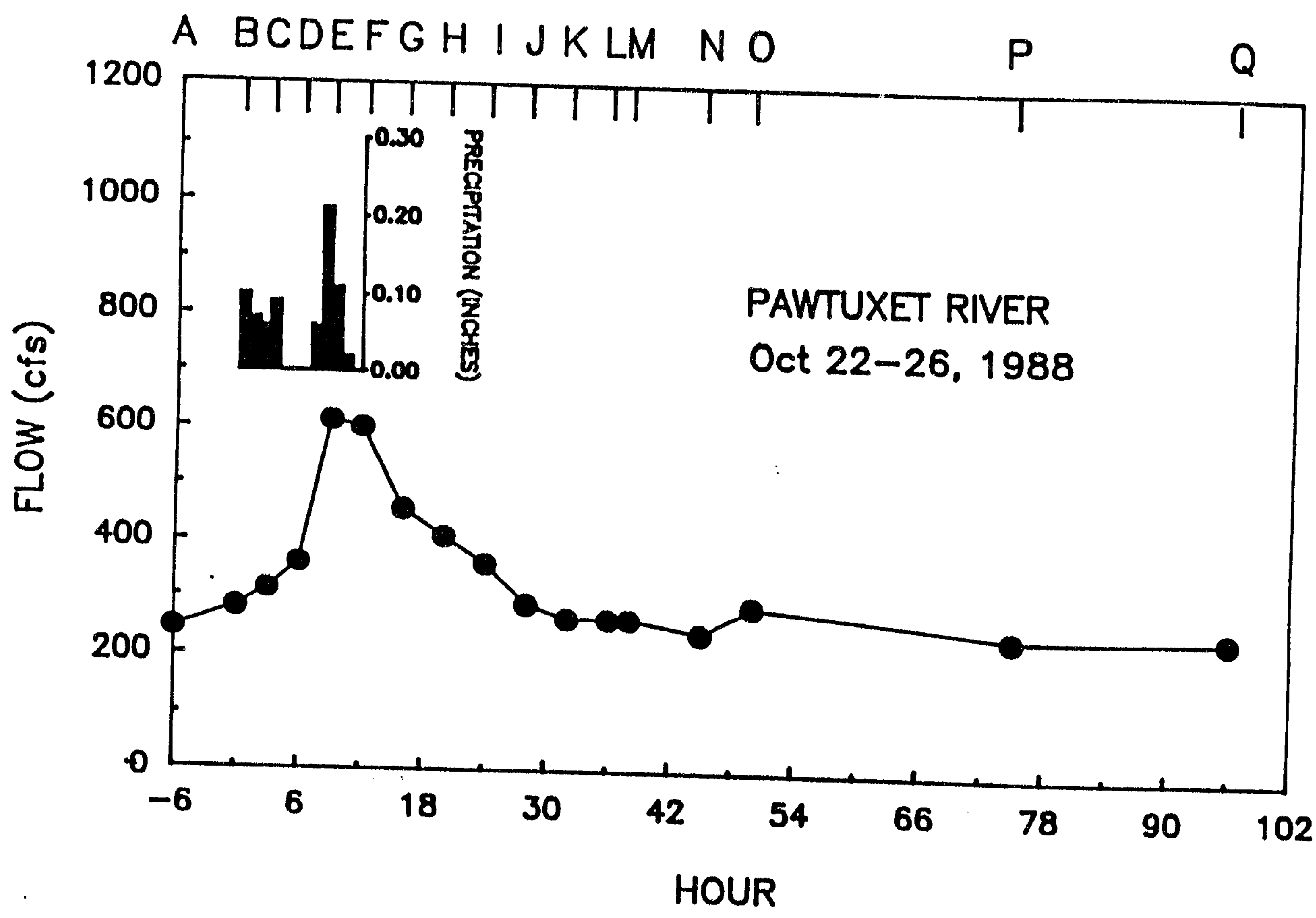

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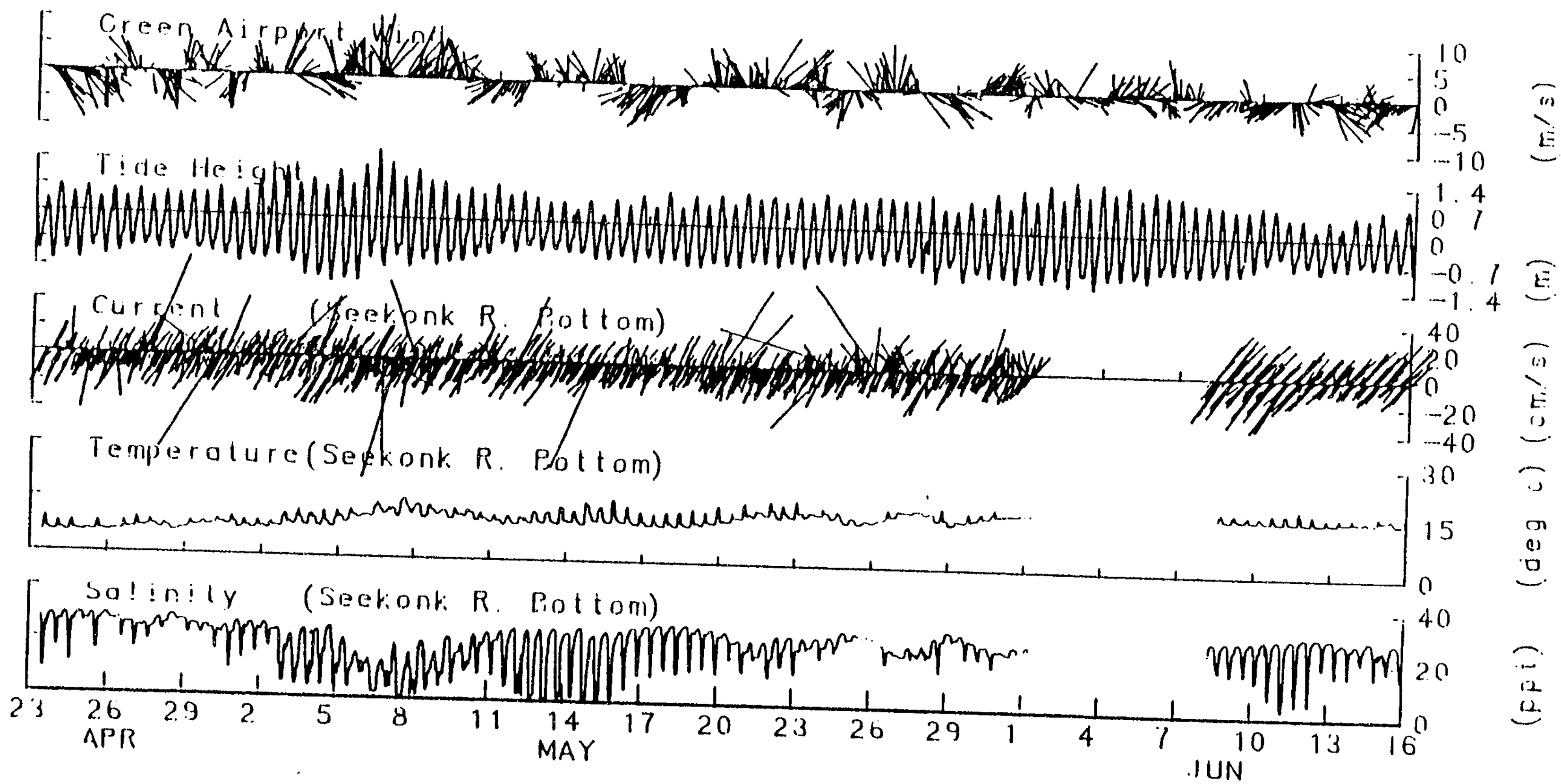
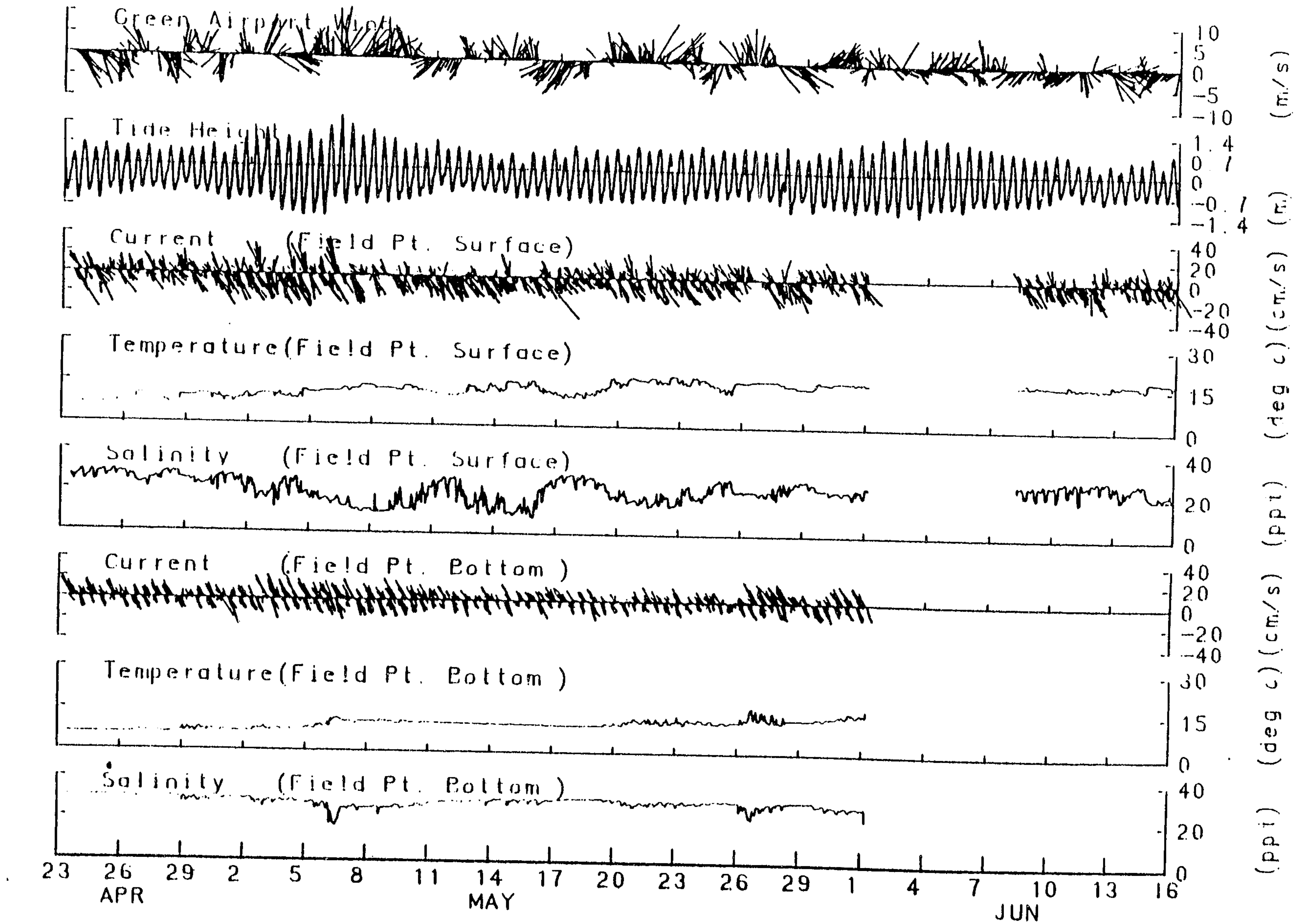
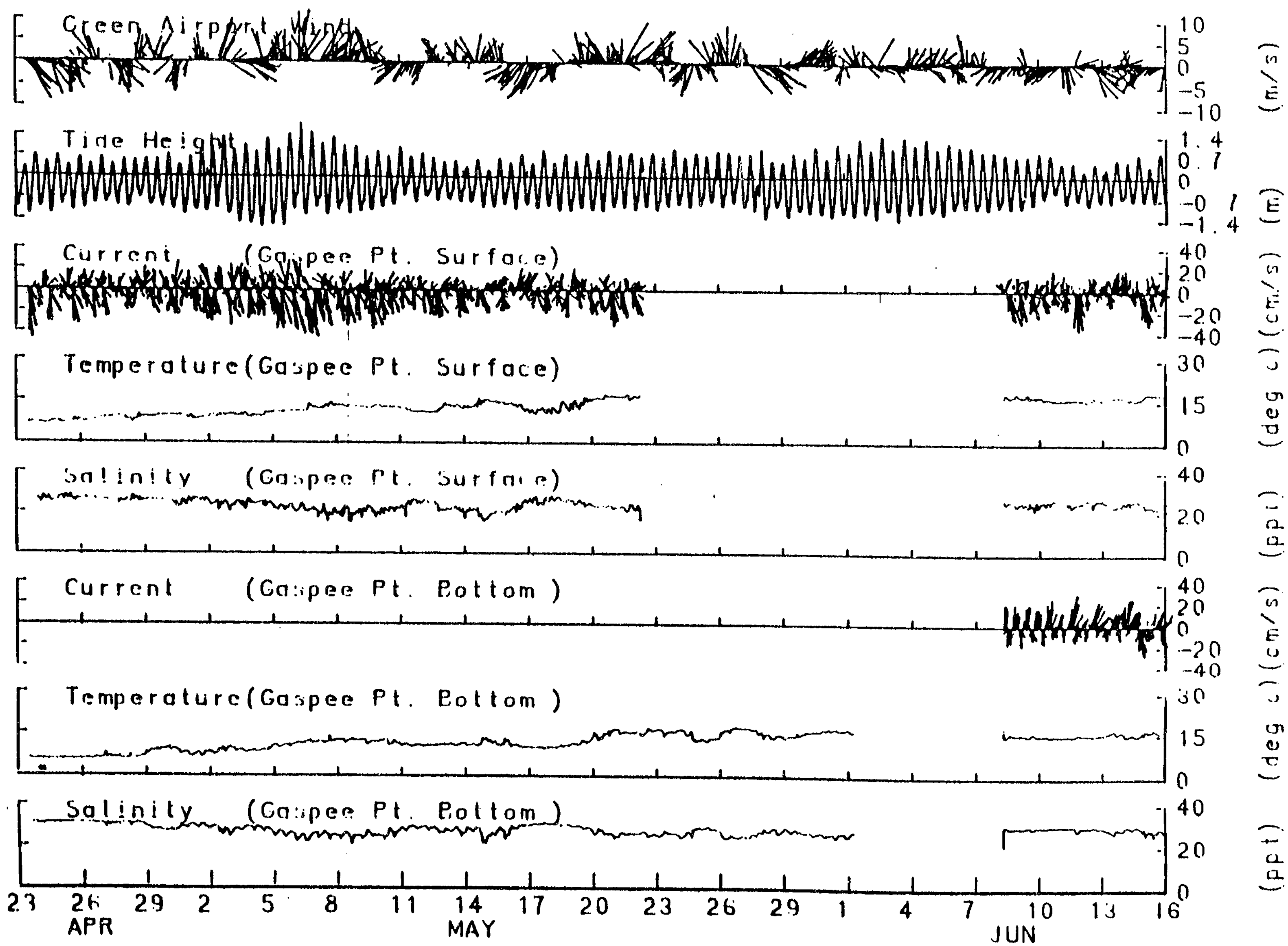


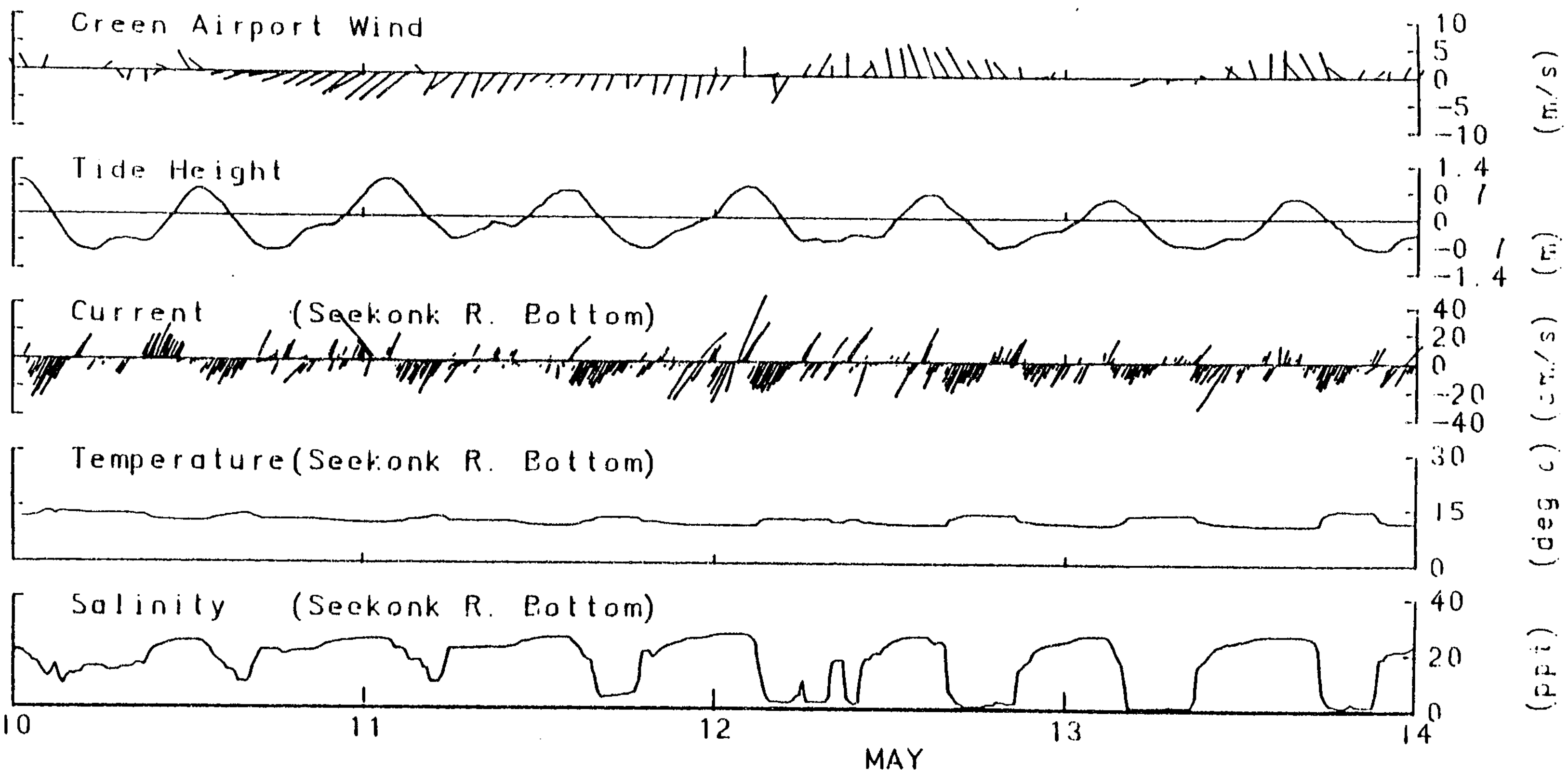
A.6 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23, - June 16, 1989.



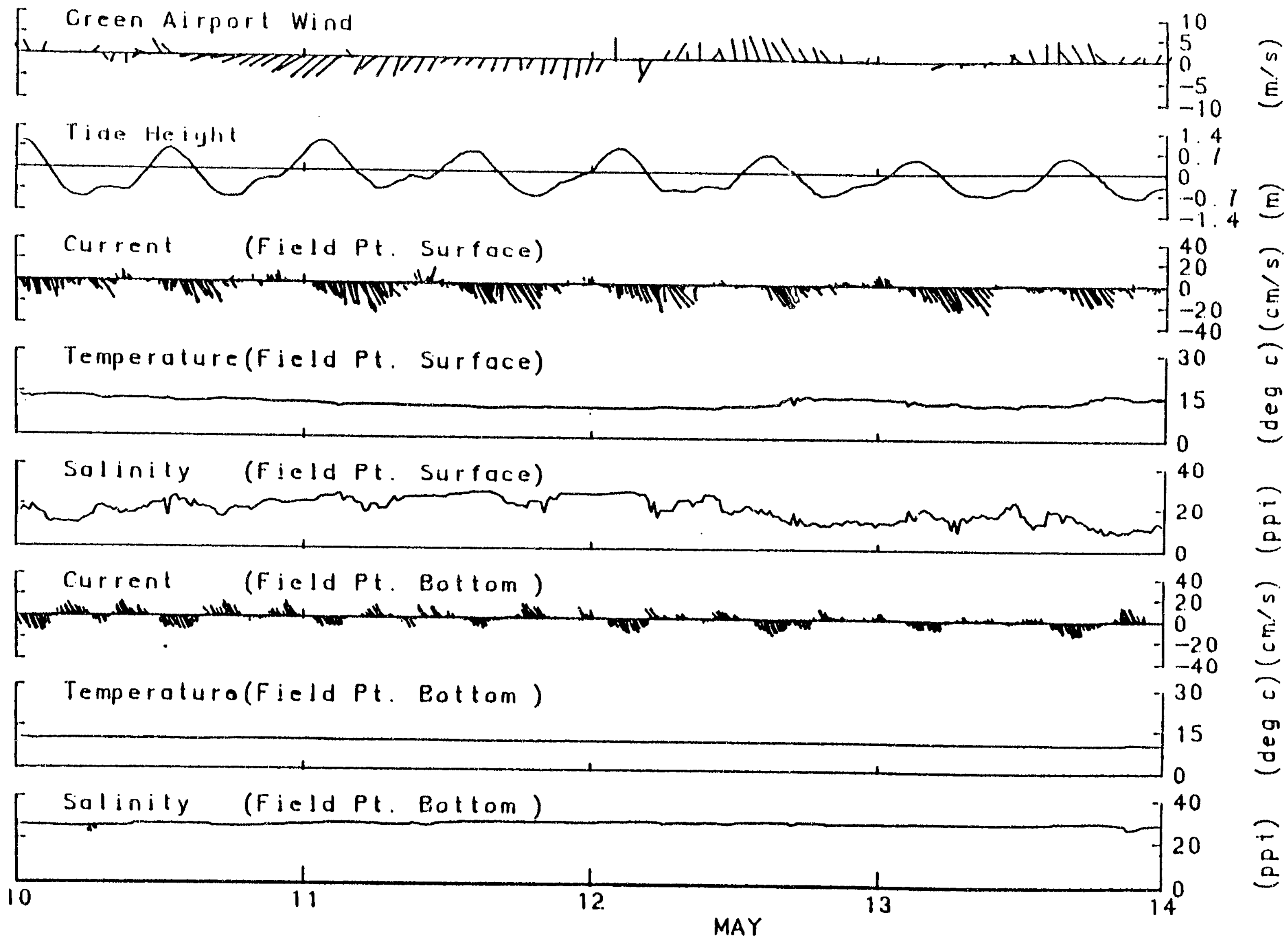
A.7 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989



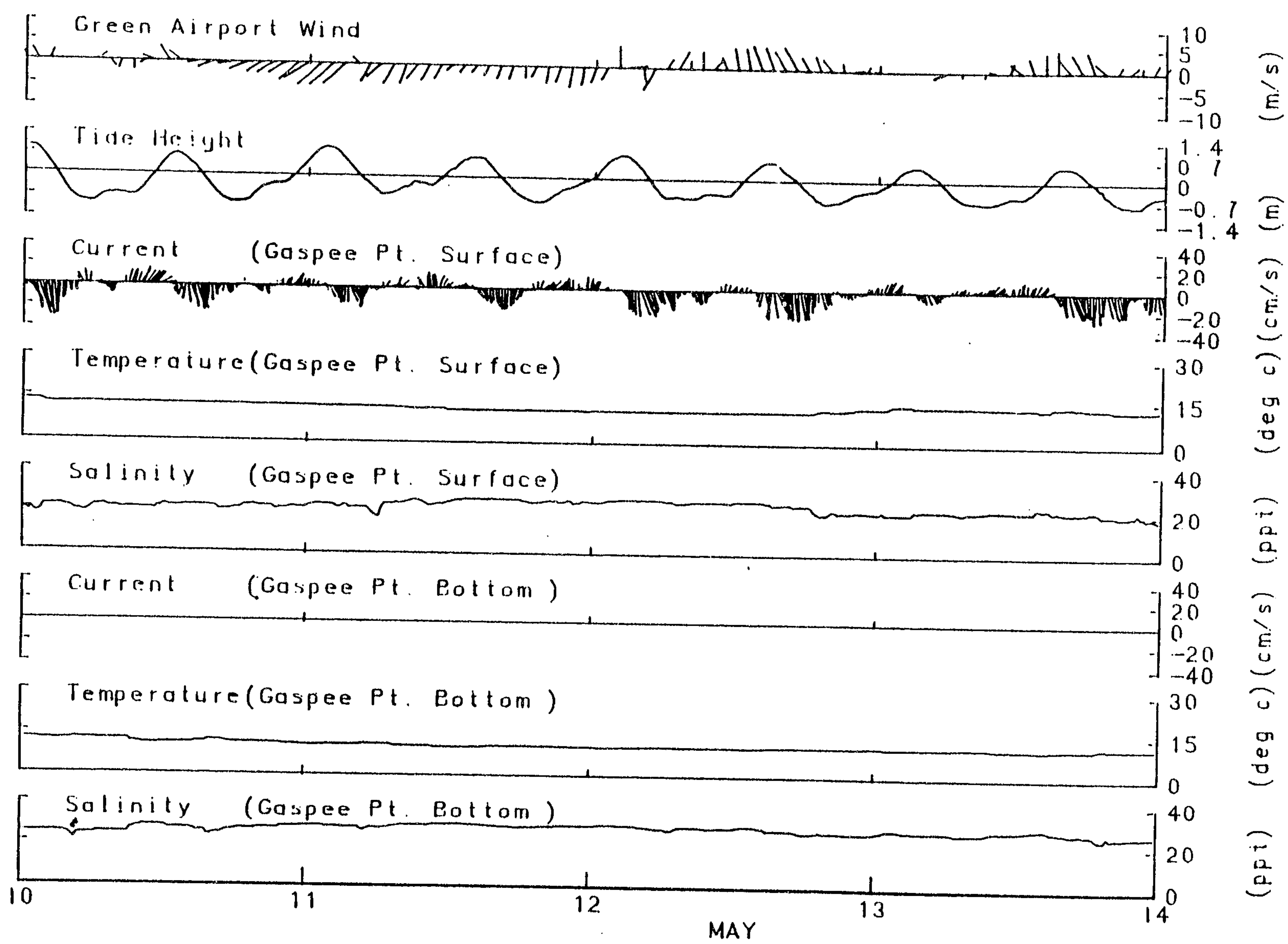
A.8 Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989.



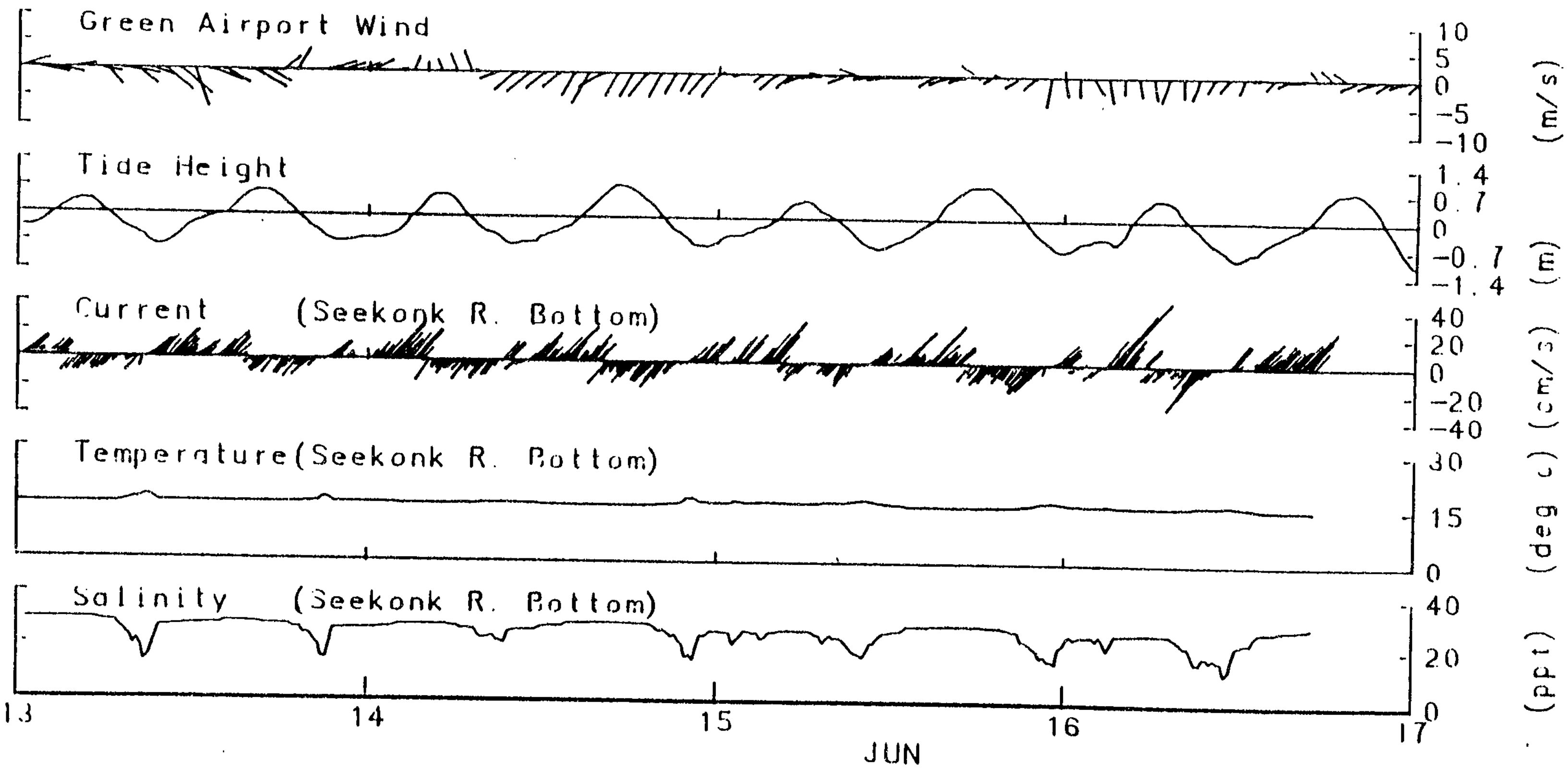
.. A.9 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000, May 10 - 1700 May 14, 1989



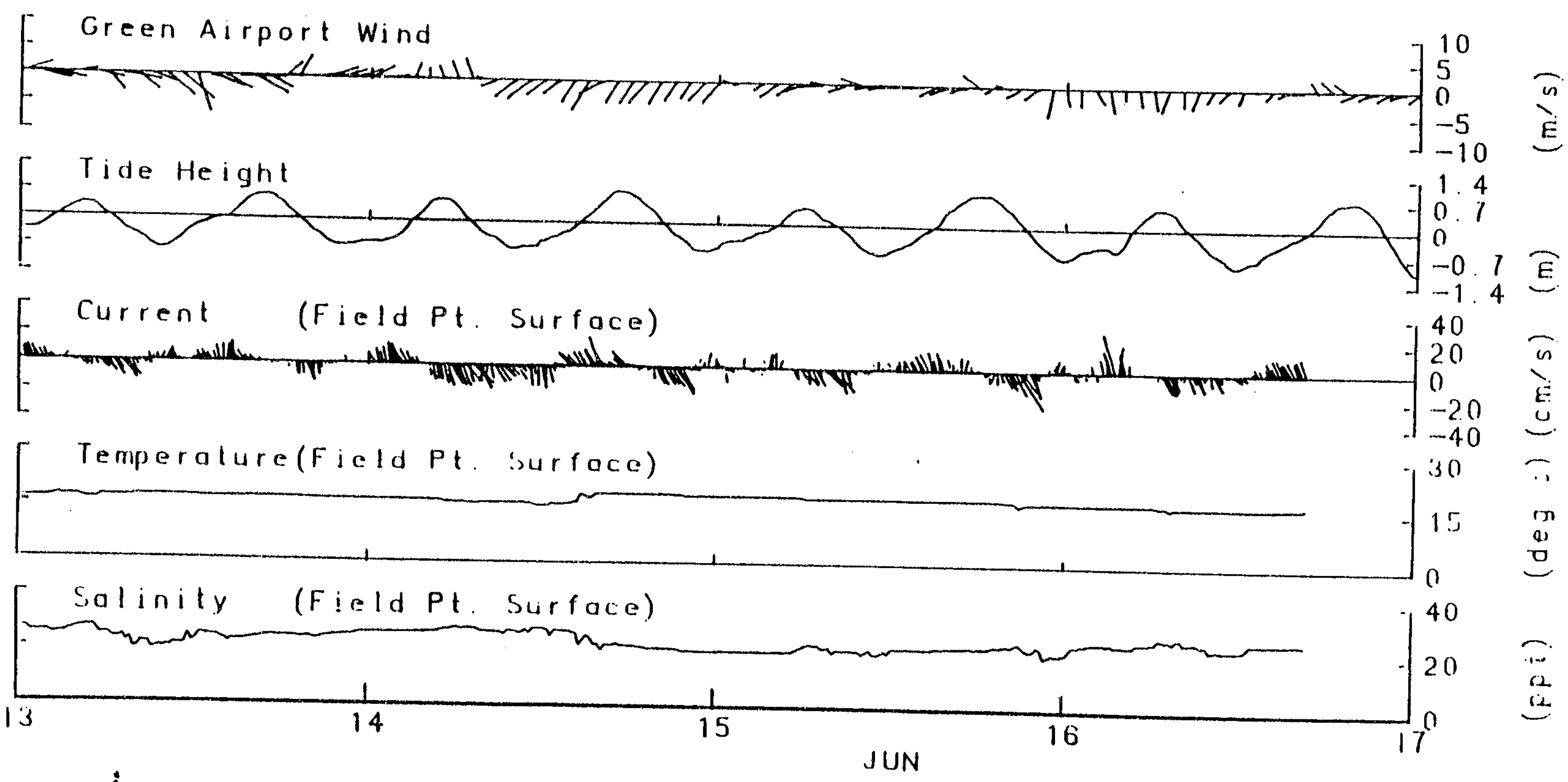
A.10 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000, May 10 - 0000 May 14, 1989.



