CM-2110
Mr. Rouse
Project 1
CZ 228
and Perdido
Bay Section
309 grant

A REPORT ON PHYSICAL AND CHEMICAL PROCESSES AFFECTING THE MANAGEMENT OF PERDIDO BAY

Results of the
PERDIDO BAY INTERSTATE PROJECT

ADEM

ALABAMA
DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

Florida Department of
Environmental Regulation

January 25, 1991

GB
991
.S37
F6
1991

AUTHENTICATED
U.S. GOVERNMENT
INFORMATION
GPO

A REPORT ON PHYSICAL AND CHEMICAL PROCESSES AFFECTING THE MANAGEMENT OF PERDIDO BAY

Results of the PERDIDO BAY INTERSTATE PROJECT

Steven J. Schropp, Ph.D.
Fred D. Calder
Gail M. Sloane
Kathleen O. Swanson

Florida Department of Environmental Regulation
Coastal Zone Management Section
2600 Blairstone Rd.
Tallahassee, Florida 32301

John C. Carlton
Gary L. Halcomb

Alabama Department of Environmental Management
Mobile Field Office
2204 Perimeter Rd.
Mobile, Alabama 36615

Herbert L. Windom, Ph.D.
Feng Huan

Skidaway Institute of Oceanography
Savannah, Georgia 31406

R. Bruce Taylor, Ph.D., P.E.
Terrence Hull

Taylor Engineering
9086 Cypress Green Dr.
Jacksonville, Florida 32216

January 25, 1991

GB 991 .S37 FL 1991

Funding for this project was provided by the Florida Department of Environmental Regulation, Coastal Zone Management Section, using funds made available through the National Oceanic and Atmospheric Administration under the Coastal Zone Management Act of 1972, as amended.

Property Of
NOAA Coastal Services Center
Library

EXECUTIVE SUMMARY

BACKGROUND AND PURPOSE OF THE STUDY

The Florida Department of Environmental Regulation and Alabama Department of Environmental Management initiated this study in response to increasing public and agency concern over the future of Perdido Bay. From a review of existing data and interviews it was evident that judgments on the effects of present activities and future development on the bay could not be supported without system-wide water chemistry and circulation information.

Objectives of this study were to describe physical and chemical processes affecting dissolved and particulate nutrient and suspended solid transport in the Perdido River basin and the fate of these materials in Perdido Bay. We also had the opportunity, under Florida's Coastal Zone Management Program, to analyze sediments for metals and organic compounds. Achieving these objectives provides information needed to answer several questions about the condition of Perdido Bay:

- How do tide, wind, and runoff affect water movement in Perdido Bay and to what extent is circulation confined in the upper bay?
- What pollutants are entering the bay and from where?
- Is Perdido Bay silting up due to man's activities in adjacent watersheds?
- What is the rate of supply of nutrients to Perdido Bay and what is man's influence on this rate?
- Does Perdido Bay trap nutrients?
- How prevalent are hypoxic conditions in Perdido Bay and what are the causes?
- How can we summarize the present condition of Perdido Bay?

As in many other coastal systems, the limited information that did exist for Perdido Bay was not on system-wide processes and could not provide answers to the questions above. While localized data are useful for individual regulatory decisions,

broader studies that integrate bay-wide physical and chemical information are essential for judging the susceptibility of the bay to development pressures, developing practical bay management objectives and plans, and providing sound guidance for maintaining conditions to support estuarine productivity.

STUDY COMPONENTS

To answer the questions posed in the preceding section, the Interstate Project conducted a multi-faceted investigation of the Perdido Bay estuarine system. Components of the study included:

- Water movement
  - Streamflow
  - Estuarine circulation
- Water chemistry
  - River chemistry
  - Estuarine chemistry
- Sediment chemistry

SUMMARY OF RESULTS

With the Interstate Project, we have attempted to identify conditions in Perdido Bay that are due to natural characteristics of the bay and watershed as opposed to those that result from anthropogenic activities. Because of the limited resources available for the Interstate Project and general perceptions regarding conditions in the upper part of the bay, information gathered during this study provides a better basis for evaluating environmental conditions in the upper bay (north of Highway 98) than in the lower bay. This is because the boundaries of the lower bay are considerably more complicated than those of the upper bay.

The results of this study show that Perdido Bay receives nutrients from anthropogenic sources, dominated during this study by materials delivered by Elevenmile Creek. The Styx and Blackwater Rivers and Bayou Marcus Creek also show evidence of anthropogenic contributions of nutrients. A substantial portion of carbon delivered to the estuary is trapped in the upper bay.

The results also show that physical conditions in Perdido Bay, controlled by the natural forces of wind, streamflow, and tide, are such that stratification and hypoxia occur during a major portion of the year. Summer and early fall months are critical periods when maximum natural stresses (hypoxia) are imposed on the bay and its biological communities. Oxidation of carbon trapped in the bay can aggravate seasonal hypoxia.

The results of sediment studies indicate that, at present, Perdido Bay does not suffer from acute toxic contamination. There is evidence of some contamination from urban runoff, although contaminants have not reached levels encountered in other, more developed, parts of Alabama and Florida.

RECOMMENDATIONS

The following recommendations are based on the need to prevent future degradation of Perdido Bay and to evaluate changes that may occur as development increases around the bay.

1. Reduce nutrient loadings from Elevenmile Creek. Due to the dominance of Elevenmile Creek in delivering anthropogenic nutrients to Perdido Bay, a first management priority should be to reduce these loadings.

2. Reduce and prevent other nutrient loadings.
   a) Determine the effects of agricultural practices in the Styx and Blackwater River watersheds on nutrient and suspended solids transport.
   b) Determine effective stormwater management strategies to control nutrients, especially during the critical summer period when stratification and concomitant hypoxic conditions are prevalent.

3. Begin system-wide monitoring of nutrient concentrations, productivity and sediment contamination, best achieved through a cooperative interstate effort. This

monitoring should be sensitive to natural variability (eg. seasonal physical, chemical, and biological changes).

4. Develop capacity to predict, based on wind, streamflow, and tides, water movements and retention times in Perdido Bay. This will allow a critical examination of management strategies based on characteristic water movements in the bay. FDER/CZM has supported the first steps toward developing a simple predictive model for net water circulation and concentrations of materials in the bay [described in the companion report *Prediction of Water Quality at Perdido Bay, Florida* (Taylor et al., 1991)].

TABLE OF CONTENTS

EXECUTIVE SUMMARY iii

LIST OF TABLES x

LIST OF FIGURES xi

ACKNOWLEDGEMENTS xv

1. INTRODUCTION 1
   - BACKGROUND AND PURPOSE OF THE STUDY 1
   - REVIEW OF HISTORICAL INFORMATION 3
   - ORGANIZATION OF THE REPORT 5

2. ENVIRONMENTAL SETTING OF THE PERDIDO BAY SYSTEM 7
   - PHYSIOGRAPHY OF PERDIDO BAY AND ITS WATERSHED 7
     - Perdido Bay 7
       - Geography 7
       - Bathymetry 8
       - Sediments 8
     - Perdido Bay Watershed 9
   - CLIMATOLOGY 10
     - General Conditions 10
     - Wind 10
     - Rainfall 11
     - Streamflow 12
     - Tides 16
   - LAND USE 16
   - WATER QUALITY 17
     - Perdido River and Tributaries 17
     - Perdido Bay 17

3. HYDROLOGIC CONDITIONS DURING PERIOD OF STUDY 25
   - OBJECTIVES 25
   - RAINFALL 25
   - STREAMFLOW 26
     - Perdido River 26
     - Styx River 27
     - Blackwater River 38
     - Elevenmile Creek 29
     - Bayou Marcus Creek 30

4. SEDIMENT CHEMISTRY 31
   - OBJECTIVES 31
   - METHODS 31
     - Station Locations and Parameters Measured 31
     - Sample Collection 32
     - Laboratory Analyses 32
       - Metals 32
       - Nutrients 33
       - Organics 33
   - RESULTS 33
     - Metals 33
     - Nutrients 34
     - Organics 35

FDER PRIORITY POLLUTANT SURVEY 36
SUMMARY 36

5. **ESTUARINE HYDROGRAPHY** 49
OBJECTIVES 49
MEASUREMENT METHODS 50
Sampling Strategy 50
Station Locations 51
Current Measurements 52
Tide Measurements 53
DATA REDUCTION 54
RESULTS 57
June 1988 57
August 1988 60
November 1988 62
February 1989 64
June 1989 67
SUMMARY OF OBSERVED CIRCULATION 71
ANALYSIS AND PREDICTION OF NET BAY CIRCULATION 74

6. **WATER CHEMISTRY** 117
OBJECTIVES 117
SAMPLING METHODS 118
Strategy 118
Station Locations 118
Sampling Dates 120
Sample Collection 120
Monthly samples 120
Storm samples 121
LABORATORY ANALYSES 121
DATA REDUCTION 123
Estimates of Annual Material Flux to Perdido Bay . 123
Extrapolation method for estimating material flux 124
Interpolation method for estimating material flux 126
Determining Behavior of Nutrients and Solids in the Estuary 127
RESULTS 128
General Chemical Characteristics of Streams 129
Chemical Transport to Perdido Bay 130
Rating curves 131
Riverine flux 133
Estuarine Nutrient Chemistry 138
Dissolved and particulate carbon 138
Dissolved and particulate nitrogen 139
Dissolved and particulate phosphorus 139
Nutrient Mass Balance in Perdido Bay 140
Carbon 142
Nitrogen 142
Phosphorus 142
Estuarine Dissolved Oxygen 142
Controls on Dissolved Oxygen 144
Chemical processes 144
Physical processes 147

7. CONCLUSIONS AND RECOMMENDATIONS 175
CONCLUSIONS 176
SUMMARY 183
RECOMMENDATIONS 184

8. REFERENCES 187

APPENDIX A: BENTHIC BIOLOGY RESULTS - SUMMARY 193

APPENDIX B: METRIC/ENGLISH UNIT CONVERSIONS 197

APPENDIX C: SEDIMENT CHEMISTRY 199

APPENDIX D: DISSOLVED AND PARTICULATE NUTRIENT CONCENTRATIONS PLOTTED AGAINST SALINITY 211

APPENDIX E: SALINITY AND DISSOLVED OXYGEN PROFILES FROM HYDROGRAPHIC CAMPAIGNS IN PERDIDO BAY 241

APPENDIX F: DISSOLVED OXYGEN AT ESTUARINE STATIONS IN PERDIDO BAY MONTHLY SAMPLES 309

LIST OF TABLES

Table 2.1. Perdido Bay watershed flood-flow recurrence intervals 14

Table 4.1. Organic compounds detected in Perdido Bay tributary sediments collected in March, 1989 38

Table 5.1. Hydrographic sampling periods and target conditions 51
Table 5.2. Current measurement station locations 52
Table 5.3. Breakdown of net circulation into components by transect 76

Table 6.1. Water chemistry sampling station locations. . . . 119
Table 6.2. Chemical parameters analyzed and methods 122
Table 6.3. Rating curve constants and levels of significance. 132
Table 6.4. Annual riverine fluxes to Perdido Bay 134
Table 6.5. Major annual material fluxes to Perdido Bay from freshwater runoff 135
Table 6.6. Estimate of material fluxes above expected natural levels from Elevenmile Creek into Perdido Bay . 137

LIST OF FIGURES

Figure 2.1. Perdido Bay 18
Figure 2.2. General features of the Perdido Bay watershed . 19
Figure 2.3. Probability distribution of freshwater inflows to upper Perdido Bay 20
Figure 2.4. Cumulative probability of exceedance of freshwater inflows to upper Perdido Bay 21
Figure 2.5. Probability distribution of annual peak flows into upper Perdido Bay 22
Figure 2.6. Seasonal probability distribution of freshwater inflows to upper Perdido Bay 23
Figure 2.7. Seasonal cumulative probability of exceedance of freshwater inflow to upper Perdido Bay 24

Figure 4.1. Sediment sampling stations in Perdido Bay, Perdido River, and Elevenmile Creek, August 1987 40
Figure 4.2. Sediment sampling stations in tributaries to Perdido Bay, March, 1989 41
Figure 4.3. Arsenic, cadmium, chromium, and copper concentrations in Perdido Bay system sediments 42
Figure 4.4. Lead, nickel, and zinc concentrations in Perdido Bay system sediments 43
Figure 4.5. TOC and TKN concentrations from natural Florida and Perdido Bay system sediments 44
Figure 4.6. TKN and TP concentrations from natural Florida and Perdido Bay system sediments 45
Figure 4.7. TOC/TKN ratios in Perdido Bay system sediment cores 46
Figure 4.8. TKN/TP ratios in Perdido Bay system sediment cores 47

Figure 5.1. Perdido Bay landmarks and major divisions . . . 84
Figure 5.2. Current measurement and tide gauge locations . 85
Figure 5.3. Examples of vertical profiles of current velocity 86
Figure 5.4. Example of horizontal profile of current velocity 87
Figure 5.5. USGS stream gauge locations in the Perdido Bay watershed 88
Figure 5.6. Flow history, Transect CT1, June 7 - 8, 1988 . 89
Figure 5.7. Flow history, Transect CT2, June 8 - 9, 1988 . 90
Figure 5.8. Flow history, Transect CT3, June 7 - 8, 1988 . 91
Figure 5.9. Flow history, Transect CT4, June 9, 1988 . . . 92
Figure 5.10. Net diurnal tidal and freshwater fluxes, June 7 - 9, 1988 93
Figure 5.11. Flow history, Transect CT1, August 24 - 25, 1988 94
Figure 5.12. Flow history, Transect CT2, August 22 - 23, 1988 95
Figure 5.13. Flow history, Transect CT3, August 23 - 24, 1988 96
Figure 5.14. Flow history, Transect CT4, August 22 - 23, 1988 97

Figure 5.15. Net diurnal tidal and freshwater fluxes, August 22 - 25, 1988 98
Figure 5.16. Flow history, Transect CT1, November 4 - 5, 1988 99
Figure 5.17. Flow history, Transect CT3, November 3 - 4, 1988 100
Figure 5.18. Flow history, Transect CT4, November 3 - 4, 1988 101
Figure 5.19. Net diurnal tidal and freshwater fluxes, November 3 - 5, 1988 102
Figure 5.20. Flow history, Transect CT1, February 8 - 9, 1989 103
Figure 5.21. Flow history, Transect CT2, February 8 - 9, 1989 104
Figure 5.22. Flow history, Transect CT3, February 7 - 8, 1989 105
Figure 5.23. Flow history, Transect CT4, February 7 - 8, 1989 106
Figure 5.24. Net diurnal tidal and freshwater fluxes, February 7 - 9, 1989 107
Figure 5.25. Flow history, Transect CT1, June 10 - 11, 1989 108
Figure 5.26. Flow history, Transect CT2, June 10 - 11, 1989 109
Figure 5.27. Flow history, Transect CT3, June 9 - 10, 1989 . 110
Figure 5.28. Flow history, Transect CT4, June 9 - 10, 1989 . 111
Figure 5.29. Net diurnal tidal and freshwater fluxes, June 9 - 11, 1989 112
Figure 5.30. Plot of wind-driven net circulation as a function of wind stress along the axis of Perdido Bay at Transect CT1 113
Figure 5.31. Plot of wind-driven net circulation as a function of wind stress along the axis of Perdido Bay at Transect CT3 114
Figure 5.32. Plot of wind-driven net circulation as a function of wind stress along the axis of Perdido Bay at Transect CT4 115

Figure 6.1. Estuarine sampling stations, March - June, 1988 150
Figure 6.2. Estuarine sampling stations, July - September, 1988 151
Figure 6.3. Estuarine sampling stations, October - December 1988 152
Figure 6.4. Estuarine sampling stations, January and February, 1989 153
Figure 6.5. Estuarine sampling stations, April - June 1989 . 154
Figure 6.6. Concentration-discharge rating relationship for dissolved, particulate and particulate-associated substances in rivers 155
Figure 6.7. General representation of concentration of constituent, X, with respect to salinity, illustrating addition, removal, and conservative mixing 156
Figure 6.8. Hydrographs of sampling stations for Perdido and Styx Rivers 157

Figure 6.9. Hydrographs of samping stations on the Blackwater River and Elevenmile Creek 158
Figure 6.10. Hydrograph for sampling station on Bayou Marcus Creek 159
Figure 6.11. Seasonal variations in temperature, pH and dissolved oxygen at river and creek sampling stations 160
Figure 6.12. DOC, TKN, NO_3+NO_2 and PO_4 variations in river and creek samples 161
Figure 6.13. Total suspended solids and particulate carbon, nitrogen, and phosphorus concentrations in river and creek samples 162
Figure 6.14. Rating curves for DOC for river and creek sampling stations 163
Figure 6.15. Material flux versus mean discharge for river and creek sampling stations 164
Figure 6.16. Storm hydrographs for Perdido and Styx Rivers. Storms occurring 1 - 11 March and 20 - 31 March 165
Figure 6.17. Storm hydrographs for the Blackwater River and Elevenmile Creek 166
Figure 6.18. Storm hydrographs for Bayou Marcus Creek . . . 167
Figure 6.19. Histograms of the daily flux of materials at each gauging station averaged over the entire year, 1 - 11 March storm, and 20 - 31 March storm 168
Figure 6.20. Freshwater residence time in Perdido Bay 169
Figure 6.21. Seasonal dissolved oxygen stratification in Perdido Bay 170
Figure 6.22. Estimated oxygen deficits in upper and lower bays by month 171
Figure 6.23. Apparent oxygen utilization versus month for upper and lower Perdido Bay 172
Figure 6.24. Dissolved oxygen versus salinity in Perdido Bay observed during hydrographic campaigns 173

ACKNOWLEDGEMENTS

Agencies hesitate to conduct management-oriented investigations of coastal systems for many reasons, including concerns about the availability and cost of skills to conduct estuarine studies. The Perdido Bay work illustrates the fact that skilled people are available and will go beyond their routine obligations to help stretch public funds and make a project successful.

This study involved complex field and laboratory activities which could not have been executed without the personal interest and professional assistance of the following people: Eddie Wolfe, David Wigger, Clinton Townsend, and Carolyn Merryman (ADEM Mobile Field Office Laboratory); James Andrews, Ph.D. (Savannah Laboratories and Environmental Services); Carla Cannon and Paul Witt (Taylor Engineering, Inc.); and James Stoutamire, Ph.D., Louis Burney, Ted Hoehn, Peggy Mathews, David Worley, and Jerrell Daigle (FDER). Thanks also to the Bureau of Information Systems (FDER) for their assistance in preparing figures for this report.

Our field operations required a secure staging area and communications center at Perdido Bay. Special thanks are extended to Chris and Rose Russo at Kit's Marina, Lillian, Alabama, for their generosity in providing facilities and helping us overcome the problems that can impair a field program.

Personnel from various state, federal and private organizations assisted us by providing ancillary information crucial to the interpretation of our chemical and hydrographic data. We thank the Alabama Forestry Commission, Florida Division of Forestry, U.S. Navy, U.S. Department of Agriculture Soils Conservation Service, U.S. Geological Survey and Champion International Corporation for providing ancillary information.

Individuals throughout the Perdido Bay area made us welcome during the course of our work. We especially appreciate the help

beyond the call of duty by the people at the Original Point Restaurant, Ross Hardware, and the Comfort Inn at Perdido Key. Also appreciated were the good meals at the Wolf Bay Lodge, home of the "Perdido Bay Padres".

Under provisions of Section 309 of the Coastal Zone Management Act of 1972, as amended, Florida and Alabama joined to compete nationally for a grant from the National Oceanic and Atmospheric Administration (NOAA). This section of the Act was created to encourage joint state actions to protect coastal systems. The grant proposal was submitted to NOAA in March 1987 and late that year an award was made to the states for the joint investigation of Perdido Bay.

1. INTRODUCTION

BACKGROUND AND PURPOSE OF THE PROJECT

The Florida Department of Environmental Regulation (FDER) and Alabama Department of Environmental Management (ADEM) initiated this project in response to increasing public and agency concern over the future of Perdido Bay. From a review of existing data and interviews it was evident that judgments about effects of present activities and future development on the bay could not be supported without system-wide water chemistry and circulation information. Since management of the bay is in the hands of both states, it was necessary for the agencies to combine efforts to produce this basic information.

Objectives of this project were to describe physical and chemical processes affecting dissolved and particulate nutrient and suspended solid transport in the Perdido River basin and the fate of these materials in Perdido Bay. This effort involved several components including measurements of stream discharge, currents, and nutrients, dissolved oxygen, and salinity in tributaries and the bay, and the collection of local weather records. Achieving these objectives provides information needed to answer several questions about the condition of Perdido Bay:

- How do tide, wind, and runoff affect water movement in Perdido Bay and to what extent is circulation confined in the upper bay?
- What pollutants are entering the bay and from where?
- Is Perdido Bay silting up due to increased erosion resulting from man's activities in adjacent watersheds?
- What is the rate of supply of nutrients to Perdido Bay and what is man's influence on this rate?
- Does Perdido Bay trap nutrients?
- How prevalent are hypoxic conditions in Perdido Bay and what are the causes?
- How can we summarize the present condition of Perdido Bay?

As in many other coastal systems, the limited information that does exist for Perdido Bay is not on system-wide processes and cannot provide answers to the questions above. While localized data are useful for individual regulatory decisions, broader studies that integrate bay-wide physical and chemical information are essential for judging the susceptibility of the bay to development pressures, developing practical bay management objectives and plans, and providing sound guidance for maintaining conditions to support estuarine productivity.

Estuarine living resources exist under dynamic physical and chemical conditions. Delivery of nutrients from the watershed, variations in the mixture of fresh and salt water, and seasonal changes in temperature and light intensity form the basis of estuarine productivity. However, these processes also impose natural stresses. Thus, during low rainfall periods, increases in salinity may be accompanied by widespread low dissolved oxygen levels. Similarly, the absence of wind to induce mixing of bay waters increases the likelihood of stratification and low dissolved oxygen.

Estuaries differ in the degree to which man can affect basic chemical and physical processes without magnifying the natural stresses. In this regard, Perdido Bay is clearly an estuary of priority concern, for it has features which could profoundly affect the bay's tolerance to stress.

A glance at a chart of Perdido Bay indicates why a system-wide understanding of the bay's physical and chemical environment is imperative. The bay has limited connection with the Gulf of Mexico and its tidal flushing effects. Moreover, it appears that constrictions within the bay could further reduce water movement and restrict delivery of nutrients and solids through the system. The National Oceanic and Atmospheric Administration (NOAA) has classified Gulf coast estuaries according to their "pollution susceptibility", defined as an estuary's ability to concentrate dissolved and particulate pollutants. Perdido Bay received a

rating of high and medium for dissolved and particulate susceptibility, respectively (NOAA/EPA, 1989). Limited historical data indicated that the upper portion of the bay is subject to stratification with concurrent hypoxia (low dissolved oxygen) in deeper water.

REVIEW OF HISTORICAL INFORMATION

Prior to beginning the study, we consulted with various state and federal agencies and Champion International Corporation to determine the extent that previous information on the Perdido Bay system could be used to meet project objectives. A fragmented set of historical data does exist for the Perdido Bay system. Compilation and organization of these data is part of a separate "Perdido Bay Cooperative Management Project" funded by the U.S. Environmental Protection Agency (EPA).

Much of the historical information was produced as part of state and federal pollution monitoring requirements pertaining to issuance and renewal of permits. These data are available in the EPA STORET system. The Florida Department of Natural Resources has a limited amount of water temperature, salinity, pH, and dissolved oxygen information taken in conjunction with shellfish surveys. FDER has supported collection of similar water quality data by a local environmental interest group, the Bream Fisherman's Association.

The Alabama Department of Conservation and Natural Resources has collected biological samples from a few stations in lower Perdido Bay. Biological surveys, which included some water quality parameters, were conducted for St. Regis Paper Company and continued by Champion International Corporation. FDER also has collected limited biological data from the bay. The Dauphin Island Sea Lab collected benthic invertebrates from four stations in the bay in 1987. ADEM has limited water chemistry data from 10 stations sampled in 1987 and routinely collects data from one continuing trend station established in the bay in 1987.

The most comprehensive recent work on Perdido Bay was done by EPA as a part of a wasteload allocation study on Elevenmile Creek. The study began in July 1986 and ended in April 1987. It included measurements of total nutrients and other water quality parameters from the bay and its major tributaries, current measurements, and dye studies of water movement. Preliminary results available as the Interstate Project was getting underway indicated that Elevenmile Creek accounted for 30 - 50% of the nutrient loading to Perdido Bay and that water from Elevenmile Creek tended to move down the northeastern side of upper Perdido Bay. Dramatic salinity and dissolved oxygen stratification were observed at times in both upper and lower Perdido Bay.

Since much historical data were permit-related, they address "near-field" objectives and have limited usefulness in describing bay-wide processes. The above-mentioned information on Perdido Bay was collected from different stations under various, often unknown, tidal and climatic conditions. Different parameters were measured using a variety of techniques. Consequently, the data from existing sampling stations do not have the required spatial distribution, common parameters, or synopticity to be useful in assessing nutrient and suspended solids transport and the fate of these materials in the Perdido Bay watershed and estuary.

This investigation attempts to help remedy these deficiencies and provide better scientific foundations for managing activities that affect the Perdido Bay estuarine system. Since the inception of the Interstate Project in 1988, Perdido Bay has become the subject of other studies under the EPA-sponsored Perdido Bay Cooperative Management Project and investigations commissioned by Champion International Corporation.

ORGANIZATION OF THE REPORT

To give the reader a perspective on Perdido Bay, Chapter 2 provides a summary of the environmental setting of the Perdido Bay watershed and estuarine system. Hydrologic conditions during the study period are discussed in Chapter 3 and those conditions are compared to the long-term norms for the area. Sediment chemistry, estuarine hydrography, and water chemistry are discussed in Chapters 4, 5, and 6, respectively. For the work component presented in each of these chapters, objectives, sampling and analytical techniques, and results are discussed. Finally, in Chapter 7, results are synthesized to answer the questions posed at the beginning of this introduction.

In addition to the physical and chemical studies described in this report, there was also a biological component of the Interstate Project. Benthic community structure was determined at several locations in the bay during the study period. Results are summarized in Appendix A and a complete report is available from the ADEM Mobile Field Office.

2. ENVIRONMENTAL SETTING OF THE PERDIDO BAY SYSTEM

The environmental setting of the Perdido Bay system is more modest than other nearby Gulf coast estuaries. The bay is smaller and has less freshwater inflow. Its watershed is less urbanized and, although shared by two states, contains fewer political jurisdictions. However, from a management point of view, the bay should not be subordinate to other estuaries. Precisely because of its limited scale it is both more susceptible to degradation and more amenable to successful management. The high level of public attention now being focussed on the bay increases the likelihood for successful protective actions.

Physical and chemical conditions in Perdido Bay and its tributaries are influenced by myriad geological, climatological, hydrological and biological factors in the watershed, as well as perturbations of the natural regime due to man's activities. Although it is beyond the scope of this project to present a detailed report on the environmental setting of Perdido Bay and its watershed, a general knowledge of the area is useful for interpreting data collected during this project. This chapter provides a synopsis of the environmental setting of Perdido Bay, compiled from existing sources of information. It is not intended to be a comprehensive analysis of watershed features.

PHYSIOGRAPHY OF PERDIDO BAY AND ITS WATERSHED

Perdido Bay

Geography. Perdido Bay (Figure 2.1) encompasses an area of about 130 square kilometers[1] between Alabama and Florida with the state line running approximately down the centerline of the bay (Hand et al., 1988). It has an elongated shape along a northeast-southwest axis.

---

[1]Metric units are used throughout this report. Some relevant conversion factors are listed in Appendix B.

Bathymetry. Starting at the mouth of the Perdido River, maximum depth where the river enters the bay is approximately 2 meters, but depths increase upstream in the river. The river is about 3 meters deep for at least 16 km upstream but there are irregularly spaced depressions up to 12 meters deep in the river bed.

Perdido Bay proper is a relatively shallow estuary. Maximum depths generally occur closer to the Alabama side of the bay but there is no evidence of a well defined channel up into the bay except in the Gulf Intracoastal Waterway (GICWW) between Mill Point and Inerarity Point.

National Ocean Service charted depths in the center of the upper bay (above Grassy Point) range from 1.5 to 2.8 meters. Depths in the middle bay, from Grassy Point to DuPont Point, range from 2.8 to 3.7 meters in the center of the bay. Along the edge of the bay is a shelf up to 0.4 km wide with depths of 0.6 to 0.9 meter. South of DuPont Point, depths increase from 3 to 3.4 meters to a maximum of 6.1 meters in the GICWW channel between Mill Point and Inerarity Point. A shallow shelf (0.3 - 0.9 meter depth) extends about 0.4 to 0.8 km from the shoreline. Fathometer transects across several portions of the estuary, obtained during this study, confirmed the general accuracy of these charted features.

Sediments. Sediments in Perdido Bay are largely terrigenous clastics delivered to the bay by the Perdido River and other tributaries (Parker, 1968). The perimeter of the bay contains predominately quartz sands. Nearshore sediments are winnowed by wave action and fine materials are removed and transported toward the central part of the bay. The fines settle in the deeper portions of the bay, resulting in accumulation of clayey silt and silty clay sediments. Sediment grain size generally increases seaward.

Perdido Bay Watershed

The Perdido Bay drainage basin covers 3121 km^2 (NOAA, 1985) in the Coastal Plain geological province and encompasses parts of Baldwin and Escambia Counties, Alabama and western Escambia County, Florida. Numerous tributary streams in the upper basin drain hilly country, forming the Perdido River and its two major tributaries, the Styx and Blackwater Rivers (Figure 2.2).

The fall of the Perdido stream bed from the Alabama/Florida state line to Muscogee, Florida is 45.7 meters for a channel length of 64 km. The fall from Muscogee south to Perdido Bay is 4.6 meters, with a channel length of 32 km (Musgrove et al. 1965). Lower in the watershed, Elevenmile Creek and Bayou Marcus Creek are the only significant streams entering the bay. Small streams (eg. Soldier and Palmetto Creeks) and general runoff around the bay constitute the balance of fresh water contributions to the estuary.

Principal soils of the area include unconsolidated sands, silts and clays deposited from prehistoric seas and alluvial Appalachian deposits. Two topographic divisions are evident: the western highlands consisting of a southward sloping plateau, and the Gulf or Coastal western lowlands, a relatively continuous, near level plain, less than 30 meters above sea level (Marsh, 1966).

The Plio-Pleistocene Citronelle Formation caps most of the western highlands and consists primarily of quartz sands, with beds of clay, gravel, layers of hardpan, fossil wood, a few shells, and kaolinitic burrows of aquatic animals. Solution activities (Karst topography) are precluded by the depth of the Citronelle formation, and by older impermeable clastics. The Gulf Coastal or Western lowlands are characterized by broad, level marine terraces of Plio-Pleistocene sand extending several kilometers inland from the coast. These merge with narrow terraces along the Perdido River (Marsh, 1966).

CLIMATOLOGY

General Conditions

Weather records have been kept for Pensacola, Florida, a few kilometers east of Perdido Bay, since 1879. The primary sources for weather observations are the Pensacola commercial airport and the Pensacola Naval Air Station. Summaries of weather conditions were obtained from the National Climatic Data Center. The Perdido Bay system lies in a humid temperate climatic zone. Temperature, rainfall, and wind speed and direction vary seasonally. Average temperature for the summer (June, July, and August) is 26.7°C. Winters (December, January, February) are relatively warm with an average temperature of 12.2°, although the area is affected by periodic frontal systems. The area is also subject to tropical storm systems, being struck by hurricanes about once every 17 years and receiving fringe effects approximately every 5 years.

Wind

Wind speed and direction are key influences over the movement of water in Perdido Bay and are important parts of the analyses used in this study. The following summary of wind patterns in the Perdido Bay region was extracted from information in the 1986 Coast Pilot and weather records for Pensacola from the National Climatic Data Center.

Winds in the area are subject to seasonal variations with relatively distinct seasonal northerly and southerly components. Southerly wind directions dominate from April through August (frequency greater than 65.8 percent). The distribution of wind directions between easterly and westerly sectors is less clear during this period. However, diurnal patterns are clearly present as rising surface temperatures create afternoon convective air currents. The lowest average wind speeds for the year occur during July and August (7.4 and 7.0 knots, respectively). Because of the northeast-southwest orientation of the bay system, typical conditions during this period tend to enhance flood tide flow and impede ebb flow.

During the months of September and October the north-south wind components diminish. This is a transitional period during which easterly winds dominate 61 percent or more of the time. The period from November through February is marked by frequent occurrence of strong frontal systems. The northerly winds associated with these systems tend to reduce flood tide flows into the bay while reinforcing ebb flows out of the bay. Due to the persistent nature of these winds, effects on tidal flow are magnified and may last for extended periods of time.

Diurnal wind patterns during the late fall-winter period are less pronounced as a result of lower daytime surface temperatures. Winds become stronger in February reaching an average speed of 10.3 knots. This trend continues into March making these two months the period of highest wind speeds of the year.

Rainfall

Along with wind, rainfall in the Perdido Bay basin exerts a dominant influence on the composition and movement of bay waters. Following is a brief description of rainfall in the basin.

Daily average rainfall data were obtained from five monitoring stations in the Perdido Basin. Four of these are located in Escambia County, Florida. The Oak Grove Tower and Molino Tower stations, operated by the Florida Division of Forestry, provided rainfall data for the period of June 1977 through June 1989. The third and fourth stations, located at Champion International's Cantonment Mill and the Pensacola Naval Air Station provide records covering January 1987 through June 1989 and January 1988 through June 1989, respectively. The fifth recording station, Carpenter Tower, is 9.7 km south of Bay Minette, Alabama, and is operated by the Alabama Forestry Commission. Data obtained from this station cover the period January 1983 through June 1989. An overview of all of these provide a characteristic profile of the rainfall patterns within the watershed.

Average annual rainfall at Pensacola is approximately 152 cm. Highest rainfall occurs in July and August; storms during this time of the year are normally convective, of short duration, and intense. They also tend to be more localized, affecting smaller areas of the drainage basin. The drier months of the year occur in the fall with November being the driest. Winter storms tend to produce lower rates of rainfall at all of the stations when compared to storms occurring during the summer months. Winter storms, however, tend to cover larger areas and last over longer periods of time.

Streamflow

The majority of freshwater inflow to Perdido Bay enters by way of five tributary drainage basins - the Perdido River, Styx River, Blackwater River, Elevenmile Creek, and Bayou Marcus Creek. Streamflow in the largest of these, the Perdido River, has been monitored by a United States Geological Survey (USGS) gauging station at Barrineau Park, Florida since 1941 (Meadows et al., 1988). This gauging station is the sole source of long term streamflow data within the Perdido Bay watershed. Therefore, these data were used to develop a long term profile of freshwater inflow to the Bay. This profile, discussed below, provides a historical background against which the hydrologic events of the study period can be weighed.

The flow of fresh water in the Perdido Bay basin is affected by factors that exhibit inherently random characteristics within somewhat predictable seasonal bounds (e.g., rainfall frequency and intensity). Therefore, in an effort to put the hydrologic conditions of the study period into historical perspective, a statistical profile of long-term streamflow patterns was developed. This was accomplished through the application of statistical analyses commonly used in the analysis of hydrologic phenomena.

Mean daily discharges of the Perdido River at Barrineau Park for the years 1959 through 1989 were adjusted upward by a factor

of 2.6 to reflect the ratio of the entire five tributary watershed to that portion drained by the Perdido River above the Barrineau Park gauging station. The value of 2.6 was obtained by first determining the total drainage area of the five tributary basins using standard USGS topographic quadrangle maps and then dividing that by the published value for the basin area serving the Barrineau Park gauge. The adjustment factor (2.6) should be generally adequate, but its uncertainty increases in estimating flood peaks. Results of the statistical analyses of the adjusted Barrineau Park data are presented below.

For the period of record, January 1, 1959 to August 31, 1989, flows in the 14.2 to 42.5 m^3 sec^{-1} range (Figure 2.3) had the highest probability of occurrence, at 29 percent. The median flow of 37.1 m^3 sec^{-1} fell within this range, while the mean flow of 56.2 m^3 sec^{-1} fell slightly above this range. This suggests that extreme events have some influence on the mean statistic, but their affect on the overall distribution of flows is relatively minor. Flow rates of 20.1 and 156 m^3 sec^{-1} were calculated to have exceedance probabilities of 95 and 5 percent, respectively (Figure 2.4).

A flood-frequency analysis was also performed to examine the distribution of return periods for flows of larger magnitude which can be expected to occur within the Perdido Bay basin. A frequency curve for annual peak flows into the upper bay (Figure 2.5) was developed following the guidelines set forth Bridges (1982). A log Pearson Type III distribution function was used to fit annual peak flows to a log-probability curve. Flood flow recurrence intervals interpolated from the curve are summarized in Table 2.1.

The likelihood that a flood of given magnitude will occur during any given period of time can be easily obtained from the application of standard risk analyses. Applying these types of analyses to the flood values listed in Table 2.1 yields the following results:

Table 2.1. Perdido Bay watershed flood-flow recurrence intervals.

Interval (yrs)	Flow (m^3 sec^{-1})
1	223
5	856
25	1477
50	1764
100	2066

- A 5-year flood of 856 m^3 sec^{-1} has a 89 per cent chance of occurrence during any given 10 year period, and a 96 per cent chance of occurrence during any given 15 year period.
- A 25-year flood of 1477 m^3 sec^{-1} has a 34 per cent chance of occurrence during any given 10 year period, and a 46 per cent chance of occurrence during any given 15 year period.
- A 50-year flood of 1764 m^3 sec^{-1} has a 18 per cent chance of occurrence during any given 10 year period, and a 26 per cent chance of occurrence during any given 15 year period.
- A 100-year flood of 2066 m^3 sec^{-1} has a 10 per cent chance of occurrence during any given 10 year period, and a 14 per cent chance of occurrence during any given 15 year period.

Finally, additional analyses were carried out to evaluate seasonal variations in tributary inflows to the bay. To accomplish this the adjusted daily mean discharge record was divided into four component data sets, each corresponding to a season of occurrence (e.g. June - August (Summer), Sept - Nov (Fall), Dec - Feb (Winter), and March - May (Spring)). Probability distribution functions and cumulative probability of exceedance functions were then developed for each seasonal record (Figures 2.4 and 2.5).

During the winter months, flows in the 28.3 to 56.6 m^3 sec^{-1} range exhibit the highest frequency of occurrence, 27 percent (Figure 2.6). Flows of 25.3 and 161 m^3 sec^{-1} exceedance probabilities of 95 and 5 per cent, respectively (Figure 2.7). Conditions in the spring months are similar to those of the winter months with flows in the 28.3 to 56.6 m^3 sec^{-1} range again occurring with a frequency of 27 percent. However, for this season more variation in streamflow is apparent with 20.7 and 190 m^3 sec^{-1} representing the 95 and 5 per cent exceedance probability values.

In contrast to conditions characteristic of the winter and spring seasons, a marked reduction in streamflow is apparent during the summer months. Here, flows in the 14.2 to 42.5 m^3 sec^{-1} range occur with the greatest frequency, 32 percent. The corresponding 95 and 5 per cent exceedance probability flows for summer were found to be 18.6 and 136 m^3 sec^{-1}, respectively. While extremely high flow rates do occur during this time of year, these events are of infrequent occurrence, and are therefore statistically insignificant.

The smallest streamflows during the four seasons were observed during the fall months. During this season flows in the 14.2 to 28.3 m^3 sec^{-1} range can be expected to occur 49 percent of the time. Flows of 28.3 to 42.5 m^3 sec^{-1} make up another 28 percent of all occurrences (Figure 2.6). Thus, 77 percent of all daily mean discharge rates are less than 42.5 m^3 sec^{-1} during this time of the year. The 95 and 5 percent exceedance probability values for the fall season are 18.3 and 108 m^3 sec^{-1} respectively (Figure 2.7).

The information presented above provides a perspective for the hydrologic conditions experienced during the Interstate project. These conditions are discussed in more detail in Chapter 3.

Tides

Information on tides in Perdido Bay was obtained from the Florida Department of Natural Resources, Bureau of Survey and Mapping. Mean tidal ranges throughout the bay are surprisingly uniform, varying from 0.18 meter in Old River to 0.22 meter at Millview, midway along the eastern shore of the Upper Bay. Thus, there appears to be a slight amplification of the tide due to a gradual reduction in bay plan area as one proceeds away from Perdido Pass. Moreover, any accompanying frictional dampening of the tidal wave as it propagates inland appears to be negligible. The character of the tide is expected to be similar to the tide in Pensacola Bay, predominantly diurnal during most of the lunar cycle and becoming very small at neap.

LAND USE

The Alabama Department of Economic and Community Affairs and West Florida Regional Planning Council provided information about present and projected land use in the basin. Land use in the Perdido Bay watershed is predominantly agriculture and silviculture. Although there are two small cities, Bay Minette and Atmore, in the upper portion of the watershed, most urban and light commercial land use is concentrated on the lower part of the system.

Most growth in the Perdido Bay drainage area is projected to occur in Baldwin County, Alabama and Escambia County, Florida in association with increased recreation and tourism. Permanent population in the Baldwin County portion of the watershed adjacent to the bay is projected to increase from 5004 in 1980 to 9250 by the year 2000, primarily along lower Perdido Bay and around Lillian. Additional urban growth is expected in the upper watershed around Bay Minette. Population in Escambia County, Florida is projected to increase from 269,800 in 1987 to 298,300 by 1995. Growth is expected to occur southwest of the City of Pensacola in the Perdido Bay and Perdido Key area. Population growth in both states is expected to result in the construction of additional package sewage treatment plants and increased use

of septic tanks. Non-point discharges are also expected to increase. However, it is expected that population growth in the upper portions of the watershed will be slower and large tracts are projected to remain in agriculture and silviculture.

WATER QUALITY

Perdido River and Tributaries

There are several industrial and municipal wastewater treatment facilities in the Perdido Bay watershed with National Pollution Discharge Elimination System (NPDES) permits. The majority of these are small facilities on tributaries to the upper reaches of the main streams of the watershed. The Styx, Blackwater, and Perdido Rivers, do not appear to be adversely affected by these discharges. Water quality in the upper Perdido River is considered to be very good. Bushy Creek, a tributary to the Perdido River, has historically had only fair water quality, presumably being affected by the City of Atmore Wastewater Treatment Plant (WWTP) and light industry. Water quality has shown signs of improvement following an upgrade of the WWTP in 1984 (ADEM, 1986).

Elevenmile Creek, which drains directly into upper Perdido Bay, has historically had poor water quality, due to the discharge of pulp mill wastewater by St. Regis Paper Company and, more recently, Champion International Corporation. Eightmile Creek, a tributary to Elevenmile Creek, receives urban runoff. Bayou Marcus, classified as having fair water quality, also drains into upper Perdido Bay and receives discharge from the Avondale WWTP as well as urban runoff (Hand et al., 1988).

Perdido Bay

Water quality in upper Perdido Bay is considered to be poor, due primarily to the influence of Elevenmile Creek. The mid-portion of the bay down to Inerarity Point is described as having fair water quality and may be adversely affected by increased runoff from development around the bay (Hand et al., 1988).

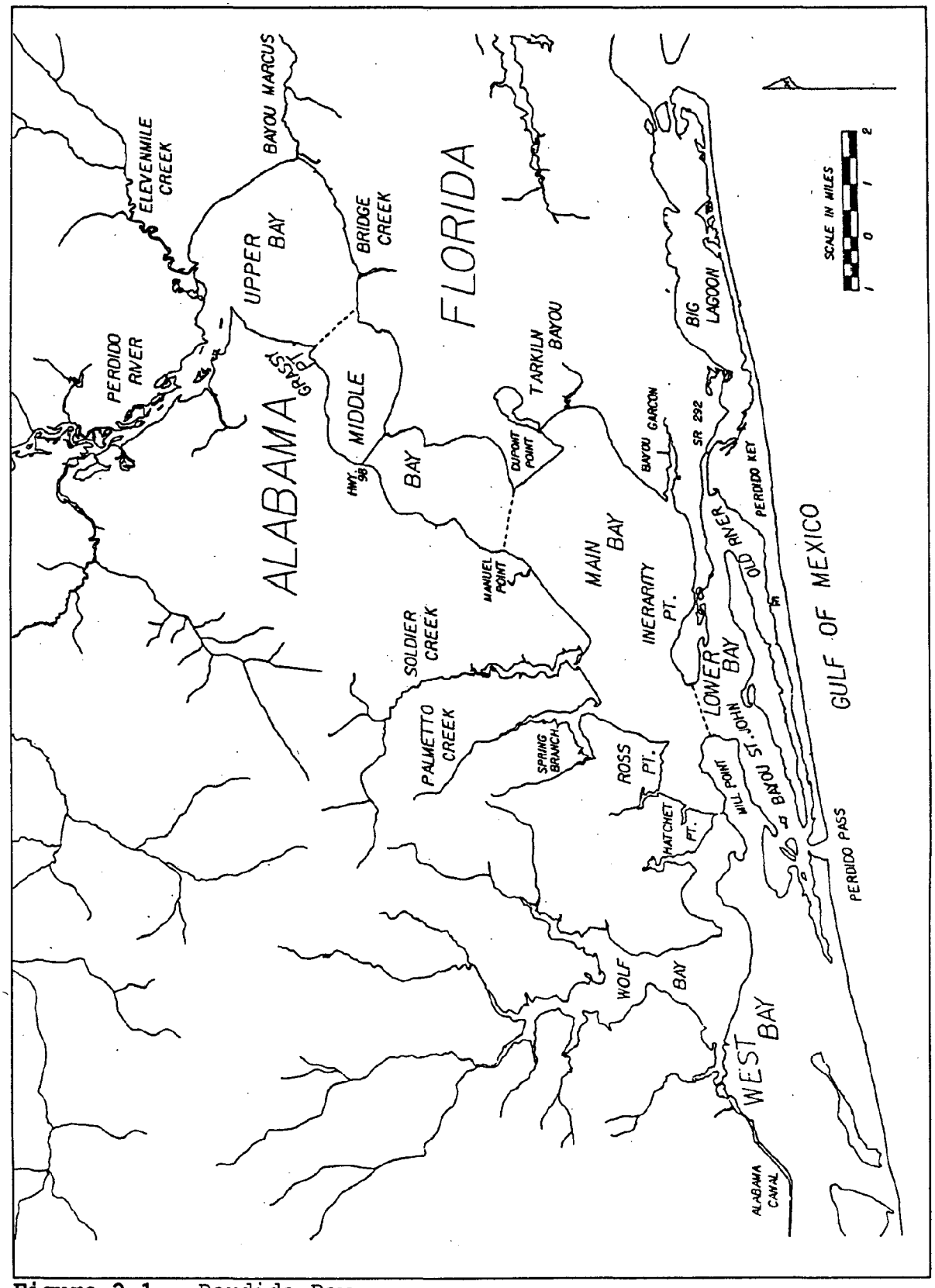


Figure 2.1. Perdido Bay.

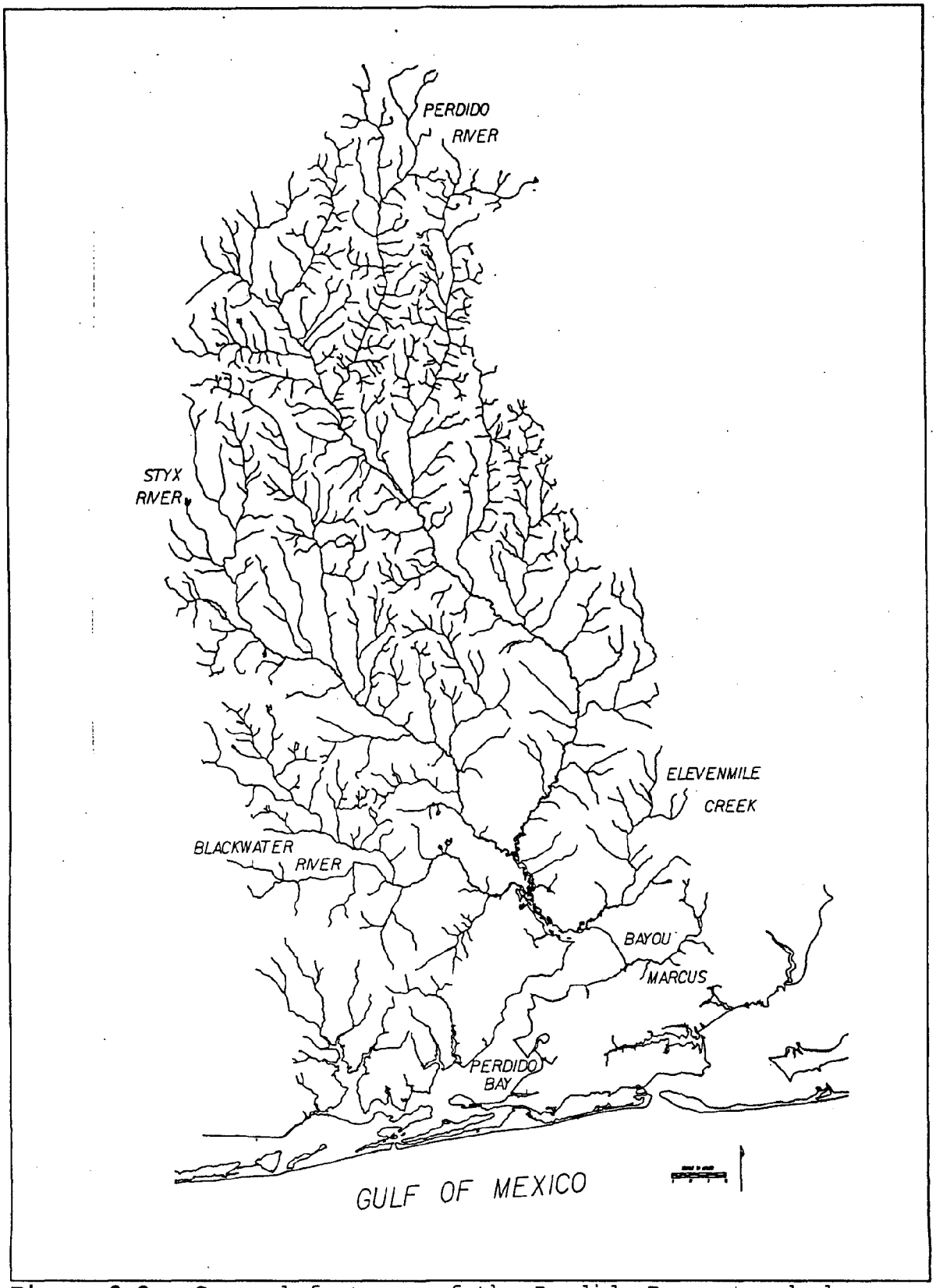


Figure 2.2. General features of the Perdido Bay watershed.

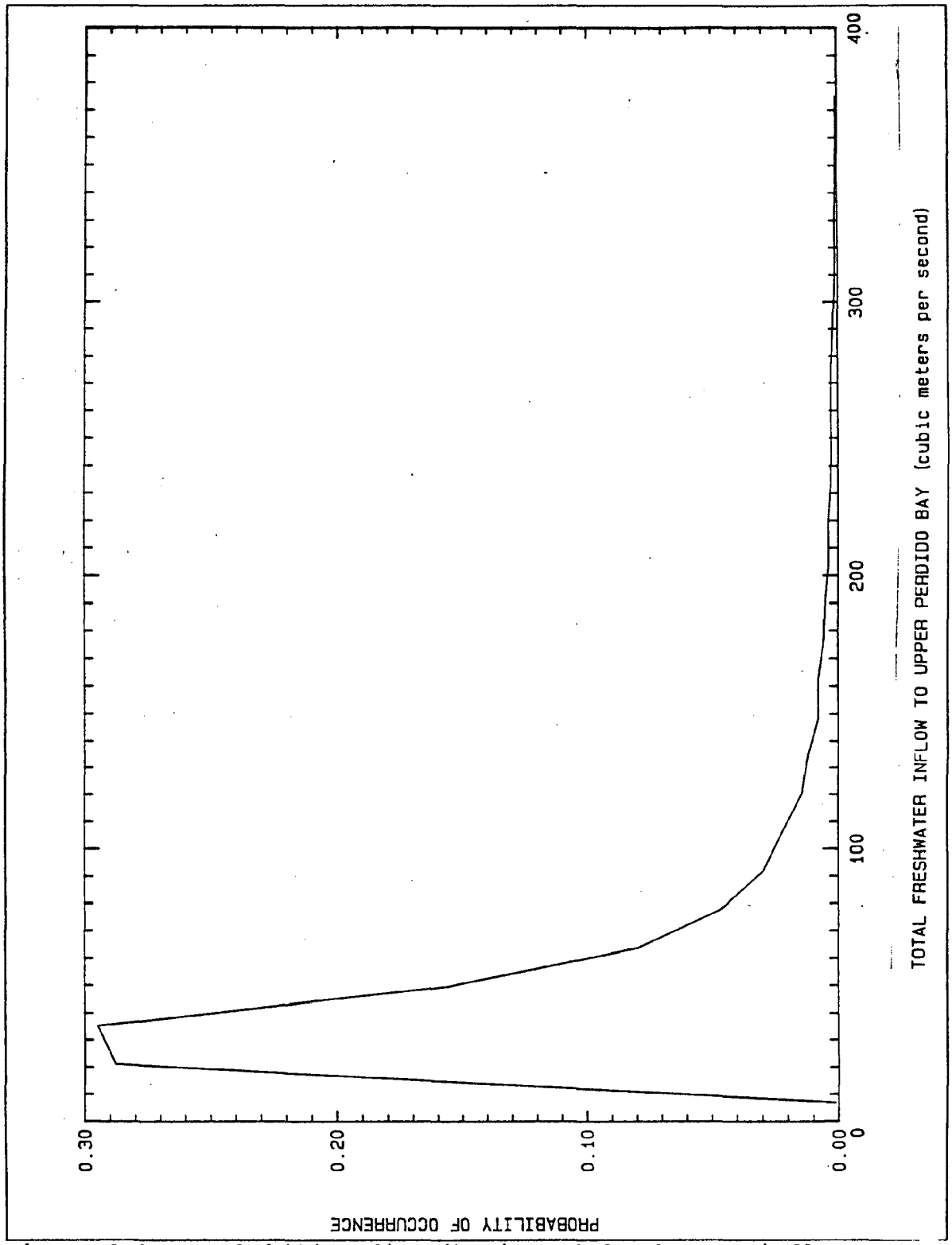


Figure 2.3. Probability distribution of freshwater inflows to upper Perdido Bay.

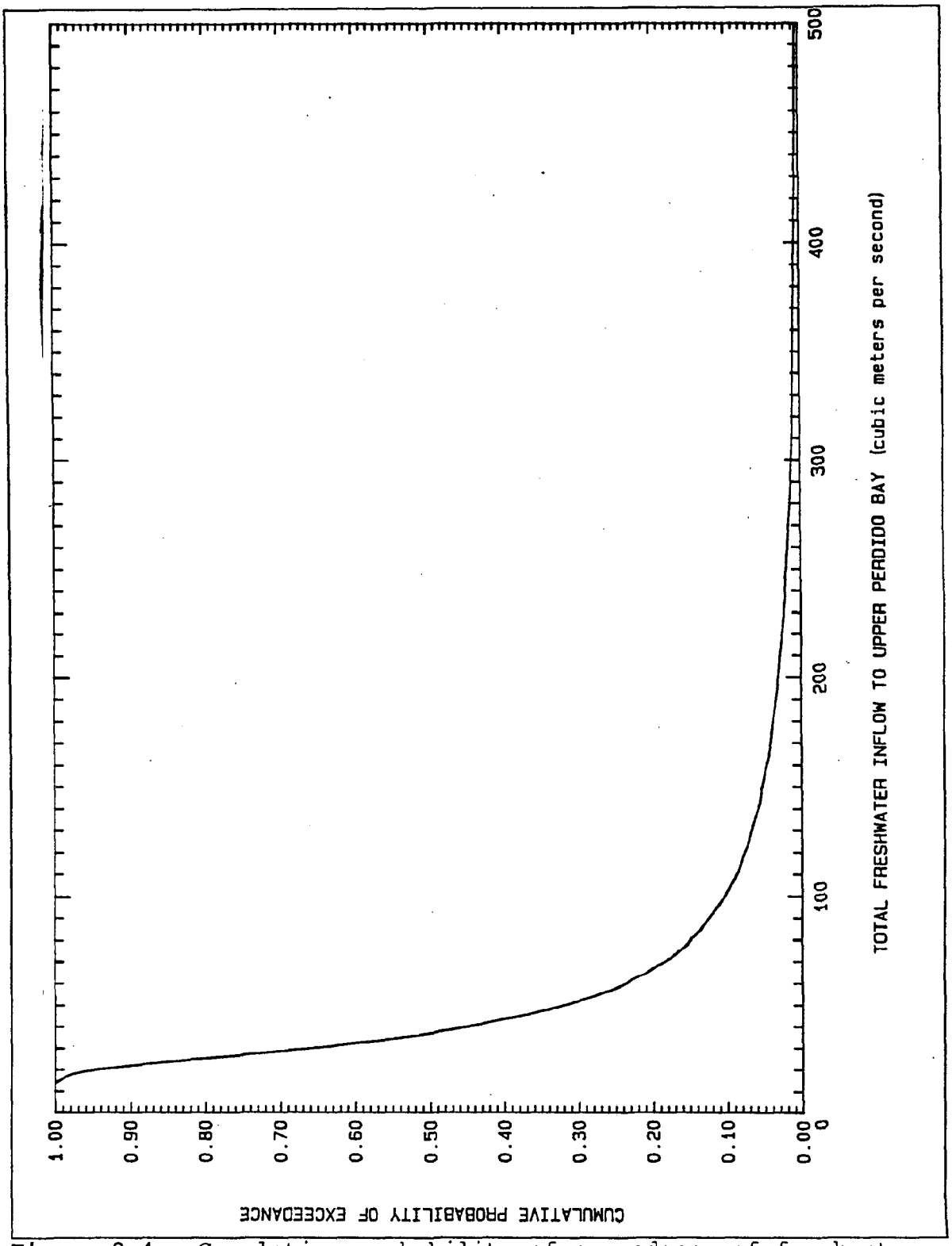


Figure 2.4. Cumulative probability of exceedance of freshwater inflows to upper Perdido Bay.

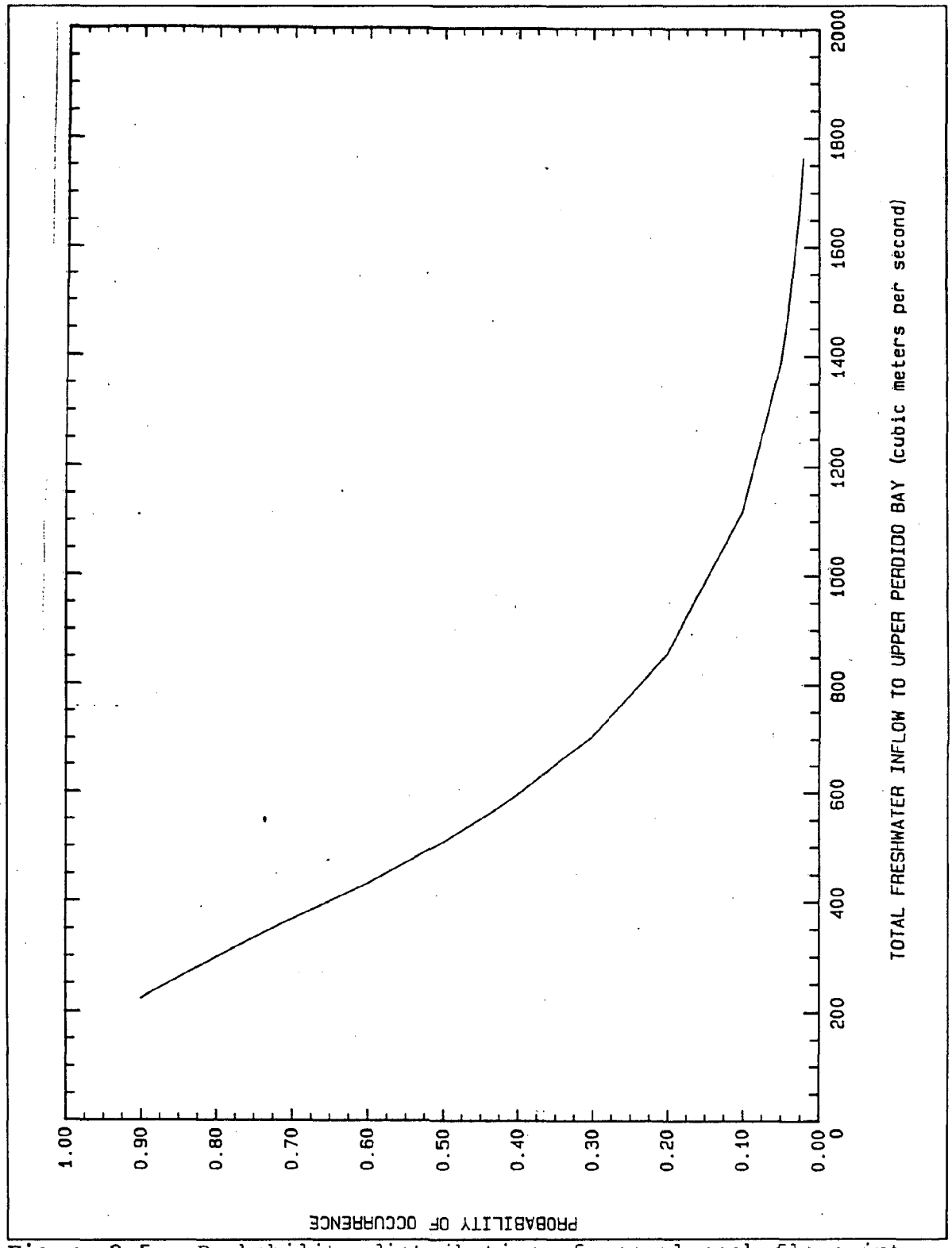


Figure 2.5. Probability distribution of annual peak flows into upper Perdido Bay.

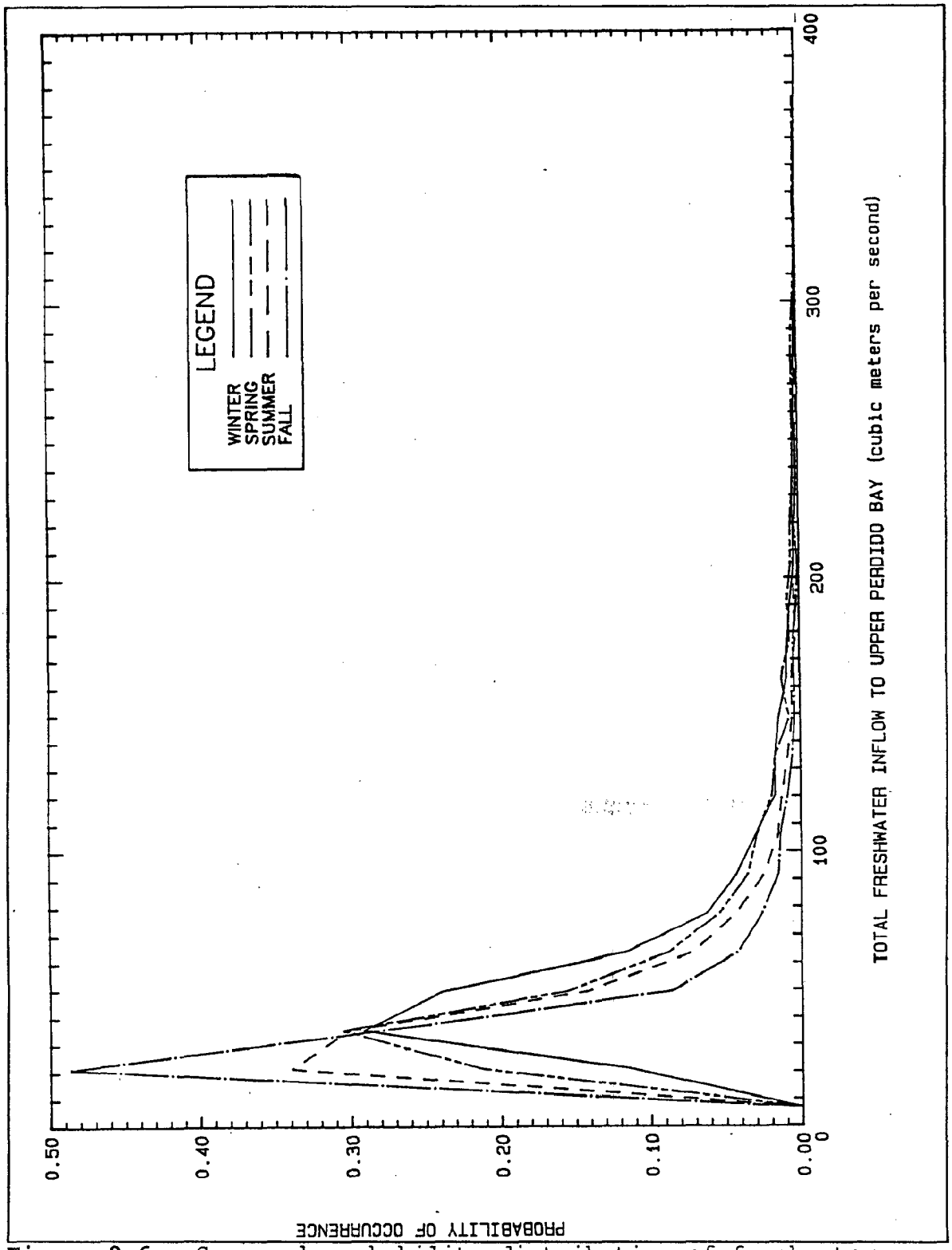


Figure 2.6. Seasonal probability distribution of freshwater inflows to upper Perdido Bay.

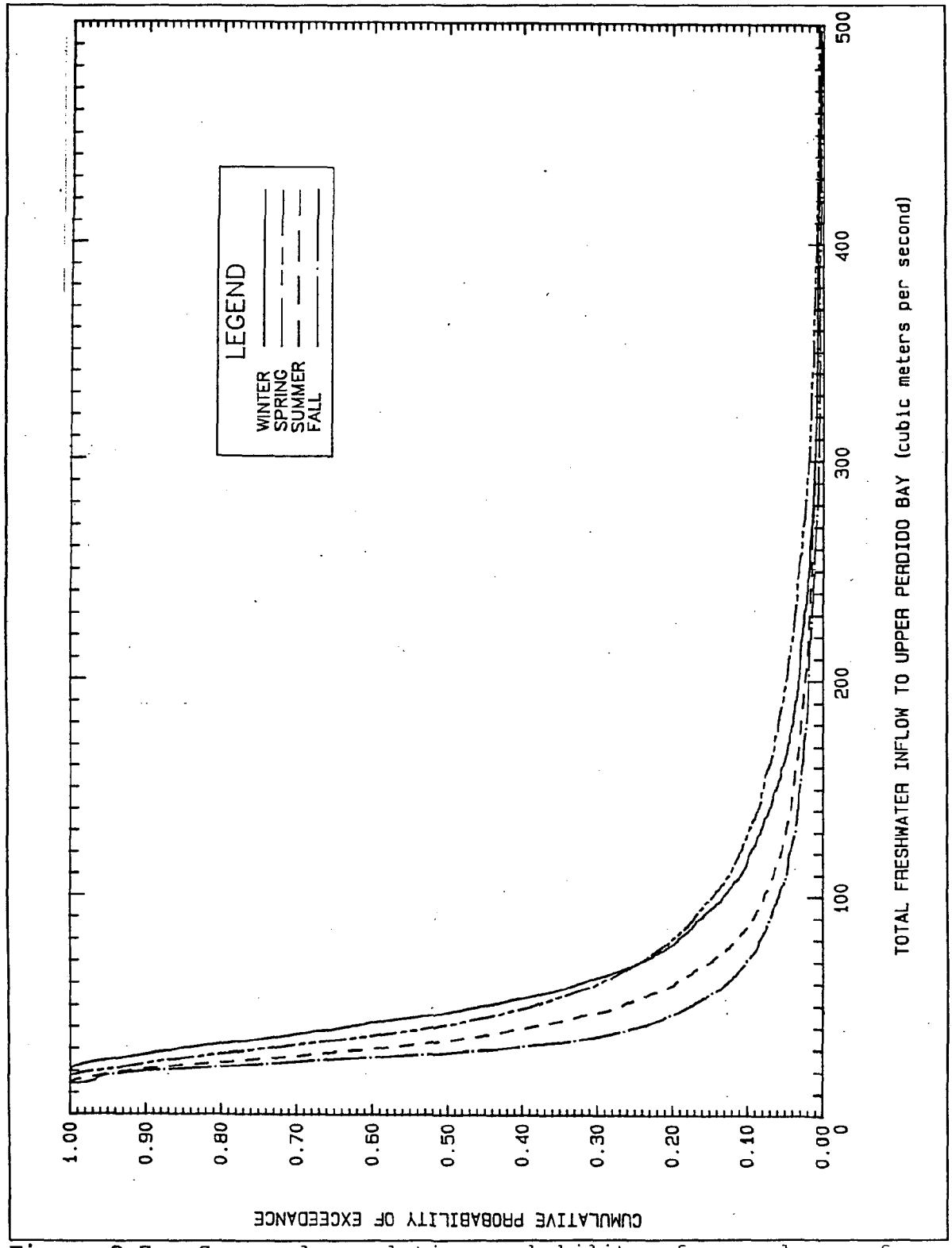


Figure 2.7. Seasonal cumulative probability of exceedance of freshwater inflow to upper Perdido Bay.

3. HYDROLOGIC CONDITIONS DURING PERIOD OF STUDY

OBJECTIVES

The Perdido River, its tributary streams, and the various other streams entering the bay are the major sources of nutrients to the estuary. These streams therefore have a major role in determining the chemical composition of Perdido Bay water and sediments and, along with the forces of wind and tide, the movement of Perdido Bay estuarine waters.

The primary objectives of the hydrologic analyses presented in this section of the report were to (1) document the hydrologic conditions which occurred during the study sampling year, (2) characterize these conditions in terms of their relationship to the long term hydrologic patterns of the system, and (3) provide an empirical basis for later use in the analysis of bay system transport processes and water chemistry. In general, the hydrologic conditions observed during the sampling year were representative of documented long term patterns. A discussion of these conditions follows.

RAINFALL

Rainfall records were analyzed for the period from July 1, 1988 until June 30, 1989. This period was chosen for analysis to be concurrent with the Perdido Bay hydrographic measurements. Total rainfall for the study period recorded at the Carpenter Tower (near Bay Minette, Alabama), Champion International's Cantonment Mill (Elevenmile Creek basin), and Pensacola Naval Air Station (south of the Bayou Marcus basin) gauging stations was 214, 165, and 196 cm, respectively. These are all greater than the 40-year average annual rainfall of 152 cm yr^{-1} recorded at Pensacola.

During the study period a total of forty-five storm events occurred at the rainfall stations in the Perdido Bay area. Twenty-two of these storms had a recorded rainfall of less than 2.5 cm in a 24 hour period. The remaining storms had peak 24

hour rainfalls of between 2.5 and 40 cm being reported at various stations. Detailed discussions of these more intense storms are provided in the following sections on individual stream hydrology.

STREAMFLOW

The majority of the freshwater inflow to Perdido Bay enters by way of five major tributaries: the Perdido River, Styx River, Blackwater River, Elevenmile Creek, and Bayou Marcus Creek. In October 1987, the USGS, with funding from Champion International Corp., established gauging stations on the Styx and Blackwater Rivers, Elevenmile Creek, and Bayou Marcus Creek. Daily streamflow data from these gauges and the Perdido River gauge at Barrineau Park were used to generate storm hydrographs for selected rainfall events occurring during the period of July 1, 1988 through June 30, 1989.

Perdido River

Mean discharge of the Perdido River during the study period was 20.6 m^3 sec^{-1}. This flow is approximately 94% of the 47 year mean value and is well within the expected annual range.

Hydrographs for the Perdido River are based on rainfall data collected at Carpenter Tower near Bay Minette, Alabama and Oak Grove Tower located in north central Escambia County, Florida. Of the twenty-two storm events studied, peak 24 hour rainfalls ranged from 1.8 to 40 cm.

Low intensity rainfall events were frequent in the months of July and August 1988. These storms were typical for this period, short in duration and causing only minimal increases in river flow. Rainfall events during the month of September 1988 produced streamflows typical of long term seasonal patterns. Three storms occurred in September in which peak 24 hour rainfalls of between 6.4 and 7.6 cm were recorded. Peak discharges associated with these events ranged from 63.1 m^3 sec^{-1} to a seasonal high of 118 m^3 sec^{-1}. Peak flows lagged behind the

center of rainfall mass by an average of 31 hours. An average of ten days was required for flow to return to a steady base rate after each storm. During the months of October 1988 through April 1989 rainfall was infrequent with events of 3.8 cm or less occurring on an average of every ten days. As in July and August of 1988, these events caused only minimal increases in streamflow.

Storm activity intensified during the months of May and June 1989, culminating on June 8 when 40 cm of rain fell at Carpenter Tower in one 24 hour period. The Perdido River's base flow just prior to this event was approximately 10.8 m^3 sec^{-1}. An instantaneous peak flow of 476 m^3 sec^{-1} occurred on June 9 after which a little over six days passed before river flow returned to a steady rate near base flow. Events of this magnitude or greater have occurred on three other occasions since 1980 and occur on average every two to five years.

The sequence of events occurring from July 1, 1988 to June 30, 1989 generally reflects the long term hydrologic patterns of the Perdido River. It is assumed that this characterization holds true for the four remaining tributaries.

Styx River

The mean discharge rate of the Styx River during the study period was 15.1 m^3 sec^{-1}. Hydrographs for the Styx River were based on rainfall data collected at the Carpenter and Molino towers.

Of the twenty-two events for which hydrographs were generated, four had peak 24 hour rainfall values of less than 2.5 cm. Flow rates of the Styx River were more responsive to events having peak rainfalls of less than 3.8 cm when compared to the Perdido River. Therefore the low intensity storms of July and August 1988, and October 1988 through April 1989, had significantly greater effect. Base flow during July and August 1988 increased from 3.4 to 5.9 m^3 sec^{-1}. Storm events during

July brought about peak flow rates averaging 15.8 m^3 sec^{-1}. Peak flows increased sharply in August averaging 71.2 m^3 sec^{-1}, while lag times remained fairly consistent with those of the two previous months at an average of 36 hours.

Four events occurred in September 1988 of 4.2 to 7.6 cm per 24 hour period with a mean peak flow rate of 71.7 m^3 sec^{-1}. Lag times averaged 24 hours and periods in excess of five days were required to return flow rates to base value. The short duration, high intensity storms occurring in May and June of 1989 brought about peak flows averaging 49.3 m^3 sec^{-1} with a mean lag time of 54 hours.

Blackwater River

Owing to the close proximity of the two watersheds, the Blackwater and Styx rivers are normally affected by the same storm events. However, the Blackwater River, with a mean discharge of 4.6 m^3 sec^{-1}, drains a somewhat smaller watershed.

Peak flows for the months of July through September, 1988 averaged 22.1 m^3 sec^{-1}. Stream flows varied from 1.0 to 58.0 m^3 sec^{-1}. Lag time between the center of rainfall mass and time of peak flow was typically 41 hours with an average of six days passing before river flow returned to a steady base rate. Storm events occurring in the months of October 1988 through February 1989 caused only minor fluctuations in the steadily decreasing flow rate.

A significant increase in storm activity beginning in March 1989 initiated a trend of increasing streamflow that continued through June. During this period peak 24 hour rainfalls ranged from 2.5 to 40 cm. Peak flows typically averaged 20 m^3 sec^{-1} with lag times of 24 to 48 hours. The storm of June 8, with a peak 24 hour rainfall of 40 cm, produced a peak flow of 269 m^3 sec^{-1} after a lag of 24 hours.

Elevenmile Creek

Rainfall data from Champion International's Cantonment Mill gauging station was used in the development of hydrographs for Elevenmile Creek. Records for the study period, July 1, 1988 through June 30, 1989, indicate that the precipitation pattern for the Elevenmile Creek watershed differed significantly from the pattern of rainfall in the watersheds of the Perdido, Styx and Blackwater Rivers. Seasonal variations in storm frequency and intensity were much less distinct in the vicinity of the Elevenmile Creek watershed.

Of the twenty-six storm events that occurred during the study period, ten produced peak 24 hour rainfalls of less than 2.5 cm. Not surprisingly, these produced minimal increases in streamflow. The mean flow rate during this study period was 2.9 m^3 sec^{-1}. Nine storm events produced peak 24 hour rainfalls of between 2.5 and 5.1 cm. These storms were typically one to three days in duration, and on average produced peak flow rates of 7.2 m^3 sec^{-1} with lag times usually 24 hours or less. Return to base flow rate conditions in most cases required five to seven days. Five events produced peak 24 hour rainfalls of between 5.1 and 10.2 cm. These storms produced peak flows averaging 14.4 m^3 sec^{-1} with lag times again 24 hours or less. The time required to return to base flow conditions for these events generally ranged from eight to fifteen days.

Two events occurred in June 1989 during which peak 24 hour rainfalls of greater than 12.7 cm were recorded. The first of these occurred on June 8, and produced a peak 24 hour rainfall of 16.6 cm with a corresponding peak streamflow of 179 m^3 sec^{-1}. Seven days after the passage of the center of rainfall mass of the first storm, a second event occurred on June 15. This event produced a peak 24 hour rainfall of 15.9 cm. Streamflow again increased and culminated with a peak of 125 m^3 sec^{-1} after a lag of approximately 24 hours.

Bayou Marcus Creek

Bayou Marcus Creek is the smallest of the five drainage basins discussed thus far. The mean flow rate for this tributary is 1.0 m^3 sec^{-1}. Rainfall data from Champion International's Cantonment Mill and the Pensacola Naval Air Station monitoring stations were used to generate hydrographs for thirty storm events that occurred during the study period. Twenty of these produced peak 24 hour rainfalls of less than 5.1 cm with a mean peak flow rate of 1.7 m^3 sec^{-1}. Lag times were typically less than 24 hours with return to base flow rate occurring after an average of six days. Eight storms with peak 24 hour rainfalls of 5.1 to 10.2 cm occurred during the study period. These storms produced peak flow rates having a mean value 3.0 m^3 sec^{-1}. Lag times were slightly higher, typically 30 hours, and return to base flow rate required nine days on average.

During this same period, two storms with peak 24 hour rainfalls in excess of 12.7 cm occurred. The first occurred in August 1988, producing a peak 24 hour rainfall of 12.8 cm. A peak flow of 8.6 m^3 sec^{-1} was reached after a lag time of less than 24 hours. The second event began on June 8, 1989 and continued through June 9. This event generated a peak 24 hour rainfall of 13.6 cm. Streamflow rate reached a peak of 10.6 m^3 sec^{-1}, less than 24 hours after the center of mass of rainfall. The time required to return to base flow rate was in excess of nine days.

4. SEDIMENT CHEMISTRY

OBJECTIVES

Examination of sediments can offer insight into past conditions as well as indicating the present "pollution climate" because sediments represent a temporally integrated record of chemical conditions in an estuary. Many contaminants entering an estuary tend to be sequestered in the sediments. The objective of the project sediment sampling program was to determine the presence of metals, synthetic organic compounds, and nutrients in the bay as well as in streams contributing materials to the bay. Samples were also taken to determine if recent temporal trends in nutrient enrichment were apparent. For interpretation, these results were compared to results of a statewide (Florida) survey of natural estuarine sediments.

In addition to the sediment samples collected for the Interstate Project, sediment samples have been collected and analyzed for priority pollutants in Elevenmile Creek, Perdido River, and Jacks Branch, a tributary entering the Perdido River about 9 km downstream from Barrineau Park. These samples were collected as a part of an FDER project to identify priority pollutants in the vicinity of known or suspected sources of toxic materials. Results from these samples are also discussed in this chapter.

METHODS

Station Locations and Parameters Measured

On August 18, 1987, sediment samples were collected from seven stations in Perdido Bay, and one each in the Perdido River, Elevenmile Creek, Palmetto Creek, and Soldier Creek (Figure 4.1). These samples were analyzed for nutrients and metals. On March 27, 1989, sediments were collected from one station in each of the five tributaries at the locations shown in Figure 4.2 and analyzed for nutrients, metals, and a variety of organic compounds.

Sample Collection

The August 1987, sediment samples were collected by divers using cellulose-acetate-butyrate core tubes. Diver collection ensured the retrieval of undisturbed sediment cores. Replicate cores were taken at each station and subsamples taken from the 0 - 2 cm depth interval. Single subsamples were taken from one core at each station at 5 - 7, 10 - 12, 15 - 17, and 20 - 22 cm depth intervals.

The March 1989, sediment samples were collected with a stainless steel Ponar grab. The grab samples represented surficial sediments to a depth of approximately 5 cm. At each station, triplicate grabs were taken and two were analyzed. The third was held in reserve for use in the event of problems.

All samples were placed in pre-cleaned plastic containers, stored on ice, and shipped to the laboratory for processing within 24 hours.

Laboratory Analyses

Metals. Sediment metal concentrations were determined for nine metals: aluminum, arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc. For all metals except mercury, sediment was dried at 80° C, thoroughly mixed, and a 0.3 to 0.5 g portion weighed into a 100 ml polytetrafluoroethylene vial. Five ml of Ultrex HF and 10 ml concentrated Ultrex HNO_3 were added, the vials capped, and the sample digested by refluxing at 100° C for 48 hours. After digestion, the sample was taken to dryness and the residue dissolved in 1 ml concentrated Ultrex HNO_3 and 9 ml deionized, double distilled water. Total digestion using HF is essential for releasing all metals from aluminosilicate mineral lattices. Sediment samples for mercury were first digested with H_2SO_4 and HNO_3 on a water bath at 60° C and then further oxidized with potassium permanganate.

Aluminum and zinc were analyzed using flame atomic absorption spectroscopy (AAS). Cadmium, chromium, copper, lead,

and nickel were analyzed by flameless AAS using a Zeeman furnace. Flameless AAS methods were used for arsenic (hydride) and mercury (cold vapor). The AAS methods are described in APHA (1985).

Duplicate laboratory analyses and spikes were performed on 10% of all samples. National Bureau of Standards (NBS) Estuarine Sediment Standard Reference Material 1646 was run with each batch of sediment samples. Recovery of metals from the reference material ranged from 94 - 105% with relative standard deviations (RSD) of 2 - 7%, most being <5%. The exception was arsenic with approximately 90% recovery and RSD of 8.5%. If analytical results of the Standard Reference Material deviated by more than two standard deviations (lab results) from the mean reported by NBS, then the analyses of all sediment samples in that batch were repeated.

Nutrients. Total organic carbon (TOC), total Kjeldahl nitrogen (TKN) and total phosphorus (TP) were determined according to methods described in APHA (1985).

Organics. Chlorinated pesticides and polychlorinated biphenyls (PCB) were analyzed by Method 608 (40 CFR, Part 136). Semi-volatile organics and polynuclear aromatic hydrocarbons (PAH) were analyzed by Methods 8270 and 8310 (EPA SW 846), respectively. The compounds measured and detection limits are listed in Appendix C (Table C.1).

RESULTS

Metals

Results of sediment metal analyses are listed in Appendix C (Table C.2). The concentrations of seven trace metals (arsenic, cadmium, chromium, copper, lead, nickel, zinc, and mercury) were compared to the concentration of aluminum as described in Schropp et al. (1990) to determine whether Perdido Bay sediments were enriched with trace metals. Since the interpretive approach is based on analyses of surficial sediments, only the results from

the 0 - 2 cm depth interval are used for the August 1987 samples. Results of these comparisons are shown in Figures 4.3 and 4.4.

Aluminum concentrations ranged from 5000 to 114000 ppm. Sediments from the tributaries generally contained the lowest aluminum concentrations, reflecting the coarser nature of these sediments. The finer-grained, silty-clay sediments of Perdido Bay contained higher concentrations of aluminum. Concentrations of metals at most stations fell within expected natural ranges (based on the metal:aluminum relationships). Exceptions were lead in Bayou Marcus and zinc in Elevenmile Creek and Bayou Marcus. Lead and zinc enrichment in Bayou Marcus sediments is consistent with the urban nature of the watershed in contrast to the predominately rural nature of the other four watersheds. Zinc enrichment in Elevenmile Creek is perhaps related to paper mill operations in the watershed.

Mercury cannot be evaluated by its relationship to aluminum. Nevertheless, in a statewide survey of metals in sediments from natural estuarine sites, FDER found that mercury concentrations did not exceed 0.21 ppm (FDER, 1988). Mercury concentrations from all stations sampled in Perdido Bay, Perdido River, and Elevenmile Creek were less than 0.21 ppm, indicating that mercury was within natural ranges.

Nutrients

Concentrations of TOC, TKN, and TP in Perdido Bay and tributary sediments are listed in Appendix C (Table C.3). Differences in sediment nutrient concentrations between stations appear due primarily to sediment grain size. Stations with the greatest nutrient concentrations were those that had the highest aluminum concentrations, high aluminum being an indicator of fine-grained sediments.

Sediment nutrient concentrations in Perdido Bay were compared to concentrations in natural sediments throughout Florida. Figure 4.5 shows TOC/TKN relationships from four

statewide (Florida) surveys of sediment nutrients in 1986 - 1987, and, for comparison, TOC/TKN relationships for Perdido Bay surface sediments. Data from Perdido Bay are plotted in the bottom of Figure 4.5 with the best fit lines from the April - June and November - December 1987 statewide data (from the top of the figure). TKN/TP relationships are shown similarly in Figure 4.6. Concentrations of TOC, TKN, and TP in Perdido Bay system sediments are relatively high, but are within the range of concentrations found in natural sediments throughout Florida. TOC/TKN and TKN/TP ratios in Perdido Bay sediments are also similar to those of natural sediments. Although not statistically rigorous, these comparisons indicate little or no deviation from nutrient conditions observed in natural sediments of other estuaries.

TOC/TKN and TKN/TP ratios in cores from the Perdido Bay stations are shown in Figures 4.7 and 4.8. In the upper bay (stations PRB-3,4,5) TOC/TKN ratios decrease with depth in the sediment column, suggesting that organic carbon inputs have increased over time relative to nitrogen in upper bay sediments. In the lower bay TOC/TKN ratios generally increase with depth in the sediments suggesting a decrease in nitrogen, perhaps lost by remineralization and denitrification, which is more consistent with natural conditions. TKN/TP ratios show less of a trend with depth in the sediments. There are no immediately obvious trends in nutrient distribution with depth in the sediment in relation to station location.

Organics

Organic compounds identified in the tributary sediment samples collected in March 1989 are listed in Table 4.1. Polychlorinated biphenyls were found in low concentrations in the Blackwater and Styx Rivers. No PCBs were detected in any other tributary. Higher molecular weight aliphatic hydrocarbons were detected in all streams except the Styx River. Several types of PAHs were found in all five tributaries. Greatest concentrations of PAH were found in Bayou Marcus sediments, probably reflecting

the more urban nature of the Bayou Marcus watershed. One PAH, phenanthrene, was found only in the Styx and Blackwater Rivers.

FDER PRIORITY POLLUTANT SURVEY

In June 1989, sediments were collected from 18 stations in Elevenmile Creek, Perdido River, and Jacks Branch (Delfino, 1990). Station locations are listed in Appendix C (Table C.4). These sites were selected because of the potential for sediment contamination from the Champion International Corporation mill on Elevenmile Creek and Dubose Oil Products facility on Jacks Branch. The sediments were analyzed for 83 priority organic pollutants. Results are listed in Appendix C (Tables C.5 and C.6).

In Elevenmile Creek, the only quantified contaminant was the PAH phenanthrene at one station. The measured concentration, 0.05 mg kg^{-1}, was at the detection limit for this compound. In Jacks Branch and the Perdido River, phenanthrene was present above the detection limit at 5 stations, in concentrations ranging from 0.05 to 0.19 ug kg^{-1}. The stations with highest concentrations were located in drainage ditches from the Dubose facility. Another PAH, benzo(a)anthracene was present at the detection limit (0.04 ug kg^{-1}) at one station on Jacks Branch. It should be noted that samples for the priority pollutant project were taken shortly after the June 1989 storm which probably flushed an unknown amount of sediment from the tributaries.

SUMMARY

The sediment chemistry data from the Interstate Study indicate that, at present, Perdido Bay and its tributaries are not seriously contaminated by toxic pollutants. Results of the priority pollutant survey and preliminary results from the EPA Cooperative Management Project and Champion-supported studies support this conclusion. The tributaries most influenced by man's activities do, however, contain small concentrations of contaminants in the sediments.

The studies discussed above did not include measurement of dioxin, an organic compound associated with pulp mill operations. Dioxin measurements are being done by EPA and Champion International.

Table 4.1. Organic compounds detected in Perdido Bay tributary sediments collected in March, 1989.

Compound	Station	Concentration[a] ($\mu g\ kg^{-1}$)
Polychlorinated biphenyls (PCB)		
Aroclor 1254	BWR-1	7
	STX-1	8
Aliphatic hydrocarbons		
C24 aliphatics	PRR-4	86
	BWR-1	235
	EMC-4	65
	BMC-1	165
C25 aliphatics	PRR-4	88
	PRR-4	205
	EMC-4	130
	BMC-1	275
C26 aliphatics	PRR-4	145
	BWR-1	250
	EMC-4	315
	BMC-1	470
C28 aliphatics	PRR-4	105
	BWR-1	525
	EMC-4	375
	BMC-1	450
C30 aliphatics	PRR-4	170
	BWR-1	750
	EMC-4	245
	BMC-1	550
Polynuclear Aromatic Hydrocarbons (PAH)		
Benzo(k)fluoranthene		
	PRR-4	150
	STX-1	250
	BWR-1	150
	EMC-4	180
	BMC-1	495

Table 4.1. Continued.

Compound	Station	Concentration ($\mu g\ kg^{-1}$)
Polynuclear Aromatic Hydrocarbons (PAH)		
Chrysene	PRR-4	320
	STX-1	570
	BWR-1	415
	EMC-4	120
	BMC-1	675
Fluoranthene	PRR-4	180
	STX-1	160
	BWR-1	76
	EMC-4	69
	BMC-1	315
Pyrene	PRR-4	315
	STX-1	400
	BWR-1	435
	EMC-4	140
	BMC-1	1050
Phenanthrene	STX-1	65
	BWR-1	81

[a]Mean of replicate samples.

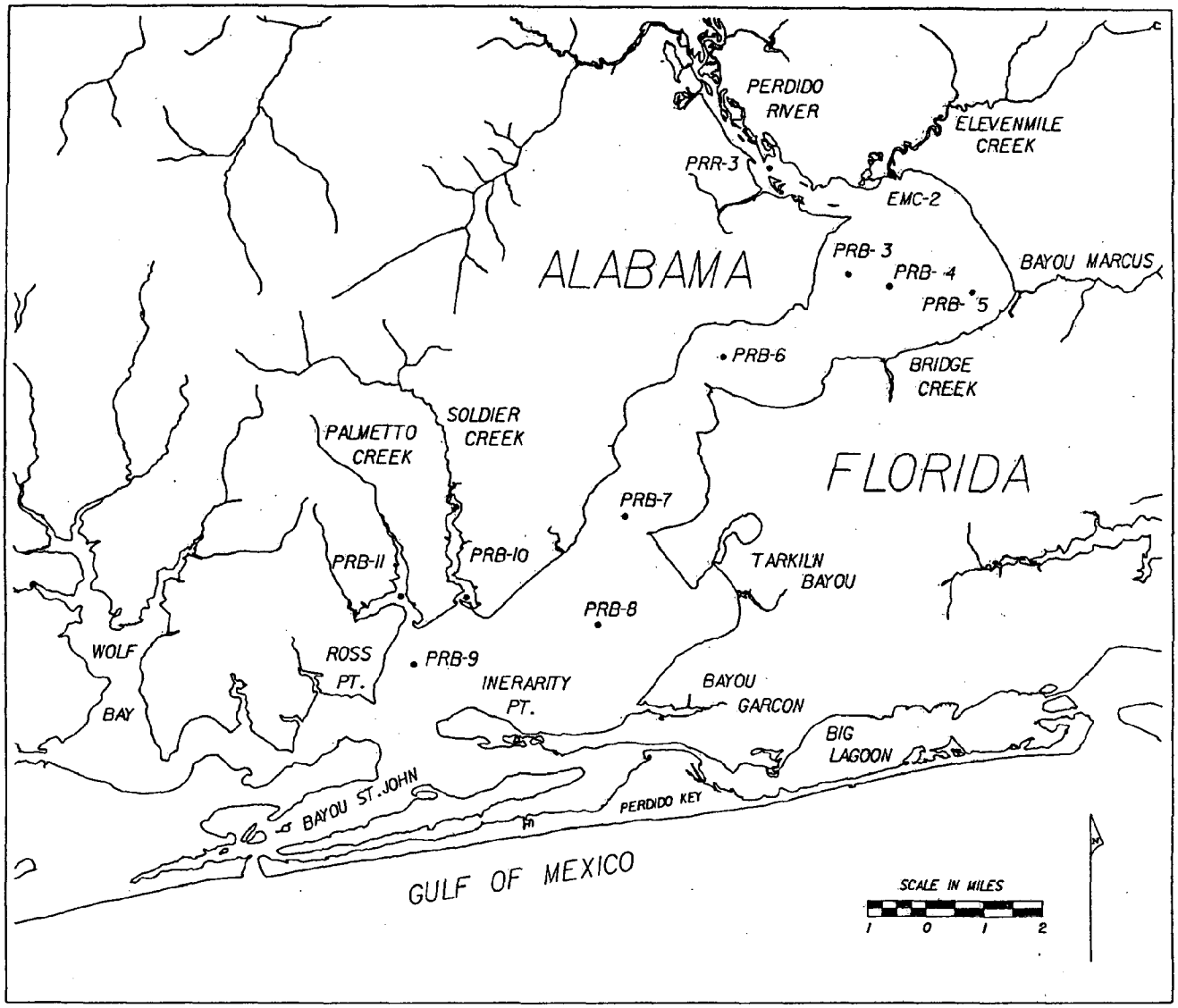


Figure 4.1. Sediment sampling stations in Perdido Bay, Perdido River, and Elevenmile Creek, August 1987.

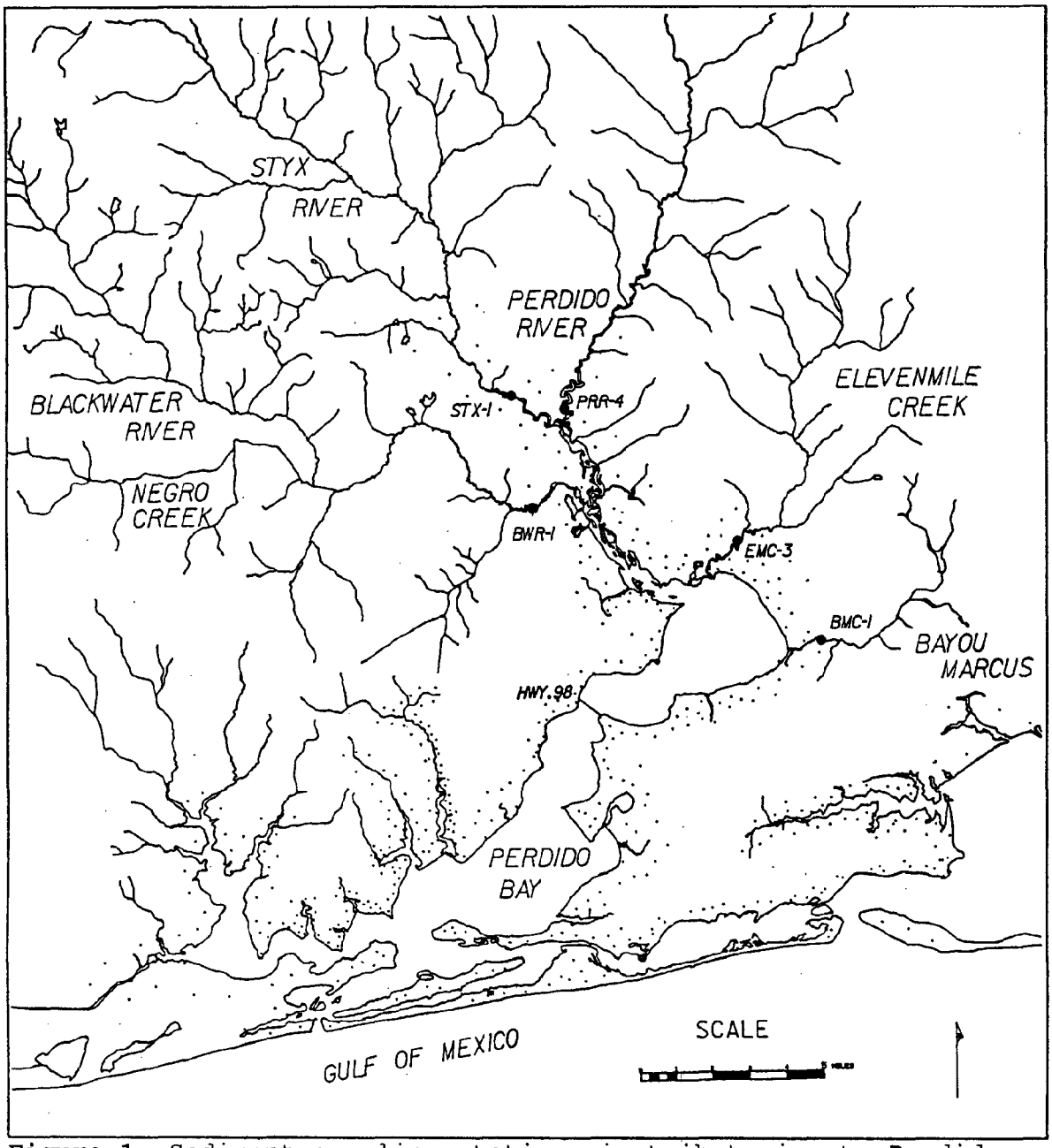


Figure 1. Sediment sampling stations in tributaries to Perdido Bay, March, 1989.

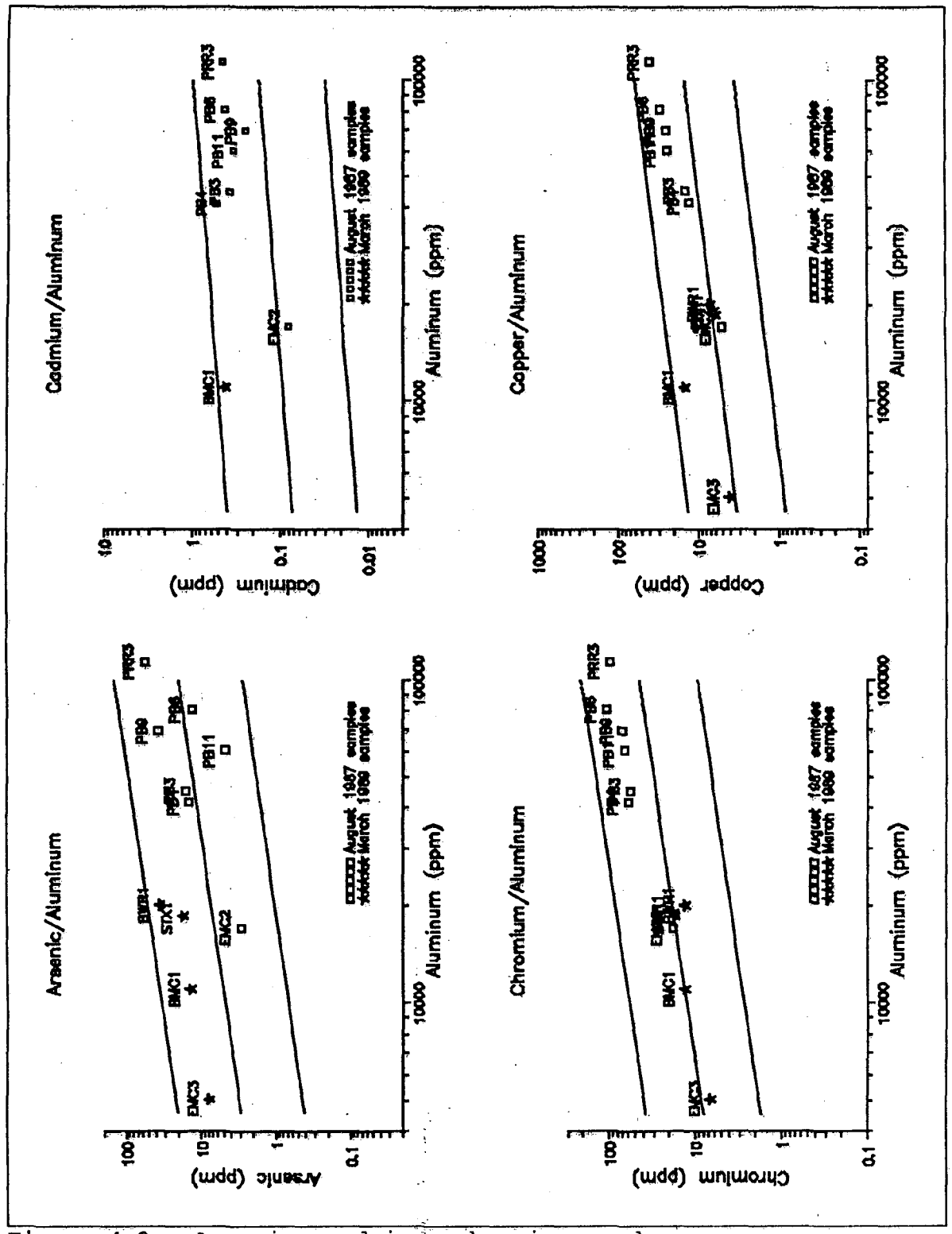


Figure 4.3. Arsenic, cadmium, chromium, and copper concentrations in Perdido Bay system sediments. Points within the two outer lines are considered to be within the range of natural sediments (Schropp et al., 1990).

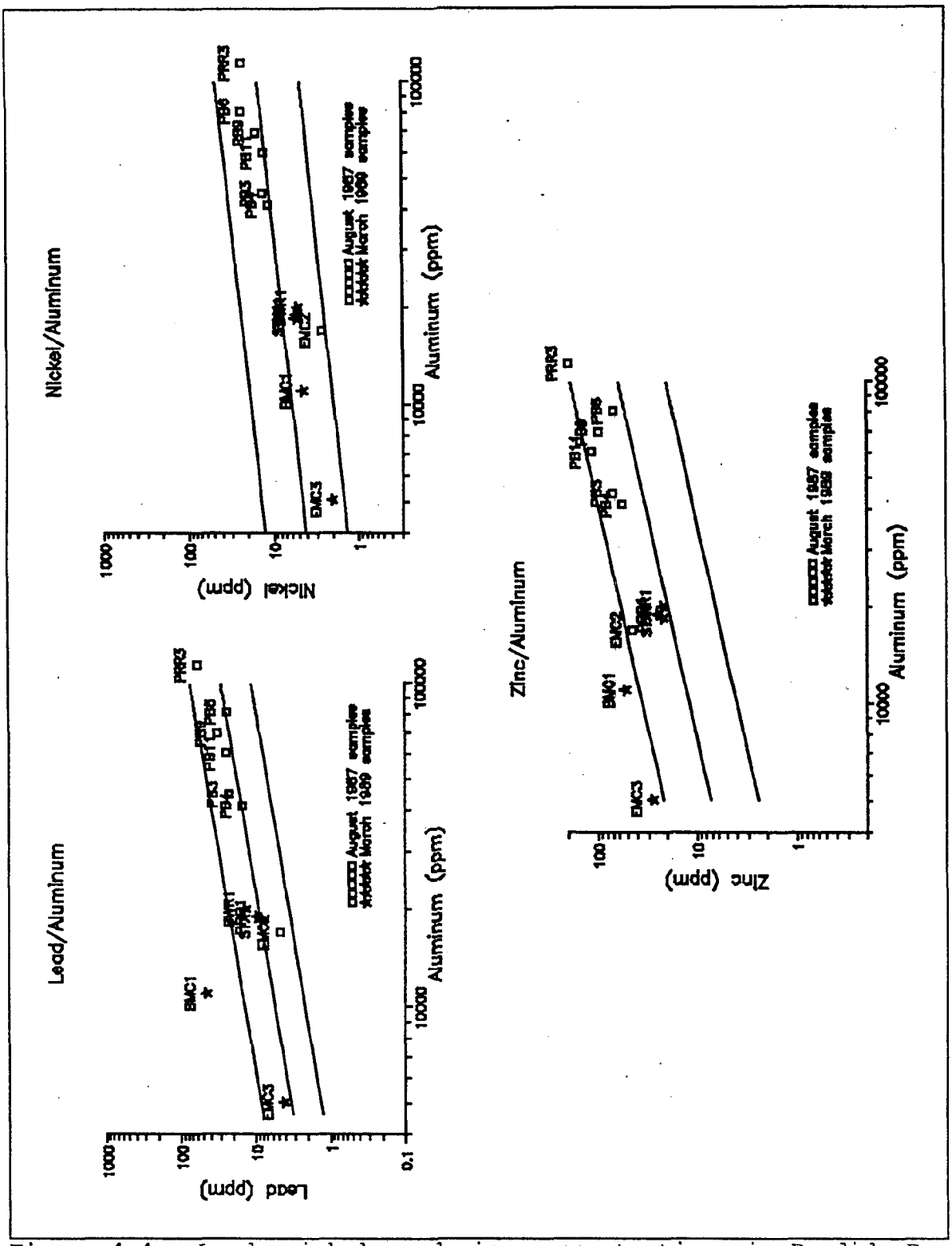


Figure 4.4. Lead, nickel, and zinc concentrations in Perdido Bay system sediments. Points within the two outer lines are considered to be within the range of natural sediments (Schropp et al., 1990).

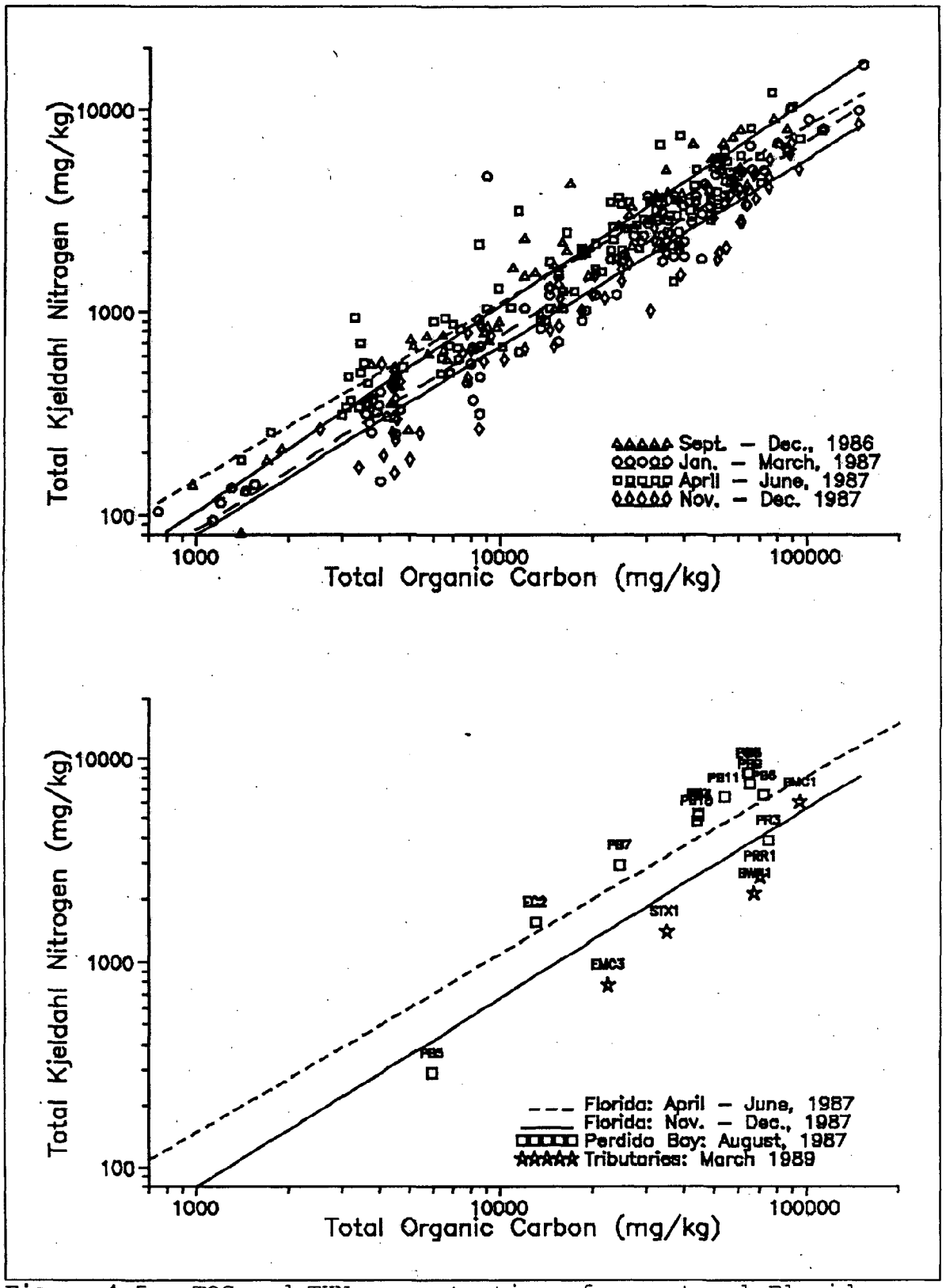


Figure 4.5. TOC and TKN concentrations from natural Florida (upper) and Perdido Bay system (lower) sediments.

