# NBP-91-77

Providence River Wet Weather Dye Study Data Report 85 pp

Copies of the Appendices are available for reference only at Pell Marine Library□GSO, EPA Region I Reference Library and the NBP office

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

Narragansett Bay Estuary Program

Current Report

The Narragansett Bay Project

# PROVIDENCE RIVER WET WEATHER DYE STUDY DATA REPORT


Prepared by:

A. Christian Turner
Stephane Asselin
Shih-shing Feng
Suzanna Puckett

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





#NBP-91-77



The Narragansett Bay Project is sponsored by the U.S. Environmental Protection Agency and the R.I. Department of Environmental Management.

# PROVIDENCE RIVER WET WEATHER DYE STUDY DATA REPORT


Prepared by:

A. Christian Turner
Stephane Asselin
Shih-shing Feng
Suzanna Puckett

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



#NBP-91-77

# 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. Appendices A-K are available for reference at URI Graduate School of Oceanography Pell Marine Library, EPA Region I Reference Library and the Narragansett Bay Project Office.

TABLE OF CONTENTS


| | Page |
|---|---|
| Executive Summary | ii |
| List of Figures | iv |
| List of Tables | viii |
| 1. Introduction | 1 |
| 1.1 Context of the Study | 1 |
| 1.2 Description of the Study Area | 1 |
| 2. Study Objectives | 6 |
| 3. Field Methods | 9 |
| 3.1 Overview | 9 |
| 3.2 Dye Release Methods | 9 |
| 3.3 In-situ Measurement Methods | 10 |
| 3.3.1 Dye Measurements | 10 |
| 3.3.2 Hydrographic Measurements | 16 |
| 3.4 Execution of the Field Measurements | 16 |
| 4. Experimental Results | 21 |
| 4.1 Study Narratives | 21 |
| 4.1.1 October 21-26, 1989 Survey | 21 |
| 4.1.2 May 10-15, 1989 Survey | 23 |
| 4.1.3 June 13-16, 1989 Survey | 27 |
| 4.2 Dye Distributions | 32 |
| 4.2.1 Spatial Distribution and Movements | 32 |
| 4.2.2 Dye Decay Rates | 56 |
| 4.2.3 Correlations Between Dye Concentrations and Pollutant Indicators | 65 |
| 4.3 Salinity and Dissolved Oxygen | 73 |
| 5. Conclusions | 82 |
| 6. References | 84 |
| Appendices | |

# EXECUTIVE SUMMARY

A program of studies, the Wet Weather Study Program, funded by the Narragansett Bay Project (NBP) and Narragansett Bay Commission (NBC) were conducted during the fall of 1988 and spring of 1989 in the upper Narragansett Bay and Providence and Seekonk Rivers. The study area included the Providence River watershed, which included five tributaries: the Blackstone, Ten Mile, Moshassuck, Woonasquatucket and Pawtuxet Rivers.

The main goal of the project was to quantify storm-related pollutant loadings to the Providence River from both point and distributed sources. The information collected by the study would be of sufficient detail to support a modeling study of pollutant transport in the River. The program was led by Dr. Raymond Wright of the Department of Civil and Environmental Engineering at the University of Rhode Island (URI/CE). Dr. Wright and his group were responsible for quantifying pollutant loadings from selected point sources and tributaries, and some in-stream stations in the Providence River. The URI/CE group also performed analyses for nutrients, metals and conventional pollutants on all the samples. Analysis for a series of organic parameters were performed by a team led by Drs. James Quinn and James Latimer of the University of Rhode Island Graduate School of Oceanography (URI/GSO). Analysis of the samples for a suite of microbiological indicators was performed by a group at the Food and Drug Administration facility in North Kingstown, Rhode Island. This effort was headed by Drs. William Watkins and Scott Rippey.

The present study was one element of the Wet Weather Study Program. Its purpose was to provide additional detail on the transport of pollutants introduced with storm runoff through the River. The study consisted of dye releases and in-situ measurements of dye, salinity and dissolved oxygen in the Providence and Seekonk Rivers. Prior to this study, the largest sources of stormwater-related pollutants to the area had not been ranked. For this study, the four largest dry weather point-sources of metals were therefore selected as dye release sites. These were the NBC outfall at Fields Point, the Blackstone River, the Blackstone Valley District Commission outfall in East Providence, and the Pawtuxet River. The dye releases were started concurrently during periods of rain when runoff was observed to begin bypassing the Fields Point NBC sewage treatment facility. They typically lasted for four hours.

During and after the releases, dye, salinity and dissolved oxygen surveys were conducted between the mouth of the Seekonk River and Conimicut Point. The measurements were made continuously at 3 hour intervals during the first 15-24 hours of the study and at 6 hour intervals for a period of 105 hours or until the dye had disappeared from the area. A total of 16 surveys were completed during the October 1988 experiment, 21 surveys during the May 1989 experiment, and 15 surveys during the June 1989 experiment.

After its release into the study area, the dye tended to be controlled in large part by the salinity field. During the October 1988 experiment, where vertical stratification of salinity was weak (1-5 ppt difference between surface and bottom) the dye mixed through most of the water column and flushed slowly from the study area. During the May 1989 and June 1989 experiments where vertical stratification was strong (16-22 ppt), the dye remained in the upper 1 m of the water column of the Providence River throughout the study period. The dye also decayed much more rapidly with time at each measurement location in the area. The observations point to a control of mass transport by fresh water inflow rates. It is suggested that further analysis be undertaken to examine the influence of freshwater inflow on the salinity and dye distributions based on inflow data for tributaries and point sources to the study area collected by other study elements of the NBP Wet Weather Program.

Preliminary estimates of flushing times for selected reaches of the Providence River based on dye decay time histories were also made. Flushing times calculated from the rates of dye decay were 4.5 days, 0.9 days and 2.5 days for the October 1988, May 1989 and June 1989 studies, respectively. Flushing times were also calculated for the May and June 1989 experiments, based on freshwater inflow and mean salinity within the Providence River and the Upper Bay. This analysis yielded estimates of 1.1 and 1.7 days which were close to the estimates based on dye decay.

The correlation between the levels of dye and other pollutant indicators was also examined. The parameters selected for the analysis included the dissolved and particulate fractions of copper, lead and cadmium, and fecal coliforms. The analysis revealed that no general correlation exists between dye and the other indicators. The results may suggest that numerous sources release pollutants to the area during periods of rain. It may also indicate that distributed sources of metals, fecal coliforms and other pollutants may control pollutant levels in the river during these periods.

## LIST OF FIGURES


| | | Page |
|---|---|---|
| Figure 1.1 | The Providence River study area | 2 |
| Figure 1.2 | The Seekonk River study area | 3 |
| Figure 3.1 | Fluorometer regression vs. standard concentrations on the 31.6x scale | 12 |
| Figure 3.2 | Fluorometer regression vs. standard concentration on the 10x scale | 13 |
| Figure 3.3 | Sampling station locations in the Providence River | 17 |
| Figure 3.4 | Sampling station locations in the Seekonk River | 18 |
| Figure 4.1 | Time history of rainfall intensity in the area (and lead fluxes from the four point sources) on October 22, 1988 (from Wright et al., 1990) | 22 |
| Figure 4.2 | Experiment #1 (October 21-26, 1988): timing of surveys relative to tide height in Providence | 25 |
| Figure 4.3 | Time history of rainfall intensity in the area (and lead fluxes from the four point sources) between May 10-12, 1989 (from Wright et al., 1990) | 26 |
| Figure 4.4 | Experiment #2 (May 10-15, 1989): timing of surveys relative to tide height in Providence | 29 |
| Figure 4.5 | Time history of rainfall intensity in the study area (and lead fluxes from the four point sources) on June 13, 1989 (from Wright et al., 1990) | 31 |
| Figure 4.6 | Experiment #3 (June 13-16, 1989): timing of surveys relative to tide height in Providence | 34 |
| Figure 4.7 | Contoured vertical cross-section of dye concentration along the center of the Providence River survey 2, 1054-1238 October 22, 1988 | 38 |

Figure 4.8 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 4, 1836-1949 October 22, 1988 ........ 39

Figure 4.9 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 6, 1435-1645 October 23, 1988 ........ 41

Figure 4.10 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 16, 0745-1032 October 26, 1988 ........ 42

Figure 4.11 Progressive vectors of surface currents at Fields Point, 0000 October 22 - 1200 October 26, 1988 ........ 43

Figure 4.12 Progressive vectors of bottom currents near Cold Spring Point, 0000 October 22 - 1200 October 26, 1988 ........ 44

Figure 4.13 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 2, 2109-2240 May 10, 1989 ........ 46

Figure 4.14 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 3, 0035-0240 May 11, 1989 ........ 47

Figure 4.15 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 4, 0400-0523 May 11, 1989 ........ 48

Figure 4.16 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 6, 1030-1205 May 11, 1989 ........ 49

Figure 4.17 Progressive vectors of surface currents at Fields Point, 0800 May 10 - 1700 May 13, 1989 ........ 50

Figure 4.18 Progressive vectors of surface currents at Gaspee Point, 0800 May 10 - 1700 May 13, 1989 ........ 51

Figure 4.19 Dye concentrations at the near-surface and near-bottom depths in the Seekonk River as a function of distance from Slaters Mill Dam during survey 1 ........ 53

Figure 4.20 Dye concentrations at the near-surface and near-bottom depths in the Seekonk River as a function of distance from Slaters Mill Dam during survey 5, 0319-0436 May 11, 1989.... 54

Figure 4.21 Progressive vectors of bottom currents in the lower Seekonk River, 0800 May 10 -1700 May 13, 1989 .... 55

Figure 4.22 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 2, 1531-1658 June 13, 1989 .... 57

Figure 4.23 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 3, 1953-2050 June 13, 1989 .... 58

Figure 4.24 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 5, 0057-0220 June 14, 1989 .... 59

Figure 4.25 Dye concentrations at the near-surface and near-bottom depths in the Seekonk River as a function of distance from Slaters Mill Dam during survey 3, 1729-1844 June 13, 1989.... 60

Figure 4.26 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 6, 0349-0600 June 14, 1989 .... 61

Figure 4.27 Sub-sections (boxes) used in the Providence River .... 63

Figure 4.28 Natural log of vertically and a really averaged dye concentration in the Providence River as a function of time after 0500 October 22, 1988 .... 66

Figure 4.29 Natural log of vertically and areally averaged dye concentration in the Providence River as a function of time after 2200 May 10, 1989 .... 68

Figure 4.30 Dye flushing in the Seekonk River during the May 1989 Wet Weather experiment, State of tide is indicated at the top of the graph .... 69

| | | |
|---|---|---|
| Figure 4.31 | Natural log of vertically averaged dye concentration at Station 10 as a function of time after 2200 May 10, 1989 ....... | 71 |
| Figure 4.32 | Contoured vertical cross-section of the salinity field at approximately 08:00, October 23, 1988. (From Wright et al., in preparation) ........ | 74 |
| Figure 4.33 | Contoured vertical cross-section of salinity along the center of the Providence River during Survey 4, 04:00-05:23, May 11, 1989 ........ | 75 |
| Figure 4.34 | Contoured vertical cross-section of salinity along the center of the Providence River during Survey 2, 15:31-16:58, June 13, 1989 ........ | 76 |
| Figure 4.35 | Contoured vertical cross-section of dissolved oxygen along the center of the Providence River during Survey 6, 10:30-12:05, May 11, 1989 ........ | 80 |
| Figure 4.36 | Contoured vertical cross-section of dissolved oxygen along the center of the Providence River during Survey 9, 22:07 June 14 - 00:11, June 15, 1989 ........ | 81 |

# LIST OF TABLES


| | | Page |
|---|---|---|
| Table 1.1 | Narragansett Bay Project wet weather study: principal investigators and program elements | 1a |
| Table 2.1 | Pollutant parameters to be measured during the wet weather study program | 7 |
| Table 3.1 | Means and standard deviation of background survey data by depth | 15 |
| Table 4.1 | Timetable for the Providence River surveys, October 21-26, 1989 | 24 |
| Table 4.2 | Timetable for the Providence River surveys, May 10-15, 1989 | 28 |
| Table 4.3 | Timetable for the Seekonk River surveys, May 10-11, 1989 | 30 |
| Table 4.4 | Timetable for the Providence River surveys, June 13-16, 1989 | 33 |
| Table 4.5 | Timetable for the Seekonk River surveys, June 13-14, 1989 | 35 |
| Table 4.6 | Pump description measured discharge rates, and volumes released by each source during Experiments 1-3 | 37 |
| Table 4.7 | Dye decay constants, flushing times and correlation coefficients calculated from dye data for selected stations in the Providence River during the October 21-26, 1988 experiment | 64 |
| Table 4.8 | Dye decay constants, flushing times and correlation coefficients calculated from dye data for selected stations in the Providence River during the May 10-15, 1989 experiment | 67 |

Table 4.9 Dye decay constants, coefficients, flushing times and correlation coefficients calculated from dye data for selected stations in the Providence River during the June 13-16, 1989 experiment ........ 70

Table 4.10 Fresh Water Inflow in $M^3/S$ from tributaries, treatment plants and CSO9 averaged over the ten day period prior to each wet weather experiment ........ 78

# 1. INTRODUCTION

## 1.1 Context of this Study

The present study was one element of a larger program known as the "Providence River Wet Weather" Study funded by the Narragansett Bay Project (NBP) and the Narragansett Bay Commission (NBC) during 1988 and 1989. NBC funding for the project was provided as part of the Combined Sewer Overflow Area D (CSOD) study. The NBC commissioned the CSOD study to determine CSO-related pollution in the study area following periods of rain. The present study was therefore supported by the NBC to quantify the impacts of CSOD loadings resulting from selected rain storms on the receiving waters of the Providence River.

The main objectives of the NBP funded work include:

- quantification of the contributions of rivers, sewage treatment plants (STP's) and combined sewer overflows (CSO's) to the study area during and after selected storms,

- characterization of the response of the study area to the pollutant loadings.

The dye experiment study discussed in this report was one of several NBP-funded studies of the Providence and Seekonk Rivers during this period. Other studies and their principal investigators are listed in Table 1.1.

## 1.2 Description of the Study Area

The 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 Providence River is formed by the confluence of the Moshassuck and Woonasquatucket Rivers in the center of Providence. From its head to the hurricane barrier at India Point, the river is generally quite shallow and narrow. At low tide, the river empties, becoming completely fresh as far down as the I-195 bridge. Below the bridge, the river widens to 100-150 m and deepens to between 3-7 m. Just below the hurricane barrier at India Point, the Seekonk River joins the Providence River. Below this point, the Providence River is 500 m wide. The estuary expands to approximately 2 km below Fields Point and continues to widen to its mouth at Conimicut Point, 11.6 km south of India Point.

Table 1.1 Wet weather program principal investigators and study elements.

| Principal Investigator(s) | Organization | Study Focus |
|---|---|---|
| R. Wright and L. Thiem | URI, Civil and Environment Eng. | Tributary Sampling, Metals and Nutrient Analyses |
| J.G. Quinn | URI, Graduate School of Oceanography | Organic Analyses |
| W.O. Watkins and S.R. Rippey | Food & Drug Admin. North Kingstown, RI | Microbiological Analyses |

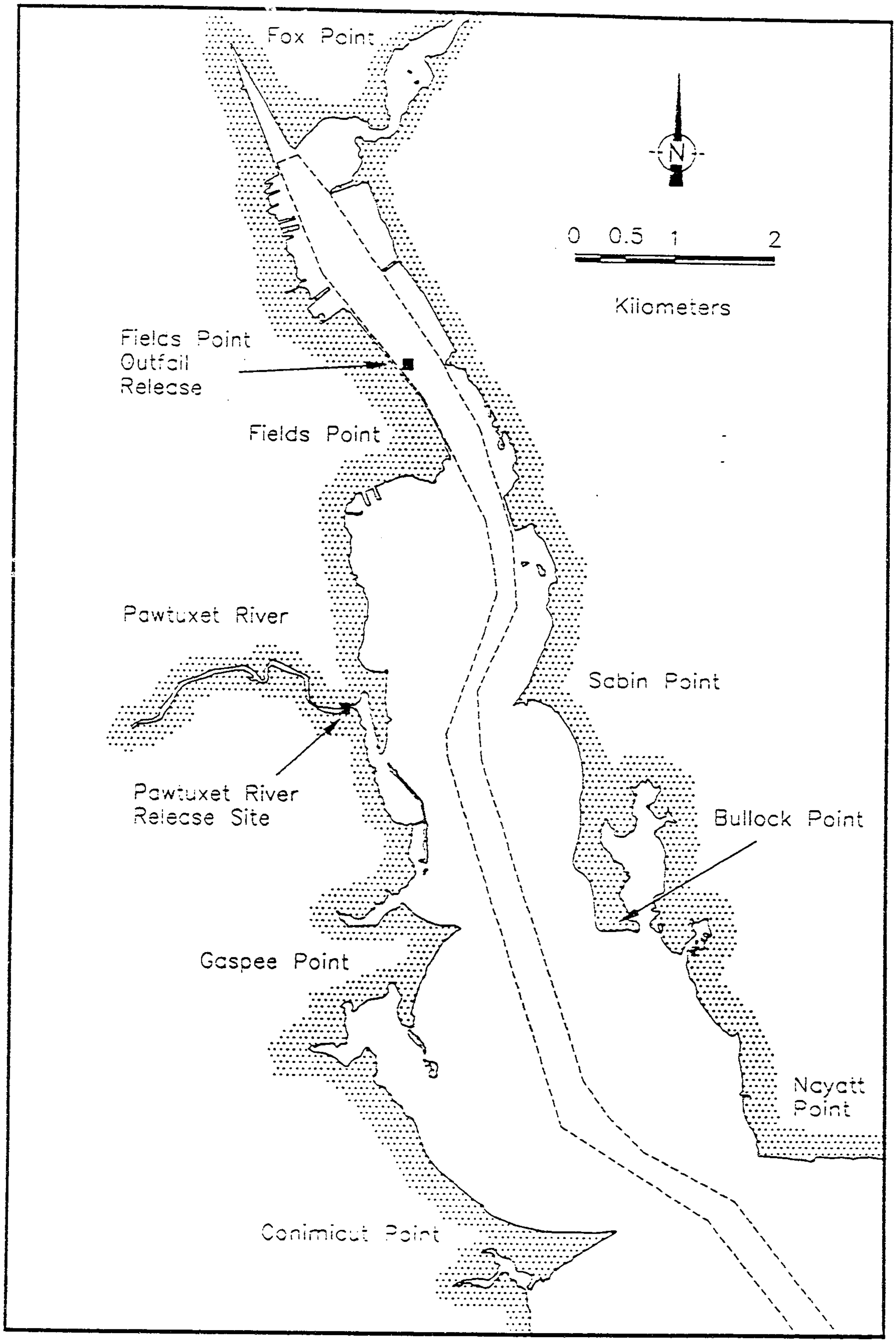


Figure 1.1 The Providence River study area

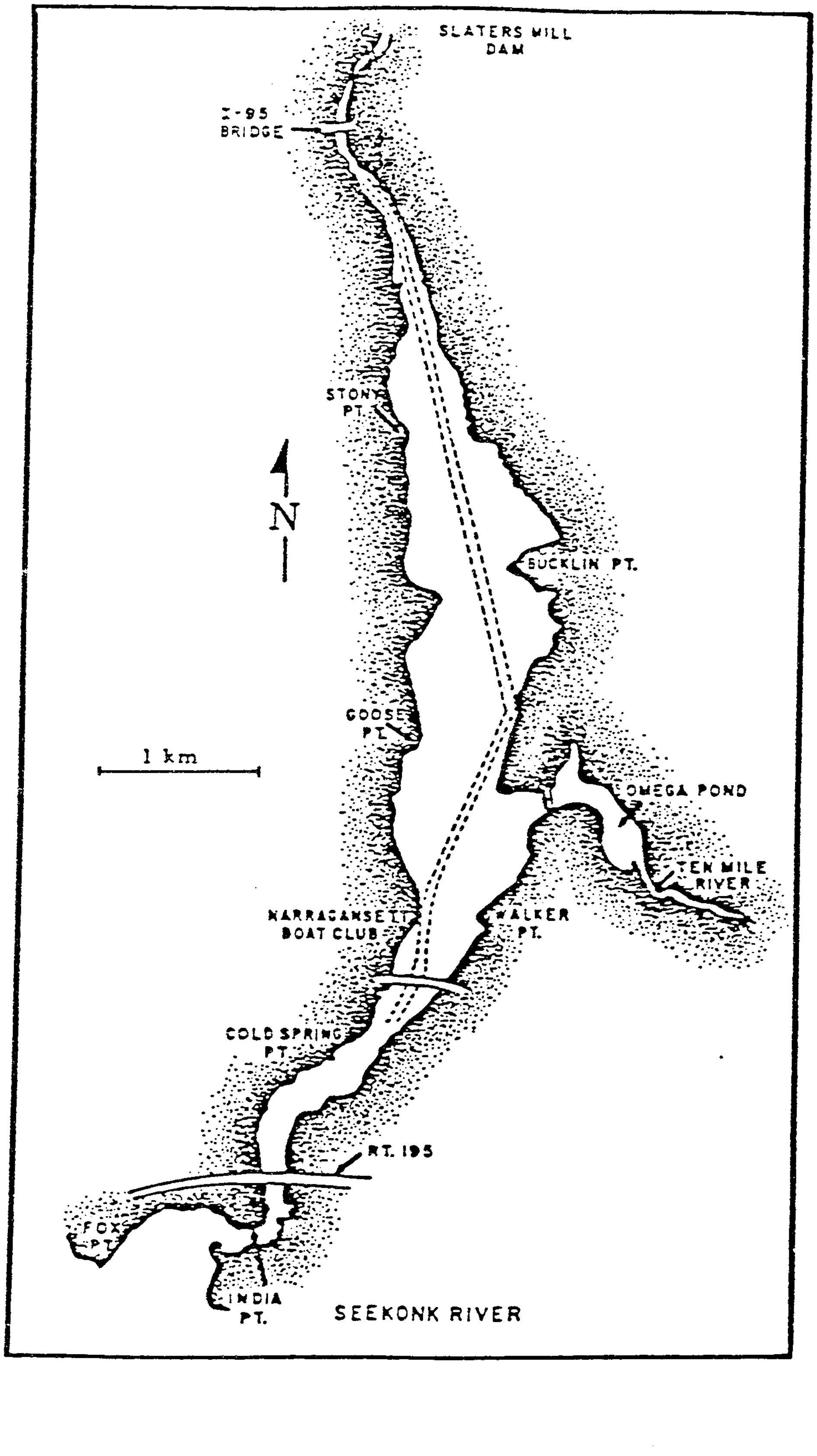


Figure 1.2 The Seekonk River study area

A navigation channel runs from the mouth of the Providence River to India Point (Figure 1.1). The channel depth is 12.2 m at Mean Low Water (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 to accommodate shipping traffic. At MLW, the surface area of the Providence River south of India Point to Conimicut Points is 21.32 $km^2$, with a volume of 8.51 x $10^7$ $m^3$ and a mean depth of 4 m (Chinman and Nixon, 1985).

Tributary flow to the study area is 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 Pawtuxet River, 9.7 $m^3/s$ (Gadoury et al., 1988). Other point inflows of freshwater 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.

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 100 to 400 m wide over much of its length. The central section from Walker to Bishop Point, however, is 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 being exposed at MLW. 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 x $10^6$ $m^3$ and the mean MLW depth is 1.29 m (Chinman and Nixon, 1985).

The circulation in the study area was characterized as part of the NBP-funded Wet Weather Study Program (Turner et al., 1989). Five current meters were deployed at three stations in the study area. Two meters were placed at the 1 m and 5 m depths between Gaspee and Bullock Point. Two meters were placed at the 1 m and 6 m depths at the south end of Fields Point. The fifth meter was placed at the 1 to 2 m depth near Cold Spring Point in the Seekonk River. The surface (1 m depth) meters were located in the fresher surface waters where the direction of net flow was down-estuary. The bottom (5-6 m depth) meters were positioned in the relatively saline bottom waters of the estuary where the net flow was up-estuary. The location of the Seekonk River instrument relative to the freshwater-saltwater interface varied with Blackstone River flow. The deployments spanned the three wet weather dye surveys discussed in this study: September 17 - November 7, 1988; April 21 - June 1, 1989; June 8 - June 16, 1989. The study found that the circulation of the Providence and Seekonk Rivers is dominated by tidal forcing at time periods shorter than a day. The strength of tidal currents was found to vary considerably with the measurement location. Tidal currents were 16 cm/s in the Gaspee-Bullock Point transect, 10 cm/s near Fields Point and 23 cm/s in the Seekonk River. Longer term variations in the net motion of water in the area were found to be dominated by the density-induced mean flow, particularly near the surface. The surface current vector was found to have a strong down-estuary mean, relative to tidal oscillations. Mean currents at the Gaspee-Bullock transect surface location were 2.2 - 4.5 cm/s in the down-estuary direction, and 3 cm/s up-estuary at the bottom. Mean currents at Fields Point were 1.8 - 3.3 cm/s down-estuary at the surface, and about 1 cm/s up-estuary at the bottom. The direction of flow near the bottom in the Seekonk River was found to vary with freshwater inflow from the Blackstone River. Mean bottom currents were 1.4 - 2.0 cm/s up-estuary during two periods of low Blackstone River flow, and 3.1 cm/s down-estuary during a period of high Blackstone River flow.

## 2. STUDY OBJECTIVES

The suite of pollutants evaluated by the NBP Wet Weather Program was fairly lengthy. It included five categories of parameters: metals, nutrients, microbiological indicators, organic and miscellaneous parameters. A listing of the parameters by category is presented in Table 2.1. As discussed in Section 3 below, the program involved continuous sampling at 3 to 12 hours intervals for a three to five day period. A list of analyses performed on samples collected is presented in Table 2.1. In order to reduce the cost of the program, the number of samples was reduced.

The principal objective of this study was to determine the spatial and temporal characteristics of pollutants discharged into the Providence and Seekonk Rivers during the study storms through a series of dye releases. The use of dye as a substitute for pollutant indicators offers a number of advantages. First, dye concentrations can be measured in the field and results determined immediately. The cost associated with the measurements is relatively low when compared with the costs of performing each of the analyses in Table 2.1. The ability to measure *in-situ*, combined with the low cost makes it possible to make a significantly greater number of measurements, thus allowing the spatial distribution of the dye to be better resolved. Since dye readings are obtained directly in the field, the measurement locations can be adjusted to follow the dye field. Finally, the dye selected for the experiments is conservative in the environment at least for the period of the surveys. The dye measurements then provide a picture of the behavior of a conservative parameter present in the study area during the wet weather study.

The dye experiment therefore allows an improved resolution of the behavior of pollutants in the study area. The use of dye also permits the behavior of a conservative constituent to be described. These features provided by the dye experiment are advantageous from the perspective of water quality model development. They provide a greater number of observations to which a model can be calibrated and verified. The constituent mass equation may also be balanced for the case of no decay in each model element.

The second objective of the study was to collect information on other parameters during the surveys, specifically the distributions of salinity and dissolved oxygen. These parameters were collected to characterize the hydrography and oxygen levels in the river and to provide additional information for the calibration and verification of models for the area.

Table 2.1 Pollutant parameters to be measured by the Wet Weather Study Program.

| | |
|---|---|
| <u>Metals</u> | |
| Cadmium: | dissolved and particulate |
| Chromium: | dissolved and particulate |
| Copper: | dissolved and particulate |
| Lead: | dissolved and particulate |
| Nickel: | dissolved and particulate |
| <u>Nutrients</u> | |
| Ammonia: | filtered |
| Nitrate: | filtered |
| Ortho-phosphorus: | filtered |
| Total Kjeldahl Nitrogen | |
| Total Phosphorus | |
| <u>Organic Indicators</u> (to be measured for tributaries and point sources only) | |
| Suspended solid | |
| Polychlorinated biphenyl (PCB's) | |
| DDT, DDD, DDE | |
| Petroleum hydrocarbons (total saturated) | |
| Polycyclic aromatic hydrocarbons (PAH's) | |
| Substituted benzotriazoles | |
| Phthalic acid esters | |
| Coprostanol | |
| <u>Microbiological Indicators</u> | |
| Fecal coliforms | |
| Escherichia coli | |
| Enterococci | |
| Clostridium perfringens spores | |
| F male-specific bacteriophage | |
| <u>Other Parameters</u> | |
| Effluent toxicities | |
| Total suspended solids | |
| Biochemical oxygen demand | |

This report describes the methods and results of the study. It outlines the procedures followed in making the measurements and describes problems encountered. A series of graphics and tables are presented in the report and its appendices to facilitate interpretation of the results by other researchers. The data collected during the study are listed in Appendices I-K to this report and will be submitted in magnetic form to the Narragansett Bay Project.

## 3. FIELD METHODS

### 3.1 Overview

The study consisted of three dye release and measurement experiments. As planned, each survey was to begin a few hours before the start of a period of rain where the expected accumulation of rain would be at least 0.5 inches. Dye was released from four locations in the study area over a four hour period. The releases were started after runoff related to the storm, combined with untreated sewage, would begin to bypass the treatment facility at Fields Point, the largest point source in the area. The dye surveys started with the background measurement before the start of the storm. After the start of the storm, surveys were made at three hour intervals, for the first 15-24 hours, then every six hours until the end of the study.