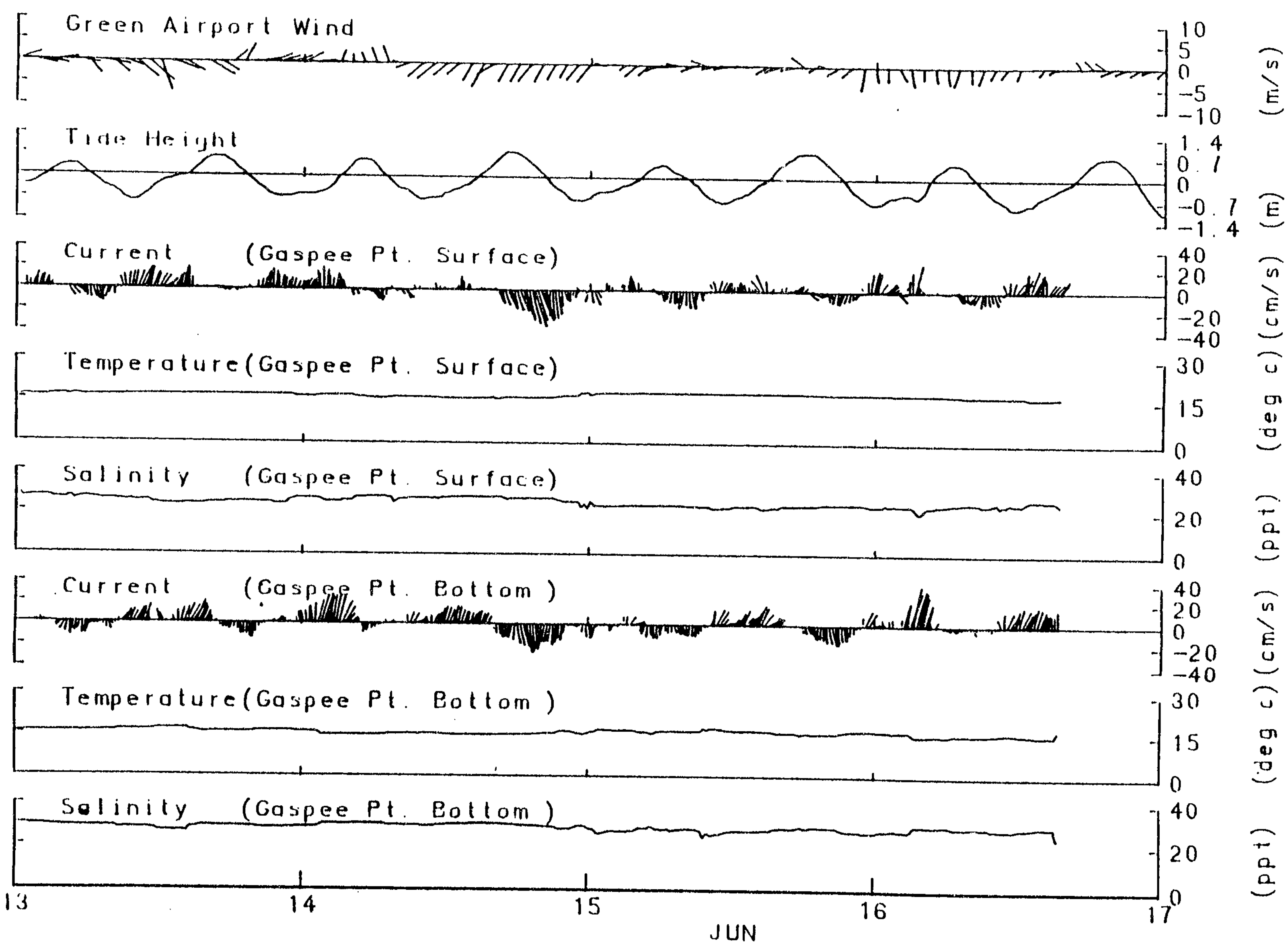
A.11 Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000, May 10 - 0000 May 14, 1989.



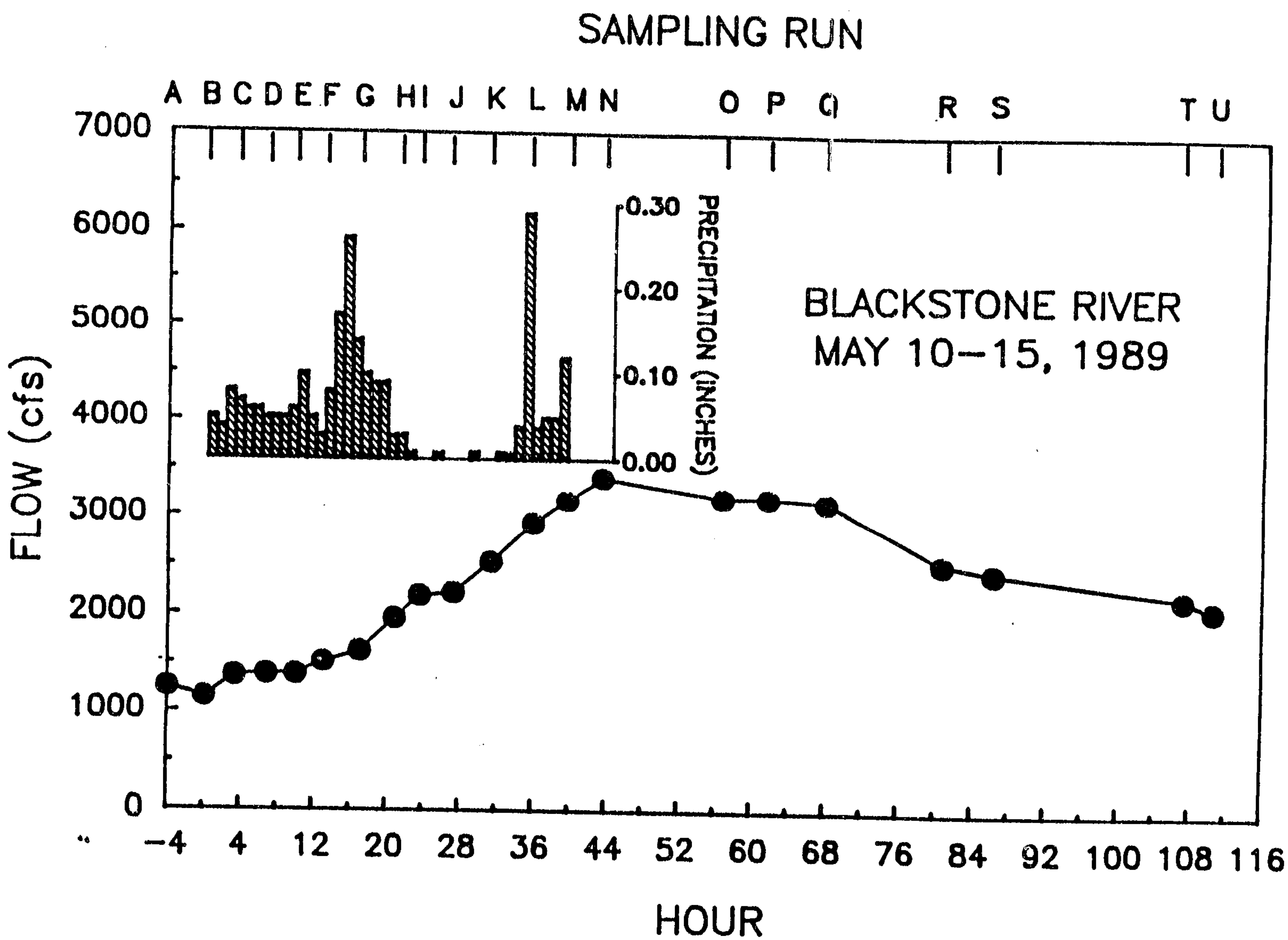
A.12 Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 June 13 - 0000 June 17, 1989.



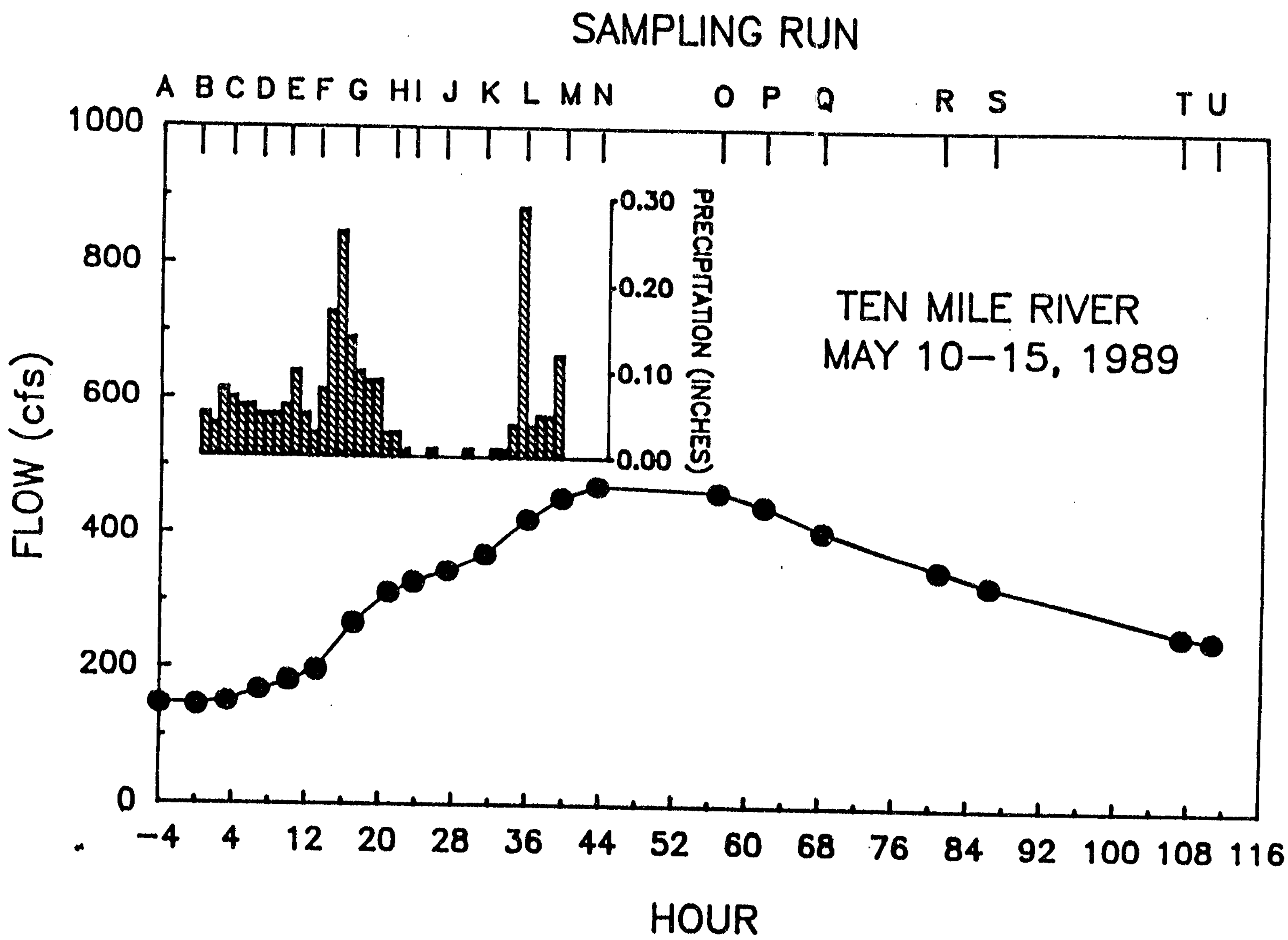
A.13 Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 June 13, - 0000 June 17, 1989.



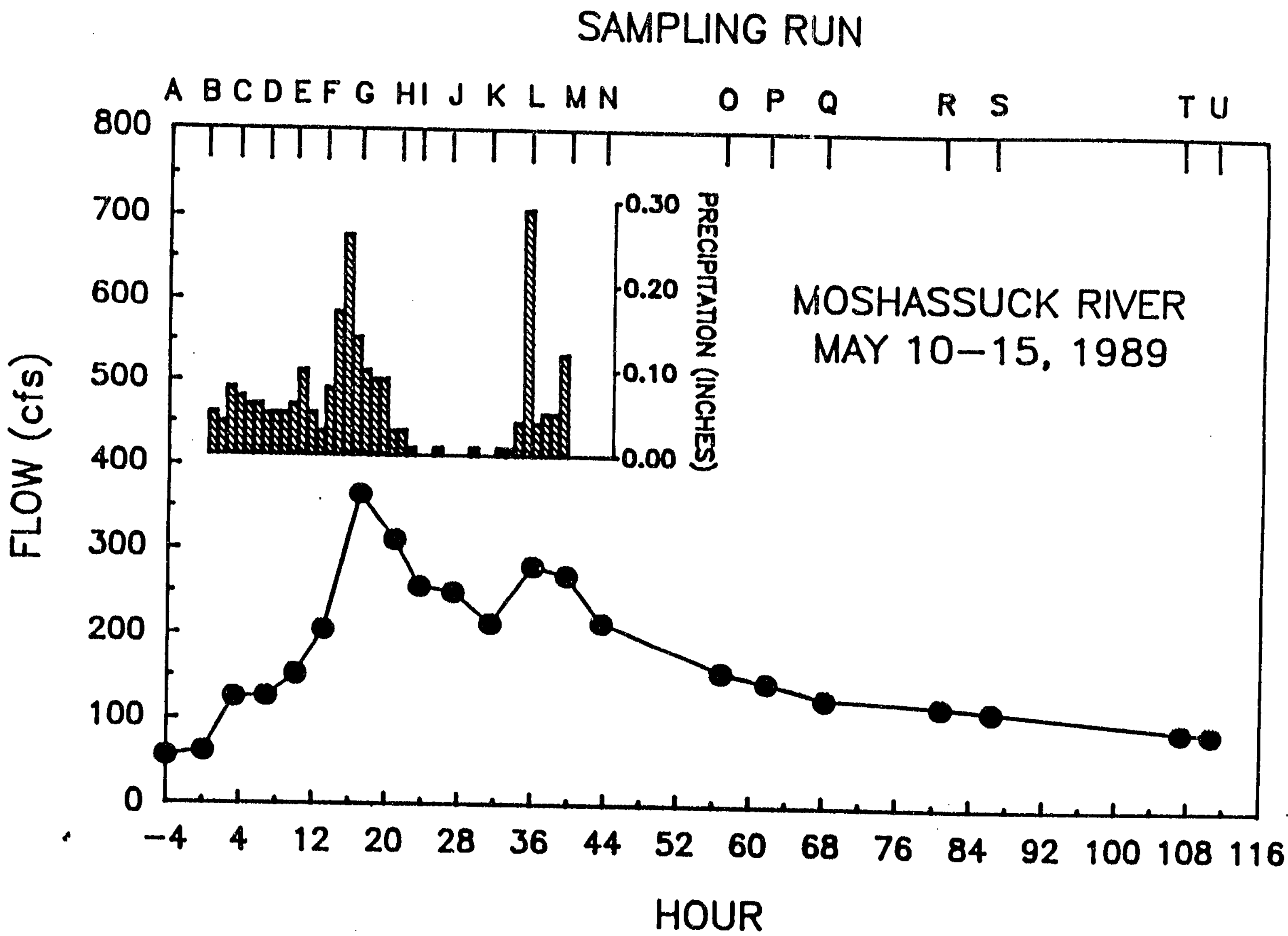
A.14 Gaspee-Bullock Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 June 13 - 0000 June 17, 1989.



A.15 Flows for the Blackstone Ten Mile, Moshassuck, Woonasquatucket and Pawtuxet Rivers during wet weather study #2, May 10 - May 15, 1989.



A.15 continued



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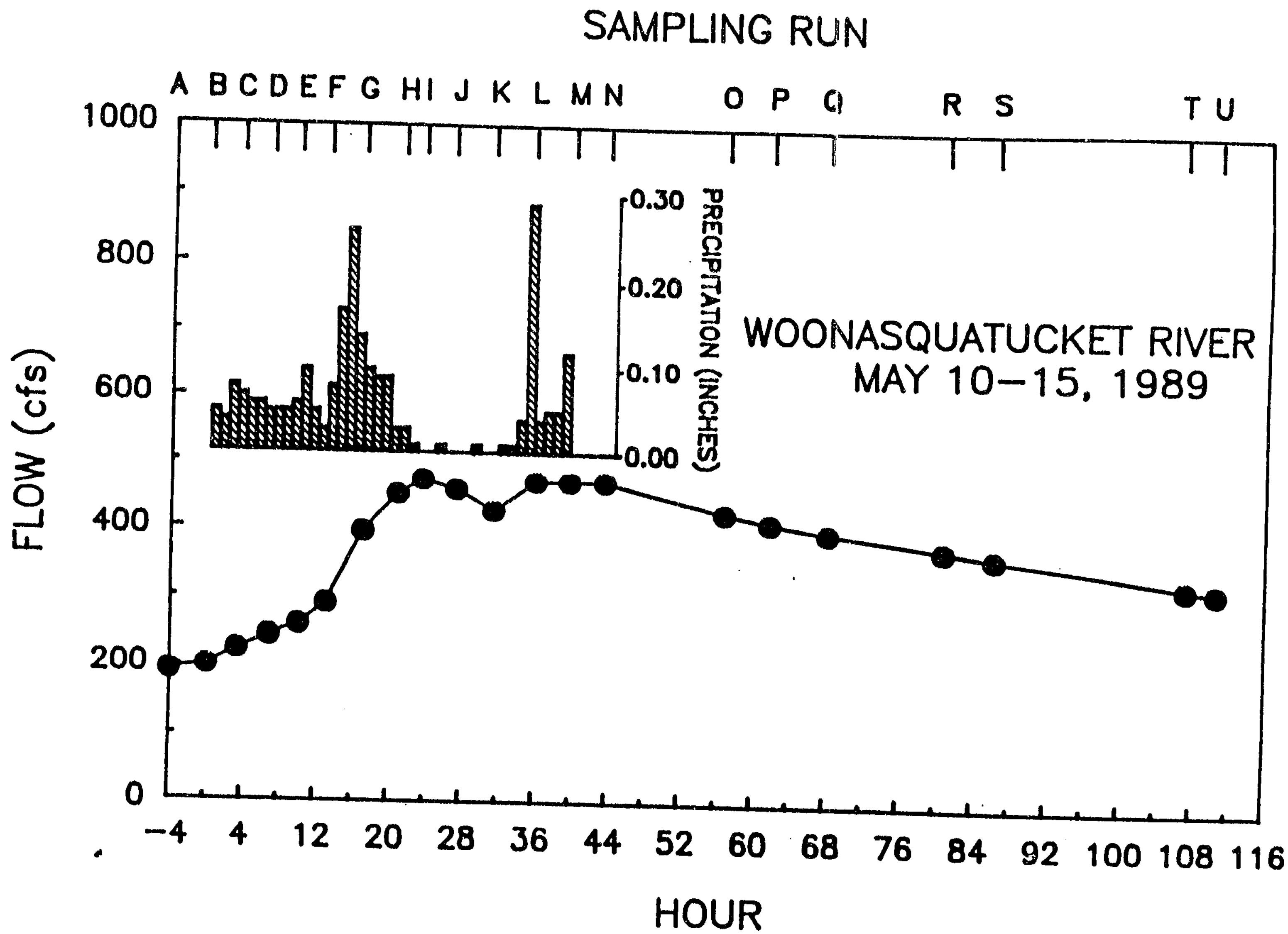
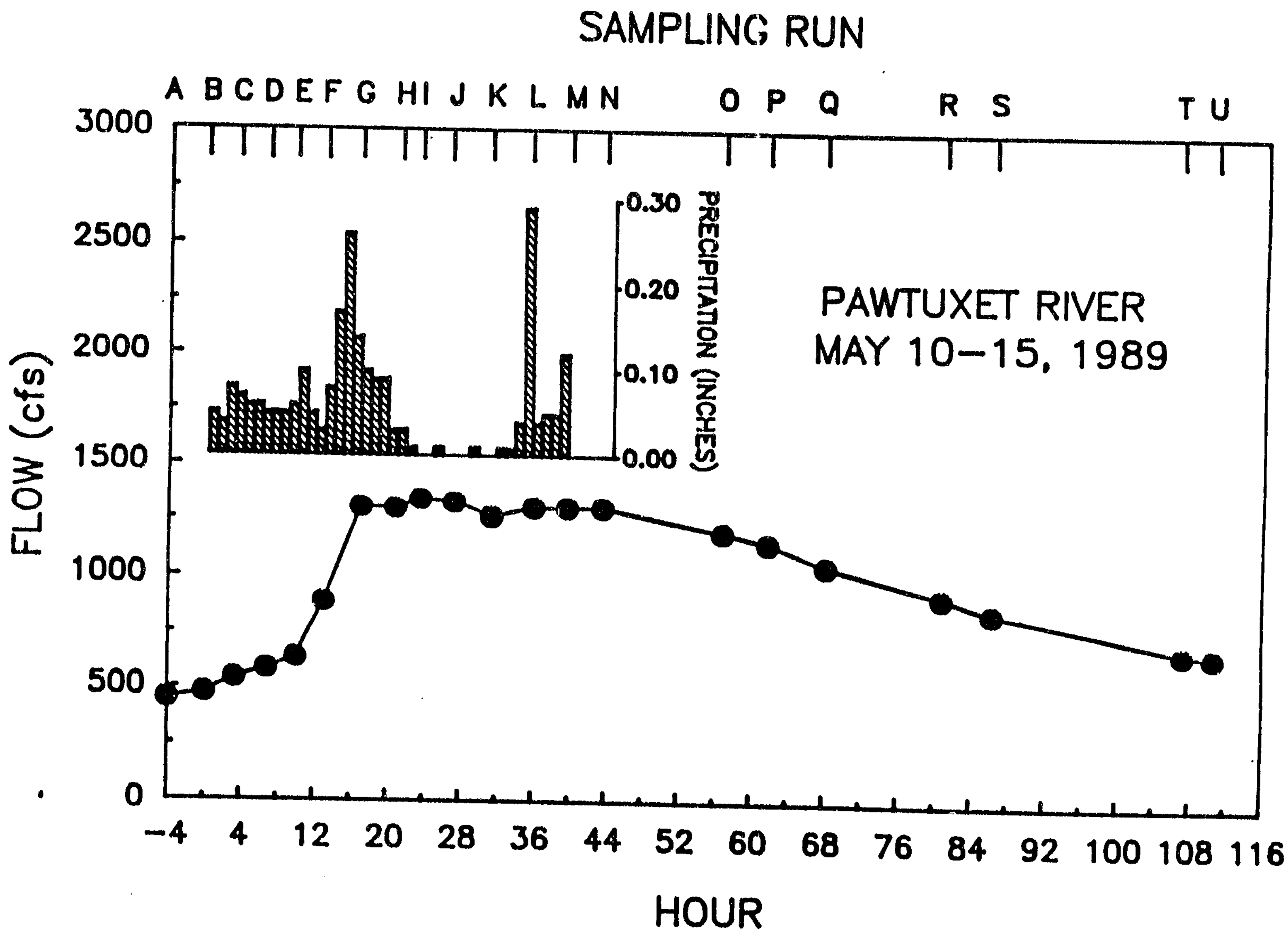
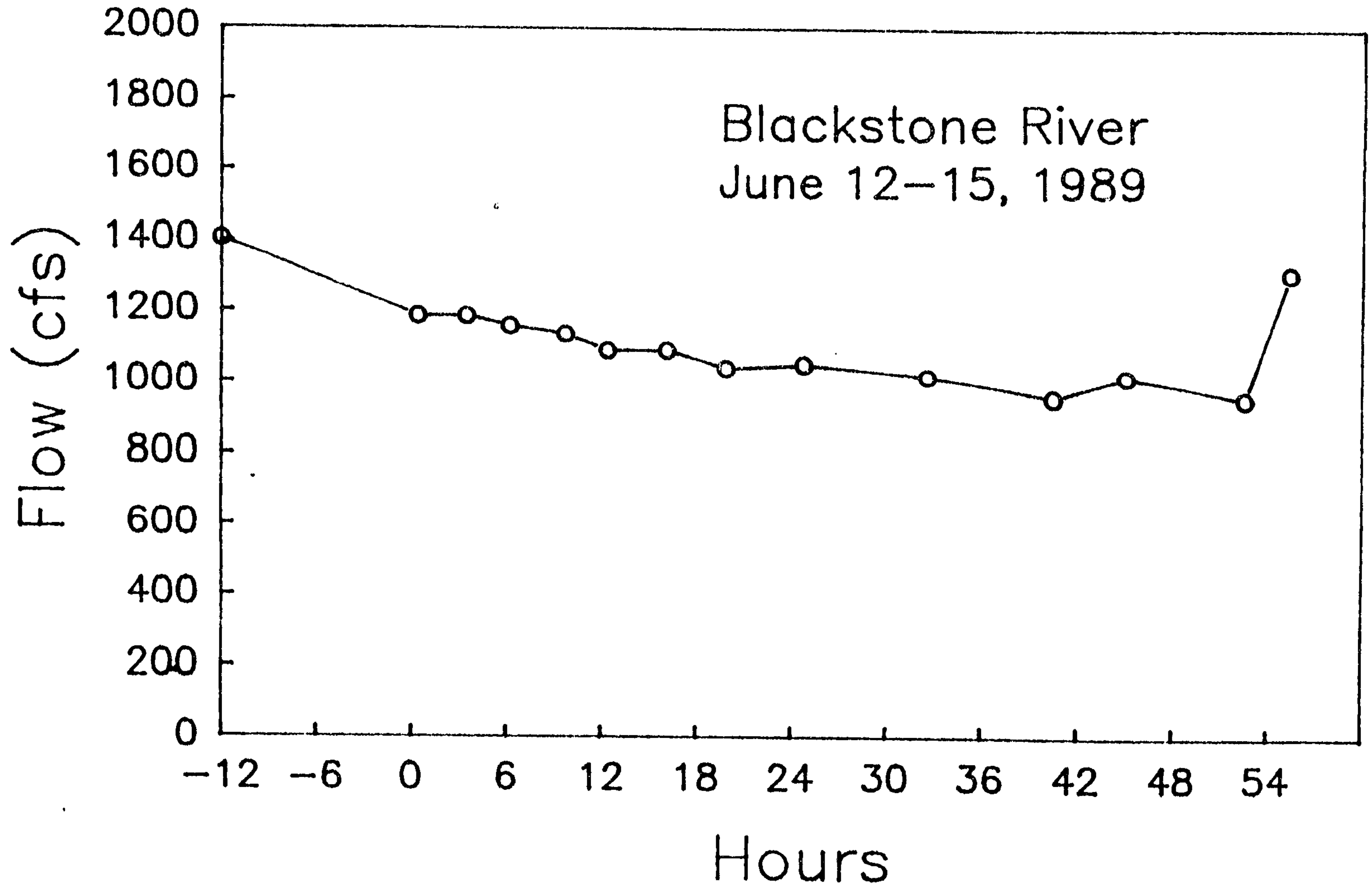


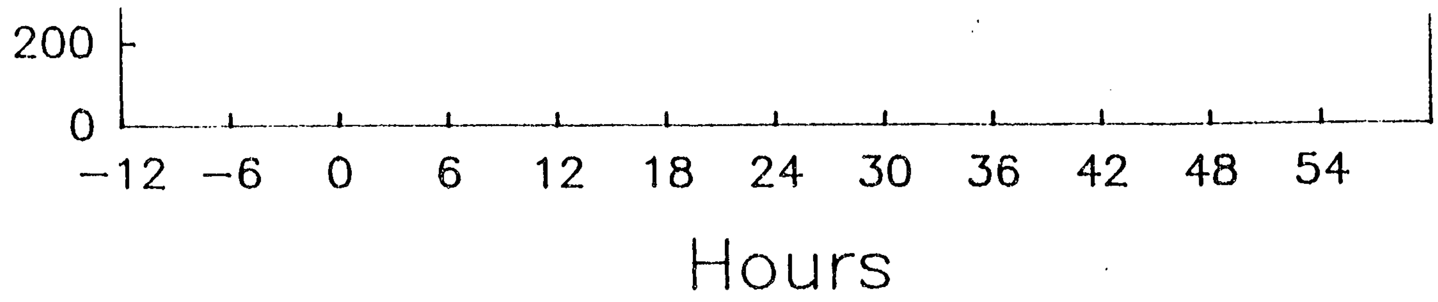
A.15 continued



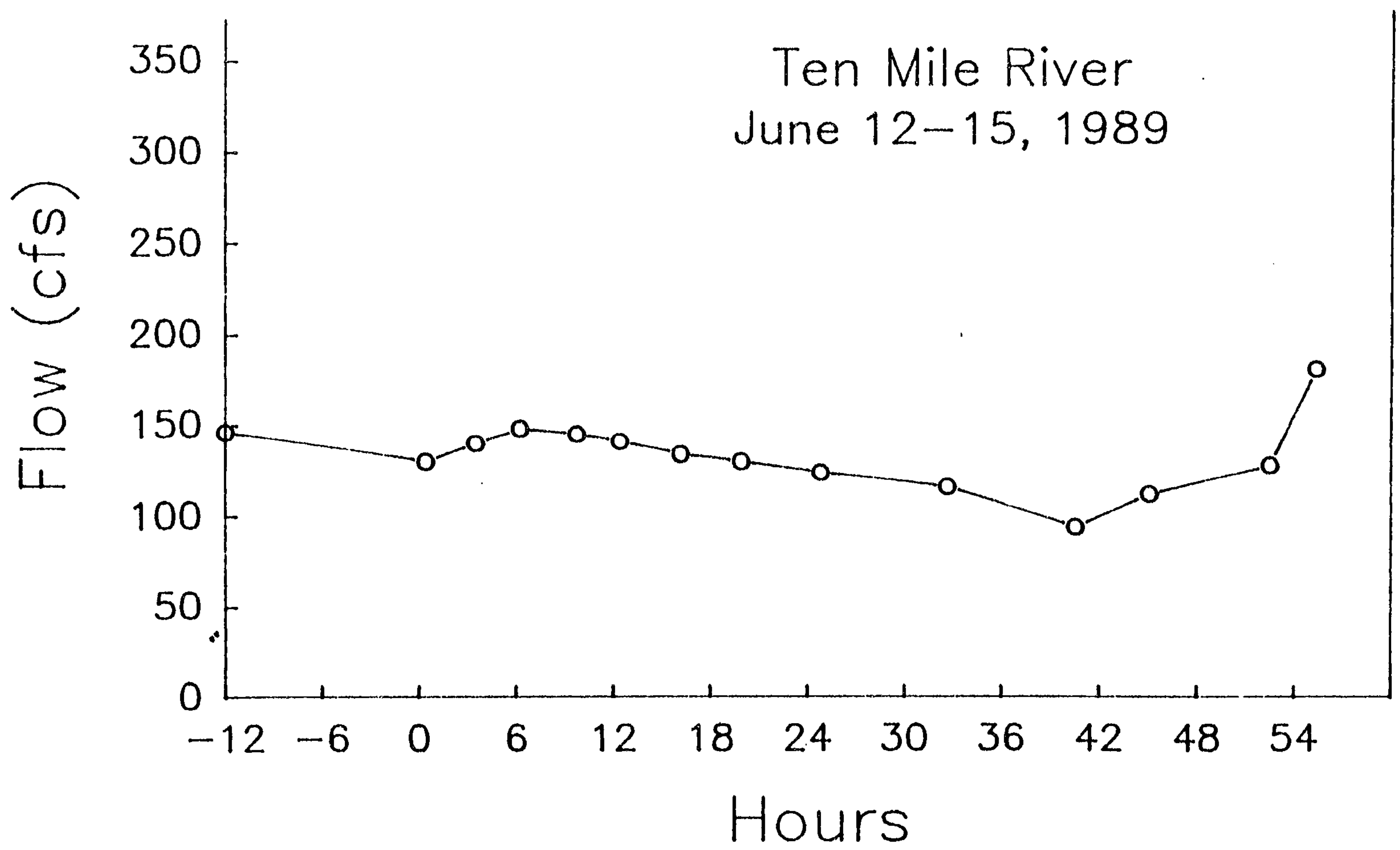
A.15 continued



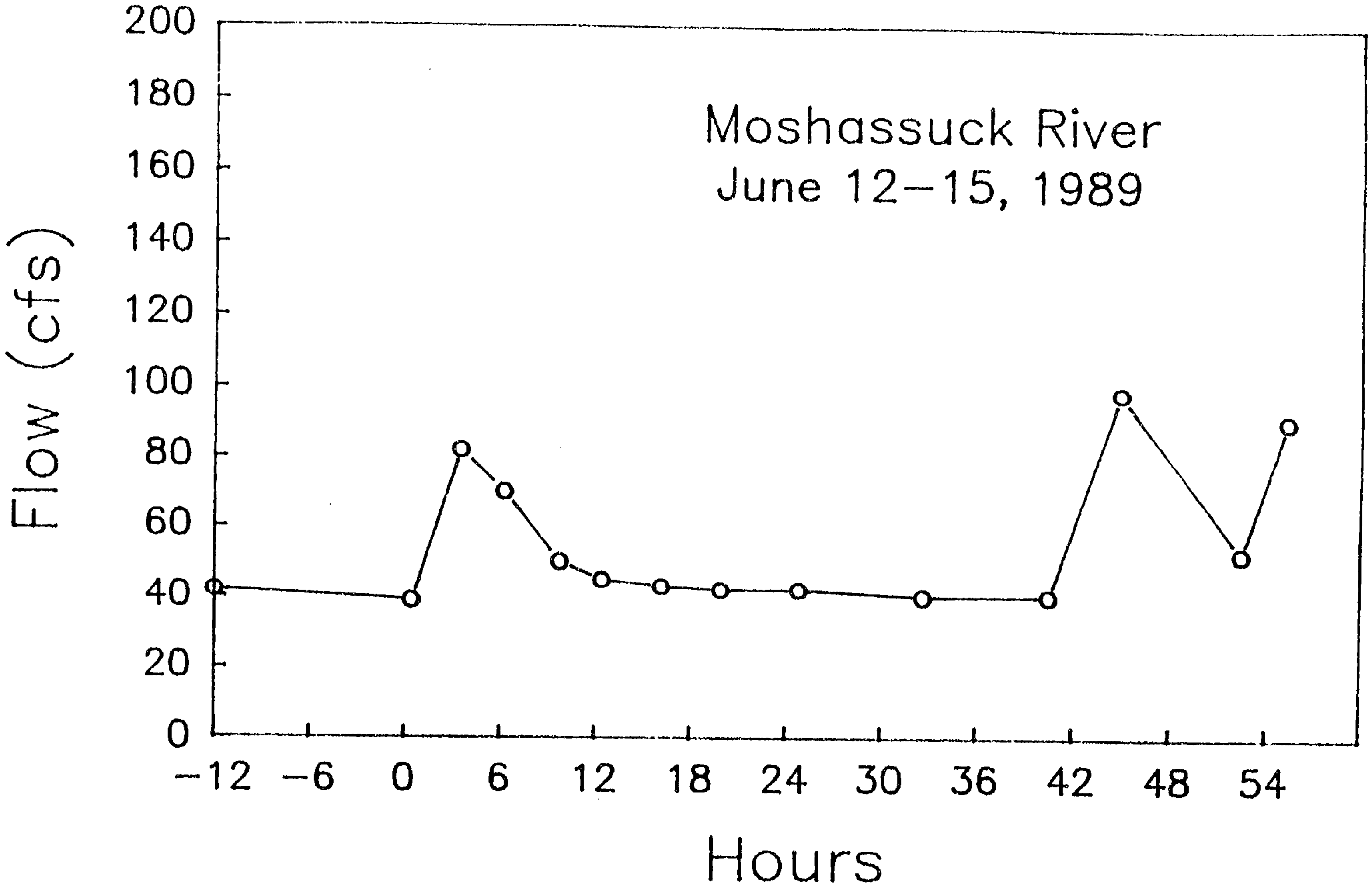
A.16 Flows for the Blackstone, Ten Mile, Moshassuck, and Pawtuxet Rivers during wet weather study #3, June 13 - June 16, 1989. Data for the Woonasquatucket River were not available for this period.