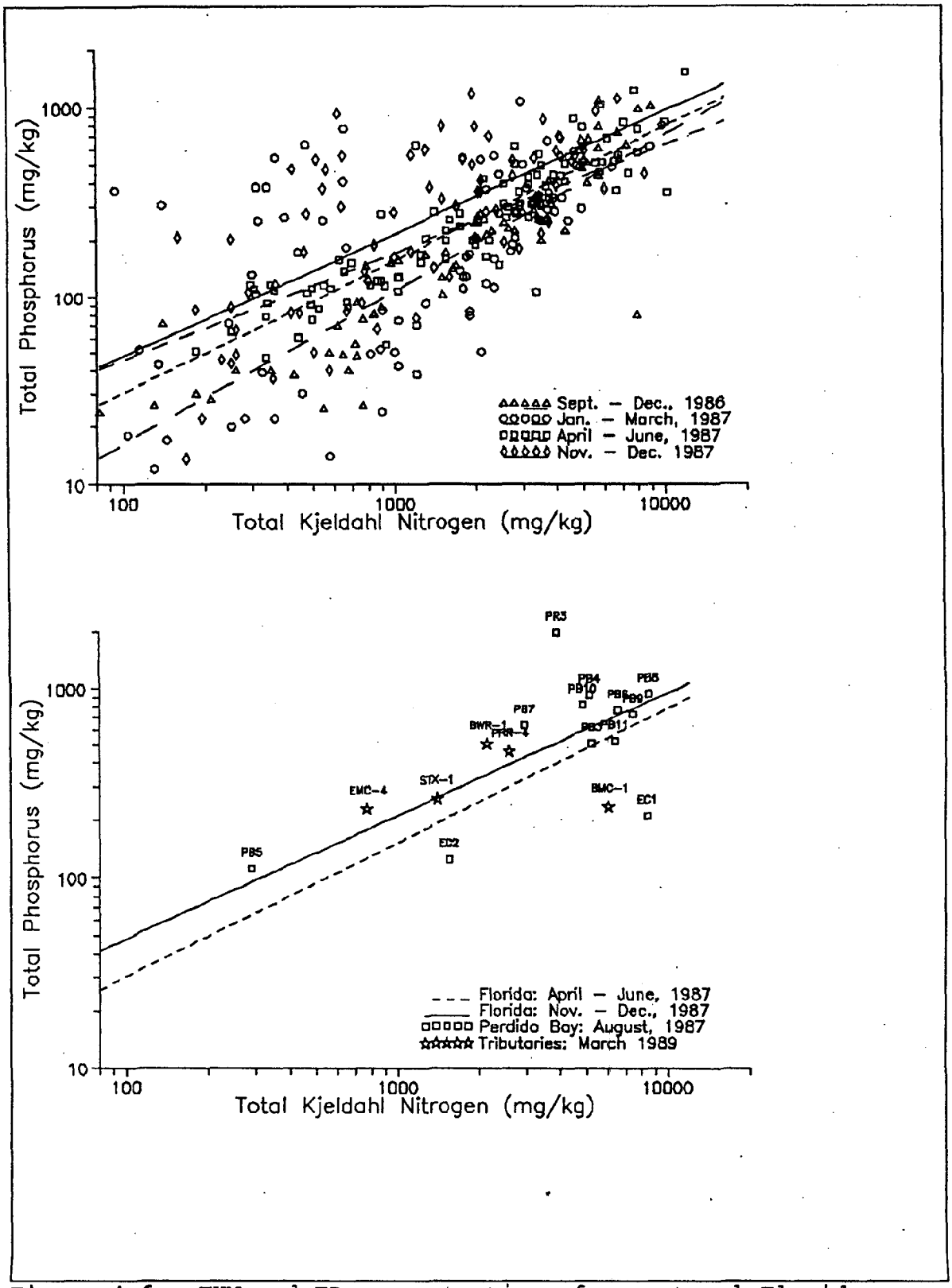


Figure 4.6. TKN and TP concentrations from natural Florida (upper) and Perdido Bay system (lower) sediments.

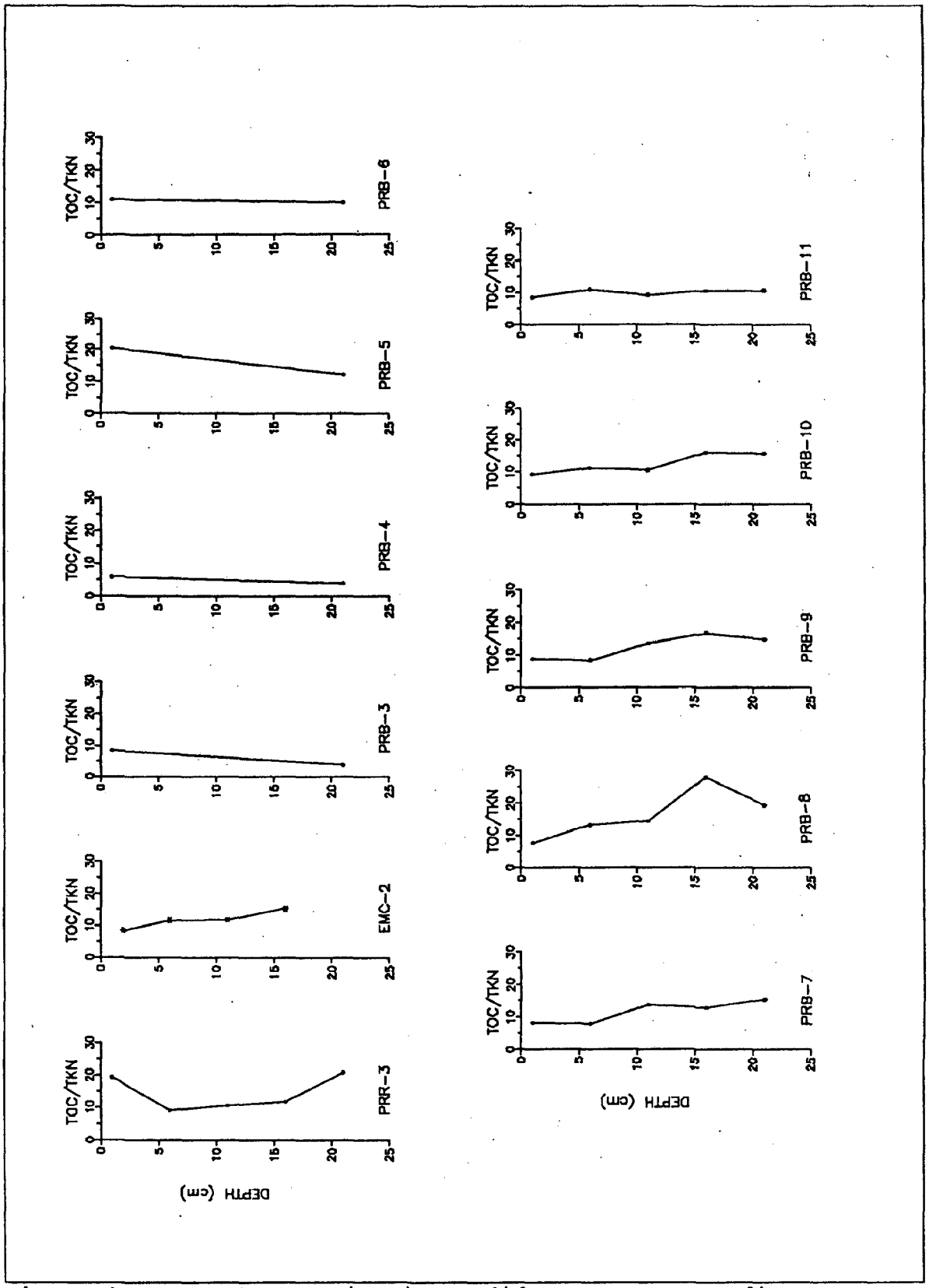


Figure 4.7. TOC/TKN ratios in Perdido Bay system sediment cores.

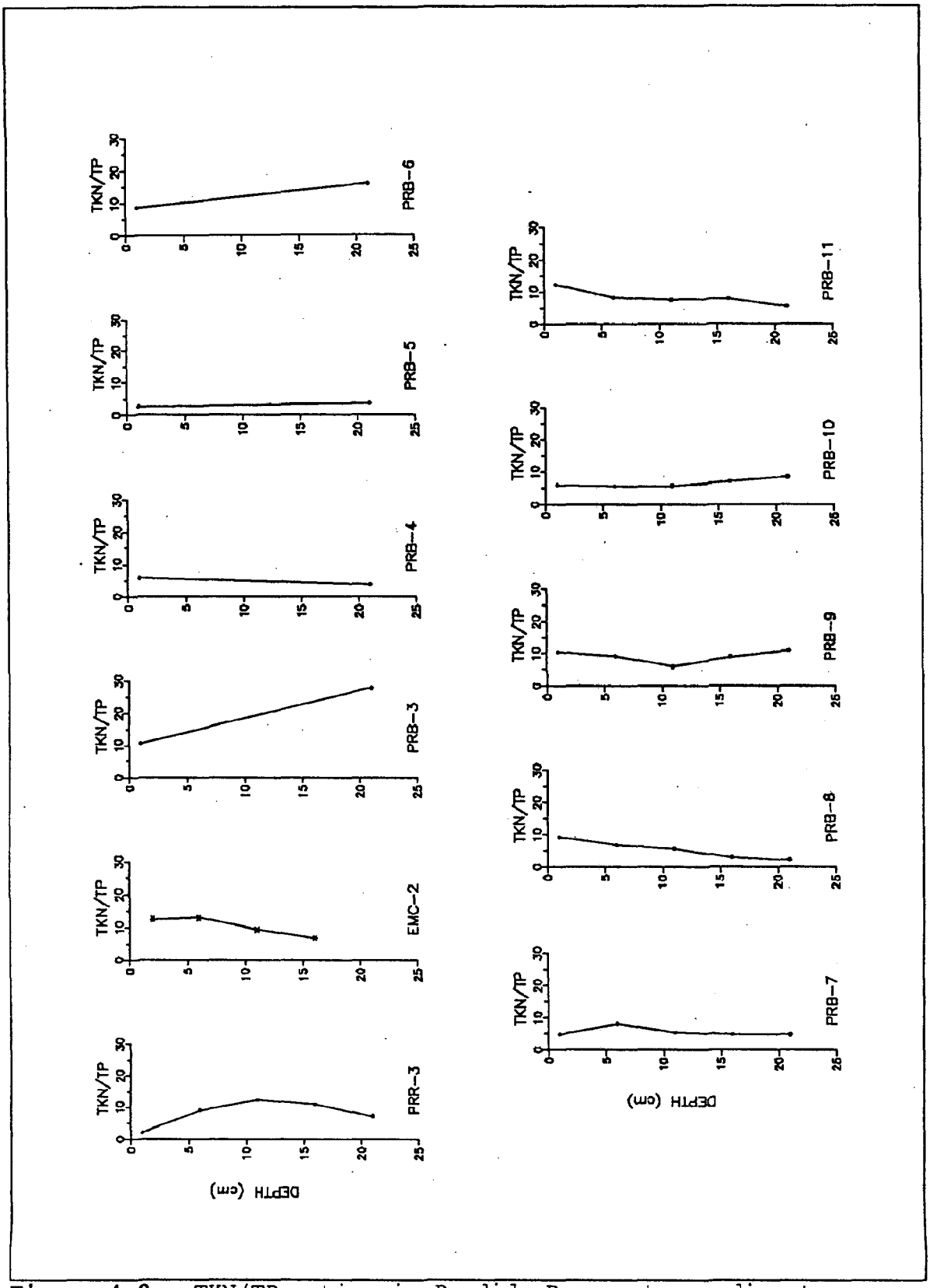


Figure 4.8. TKN/TP ratios in Perdido Bay system sediment cores.

5. ESTUARINE HYDROGRAPHY

OBJECTIVES

The ability of the bay to flush waterborne substances through its domain is in large part governed by the residual or net movement of water outward across the bay boundaries over a specified period of time. This movement is referred to as net circulation. The objective of the hydrographic portion of this investigation was to develop an understanding of the physical processes that govern net circulation. Thus, the hydrographic sampling program was designed to document the movement of water, the transporting medium for nutrients and solids, between the major sub-basins comprising Perdido Bay in such a way that mass balances and changes in mass storage for each sub-basin could be determined. Once developed, it was hoped that these empirical water budgets, in combination with the application of the deterministic principles of estuarine hydrodynamics and conservation of mass, could be used as the basis for a simple predictive model of the transport and storage of waterborne substances in the bay. These objectives were accomplished as described in the following sections.

In order to examine flushing patterns and transport and fate of nutrients in the bay, three types of physical measurements were taken to evaluate water movement in the watershed and estuarine system. In the watershed, stream discharges were measured (by the USGS with funding from Champion International Corp.) to estimate the amounts of freshwater and calculate the delivery of nutrients to the bay (Chapter 6). In the bay, current speed and direction were measured to help determine volumes of water exchanged between various compartments of the bay. Finally, tidal elevations in the bay were measured during the current measurement periods. This data was used to estimate the Gulf's influence on water movement and the exchange of fresh and salt water in the bay.

Since weather patterns are the major influence, along with tides, of water movement in the streams and bay, weather data were used not only in interpreting the physical measurements, but also were critical in identifying when and how the field program would be conducted.

MEASUREMENT METHODS

Sampling Strategy

From examining its configuration it appeared that the Perdido Bay estuarine system can be divided into five compartments (Figure 5.1). These divisions are formed by natural constrictions in the bay. The first compartment, referred to as the Upper Bay, extends from the mouths of the Perdido River and Eleven Mile Creek southwest to the constriction in the bay formed by Grassy and Double Points. The next compartment is the Middle Bay, whose lower limit can be defined by a line extending from Manuel to DuPont Points. The Middle Bay is an irregular, transitional reach connecting the more open Upper Bay and Main Bay basins. Lower boundaries of the Main Bay are defined by two lines: one from Mill Point to Inerarity Point and the other south across the GICWW from Hatchet Point. The Lower Bay connects the Main Bay to the Gulf of Mexico via Perdido Pass and extends east to the Florida SR 292 bridge where it joins Big Lagoon. The West Bay consists of the open water from Hatchet Point westward to the narrow entrance of the GICWW's "Alabama Canal".

The sampling strategy was designed to capture characteristic water movements between these compartments under various representative conditions of tide, wind, and tributary inflow. Based on climatological records, four periods were chosen to be representative of typical seasonal conditions (Table 5.1). The sampling periods were selected to isolate, as much as possible, individual influences of tide, wind, and freshwater inflow. For example, the August sampling period was intended to examine the influence of maximum tide and maximum freshwater inflow. In November and March emphasis was placed on northerly wind conditions, while in June primary interest was focused on the

Table 5.1. Hydrographic sampling periods and target conditions.

Time	Tide Range	Wind	Runoff
March, neap tide	Minimum	Maximum, northerly	Medium
June, neap tide	Minimum	Light, southerly	Medium
August, spring tide	Maximum	Light, southerly	High
November, neap tide	Minimum	Moderate, northerly	Low

effects of a southerly wind.

The first current measurements were conducted June 7 - 9, 1988. This field exercise was used to test instruments and procedures and to gather preliminary data. Following this, current measurements were obtained August 22 - 25, 1988; November 3 - 5, 1988; February 7 - 9, 1989; and June 9 - 11, 1989.

In general, the observed conditions of tide, wind, and freshwater inflow were in good agreement with the target conditions upon which the timing of the field program was based. The most notable exceptions to this were the strong southerly winds which occurred during the November 1988 campaign, and the abnormally high freshwater inflow observed during the June 1989 campaign. The occurrence of these unexpected conditions was not in any way detrimental to the success of the project in that a primary objective of the sampling program was to capture a variety of conditions. This was accomplished.

Station Locations

Current measurements were made along four transects that formed the boundaries of the Upper, Middle, and Main Bays (Figure 5.2). Three stations were established on the boundary between the Upper and Middle Bays (transect CT1); three stations on the boundary between the Middle and Lower Bays (transect CT2), and three stations on the boundary between the Main and Lower Bays (transect CT3). One station was located at the boundary of the

Main and West bays (transect CT4). Station locations are listed in Table 5.2.

Table 5.2. Current measurement station locations.

Transect	Station	LORAN LOPs[a]		Latitude	Longitude
CT1	1	13169.5	47142.4	30°25.32'N	87°23.95'W
CT1	2	13170.7	47141.5	30°25 13'N	87°23.80'W
CT1	3	13172.4	47140.3	30°24.86'N	87°23.61'W
CT2	1	13130.4	47126.3	30°22.02'N	87°27.35'W
CT2	2	13133.5	47126.3	30°22.00'N	87°27.04'W
CT2	3	13136.2	47126.3	30°22.01'N	87°26.76'W
CT3	1	13091.7	47109.7	30°18.58'N	87°30.73'W
CT3	2	13094.5	47110.0	30°18.61'N	87°30.47'W
CT3	3	13096.1	47110.1	30°18.65'N	87°30.31'W
CT4	1	13074.6	47108.3	30°18.36'N	87°32.36'W

[a]LORAN lines of position (time differences)

Current Measurements

The objective of the current measurement sampling plan was to obtain a synoptic set of current measurements for paired transects over a complete tidal cycle. Prior to beginning current measurements, moorings were set in place at each station. Two boats and field crews were then deployed simultaneously, each working on a separate transect. Beginning with Station 1, each station on a transect was occupied repeatedly, in sequence, over a 24 - 26 hour period. When measurements were concluded on the first two transects, the field crews immediately moved to the remaining two transects and collected a similar set of measurements over the next 24 - 26 hours.

Although the ideal sampling procedure would have deployed a minimum of four crews working all four transects simultaneously, this was not possible due to the limited availability of personnel and equipment. Therefore, it was decided to deploy the crews such that the two most complex and least understood basin

boundaries would be sampled simultaneously. These boundaries were located at transects CT3 and CT4. Following the completion of sampling at these two locations the crews were then deployed simultaneously at transects CT1 and CT2. Of these two, transect CT1 was considered to be the more important because it best defined the lower boundary of the Upper Bay and the seaward movement of freshwater.

Measurements were performed as follows. Upon securing the boat to a station mooring, wind and sea conditions were evaluated and, if necessary, an additional anchor was deployed to stabilize the boat. Wind speed and direction were measured using a hand-held wind speed indicator and hand-bearing compass. A vertical profile of water temperature, salinity, conductivity and dissolved oxygen was obtained, with measurements taken at 0.5 m intervals on both the downcast and upcast. Instruments and procedures were as described in the following chapter on water chemistry.

Current measurements were made with an Endeco Type 923 current meter or Neil Brown Model DRCM-2 current meter with Model CMDT-1 data terminal. Both instruments were calibrated and operated according to their manufacturer's instructions. Vertical profiles of current speed and direction were obtained beginning 0.5 m below the surface and at 0.5 m intervals to as near bottom as possible. At each depth interval, ten replicate measurements of current speed and direction were recorded.

Tide Measurements

Three tide gauge locations were surveyed in August 1988 and referenced to National Geodetic Vertical Datum (NGVD). Locations, shown in Figure 5.2, were selected to be as near as possible to historic tide gauge locations. Water levels at each site were recorded by Leopold & Stevens Type F water level recorders. These instruments provided a continuous record of water surface elevation at each gauging station for the duration of each current measurement period.

DATA REDUCTION

The process by which Perdido Bay water fluxes were obtained and related to climatological conditions at the time the current data were taken consisted of four major steps. The first step was to define the vertical structure of the velocity shear profile at each sampling station and to compute the corresponding integrated flow over the water column. Next, a similar definition of the horizontal distribution of flow across each transect was obtained for discrete time intervals during the diurnal sampling period. This information was then used in the third step of the analysis to develop time histories of the flow across each transect and to obtain the integrated volumetric fluxes from these data. Finally, effects of wind, tributary inflow, and storage changes in each basin were examined using available tide, climatological, and hydrologic data to compute a final mass balance for each sub-basin of the bay. A more detailed discussion of each major component of the process follows.

To begin the analytical process, a single value representing velocity at each half meter of water depth was obtained by averaging the ten magnitude and direction readings observed in the field. This was done to eliminate unnecessary biasing of the data by short-term turbulent fluctuations or movement of the boat. To accomplish this so that a true vector average was obtained, each observed value of current velocity was first decomposed into its components normal and parallel to the transect. Individual components were then averaged and the resultant of the flow velocity normal to the transect was obtained. These values were then used to define the vertical profile of the velocity at each station.

Figure 5.3 shows examples of vertical profiles at Stations 1, 2, and 3 at Transect CT3 taken on August 24, 1988. In this figure, the values for velocity at each depth represent flow normal to the transect as described in the preceding paragraph. Each profile represents the local flow characteristics for the

sampling interval at the given station, where the sampling interval is defined by the total time that current is measured at the station, from the first reading at the surface to the last reading at the bottom. The profile curve used to fit the data points was constructed graphically to better capture the influences of wind and tidal phase. This was especially useful when the data points exhibited significant scatter such that several curves could have an equal fit but only one curve would best reflect the prevailing conditions at that time. In all cases the velocity approached zero at the bottom as shown.

The vertical curves were then integrated over depth by determining the area between the plotted curve and the depth axis (zero velocity) to obtain values of the depth integrated flow. In cases where flow reversal existed between the upper and lower portions of the water column, the two layers were integrated independently, and the difference between the two areas was used to specify the net flow over depth. If flow reversal was a consistent characteristic of the vertical profiles, the upper and lower layers were kept independent throughout the analysis. However, if the flow reversal appeared to be attributable to normal vertical variations characteristic of near slack water conditions in tidal environments, then the upper and lower layers were combined and were not preserved as separate flows.

The second step in the hydrographic analysis was the horizontal integration of flow data across each transect. This was accomplished by first plotting the integrated vertical profile values at each station across the transect to construct a horizontal profile. Such a profile is shown in Figure 5.4 for Transect CT3 from the August 24, 1988 sampling period. This profile represents the flow characteristics across the transect from an aerial perspective. Each plotted point represents the depth-integrated flow value obtained from the station vertical profiles illustrated in Figure 5.3. As with the vertical profiles, a curve was then graphically fitted to the data points. Integration of the horizontal profiles was accomplished by

digitizing the areas defined by the flow curve and the transect (zero flow) axis.

The third step in the analysis was the development of time histories of the instantaneous volumetric flow rate across each transect. The integration of each horizontal profile as described above was assumed to be representative of a single volume of the instantaneous flow across the transect. Thus, plotting the complete set of these volumes for each transect yielded the required time history of the flow at that location in the bay (see Figure 5.6 for an example of these plots).

For each individual plot, areas bounded by the curve above and below the horizontal axis represent total volumes of water crossing the transect in each direction over one complete diurnal tidal period. These volumes were obtained by digitizing each flow time history. Subtracting the volume for each direction produced the net volumetric flux across the transect. Having calculated the net flux of water across each transect, the final step in the hydrographic analysis was to incorporate these values with the external influences of wind, tide, and tributary inflows to arrive at a reasonable mass balance for the bay and each of its sub-basins. This was accomplished by examining changes in basin storage volumes which occurred during each current sampling period, and by computing the total freshwater inflow to the headwaters of the bay via the Perdido River, Styx River, Blackwater River, Bayou Marcus Creek, and Elevenmile Creek.

Changes in bay sub-basin storage volumes were computed from records of the tide gauges TG1, TG2, and TG3 located at Perdido Pass, the Middle Bay south of Hwy. 98, and the Upper Bay respectively (Figure 5.2). The net change in water storage within each sub-basin was determined by subtracting the average beginning and ending water surface elevations as recorded at TG2 for the Main and Middle Bay sub-basin and TG3 for the Upper Bay sub-basin for the time periods defined by the current sampling

events and multiplying the result by the respective sub-basin plan area.

The computation of tributary inflow values was accomplished by adjusting published USGS stream discharge data to reflect the total freshwater drainage into upper Perdido Bay. Mean daily stream discharge values recorded at Barrineau Park on the Perdido River, at Baldwin County Rd. 87 on the Styx and Blackwater Rivers, and at Hwy. 90 on Bayou Marcus and Elevenmile Creeks (Figure 5.5) were adjusted upward by a factor representing the ratio of the total tributary drainage basin area to the corresponding area upstream of the gauge. A 24 hour inflow volume was then determined by multiplying the discharge, expressed as a volumetric flow rate with units of cubic meters per second, by 86,400 seconds (24 hours).

RESULTS

June 1988

The first current sampling was performed between June 7 and 9, 1988. This time period was chosen to reflect southerly wind and medium freshwater runoff conditions representative of early summer in the Perdido Bay area, as well as neap tide conditions. Although the tide was not field measured for this period, NOS tide tables suggest that tidal ranges were less than the mean range characteristic of Perdido Bay (0.18 to 0.21 m), corresponding to neap conditions. However, actual wind and runoff during the sampling period were slightly different than the expected mean June conditions.

Transects CT1 and CT3 were done concurrently June 7 - 8. Transect CT2 was done June 8 - 9, partially overlapping with transect CT4 which was done June 9. Wind patterns on the first day of sampling were generally light and variable with a few hours of stronger winds from the southwest at 10 knots. On the second day, June 8, winds became predominantly southwest to west at 10 to 14 knots which continued through most of the following day. The average diurnal flow entering the Upper Bay sub-basin

during the sampling period was calculated to be 1.4×10^6 m^3. According to the statistical analyses presented in Chapter 2, this flow rate has a 98 percent probability of exceedance and is substantially below the average summer flow rate of 4.3×10^6 m^3 day^{-1}. However, since the objective of the program was to analyze a number of differing, rather than specific, conditions, the difference between the predicted and observed conditions is not important.

The relative impacts of the tide, wind and freshwater runoff at each sub-basin boundary are illustrated by the shape of the curves in diurnal flow rate histories. These records are shown in Figures 5.6 through 5.9 for Transects CT1 through CT4, respectively.

At Transect CT1 in the upper portion of the bay, flow was predominantly southerly because of the influence of the freshwater runoff entering the Upper Bay sub-basin and the absence of predominant winds and strong tides during the sampling period. However, strong southwesterly winds can apparently reverse the southerly flow created by the runoff as shown by the flow reversal in Figure 5.6 between the hours of 1400 and 1600 on June 7 - the only occurrence of a significant southwesterly wind.

Further down the bay at Transect CT2 (Figure 5.7), the magnitude of the northerly and southerly components of flow increased probably as a result of an increase in tidal influence. Also the sinusoidal shape and period of the flow curve is typical of that produced by a diurnal tide. However, the predominant southwesterly winds during the sampling interval for this transect apparently increased the northerly component of flow.

At Transect CT3 (Figure 5.8), which defines the lower boundary of the Main Bay (near Perdido Pass), there also existed a significant tidal influence as expected during a period of predominantly light wind. However, short intervals of stronger

wind appear to have had some impact as shown by the large northerly component of flow and the less than diurnal period.

Finally, the flow rate curve for Transect CT4 (Figure 5.9) demonstrates the dominance of wind over tidal and runoff components of flow. As shown in the figure, the predominant westerly wind inhibited the full development of westerly flow that would be created by the flood stage of the tide and apparently increased the easterly component between 1200 and 1400 hours.

Figure 5.10 summarizes the net movement of water through the system for the June 1988 sampling period. The magnitude and direction of the diurnal net flow (expressed in millions of cubic meters) at each transect was determined by temporal integration of the flow rate histories. The predominant effect of westerly wind over tide and runoff influences at CT4 is shown by the large easterly net movement of water. However, in the absence of significant wind the net flux at CT1 (4.4×10^6 m^3) was created by the freshwater inflow entering the Upper Bay sub-basin along with a possible decrease in storage to relieve a previous water surface setup. The decrease in net fluxes from CT1 to CT2 can probably be attributed to the increase of southwesterly wind during the CT2 sampling interval which impeded the southerly component of flow. The net flux at CT3 did not appear to be significantly affected by the wind which was light and variable during the sampling interval. The large difference between the net fluxes at CT3 and CT4 could be attributed to the significantly different wind patterns characterizing each of the sampling intervals of the two transects; otherwise, a large setup would have occurred in the Main Bay. Water surface setups and imbalances in water storage could not be accounted for by changes in sub-basin storage because of the lack of tidal data for this period.

August 1988

The August current sampling period was selected to reflect the light wind and high freshwater runoff typical of that time of year in the area, as well as a spring tidal range. The conditions observed during the actual sampling period, August 22 through 25, 1988, well represented the predicted conditions. Transects CT2 and CT4 were sampled concurrently August 22 - 23. Transect CT3 was done August 23 - 24 and CT1 on August 24-25.

The tide, measured with water surface elevation recorders at three locations within the bay, exhibited ranges of 0.37 to 0.4 meter. These ranges were approximately twice the mean range for the area. Also as expected, winds were generally light and variable with only a few hours of stronger winds (approximately 10 knots each day usually from the southwest. The final observed condition considered in the analysis, high freshwater runoff, was also consistent with the predicted condition. Two values for the average diurnal freshwater flow entering the Upper Bay sub-basin during the sampling period were calculated. One, 6.3×10^6 m^3, omits an uncharacteristically high discharge of short duration which would have only affected the measured flow at Transect CT2. The second value, 8.7×10^6 m^3, reflects this high discharge. These flow rates, 6.3 and 8.7×10^6 m^3 day^{-1}, have exceedance probabilities of 12 and 7 percent, respectively, and are much higher than the average summer flow of 4.3×10^6 m^3 day^{-1}.

As shown in the previous discussion of the June data, the impacts of the August 1988 tide, wind, and freshwater runoff at each transect can be qualitatively determined from the characteristics of the flow rate histories. The dominance of tidal influence was particularly noticeable at Transects CT1, CT2, and CT3 as illustrated in Figures 5.11, 5.12, and 5.13, respectively. Flow at each of these transects had a definite 24 hour pattern, consistent with the tide, moving northerly through Perdido Bay for the 10 to 12 hours of flood tide and southerly during a similar interval for ebb tide. The well-behaved directional fluctuations and large magnitude of flow reversal

were consistent with a spring tide and lack of complicating factors (eg. high wind). This behavior was most evident at CT3. The exception to the tidal flow described above is illustrated in Figure 5.14 for Transect CT4. Here the flow was easterly for all but one hour of the sampling interval. This includes the period of flood tide between 2200 hours on August 22 and 1000 hours on August 23, when a westerly flow might be expected.

Wind appears to have had little impact on the flow relative to tidal influence. Even the unexpected easterly flow during flood at Transect CT4 cannot be accounted for by wind, which was very light at the time. However, freshwater runoff does appear to have influenced the flow as evidenced by the more heavily weighted southerly components of flow at CT1, CT2, and CT3. This behavior suggests that freshwater runoff was travelling southerly through the Upper, Middle, and Main Bay sub-basins, as expected, and exiting entirely through the Transect CT3 boundary instead of moving westerly through Transect CT4.

Figure 5.15 summarizes the net movement of water through the system during the August 1988 sampling period. Again the diurnal net flow (expressed in millions of cubic meters) at each transect was determined by temporal integration of the flow rate histories in Figures 5.11 through 5.14. For this period the effect of freshwater runoff is shown by the large magnitude of net fluxes southerly through the sub-basins and out through CT3. The value of the net flux at CT1 (5.0×10^6 m^3) very closely matched the magnitude of the average diurnal freshwater inflow of 6.6×10^6 m^3 entering the Upper Bay sub-basin during the sampling period (without considering the one high discharge discussed above which should have passed through the basin before CT1 was sampled). The net flux at CT2 (9.1×10^6 m^3) was representative of the higher freshwater runoff of 8.6×10^6 m^3. This may be inferred for two reasons: First, CT2 was sampled during the period immediately following the time that the high upstream discharge was measured; and second, the time required for the peak discharge to reach the transect was relatively short

(approximately 8 to 12 hours). Also shown in the figure is the large easterly net flux through CT4 as a result of the continuous easterly movement of water during the sampling period.

The imbalance of the net fluxes entering and leaving the basins was partially accounted for by analyzing the change in storage in the system. Using the average setup in water surface elevation (at TG2) measured from the tidal record shown in Figure 5.15, the increase in storage in the Main and Middle Bay sub-basins was determined to be 1.2 and 0.6 x 10^6 m^3, respectively. Taken together, these changes represent a 1.3% increase in storage volume. The increase in the Main Bay storage helped balance the high net inflow through CT2 and CT4.

November 1988

The next current sampling was performed between November 3 - 5, 1988. The conditions represented during this sampling period were a strong southerly wind, low freshwater runoff, and a neap tidal range. A predominant north wind, characteristic of November, was expected during the sampling interval instead of the observed south wind. On the final day, November 5, the wind did change to the north, but most of the sampling had been completed so the effects were not significantly revealed in the results. Again, as with the June analysis, the difference between observed and predicted conditions has little impact on this analysis. Both the tidal amplitude and freshwater runoff acted as expected. The measured tide exhibited ranges of zero to 0.27 meter. The average range was difficult to determine because of the influence of the southerly wind, but was considered to be below Perdido Bay's mean range of 0.18 to 0.21 meter. The other observed factor affecting flow characteristics, low freshwater runoff, was also consistent with the predicted condition. The average diurnal freshwater flow entering the Upper Bay during the sampling period was calculated to be 2.2 x 10^6 m^3. This is well below the average fall flow rate of 3.6 x 10^6 m^3 day^{-1}, and as presented in Chapter 2, it represents the 95 percent probability of exceedance value for fall seasonal flow.

Current was measured at three transects during the November sampling period, CT1, CT3, and CT4. Transects CT3 and CT4 were done concurrently November 3 - 4; CT1 was sampled November 4 - 5. Transect CT2 was omitted because of a substantial shift in wind direction from that encountered during the first three days and because it was the least important to the overall analysis. The flow rate histories for the three transects are shown in Figures 5.16 through 5.18 for CT1, CT3, and CT4, respectively. The influence of the wind is very noticeable in the flow curves at CT1 and CT3. At CT1 (Figure 5.16) the presence of the strong south wind created a significant northerly component of flow during the first half of the period. However, if light wind and neap tide conditions had existed, the freshwater inflow, although small, would have dominated the transect flow by forcing it south for most or all of the period as seen in the June 1988 results. The northerly flow might have been even more significant if the winds had not reversed direction during the second half of the period. At CT3 (Figure 5.17) the significant northerly component of flow is also noticeable as shown by the large area under the flow curve in the northerly direction compared to that in the southerly direction. However, the relative magnitude of flow was much less than was observed under spring tide conditions (August analysis). As in the previous two sampling periods (June and August), the flow at CT4 was erratic and did not appear to fully develop in either direction. There was, however, a significant flow to the west which was not observed in the previous two sampling periods.

Figure 5.19 illustrates the diurnal net movement of water through the system during the November 1988 sampling period, determined from the flow rate histories in Figures 5.16 through 5.18, as well as the dramatic effect of the wind on the water surface elevation. The strong southerly winds during the first three days of the tidal record (shown in the upper left corner of Figure 5.19) increased the water surface elevation as much as 0.76 meter and further damped the already low tidal amplitude of the neap tide. A result of this setup is shown by the northerly

net flux across CT3 which was not observed in other sampling periods. Another probable and unique result of the setup was the westerly net flux through CT4. Although relatively small in magnitude, the direction of this flux, like the flux at CT3, was not observed in other sampling periods. At CT1 the net flux appears to closely reflect the value for freshwater runoff entering the Upper Bay sub-basin suggesting that the runoff had a strong influence on the transect flow. However, the similarity might only have been a result of the shift in winds from south to north midway through the sampling interval. If winds had remained consistently from the south or if the sampling interval was earlier, the northerly component of flow prevalent only in the first half of the period probably would have dominated the overall period, or the southerly component would have been reduced. This would have created a net flux much smaller than the freshwater inflow and perhaps in the opposite direction.

The mass balance was determined by summing the net fluxes at the sub-basin boundaries, using a convention of positive flow inward and negative flow outward. The result was a 5.7×10^6 m^3 net increase in water volume in the Main and Middle Bays (4.0% volume increase), suggesting an increase in the internal storage of the system, as expected with the significant setup observed. For comparison, and as an internal check on the measured fluxes, internal storage was quantified from the tidal record. The calculated value was 4.9×10^6 m^3, which is fairly consistent with the mass imbalance determined from the net fluxes.

February 1989

The fourth current sampling was performed between February 7-9, 1989. The conditions represented during this sampling period were a strong north wind, low freshwater runoff, and a neap tidal range. These conditions were consistent with those expected except that the freshwater runoff was much lower than average. For the three day period winds were constantly from the north ranging on average between 12 and 16 knots. Tidal ranges, significantly affected by the wind during the current sampling

period, varied from zero to 0.18 meter and averaged much lower than Perdido Bay's mean range of 0.18 to 0.21 meter. The average diurnal freshwater runoff for the three day sampling period was computed to be 1.9×10^6 m^3. This value was unexpectedly below the average winter diurnal flow of 5.5×10^6 m^3 and had an exceedance probability of slightly greater than 98 percent. Therefore, the analysis for this period examines the effect of strong north winds on the flow characteristics during minimum freshwater runoff and tidal influence.

Current was measured at all four transects during the February sampling period. Transects CT3 and CT4 were measured concurrently February 7 - 8. Transects CT1 and CT2 were measured concurrently February 8 - 9; CT2, however, was terminated early when deteriorating weather conditions made working conditions hazardous. The record at CT2 was thus too short to analyze in detail.

The flow rate histories for the transects are shown in Figures 5.20 through 5.23 for CT1 through CT4, respectively. The influence of wind is very noticeable in the flow curves at CT1 and CT3. This is similar to the case of strong southerly wind, neap tide, and low runoff shown in the November analysis. At CT1 (Figure 5.20) the presence of the strong north wind created a southerly flow during all but five hours of the 25 hour sampling interval. The short period of northerly flow occurred in response to a very small amplitude flood tide. At CT3 (Figure 5.22) the significant southerly component of flow was also noticeable as shown by the large area under the flow curve in that direction. The smaller northerly flow occurred during a six hour flood tide that was shortened from the normal 12.4 hours because of the impeding north wind. As in the other sampling periods (June, August, and November), the flow at CT4 (Figure 5.23) was erratic and does not appear to fully develop in either direction. There was, however, a somewhat significant flow to the west. This could be a result of the similar conditions of both the November and February sampling periods: that is, neap

tide, low runoff, and wind perpendicular to the general alignment of the channel at CT4.

Figure 5.24 illustrates the diurnal net movement of water through the system during the February 1989 sampling period as determined from the flow rate histories in Figures 5.20 through 5.23 (excluding CT2 which was too short to obtain a meaningful net flux). Also, in the upper corner of the figure, the effect of the wind on the water surface elevation is shown. The strong north winds over the three day period created a significant setdown of the water surface elevation, damped the tidal amplitude, and shortened the flood stage of the tide. This setdown was accompanied by a significant southerly net flux across CT3 (13.1×10^6 m^3). At the western system interface (CT4) the net flux was very small (0.5×10^6 m^3) compared to the net fluxes of other sampling periods. Since this net had a easterly direction, all of the water leaving the system passed through CT3. In the upper portion of the bay, the flux through CT1 was very large compared to the freshwater inflow entering the Upper Bay sub-basin. This was a result of the strong north winds forcing water south from the sub-basin and impeding flood stage tidal flow moving north into the sub-basin.

The result of the mass balance, summing the net fluxes at the sub-basin boundaries, was -6.3×10^6 m^3 for the Main and Middle Bays. This represents a decrease in the internal storage of the system. The internal loss of storage in the Main and Middle Bays, quantified from the tidal record, was 7.5×10^6 m^3 (5.2% volume decrease), which adequately accounts for the mass imbalance determined by the net fluxes. A similar analysis performed for the Upper Bay sub-basin also shows good agreement between the flux imbalance and the loss in storage in that sub-basin. The flux imbalance amounted to -4.0×10^6 m^3, and the loss of water volume in the sub-basin, quantified from the tidal record, amounted to 4.1×10^6 m^3 (14% volume decrease).

June 1989

The final current sampling effort was performed between June 9 and 11, 1989 to supplement data obtained in the June 1988 sampling campaign. This additional campaign was warranted because of changes made in the sampling strategy after June 1988 (beginning in August 1988). These included the recording of concurrent water elevation (tide) data at three locations in the bay, the extension of the sampling periods to cover full diurnal periods, and the concurrent sampling of the Lower (Transect CT3) and West (Transect CT4) Bay transects.

As in the June 1988 campaign, the sampling period was chosen to reflect southerly wind, medium freshwater runoff, and neap tide conditions. Actual wind conditions observed during the campaign reveal a variable but mostly southerly wind pattern. During the first 12 hours, the wind was from the southwest at 8 knots. It then turned north at 6 knots for 10 hours, and returned back to the south at 5 knots for 12 hours. This was followed by a period of calm for 12 hours and southwesterly winds at 8 knots for the last 8 hours of sampling. Freshwater runoff was much higher than expected. The normal, or average, daily runoff entering the Upper Bay during the summer is about 4.3 x 10^6 m^3 day^{-1}. However, during and just prior to the sampling event, the freshwater inflow ranged from 27.5 to 141.1 x 10^6 m^3 day^{-1}. As shown in the annual peak flood-flow analysis (presented in Chapter 2), these values approximate the 2 year and 20 year flood events for the Perdido Bay basin, respectively. This high flow is attributable to a rainfall event on June 8 of seven to eight inches determined by averaging the gauge records from Molino, Oak Grove, Carpenter Tower, Champion International, and the Naval Air Station. This level of intensity is equivalent to a 2 - 5 year rainstorm event for this region.

The significant influence of the high freshwater inflow to the bay is evident in the diurnal flow time histories shown in Figures 5.25 through 5.28. At Transects CT1, CT2, and CT3, representing flows from the Upper to Middle Bay, Middle to Main

Bay, and Main to Lower Bay, respectively, the flow of water was quite large and remained southerly during the entire sampling period. At the Lower Bay interface, Transect CT3, the magnitude of the southerly flow averaged about 900 m^3 sec^{-1}. It was lower during periods that would normally be flood tide, such as 12:00 - 13:00 hours on June 9 when the flow is about 500 m^3 sec^{-1}. However, the combination of the southerly wind and the rising offshore tide were not of sufficient magnitude to overcome the influence of the outward moving freshwater flow. During the previous four sampling campaigns a northerly component of the flow always existed during some portion of the sampling interval at each of these transects.

The mean flow rates during the sampling period through the Upper and Middle Bays (Transects CT1 and CT2, respectively) were slightly lower than those at the Lower Bay interface. At Transect CT1, the flow averaged 700 m^3 sec^{-1}, peaking at about 850 m^3 sec^{-1} and tapering off to about 400 m^3 sec^{-1}. At Transect CT2 the flow also averaged 700 m^3 sec^{-1}, and ranged from 900 m^3 sec^{-1} to 500 m^3 sec^{-1}. The drop in flow at the two interfaces from 10:00 - 18:00 hours on June 11 could be attributed to a flooding tide, subsiding stormwater runoff, and southerly wind. However, the freshwater component of the flow remained dominant throughout, forcing the flow south.

The characteristics of the flow at Transect CT4 (Figure 5.28) were significantly different from those of the flows at Transects CT1, CT2, and CT3. Both easterly and westerly components of flow exist during the sampling period, with peak flows of about 250 m^3 sec^{-1} in each direction. The flow shifted directions every 3 - 6 hours, unlike that of a typical diurnal tide which changes directions every 12 hours. This higher than normal frequency pattern of the flow was characteristic of all of the other sampling campaigns at Transect CT4 except August 88 when the flow remained easterly for the entire sampling period. The oscillating flow at Transect CT4, compared to the unidirectional flows at the other transects, was probably due to

another high freshwater inflow entering the Western Bay. The Carpenter Tower station, which recorded 39.6 cm of rain on June 8, is located just west of the Perdido River basin in the drainage basin for the Western Bay. Therefore, a similar rainfall event most likely occurred to the west of the Perdido River basin. Such a large volume of runoff entering the Western Bay from its tributaries could neutralize the hydraulic head effects of the freshwater entering the Main Bay, thereby allowing the tide and wind to play significant roles in the water movement across Transect CT4.

An interesting characteristic of the vertical current velocity profiles at Transect CT4 (not shown) was a reversal in the flow direction over the water column during the entire sampling period. Near the surface, flow was predominantly to the east (18 hours), whereas at greater depths flow was to the west (18 hours). During the remaining 6 hours, the surface water flowed to the west and the deeper water flowed to the east. This produced a continual exchange of water between the Western and Main Bays.

Figure 5.29 illustrates the diurnal net movement of water across the four transects, the changes in storage in the Main, Middle, and Upper Bays, and the average daily freshwater flow entering the Upper Bay during the sampling period. Also shown in the figure inset are the tide gauge records for the three gauging stations TG1, TG2, and TG3 which were operational throughout the sampling period. Note the extremely large southerly movement of water from the Perdido River throughout the Upper, Middle and Main Bays, and out of the system through the Lower Bay. These values were as much as 25 times greater than those calculated from the previous four campaigns. The net flow at the Western Bay interface (Transect CT4) was similar to those of the other campaigns in magnitude. However, the net direction had changed from east to west. The reversal in the net flow at Transect CT4 was also observed during the November 1988 sampling period. The

average net flow through the Upper, Middle, and Main Bays were 260, 160, and 80 percent of the respective compartment volumes. Assuming complete mixing, this suggests that the water in the bay prior to the storm event was completely or nearly completely replaced.

Although neap astronomical tidal variations existed in the system during the campaign as expected, the variation in the actual record of the water surface elevation was much more dramatic. As shown in the inset in the upper left corner of Figure 5.29, a setdown of the mean water surface equal to about 0.15 meter per day was measured at the three tide gauges. Since no significant southerly winds existed prior to sampling, and northerly winds were not prevalent during sampling, this setdown can probably be attributed to the post-peak conditions of the storm hydrograph. For such conditions the water surface lowered in response to a decreasing stormwater discharge. In the figure, the neap astronomical tide is barely visible due to the overshadowing effects of the stormwater discharge.

The setdown in the mean water surface of the bay that occurred during this campaign was similar to that observed during the February 1989 campaign. As shown by the tide records in Figure 5.29, the water surface elevation in the Upper, Middle, and Main Bays decreased by 0.1 to 0.2 meter during each day of sampling. This corresponded to storage losses of 3.6, 3.2, and 6.0×10^6 m^3 in the Upper, Middle, and Main Bays, respectively, for the one day sampling period. These losses were 13, 8, and 7 percent of the average respective bay compartment volumes.

As shown in Figure 5.29 the calculated system fluxes balanced relatively well. In the Main Bay, 83.2×10^6 m^3 of water exited through the western and lower interfaces, while 65.0×10^6 m^3 of water entered through the Middle Bay interface. This was accompanied by a setdown in the water surface equivalent to a storage loss of 6.0×10^6 m^3. Summing these fluxes for the Main Bay yields an imbalance of 12.2×10^6 m^3 (16 percent of the

average flow). A similar analysis of the Middle Bay yields a 2.5 x 10^6 m^3 imbalance (4 percent of average flow). Performing a similar mass balance for the Upper Bay using the freshwater inflow is difficult because of the variable magnitude of streamflow (27.5 to 141.1 x 10^6 m^3 day^{-1}) during the total sampling period.

SUMMARY OF OBSERVED CIRCULATION

The net circulation patterns within Perdido Bay are predominantly influenced by prevailing wind conditions and tributary discharges entering the system. Either of these two factors can significantly alter the bay circulation driven by normal tidal variations of the water surface. Generally, without the influence of wind and under normal freshwater inflow, net flow is southerly from the Upper Bay into the Middle and Main Bays. Concurrently, there is a net movement of water from Wolf Bay (and probably Mobile Bay) easterly past Hatchet Point (Transect CT4) into the Main Bay. From the Main Bay the net movement of water is southerly past Inerarity Point and Mill Point (Transect CT3) towards Perdido Pass and, perhaps, Big Lagoon. This pattern, attributable to the tidally driven components of the flow, is present for spring and neap tides as well as low and seasonally high freshwater runoff. However, steady winds or abnormally high freshwater runoff easily change this general trend. Wind has a dramatic effect on the volume of water in the system, either lowering or elevating the mean water surface by 0.15 to 0.3 meter per day. High freshwater discharges associated with major rainfall events, such as the one observed during the June 1989 sampling period, can completely overshadow tidal flow reversals at various locations throughout the bay to produce a unidirectional movement of water south from the Upper Bay to the Gulf of Mexico.

Decreases in the mean water surface elevation of the system, resulting in large losses of water volume, were an observed manifestation of persistent northerly winds. This storage loss has a significant impact on the net movement of water through the

system. It also appears to reduce the net easterly flow from the West Bay to the Main Bay past Hatchet Point (Transect CT4). In the February 1989 analysis, the net flow past Hatchet Point was reduced to near zero by the water surface setdown. Correspondingly, at the Upper Bay - Middle Bay interface the setdown during both periods significantly increased the magnitude of the net flow. Under such conditions the net southerly flow from the Upper Bay to the Main Bay is approximately twice the net flow that would be established by baseline (no wind) conditions and average (normal) freshwater inflow. At the Main Bay's lower interface (Inerarity Point), a setdown does not significantly change either the magnitude or direction of the net flow. The loss of water in the system accompanied by a typical setdown of 0.3 meter is 25 million m^3). This corresponds to 16 percent of the total water volume in the system (160 million m^3). Based on the percent occurrence of northerly winds in the Perdido Bay area, as determined from the 1986 U.S. Coast Pilot, the changes in circulation behavior described above can be expected to occur about 142 days per year and usually during the fall and winter months.

Southerly winds also have a dramatic effect on system circulation. When such winds prevail for a day or more they create a significant setup in the system water surface and an associated increase in water storage volume. Such a setup was recorded in the November 1988 campaign in response to a 10 knot south wind. These winds noticeably reduce the southerly movement of water from the Upper Bay past Grassy Point (Transect CT1). However, these types of wind conditions were never observed to have reversed the direction of the net flow at this bay sub-basin interface.

At transects CT3 and CT4 the behavior of the net flow is more complex and less easily attributable to specific factors such as tide, wind and freshwater inflow. For a more detailed understanding of these effects and the net flow across CT3 and

CT4 the reader is referred to the discussion of net bay circulation presented later in this section.

Heavy rainfall can also produce tremendous change in the net movements of water through Perdido Bay. Moreover, the influence of such events has been observed to eliminate the tidal associated flow reversals at Transects CT1, CT2, and CT3. Dominance of freshwater flow in the Upper Bay is to be expected because of the close proximity of the tributary mouths. However, the lack of any tidally-driven northerly communication from the Lower Bay to the Main Bay after high rainfall is somewhat surprising. The persistence of this unidirectional flow over an entire tidal cycle has a tremendous impact on the net movement of water through the bay, increasing this by an order of magnitude. Corresponding impacts at the West Bay interface (Transect CT4) are less dramatic, but still significant. Although at this location the flow continues to reverse direction over the tidal cycle, the net movement of water changes from east to west.

Given all wind conditions and freshwater inflows examined and the results of the circulation analysis, the general flushing behavior of the system can be described. Under conditions of light and variable winds with low to average freshwater inflow the net circulation of the bay generally moves southward from the Upper Bay, Middle Bay, and Main Bay to the Lower Bay and Gulf of Mexico via Inerarity Point This movement of water is augmented by a net easterly flow into the Main Bay from the GICWW at Hatchet Point The Upper Bay is flushed into the Middle and Main Bays, driven mainly by freshwater discharge, and is the least affected (of the three bay compartments) by wind. Although the magnitude of flow past Grassy Point at the Upper Bay interface can be affected by wind, the direction of the net flow remains southerly for all wind conditions examined. This is not the case, however, in the Main Bay. Here the presence of either northerly or southerly wind conditions, with sustained speeds of 10 knots or greater persisting for at least 24 hours, create significant changes in the magnitude of the net movement of water

through the system, and in some cases the direction of movement. During sustained southerly winds, the Main Bay is flushed westward into the GICWW at Hatchet Point This flushing is augmented by net flows entering from the Lower Bay past Inerarity Point and to a lesser extent from the Upper/Middle Bay. During sustained northerly winds, the Main Bay is flushed into the Lower Bay. Again the flushing is augmented by a net flow entering the Main Bay from the Upper/Middle Bay. However, very little if any net flow enters through the GICWW at Hatchet Point during northerly wind conditions.

As discussed earlier, during periods of abnormally high freshwater discharge dramatic increases in the southerly movement of water from the Upper Bay to the Gulf of Mexico can be expected to occur. Net flows associated with this movement were observed during the June 1989 sampling period to be on the order of ten times normal.

ANALYSIS AND PREDICTION OF NET BAY CIRCULATION

The analysis of observed current and tide data from the five sampling campaigns, discussed in the previous sections, has provided a useful understanding of the principal factors which influence the net circulation of the bay. These factors are wind, freshwater inflow, and to a lesser extent tide. In addition, the net circulation attributable to these factors has been quantified across three sub-basin boundaries for each of the five sampling periods. However, effective management of the bay can be assisted by a predictive capability to describe net bay circulation for any combination of wind, freshwater inflow, and tide. To develop such a capability, the individual components of net circulation must be separately identified, and means must be developed which permit the prediction of individual circulation component values from either known or assumed conditions of these factors. This section describes the process by which this was accomplished.

The circulation computed from the data obtained during the five sampling campaigns corresponds to the combined or total net circulation attributable to the collective influence of wind, freshwater inflow and tide. Therefore, the computed values which were obtained are dependent upon the specific conditions, or combination of causative factors, that prevailed during that particular sampling period. However, with the knowledge of what these conditions were at the time that the data were taken it then becomes possible to separate the total net circulation into its component elements. The ease with which this is done varies significantly between individual components. This is a direct result of variations in the inherent physical complexities of the causative factors.

Of the three components of net circulation, wind-driven circulation is perhaps the most difficult to predict. It is controlled by the duration, speed, and direction of the prevailing wind. The remaining components are more easily addressed. Circulation attributable to freshwater inflow is controlled by the total discharge of the five major streams entering the Upper Bay, and can be derived from readily available stream gauge data. Tidal circulation within the bay is controlled by the magnitude of the astronomic tidal range which varies in a regular and predictable manner throughout the lunar cycle. However, the specification of these three circulation components across given bay boundaries, such as Transects CT1, CT2, and CT3, requires considerable judgement and an understanding of the physical processes involved. Moreover, as will be seen later for the case of freshwater inflow, the application of this judgement sometimes forces the investigator to make assumptions which ultimately dictate the method of prediction. Obviously, with more information on the circulation components, judgements are less prone to error.

Computed values of net circulation derived from the four field sampling campaigns performed in August and November 1988, and February and June 1989 (Figures 5.15, 5.19, 5.24, and 5.29)

Table 5.3. Breakdown of net circulation into components by transect.

Transect	Sampling Time	Net Circulation Components ($x10^6$ m^3 day^{-1}) Tidal	Freshwater	Wind	Net Circulation ($x10^6$ m^3 day^{-1})
	8/22 - 8/25/88	0	+7.0(S)	0	+7.0(S)
CT1	11/3 - 11/4/88	0	+2.9(S)	-2.5(N)	+0.4(S)
	11/4 - 11/5/88	0	+2.9(S)	-0.6(N)	+2.2(S)
	2/8 - 2/9/89	0	+2.3(S)	+4.0(S)	+6.3(S)
	8/23 - 8/24/88	+11.7(S)	+7.0(S)	-1.4(N)	+17.3(S)
CT3	11/3 - 11/4/88	0	0.0	-6.3(N)	-6.3(N)
	2/7 - 2/8/88	0	+2.3(S)	+10.8(S)	+13.1(S)
	6/9 - 6/10/89	0	+78.4(S)	-0.8(N)	+77.6(S)
	8/22 - 8/23/88	-11.7(E)	0.0	0.0	-11.7(E)
CT4	11/3 - 11/4/88	0	+2.9(W)	-0.1(E)	+2.8(W)
	2/7 - 2/8/88	0	0.0	-0.5(E)	-0.5(E)
	6/9 - 6/10/89	0	+5.6(W)	0.0	+5.6(W)

N - Northerly or Northeasterly
S - Southerly or Southwesterly
E - Easterly
W - Westerly

were used to develop estimates of the various circulation components. The results of this flow decomposition for Transects CT1, CT3, and CT4 are shown in Table 5.3. Transect CT-2 was not included because of limited data, and its secondary importance. Sampling times shown in the second column represent the period for which the net circulation was measured. The reader should note that data for Transect CT1 have not been included for the June 1989 sampling campaign. These data were omitted because of the extremely high degree of variability in recorded freshwater inflow which occurred during the period when data were obtained at this transect. However, to compensate for this loss, it was possible to identify two independent values for each circulation component at Transect CT1 for the November 1988 sampling campaign. These have been included in the data presented. Values shown in the table contain both a magnitude and direction, and represent the mean for the given diurnal period of observation. Their sum is shown in the last column, and is equal to the net circulation from which they were derived. The methods used to arrive at these values are discussed below.

Of the three components, the net circulation attributable to freshwater inflow is perhaps the easiest to identify, and to a lesser extent, one for which a relatively straightforward means of prediction can be developed. The freshwater component of circulation is created by the stream discharge entering the Upper Bay from the five major streams (discussed in Chapters II and III). Therefore, at Transect CT1 the freshwater component of the net circulation is equal to the freshwater inflow entering the Upper Bay. Moreover, its direction is always southwesterly (down the bay) at this location. In the Main Bay the situation becomes more complicated. Here the net circulation exits or enters the bay through Transects CT3 and CT4. Therefore, the following assumptions had to be made about the distribution of this component between these two transects:

(1) If the net circulation attributable to tide and wind is in phase across both Transects CT3 and CT4 (into or out of the bay at both locations) then the component of the total net circulation attributable to freshwater inflow is assumed to be apportioned between these two interfaces in accordance with the field measurements.

(2) If the net circulation attributable to tide and wind is directed into the bay across Transect CT3, and out of the bay across Transect CT4, then all of the net circulation attributable to freshwater inflow is assumed to exit the bay across Transect CT4.

(3) If the net circulation attributable to tide and wind is directed out of the bay across Transect CT3, and into the bay across Transect CT4, the all of the net circulation attributable to freshwater inflow is assumed to exit the bay across Transect CT3.

The values presented in Table 5.3 for the freshwater component of the total net circulation were derived using the streamflow data from the sampling campaigns, discussed earlier in

this section, and from the application of these assumptions to the observed data pertaining to net bay circulation. Thus, in this manner we have accomplished two objectives. First, the component of the total net circulation attributable to freshwater inflow has been identified for each of the sampling campaigns. Second, the application of the above stated assumptions in combination with specified tributary discharge values constitutes a reasonable means of predicting this circulation component across all required bay boundaries.

The wind-driven component of net circulation was next determined by subtracting the freshwater circulation components discussed above from the observed values of the total net circulation. In doing this it is assumed that the tidal contribution to the total net circulation is zero. As will be seen later, this is not universally true. However, as we shall also see, this does not invalidate the use of this assumption to initiate the wind-driven net circulation analysis. In fact, through the process of analyzing the wind component, the tidal contribution was eventually revealed and subsequently removed to produce the true wind-driven component of net circulation.

The wind-driven circulation component was easily identified at Transect CT1. Here the assumption of a zero tidal component of circulation is valid for reasons of system equilibrium and conservation of mass. Therefore, the true wind-driven component was found by subtracting the freshwater component from the total net circulation as shown in Table 5.3.

For Transects CT3 and CT4 first estimates of the wind-driven circulation component were obtained in a similar manner, i.e. by subtracting the freshwater component from the total net circulation across each boundary. To evaluate the validity of these estimates, the values were then plotted as functions of the mean daily wind stress component acting along the main axis of the bay during the period of observation. The rationale for proceeding in this manner is founded in the basic principles of

marine physics. The movement of water due to wind is directly related to the stress created on the water surface. This stress, referred to as wind stress, is proportional to the square of the wind speed and acts in the direction along which the wind is blowing. In Perdido Bay the water movement of interest is that which acts along the principal axis of the bay. Therefore, the magnitude and general direction of the circulation component due to wind should be correlated to the square of the prevailing wind speed acting along this axis. The main axis of the bay was considered to be oriented along a line running 045 - 225 degrees true.

Wind data necessary for these calculations were obtained from hourly observations taken at Saufley Field Naval Air Station, located one mile northeast of the Upper Bay between Bayou Marcus and Eleven Mile Creek. These data were then converted to the form of resultant wind vectors that represent the average wind magnitude and direction for each sampling period listed in Table 5.3. To calculate wind stress, the resultant wind speed was squared and multiplied by the cosine of the angle between the axis of the bay and the direction of the resultant wind vector.

The estimated wind-driven components of the net circulation and the computed values of wind stress described above are plotted in Figures 5.30 - 5.32 for Transects CT1, CT3, and CT4 respectively. Let us first examine the results shown in Figure 5.32. The behavior of the circulation across Transect CT4 in response to wind is significant but much different from the other two boundaries. In fact, it is evident from this figure that the net circulation across this boundary is not appreciably driven by wind. Three of the four observed data points lie along the zero flow axis, independent of the observed wind stress. The lone exception is the data point for August 1988 which is the only sampling period which included the effects of spring tide. The three remaining points were obtained during neap tide conditions when the tidal circulation was very weak or close to zero.

Therefore, it is concluded that the net circulation across Transect CT4 is a function of dominant tidal forcing and freshwater contributions and is not significantly influenced by wind. Moreover, this result identifies the magnitude and direction of the net spring tidal circulation component across both Transects CT3 and CT4, which in and of itself is a significant finding. To properly account for this the first estimates of the wind-driven circulation components across Transects CT3 and CT4 were adjusted downward, and a net outward tidal component equal in magnitude to the tidal component revealed in Figure 5.32 was introduced for the August 1988 sampling campaign at CT3.

In contrast to the results found at CT4 the distribution of data points at both Transects CT1 and CT3 reveal a definite correlation between wind stress and the wind-driven circulation component. As Figures 5.30 and 5.31 illustrate, northeast winds produce circulation down the bay through Transect CT1 and out through Transect CT3. Conversely, southwest winds produce circulation into the bay through Transect CT3 and up the bay through Transect CT1. To develop a means to predict these effects exponential curves were then fitted to these data. The curves are confined to pass through the origin to meet the assumed condition that no wind-induced circulation exists in the absence of wind. In addition, the curves are assumed to be symmetric about the origin. The primary differences between the two figures are evident by the shapes of their respective curves. The slope of the curve for Transect CT3 is steeper near the origin (light wind), and its asymptotic value of flow, Q , is higher. These differences indicate that the circulation at Transect CT3 is more sensitive to wind than is the circulation at Transect CT1. The corresponding response at Transect CT3 is much stronger, reacting more quickly to light winds and in general producing a significantly larger circulation component.

All that remains now is the development of a means to predict the net tidal circulation component across Transects CT3

and CT4 during periods when the tide is neither in a spring nor a neap condition. Remembering that the magnitude of this component was determined to be zero at all times at Transect CT1, and was found to vary between a maximum value and zero at Transects CT3 and CT4, this requirement is needed only at the latter two boundaries. The simplest approach to achieve this is to assume a linear variation in the magnitude of the tidal circulation component between the two observed extremes. Such a variation can be described as follows:

$$Q_{(tide)} = \frac{(observed\ range - neap\ range)}{(spring\ range - neap\ range)} \times 11.7 \times 10^6 m^3 day^{-1} \qquad (5.1)$$

where $Q_{(tide)}$ is the net tidal circulation on a given day, and observed range is the astronomic tidal range on the same day. Equation 5.1 applies to both Transects CT3 and CT4. The direction of the circulation is always easterly across Transect CT4, and southerly across Transect CT3. Its magnitude is zero for neap tide and 11.7×10^6 m^3 day^{-1} for spring tide.

The tabulated values presented in Table 5.3 reflect the best and final estimates of all of the computed net circulation components as discussed in the preceding paragraphs. The means to predict each of these components have also been presented. That is, the net circulation through Perdido Bay can be constructed for any given period as described in the following example.

For a typical summer day with a mean tidal range, each of the three components of net circulation can be computed as follows. The typical summer wind conditions, as published in the 1986 Coast Pilot for Pensacola, are southerly at about 8 knots. Using the wind-stress vs. wind circulation plots shown in Figures 5.30 through 5.32, an 8 knot southerly wind produces northerly flows of 1.6×10^6 m^3 day^{-1} at transect CT1 and 6.3×10^6 m^3

day^{-1} at transect CT3. At CT4, no wind-driven circulation is expected.

Similarly, the net tidal and freshwater circulation can also be determined. For this example, a mean tidal range is assumed. The net tidal circulation at transects CT3 and CT4 is determined from Equation 5.1. For a mean tidal range, the predicted net flow is southerly at 5.9×10^6 m^3 day^{-1} at CT3, and easterly at 5.9×10^6 m^3 day^{-1} at CT4. No net tidal circulation exists at transect CT1. Finally, freshwater circulation is given for typical summer conditions by Figure 2.6. From this figure, the most probable freshwater inflow to the Upper Bay during the summer months is 22 m^3 sec^{-1} or 1.9×10^6 m^3 day^{-1}. This also corresponds to the net freshwater circulation at transect CT1 and throughout the Main Bay. At the lower end of the Main Bay its movement across transects CT3 and CT4 is distributed according to the assumptions presented earlier in this section. This method yields flows of $+1.8 \times 10^6$ m^3 day^{-1} (southerly) at CT3 and +0.1 10^6 m^3 day^{-1} (westerly) at CT4.

The total daily net circulation moving through the bay is obtained by summing the three individual components at each transect described above. Thus, in the Upper Bay, 1.9×10^6 m^3 of freshwater enters the bay from the Perdido River and other streams, while 0.3×10^6 m^3 exits southward to the Main Bay through transect CT1. The imbalance of 1.6×10^6 m^3 between these two values results in an increase in storage of water in the Upper Bay. In the Main Bay, a net circulation of 5.8×10^6 m^3 enters from the west through transect CT4. At the same time, the 0.3×10^6 m^3 exiting from the Upper Bay enters through transect CT1, while 1.4×10^6 m^3 exits through transect CT3 towards sea. The imbalance between these three flows results in a storage increase of 4.7×10^6 m^3 of water in the Main Bay.

The above described method for the prediction of daily values of the net movement of water into and through the major sub-basins of Perdido Bay constitutes one of three major elements

in the development of a simplified method for the prediction and tracking of the transport of waterborne substances through the bay system. The remaining two elements required to complete this capability are (1) a means to predict the flood and ebb tidal exchange volumes that flow in and out of each sub-basin with the tide, and (2) a simple analytical method which provides for the prediction of changes in substance concentration levels in the bay in response to the net circulation and tidal exchange movements. The development of these last two elements has been completed and the results verified against observed data. A description of this work is available in a companion document, *Prediction of Water Quality at Perdido Bay, Florida* (Taylor et al., 1991). Future applications of this methodology should provide valuable insight to the effects of anthropogenic changes and varying climatology on the Perdido Bay system, thereby providing the community with an effective resource management tool. Changes in bay water quality and system fluxes can now be tracked or evaluated for any set of conditions, either short- or long-term.

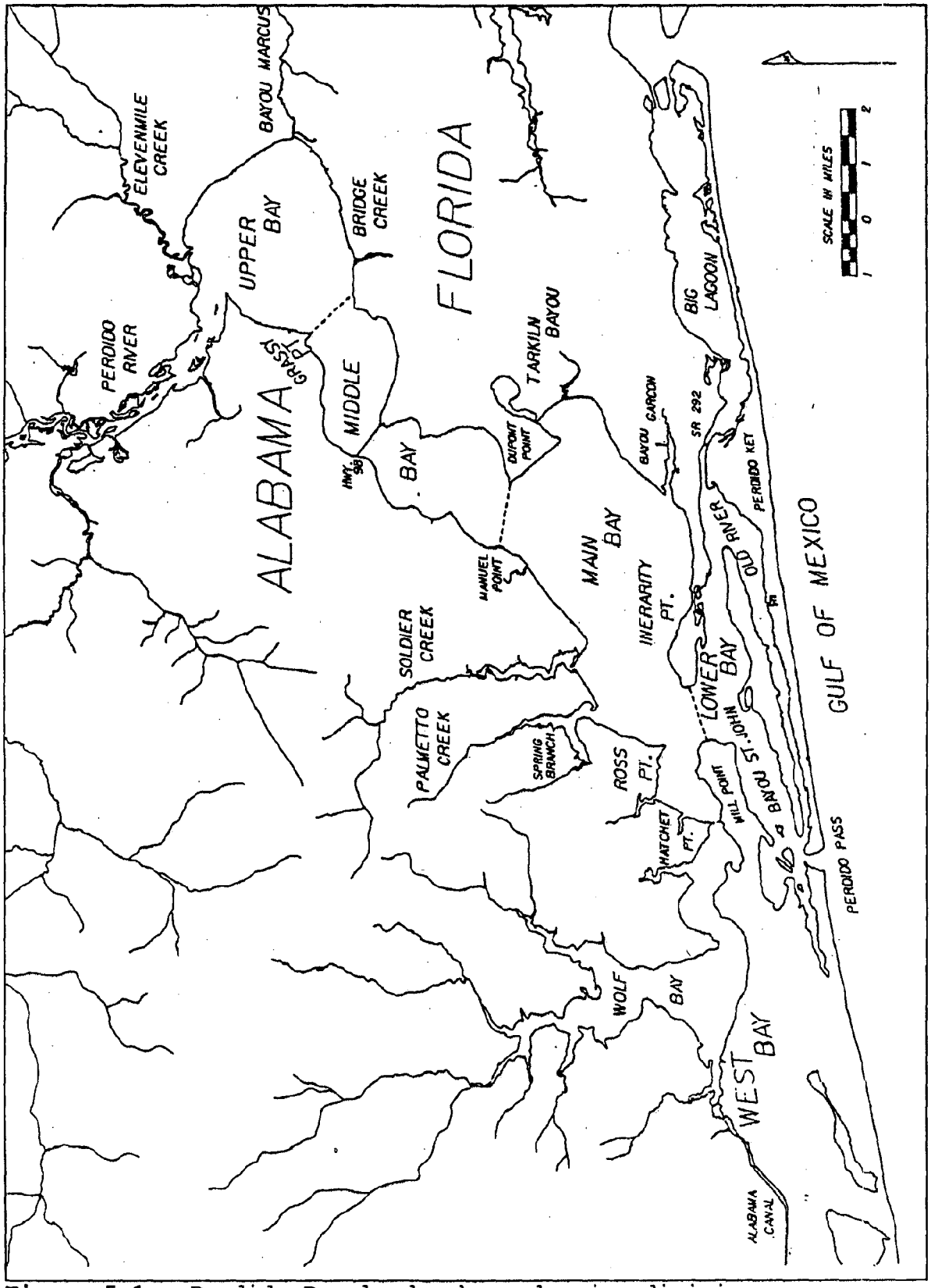


Figure 5.1. Perdido Bay landmarks and major divisions.

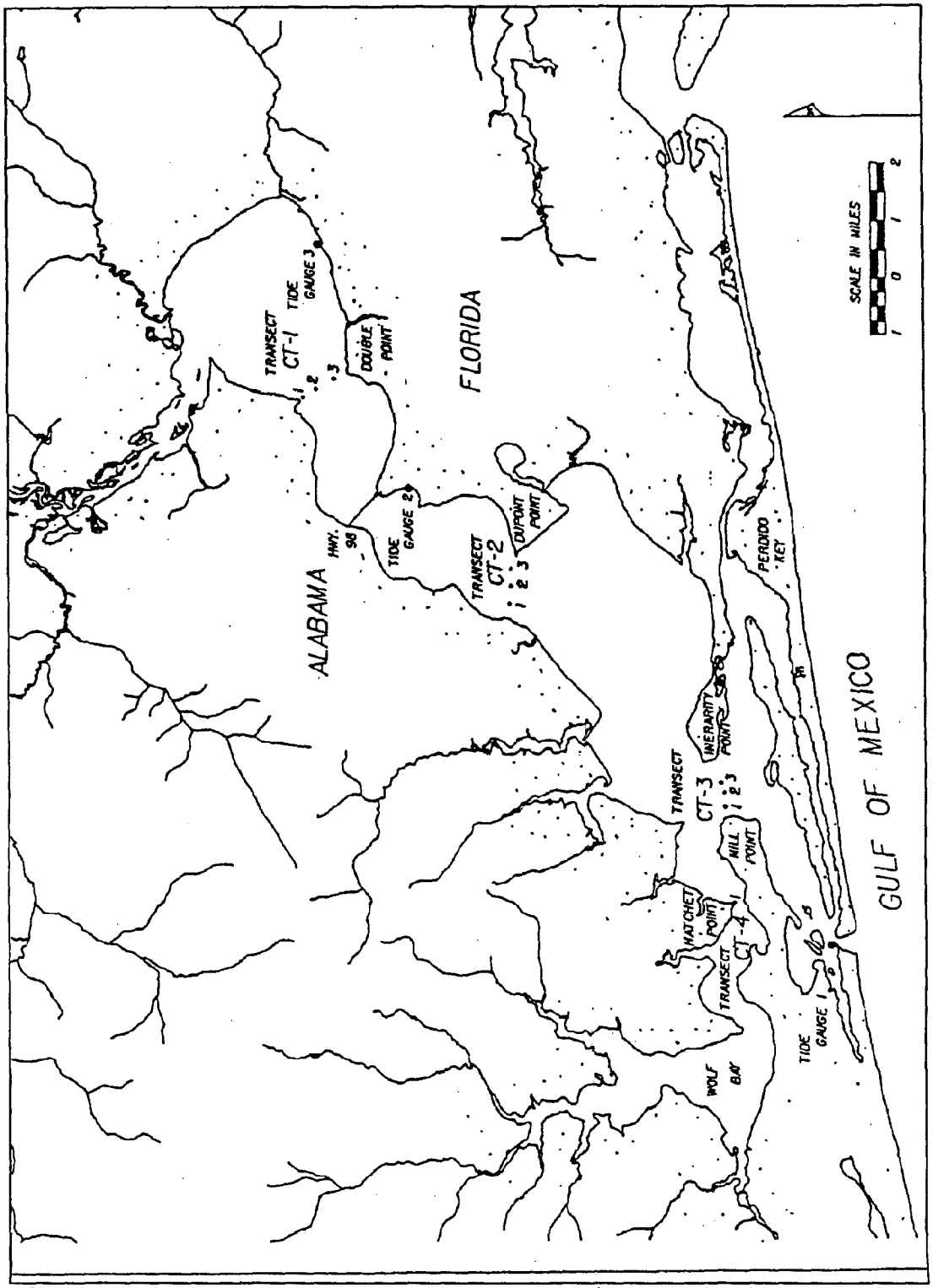


Figure 5.2. Current measurement and tide gauge locations.

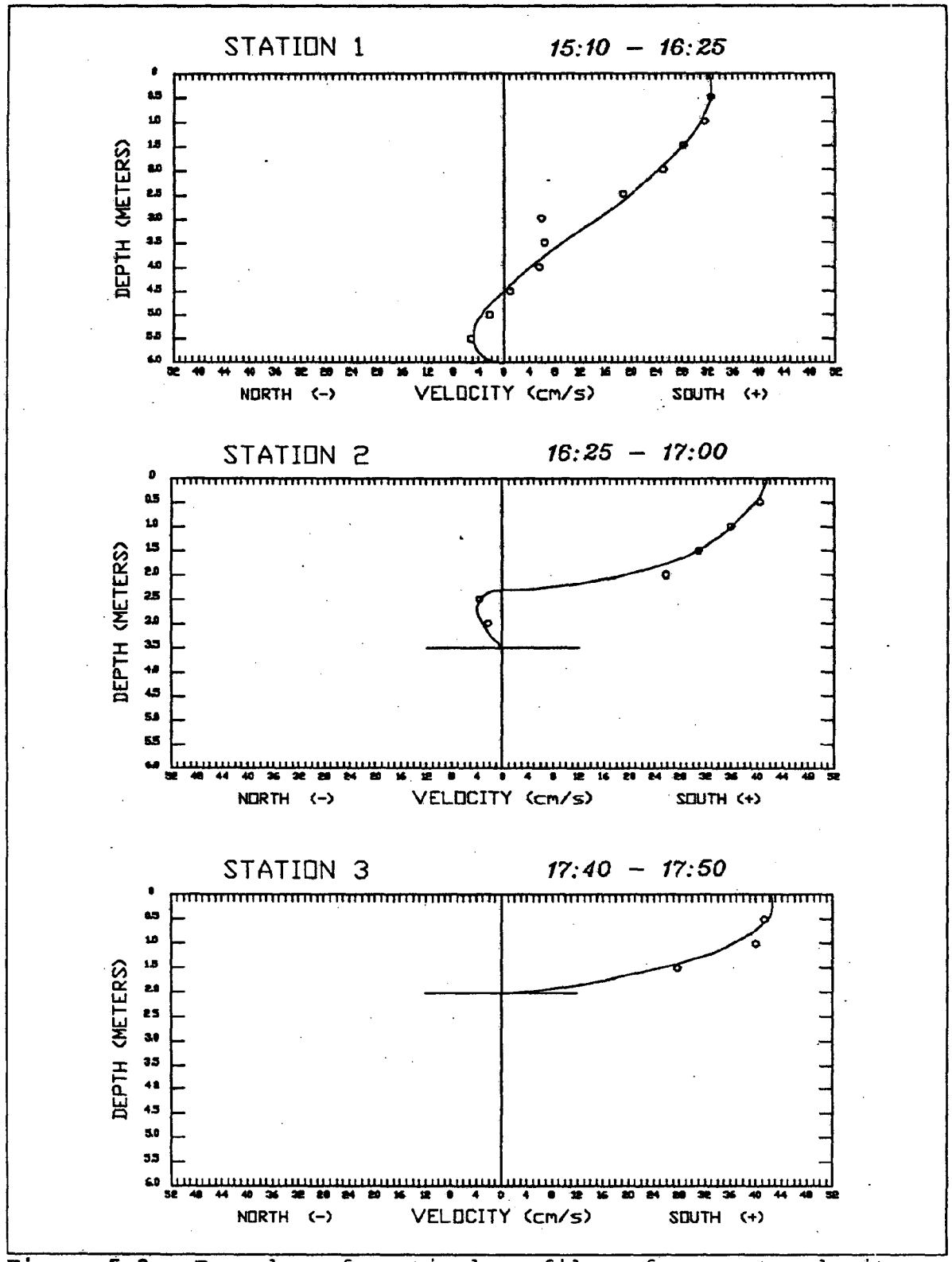


Figure 5.3. Examples of vertical profiles of current velocity, transect CT3. August 24, 1988.

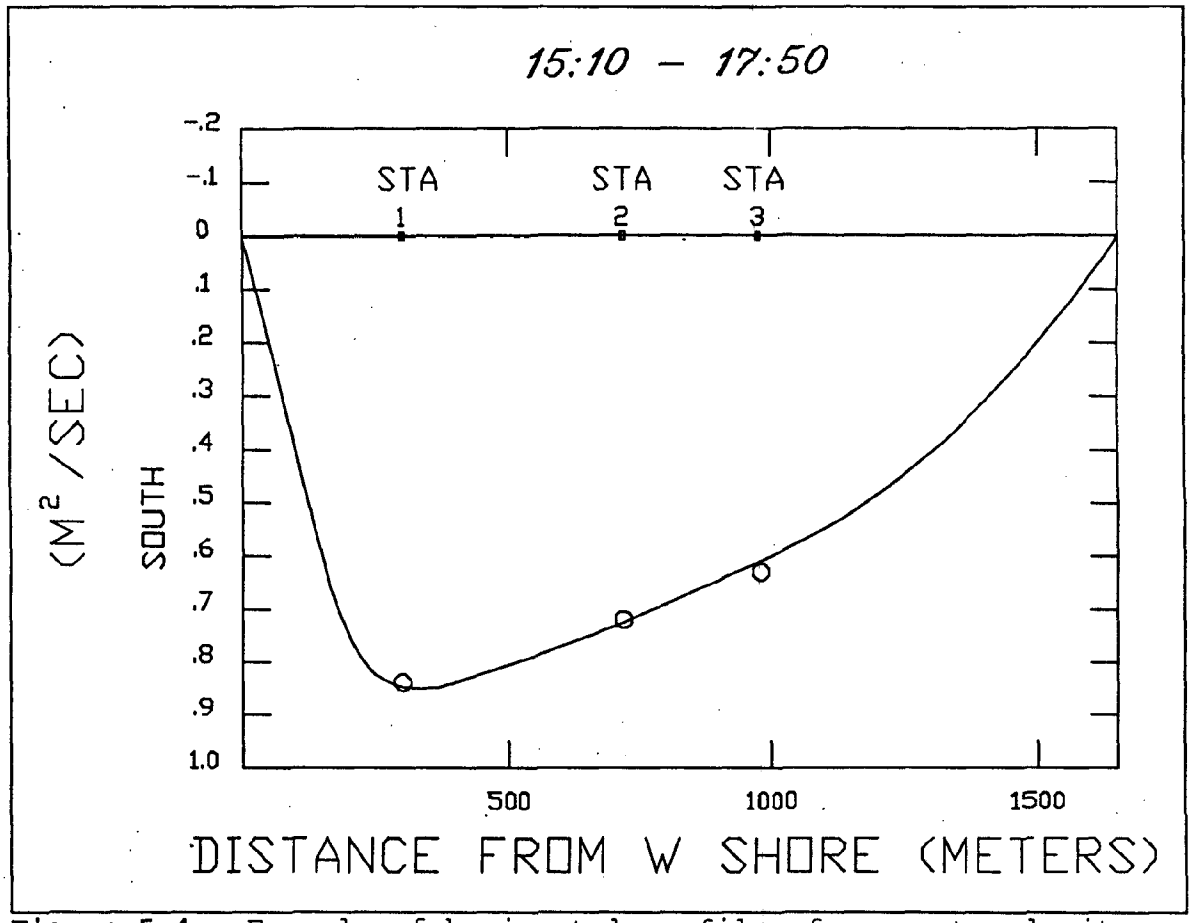


Figure 5.4. Example of horizontal profile of current velocity, transect CT3. August 24, 1988.

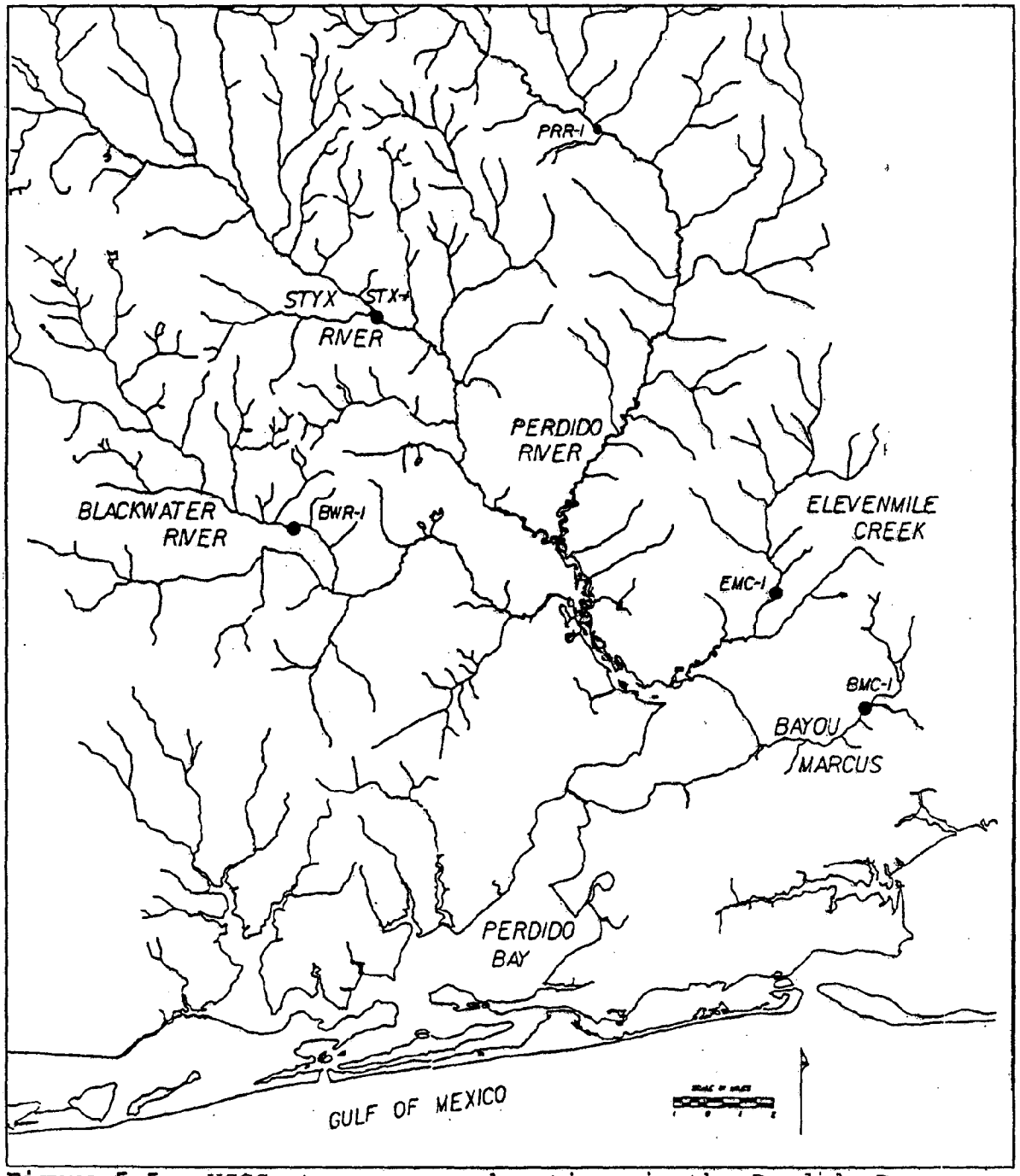


Figure 5.5. USGS stream gauge locations in the Perdido Bay watershed.

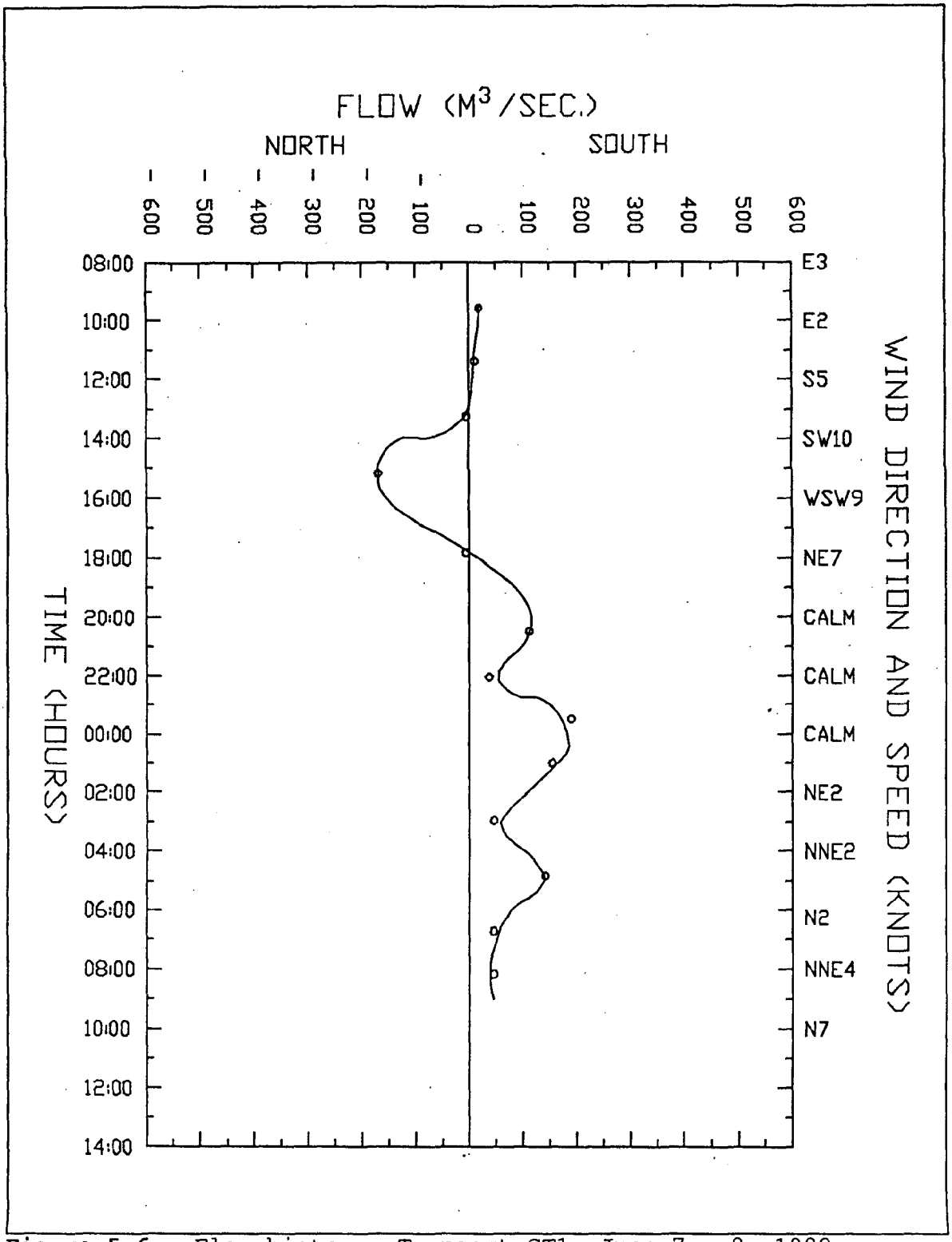


Figure 5.6. Flow history, Transect CT1, June 7 - 8, 1988.

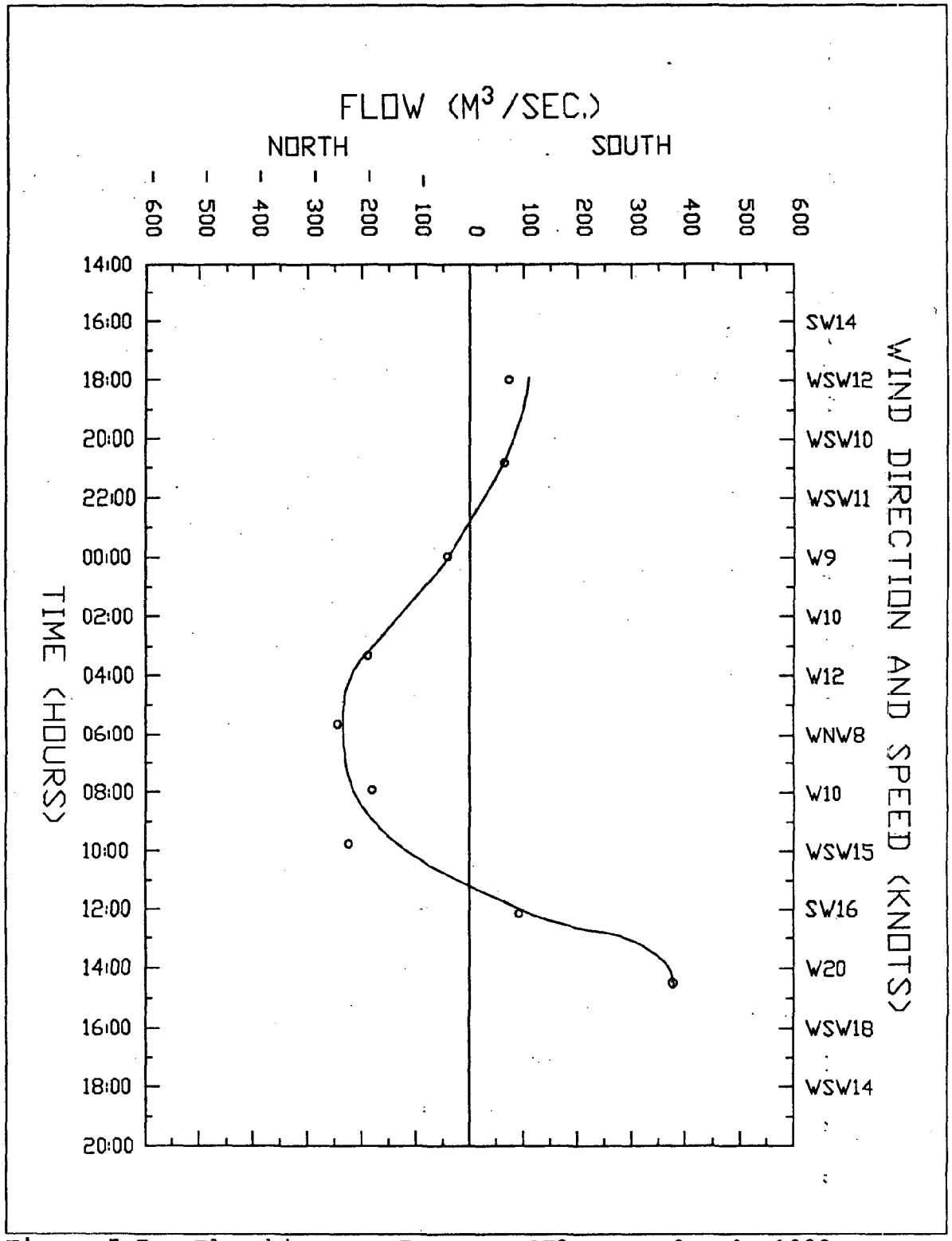


Figure 5.7. Flow history, Transect CT2, June 8 - 9, 1988.

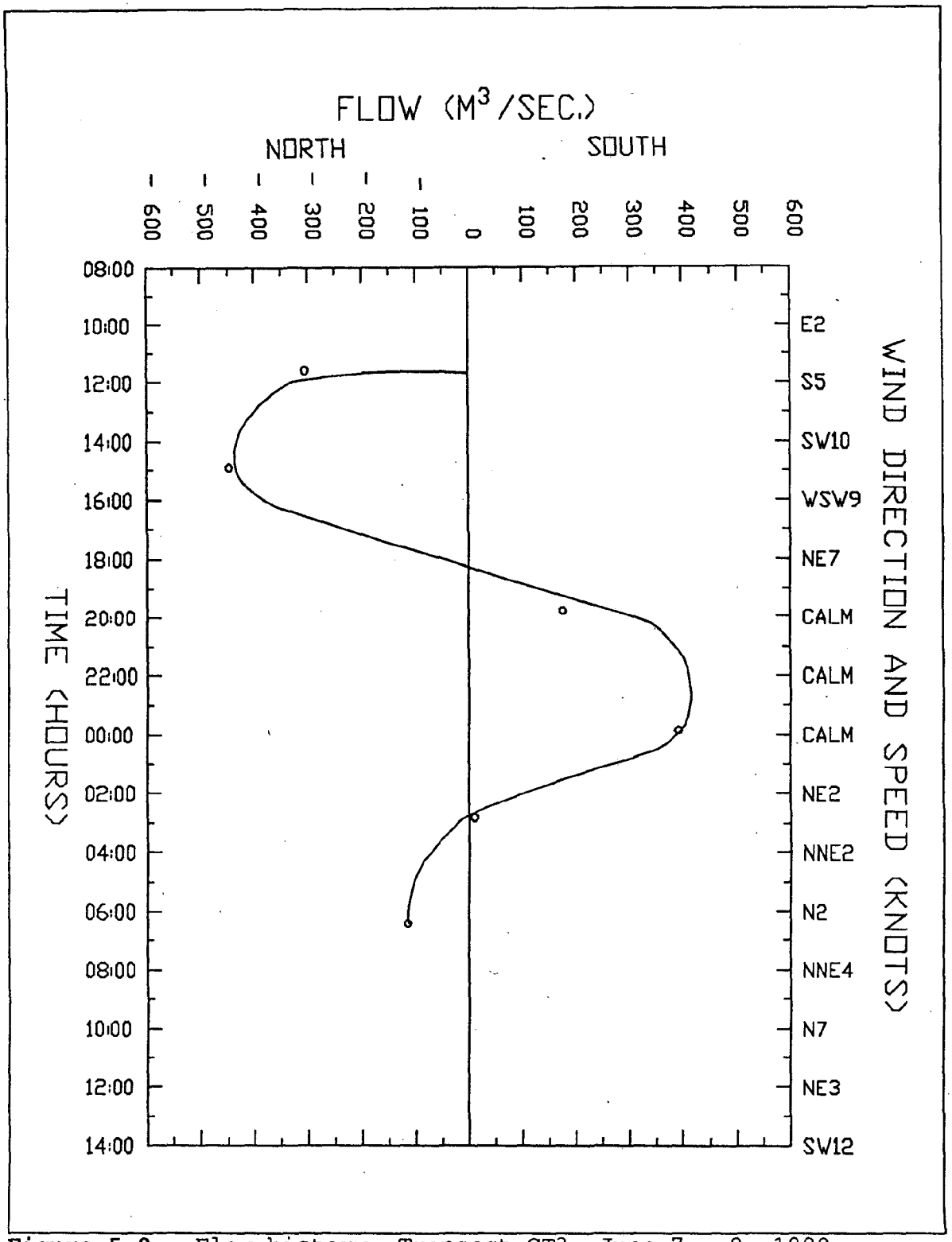


Figure 5.8. Flow history, Transect CT3, June 7 - 8, 1988.

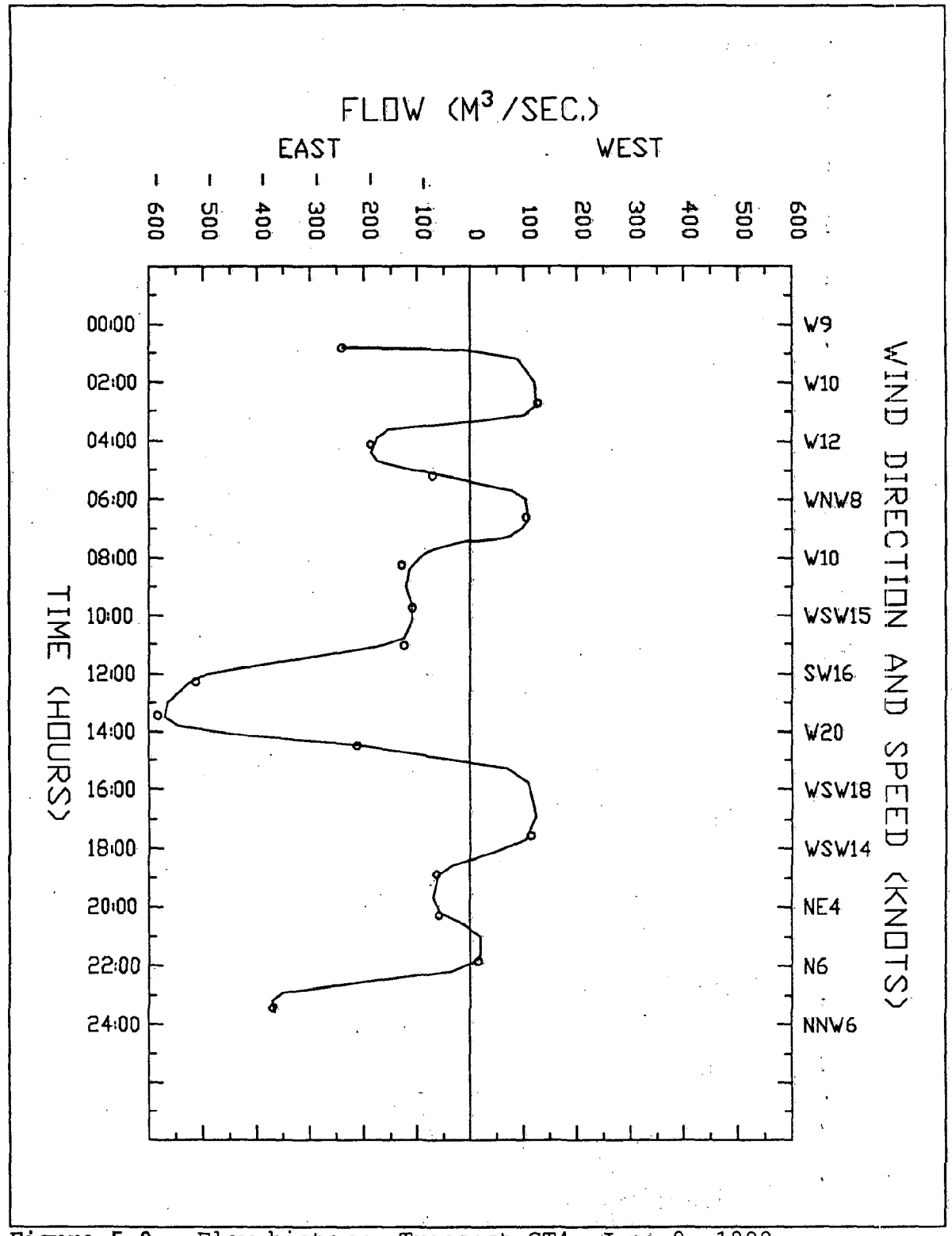


Figure 5.9. Flow history, Transect CT4, June 9, 1988.

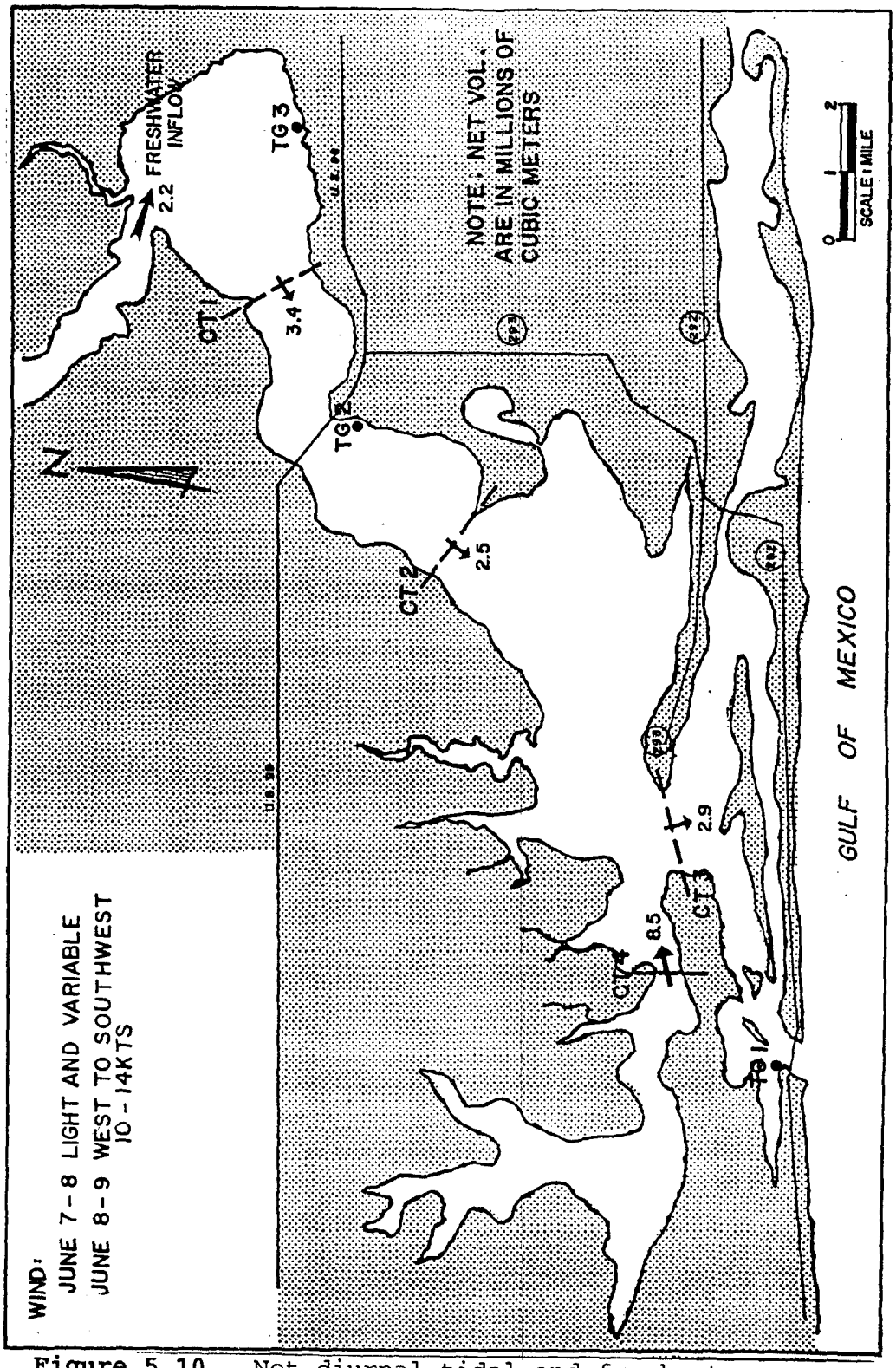


Figure 5.10. Net diurnal tidal and freshwater fluxes, June 7 - 9, 1988.

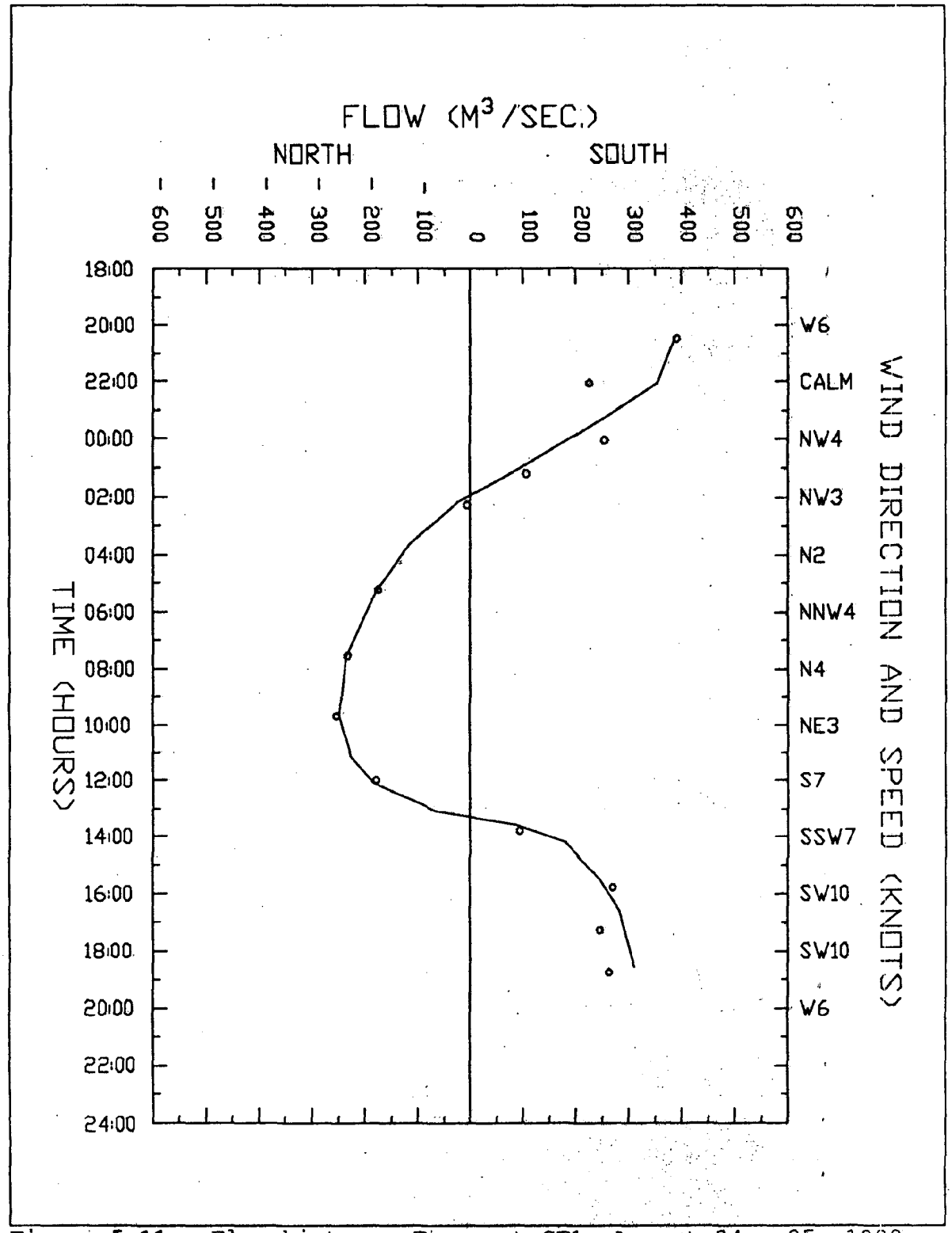


Figure 5.11. Flow history, Transect CT1, August 24 - 25, 1988.

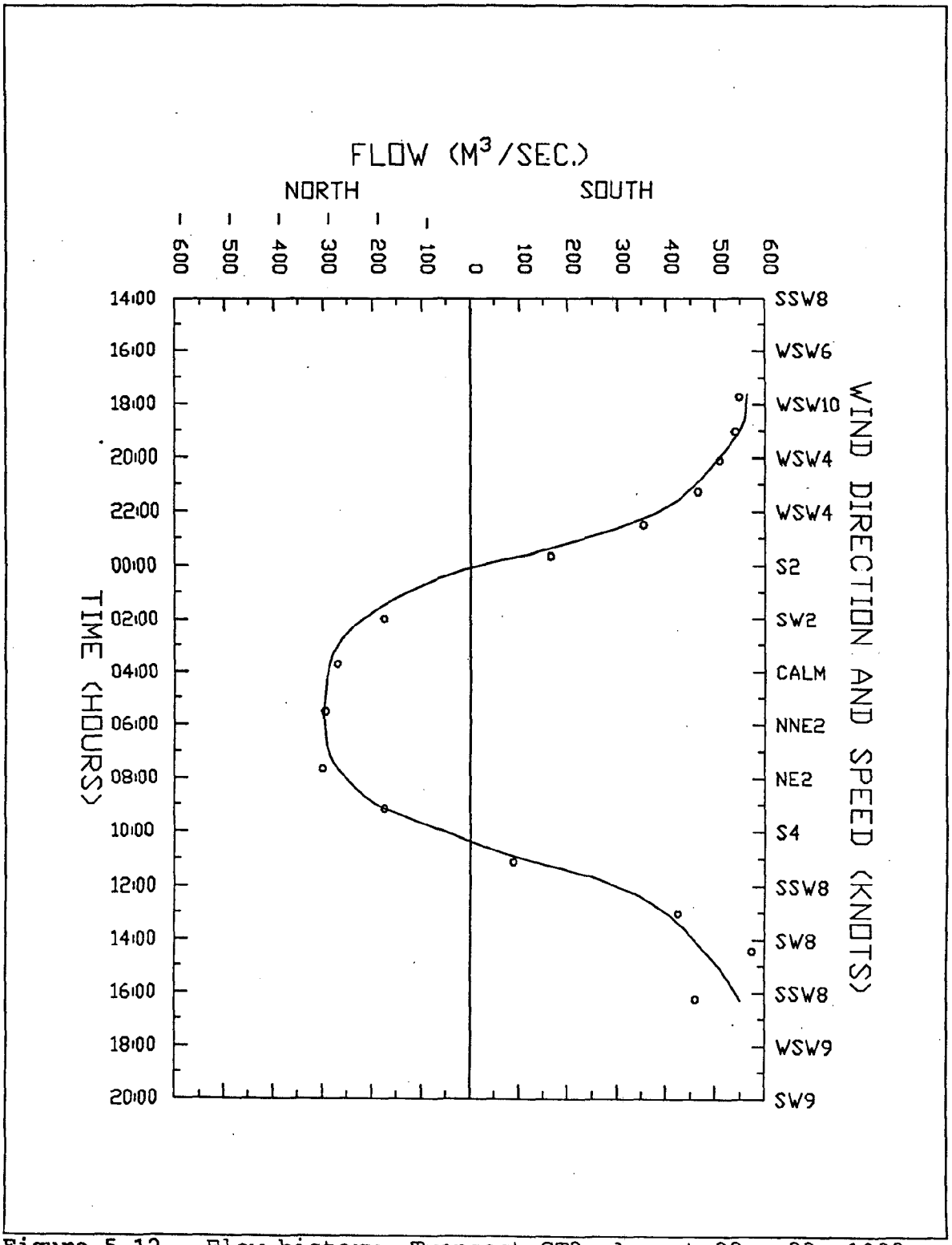


Figure 5.12. Flow history, Transect CT2, August 22 - 23, 1988.