### 3.2 Dye Release Methods

The dye tracer selected for the study was Rhodamine WT, available in a 20% solution by weight. Rhodamine WT was chosen for use because it can be considered to be conservative over the five day study period and is relatively non-toxic (Rantz et al., 1982). Rhodamine WT is also not affected by the presence of free chlorine at the levels expected in effluent from chlorine contact tanks, in the range of 1-10 mg/l (Deaner, 1973).

The four largest point sources of metals to the Providence-Seekonk River were selected as dye release sites. The sites chosen were the Fields Point outfall for the Narragansett Bay Commission Sewage Treatment Plant, the Blackstone Valley District Commission (BVDC) Sewage Treatment Plant outfall, the Blackstone River at Slaters Mill dam in Pawtucket, and the Pawtuxet River.

The dye pump discharge release at Fields Point was made at a point downstream of the weir spillway of the chlorine contact tank. The dye release at the BVDC plant was similarly made into the chlorine contact tank effluent line.

The release of dye was more difficult to accomplish at the Blackstone and Pawtuxet River sites. In its undiluted form, the 20% Rhodamine WT solution has a specific gravity of 1.2. If it is not discharged into waters having sufficient turbulence, the dye sinks to the bottom instead of mixing and being downstream. The Blackstone and Slaters Mill releases were designed, therefore, to avoid this problem. At the Blackstone River site, the dye was released, 1 m upstream of the bank and 1 m from the spillway. At the Pawtuxet River site, the dye pump was located in the basement of a building at the north side of the river immediately downstream of the Broad Street Bridge in Pawtuxet, Rhode Island. The dye discharge line was suspended along the pole out over the stream to a point 3 m from the bank where the dye was released into the river at a point where river flow is channeled under an arch of the Broad Street Bridge. Surface currents during a dry weather period before the first storm were found to be between 51-77 cm/s, sufficient to mix the dye.

Before each experiment, the desired release rate for each pump was determined and the pump was calibrated. The verification of pump flow rate was made by measuring the volume of water discharged by the pump over a known time period. Actual release volumes were checked either by weighing the dye containers before and after the releases, or by measuring out a known quantity of dye into a container and allowing the container to be pumped dry. Actual release volumes are presented in Section 4.1.

The design release rate at each site was determined using a time-dependent model (Swanson and Jayko, 1988) which had previously been applied to predict the impacts of coliform loadings from CSO Area C on the Seekonk River, Providence River and Upper Bay area. Four releases of equal strength (100 kg/s) were made into the elements of the model domain corresponding to the four actual release sites. The simulated releases were made for a period of four hours. The loadings were found to produce a peak constituent concentration of approximately 100 ppm in the Fields Point area. Because the response of constituent concentration to loading rate is virtually linear, the combined release rate from the four sources in the model could be scaled for the actual release. By scaling the release rate down by a factor of $5 \times 10^5$, a volume-averaged concentration of 0.2 ppb would be expected for the area. The combined discharge rate for the sources was estimated based on this approach. Since the Fields Point outfall emits approximately four times as much copper per year as the other sources, 50-60% of the total release of dye was made from Fields Point and 14-17% from each of the other sites.

## 3.3 In-situ Measurement Methods

### 3.3.1. Dye Measurements

The dye concentration measurements were made using a Turner Designs Model 10-005R fluorometer equipped with a continuous flowthrough cuvette. The fluorometer measures the fluorescence of water pumped from depth through the cuvette by a 12 v submersible pump. The temperature correction for fluorescence is measured by an in-line thermistor. The analog output of the fluorometer is sampled and digitized by a Campbell Scientific Model CR-10 data logger. The data logger in turn sends the digitized fluorometer and thermistar output to a laptop personal computer (PC). The PC stores the fluorometer reading, sensitivity range and the in-line temperature and stores the data on diskette along with a date/time mark, LORAN-C position and operator's comments. The raw data are displayed to the operator in the field. The raw data are later converted to concentration form after the completion of each survey using calibration data.

The response of the fluorometer was checked before the first (October, 1988) and second (May, 1989) surveys. The calibration check was not performed prior to the third survey since it was so close in time to the second survey. A set of 13 dye standards was prepared for each response check, using aliquots of the dye to be used for the release. The standard included 12 dilutions of the original dye at strengths between 0.05 ppb and 50 ppb, and one blank. A linear regression between fluorescence and dye concentration was calculated for each range and multiplier setting, producing a slope and y-intercept for each combination.

Typical regression lines calculated from the April 1989 calibration are shown in Figures 3.1 and 3.2, for the two most sensitive ranges of the fluorometer. The mean error of the estimate, in the figures are 0.004 and 0.05 ppb respectively. The mean error for the most sensitive (31.6x) range of the fluorometers used, was less than 0.01 ppb in all cases, and less than 0.1 ppb for the second most sensitive (10x) range. These errors correspond to measurements ranging between 0-0.25 ppb (31x scale) and 0.2-0.08 ppb (10x scale).

Dye fluorescence data obtained during the study were processed in the following manner. The fluorescence data were corrected for the temperature effect on fluorescence using the following equation

$$F_{ref} = F_{obs} \cdot \exp [0.026 \cdot (T_{obs} - T_{ref})] \qquad (3.1)$$

where $F_{ref}$ is the temperature compensated fluorescence (ppb),

$F_{obs}$, $T_{obs}$ are fluorescence (ppb) and temperature (°C) measured in the field,

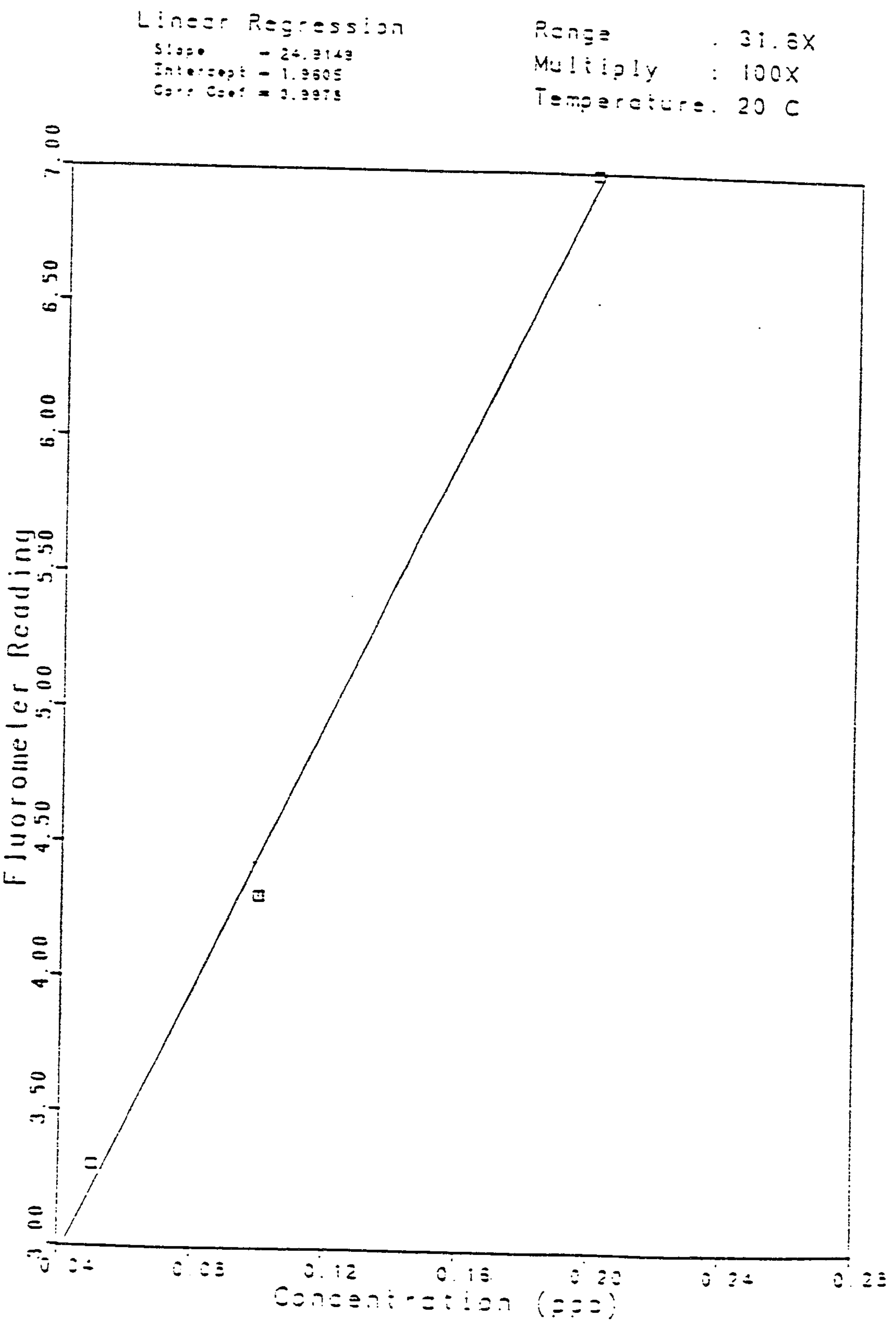


Figure 3.1 Fluorometer calibration line vs. standard concentrations on the 31.6x scale

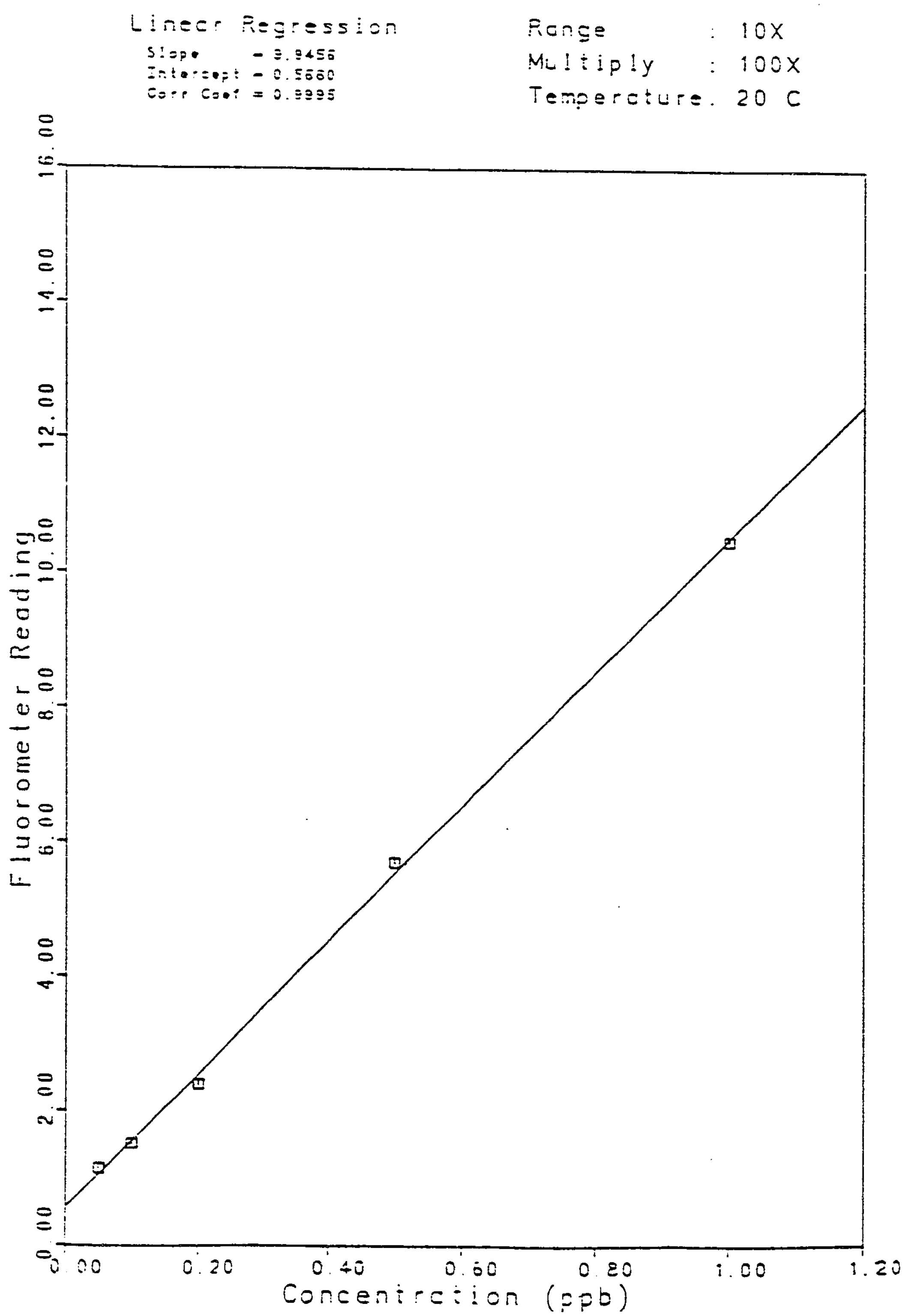


Figure 3.2 Fluorometer calibration line vs. standard concentration on the 10x scale

$T_{ref}$ is the temperature (°C) at which the fluorometer calibration was performed.

The fluorescence, $F_{ref}$, was next converted to dye concentration in units of ppb C, with an equation of the form

$$C = m \cdot F_{ref} + C_0 \tag{3.2}$$

where m is the slope of the regression curve at the appropriate sensitivity range, and $C_0$ is the y-intercept.

The influence of ambient fluorescence in the water column on the post-release measurements was determined through background measurements conducted before the start of each storm. Measurements were made at the 1, 3, 6 and 10 m depths at as many of the stations as possible and at the Fields Point outfall before the onset of the storm. The fluorescence and temperature data were later converted to equivalent dye concentration units using the regression equations and temperature corrections.

Background fluorescence was found to vary principally with depth, with values near the surface. Means and standard deviations of the background data for each depth are given in Table 3.1. The tables show background fluorescence ranging from 0.02-0.07 ppb at 1 m to less than 0.01 ppb below 3 m during the April and June studies and below 6 m during the October study. No longitudinal trends in background levels was evident. Background levels in the Fields Point outfall boil were not higher than those seen elsewhere in the area.

The principal means of positioning control used during the surveys was LORAN-C. A Furuno Model LC-90 LORAN-C was used for the measurements. The FURUNO has an NMEA 0180/0183 format output which is directly readable by the onboard PC. The data from the fluorometer could therefore be recorded along with concurrent longitude and latitude information by the PC.

Because the study area is located inland, the absolute accuracy of the LORAN-C data is affected by phase delays caused by the adjacent land mass, land-water interfaces and the presence of tall buildings and bridges. This transmission-path delay effect was found to offset the LORAN-C data for the study area by about 550 m. The repeatable accuracy of the LORAN-C was quite good over the study area however. A good repeatable accuracy means that if the boat were taken to the same location several times during the study, the position reported by the LORAN would be virtually

Table 3.1 Means and standard deviations of background survey measurements

| Date | | Background Concentration (ppb) | |
|---|---|---|---|
| | | Mean | Standard Dev. |
| October 1989 | 1 | .07 | .04 |
| | 3 | .04 | ____* |
| | 6 | .03 | .01 |
| | 10 | .01* | ____* |
| May 1989 | 1 | .06 | .03 |
| | 3 | .02 | <.01 |
| | 6 | <.01 | <.01 |
| | 10 | <.01 | <.01 |
| June 1989 | 1 | .02 | .01 |
| | 3 | .01 | .01 |
| | 6 | <.01 | <.01 |
| | 10 | <.01 | <.01 |

* only two samples

constant for each fix. This exercise was conducted over a three day period at a location near Fields Point during the first study. The mean observed error in the readings made at six hour intervals over the three day period was found to be 31 m. Since the offset error was uniform over the period of the measurements, and was constant over the study area, the LORAN-C data could be corrected by applying constant latitude and longitude corrections. The corrections were determined by obtaining a LORAN-C fix at a location of known latitude and longitude, determined from a chart. This offset was then applied to the raw LORAN-C readings. The accuracy of the data could then be assumed on the order of 30 m, which is consistent with published differential LORAN-C accuracies of ± 20 m for the coastal United States (Tetra Tech, 1987).

### 3.3.2 Hydrographic Measurements

Other parameters pertinent to the study included the salinity, temperature and dissolved oxygen fields. The salinity and temperature measurements were made with an Applied Microsystems, Ltd Model STD-12 instrument. The STD-12 is a small, self-contained profiler designed for measurements of conductivity, temperature, pressure, and time. The instrument has an internal microprocessor which can be set to sample either on a time step or a pressure (depth) change basis. The data are then stored internally for subsequent offloading. The data is transferred to the PC in the field. At the time of offloading, the conductivity and temperature data are converted to salinity (ppt) and density ($\sigma_t$) by the internal microprocessor using algorithms given in Perkin and Lewis (1980) and calibration coefficients.

Dissolved oxygen measurements were made with a Yellow Springs Instruments Model YSI-57 instrument. YSI was air calibrated at the start of each survey. The dissolved oxygen data were corrected for temperature and salinity effects during post-processing.

## 3.4 Execution of the Field Measurements.

The study area showing station locations are presented in Figures 3.3 and 3.4 for the Providence and Seekonk Rivers. The Providence River stations are the same as those occupied during the NBP SPRAY study (Doering et al., 1988). The Seekonk River stations corresponded to those used by the Rhode Island Department of Environmental Management (RIDEM) Division of Water Resources (J. Migliore, personal communication) for periodic monitoring in the Seekonk River.

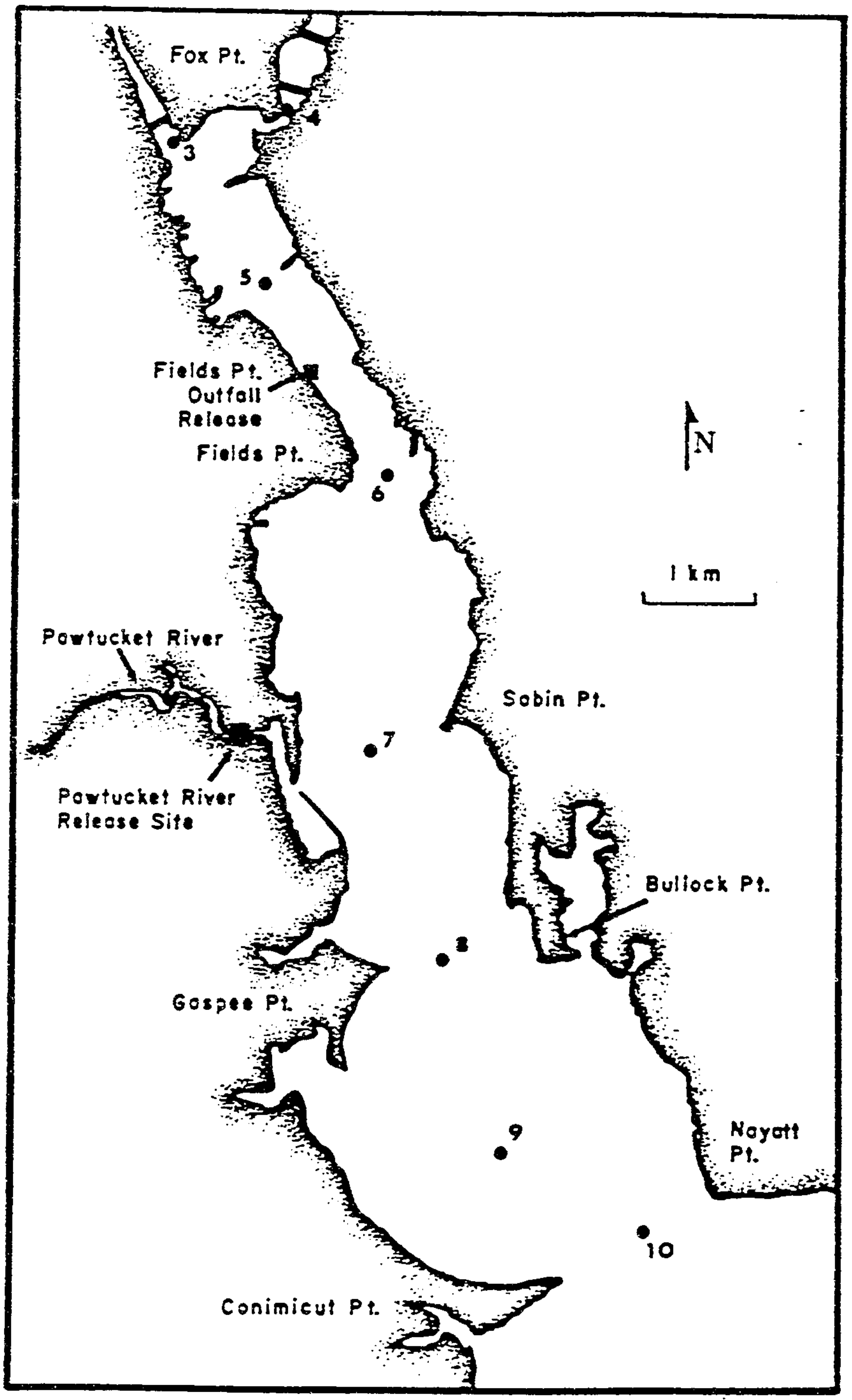


Figure 3.3 Sampling station locations in the Providence River

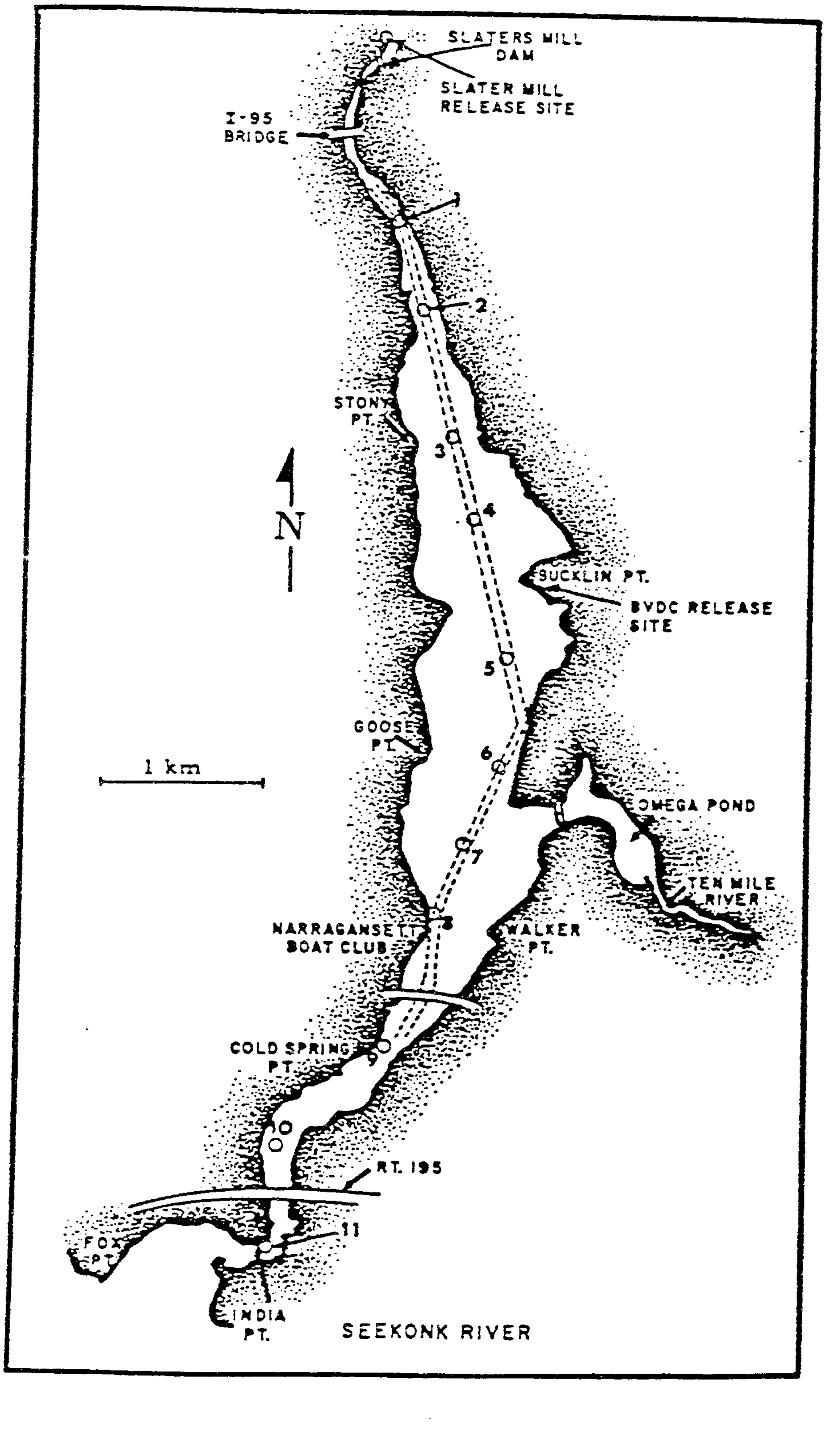


Figure 3.4 Sampling station locations in the Seekonk River

The joint NBP-NBC wet weather study program was to be conducted during three storms. As conceived by the NBP, the storms would have different total accumulations: 0.6 - 1.7 cm, 1.7 - 2.8 cm, and greater than 2.8 cm. It was hoped that the storms would be of at least a five hour duration and be preceded by a dry period minimum of at least three days. The expectations of the NBC were slightly different: the storms would have 1.3 cm minimum accumulation, a minimum duration of five hours, and be preceded by a five day dry period.

The field study protocol was developed with the above conditions in mind. The decision to proceed with an experiment was made 6-12 hours before the start of the rain. This allowed a three hour period for crews to be notified, equipment to be assembled and tested, and time for the ASA boat to be brought into the study area. A dye and hydrographic survey was then conducted at the stations before the storm.

The purpose of the dye release was to simulate the release of metals, nutrients and bacterial loadings by the large point sources during the studies. The dye release therefore was not expected to start until 2-4 hours after the start of the storm, when untreated sewerage and CSO discharges to the area would be approaching their peak values. It was assumed that this condition could be concurrent with the start of the secondary bypass flow at the NBC Fields Point sewage treatment plant. The dye releases lasted for four hours.

The dye and hydrographic measurements during the 14 hours after the start of the dye releases concentrated on measuring the near-field dye plumes from each source. This task required the use of two boats: an ASA team on board R/V *Julianne* in the Providence River and a DEM team in the Seekonk River. From the start of the releases to 6-10 hours after the release, measurements were made at 3 hour intervals by both teams. The Providence River team would make measurements along the axis of the plume at 1, 3, 6 and 10 m depths, and one to four lateral transects. The DEM team in the Seekonk River made near-surface and near-bottom dye measurements at the 11 DEM stations in the Seekonk River. Hydrographic measurements were to be made at stations 4, 6, and 8 by the ASA team as time allowed.

Between 14-24 hours after the start of the study, the Providence River team shifted to a six-hour coverage of its assigned area. When possible, the measurements were centered on the times of high and low tide. During this time, measurements were made in transects at stations 4, 6, and 8 at depths of 1, 3, 6 and 10 m. Additional measurements were made through any dye patches or "hot spots" remaining near the surface. The Seekonk River crew continued as before, sampling at the 11 stations in the Seekonk River at three hour intervals. At the end of the first 24 hour period, the Seekonk River surveys were ended.

Between 30 hours after the start of the study and the end, the dye and hydrographic surveys continued at six hour intervals, centered around high and low slack water. Dye surveys were made in the transects at stations 4, 5, 6, 8 and 10, accompanied by hydrographic measurements at the center of each transects. An additional measurement was to be made along the center of the channel at stations 7 and 9.

# 4. EXPERIMENTAL RESULTS

## 4.1 Study Narratives

### 4.1.1. October 21-26, 1988 Survey

The first wet weather study began during the afternoon of October 21, 1988. The storm was a characteristic "Nor'easter". During the approach of the storm on the evening of October 21, winds came from the ENE, increasing from 5.7 m/s at 1900 to 17 kt, gusting to 11.3 m/s by midnight (National Weather Service, 1989). On the morning of October 22, winds shifted to the E-ESE at 0.3-11.3 m/s gusting to 21 m/s. The impact of the storm on Narragansett Bay was quite dramatic, particularly on its lower Narragansett Bay when East to west fetches are greater. The winds were accompanied by a surge which peaked at 0430 EST on the morning of October 22, (NOS, 1989) shortly before the time of the astronomical high tide at 0457. The peak height was 1.66 m above MSL, 0.97 m above MHW, and 0.4 m above the predicted high tide (NOS, 1989).

The storm proved to be a significant obstacle to the progress of the study during its first 24 hours. The boat used by DEM in the Seekonk River was moored in Wickford at the southern end of the bay. This boat was turned back on the evening of October 21 by mechanical problems. A second attempt was made on October 22, however, the wind and wave conditions in the lower bay prevented it from transiting to the study area. Consequently, no measurements were made in the Seekonk River during the first study. In spite of the winds, the Providence River team was able to complete the background surveys during the evening of October 21 (2046-2218).

After arriving in the study area, the Providence River team found that the STD-12 profiler would not operate. Attempts made through the early morning of October 22 to power up the instrument proved fruitless. As a result, no salinity data were obtained for the October study.