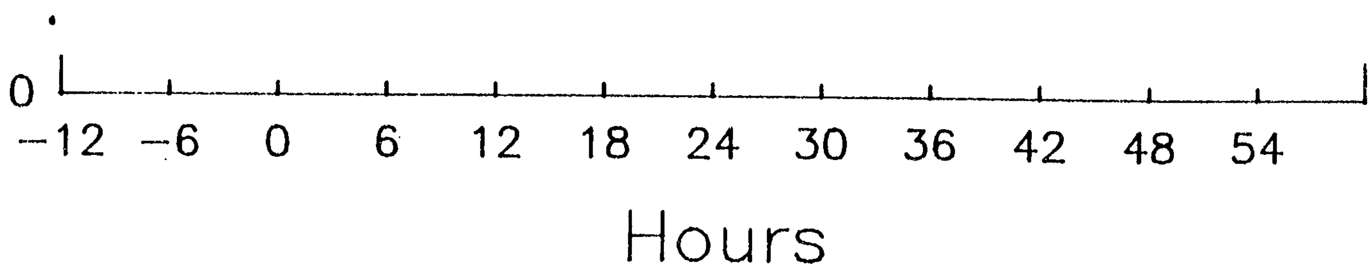
A.16 Flows for the Blackstone, Ten Mile, Moshassuck, and Pawtuxet Rivers during wet weather study #3, June 13 - June 16, 1989. Data for the Woonasquatucket River were not available for this period.



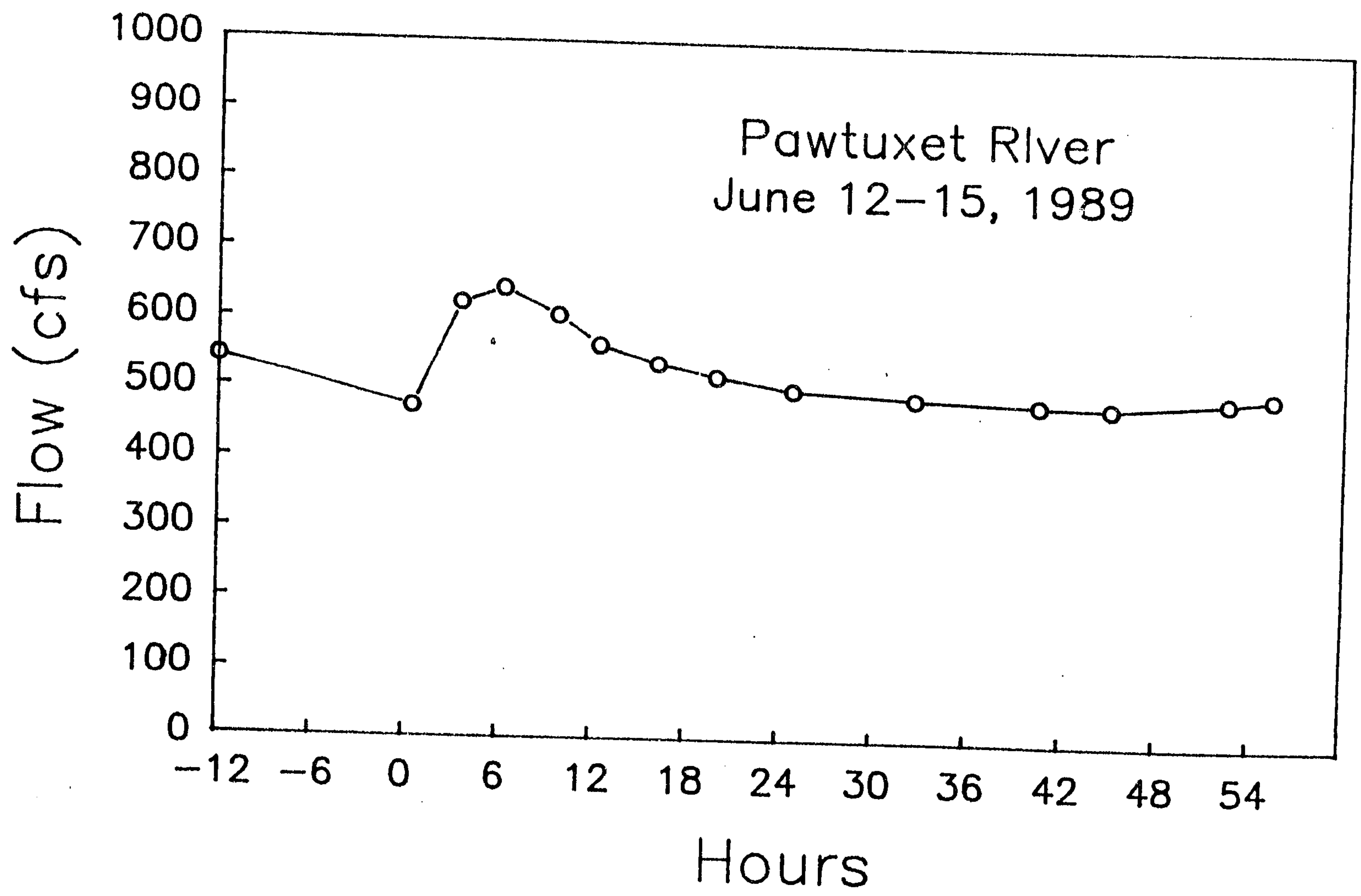
A.16 Continued



A.16 Continued



A.16 Continued



A.16 Continued

APPENDIX B: CURRENT SPEED AND DIRECTION DISTRIBUTIONS

<u>Study #1</u>

B.1 Seekonk River Bottom Current Speed and Direction, September 17 - November 7, 1988.

B.2 Fields Point Surface Current Speed and Direction, September 17 - November 6, 1988.

B.3 Fields Point Bottom Current Speed and Direction, September 17 - November 7, 1988.

<u>Study #2</u>

B.4 Seekonk River Bottom Current Speed and Direction, April 23 - June 1, 1989.

B.5 Fields Point Surface Current Speed and Direction, April 23 - June 1, 1989.

B.6 Fields Point Bottom Current Speed and Direction, April 23 - June 1, 1989.

B.7 Gaspee-Bullock Transect Surface Current Speed and Directions, April 23 - May 22, 1989.

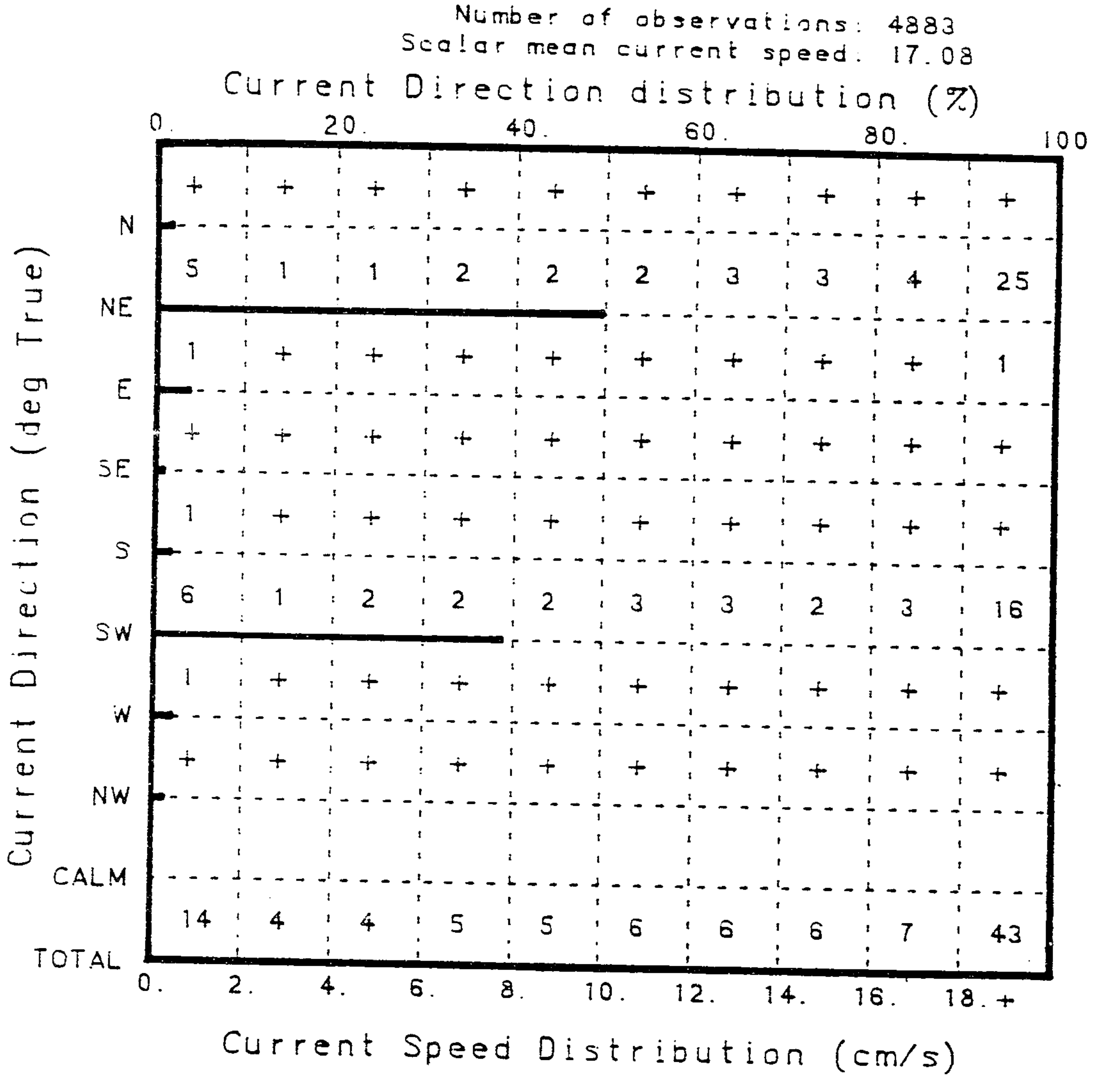
<u>Study #3</u>

B.8 Seekonk River Bottom Current Speed and Direction, June 8 - June 16, 1989.

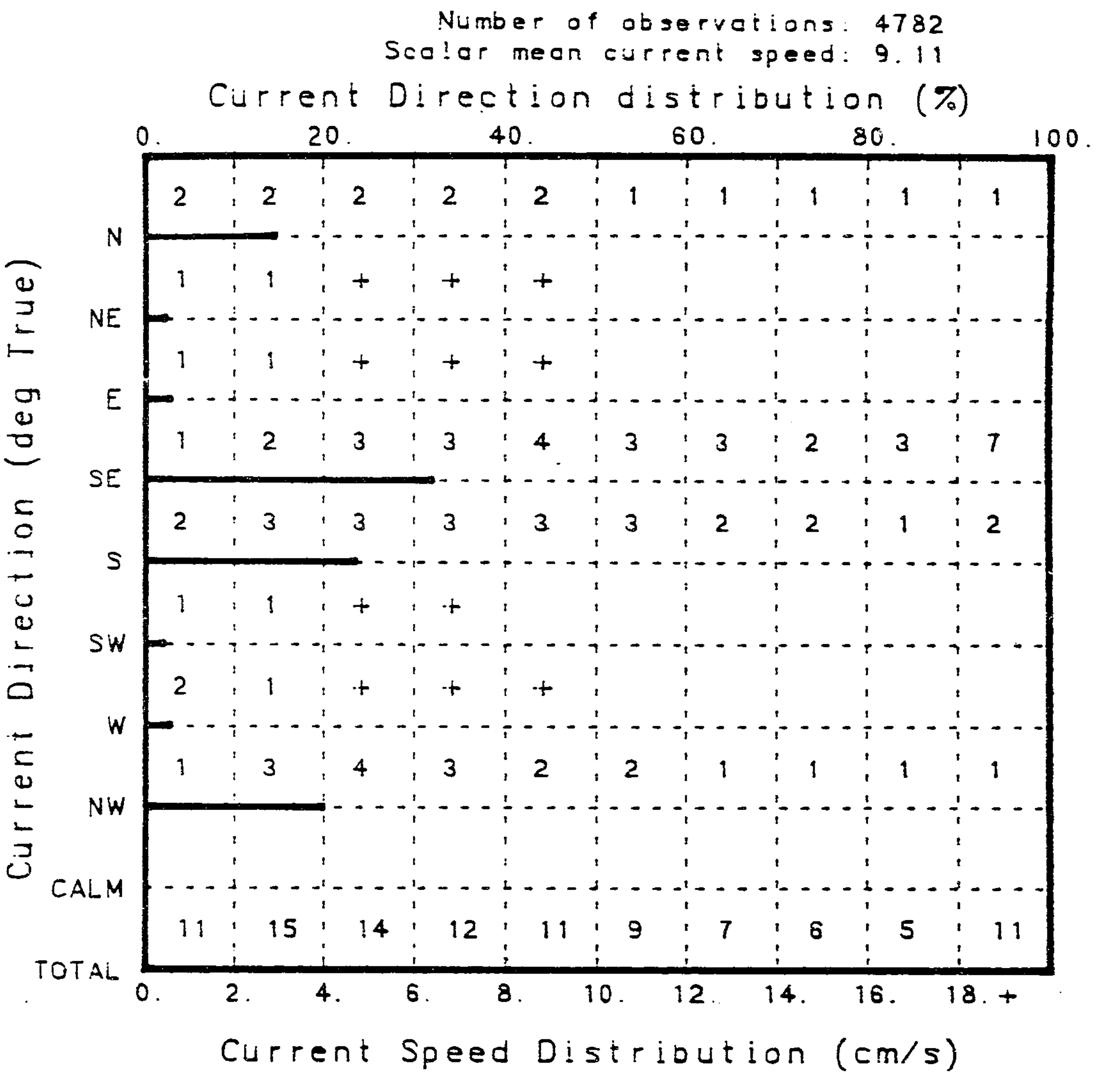
B.9 Fields Point Surface Current Speed and Direction, June 8 - June 16, 1989.

B.10 Gaspee-Bullock Transect Surface Current Speed and Direction, June 8 - June 16, 1989.

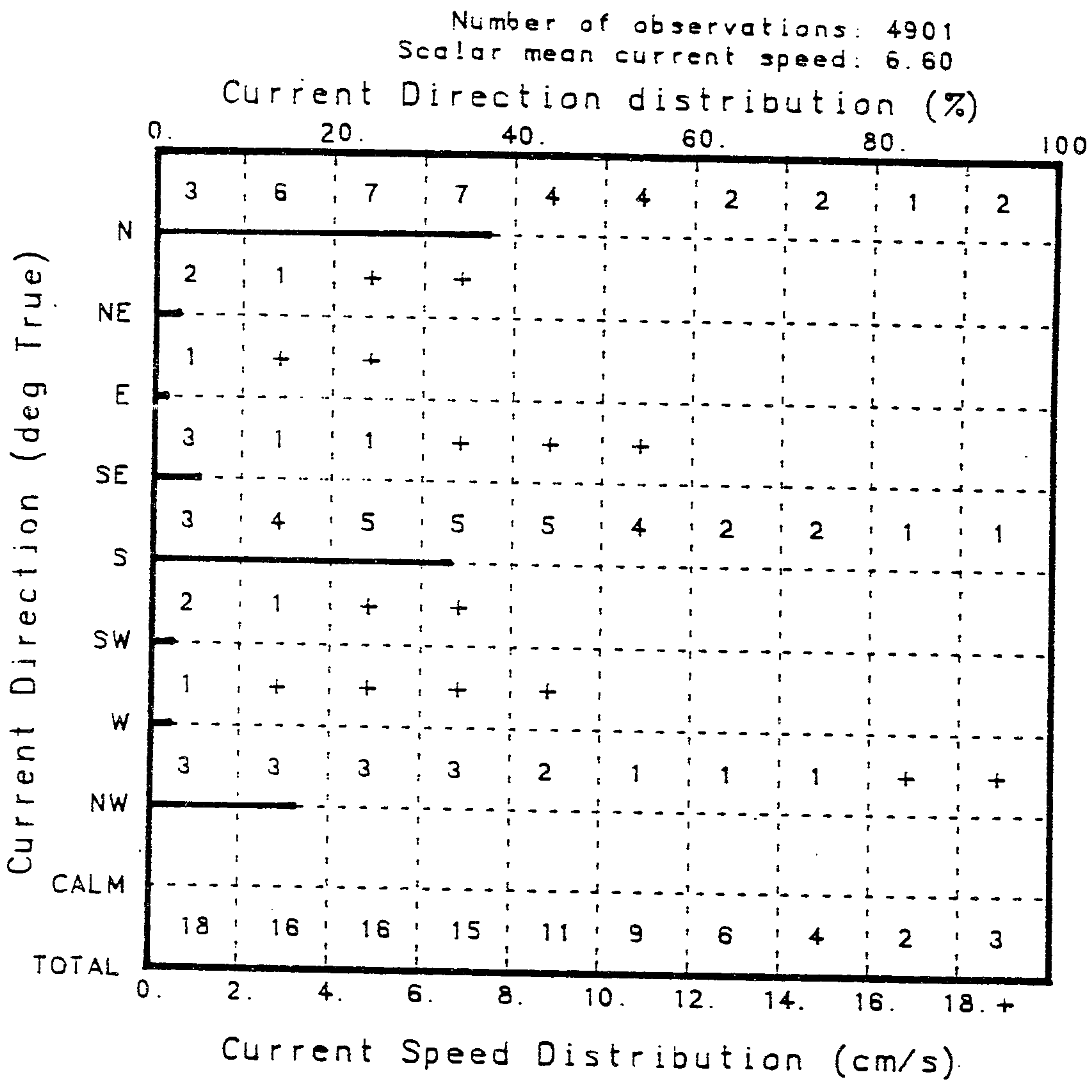
B.11 Gaspee-Bullock Transect Bottom Current Speed and Direction, June 8 - June 16, 1989.



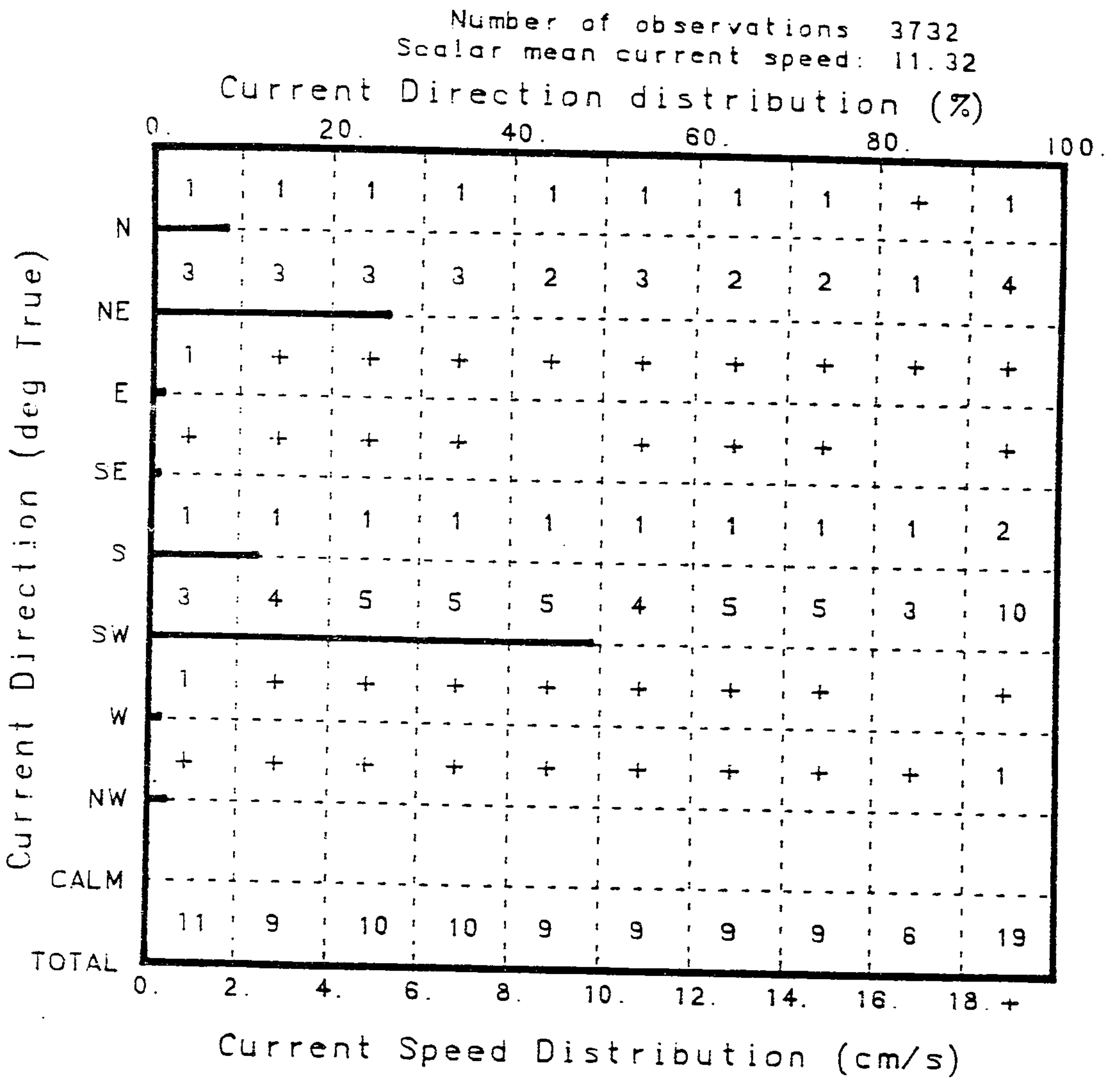
B.1 Seekonk River Bottom Current Speed and Direction, September 17 - November 7, 1988.



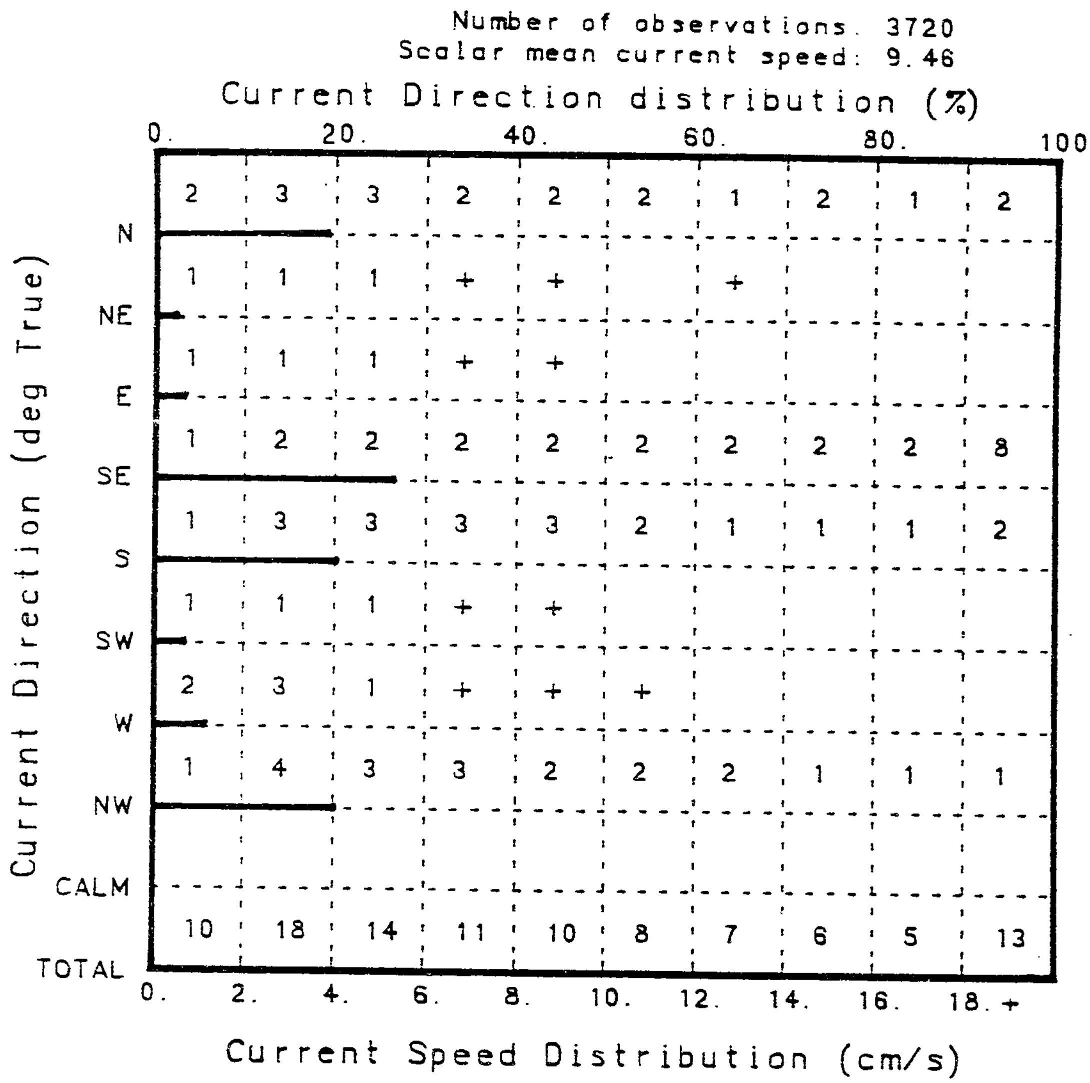
B.2 Fields Point Surface Current Speed and Direction, September 17 - November 6, 1988.



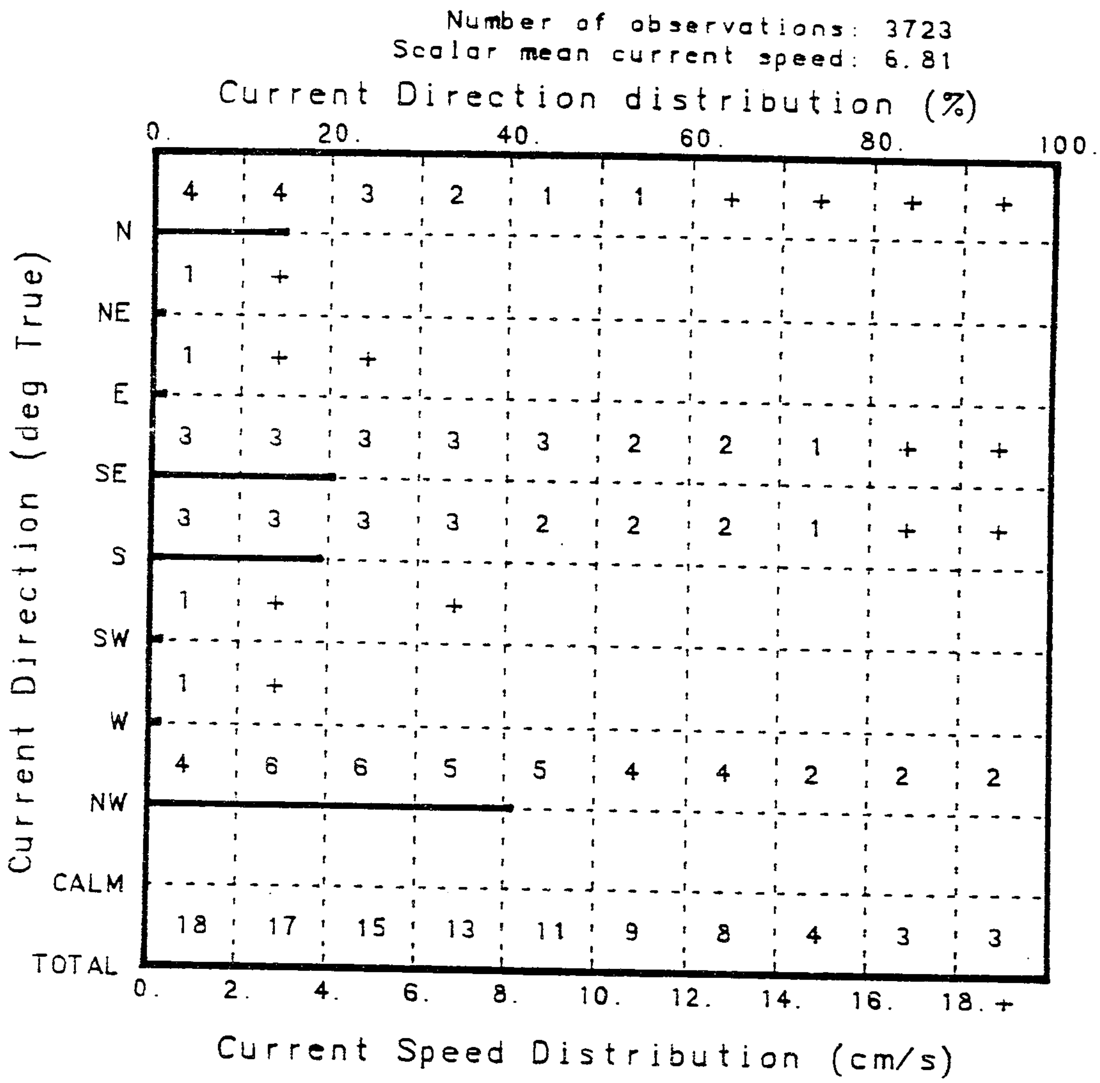
B.3 Fields Point Bottom Current Speed and Direction, September 17 - November 7, 1988.



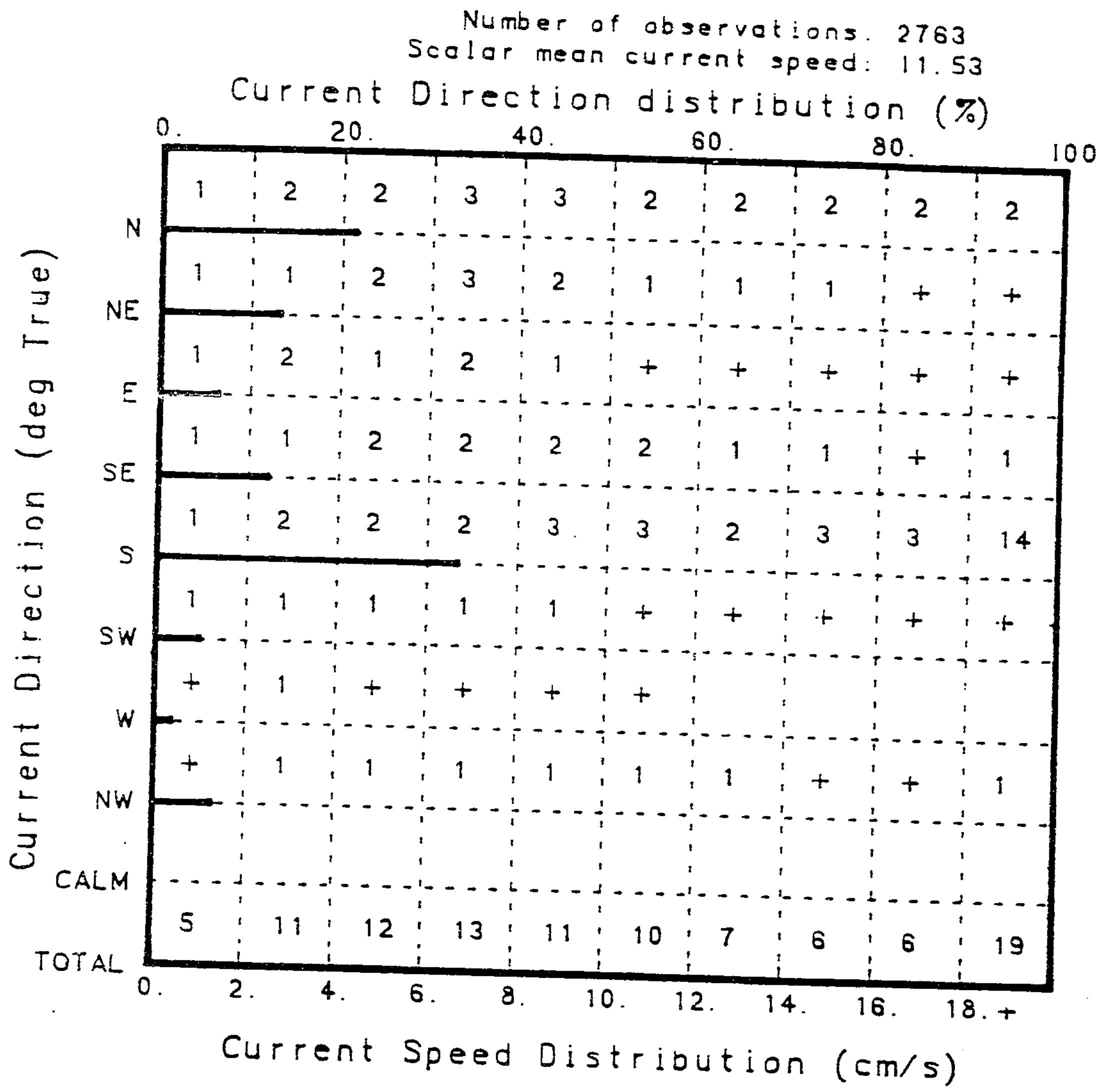
B.4 Seekonk River Bottom Current Speed and Direction, April 23 - June 1, 1989.