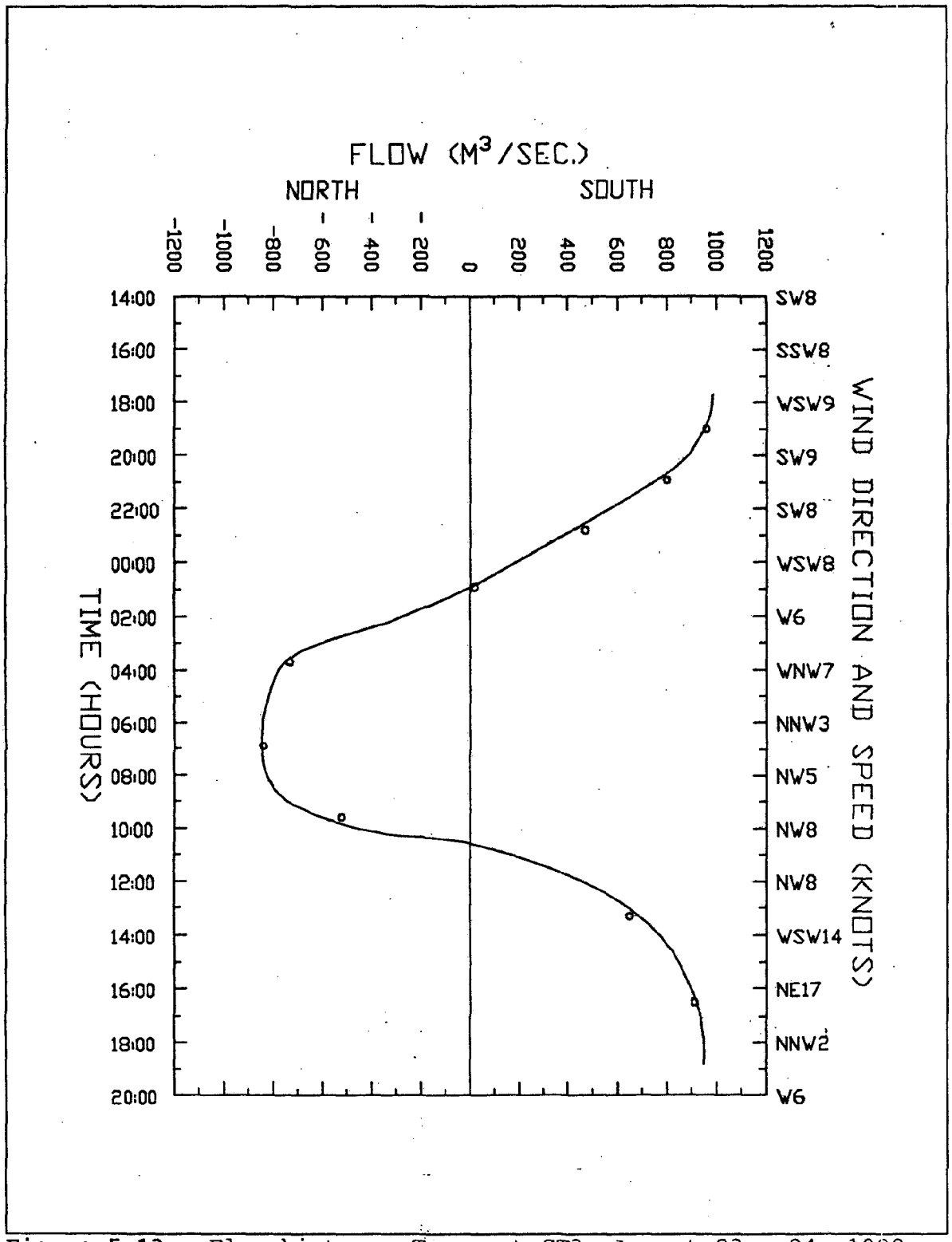


Figure 5.13. Flow history, Transect CT3, August 23 - 24, 1988.

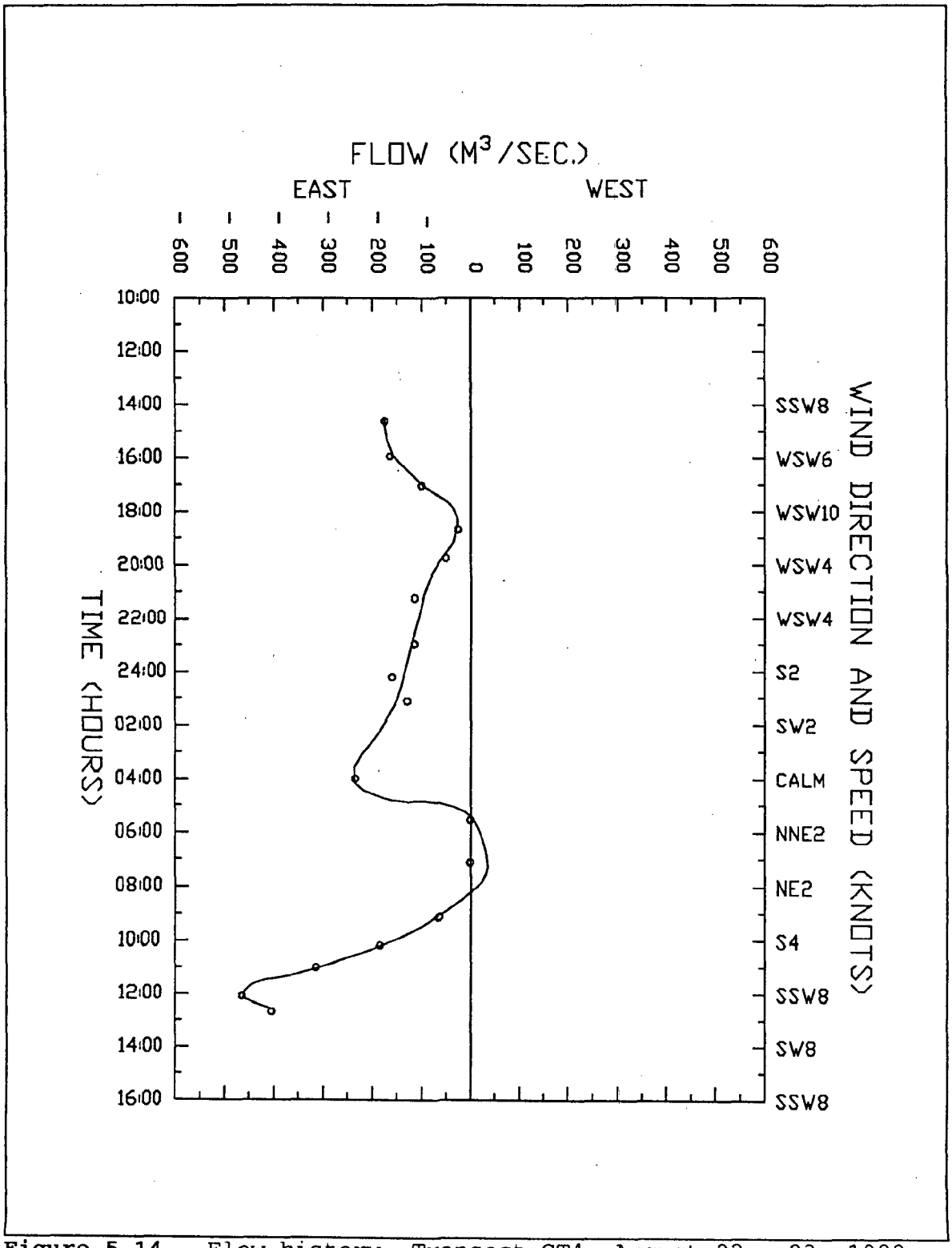


Figure 5.14. Flow history, Transect CT4, August 22 - 23, 1988.

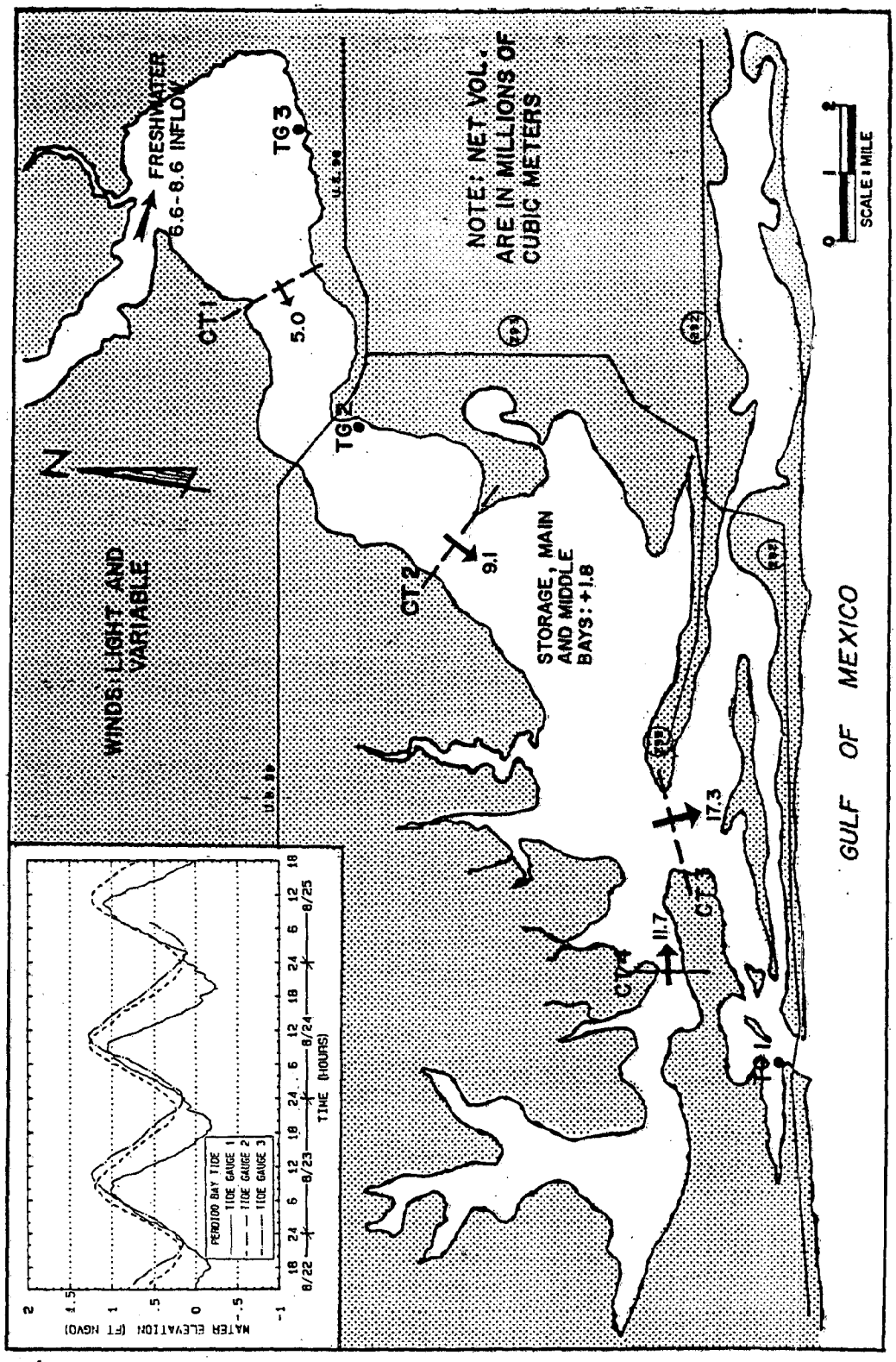


Figure 5.15. Net diurnal tidal and freshwater fluxes, August 22 - 25, 1988.

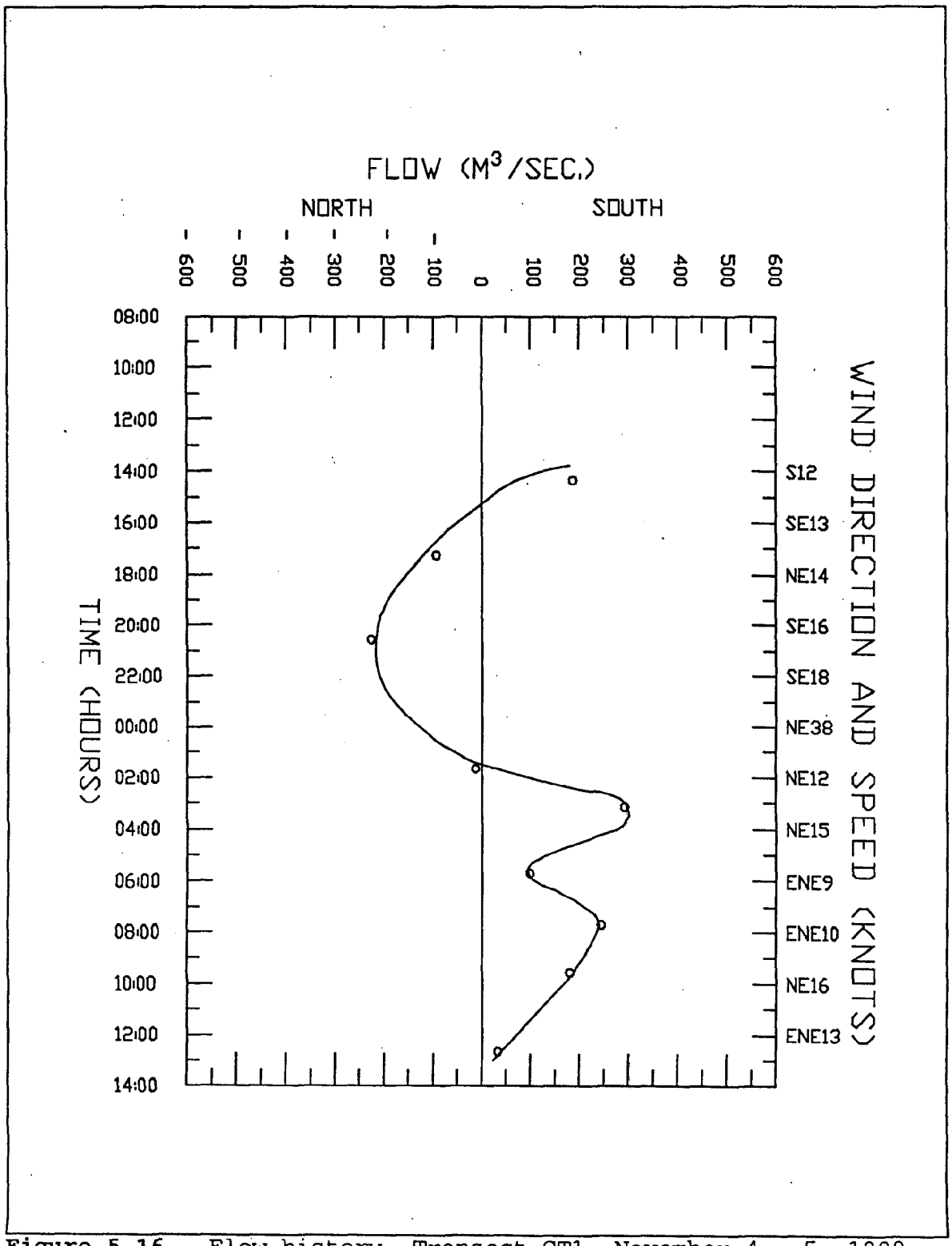


Figure 5.16. Flow history, Transect CT1, November 4 - 5, 1988.

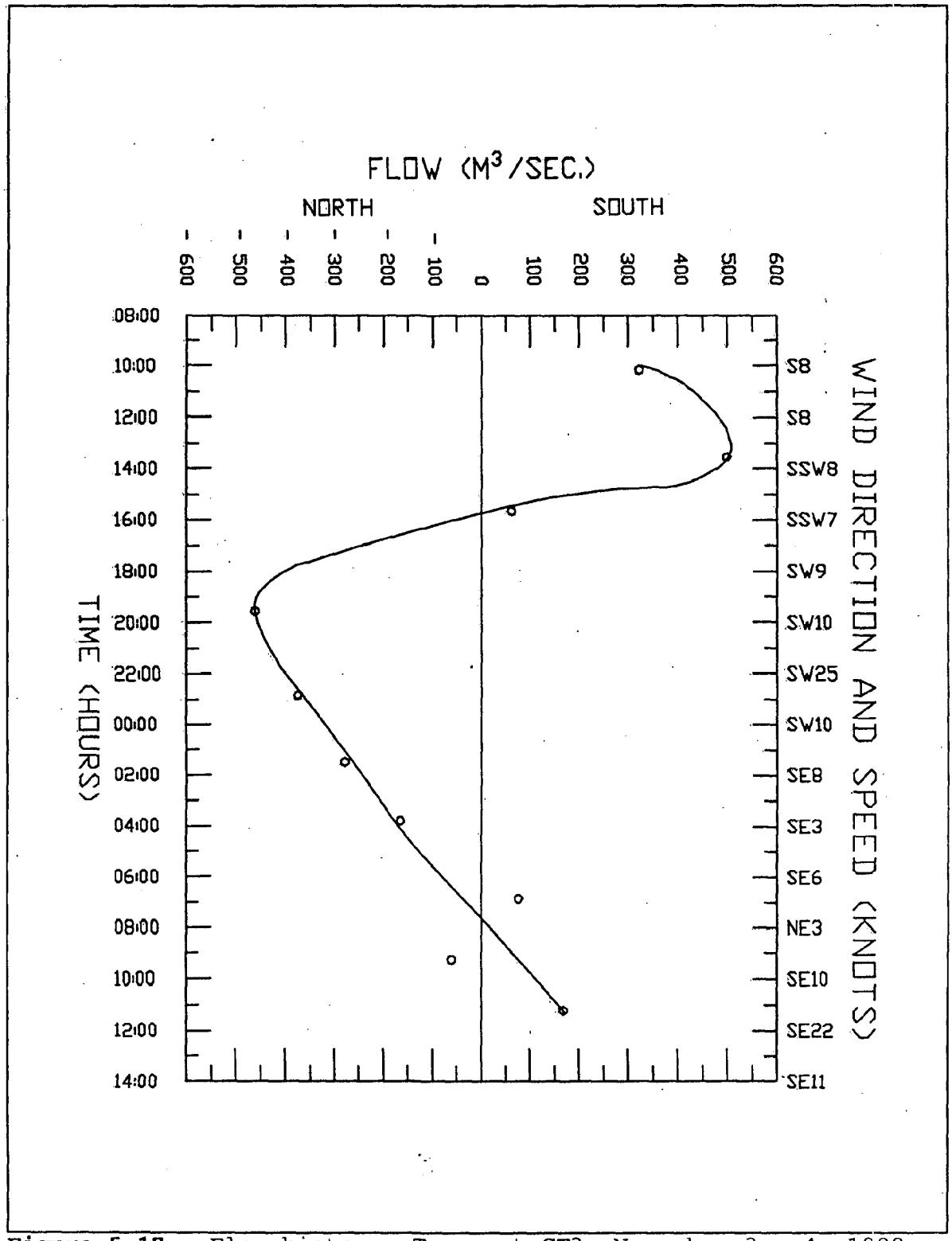


Figure 5.17. Flow history, Transect CT3, November 3 - 4, 1988.

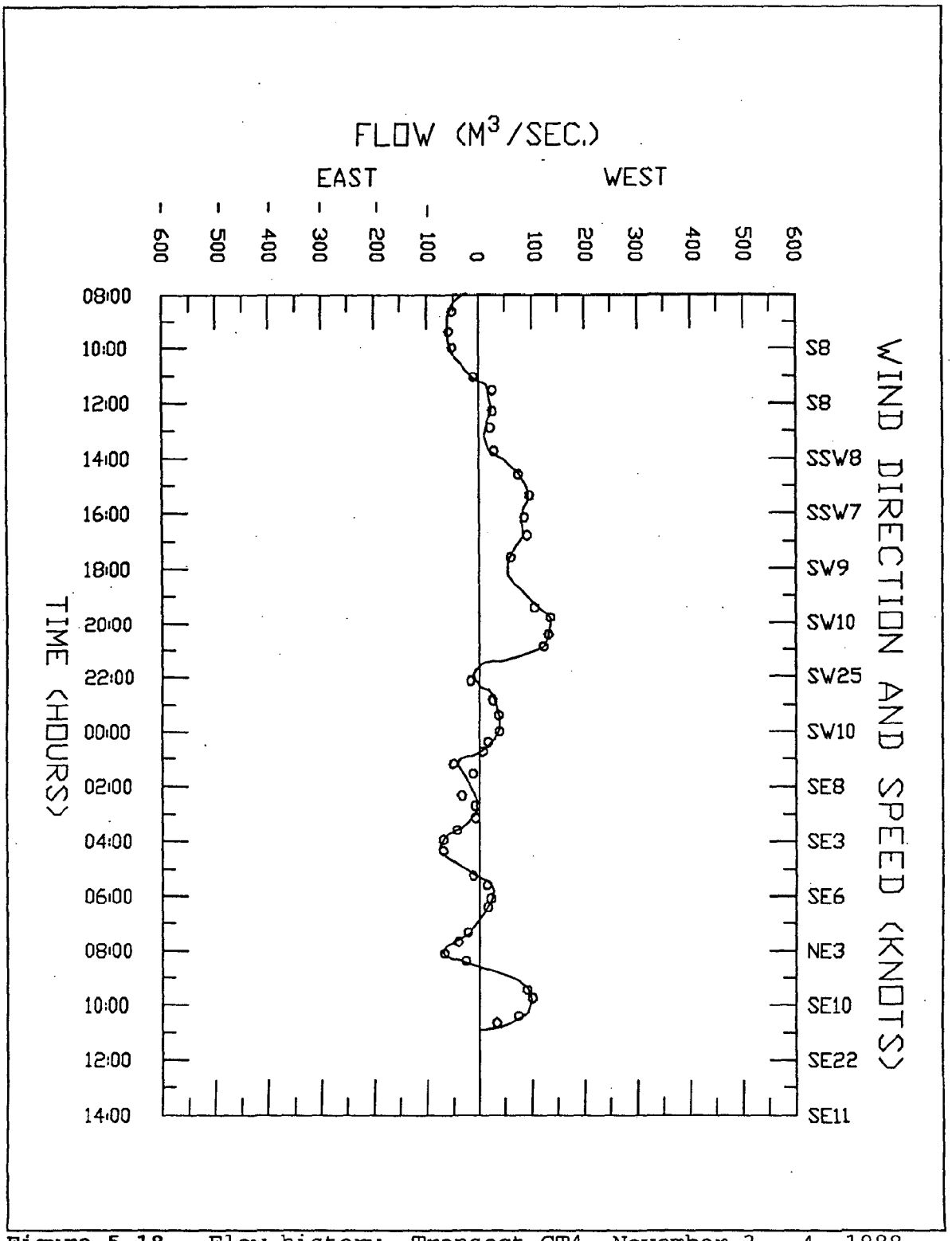


Figure 5.18. Flow history, Transect CT4, November 3 - 4, 1988.

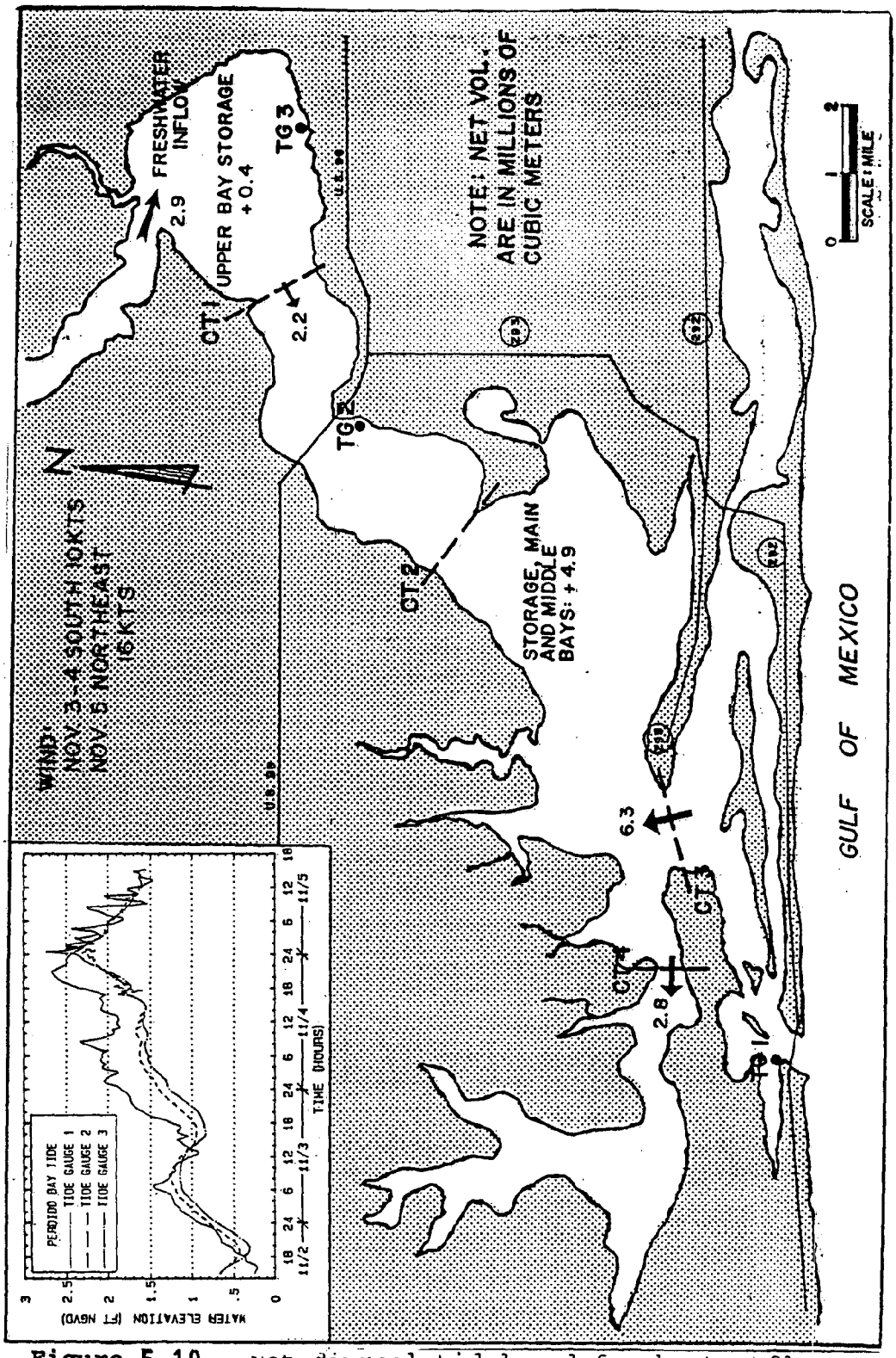


Figure 5.19. Net diurnal tidal and freshwater fluxes, November 3 - 5, 1988.

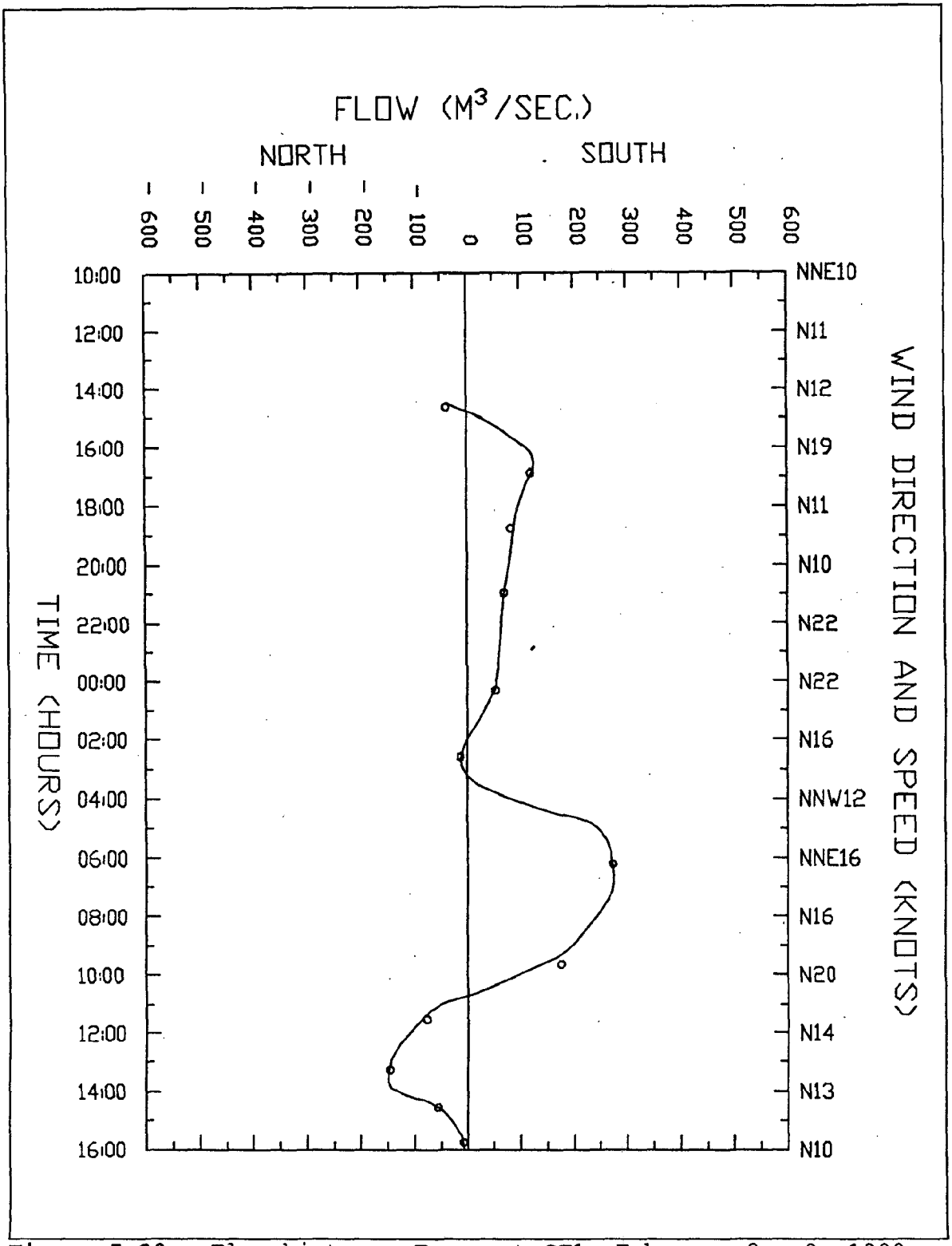


Figure 5.20. Flow history, Transect CT1, February 8 - 9, 1989.

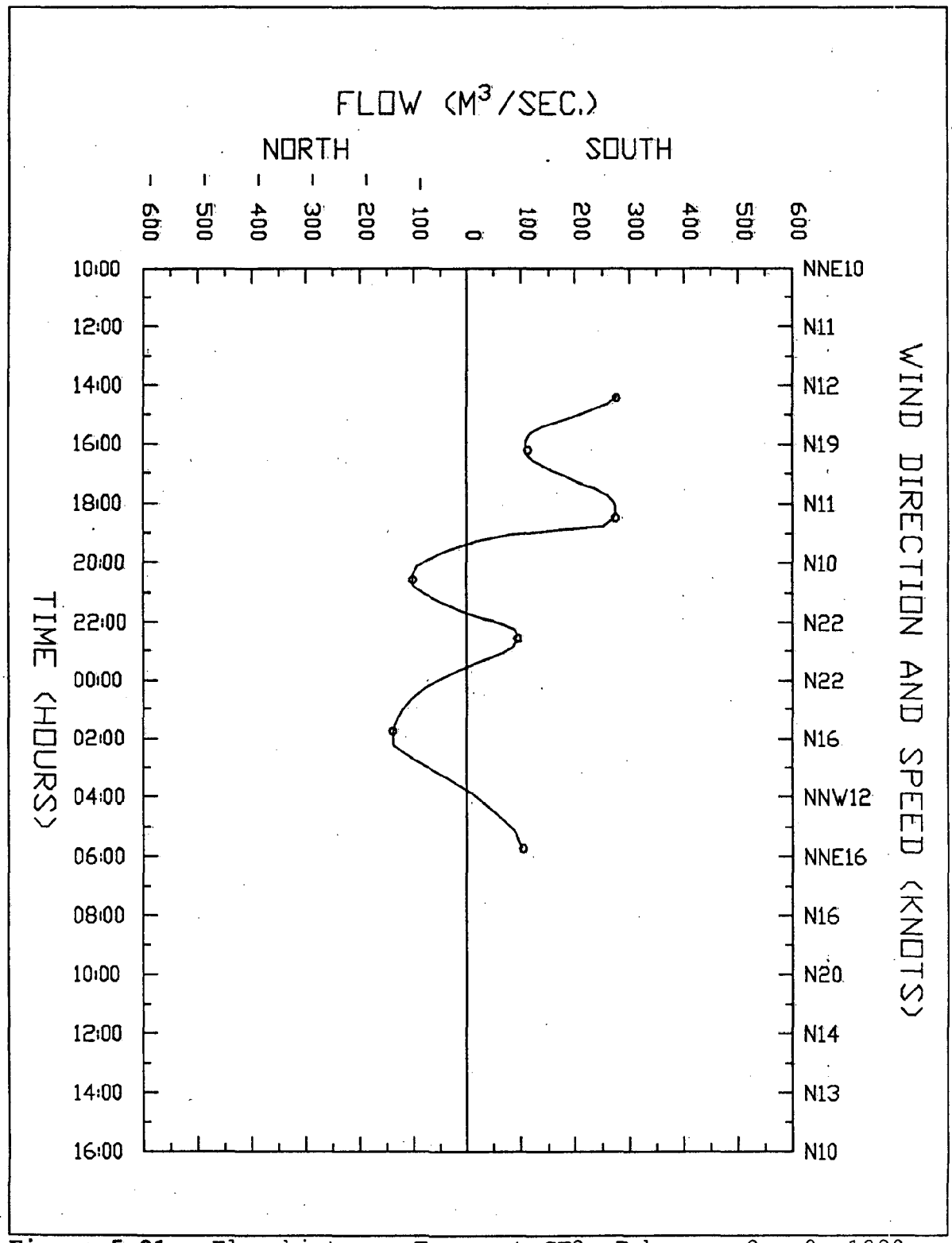


Figure 5.21. Flow history, Transect CT2, February 8 - 9, 1989.

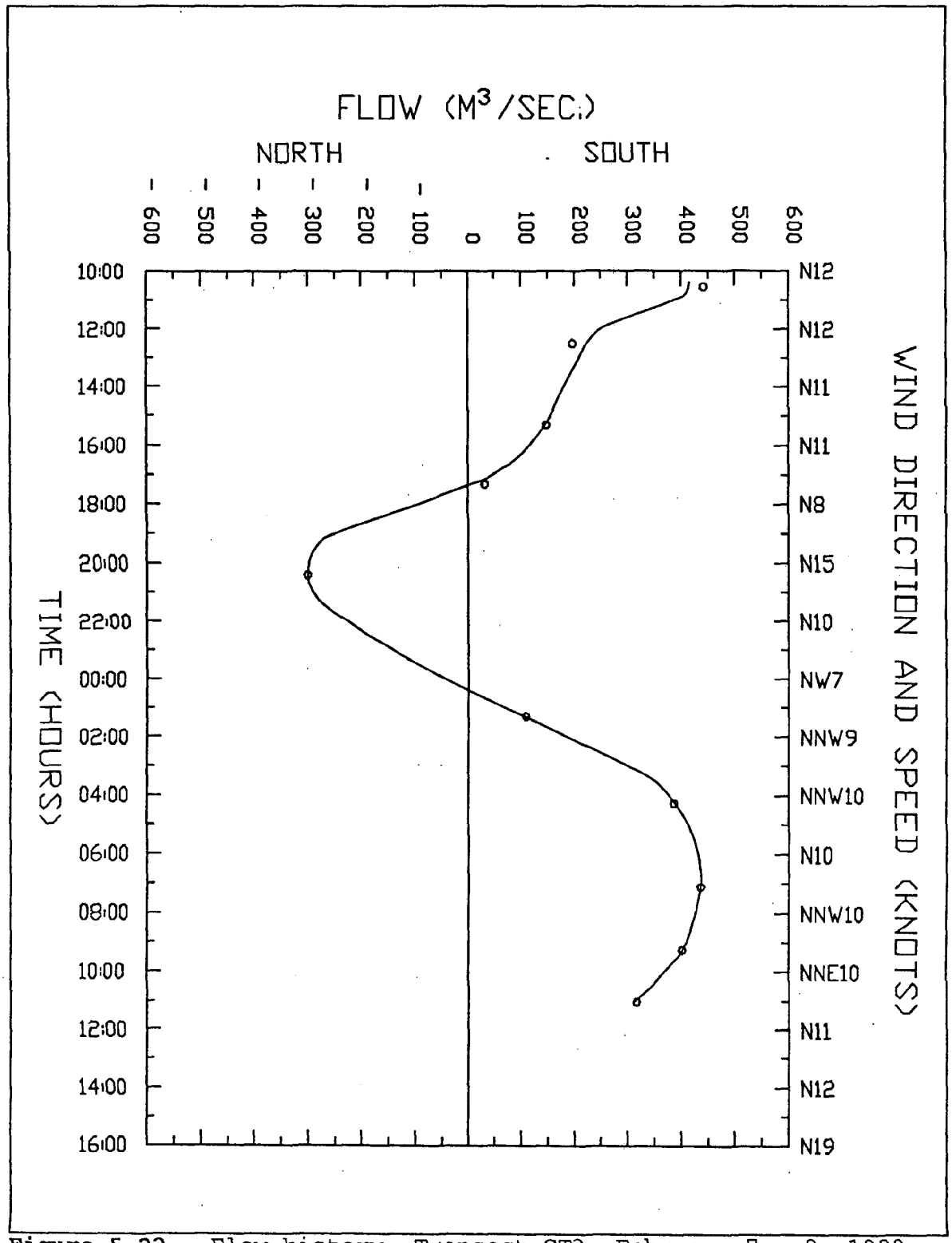


Figure 5.22. Flow history, Transect CT3, February 7 - 8, 1989.

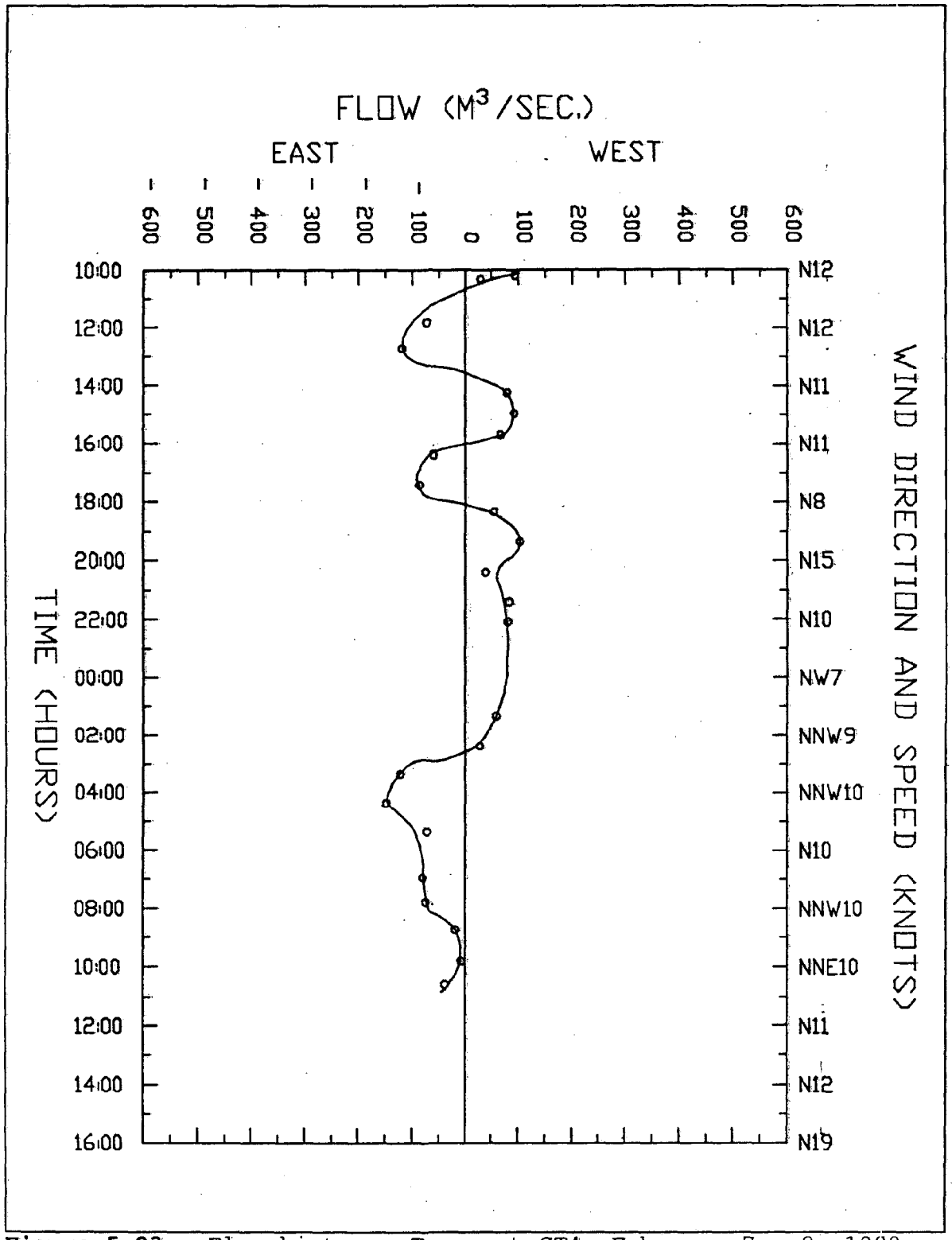


Figure 5.23. Flow history, Transect CT4, February 7 - 8, 1989.

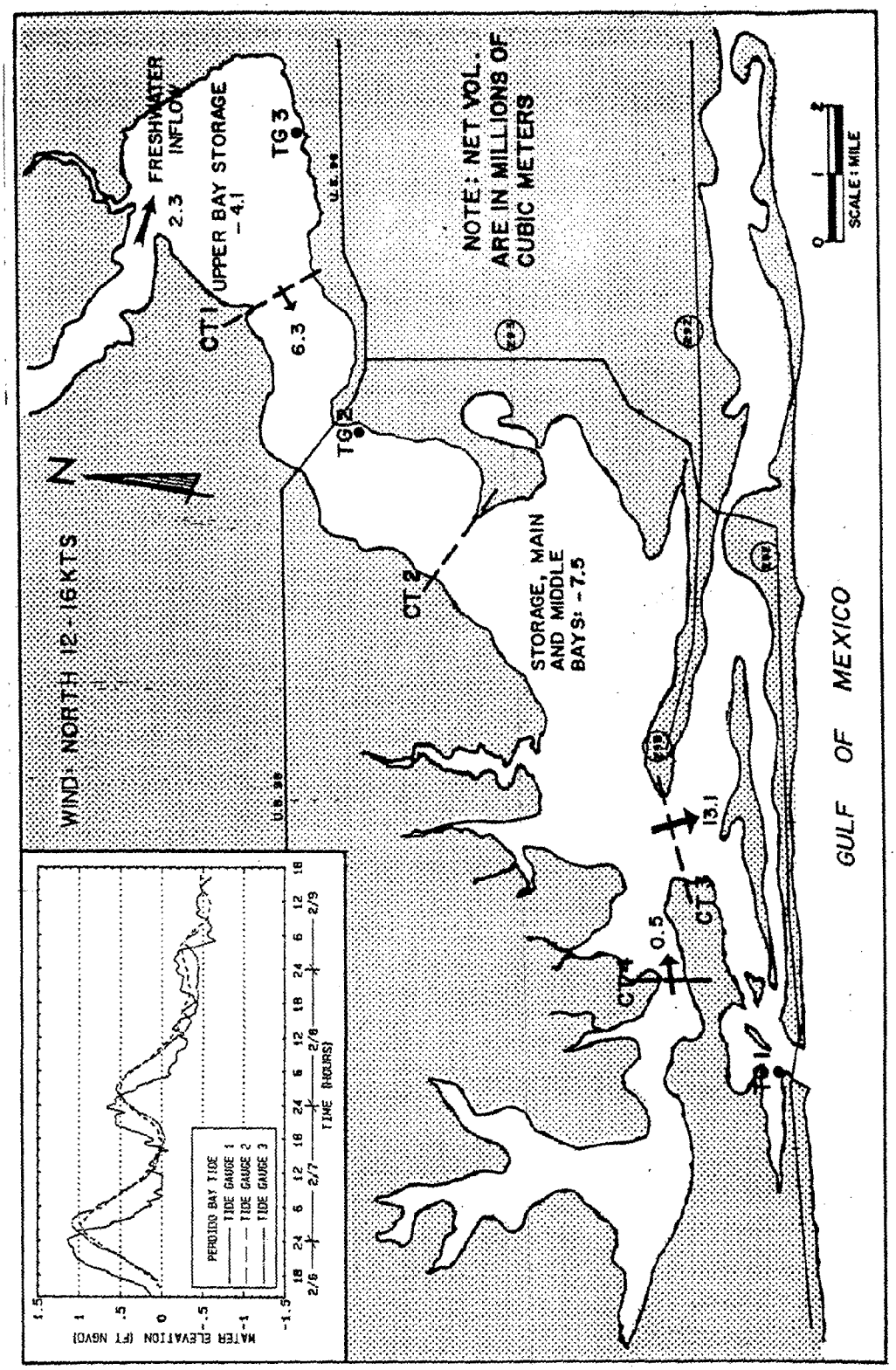


Figure 5.24. Net diurnal tidal and freshwater fluxes, February 7 - 9, 1989.

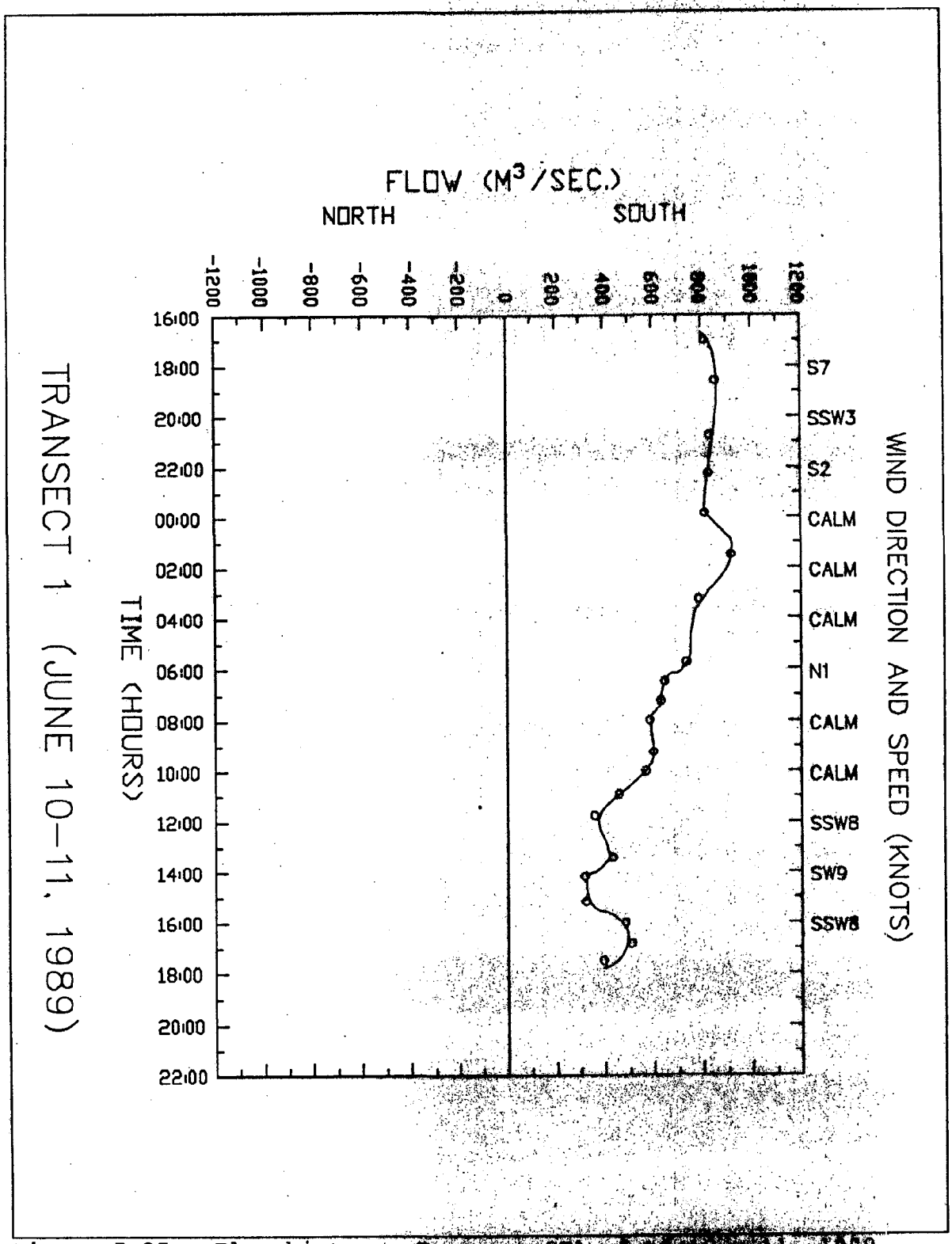


Figure 5.25. Flow history, Transect CT1, June 10-11, 1989.

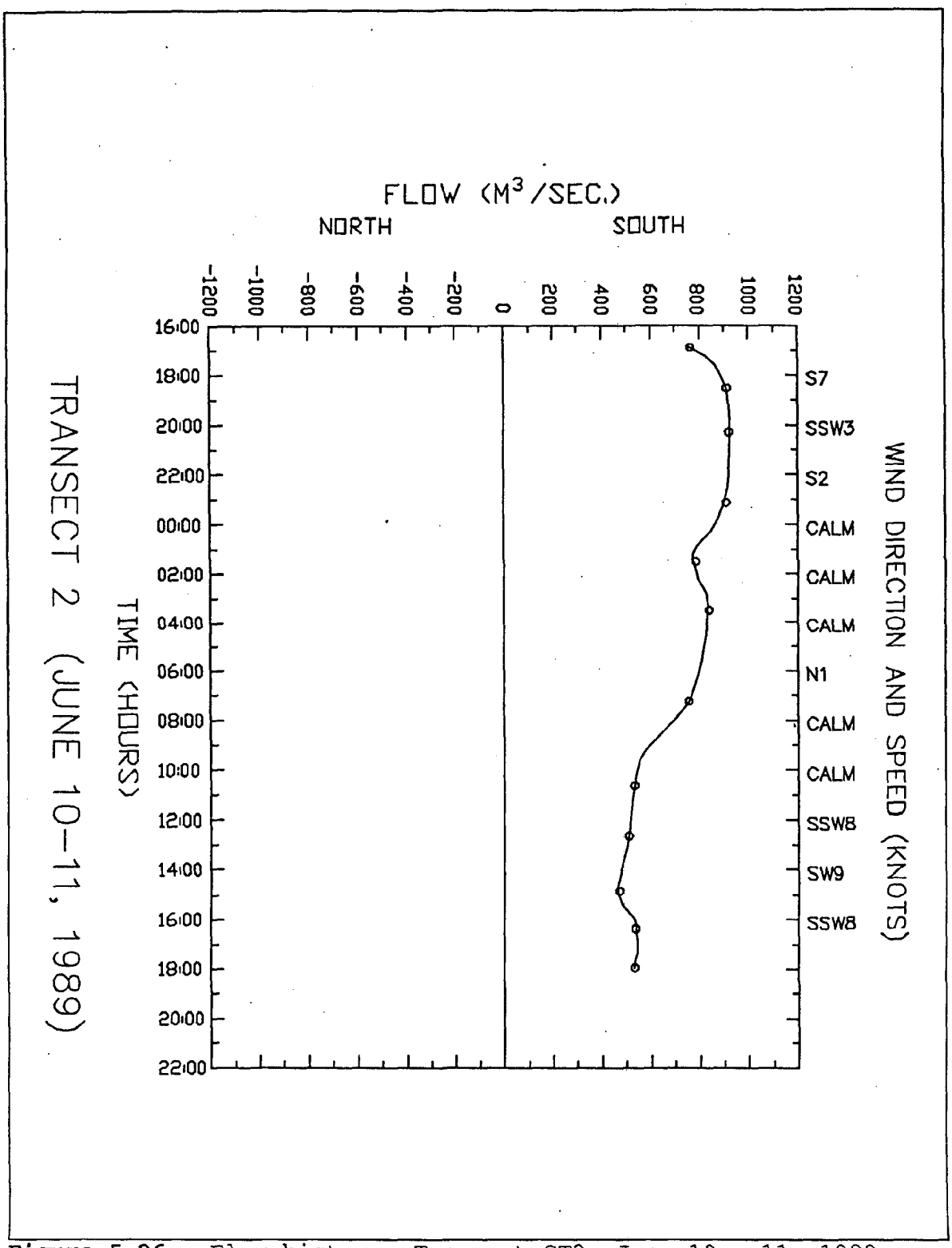


Figure 5.26. Flow history, Transect CT2, June 10 - 11, 1989.

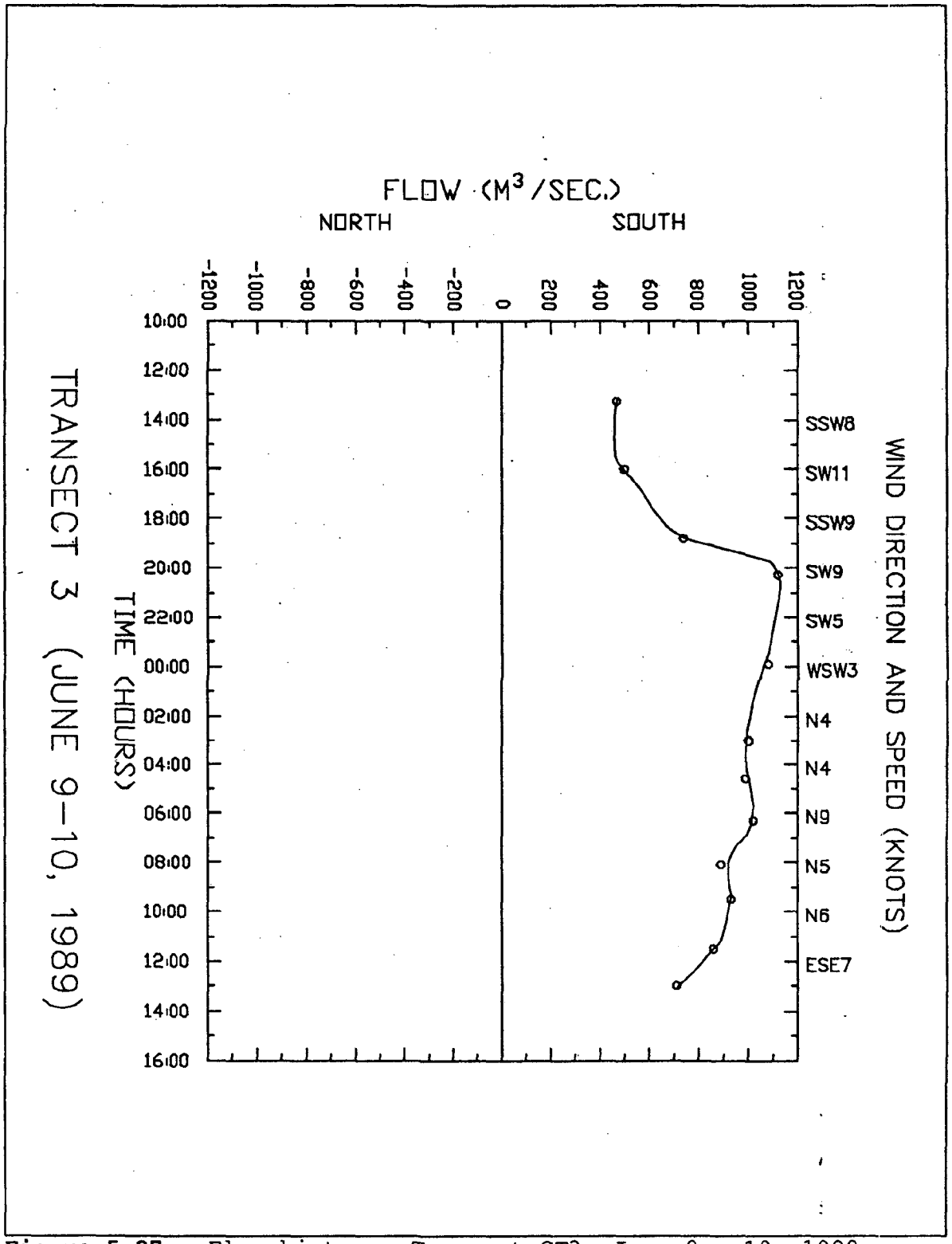


Figure 5.27. Flow history, Transect CT3, June 9 - 10, 1989.

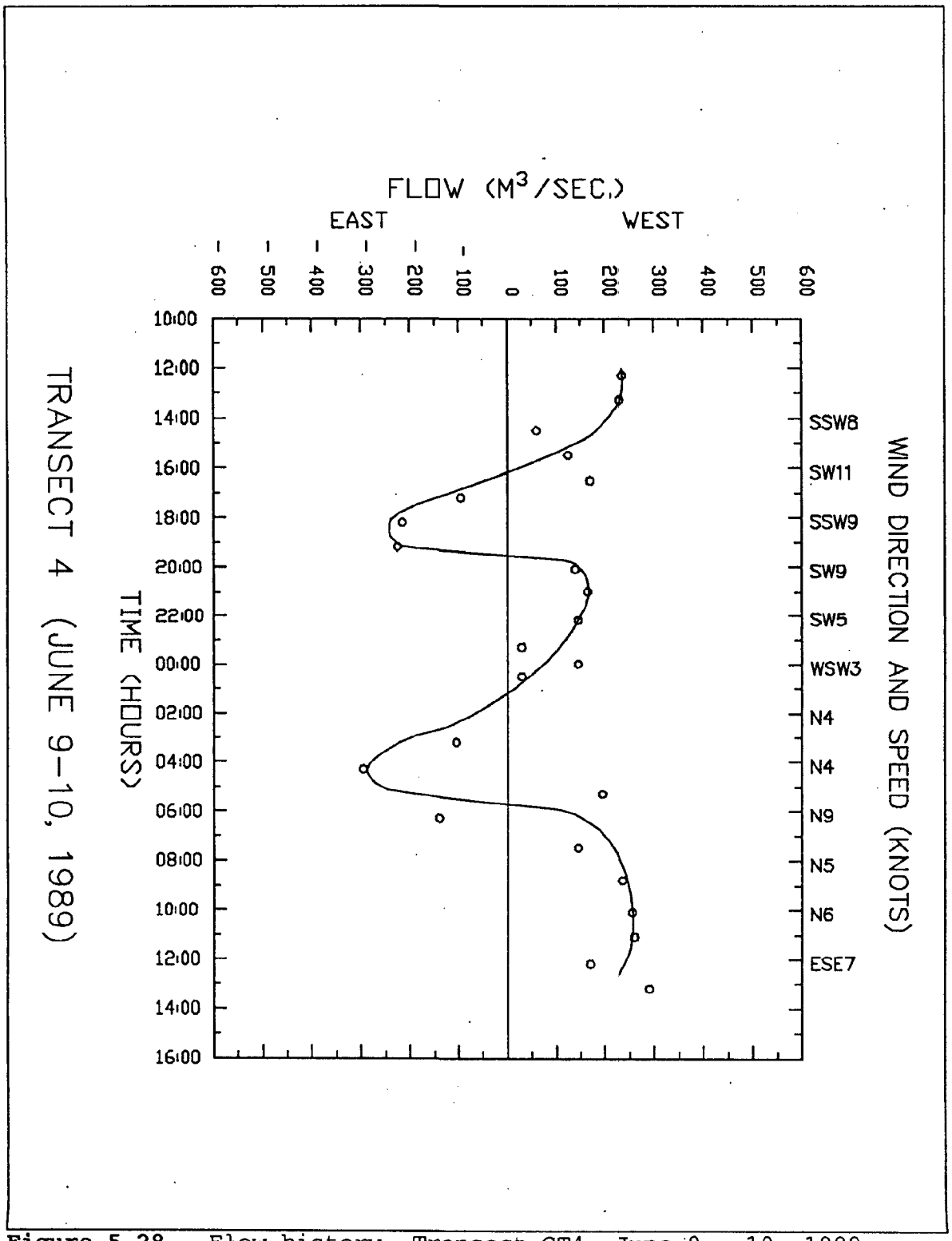


Figure 5.28. Flow history, Transect CT4, June 9 - 10, 1989.

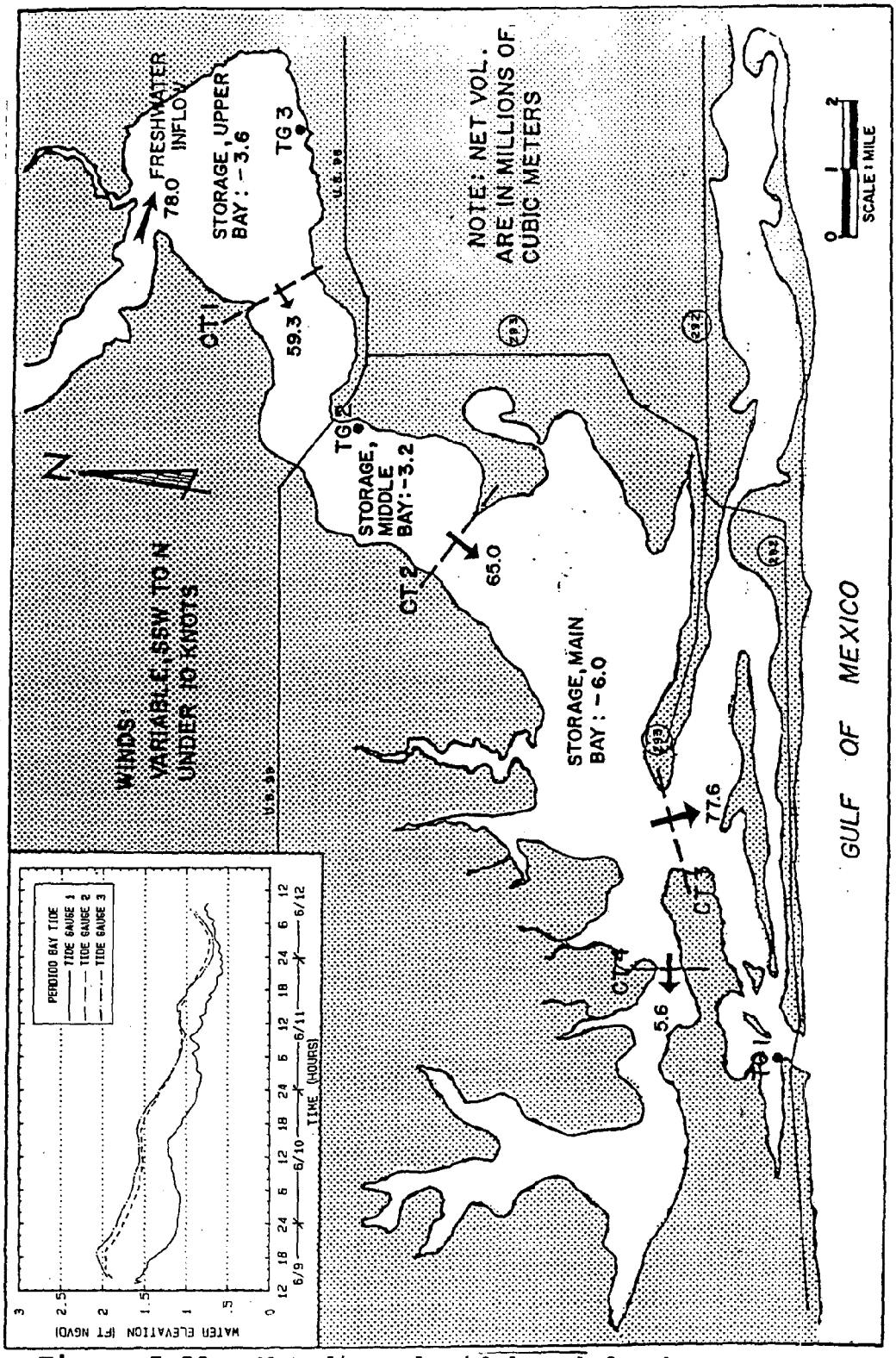


Figure 5.29. Net diurnal tidal and freshwater fluxes, June 9 - 11, 1989.

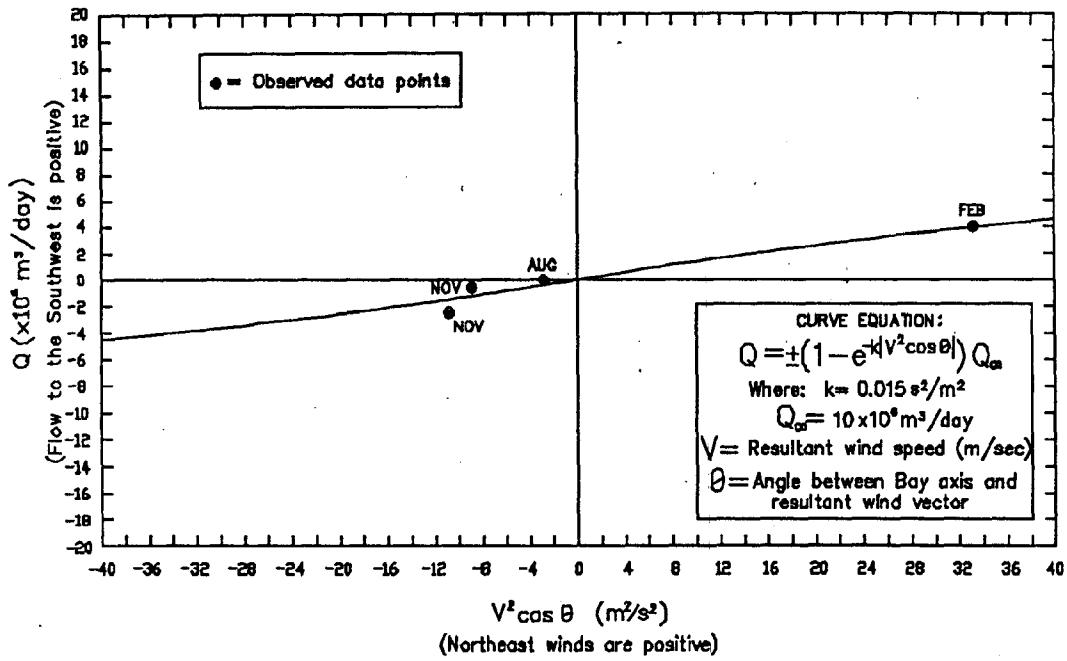


Figure 5.30. Plot of wind-driven net circulation as a function of wind stress along the axis of Perdido Bay at Transect CT1.

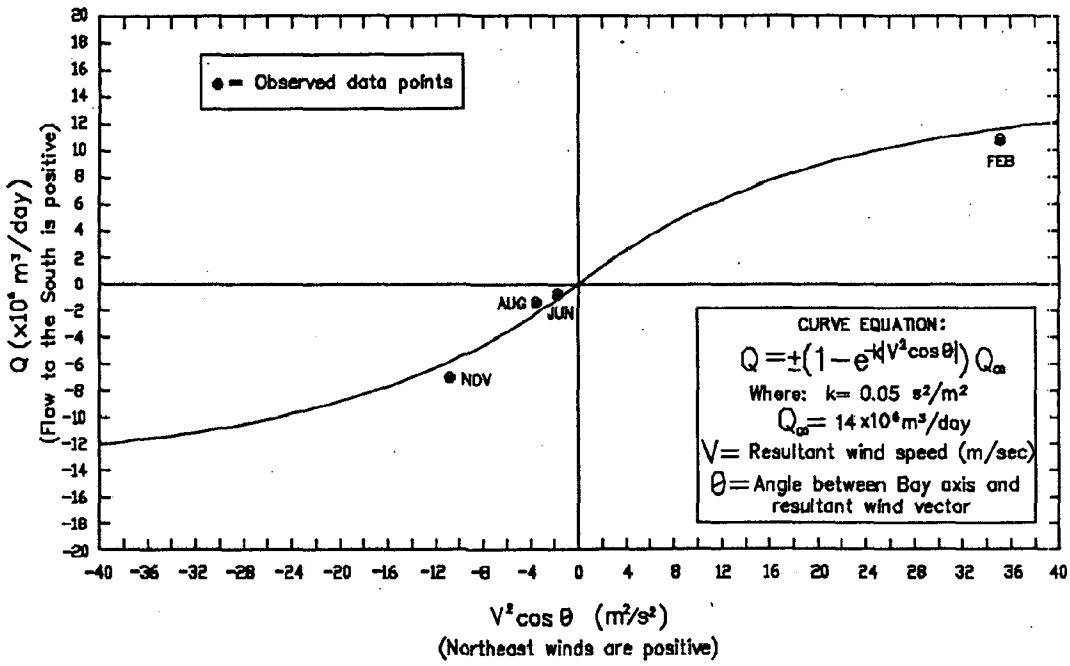


Figure 5.31. Plot of wind-driven net circulation as a function of wind stress along the axis of Perdido Bay at Transect CT3.

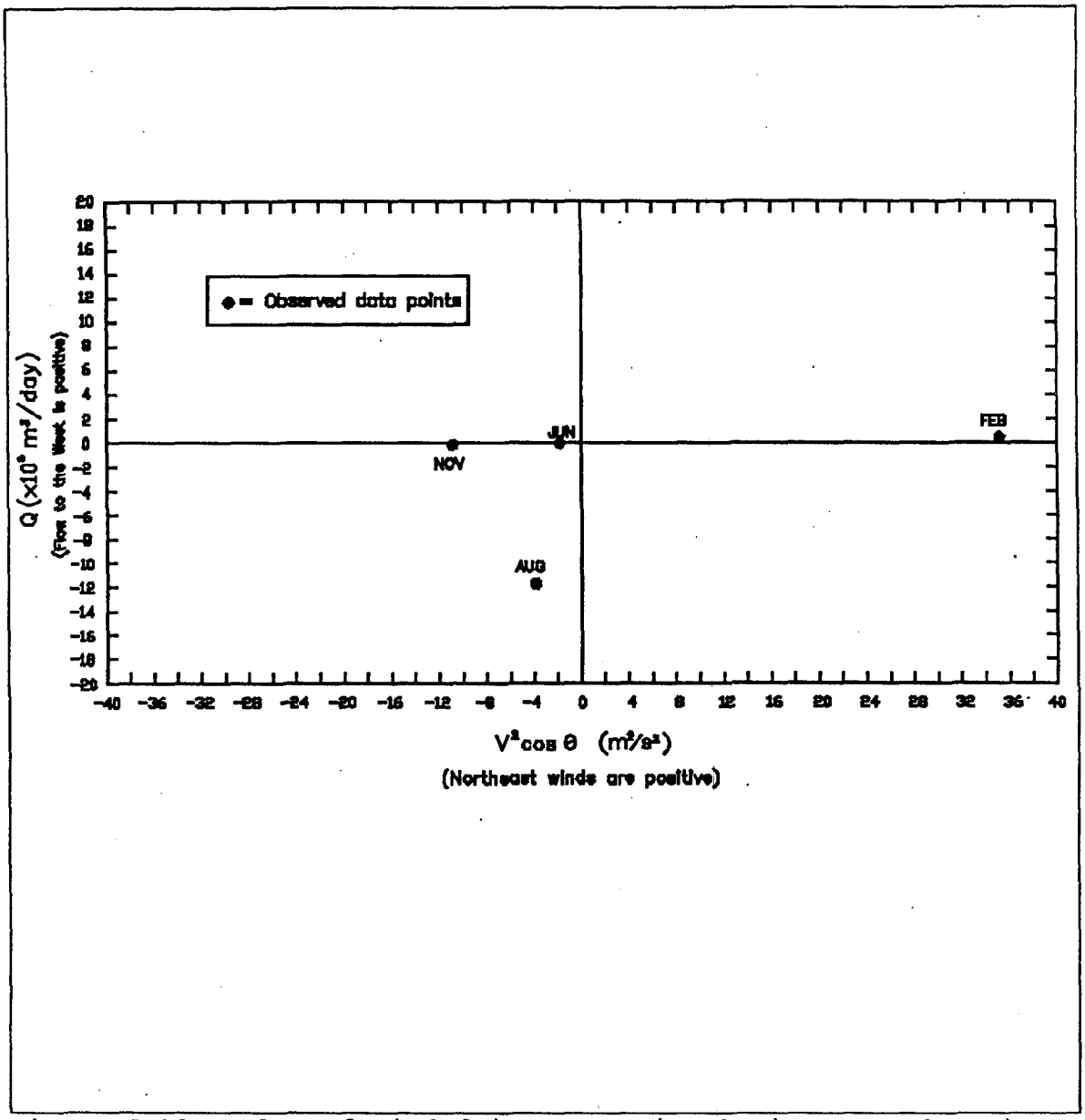


Figure 5.32. Plot of wind-driven net circulation as a function of wind stress along the axis of Perdido Bay at Transect CT4.

6. WATER CHEMISTRY

OBJECTIVES

Water quality in an estuary is the result of a complex interplay of factors including water movement, nutrient delivery, and *in situ* biological and chemical processes. The goal of the water chemistry part of the Interstate Project was to describe basic chemical conditions in Perdido Bay and its tributaries, based on an annual budget of nutrients and suspended solids and their distribution in the Perdido Bay system, and salinity and dissolved oxygen distribution in the bay. This included an evaluation of removal or retention of materials in the system and processes affecting the chemical behavior of nutrients entering the system.

To meet this goal the water chemistry sampling program was designed to address three objectives:

1) to describe the transport of nutrients and suspended solids by the major freshwater sources to Perdido Bay during typical seasonal conditions and during high flow events,
2) to evaluate the general movement (including transport, removal and addition) of these materials in Perdido Bay, and
3) to determine the seasonal variations in dissolved oxygen in the Bay and elucidate the causes for observed periodic hypoxia.

The study team selected a mass balance approach to interpret conditions in Perdido Bay. This approach was used to evaluate nutrients and dissolved oxygen employing a simple box models for evaluating net movement of water and nutrients through the bay. This approach is best suited for understanding longer term, broad scale processes. It was chosen because of the lack of historical data for Perdido Bay and the level of funding and manpower available for this project. This approach is simple in concept, rapid to develop, and practical for establishing useful goals

which allow identification of specific data collection objectives. The approach used represented the best compromise between conducting an affordable system-wide effort and establishing technically sound management foundations.

SAMPLING METHODS

Strategy

Water samples were collected approximately monthly from five tributaries to Perdido Bay (Perdido River, Blackwater River, Styx River, Elevenmile Creek, and Bayou Marcus) and from ten stations in the estuary. Tributary samples were collected on one day, followed a day later by the estuarine samples. To obtain a better estimate of movement of materials during high flow conditions, water samples were also collected during and after two storms. Storm event samples were collected from the tributaries during rising, peak, and falling periods of storm hydrographs.

Station Locations

Samples from the five tributaries were collected at the USGS streamflow gaging sites (Figure 5.5) so that water chemistry data could be used in conjunction with streamflow information to calculate nutrient-discharge rating curves. Tributary water quality and streamflow station locations are identified in Table 6.1.

Four stations in Perdido Bay were located at fixed positions. One fixed station (PRB-1) was located near the mouth of the bay off Ross Point and served as a high salinity end member. Another fixed station (PRB-5) was located mid-bay just above the Highway 98 bridge. Two fixed stations were located within tidally influenced tributaries to the main bay, one in Soldier Creek (SDC-1) and the other (PMC-1) near the confluence of Palmetto Creek and Spring Branch.

Six stations were placed along the surface salinity gradient at the time of sampling. This approach allowed interpretation of

Table 6.1. Water chemistry sampling station locations.

Station	Location and comments
PRR-1	Perdido River at Barrineau Park. Approximately 0.5 mile southwest of Barrineau Park, Florida, on bridge on unpaved county road.
STX-1	Styx River at bridge on Baldwin County Road 87.
BWR-1	Blackwater River at bridge on Baldwin County Road 87. Samples were collected from September 1988 through the end of the project.[a]
EMC-1	Eleven Mile Creek at bridge on U.S. Highway 90.
BMC-1	Bayou Marcus Creek at bridge on U.S. Highway 90.
PRB-1	Perdido Bay off Ross Point. 30°19.45′ N, 87°30.58′ W. LORAN LOPs[b]: 13094.3, 47113.8.
PRB-5	Perdido Bay, mid-bay approximately 1/4 mile north of center span of U. S. Hwy 98 bridge. 30°24.45′ N, 87°25.82′ W. LORAN LOPs: 13148.9, 47137.5.
SDC-1	Soldier Creek, approximately 0.5 mile into creek from mouth. 30°21.33′ N, 87°29.84′ W. LORAN LOPs: 13104.0, 47122.5.
PMC-1	Palmetto Creek, at confluence with Spring Branch. 30°20.76′ N, 87°30.71′ W. LORAN LOPs: 13094.3, 47119.7.
PRB-2 PRB-3 PRB-4	Perdido Bay, lower portion of bay between PRB-1 and PRB-5, locations variable, depending on salinity gradient at time of sampling.
PRB-6 PRB-7 PRB-8	Perdido Bay, upper portion of bay above PRB-5, locations variable, depending on salinity gradient at time of sampling.

[a]Samples were also taken from Negro Creek, a tributary to the Blackwater River; however, since no stream discharge information was available from this site, interpretation of these samples is not included in this report.

[b]LORAN lines of position (time differences)

nutrient and suspended solid concentrations with respect to salinity, a conservative tracer. Three of these moveable stations were placed at equal salinity intervals in the lower half of the bay between PRB-1 and PRB-5 and three were placed at equal salinity intervals in the upper half of the bay. At some times of the year the lowest salinity station (PRB-8) was actually located in the lower Perdido River. Fixed estuarine station locations are described in Table 6.1; estuarine station locations for all sampling periods are shown in Figures 6.1 - 6.5.

Sampling Dates

Sampling commenced in March 1988. Tributary and estuarine samples were collected approximately monthly through June 1989 with the exception of April 1988 and March 1989. Water samples were also collected from the tributaries during and after two storms, March 1 - 11 and March 20 - 31, 1989.

Sample Collection

Monthly samples. Field teams from ADEM and FDER worked concurrently so that samples could be collected and returned to the laboratory as quickly as possible. At each station, vertical profiles of water temperature, salinity, conductivity and dissolved oxygen were taken at 0.5 m depth intervals. Measurements were obtained both on a downcast and upcast using Yellow Springs Instruments Model 33 S-C-T meters and Model 57 dissolved oxygen meters. Prior to commencing sampling each day, all primary and backup instruments were intercalibrated by immersing all probes simultaneously into a 20-L container of bay water. Dissolved oxygen meters were calibrated to the oxygen content of the bay water as determined by a modified Winkler dissolved oxygen technique (APHA, 1980). S-C-T meter calibration was checked using laboratory-prepared conductivity and salinity standards.

Wind speed and direction were measured using a hand-held wind speed indicator (Dwyer) and hand-bearing or boat's compass. Depths were measured with recording fathometers or lead lines.

Water samples were collected using Kemmerer or Beta bottles (Wildco) and placed into clean 3.8-L plastic bottles. When the water column was stratified (defined as a change in salinity of 3°/oo or greater over a 0.5 m depth interval), samples were taken from both upper and lower strata; water was collected from mid-depth when the water column was vertically mixed. Replicate samples were collected and analyzed from each station and each depth. Samples were immediately placed on ice and delivered to the ADEM laboratory in Mobile, normally within two hours of completion of sampling.

Storm samples. Storm samples were collected from the surface of the tributaries as described above with the exception that no profiles of temperature, conductivity, and dissolved oxygen were taken. Temperature and salinity were measured in the samples. It was assumed that the streams were thoroughly mixed vertically during the high flow conditions. ADEM and FDER field teams worked alternately to collect samples from each tributary every six hours (12 hours for Perdido River) during peak flow. After peak flow, sampling was continued at reduced frequency until each tributary returned to base flow. Based on field measurements of stream stage, a subset of the samples collected from each stream, representing rising, peak, and falling portions of storm hydrographs, was chosen for analysis.

LABORATORY ANALYSES

Parameters analyzed and methods used are listed in Table 6.2. Dissolved components, turbidity, and total suspended solids were analyzed by the ADEM Mobile Field Office laboratory. Particulate components (ie., materials retained on a glass fiber filter, nominal pore size 0.4 µm) were analyzed by Savannah Laboratories and Environmental Services (SL&ES, Savannah, GA). The ADEM laboratory prepared, froze and shipped filters to SL&ES.

Table 6.2. Chemical parameters analyzed and methods.

Parameters	Abbreviation	Methods	Units
DISSOLVED COMPONENTS			
Total organic carbon	DOC	EPA[a] 415.2	mg-C L^{-1}
Nitrate + Nitrite	NO_3+NO_2	EPA 353.2[b]	mg-N L^{-1}
Total Kjeldahl nitrogen	TKN	EPA 351.2[c]	mg-N L^{-1}
Ortho-phosphate	DPO_4	EPA 365.3[d]	mg-P L^{-1}
PARTICULATE COMPONENTS			
Total Carbon	PC	P.E. (1972)[e]	mg-C L^{-1}
Total Nitrogen	PN	P.E. (1972)[e]	mg-N L^{-1}
Total Phosphorus	PP	EPA 365.1	mg-P L^{-1}
OTHER PARAMETERS			
Total suspended solids	TSS	EPA 160.3	mg L^{-1}
Turbidity	-	EPA 180.1	NTU

[a]Methods for chemical analysis of water and wastes, EPA 600 4-79-020.
[b]Modified for autoanalyzer according to Lachat (1988) method 10-107-04-1-B.
[c]Modified for autoanalyzer according to Lachat (1988) method 10-107-06-2.
[d]Modified for autoanalyzer according to Lachat (1988) method 10-115-01-1-13.
[e]Perkin-Elmer 240 Elemental Analyzer Manual, December 1972 Revision.

DATA REDUCTION

The data for water samples collected monthly from the tributary and estuarine stations were evaluated to determine fluxes of materials (nutrients and solids) from the main tributaries (Perdido, Styx, and Blackwater Rivers, Elevenmile and Bayou Marcus Creeks) to Perdido Bay and to elucidate processes influencing the transport of these materials through Perdido Bay.

Data on water chemistry collected from storm sampling campaigns were used to assess the importance of storm events on the flux of materials to the Bay. The estuarine chemistry data were also coupled with hydrographic data to quantify transport of material through Perdido Bay and to assess what climatologic conditions favored storage or removal.

The monthly dissolved oxygen, salinity and temperature data for Perdido Bay and that collected during the hydrographic campaigns were evaluated separately to describe temporal and spatial variations in dissolved oxygen and to assess how factors such as freshwater discharge, wind, season and tide affect these variations.

The following sections describe methods used to reduce and analyze the data for the objectives described in the introduction to this chapter.

Estimates of Annual Material Flux to Perdido Bay.

The Perdido, Blackwater and Styx Rivers and Elevenmile and Bayou Marcus Creeks are the major sources of freshwater to Perdido Bay. Thus they, (along with the Gulf of Mexico via Perdido Pass, Big Lagoon, and the Alabama Canal at the mouth of the bay), are the major sources of materials, such as nutrients, supplied to the bay.

The flux or load of a chemical substance transported by each of the rivers is simply the product of the chemical concentration and water discharge. Instantaneous values of flux are relatively simple to derive for each river station using measured substance concentrations and instantaneous or daily mean discharge at the time of sampling. It is much more difficult to estimate, with a high degree of accuracy, fluxes over longer periods of time such as a year or more since this requires long term records of concentration (C) and discharge (Q), so that flux (F) can be calculated by integration using the equation:

$$F = \int_0^t CQdt \tag{6.1}$$

It would be simple to calculate fluxes if concentrations of substances were constant over all variations in discharge. This, however, is not the case since the concentrations of virtually all substances, both particulate and soluble, vary with discharge. Nonetheless, several approaches have been used to calculate fluxes with limited data collected over various flow conditions of a watershed. Generally the approaches used involve either extrapolation or interpolation of the data. Both approaches were used in this study and are discussed below.

Extrapolation method for estimating material flux. These procedures attempt to extrapolate the available database by developing rating relationships which link chemical concentrations measured at infrequent intervals to river discharge at the time of sampling. Rating relationships are normally developed for sites with discharge monitoring facilities so that the rating function may be applied to a continuous flow record thus allowing for extrapolation of chemical concentration (and flux) between periods of sample collection. Simple power functions of the form:

$$Concentration = aQ^b \tag{6.2}$$

are used to relate the concentration of a substance and river flow, Q. Such relationships have been routinely documented by many studies. For example, suspended sediments generally show increased concentration with discharge following a relationship described in Equation 6.2 with b being a positive number. In the case of total dissolved solids a similar relationship is observed, but b is often negative (Figure 6.6). Rating relationships or rating curves have been demonstrated for many specific substances, for both natural and anthropogenically disturbed (e.g., agricultural areas) watersheds (Nilsson, 1971; Turvey, 1975; Walling and Webb, 1983; Walling and Kane, 1984).

Although rating relationships for total dissolved solids often exhibit decreasing concentrations with increasing discharge, specific dissolved substances such as nutrients often show increases with discharge (Walling and Webb, 1984; Webb and Walling, 1985).

Rating curves are developed by obtaining concentration data over seasonal variations in discharge for a given watershed. Fitting concentration data to discharge is usually accomplished by least-squares regression techniques. This approach was employed in this study using the individual monthly concentrations of constituents and mean discharge for the station on the day of sample collection using a log transformation of Equation 6.2.

Other authors (e.g., Jansson, 1985) have argued that other methods of curve fitting are more appropriate, and in some cases (e.g., Hall, 1970; Davis and Zobrist, 1978; Foster, 1980), the relationship between concentration and discharge will not be described by a simple power function. Nonetheless, we felt that the approach used in this study (ie., linear regression of log transforms of Equation 6.2) was more appropriate given the limited data set for each station.

Many investigators have stressed the complexity and variability of storm-period sediment and solute responses to discharge (Walling and Foster, 1978; Miller and Drever, 1977; Foster, 1978a,b; Reid et al., 1981; Dupraz et al., 1982; Webb and Walling, 1983; Walling and Webb 1986a,b). Thus it is important to determine concentration relationships to storm related variations in flow. In practice, for a given watershed, separate rating curves are developed for seasonal flow and storm related flow. For this study data collected during storm event campaigns is related to discharge averaged over hourly intervals also using the least squares regression approach.

Once the rating curves were developed, annual flux of a given material by each river was calculated using the following equation,

$$Flux = \sum_{i=1}^{n} aQ_i^{b+1}\Delta t \tag{6.3}$$

where Q_i is the mean daily (hourly from storm event) discharge recorded at the specific stream gage, n = 365 (or the number of 15 minute intervals represented by the storm event), a and b are constants derived from the least square regression analysis of concentration on discharge, and t is the time over which Q_i is averaged.

<u>Interpolation method for estimating material flux</u>. Several interpolation procedures have been used for estimating total loads or fluxes of materials. Five representative numerical procedures are presented in equations 6.4 - 6.8:

$$Total\ Load = K\left(\sum_{i=1}^{n}\frac{C_i}{n}\right)\left(\sum_{i=1}^{n}\frac{Q_i}{n}\right) \tag{6.4}$$

$$Total\ Load = KQ_r\left(\sum_{i=1}^{n}\frac{C_i}{n}\right) \tag{6.5}$$

$$Total\ Load = K\sum_{i=1}^{N}\left(\frac{C_iQ_i}{n}\right) \tag{6.6}$$

$$Total\ Load = K\sum_{i=1}^{n}(C_iQ_p) \tag{6.7}$$

$$Total\ Load = \frac{K\sum_{i=1}^{n}(C_iQ_p)}{\sum_{i=1}^{n}Q_i}Q_r \tag{6.8}$$

where K = conversion factor to take account of period of record,

C_i = instantaneous concentration associated with individual samples, Q_i = instantaneous discharge at time of sampling, Q_r = mean discharge for period of record, Q_p = mean discharge for interval between samples, and n = number of samples.

These procedures make the assumption that the chemical concentration of a water sample is representative of conditions in the river for the period between sampling. These approaches essentially attempt to weight the concentration to discharge. Considerable differences in flux values were generated by the application of the different procedures to our data, thus the two that gave the best agreement were chosen: Equations 6.6 and 6.8. In each case the calculations were carried out using the results from the fourteen monthly samples collected between March 1988 and June 1989. Thus n = 14 and the conversion factor K was adjusted for a discharge record of 12 months.

Determining Behavior of Nutrients and Solids in the Estuary

Advection-diffusion models have been used by many investigators to interpret estuarine chemical data (e.g., Li and Chan, 1979; Kaul and Froelich, 1984). These models use salinity as a tracer. The distribution of a constituent in estuarine waters can be compared to salinity to determine whether a substance is: 1) conservatively transported through the estuary, (2) removed from the water column or (3) added to the water column due to local input (e.g. anthropogenic, release from sediments, etc.). These types of estuarine behaviors are demonstrated in Figure 6.7.

From the advection-diffusion models using salinity as a conservative tracer, the intercept of the extrapolation (or tangent) of the constituent-salinity curve at the high salinity end of the curve, where change in constituent concentration with change in salinity is constant, is defined as the apparent zero salinity end-member (AZE). It can be demonstrated mathematically that river discharge multiplied by the difference in the observed zero salinity concentration and the AZE value gives the rate of

removal, or release, of the constituent per unit time necessary to produce the observed concentration distribution. The only assumption required is that the concentration of the constituent in the freshwater input is constant over the residence time of the estuary. For Perdido Bay, this is assumed to be satisfied sufficiently to draw conclusions.

Following the approach described above, monthly data for concentrations of dissolved nitrate + nitrite (NO_3+NO_2), orthophosphate (PO_4), organic carbon (DOC), and total Kjeldahl nitrogen (TKN); total suspended solids (TSS); and particulate carbon (PC), nitrogen (PN) and phosphorus (PP) were plotted against salinity. The zero salinity concentration was taken to be the mean value of the monthly concentrations observed at the five freshwater stations (PRR, STX, BWR, EMC, BMC) weighted by their mean daily discharge at the time of sampling. This value was then plotted on the constituent vs. salinity curves for each month.

RESULTS

Two sets of data are discussed in this section. The first includes the results of analyses of monthly water samples collected at the five river stations and samples collected during two storm events. The second data set contains the results of the analyses of water samples collected at the estuarine stations.

The discussion of river chemistry results will first address seasonal variations in chemistry. These results will then be combined with river hydrology to describe and quantify fluxes of nutrients and suspended solids to Perdido Bay. Results from samples collected during two storm events will also be discussed with regard to the significance of such episodes on material flux to Perdido Bay.

The discussion of estuarine chemistry will first address seasonal variations in nutrient and suspended solid

concentrations. Following that will be a discussion of mass balance calculations for nutrients in the upper bay to estimate the efficiency of material transport through that system.

General Chemical Characteristics of Streams

Hydrographs for the five streams during the period of study are shown in Figure 6.8 - 6.10. Dates of routine sample collection are shown by arrows. Compared to historical streamflow data for the Perdido River, the sampling appeared to capture a fairly wide range of discharge conditions. Seasonal variations in water temperature, with maximum values of around 25-27°C, were similar for all tributary stations sampled (Figure 6.11). Maximum temperatures occurred during June, July, August and September.

The Perdido and Styx Rivers generally had the highest percent dissolved oxygen (DO) saturation values. Dissolved oxygen saturation values were consistently lower in Elevenmile Creek. Dissolved oxygen in the streams showed only slightly lower saturation values during summer months when water temperatures were highest.

pH varied from less than 5 (observed in the Perdido and Styx Rivers during periods of high discharge and high DOC) to about 7.5. The highest pH values were observed in samples from Elevenmile Creek even though they had the highest DOC concentrations, which is contrary to most natural systems where organic acids account for much of the DOC. The Styx River had the lowest pH during most of the year.

Of the dissolved species analyzed (i.e., DOC, TKN, NO_3+NO_2 and PO_4) only DOC exhibited a distinct seasonal variation in all streams (Figure 6.12). With the exception of Elevenmile Creek, DOC concentrations were similar at all sampling stations and were greatest during high runoff. At Elevenmile Creek DOC concentrations were consistently greater than for the other streams and were lowest during periods of highest runoff.

The other dissolved materials studied showed little seasonal variation with the exception perhaps of NO_3+NO_2, the concentrations of which appeared to be lowest during high discharge. The Perdido River tended to have the lowest NO_3+NO_2 concentrations; Elevenmile Creek had the greatest NO_3+NO_2. Concentrations of TKN, and PO_4 were also highest in samples from Elevenmile Creek.

For the river and creek stations, particulate carbon, nitrogen and phosphorus showed slight concentration maxima during periods of high runoff (Figure 6.13). The exception to this was Elevenmile Creek, samples from which had the highest particulate carbon, nitrogen and phosphorous concentrations with no obvious seasonal maxima.

Elevenmile Creek generally had the largest concentration of total suspended solids. Of the other streams, TSS was usually greatest in the Perdido River, especially during periods of high flow. Occasionally, the Styx River had relatively large TSS concentrations.

In general, with the exception of Elevenmile Creek, the range of values and relationships among chemical constituents were similar to observations of other streams in the southeastern United States (H. Windom, unpublished data).

Chemical Transport to Perdido Bay

As was discussed in the methods section, annual fluxes of dissolved and particulate nitrogen, phosphorus, and carbon and total suspended solids were calculated using two different approaches: extrapolation and interpolation. The first approach is accomplished by developing rating curves and integrating these over the annual hydrographs. For the second approach, two interpolation procedures were used to calculate annual fluxes.

Because the rating curves provide information from which other conclusions can be drawn (ie., they provide information on

relationships between discharge and concentration), the statistical significance of the relationships between measured constituents and streamflow will be discussed first. Following that, annual flux estimates based on both the extrapolation and interpolation approaches will be presented, compared and discussed.

Rating curves. The results of the least square regression fit of the data for the various parameters to discharge are given in Table 6.3. For dissolved constituents, significant rating curves could be established for NO_3+NO_2 and DOC at all of the streamflow gauging locations with the exception of Bayou Marcus Creek. For the other dissolved components, only the Perdido River and Bayou Marcus Creek had significant rating curves for PO_4 and only Elevenmile Creek had a significant rating curve for TKN. The Styx and Bayou Marcus watersheds exhibited significant rating curves for PC; the Styx, Blackwater, and Bayou Marcus watersheds had significant rating curves for PN; the Elevenmile Creek watershed had the only significant rating curve for PP; and the Styx, Blackwater and Elevenmile Creek watersheds had significant rating curves for TSS.

The lack of observed significant rating relationships for PO_4 and TKN generally reflects the more complicated behavior of these dissolved parameters in rivers. For example, it has been demonstrated by Fox (1989) that concentrations of PO_4 in rivers are controlled by inorganic chemical reactions, chiefly involving the formation of iron phosphates. This complicates PO_4 as well as particulate phosphorus variations with discharge since iron is also expected to have a discharge dependent concentration. TKN is a measure of organic nitrogen and ammonia, each of which has its own concentration- discharge relationship, thus complicating the TKN-discharge relationship.

For the relatively limited set of observations (14) it is not surprising that significant rating curves for many constituents could not be developed. Nonetheless the significant

Table 6.3. Rating curve constants[a] and levels of significance.

	NO_3+NO_2			PO_4			TKN		
	b	a	r^2	b	a	r^2	b	a	r^2
PRR[b]	-0.77	5.5	0.80	-1.30	8.4	0.30	0.15	-3.0	0.08
STX	-0.63	4.3	0.84	0.07	-4.5	0.01	0.24	-3.7	0.06
BWR	-1.04	7.4	0.70	-0.24	-1.4	0.13	0.20	-2.8	0.11
EMC	-0.68	5.4	0.47	-0.22	0.3	0.05	-0.65	5.7	0.43
BMC	-0.40	1.7	0.19	-0.95	2.5	0.40	-0.35	1.0	0.10

	DOC			PC			PN		
	b	a	r^2	b	a	r^2	b	a	r^2
PRR	0.64	-4.8	0.57	0.16	-2.1	0.07	0.29	-5.8	0.12
STX	0.57	-3.7	0.74	0.46	-4.7	0.65	0.38	-6.5	0.49
BWR	0.79	-4.9	0.75	-0.03	-0.5	0.01	0.74	-9.0	0.41
EMC	-0.54	8.0	0.82	-0.07	1.7	0.01	-0.17	0.47	0.02
BMC	0.57	3.0	0.28	0.48	-4.2	0.57	0.68	-8.1	0.39

	PP			TSS		
	b	a	r^2	b	a	r^2
PRR	0.36	-8.1	0.21	0.48	-3.0	0.19
STX	0.35	-8.1	0.20	0.93	-6.7	0.48
BWR	-0.15	-4.0	0.02	-0.20	2.5	0.03
EMC	-0.35	0.27	0.29	0.65	-2.0	0.54
BMC	0.48	-8.2	0.12	0.98	-5.7	0.29

[a]Constants are for the equation of the form $\ln C = b \ln Q + a$, where C = concentration and Q = stream discharge. Underlined values of r^2 are significant at $P < .05$.

[b]PRR = Perdido River, STX = Styx River, BWR = Blackwater River, EMC = Elevenmile Creek, BMC = Bayou Marcus Creek.

rating curves developed for DOC and NO_3+NO_2 for most of the watersheds are useful for predicting future loadings as well as for estimating fluxes over the period for which the data were gathered. In addition, these rating curves allow us to draw further conclusions on the nature of the discharges of materials from the different watersheds. For example, the rating curves for DOC were similar for all of the watershed except Elevenmile

Creek (Figure 6.14). The slopes of the rating curves for the Perdido, Styx and Blackwater Rivers and Bayou Marcus Creek were all positive whereas the Elevenmile Creek DOC rating curve had a negative slope. This indicates that the concentration of DOC in Elevenmile Creek water is diluted as discharge increases, suggesting a dominant unnatural source of DOC.

Riverine flux. Although the rating curves provide an evaluation of the results of the stream nutrient concentration data, they are overall of limited use for riverine flux estimates. Thus we use interpolation methods for this purpose, as discussed below, along with the extrapolation method when results using this procedure agree with those of the interpolation procedure.

The annual fluxes of dissolved nitrate + nitrite, phosphate, total Kjeldahl nitrogen, organic carbon; particulate carbon, nitrogen and phosphorous; and total suspended solids from the four watersheds emptying into Perdido Bay were estimated using the three methods described in the water chemistry data reduction section. In general, the results of all three methods agreed well (Table 6.4). The only exceptions were six cases where the extrapolation method gave results considerably higher than the two interpolation methods. Excluding these six results, the estimates of fluxes for each constituent for each watershed were used to calculate mean annual fluxes. With one exception (PO_4 for the Perdido River), the coefficient of variation for the different estimates of flux was less than 20%.

The total fluxes of the various constituents due to discharges from all watersheds are presented in Table 6.5. The relative contribution to these fluxes from each stream are also given in this table. In general, Elevenmile Creek accounted for around 30% of the total flux of all the constituents while it only accounted for 8% of the total freshwater inflow. Total fluxes given in Table 6.5 are conservative estimates of the amount of material delivered to

Table 6.4. Annual riverine fluxes to Perdido Bay (kg yr^{-1}).

River[a]	Met[b]	NO_3+NO_2 (10^4)	PO_4 (10^3)	TKN (10^5)	DOC (10^6)	PC (10^5)	PN (10^4)	PP (10^3)	TSS (10^6)
PRR	1	6.2	7.8	(4.4)[c]	3.0	3.2	(2.9)	6.2	3.3
	2	6.1	12.1	1.4	3.6	3.1	3.1	7.2	3.5
	3	7.2	8.8	1.6	4.2	4.0	3.8	8.7	4.5
	Mean	6.5	9.5	1.5	3.6	3.5	3.4	7.4	3.8
	sd	±0.6	±2.2	±0.2	±0.6	±0.6	±0.5	±1.2	±0.6
STX	1	7.0	8.3	1.0	2.5	3.2	2.4	3.6	(5.9)
	2	7.0	9.8	1.2	2.4	3.0	2.4	3.9	3.8
	3	7.2	8.4	1.2	2.5	3.4	2.5	4.6	2.9
	Mean	7.1	8.8	1.1	2.5	3.2	2.4	4.0	3.3
	sd	±0.1	±0.9	±0.1	±0.1	±0.2	±0.1	±0.5	0.6
BWR	1	4.1	3.7	0.4	(1.7)	0.6	(1.8)	0.6	0.3
	2	5.6	4.4	0.4	0.6	0.5	0.9	0.7	0.3
	3	4.6	3.6	0.3	0.5	0.5	0.7	0.7	0.3
	Mean	4.8	3.9	0.4	0.6	0.5	0.8	0.7	0.3
	sd	±0.8	±0.4	±0.1	±0.1	±0.1	±0.1	±0.1	±0.01
EMC	1	7.8	19.3	1.3	3.2	2.5	3.9	7.0	2.5
	2	8.0	19.1	1.1	3.1	2.5	4.1	6.8	3.0
	3	8.9	21.3	1.3	3.4	3.1	4.4	7.6	3.3
	Mean	8.2	19.9	1.3	3.3	2.7	4.1	7.1	3.2
	sd	±0.6	±1.2	±0.1	±0.2	±0.3	±0.2	±0.4	±0.2
BMC	1	1.1	0.5	0.07	0.1	0.1	(0.7)	0.3	0.1
	2	1.1	0.6	0.08	0.1	0.1	0.1	0.4	0.1
	3	1.1	0.6	0.09	0.1	0.1	0.1	0.4	0.1
	Mean	1.1	0.6	0.08	0.1	0.1	0.1	0.4	0.1
	sd	±0.05	±0.1	±0.01	±0.01	±0.01	±0.0	±0.06	±0.01

[a]PRR = Perdido River, STX = Styx River, BWR = Blackwater River, EMC = Elevenmile Creek, BMC = Bayou Marcus Creek.

[b]Calculation methods described in data reduction section.
1 = extrapolation, 2 = interpolation (Equation 6.6),
3 = interpolation (Equation 6.8).

[c]Numbers in parentheses not included in calculation of means.

Perdido Bay because we have not considered smaller sources of materials such as direct surface runoff and contributions downstream of the riverine sampling stations. We also have not considered removal processes that may be occurring downstream of the gauging sites.

When the fluxes of material from Elevenmile Creek are compared to those from the other watersheds in the Perdido River basin, the former appears to be considerably larger than one would expect given the relative freshwater discharge and the drainage basin size of Elevenmile Creek. This is even more apparent when the fluxes of given constituents for each watershed are compared to their mean freshwater discharge (Figure 6.15).

Table 6.5. Major annual material fluxes to Perdido Bay from freshwater runoff.

Material	Total Flux (metric tons yr^{-1})	Contribution (%) from PRR[a]	STX	BWR	EMC	BMC
Dissolved						
Nitrate + Nitrite	277	23	26	17	30	4
Phosphate	43	22	21	9	47	1
Total Kjeldahl Nitrogen	438	34	25	9	30	2
Organic Carbon	10,100	35	25	6	33	1
Particulate						
Carbon	1,000	35	32	5	27	1
Nitrogen	108	32	22	7	38	1
Phosphorus	20	38	20	4	36	2
Suspended Solids	10,700	35	31	3	30	1

[a]PRR = Perdido River, STX = Styx River, BWR = Blackwater River, EMC = Elevenmile Creek, BMC = Bayou Marcus Creek.

There appears to be a systematic trend between material flux and discharge for all of the watersheds except Elevenmile Creek. If it is assumed that the natural features (i.e. relief,

vegetation, cover, soils, etc.) are similar, and that, under "natural" conditions, total chemical flux is proportional to discharge, then for each constituent shown in Figure 6.15 a line drawn from Perdido River data point to the origin (no flow, no flux) represents naturally expected constituent concentrations. For all measured constituents, the plotted point from Elevenmile Creek lies well above that line, indicating unnatural concentrations of nutrients in Elevenmile Creek. For several constituents (DOC, TKN, PN) points from the remaining streams all fall reasonably close to that line. There is some indication that the Styx and Blackwater Rivers and Bayou Marcus Creek are affected by agriculture or urban development. The Styx and Blackwater Rivers appear to have slightly higher than expected levels of NO_3+NO_2 and PO_4, perhaps from agricultural runoff. Bayou Marcus Creek appears to have excess NO_3+NO_2 which could result from urban development in the watershed.

Following this line of reasoning, the flux of materials that exceeds the expected natural flux can be estimated. We have done this for Elevenmile Creek where the data clearly indicates substantial unnatural fluxes of materials. This is accomplished by calculating the additional flux of a given constituent necessary to move the data point for Elevenmile Creek off the systematic trend observed between flux and discharge for the other watersheds. The results of such calculations are given in Table 6.6.

Water samples were collected at each of the five gauging stations during two separate storms to assess the importance of material flux during these events. The variations in discharge at each gauging station during these storms are shown in Figure 6.16 - 6.18. Comparing these storm hydrographs to the annual hydrographs shown in Figure 6.8 - 6.10 indicates that the first storm was relatively small. The second storm, however, represents about the average intensity of storms that occur throughout the year.

Table 6.6. Estimate of material fluxes above expected natural levels from Elevenmile Creek into Perdido Bay.

Material	(metric tons yr^{-1})
Dissolved	
Nitrate + nitrite	48
Phosphate	17.5
Total Kjeldahl nitrogen	95
Organic carbon	2800
Particulate	
Carbon	210
Nitrogen	36
Phosphorus	6.2
Suspended Solids	2700

Approximately 9 samples from each gauging site were analyzed for the first storm and 10 for the second, spaced throughout the rising, peak, and falling portions of storm hydrographs. Results of analyses of these samples were used along with the hydrographic data to estimate fluxes during each storm. The interpolation method was used to make these estimates; results are shown in Figure 6.19.

A comparison of the estimated daily fluxes of materials during storms to the average daily flux for the year yield the following conclusions:

1. For dissolved organic carbon (not analyzed in samples collected from the first storm), inorganic nitrogen species, and all particulate materials there is little difference in material flux during storms as compared to average conditions. Elevenmile Creek, however, is an exception.
2. Fluxes of dissolved phosphate are significantly greater during the second storm period for all of the gauging stations.

3. Fluxes of TKN are less during storms.
4. Fluxes of all particulate materials are greater during storm events than during normal discharge conditions in Elevenmile Creek.

Estuarine Nutrient Chemistry

The changing chemical and physical conditions encountered in estuaries along the salinity gradient (ie., from freshwater to saltwater) may lead to changes in the solubility of substances such that they may be removed from solution to particles or may be leached from particles into solution. Chemical precipitation of substances may lead to the formation of particles which are preferentially removed from the water column during transport through estuarine systems. The effect of these processes can be evaluated from constituent-salinity relationships as discussed earlier. The results of the analyses of dissolved and particulate nutrients in estuarine samples are plotted against salinity in Appendix D. Comparing the weighted freshwater concentration of a substance to its concentrations at higher salinities provides a basis for judging estuarine behavior of the substance. For this purpose a line is subjectively drawn through the data for concentration versus salinity connecting weighted mean freshwater concentration to concentration at highest salinity and interpreted as in Figure 6.7. Data at lowest salinities sometime fall below the lines because these samples were collected in the mouth of the Perdido River and are biased by that freshwater source. Also, samples collected in Soldier Creek (SD) and Palmetto Creek (PM) are indicated since they may be influenced by other local inputs. Taking into account the above, the following discussion summarizes the behavior of the nutrients based on their estuarine distributions.

Dissolved and particulate carbon. The estuarine distribution of DOC indicates that DOC was removed from the water (ie., either chemically broken down or incorporated into particles) column in the upper part of Perdido Bay during March through June 1988 and November 1988 through May 1989. During

July through October 1988 DOC was mixed relatively conservatively. This was the higher discharge period and thus residence time in the upper bay was shortest. Conversely, PC was generated or conservatively mixed in the bay during most of the study period.

Dissolved and particulate nitrogen. NO_3+NO_2 was removed during estuarine transport throughout Perdido Bay between March and November 1988. This period of removal was followed by a period of more or less conservative transport in the upper bay and perhaps some removal in the lower bay between December 1988 and February 1989, periods of lowest production. NO_3+NO_2 removal occurred again throughout the estuary from April - June 1989. TKN distribution generally appeared to be conservative although the values were scattered.

Particulate nitrogen was enriched in the water column throughout Perdido Bay during most of the year. Concentrations were highest in bottom waters during stratified conditions which may be the result of sediment resuspension and/or settling of plankton detritus. Presumably, biogenic formation of particulate nitrogen in the upper part of the water column was responsible for the observed removal of NO_3+NO_2. Relatively high chlorophyll concentrations, indicating high phytoplankton biomass, have been measured in the upper bay (David Flemer, personal communication).

Dissolved and particulate phosphorus. Like nitrate, dissolved phosphate was removed from the water column during most of the year. This removal took place in the upper half of the bay. The rest of the bay experienced very little variation in phosphate.