The time history of rainfall intensity during the experiment is presented in Figure 4.1. Fluxes of lead from the four point sources (Wright et al., 1989): the Blackstone River, BVDC, NBC (Fields Point) and the Pawtuxet River are also show in the figure to illustrate how the dye fluxes coincided with metals fluxes. Total lead has been arbitrarily selected for the comparison. The steady rainfall began before midnight on October 21, 1988. Dye releases were started between 0040-0125 on October 22 and stopped between 0445-0530. An attempt was made by the Providence River team to begin dye surveys at 0130, and some measurements were made at the relatively

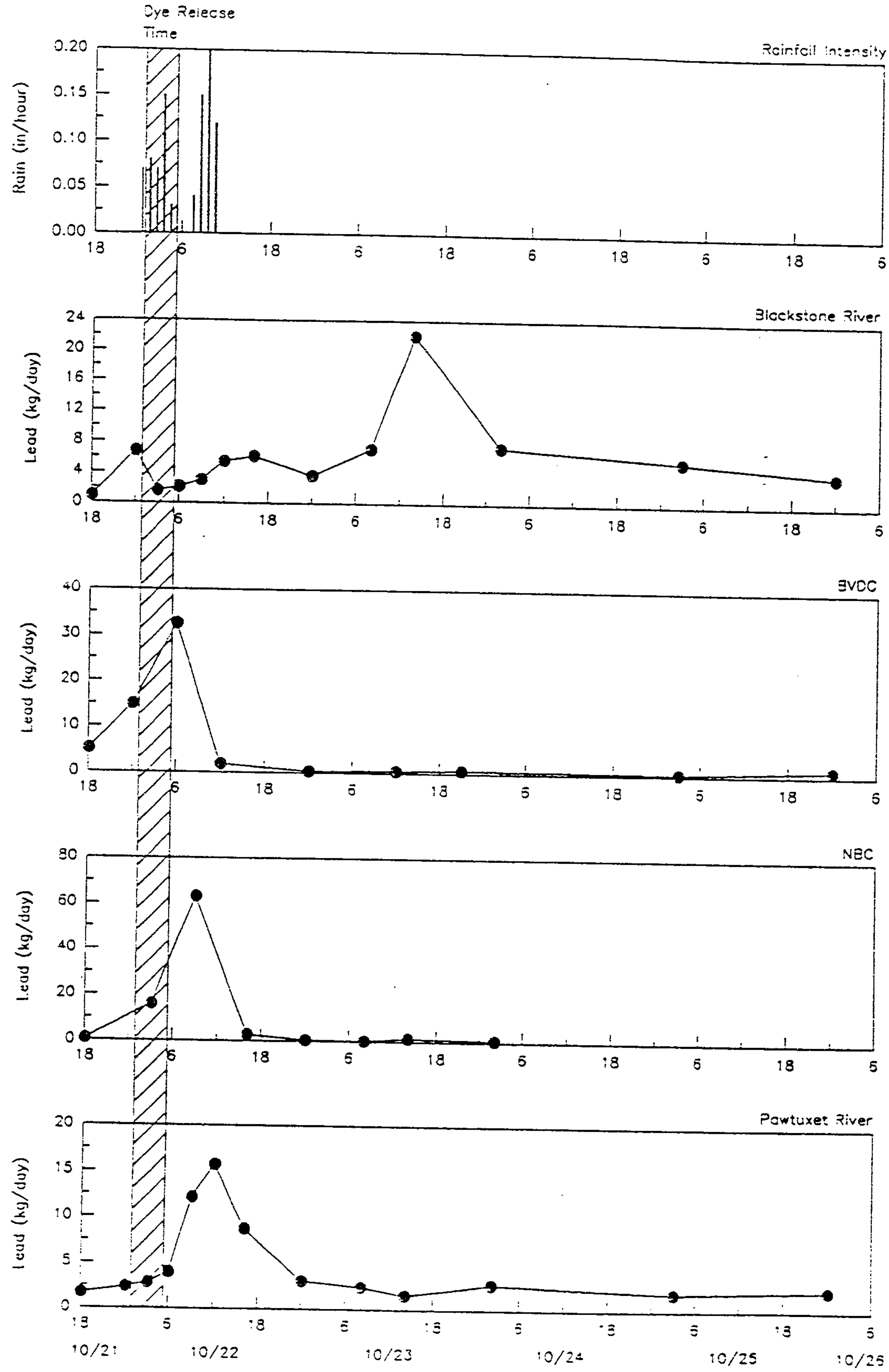


Figure 4.1 Time history of rainfall intensity in the area (and lead fluxes from the four point sources) on October 22, 1988 (from Wright et al., 1990)

sheltered station 4. Measurements at the other stations were not made due to safety considerations and storm related equipment damage until the winds abated.

The timetable for the surveys is shown in Table 4.1. The timing of the surveys relative to state of the tide is shown in Figure 4.2. Regular measurements in the study area began at 1054 on October 22, 10.2 hours after the start of the release. Because the dye releases had ended some five hours earlier, the measurements were focussed on measuring the time rate of change of dye concentrations in the station transects. After measurement number 5 which was begun 20.8 hours after the start of the dye release, the measurement period was increased to six hours.

The dye and survey measurements continued until 1032 on the morning of October 26, about 106 hours after the start of the dye releases. Two interruptions occurred in the measurements, between surveys 5 and 6 and between surveys 11 and 12. The interruptions were a result of engine or steering failures on the ASA boat.

#### 4.1.2. Experiment #2: May 10-15, 1989

The second dye experiment began on the morning of May 10, 1989. The environmental conditions of the second survey were significantly different from those of the first study. Winds were light throughout the period of the experiment, and no significant tidal surge accompanied the storm. Fresh water inflows to the area were significantly greater during May 10-15 and the 2.47 in rainfall accumulation was significantly higher than the 0.72 in accumulation during the first experiment (Wright et al., in preparation). For example, Blackstone flow at the Slaters Mill Dam was in excess of 28 $m^3/s$ prior to the storm on May 10, while its pre-storm value on October 21, 1988 had been approximately 4 $m^3/s$.

A summary of rainfall intensity flow during the second experiment is shown in Figure 4.3, along with dye and lead fluxes from the point sources. Rainfall was light (0.5 mm/hr) until 1000 on May 10, when it increased to 1.3-1.8 mm/hr. Rainfall intensity then increased to between 3-5 mm/hr through the night and abated after 0700 on the morning of May 11. A second period of rainfall accompanied by locally-intense thunderstorms began at around 2300 on May 11 and continued until 0300 on May 12.

Table 4.1 Timetable for the October 21-26, 1988 Providence River Surveys.

| Measurement Number | Start Time | End Time | Hours After Start of Releases |
|---|---|---|---|
| Background | 2046 | 2218, 10/21/88 | --- |
| 1 | 0152 | 0154 10/22/88 | 1.2 |
| 2 | 1054 | 1238 10/22/88 | 10.2 |
| 3 | 1452 | 1645 10/22/88 | 14.2 |
| 4 | 1836 | 1949 10/22/88 | 17.9 |
| 5 | 2127, 10/21/83 | 0008 10/23/88 | 20.8 |
| 6 | 1435 | 1645 10/23/88 | 37.9 |
| 7 | 1713 | 2117 10/23/88 | 40.6 |
| 8 | 0000 | 0320 10/24/88 | 47.3 |
| 9 | 0718 | 0953 10/24/88 | 54.6 |
| 10 | 1320 | 1845 10/24/88 | 60.7 |
| 11 | 1946, 10/24/88 | 0022 10/25/88 | 67.1 |
| 12 | 1200 | 1326 10/25/88 | 83.3 |
| 13 | 1508 | 1726 10/25/88 | 86.5 |
| 14 | 1832 | 2205 10/25/88 | 89.9 |
| 15 | 0030 | 0318 10/26/88 | 95.8 |
| 16 | 0745 | 1032 10/26/88 | 105.9 |

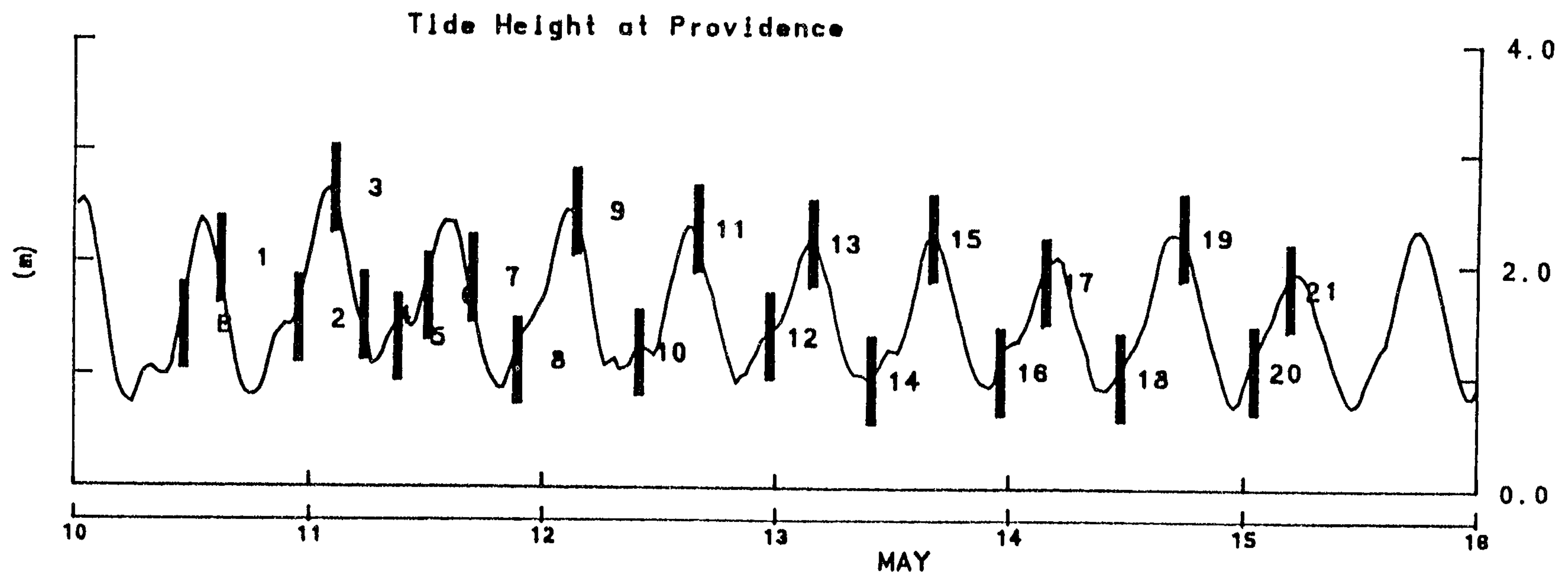


Figure 4.2 Experiment #1 (October 21-26, 1988): timing of surveys relative to tide height in Providence

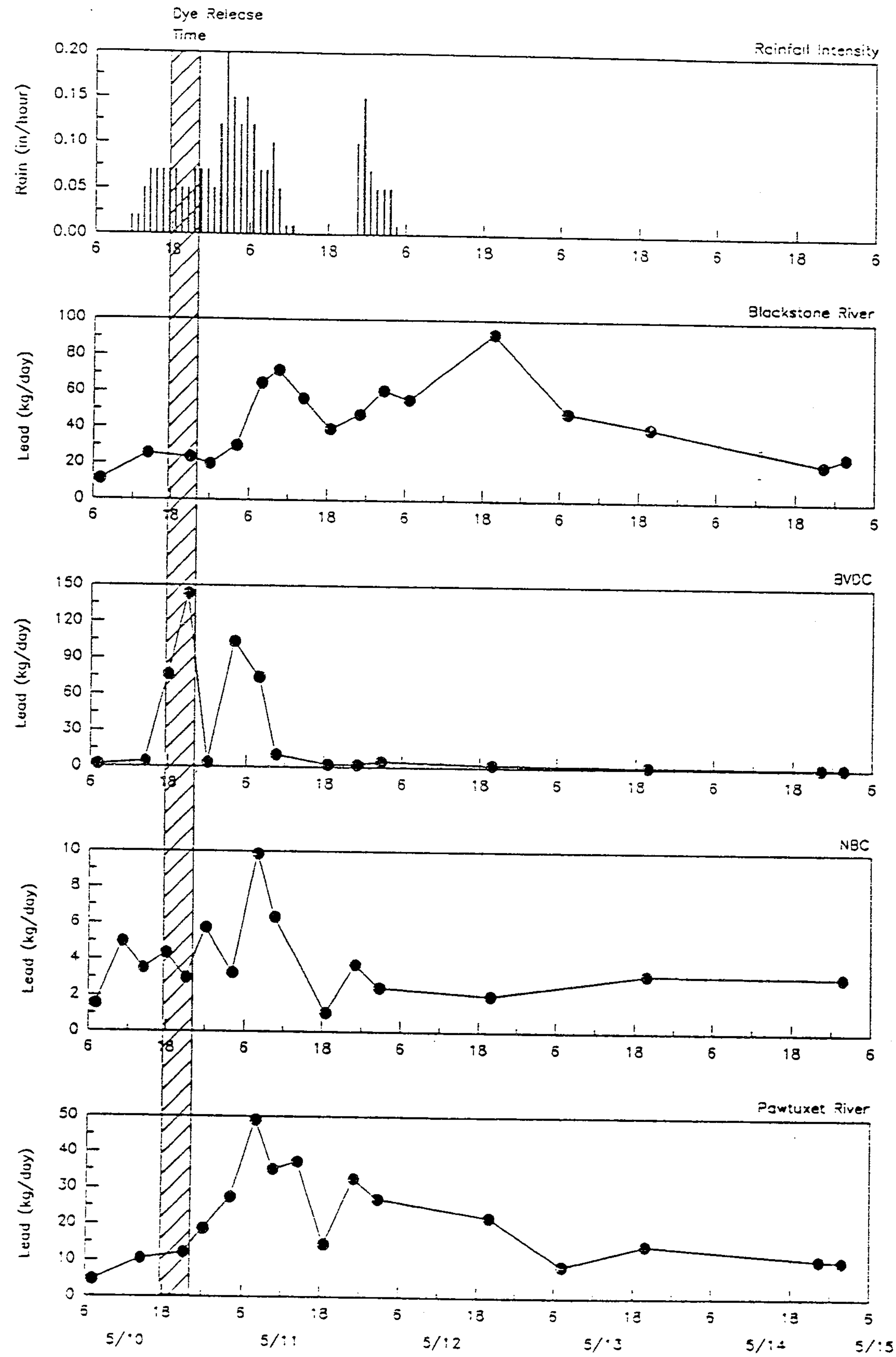


Figure 4.3 Time history of rainfall intensity in the area (and lead fluxes from the four point sources) between May 10-12, 1989 (from Wright et al., 1990)

The ASA Providence River team arrived in the study area at 0830 on May 10 and conducted the background survey between 0858-1129. The dye releases were started between 1750-1806 in the evening of May 10 and ended without incident between 2150 and 2215.

The time of surveys in the Providence River is shown in Table 4.2. The timing of the surveys relative to the state of the tide is shown in Figure 4.4. The dye field measurements began on 1824, May 10, shortly after the start of the releases. The study schedule was interrupted somewhat on the night of May 11 (survey #8) and in the early morning of May 14 (survey #17) by fog and rain. In both cases, visibility dropped to below 250 m. Navigation was possible only with the use of radar, and shipping traffic was present in the river. In both cases, the decision was made to discontinue the surveys of the lower Providence River for safety reasons.

The dye surveys were discontinued after survey #11 on May 12 because the dye was no longer detectable in the area. The dissolved oxygen and salinity surveys continued until 0300 on May 15, approximately 106 hours after the start of the dye releases.

The Seekonk River measurements were also successful. The measurement schedule is presented in Table 4.3. Background measurements were made during the early afternoon of May 10. The surveys began at 1803, a few minutes after the start of the release at Slaters Mill dam and continued at intervals of roughly 2.5 hours until 1730 on May 11.

### 4.1.3. Experiment #3: June 13-16, 1989

The third storm began in the early morning of June 13, 1989. In terms of total rainfall (0.68 in) (Wright et al., in preparation) and winds (less than 10 kts), this storm was mild in comparison to the first two storms. A time history of rainfall intensity in the area is shown in Figure 4.5, along with dye and lead fluxes from the point sources. Light rain began falling at 0400 in the area (National Weather Survey, 1989). The rain became heavy (3 mm/hr) at around 0900, tapering off around 1400. The dye releases were started at 1100 and ended at 1500. By the late afternoon and early evening, the rain had ended, but returned late on June 14, persisting through the 15th. The rain was accompanied by intense thunderstorms which moved quickly through the area during the late evening (2200-2400) on June 15. Winds were from the east to northeast, generally at speeds less than 10 kt through the study period.

Table 4.2 Timetable for the Providence River Surveys, May 10-15, 1989.

| Measurement Number | Start Time | End Time | Hours After Start of Releases |
|---|---|---|---|
| Background | 0858 | 1129, 5/10/89 | -- |
| 1 | 1824 | 1931, 5/10/89 | 0.6 |
| 2 | 2109 | 2240, 5/10/89 | 3.3 |
| 3 | 0035 | 0240, 5/11/89 | 6.7 |
| 4 | 0400 | 0523, 5/11/89 | 10.2 |
| 5 | 0713 | 0910, 5/11/89 | 13.4 |
| 6 | 1030 | 1205, 5/11/89 | 16.7 |
| 7 | 1510 | 1635, 5/11/89 | 21.3 |
| 8 | 1947 | 2112, 5/11/89 | 26.0 |
| 9 | 0125 | 0340, 5/12/89 | 31.6 |
| 10 | 0752 | 1008, 5/12/89 | 38.0 |
| 11 | 1400 | 1602, 5/12/89 | 44.2 |
| 12 | 2125 | 1210, 5/12/89 | 51.6 |
| 13 | 0208 | 0327, 5/13/89 | 56.3 |
| 14 | 0800 | 0938, 5/13/89 | 62.2 |
| 15 | 1420 | 1604, 5/13/89 | 68.5 |
| 16 | 2225 | 2355, 5/13/89 | 76.6 |
| 17 | 0205 | 0329, 5/14/89 | 80.3 |
| 18 | 0944 | 1116, 5/14/89 | 87.9 |
| 19 | 1606 | 1742, 5/14/89 | 94.3 |
| 20 | 2311, 5/14/89 | 0100, 5/15/89 | 101.4 |
| 21 | 0300 | 0436, 5/15/89 | 105.2 |

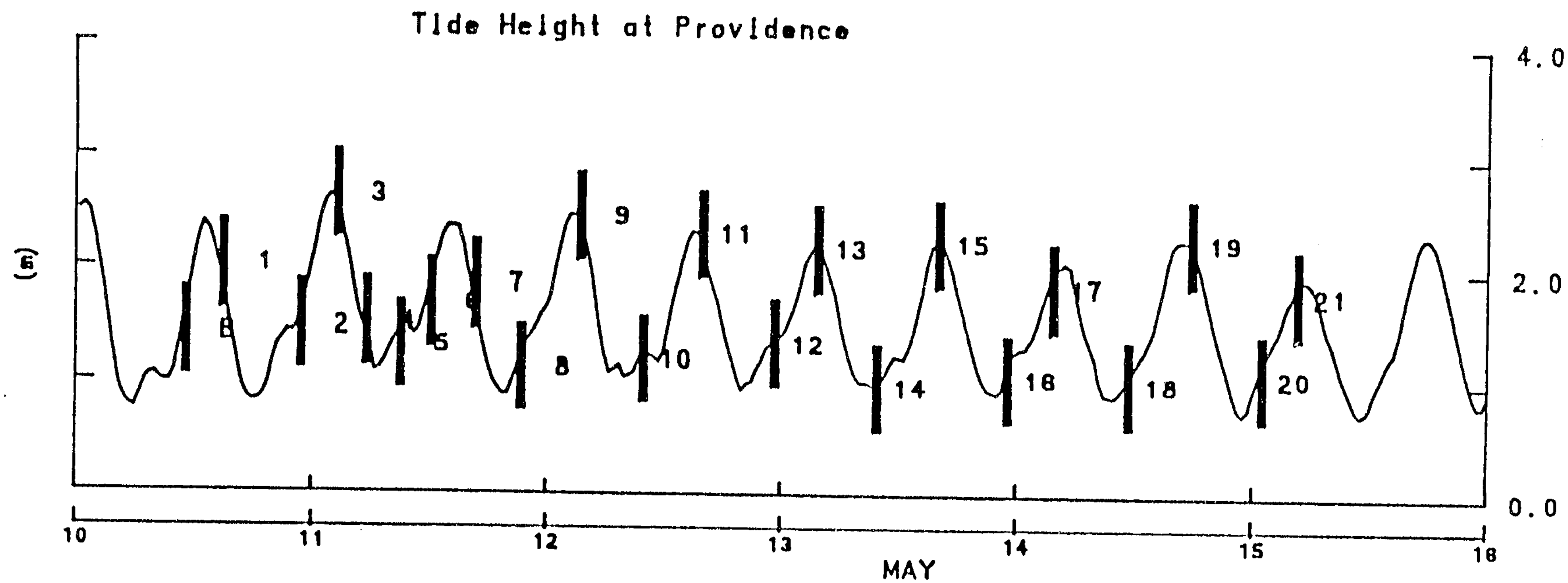


Figure 4.4 Experiment #2 (May 10-15, 1989): timing of surveys relative to tide height in Providence

Table 4.3 Timetable for the Seekonk River Surveys, May 10-11, 1989.

| Measurement Number | Start Time | End Time | Hours After Start of Releases |
|---|---|---|---|
| Background | 1145 | 1304, 5/10/89 | -- |
| 1 | 1803 | 1857, 5/10/89 | 0.2 |
| 2 | 2030 | 2125, 5/10/89 | 2.7 |
| 3 | 2206 | 2334, 5/10/89 | 4.3 |
| 4 | 0028 | 0133, 5/11/89 | 6.6 |
| 5 | 0319 | 0436, 5/11/89 | 9.5 |
| 6 | 0615 | 0737, 5/11/89 | 12.4 |
| 7 | 0903 | 1017, 5/11/89 | 15.2 |
| 8 | 1205 | 1315, 5/11/89 | 18.3 |
| 9 | 1400 | 1453, 5/11/89 | 20.2 |
| 10 | 1600 | 1732, 5/11/89 | 22.2 |

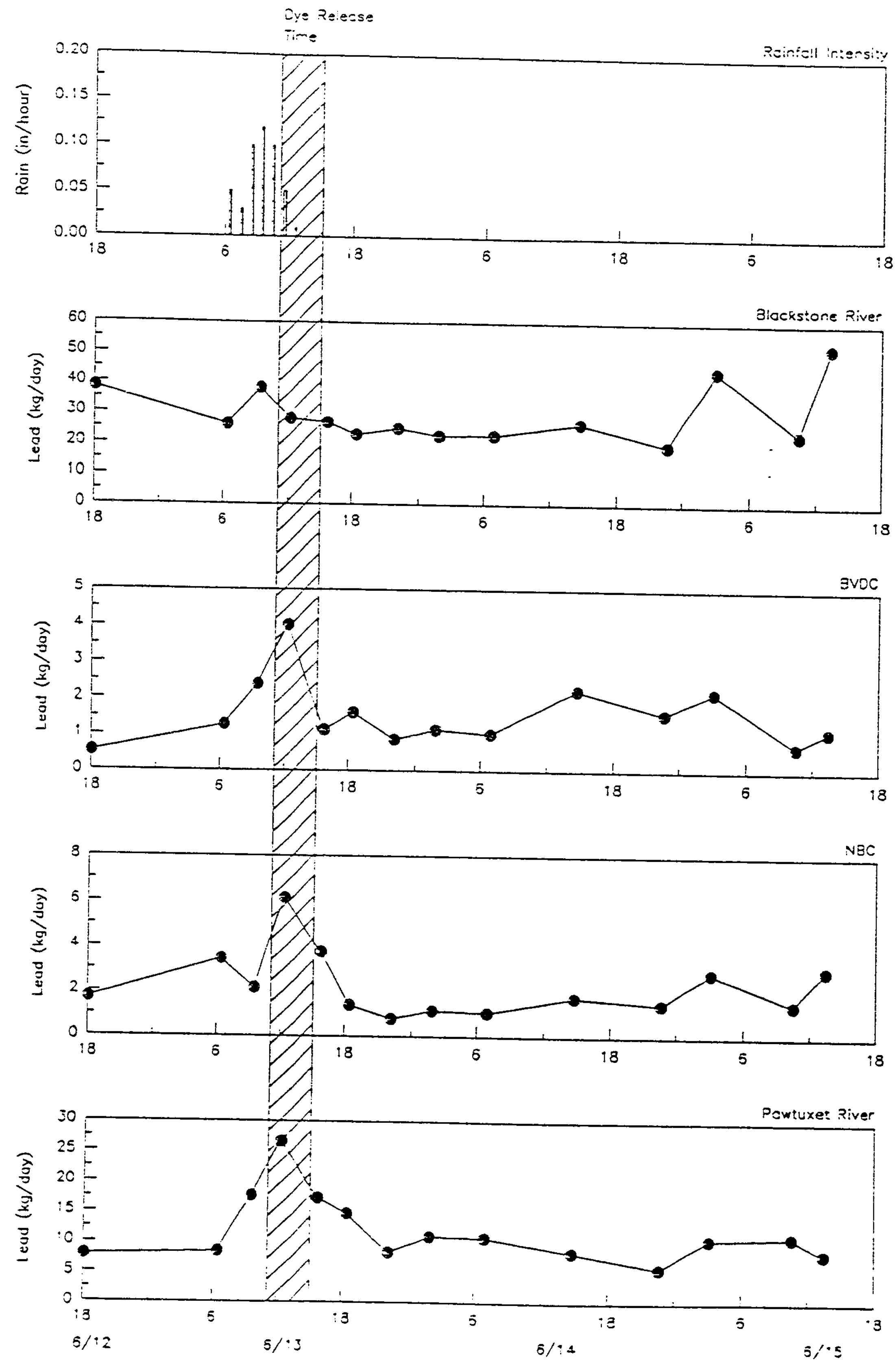


Figure 4.5 Time history of rainfall intensity in the study area (and lead fluxes from the four point sources) on June 13, 1989 (from Wright et al., 1990)

The measurement schedule for the Providence River is shown in Table 4.4. The timing of the surveys relative to the state of the tide is shown in Figure 4.6. The Providence River team was in the study area at 0700 and conducted background surveys between 0726-0930. The DEM Seekonk River team conducted its background survey between 1016-1110. Immediately after the Seekonk River background survey was completed the dye discharges at BVDC and Slaters Mill were started (1110). The Fields Point and Pawtuxet River discharges were started at 1140 and 1129, respectively. The dye surveys in the Providence and Seekonk Rivers began at 1135 as per the timetables listed in Tables 4.4 and 4.5.

By midnight on June 15, the dye had nearly disappeared from the study area. The surveys were therefore discontinued after the end of the 15th survey, at 1314 June 16.

### 4.2 Dye Distributions

The purpose of this section is to summarize the behavior of dye in the study area during the three experiments. The characteristics examined include:

- How the dye was distributed in the vertical and horizontal planes over time following the release.
- How rapidly the dye traveled through the study area during each experiment.
- How dye levels decreased with time following each release.
- How well the dye served as an indicator for various pollutant species during the experiments.

A series of graphical products are included in Appendices A-H to assist in describing the results of the experiments. The dye data also listed in Appendices I-K.