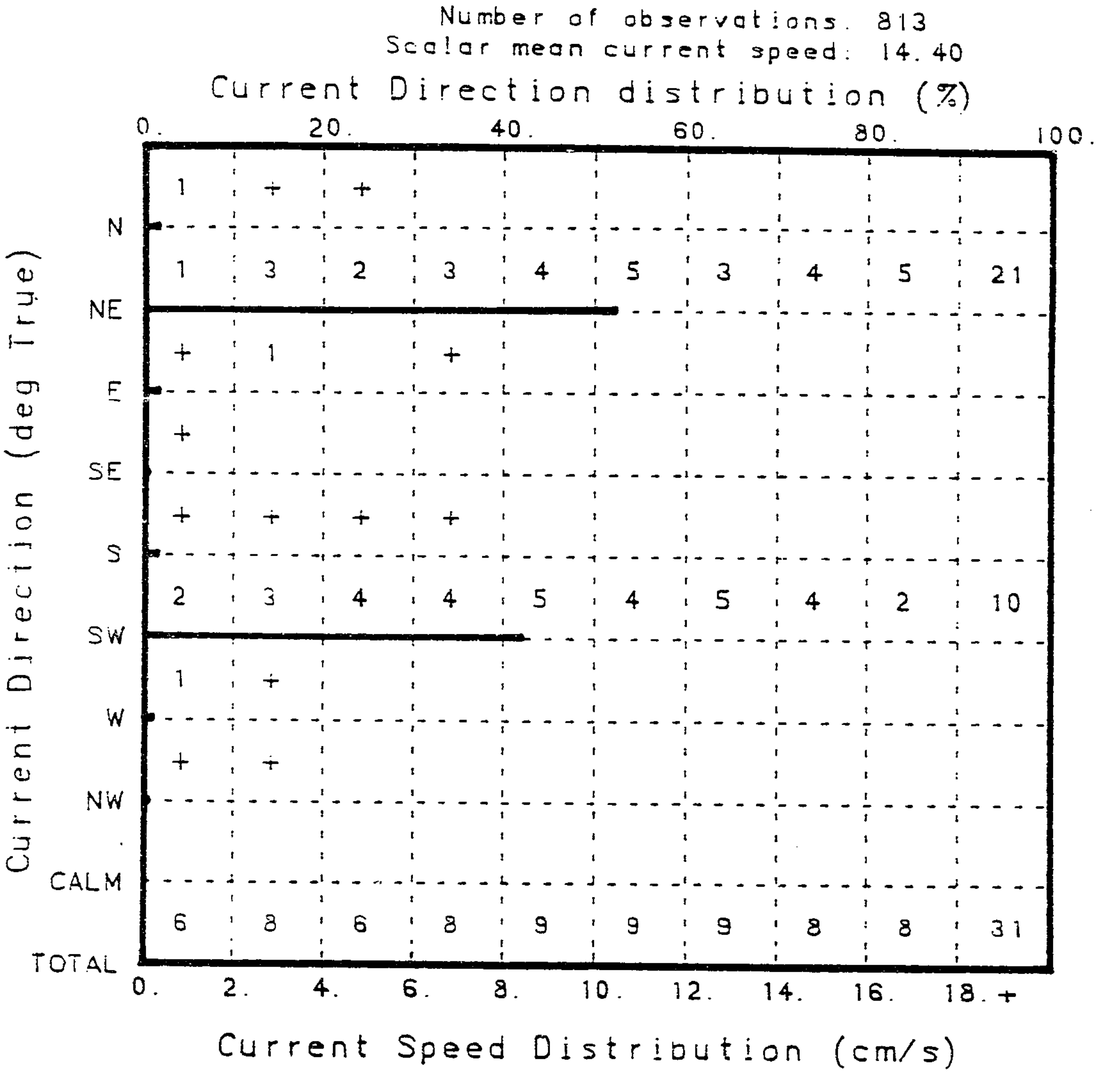
B.5 Fields Point Surface Current Speed and Direction, April 23 - June 1, 1989.



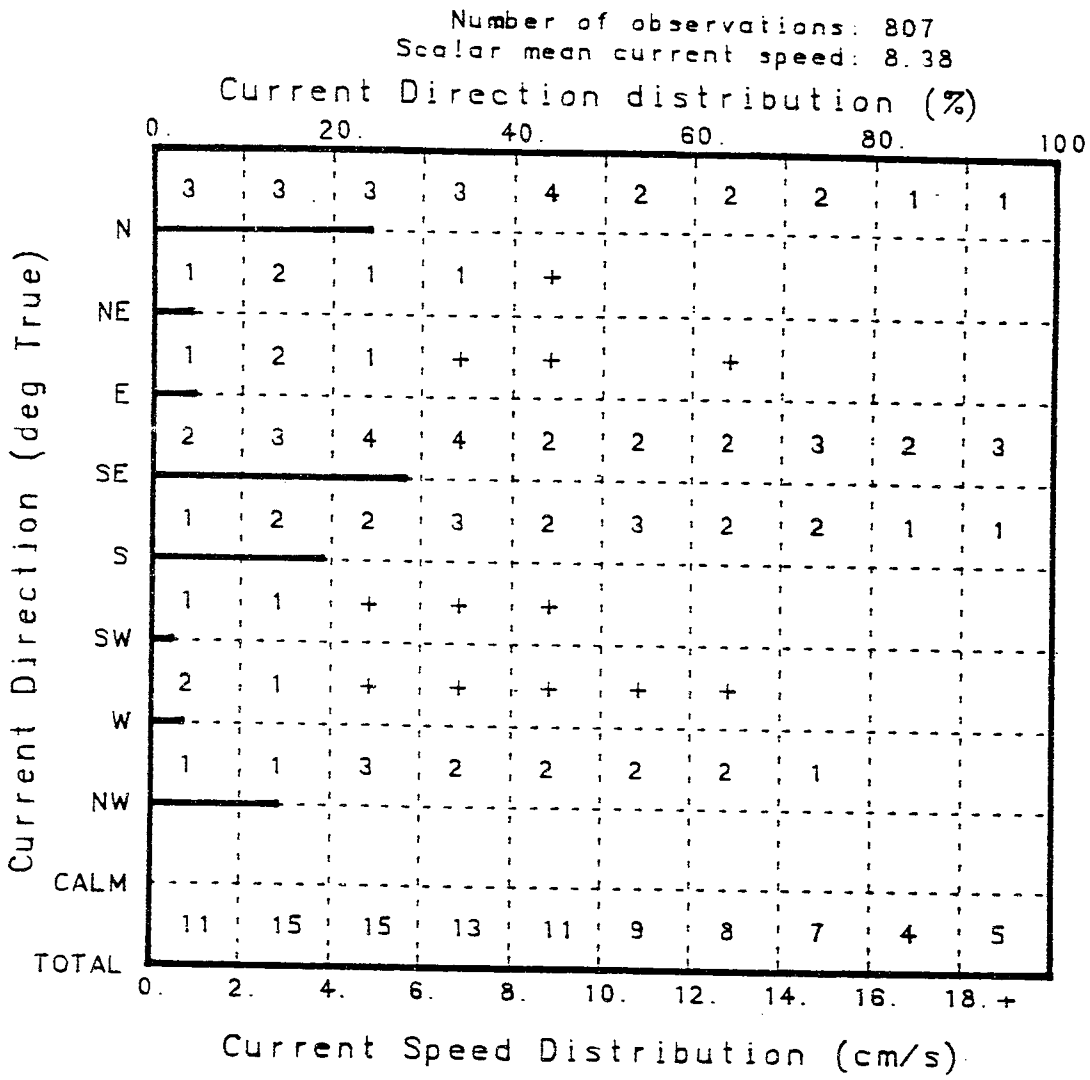
B.6 Fields Point Bottom Current Speed and Direction, April 23 - June 1, 1989.



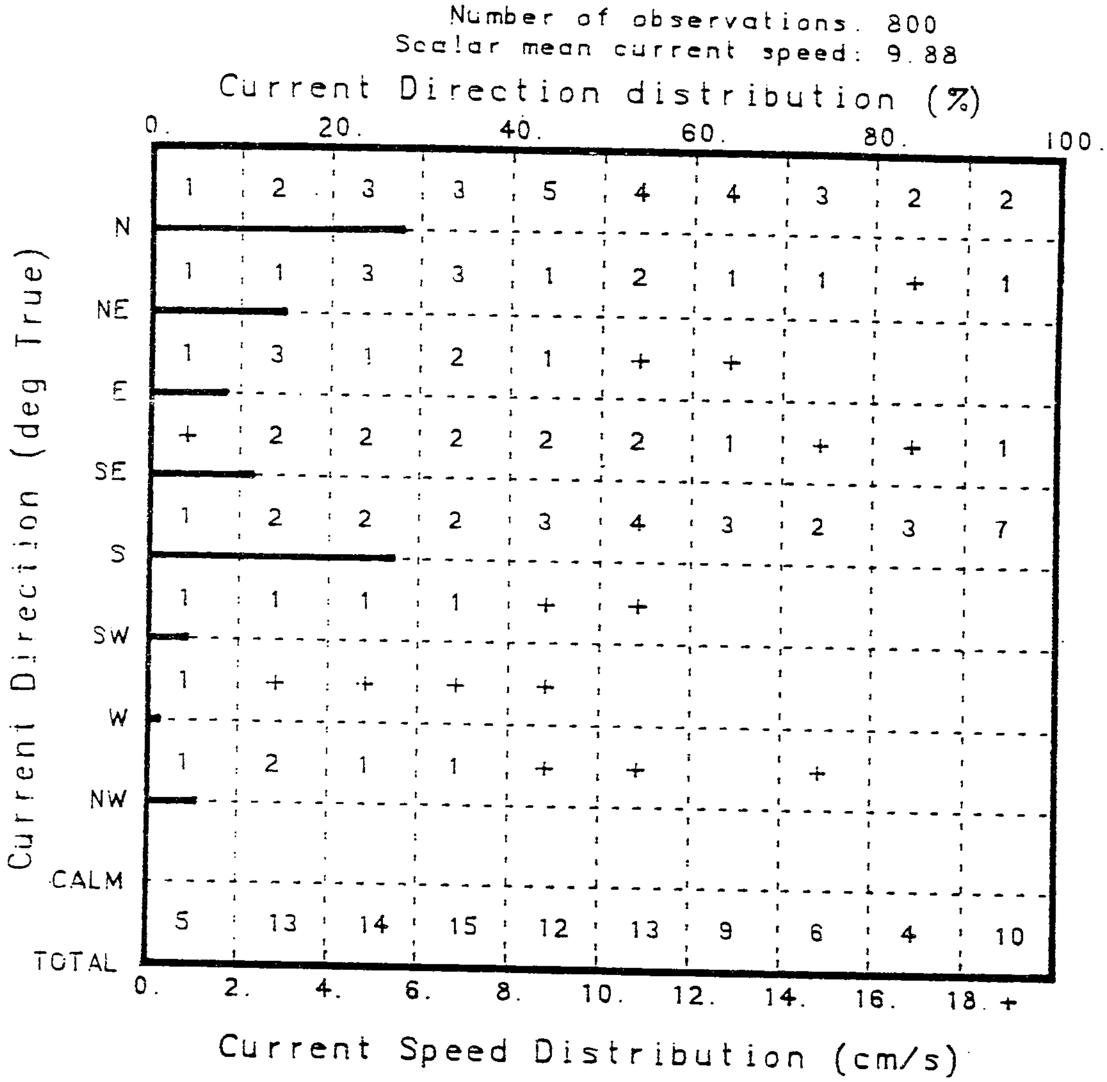
B.7 Gaspee-Bullock Transect Surface Current Speed and Directions, April 23 - May 22, 1989.



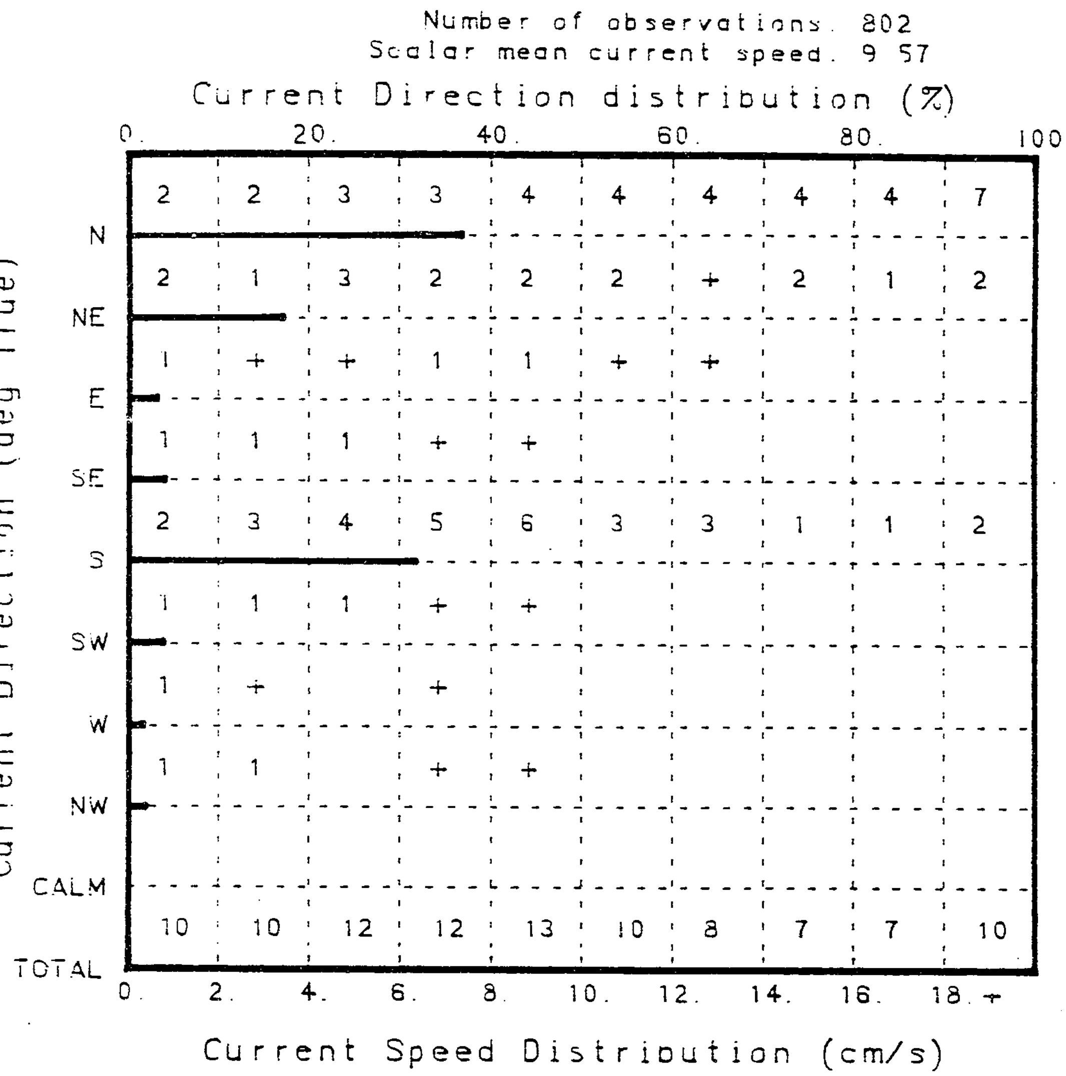
B.8 Seekonk River Bottom Current Speed and Direction, June 8 - June 16, 1989.



B.9 Fields Point Surface Current Speed and Direction, June 8 - June 16, 1989.



B.10 Gaspee-Bullock Transect Surface Current Speed and Direction, June 8 - June 16, 1989.



B.11 Gaspee-Bullock Transect Bottom Current Speed and Direction, June 8 - June 16, 1989.

APPENDIX C: LOW PASSED FILTERED TIME SERIES DATA

<u>Study #1</u>

C.1 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.

C.2 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.

C.3 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.

C.4 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.

<u>Studies #2 and #3</u>

C.5 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23, - June 16, 1989.

C.6 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989

C.7 Low Passed Filtered Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989.

C.8 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0800, May 10 - 0000 May 14, 1989

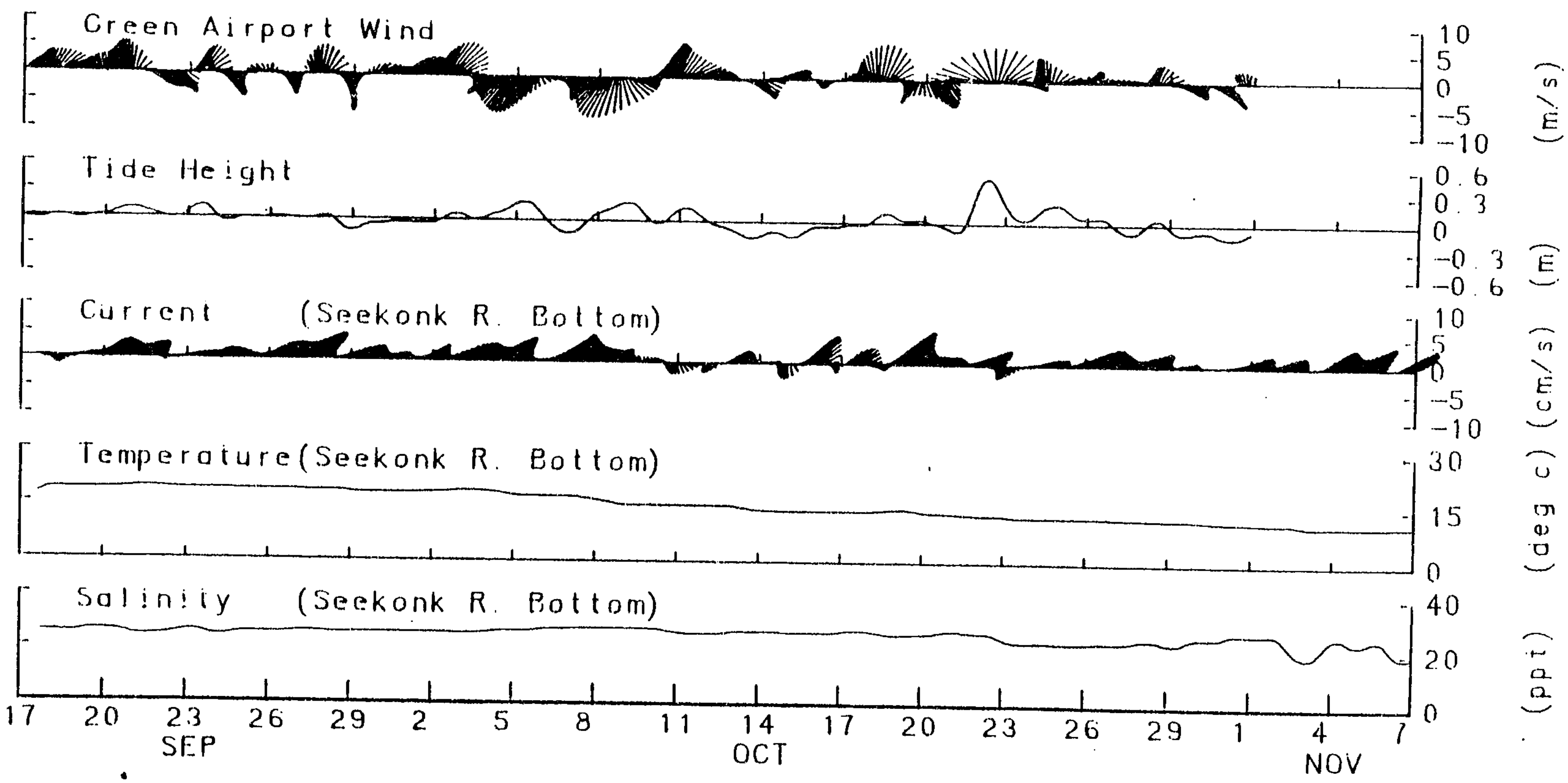
C.9 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0800, May 10 - 0000 May 14, 1989.

C.10 Low Passed Filtered Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0800, May 10 - 0000 May 14, 1989.

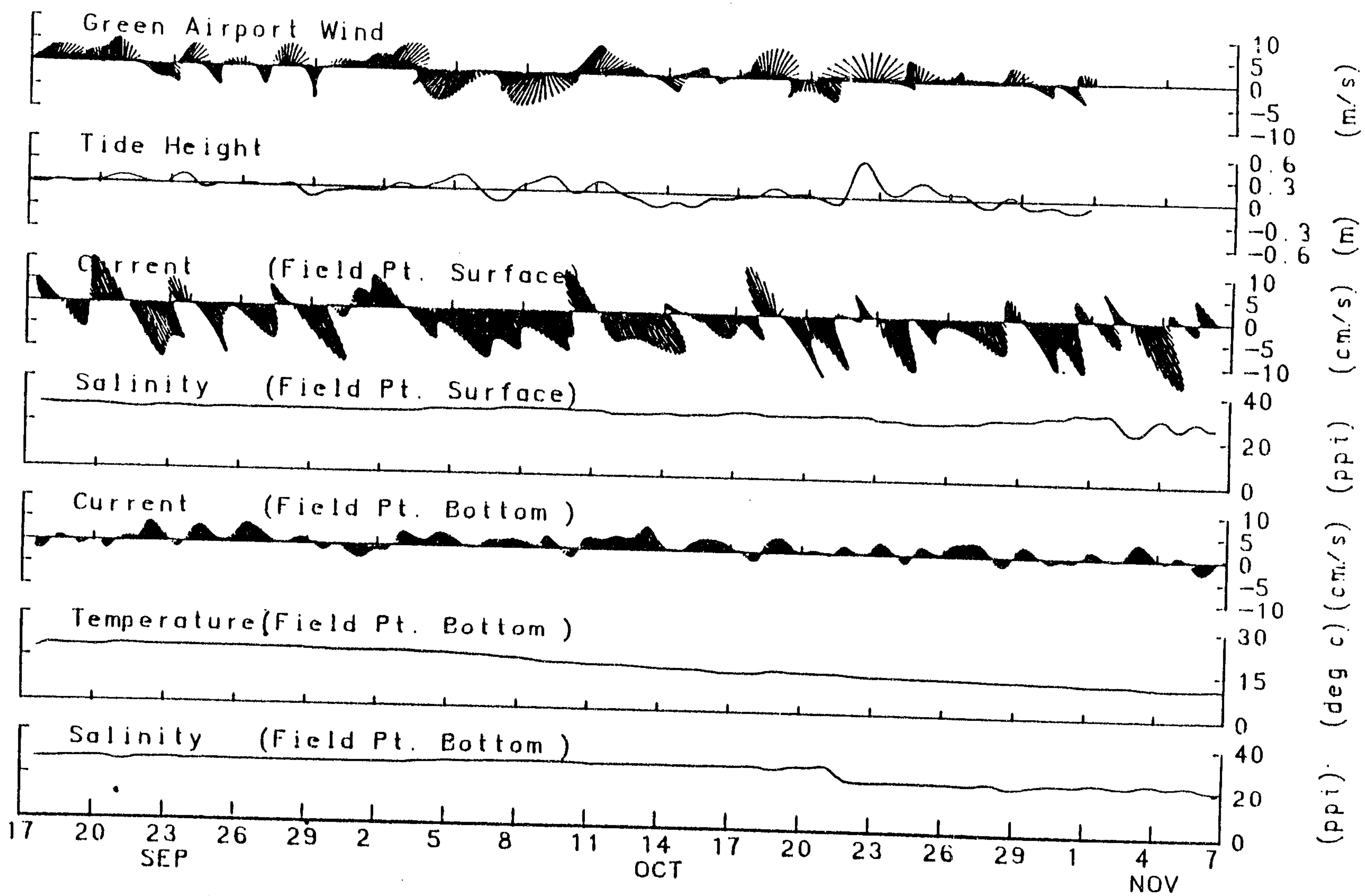
C.11 Low Passed Filtered Seekonk River, current, temperature and salinity, time histories with tide height at Providence and winds at Green Airport, 0700 June 13 - 1400 June 16, 1989.

C.12 Low Passed Filtered Fields Point, current, temperature and salinity, time histories with tide height at Providence and winds at Green Airport, 0700 June 13, - 1400 June 16, 1989.

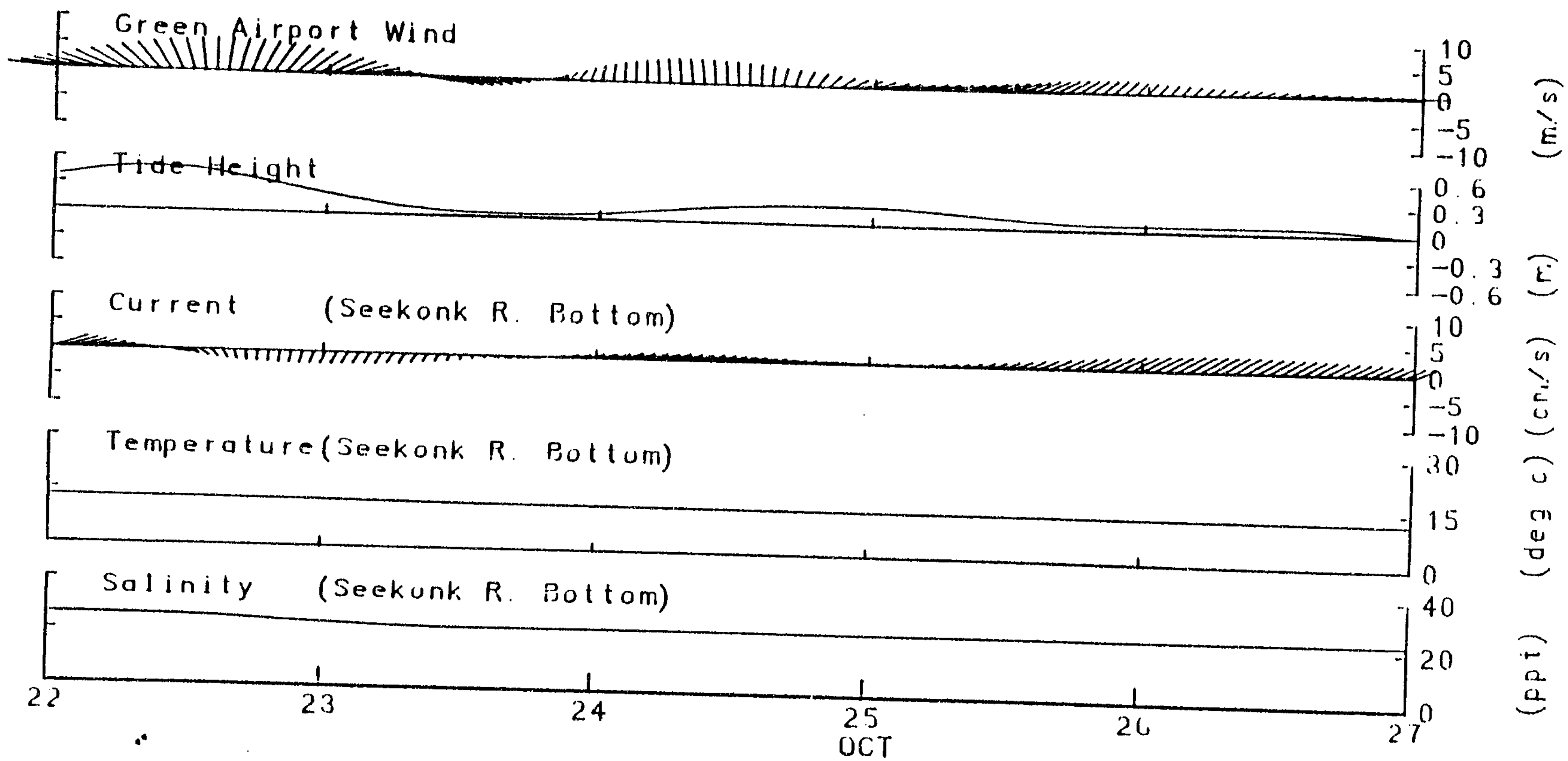
C.13 Low Passed Filtered Gaspee-Bullock Transect, current, temperature and salinity, time histories with tide height at Providence and winds at Green Airport, 0700 June 13 - 1400 June 16, 1989.



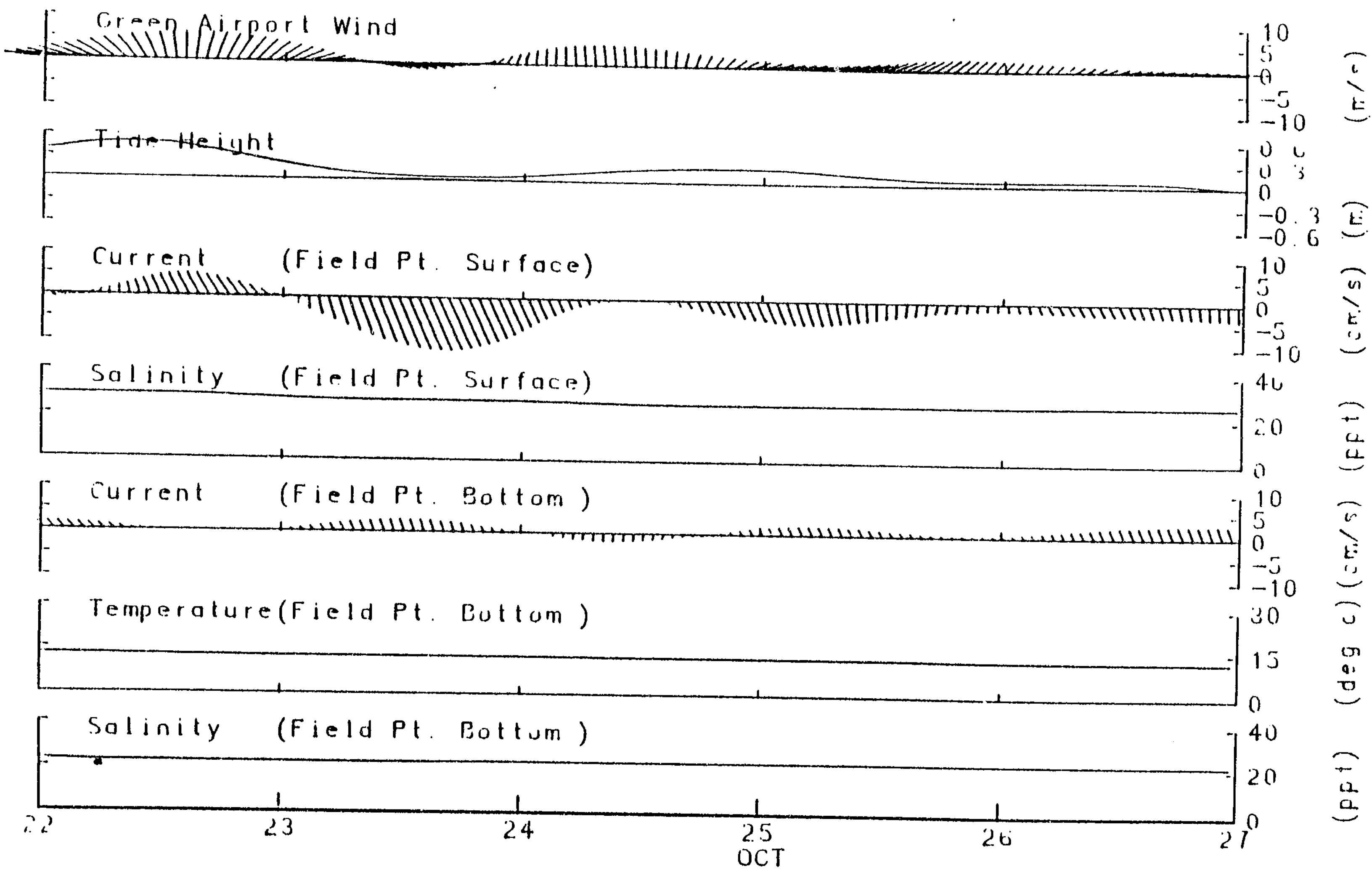
C.1 **Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.**



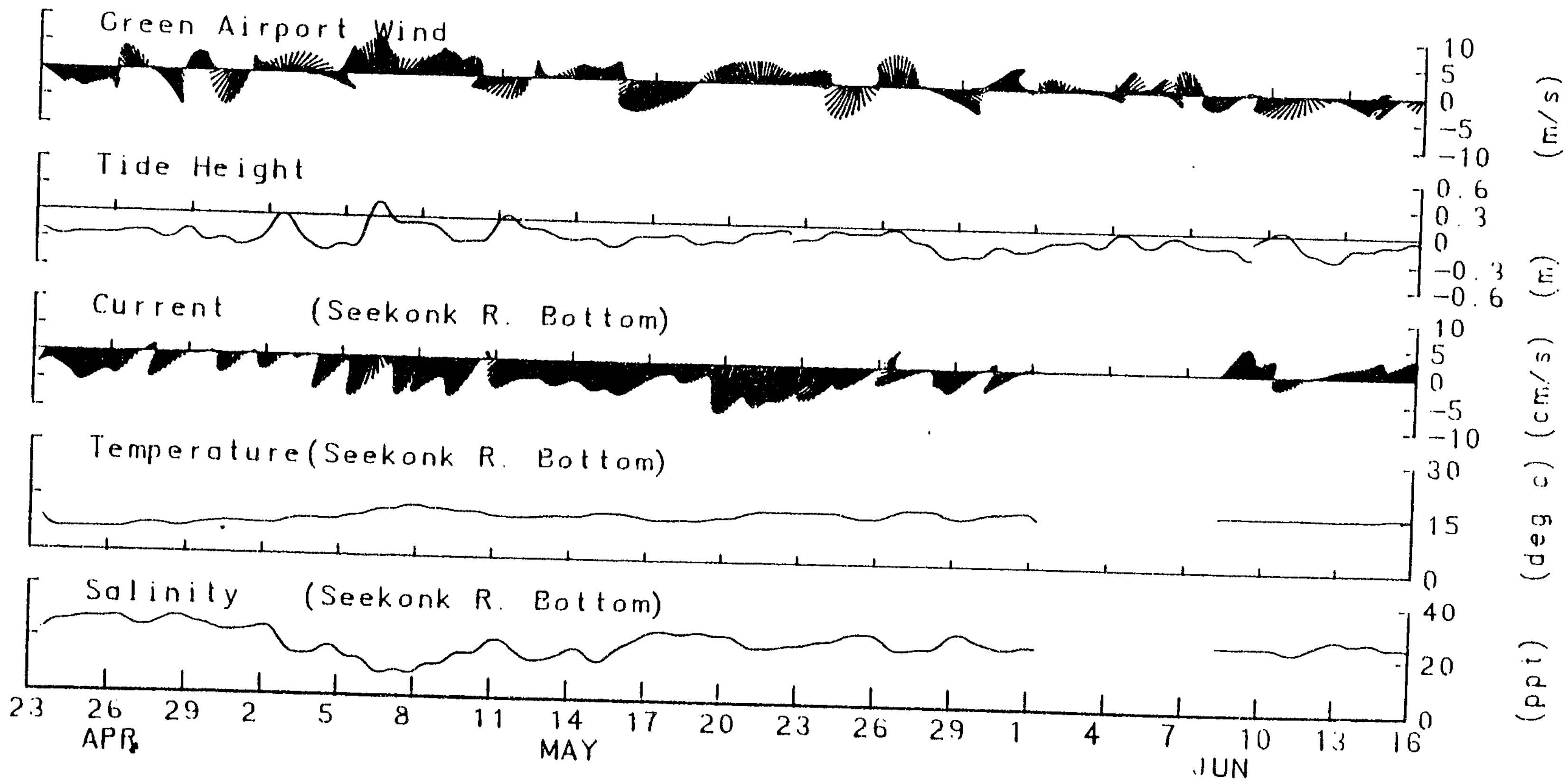
C.2 **Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, September 17 - November 7, 1988.**



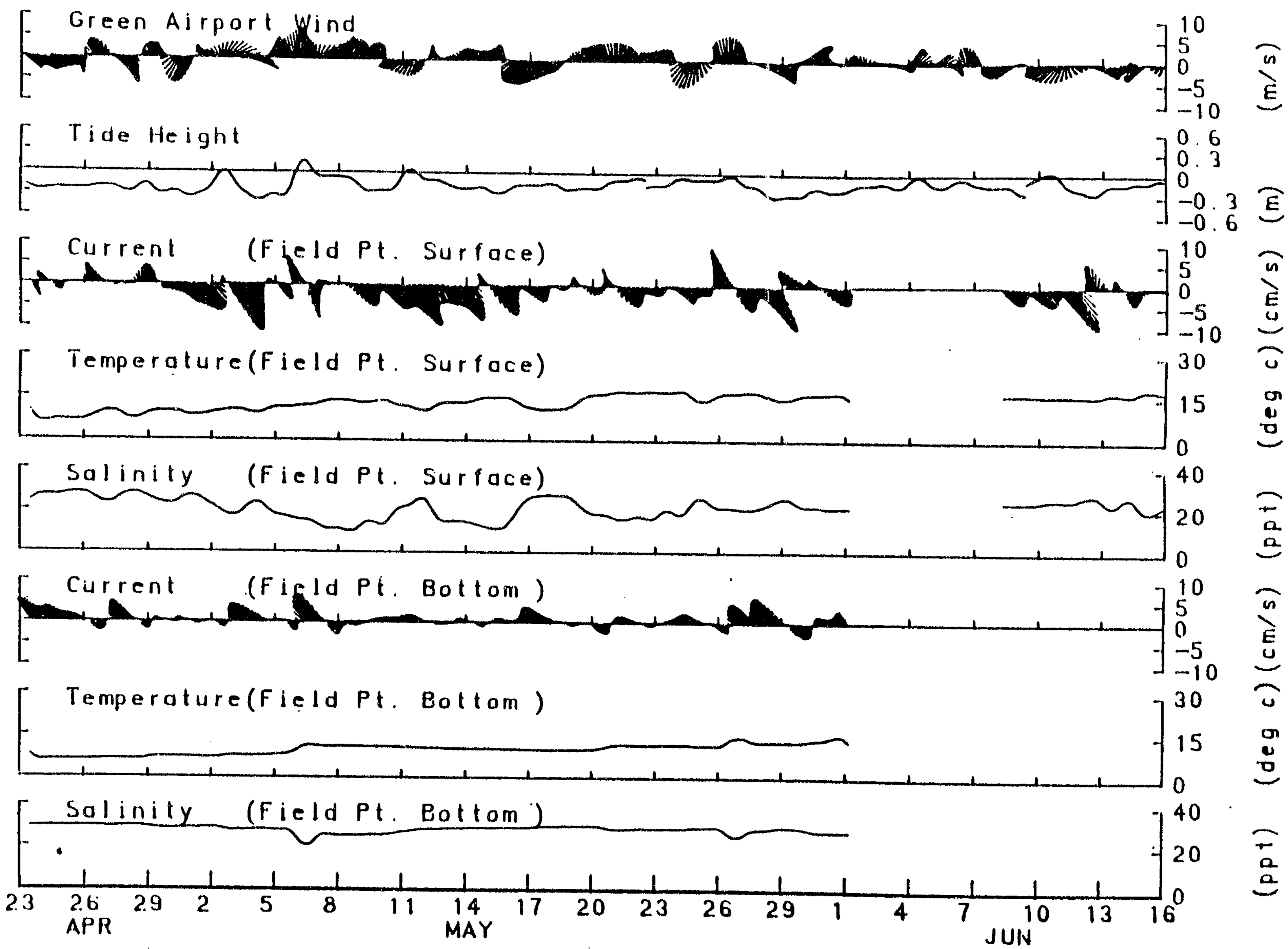
C.3 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.