Particulate phosphorus was produced in the estuary most of the year. Occasionally, particulate phosphorus was relatively conservative with highest values observed in the lower half of the bay, perhaps due to sediment resuspension.

Nutrient Mass Balance in Perdido Bay

The following mass balance calculations for carbon, nitrogen and phosphorus are an attempt to assess whether or not there was significant storage of nutrients in Perdido Bay over an annual cycle. The calculations assume that the system was in steady state (averaged over the year) and that the only significant inputs of nutrients and freshwater are from the five gauged tributaries which empty into the upper bay.

Perdido Bay can be divided into a two-box model. The first box is the upper bay above highway US 98 and the second box is the lower bay below the highway. Using freshwater as a tracer of conservative substances (i.e. those which are not removed or formed within the system or boxes) the residence time, T, of conservative materials can be calculated for the upper bay using the equation,

$$T = \frac{V_{fw}}{Q} \tag{6.9}$$

where V_{fw} is the volume of freshwater in the upper bay and Q is the total discharge for the rivers. A similar calculation can be made for the lower bay. However, the practical utility of this approach for the lower bay is somewhat questionable because of the additional complexities introduced by tidal circulation across multiple boundaries (ie. mouth of bay and Alabama Canal).

From the results of the seasonal field studies of Perdido Bay the volume of freshwater in the upper and lower bays can be estimated from salinity measurements. Thus for each period for which field data are available the numerator of Equation (6.9) can be estimated and the denominator can be obtained by averaging the discharge, from the hydrographs (Figure 6.8), over a period approximately equal to T prior to the time of data collection. By iterative calculations the value of T calculated for each period of time over which Q is averaged will become equal.

By this process, the variation in residence time of freshwater in upper and lower Perdido Bay was estimated for each sampling period included in the study (Figure 6.20). The observed seasonality was dominated by variation in runoff as expected from the assumptions upon which this analytical approach is founded. However, the inconsistent correlation of these results during portions of the year also serves to demonstrate the significance of the other factors influencing transport processes in the bay, namely wind and, to a lesser degree, tide.

The mass balance of nutrients can be estimated by first assuming that they behave conservatively, thus their residence time, T_i, for a sampling period i, would be the same as for freshwater. If such is the case, then the total content of a given nutrient in the upper bay, C_{ub}, would be approximately given by the following equation,

$$C_{ub} = T_i C_u Q_i \tag{6.10}$$

where C_u is the composite concentration of the nutrient in the freshwater input from the rivers during sampling period i and Q_i is the mean freshwater discharge for the period. C_{ub} can also be estimated from the results of the estuarine samples collected during each sampling period i. The difference between the observed and calculated C_{ub} implies either a deficiency or an excess in the given nutrient. In other words, an additional input or removal term must be added to Equation (6.10). This additional input or removal is needed to balance the input for each sampling period. A plot of the excess or deficit can then be integrated over the annual cycle to estimate the net excess or deficiency of the nutrient in the upper bay. Similar mass balance estimates were attempted for the lower bay but results indicated additional significant inputs of nutrients, presumably through CT3 and CT4. Thus, the assumption used in the mass balance calculations for the upper bay were clearly not met in the lower bay. Net budgets for nutrients in the upper bay can be calculated as follows.

Carbon. The integrated dissolved organic carbon content of the upper bay indicates that there was a 1.3×10^6 kg loss over the annual cycle during the study period. For particulate carbon there was an excess of about 0.1×10^6 kg, which could be due to primary production, secondary production, or adsorption of organic carbon to particles. However, most of the deficiency in carbon, ca., 1.2×10^6 kg, must be explained by removal to upper bay sediments and oxidation to CO_2. The carbon removed in the upper bay represents 10% of the total annual organic carbon input to the bay by rivers (Table 6.5). This will be further considered with regard to dissolved oxygen consumption in a subsequent section.

Nitrogen. Over the annual cycle there was a 1.4×10^5 kg deficiency in NO_3+NO_2 nitrogen in the water column of the upper bay. During this time, 0.6×10^5 kg of excess TKN was produced along with about 0.6×10^5 kg of particulate nitrogen. This resulted in a net deficit of about 2×10^4 kg of nitrogen, representing about 2.5% of the 8.23×10^6 kg of nitrogen supplied to the upper bay and certainly within the error of the estimate. Thus, it is concluded that, over a year, no significant part of the nitrogen supplied by the rivers accumulated in the upper bay.

Phosphorus. A 1.2×10^4 kg PO_4 phosphorus deficiency was estimated for the annual cycle in the upper bay. In the case of particulate phosphorus there was a 0.9×10^4 kg gain. Here again, the difference (3×10^3 kg) is less than 5% of the 6.3×10^5 kg of phosphorus transported to the upper bay. Thus, phosphorus inputs to the bay were also not significantly stored there.

Estuarine Dissolved Oxygen

Vertical profiles of dissolved oxygen and salinity from the hydrographic campaigns in June, August, and November 1988 and February and June 1989 are given in Appendix E. Vertical profiles of dissolved oxygen at stations along the axis of the

bay, sampled at monthly intervals (March 1988 to June 1989) are given in Appendix F.

These results clearly indicate that Perdido Bay often experiences density stratification, which results in dissolved oxygen stratification as well. Such conditions often lead to bottom water hypoxia.

The results of the seasonal assessment of dissolved oxygen conditions in Perdido Bay, given in Appendix F, are summarized in Figure 6.21. In this figure the difference between the surface and bottom-most water dissolved oxygen are represented by the width of shading. These results indicate the following general trends:

1. During the winter (December through March) oxygen stratification and bottom water depletion were minimal throughout the bay although surface DO during December was only about 80% saturated.
2. During the spring (April through May) DO stratification was detected in the upper and lower bays.
3. During the summer (June through September) DO stratification was pronounced in the upper and lower bay with extreme hypoxia bordering on anoxia in the lower bay.

There are, of course, other features that add complexity to the simple seasonal scenario described above (eg., sediment oxygen demand, water column respiration), but most of the DO variability appears to be advectively dominated as demonstrated by the covariance of DO and salinity. Dissolved oxygen was inversely correlated to salinity for data sets for each month. Only the slope of the regression curves are different between months.

Schroeder and Wiseman (1988) report similar DO stratification in Mobile Bay and indicate that the condition there is advectively controlled. Due to the paucity of

hydrographic data, however, these authors were unable to elucidate the specific advective processes that dominate the stratification. Fortunately, for the Interstate Study of Perdido Bay, extensive hydrographic data are available. These data, discussed in the next section, give some insight about the conditions conducive to stratification and consequent hypoxia.

Controls on Dissolved Oxygen

From Chapter 4 (Sediment Chemistry) it can be concluded that toxic pollutants are probably not a significant problem today in Perdido Bay. Low dissolved oxygen, on the other hand, is not only perceived as a problem but has been documented to occur on a regular basis in the bay. Because of the insidious nature of the contributing causes of decreased dissolved oxygen, this problem is not as easily managed by existing environmental regulations as, for example, are toxic discharges.

Periodic hypoxic conditions in the bay are clearly influenced, and perhaps dominated by natural conditions, but anthropogenic inputs of oxygen demanding materials and nutrients contribute to the problem. In this section, the processes that contribute to dissolved oxygen conditions in Perdido Bay will be discussed and summarized. An attempt is made to break down the causes of decreased oxygen or hypoxia into specific categories so that a better basis for developing management strategies might result.

In general, the causes for decreased dissolved oxygen can be divided into two basic categories, chemical and physical. Chemical processes directly and indirectly determine how and in what quantities dissolved oxygen is consumed. Physical conditions (e.g., tides, winds freshwater discharge) generally influence the rate at which the chemical processes proceed.

Chemical processes. In Perdido Bay, the major process leading to dissolved oxygen consumption is the oxidation of

organic matter. Both allochthonous and autochthonous[1] organic matter are involved.

In previous sections, budgets for carbon and nutrients were discussed. It was calculated that 1.3×10^6 kg of dissolved organic carbon was removed from the water column in the upper bay. This organic carbon is part of the allochthonous organic matter transported into the bay from runoff. An additional amount of autochthonous organic matter is produced in the upper bay by primary production. If all of the removed inorganic nitrogen (NO_3+NO_2) in the upper bay (i.e., 1.4×10^5 kg yr^{-1} is converted to plant detritus having a C:N ratio of 10 (due to the "fixing" of inorganic carbon) then the amount of additional autochthonous organic carbon that is produced is 1.4×10^6 kg yr^{-1}. Of the particulate organic carbon produced, 0.1×10^6 kg yr^{-1} can be accounted for by the excess particulate carbon estimated from the mass balance calculation discussed previously. The rest (1.3×10^6 kg yr^{-1}) and the 1.3×10^6 kg yr^{-1} of dissolved organic carbon removed in the upper bay must be accounted for by removal to bottom sediments and by oxidation to CO_2.

The total annual input of suspended sediments to the upper bay was determined to be 10,700 metric tons. The supply of sediments to the upper bay could easily be double this amount due to direct inputs, inputs downstream of the gaging stations, bed load transport and exchange with the lower bay. Therefore, we can conservatively estimate that the total sediment input to the upper bay is 25,000 metric tons per year. This sediment has an average organic carbon content of about 4.5%. Thus, 1.1×10^6 kg yr^{-1} of organic carbon could be accommodated here. This leaves 1.5×10^6 kg of organic carbon to be accounted for annually.

---

[1]Allocthonous - brought to the system from elsewhere. For example, material transported by rivers.
Autochthonous - produced in the system. For example, organic matter produced by primary production.

Some organic carbon entering the bay is undoubtedly refractory lignin-carbon from pulp mill wastewater and other sources and is deposited in the sediments. We did not attempt to determine the percentage of refractory material. Nevertheless, we can reasonably assume that oxidization accounts for much of the remaining carbon.

If it is assumed that the excess 1.5×10^6 kg of organic carbon is accounted for by the following oxidation process:

$$C_{org} + O_2 \rightarrow CO_2$$

where 2.7 g of oxygen are consumed for every gram of carbon oxidized, then a total of 4×10^6 kg of dissolved oxygen is therefore required to oxidize the organic carbon that is not accounted for by burial in upper bay sediments.

The estimated amount of dissolved oxygen necessary to oxidize the organic carbon can be compared to the estimated dissolved oxygen budget for the upper bay. This budget is calculated by plotting the oxygen deficit, shown in Figure 6.22, divided by the residence time calculated for a conservative property (Figure 6.20), against month. Results of this calculation are shown in Figure 6.23. By integrating the apparent oxygen utilization rate for the upper bay over a year, corresponding to the time over which the carbon budget was estimated, the total annual dissolved oxygen utilization is estimated to be 3.9×10^6 kg. This is in excellent agreement with the amount of oxygen needed to oxidize the organic carbon not buried in upper bay sediments (4×10^6 kg).

The annual oxygen utilization for the lower bay was estimated to be about 3.5×10^6 kg. By dividing the annual apparent oxygen utilization of the upper bay and lower bay by their volumes (4.7 and 12.8×10^7 m^3, respectively) it is apparent that the rate of oxygen utilization in the upper bay is about four times that in the lower bay.

While the above discussion and calculations are a simple representation of complex nutrient, carbon and oxygen cycles in Perdido Bay, they nonetheless serve to demonstrate important aspects of the chemical processes that influence dissolved oxygen variability in the bay. A main conclusion is that at the present time nutrient inputs and inputs of organic carbon have about an equal control on oxygen depletion in the bay.

Physical processes. The rates at which the chemical processes described above proceed are controlled by physical conditions in the bay. Physical conditions control the rate at which oxygen diffuses into and through the water column, mixing of material in the water column and input and exchange of materials. Input and exchange are controlled by freshwater inflow, wind, and, to a lesser extent, tide. This section will attempt to summarize the influence of physical conditions on diffusion and the mixing of dissolved oxygen using information gained during this project. While the discussion of chemical processes was based primarily on data from the upper bay, data throughout the bay are useful in considering effects of physical conditions.

In general, seasonal variations in physical conditions such as freshwater input, tidal range and winds control stratification or mixing of the water column. Stratification, in turn, controls the rate at which dissolved oxygen diffuses into and through the water column to be available for oxidation of organic matter. During the course of this project, detailed analysis of the dissolved oxygen and salinity distribution in the bay was carried out, as a part of hydrographic studies, during different climatic and seasonal conditions. Dissolved oxygen and salinity profiles are presented in Appendices E and F.

Observed dissolved oxygen is plotted against salinity in Figure 6.24 for the five hydrographic campaigns conducted during this project. These results will be discussed in relation to observed wind and tidal conditions and freshwater discharge.

During the June 1988 hydrographic campaign, freshwater runoff was relatively low and winds were generally light and variable, and the tidal range was below the average. The linear relationship between dissolved oxygen and salinity during this time indicates stratification which is greatest in the upper bay where lowest dissolved oxygen is observed in bottom waters. Stratification is still obvious in the lower bay but bottom waters are not as depleted in dissolved oxygen.

Results from the August campaign indicate that the entire bay is stratified owing to the effects of relatively high runoff, spring tides and light winds. The high runoff and large tidal range lead to large top-to-bottom salinity gradients throughout the bay. The dissolved oxygen-salinity relationship (concave curvature) indicates a relatively stable stratification that has allowed oxygen consumption to proceed in bottom waters while cutting off oxygen supply from the surface.

Later in the year (November), strong southerly winds, low runoff and smaller tides conspire to enhance better mixing. This leads to a flatter dissolved oxygen-salinity curve, indicating less stratification everywhere except the upper bay.

Strong north winds during the winter (February 1988), low freshwater input, and low water temperatures continue to reduce stratification by improving mixing resulting in smaller salinity and dissolved oxygen variation throughout the bay. Low temperatures in winter probably also limit biological oxygen consumption.

During June 1989, heavy rains resulted in a large freshwater inflow into the upper bay. This led to lower dissolved oxygen in the upper bay because of increased organic carbon input and lower dissolved oxygen associated with the freshwater. The rest of the bay was still stratified although some of the stratification was beginning to break down due to the increased freshwater input.

These results suggest that during periods of relatively high freshwater discharge (but after peak discharge season), spring tides and light winds, stratification exists throughout the bay. These physical conditions are most conducive to oxygen depletion in the bay. Periods of low discharge and high winds (either southerly or northerly), however, favor mixing. During such periods the bay is less susceptible to the development of low dissolved oxygen conditions.

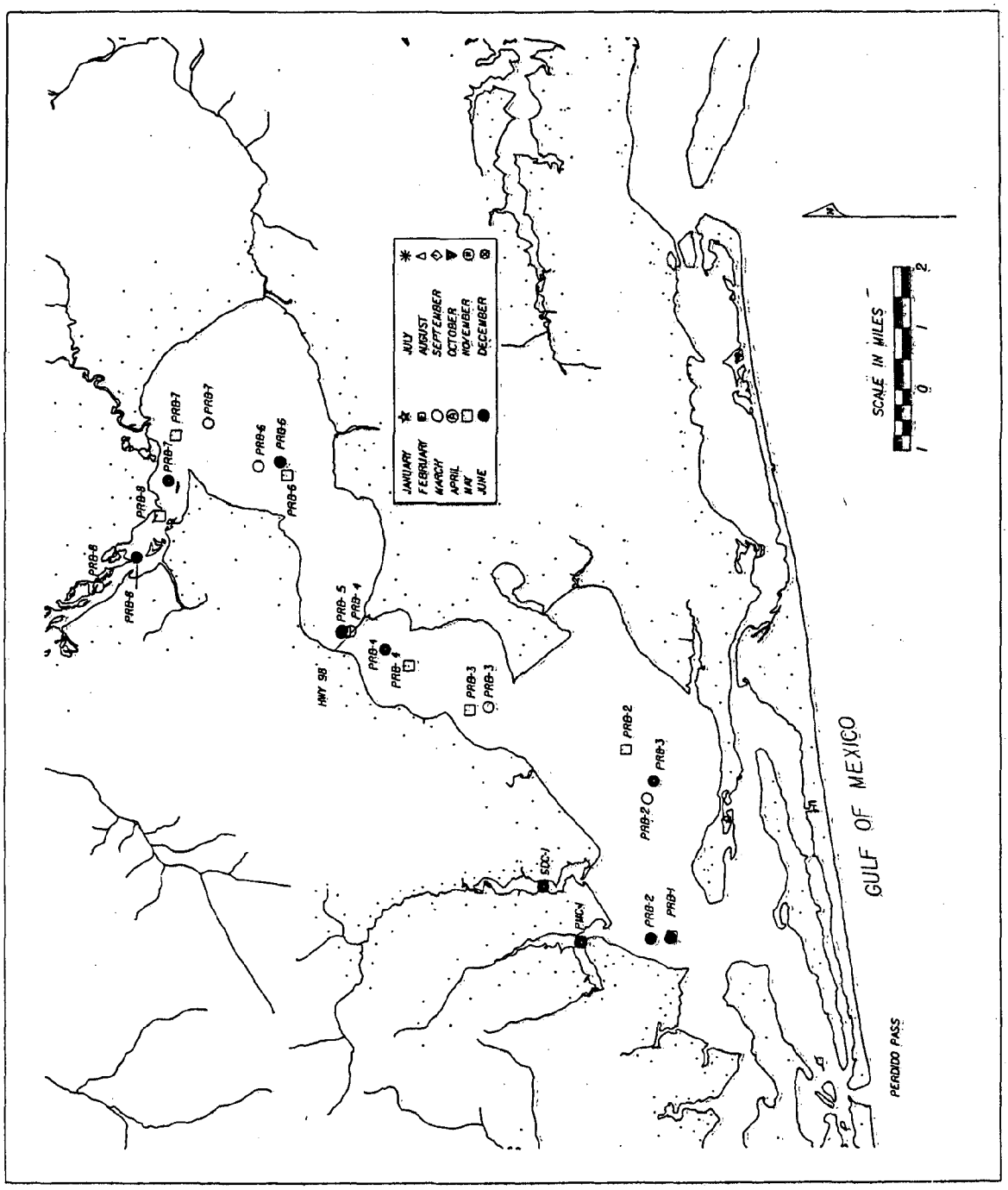


Figure 6.1. Estuarine sampling stations, March - June, 1988.

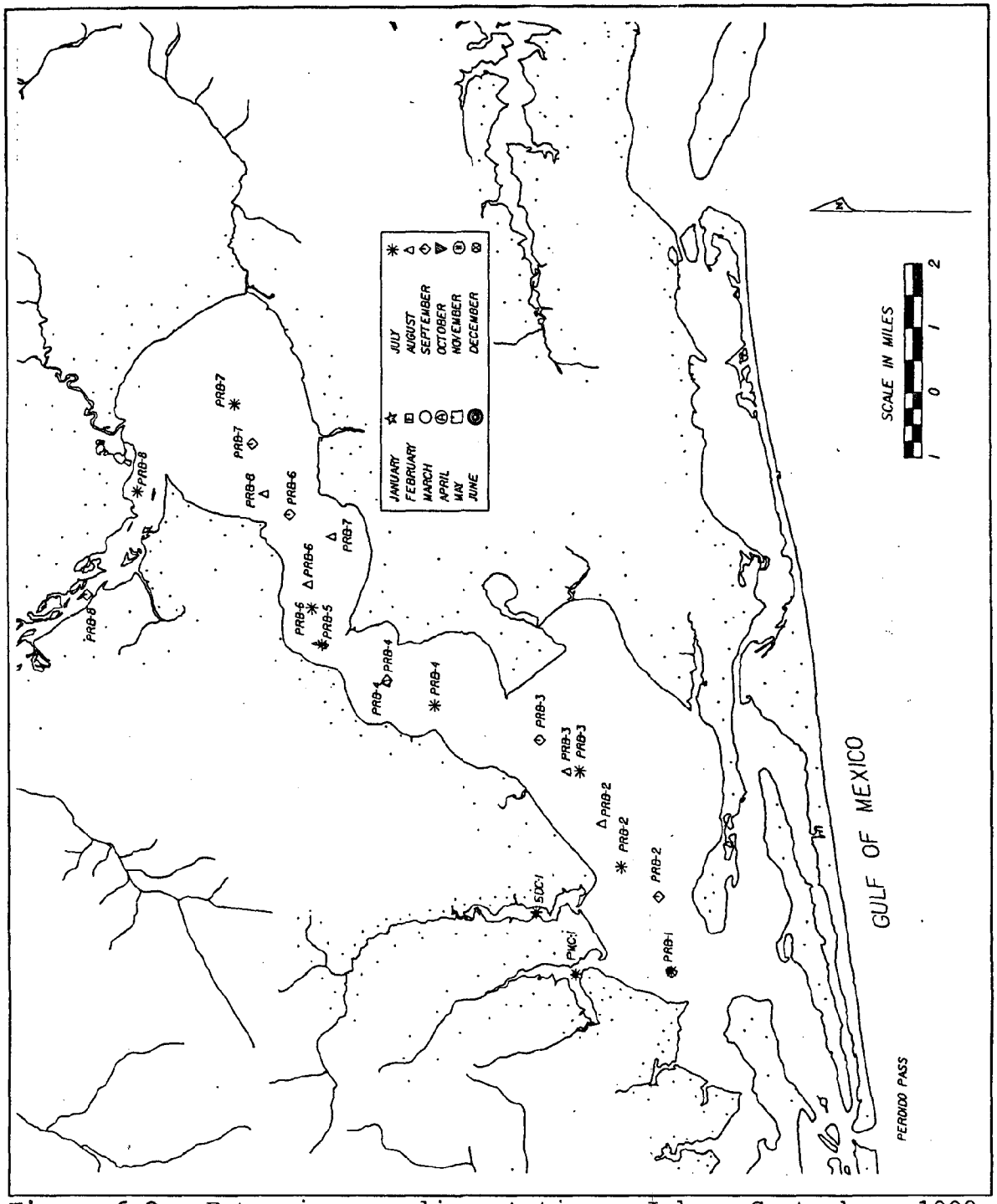


Figure 6.2. Estuarine sampling stations, July - September, 1988.

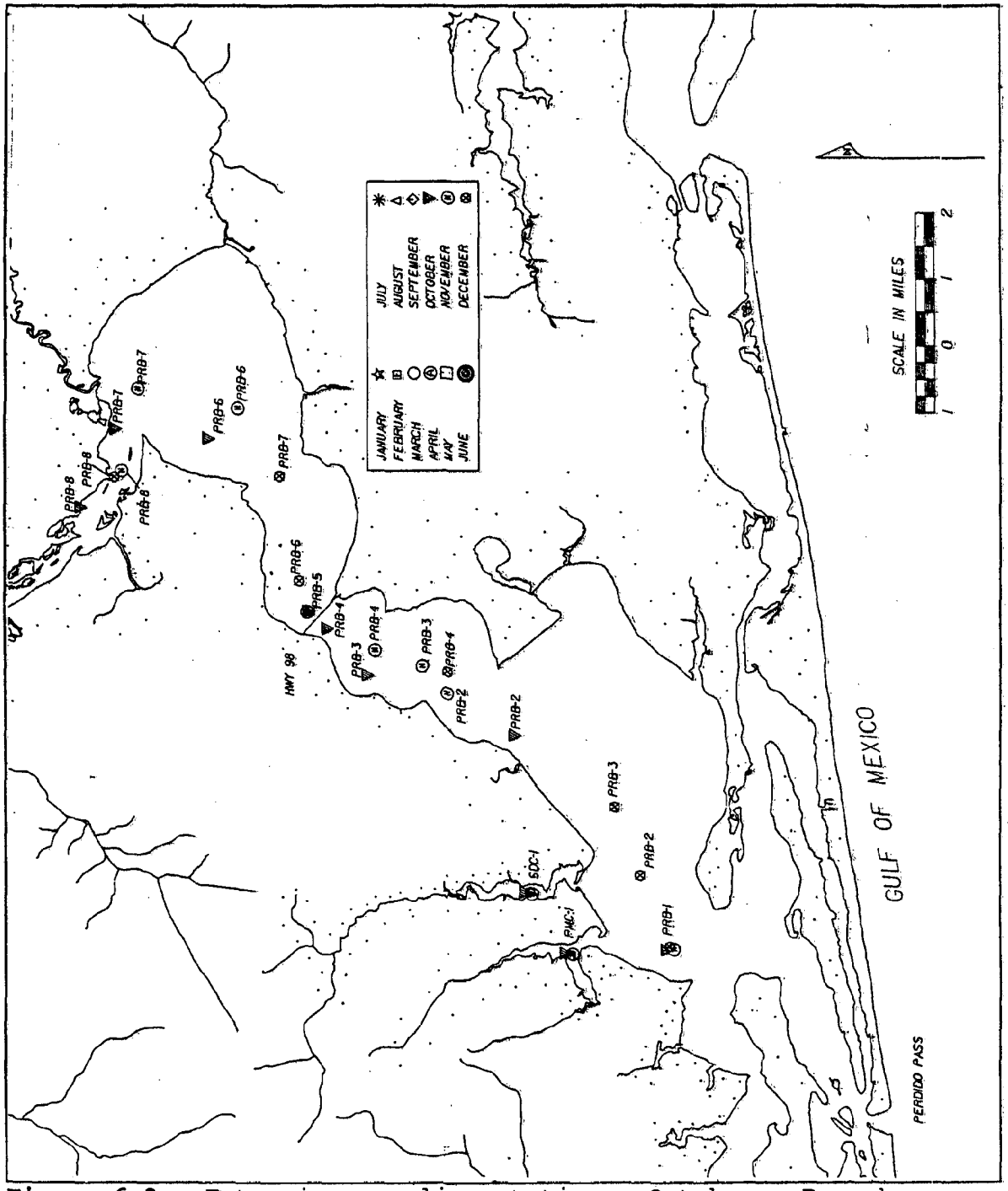


Figure 6.3. Estuarine sampling stations, October - December 1988.

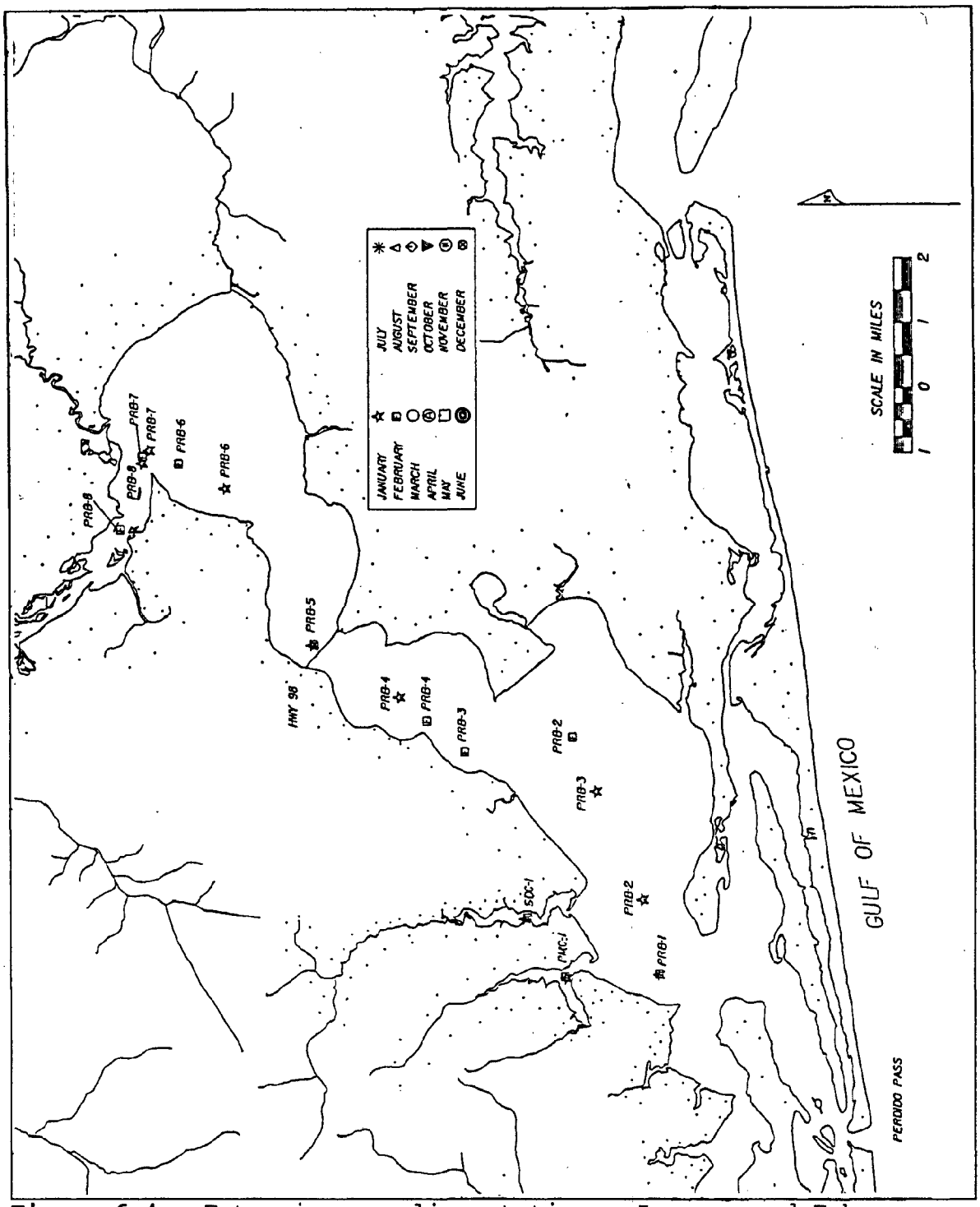


Figure 6.4. Estuarine sampling stations, January and February, 1989.

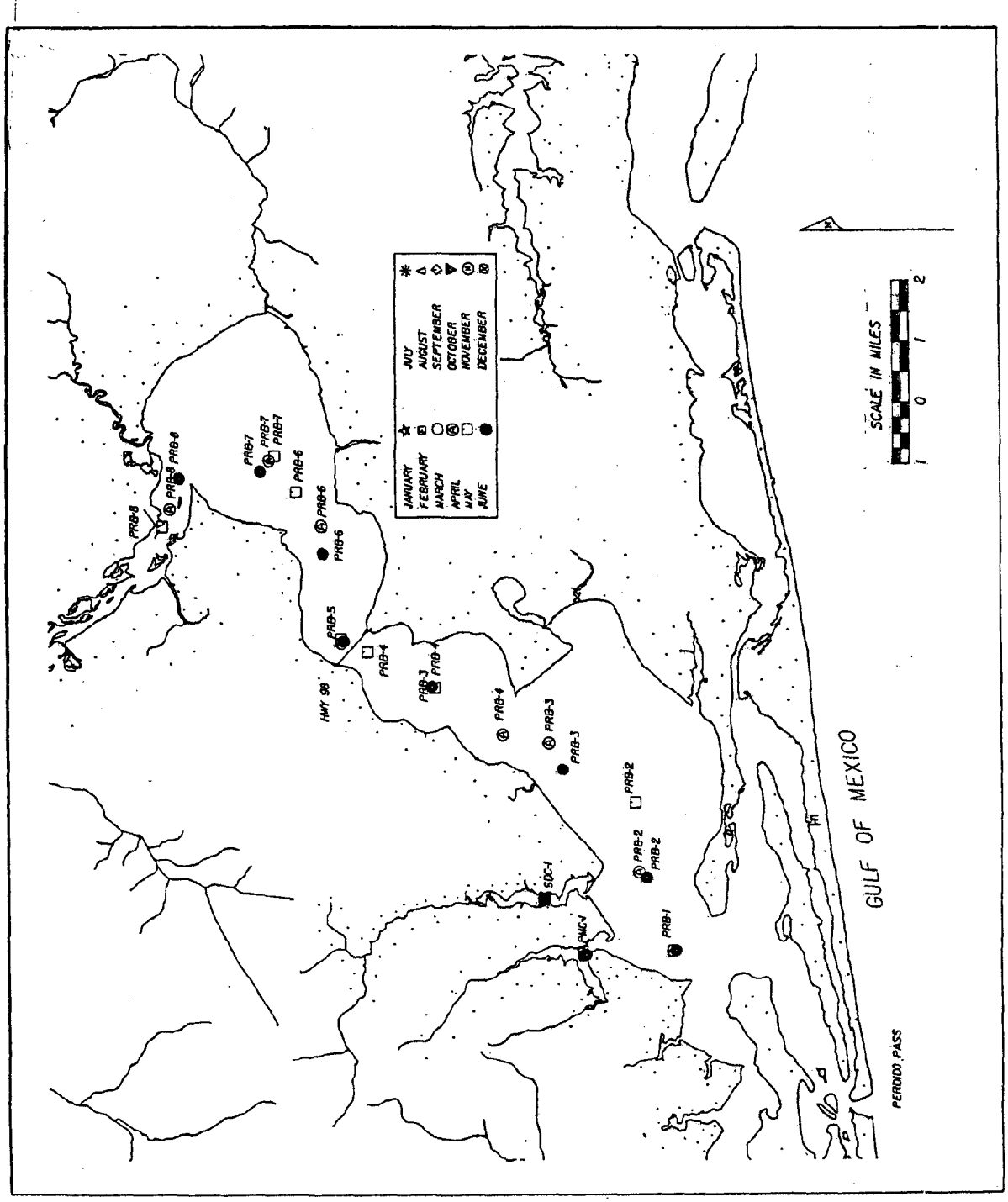


Figure 6.5. Estuarine sampling stations, April - June 1989.

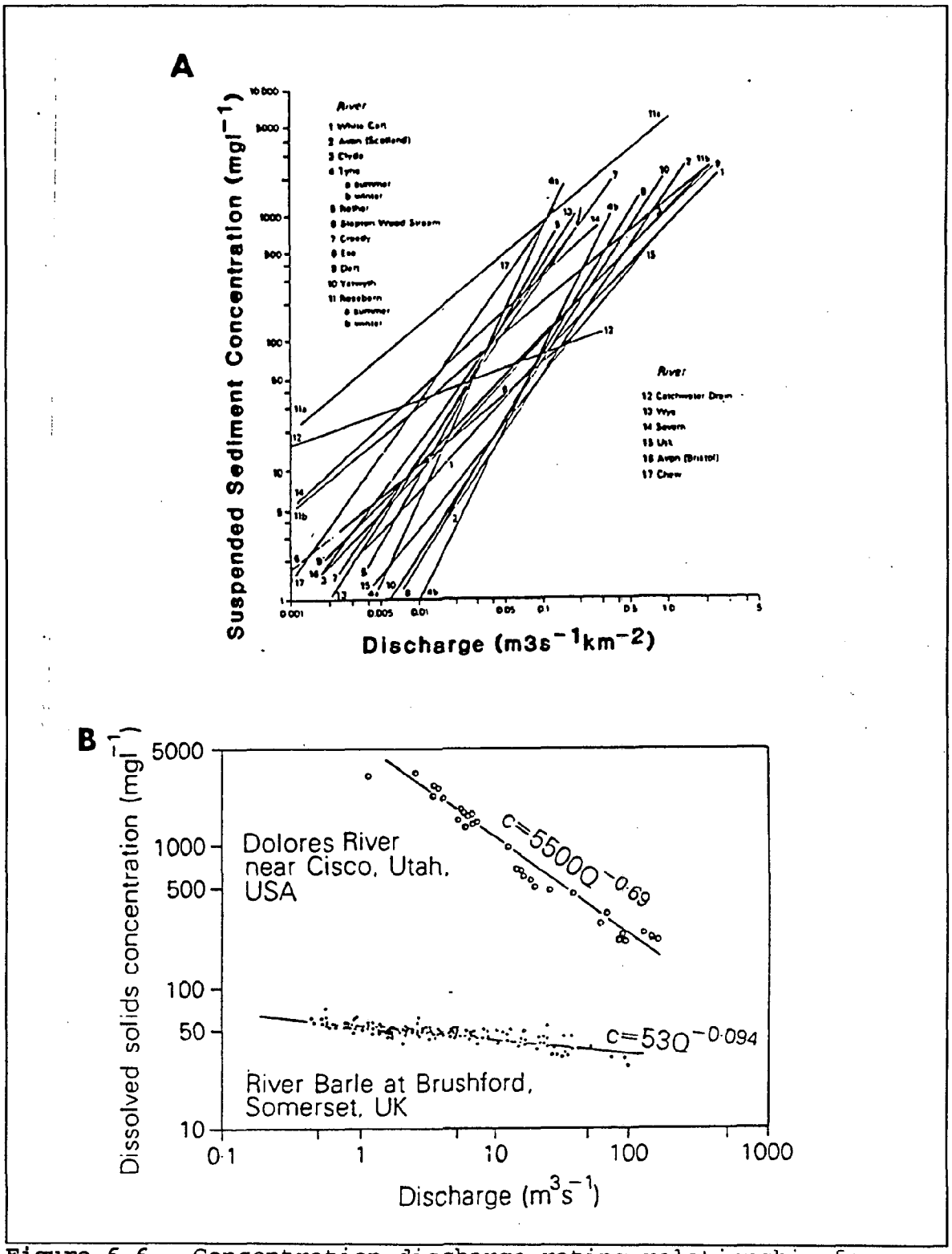


Figure 6.6. Concentration-discharge rating relationship for dissolved, particulate and particulate-associated substances in rivers (after Walling and Webb, 1983 (A) and Walling and Webb 1981 (B)).

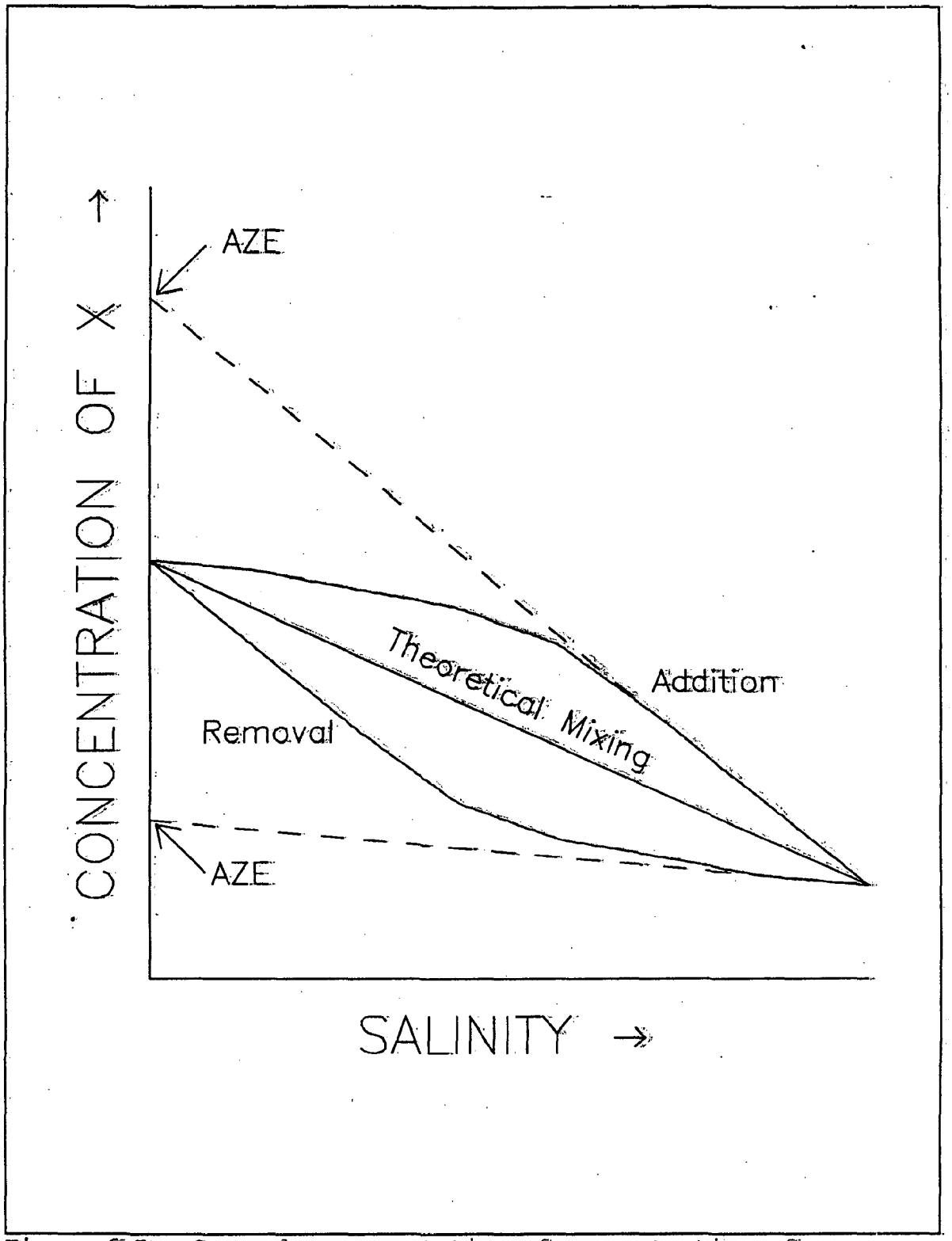


Figure 6.7. General representation of concentration of constituent, X, with respect to salinity, illustrating addition, removal, and conservative mixing of X. After Liss, 1976. AZE = apparent zero salinity end member.

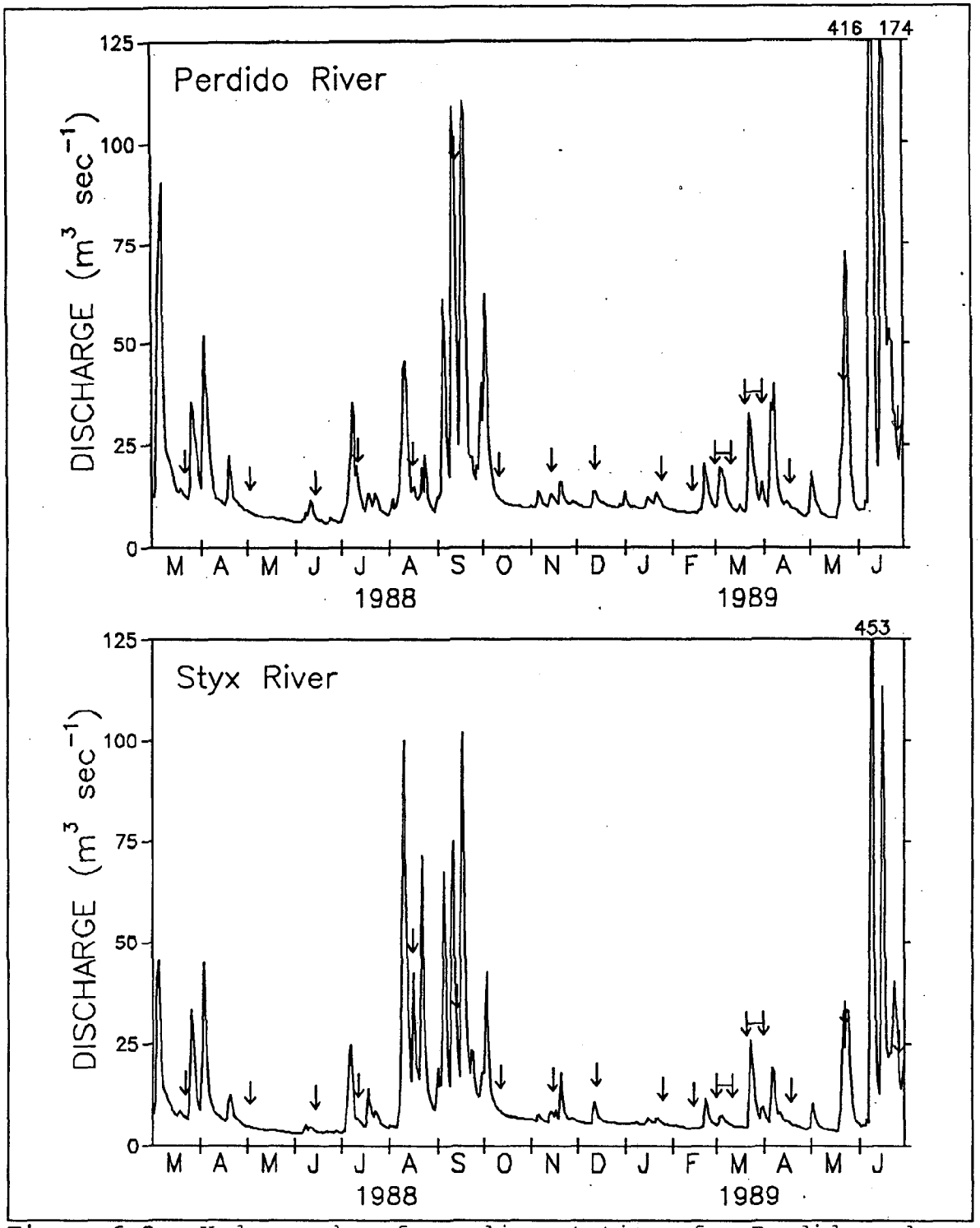


Figure 6.8. Hydrographs of sampling stations for Perdido and Styx Rivers. Arrows indicate dates of sample collection.

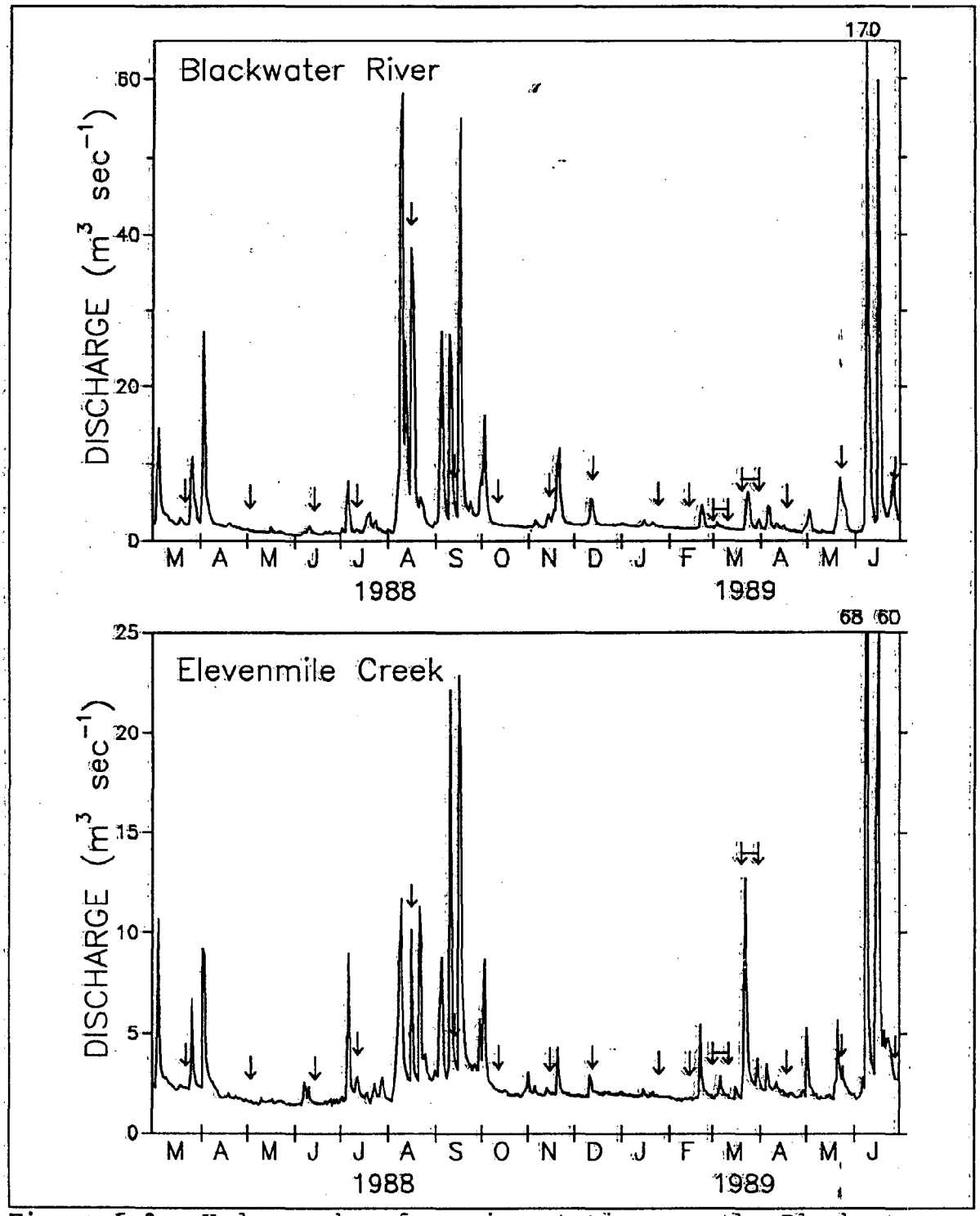


Figure 6.9. Hydrographs of samping stations on the Blackwater River and Elevenmile Creek. Arrows indicate dates of sample collection.

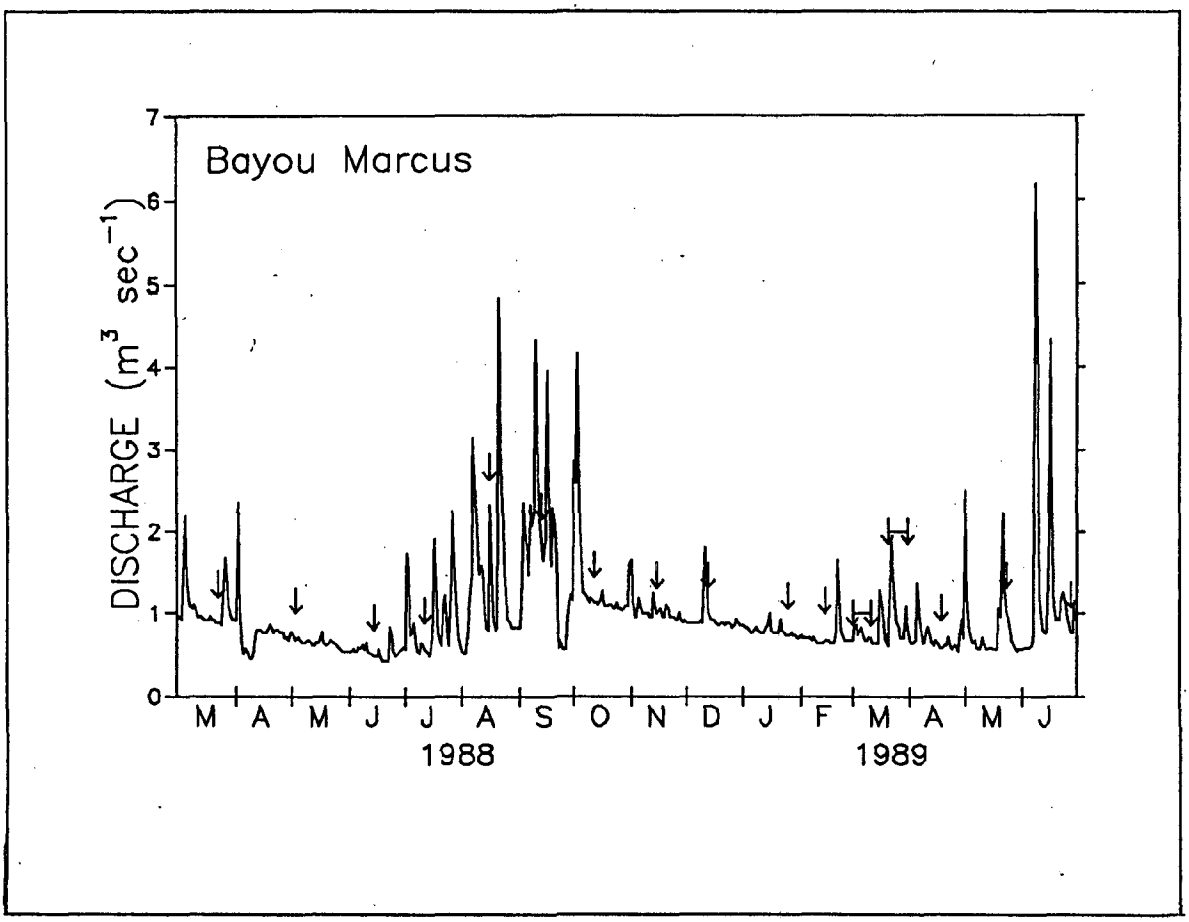


Figure 6.10. Hydrograph for sampling station on Bayou Marcus Creek. Arrows indicate dates of sample collection.

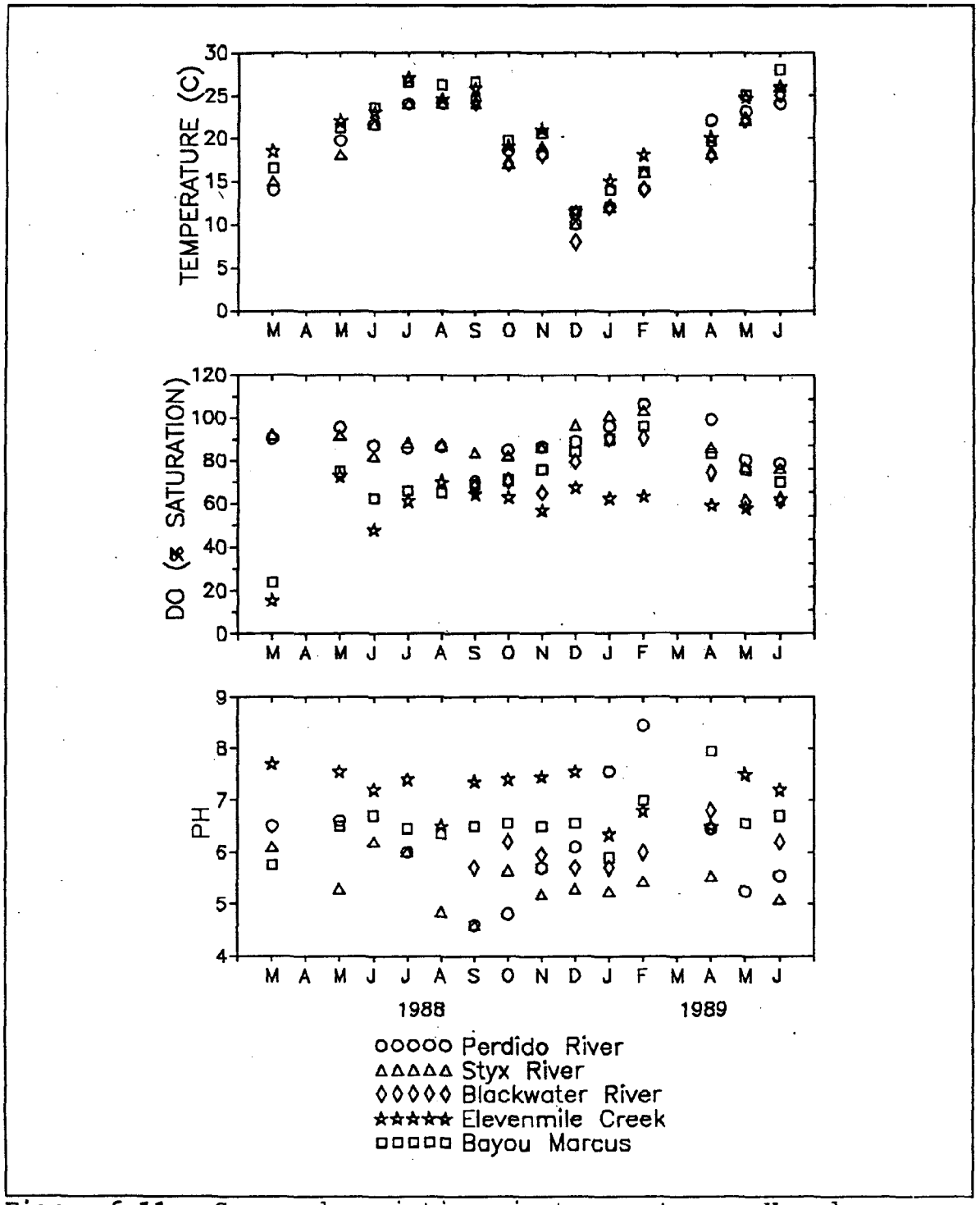


Figure 6.11. Seasonal variations in temperature, pH and dissolved oxygen at river and creek sampling stations.

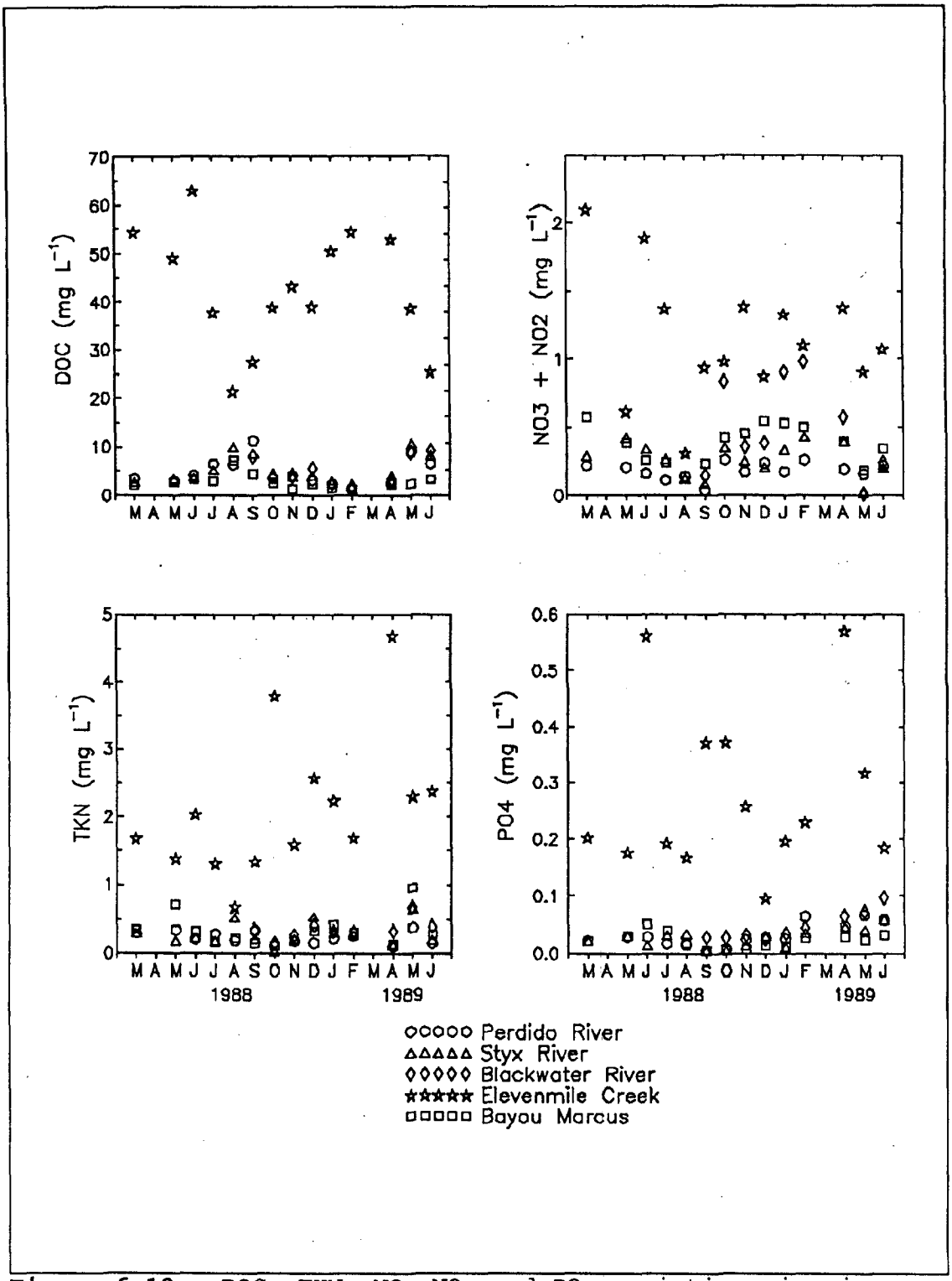


Figure 6.12. DOC, TKN, NO_3+NO_2 and PO_4 variations in river and creek samples.

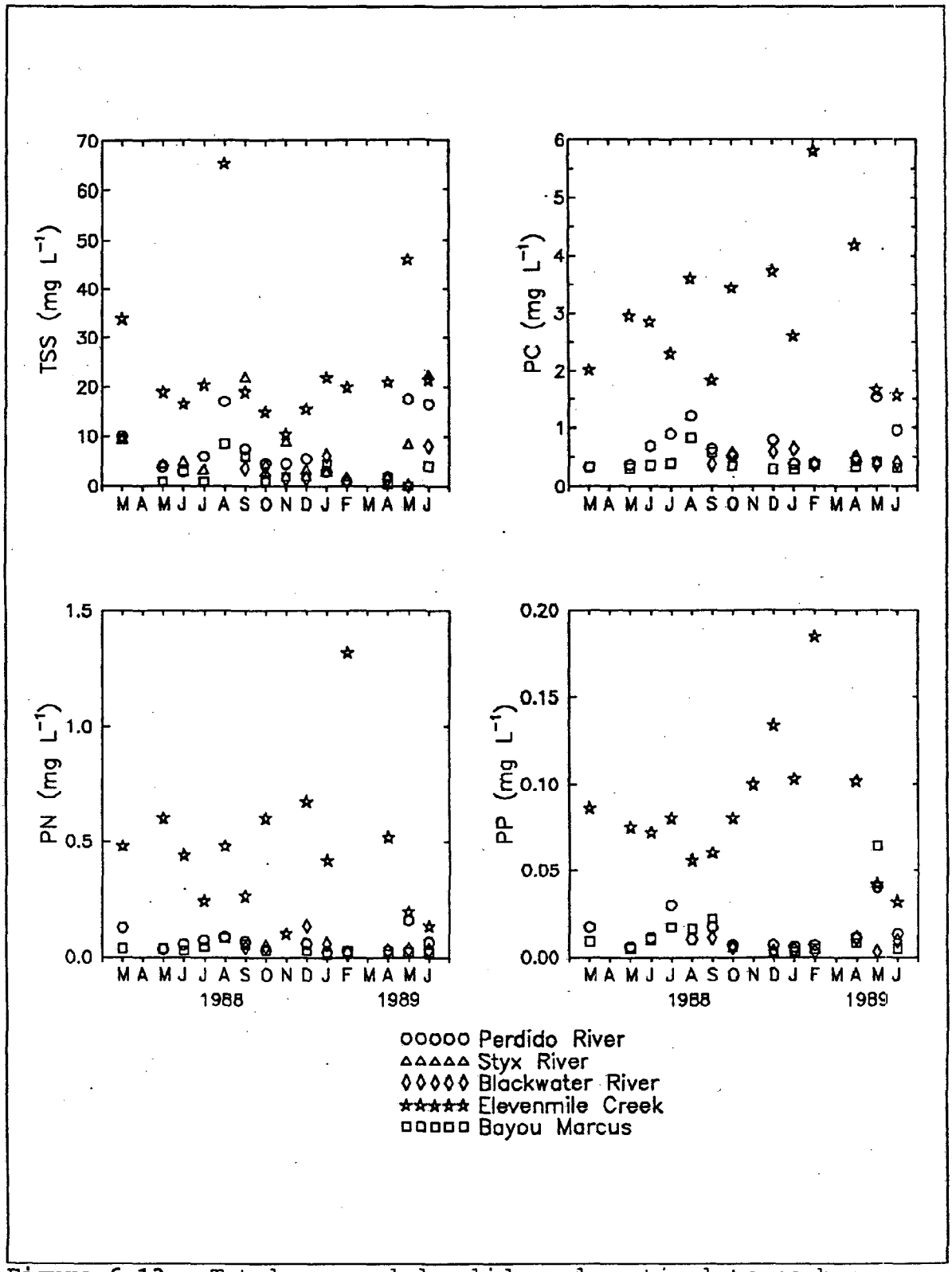


Figure 6.13. Total suspended solids and particulate carbon, nitrogen, and phosphorus concentrations in river and creek samples.

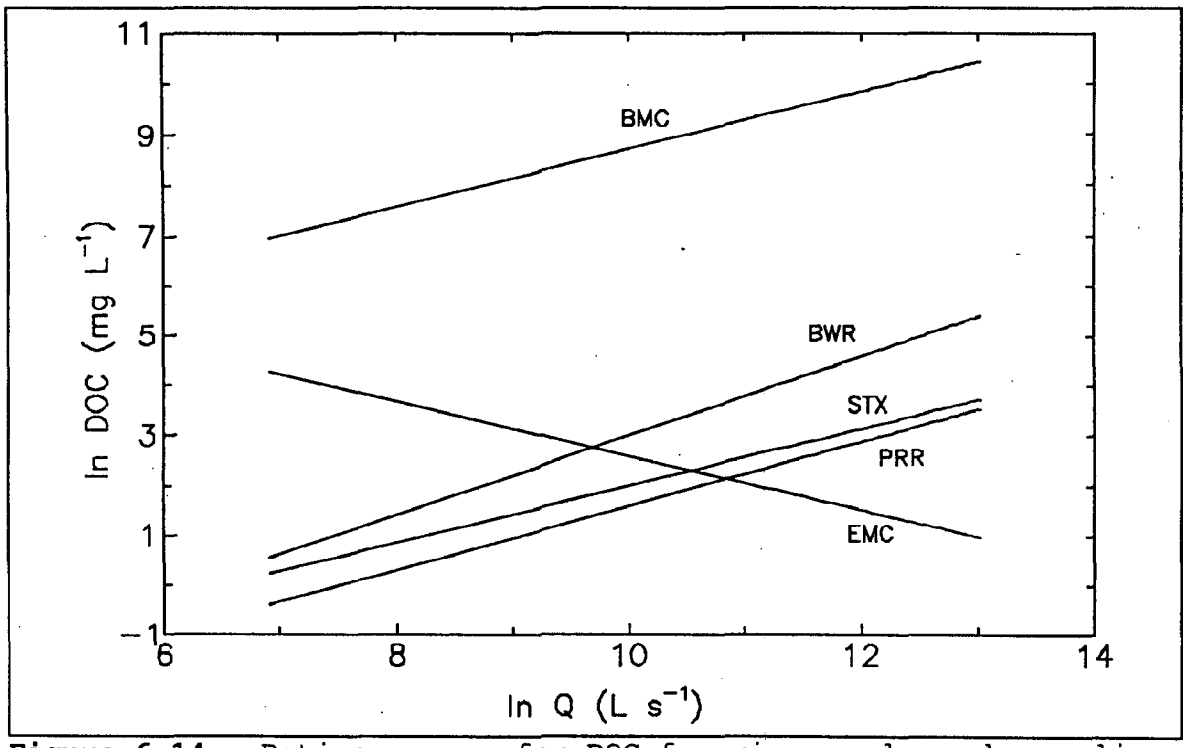


Figure 6.14. Rating curves for DOC for river and creek sampling stations.

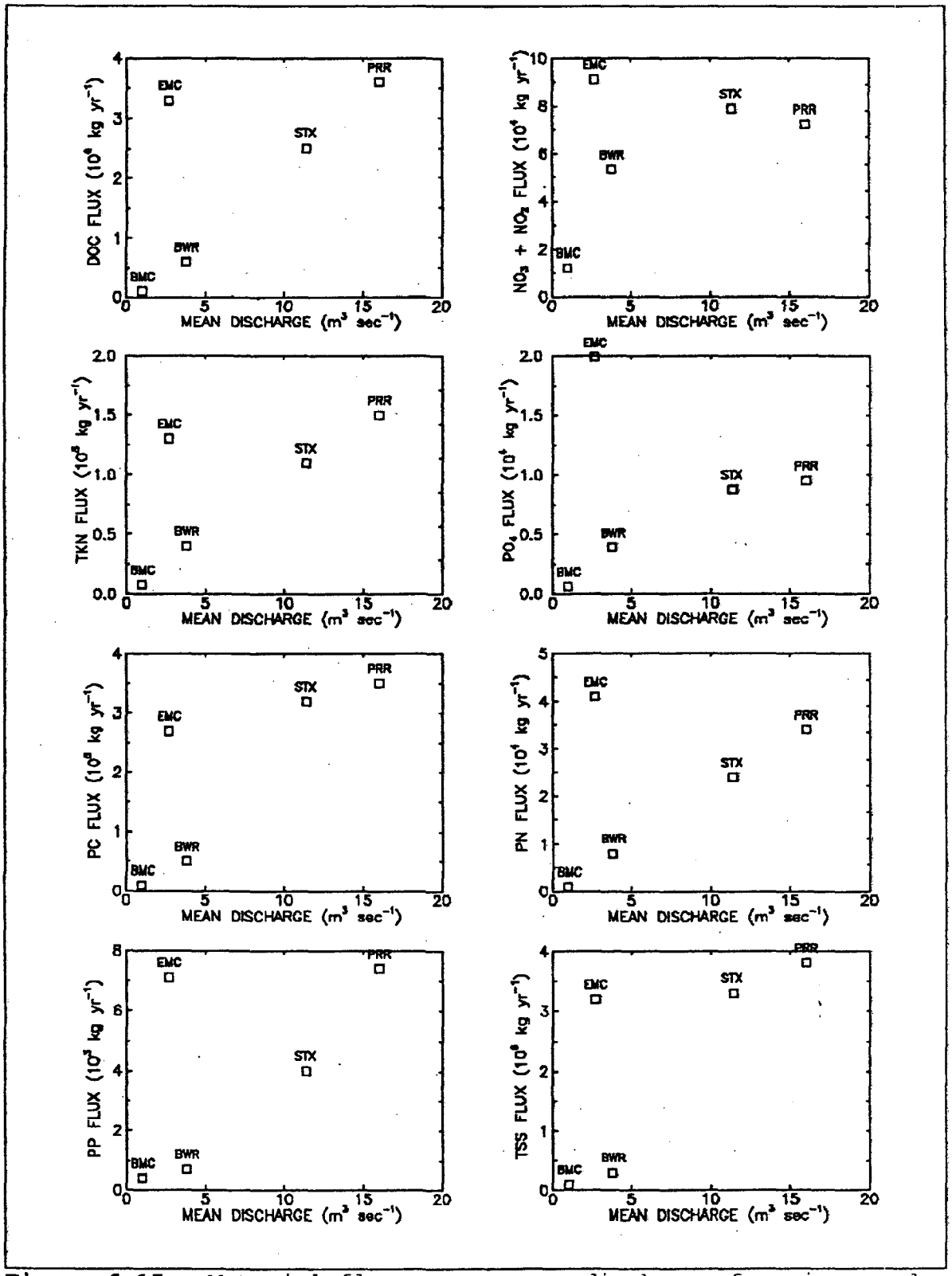


Figure 6.15. Material flux versus mean discharge for river and creek sampling stations.

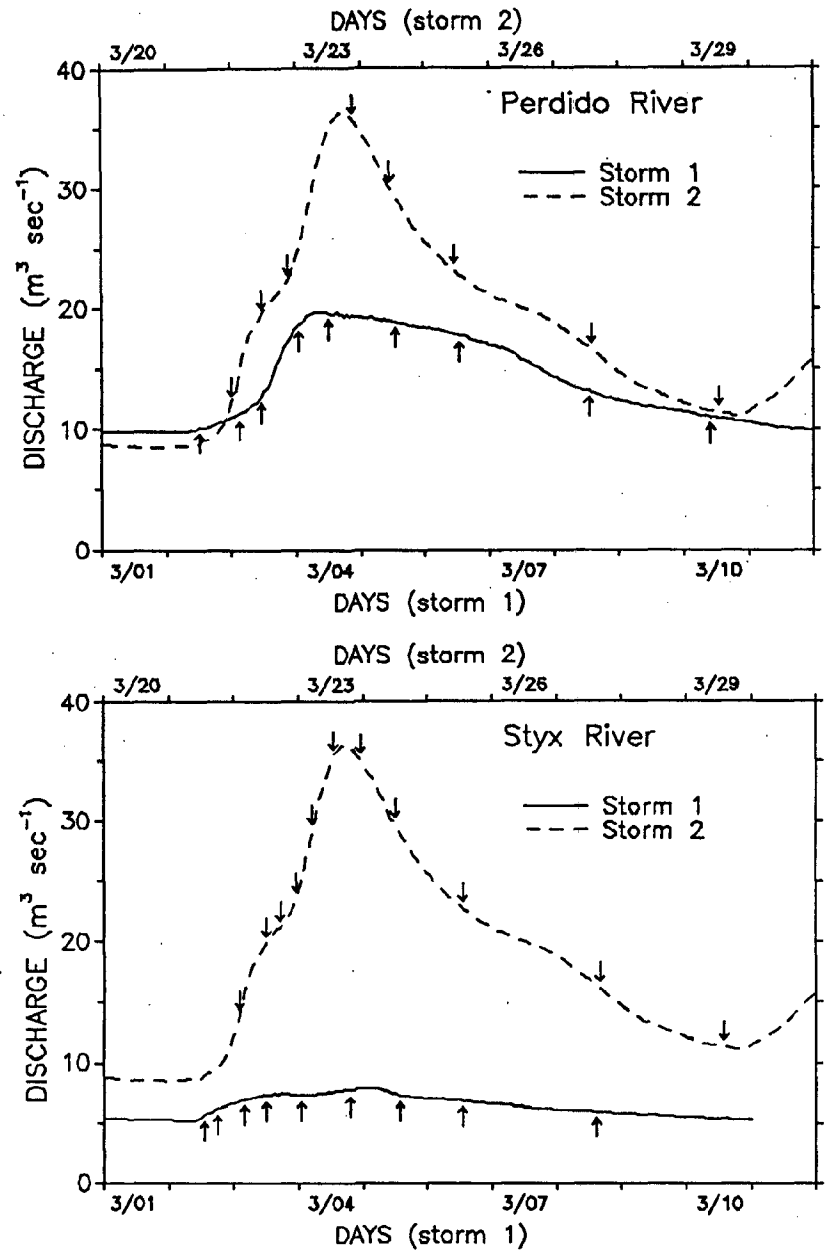


Figure 6.16. Storm hydrographs for Perdido and Styx Rivers. Storms occurring 1 - 11 March (lower curves) and 20 - 31 March (upper curves). Arrows indicate time of sample collection.

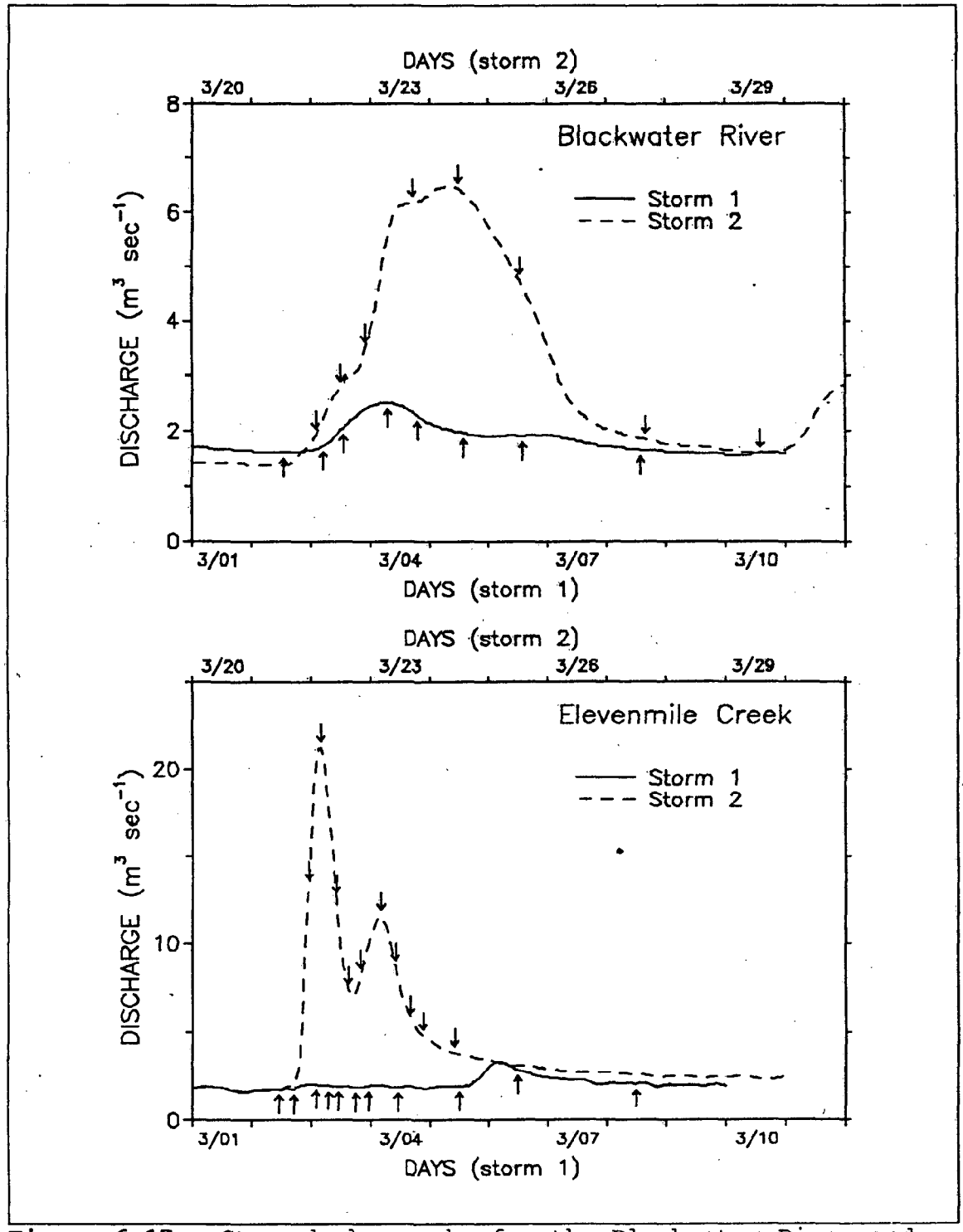


Figure 6.17. Storm hydrographs for the Blackwater River and Elevenmile Creek. Storms occurring 1 - 11 March (lower curve) and 20 - 31 March (upper curve). Arrows indicate time of sample collection.

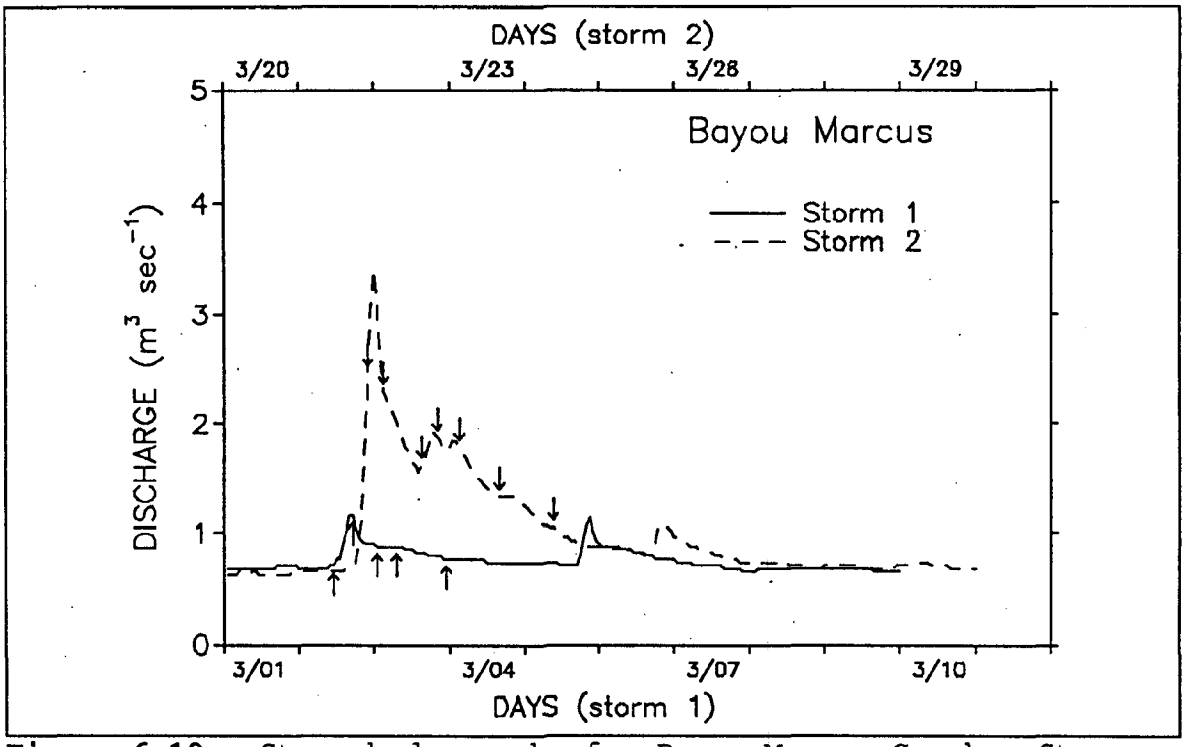


Figure 6.18. Storm hydrographs for Bayou Marcus Creek. Storms occurring 1 - 11 March (lower curve) and 20 - 31 March (upper curve). Arrows indicate time of sample collection.

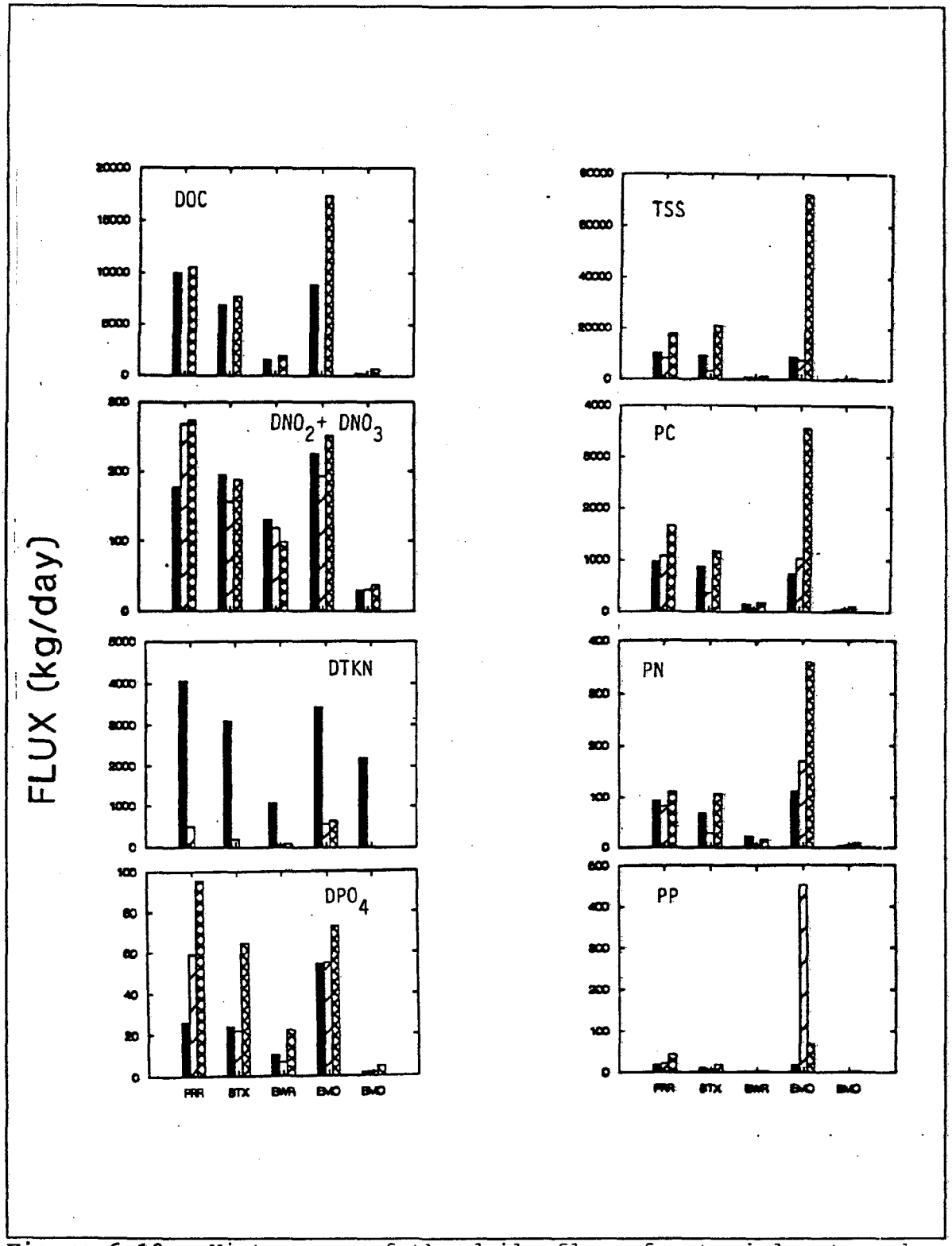


Figure 6.19. Histograms of the daily flux of materials at each gauging station averaged over the entire year (solid), 1 - 11 March storm (cross hatched), and 20 - 31 March storm (double cross hatched).

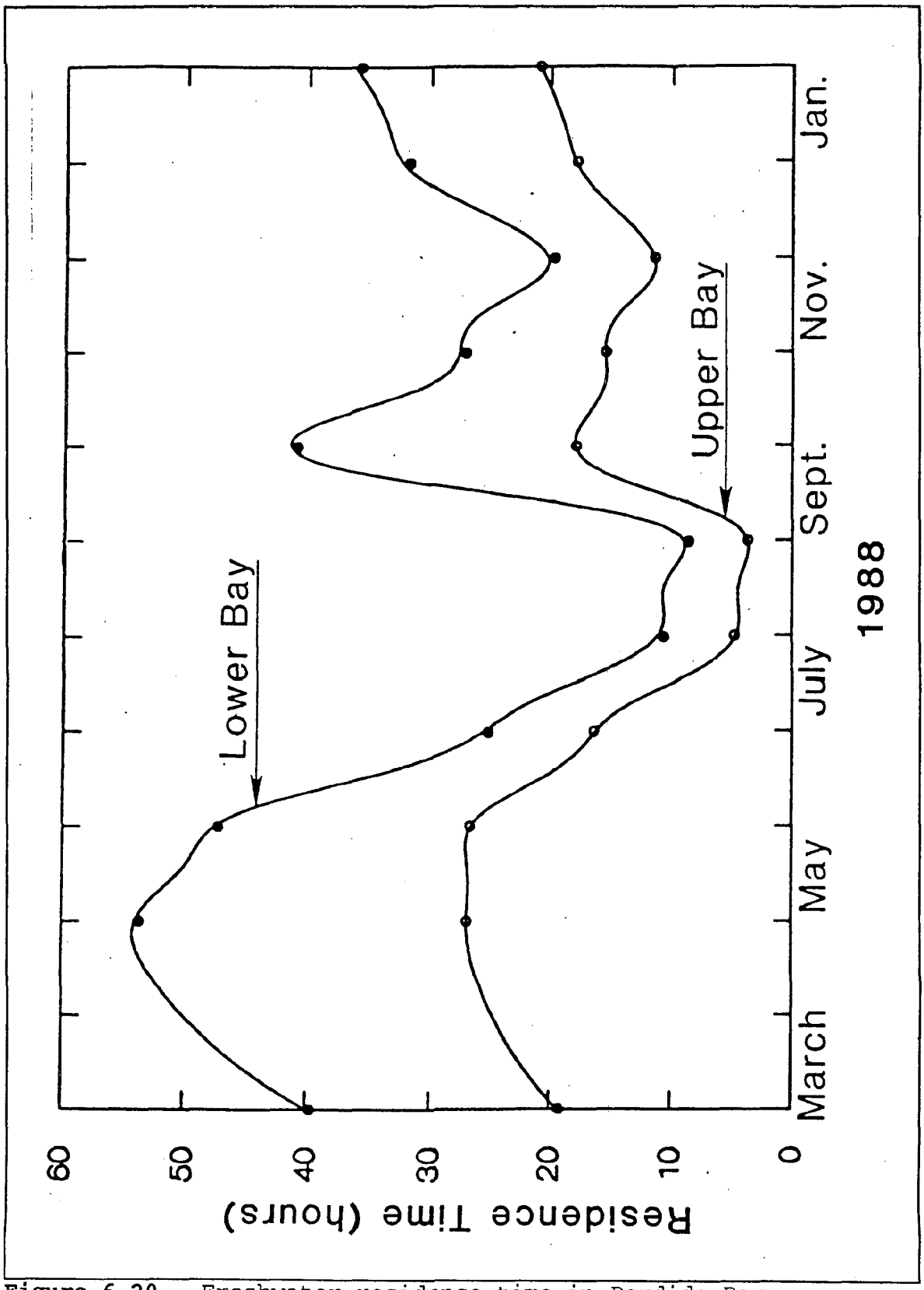


Figure 6.20. Freshwater residence time in Perdido Bay.

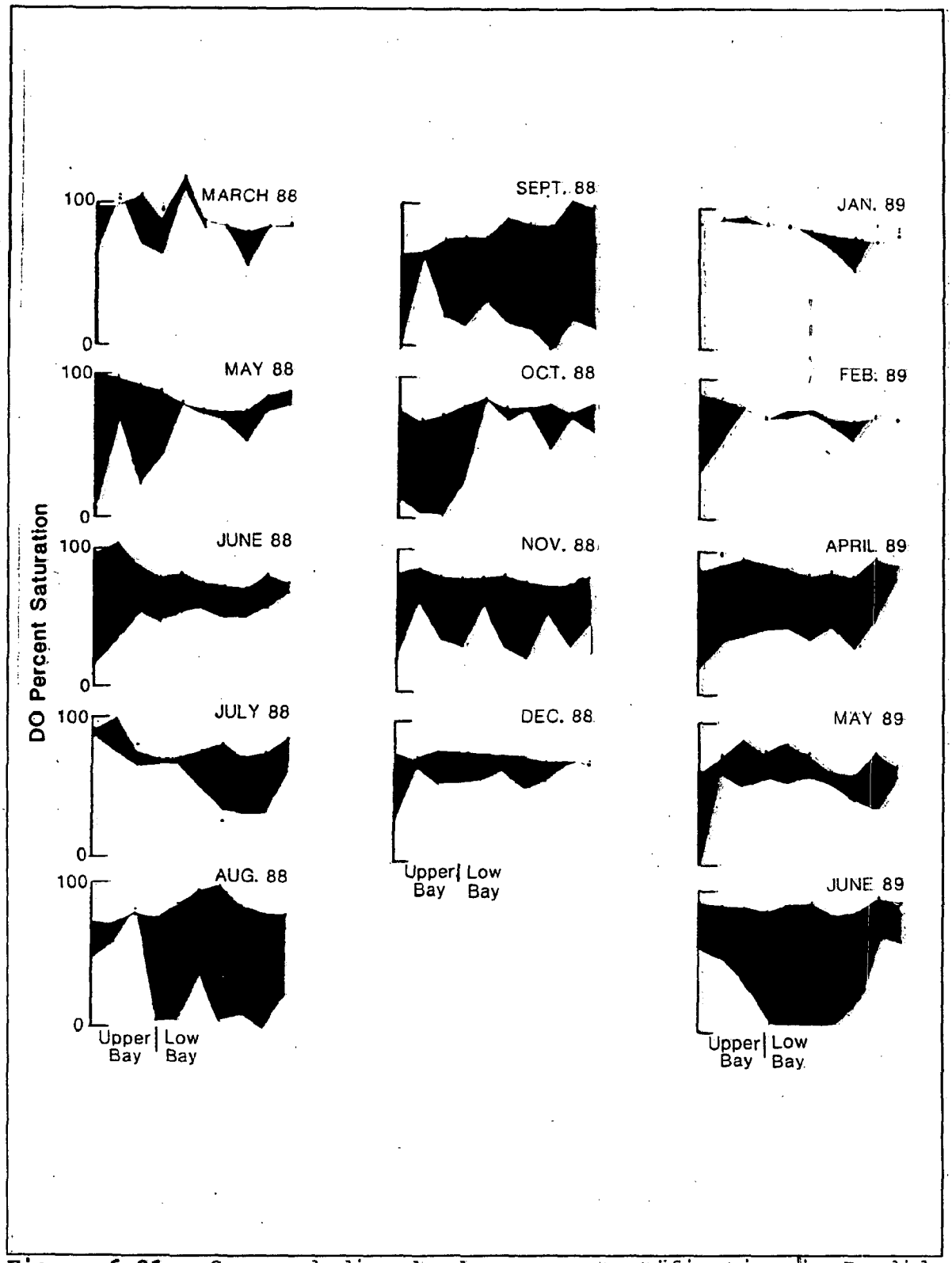


Figure 6.21. Seasonal dissolved oxygen stratification in Perdido Bay. Width of shading represents difference between surface and bottom waters.

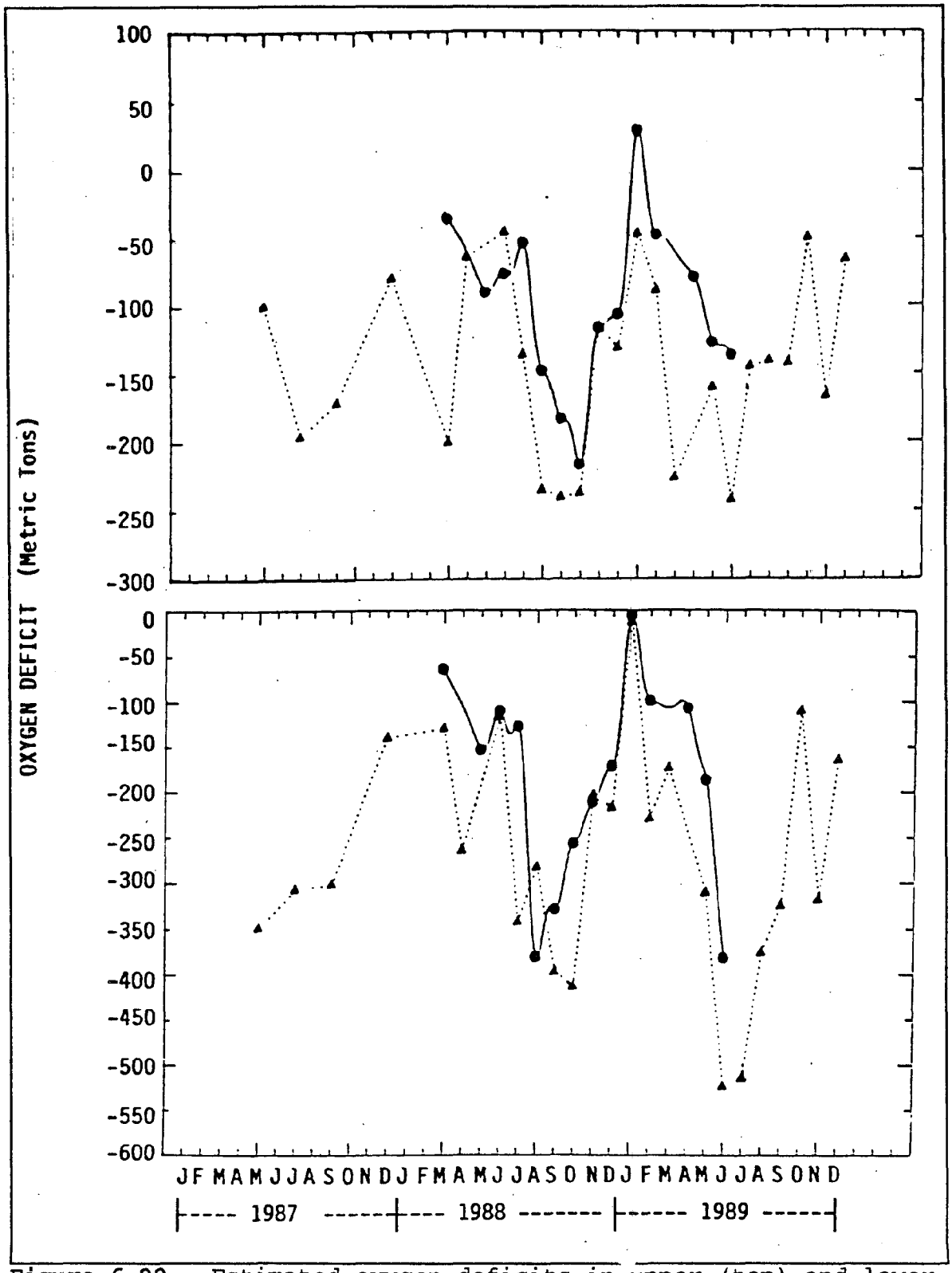


Figure 6.22. Estimated oxygen deficits in upper (top) and lower (bottom) bays by month. Dots indicate data from this study; triangles indicate EPA data (provided by David Flemer).

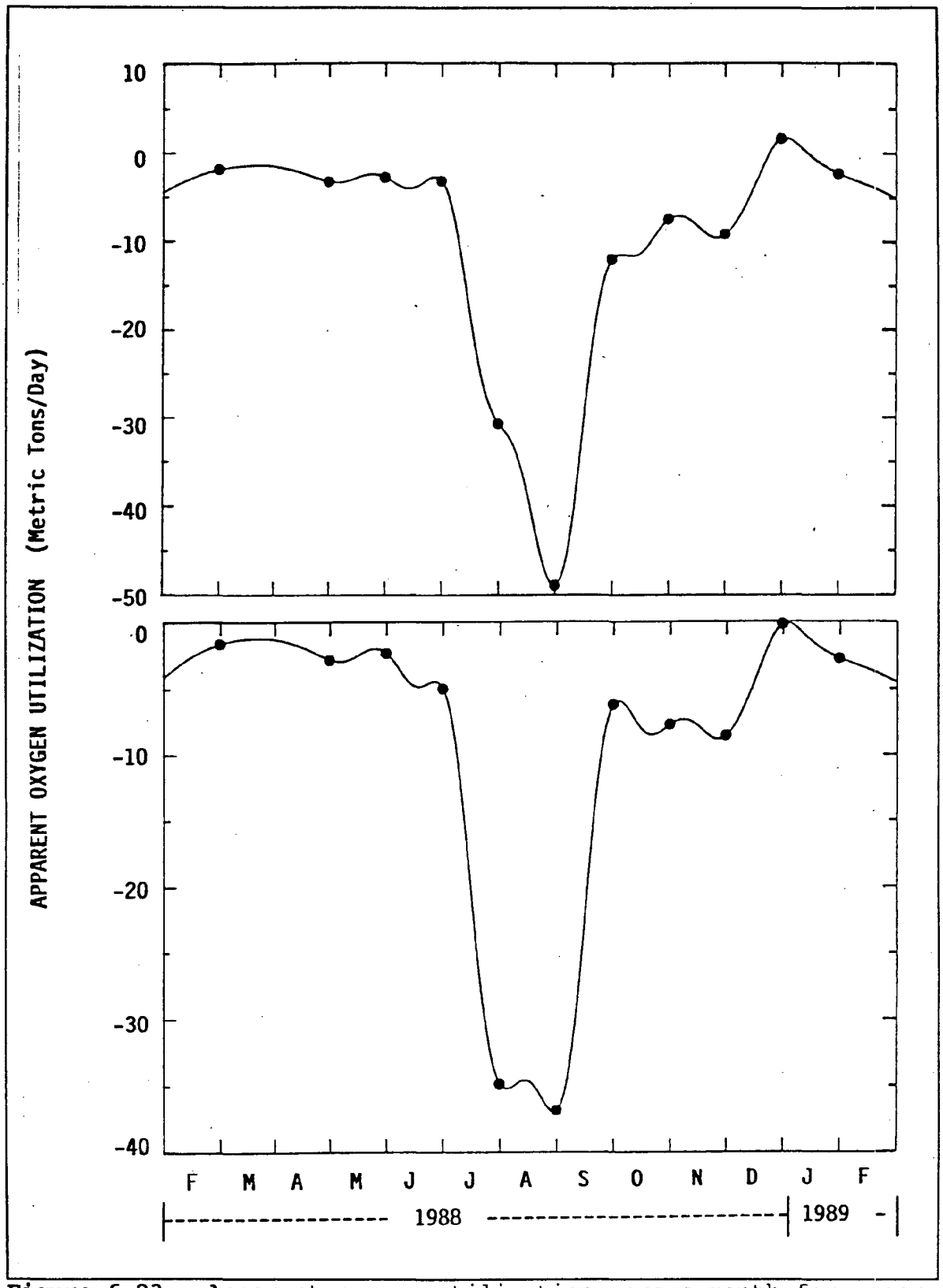


Figure 6.23. Apparent oxygen utilization versus month for upper (top) and lower (bottom) Perdido Bay.

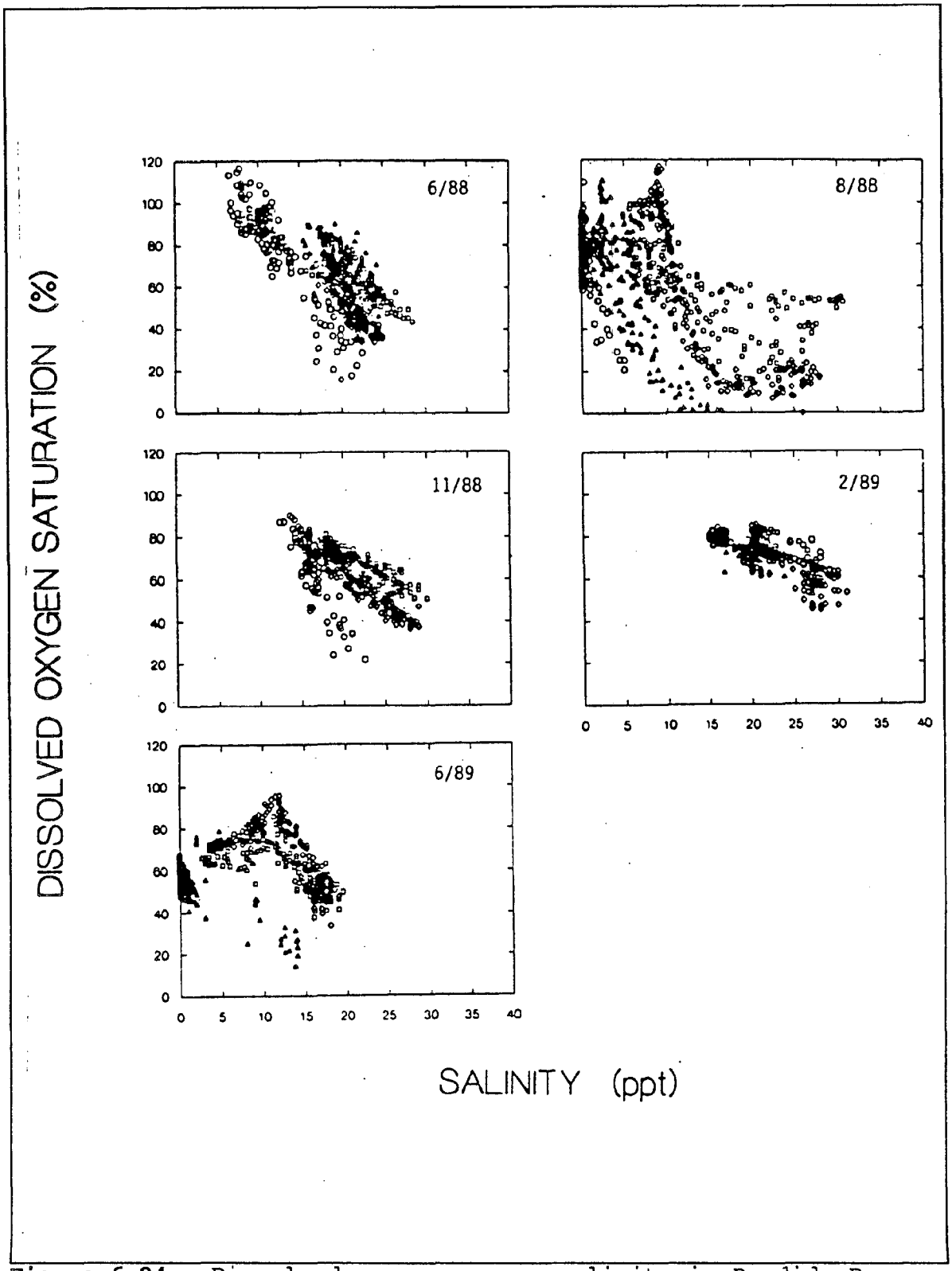


Figure 6.24. Dissolved oxygen versus salinity in Perdido Bay observed during hydrographic campaigns. Symbols refer to transects: O CT1, △ CT2, □ CT3, ◊ CT4.

7. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes results discussed in previous sections of this report regarding the environmental quality of Perdido Bay and recommends management responses to priority issues. The discussions in this chapter focus on questions concerning present environmental conditions of the bay. In the discussions, attempts will be made to identify conditions that are due to natural characteristics of the bay as opposed to those that result from anthropogenic activities.

Because of the limited resources available for the Interstate Study and general perceptions regarding conditions in the upper part of the bay, information gathered during this study provides a better basis for evaluating environmental conditions in the upper bay (north of Highway 98) than in the lower bay. Although results of this study provide an understanding of how the whole bay works hydrographically and, to some extent, chemically, the study did not take into detailed account material inputs to the lower bay. This is because the boundaries of the lower bay are considerably more complicated than those of the upper bay. For example, inputs to the upper bay are dominantly related to fresh-water runoff and, as we have shown, material inputs can be reasonably estimated. However, material inputs to the lower bay are controlled by freshwater input and exchange with the upper bay, Gulf Intracoastal Waterway (GICWW) and Gulf of Mexico. Quantification of inputs due to these exchanges is difficult to assess without considerably more effort than was possible under this study.

Given the above limitations, the conclusions presented below are intended to address some of the most commonly asked questions concerning the environmental quality of Perdido Bay.

CONCLUSIONS

How do tide, wind, and runoff affect water movement in Perdido Bay and to what extent is circulation confined in the upper bay?

The characteristic circulation of Perdido Bay, and the net movement of water and waterborne substances, are both strongly influenced by the interplay of tide, wind, and tributary freshwater inflow. Although the relative significance of these factors varies both spatially within the bay, and temporally with changes in the area climatology, each is important.

The regular influence of the tide is exerted throughout the Upper and Main Bays during each semi-diurnal portion tidal cycle lasting approximately 12 hours, transporting significant volumes of water into and out of the bay sub-basins with the ebb and flood. The magnitudes of these volumes are determined by the amplitude of the tide which varies every 7± days from a maximum of about 0.4 meter at spring tide, to a minimum of about 0.06 meter at neap tide. For average conditions corresponding to a mean tidal range of 0.2 meter, tidal exchange volume is especially significant in the Upper Bay where it represents approximately 14 per cent of the mean volume of the sub-basin. In the Main Bay the corresponding tidal exchange volume represents approximately 8 per cent of the mean sub-basin volume.

The contribution of the tide to the net movement of water through the bay is determined by the inequality of the ebb and flood tidal exchange volumes. At transect CT1, these volumes are nearly equal. Therefore, no net movement of the bay water is produced across this boundary as a result of tidal forcing. However, at transects CT3 and CT4 the flood and ebb tidal exchange volumes are not equal because of complex differences in the hydrodynamic characteristics of the tidal entrances at Mobile Bay and Perdido Pass. Thus, a significant net tidal circulation, or movement of water across these two boundaries is evident during portions of the lunar cycle. At transect CT4, in the GICWW near Hatchet Pt., the net tide-induced movement of water is to the east. At transect CT3, the net tide-induced movement is

southward towards Perdido Pass. These net movements were observed to be greatest during spring tide and near zero during neap tide.

The effects of wind on the movement of water in Perdido Bay also vary with location and time. In the GICWW near Hatchet Pt. wind was observed to have no significant effect on the net movement of water across transect CT4. This was not the case at other more exposed locations in the bay. At the entrance to the Main Bay, between Mill Pt. and Inerarity Pt. (transect CT3), the wind was seen to produce significant changes in the net water movement. Here, southerly winds push water northward into the Main Bay in opposition to the characteristic net tidal circulation described above. Conversely, northerly winds push the water southward at this location out of the Main Bay, thereby acting in concert with the net tidal movement. The net volume of water transported across transect CT3 in response to the wind was observed to represent as much as 5 per cent of the mean volume of the Main Bay.

At the entrance to the Upper Bay at Grassy Pt. (transect CT1) the wind has a similar effect on the movement of water and the overall net circulation of the Upper Bay. This wind-induced net movement was observed to comprise as much as 14 per cent of the mean volume of the Upper Bay, even though the absolute magnitudes of the volumes are lower than the corresponding movements across the Main Bay entrance at transect CT3.

The contribution of freshwater inflow to the net circulation of the bay is the most predictable of the three causative factors. This predictability is attributable to the relative ease with which the freshwater discharge into the Upper Bay is quantified, and the fact that the flow, once having entered the bay, acts as a net movement of water towards sea. It first passes southward through the Upper Bay, without contributing to long term changes in the sub-basin storage volume, and exits into the Main Bay at Grassy Pt. with the same magnitude. The

freshwater then moves through the Main Bay and exits to the GICWW to the west, or to the south past Inerarity Point and Mill Point towards sea. The distribution of the total freshwater movement between these two exits is a function of the particular conditions of tide and wind which exist at the time of interest.

What pollutants are entering the bay and from where?

The results of the chemical studies of Perdido Bay sediments (Chapter 4) provide a basis for evaluating anthropogenic contributions of metals, synthetic organic compounds and petroleum hydrocarbons, all of which tend to concentrate on particles and ultimately in sediments. Metal concentrations in sediments throughout the bay appear to be at natural levels except for a slight enrichment of lead in sediments from Bayou Marcus Creek and zinc in sediments from Bayou Marcus Creek and Elevenmile Creek. Metal enrichment in these creeks indicates that these watersheds are probable sources of anthropogenic metals to Perdido Bay.

PCBs were detected in only two sediment samples, at levels approaching detection limits. Somewhat surprisingly, these two samples were taken from the Styx and Blackwater Rivers. Hydrocarbon compounds were more commonly found in the upper bay, but levels were always below 1 ppm. Sediments in Bayou Marcus have the highest concentrations, suggesting this watershed as a source of hydrocarbons. This is consistent with the more urban nature of the Bayou Marcus watershed.

The main conclusion from the above is that, up to now, Perdido Bay has not received significant inputs of metals, synthetic organic compounds or hydrocarbons as a result of anthropogenic activities. The evidence does indicate the potential for increased inputs of pollutants from the urban watersheds.

Is Perdido Bay silting up due to increased erosion resulting from man's activities in adjacent watersheds?

In Chapter 6, we estimated that the annual supply of sediments to the upper bay could easily be 25,000 metric tons. Assuming that the solids in this sediment have a specific gravity of 2.6 g cm^{-1}, the water content is about 50%, and that it accumulates in the 28 km^2 area of the upper bay, this would result in a sedimentation rate of less than 1.0 mm yr^{-1}.