#### 4.2.1. Spatial Distributions and Movements

A series of graphic products are included in Appendices A through H of the report to assist in the interpretation of the data. The appendices contain:

| Appendix # | Description of contents |
|---|---|
| A | Vertically contoured cross-section of dye concentration versus depth along the center of the Providence River for all surveys. |

Table 4.4 Timetable for the Providence River Surveys, June 13-16, 1989.

| Measurement Number | Start Time | End Time | Hours After Start of Releases |
|---|---|---|---|
| Background | 0726 | 0930, 6/13/89 | -- |
| 1 | 1135 | 1335, 6/13/89 | 0.6 |
| 2 | 1531 | 1658, 6/13/89 | 6.0 |
| 3 | 1953 | 2050, 6/13/89 | 8.9 |
| 4 | 2130 | 2238, 6/13/89 | 10.5 |
| 5 | 0057 | 0220, 6/14/89 | 14.0 |
| 6 | 0349 | 0600, 6/14/89 | 16.8 |
| 7 | 0728 | 1020, 6/14/89 | 20.5 |
| 8 | 1300 | 1728, 6/14/89 | 26.0 |
| 9 | 2207, 6/14/89 | 0011, 6/15/89 | 35.1 |
| 10 | 0339 | 0607, 6/15/89 | 40.7 |
| 11 | 0845 | 1153, 6/15/89 | 45.8 |
| 12 | 1558 | 1858, 6/15/89 | 53.0 |
| 13 | 2340, 6/15/89 | 0304, 6/16/89 | 60.7 |
| 14 | 0513 | 0701, 6/16/89 | 66.2 |
| 15 | 1045 | 1314, 6/16/89 | 71.8 |

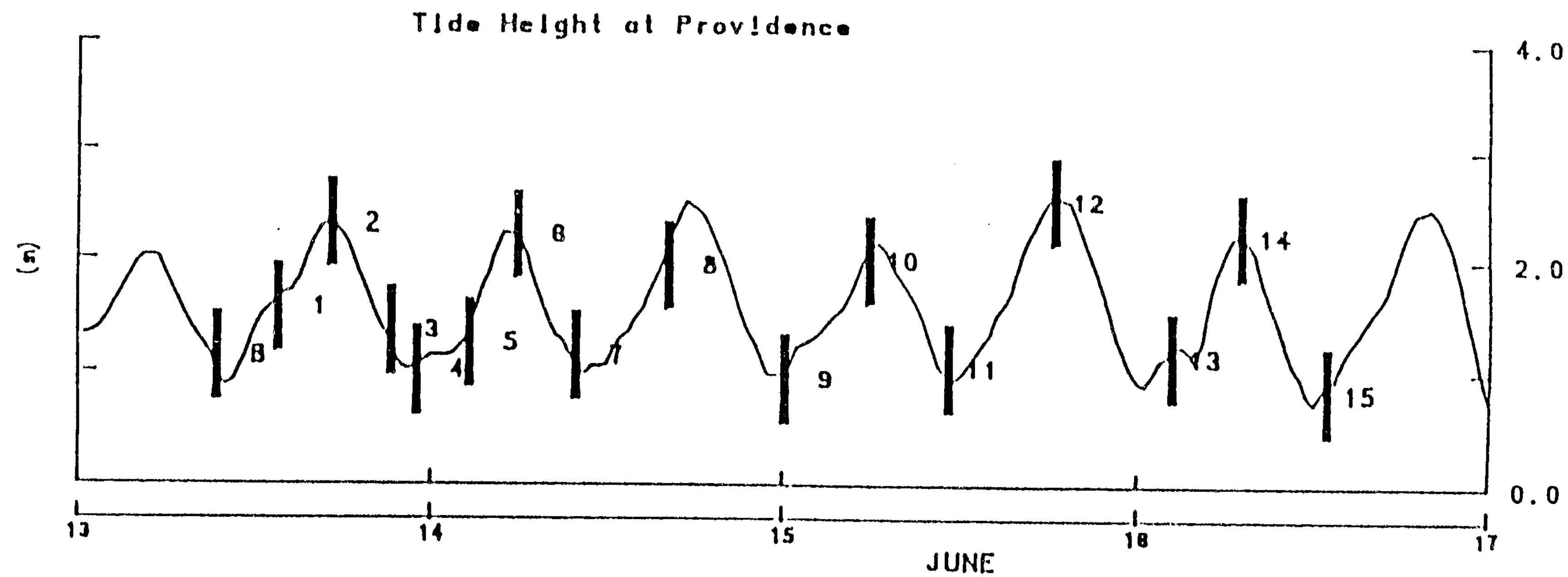


Figure 4.6 Experiment #3 (June 13-16, 1989): timing of surveys relative to tide height in Providence

Table 4.5 Timetable for the Seekonk River Surveys, June 13-16, 1989.

| Measurement Number | Start Time | End Time | Hours After Start of Releases |
|---|---|---|---|
| Background | 1016 | 1110, 6/13/89 | -- |
| 1 | 1205 | 1301, 6/13/89 | 1.1 |
| 2 | 1442 | 1551, 6/13/89 | 3.7 |
| 3 | 1729 | 1844, 6/13/89 | 6.5 |
| 4 | 2036 | 2146, 6/13/89 | 9.6 |
| 5 | 2317, 6/13/89 | 0016, 6/14/89 | 12.3 |
| 6 | 0200 | 0243, 6/14/89 | 15.0 |
| 7 | 0420 | 0500, 6/14/89 | 16.3 |
| 8 | 0625 | 0725, 6/14/89 | 19.4 |
| 9 | 0900 | 0954, 6/14/89 | 22.0 |
| 10 | 1138 | 1222, 6/14/89 | 24.6 |

| | |
|---|---|
| B | Dye Concentrations at the near-surface and near-bottom depth versus distance from the dam in the Seekonk River during the May, 1989 and June 1989 experiments. |
| C | Plan views of dye concentration isopleths of selected depths in the Providence River during all surveys. |
| D | Natural log of volume mean dye concentration vs. time for selected reaches of the Providence River for each experiment |
| E | Plots of fecal coliform (log concentrations) versus dye concentration at stations 4, 6 and 8 during each experiment. The numbers in each figure are referenced to survey times at the start of the appendix. |
| F | Plots of metals concentration versus dye concentration at Stations 4 and 6 during each experiment. The number in each figure are referenced to survey times at the start of the appendix. |
| G | Contoured vertical cross sections of the salinity field along the center of the river during each experiment. |
| H | Contoured vertical cross sections of the dissolved oxygen field along the center of the river during each experiment. |

Experiment #1: October 21-26, 1988

A total of 87.9 L of 20% dye solution was released during the first study. As Table 4.6 shows, half of the dye (44.1 L) was released from Fields Point. The figures in Appendices A and C show that after being released to the river, dye in the Providence River accumulated in a large area adjacent to and generally up-estuary from the Fields Point outfall. During the third post-release survey, Figure 4.7, which began 14.2 hours after the start of the release, the dye remained upstream of Fields Point. During the following survey, Figure 4.8 (1836-1949, October 20), no dye measurements were made

Table 4.6: Pump descriptions, measured discharge rates and volumes for each source using Experiments 1-3.

| Source Location | Pump Brand and Model | Discharge Rates and Volumes October, 1988 ml/sec | L | May, 1989 ml/sec | L | June, 1989 ml/sec | L |
|---|---|---|---|---|---|---|---|
| Fields Point | Blue/White Peristaltic | 3.0 | 44.1 | 1.1 | 15.8 | 2.6 | 37.2 |
| Pawtuxet River | Masterflex Peristaltic | 1.0 | 14.7 | 0.3 | 4.8 | 0.9 | 12.9 |
| BVDC Bucklin Point | Masterflex Peristaltic: | 1.0 | 14.4 | 0.3 | 4.8 | 0.7 | 10.4 |
| Slaters Mill | Piston Metering: March Mfg. Co. Model 210-10 | 1.0 | 14.7 | 0.3 | 4.5 | 0.5 | 7.6 |
| | Total Volume (L) | | 87.9 | | 29.9 | | 58.9 |

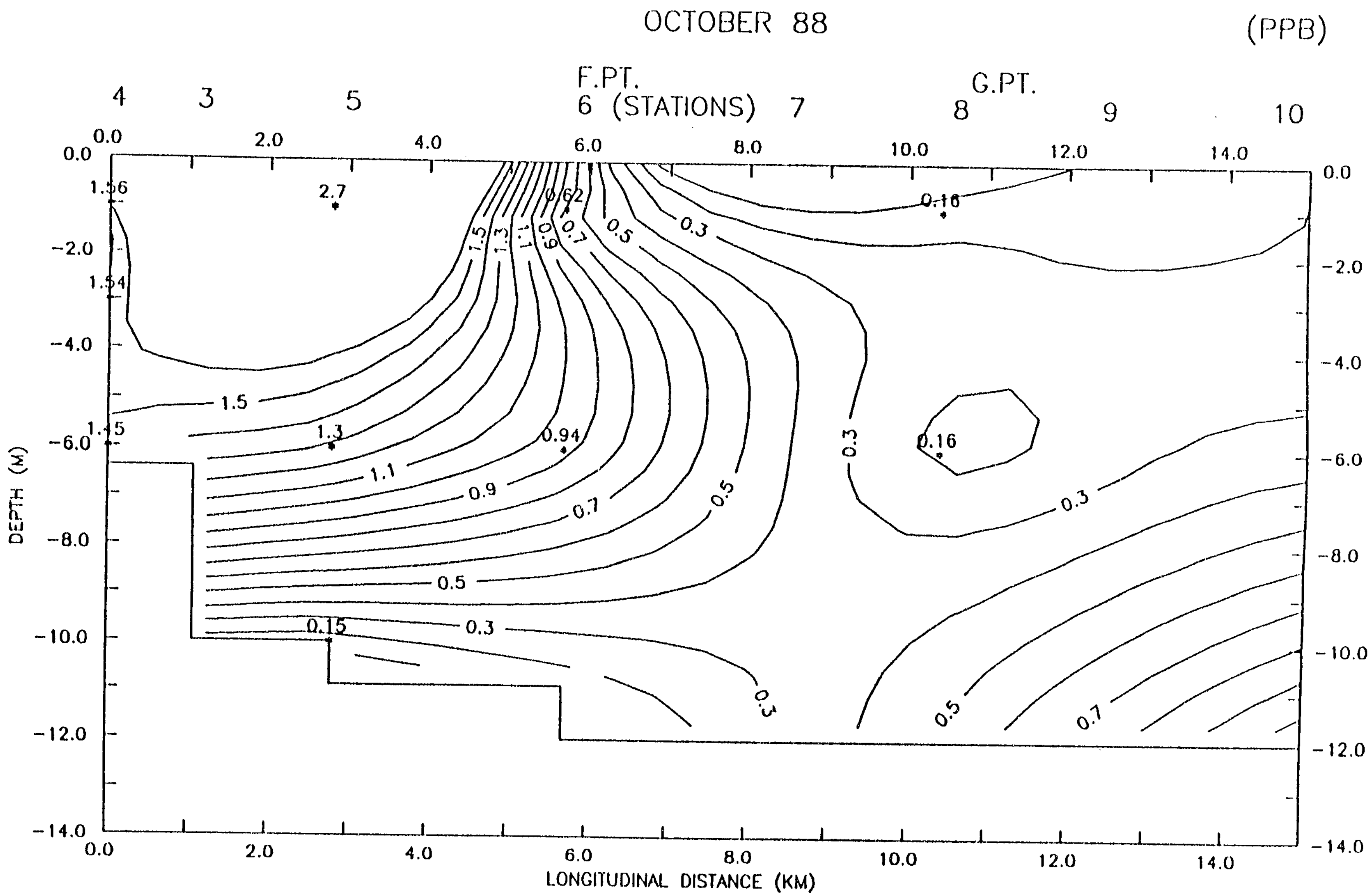


Figure 4.7 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 3, 1452-1645 October 22, 1988.

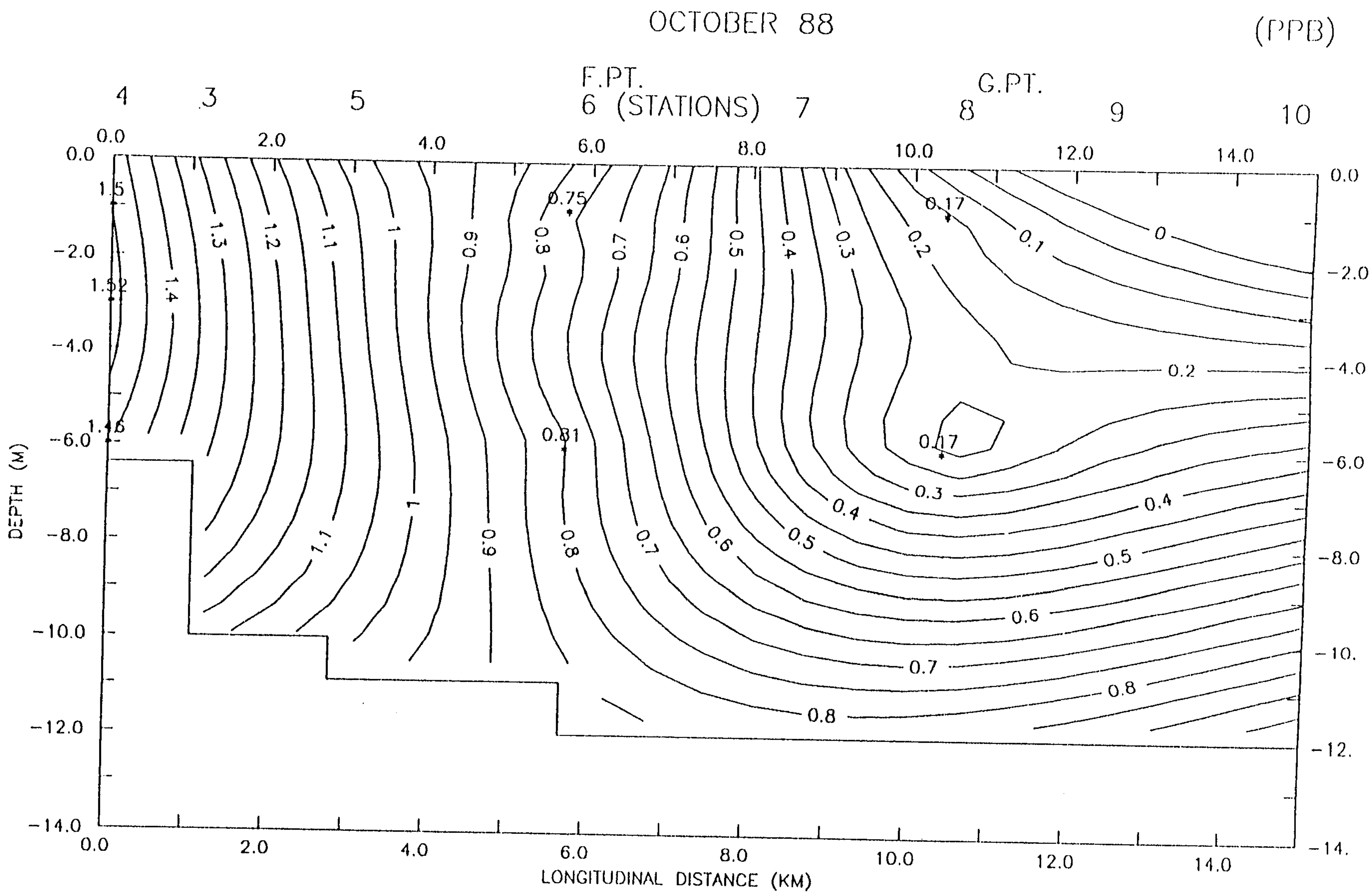


Figure 4.8 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 4, 1836-1949 October 22, 1988.

between Stations 4 and 6. The dye field was apparently under-resolved during this period because dye concentrations did not increase at Station 6. It is likely that the dye cloud remained north of Fields Point until after the completion of the survey.

The movement of dye down-bay was also fairly slow south of Fields Point. The leading edge of the dye plume was first observed at Station 10, at the mouth of the river 37.9 hours after the start of the release (Figure 4.9). Although a 17 hour gap is present between Surveys 5 and 6, it is apparent that the leading edge of the dye plume did not reach the mouth of the river until at least 24 hours after the start of the release.

The location of the area of highest dye concentrations appeared to remain in the vicinity of Fields Point over the duration of the study. During the final survey (#16) (Figure 4.10) which began 105.9 hours after the start of the release, the area of the highest dye concentration was at Station 5, although roughly similar levels were observed down to Station 7. The slow movement of the dye cloud may be linked to low net down-estuary currents during the experiment. A time series of the integrated surface current measured at Fields Point is shown in Figure 4.11 (Turner et al., 1989). The integrated movement of water past Fields Point during the period, particularly during the first 1.5 days, was quite small. The net motion between 0000, October 22 and 1200, October 26, 1988, was also small: 12 km. This net movement through the narrow cross-section at Fields Point translates to an even smaller down-estuary transport in the areas south of Fields Point, where the estuary is approximately four times wider on average (2 km versus 0.5 km) than at Fields Point.

Another possible reason for the slow down-estuary movement of the dye is from trapping in the area south of Fields Point. It is not possible to resolve whether trapping did occur, because the resolution of the dye field between Stations 6 and 7 was inadequate during the experiment.

The dye also persisted in the Seekonk River over the duration of the study. This behavior may also have been related to low net transport in the Seekonk during the period. The time history of the progressive current vector at Cold Spring Point is shown in Figure 4.12. The net excursion of bottom currents during the 4 1/2 day study period is 6-8 km, half that expected based on the mean vector calculated for the September 17-November 7, 1988 period, 3.3 cm/s (Turner et al, 1989), which would integrate to a net excursion of nearly 13 km.

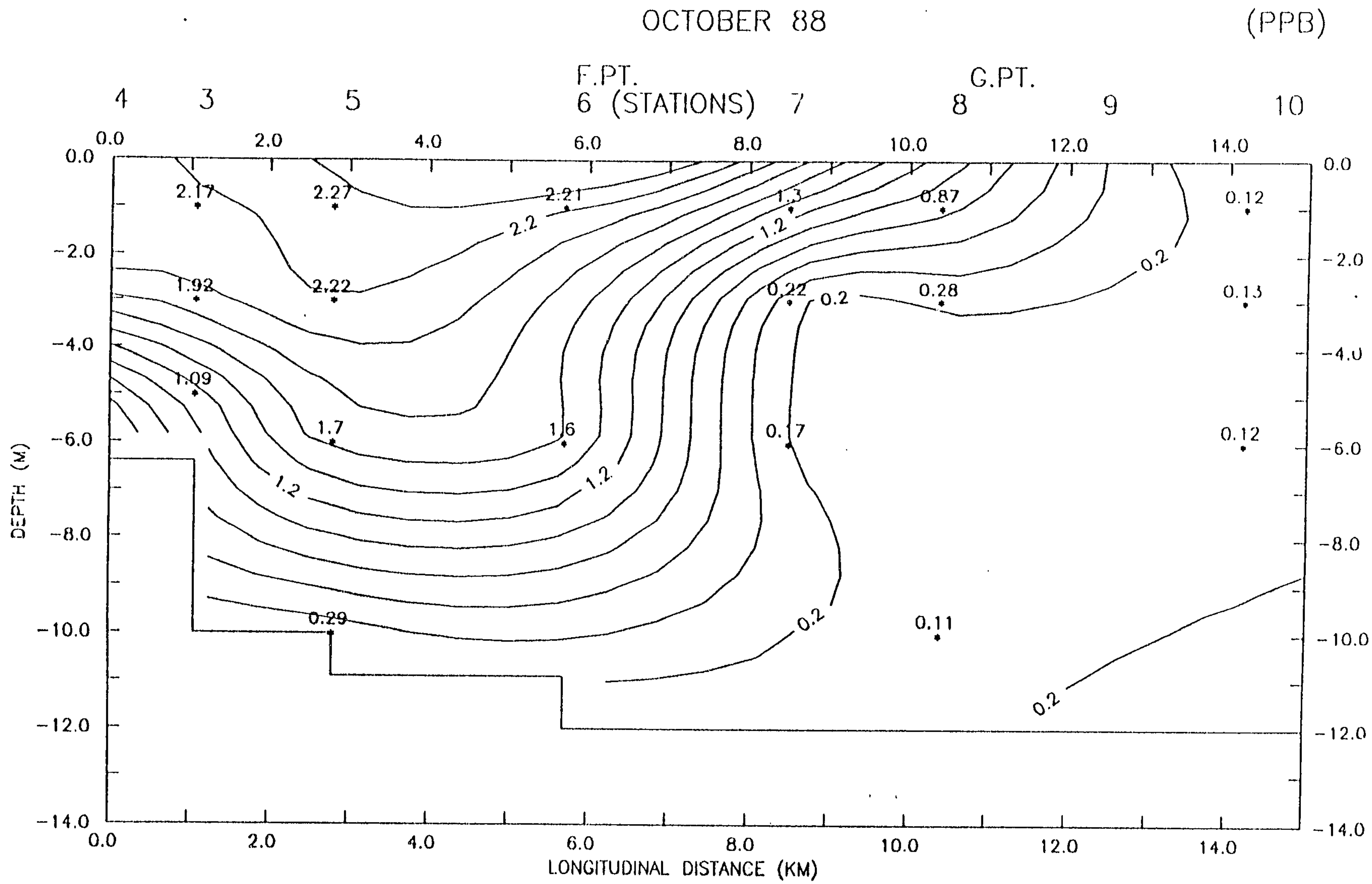


Figure 4.9 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 6, 1435-1645 October 23, 1988

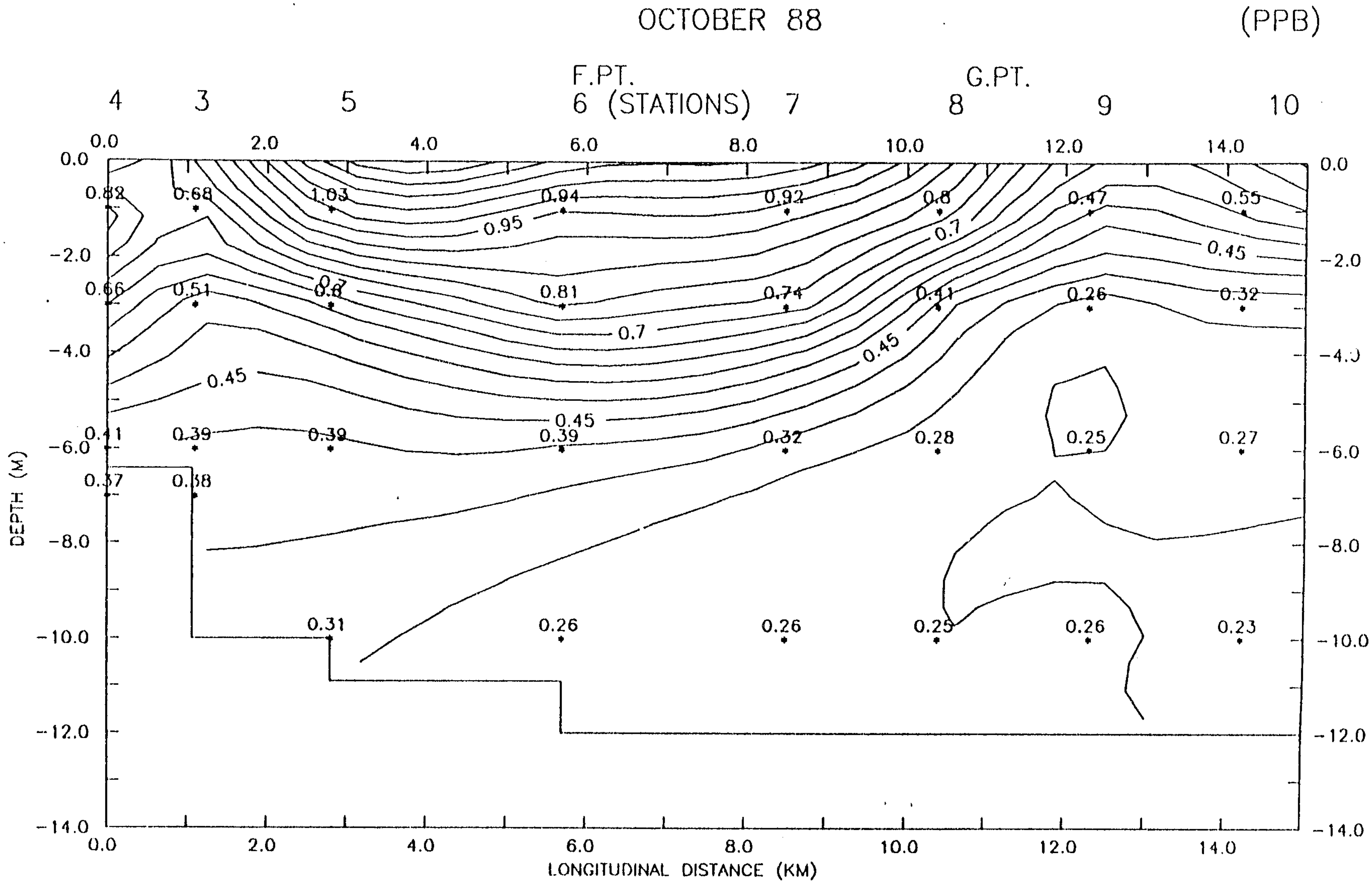


Figure 4.10 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 16, 0745-1032 October 26, 1988

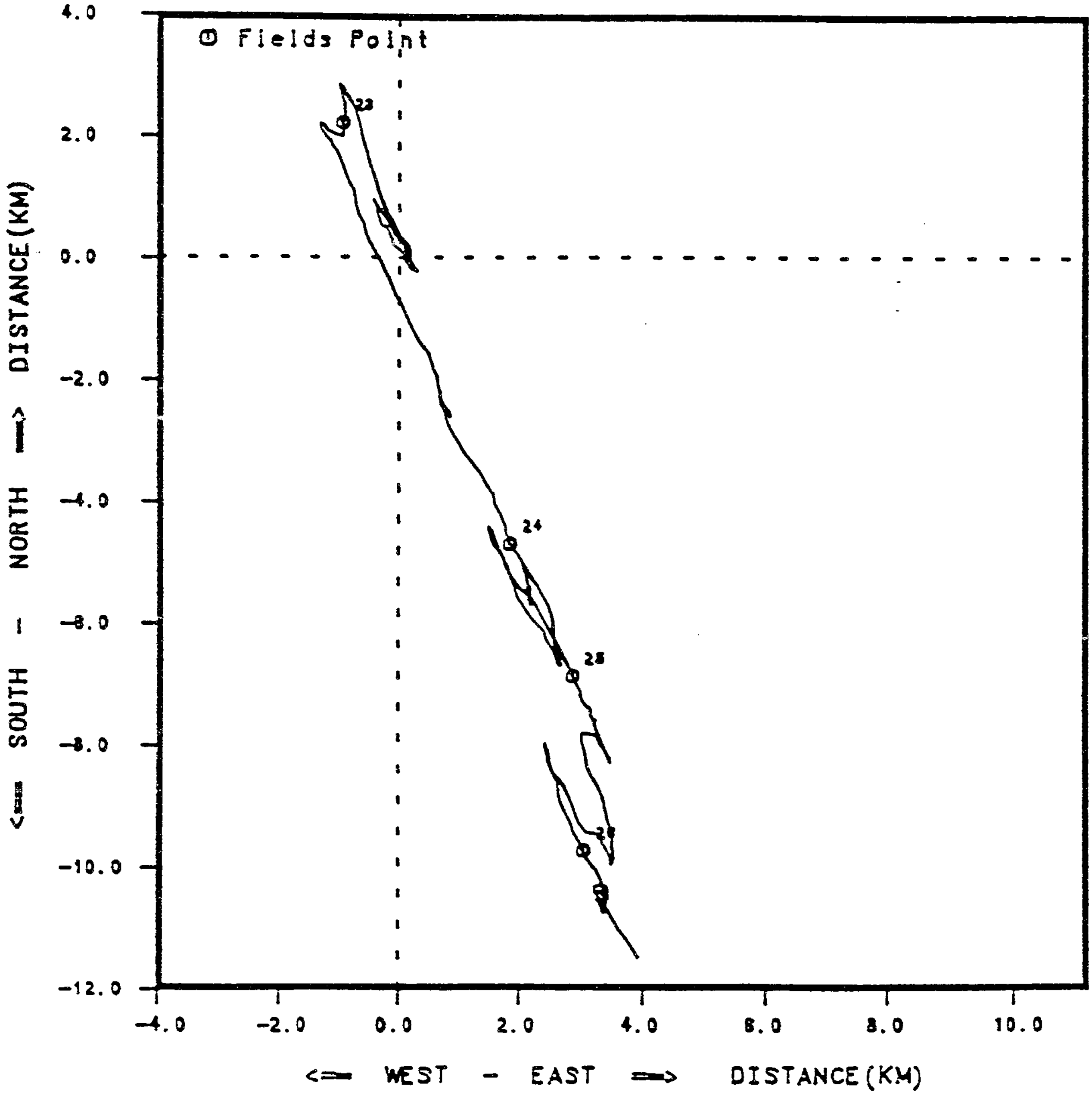


Figure 4.11 Progressive vectors of surface currents at Fields Point, 0000 October 22 - 1200 October 26, 1988

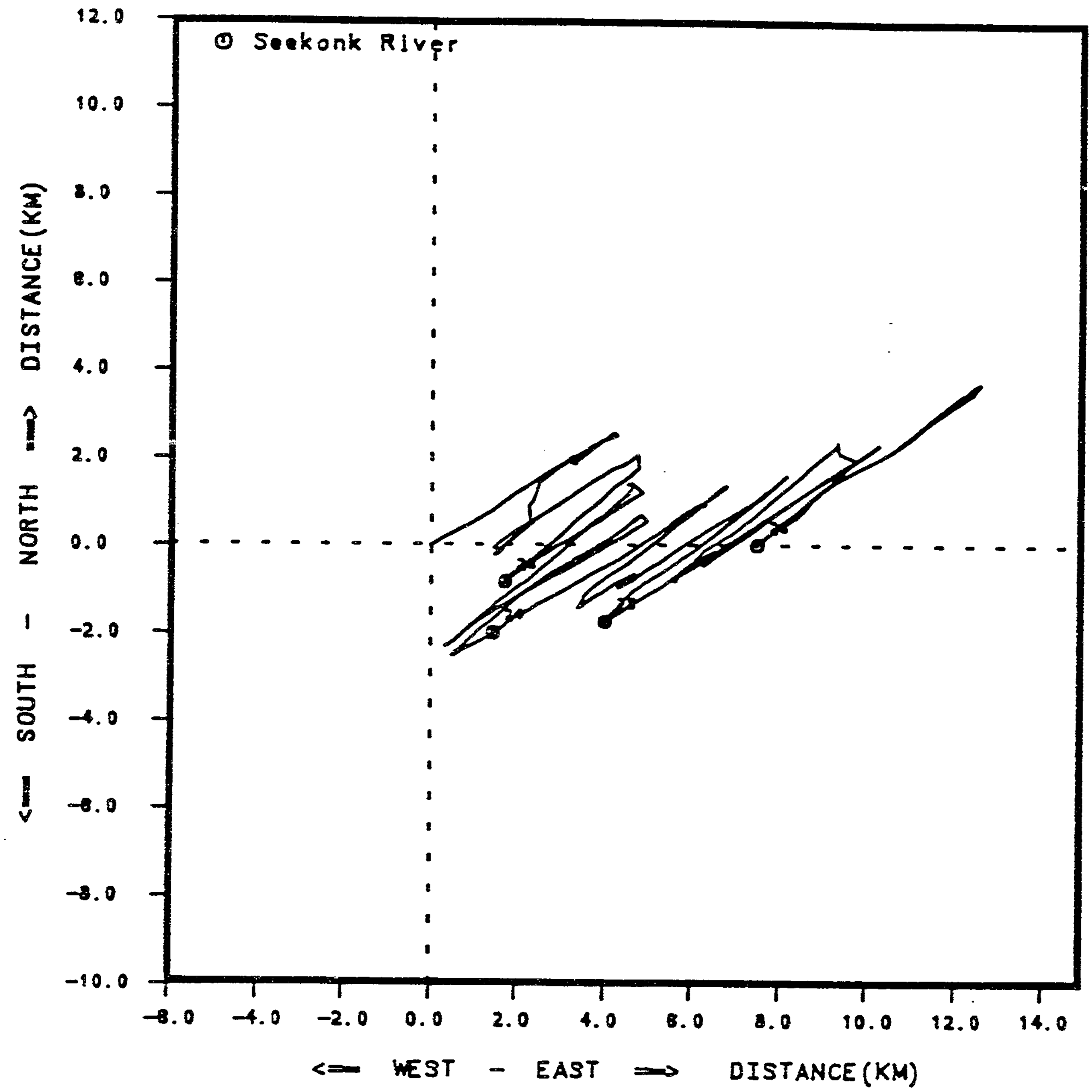


Figure 4.12 Progressive vectors of bottom currents near Cold Spring Point, 0000 October 22 - 1200 October 26, 1988

Experiment #2: May 10-15, 1989

The levels of dye observed in the study area during the October 1988 experiment were about a factor of 10 higher than the detection limit of the fluorometer. The release rate for the second study was therefore reduced by a factor of four. This provided adequate dye concentrations to measure and reduced the amount of dye required. A total of 29.9 L of Rhodamine were released during the second experiment (Table 4.6). Again, slightly more than half of the dye was released from Fields Point.