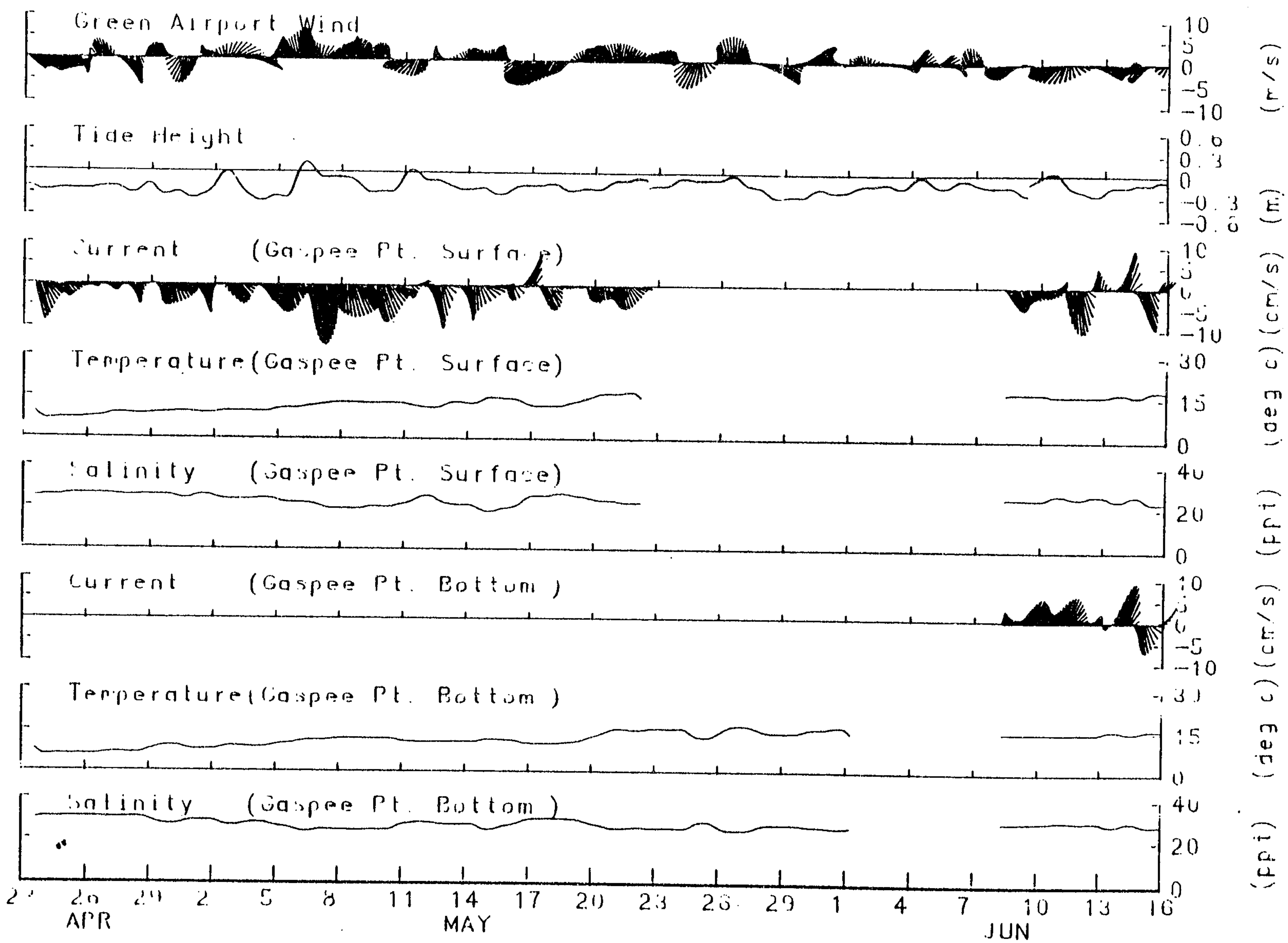
C.4 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0000 October 22 - 0000 October 27, 1988.



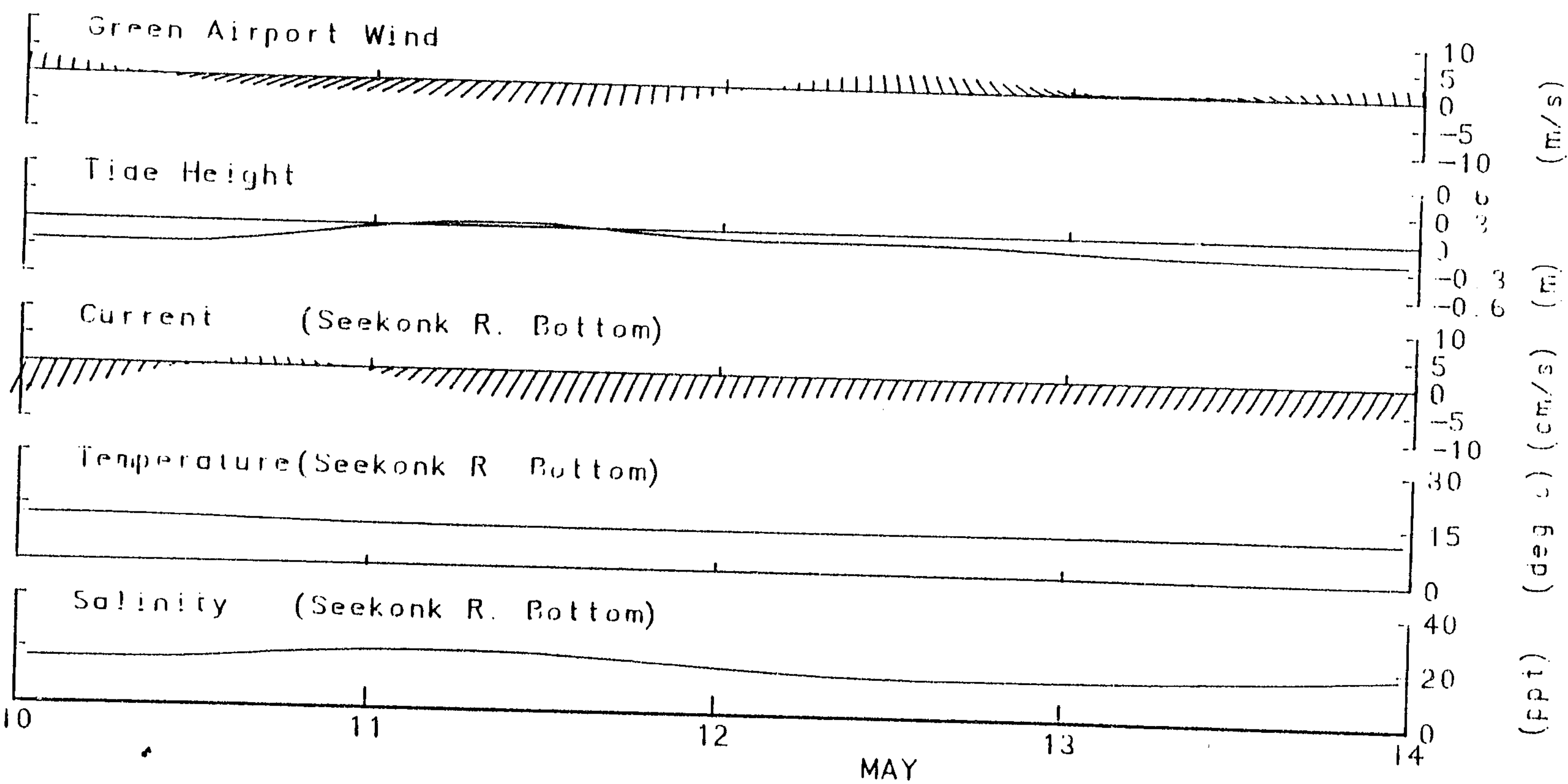
C.5 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23, - June 16, 1989.



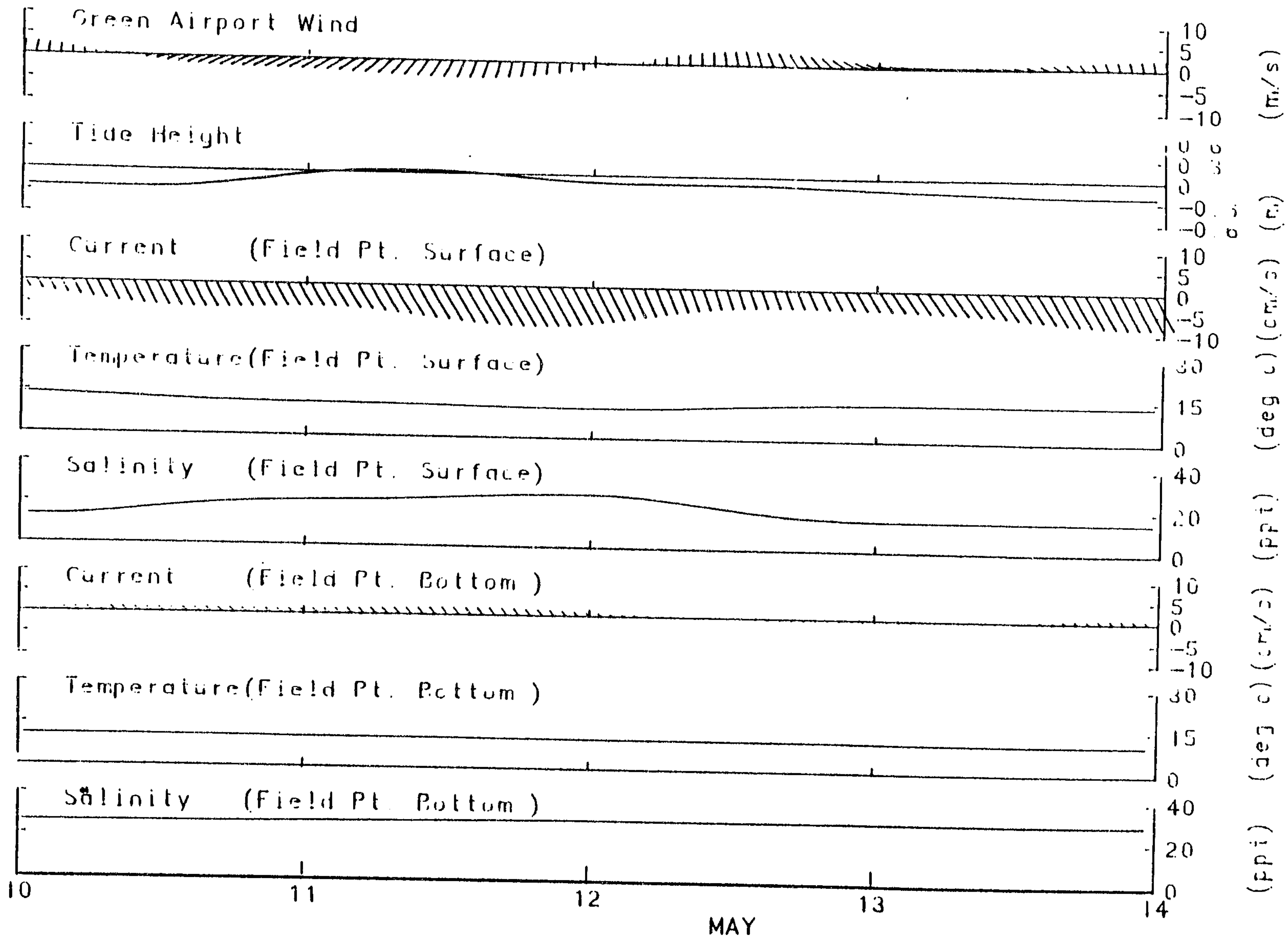
C.6 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989



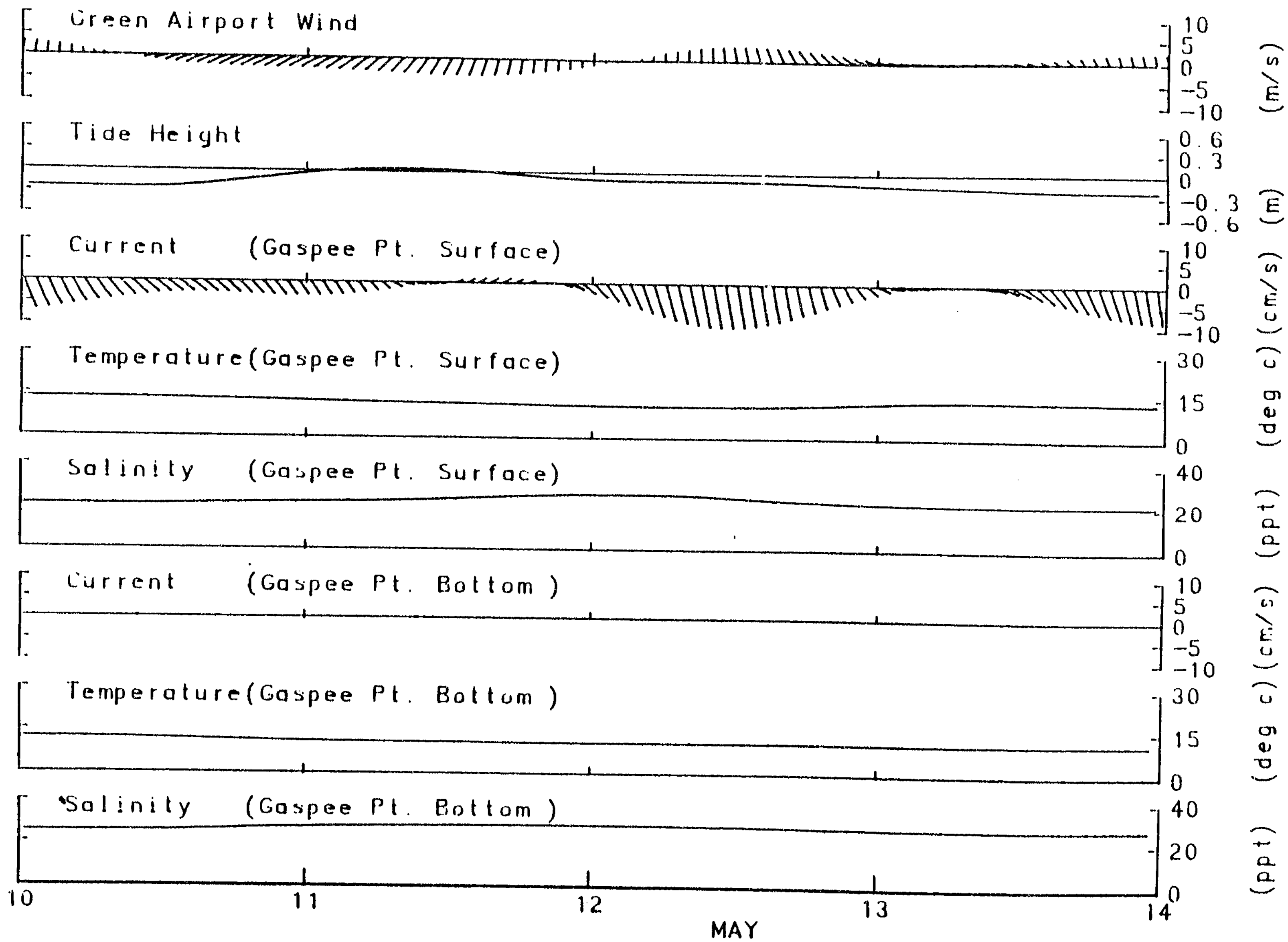
C.7 **Low Passed Filtered Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, April 23 - June 16, 1989.**



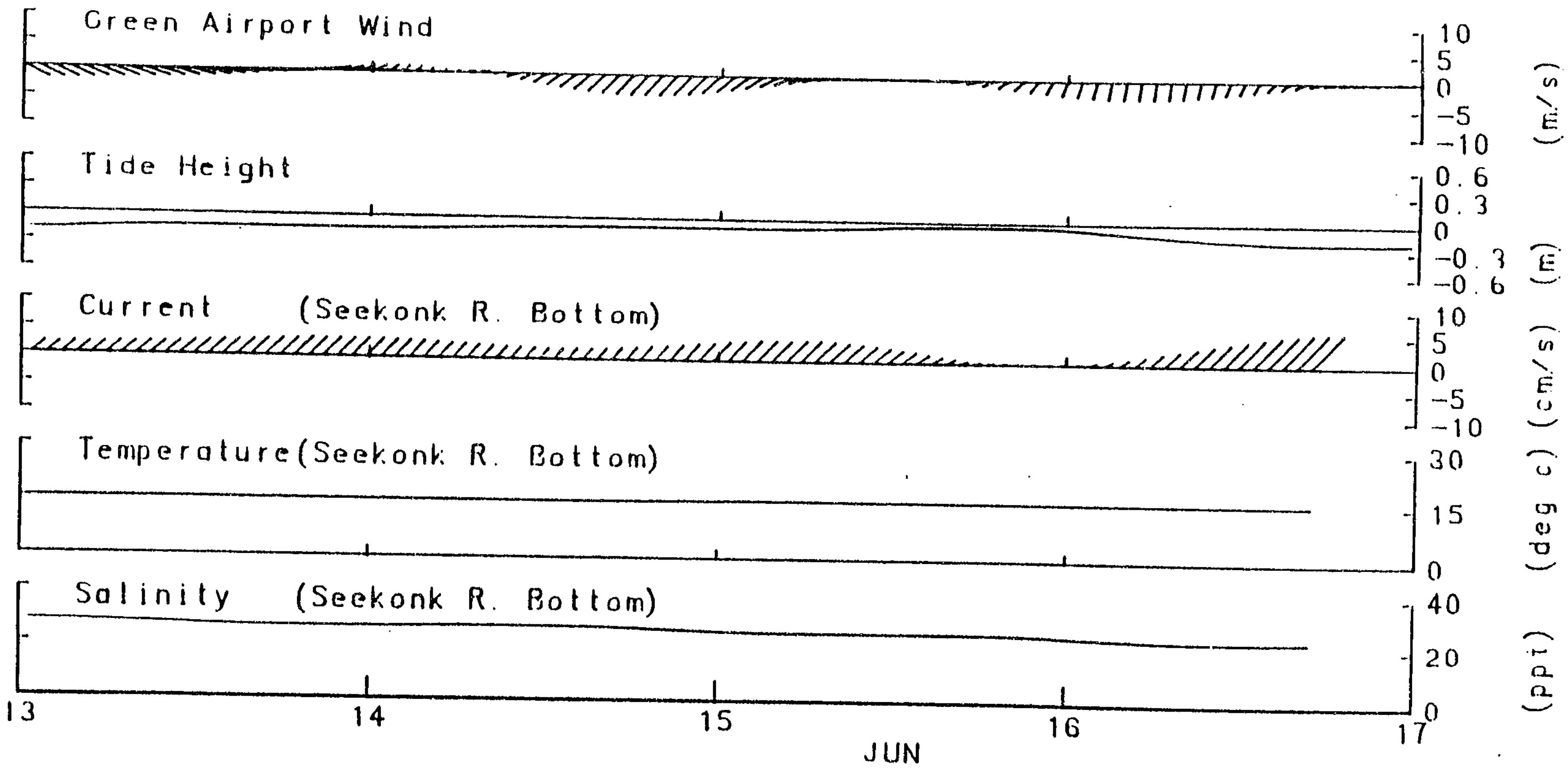
C.8 Low Passed Filtered Seekonk River, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0800, May 10 - 0000 May 14, 1989



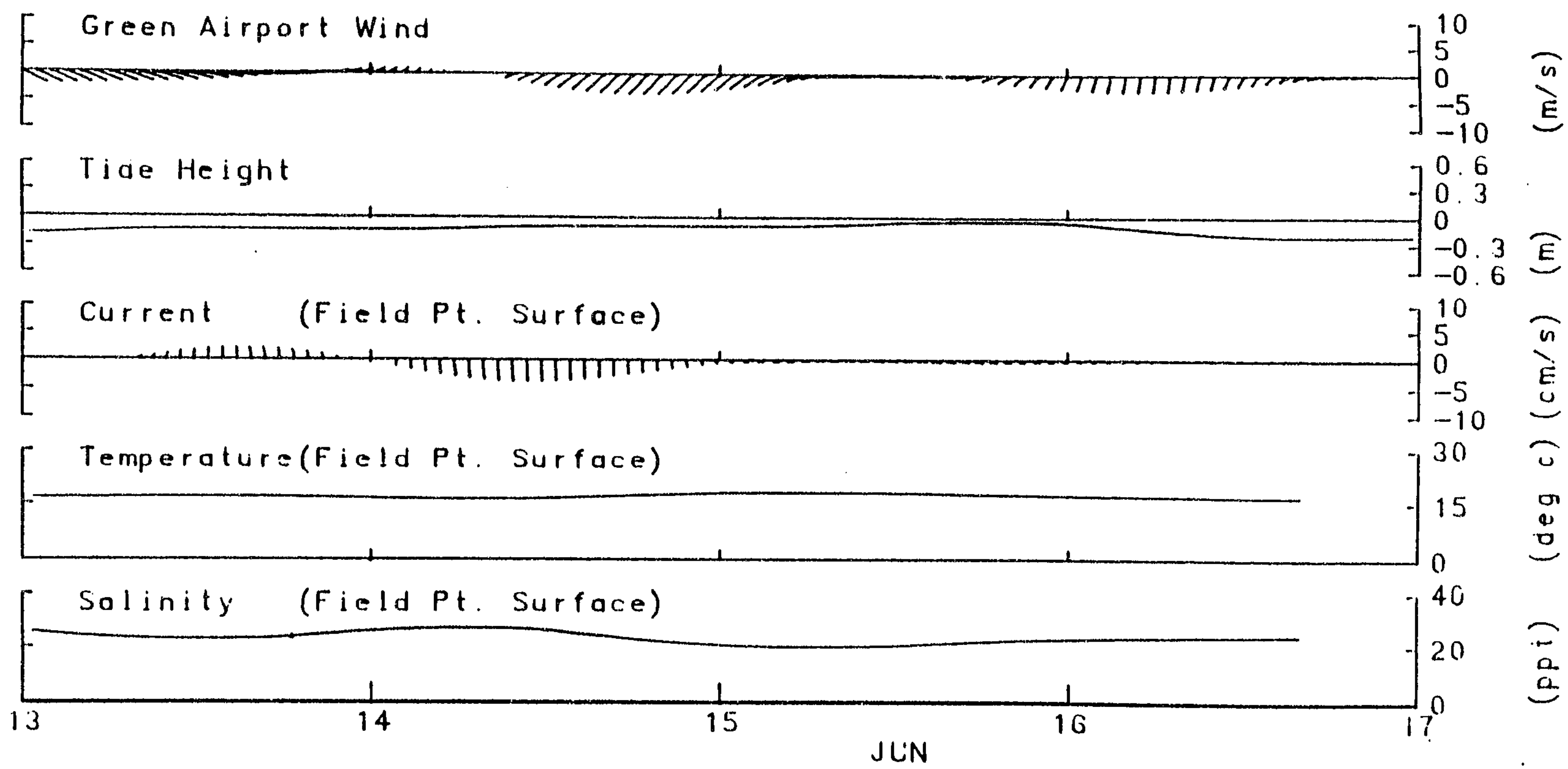
C.9 Low Passed Filtered Fields Point, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0800, May 10 - 0000 May 14, 1989.



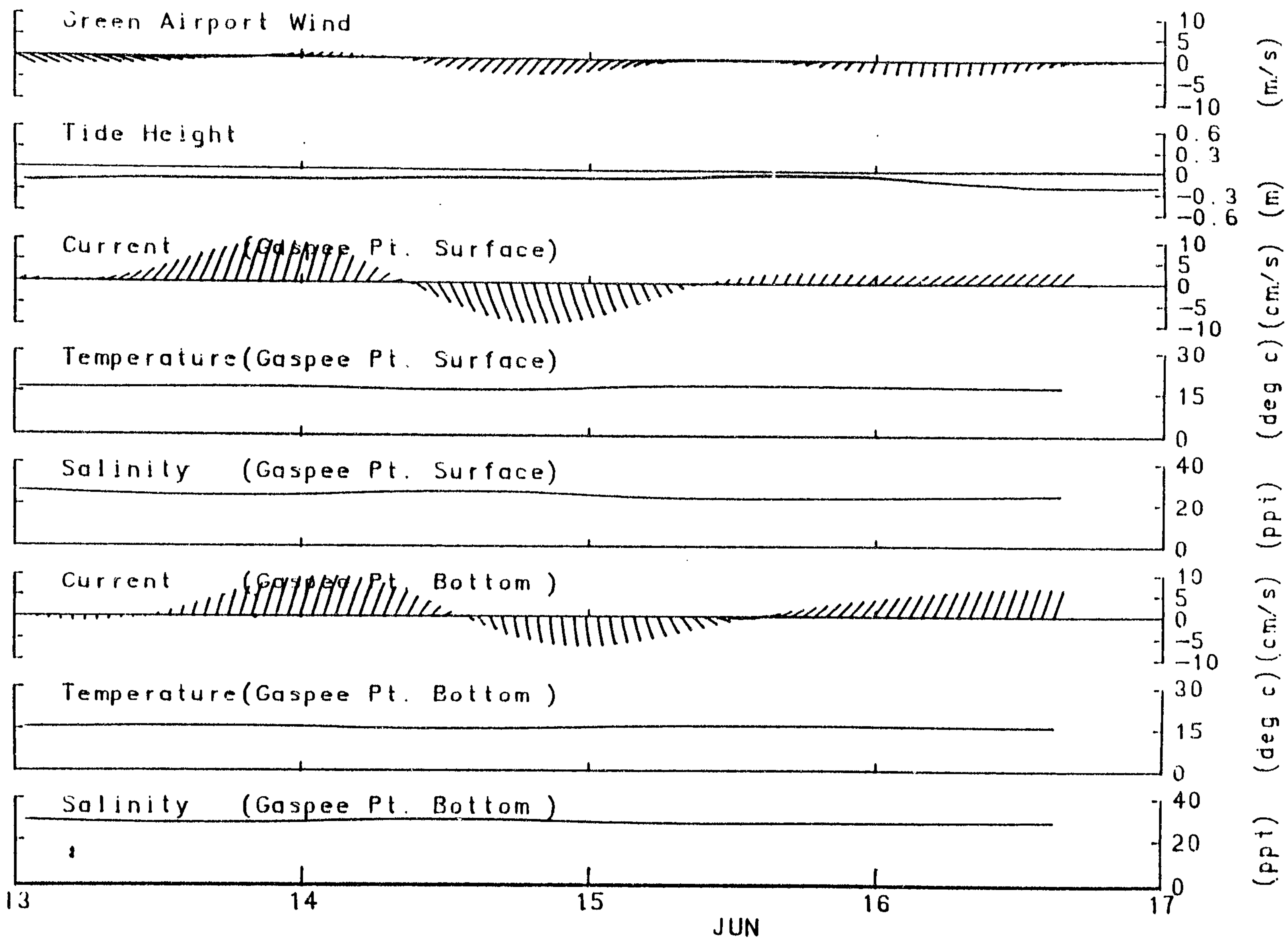
C.10 Low Passed Filtered Gaspee-Bullock Point Transect, current, temperature and salinity time histories with tide height at Providence and winds at Green Airport, 0800, May 10 - 0000 May 14, 1989.



C.11 Low Passed Filtered Seekonk River, current, temperature and salinity, time histories with tide height at Providence and winds at Green Airport, 0700 June 13 - 1400 June 16, 1989.

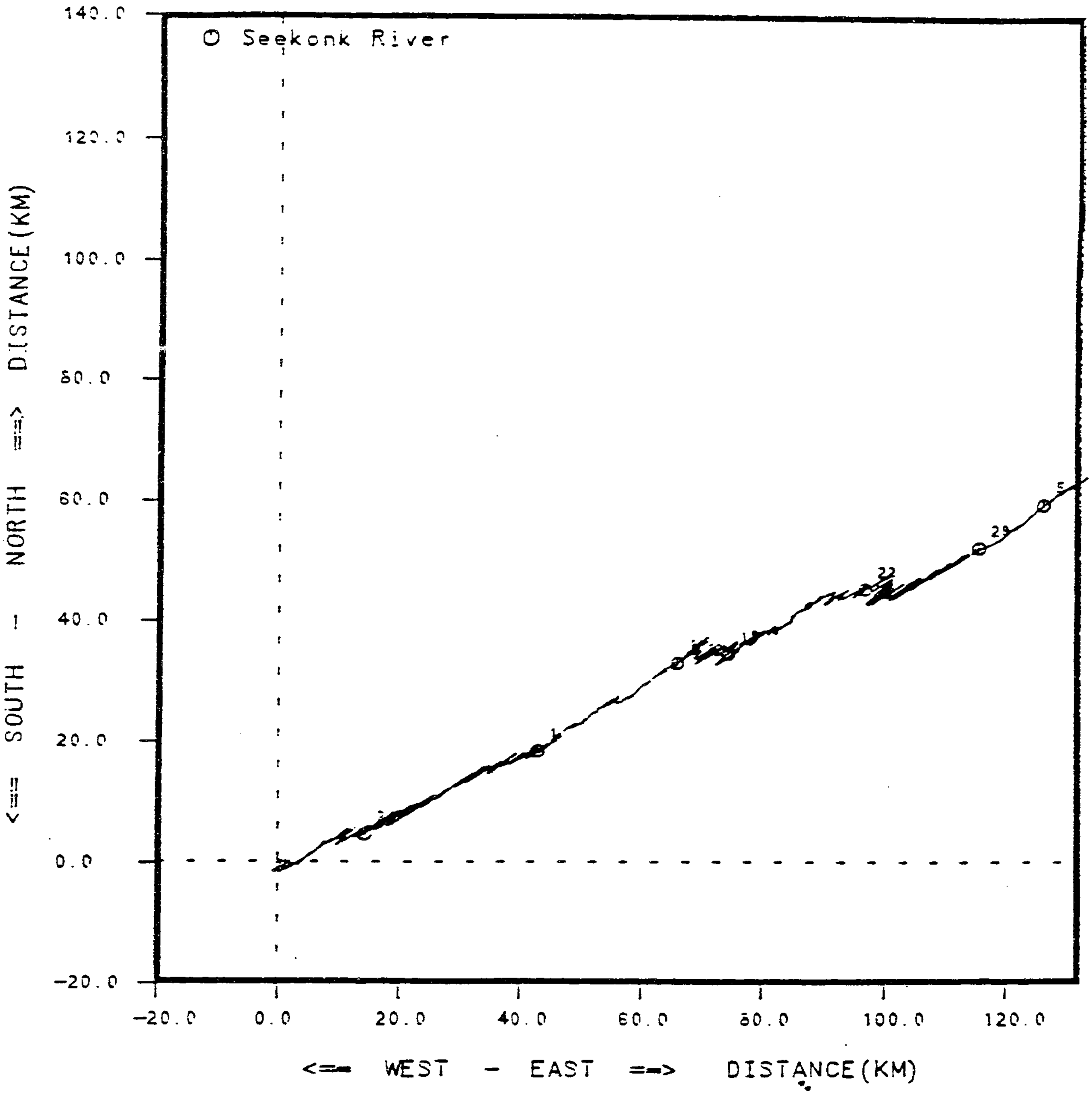


C.12 Low Passed Filtered Fields Point, current, temperature and salinity, time histories with tide height at Providence and winds at Green Airport, 0700 June 13, - 1400 June 16, 1989.