Coastal and estuarine sediments of the southeast U.S. typically accumulate at a rate of about 5 mm yr^{-1} or approximately equal to the present rate of sea level rise. Thus, even though it was argued in Chapter 6 that about 25 percent of the suspended solids transported to the upper bay by streams (Table 6.6) may be due to anthropogenic activities, the net result on sedimentation rate is relatively insignificant.

This study did not examine bed load transport. Erosion in the watershed can lead to slow, but profound changes in sediment delivery (Meade, 1982). Agriculture, silviculture, and urban activities can result in increased sediment loadings which are not yet evident in the downstream estuarine reaches.

What is the rate of supply of nutrients to Perdido Bay and what is man's influence on this rate?

The rates of input of dissolved and particulate nitrogen, phosphorus, and carbon in the upper bay were presented in Chapter 6. Estimated total fluxes to the upper bay were based on fluxes calculated for each of the gaging stations on the five tributaries discharging into the bay. These are minimum estimates since they do not account for additional inputs directly into the bay or additional sources downstream of the gaging stations.

The similarities of the rating relationships (i.e. concentration vs. discharge) for DOC, TKN, and PC transported by Bayou Marcus Creek, Perdido River, Blackwater River and Styx

River and their similar flux:discharge ratios (Figure 6.15) suggest that nutrients are mobilized in these watersheds with similar efficiencies. It is plausible to assume that mobilization is dominated by natural processes since anthropogenic activities would have to be constant per unit area of watershed for all watersheds to give similar results.

The mobilization of all measured nutrients in the watershed of Elevenmile Creek is considerably greater than that in the other watersheds. There is no compelling reason that this watershed should be different in its natural characteristics from the others. Thus, it follows that the excess flux from this watershed (Table 6.6) is due to anthropogenic activities. Certainly, the operation of the Champion International paper mill must be considered as a likely source of the excess nutrients. Of the total estimated nutrient supply to upper Perdido Bay, 27, 24, and 38 percent of the carbon, nitrogen and phosphorus, respectively, is estimated to be anthropogenic, from Elevenmile Creek.

The flux:discharge ratios (Figure 6.15) also suggest anthropogenic contributions of dissolved NO_3+NO_2 and PO_4 from the Styx and Blackwater Rivers and NO_3+NO_2 from Bayou Marcus Creek. These nutrients could come from agricultural activities in the Styx and Blackwater watersheds and urban sources in the Bayou Marcus watershed.

Does Perdido Bay trap nutrients?

Trapping of nutrients occurs in virtually all southeastern estuaries. In the case of Perdido Bay, the concern is related to the efficiency of trapping. While natural estuarine systems equilibrate to the natural inputs and internal cycles of nutrients which in part control seasonal fluctuations of primary production and dissolved oxygen, perturbation due to anthropogenic nutrient inputs will vary in severity in relation to trapping efficiency.

In Chapter 6, mass-balance calculations were made for carbon, nitrogen and phosphorus in the upper bay. Results indicated that about 1.1×10^6 kg C, 2×10^4 kg N and 3×10^3 kg P are removed from the water column annually in the upper bay.

In the case of nitrogen and phosphorus, the losses represent less than five percent of the total annual input. These losses are probably accounted for by accumulation in bottom sediments where the N:P ratios (Figure 3.8) are about the same as the ratio of the loss (i.e., 20.3). If the 2×10^4 kg of nitrogen and the 3×10^3 kg of phosphorus accumulated in upper bay sediments with the total annual suspended flux of 10.7×10^6 kg yr^{-1}, then the resulting nitrogen and phosphorus concentrations in upper bay sediments would be about 2000 and 300 mg kg^{-1} respectively. This is certainly within the range of observed concentrations. These results suggest that although some nutrients may be retained in the upper bay, the upper bay is not a particularly efficient trap for these nutrients.

The mass-balance calculations indicated that 1.1×10^6 kg of carbon is removed from the water column in the upper bay. This represents more than 10% of the organic carbon entering the upper bay.

As mentioned in the introduction to this chapter, mass balance calculations could not be made adequately in the lower bay. An attempt to assess nutrient concentrations in lower bay waters in relation to inputs from the upper bay, however, was made. If it is assumed that the residence times calculated for conservative substances in the lower bay are accurate (Figure 6.17) then the average observed concentrations of nutrients in lower bay waters are considerably higher than expected. This implies that additional nutrient inputs from adjacent areas, perhaps through transect CT3 and CT4, have occurred. Consistent with this are the generally higher nitrogen and phosphorus concentrations in lower bay sediments. Thus, the lower bay may trap a greater amount of nutrients per unit area, but its overall

efficiency in relation to inputs has not been assessed with the existing data.

How prevalent are hypoxic conditions in Perdido Bay and what are the causes?

The environmental condition in Perdido Bay that generates the greatest concern is periodic hypoxia. The results of this study and those from EPA provide an adequate basis for evaluating both the frequency and the causes of hypoxic conditions in Perdido Bay. Dissolved oxygen, temperature, and salinity were measured in depth profiles at a number of stations within Perdido Bay as a part of this study and by EPA. If it is assumed that these profiles give a reasonable representation of the dissolved oxygen structure of the bay, then the total oxygen content of the upper and lower bays can be estimated. The mean salinity and temperature of the bay taken from the results of the profiles can be used to calculate what the oxygen content of the upper and lower bay should be, assuming dissolved oxygen saturation. The difference between the observed dissolved oxygen content and the theoretical, saturated content can then be calculated as an apparent oxygen deficit (Figure 6.22).

This analysis of the data provides a basis for evaluating dissolved oxygen conditions over a two-to-three year period. The results show that hypoxic conditions are periodic and associated with season in both the upper and lower bays. The period between June and October is the time when hypoxic conditions are more prevalent. During the sampling year, this was also the time of highest runoff to the bay (Figures 6.8 - 6.10) and the time when the concentrations of dissolved and particulate organic carbon are highest in the "natural" rivers and creeks (Figures 6.12 and 6.13).

The major process leading to oxygen uptake is oxidation of organic matter. Reduced mixing caused by stratification during the spring through early fall allows oxygen to be consumed in the water column and by the benthic community faster than it can be

replaced from the surface. Hypoxic periods coincide with the periods of greatest total organic carbon input and with higher water temperatures. Biological oxygen consumption is greatest during these months of higher water temperatures.

Stratification and hypoxia are natural conditions that can be exacerbated by man's activities. We cannot, from our data, quantify oxygen demand from different sources (eg. oxidation of organic carbon deposited in the sediments throughout the year, oxidation of DOC delivered during the warm months, phytoplankton respiration). Nevertheless, the upper half of the bay does serve as a trap for carbon and oxidation of anthropogenic carbon deposited in the upper bay certainly contributes to the observed hypoxic conditions. It must be noted, however, that stratification and hypoxia are natural conditions and that total elimination of anthropogenic nutrient loadings will probably not completely eliminate hypoxia during part of the year.

How can we summarize the present condition of Perdido Bay?

The results of this study show that physical conditions in Perdido Bay, controlled by the natural forces of wind, streamflow, and tide, are such that stratification and hypoxia occur during a major portion of the year. Summer and early fall months are critical periods when maximum natural stresses (hypoxia) are imposed on the bay and its biological communities. The results also show that Perdido Bay receives nutrients from anthropogenic sources, dominated during this study by materials delivered by Elevenmile Creek. The Styx and Blackwater Rivers and Bayou Marcus Creek also show evidence of anthropogenic contributions of nutrients. A substantial portion of carbon delivered to the estuary is trapped in the upper bay where oxidation of this material can aggravate seasonal hypoxia.

SUMMARY

The results of the Interstate Study indicate that, at present, Perdido Bay does not suffer from acute toxic contamination. The results of sediment studies indicate that the

bay is, however, subject to contamination from urban runoff, although contaminants have not reached levels encountered in other more developed parts of Alabama and Florida.

Nutrient inputs to the bay are increased above natural levels by man's activities in the watershed. Excess carbon appears to contribute to seasonal oxygen deficiencies. Nitrogen and phosphorus do not appear to be trapped in the bay but could contribute to increased productivity, also exacerbating seasonal oxygen deficiencies.

RECOMMENDATIONS

The following recommendations are based on the need to prevent future degradation of Perdido Bay and to evaluate changes that may occur as development increases around the bay.

1. Reduce nutrient loadings from Elevenmile Creek. Due to the dominance of Elevenmile Creek in delivering anthropogenic nutrients to Perdido Bay, a first management priority should be to reduce these loadings. Champion International has already begun to examine alternate treatment strategies for its pulp mill wastewater.

2. Reduce and prevent other nutrient loadings.
   a) Determine the effects of agricultural practices in the Styx and Blackwater River watersheds on nutrient and suspended solids transport.
   b) Determine effective stormwater management strategies to control nutrients, especially during the critical summer period when stratification and concomitant hypoxic conditions are prevalent.

3. Begin system-wide monitoring of nutrient concentrations, productivity and sediment contamination which can best be done through a cooperative interstate program. This monitoring should be sensitive to natural variability

(eg. seasonal physical, chemical, and biological changes). With proper training, some aspects of monitoring could be carried out by concerned citizen groups.

A) Nutrient monitoring program. This program should be designed to address the following objectives: 1) assess the amounts of nutrients entering, leaving, and stored in the estuary and changes in these amounts, 2) determine the relationship of nutrient levels to estuarine productivity and dissolved oxygen, 3) determine what valued resources are vulnerable to or presently affected by changing nutrient levels.

B) Supplement Interstate Project data with measurements of nutrients and water movement in the lower portions of Perdido Bay. Because of the higher pace of urban development around the southern portion of the bay and the influence of the GICWW on that part of the bay, better information is needed to assess potential problems and management strategies for the lower bay.

C) Sediment monitoring program. The objectives of sediment monitoring should be to assess inputs of pollutants and effectiveness of controls. Results from this study indicate pollutant input from the Bayou Marcus and Elevenmile Creek watersheds. A sediment monitoring program should include these streams as well as other areas in the lower bay likely to be impacted by development. Given the sediment information collected by this and other recent projects, follow-up surveys are not needed immediately but should form major components of a future monitoring strategy.

4. Develop capacity to predict, based on wind, streamflow, and tides, water movements and retention times in Perdido Bay. This will allow a critical examination of management strategies based on characteristic water

movements in the bay. During the summer of 1990, the FDER/Coastal Zone Management program took the first steps towards developing a simple predictive model for net water circulation and concentration of substances in the bay. The results are presented in a companion report, *Prediction of Water Quality at Perdido Bay, Florida* (Taylor et al., 1991).

8. REFERENCES

ADEM. 1986. Brushy Creek/Boggy Branch water quality survey. Alabama Department of Environmental Management.

APHA. 1985. Standard methods for the examination of water and wastewater, 16th edition. American Public Health Association, Washington, D.C.

APHA. 1980. Standard methods for the examination of water and wastewater, 15th edition. American Public Health Association, Washington, D.C.

Bridges, W.C. 1982. Technique for estimating magnitude and frequency of floods on natural-flow streams in Florida. United States Geological Survey and the Florida Department of Transportation, Tallahassee, Florida.

Davis, J. S. and J. Zobrist. 1978. The interrelationships among chemical parameters in rivers - analysing the effect of natural and anthropogenic sources. Progress Water Technology 10: 65-78.

Delfino, J. J. 1990. Toxic pollutants in discharges, ambient waters, and bottom sediments. Quarterly Progress Report No. 6, FDER Contract No. WM266. Florida Department of Environmental Regulation. Tallahassee, Florida.

Dupraz, C., F. LeLong, J. P. Trop and B. Dumazet. 1982. Comparative study of the effects of vegetation on the hydrological and hydrochemial flows in three minor catchments of Mount Lozere (France) - methodological aspects and first results. In Hydrological Research Basins and Their Use in Water Resources Planning. Landeshydrologie, Berne, pp. 671-682.

FDER. 1988. A guide to the interpretation of metal concentrations in estuarine sediments. Florida Department of Environmental Regulation. Tallahassee, Florida.

Foster, I. D. L. 1978a. Seasonal solute behaviour of stormflow in a small agricultural catchment. Catena. 5: 151-163.

Foster, I. D. L. 1978b. A multivariate model of storm-period solute behaviour. J. Hydrol. 39: 339-353.

Foster, I. D. L. 1980. Chemical yields in runoff and denudation in a small arable catchment, East Devon, England. J Hydrol. 47: 349-368.

Fox, L. E. 1989. A model for inorganic control of phosphate concentrations in river waters. Geochim. Cosmochim. Acta 53: 417- 428.

Hall, F. R. 1970. Dissolved solids-discharge relationships. 1: Mixing models. Water Resources Res. 6: 845-850.

Hand, J.; V. Tauxe, and M. Friedemann. 1988. 1988 Florida water quality assessment-305(b). Technical Appendix. Florida Department of Environmental Regulation.

Jansson, M. 1985. A comparison of detransformed logarithmic regressions and power function P regressions. Geografiska Annaler 67A: 61-70.

Kaul, L. W. and P. N. Froelich, 1984. Modeling estuarine nutrient geochemistry in a simple system. Geochem. Cosmochim. Acta. 48: 1417-1433.

Lachat Instruments. 1988. Methods manual for the Quikchem Automated Ion Analyzer.

Li, Y. and L. Chan. 1979. Desorption of Ba and ^{226}Ra from river-borne sediments in the Hudson estuary. Earth Plant. Sci. Lett. 43: 343-350.

Liss, P.S. 1976. Conservative and non-conservative behaviour of dissolved constituents during estuarine mixing. In Estuarine Chemistry, J.D. Burton and P.S. Liss, editors. Academic Press, London, p. 93 - 130.

Marsh, O. T. 1966. Geology of Escambia and Santa Rosa Counties, Western Florida panhandle. Bulletin # 46, Florida Geological Survey, State of Florida, State Board of Conservation, Division of Geology.

Meade, R. H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the U.S. J. Geol. 90: 235 - 252.

Meadows, P. E., J. B. Martin, and P. R. Mixson. 1988. Water Resources Data Florida. Volume 4. Northwest Florida. U.S. Geological Survey Water-Data Report FL-87-4.

Miller, W. R. and R. H. Drever. 1977. Water chemistry of a stream following a storm, Absarokah Mountains, Wyoming. Geol. Soc. Am. Bull. 88: 286-290.

Musgrove, R. H. , J. T. Barraclough, and R G. Grantham. 1965. Water resources of Escambia and Santa Rosa Counties, Florida. Report of Investigations No. 40. Florida Geological Survey, State of Florida, State Board of Conservation, Division of Geology.

Nilsson, B. 1971. Sediment transport i svenska vattendrag. Ett IHD-projekt. Del. 1, Methodik, PUNGI Rapport 4, Uppsala.

NOAA. 1985. National estuarine inventory data atlas. Vol. 1. Physical and hydrologic characteristics. Strategic Assessments Branch, Office of Oceanography and Marine Assessment, National Ocean Service.

NOAA/EPA. 1989. Susceptibility and status of Gulf of Mexico estuaries to nutrient discharges. Strategic Assessment Branch, Ocean Assessments Division, National Oceanic and Atmospheric Administration, Rockville, MD.

Parker, N. M. 1968. A sedimentologic study of Perdido Bay and adjacent offshore environments. Thesis. Florida State University.

Reid, J. M., D. A. MacLeod and M. S. Cresser. 1981. Factors affecting the chemistry of precipitation and river water in an upland catchment. J. Hydrol. 50: 129-145.

Schroeder, W. W. and W. J. Wiseman. 1988. The Mobile Bay estuary: stratification, oxygen depletion and jubilees. In: Hydrodynamics of Estuaries, Vol. II. Estuarine Case Studies. CRC Press, Boca Raton, pp. 41 - 52.

Schropp, S. J., F. G. Lewis, H. L. Windom, J. D. Ryan, F. D. Calder, and L. C. Burney. 1990. Interpretation of metal concentrations in estuarine sediments of Florida using aluminum as a reference element. Estuaries 13: 227 - 235.

Taylor, R. B., M. A. Yanez and T. J. Hull. 1991. Prediction of water quality at Perdido Bay, Florida. Report prepared for Florida Department of Environmental Regulation by Taylor Engineering, Inc., Jacksonville, Florida.

Turvey, N. D. 1975. Water quality in a tropical rain forested catchment. J. Hydrol. 27: 111-125.

Walling, D. E. and I. D. L. Foster. 1978. The 1976 drought and nitrate levels in the River Exe Basin. J. Institution Water Engineers and Scientists 32: 341-352.

Walling, D. E. and P. Kane. 1984. Suspended sediment properties and their geomorphological significance. In: Catchment Experiments in Fluvial Geomorphology, T. P. Burt and D. E. Walling, Editors. Geo Books, Norwich, pp. 311-334.

Walling, D. E. and B. W. Webb. 1981. The reliability of suspended sediment load data. IAHS Publication 133: 177-194.

Walling, D. E. and B. W. Webb. 1983. The dissolved loads of rivers: A global overview. IAHS Publication 141: 3-20.

Walling, D. E. and B. W. Webb. 1984. Local variation of nitrate levels in the Exe Basin, Devon, UK. Beitrage Zur Hydrologie 10: 71-100.

Walling, D. E. and B. W. Webb. 1986a. Solutes in river systems. In: Solute Processes, S.T. Trudgill, Editor. Wiley, Chichester, pp. 251-327.

Walling, D. E. and W. B. Webb. 1986b. Suspended load in gravel bed rivers: UK experience. In: Problems of Sediment Transport in Gravel-Bed Rivers, C.R. Thorne, R. D. Hey and J. C. Bathurst, editors. Wiley, Chichester (in press).

Webb B. W. and D. E. Walling. 1983. Stream solute behaviour in the River Exe basin, Devon, 4 UK. IAHS Publication 414: 153-169.

Webb, B. W. and D. E. Walling. 1985. Nitrate behavior in streamflow from a grassland catchment in Devon, U.K. Water Res. 19: 1005-1016.

APPENDIX A

BENTHIC BIOLOGY RESULTS - SUMMARY[1]

The structure of a benthic community in an estuary is governed by various factors including dissolved oxygen, salinity, nutrient loading, and sediment characteristics. The study of benthic communities has become a valuable component of monitoring strategies, providing information above and beyond that which is obtained through projects focusing only on physical and chemical parameters. When such information is combined with a knowledge of a system-wide water chemistry and hydrography, more effective management plans and regulatory decisions may be developed.

The objective of the benthic biology program was to characterize the benthic macroinvertebrate community of Perdido Bay with respect to spatial and temporal variations and to evaluate the water quality data for chemical and physical factors influencing the distribution of species and diversity of the community. More specifically, the program sought to quantify abundance of individuals and species; determine diversity, evenness and richness of the community in upper, middle, and lower bay segments; examine for seasonal variations of these biological parameters; and compare biological data with data on water chemistry and hydrography for possible associations between changes in community structure and variations in physico-chemical parameters.

Four stations were established for collecting benthic invertebrate samples, one in the upper bay (Station PBB-1 approximately one-half mile west of Bayou Marcus), two in the middle bay (Station PBB-2 approximately one-fourth mile north of the Hwy. 98 bridge and Station PBB-3 between DuPont Point and Manuel Point) and one in the lower bay (Station PBB-4 between

---

[1]The complete report on benthic biology results is available from the ADEM Mobile Field Office, 2204 Perimeter Rd., Mobile, Alabama 36615.

Ross Point and Inerarity Point). Samples were collected eight times during the period March 1988 to February 1989 with each collection occurring within one week of water quality sampling.

At each station a vertical profile of water temperature, salinity, conductivity, and dissolved oxygen was obtained using a Yellow Springs Instrument Co. Model 33 Salinity, Conductivity and Temperature meter and Model 57 Dissolved Oxygen meter. Measurements were taken at 0.5 meter intervals from immediately below the surface of the water to near bottom. This information was combined with profile and nutrient data for determining which of these factors influenced abundance, diversity and distribution of species collected.

Variations in dissolved oxygen (D.O.) and salinity appeared to affect diversity, abundance and richness of the benthic community. These community parameters displayed a negative correlation with the range in D.O. and salinity values observed at each station (i.e., the station with the least variable D.O. and salinity had the most diverse benthic community). Additionally, the stations with lower D.O. and salinity values showed lower diversity and abundance of species.

Concentrations of nutrients also appeared to strongly influence the benthic community of Perdido Bay. Species diversity and evenness showed a significant negative correlation with the concentration of particulate carbon and particulate nitrogen. The stations with the most variable salinity and D.O. and the lowest D.O. values (Stations PBB-1, PBB-2, and PBB-3) also were the stations with the highest concentrations of particulate carbon and nitrogen. Station PBB-4 had the least variation in salinity and D.O., the highest average D.O. and salinity values throughout the year, and the lowest concentrations of particulate organic carbon and nitrogen. This station also had the most diverse benthic community of all stations monitored during the study.

Some variability of the benthic community with respect to the seasons of the year also was observed. During the summer and fall the lowest diversities and numbers of species observed during the study were recorded at the upper and middle bay stations. This corresponded with the occurrence of strong stratification and the lowest values of D.O. measured during the study. Station PBB-4 with a more stable regime of D.O. and salinity and lower concentrations of organic carbon and nitrogen did not exhibit as severe a decline in species abundance and diversity as that observed at the other three stations.

APPENDIX B

METRIC/ENGLISH UNIT CONVERSIONS

1 centimeter (cm) = 0.39 inch

1 meter (m) = 3.28 feet

1 kilometer (km) = 0.62 mile

$1\ km^2 = 0.39\ mi^2$

$1\ cm\ sec^{-1} = 0.022\ mi\ hr^{-1}$

$1\ m^3 = 35.3\ ft^3$

$^{o}C = (^{o}F - 32) \times 0.555$

$(^{o}C \times 1.80) + 32 = {}^{o}F$

APPENDIX C

SEDIMENT CHEMISTRY

Table C.1. Organic compounds measured and detection limits for March 1989 sediment samples.

Table C.2. Metal concentrations in Perdido Bay sediments.

Table C.3. Nutrient concentrations in Perdido Bay sediments.

Table C.4. Sampling stations for FDER priority pollutant survey.

Table C.5. Organics concentrations in FDER priority pollutant survey samples in Elevenmile Creek.

Table C.6. Organics concentrations in FDER priority pollutant survey samples in Jacks Branch, Perdido River basin.

Table C.1. Organic compounds measured and detection limits for March 1989 sediment samples.

Compound	Detection Limit
Chlorinated Pesticides	
Aldrin	1 $\mu g\ kg^{-1}$
alpha-BHC	1
beta-BHC	1
delta-BHC	1
gamma-BHC	1
Chlordane	10
4,4'-DDD	2
4,4'-DDE	2
4,4'-DDT	5
Dieldrin	2
Endosulfan I	2
Endosulfan II	5
Endosulfan sulfate	5
Endrin	2
Endrin Aldehyde	5
Heptachlor	1
Heptachlor epoxide	2
Toxaphene	20
Polychlorinated biphenyls (PCB)	
Aroclor 1016	5 $\mu g\ kg^{-1}$
Aroclor 1221	5
Aroclor 1232	5
Aroclor 1242	5
Aroclor 1248	5
Aroclor 1254	5
Aroclor 1260	5
Aliphatic hydrocarbons	
C10 aliphatics	50 $\mu g\ kg^{-1}$
C11 aliphatics	50
C12 aliphatics	50
C13 aliphatics	50
C14 aliphatics	50
C15 aliphatics	50
C16 aliphatics	50
C17 aliphatics	50
C18 aliphatics	50
C19 aliphatics	50
C20 aliphatics	50
C21 aliphatics	50
C22 aliphatics	50
C23 aliphatics	50

Table C.1. Continued.

Compound	Detection Limit
C24 aliphatics	50 $\mu g\ kg^{-1}$
C25 aliphatics	50
C26 aliphatics	100
C27 aliphatics	100
C28 aliphatics	100
C29 aliphatics	100
C30 aliphatics	100
Polynuclear Aromatic Hydrocarbons (PAH)	
Acenapthene	400 $\mu g\ kg^{-1}$
Acenapthylene	100
Anthracene	30
Benzo(a)anthracene	50
Benzo(a)pyrene	200
Benzo(b)fluoranthene	50
Benzo(g,h,i)perylene	100
Benzo(k)fluoranthene	50
Chrysene	50
Dibenzo(a,h)anthracene	600
Fluoranthene	50
Fluorene	150
Indeno(1,2,3-cd)pyrene	50
Napthalene	500
Pyrene	50
Phenanthrene	50
1-Methylnaphthalene	400
2-Methylnaphthalene	400
Benzonitrile	400
Quinoline	1500
Quinaldine	150
8-Methylquinaline	100
7,8-Benzoquinoline	50
2,4-Dimethylquinoline	600
Acridine	50
Carbazole	75

Table C.2. Metal concentrations in Perdido Bay sediments.

Station	Core Depth (cm)	Al	As	Cd	Cr	Cu	Pb	Ni	Zn	Hg
					(mg kg^{-1})					
August 1987										
PRR-3	0 - 2[a]	114000	56.5	0.46	96.0	40.0	60.5	23.0	195	0.11
PRR-3	5 - 7	110000	46.0	0.53	87.0	52.0	57.0	21.0	190	0.07
PRR-3	11 - 13	96000	63.0	0.46	110.0	42.0	52.0	27.0	120	0.11
PRR-3	15 - 17	99000	42.0	0.47	100.0	43.0	58.0	31.0	210	0.07
PRR-3	20 - 22	104000	47.0	0.42	97.0	42.0	59.0	20.0	230	0.06
EMC-2	0 - 2	17000	2.9	0.08	18.0	5.0	4.8	2.7	45	0.02
EMC-2	5 - 7	14000	3.4	0.07	14.0	4.2	5.7	3.6	37	0.02
EMC-2	11 - 13	18000	3.0	0.06	17.0	5.8	5.7	2.7	32	0.01
EMC-2	15 - 17	16000	3.6	0.07	19.0	5.6	5.5	2.9	27	0.01
PRB-3	0 - 2	45000	16.0	0.38	56.0	14.5	23.0	13.2	70	0.04
PRB-3	20 - 22	33000	10.0	0.41	54.0	14.0	17.0	6.2	91	0.05
PRB-4	0 - 2	41500	14.5	0.54	59.0	12.8	15.3	11.3	56	0.04
PRB-4	20 - 22	54000	17.0	0.32	89.0	21.0	21.0	21.0	93	0.02
PRB-6	0 - 2	81000	13.5	0.43	106.0	30.0	24.5	23.5	69	0.05
PRB-6	20 - 22	83000	11.0	0.37	107.0	22.0	28.0	20.0	83	0.04
PRB-9	0 - 2	69500	37.5	0.25	70.0	25.0	33.0	16.0	99	0.13
PRB-9	5 - 7	57000	37.0	0.31	97.0	21.0	32.0	12.0	110	0.07
PRB-9	10 - 12	54000	36.0	0.38	65.0	27.0	36.0	17.0	110	0.07
PRB-9	15 - 17	59000	32.0	0.36	62.0	23.0	32.0	18.0	92	0.03
PRB-9	20 - 22	56000	30.0	0.24	67.0	27.0	27.0	21.0	110	0.03
PRB-11	0 - 2	60500	4.8	0.35	66.0	24.5	25.0	13.0	115	0.04
PRB-11	5 - 7	59000	4.2	0.28	57.0	23.0	24.0	12.0	110	0.04
PRB-11	10 - 12	52000	4.7	0.37	72.0	21.0	32.0	19.0	120	0.04
PRB-11	15 - 17	54000	5.3	0.32	73.0	21.0	24.0	14.0	100	0.04
PRB-11	20 - 22	52000	5.9	0.35	70.0	18.0	25.0	19.0	97	0.05
March 1989										
PRR-4	NA[b]	1900	1.2[c]	<0.20	17.5	6.5	9.3	5.0	25	<0.086
STX-1	NA	18500	17.5	<0.17	17.0	6.2	8.5	5.6	22	<0.058
BWR-1	NA	20000	36.0	0.31[c]	13.0	7.2	14.0	5.0	23	<0.082
EMC-4	NA	5050	7.9	0.14[c]	6.6	4.1	4.2	2.0	28	0.069
BMC-1	NA	11000	14.0	0.42	13.0	15.0	46.0	4.6	53	0.17

[a]Metal concentrations for 0 - 2 cm core depth from August 1988 and surficial grab samples from March 1989 are mean values of replicate samples. Other values are results from single samples.

[b]NA = Not applicable. Samples were surficial (ca. 0 - 5 cm) sediments from Ponar grab.

[c]Value is for single replicate, second replicate was below detection limit.

Table C.3. Nutrient concentrations in Perdido Bay sediments.

Station	Core Depth (cm)	TOC (mg-C kg^{-1})	TKN (mg-N kg^{-1})	TP (mg-P kg^{-1})
August 1988				
PRR-3	0 - 2[a]	75000	3900	1985
PRR-3	5 - 7	21000	2300	260
PRR-3	11 - 13	39000	3700	300
PRR-3	15 - 17	34000	2900	270
PRR-3	20 - 22	46000	2200	310
EMC-2	0 - 2	13000	1550	125
EMC-2	5 - 7	16000	1400	110
EMC-2	11 - 13	14000	1200	130
EMC-2	15 - 17	11000	730	110
PRB-2	20 - 22	22000	1900	130
PRB-3	0 - 2	44500	5250	505
PRB-3	20 - 22	14000	3600	130
PRB-4	0 - 2	44500	5150	915
PRB-4	20 - 22	40000	3200	860
PRB-5	0 - 2	5950	290	112
PRB-5	20 - 22	4900	400	110
PRB-6	0 - 2	72500	6550	760
PRB-6	20 - 22	79000	8100	510
PRB-7	0 - 2	24500	2950	630
PRB-7	5 - 7	23000	2900	360
PRB-7	11 - 13	19000	1400	260
PRB-7	15 - 17	14000	1100	230
PRB-7	20 - 22	14000	920	200
PRB-8	0 - 2	65000	8500	925
PRB-8	5 - 7	67000	5100	755
PRB-8	11 - 13	62000	4300	750
PRB-8	15 - 17	53000	1900	620
PRB-8	20 - 22	31000	1600	720
PRB-9	0 - 2	65500	7450	720
PRB-9	5 - 7	56000	6700	740
PRB-9	11 - 13	57000	4200	730
PRB-9	15 - 17	68000	4100	460
PRB-9	20 - 22	53000	3600	330
PRB-10	0 - 2	44000	4850	810
PRB-10	5 - 7	47000	4200	750
PRB-10	11 - 13	44000	4200	740
PRB-10	15 - 17	51000	3200	460
PRB-10	20 - 22	42000	2700	320

Table C.3. Continued.

Station	Core Depth (cm)	TOC (mg-C kg^{-1})	TKN (mg-N kg^{-1})	TP (mg-P kg^{-1})
PRB-11	0 - 2	54000	6400	520
PRB-11	5 - 7	55000	5000	600
PRB-11	11 - 13	47000	5100	680
PRB-11	15 - 17	50000	4700	590
PRB-11	20 - 22	45000	4200	760
March 1988				
PRR-4	NA[b]	70500	2600	460
STX-1	NA	35000	1400	260
BWR-1	NA	67500	2150	505
EMC-1	NA	22500	770	230
BMC-1	NA	95000	6050	236

[a]Metal concentrations for 0 - 2 cm core depth from August 1988 and surficial grab samples from March 1989 are mean values of replicate samples. Other values are results from single samples.

[b]NA = Not applicable. Samples were surficial (ca. 0 - 5 cm) sediments from Ponar grab.

Table C.4. Sampling stations for FDER priority pollutant survey[a].

Station Code	Latitude/ Longitude	Description	Date Sampled
ESC-07-01	30°28'33" 87°21'25"	Champion Paper Co./Eleven Mile Cr. Eleven Mile Cr. W of USN Saufley Field [1.8 m deep]	06/27/89
ESC-07-02	30°28'33" 87°21'46"	Champion Paper Co./Eleven Mile Cr. Eleven Mile Cr. d/s Sta. 01 just u/s Confl. with Hurst Br. Cr. [0.6 m deep]	06/27/89
ESC-07-03	30°28'05" 87°21'55"	Champion Paper Co./Eleven Mile Cr. Eleven Mile Cr. d/s Sta. 02 on inside of wide curve [4.5 m deep]	06/27/89
ESC-07-04	30°27'22" 87°22'36"	Champion Paper Co./Eleven Mile Cr Mouth of Eleven Mile Cr. at Perdido Bay [2.1 m deep]	06/27/89
ESC-07-05	30°27'00" 87°22'15"	Champion Paper Co./Eleven Mile Cr. 200 m into Perdido Bay SE of mouth of Eleven Mile Creek [1.5 m deep]	06/27/89
ESC-07-10		Field duplicate of ESC-07-05	06/27/89
ESC-07-06	30°34'59" 87°19'42"	Champion Paper Co./Eleven Mile Cr. NW Tributary to Eleven Mile Cr. at Hwy 297A Br. [0.4 m deep]	06/28/89
ESC-07-07	30°34'22" 87°19'18"	Champion Paper Co./Eleven Mile Cr. 15 m N of Hwy 86 Br. just u/s of Cantonment STP Outfall [0.75 m deep]	06/28/89
ESC-07-08	30°34'21" 87°19'18"	Champion Paper Co./Eleven Mile Cr. 100 m d/s Hwy 86 Br. at Champion Discharge "Boil" [0.9 m deep]	06/28/89
ESC-07-09	30°32'29" 87°19'48"	Champion Paper Co./Eleven Mile Cr. 1.6 km d/s Sta. 08 at Hwy 297A Br. [0.6 m deep]	06/28/89
ESC-08-01	30°31'17" 87°26'51"	DuBose Oil Prod./Jacks Br. Perdido R. 100 m d/s Hwy 90 Br. [5.1 m deep]	06/27/89
ESC-08-02	30°27'00" 87°23'21"	DuBose Oil Prod./Jacks Br. Mouth of Perdido R. at Perdido Bay [2.4 m deep]	06/27/89
ESC-08-03	30°37'12" 87°22'30"	DuBose Oil Prod./Jacks Br. Drainage Ditch from Dubose at rear of Whitehurst Property 701 Hwy 97 [7.6 cm deep]	06/27/89
ESC-08-10		Field Duplicate of ESC-08-03	06/27/89
ESC-08-04	30°37'11" 87°22'38"	DuBose Oil Prod./Jacks Br. Drainage Ditch from DuBose Pond at Base of Dam on Whitehurst Property [7.6 cm deep]	06/27/89
ESC-08-05	30°37'11" 87°22'38"	DuBose Oil Prod./Jacks Br. Drainage Ditch from DuBose Pond 15 m d/s from Station 04 [7.6 cm deep]	06/27/89
ESC-08-06	30°37'48" 87°22'55"	DuBose Oil Prod./Jacks Br. Creek u/s of Confl. w/ Jacks Br. 1.6 km d/s from Station 05 [15 cm deep]	06/27/89
ESC-08-07	30°38'13" 87°22'24"	DuBose Oil Prod./Jacks Br. Jacks Br. at Hwy 97 Br. [1.7 m deep]	06/27/89
ESC-08-08	30°37'43" 87°23'13"	DuBose Oil Prod./Jacks Br. Jacks Br. off Old Br. Rd. 700 m d/s Station 07 [0.45 m deep]	06/27/89
ESC-08-09	30°36'10" 87°24'09"	DuBose Oil Prod./Jacks Br. Perdido R. 100 m u/s Hwy 184 Br. [0.6 m deep]	06/27/89

[a]From Delfino, 1990.

Table C.5. Organics concentrations (mg kg^{-1})[a] in FDER priority pollutant survey samples from Elevenmile Creek.[b]

Organic priority pollutant	Station ESC07-01	ESC07-02	ESC07-03	ESC07-04	ESC07-05	ESC07-06	ESC07-07	ESC07-08	ESC07-09	ESC07-10
2-chlorophenol	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U
2,4-dichlorophenol	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U
2,4-dimethylphenol	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U
4,6-dinitro-o-cresol (2-methyl-4,6-dinitrophenol)	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U
2,4-dinitrophenol	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U
2-nitrophenol	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U
4-nitrophenol	1.36 U	1.36 U	1.36 M	1.36 U	1.36 U	1.36 U	1.36 U	1.36 U	1.36 U	1.36 U
p-chloro-m-cresol (4-chloro-3-methylphenol)	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U
pentachlorophenol	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U
phenol	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
2,4,6-trichlorophenol	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U
acenaphthene	0.08 U	0.08 U	0.08 M	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U
acenaphthylene	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
anthracene	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
benzidine	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U
benzo(a)anthracene	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U
benzo(a)pyrene	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
3,4-benzofluoranthene (benzo(b)fluoranthene)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
benzo(ghi)perylene	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
benzo(k)fluoranthene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
bis(2-chloroethoxy)methane	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U
bis(2-chloroethyl)ether	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
bis(2-chloroisopropyl)ether	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U
bis(2-ethylhexyl)phthalate	0.06 M	0.06 M	0.06 M	0.06 M	0.06 M	0.06 M	0.06 M	0.06 M	0.06 M	0.06 M
4-bromophenyl phenyl ether	0.37 U	0.37 M	0.37 U	0.37 U	0.37 U	0.37 U	0.37 U	0.37 M	0.37 U	0.37 U
butyl benzyl phthalate	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U
2-chloronaphthalene	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U
4-chlorophenyl phenyl ether	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
chrysene	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U
dibenzo(a,h)anthracene	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U
1,2-dichlorobenzene	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U
1,3-dichlorobenzene	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U
1,4-dichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3,3-dichlorobenzidine	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
diethyl phthalate	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U
dimethyl phthalate	0.09 U	0.09 M	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 M	0.09 U	0.09 U
di-n-butyl phthalate	0.03 M	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 M
2,4-dinitrotoluene	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U
2,6-dinitrotoluene	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U
di-n-octyl phthalate	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U
1,2-diphenylhydrazine (azobenzene)	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U
fluoranthene	0.05 U	0.05 U	0.05 M	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
fluorene	0.08 U	0.08 U	0.08 M	0.08 U	0.08 U	0.08 U	0.08 U	0.08 M	0.08 U	0.08 U
hexachlorobenzene	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U
hexachlorobutadiene	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U
hexachlorocyclopentadiene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
hexachloroethane	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U
indeno(1,2,3-c,d)pyrene	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U
isophorone	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U
naphthalene	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U
nitrobenzene	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U
N-nitrosodimethylamine	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-nitrosodi-n-propylamine	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U
N-nitrosodiphenylamine	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
phenanthrene	0.05 U	0.05 M	0.05[c]	0.05 U	0.05 U	0.05 U	0.05 U	0.05 M	0.05 U	0.05 U
pyrene	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U
1,2,4-trichlorobenzene	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U
aldrin	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U
alpha-BHC	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U
beta-BHC	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U
gamma-BHC	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U
delta-BHC	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
chlordane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4,4'-DDT	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U
4,4'-DDE	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
4,4'-DDD	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U
dieldrin	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U
alpha-endosulfan	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
beta-endosulfan	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
endosulfan sulfate	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U
endrin	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U
endrin aldehyde	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
heptachlor	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U
heptachlor epoxide	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U

Table C.5. Continued.

Organic priority pollutant	Station									
	ESC07-01	ESC07-02	ESC07-03	ESC07-04	ESC07-05	ESC07-06	ESC07-07	ESC07-08	ESC07-09	ESC07-10
PCB-1242	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U
PCB-1254	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U
PCB-1221	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1232	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1248	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1260	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1016	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Toxaphene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
benzo(b+k)fluoranthene	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U

[a]Codes indicate as follows:

U -> Indicates material was analyzed for but not detected. Value indicates a calculated detection limit.

M -> Indicates presence of material was verified but not quantified.

ND -> Indicates no calculated detection limit.

na -> Indicates no anaylsis performed.

[b]From Delfino, 1990.

[c]Concentrations above detection limit are in bold type.

Table C.6. Organics concentrations (mg kg^{-1})[a] in FDER priority pollutant survey samples from Jacks Branch, Perdido River basin.[b]

Organic priority pollutant	Station ESC08-01	ESC08-02	ESC08-03	ESC08-04	ESC08-05	ESC08-06	ESC08-07	ESC08-08	ESC08-09	ESC08-10
2-chlorophenol	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U	0.25 U
2,4-dichlorophenol	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U	0.39 U
2,4-dimethylphenol	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U	0.35 U
4,6-dinitro-o-cresol (2-methyl-4,6-dinitrophenol)	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U	1.49 U
2,4-dinitrophenol	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U	14.29 U
2-nitrophenol	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U	0.48 U
4-nitrophenol	1.36 U	1.36 U	1.36 M	1.36 U	1.36 U	1.36 U	1.36 U	1.36 U	1.36 U	1.36 U
p-chloro-m-cresol (4-chloro-3-methylphenol)	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U
pentachlorophenol	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U	1.30 U
phenol	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
2,4,6-trichlorophenol	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U	0.47 U
acenaphthene	0.08 U	0.08 U	0.08 U	0.08 U	0.08 M	0.08 U	0.08 M	0.08 U	0.08 U	0.08 U
acenaphthylene	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
anthracene	0.05 U	0.05 U	0.05 U	0.05 U	0.27	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
benzidine	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U	0.49 U
benzo(a)anthracene	0.04 U	0.04 U	0.04 U	0.04 U	0.04	0.04 U	0.04 U	0.04 M	0.04 U	0.04 U
benzo(a)pyrene	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
3,4-benzofluoranthene (benzo(b)fluoranthene)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
benzo(ghi)perylene	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
benzo(k)fluoranthene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
bis(2-chloroethoxy)methane	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U
bis(2-chloroethyl)ether	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
bis(2-chloroisopropyl)ether	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U	1.37 U
bis(2-ethylhexyl)phthalate	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U
4-bromophenyl phenyl ether	0.37 M	0.37 M	0.37 U	0.37 U	0.37 U	0.37 U	0.37 U	0.37 M	0.37 U	0.37 U
butyl benzyl phthalate	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U
2-chloronaphthalene	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U	0.11 U
4-chlorophenyl phenyl ether	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
chrysene	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U
dibenzo(a,h)anthracene	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U
1,2-dichlorobenzene	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U
1,3-dichlorobenzene	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U	0.22 U
1,4-dichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3,3-dichlorobenzidine	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
diethyl phthalate	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U	0.08 U
dimethyl phthalate	0.09 M	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U	0.09 U
di-n-butyl phthalate	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 M
2,4-dinitrotoluene	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U	0.42 U
2,6-dinitrotoluene	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U	0.52 U
di-n-octyl phthalate	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U	0.03 U
1,2-diphenylhydrazine (azobenzene)	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U
fluoranthene	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U	0.05 U
fluorene	0.08 M	0.08 U	0.08 M	0.08 U	0.08 M	0.08 U	0.08 M	0.08 M	0.08 U	0.08 U
hexachlorobenzene	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U	0.18 U
hexachlorobutadiene	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U	0.45 U
hexachlorocyclopentadiene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
hexachloroethane	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U
indeno(1,2,3-c,d)pyrene	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U
isophorone	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U	0.07 U
naphthalene	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U	0.06 U
nitrobenzene	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U
N-nitrosodimethylamine	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-nitrosodi-n-propylamine	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U	0.17 U
N-nitrosodiphenylamine	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
phenanthrene	**0.05**[c]	0.05 U	0.05 U	**0.06**	**0.09**	0.05 U	**0.10**	0.05 M	0.05 U	**0.19**
pyrene	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U
1,2,4-trichlorobenzene	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U	0.29 U
aldrin	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U	0.19 U
alpha-BHC	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U	0.28 U
beta-BHC	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U
gamma-BHC	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U	0.36 U
delta-BHC	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
chlordane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4,4'-DDT	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U	0.30 U
4,4'-DDE	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U	0.21 U
4,4'-DDD	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U	0.13 U
dieldrin	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U	0.14 U
alpha-endosulfan	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
beta-endosulfan	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
endosulfan sulfate	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U	0.55 U
endrin	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U	1.90 U
endrin aldehyde	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
heptachlor	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U	0.33 U
heptachlor epoxide	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U	0.40 U

Table C.6. Continued.

Organic priority pollutant	Station									
	ESC08-01	ESC08-02	ESC08-03	ESC08-04	ESC08-05	ESC08-06	ESC08-07	ESC08-08	ESC08-09	ESC08-10
PCB-1242	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U	12.68 U
PCB-1254	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U	9.89 U
PCB-1221	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1232	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1248	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1260	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCB-1016	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Toxaphene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
benzo(b+k)fluoranthene	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U

[a]Codes indicate as follows:

U -> Indicates material was analyzed for but not detected. Value indicates a calculated detection limit.

M -> Indicates presence of material was verified but not quantified.

ND -> Indicates no calculated detection limit.

na -> Indicates no anaylsis performed.

[b]From Delfino, 1990.

[c]Concentrations above detection limit are in bold type.

APPENDIX D

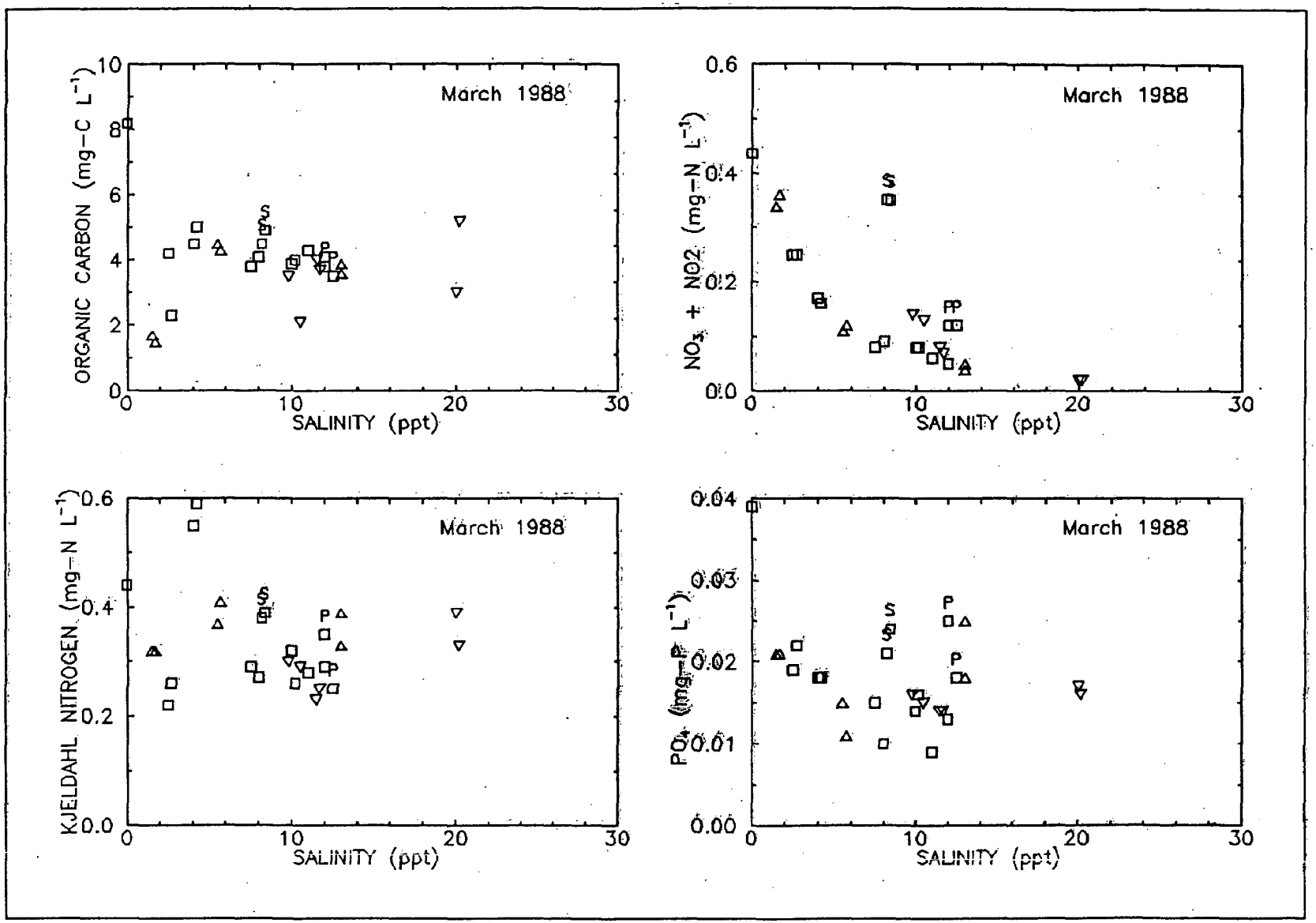
DISSOLVED AND PARTICULATE NUTRIENT CONCENTRATIONS PLOTTED AGAINST SALINITY

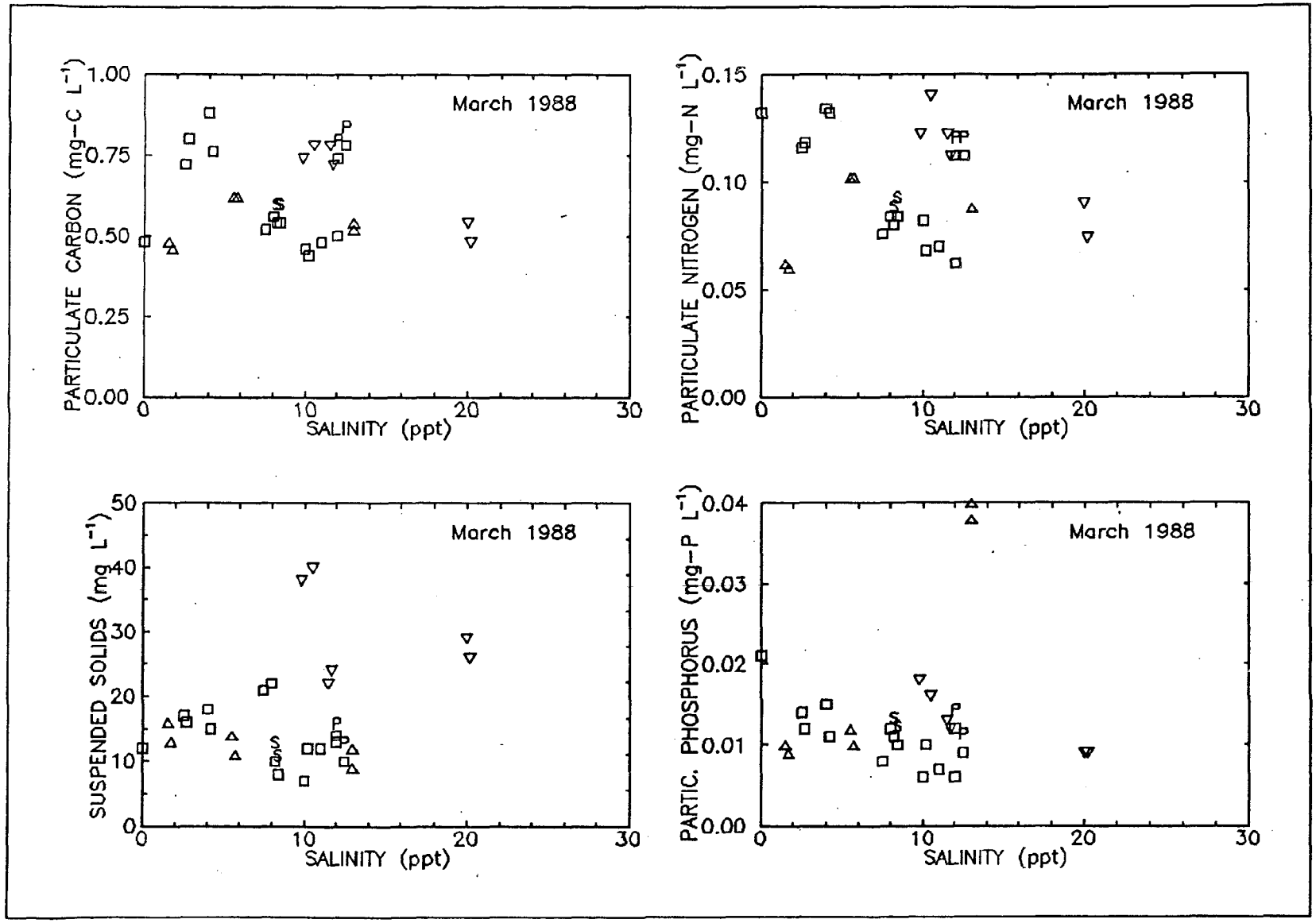
All concentrations are in mg L^{-1} (see Table 6.2) and salinity is in parts per thousand.

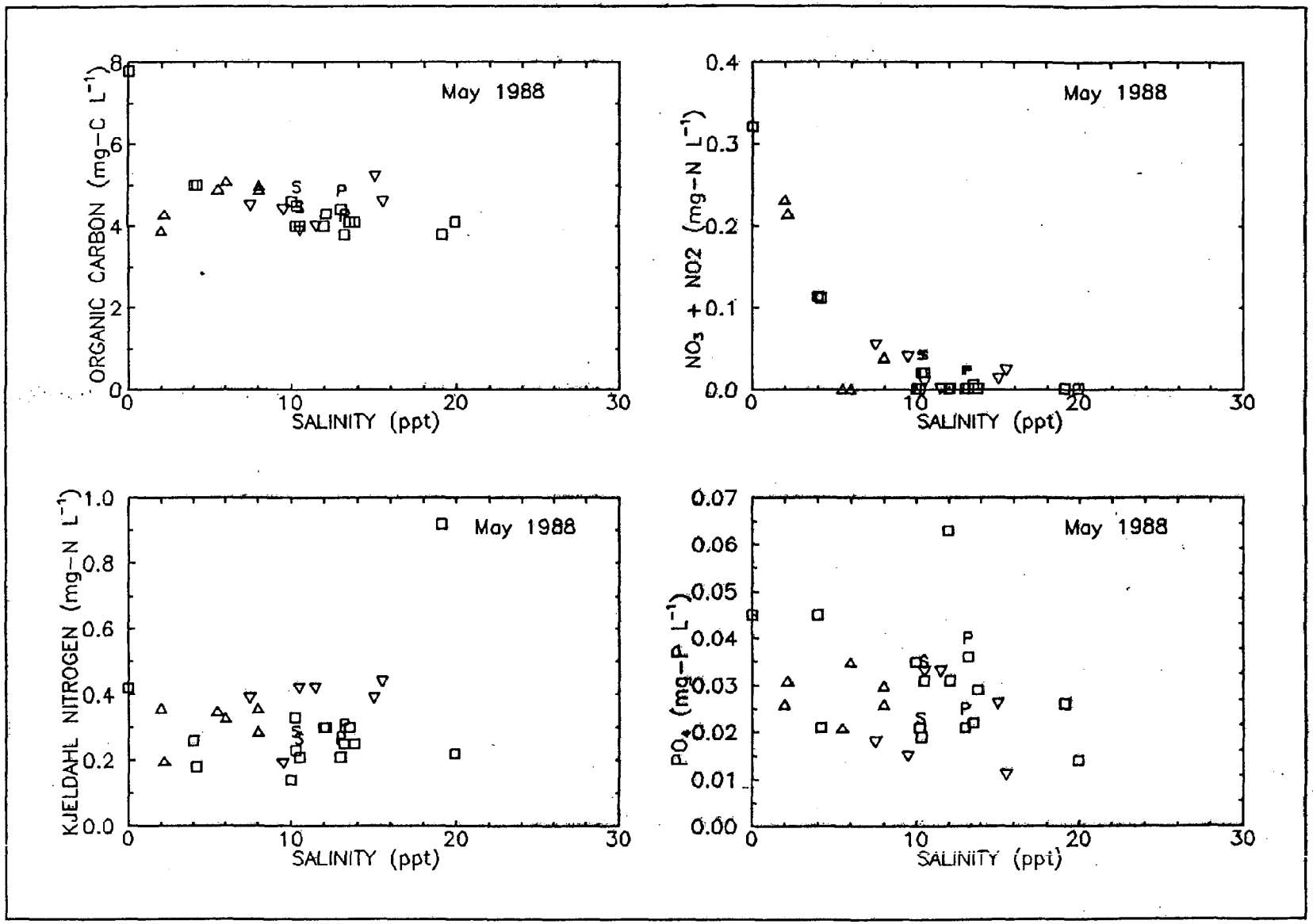
Explanation of Symbols:

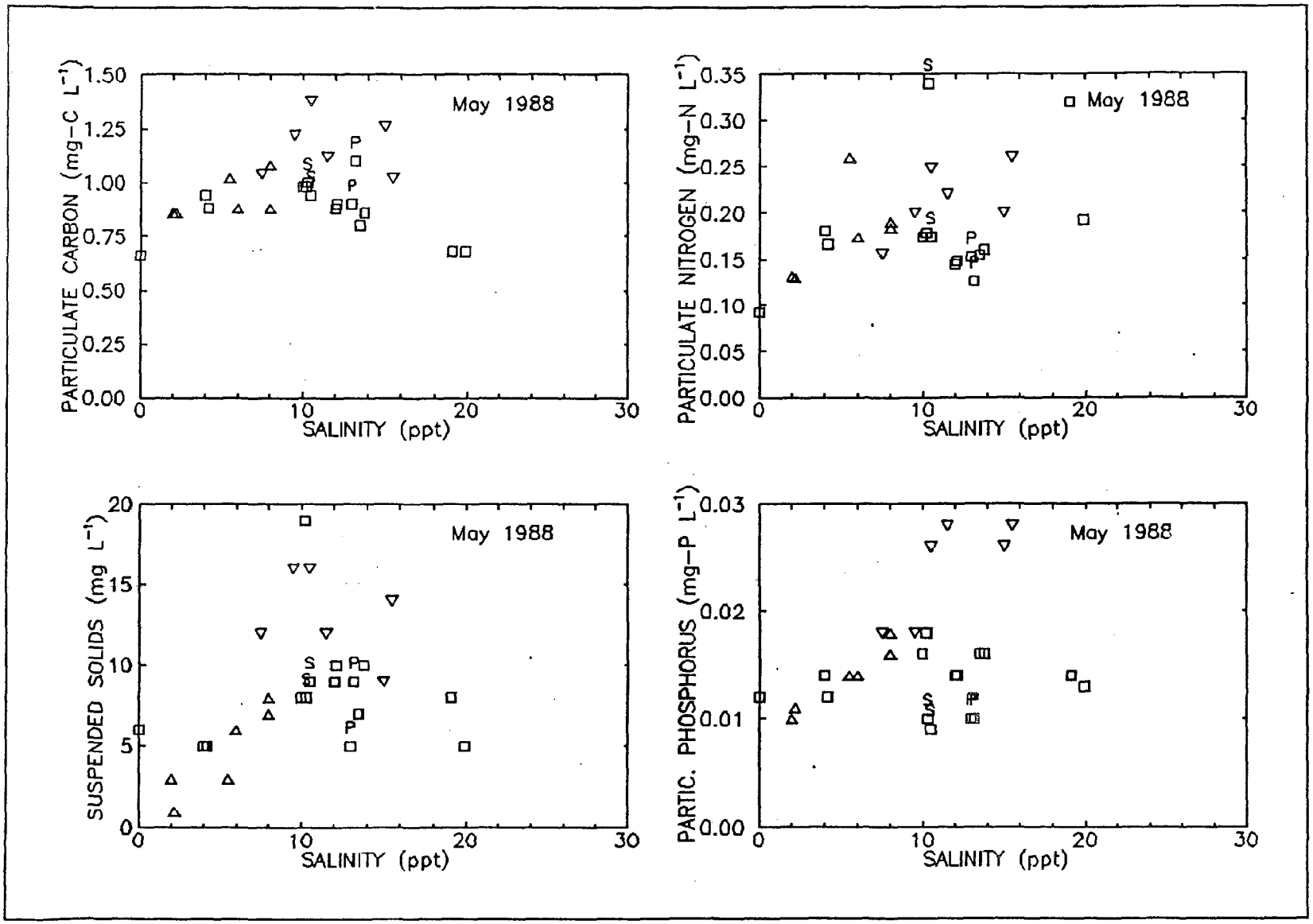
Square - sample collected from mid-depth (no stratification).
Triangle - near surface sample (stratification)
Inverted triangle - near-bottom sample (stratification).
SD - Soldier Creek
PM - Palmetto Creek

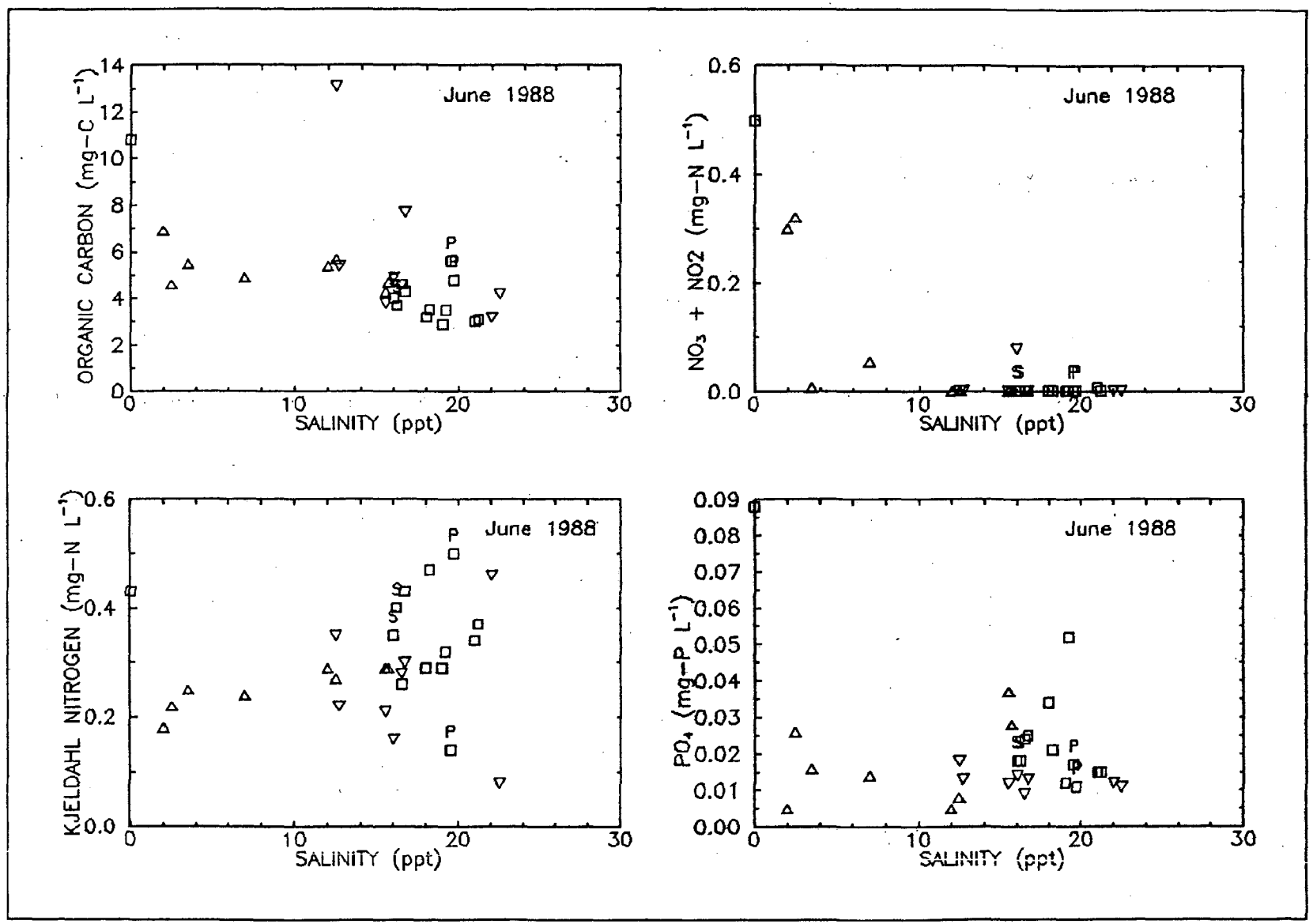
Zero salinity value is weighted mean from the five tributary stations.

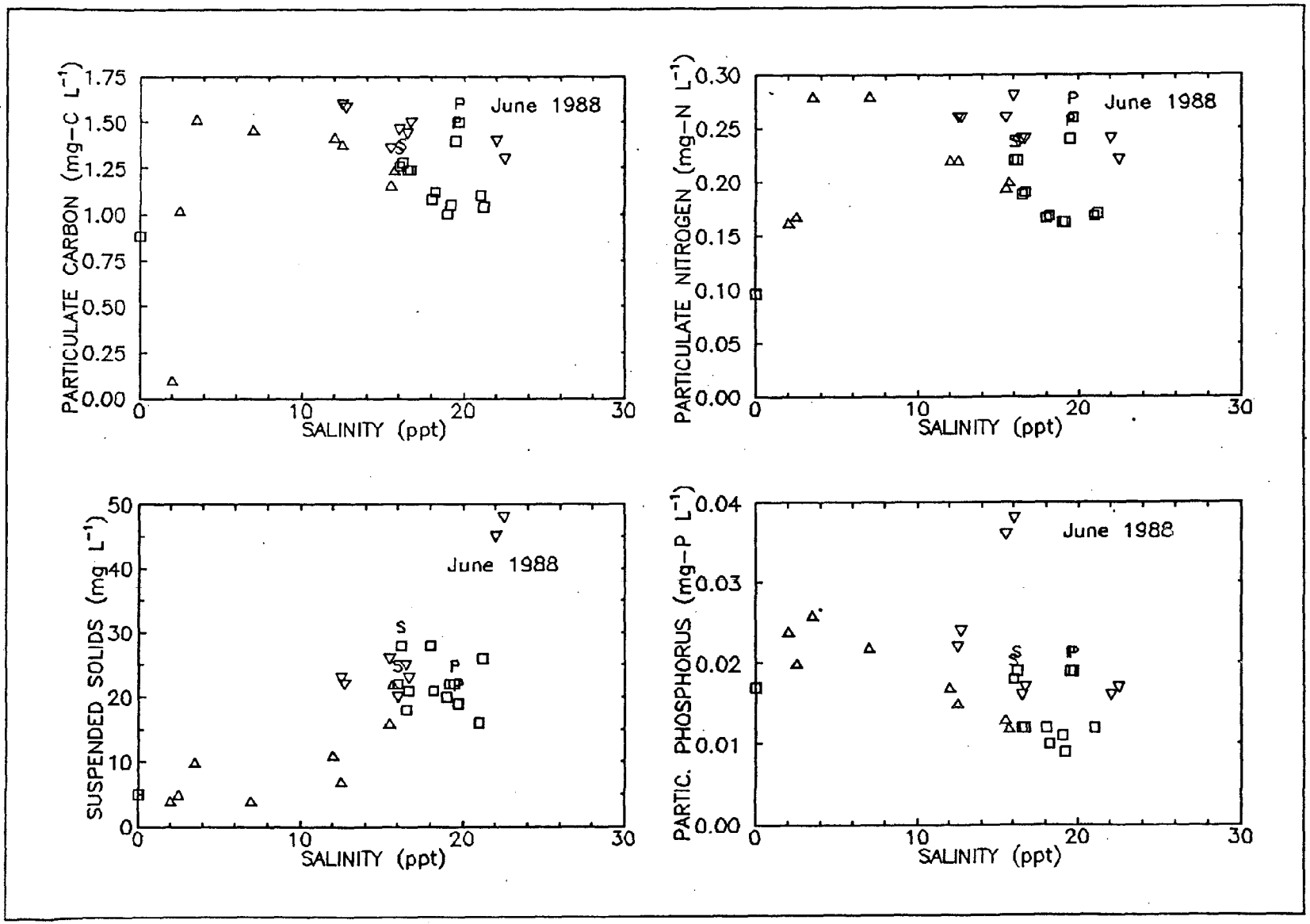

March 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
March 1988
NO_3 + NO_2 (mg-N L^{-1})
SALINITY (ppt)
March 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
March 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

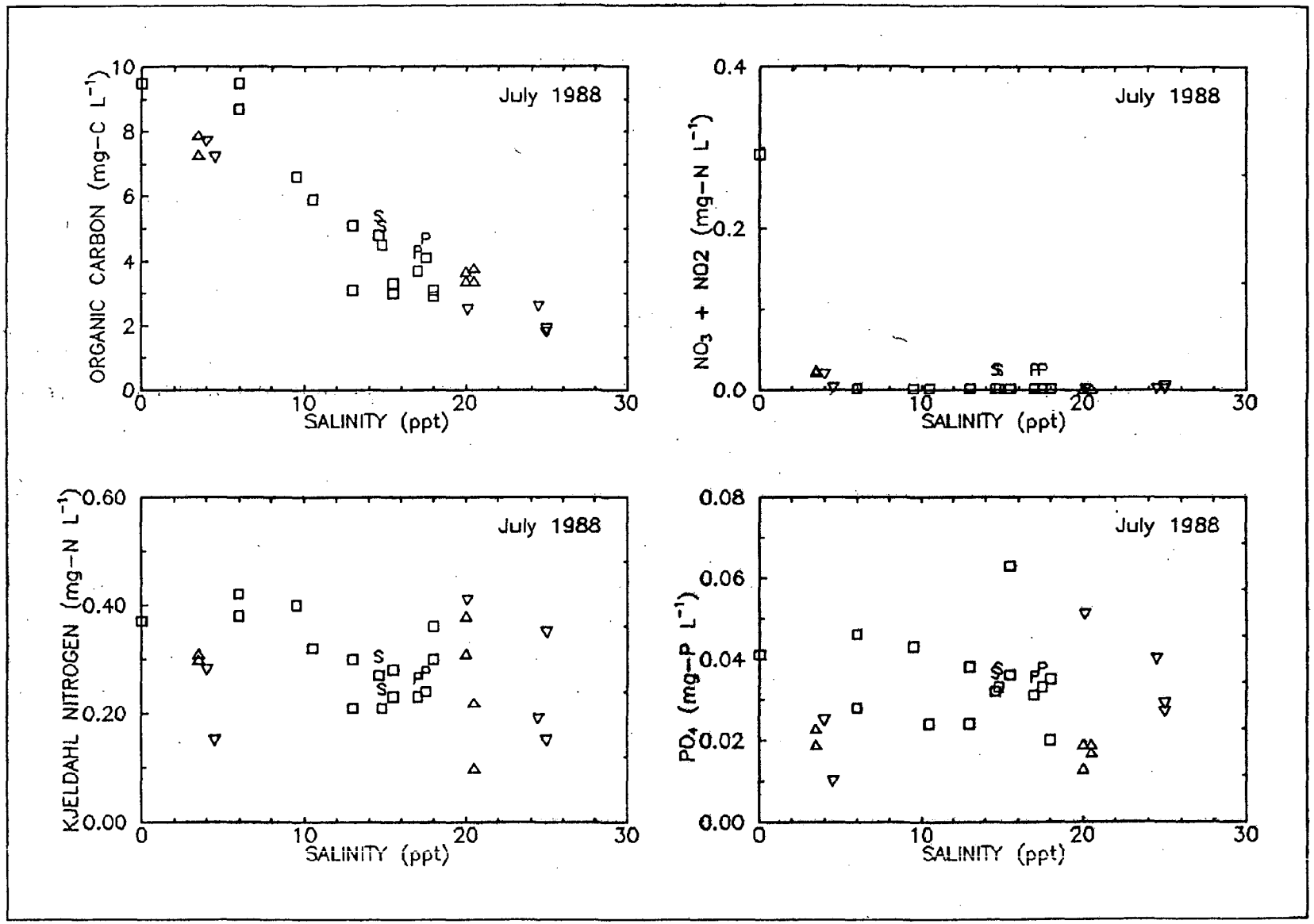

March 1988
PARTICULATE CARBON (mg-C L^{-1})
1.00
0.75
0.50
0.25
0.00
0
10
20
30
SALINITY (ppt)
March 1988
PARTICULATE NITROGEN (mg-N L^{-1})
0.15
0.10
0.05
0.00
0
10
20
30
SALINITY (ppt)
March 1988
SUSPENDED SOLIDS (mg L^{-1})
50
40
30
20
10
0
0
10
20
30
SALINITY (ppt)
March 1988
PARTIC. PHOSPHORUS (mg-P L^{-1})
0.04
0.03
0.02
0.01
0.00
0
10
20
30
SALINITY (ppt)

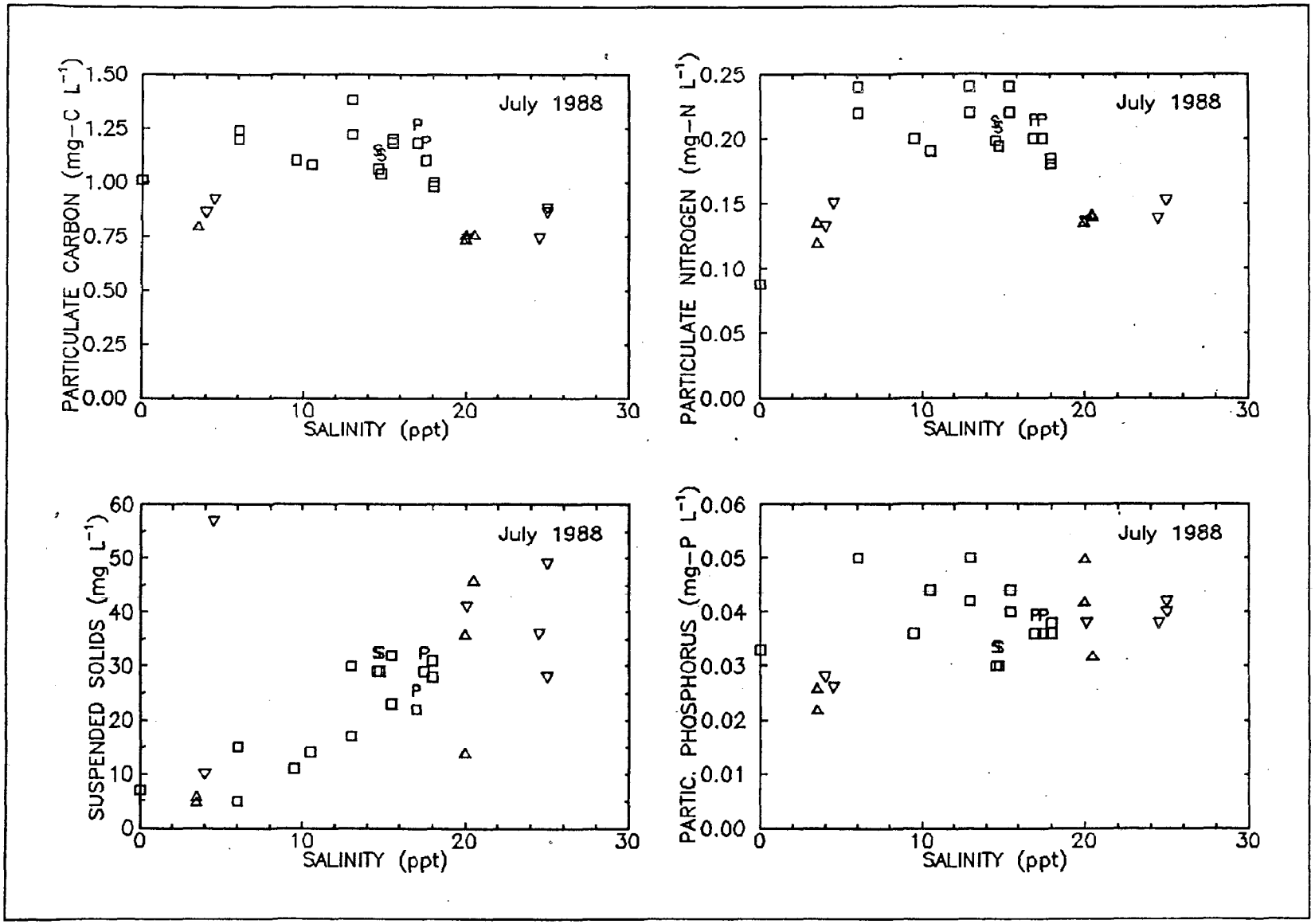

May 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
May 1988
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
May 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
May 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

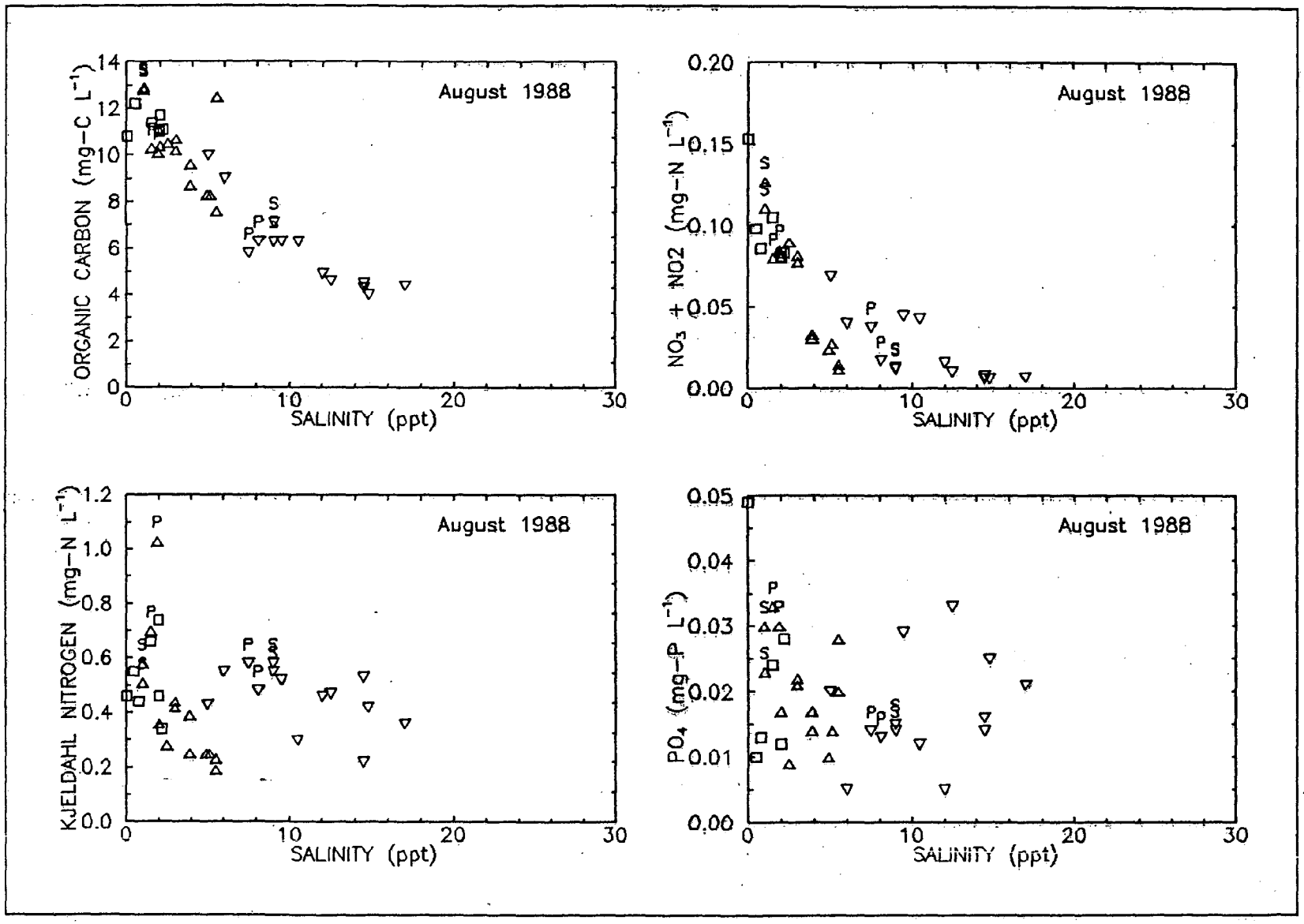

PARTICULATE CARBON (mg-C L⁻¹)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
May 1988
SALINITY (ppt)
0
10
20
30
PARTICULATE NITROGEN (mg-N L⁻¹)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
May 1988
SALINITY (ppt)
SUSPENDED SOLIDS (mg L⁻¹)
20
15
10
5
0
May 1988
SALINITY (ppt)
PARTIC. PHOSPHORUS (mg-P L⁻¹)
0.03
0.02
0.01
0.00
May 1988
SALINITY (ppt)

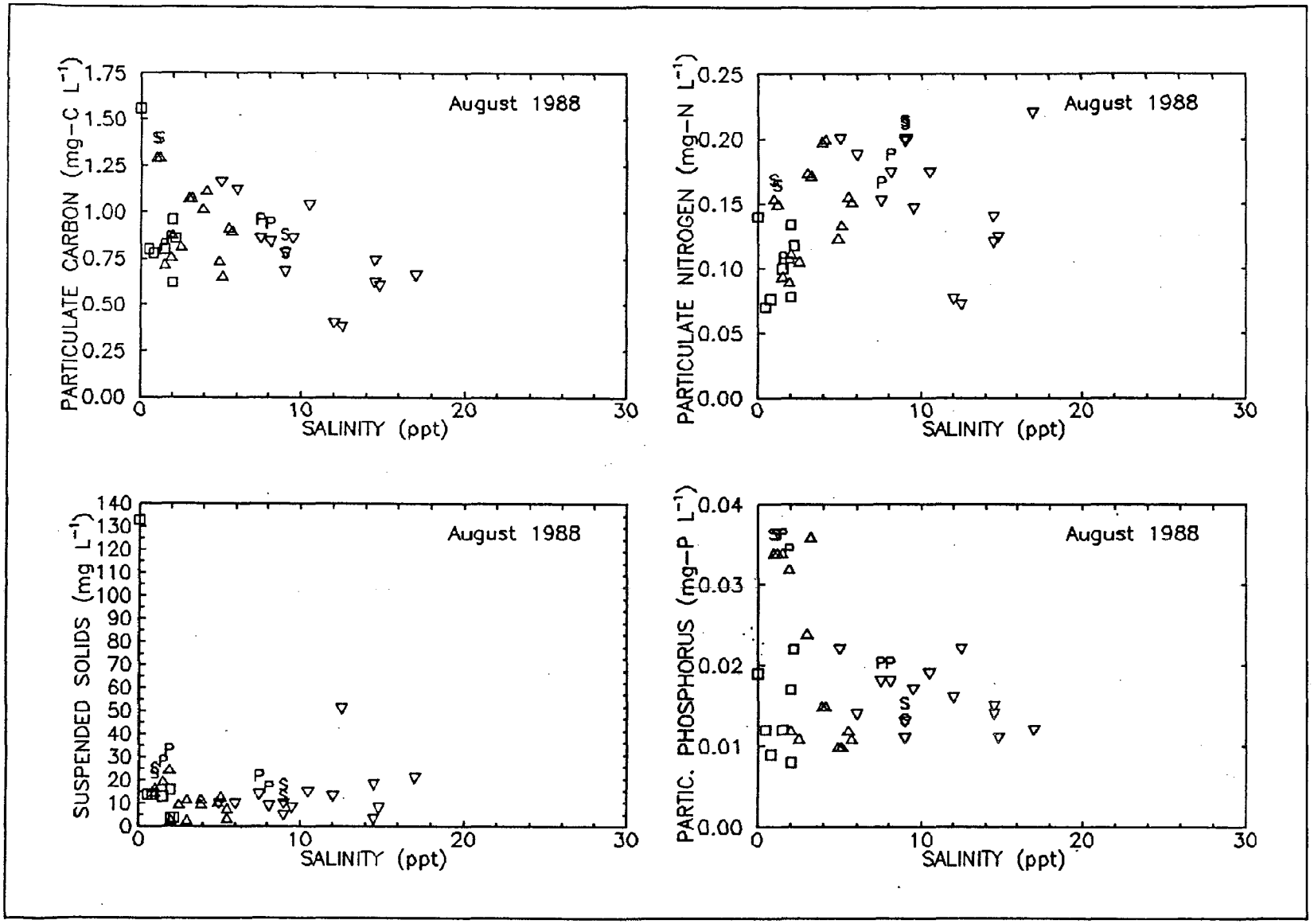

June 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
June 1988
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
June 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
June 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

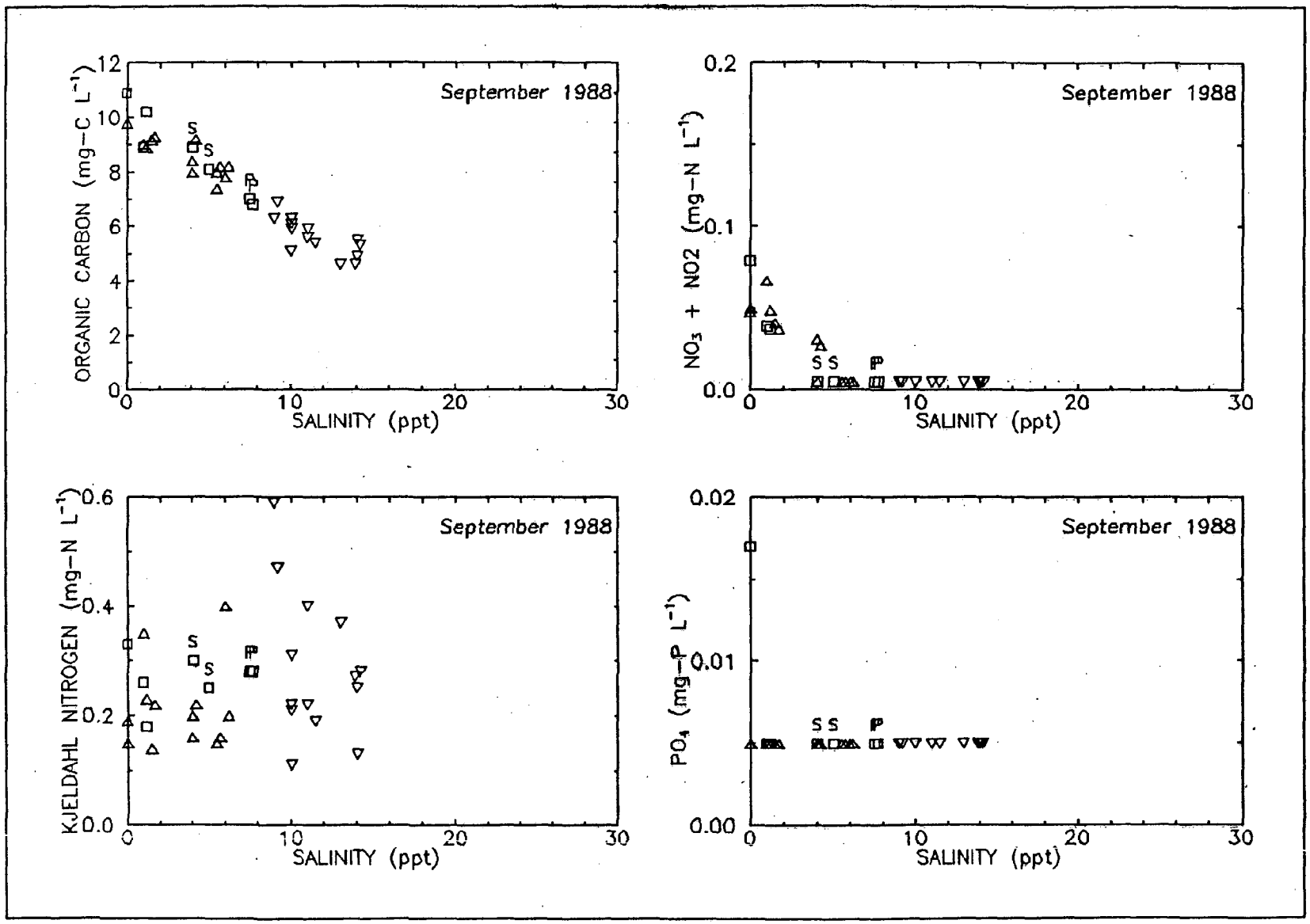

PARTICULATE CARBON (mg-C L^{-1})
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
10
20
30
SALINITY (ppt)
June 1988
PARTICULATE NITROGEN (mg-N L^{-1})
0.30
0.25
0.20
0.15
0.10
0.05
0.00
SUSPENDED SOLIDS (mg L^{-1})
50
40
30
20
10
PARTIC. PHOSPHORUS (mg-P L^{-1})
0.04
0.03
0.02
0.01
P
S

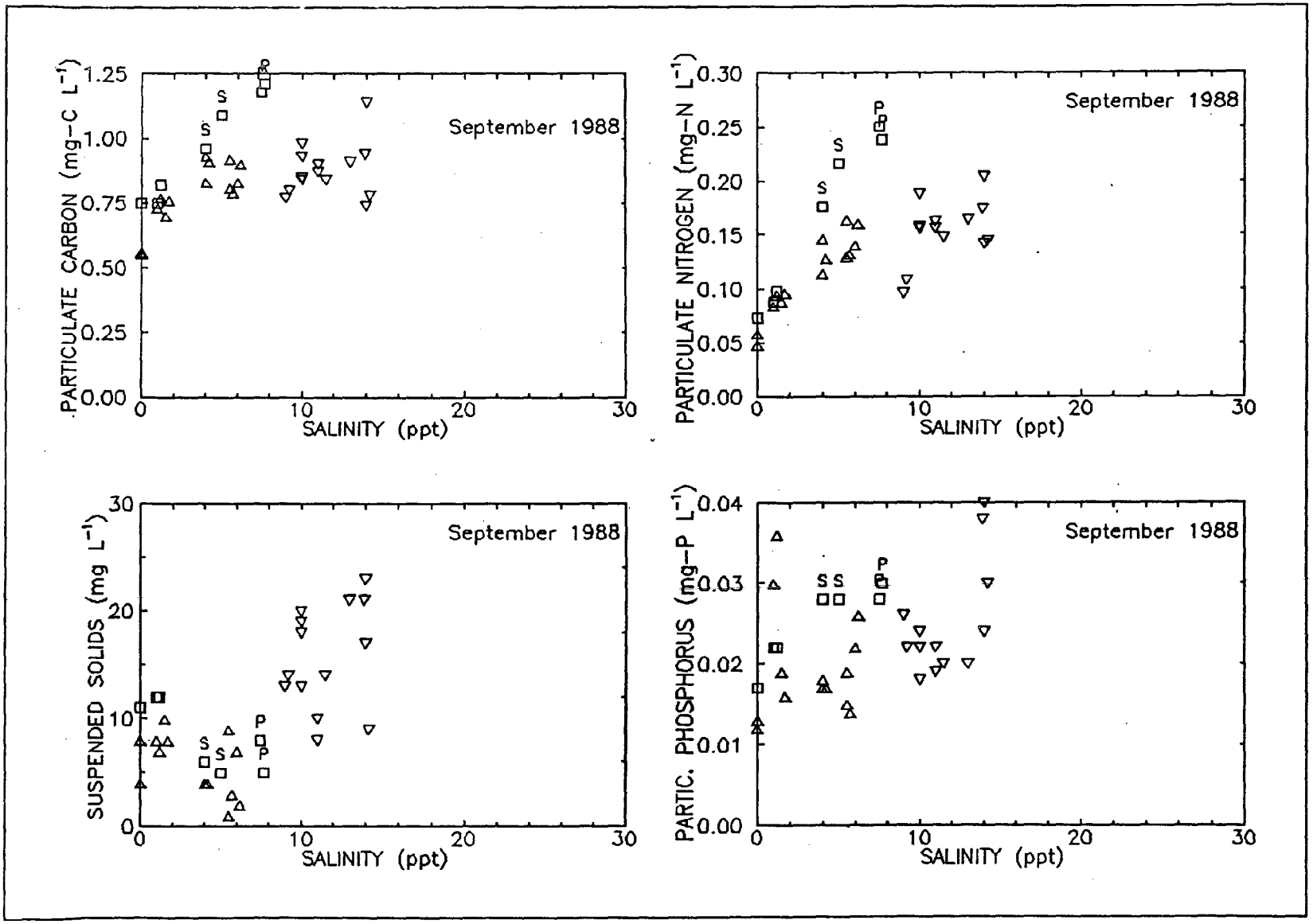

July 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
July 1988
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
July 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
July 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

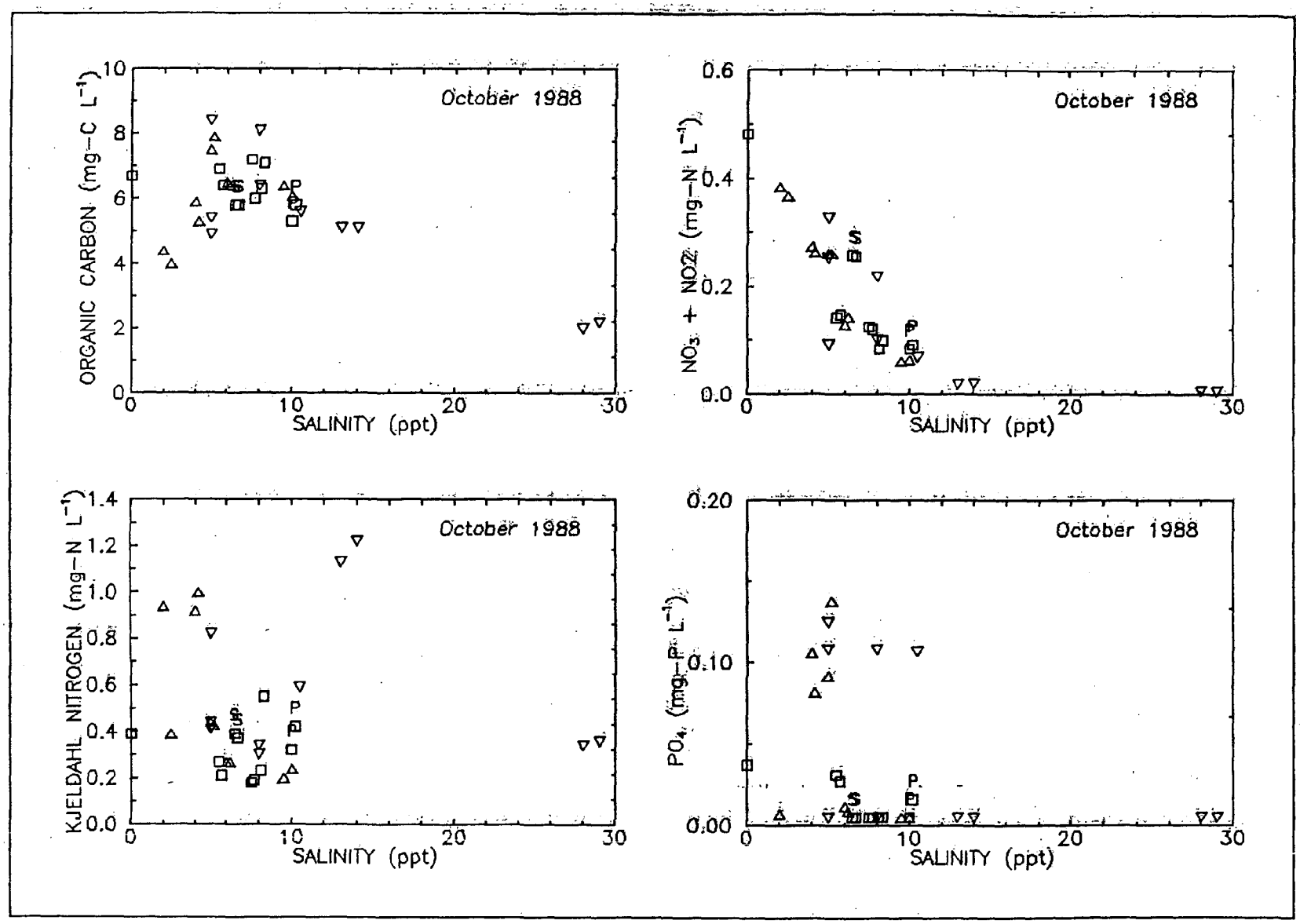

July 1988
PARTICULATE CARBON (mg-C L^{-1})
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
10
20
30
SALINITY (ppt)
July 1988
PARTICULATE NITROGEN (mg-N L^{-1})
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
SALINITY (ppt)
July 1988
SUSPENDED SOLIDS (mg L^{-1})
60
50
40
30
20
10
0
0
10
20
30
SALINITY (ppt)
July 1988
PARTIC. PHOSPHORUS (mg-P L^{-1})
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
10
20
30
SALINITY (ppt)

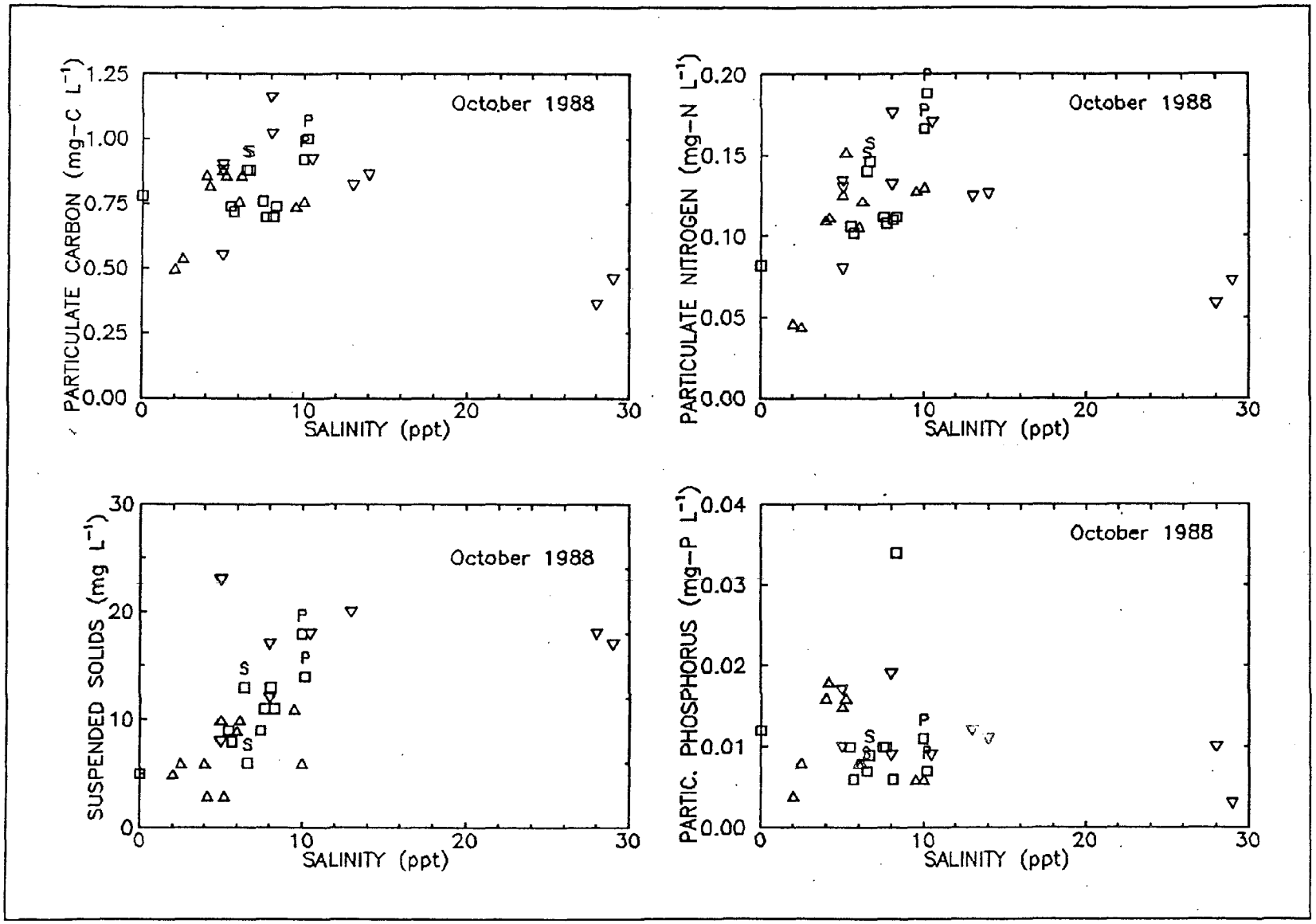

August 1988
ORGANIC CARBON (mg-C L-1)
SALINITY (ppt)
August 1988
NO3 + NO2 (mg-N L-1)
SALINITY (ppt)
August 1988
KJELDAHL NITROGEN (mg-N L-1)
SALINITY (ppt)
August 1988
PO4 (mg-P L-1)
SALINITY (ppt)

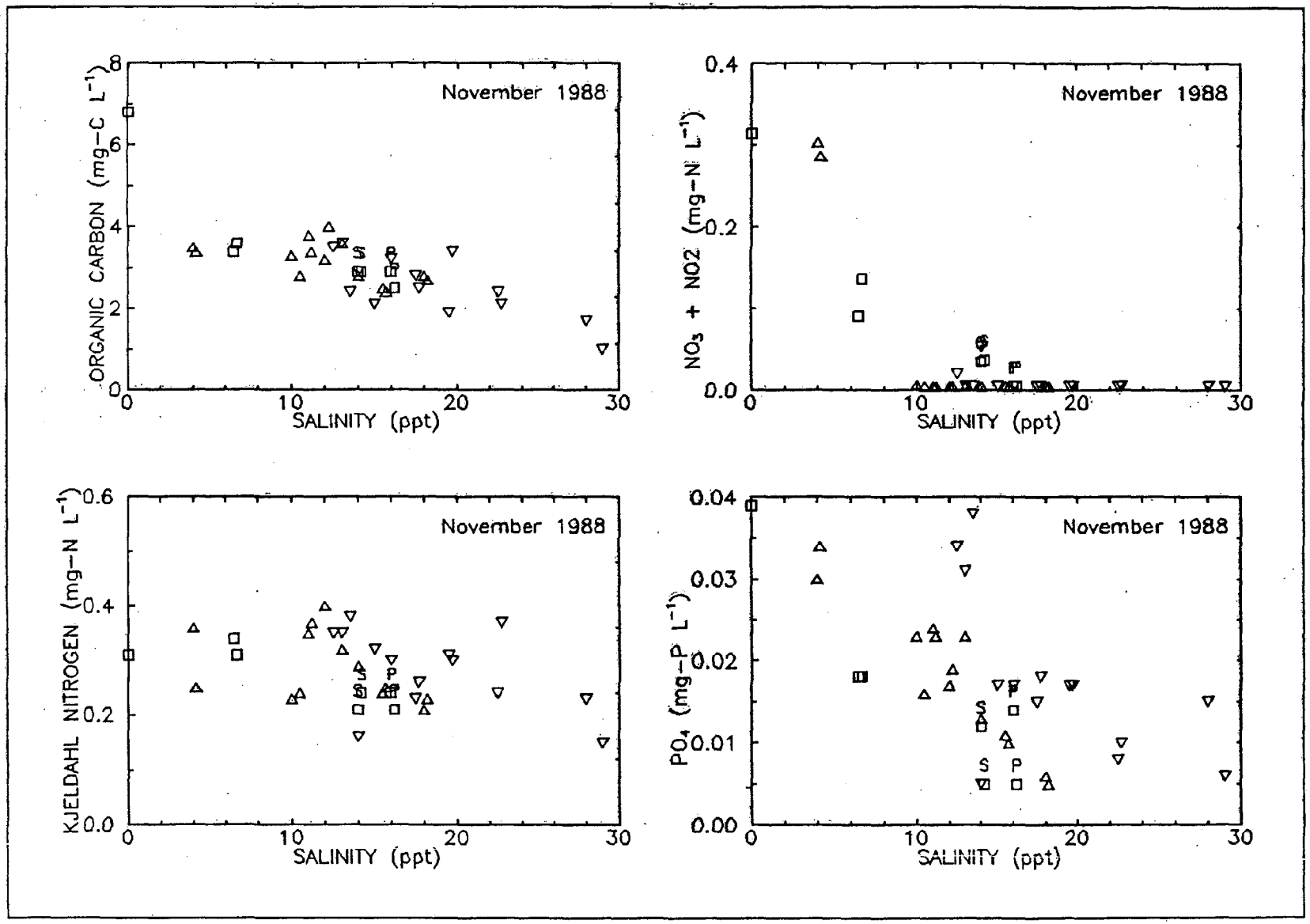

August 1988
PARTICULATE CARBON (mg-C L^{-1})
SALINITY (ppt)
PARTICULATE NITROGEN (mg-N L^{-1})
SUSPENDED SOLIDS (mg L^{-1})
PARTIC. PHOSPHORUS (mg-P L^{-1})

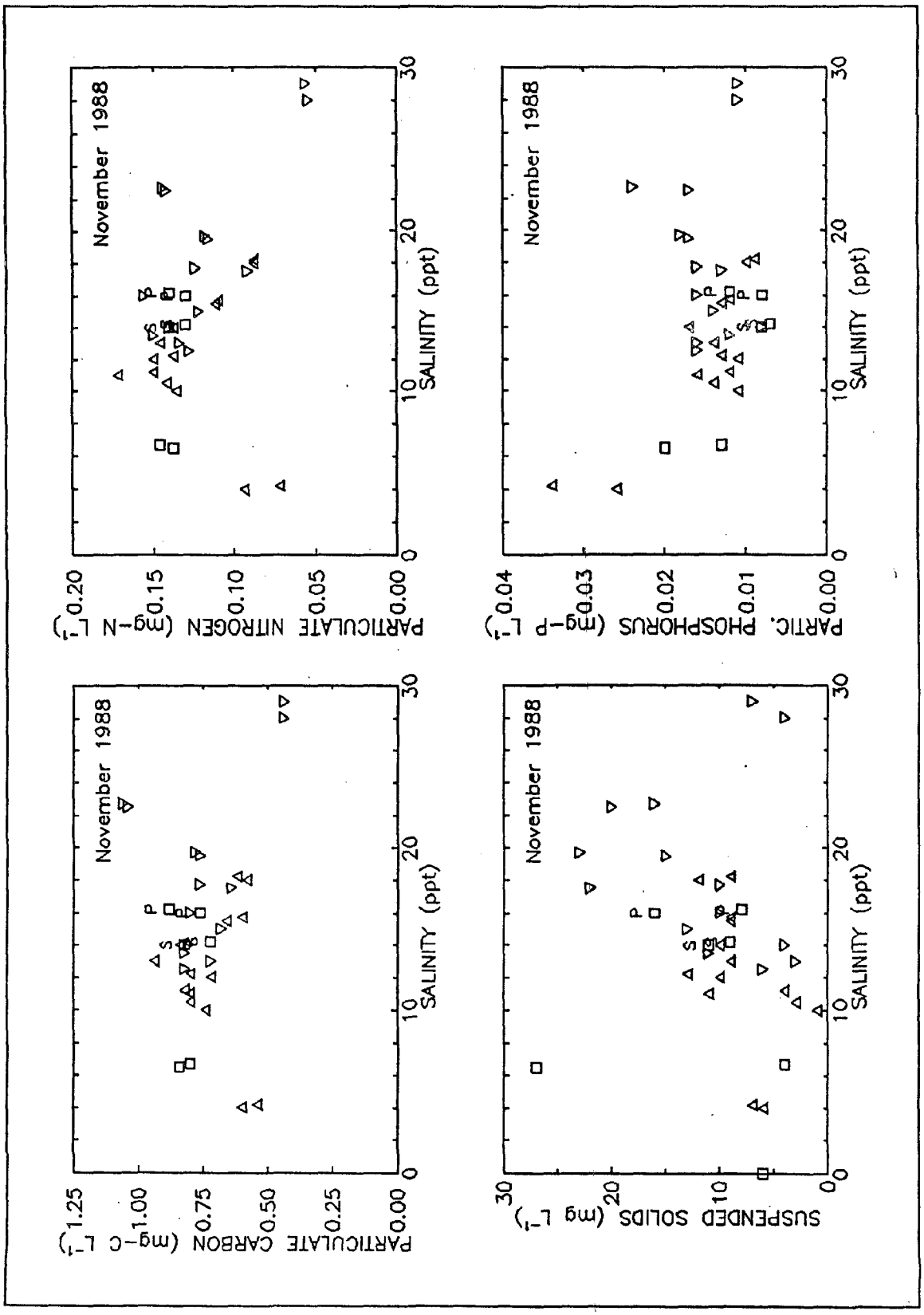

September 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
September 1988
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
September 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
September 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

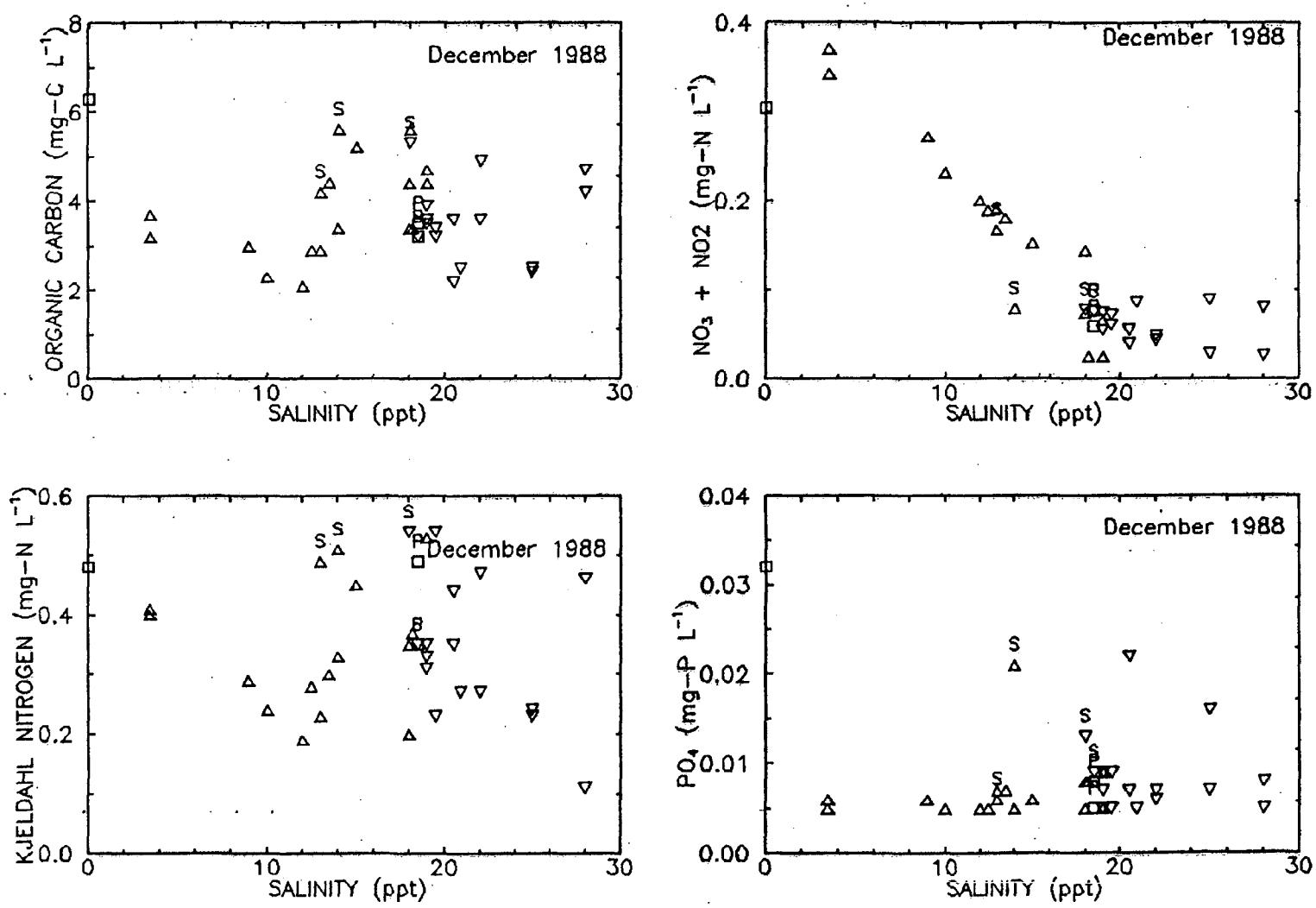

PARTICULATE CARBON (mg-C L^{-1})
1.25
1.00
0.75
0.50
0.25
0.00
0
10
20
30
SALINITY (ppt)
September 1988
PARTICULATE NITROGEN (mg-N L^{-1})
0.30
0.25
0.20
0.15
0.10
0.05
0.00
SUSPENDED SOLIDS (mg L^{-1})
PARTIC. PHOSPHORUS (mg-P L^{-1})
0.04
0.03
0.02
0.01
S
P