Dye measurements made in the second release revealed that the vertical distribution of dye was quite different from the October 1988 experiment. The vertically contoured fields from the May experiment shown in Appendix A indicate that virtually none of the dye could be detected below the 1 m depth throughout the experiment. The measurements were accordingly made at the 1 m depth for the duration of the experiment. Occasional measurements were made at the 3 m and 6 m depths later in the experiment to confirm this assumption.

The movement of the dye toward the mouth of the Providence River was more rapid during the second experiment. Figures 4.13 - 4.15 made 4, 7 and 11 hours after the start of the release, respectively, indicate that the dye cloud began to move south. At hour 4 (Figure 4.13), dye levels were highest between Stations 5 and 6.

At hour 7 (Figure 4.14) the highest dye levels at the center of the river were found at station 6. The peak moved south to near Station 7 during the subsequent ebb tide, then upstream to the vicinity of Station 6 during the subsequent flood tide. After 17 hours (Survey #6), Figure 4.16 dye is present at Station 9. The dye persisted in the area of Station 9 until the end of Survey #11, 46 hours after the start of the release. By Survey #11, virtually all of the dye released had diluted to below detectable levels or had left the study area. The highest dye concentrations at this time were found at Station 10.

To travel from the release site at Fields Point and Station 10 in the 46 hour period between the start of the release and the end of Survey #11, the dye cloud had to move at a mean speed of 6 cm/s down the estuary. This observation generally agrees with the net motion measured by current meters at the 1 m depth at Fields Point and near Gaspee Point during the same period (Figures 4.17 and 4.18, respectively). The mean current speed at Fields Point during the study was 7.1 cm/s down-estuary, while near Gaspee Point, the mean speed was 3.9 cm/s also down-estuary.

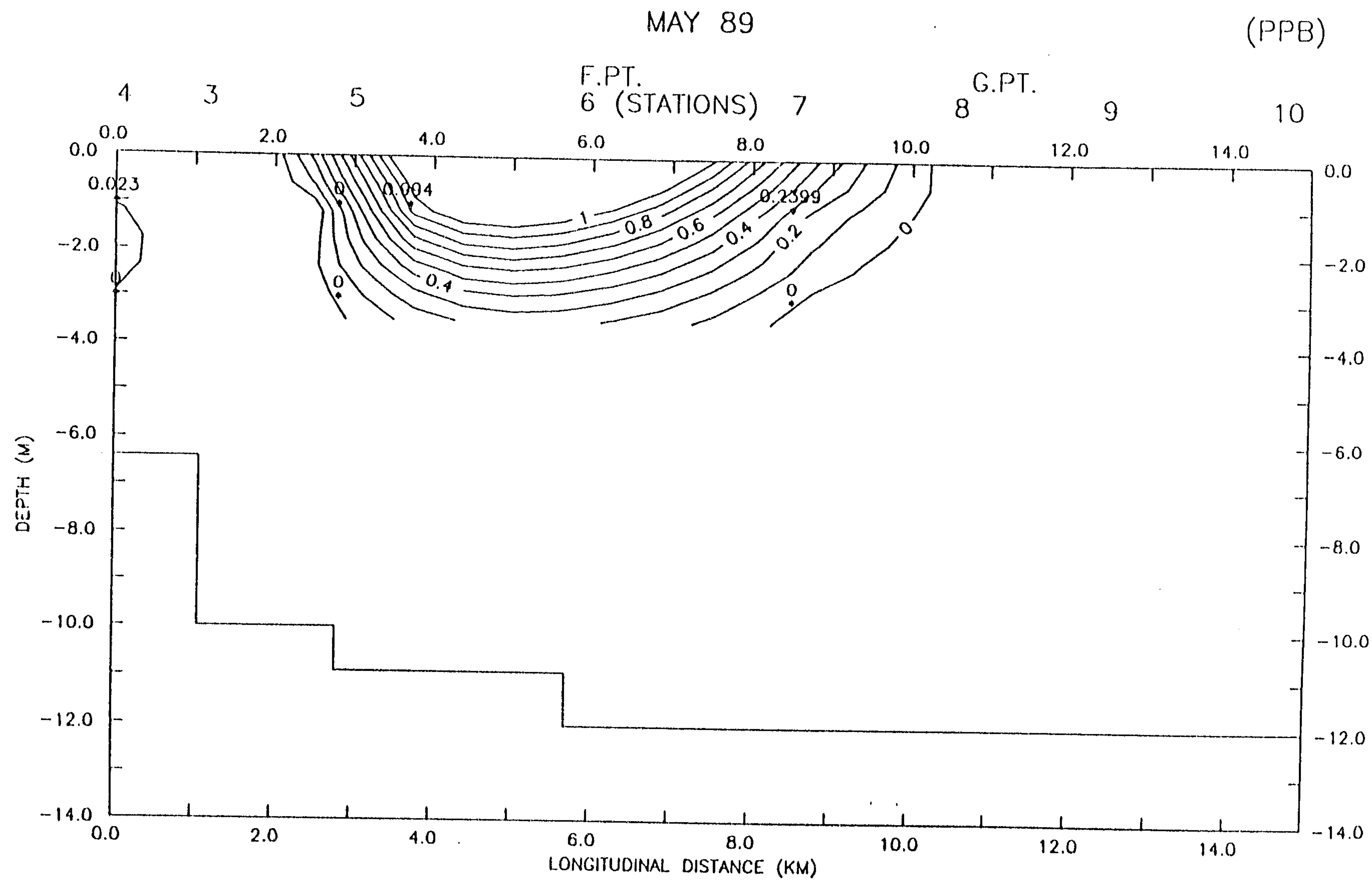


Figure 4.13 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 2, 2109-2240 May 10, 1989

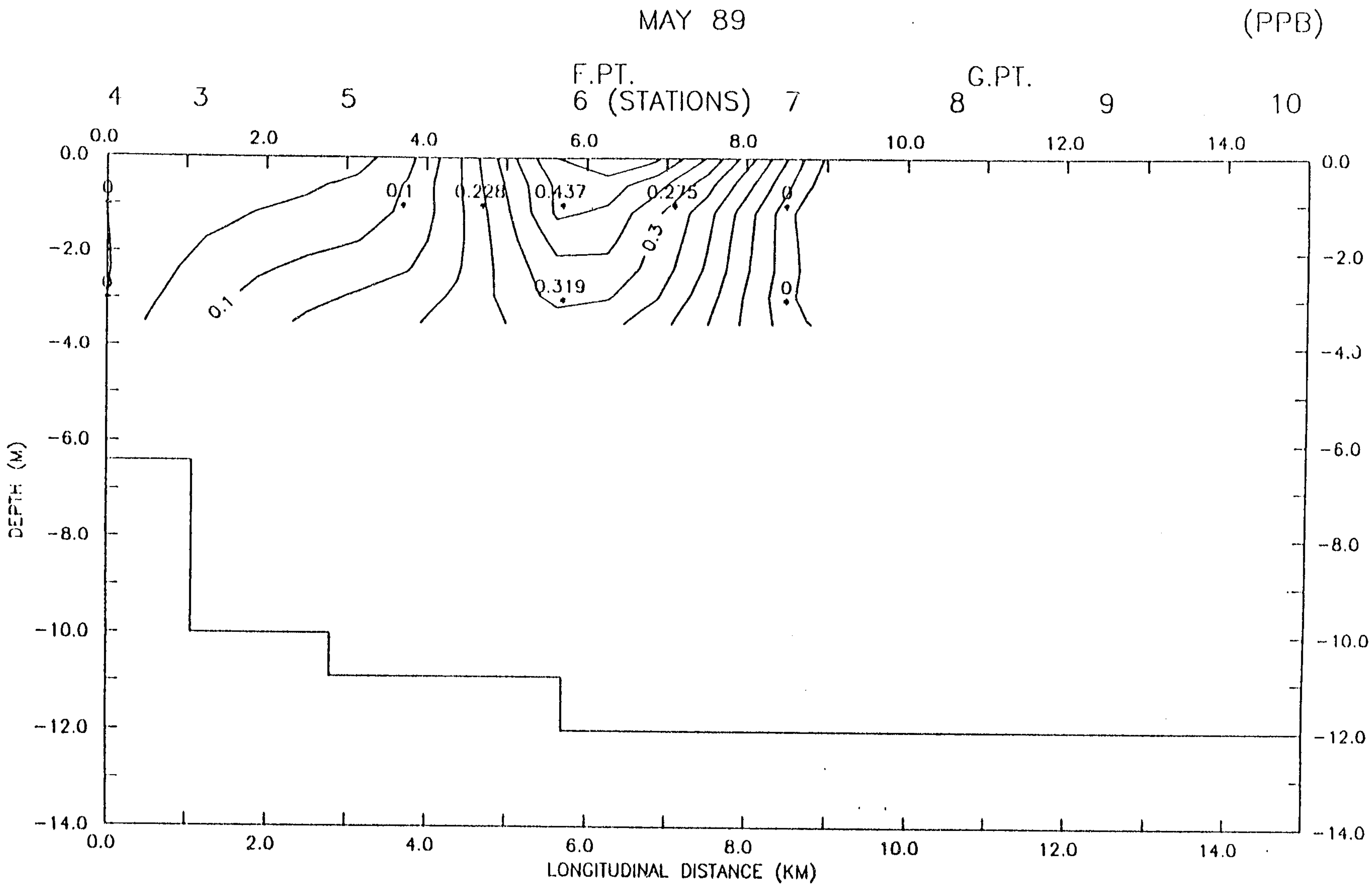


Figure 4.14 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 3, 0035-0240 May 11, 1989

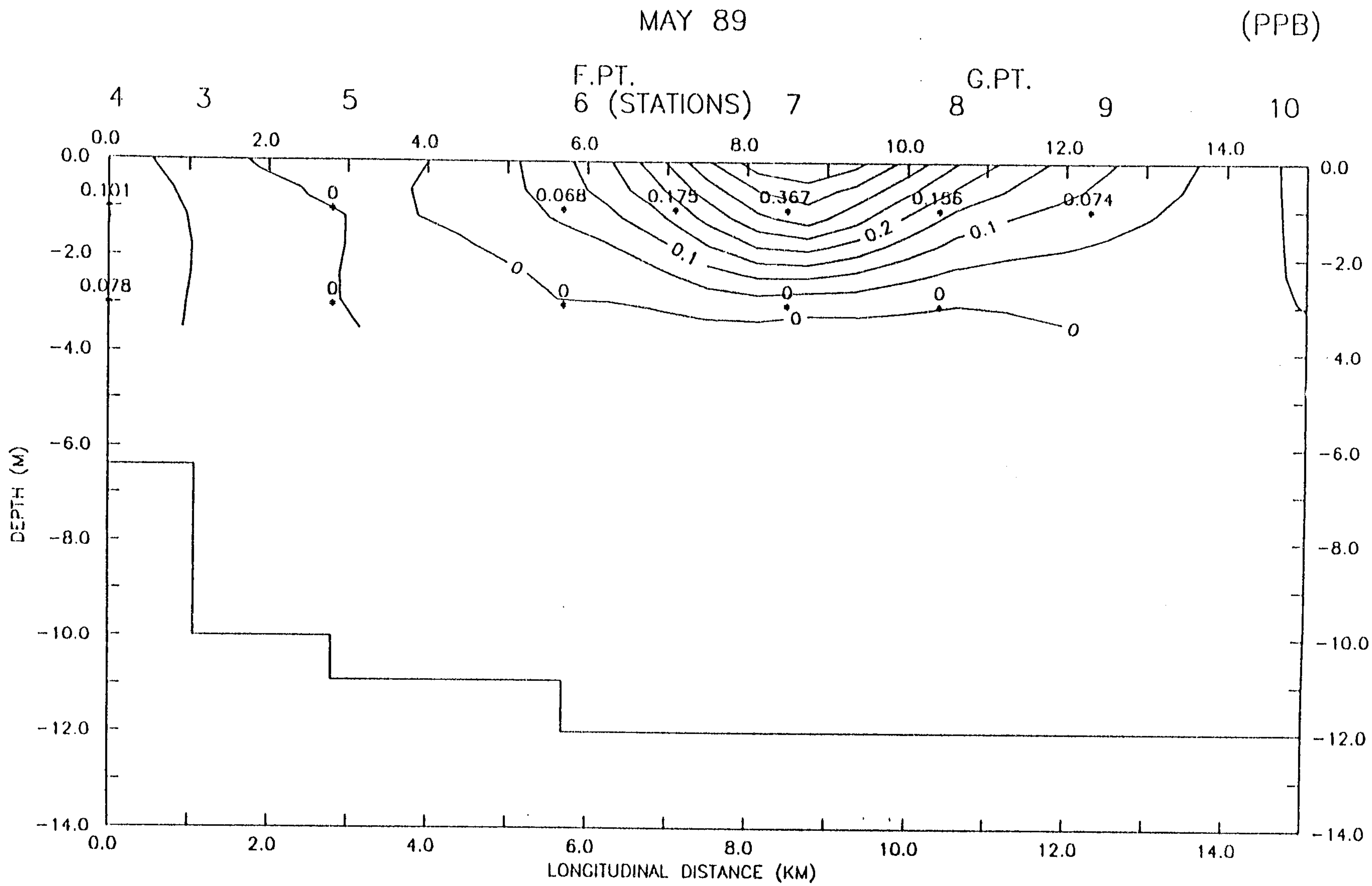


Figure 4.15 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 4, 0400-0523 May 11, 1989

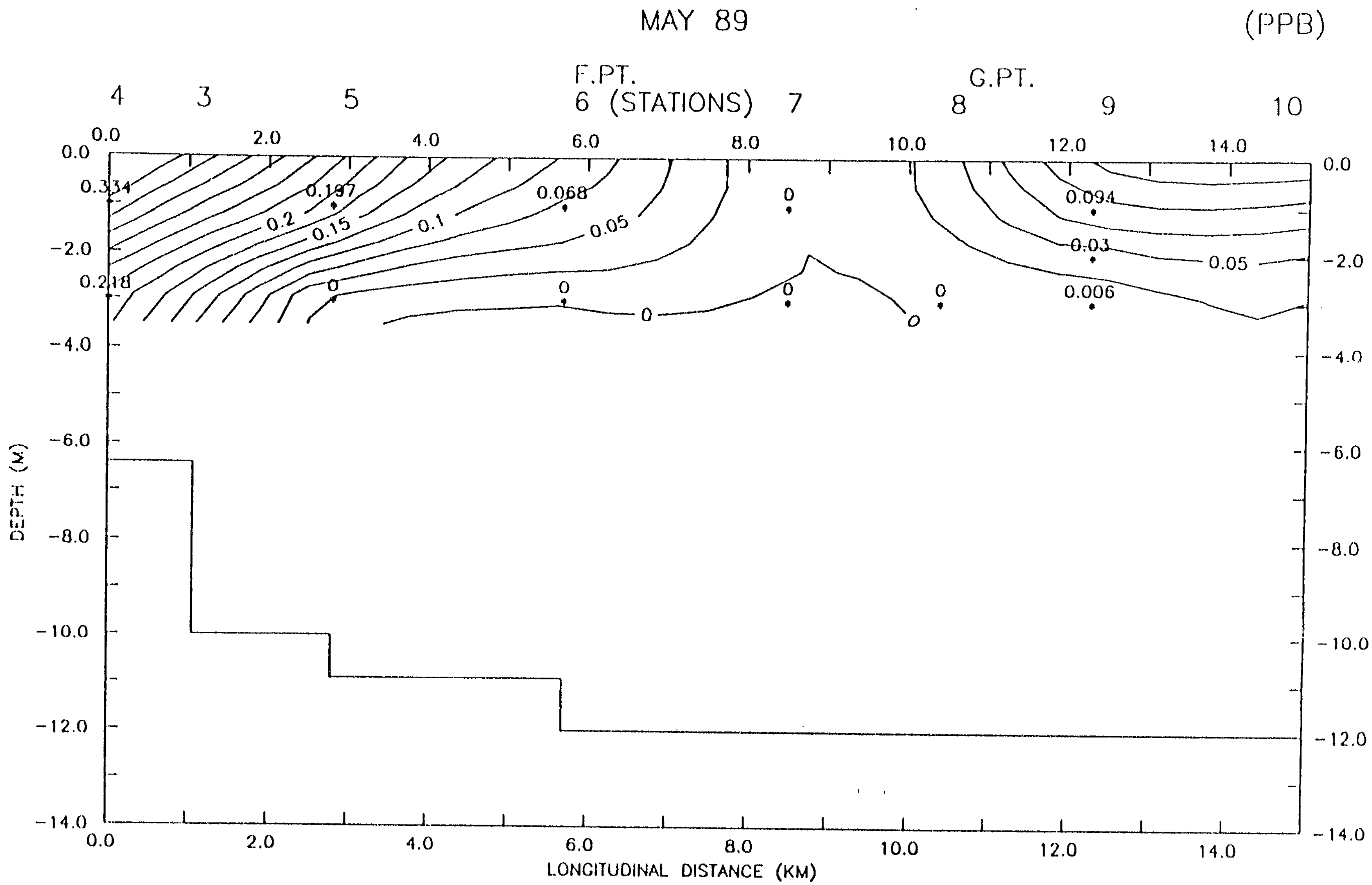


**Figure 4.16** Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 6, 1030-1205 May 11, 1989

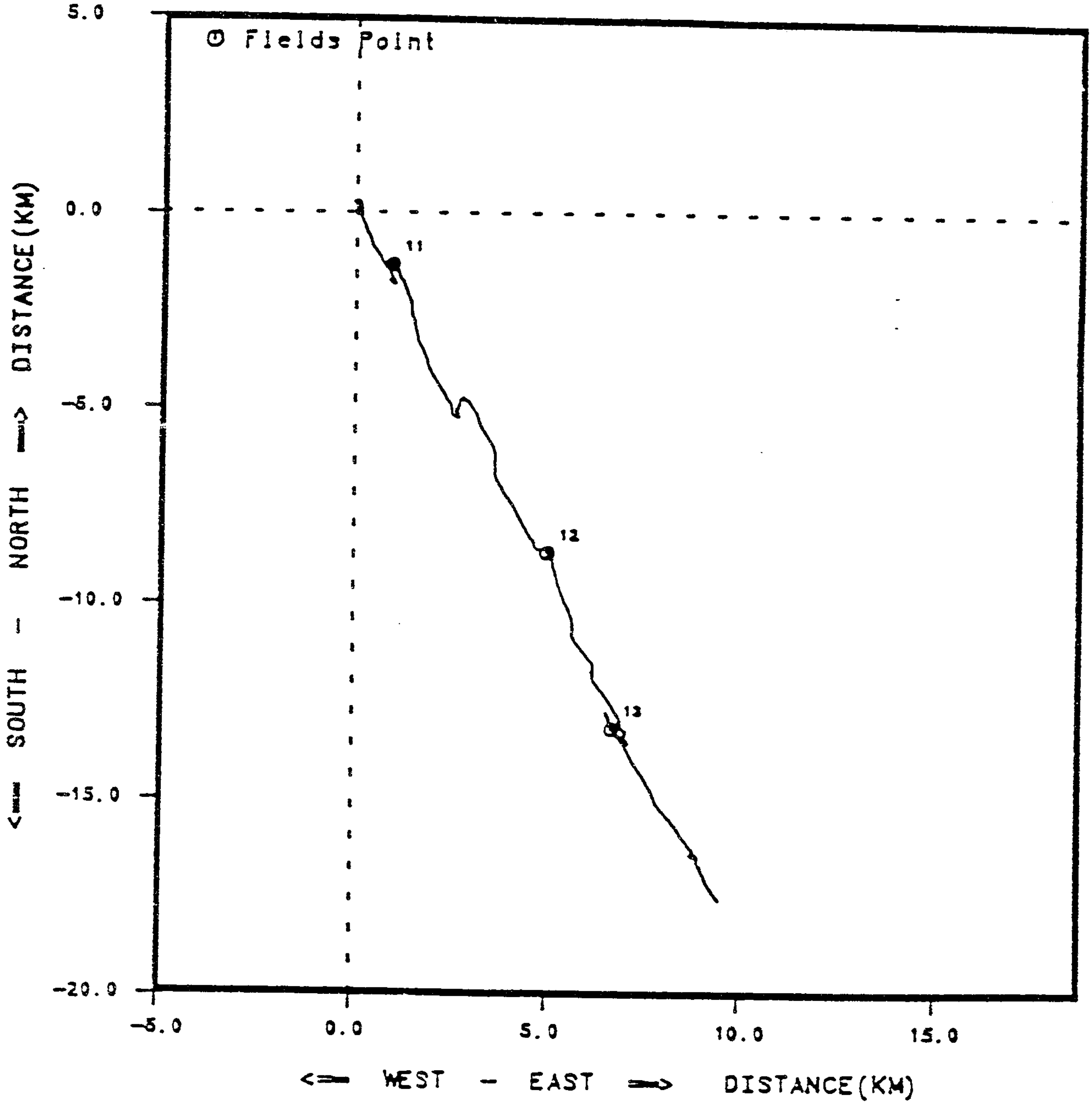


Figure 4.17 Progressive vectors of surface currents at Fields Point, 0800 May 10 - 1700 May 13, 1989

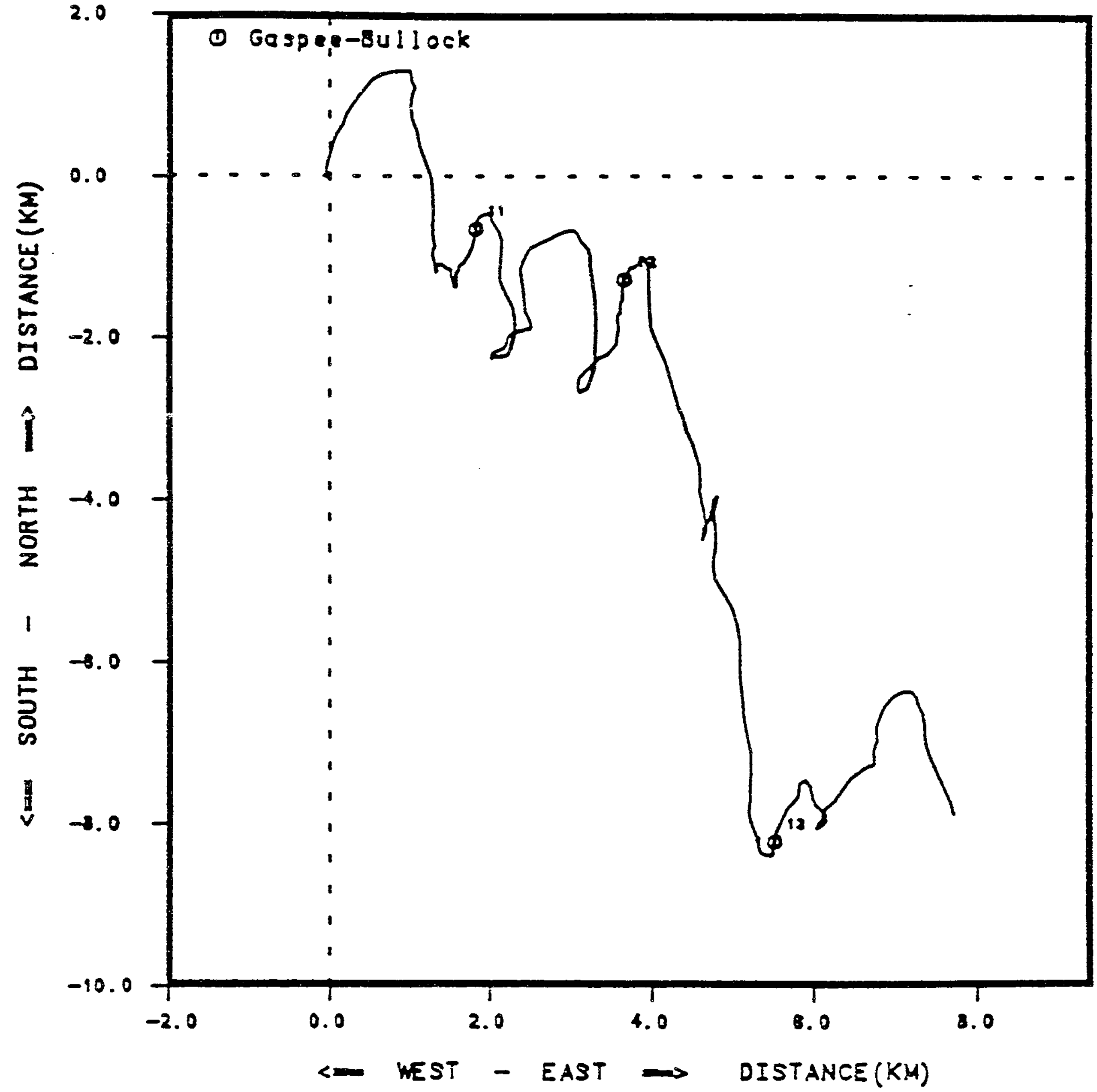


Figure 4.18 Progressive vectors of surface currents at Gaspee Point, 0800 May 10 - 1700 May 13, 1989

The dye surveys were discontinued after Survey #11, because dye levels at all points in the study area, with the exception of Station 10, had dropped to near or below the detection limit.

The movement of dye through the Seekonk River during May 10-11, 1989 is shown in Figures B.1-B.11 in Appendix B. The data showed a well-defined peak moving through the estuary between Survey #1 (Figure 4.19) and Survey #5 (Figure 4.20). No distinct signal from the BVDC outfall was observed during the experiment, apparently because the dye plume remained outside of the channel. The movement of the dye cloud near the bottom appeared to lag movement at the surface until the dye cloud reached Station 7 during Survey #5. Its down-estuary movement beyond that point appears to stop. The near-bottom peak remains at Station 7 through 8; the concentration of dye at this point drops steadily to pre-study background levels of 0.10-0.16 ppb. Near-bottom dye concentrations at downstream stations never rose above pre-release background levels.

The movement of dye along the bottom of the river in the vicinity of Station 7 agrees well with currents observed near the bottom during the period. The ASA Seekonk River current meter mooring was located approximately 200 m down-estuary from Station 7 during the May 10-15 study. A time series of the integrated current vector from the meter, in Figure 4.8 shows that the net up and down-estuary movement of water around 0000 May 11, corresponding to the number 11 in the figure was less than 1 km.

<u>Experiment #3: June 13-16, 1989</u>

The amount of dye released during the May 1989 survey was 1/3 the amount released during the October 1988 survey. The strength of the dye signal was accordingly much smaller, and could only be observed for 1.5 days. The planned release rate for each source was therefore increased to the same level as the October 1988 survey.

The actual volumes released by each source are listed in Table 4.6. As shown in the table, the actual volume released was 67% of that released in October 1988, and two times the amount released in May, 1989.