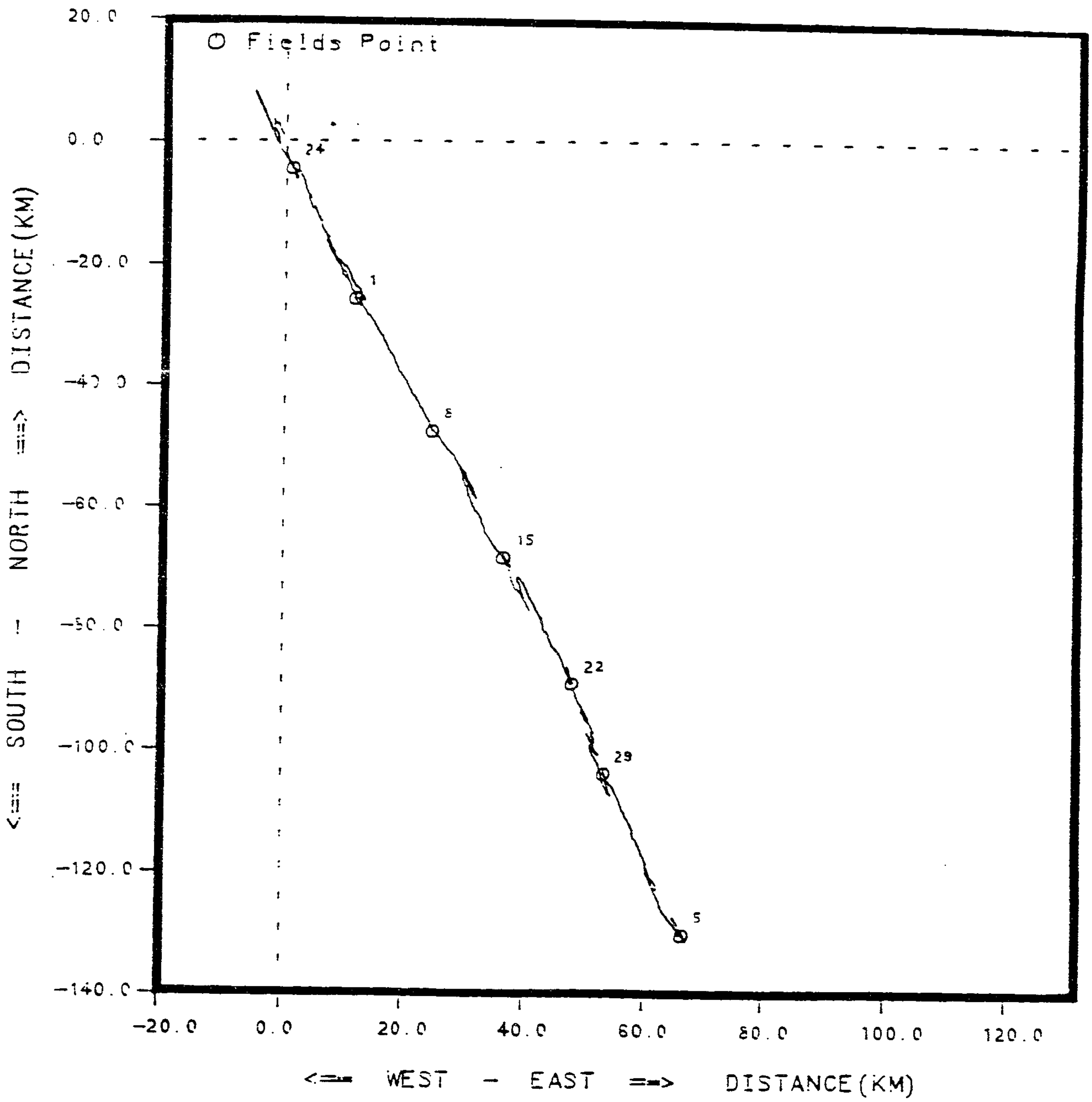


C.13 Low Passed Filtered Gaspee-Bullock Transect, current, temperature and salinity, time histories with tide height at Providence and winds at Green Airport, 0700 June 13 - 1400 June 16, 1989.

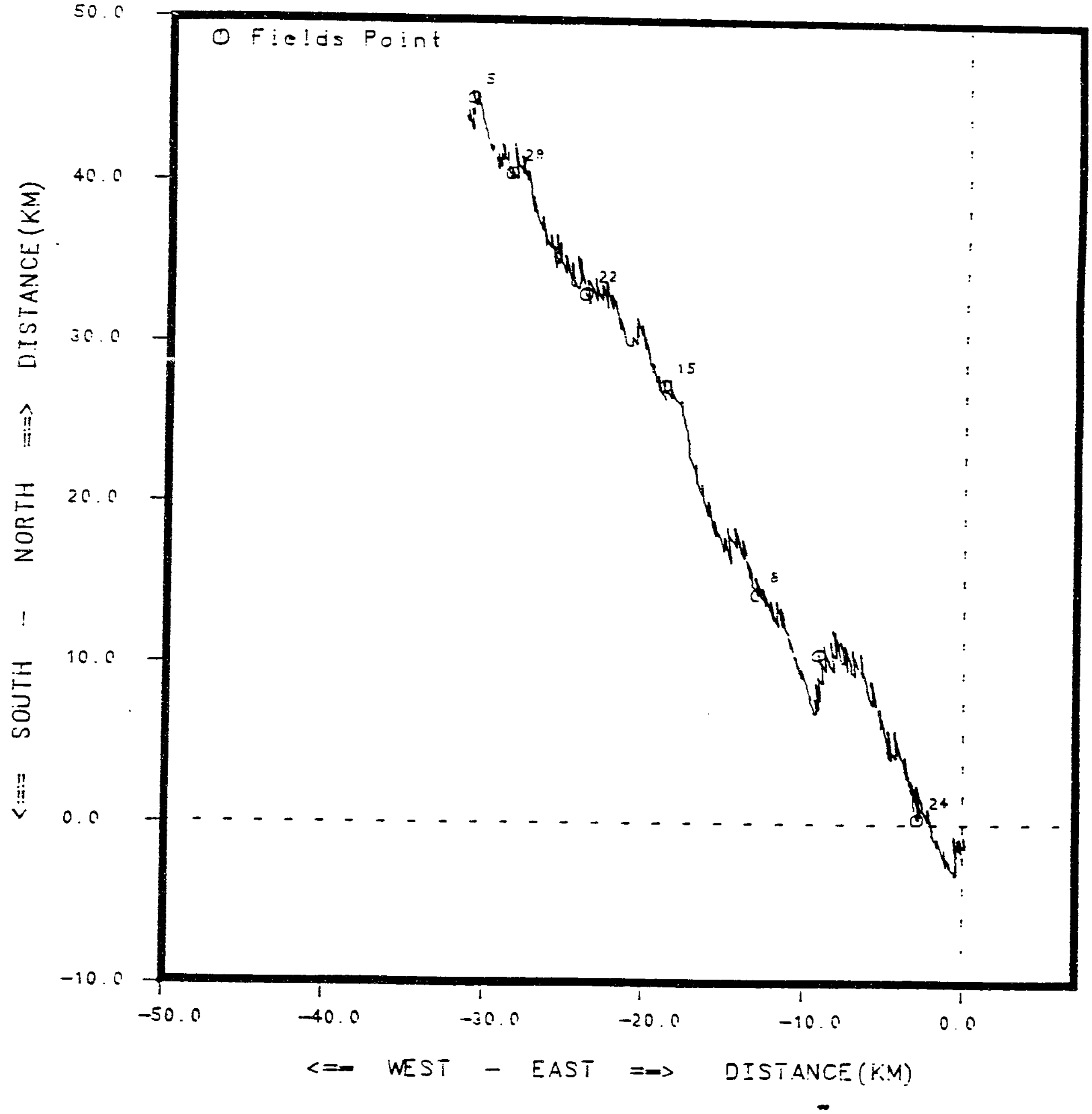
APPENDIX D: PROGRESSIVE VECTORS OF CURRENT TIME SERIES



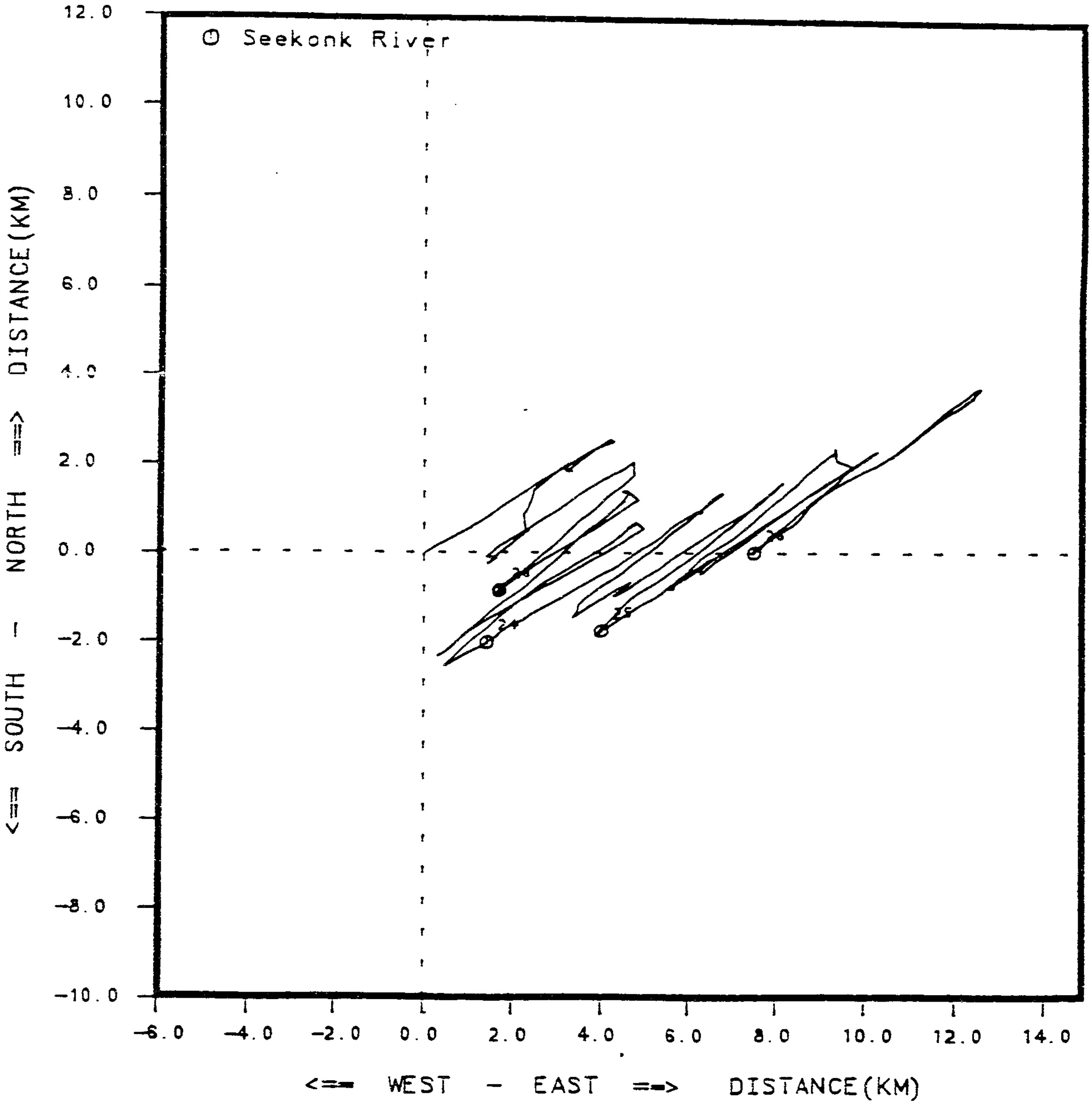
D.1 Seekonk River Bottom Current, September 17 - November 7, 1988.



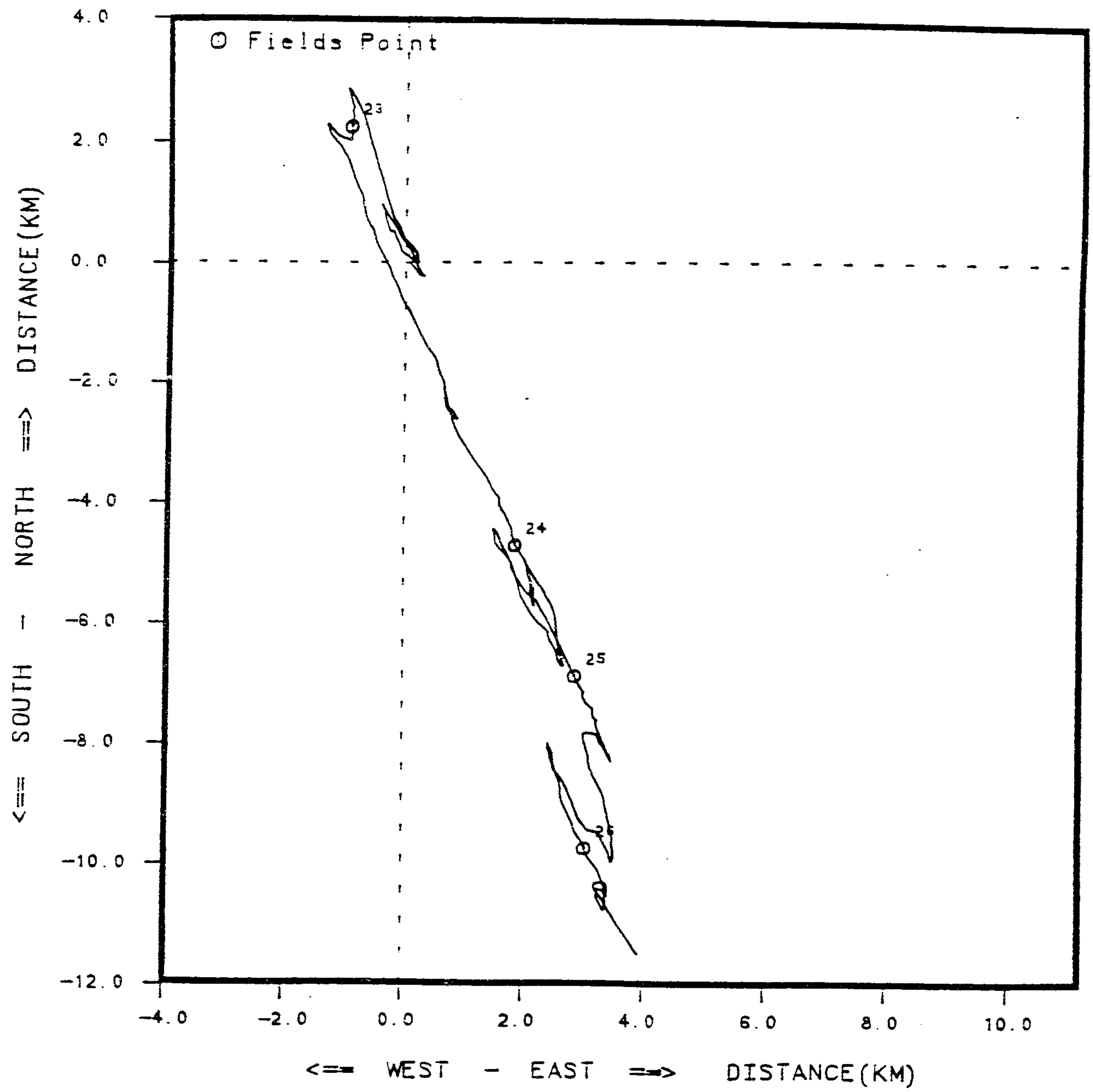
D.2 Fields Point Surface Current, September 17 - November 6, 1988.



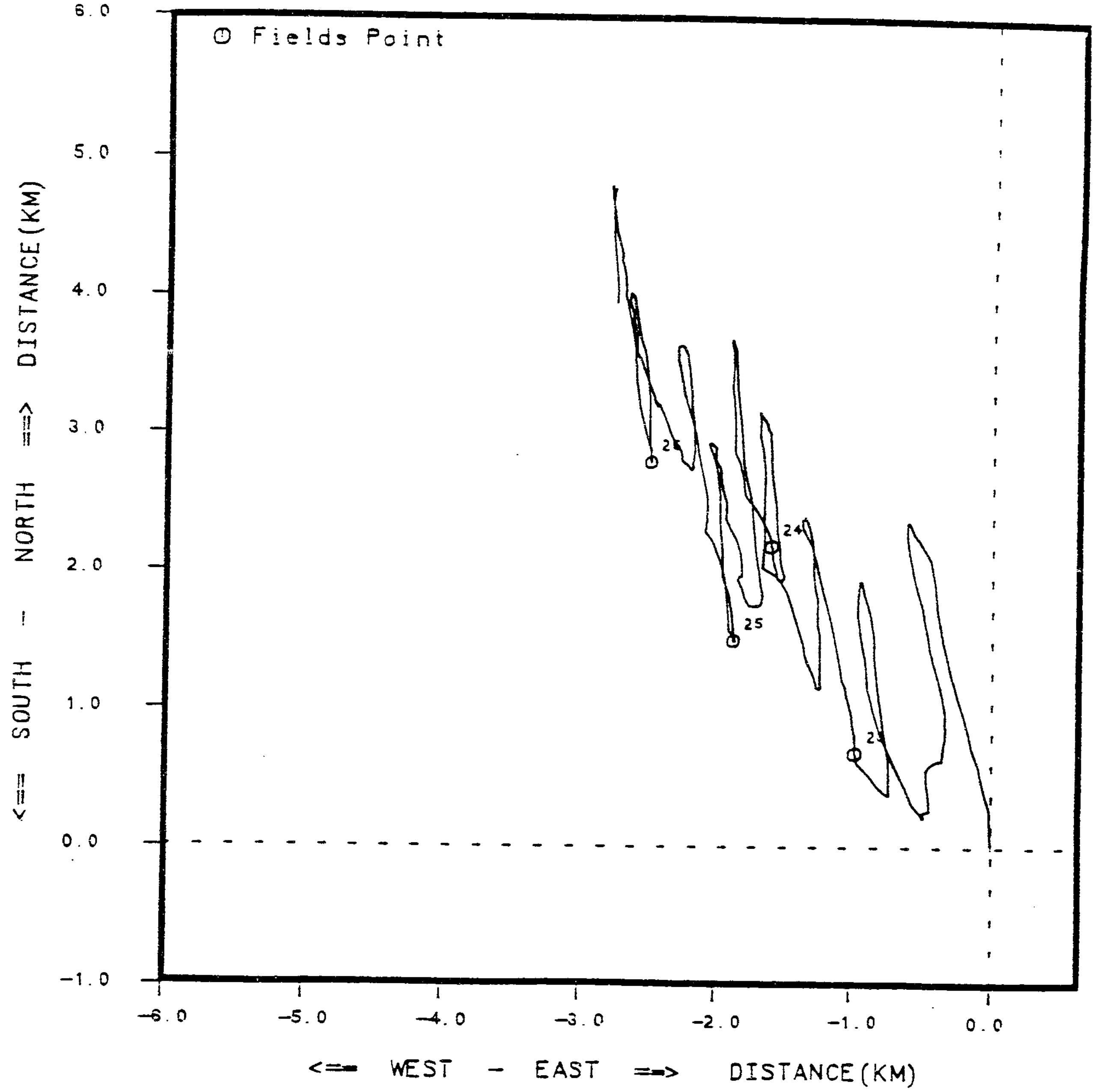
D.3 Fields Point Bottom Current, September 17 - November 7, 1988.



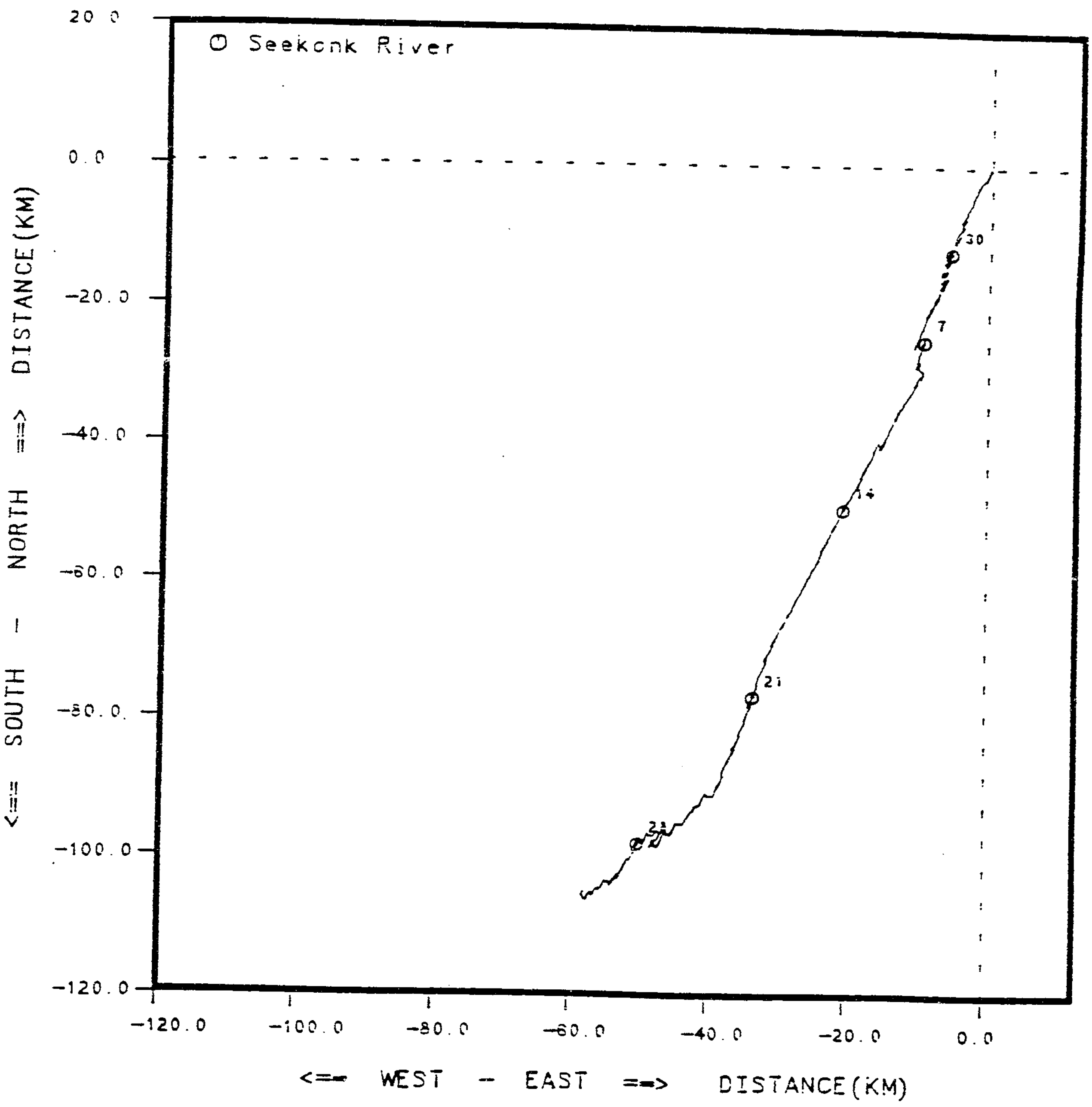
D.4 Seekonk River Bottom Current 0000 October 22 - 1200 October 26, 1988.



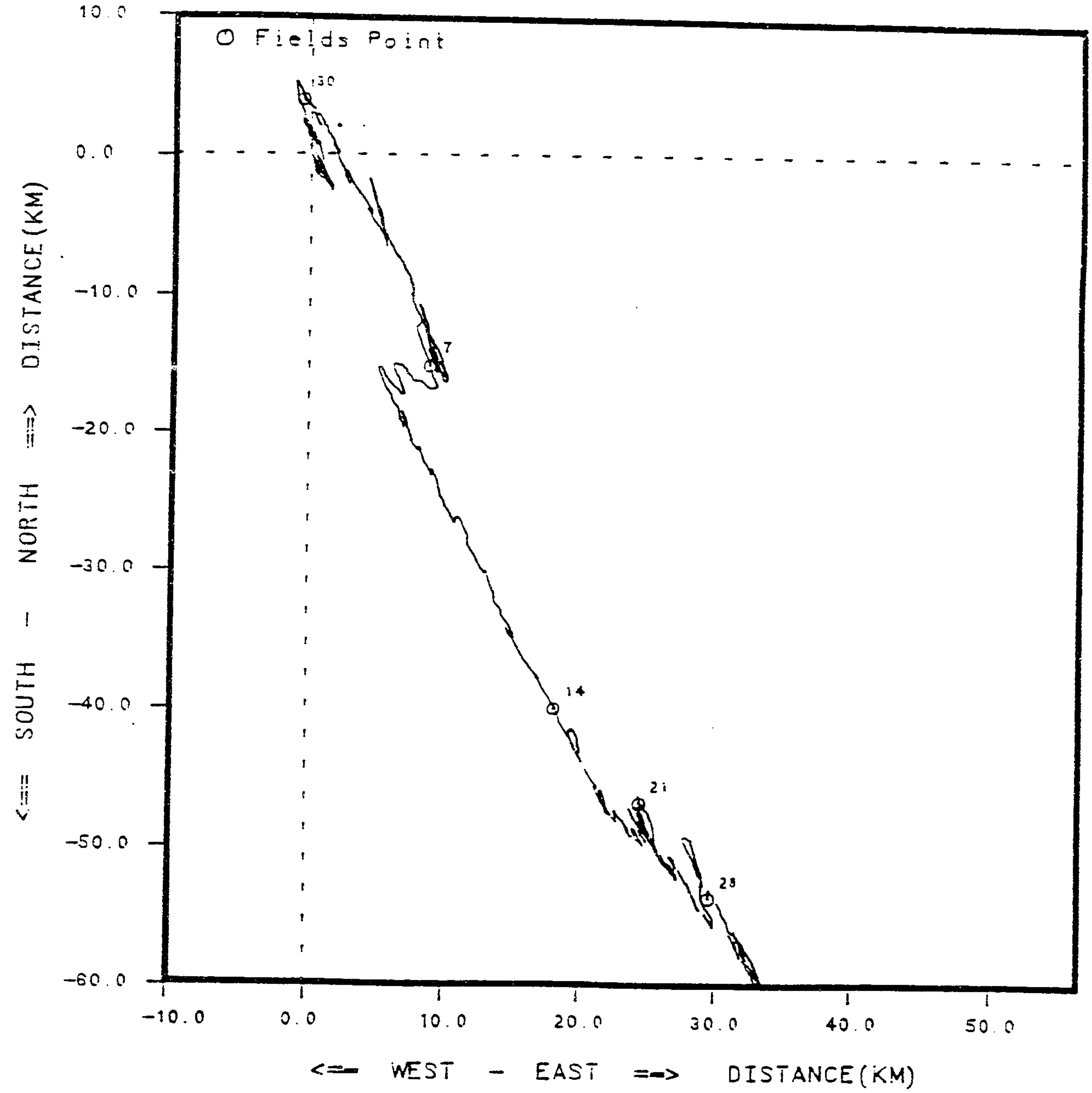
D.5 Fields Point Surface Current 0000 October 22 - 1200 October 26, 1988



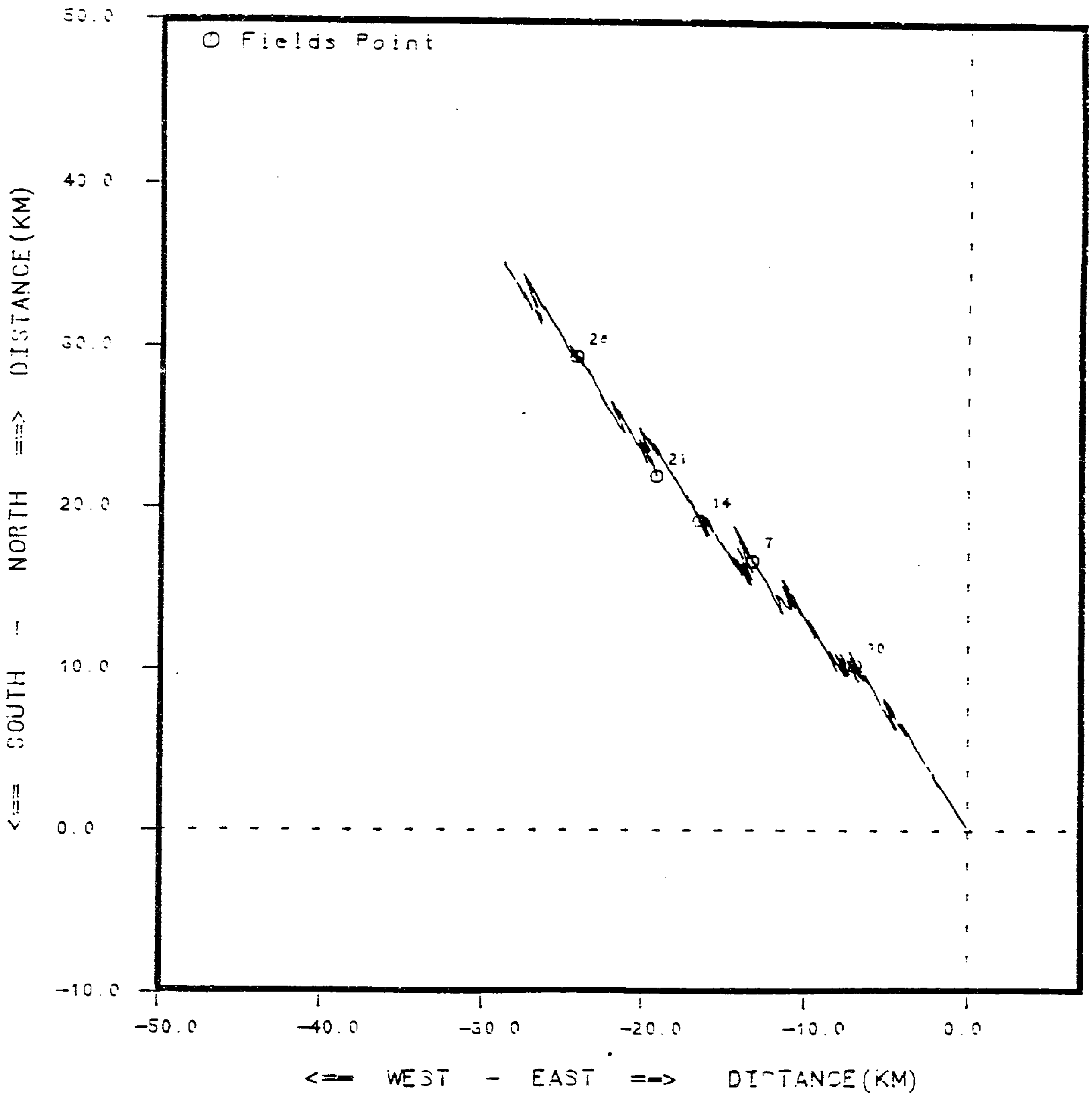
D.6 Fields Point Bottom Current 0000 October 22 - 1200 October 26, 1988



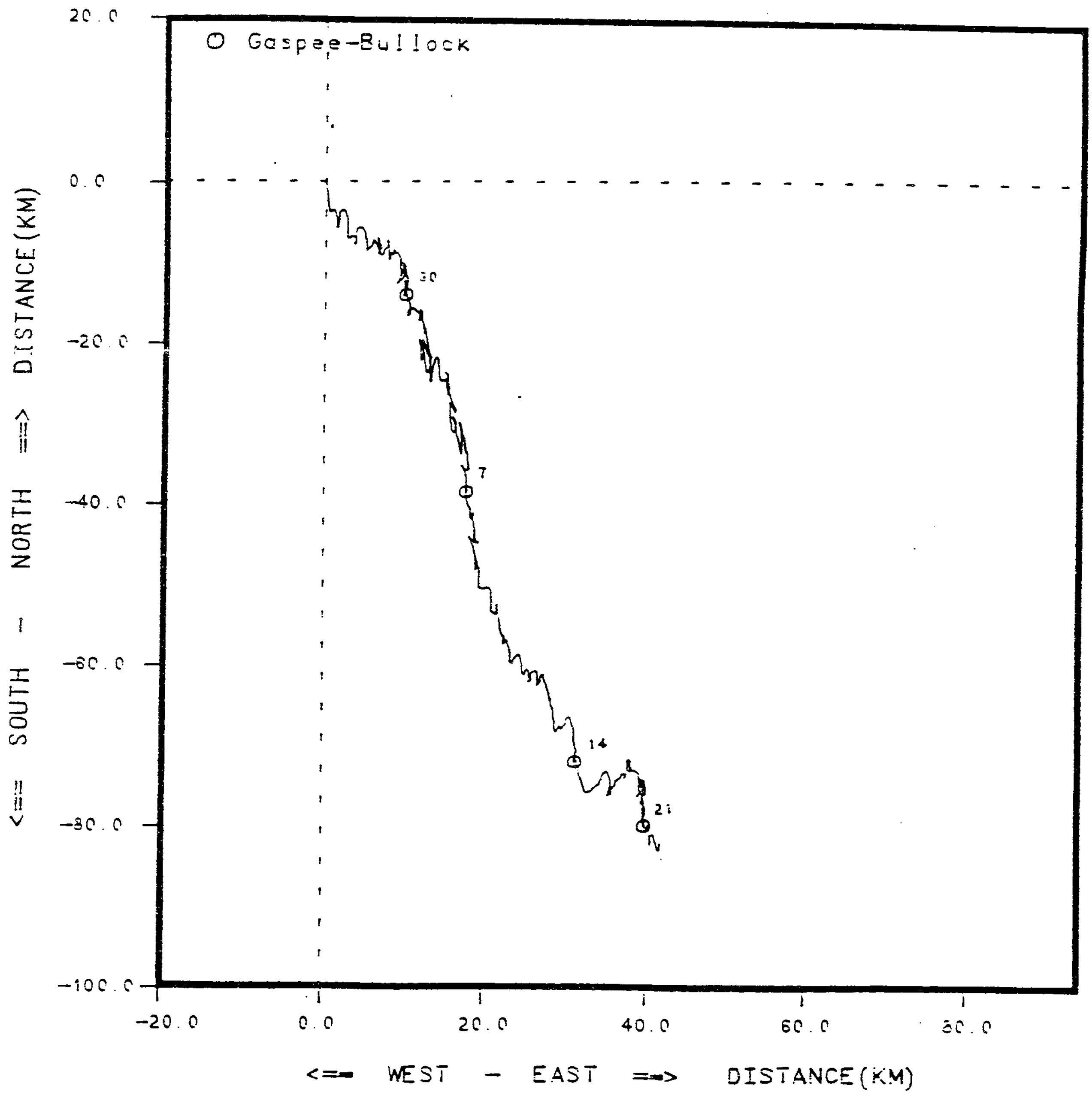
D.7 Seekonk River Bottom Currents, April 23 - June 1, 1989.