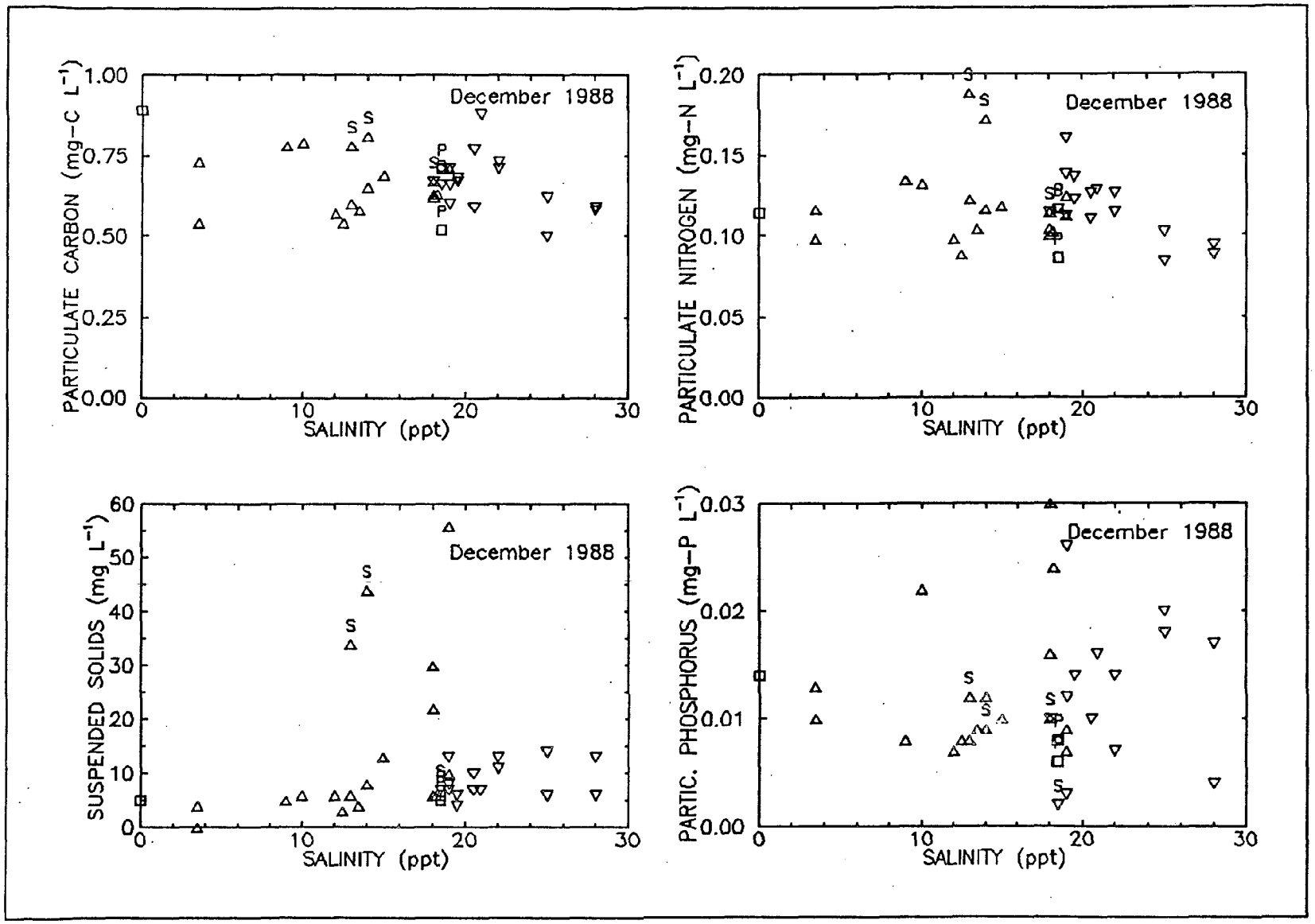

October 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
October 1988
NO_3 + NO_2 (mg-N L^{-1})
SALINITY (ppt)
October 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
October 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

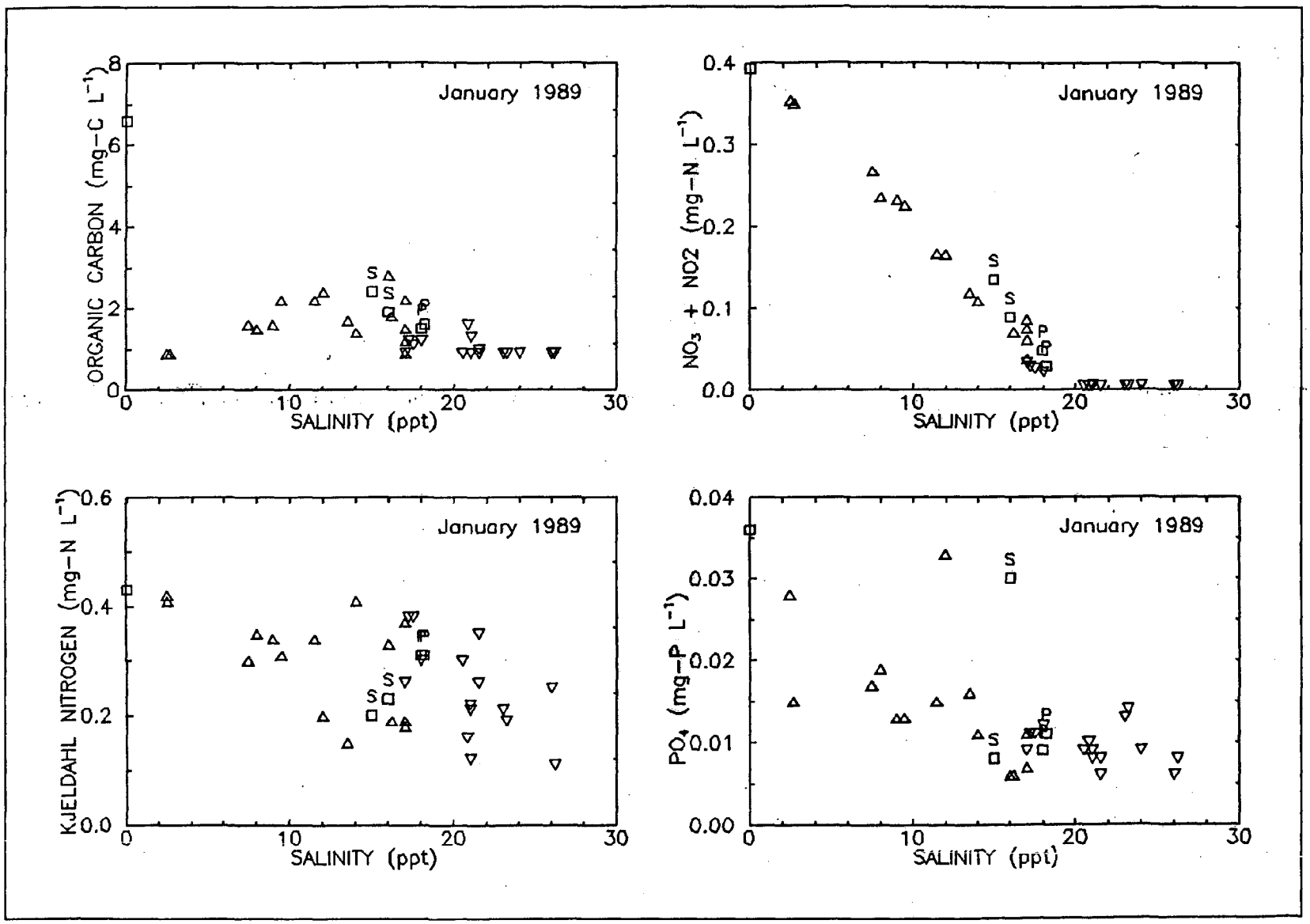

October 1988
PARTICULATE CARBON (mg-C L-1)
SALINITY (ppt)
PARTICULATE NITROGEN (mg-N L-1)
SUSPENDED SOLIDS (mg L-1)
PARTIC. PHOSPHORUS (mg-P L-1)

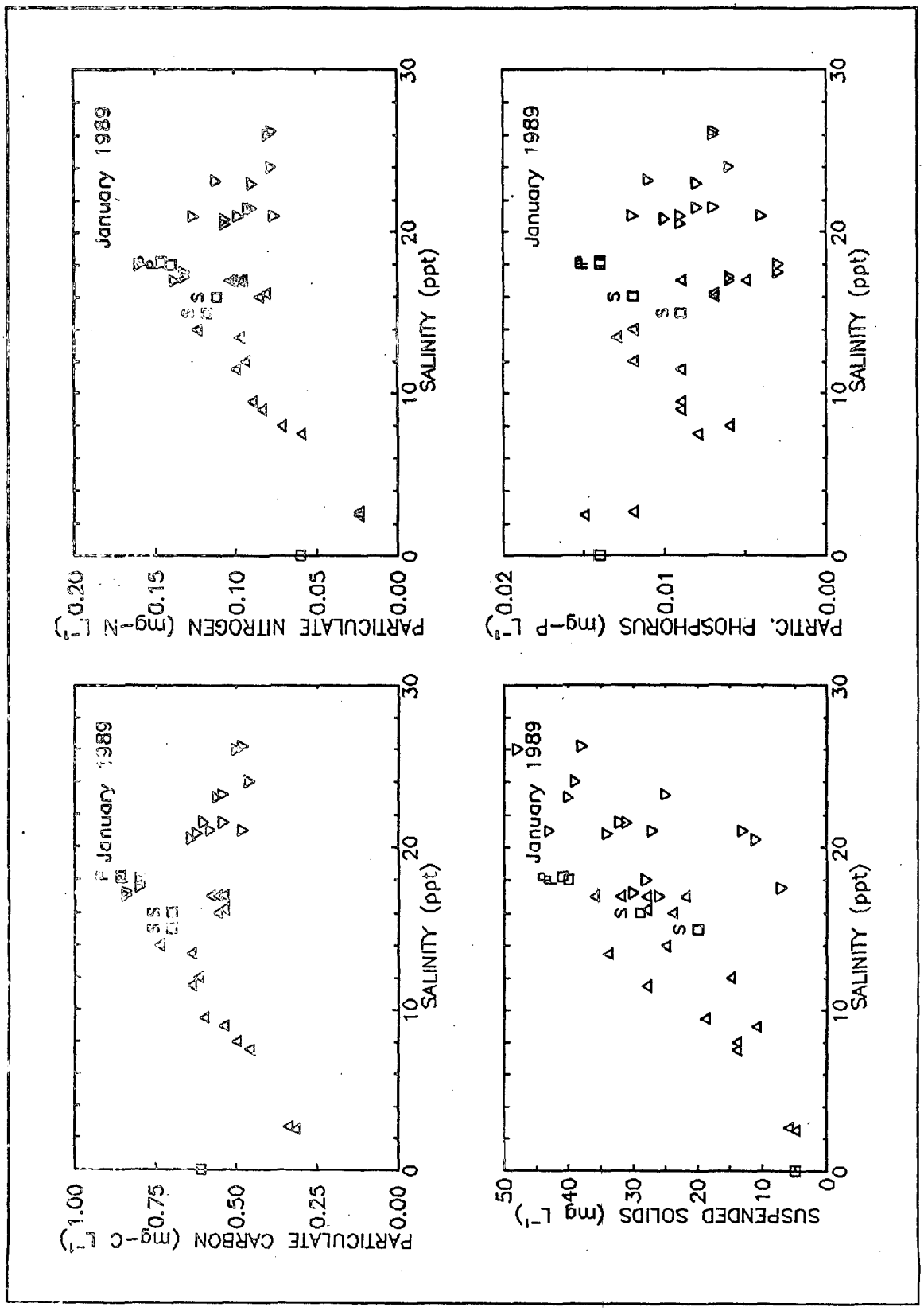

November 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
November 1988
NO_3 + NO_2 (mg-N L^{-1})
SALINITY (ppt)
November 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
November 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

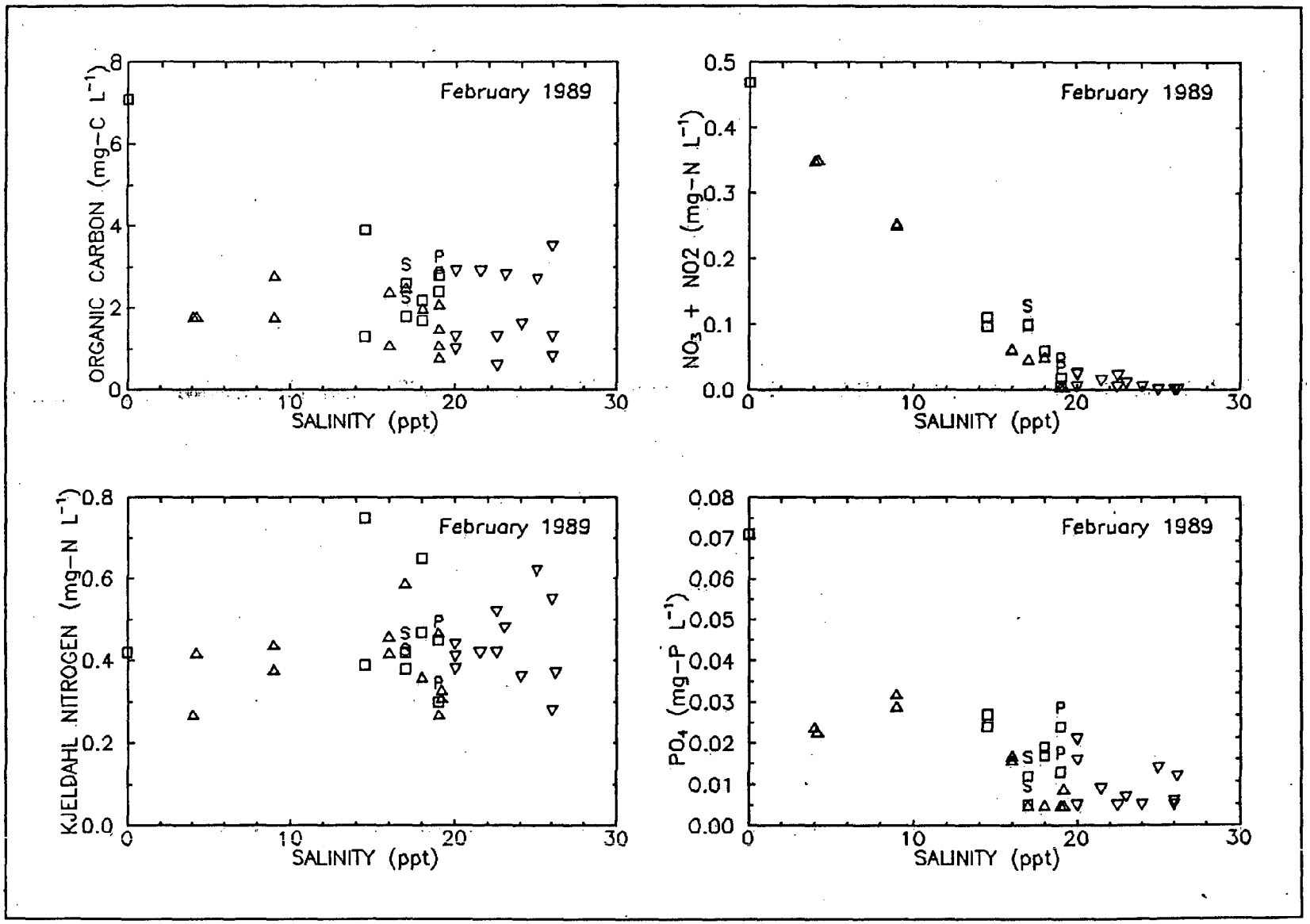

November 1988
PARTICULATE CARBON (mg-C L-1)
PARTICULATE NITROGEN (mg-N L-1)
PARTIC. PHOSPHORUS (mg-P L-1)
SUSPENDED SOLIDS (mg L-1)
SALINITY (ppt)
P
S

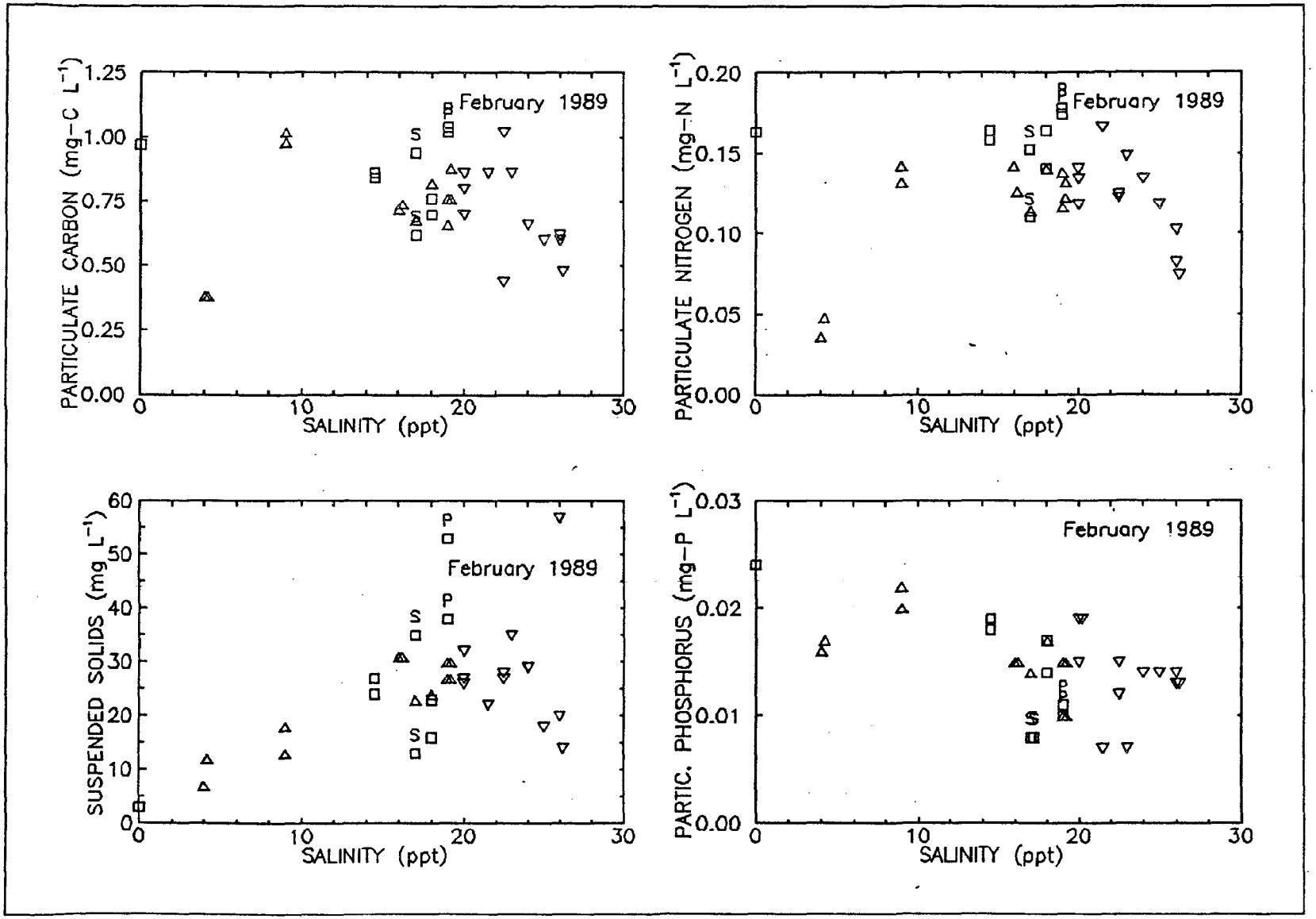

December 1988
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
December 1988
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
December 1988
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
December 1988
PO_4 (mg-P L^{-1})
SALINITY (ppt)

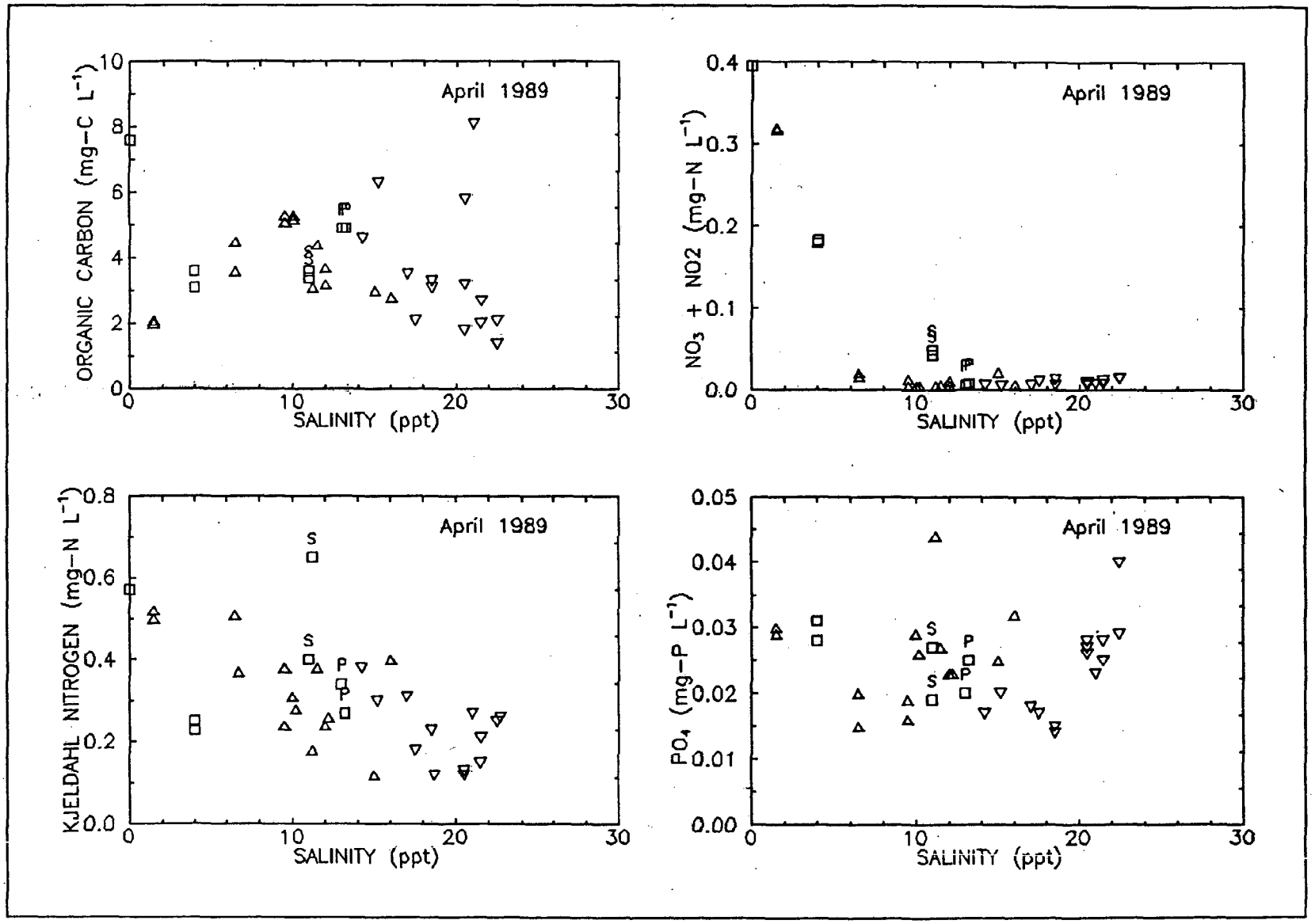

December 1988
PARTICULATE CARBON (mg-C L^{-1})
PARTICULATE NITROGEN (mg-N L^{-1})
SUSPENDED SOLIDS (mg L^{-1})
PARTIC. PHOSPHORUS (mg-P L^{-1})
SALINITY (ppt)

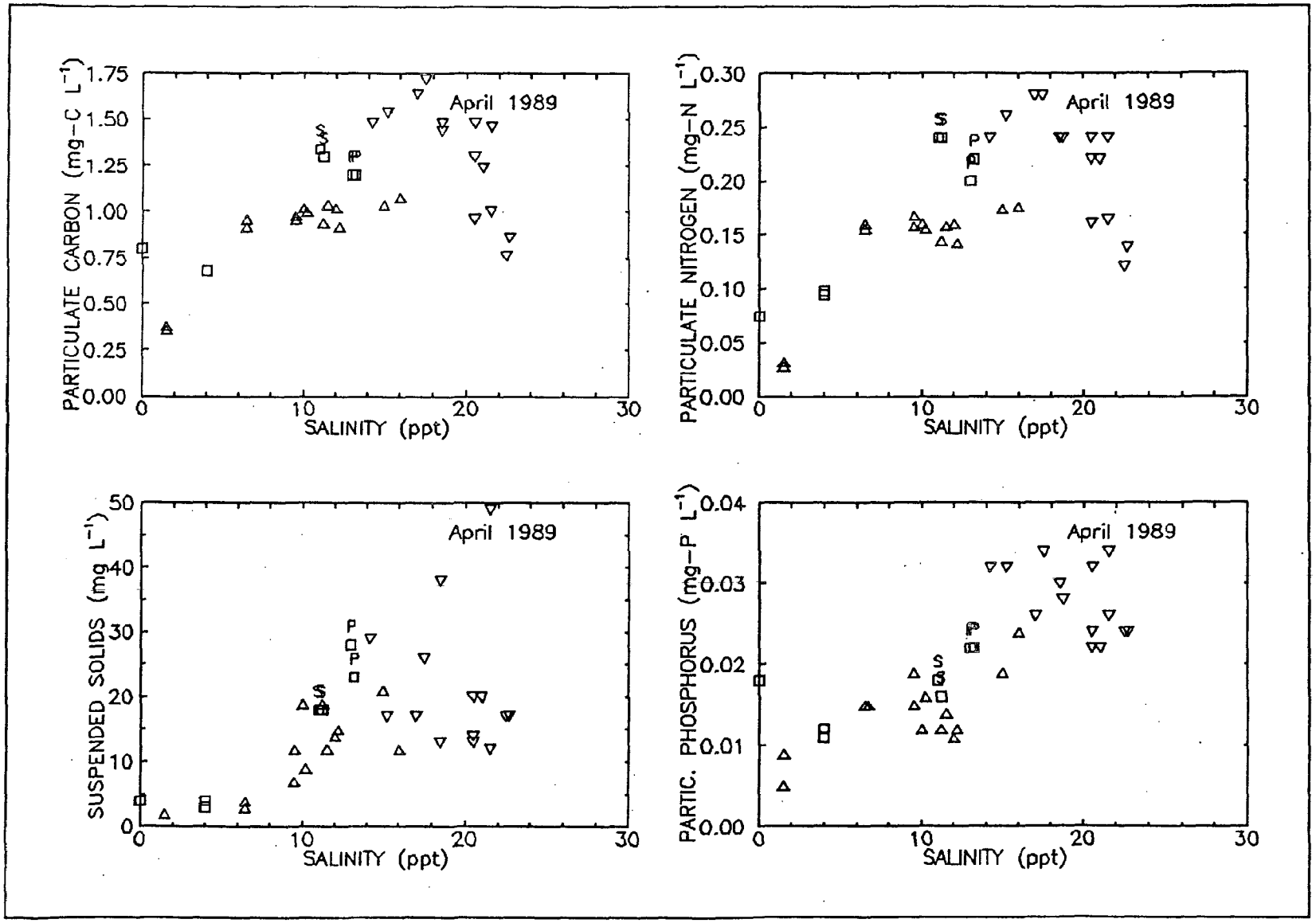

January 1989
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
January 1989
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
January 1989
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
January 1989
PO_4 (mg-P L^{-1})
SALINITY (ppt)

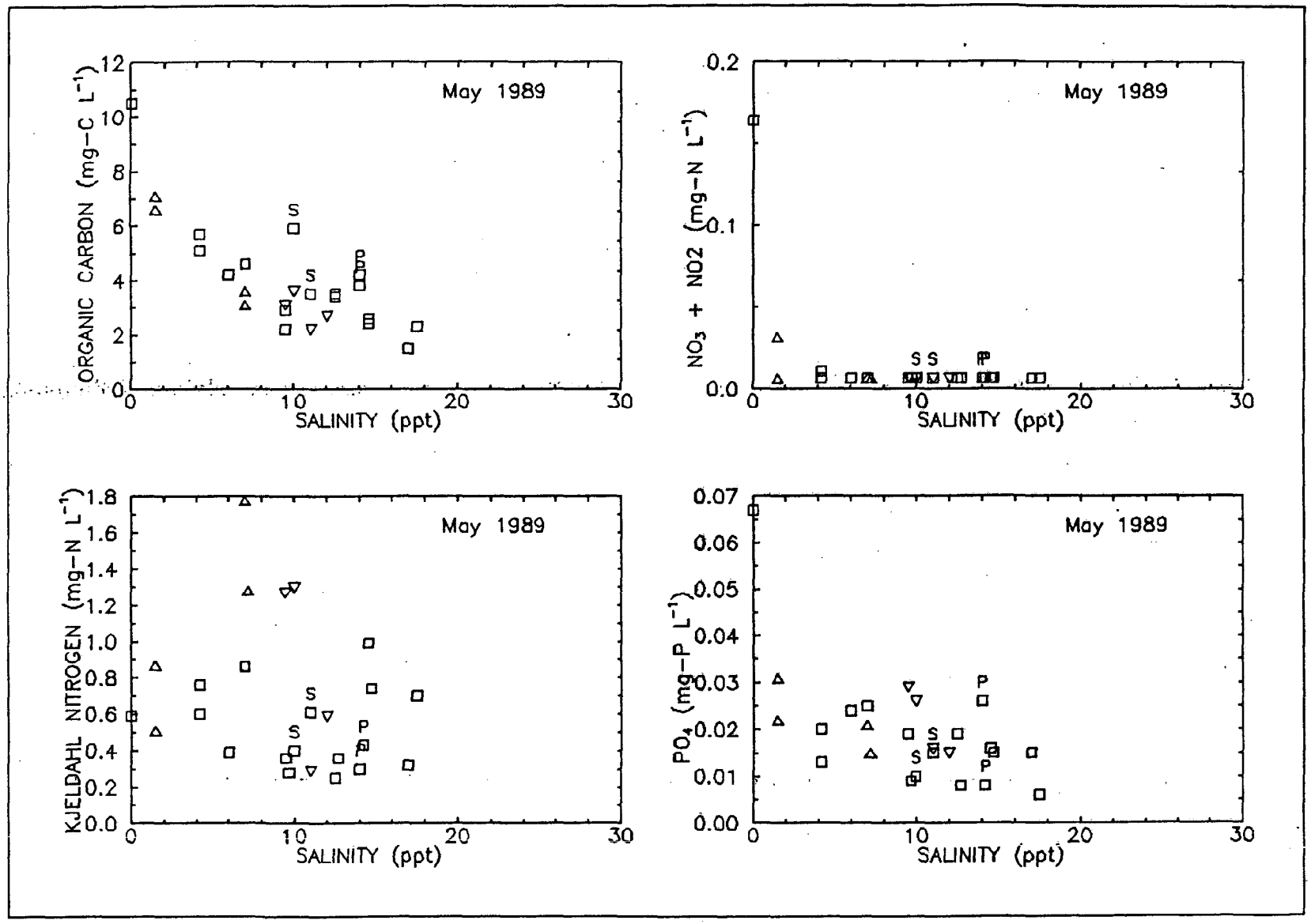

January 1989
PARTICULATE NITROGEN (mg-N L⁻¹)
0.00
0.05
0.10
0.15
0.20
SALINITY (ppt)
0
10
20
30
January 1989
PARTIC. PHOSPHORUS (mg-P L⁻¹)
0.00
0.01
0.02
SALINITY (ppt)
0
10
20
30
January 1989
PARTICULATE CARBON (mg-C L⁻¹)
0.00
0.25
0.50
0.75
1.00
SALINITY (ppt)
0
10
20
30
January 1989
SUSPENDED SOLIDS (mg L⁻¹)
0
10
20
30
40
50
SALINITY (ppt)
0
10
20
30

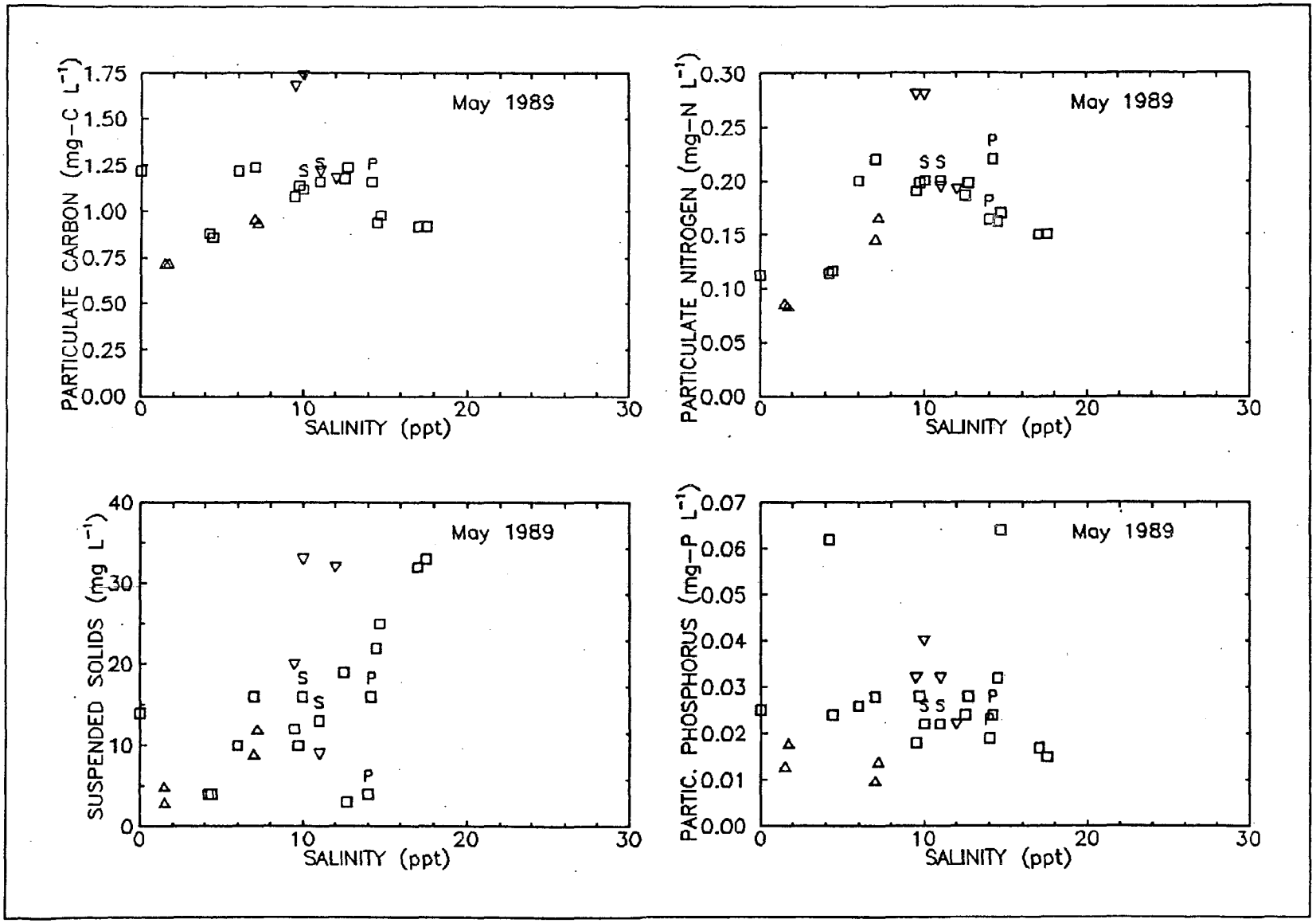

February 1989
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
February 1989
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
February 1989
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
February 1989
PO_4 (mg-P L^{-1})
SALINITY (ppt)

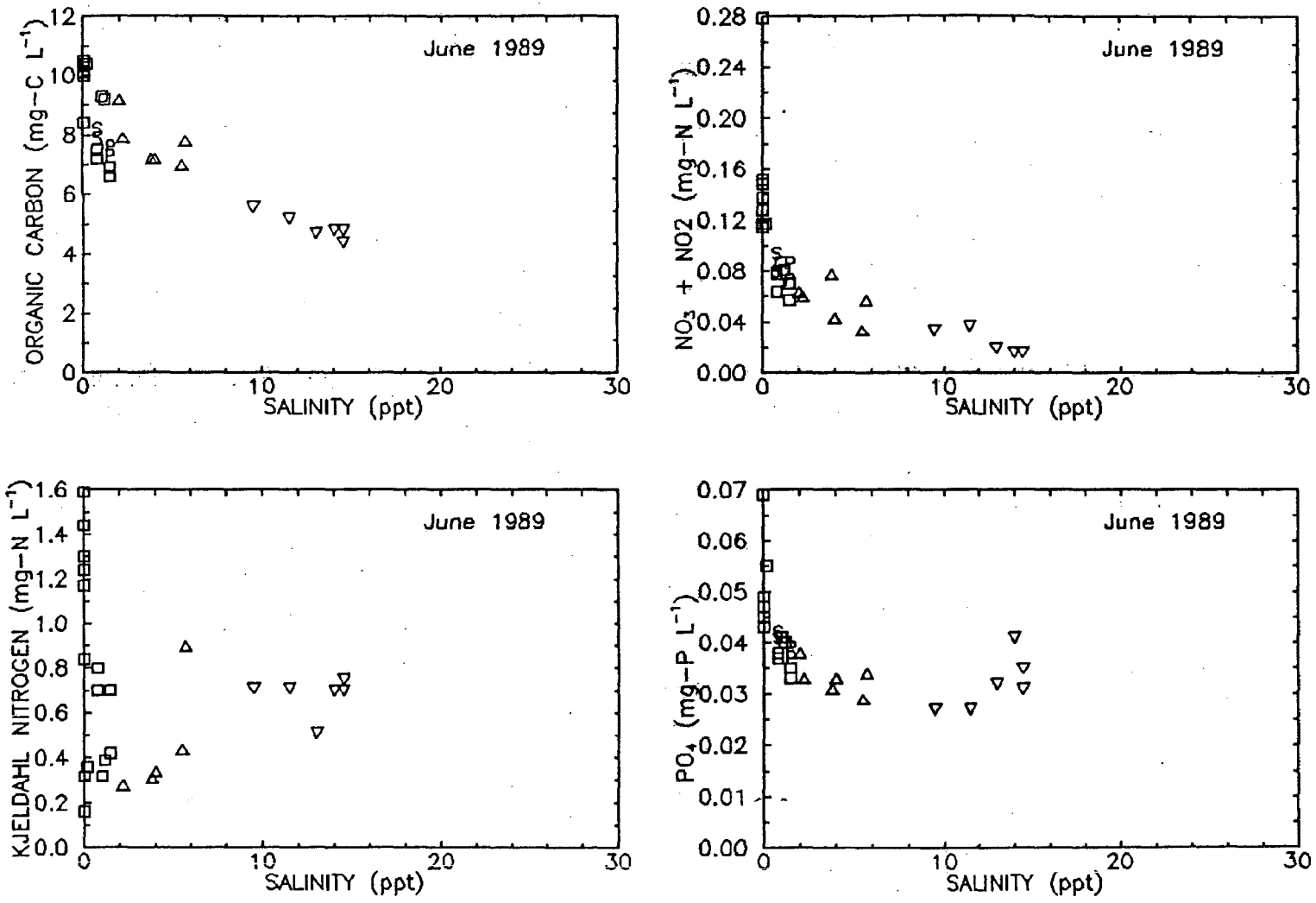

PARTICULATE CARBON (mg-C L^{-1})
1.25
1.00
0.75
0.50
0.25
0.00
February 1989
SALINITY (ppt)
0
10
20
30
PARTICULATE NITROGEN (mg-N L^{-1})
0.20
0.15
0.10
0.05
0.00
February 1989
SALINITY (ppt)
SUSPENDED SOLIDS (mg L^{-1})
60
50
40
30
20
10
0
February 1989
SALINITY (ppt)
PARTIC. PHOSPHORUS (mg-P L^{-1})
0.03
0.02
0.01
0.00
February 1989
SALINITY (ppt)

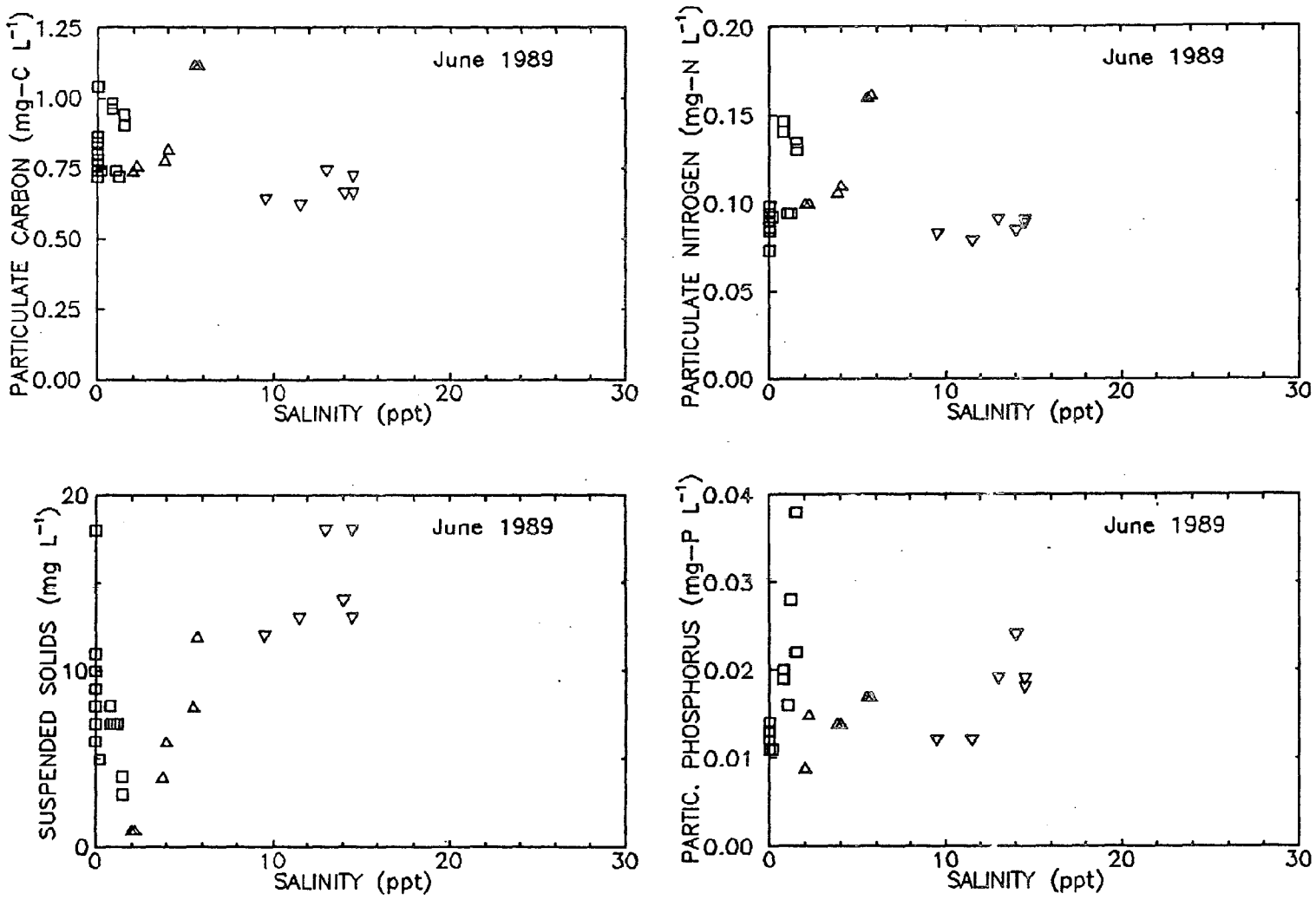

April 1989
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
April 1989
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
April 1989
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
April 1989
PO_4 (mg-P L^{-1})
SALINITY (ppt)


April 1989
PARTICULATE CARBON (mg-C L^{-1})
SALINITY (ppt)
PARTICULATE NITROGEN (mg-N L^{-1})
SUSPENDED SOLIDS (mg L^{-1})
PARTIC. PHOSPHORUS (mg-P L^{-1})


May 1989
ORGANIC CARBON (mg-C L^{-1})
SALINITY (ppt)
May 1989
NO_3 + NO2 (mg-N L^{-1})
SALINITY (ppt)
May 1989
KJELDAHL NITROGEN (mg-N L^{-1})
SALINITY (ppt)
May 1989
PO_4 (mg-P L^{-1})
SALINITY (ppt)


May 1989
PARTICULATE CARBON (mg-C L^{-1})
SALINITY (ppt)
PARTICULATE NITROGEN (mg-N L^{-1})
SUSPENDED SOLIDS (mg L^{-1})
PARTIC. PHOSPHORUS (mg-P L^{-1})


June 1989
ORGANIC CARBON (mg-C L-1)
SALINITY (ppt)
June 1989
NO3 + NO2 (mg-N L-1)
SALINITY (ppt)
June 1989
KJELDAHL NITROGEN (mg-N L-1)
SALINITY (ppt)
June 1989
PO4 (mg-P L-1)
SALINITY (ppt)


June 1989
PARTICULATE CARBON (mg-C L^{-1})
1.25
1.00
0.75
0.50
0.25
0.00
0
10
20
30
SALINITY (ppt)
June 1989
PARTICULATE NITROGEN (mg-N L^{-1})
0.20
0.15
0.10
0.05
0.00
0
10
20
30
SALINITY (ppt)
June 1989
SUSPENDED SOLIDS (mg L^{-1})
20
10
0
0
10
20
30
SALINITY (ppt)
June 1989
PARTIC. PHOSPHORUS (mg-P L^{-1})
0.04
0.03
0.02
0.01
0.00
0
10
20
30
SALINITY (ppt)

APPENDIX E

SALINITY AND DISSOLVED OXYGEN PROFILES FROM HYDROGRAPHIC CAMPAIGNS IN PERDIDO BAY

Explanation:

Dissolved oxygen is reported in percent saturation and salinity is in parts per thousand.

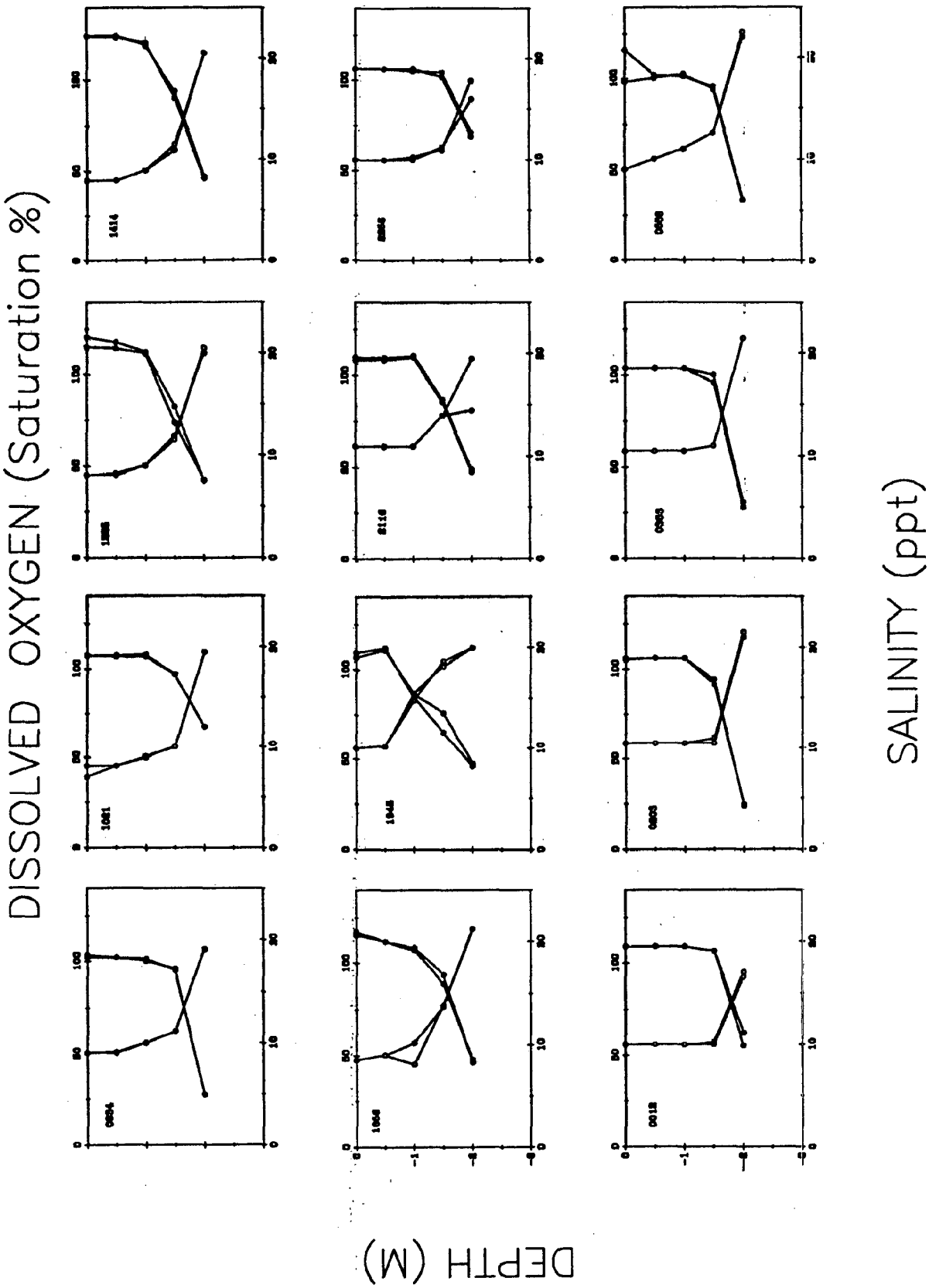
Data is plotted for each station and presented in a time series.

Time of cast (start) is given in upper left corner of each figure.

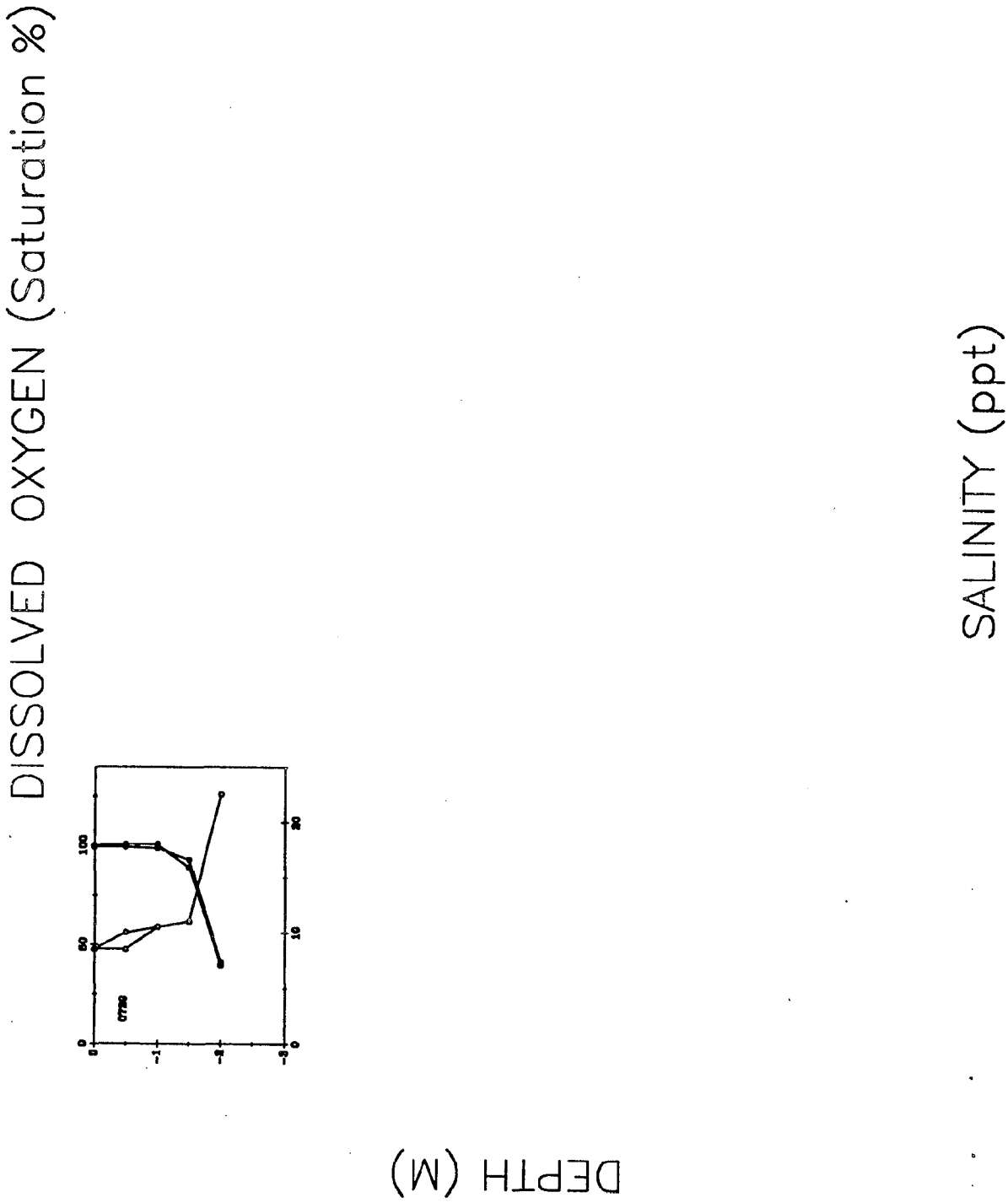
Salinity is represented by open circles.

Oxygen is represented by dots.