Spatial distributions and movements of the dye during the June 1989 experience were quite similar to those observed during the May 1988 experiment. Virtually all the dye remained in the upper 1 m of the water column during the experiment. This

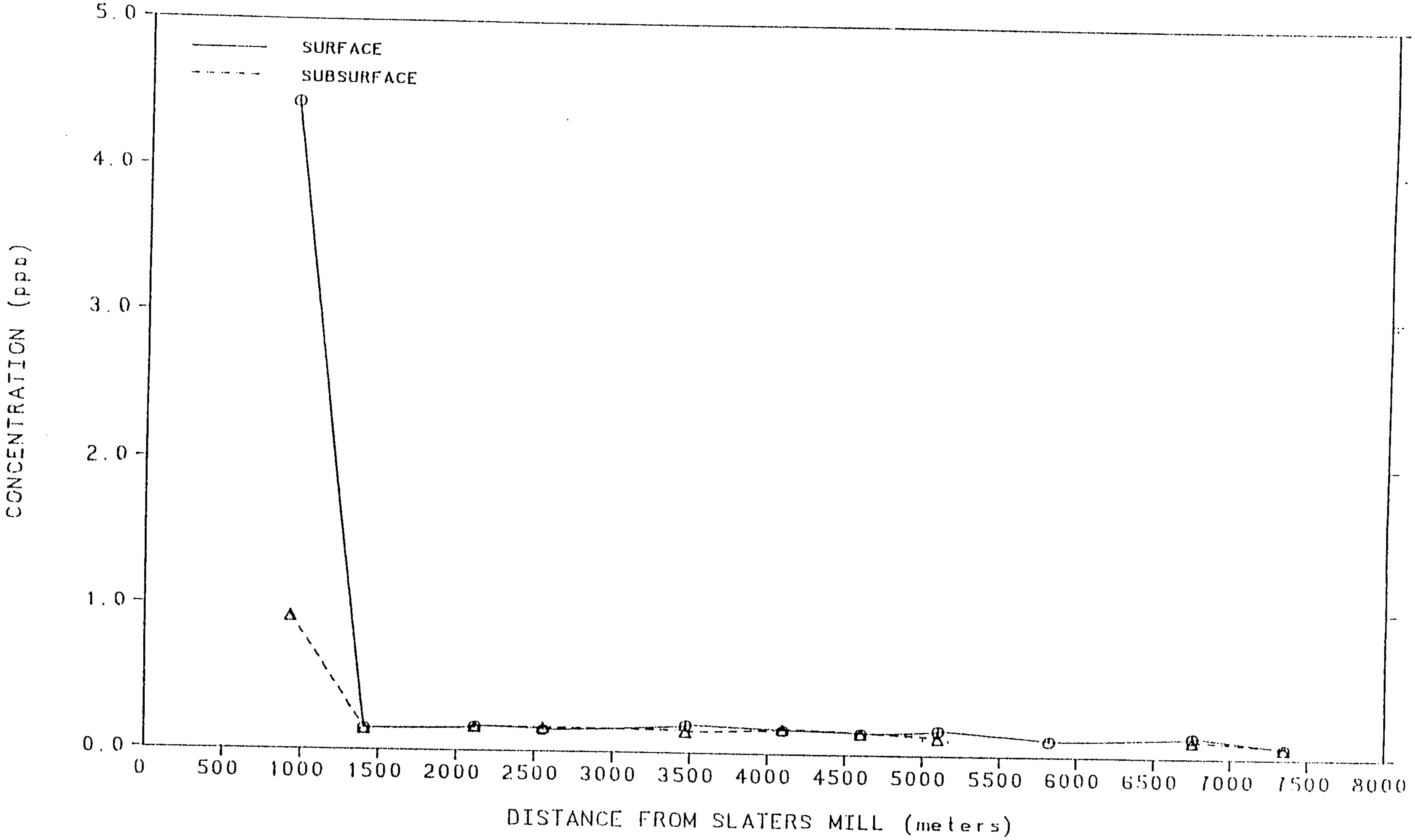


Figure 4.19 Dye concentrations at the near-surface and near-bottom depths in the Seekonk River as a function of distance from Slaters Mil Dam during survey I

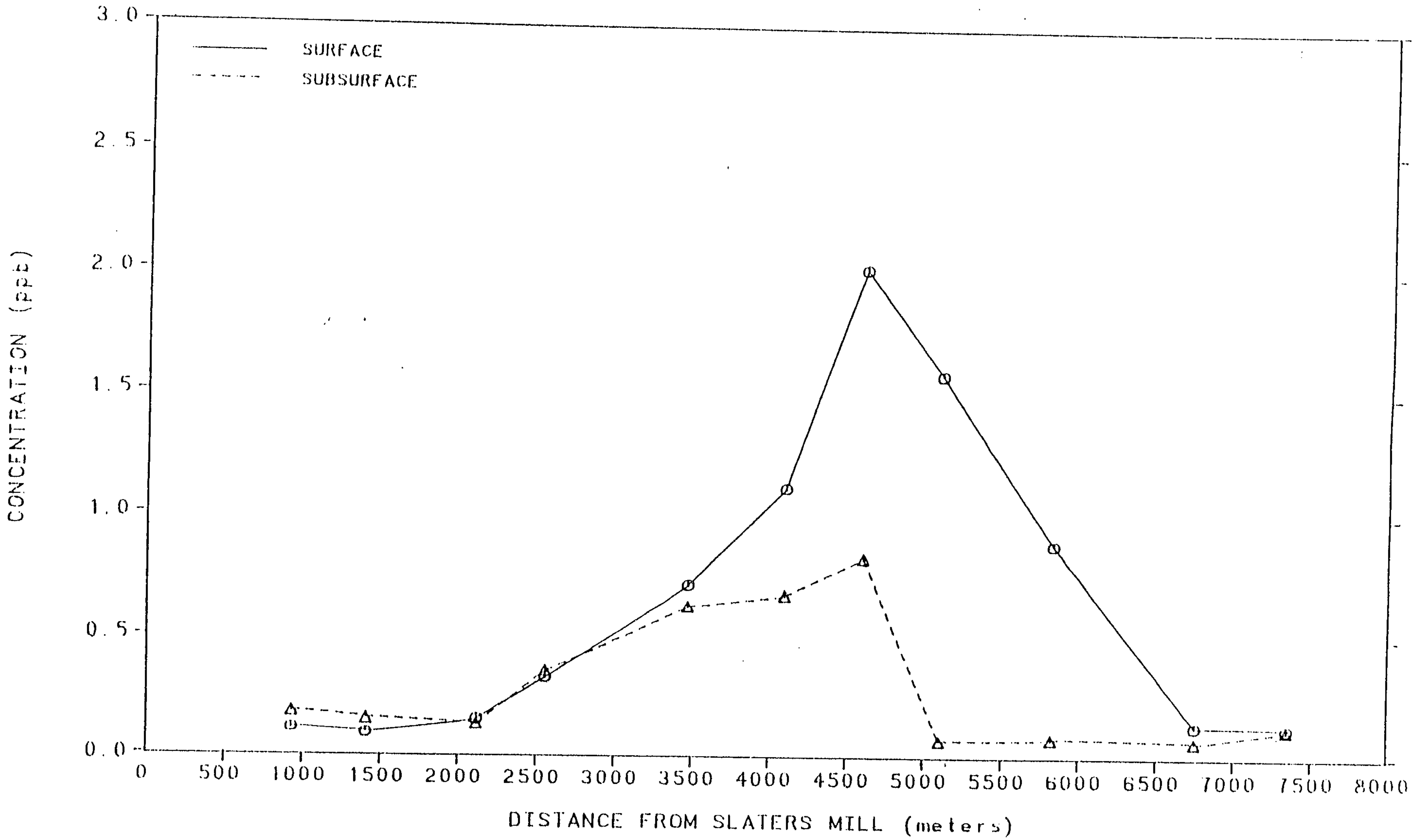


Figure 4.20 Dye concentrations at the near-surface and near-bottom depths in the Seekonk River as a function of distance from Slaters Mill Dam during survey 5, 0319-0436 May 11, 1989.

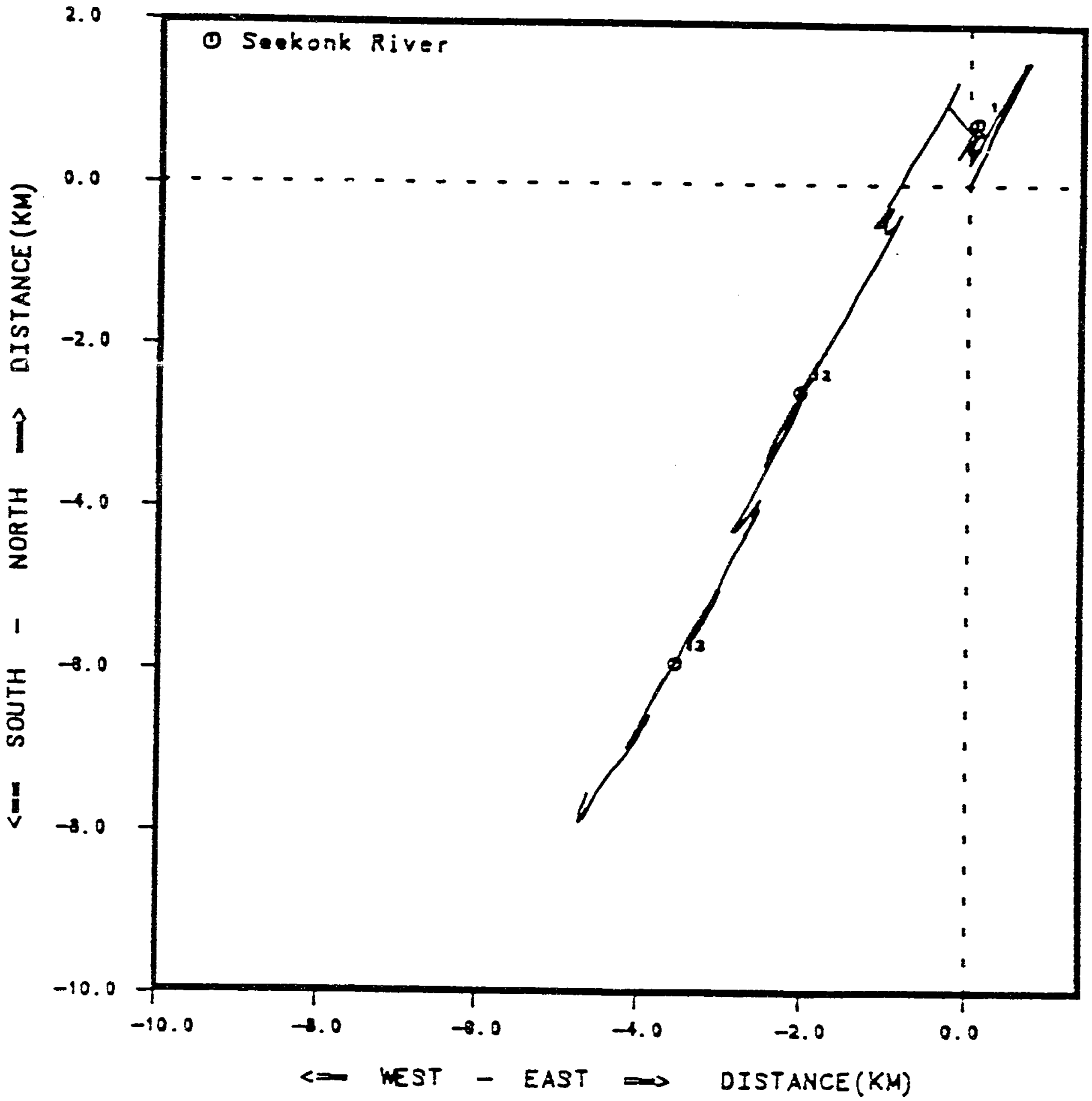


Figure 4.21 Progressive vectors of bottom currents in the lower Seekonk River, 0800 May 10 -1700 May 13, 1989

characteristic was observed during surveys # 1-3 on June 13. Subsequent sampling at the 3, 6, and 10 m depths was infrequent but did confirm the initial observations.

Once released, the leading edge of the dye cloud moved rapidly down estuary. Dye released from Fields Point (Figure 4.22) moved south to station 6, where it was visible during survey 3 at 8.9 hours (Figure 4.23). It subsequently appears to have been diluted in the area south of Fields Point and does not appear as a distinct mass on subsequent surveys (Figure 4.24). The dye was first observed at station 9, 14 hours after the start of the releases. By the end of survey 6, 19 hours after the start of the releases, the dye was detected at the mouth of the river (station 10).

The movement of dye down the Seekonk River was quite rapid. Figures B.12 - B.22 in Appendix B show the peak moving through the river to its mouth by 2100. Measurements located the leading edge of the dye at the mouth of the Seekonk River (station 4) at 2129, 10.5 hours after the start of the release. (Figure 4.25) The Seekonk River dye cloud is also visible at station 4 in the Providence River (Figure 4.24). During survey 6, 17 hours after the start of the release, the trailing edge of the Seekonk River dye plume was near station 5 in the Providence River (Figure 4.26) and its leading edge was near station 7. Residual dye appeared at station 4 through survey 15, indicating that some of the dye released was trapped (hour 26). The dye generally appears to have remained in the area south of Fields Point, decreasing with time. Some movements of area of higher dye concentrations in response to tidal excursion were evident. By the last survey at 71.8 hours, dye was detectable only in the area south of station 8 and around station 4.

### 4.2.2 Dye Decay Rates

Time series of the natural log of dye concentrations at selected stations in the Providence River as a function of time are presented in Appendix D for the three dye experiments. The changes in dye concentration over time may be used to establish a loss rate using the simple mass balance.

$$\frac{d(\rho CV)}{dt} = -\frac{Q}{V}(\rho CV) \qquad (4.1)$$

where $\rho$ is the density of dye,

C is the dye concentration,

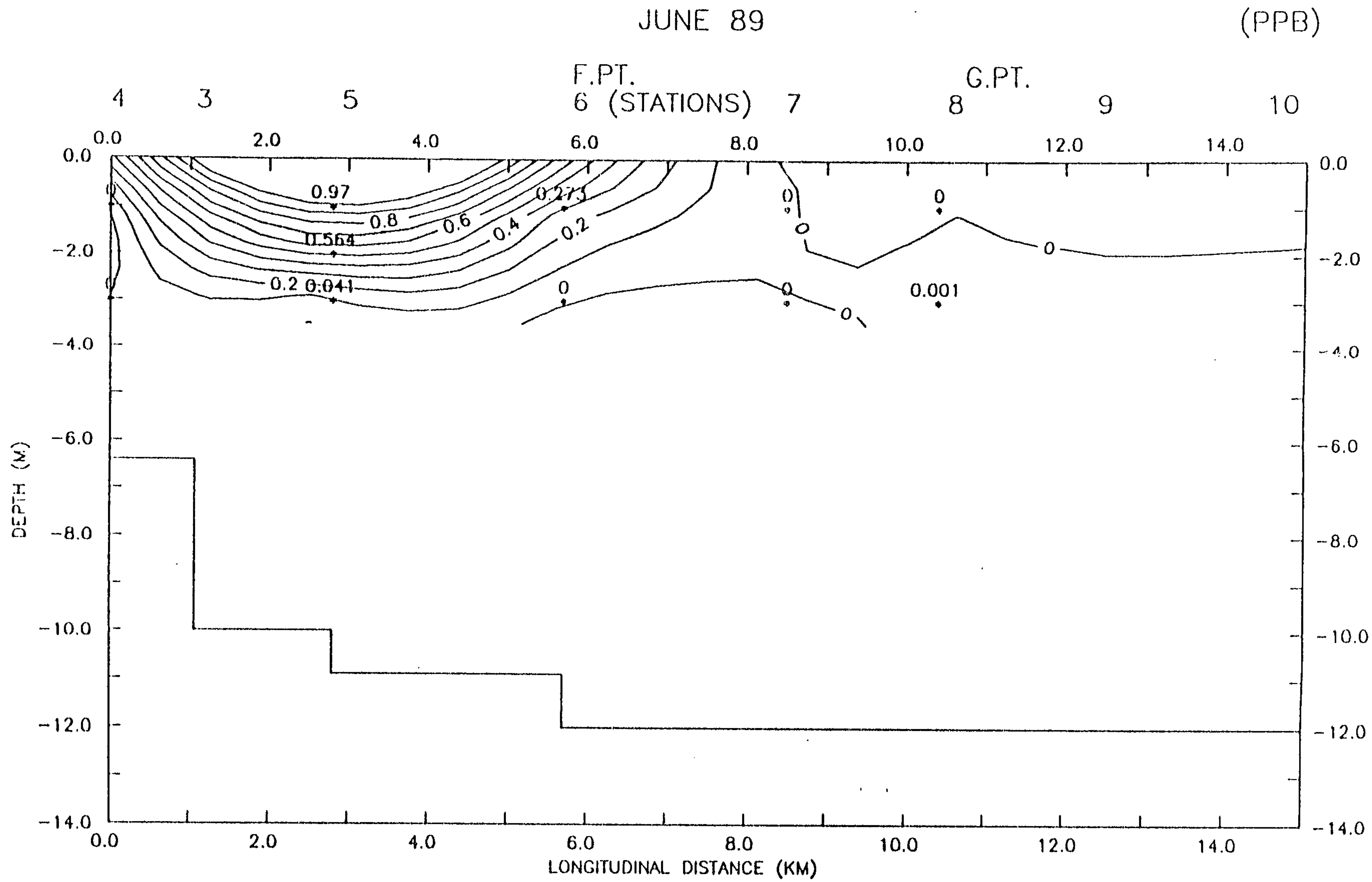


Figure 4.22 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 2, 1531-1658 June 13, 1989.

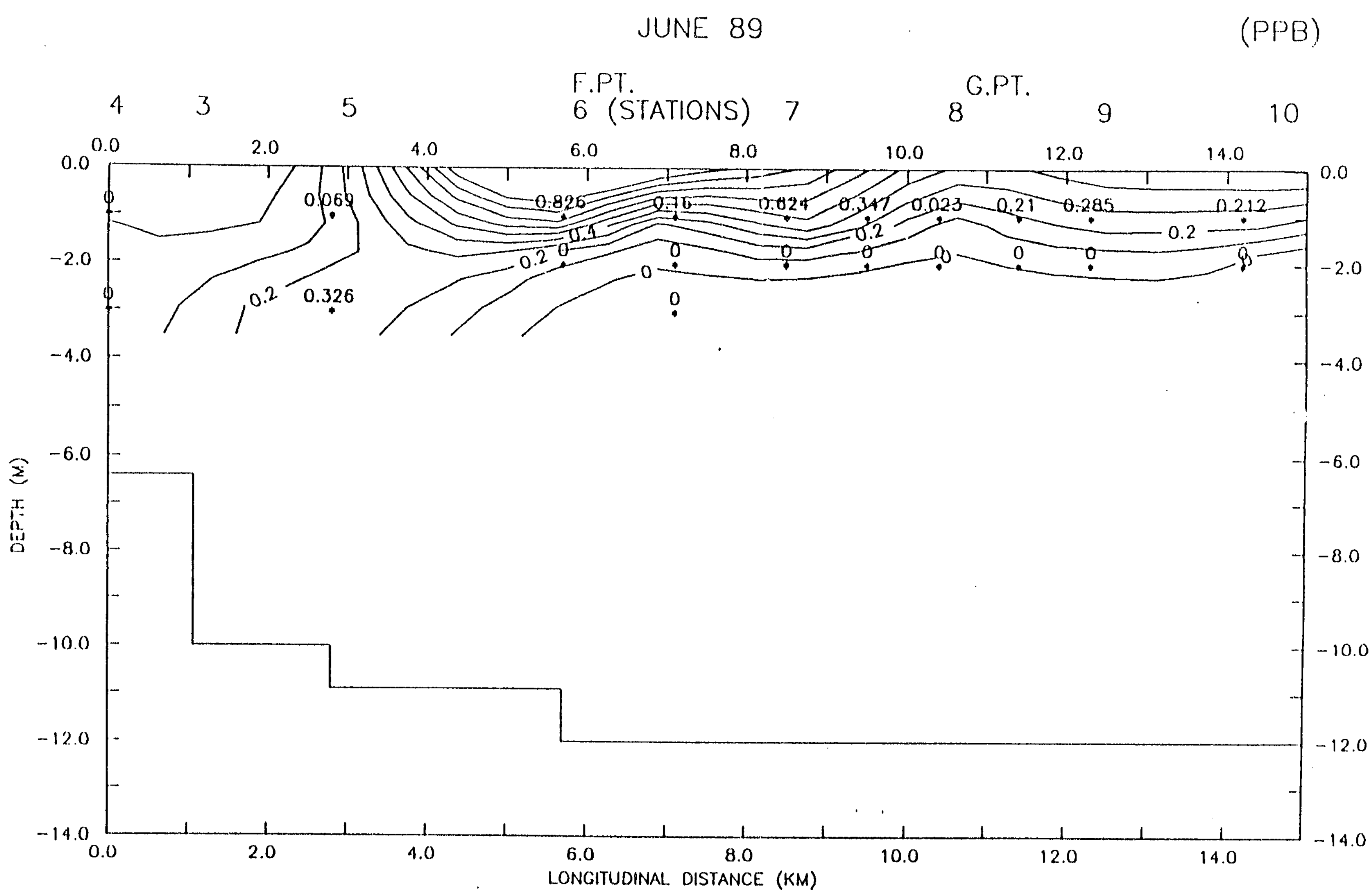


Figure 4.23 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 3, 1953-2050 June 13, 1989.

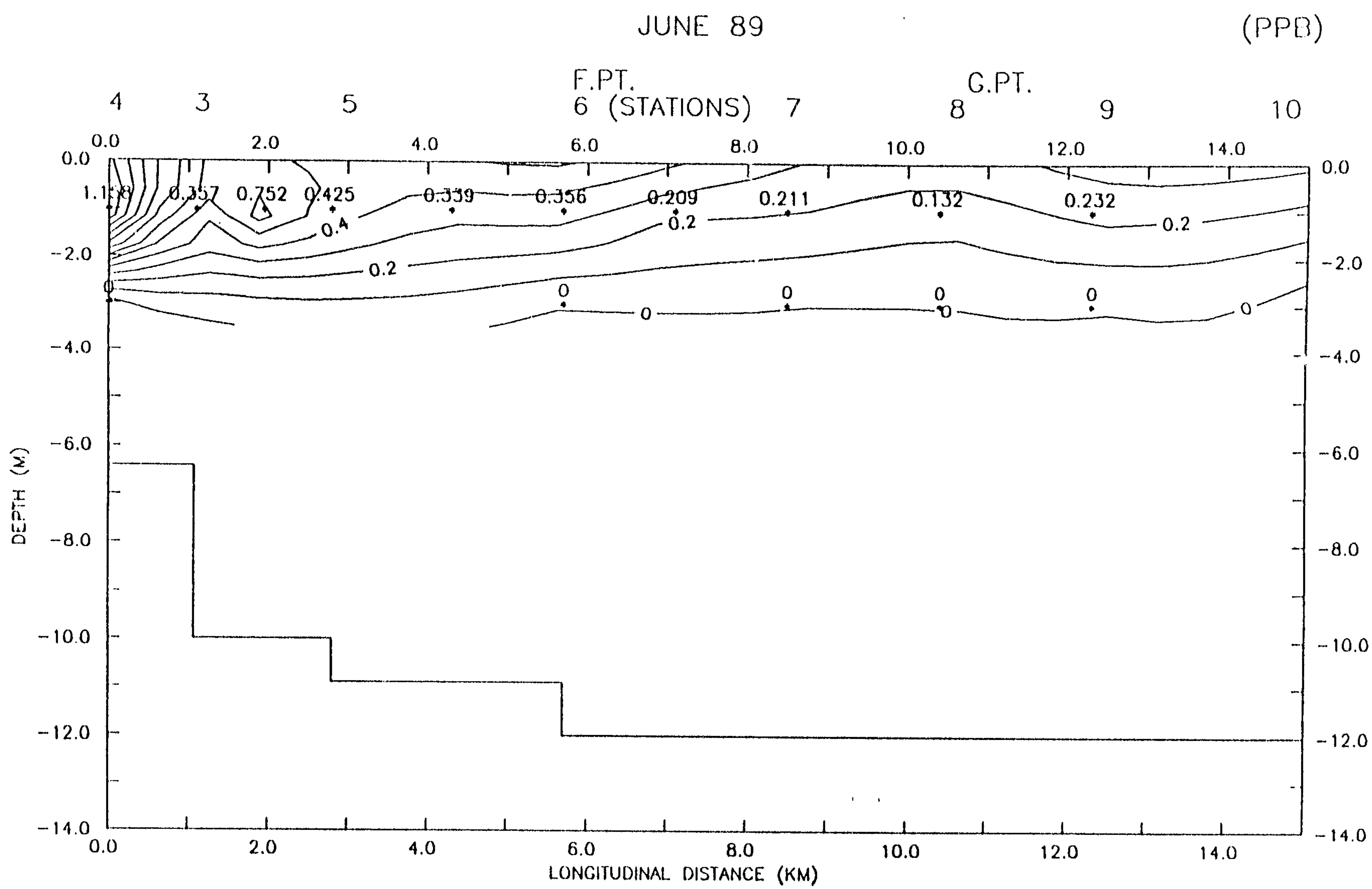


Figure 4.24 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 5, 0057-0220 June 14, 1989.

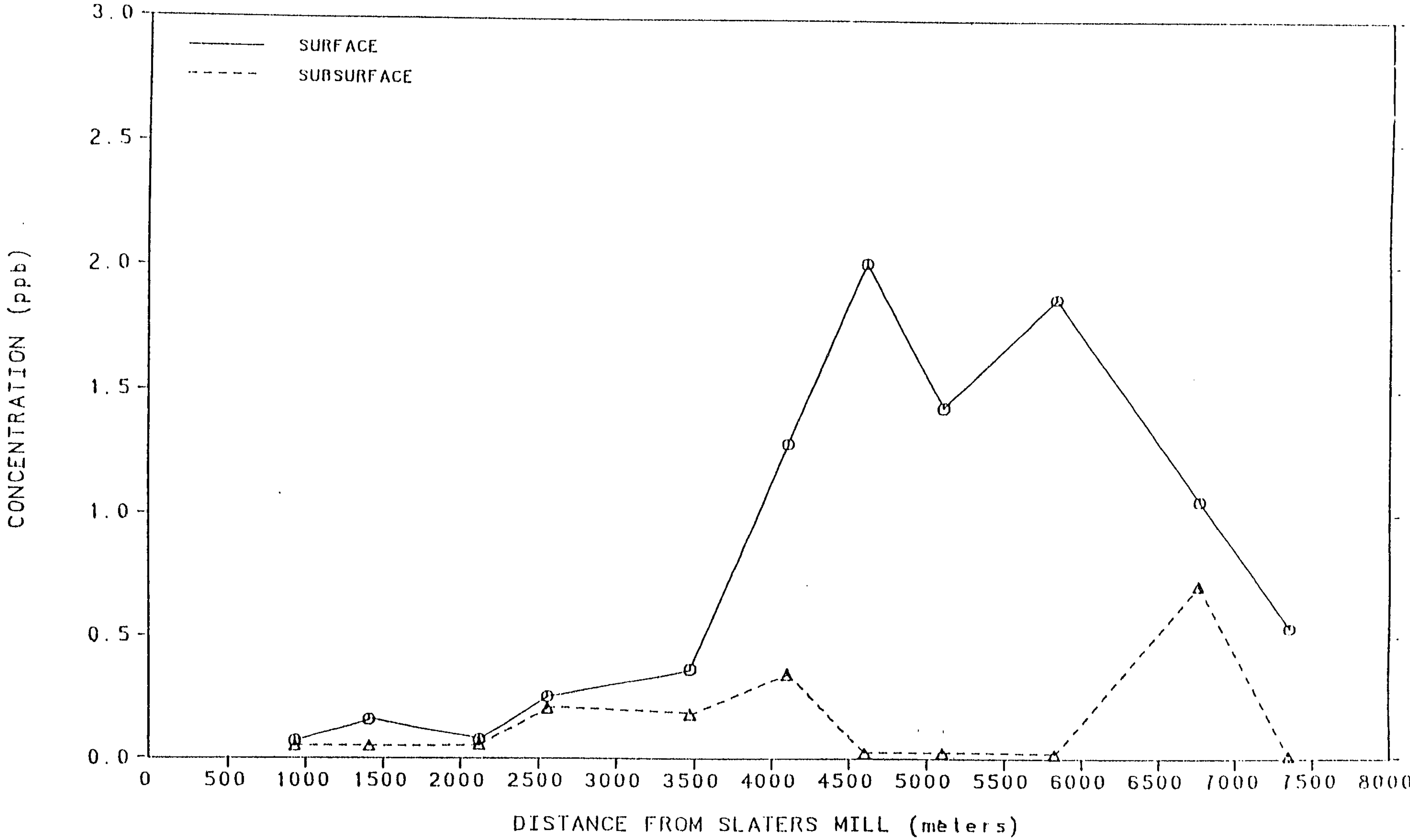


Figure 4.25 Dye concentrations at the near-surface and near-bottom depths in the Seekonk River as a function of distance from Slaters Mill Dam during survey 3, 1729-1844 June 13, 1989.