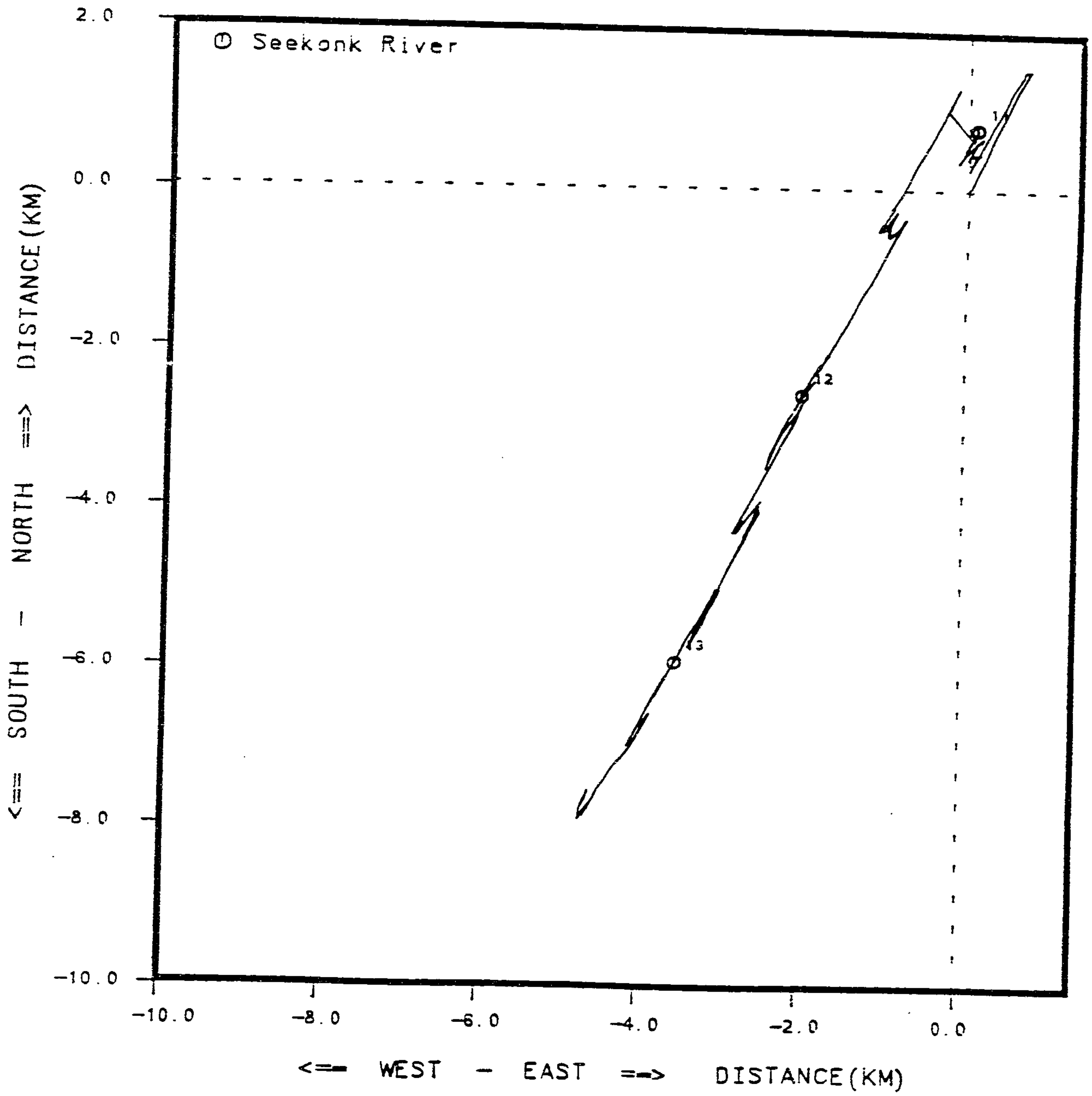
D.8 Fields Point Surface Current, April 23 - June 1, 1989.



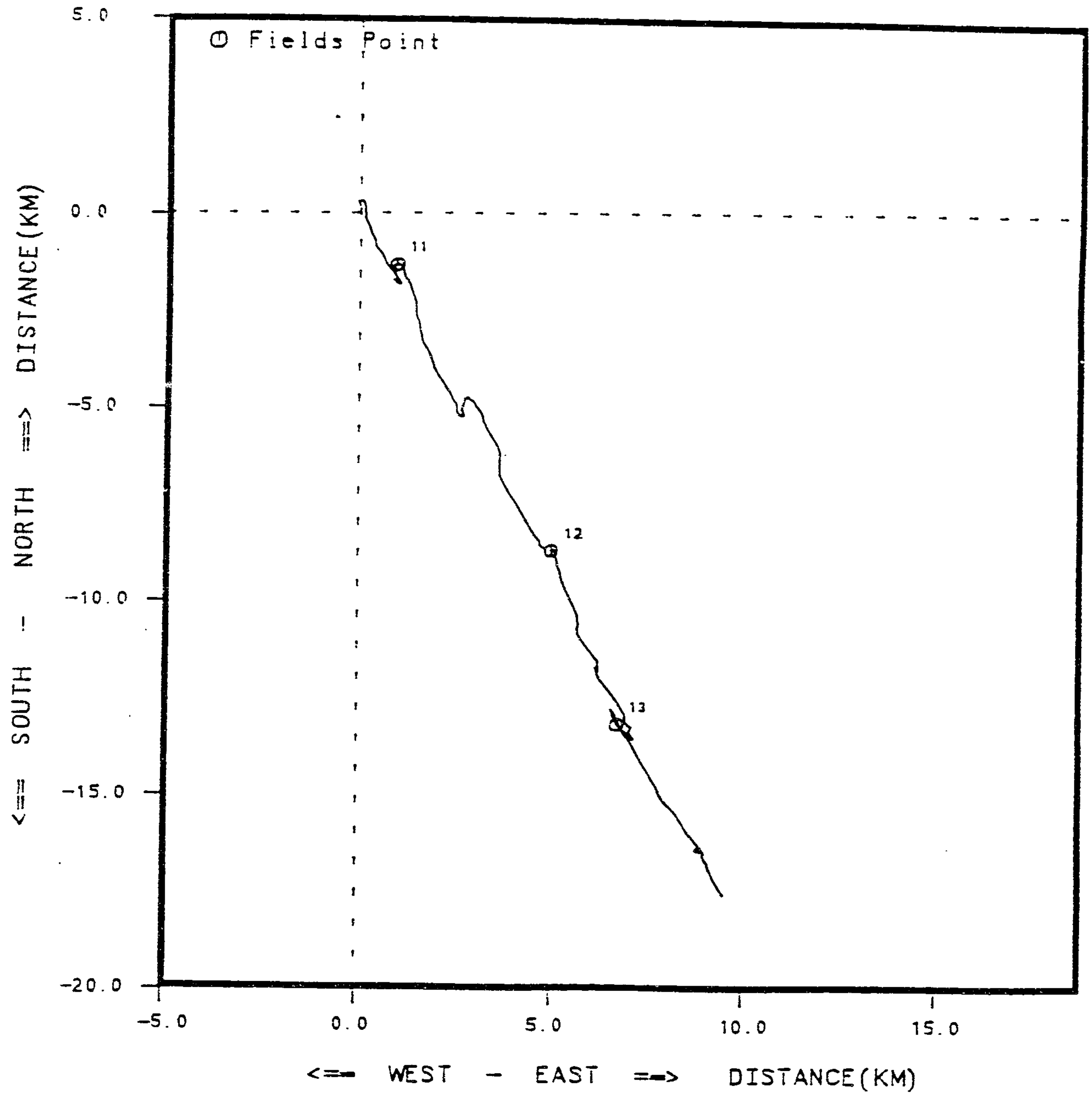
D.9 Fields Point Bottom Current, April 23 - June 1, 1989.



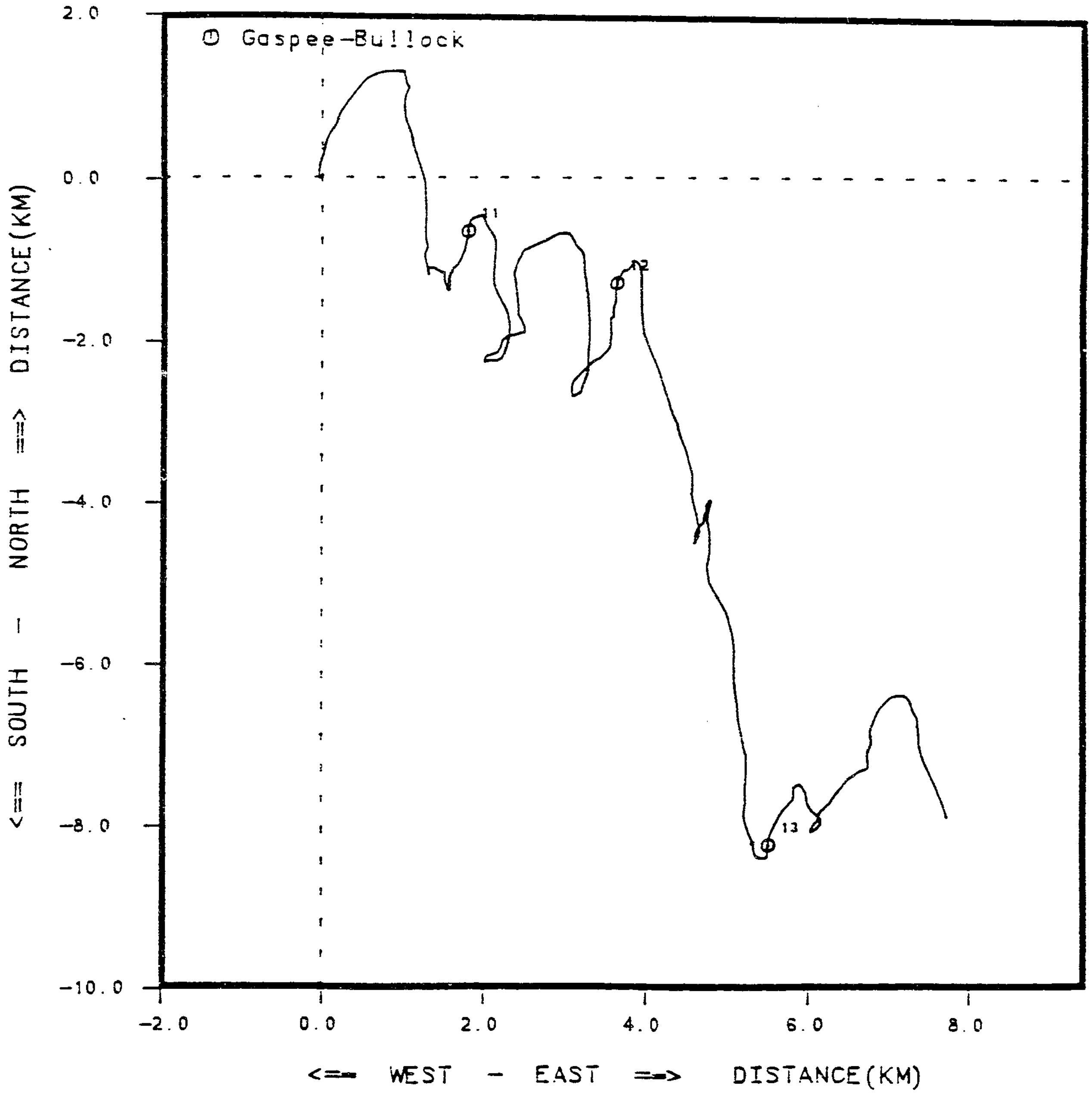
D.10 Gaspee-Bullock Transect Surface Current, April 23 - May 22, 1989.



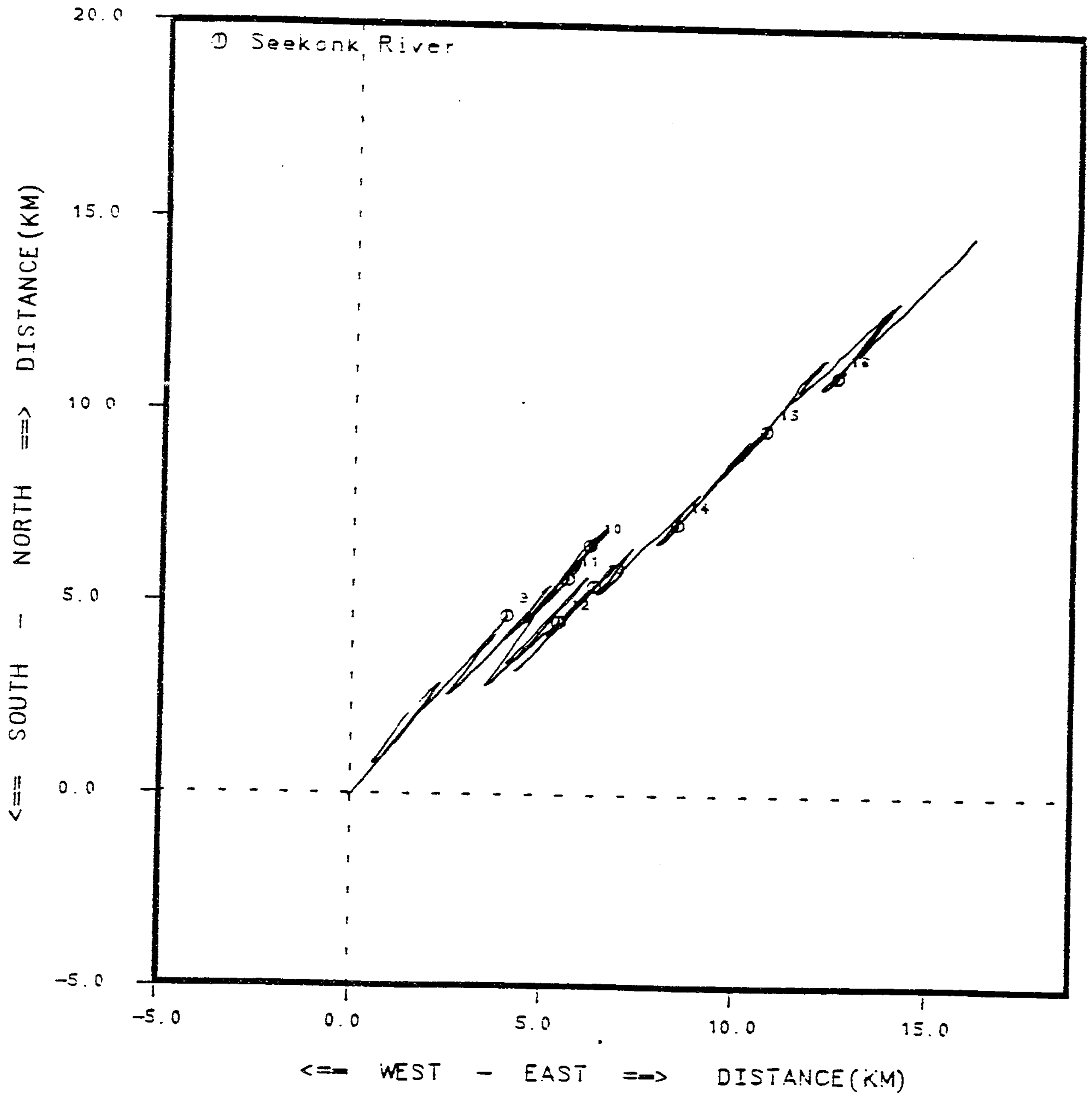
D.11 Seekonk River Bottom Currents, 0800 May 10 - 1700 May 13, 1989.



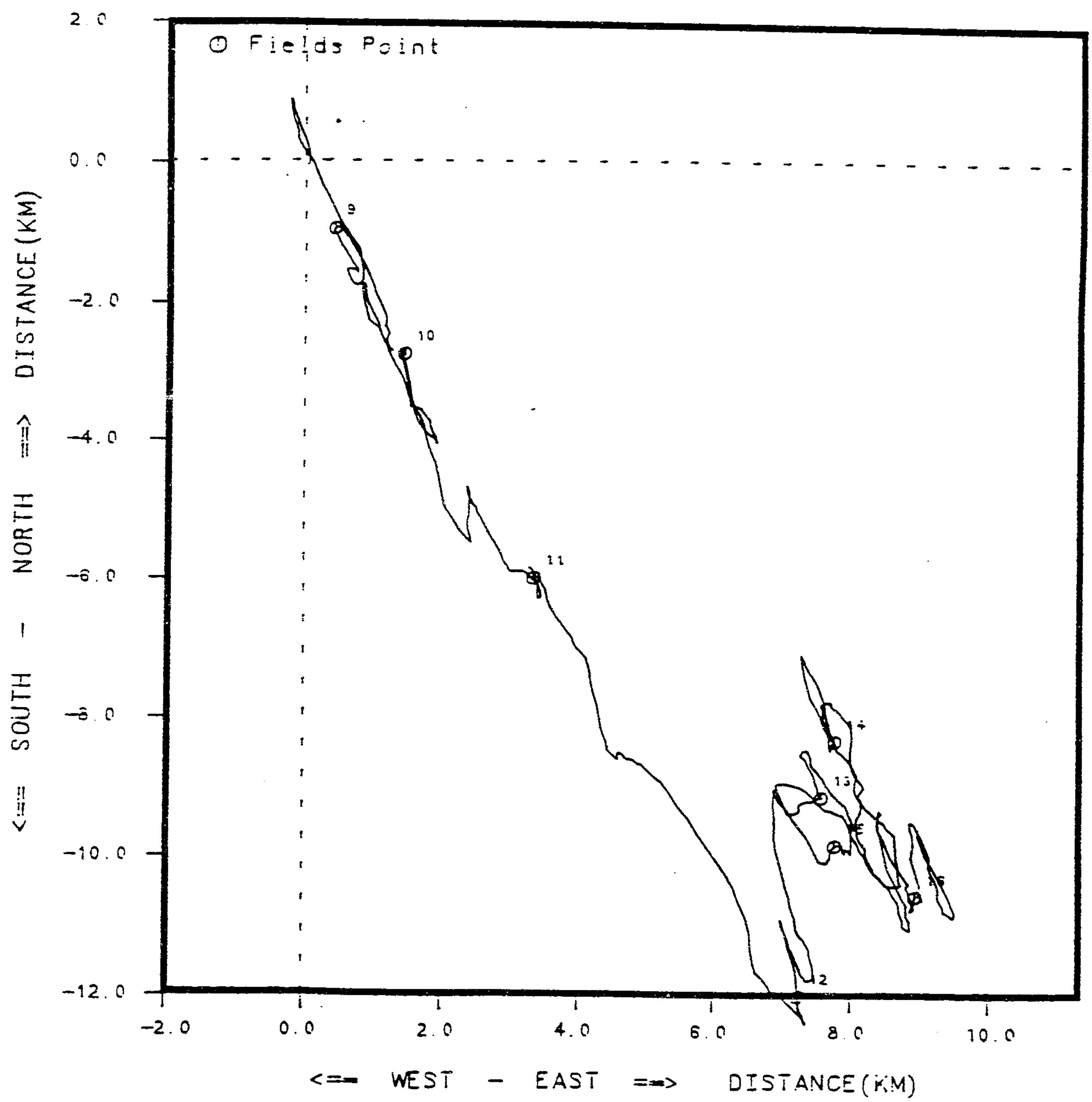
D.12 Fields Point Surface Currents, 0800 May 10 - 1700 May 13, 1989.



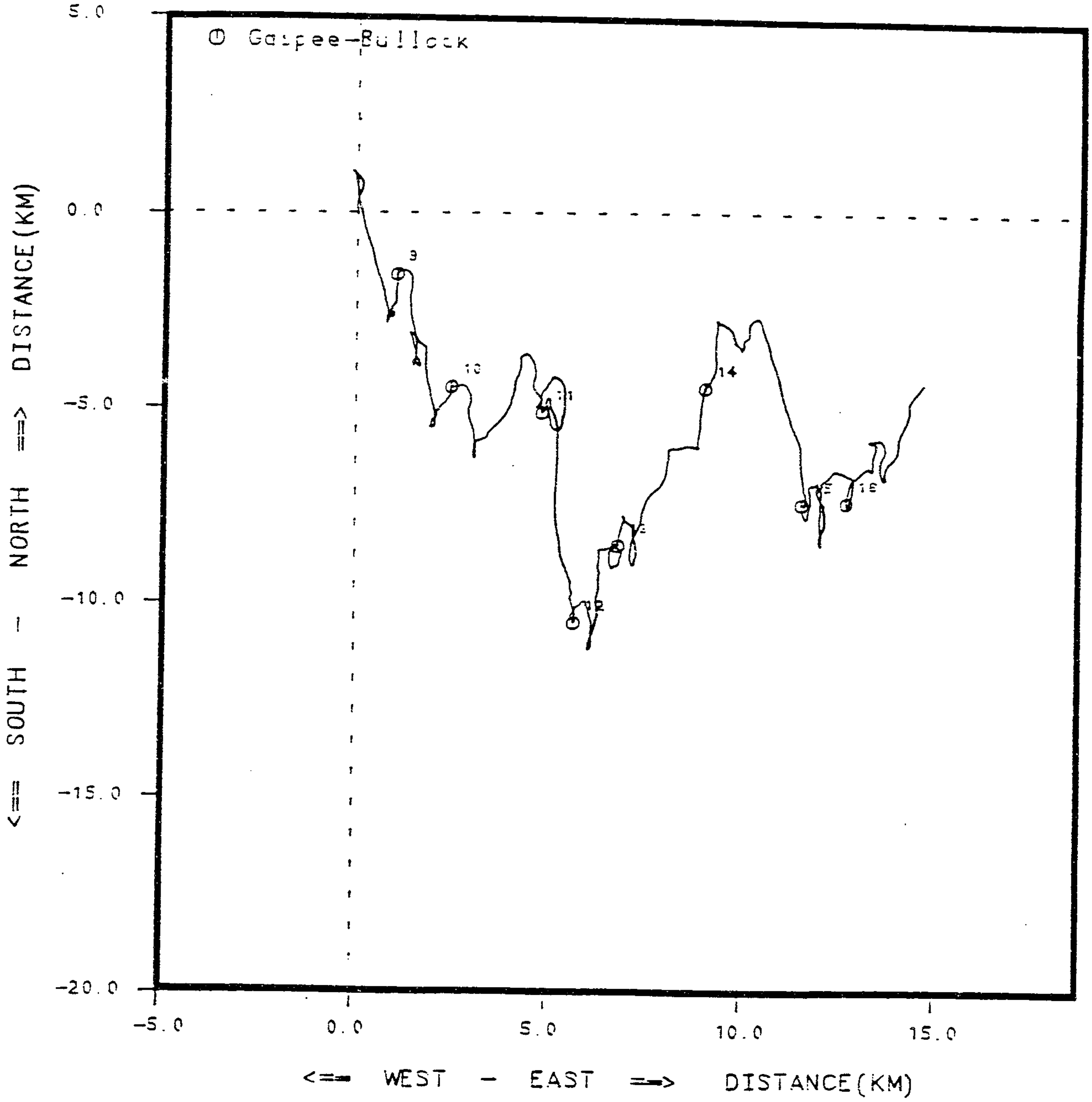
D.13 Gaspee-Bullock Transect Surface Currents, 0800 May 10 - 1700 May 13, 1989.



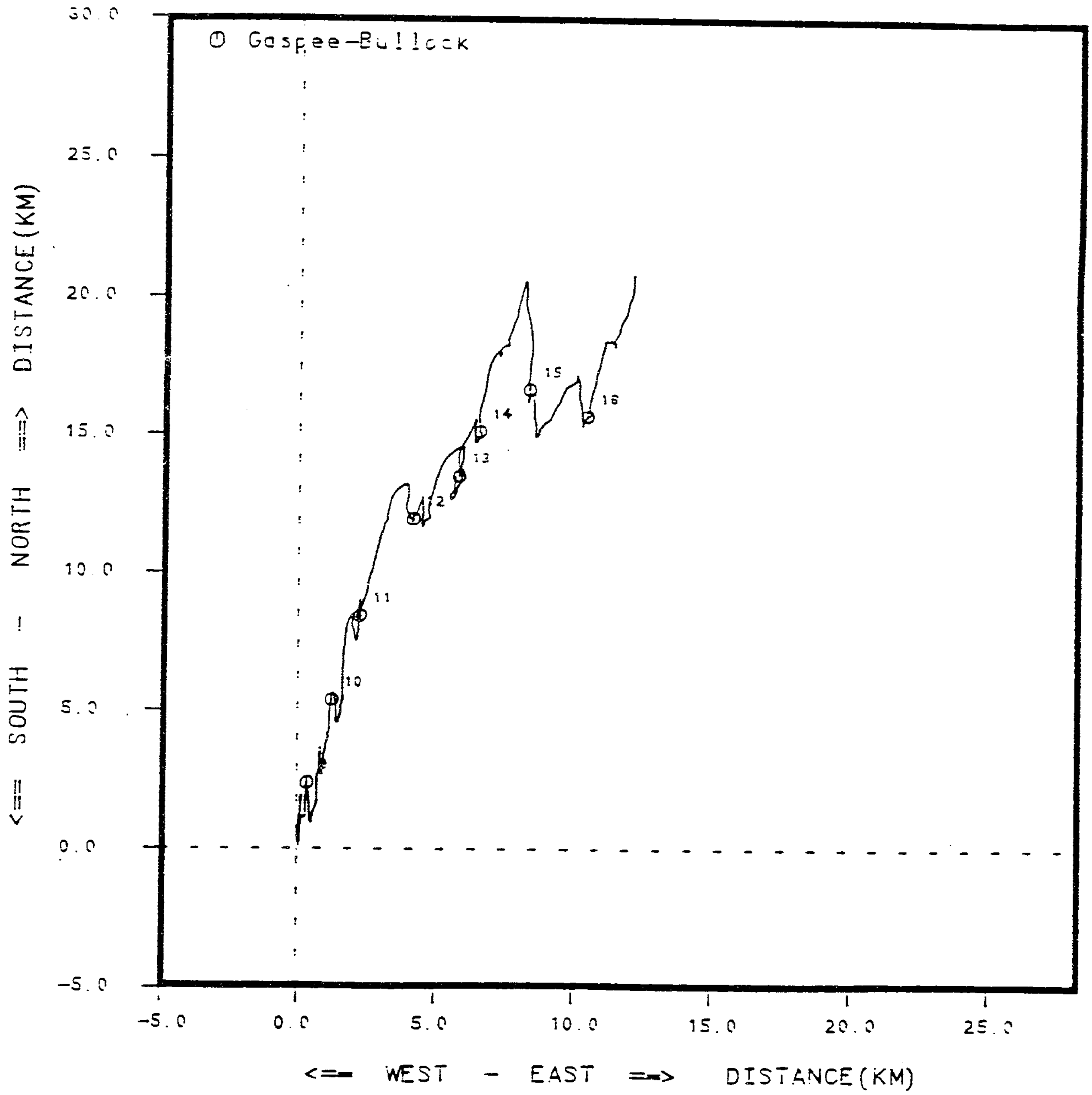
D.14 Seekonk River Bottom Currents, June 8 - June 16, 1989.



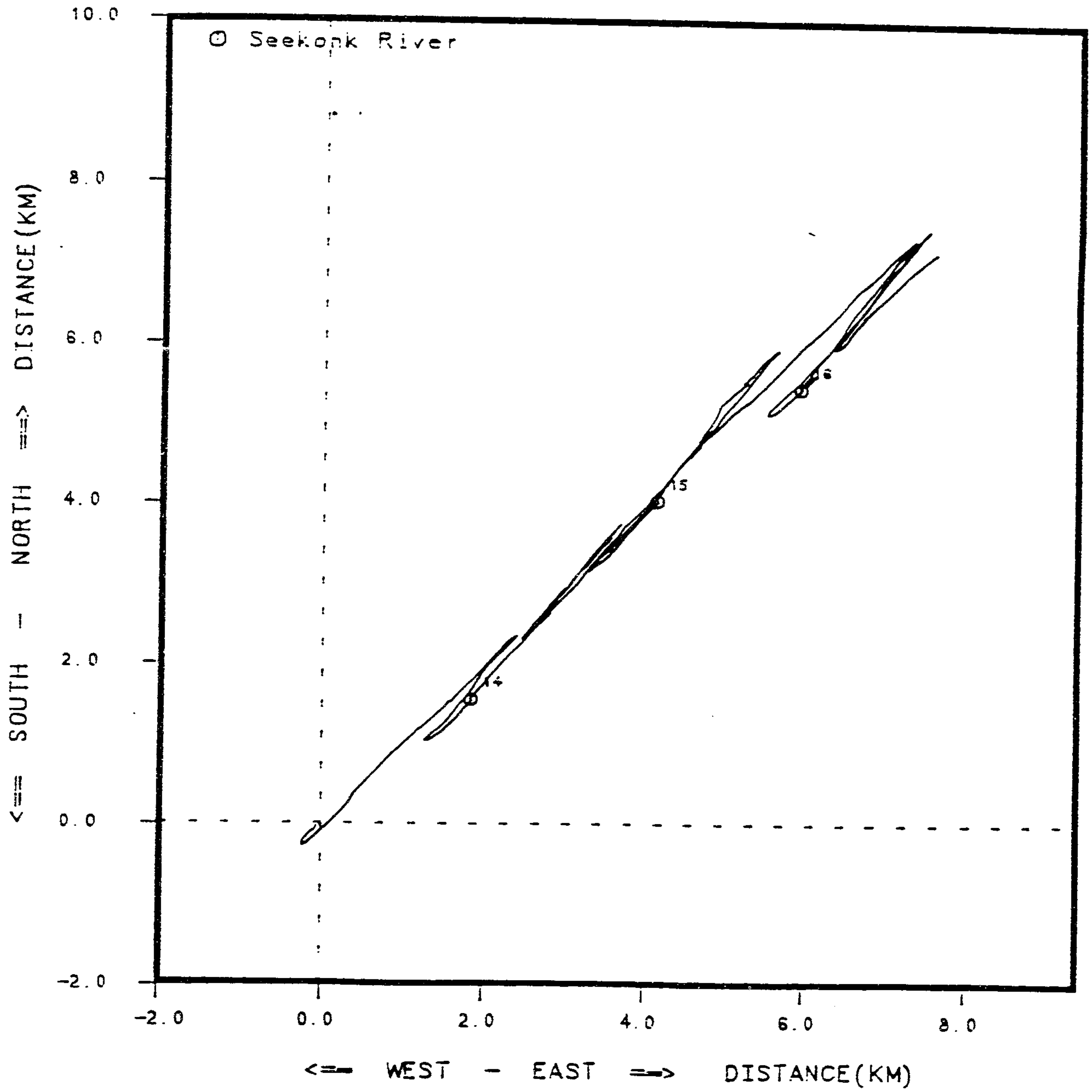
D.15 Fields Point Surface Currents, June 8 - June 16, 1989.



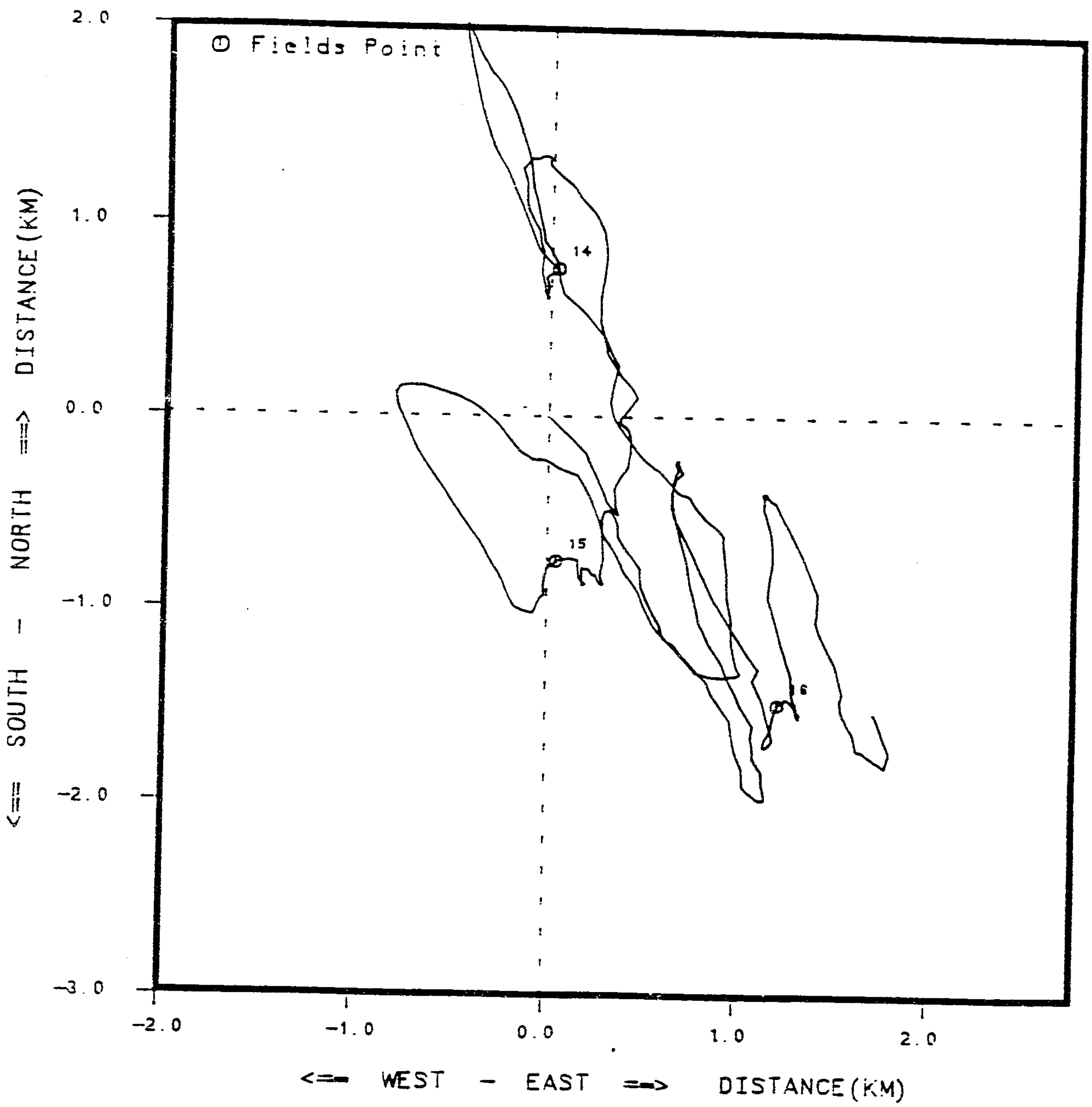
D.16 Gaspee-Bullock Transect Surface Currents, June 8 - June 16, 1989.