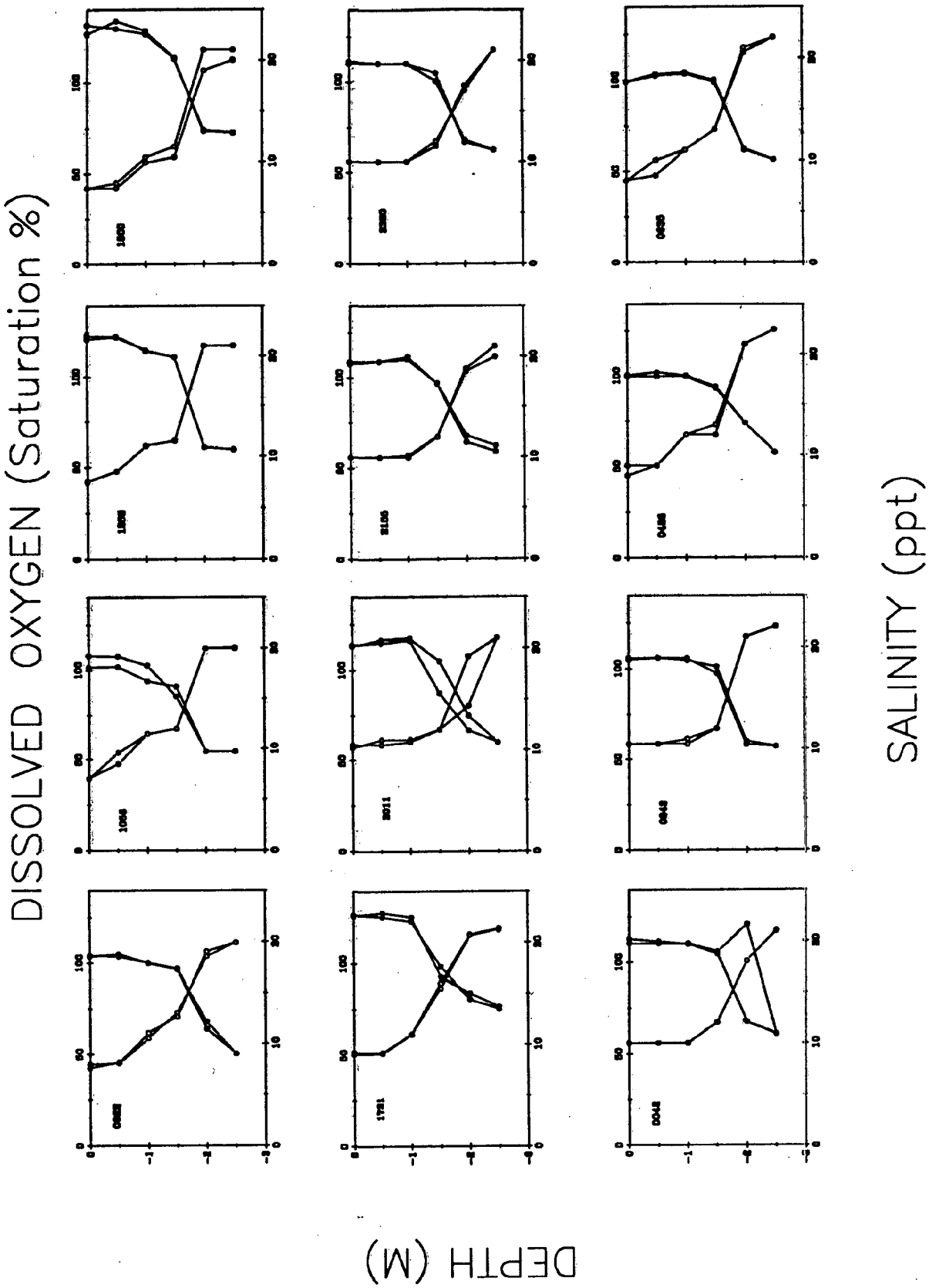
June 1988, Transect CT1, Station 1



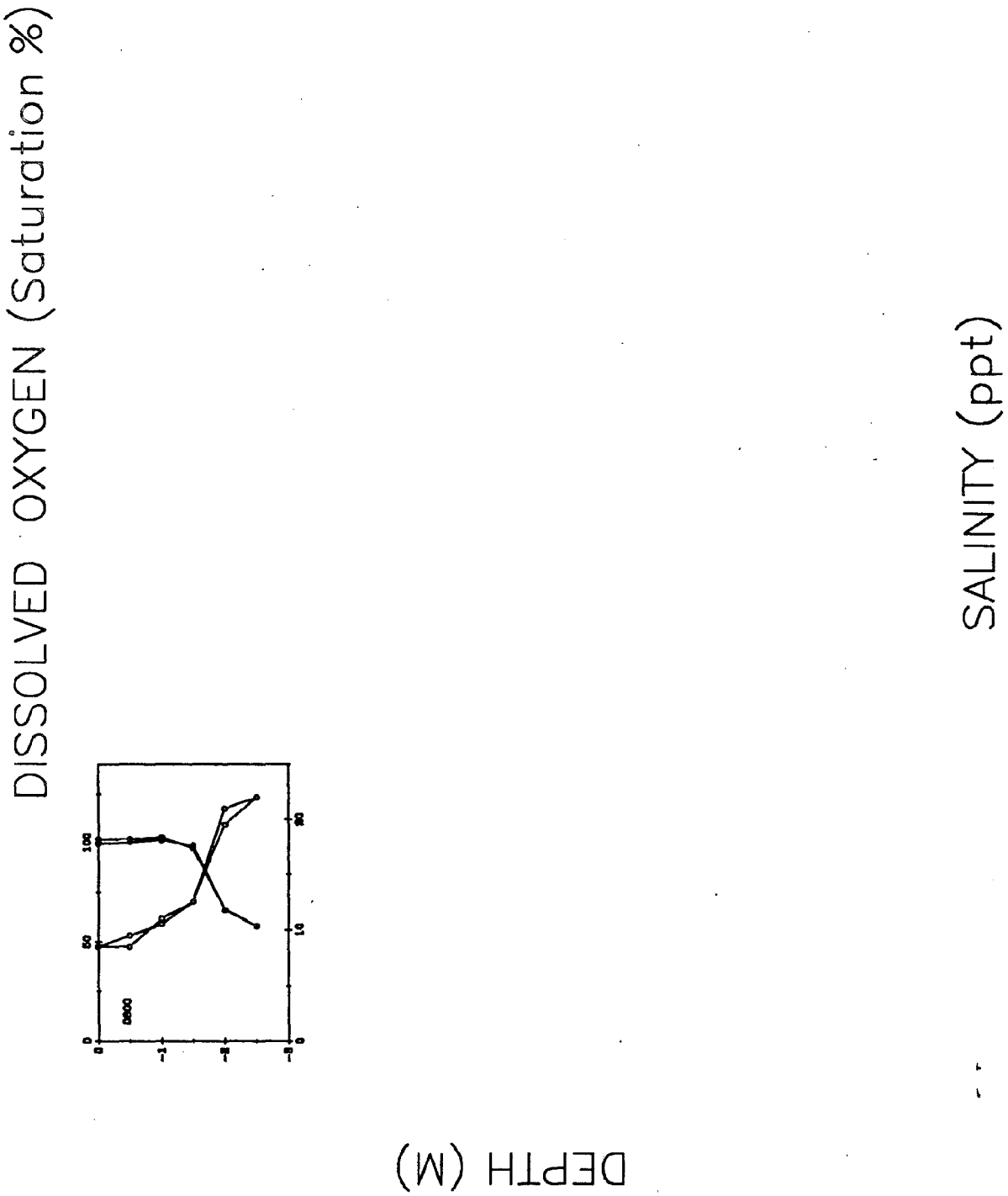
June 1988, Transect CT1, Station 1



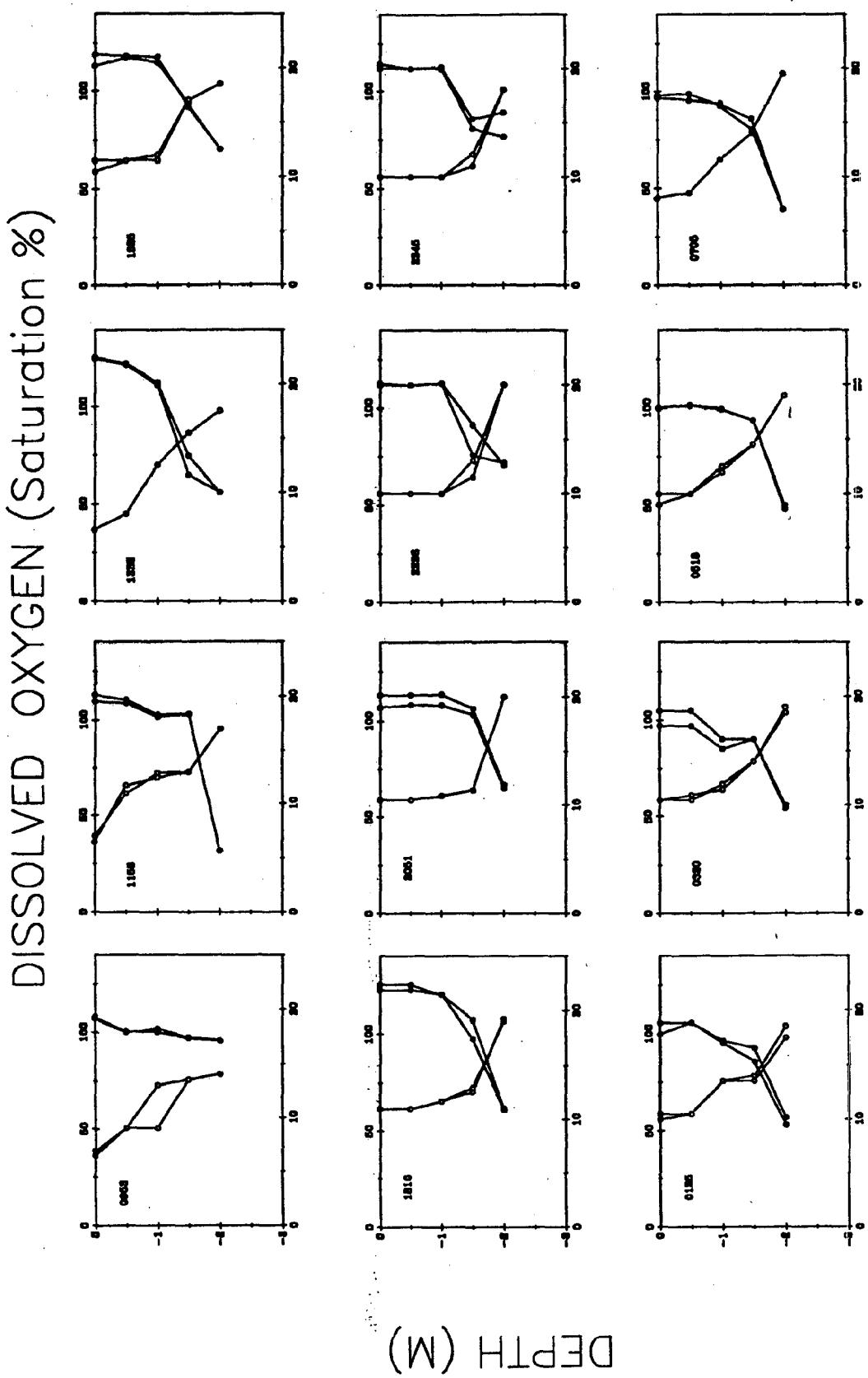
June 1988, Transect CT1, Station 2



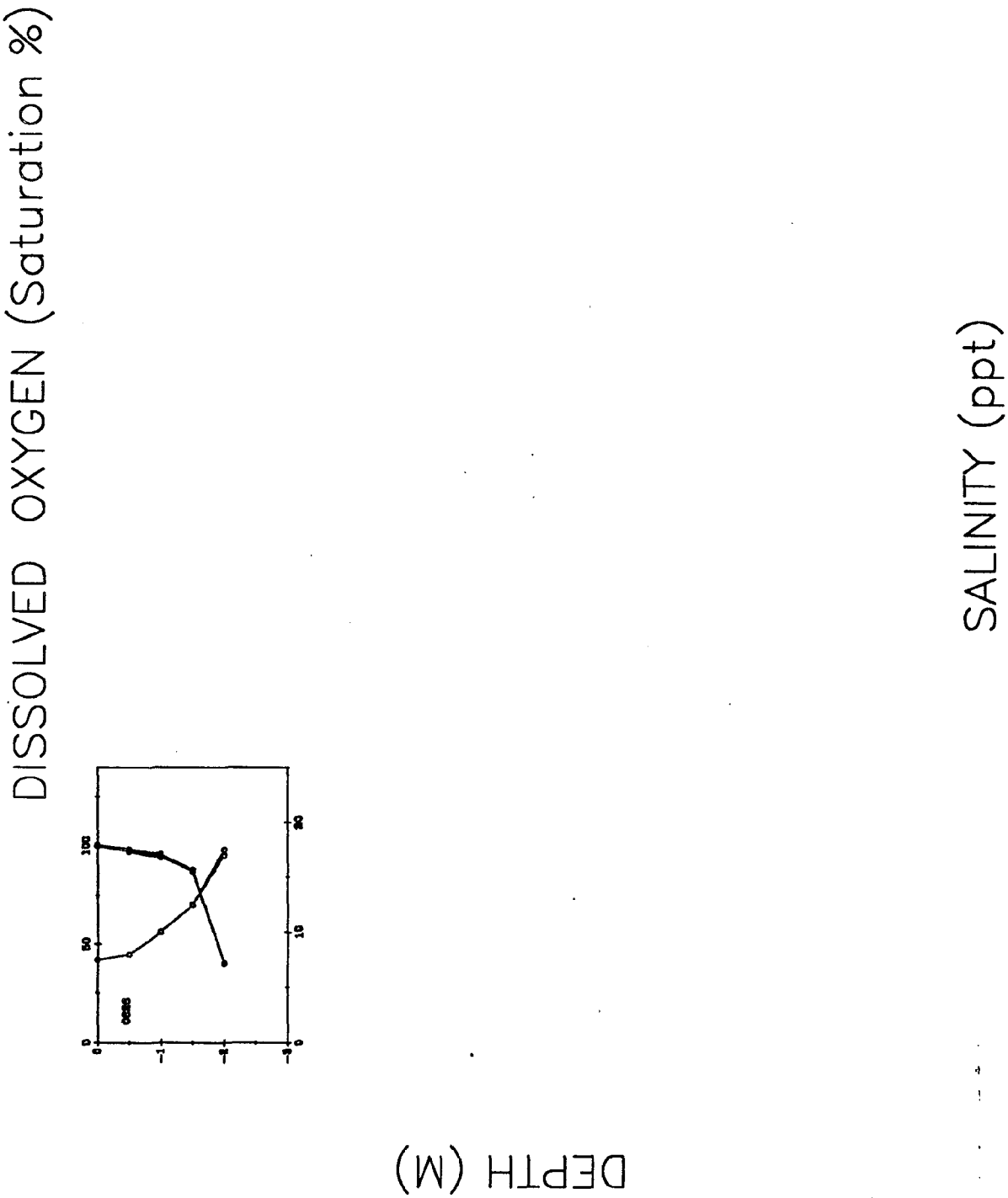
June 1988, Transect CT1, Station 2



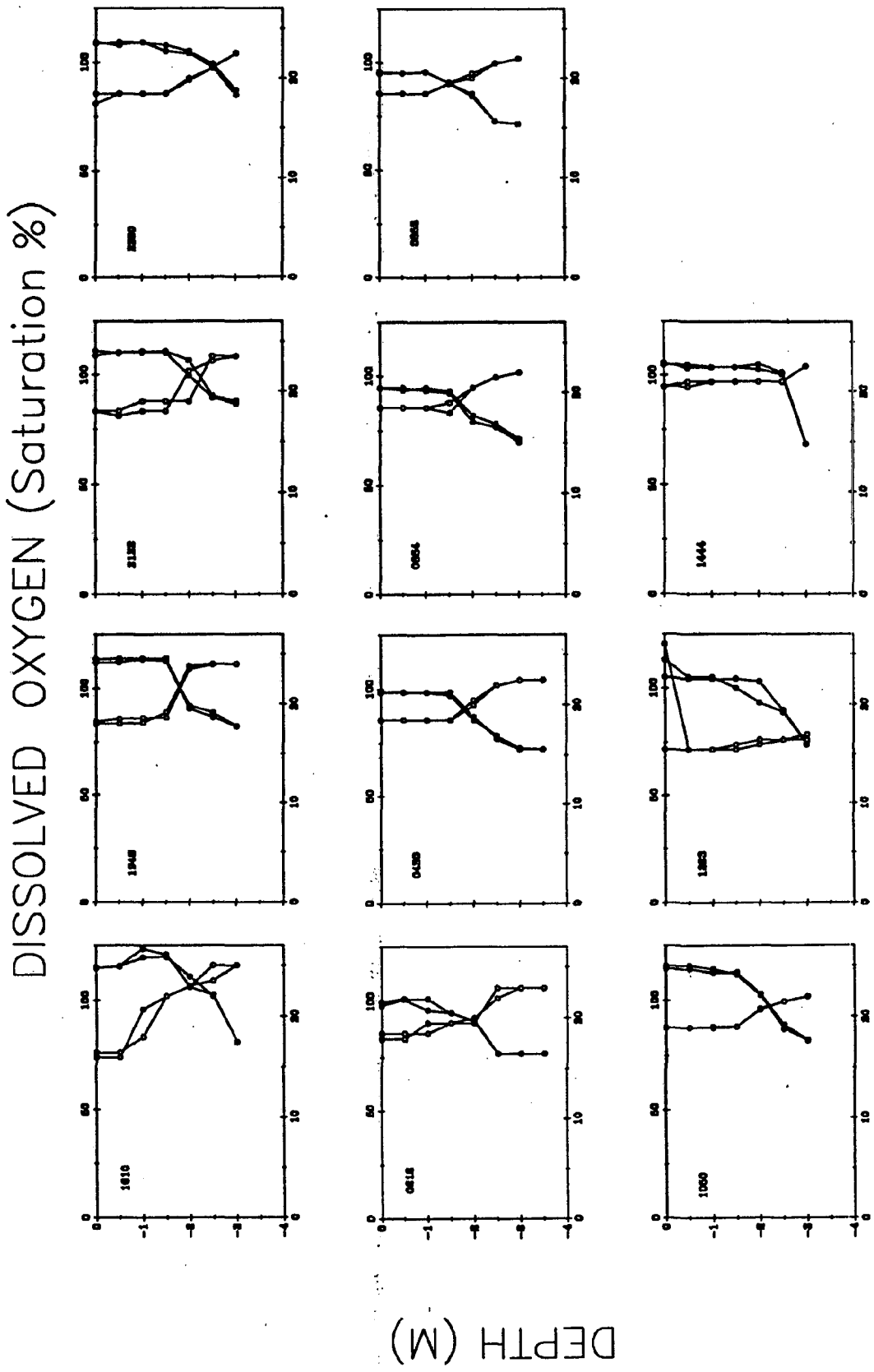
June 1988, Transect CT1, Station 3



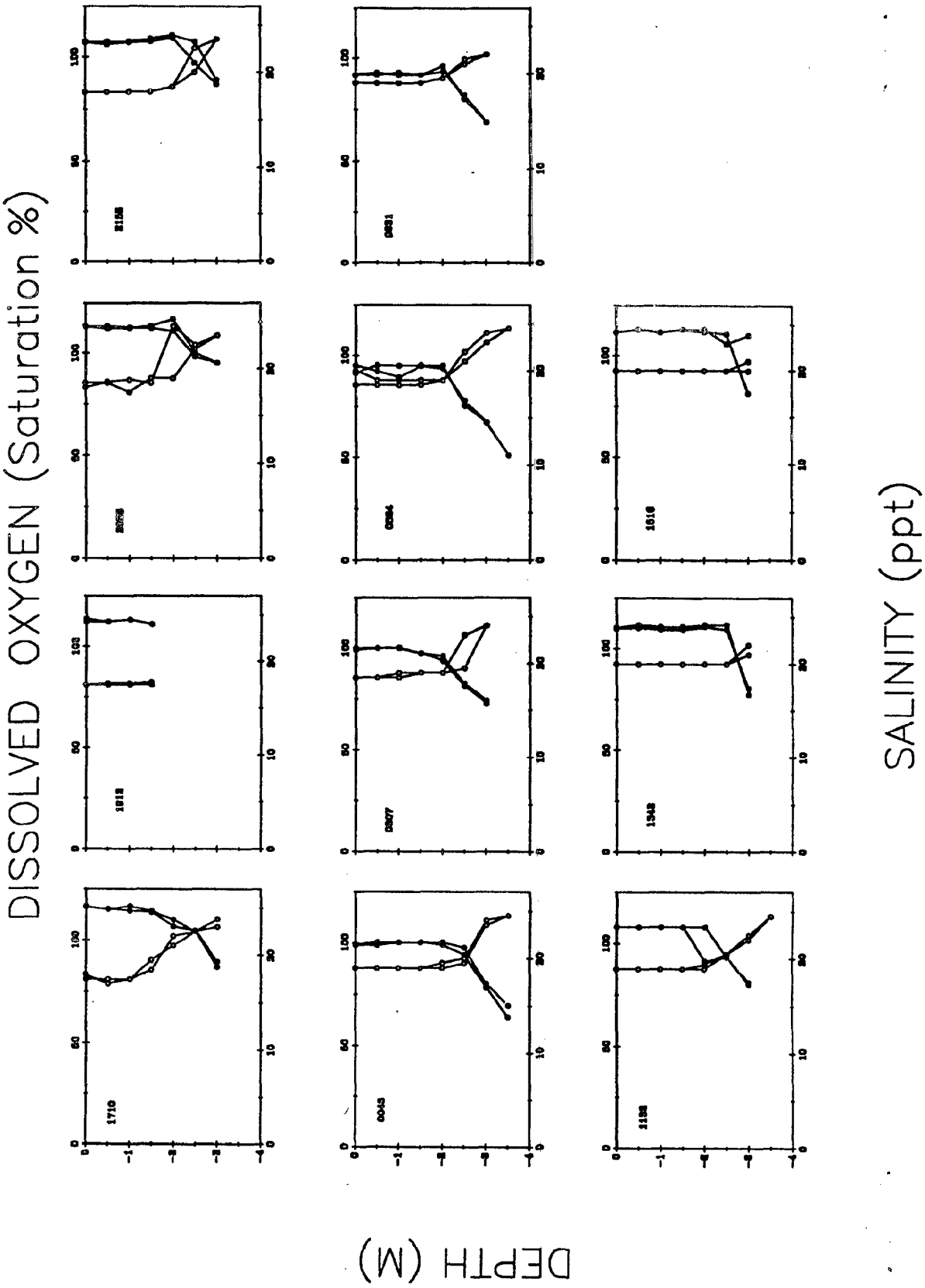
June 1988, Transect CT1, Station 3



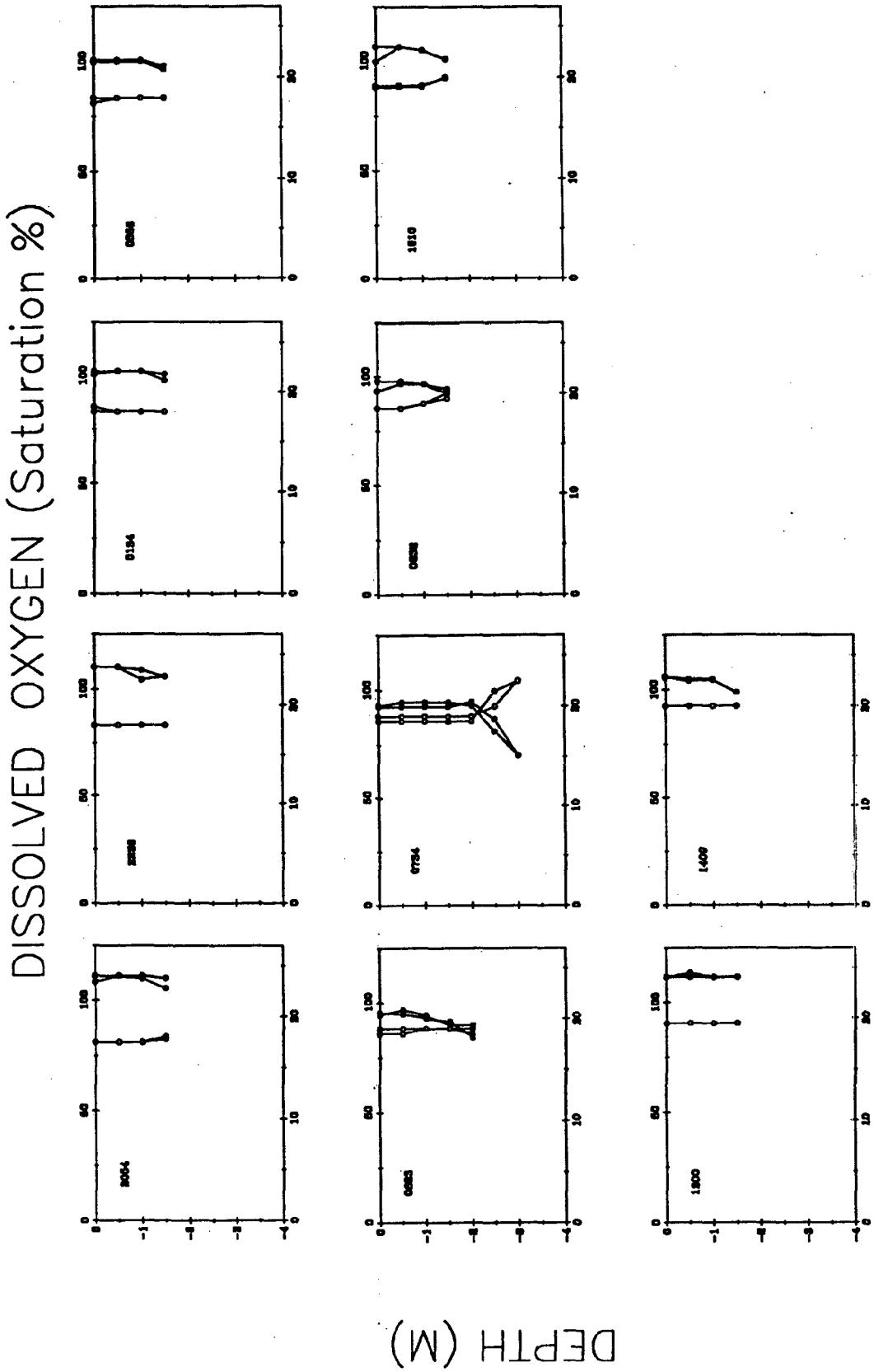
June 1988, Transect CT2, Station 1



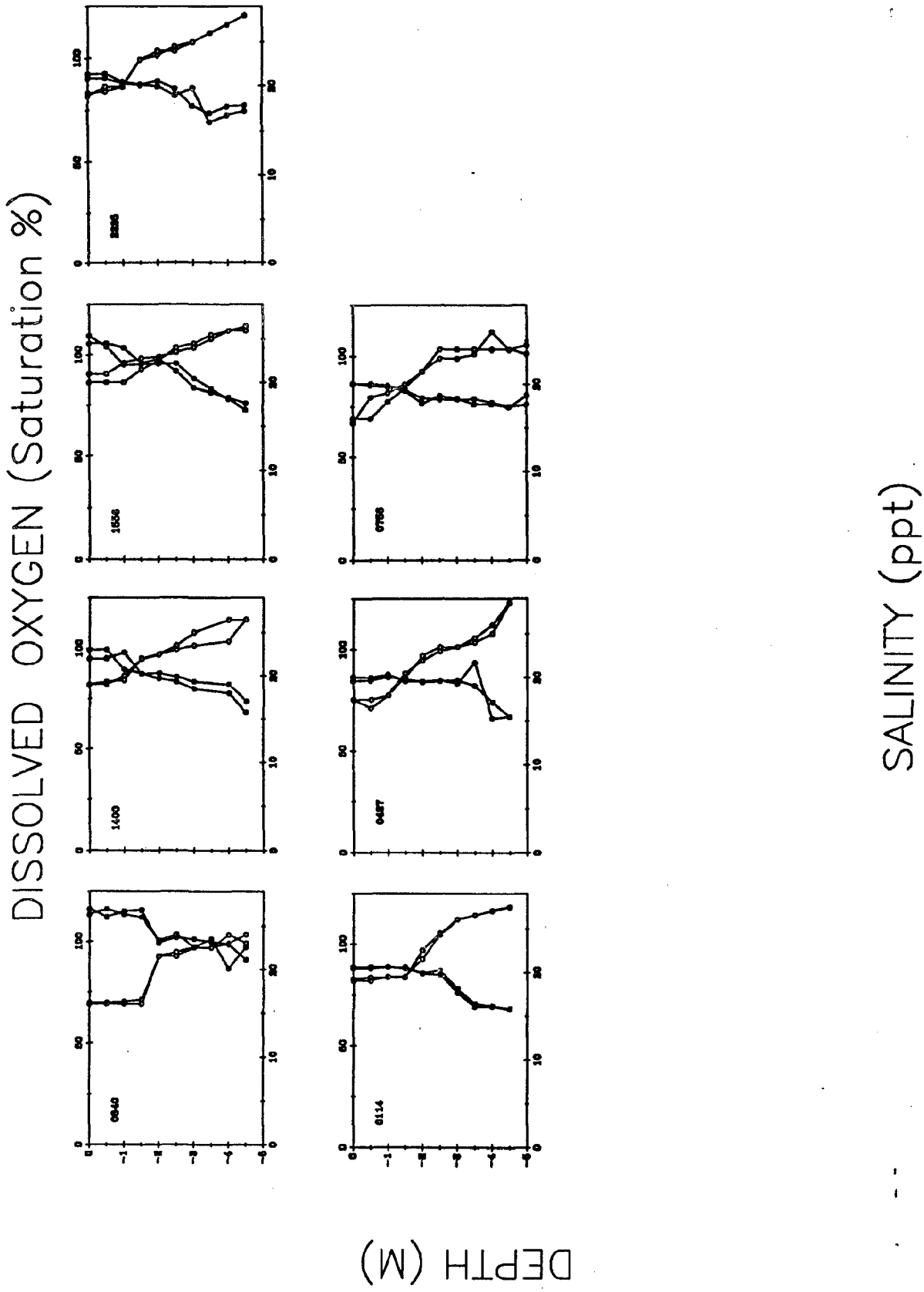
June 1988, Transect CT2, Station 2



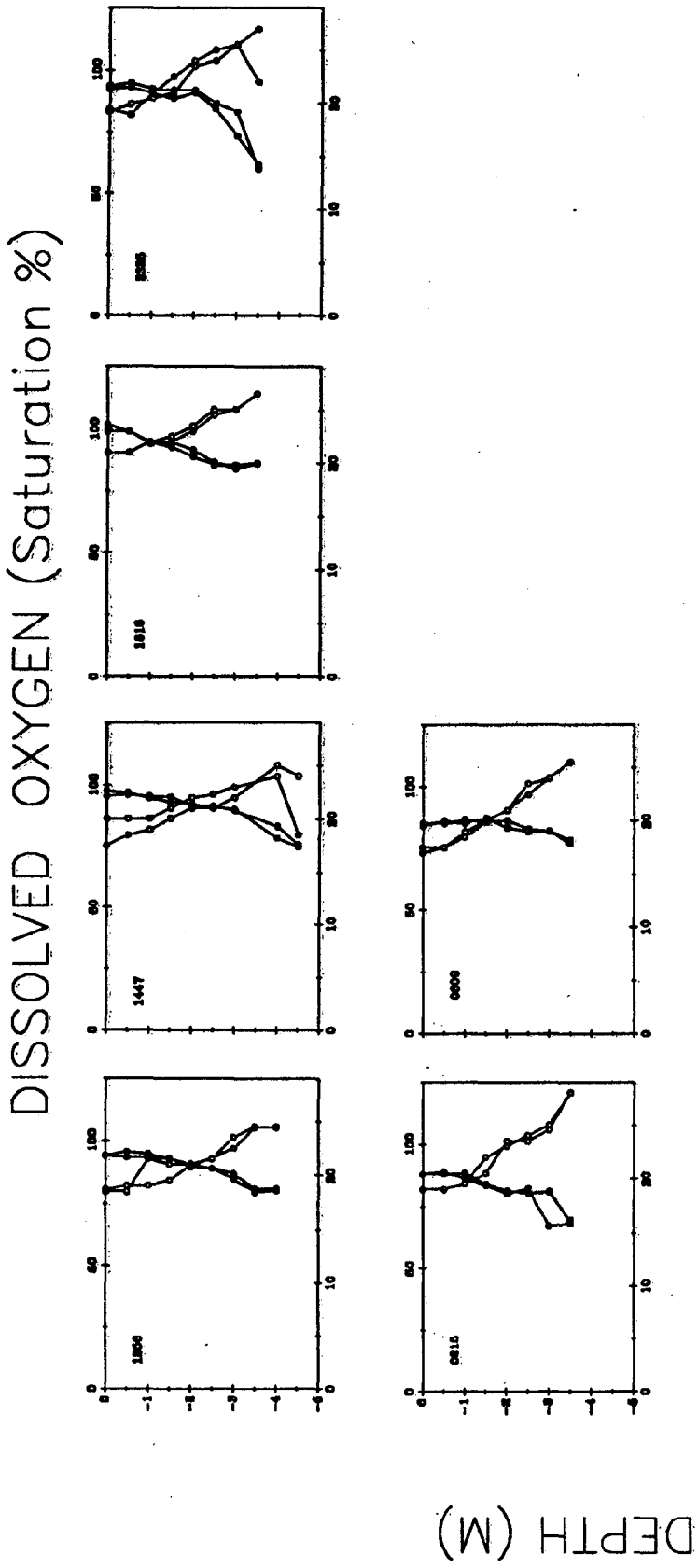
June 1988, Transect CT2, Station 3



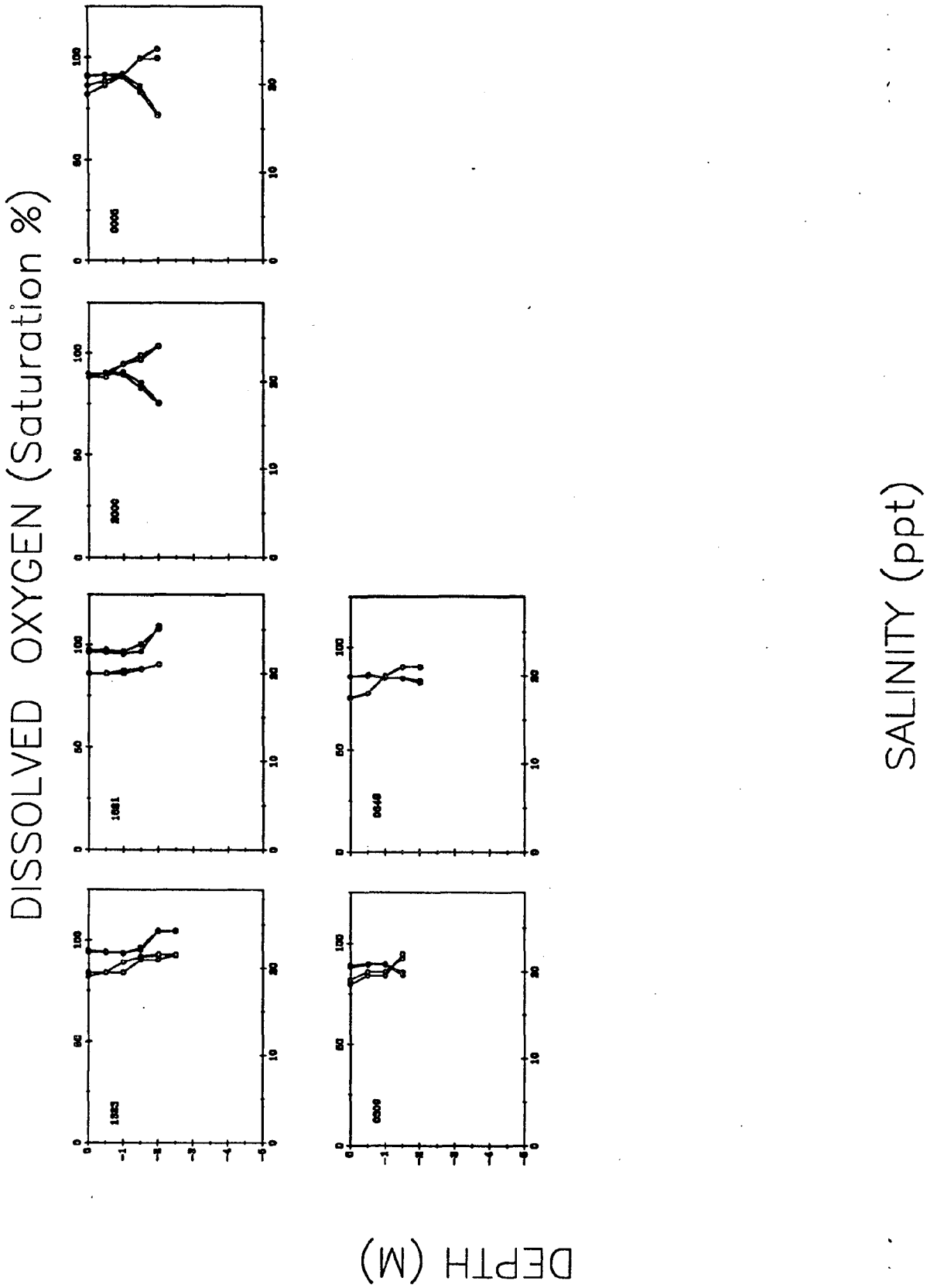
June 1988, Transect CT3, Station 1



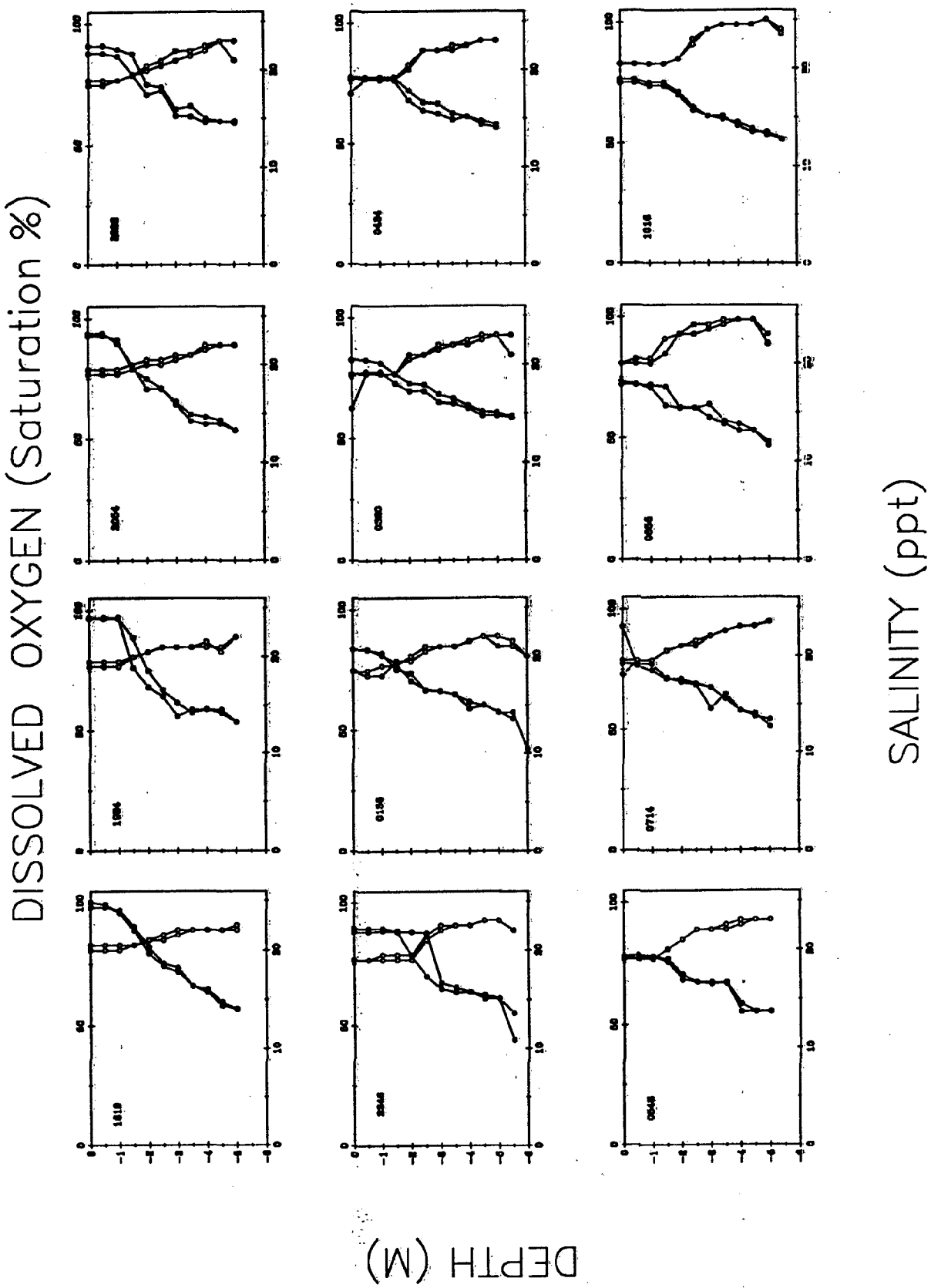
June 1988, Transect CT3, Station 2



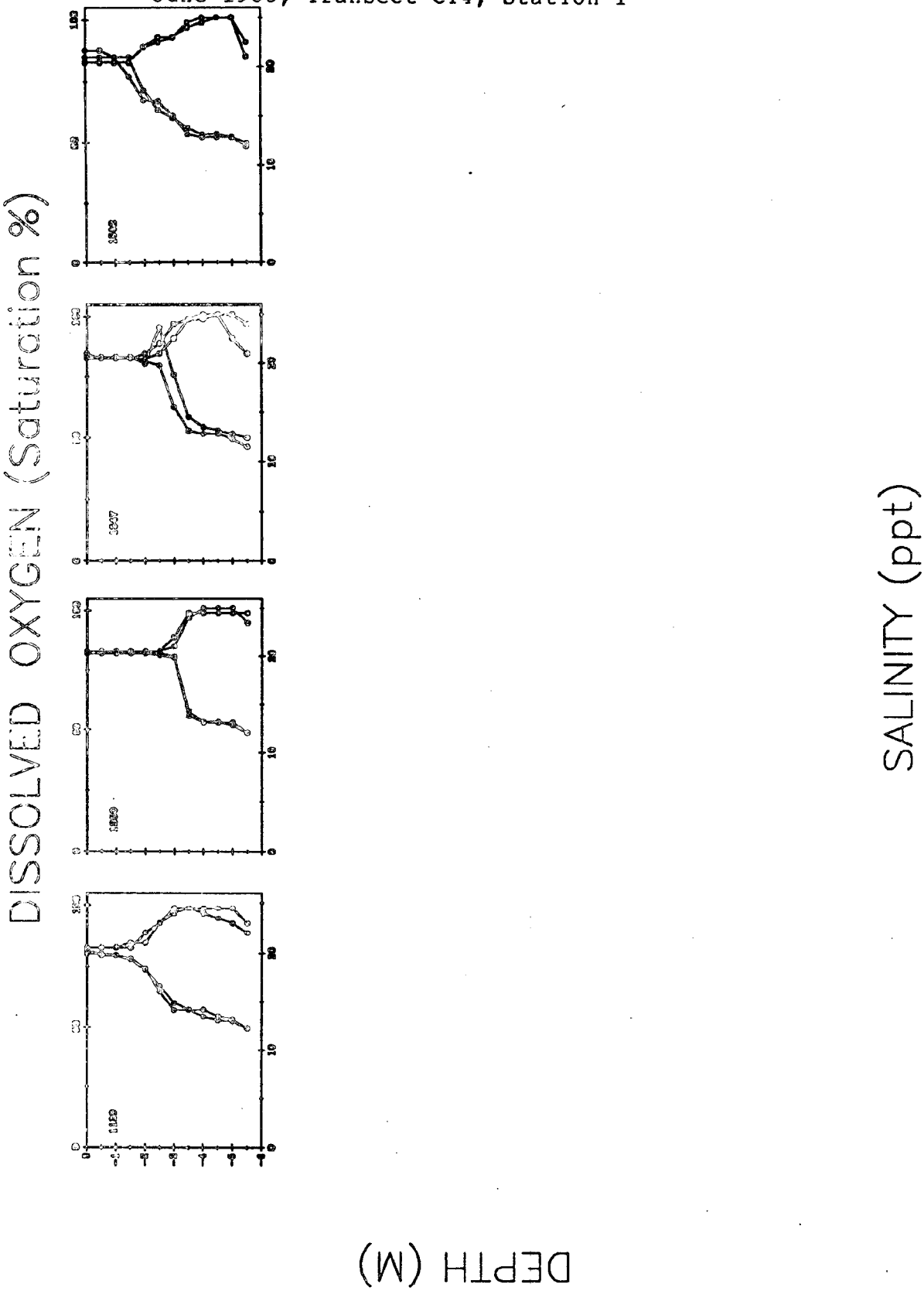
June 1988, Transect CT3, Station 3



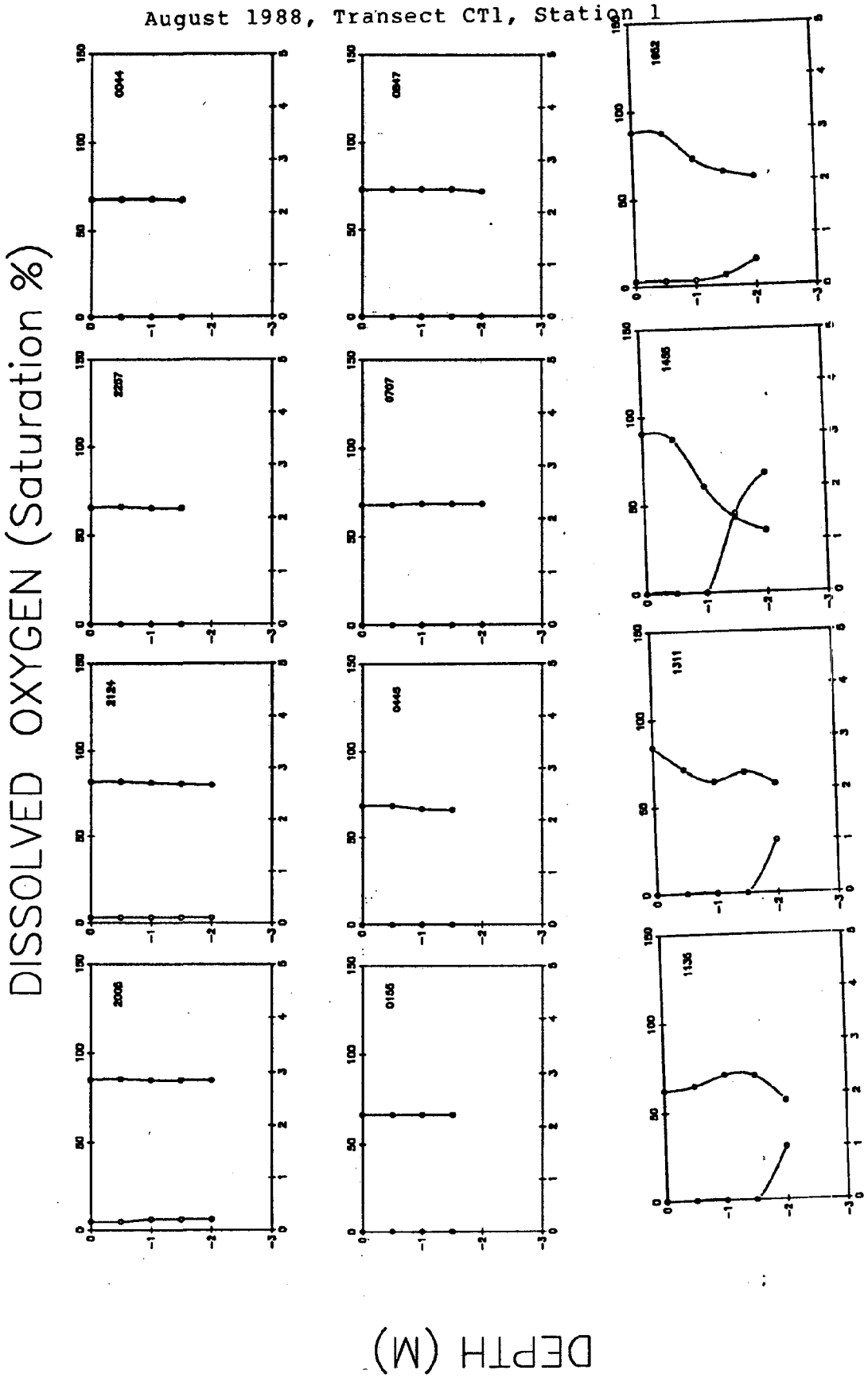
June 1988, Transect CT4, Station 1



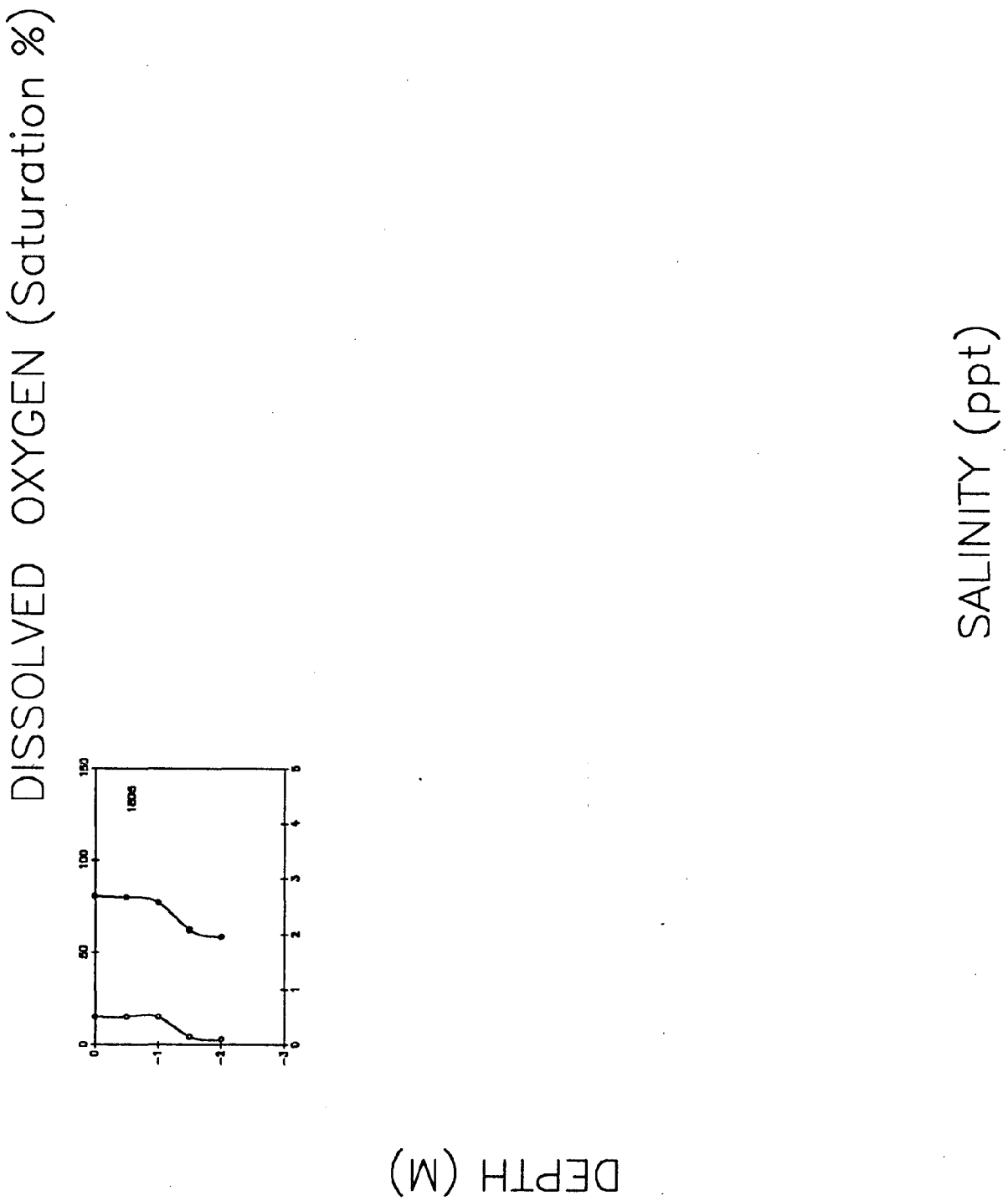
June 1988, Transect CT4, Station 1



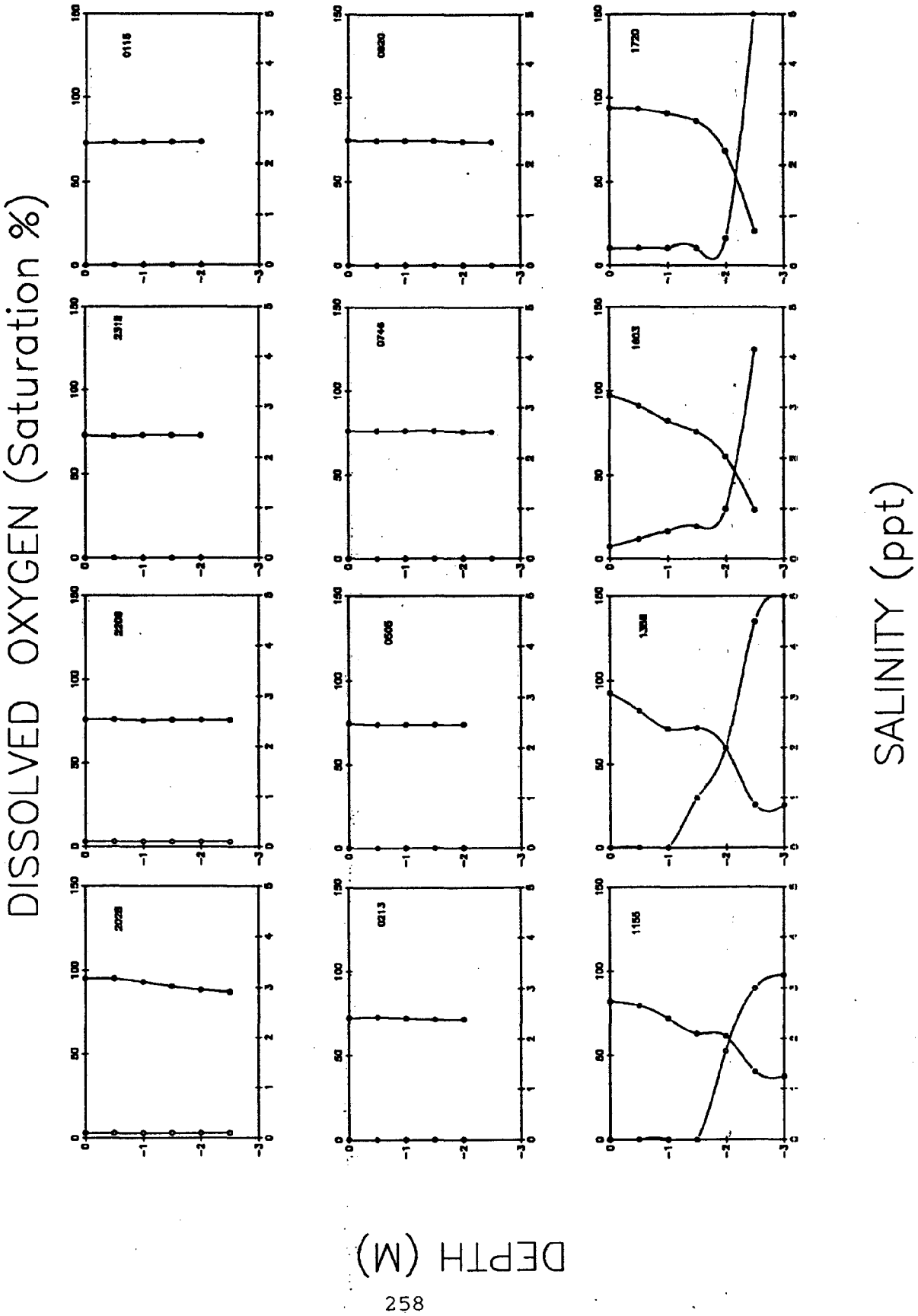
August 1988, Transect CT1, Station 1



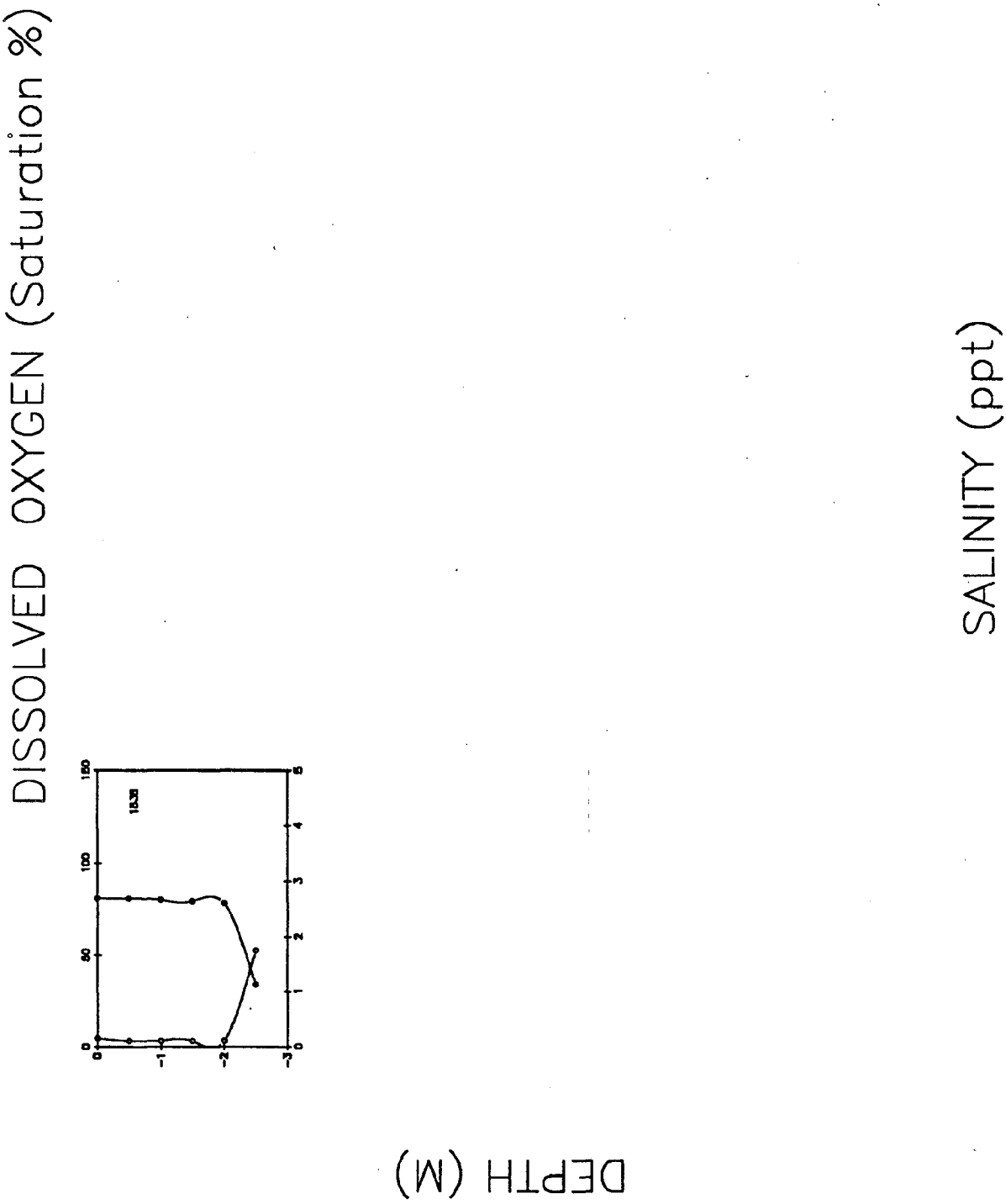
August 1988, Transect CT1, Station 1



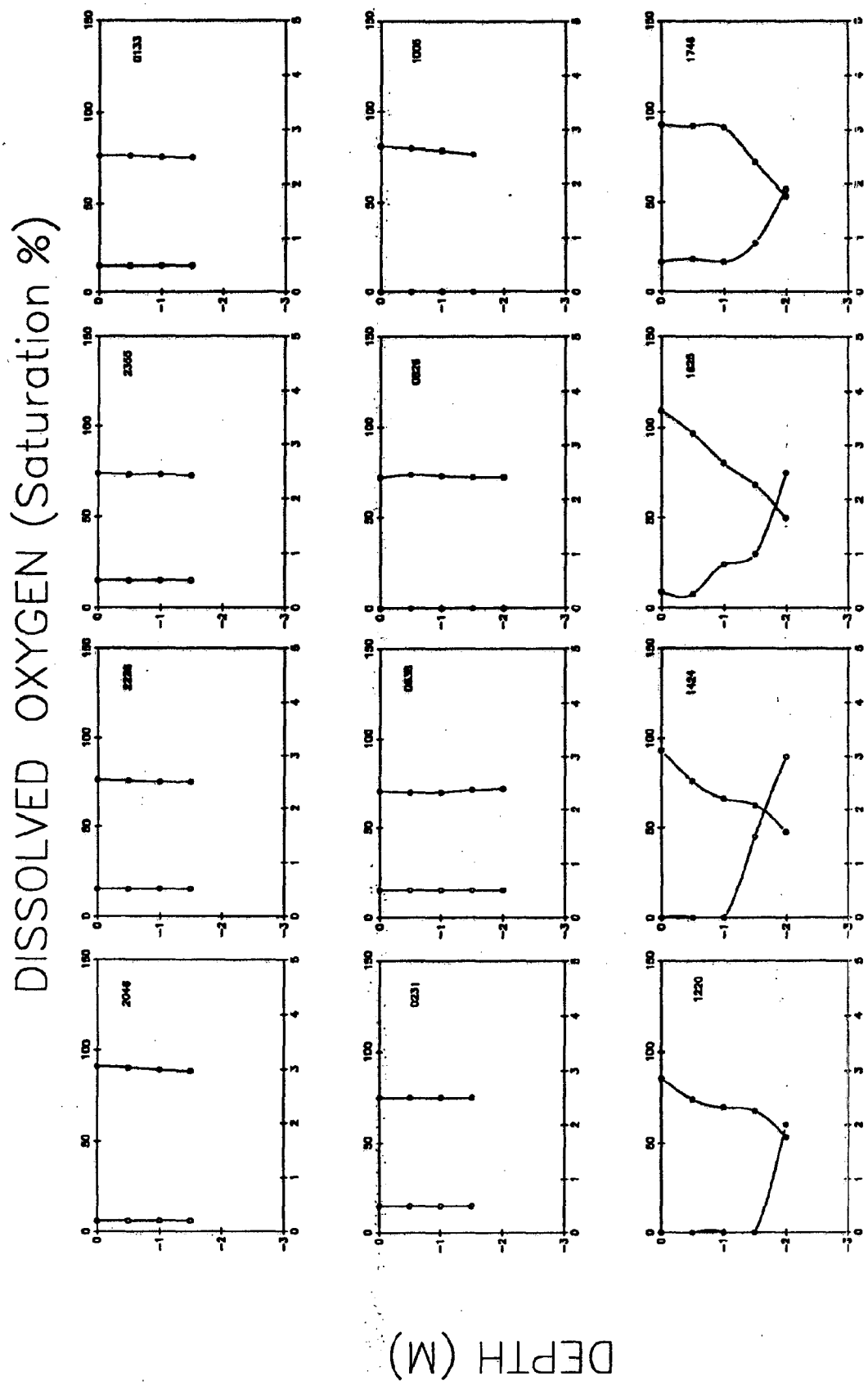
August 1988, Transect CT1, Station 2



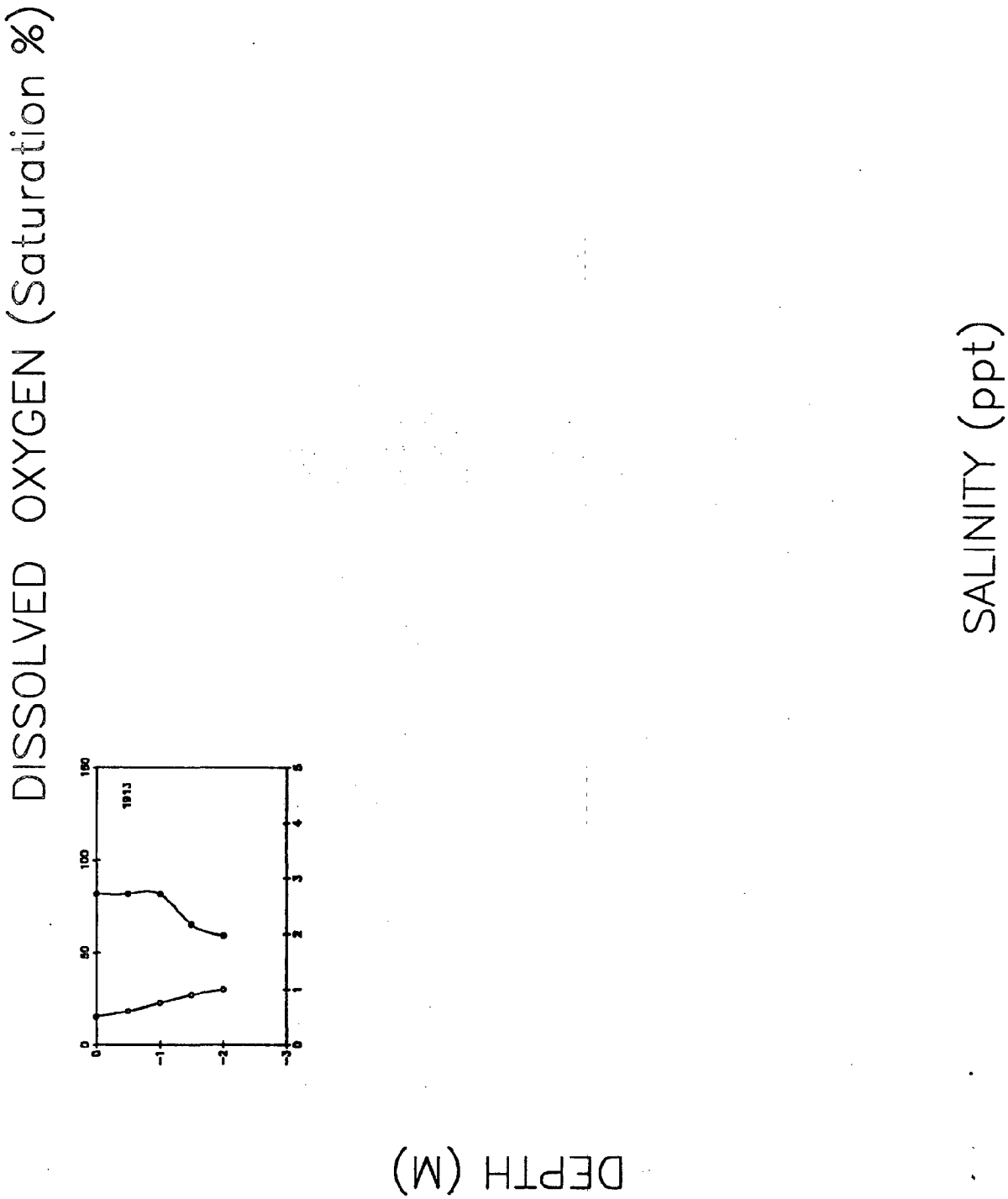
August 1988, Transect CT1, Station 2



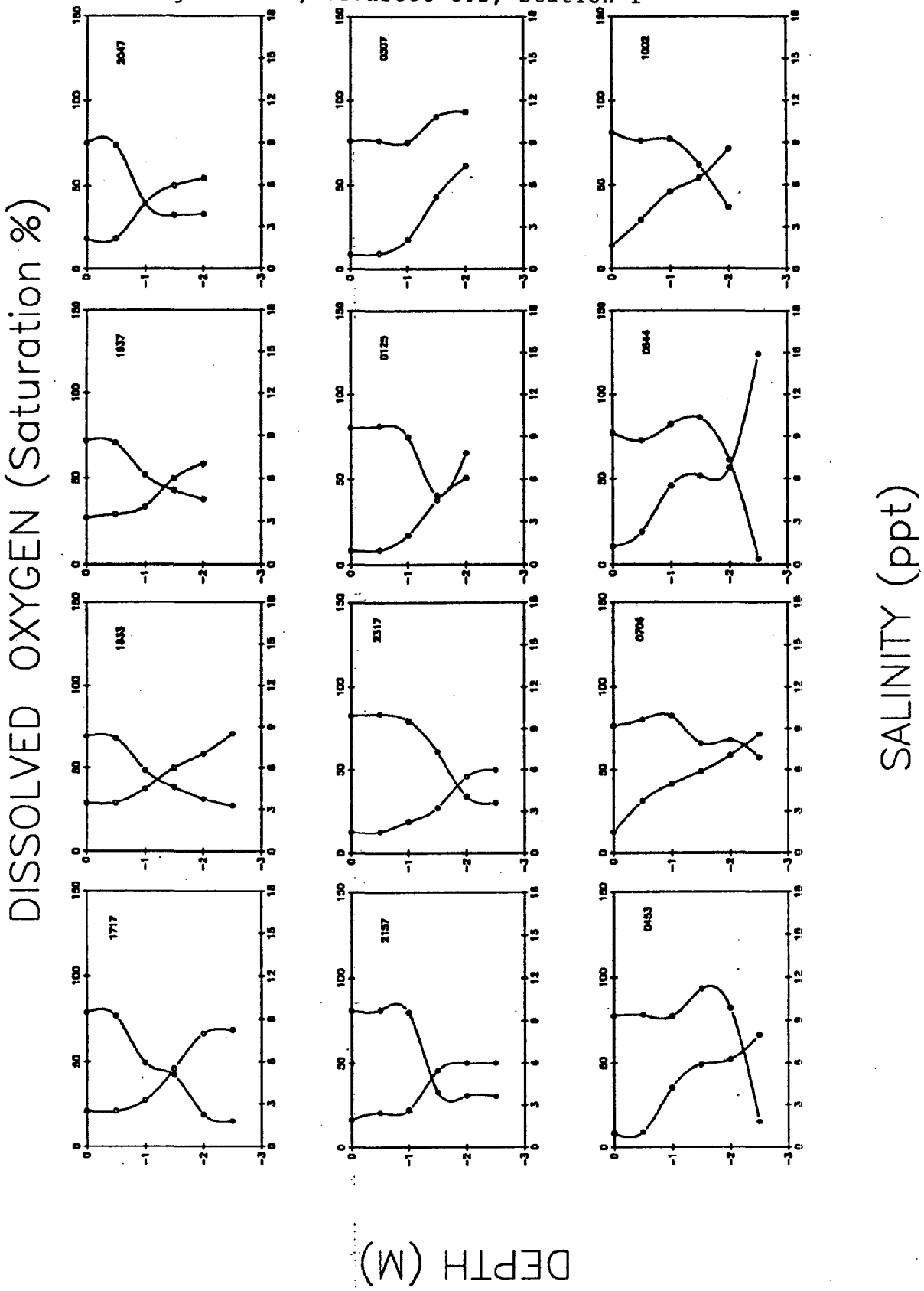
August 1988, Transect CT1, Station 3



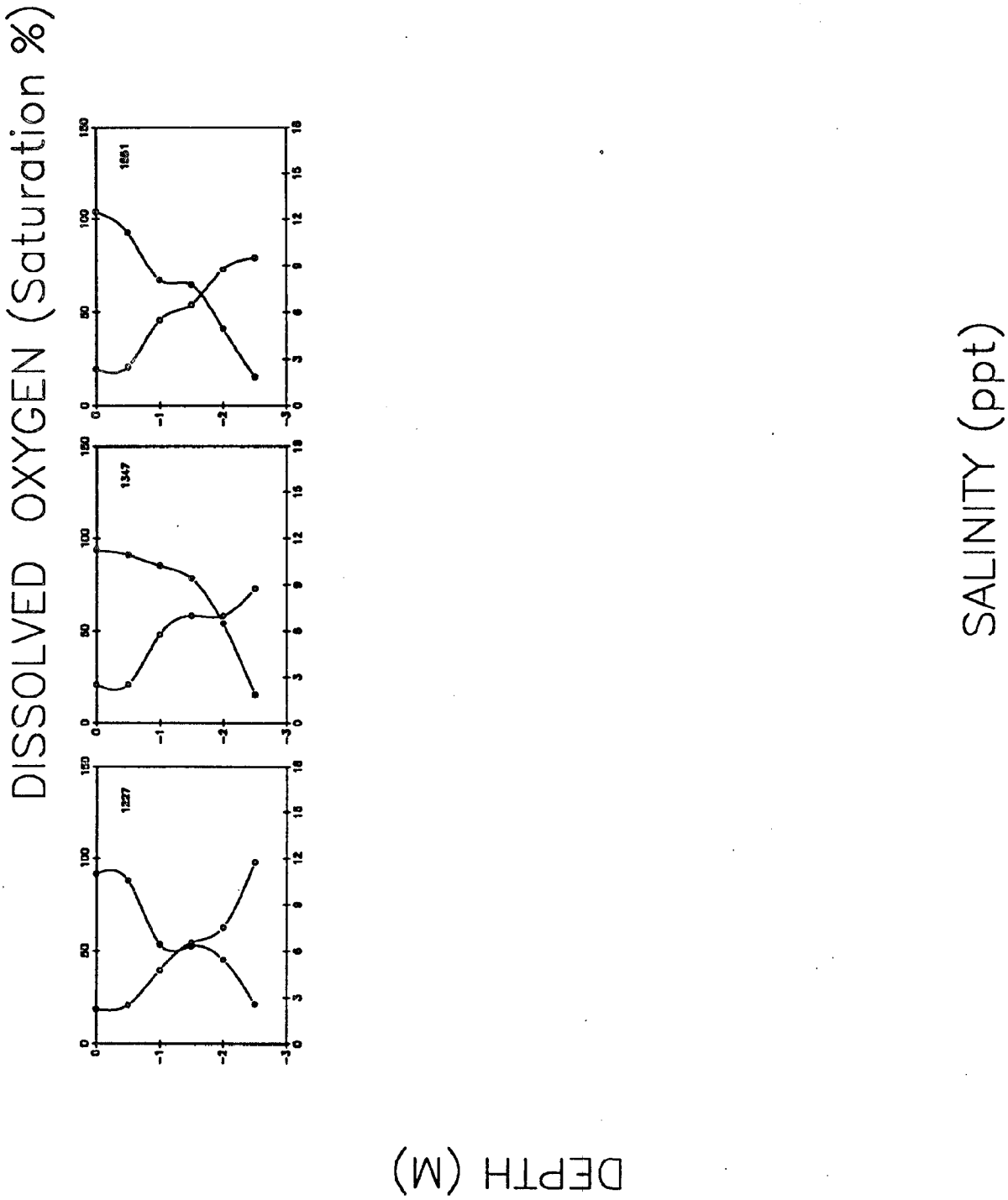
August 1988, Transect CT1, Station 3



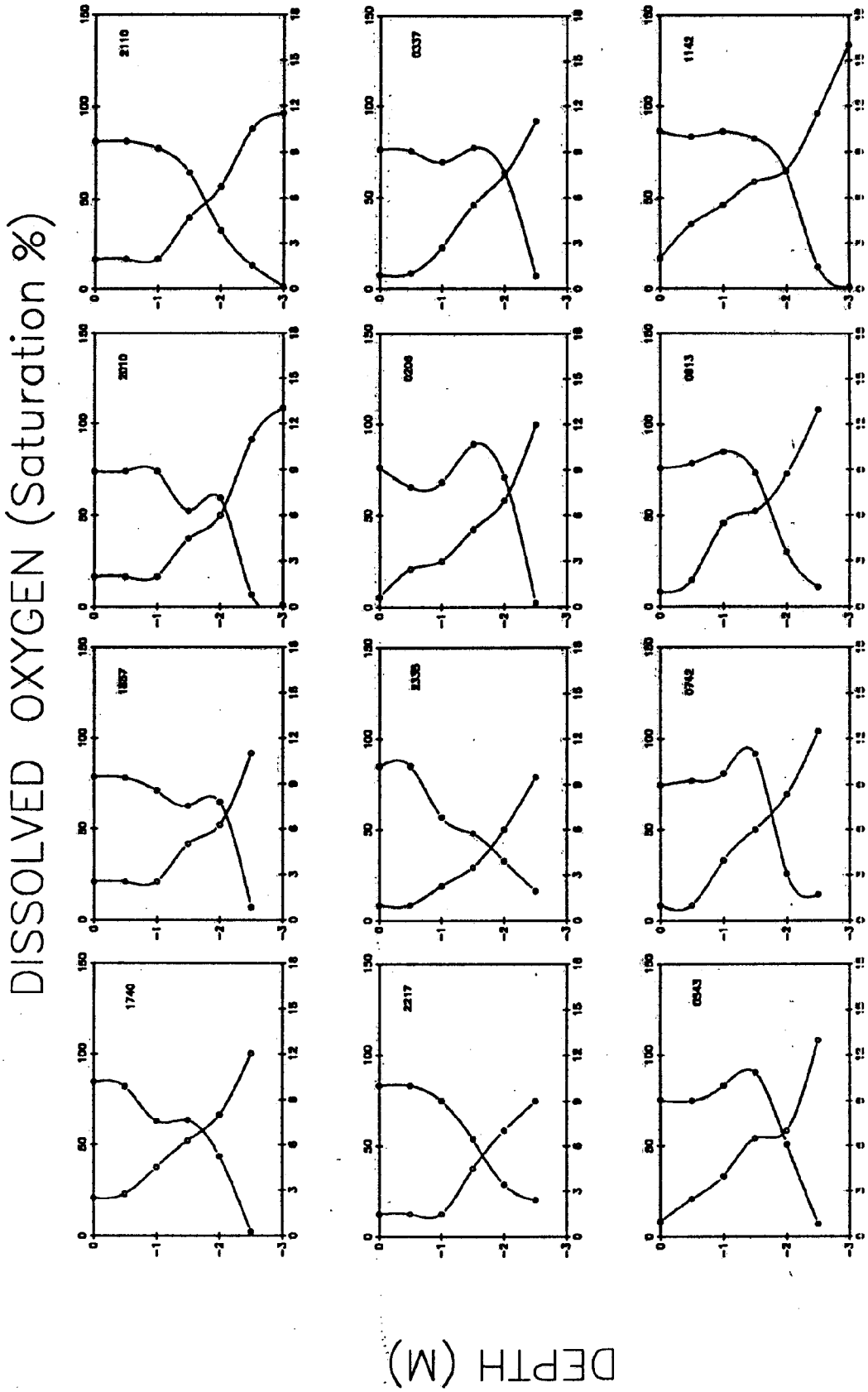
August 1988, Transect CT2, Station 1



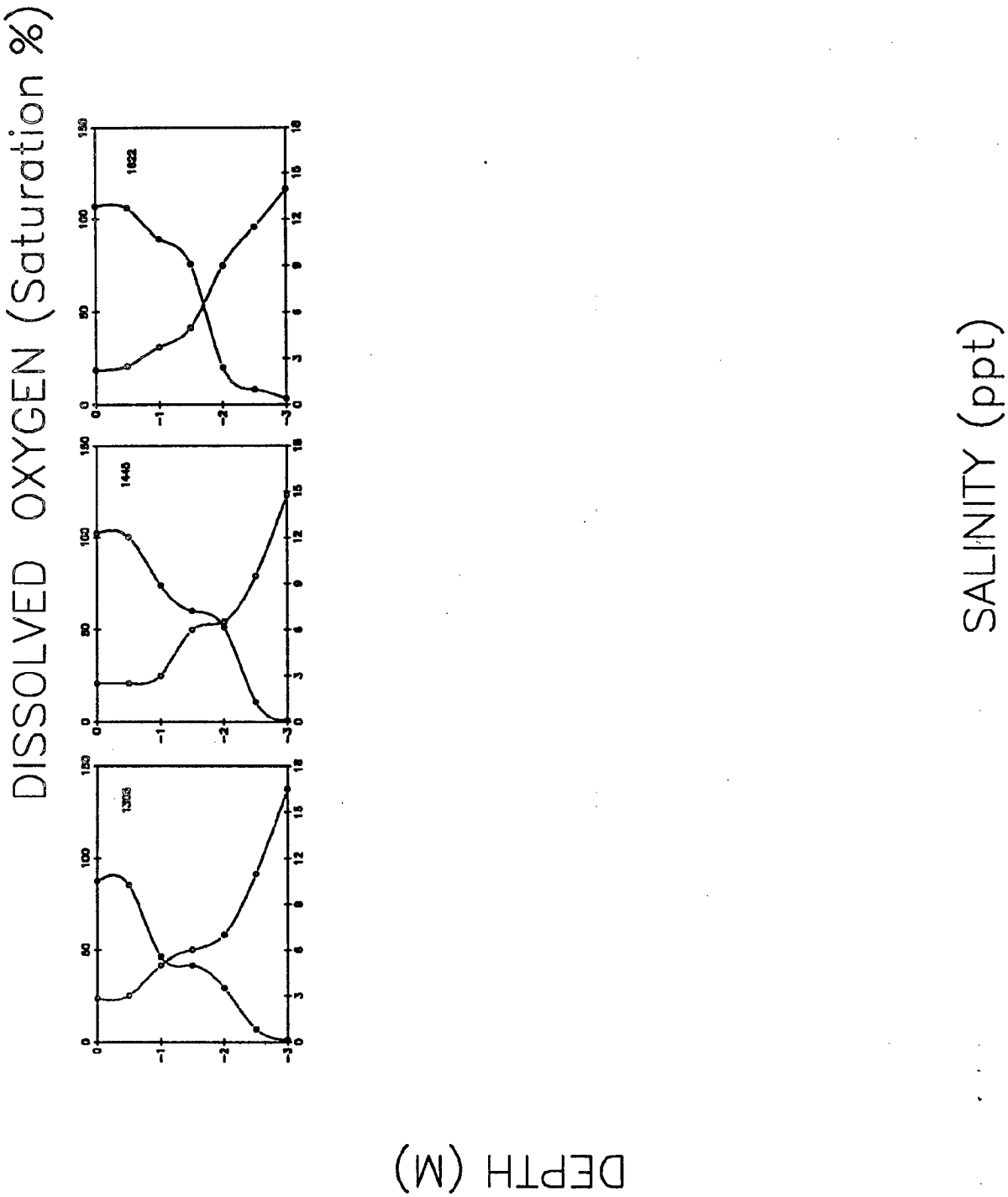
August 1988, Transect CT2, Station 1



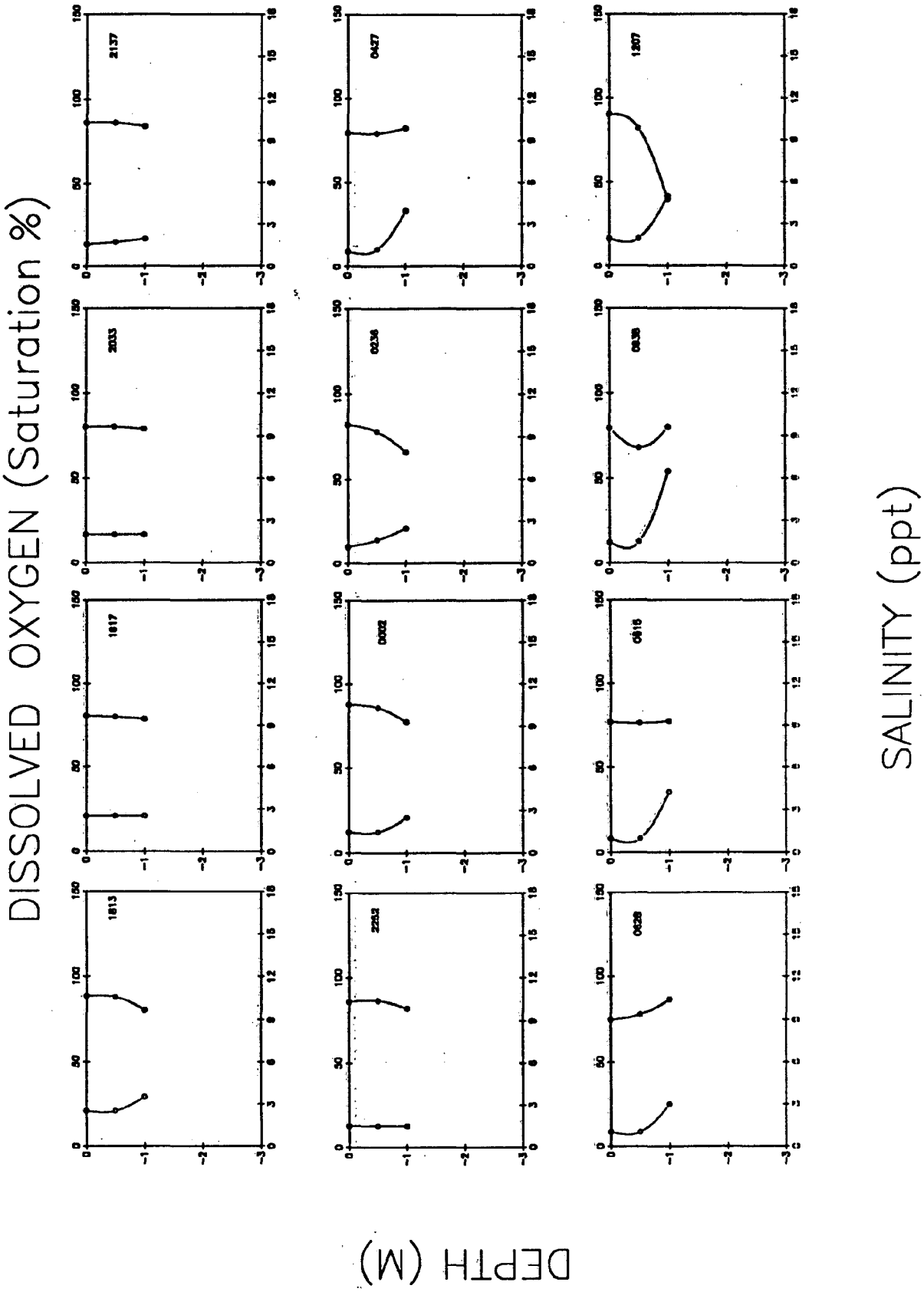
August 1988, Transect CT2, Station 2



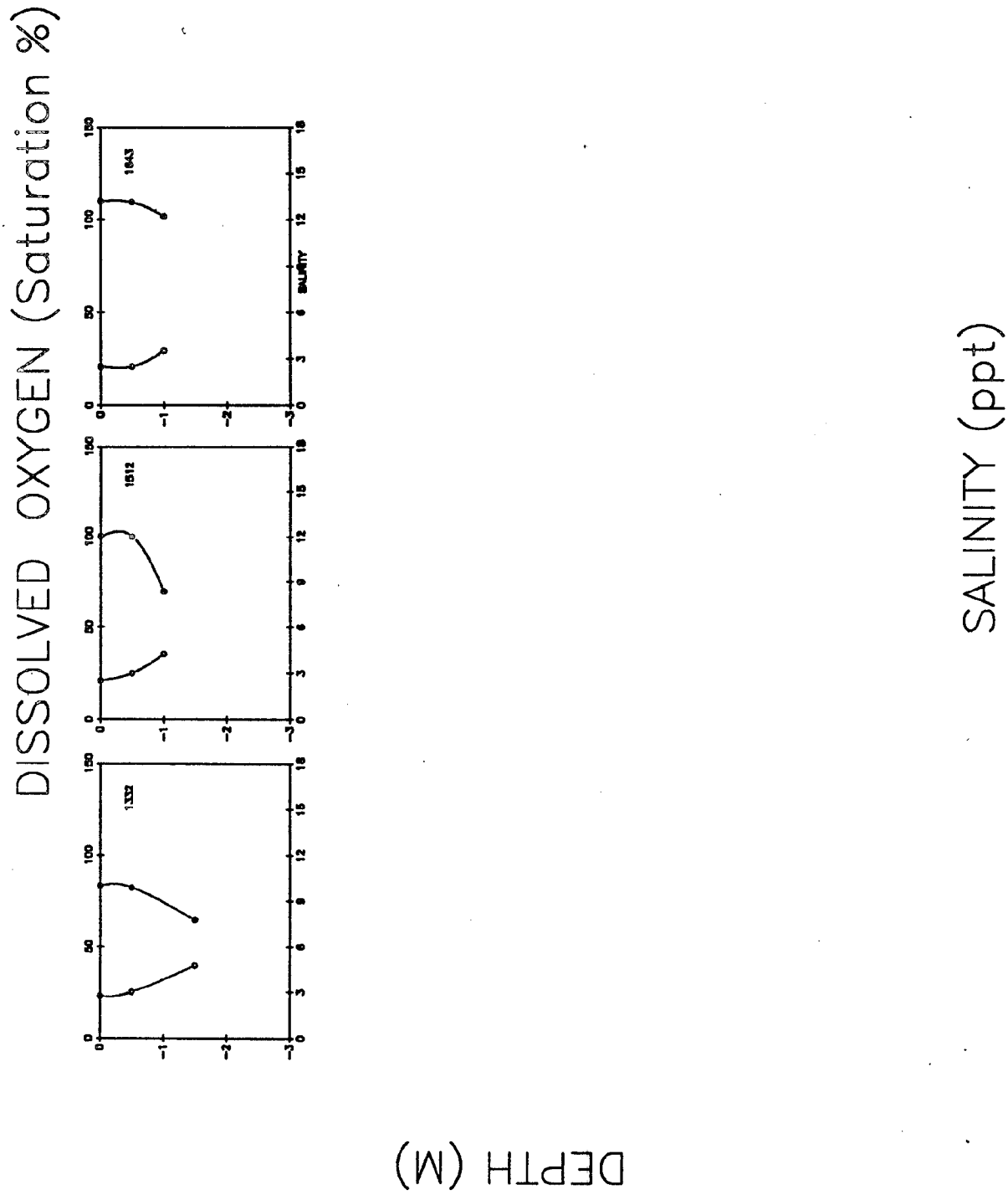
August 1988, Transect CT2, Station 2



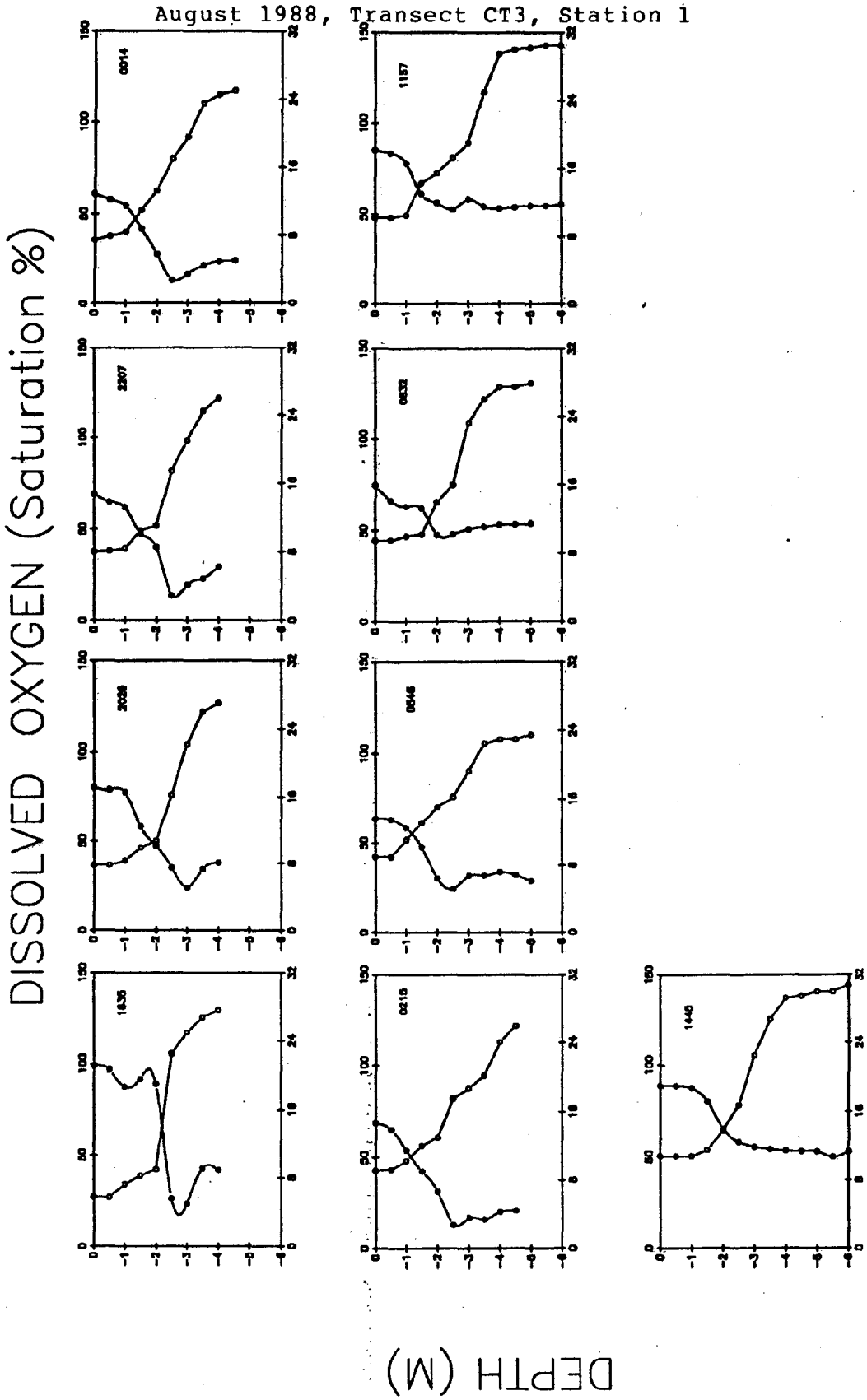
August 1988, Transect CT2, Station 3



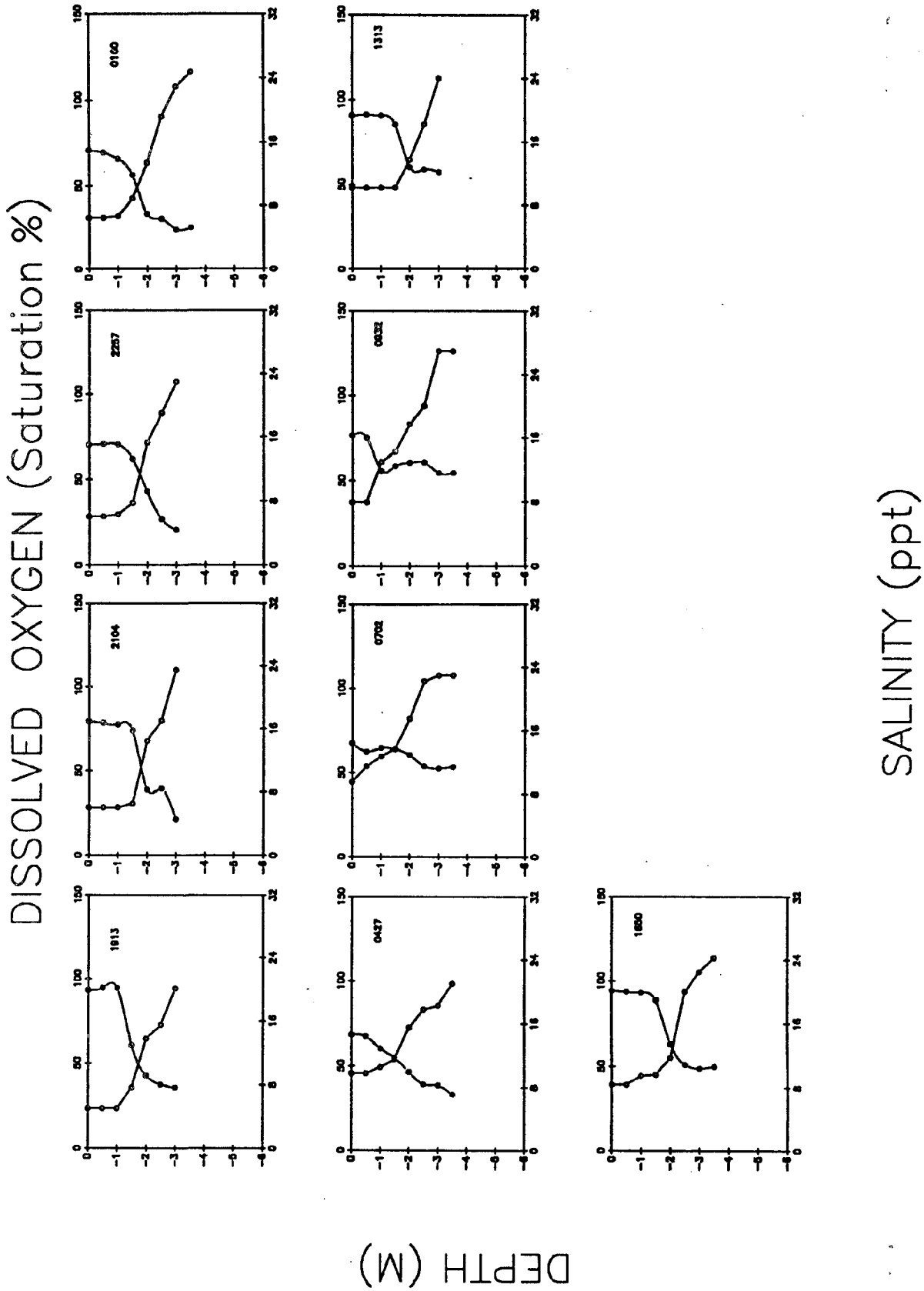
August 1988, Transect CT2, Station 3



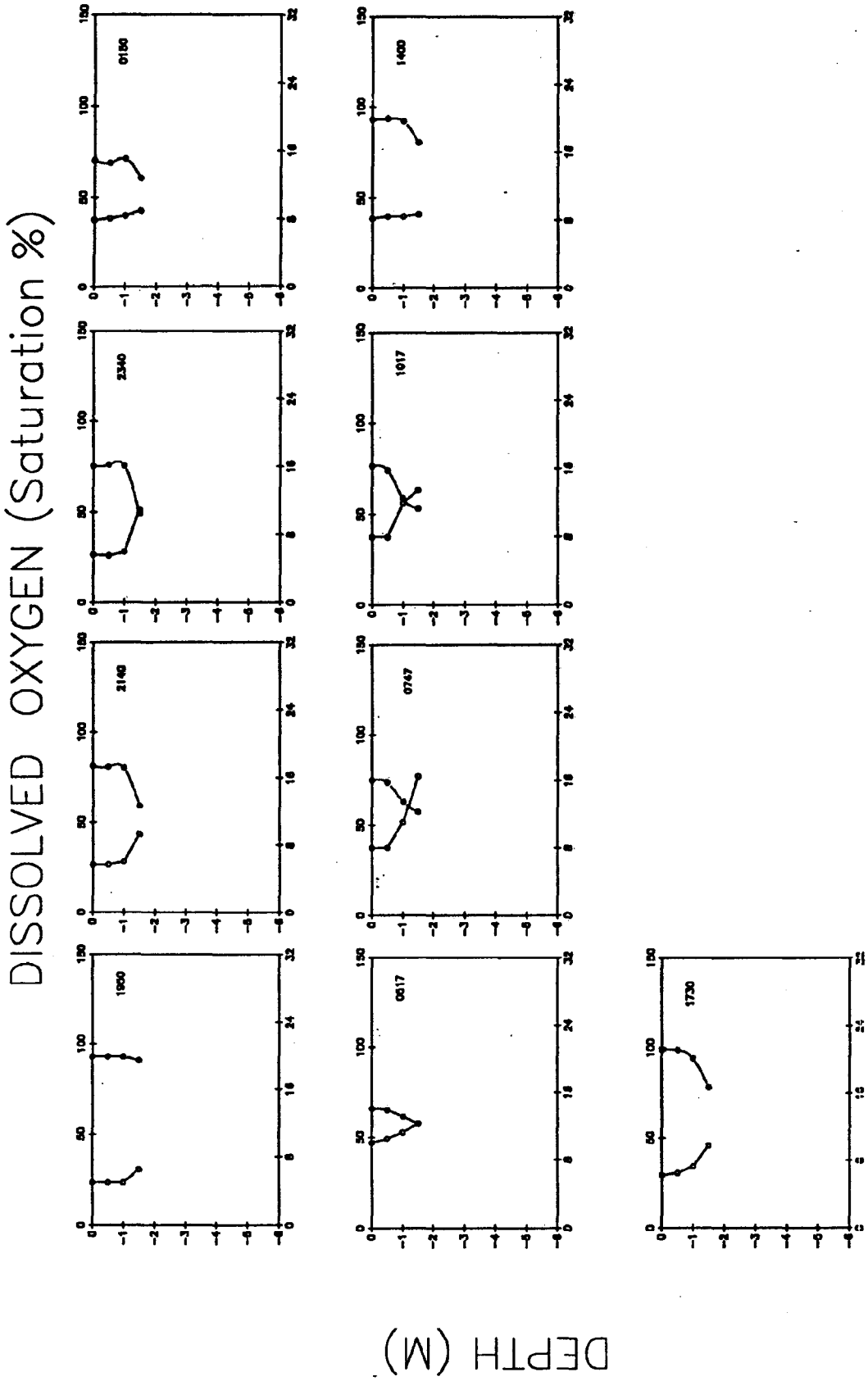
August 1988, Transect CT3, Station 1



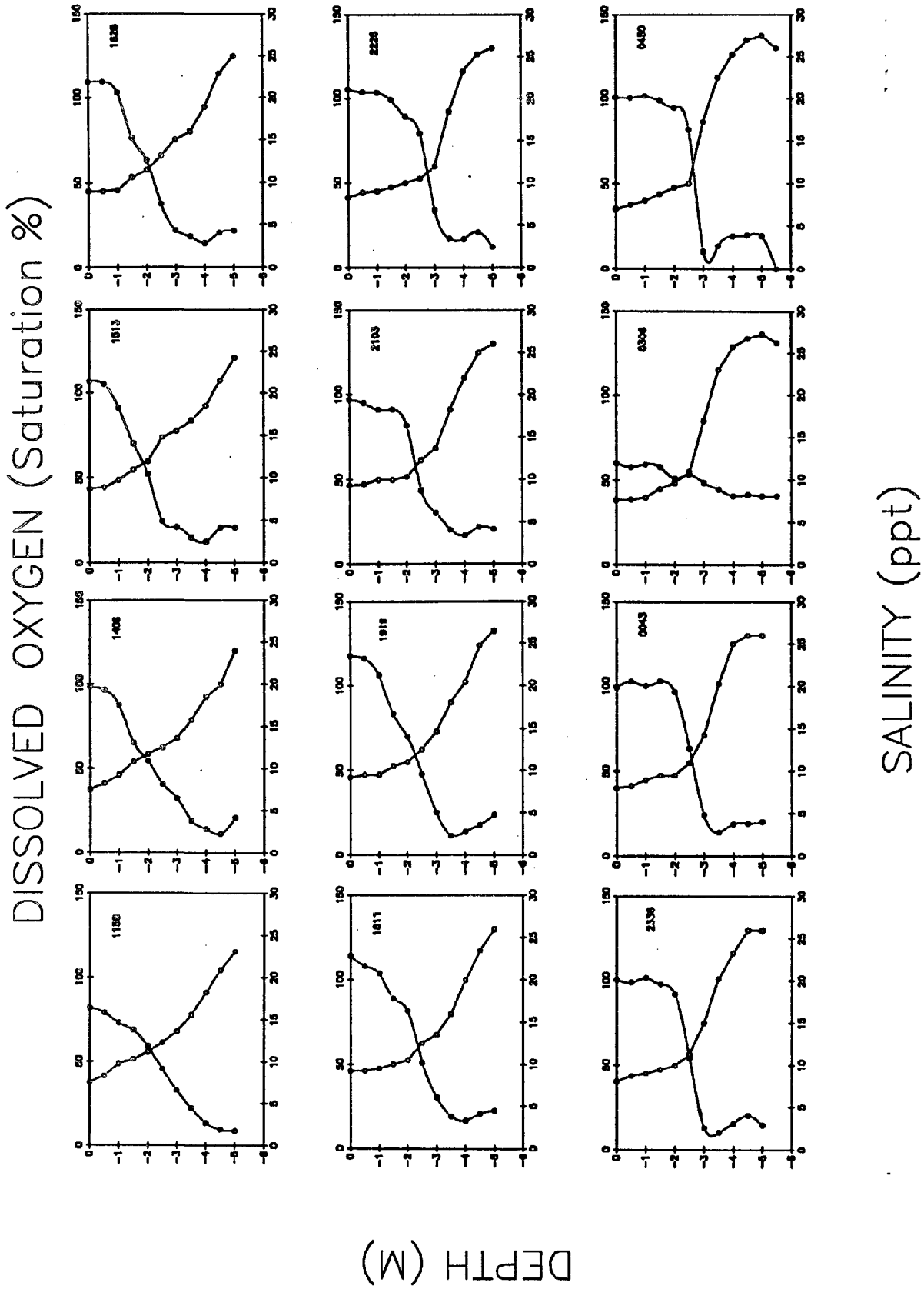
August 1988, Transect CT3, Station 2



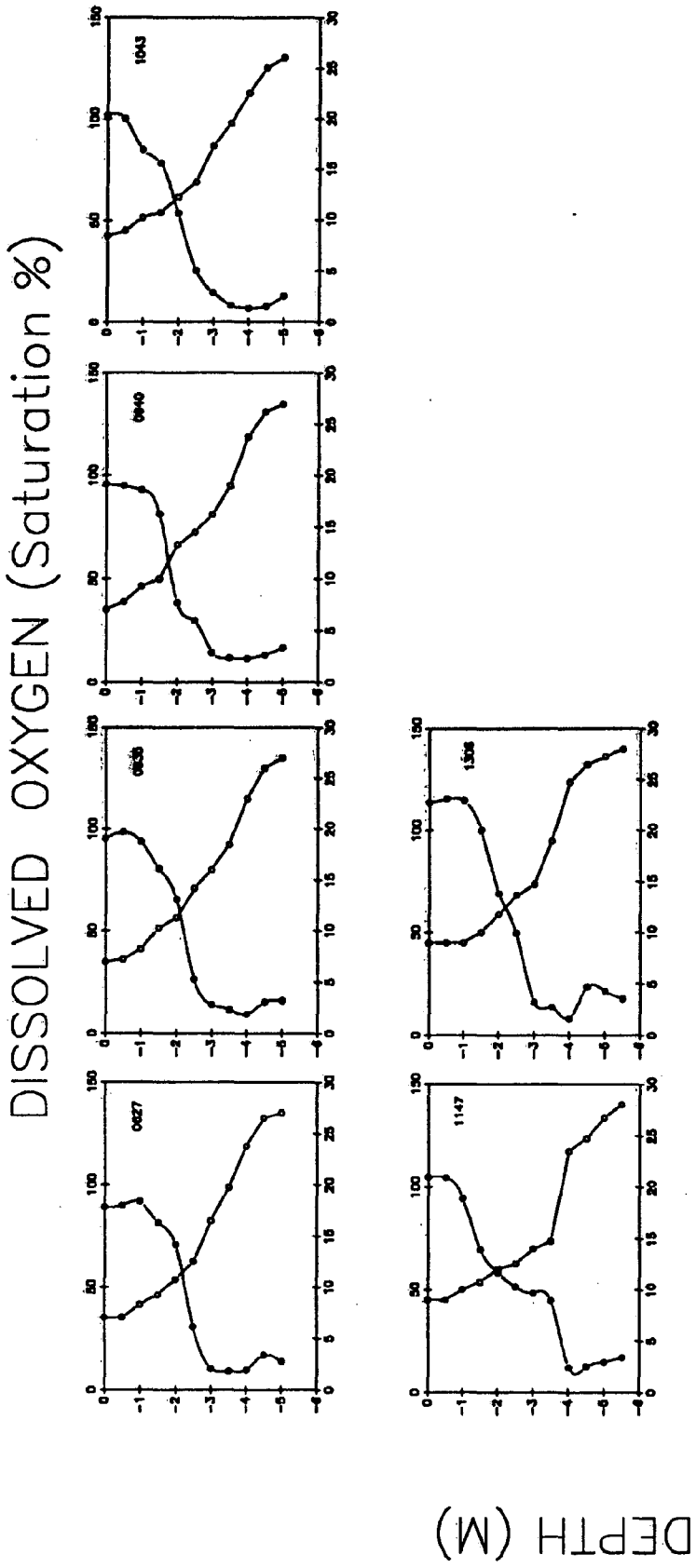
August 1988, Transect CT3, Station 3



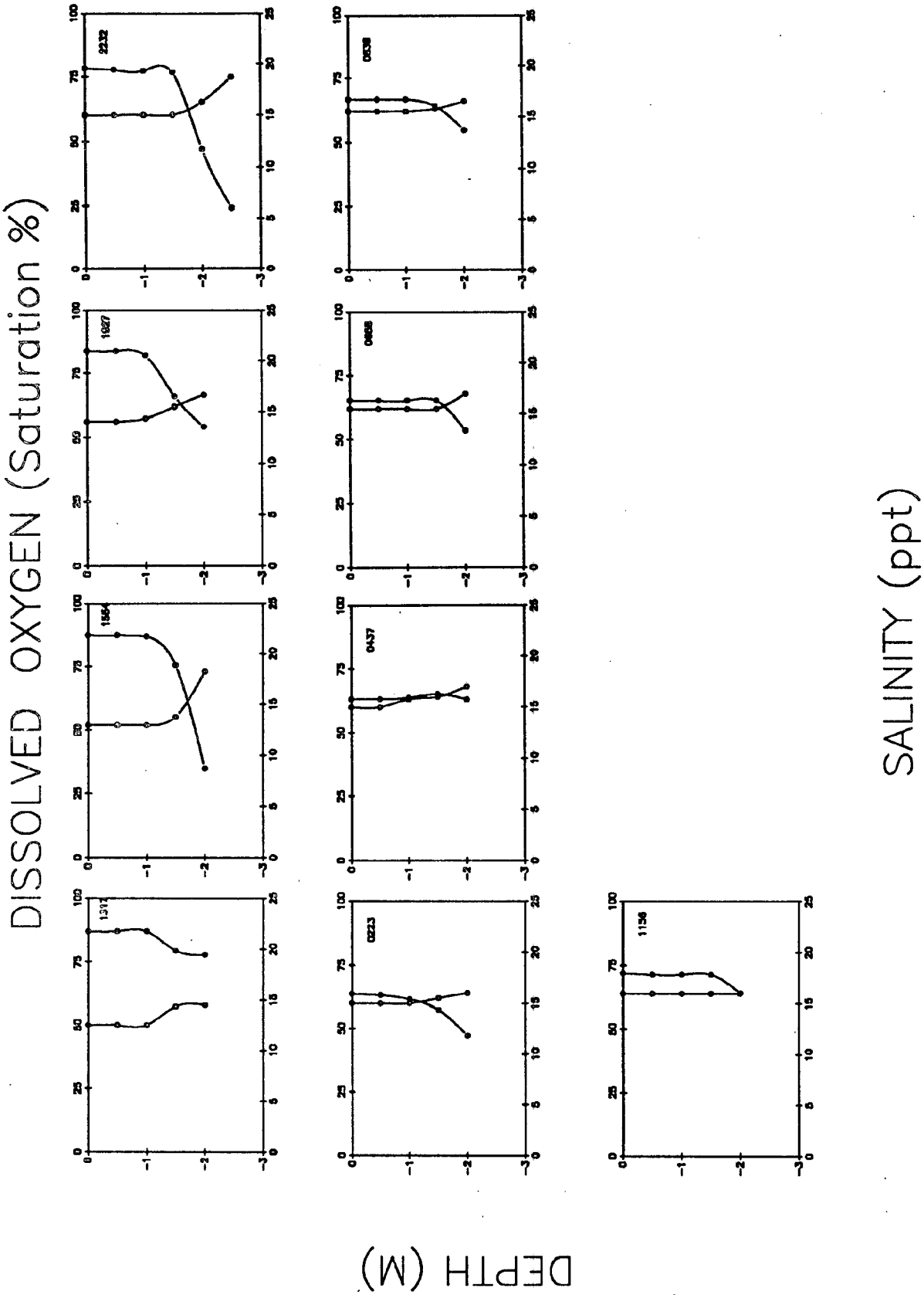
August 1988, Transect CT4, Station 1



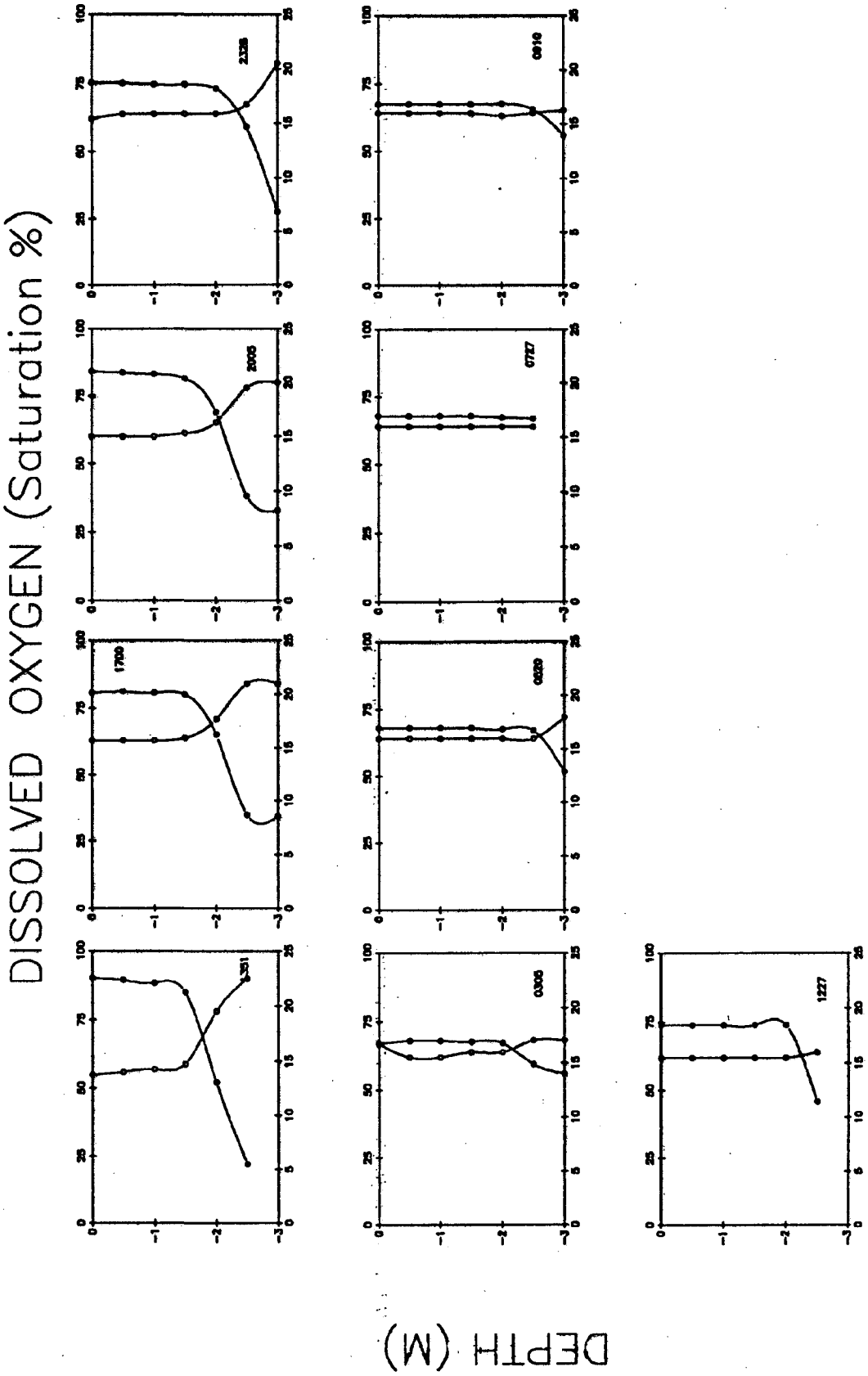
August 1988, Transect CT4, Station 1



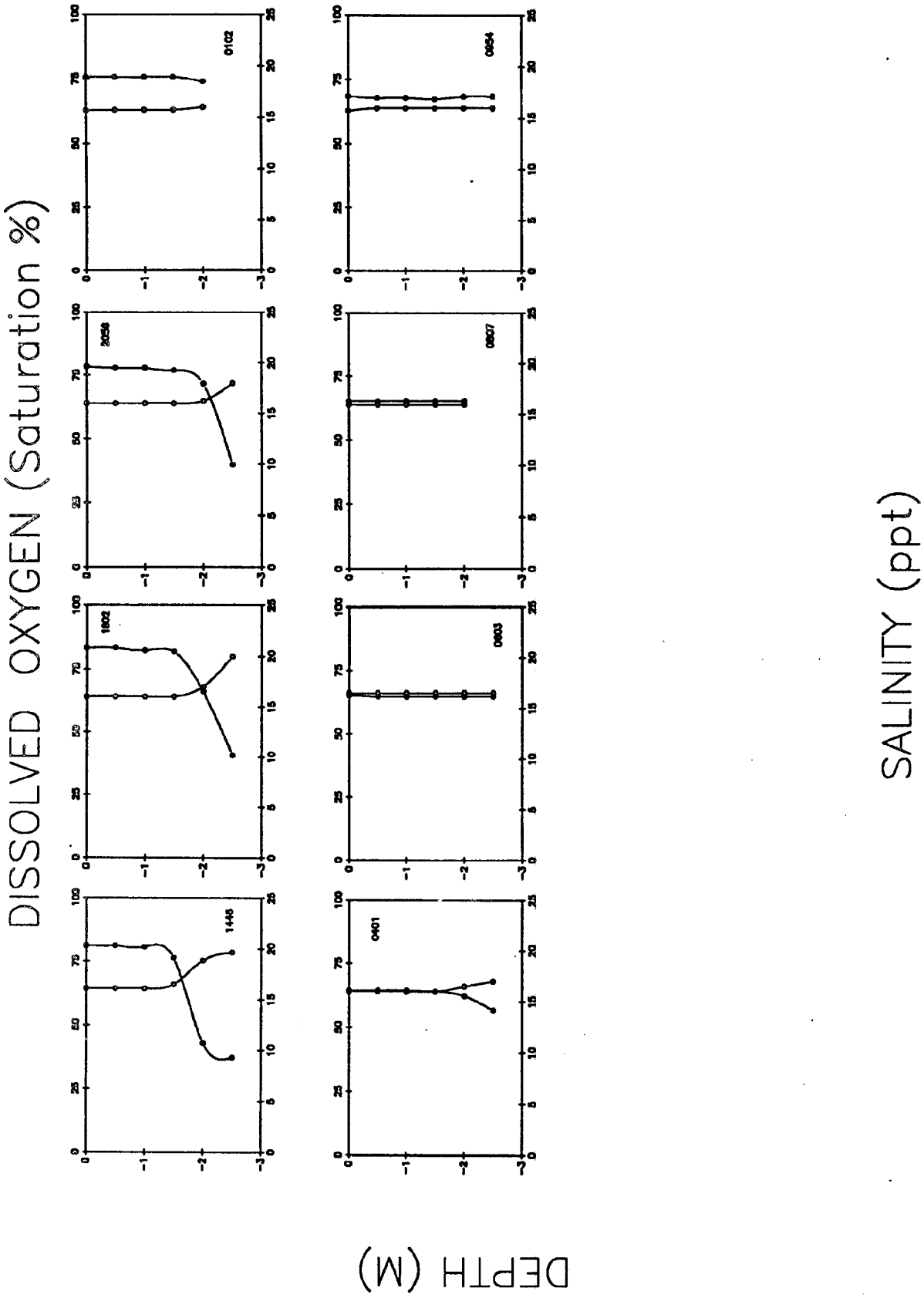
November 1988, Transect CT1, Station 1



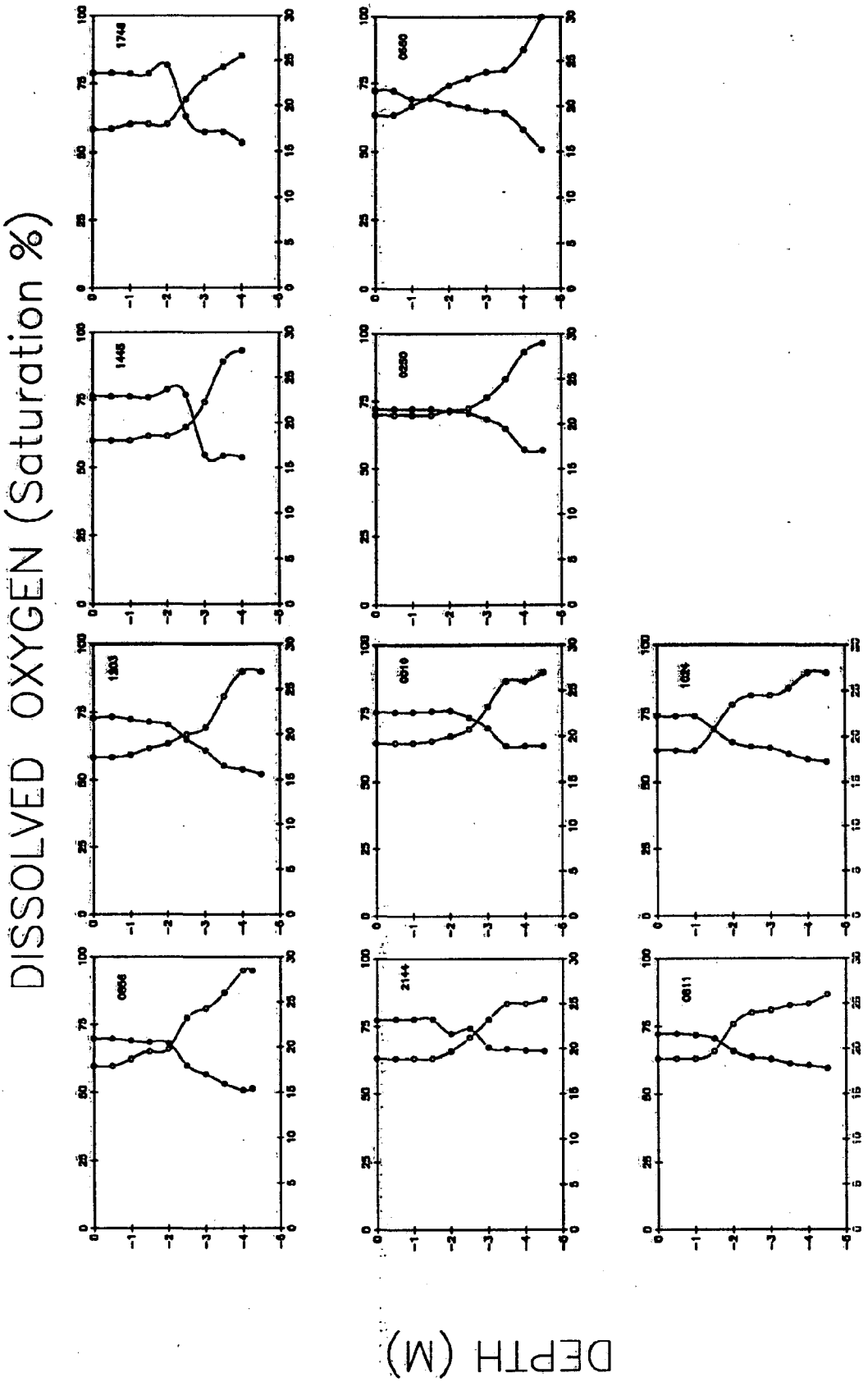
November 1988, Transect CT1, Station 2



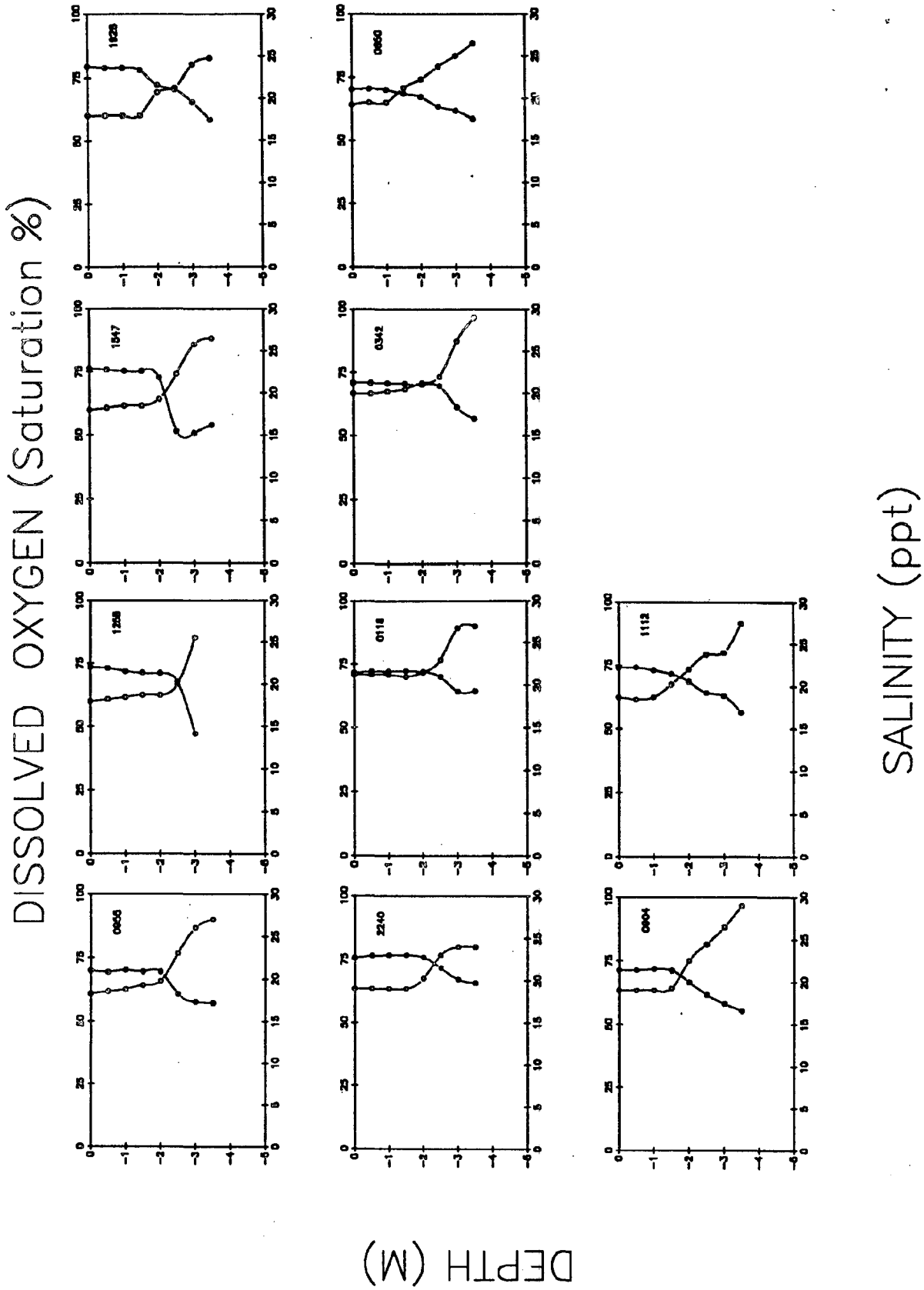
November 1988, Transect CT1, Station 3



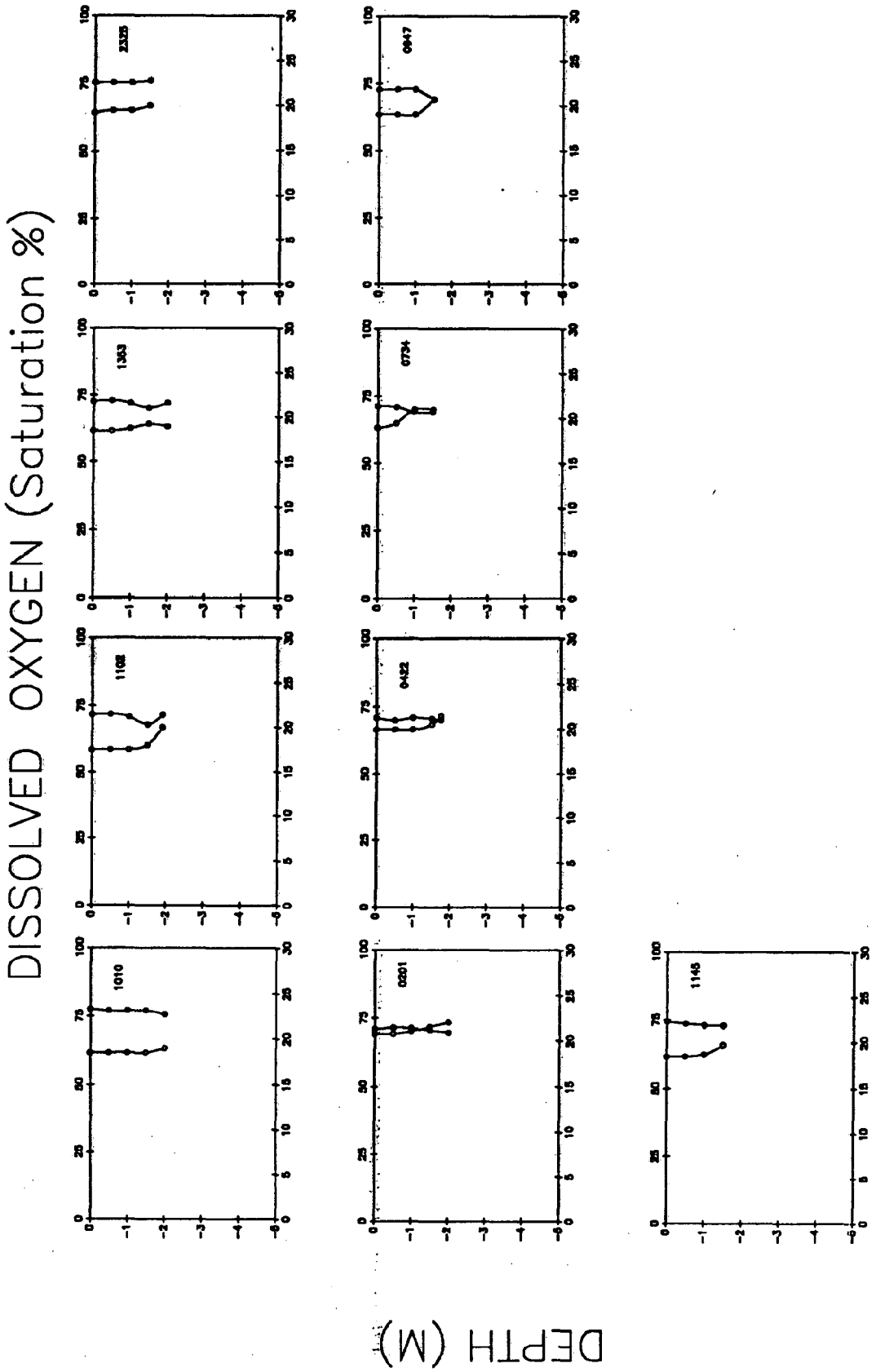
November 1988, Transect CT3, Station 1



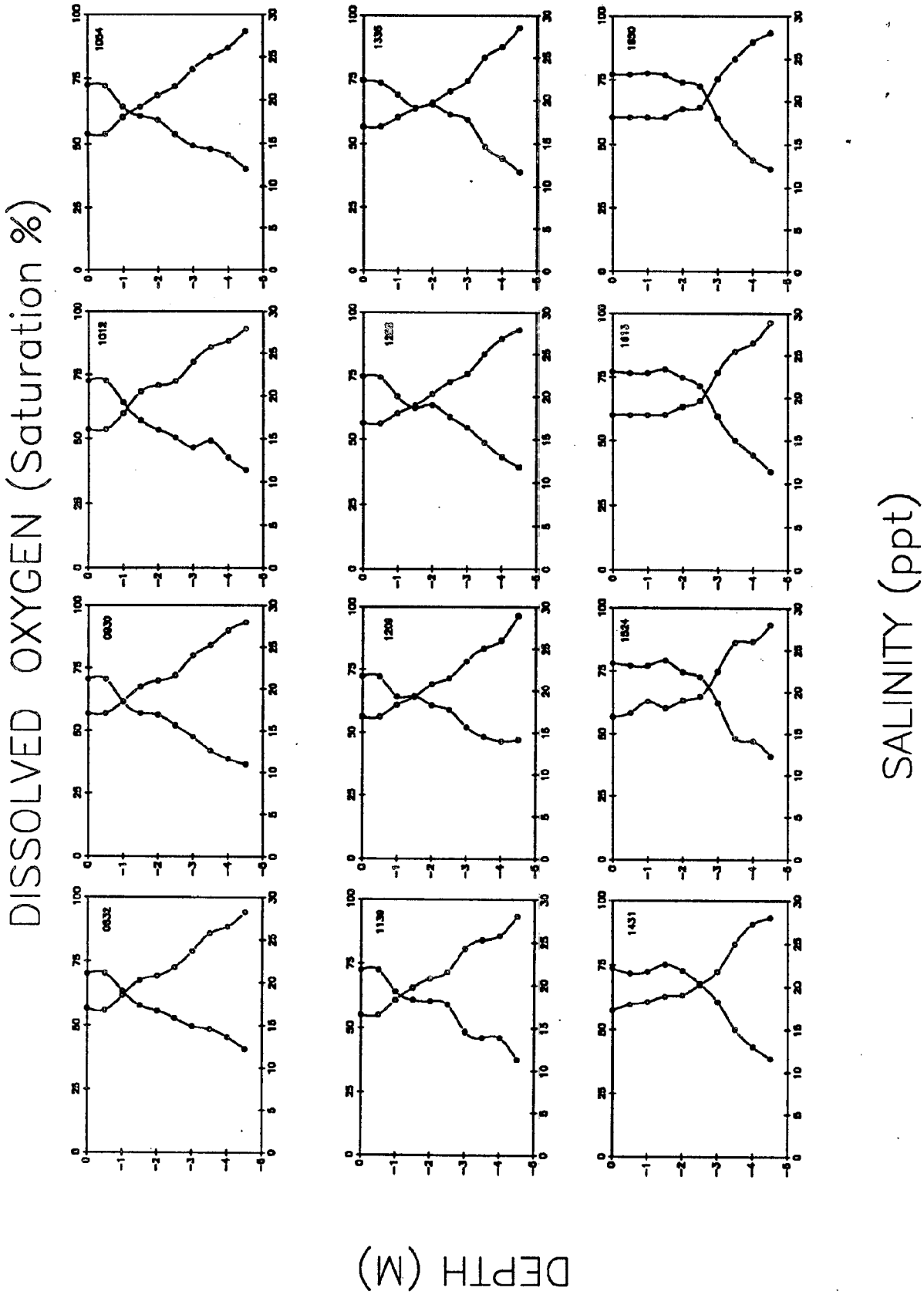
November 1988, Transect CT3, Station 2



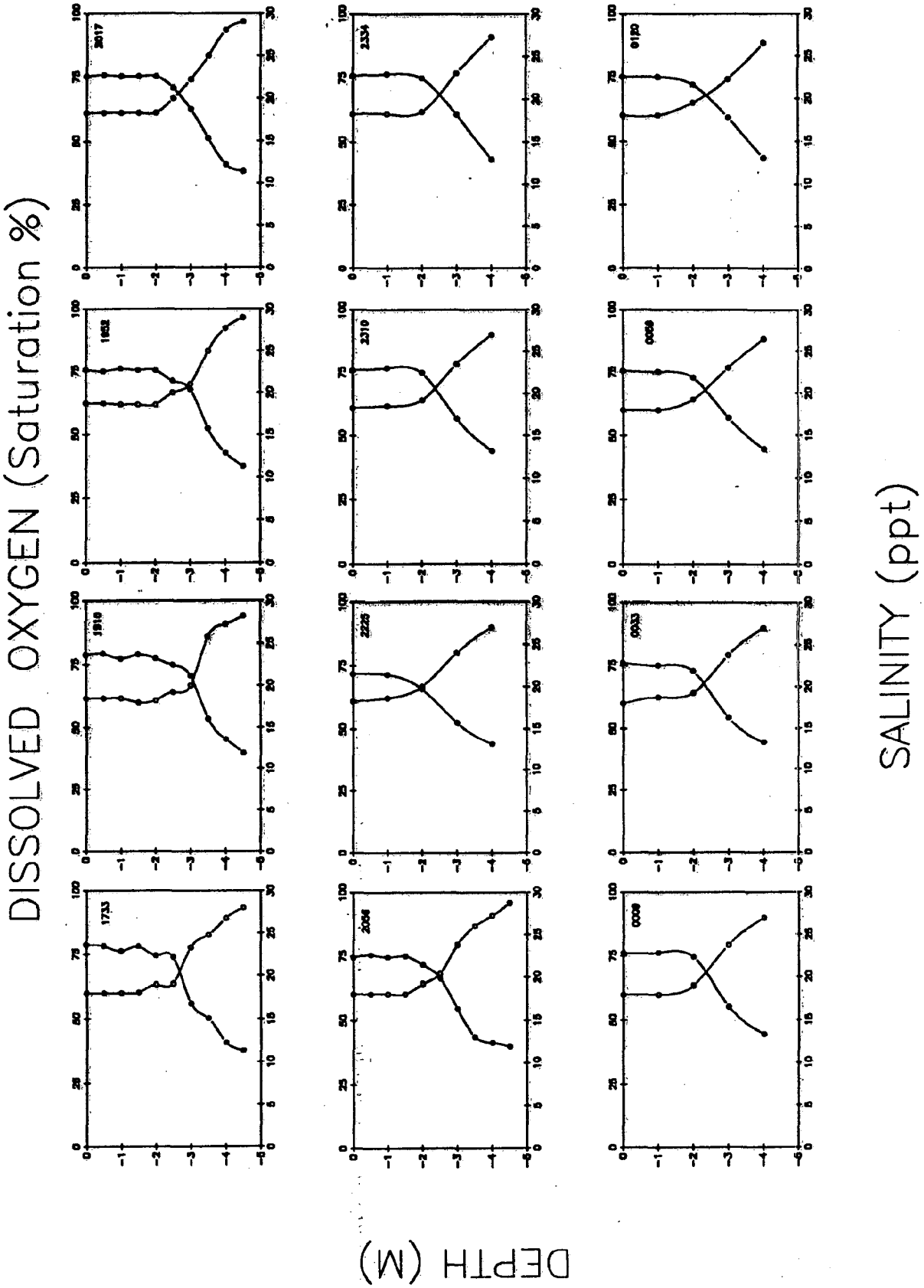
November 1988, Transect CT3, Station 3



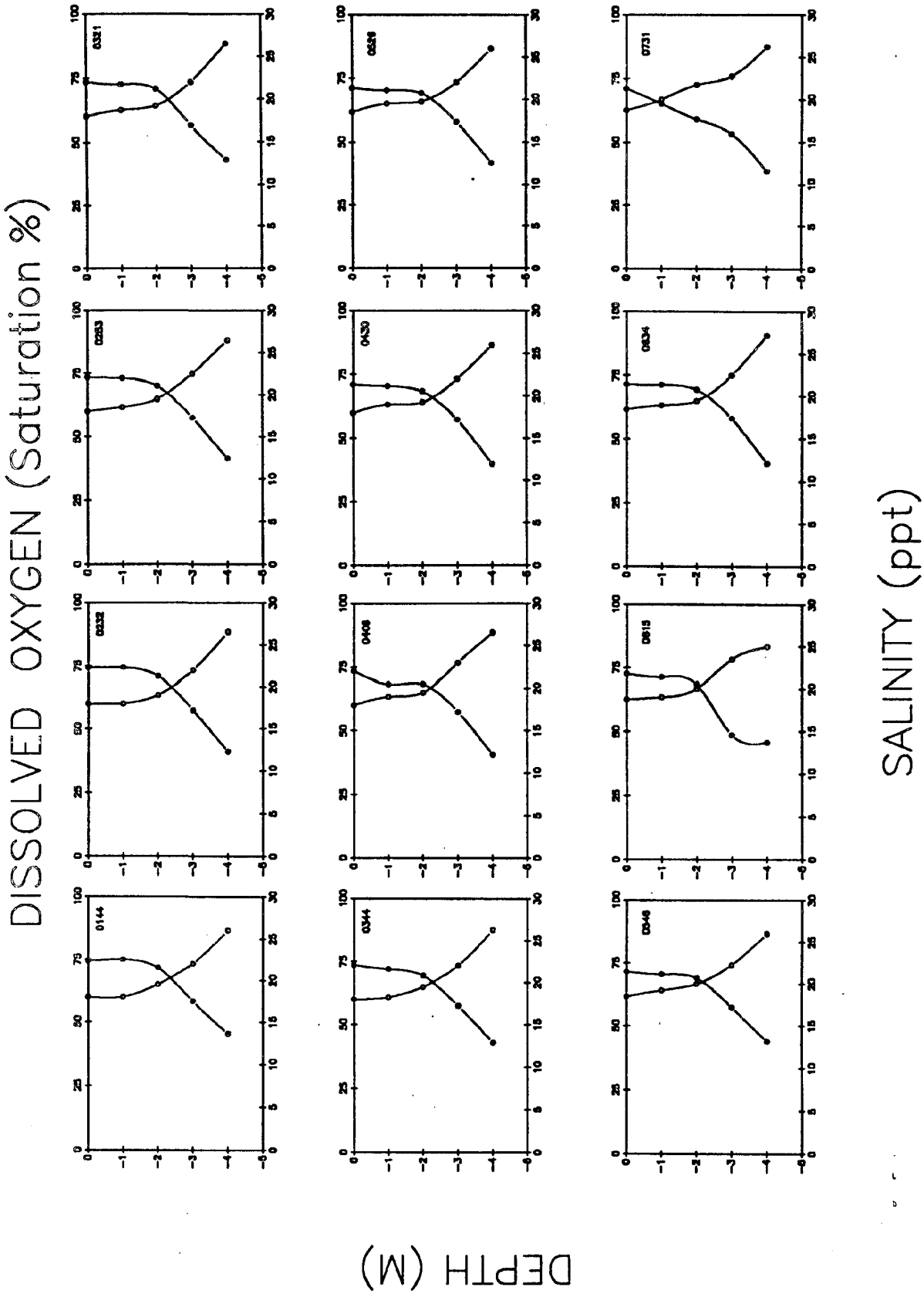