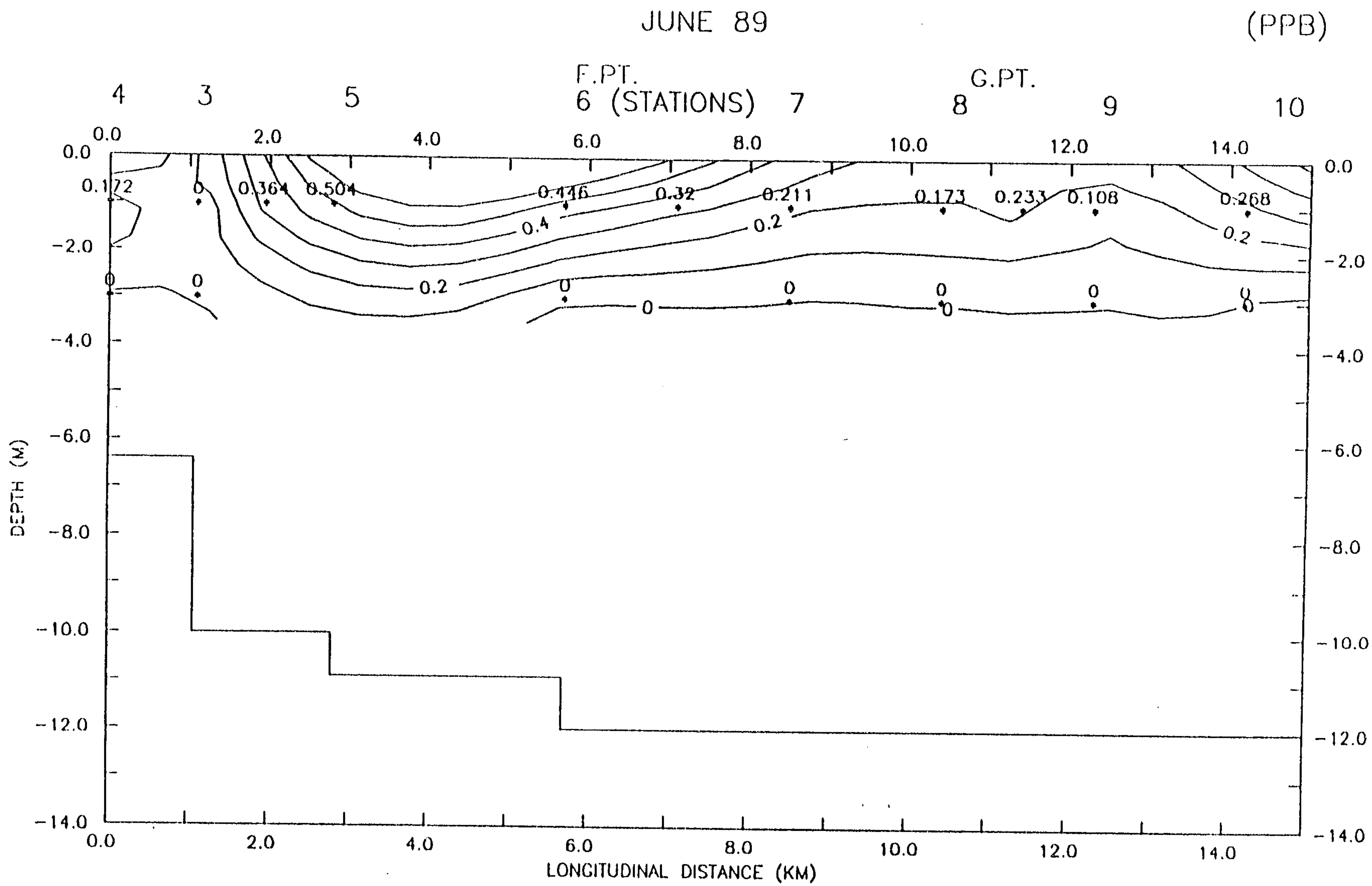


Figure 4.26 Contoured vertical cross-section of dye concentration along the center of the Providence River during survey 6, 0349-0600 June 14, 1989.

V is the mean volume of the area

Q is the time-averaged exchange rate

This has as a solution of the form:

$$C(t) = C_o \exp\left(- \frac{Qt}{V}\right) \tag{4.2}$$

where

$$k = \frac{Q}{V} \tag{4.3}$$

is a decay constant which is equal to the slope of the natural logarithm of C versus time. For the case of an instantaneous injection, it can be shown that (van de Kreeke, 1983):

$$t_f = \frac{1}{k} \tag{4.4}$$

where $t_f$ is the residence or flushing time of the water body. In this case, it also represents the e-folding time for decrease in dye concentration.

The flushing time for calculation for the reach of the river was performed by sorting the dye observations into the reaches shown in Figure 4.27. The observations were then averaged by depth and a weighting factor was applied to account for the variation in volume with depth in each reach. The weighted dye observations were summed then divided by the reach volume to produce a mean dye concentration for each reach by survey. The slope of the time history of the natural log of mean dye concentration could then be determined by linear regression. The area-wide flushing time was similarly determined by summing the volume-weighted reach flushing times, then dividing by the area volume.

Table 4.7 lists the results obtained for each station during the October, 1988 experiment. Correlation coefficient ($R^2$) values above 0.5 were obtained for stations 3, 4, 5 and 6. The flushing times calculated for these stations ranged between 1.8 days-3.3 days. Flushing times for the remaining downstream stations varied between 3.1 and 5.1 days, however the correlation coefficients ($R^2$) were low. Peak concentrations at stations 7, 8, 9 and 10 occurred 50 hrs., 70 hrs., 100 hrs. and 70 hrs. respectively, after the start of the release as the dye cloud moved down-river. It is apparent that the low correlation coefficients are attributable to the fact that the dye moved through these

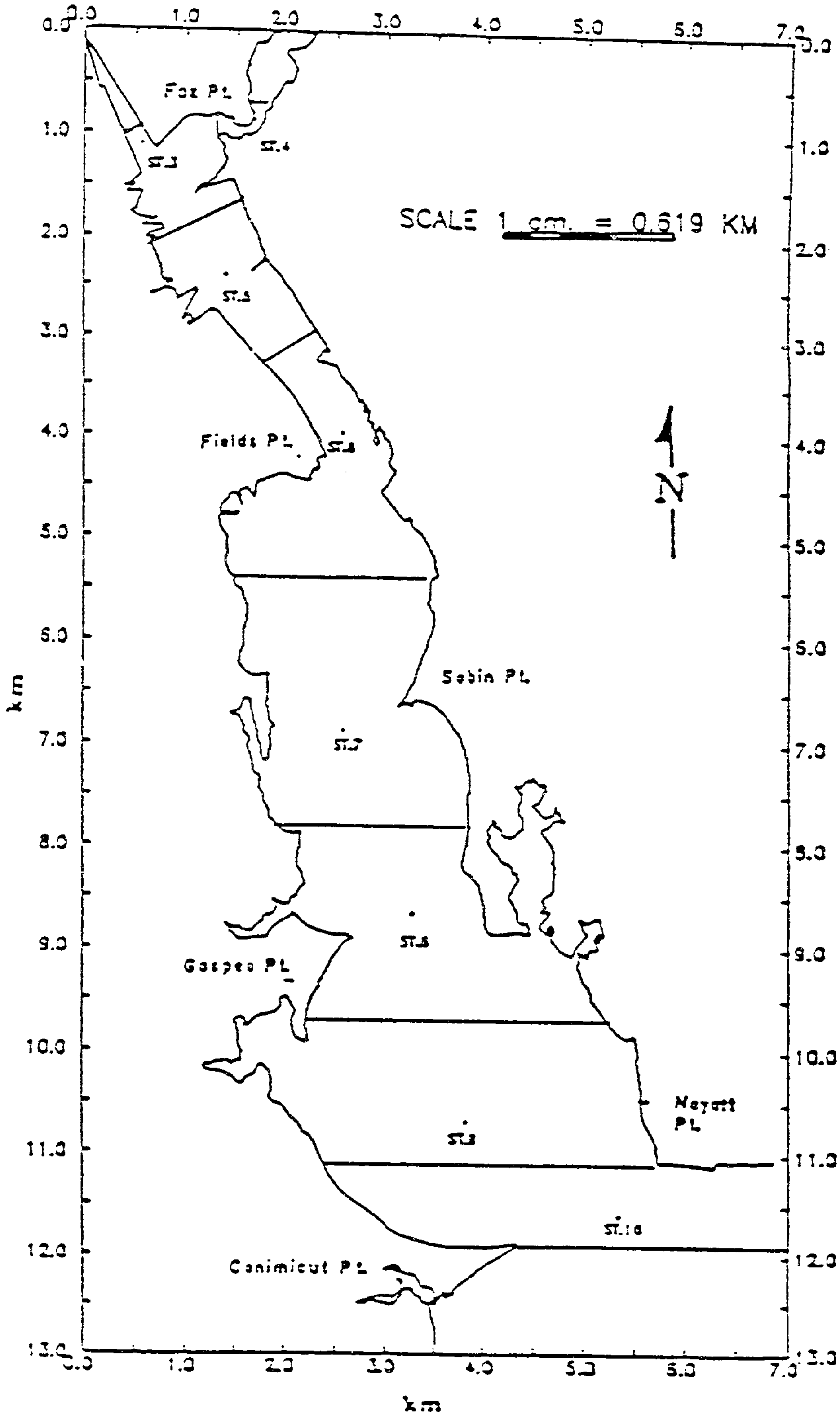


Figure 4.27 Sub-sections (boxes) used in the Providence River

Table 4.7 Dye decay constants, flushing times and correlation coefficients calculated from dye data for selected stations in the Providence River during the October 21-26, 1988 experiment.

| Station Number | Decay Constant ($hr^{-1}$) | Flushing Time (days) | Square of Corr. Coeff. ($R^2$) |
|---|---|---|---|
| 3 | 0.0230 | 1.8 | 0:575 |
| 4 | 0.0157 | 2.6 | 0.880 |
| 5 | 0.0169 | 2.5 | 0.796 |
| 6 | 0.0128 | 3.3 | 0.774 |
| 7 | 0.0133 | 3.1 | 0.188 |
| 8 | 0.0082 | 5.1 | 0.070 |
| 9 | --- | --- | ---- |
| 10 | 0.0105 | 4.0 | 0.0282 |

reaches as a cloud rather than spreading and decaying uniformly. The volume weighted dye concentration of the Providence River as a whole versus time is shown in Figure 4.28 for the October 1988 experiment. The mean dye concentration drops rapidly, as the Fields Point Plume moves south of Station 6, then rises as it is again detected at the downstream stations. After survey 7 on October 23, the mean becomes less variable and declines in a more regular fashion through the end of the experiment.

Table 4.8 lists the dye decay coefficients flushing time and $R^2$ for each station in the Providence River during the May 1989 experiment. No data were obtained for station 3. The flushing time estimates are short ranging from a low of 2 hours at station 8 to 34 hours at station 9. The correlation coefficients ($R^2$) are above 0.5 at all station. Four stations (4, 6, 9, 10) have $R^2$ values above 0.80.

Figure 4.29 presents the time histories of log of dye concentration in the Providence River. Following the start of the release the rate of decay of the dye was relatively rapid. The calculated flushing time was 0.9 however by the 20 hour point, dye concentrations were near pre-storm background level.

Dye concentrations measurements were obtained in the Seekonk River for a period of twenty-three hours following the start of the dye release. Figure 4.30 shows the natural log of dye concentration versus time for the Seekonk River. The flushing time was 0.9 days, slightly shorter than the flushing time of the Providence River. The correlation coefficient was 0.734. The flushing time of the combined Providence and Seekonk River area during the May 1989 experiment was 1.7 days.

Table 4.9 lists dye decay constants, flushing time and $R^2$ values for the different stations. Flushing time estimates for the stations ranged from 10 to 42 hours.

The natural log of dye concentration versus time is shown in Figure 4.31 for the Providence River. The flushing time of the area was 2.5 days. The flushing time for the Seekonk River was estimated at 0.54 days with a correlation ($R^2$) of 0.861. The combined flushing time of the Seekonk and Providence Rivers was 3.0 days.

### 4.2.3 Correlations Between Dye Concentrations and Pollutant Indicators

Scatter plots of fecal coliform concentrations versus dye are presented in Appendix E. The figures are presented in log-linear form because fecal coliform levels typically

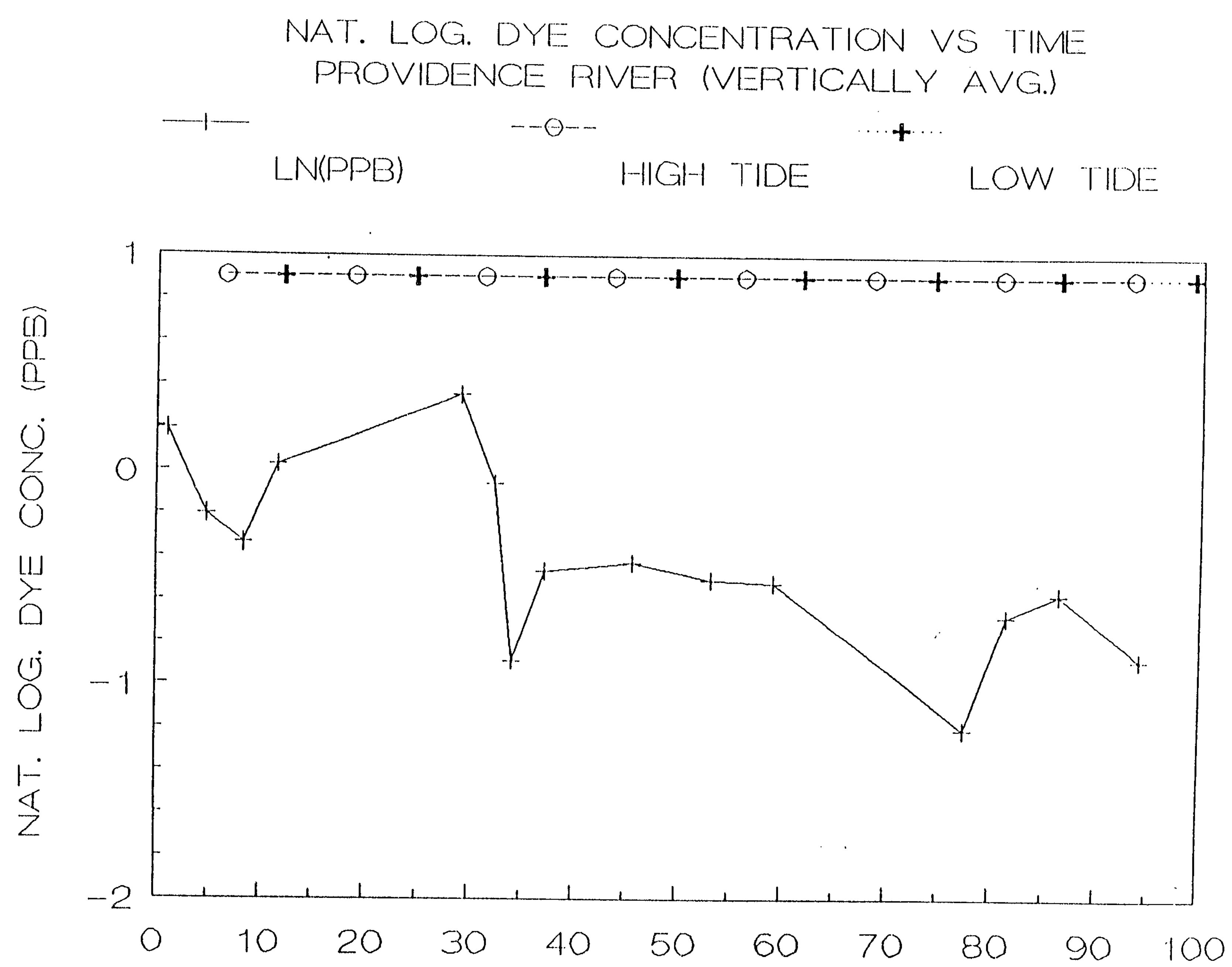


Figure 4.28 Natural log of vertically and a really averaged dye concentration in the Providence River as a function of time after 0500 October 22, 1988.

Table 4.8 Dye decay constants, flushing times and correlation coefficients calculated from dye data for selected stations in the Providence River during the May 10-15, 1989 experiment.

| Station | Decay Constant (K) ($hr^{-1}$) | Flushing Time (days) | Square of Corr. Coeff. ($R^2$) |
|---|---|---|---|
| 3 | --- | ----- | ----- |
| 4 | 0.0886 | 0.47 | 0.829 |
| 5 | 0.0886 | 0.47 | 0.512 |
| 6 | 0.1668 | 0.25 | 0.930 |
| 7 | 0.0834 | 0.50 | 0.724 |
| 8 | 0.0599 | 0.70 | 0.618 |
| 9 | 0.0687 | 0.61 | 0.813 |
| 10 | 0.1099 | 0.38 | 0.889 |

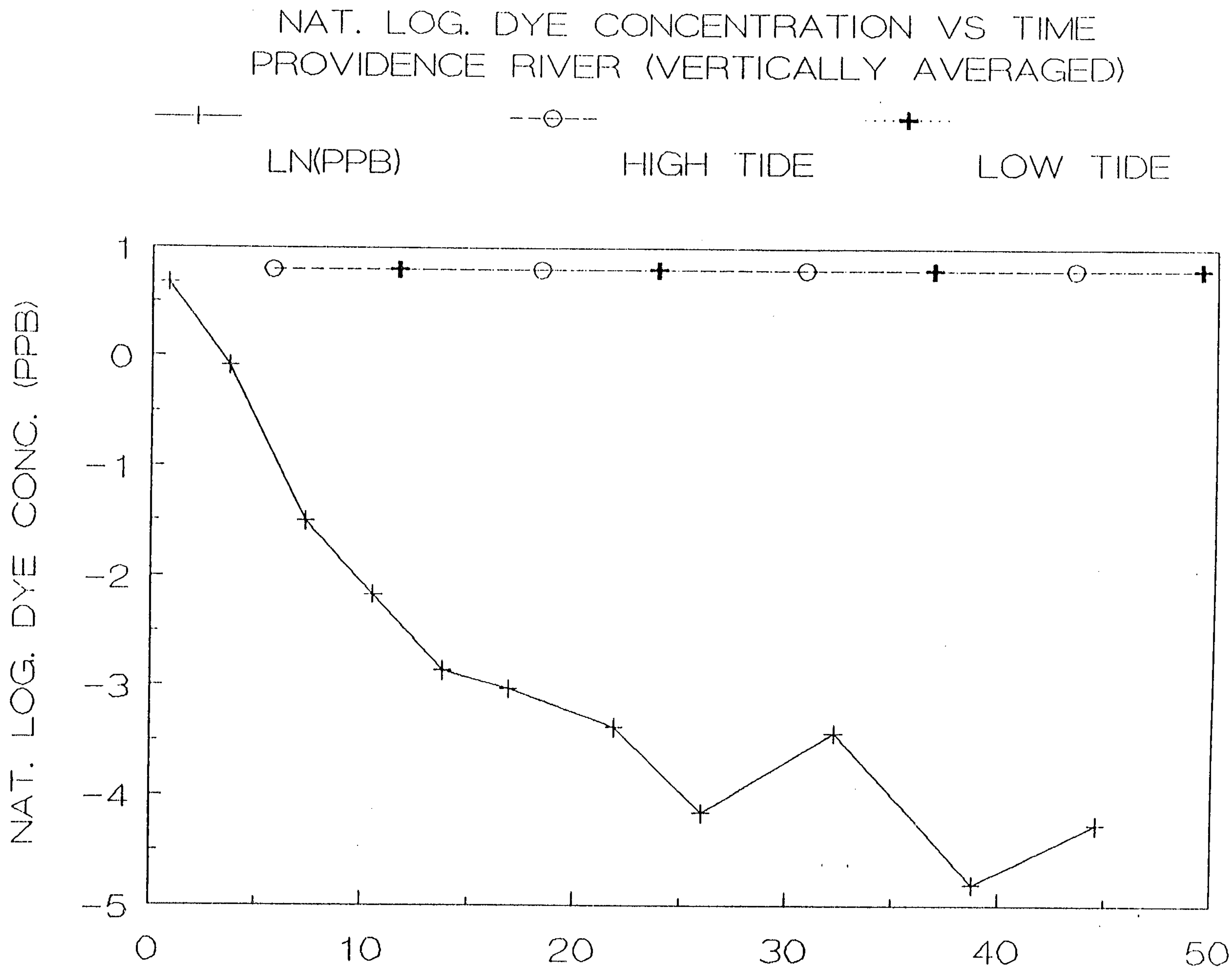


Figure 4.29 Natural log of vertically and areally averaged dye concentration in the Providence River as a function of time after 2200 May 10, 1989.

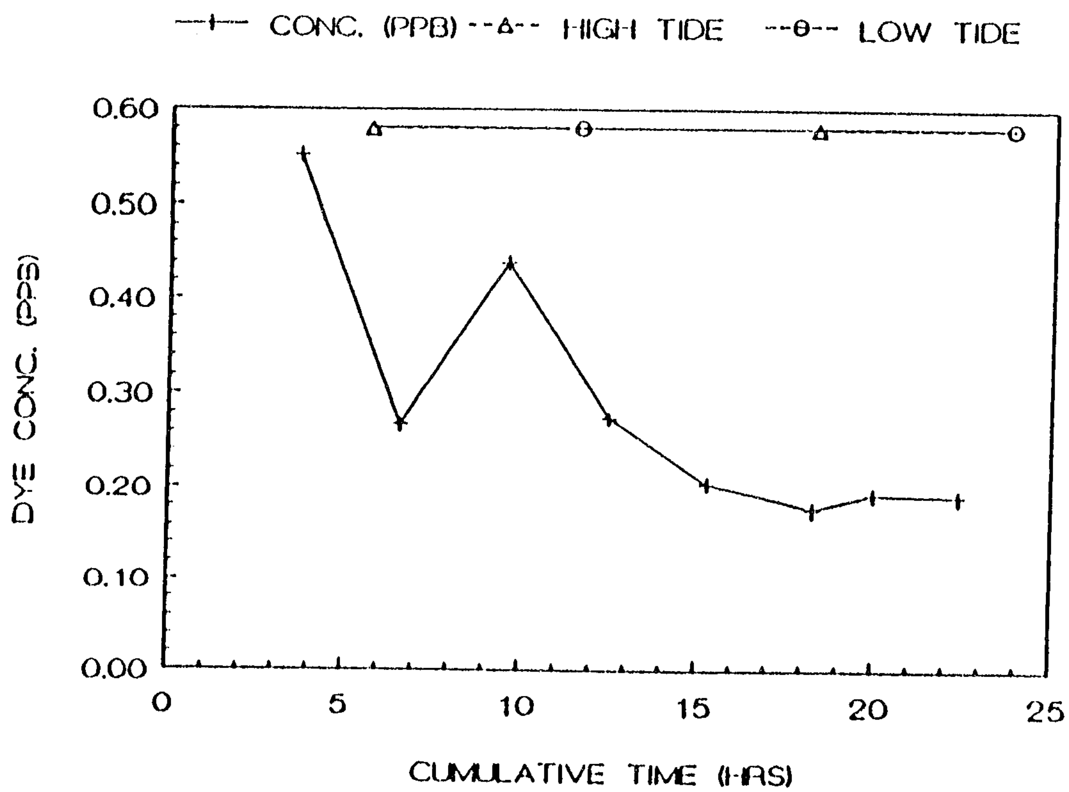


Figure 4.30 Dye flushing in the Seekonk River during the May 1989 Wet Weather experiment, State of tide is indicated at the top of the graph

Table 4.9 Dye decay constants, coefficients, flushing times and correlation coefficients calculated from dye data for selected stations in the Providence River during the June 13-16, 1989 experiment.

| Station | Flushing constant (K) | Flushing Time (days) | Square of Corr. Coeff. ($R^2$) |
|---|---|---|---|
| 3 | 0.0330 | 1.3 | 0.872 |
| 4 | 0.0310 | 1.3 | 0.555 |
| 5 | 0.0234 | 1.8 | 0.460 |
| 6 | 0.0298 | 1.4 | 0.468 |
| 7 | 0.0166 | 2.5 | 0.508 |
| 8 | 0.0223 | 1.9 | 0.605 |
| 9 | 0.0036 | 11.5 | 0.010 |
| 10 | 0.0275 | 1.5 | 0.724 |

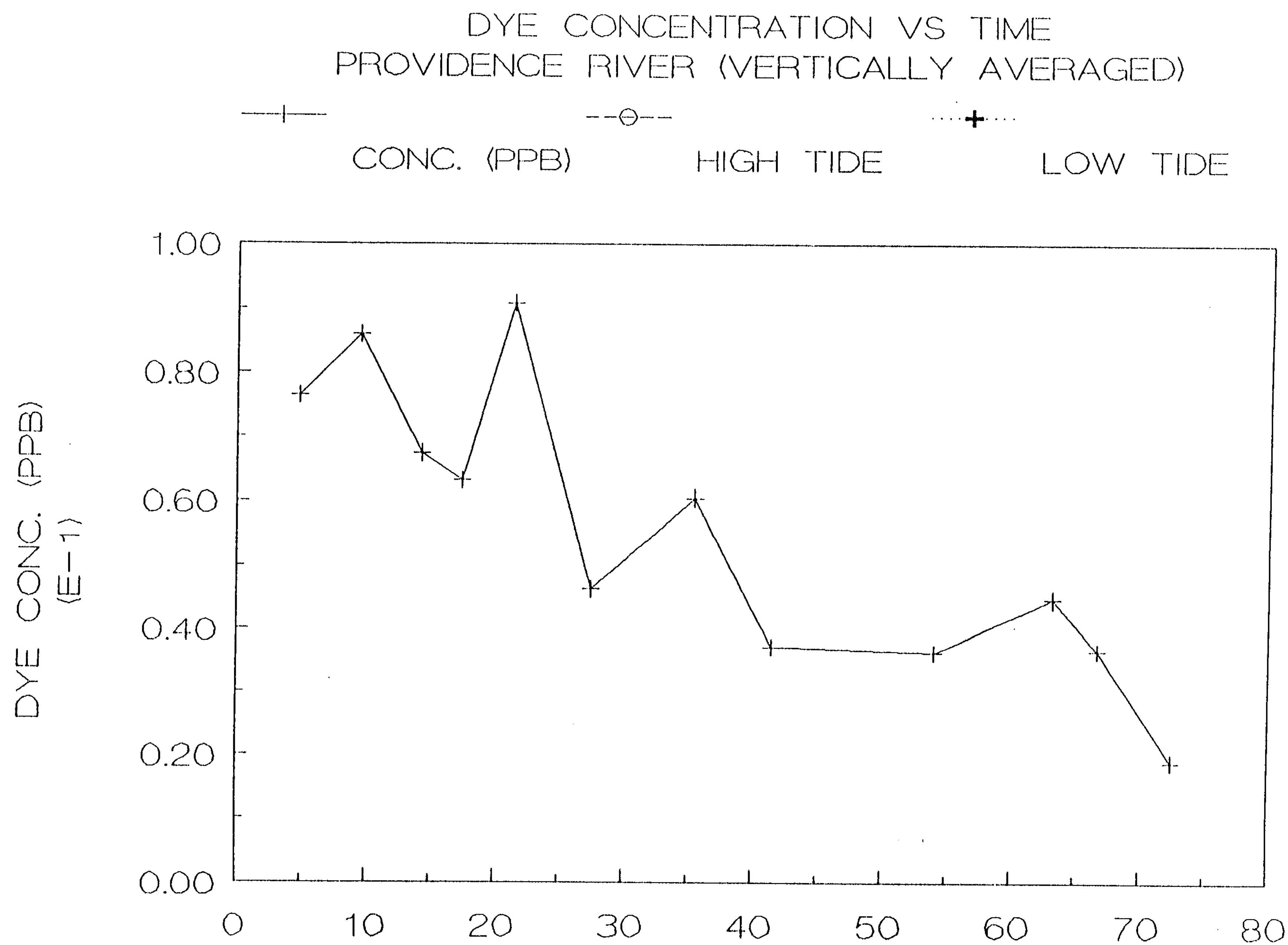


Figure 4.31 Natural log of vertically averaged dye concentration at Station 10 as a function of time after 2200 May 10, 1989.

varied by the factor of 100 over each experiment, while dye concentrations varied by only a factor of 5-10. The data points in each figure are presented as numbers, to signify the survey numbers in Tables 4.1, 4.2, and 4.4 during which the dye observations and water sample collections were made. Data points were not included in the scatter plot when the time separation between the dye measurement and water sample collection exceeded 10 minutes. Data points were also omitted when either the dye measurements or water sample collection were not conducted.

The scatter plots generally show a weak correlation between dye and fecal coliform concentrations. The lack of a distinct relationship in the two parameters may be due to the contrasting release conditions of the two indicators. Whereas the dye was released from four points in the study area during a well-defined period, fecal coliforms were released over a multitude of sources such as CSO's. The rates at which coliforms were released and periods of release were also variable during each study.

Scatter plots of metals concentrations versus dye concentration are shown in Appendix F for selected stations in the Providence River for experiment 2. The dissolved and particulate phases of copper, lead, and cadmium have been arbitrarily selected for comparison at stations 4 and 6. The data are plotted by survey number to provide insight on the timing of the data. Survey numbers are referenced to times in Tables 4.1, 4.2 and 4.4.

The scatter plots show a positive correlation between dissolved phases of the three metals at the surface and bottom at station 4 during the first study. No correlation is evident between dye and particulate metals concentrations at station 4. Dissolved metals concentrations were relatively constant near the surface at station 6, with the result that the slope of the trend is essentially zero. No clear relationship between surface dye and dissolved metals concentrations is evident. Also, no relationship between dye and particulate metals concentrations at the surface and bottom is evident at station 6.

The metals versus dye scatter plots were created only for the surface water samples during the second experiment (May 10-15, 1989) because dye was detected only at that depth. The figures in Appendix F indicate that virtually no relationship is evident between dye and metals constituents during the experiment.

The lack of the reasonable relationship between dye and metals concentration is attributable to a number of reasons. First among these is that the sources of metals to the Providence and Seekonk River system are distributed along the length of the area. The sources rates were probably quite variable, following rainfall intensities at least early in the study. The results may also indicate that the point sources selected for the study do not represent the principal storm-related sources of metals to the study area. This may be supported by the observation that the variations in metals levels at station 6 adjacent to the Fields Point outfall, do not correspond with variations in dye levels.

### 4.3 Salinity and Dissolved Oxygen

Contoured vertical cross-sections of the salinity field along the center of the Providence River are presented in Appendix G for the three experiments. The results shown for the October 1988 survey were obtained from measurements made by Wright et al. (in preparation) because of the failure of the STD-12 instrument used for this study. Observations for that survey #1 are given with the contoured fields to illustrate how the salinity contours generated for the figures relate to the data. The vertical spacing of data obtained from the STD-12 instrument for the second and third surveys was 0.3 m thus the volume of information used to generate the contoured fields was considerable. The observations for these surveys have therefore not been superimposed on the contoured fields for the sake of clarity.