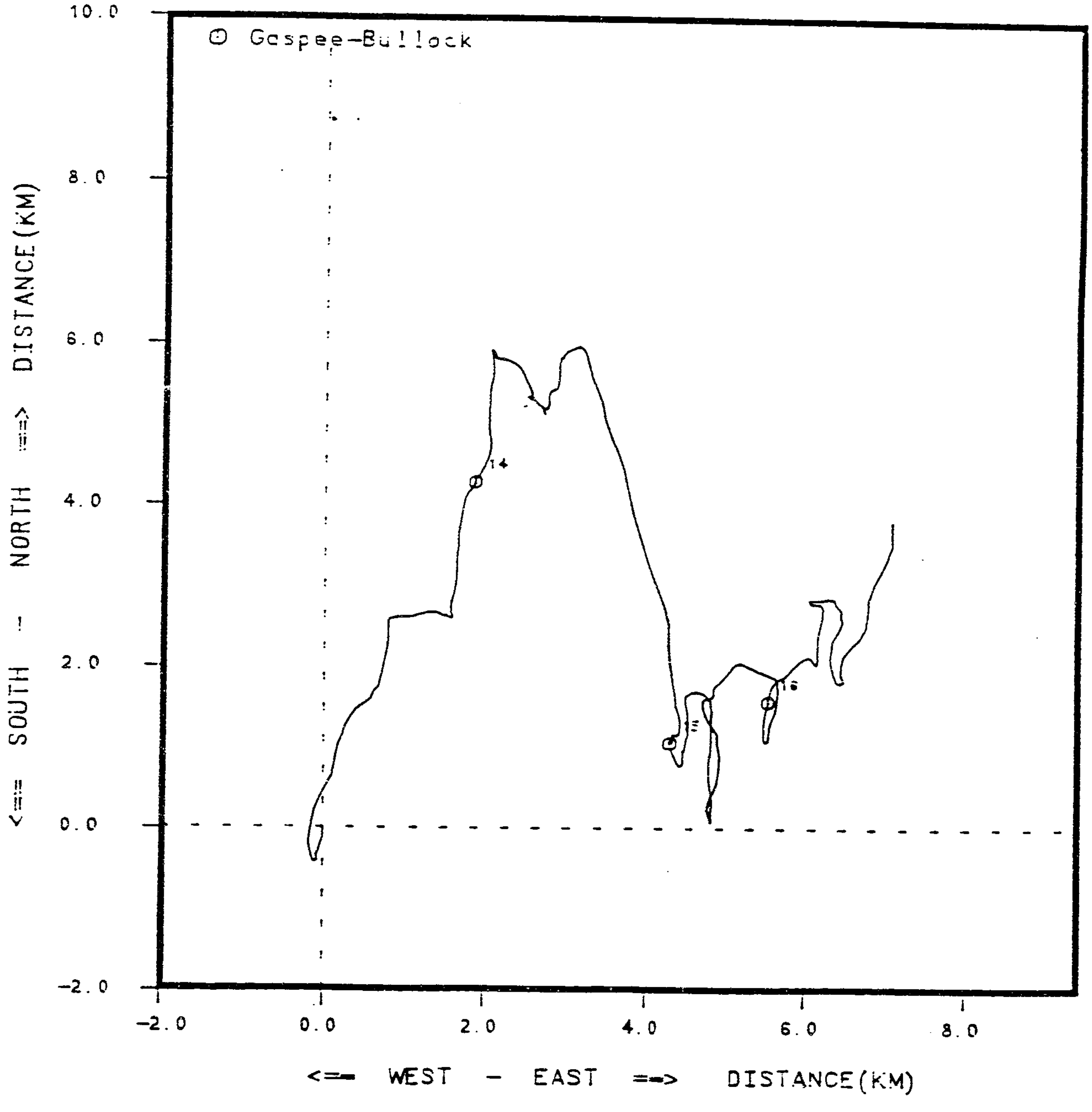
D.17 Gaspee-Bullock Bottom Currents, June 8 - June 16, 1989.



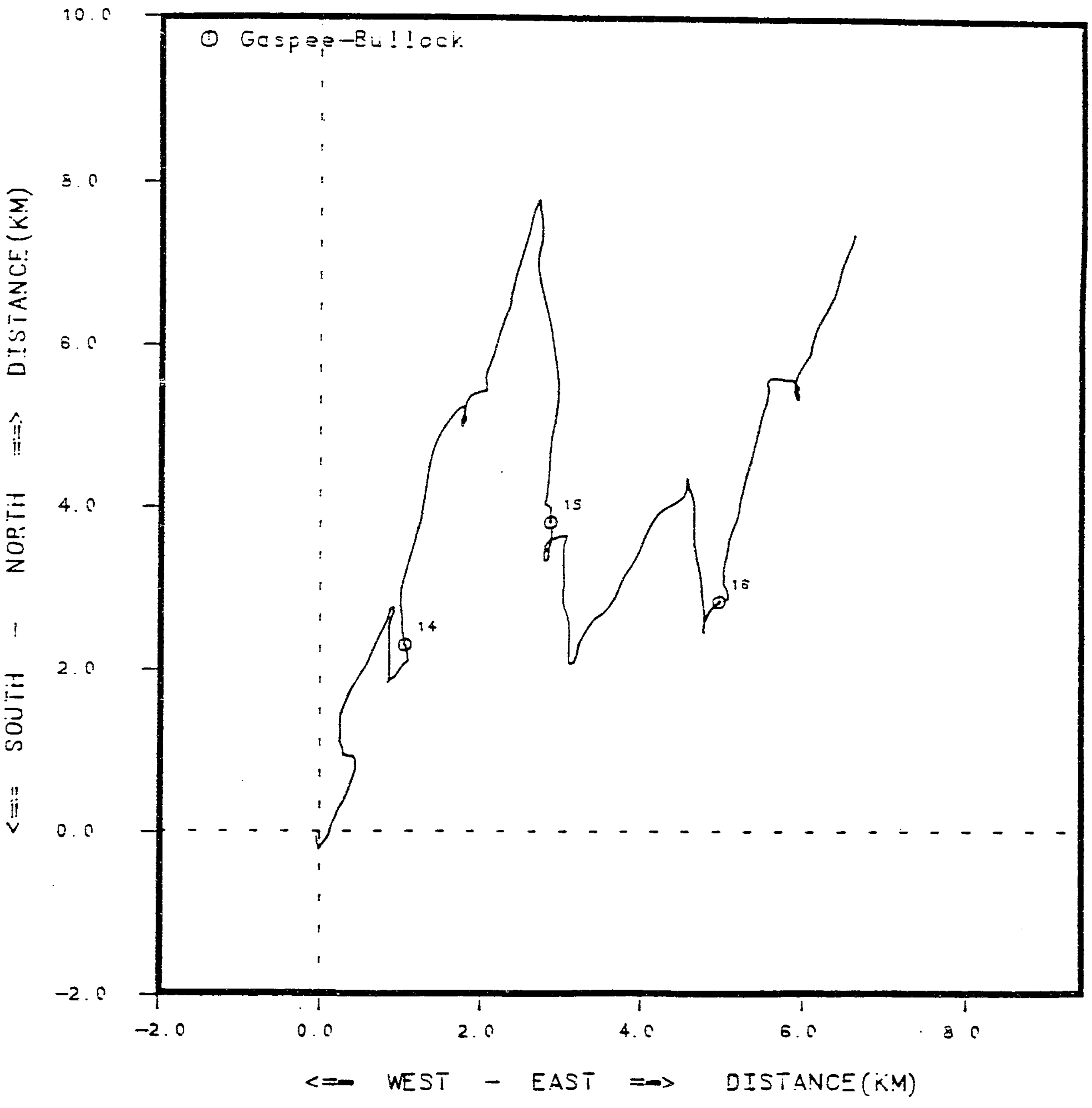
D.18 Seekonk River Bottom Currents, 0700 June 13 - 1400 June 16, 1989.



D.19 Fields Point Surface Currents, 0700 June 13 - 1400 June 16, 1989.

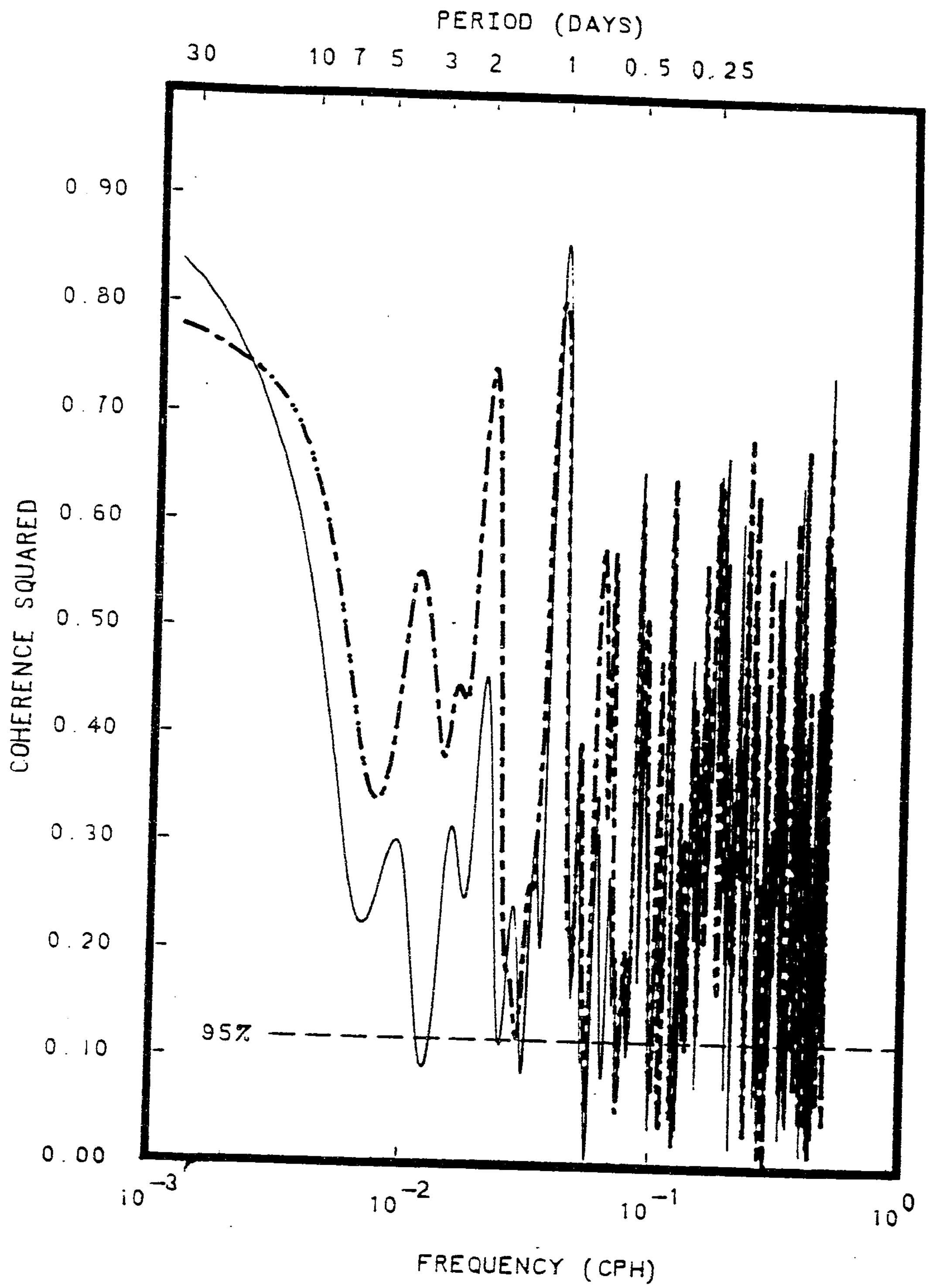


D.20 Gaspee-Bullock Transect Surface Currents, 0700 June 13 - 1400 June 16, 1989.

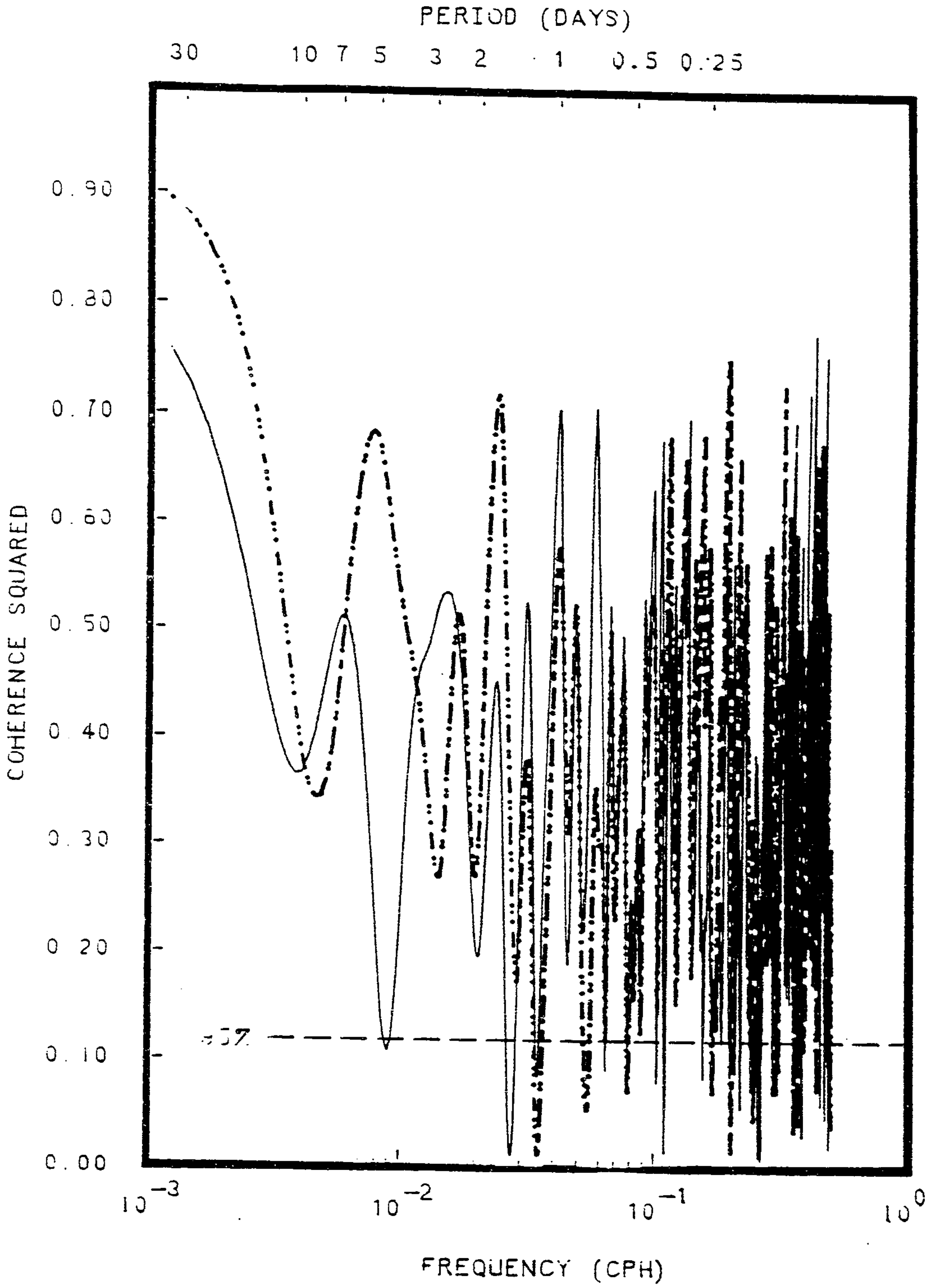


D.21 Gaspee-Bullock Bottom Currents, 0700 June 13 - 1400 June 16, 1989.

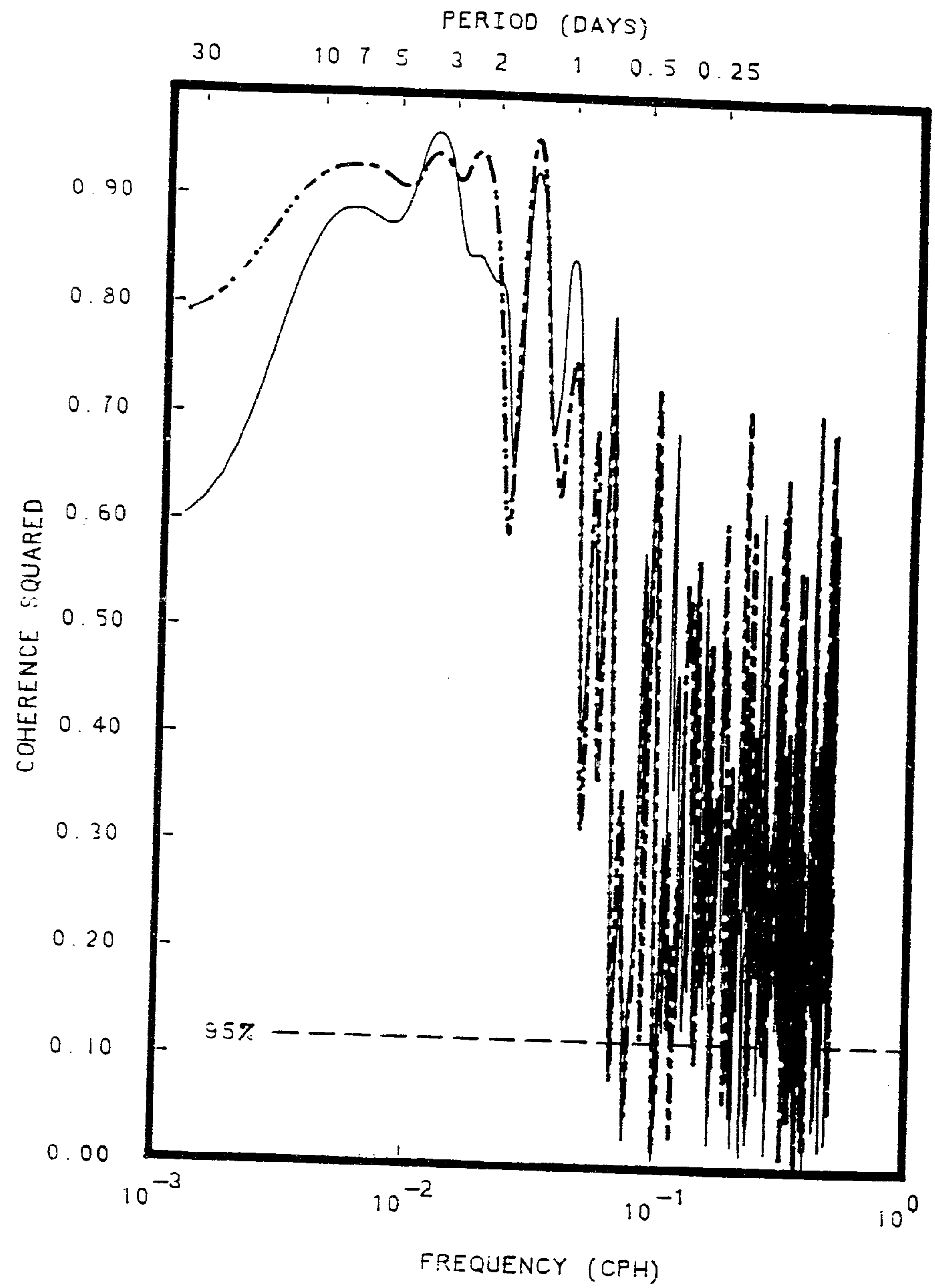
APPENDIX E: WIND-CURRENT MULTIPLE COHERENCE SPECTRA



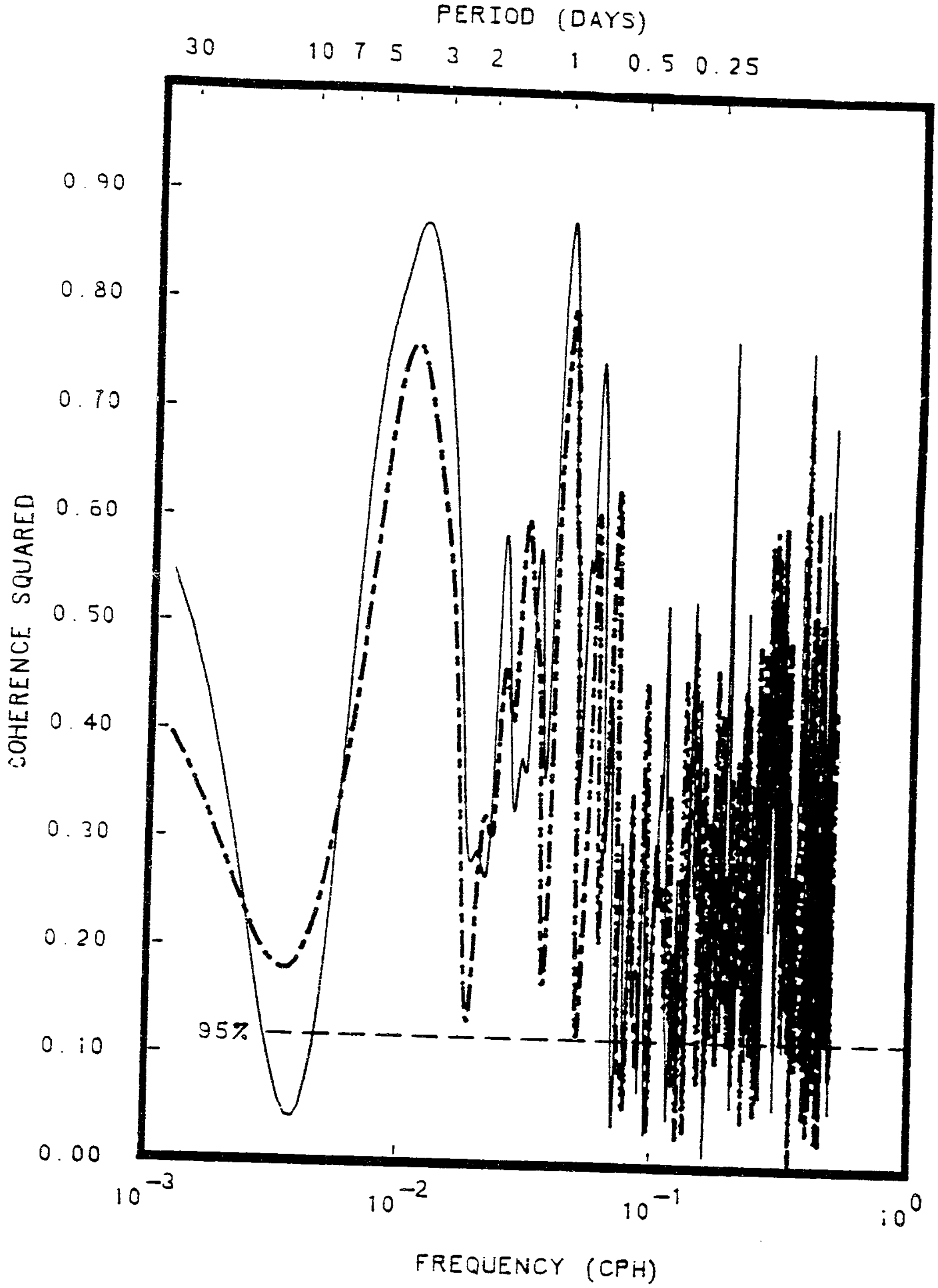
E.1 Seekonk River Bottom Current Multiple Coherence Spectra, September 17 - November 7, 1988.



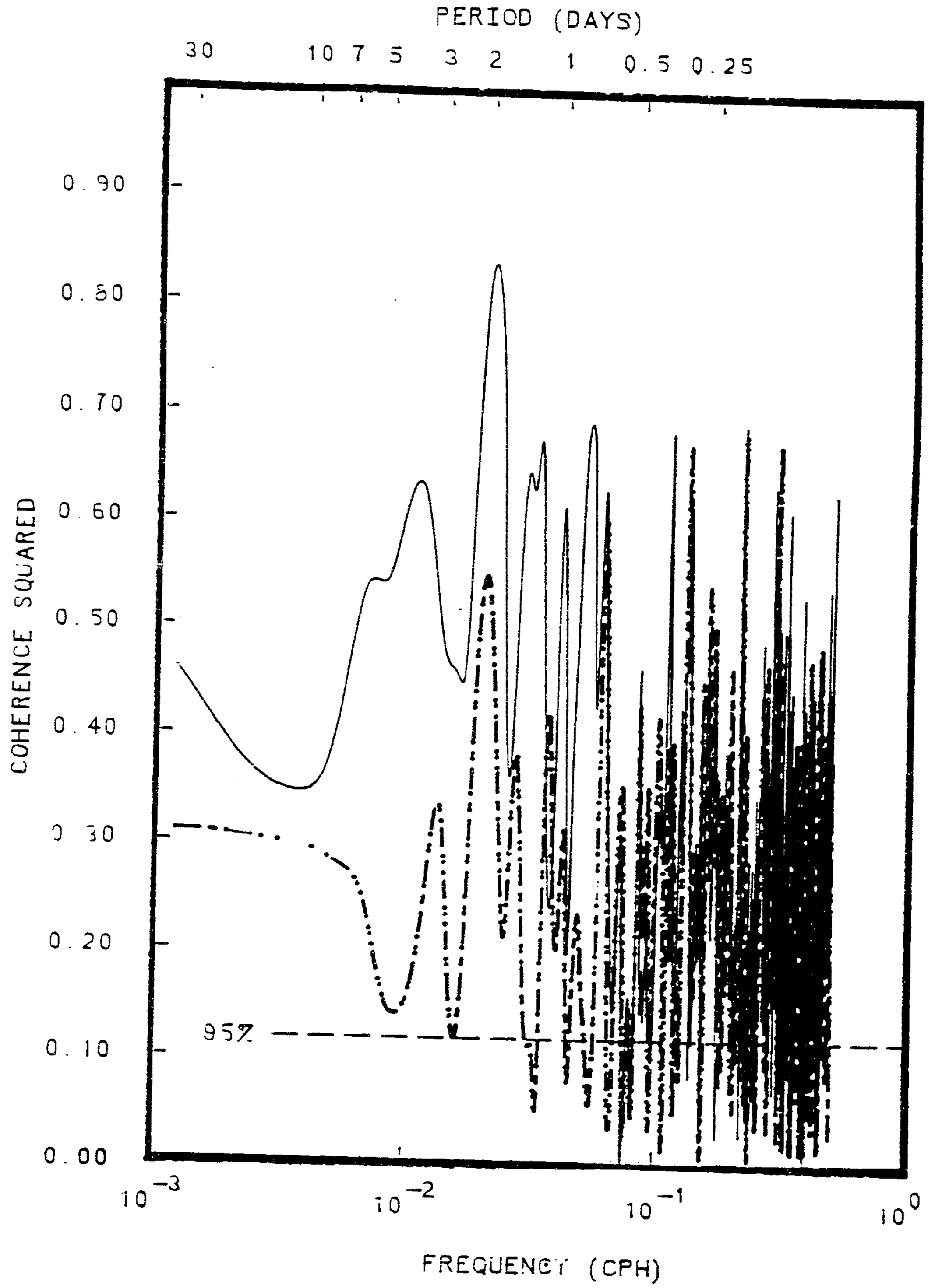
E.2 Seekonk River Bottom Current Multiple Coherence Spectra, April 23 - June 1, 1989



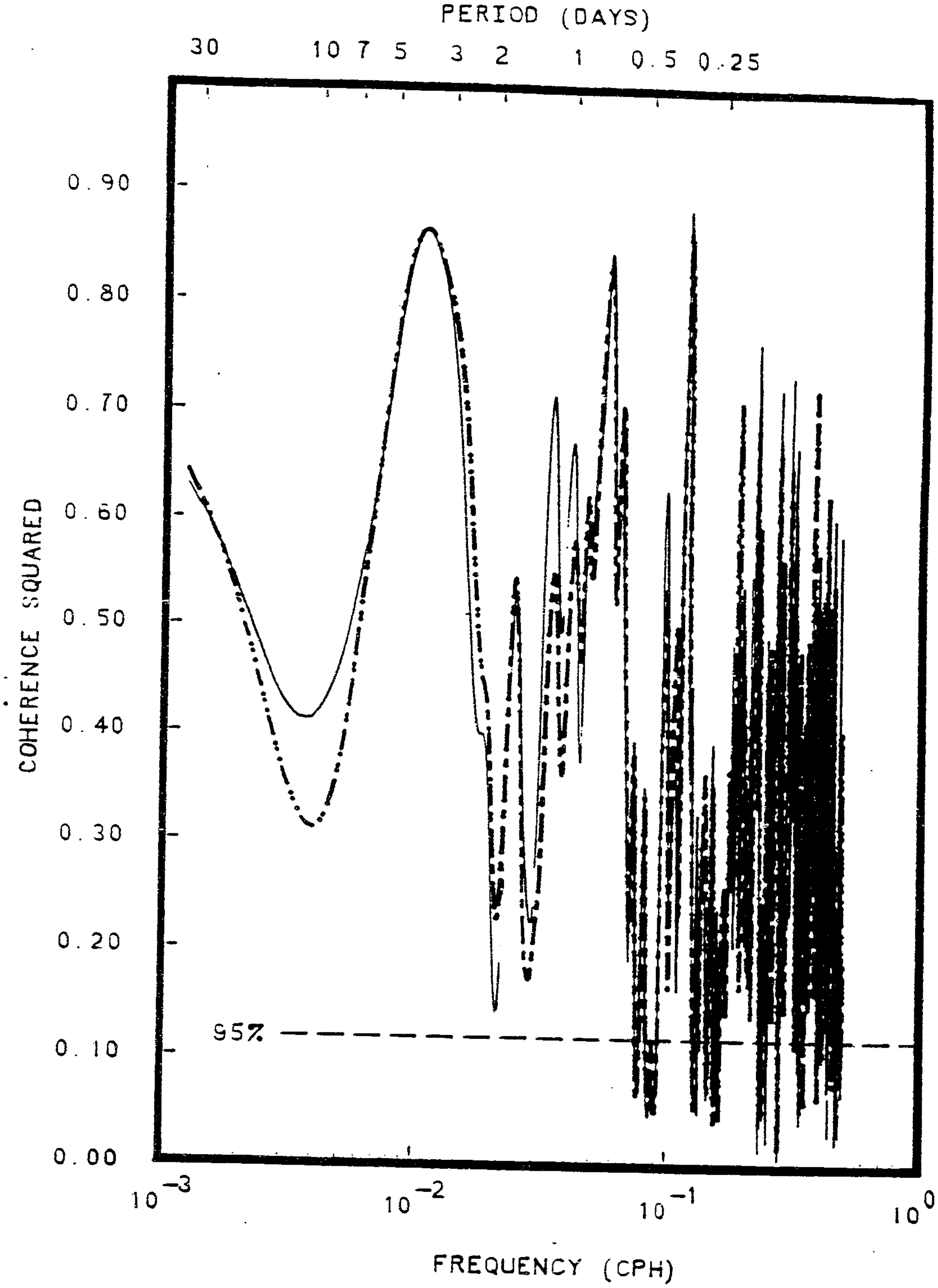
E.3 Fields Point Surface Current Multiple Coherence Spectra, September 17 - November 6, 1988.



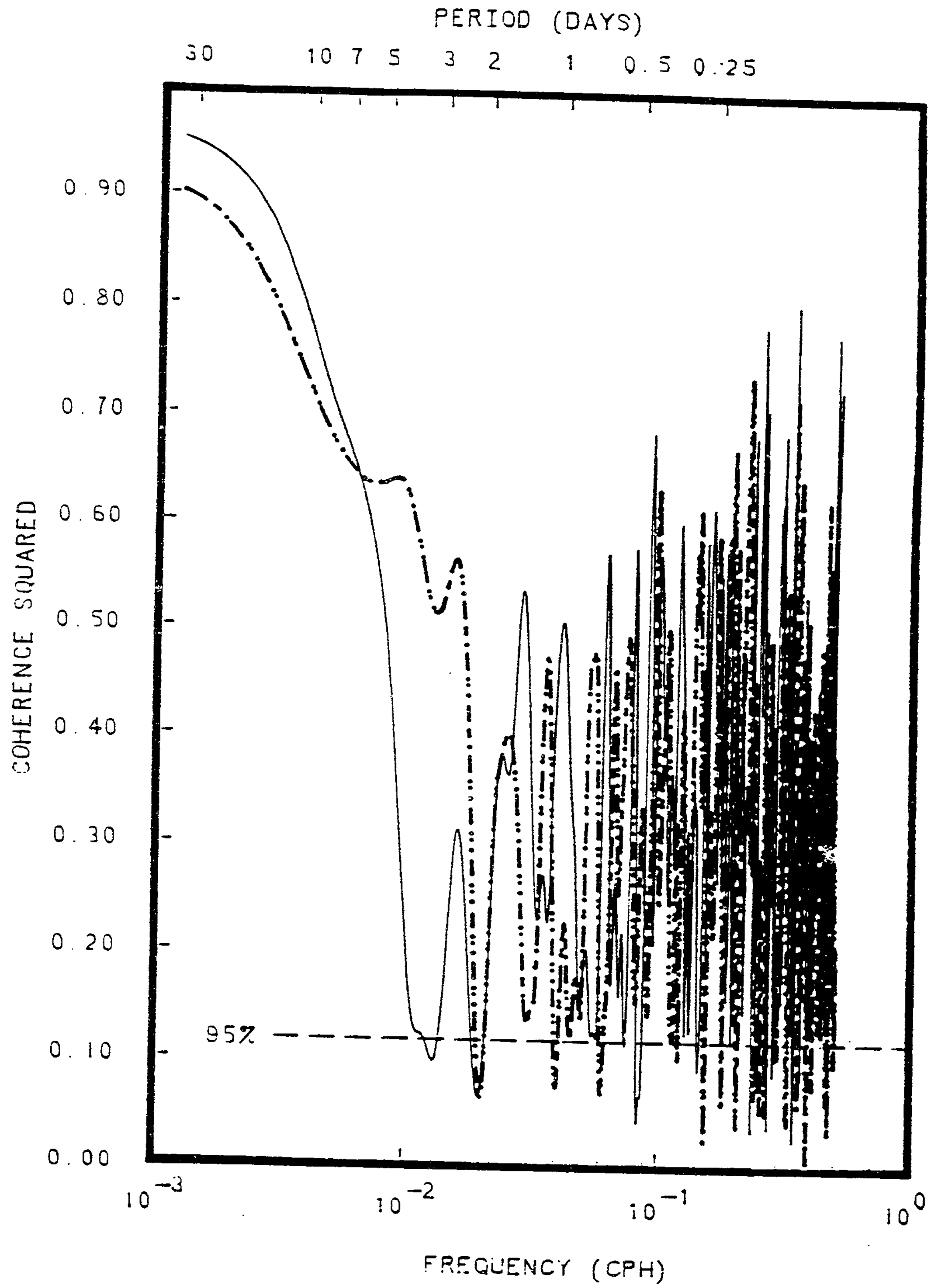
E.4 Fields Point Surface Current Multiple Coherence Spectra, April 23 - June 1, 1989.



E.5 Fields Point Bottom Current Multiple Coherence-Spectra, September 17 - November 7, 1989.



E.6 Fields Point Bottom Current Multiple Coherence Spectra, April 23 - June 1, 1989.



E.7 Gaspee Point Surface Current Multiple Coherence Spectra, April 23 - May 22, 1989.