The October 1988 data (Figure 4.32) show a weakly stratified salinity structure existing in the river. Near-bottom salinities vary between 28.2 and 30.0 ppt at stations 6 and 8. The surface to bottom salinity difference is between 1-5 ppt. These observations are consistent with earlier data for the area (Doering et al., 1988).

The May 1989 and June 1989 data portray a significantly different view of the salinity field. (Figures 4.33 and 4.34) Surface salinities approach 2-4 ppt at station 4 and vary from less than 6 ppt to about 12 ppt in the center reach of the river. The water column is highly stratified with surface-bottom salinity differences exceeding 20 ppt for many observations near stations 6-8. Near-bottom values are 28-31 ppt in the center reach of the river.

The flushing time of the study area was also calculated based on the salinity data and freshwater inflow data for the May and June 1989 experiment.

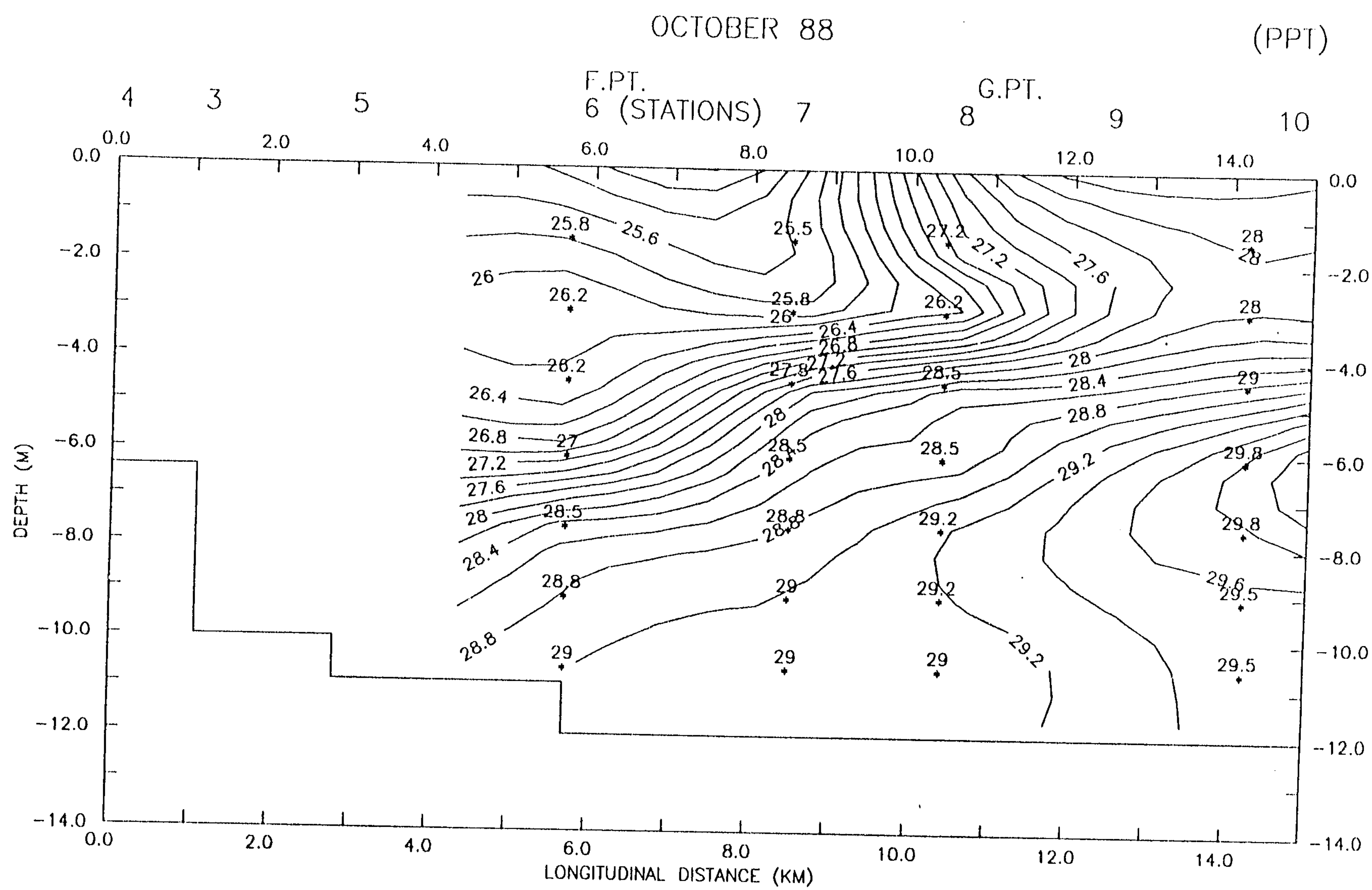


Figure 4.32 Contoured vertical cross-section of the salinity field at approximately 08:00, October 23, 1988. (From Wright et al., in preparation)

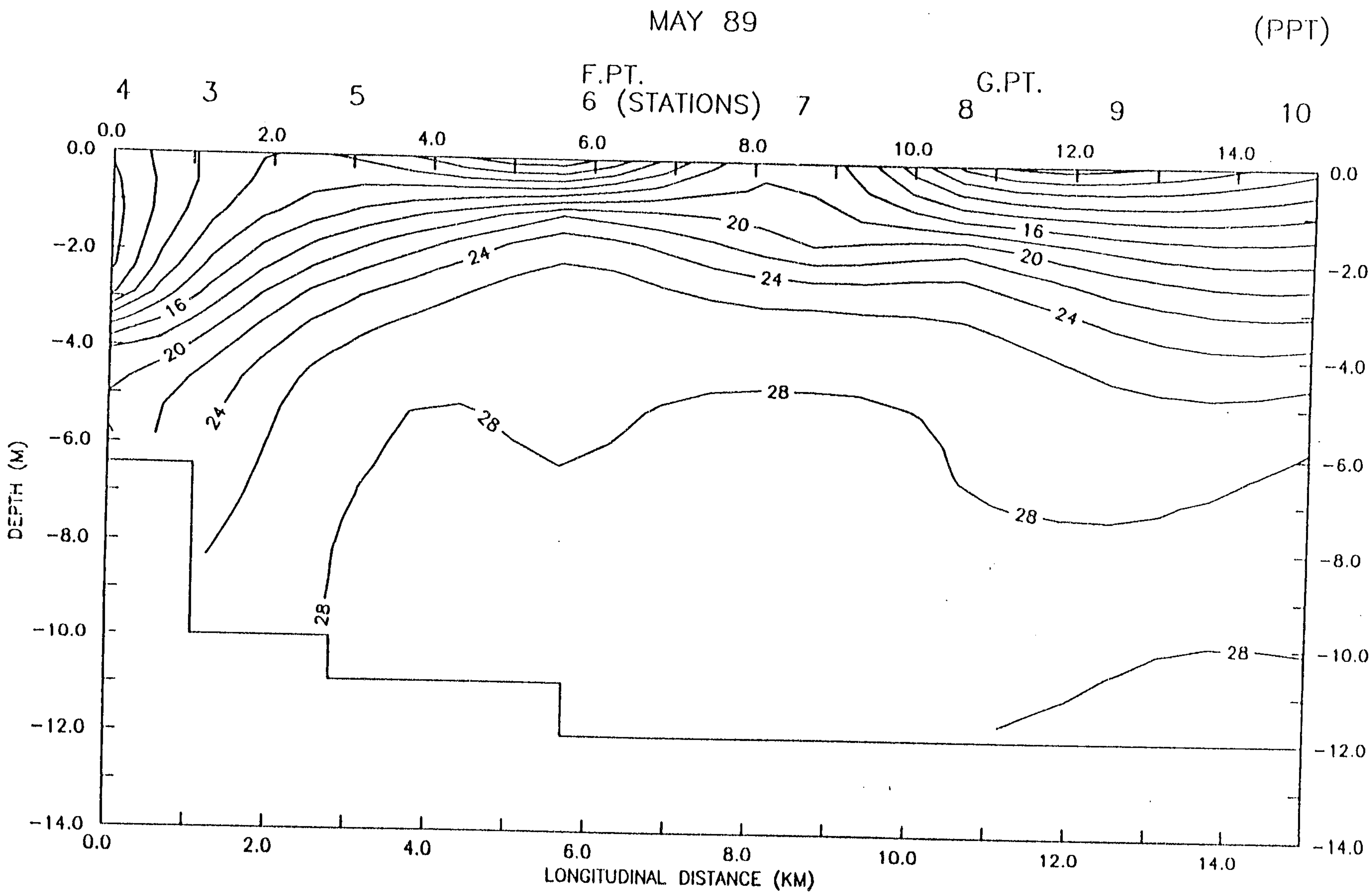


Figure 4.33 Contoured vertical cross-section of salinity along the center of the Providence River during Survey 4, 04:00-05:23, May 11, 1989.

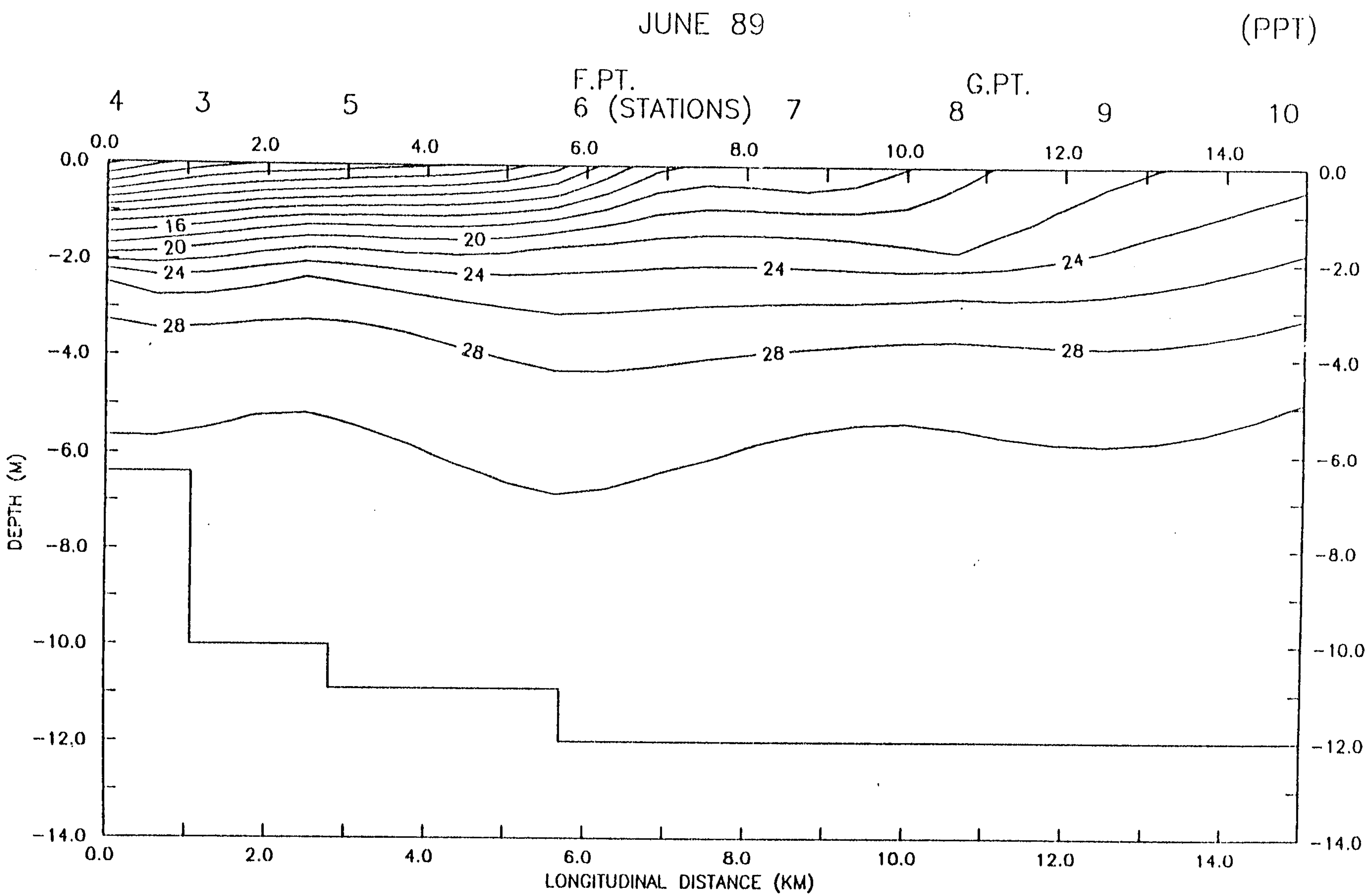


Figure 4.34 Contoured vertical cross-section of salinity along the center of the Providence River during Survey 2, 15:31-16:58, June 13, 1989.

Given the freshwater source rate, R and a freshwater volume, $V_f$, the flushing time $t_f$ is determined by the expression $t_f = V_f/R$ (Officer, 1976). The freshwater volume term is expressed as:

$$V_f = f\ V,$$

$$\text{where } f = \frac{So - S}{So},$$

V is the mean volume of the water body
S is the mean salinity of the body
So is the mean salinity of the area to which the water body empties. In this case So is taken to be the water column averaged salinity of the Upper Bay near the mouth of the Providence River.

Salinity data obtained during the May and June 1989 experiments were used to calculate values of S and So during each period. The weightings assigned to the salinity data were identical to the volume weighting factors applied earlier to the dye data which reflect the variation of cross-section volume with depth in the area of each station. The calculation for S was based on data for stations 3-9 and yielded mean salinities of 22.356 ppt and 25.466 ppt in the Providence River during the May and June experiments, respectively. The calculation of So was based on data for station 10 and yielded values of 24.168 and 27.826 ppt for the May and June experiments, respectively.

Estimates of the freshwater inflow term, R, were obtained from Asselin (1991). Asselin based the inflow estimated principally on USGS and treatment plant records, and on flow measurements by Wright et al during the three experiments. The sources included five tributaries, three treatment plants and the largest CSO, CSO9 near Fields Point. Other CSO's were found to represent a negligible increment in the total inflow term. The tributary data were scaled up to account for flows from areas downstream of the gauges. The inflows were than averaged over the ten-day period preceding the storm. Summaries of the freshwater inputs are presented in Table 4.10. The combined mean inflows were estimated to be 16.2 $m^3/s$, 80.33 $m^3/s$ and 59.4 $m^3/s$ for the October 1988, May 1989 and June 1989 events, respectively.

The May and June 1989 salinity and inflow data yielded flushing time estimates of 1.1 days and 1.7 days, respectively. These values compare reasonably well with the estimates of 0.9 days and 2.5 day obtained from the dye decay analyses.

Table 4.10 Fresh water inflows in $m^3/s$ from tributaries, treatment plants and CSO9 averaged over the ten day period prior to each Wet Weather experiment (from Asselin, 1991).

| Source | October 1988 | May 1989 | June 1989 |
|---|---|---|---|
| Woonasquatucket River | 0.62 | 4.67 | 2.93 |
| Moshassuck River | 0.19 | 2.56 | 1.58 |
| Pawtuxet River | 4.06 | 11.59 | 9.10 |
| Ten Mile River | 0.61 | 8.46 | 4.34 |
| Blackstone River | 8.44 | 48.51 | 37.64 |
| Field's Point STP | 1.19 | 2.96 | 2.45 |
| BVDC STP | 0.89 | 1.14 | 1.08 |
| East Providence STP | 0.18 | 0.35 | 0.26 |
| CSO 9 | 0.01 | 0.04 | 0.05 |
| Mean total inflow | 16.2 | 80.3 | 59.4 |

Contoured vertical cross sections of the dissolved oxygen (DO) field in the river are shown in Appendix H. The October 1988 date could not be corrected for salinity and are not shown in the appendix. The data shown for May and June 1989 have been corrected for salinity.

Typical views of the DO field during the May and June experiments are presented in Figures 4.35 and 4.36, respectively. The May data typical show an area of lower DO, between 7-8 mg/l which is relatively uniform in the vertical directions, in the reach between stations 6 and 8. The upper harbor area is relatively stratified, with surface DO ranging between 7.8-10.7 mg/l and bottom values ranging from 4.9-8.0 mg/l. The area downstream of station 8 is also somewhat stratified, with values between 6.8-8.5 mg/l near the bottom, increasing to 8.0 to 12.5 mg/l near the surface. Peak values were sometimes observed at the 2-3 m depth during this period.

During the June 1989 experiment, the structure of the DO field was similar to that of the salinity field. The principal features of the field was the presence of an area of high DO, between 7.0 to above 13 mg/l near the surface downstream of station 6. DO was low near the bottom throughout the river, between 2.5-5.5 mg/l, with DO generally increasing in the seaward direction. Levels at the upstream station are also relatively low and vary between 3.2-4.2 mg/l at the bottom to 6.0-8.6 mg/l at the surface.

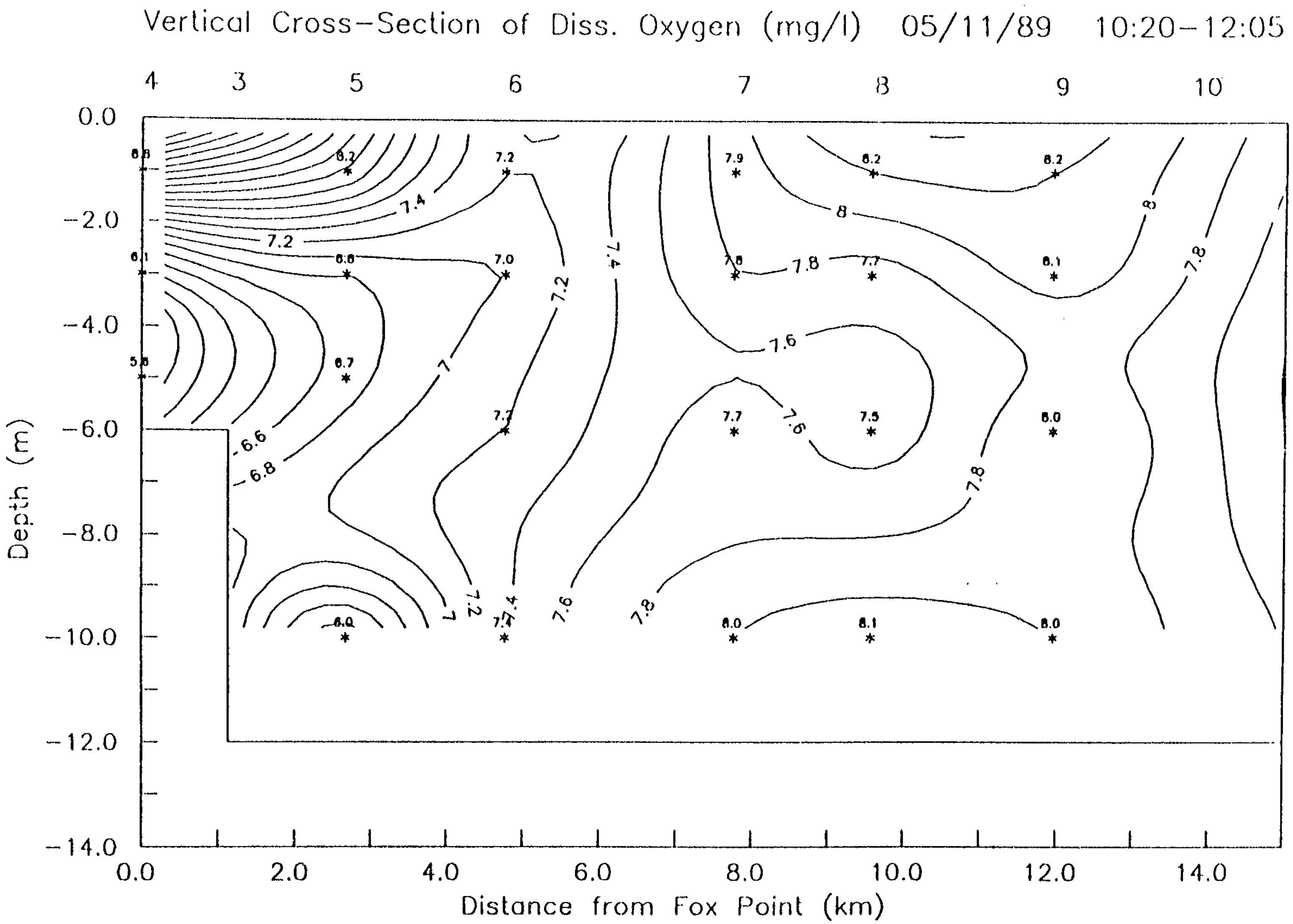


Figure 4.35 Contoured vertical cross-section of dissolved oxygen along the center of the Providence River during Survey 6, 10:30-12:05, May 11, 1989.

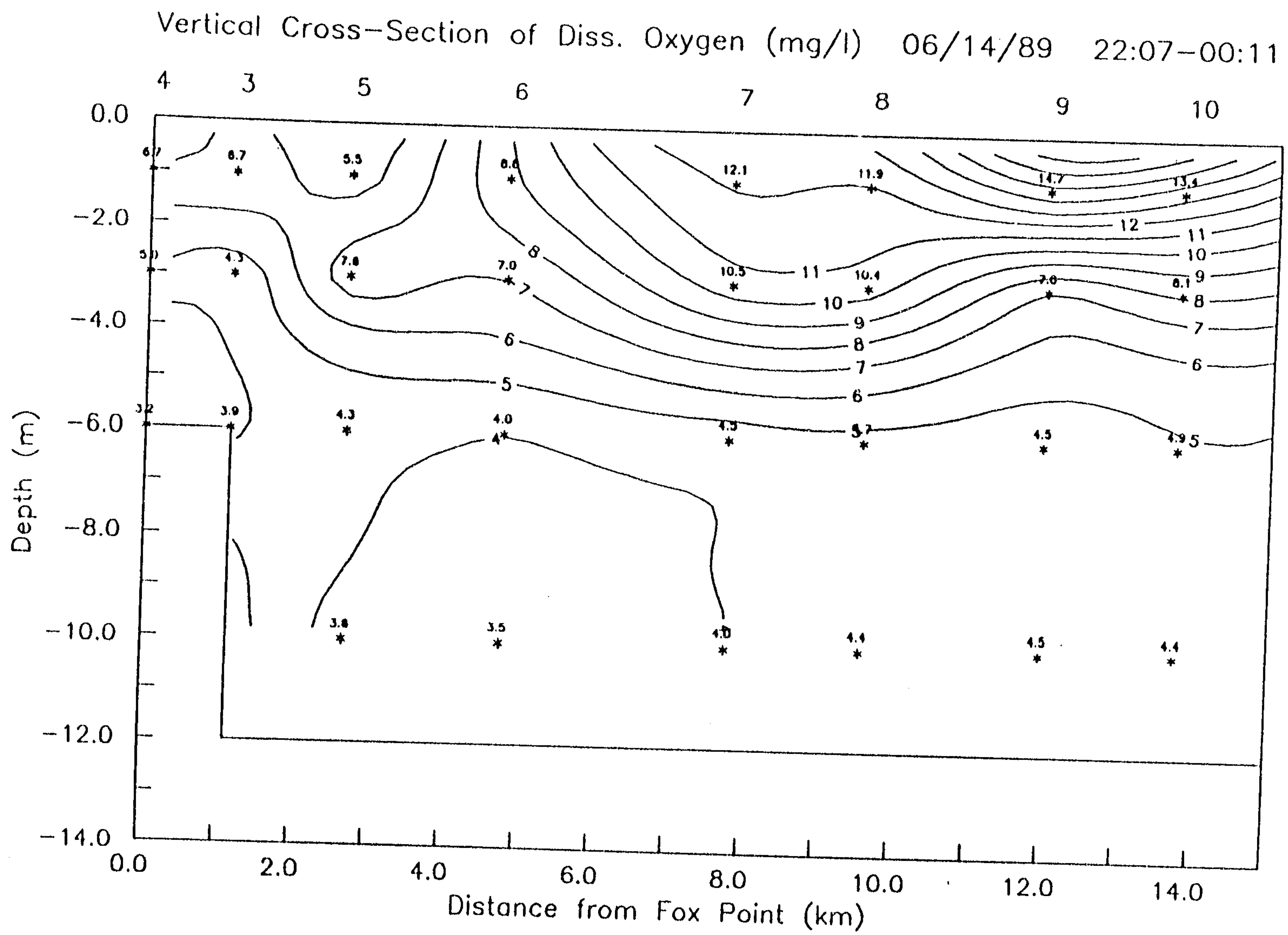


Figure 4.36 Contoured vertical cross-section of dissolved oxygen along the center of the Providence River during Survey 9, 22:07 June 14 - 00:11, June 15, 1989.

## 5. CONCLUSIONS

The measurements produced contrasting pictures of the behavior of dye and other pollutants among the three experiments. During the October 1988 surveys, the dye was found to mix vertically to a greater extent. The rate of decrease of dye concentration at a fixed point in the area was also much slower, implying that flushing was slower. Salinity measurements made by Wright et al. (in preparation) indicated that vertical stratification of salinity was lower than for the two succeeding surveys.

The Providence River was significantly more stratified with much lower surface salinity values during the May 1989 experiment. Once released into the Providence River, the dye remained in the top 1 m of the water column and moved rapidly down estuary. Within 72 hours after the start of the release, dye was only detectable at the mouth of the estuary. The movement of dye down the Seekonk River was similarly rapid. A majority of the dye released to the Seekonk River had left the river 12 hours after the start of the releases. The movements of the dye in the Providence and Seekonk Rivers were consistent with observed current excursions from moored instruments in the area during the same period.

The characteristics of the dye and salinity fields during the June 1989 study were similar to those seen during the May 1989 experiment in that the dye remained concentrated at the surface of the Providence and Seekonk Rivers and dispersed rapidly in the area. Similarly, surface salinities were very fresh, ranging from 2-10 ppt in the upper river and with differences of 20 ppt or more over the water column.

The time rate of change of dye concentrations were determined for selected stations and for the Providence River as a whole. The flushing time estimates for the Providence River varied by nearly a factor of 5, from a low value of 0.9 days in May 1988 to 4.5 days in October 1989. The dye-based flushing calculations compared well with those calculated from freshwater inflow and salinity data.

The validity of the hypothesis that the dye would serve as an indicator for other pollutant species was tested by comparing concentrations of dye with fecal coliform, and dissolved and particulate concentrations of copper, lead and cadmium obtained from analyses of water samples collected along with the dye measurements. The analysis revealed that a weak relationship between dye and dissolved metals levels was observable at station 4. No relationships could be seen at station 6 south of Fields

Point. The results support a conclusion that the characteristics of pollutant loadings, rates as a function of time and source distributions, are complex in the area. They also indicate that distributed sources may play a large role in controlling pollutant levels in the study area.

## 6. REFERENCES


Asselin, S., 1991. Flushing times in the Providence River based on tracer experiment. MS Thesis, Dept. of Ocean Engineering, University of Rhode Island, Kingston. 247 p.

Chinman, R.A. and S.W. Nixon, 1985. Depth-Area-Volume Relationships in Narragansett Bay, NOAA Sea Grant, University of Rhode Island Sea Grant Marine Technology Report #87.

Deaner, D.G., 1973. Effect of chlorine on fluorescent dyes, J. Water Pollution Cont. Fed. Vol. 45, No. 3, pp 507-514, March 1973.

Doering, P.H., L. Weber, W.M. Warren, G.Hoffman, K. Schweitzer, M.E.Q. Pilson, C.A. Oviatt, J.D. Cullen, C.W. Brown, 1988. Monitoring of the Providence and Seekonk Rivers for Trace Metals and Associated Parameters. Data report, SPRAY Cruises IV, V, and VI. May 5, 1988.

Gadoury, R.A., D.J. Kent, K.G. Rieq, III, and H.L. White, 1988. Water Resources Data Massachusetts and Rhode Island Water Year 1986 USGS, Boston, Massachusetts.

Migliore, J., Department of Environmental Management, Division of Water Resources, 1989. Personal communication.

NOS, 1989. Tide height data for Providence, RI (unpublished) Tidal Datum Quality Assurance Section, Sea and Lake Levels Branch, Rockville, Md.

National Weather Service, 1989. Surface weather observation data for T.F. Green Airport, Warwick, RI.

Perkin, R.C. and E.L. Lewis, 1980. The practical salinity scale 1978: fitting the data IEEE Journal of Ocean Engineering, Vol. OE-5, No. 1, pp. 9-16.

Rantz, W.E., et al 1982. *Measurement and Computation of Stream Flow:* Vol 1. Measurement of stage and discharge geological survey water-supply paper 2175. USGPO, Washington, D.C. pp 226-230.

Swanson, J.C. and K. Jayko, 1988. Analysis of impacts of loads from CSO area C on upper Narragansett Bay. Submitted to Camp, Dresser and McKee, Boston, Massachusetts, ASA Project #85-32.

Tetra Tech, Inc., 1987. Evaluation of survey positioning methods for nearshore marine and estuarine waters. For Marine Operations Division, Washington, D.C., EPA Contract Number 68-01-6938, TC 3953-03. Final Report.

van de Kreeke, J.M., 1983. Residence time: application to small boat basins. Journal of Waterway, Port Coastal and Ocean Engineering, Vol. 109, No. 4, November. Paper No. 18388.