November 1988, Transect CT4, Station 1



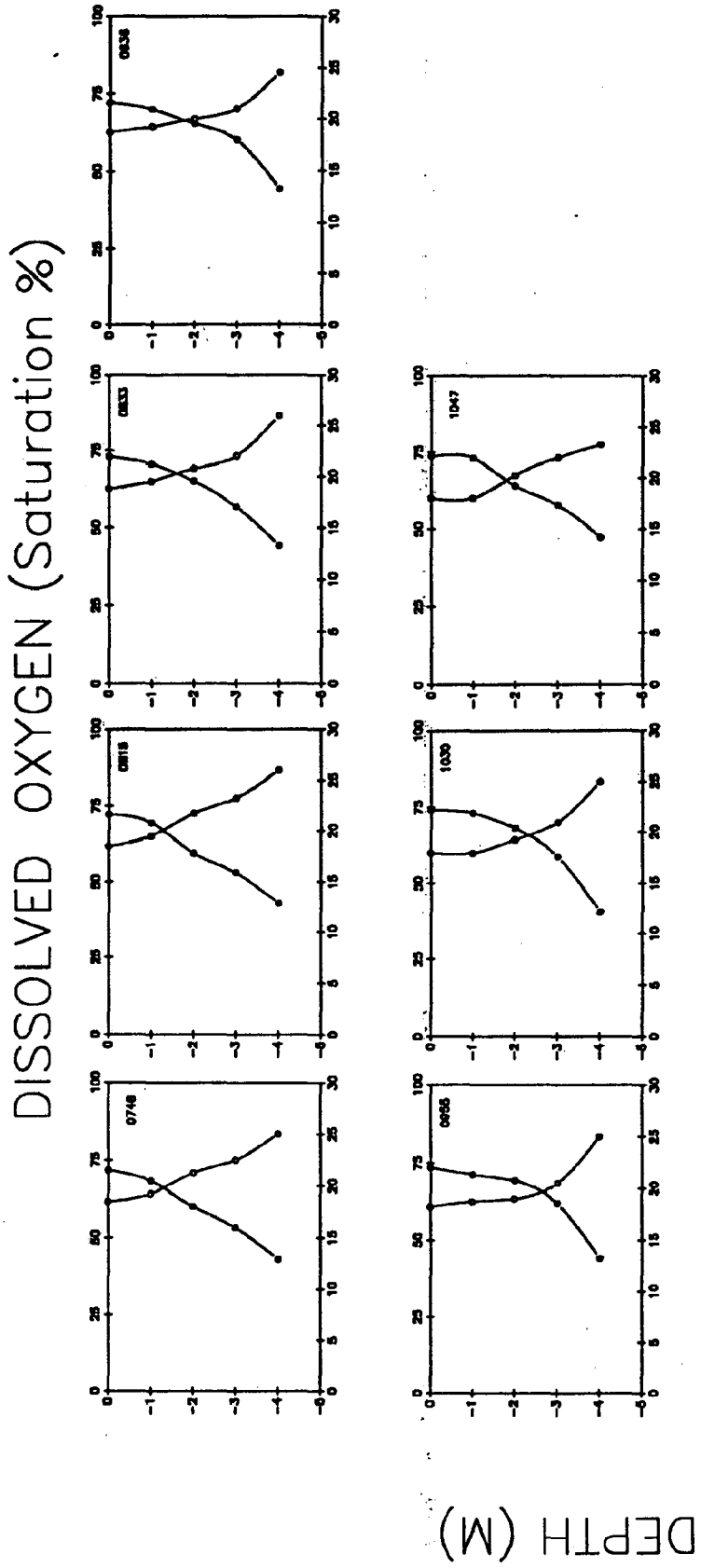
November 1988, Transect CT4, Station 1



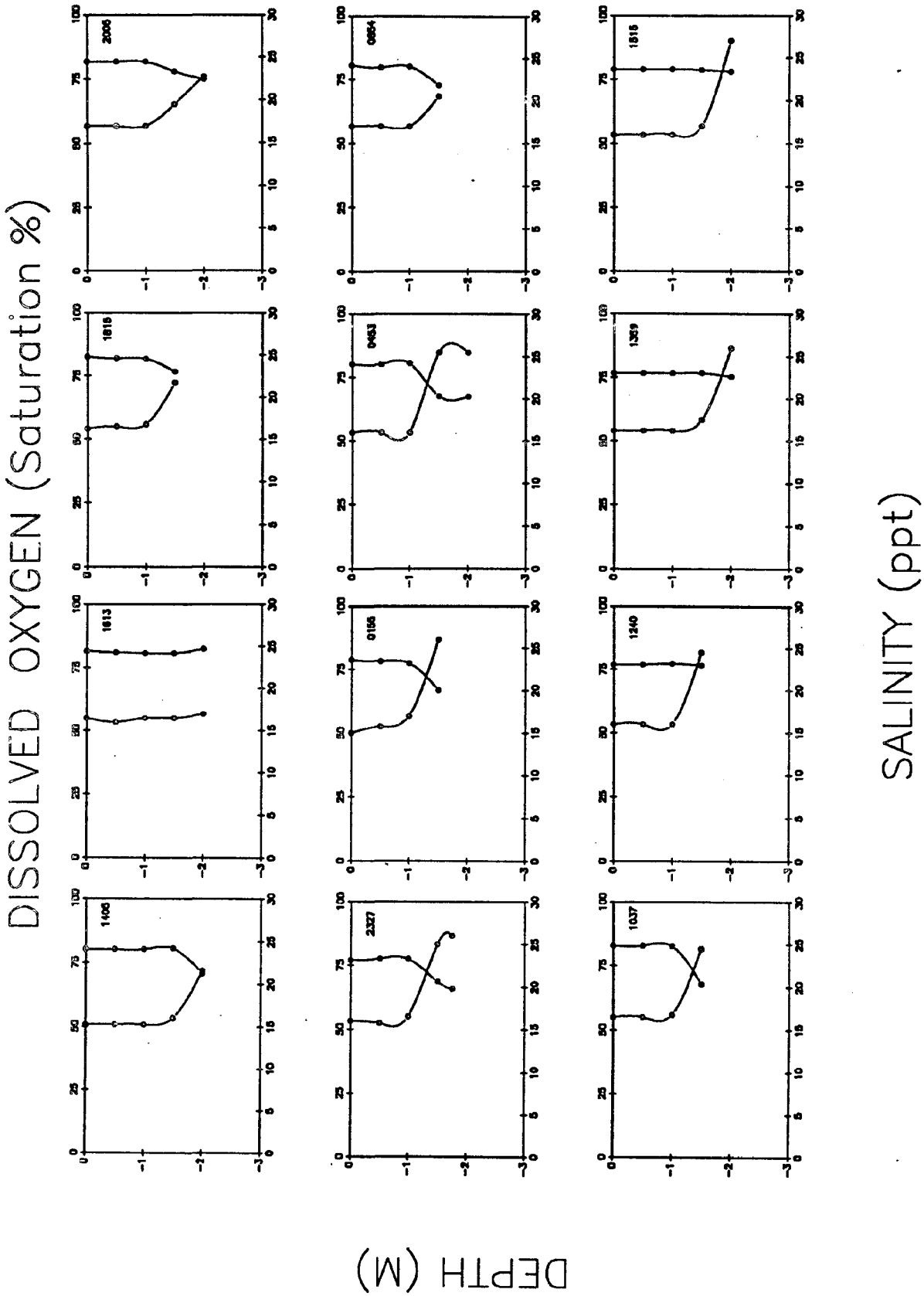
November 1988, Transect CT4, Station 1



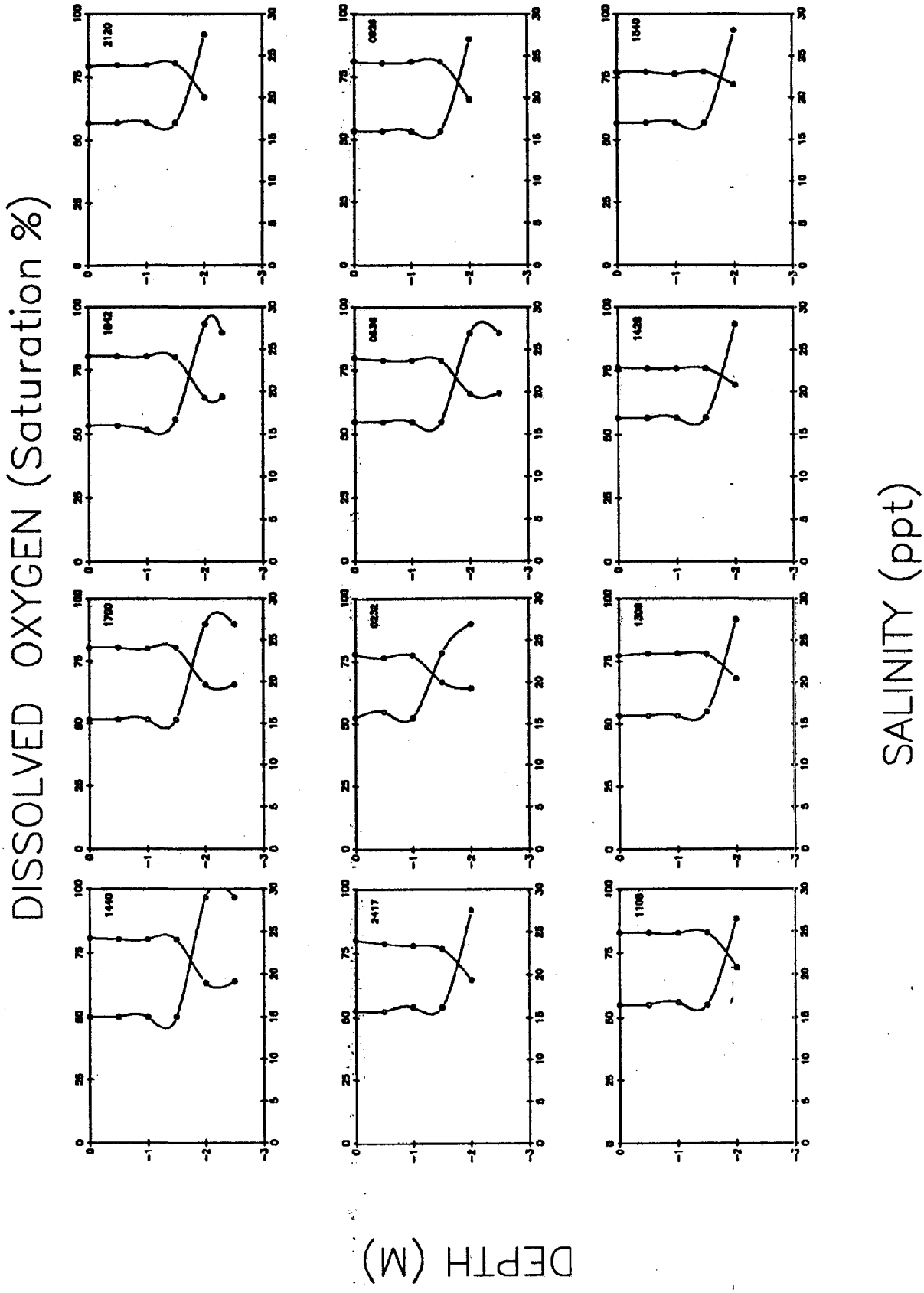
November 1988, Transect CT4, Station 1



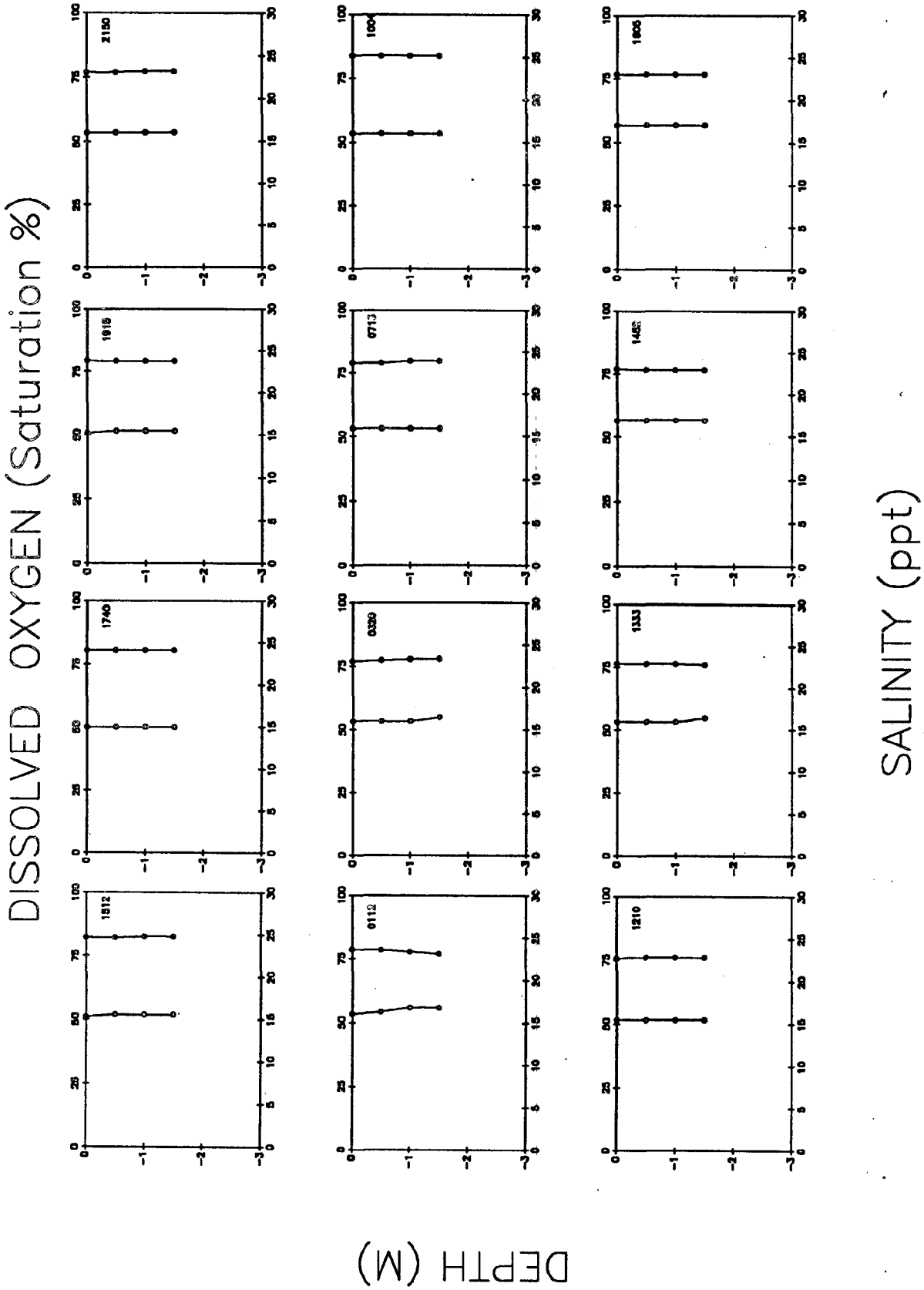
February 1989, Transect CT1, Station 1



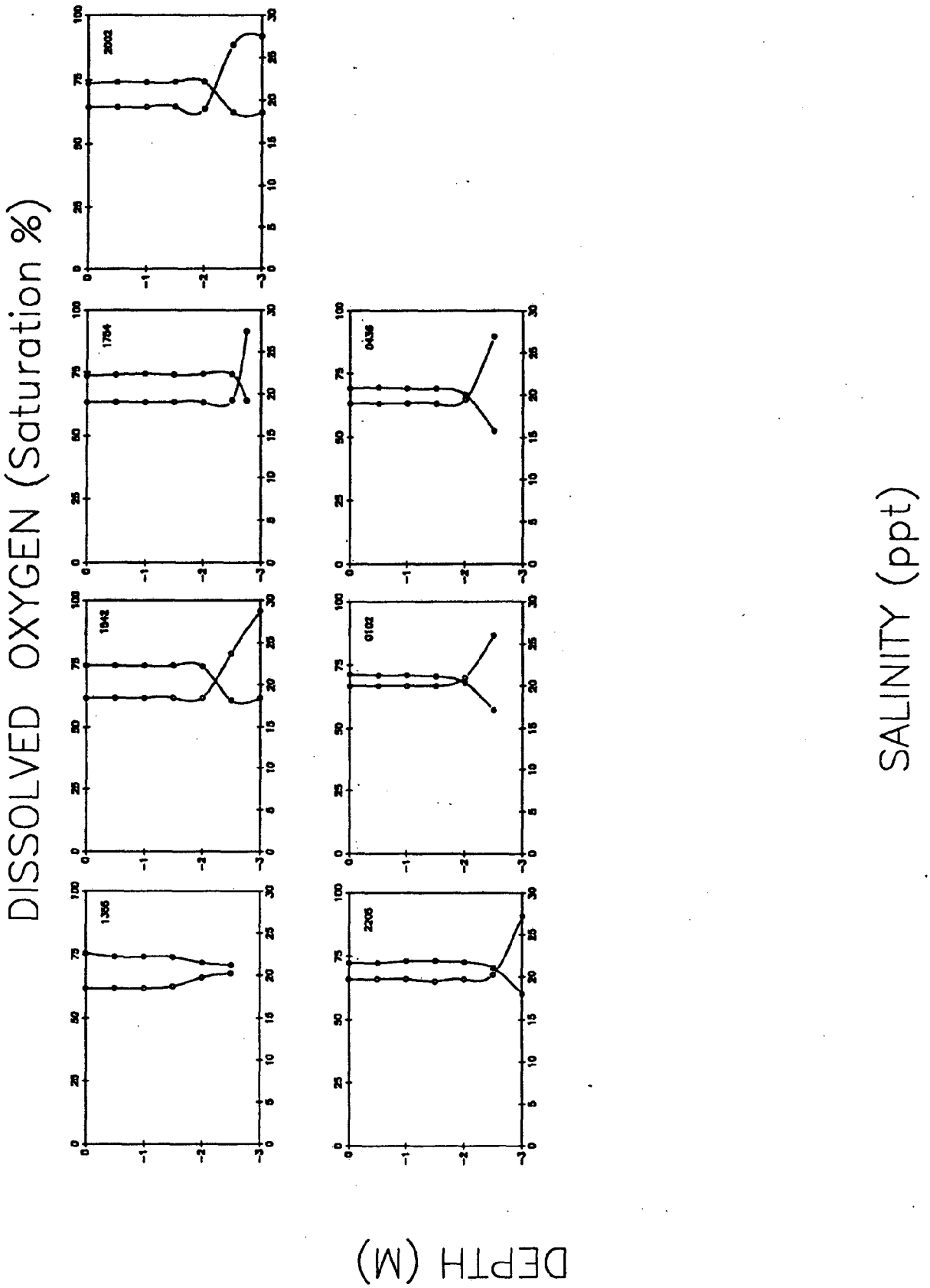
February 1989, Transect CT1, Station 2



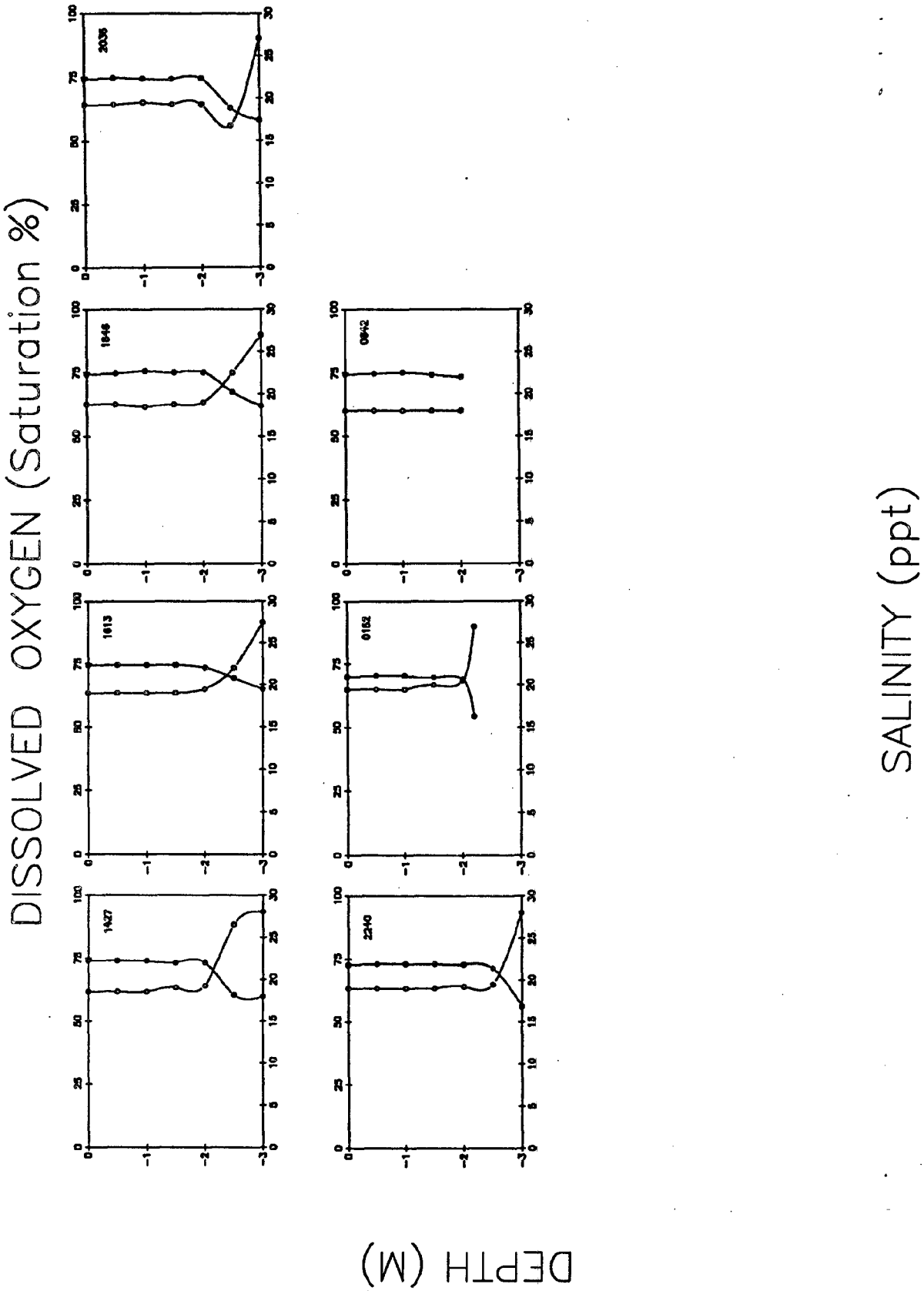
February 1989, Transect CT1, Station 3



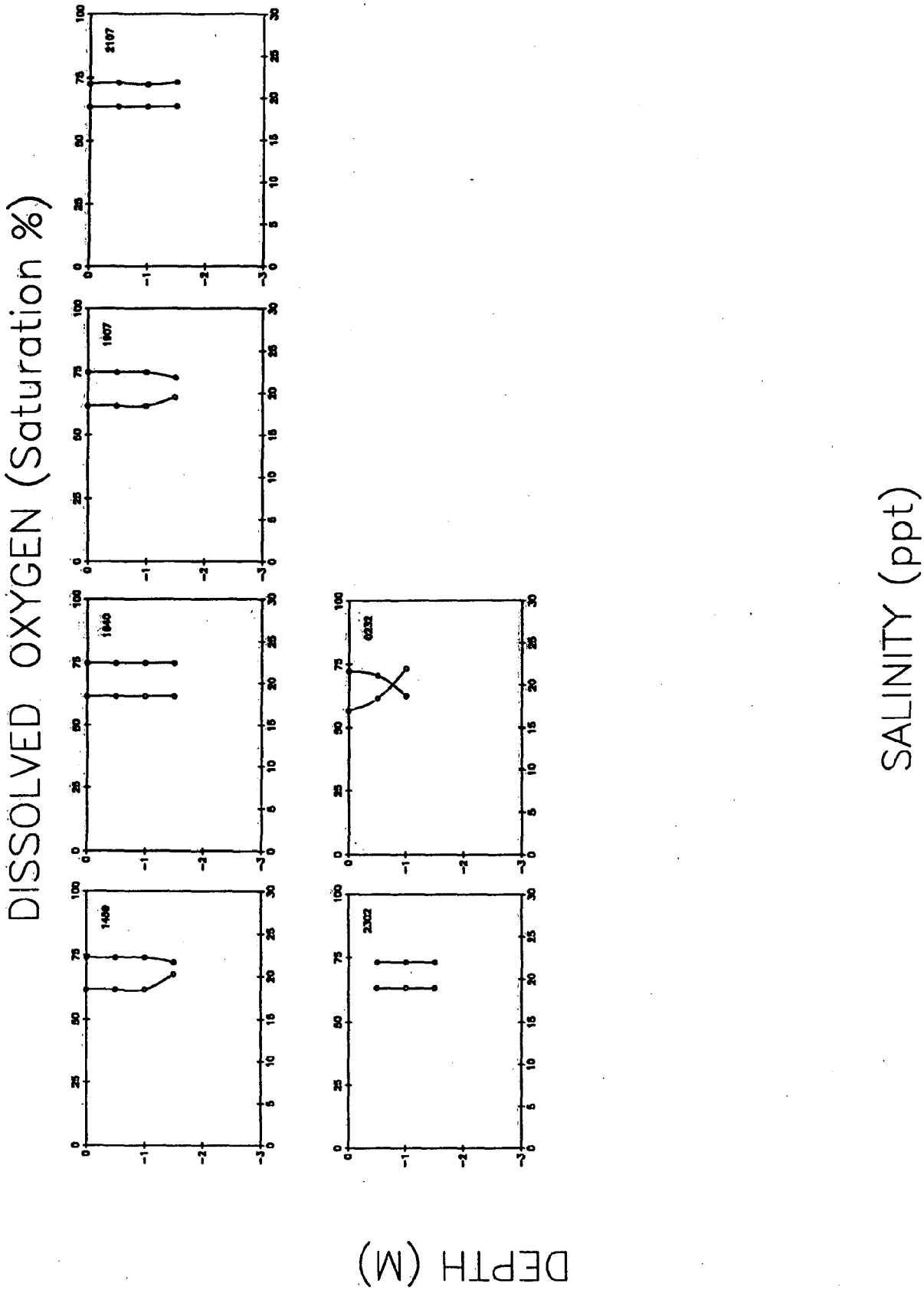
February 1989, Transect CT2, Station 1



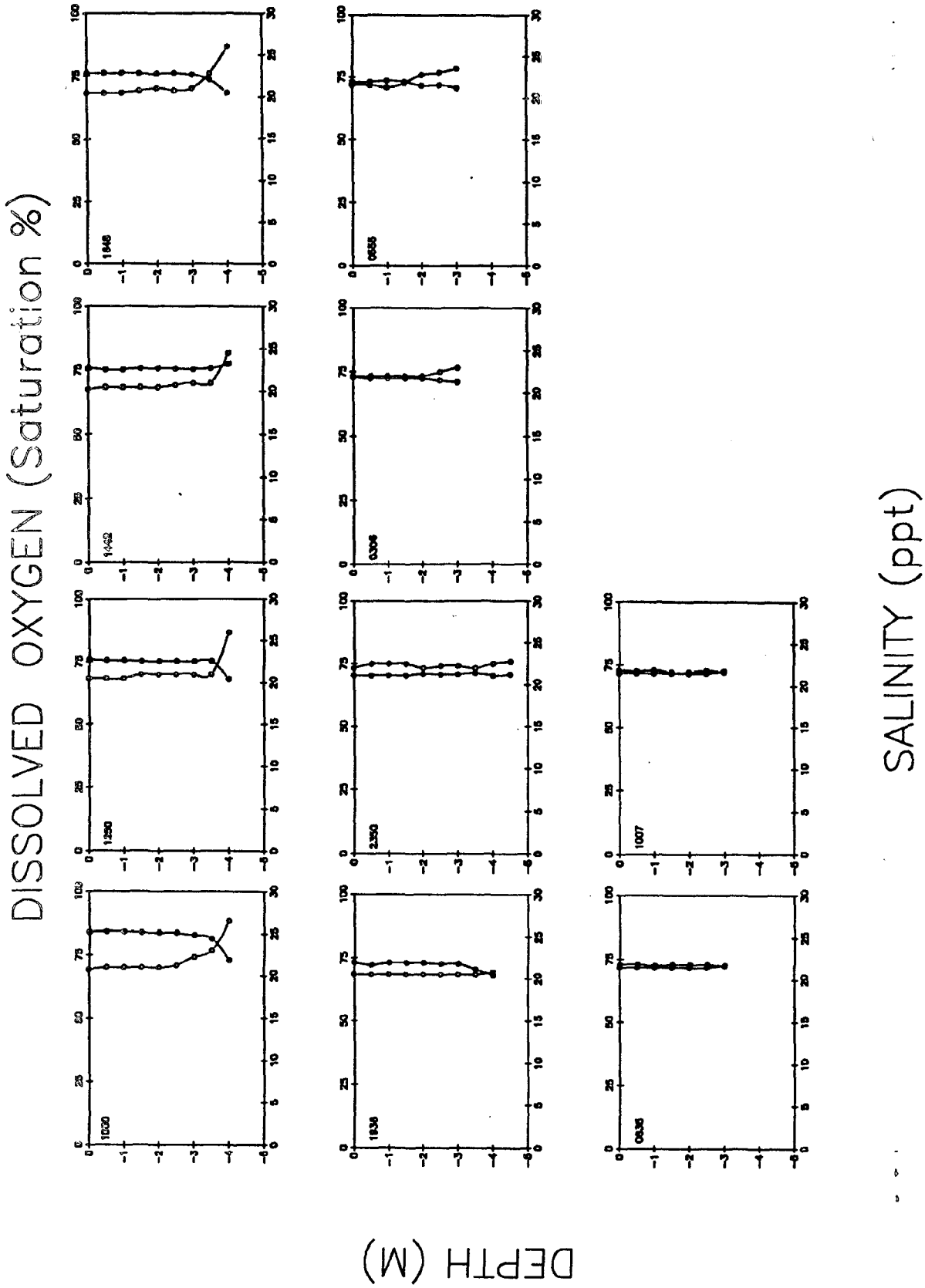
February 1989, Transect CT2, Station 2



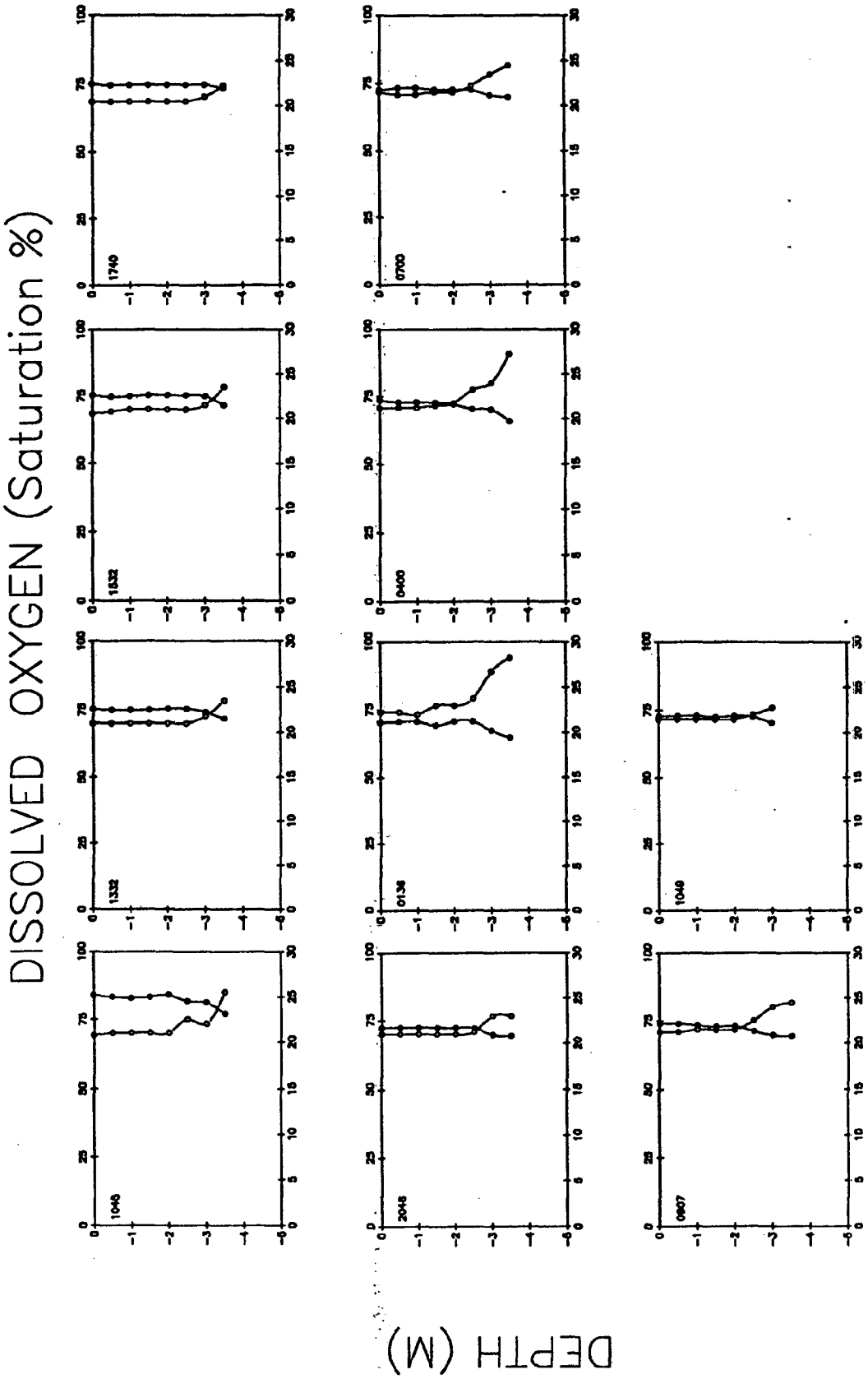
February 1989, Transect CT2, Station 3



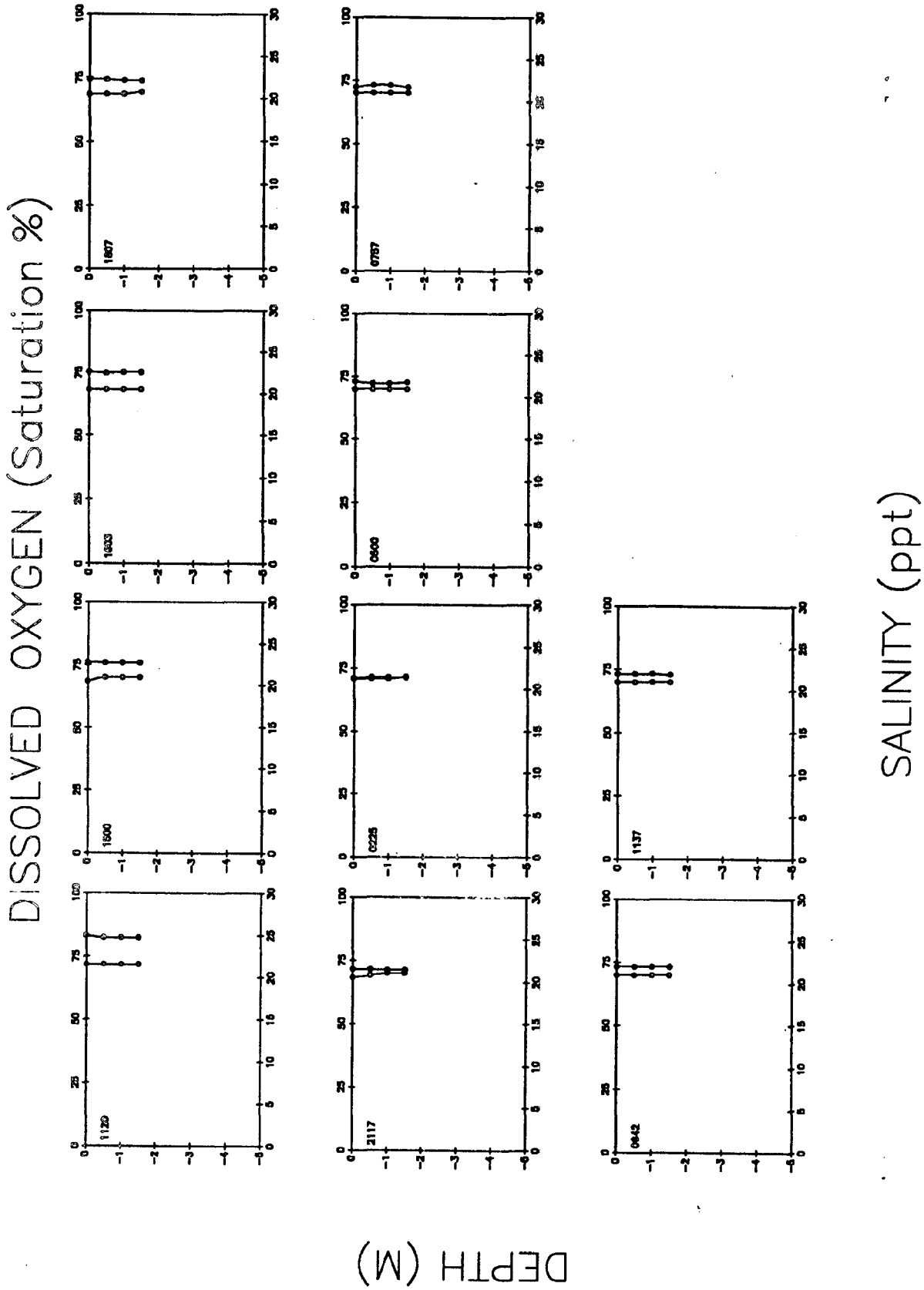
February 1989, Transect CT3, Station 1



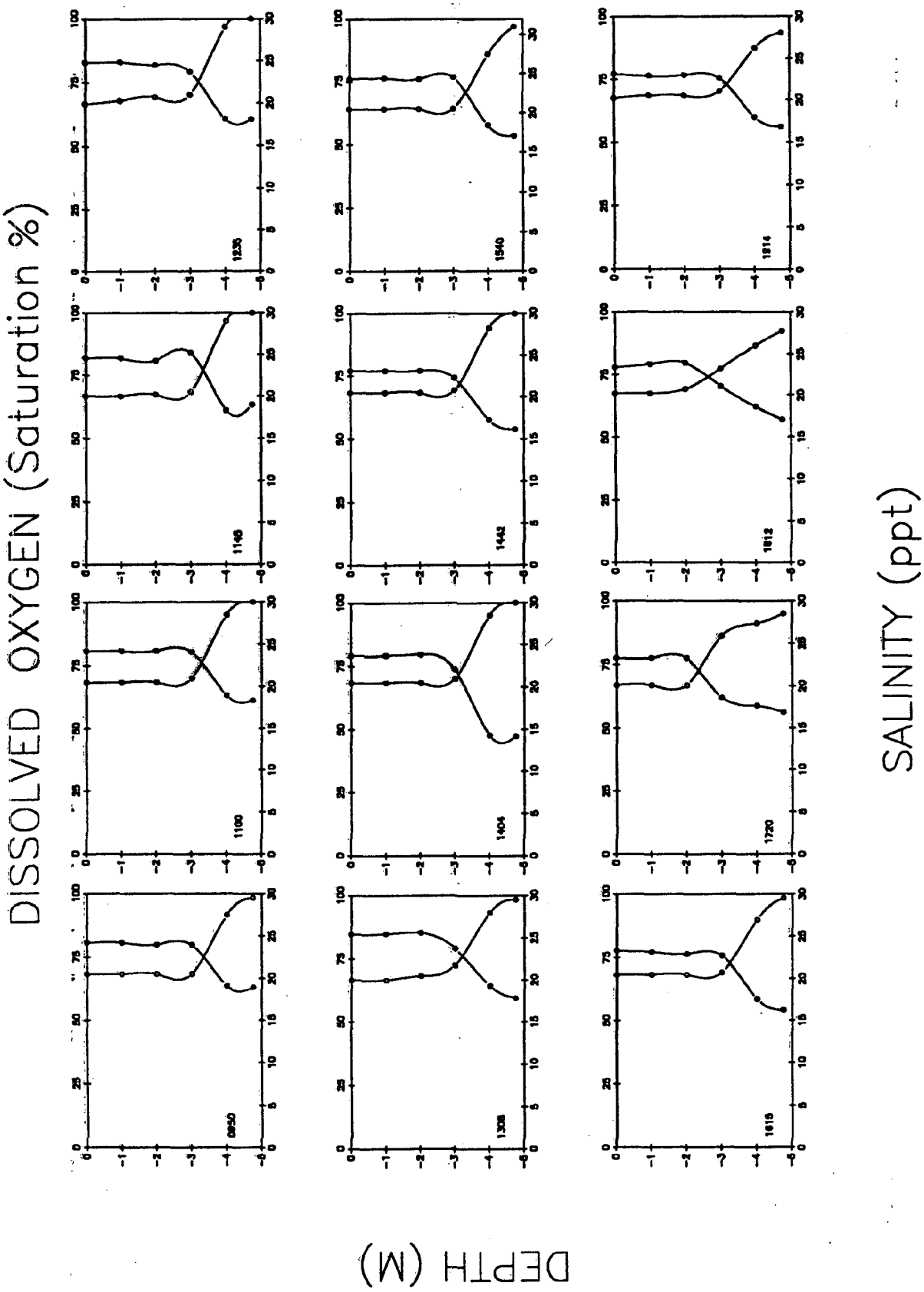
February 1989, Transect CT3, Station 2



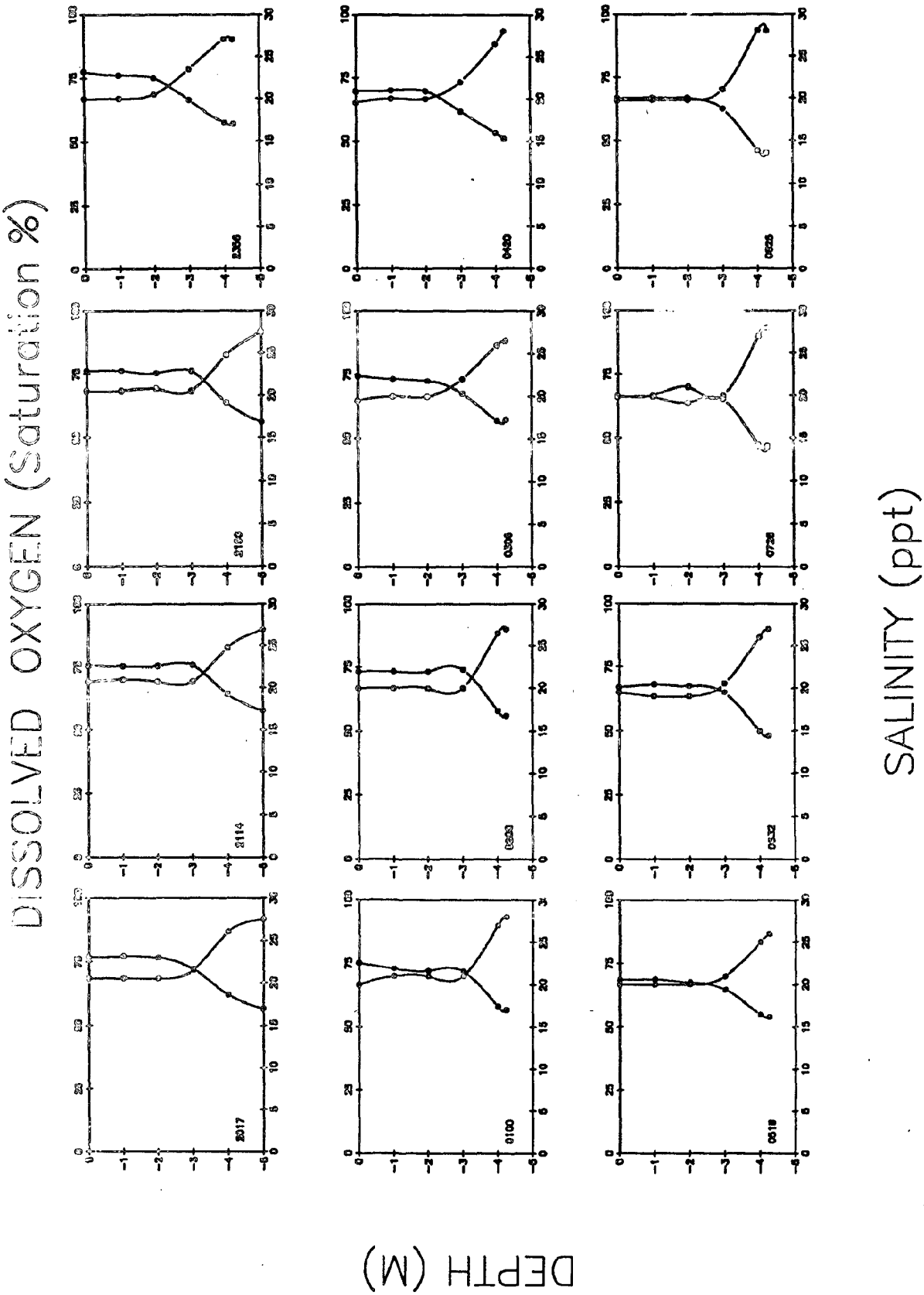
February 1989, Transect CT3, Station 3



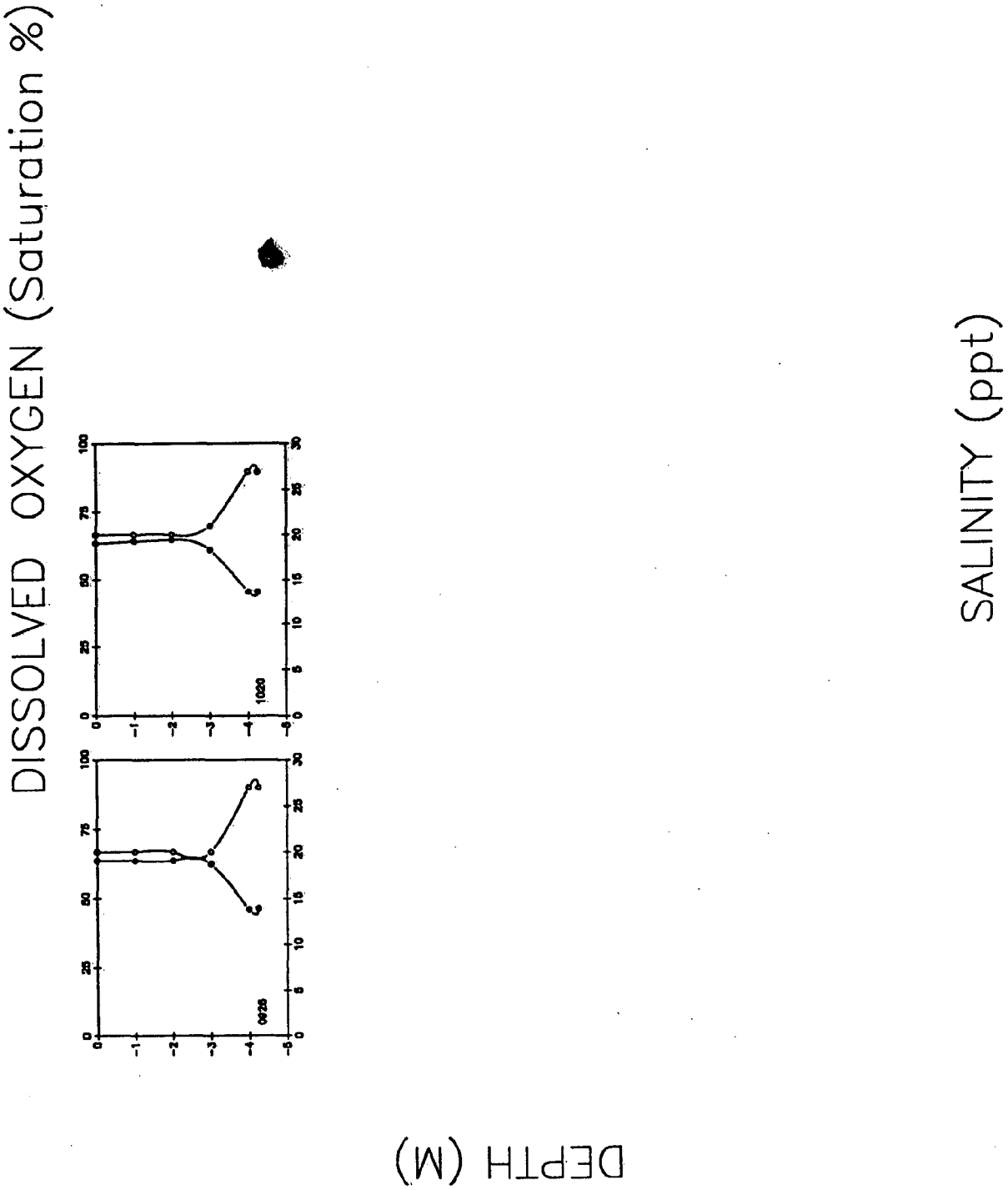
February 1989, Transect CT4, Station 1



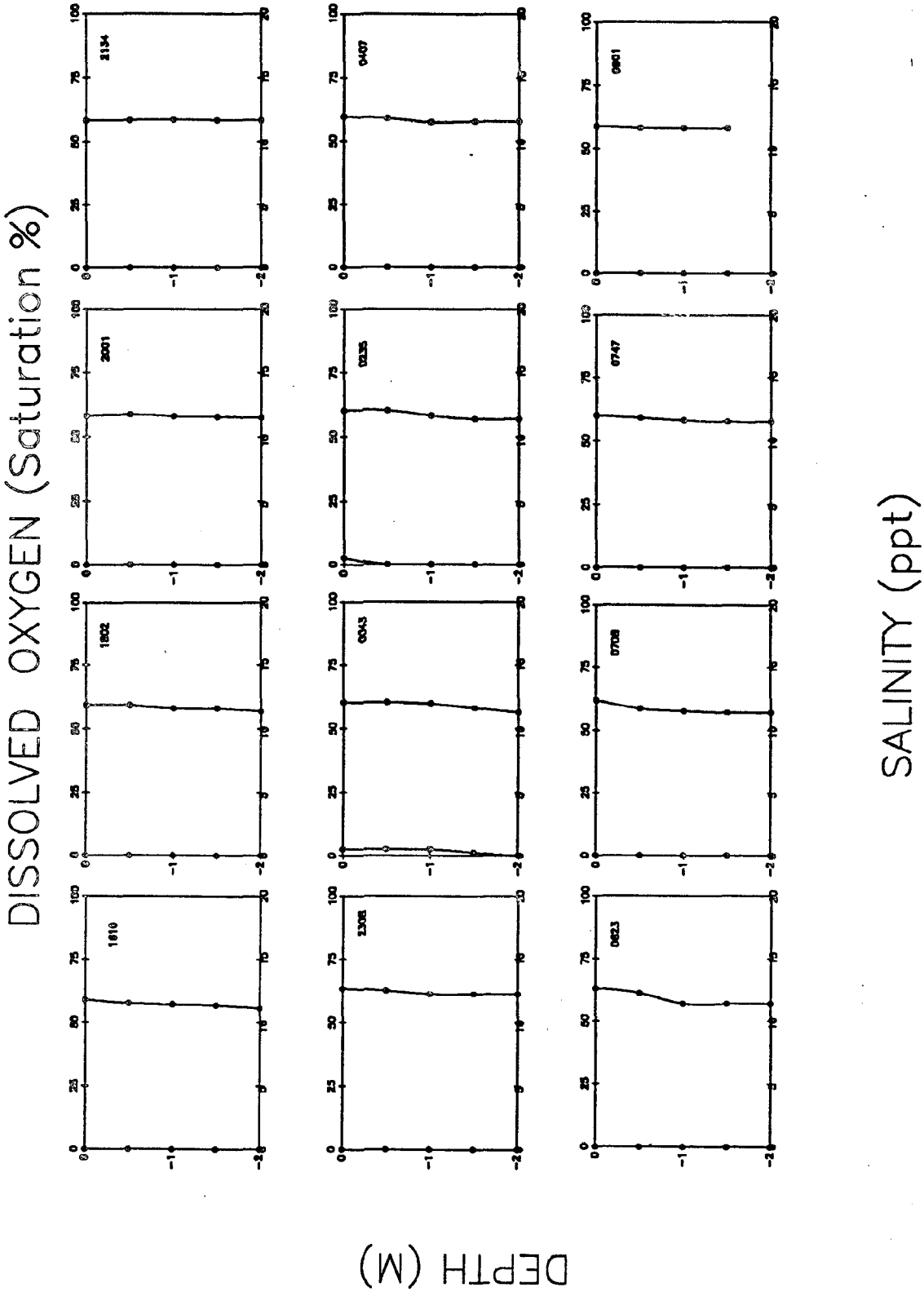
February 1989, Transect CT4, Station 1



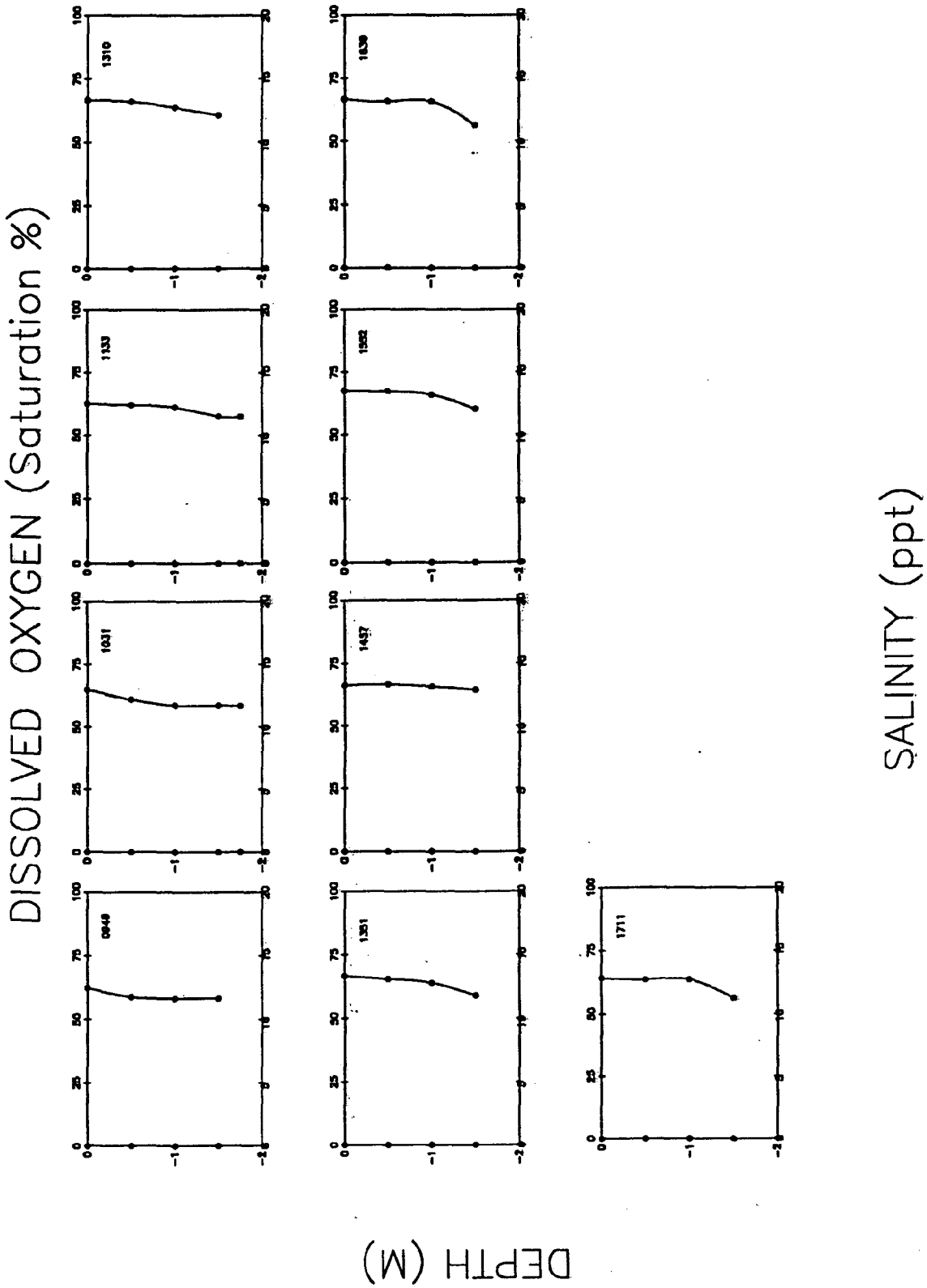
February 1989, Transect CT4, Station 1



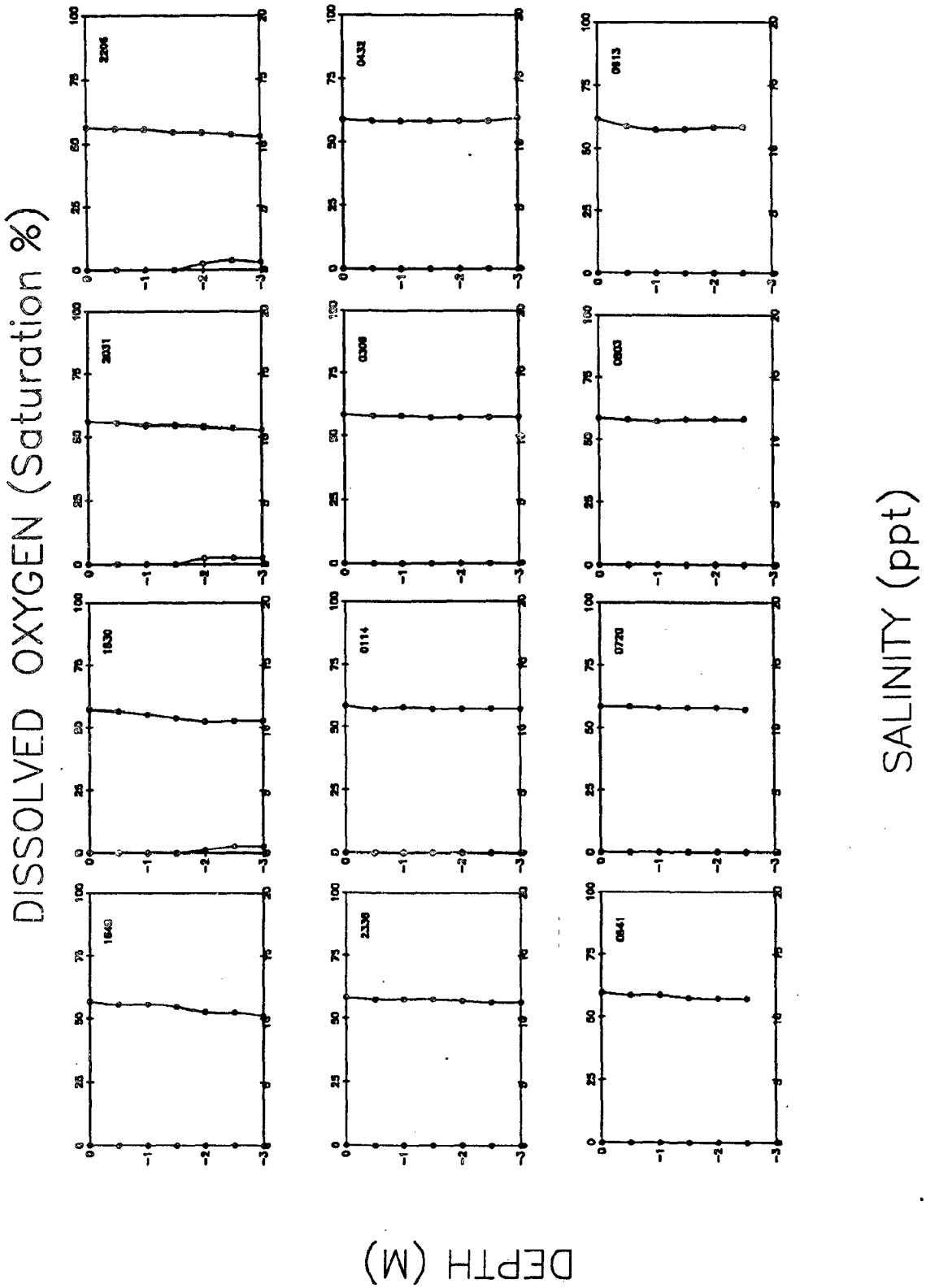
June 1989, Transect CT1, Station 1



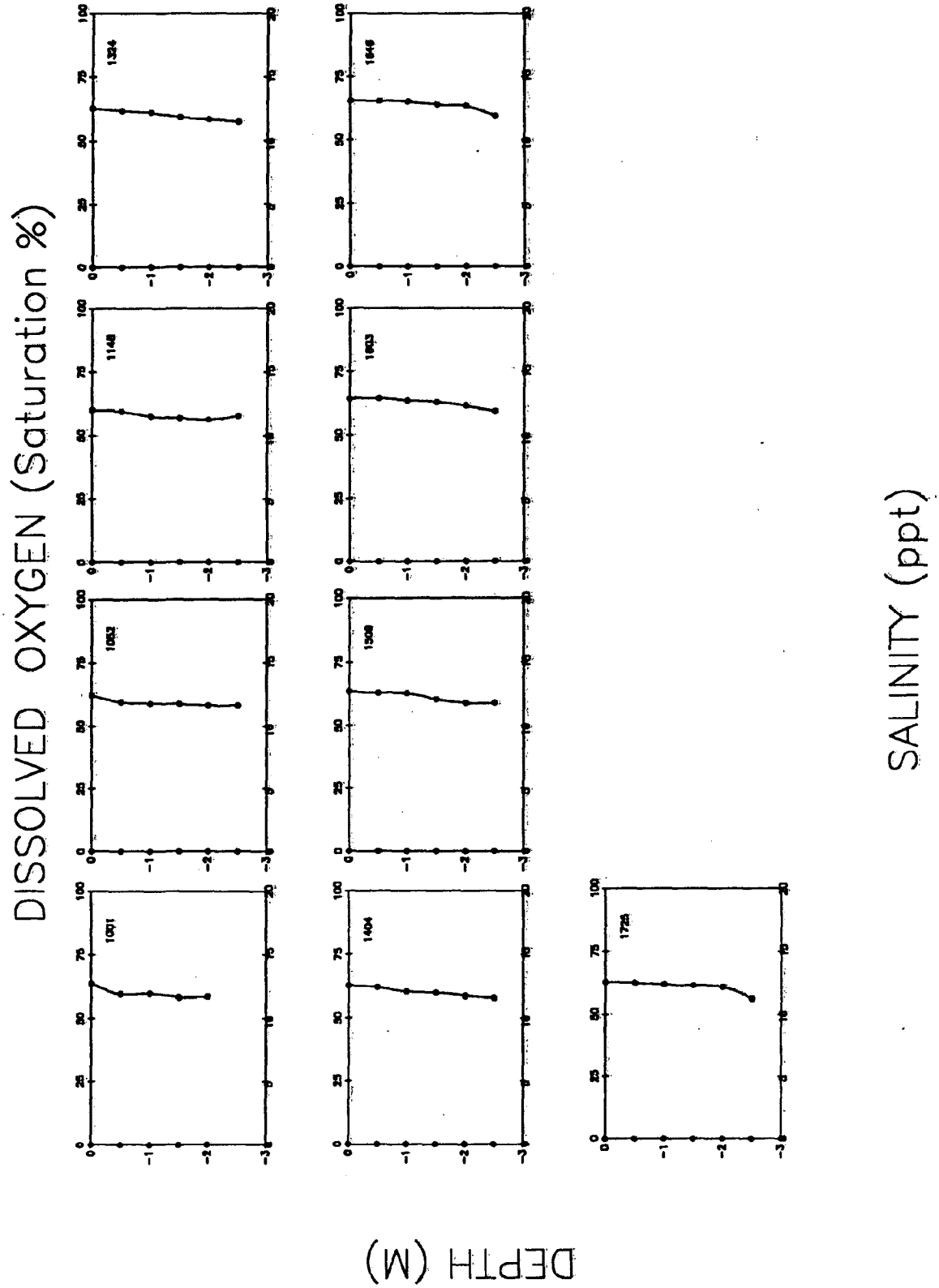
June 1989, Transect CT1, Station 1



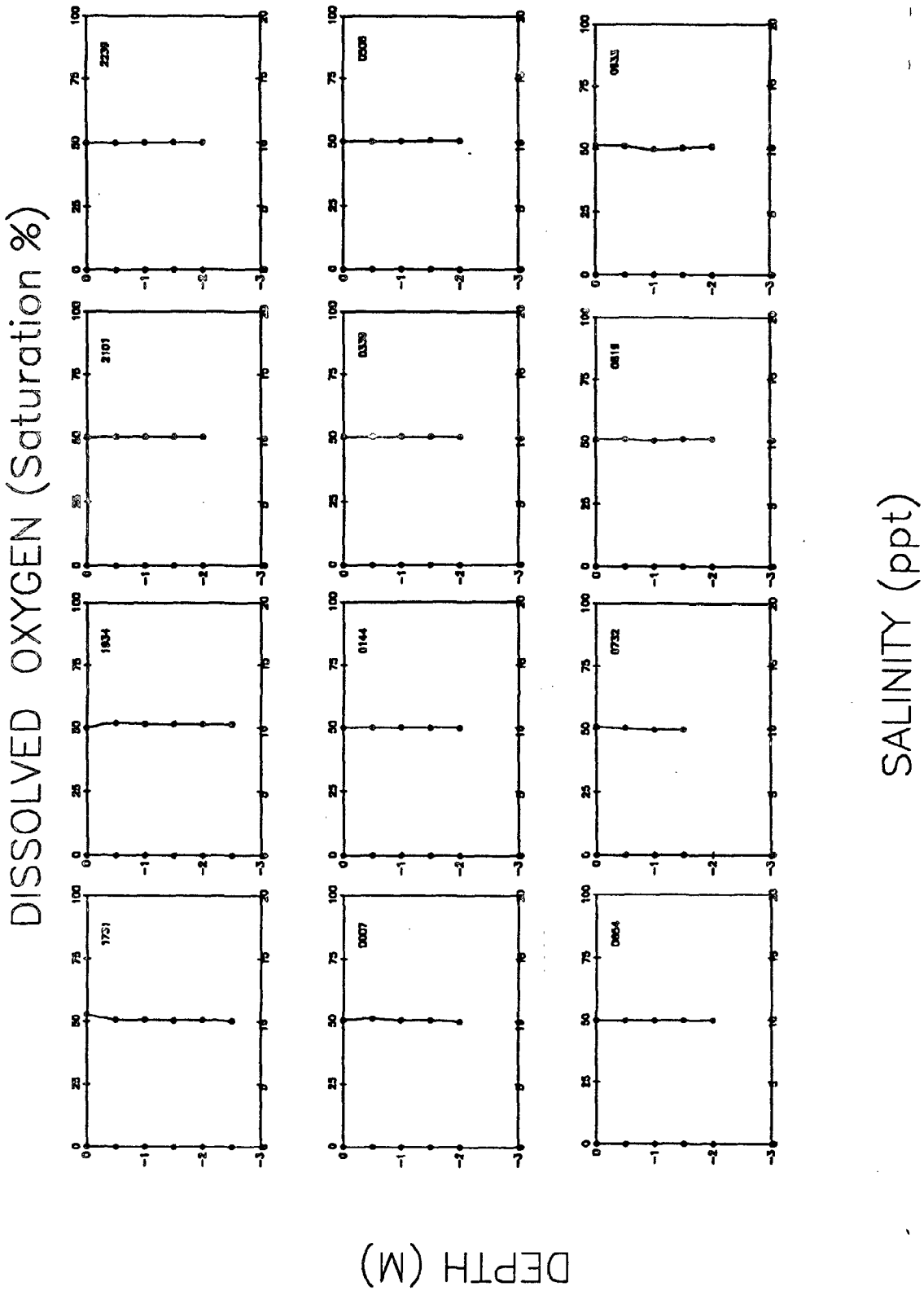
June 1989, Transect CT1, Station 2



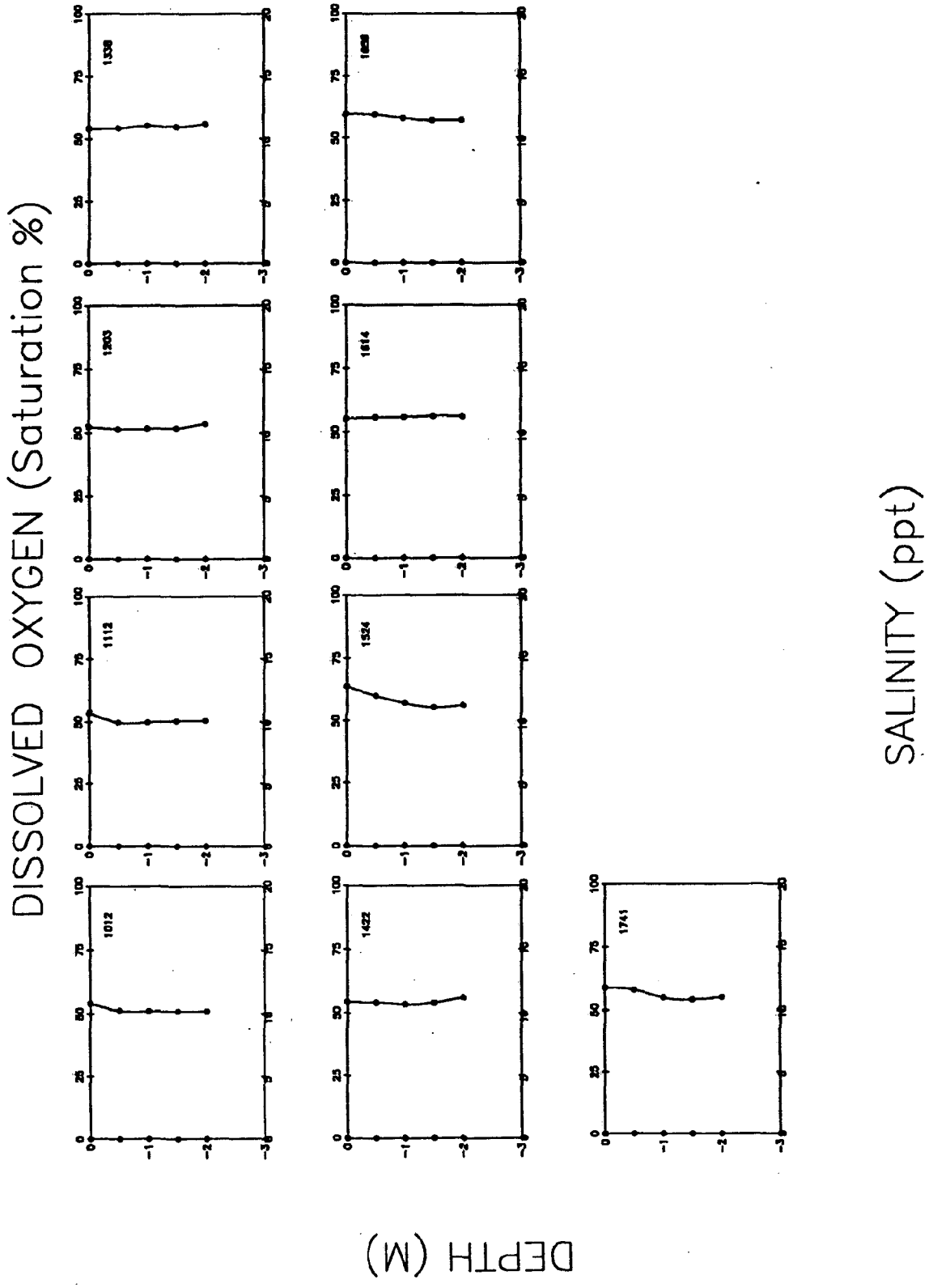
June 1989, Transect CT1, Station 2



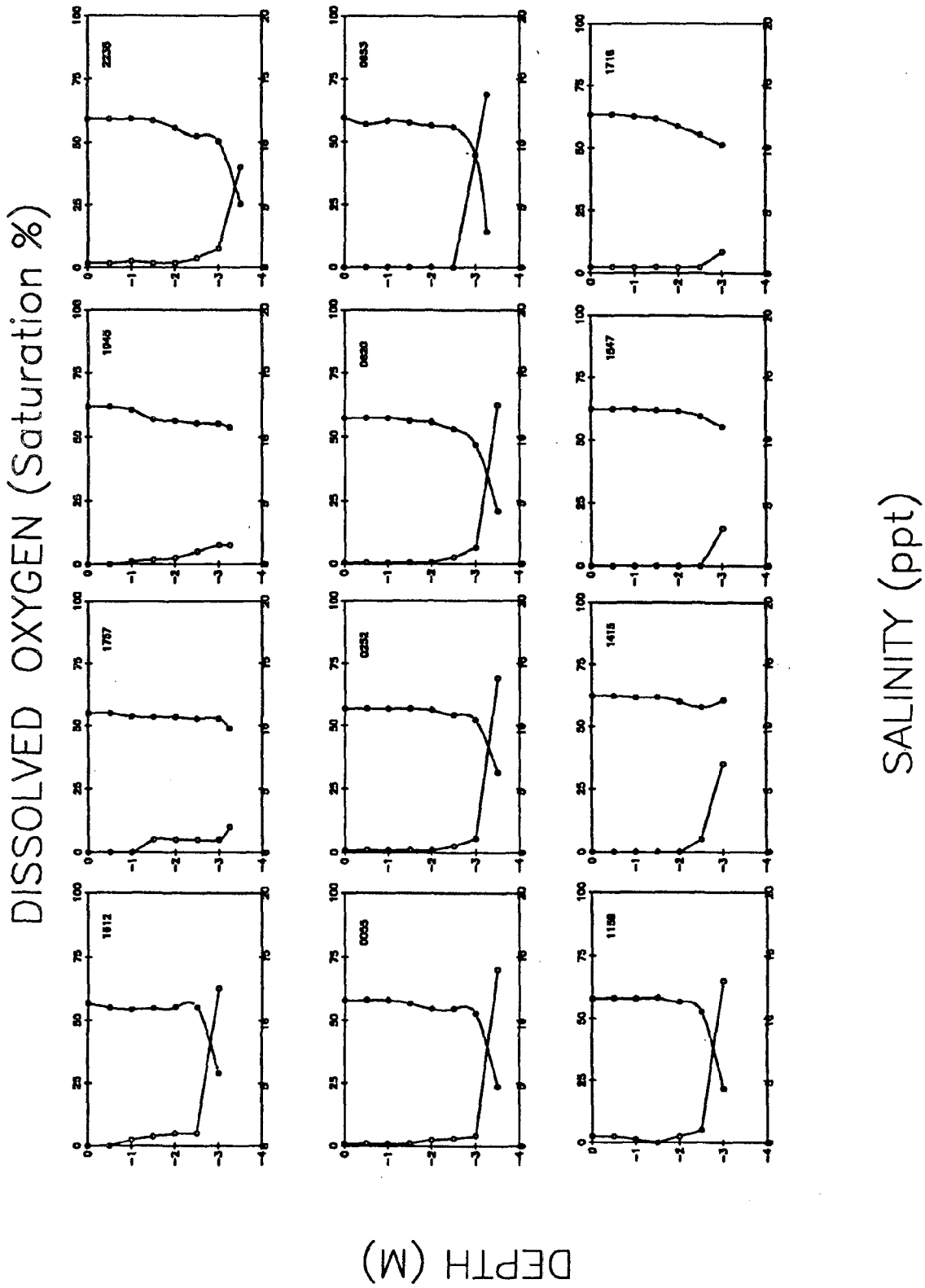
June 1989, Transect CT1, Station 3



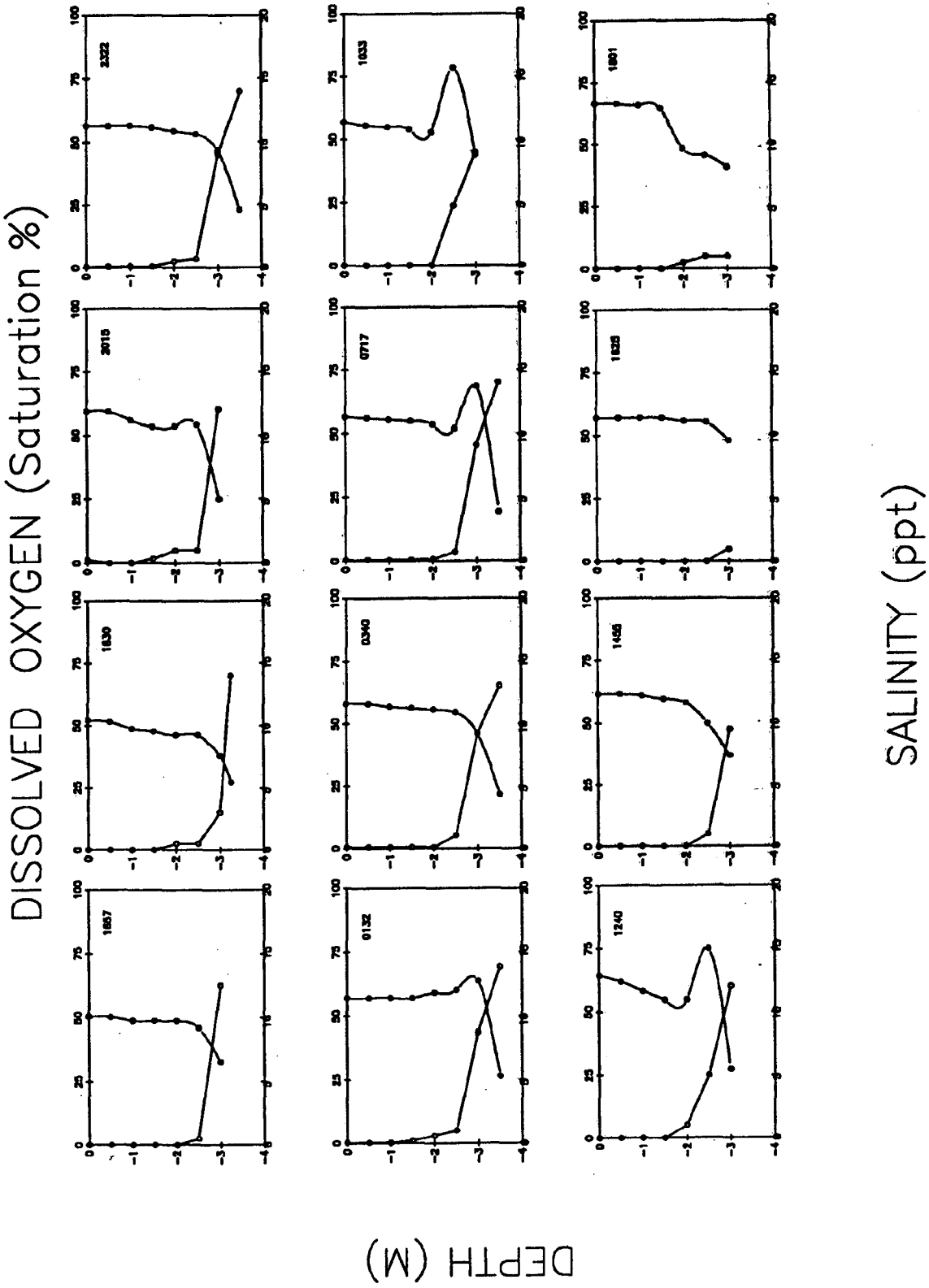
June 1989, Transect CT1, Station 3



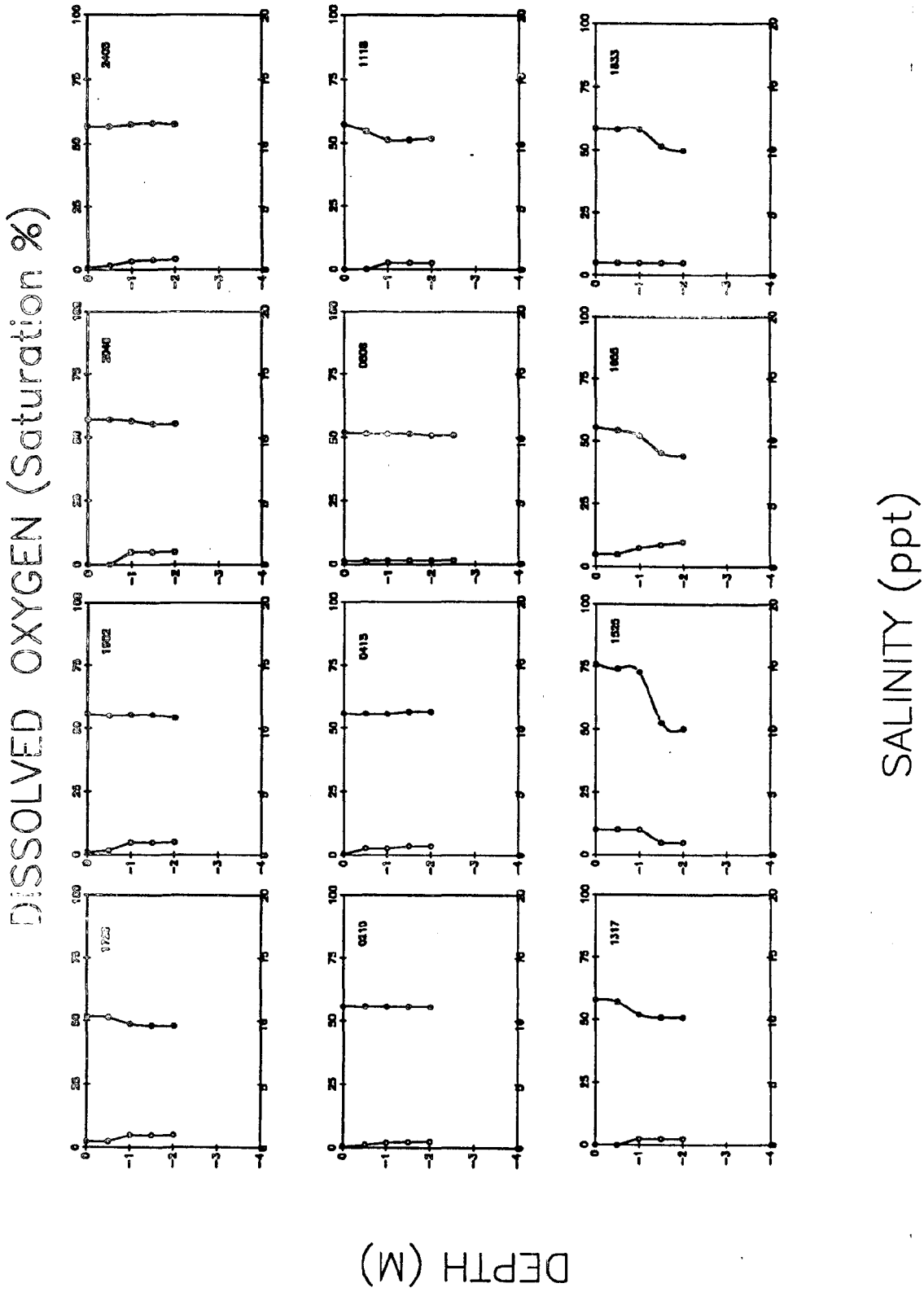
June 1989, Transect CT2, Station 1



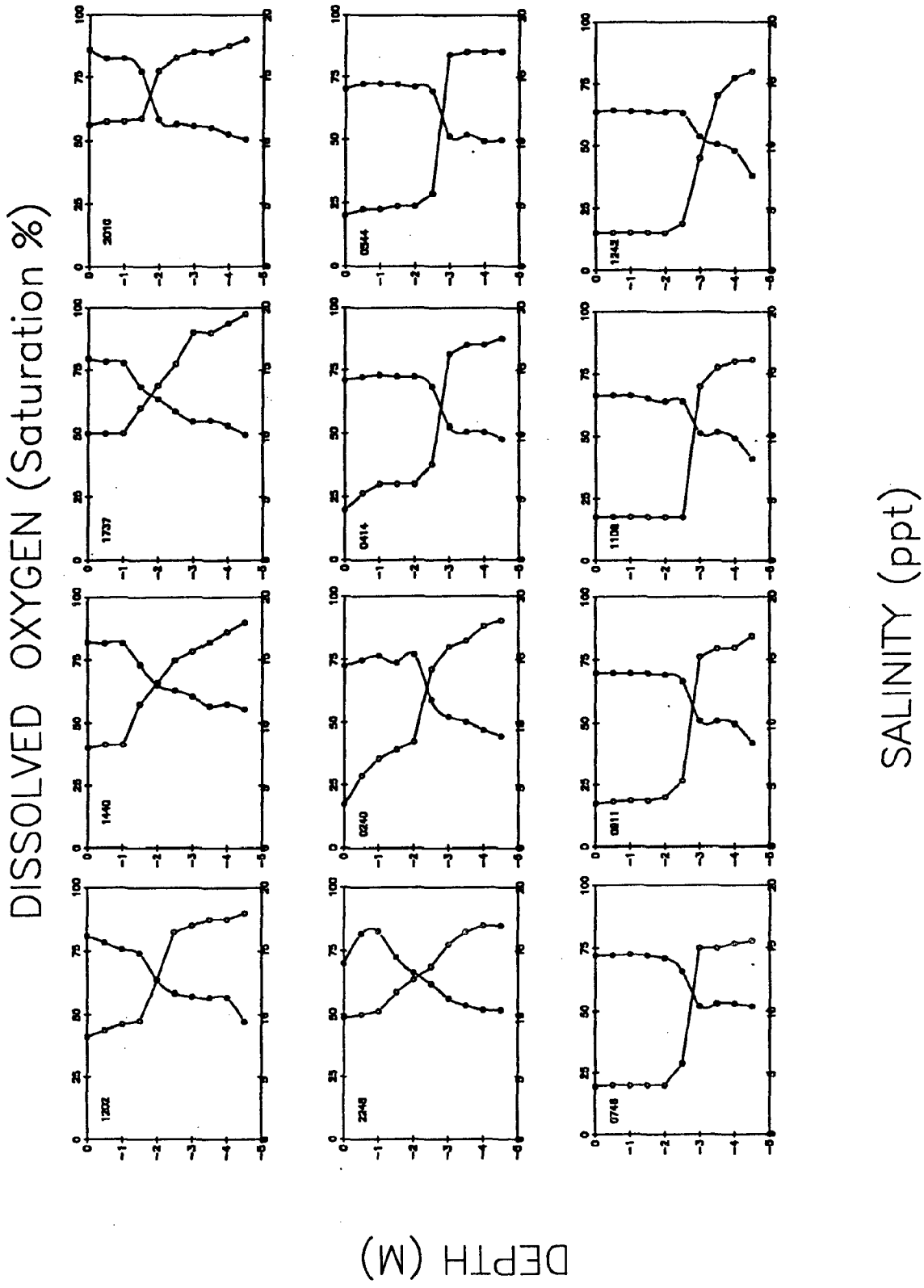
June 1989, Transect CT2, Station 2



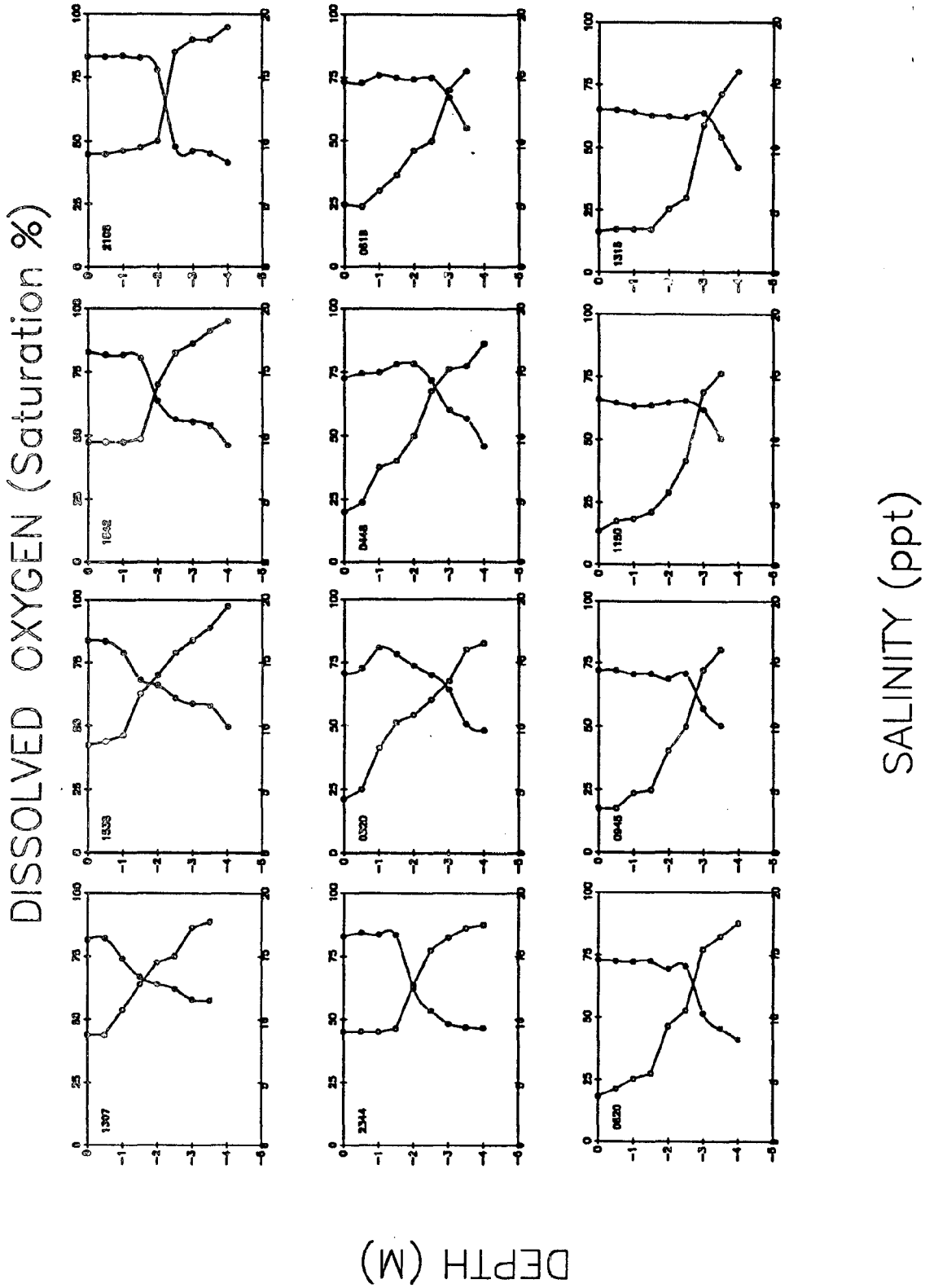
June 1989, Transect CT2, Station 3



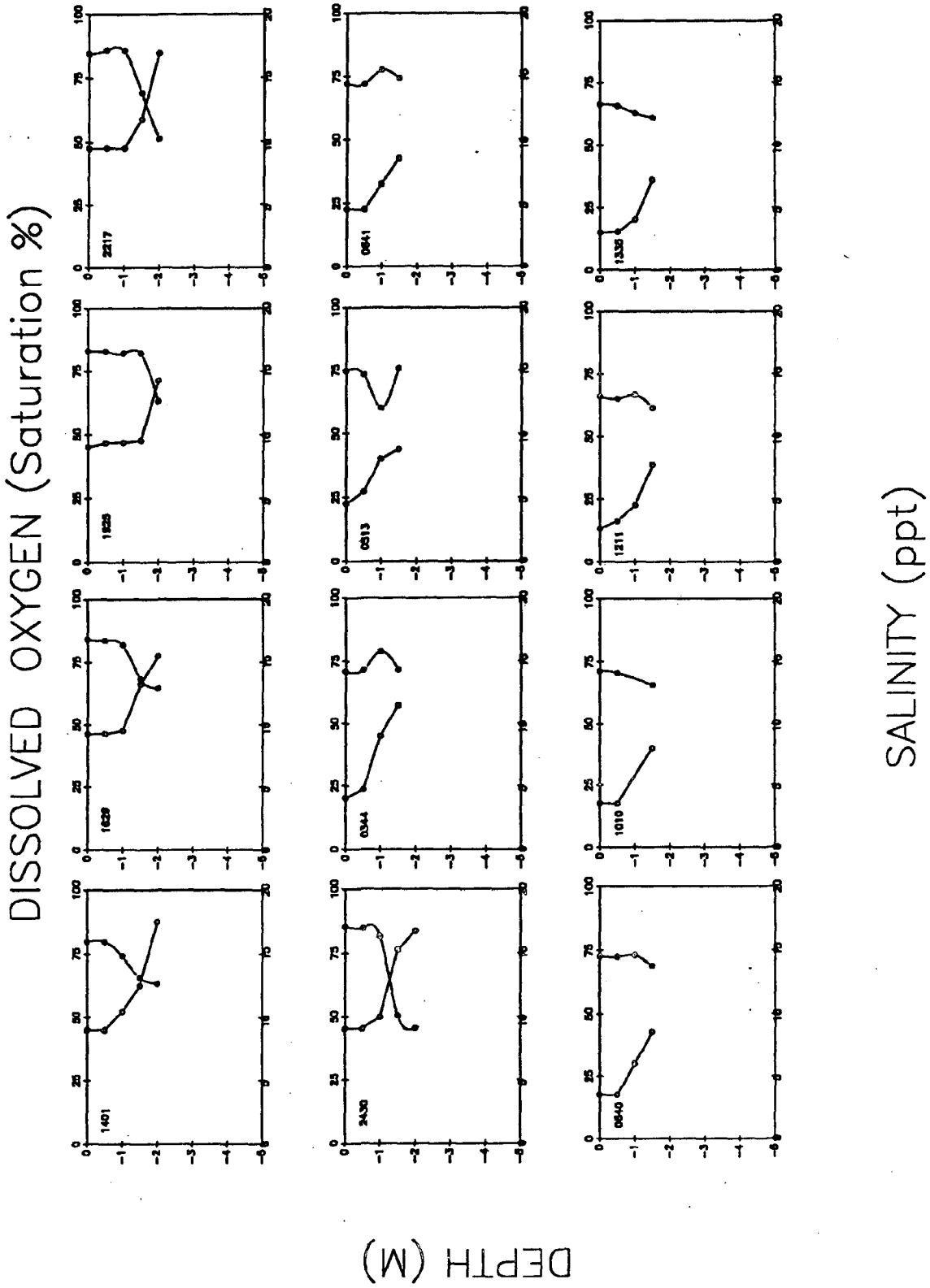
June 1989, Transect CT3, Station 1



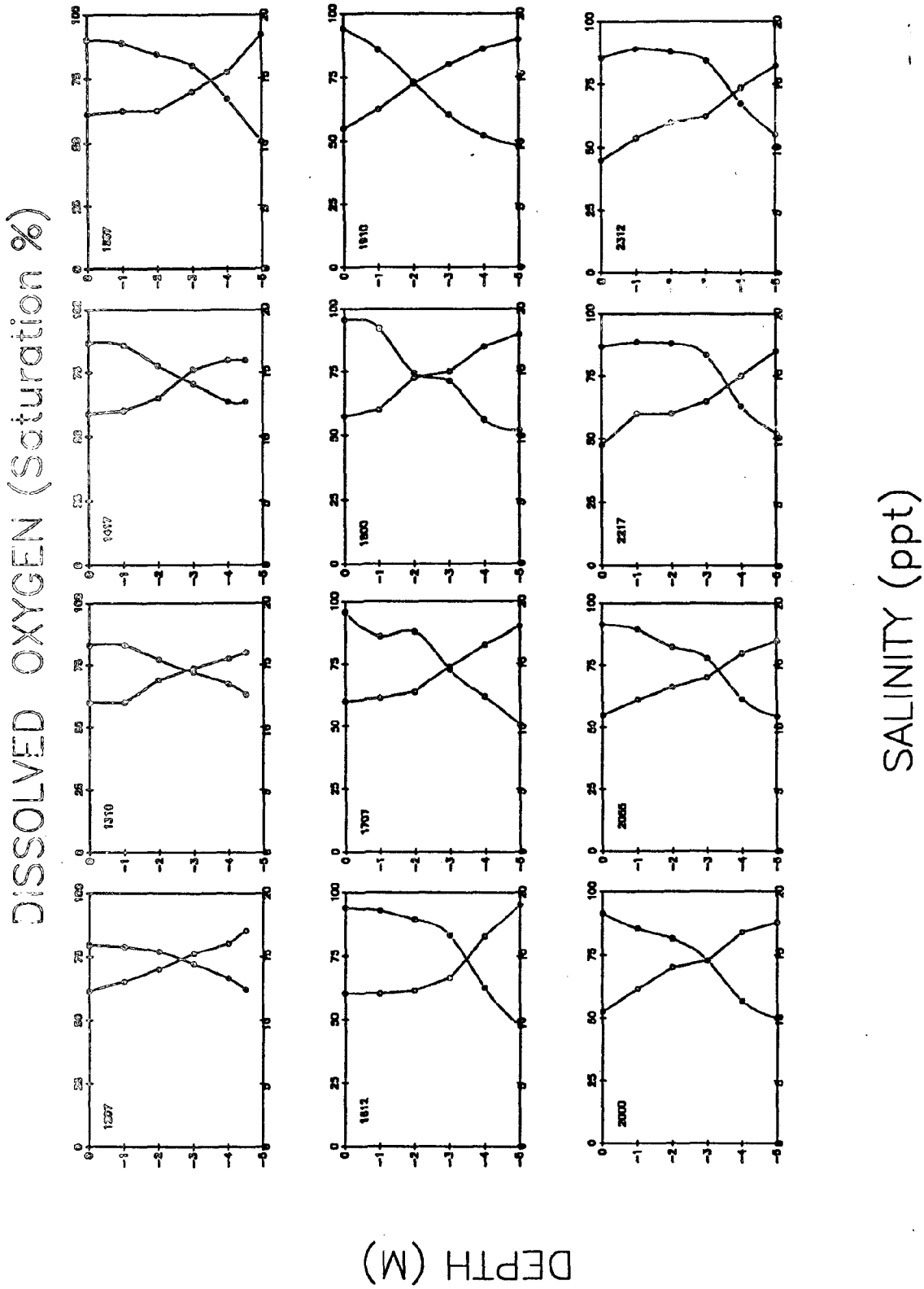
June 1989, Transect CT3, Station 2



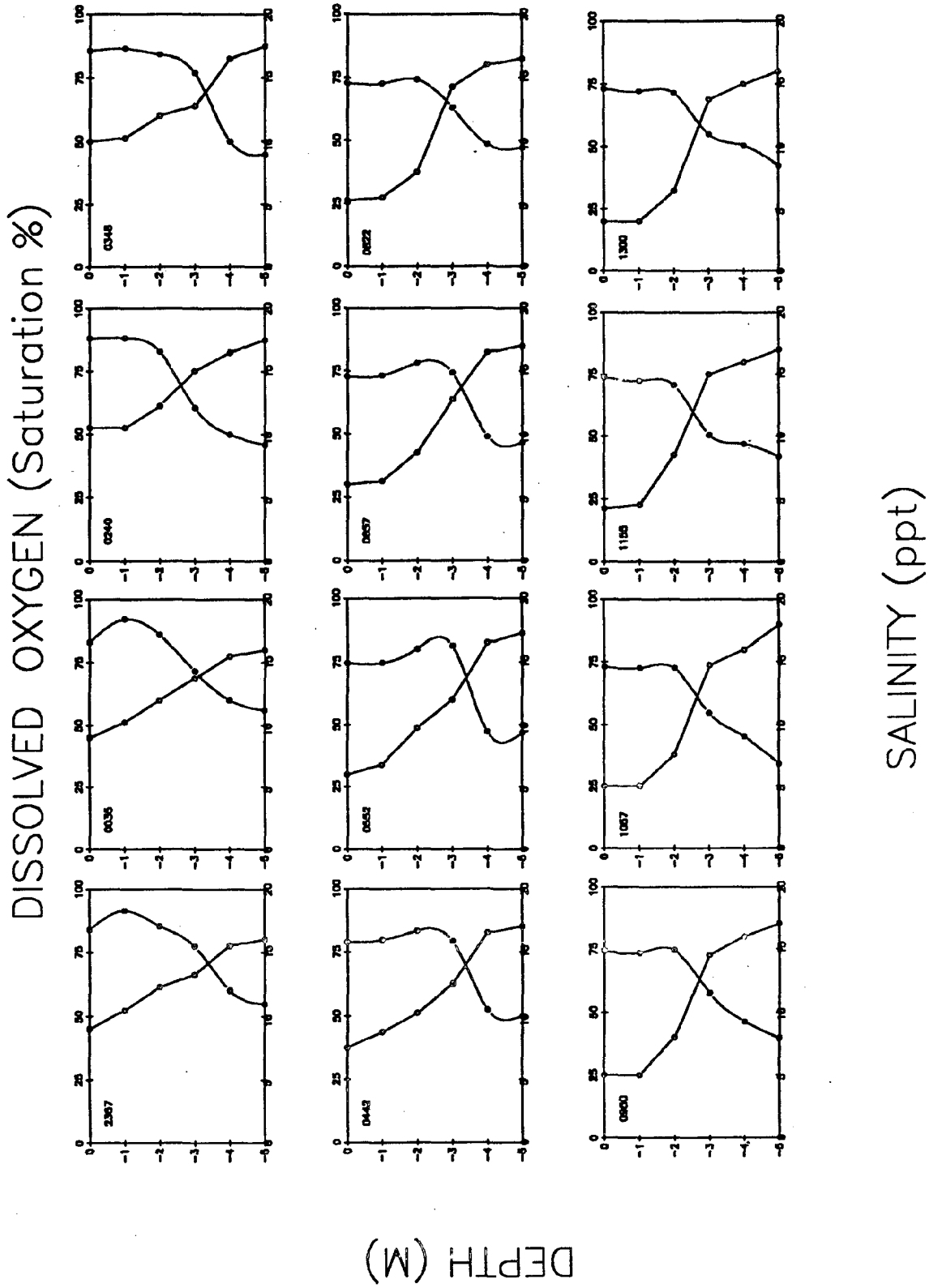
June 1989, Transect CT3, Station 3



June 1989, Transect CT4, Station 1



June 1989, Transect CT4, Station 1

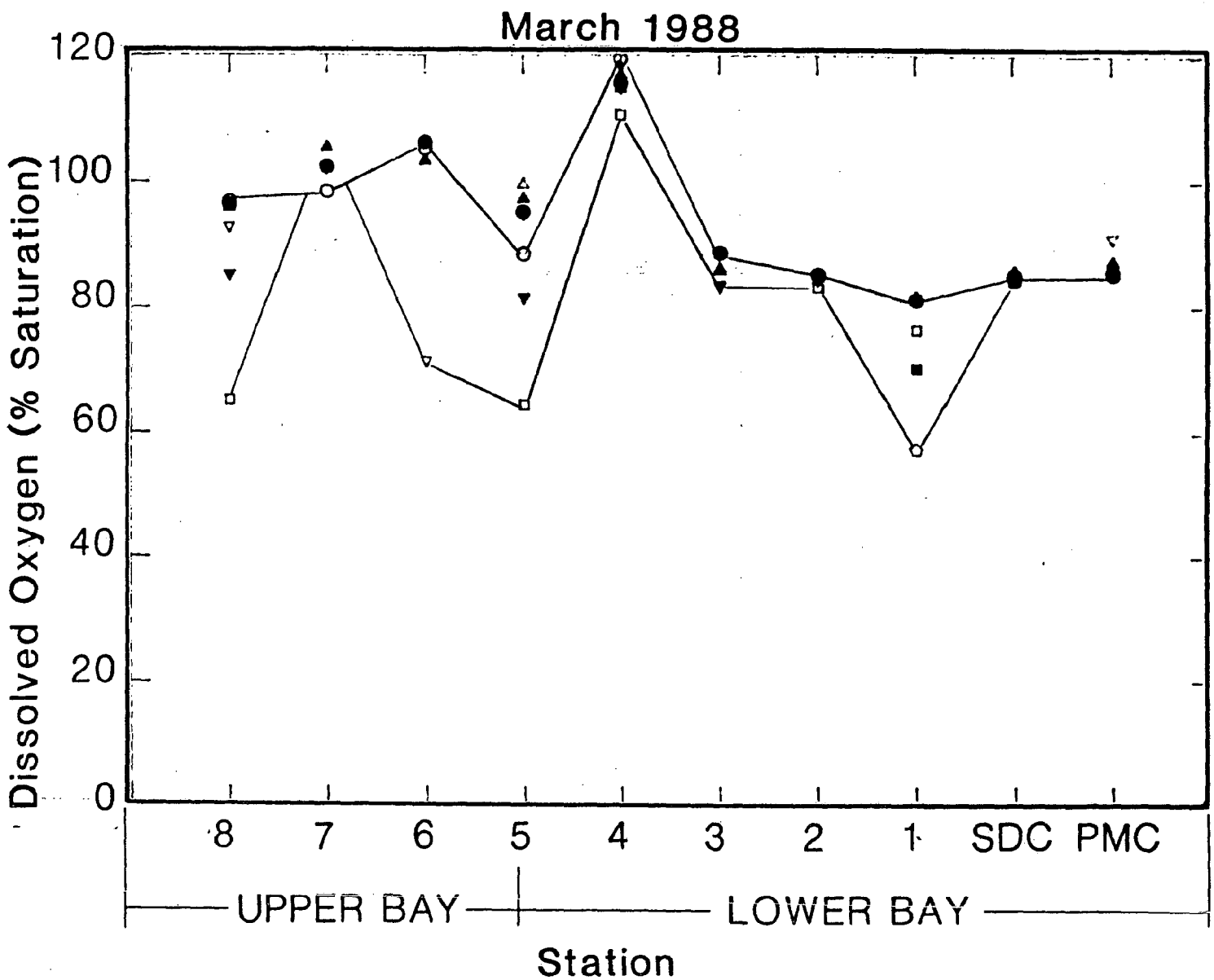


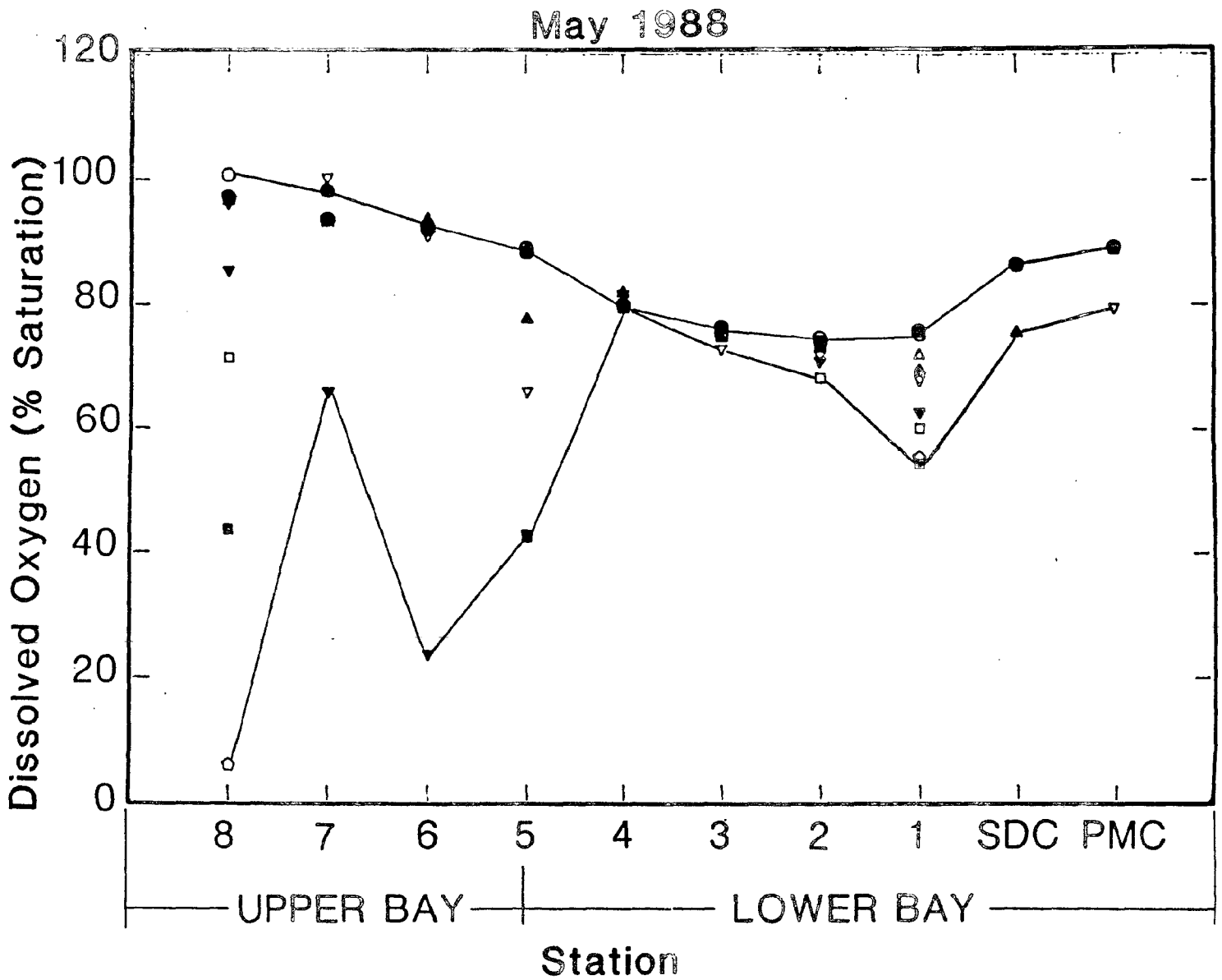
APPENDIX F

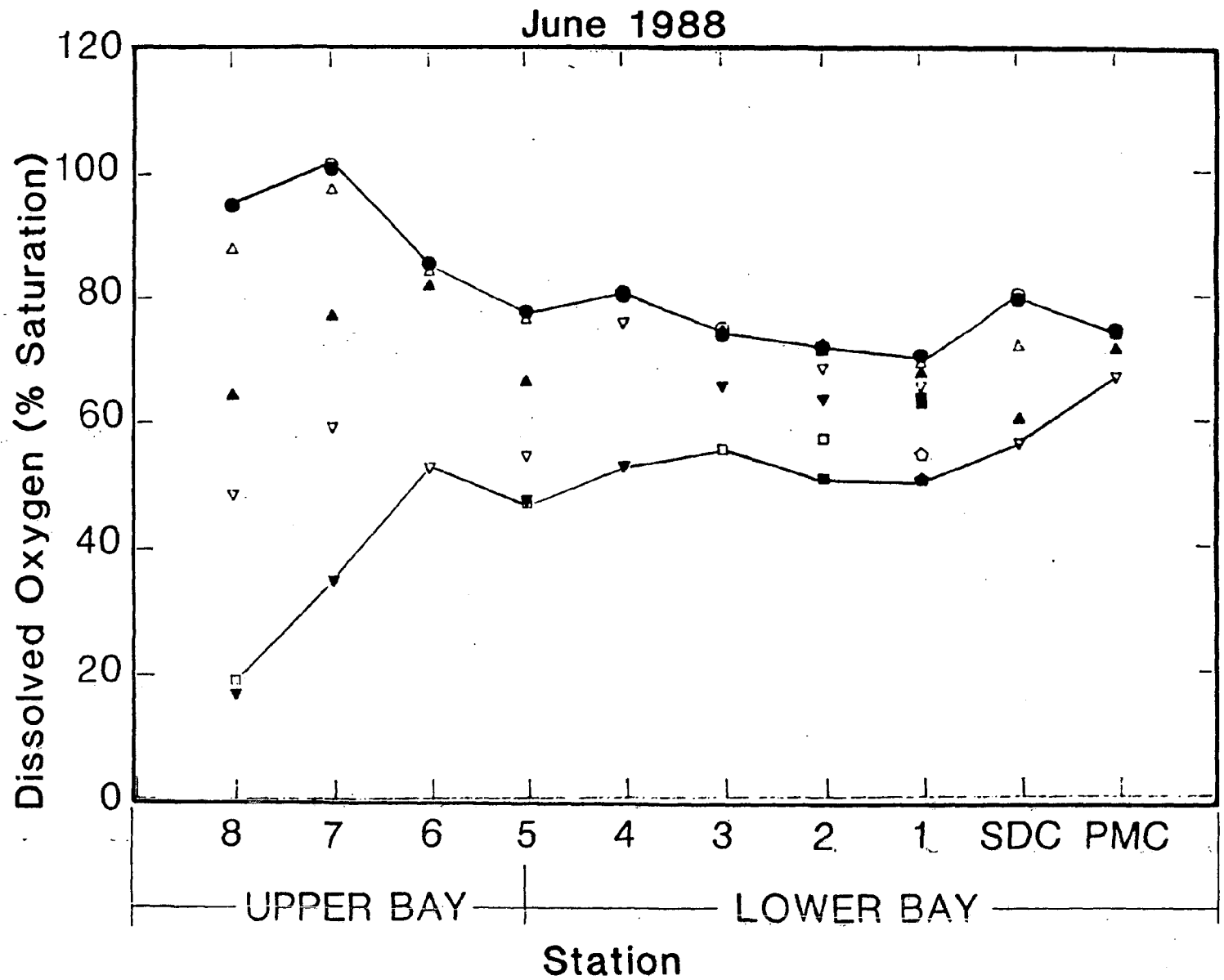
DISSOLVED OXYGEN AT ESTUARINE STATIONS IN PERDIDO BAY MONTHLY SAMPLES

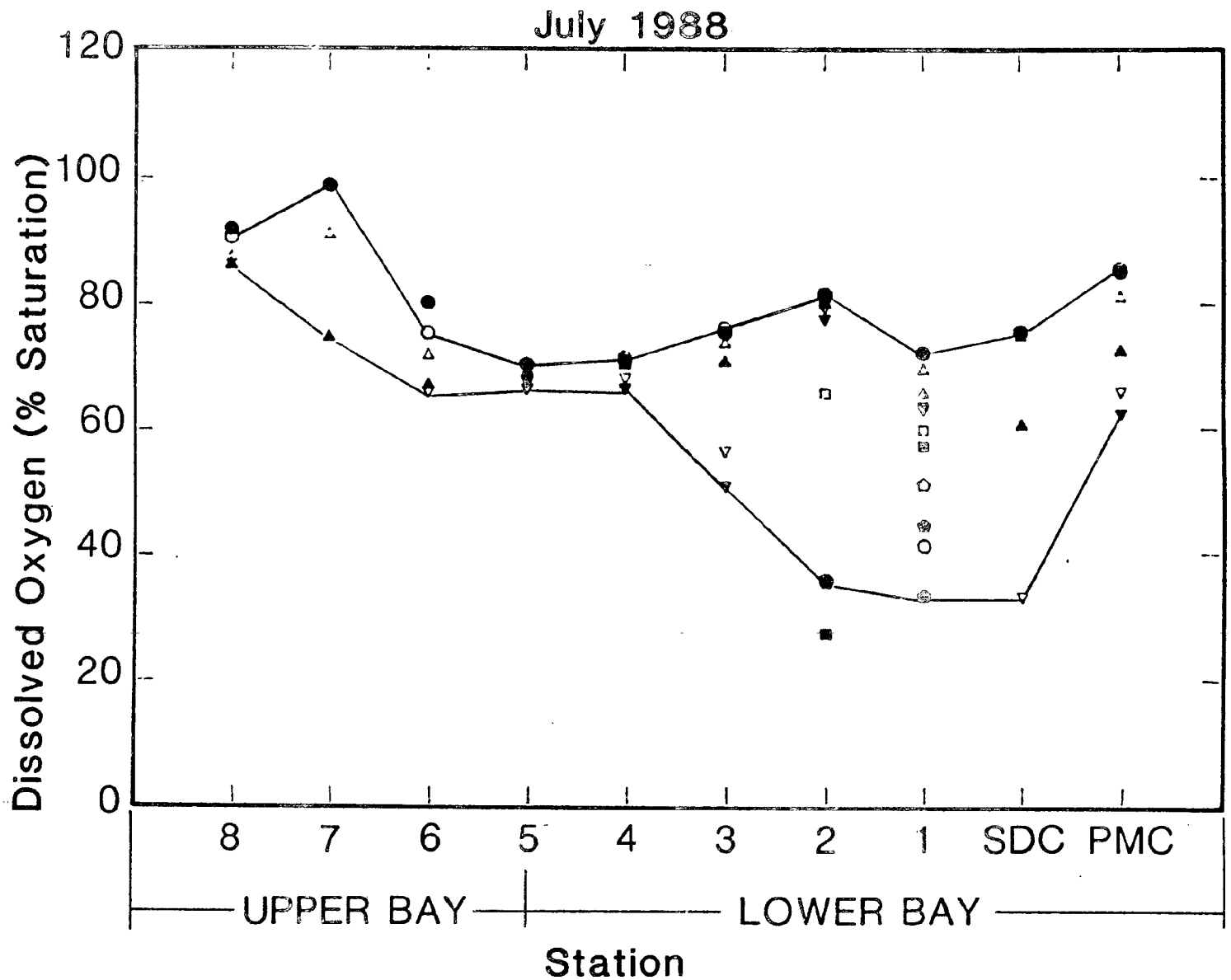
Explanation of symbols:

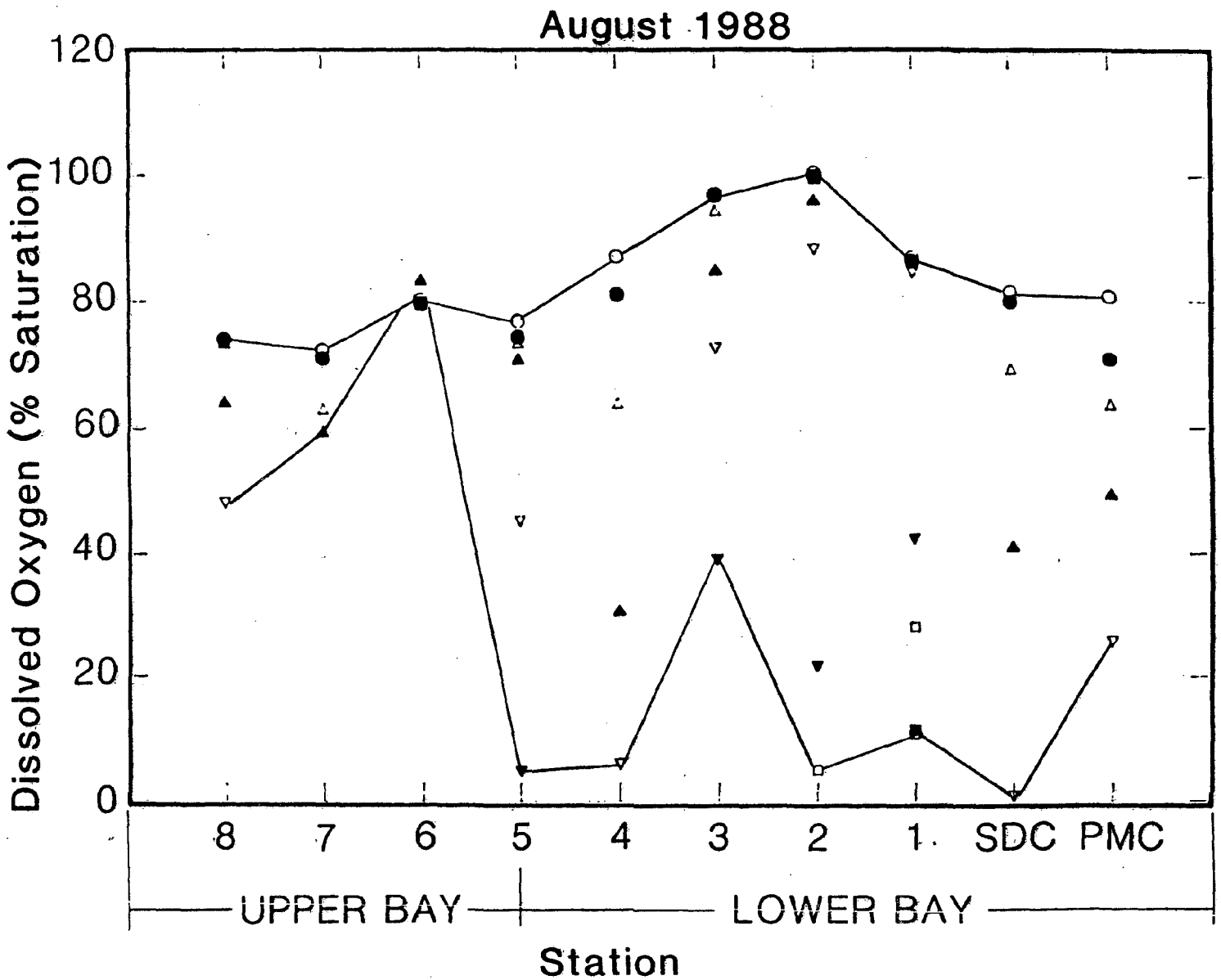
Depth (m)	Symbol
0.0	○
0.5	●
1.0	△
1.5	▲
2.0	▽
2.5	▼
3.0	□
3.5	■
4.0	⌂
4.5	⌂

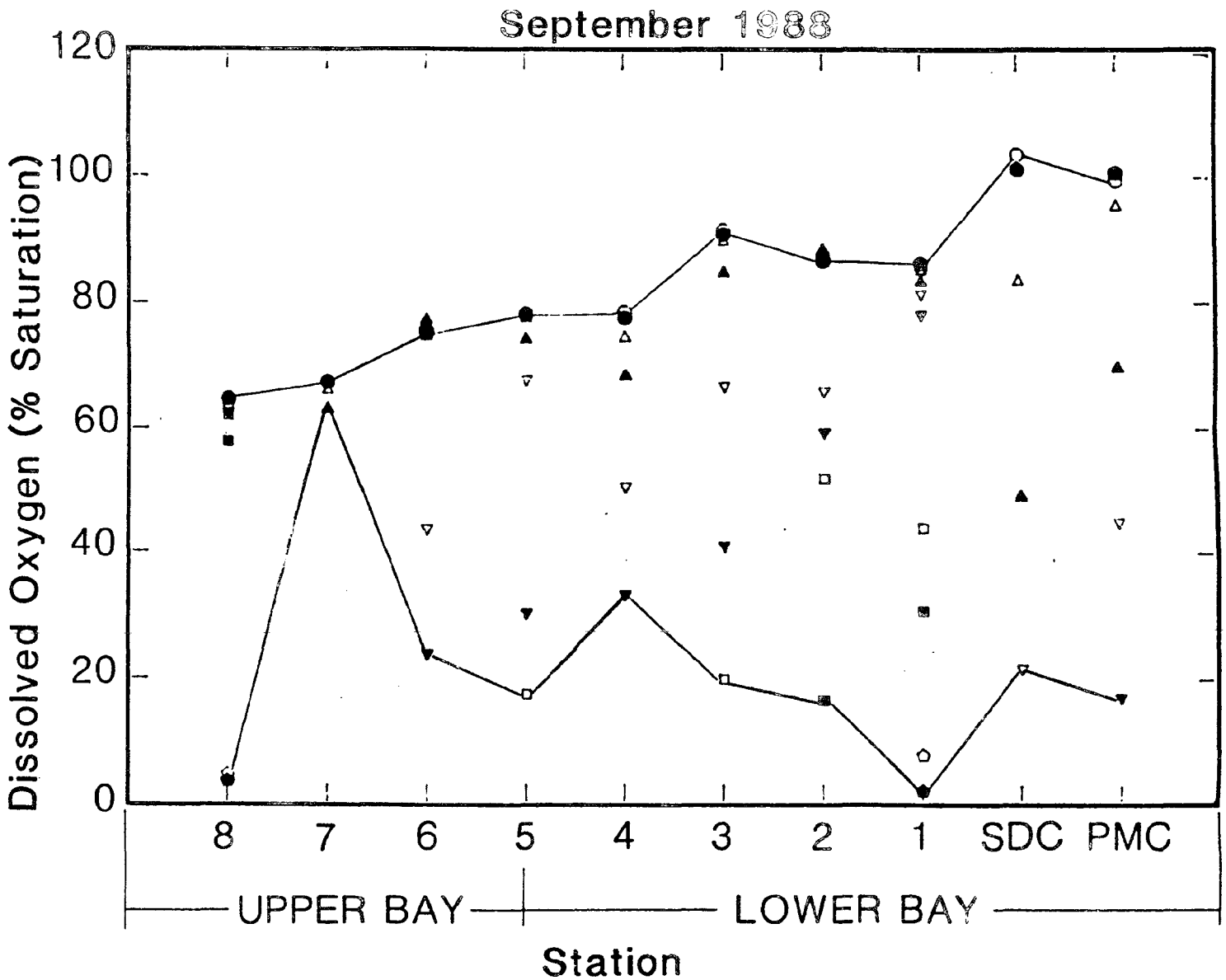

March 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

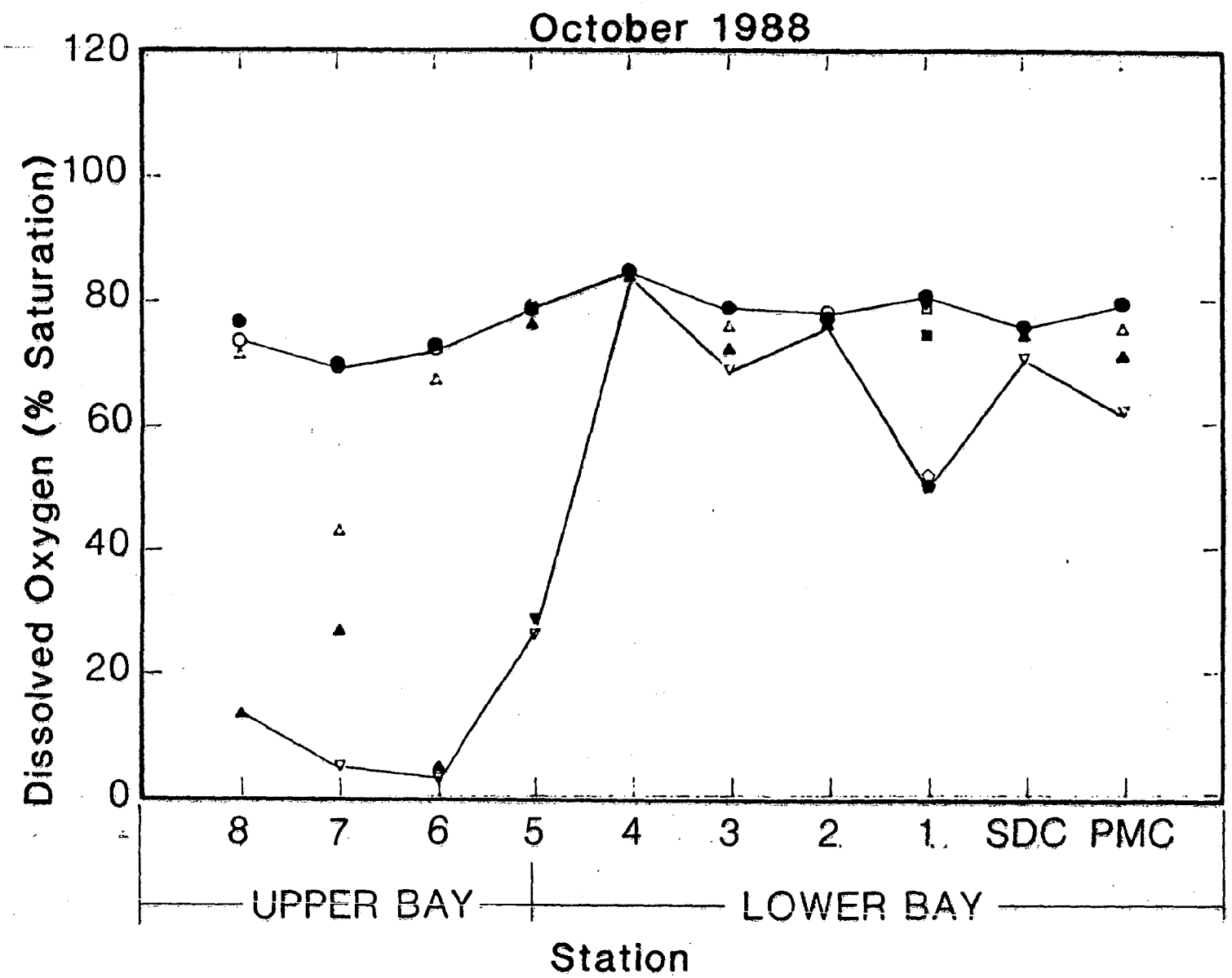

May 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

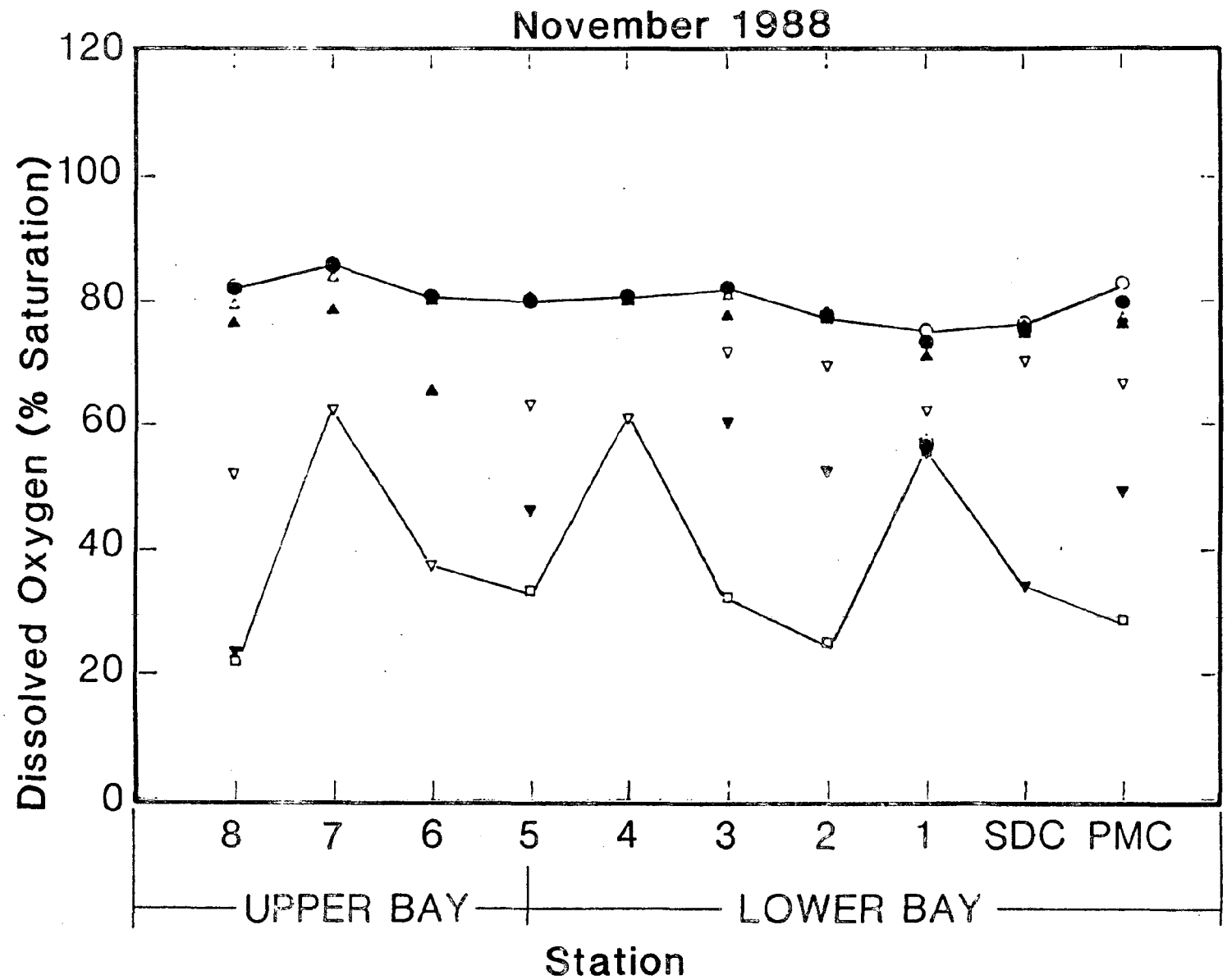

June 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

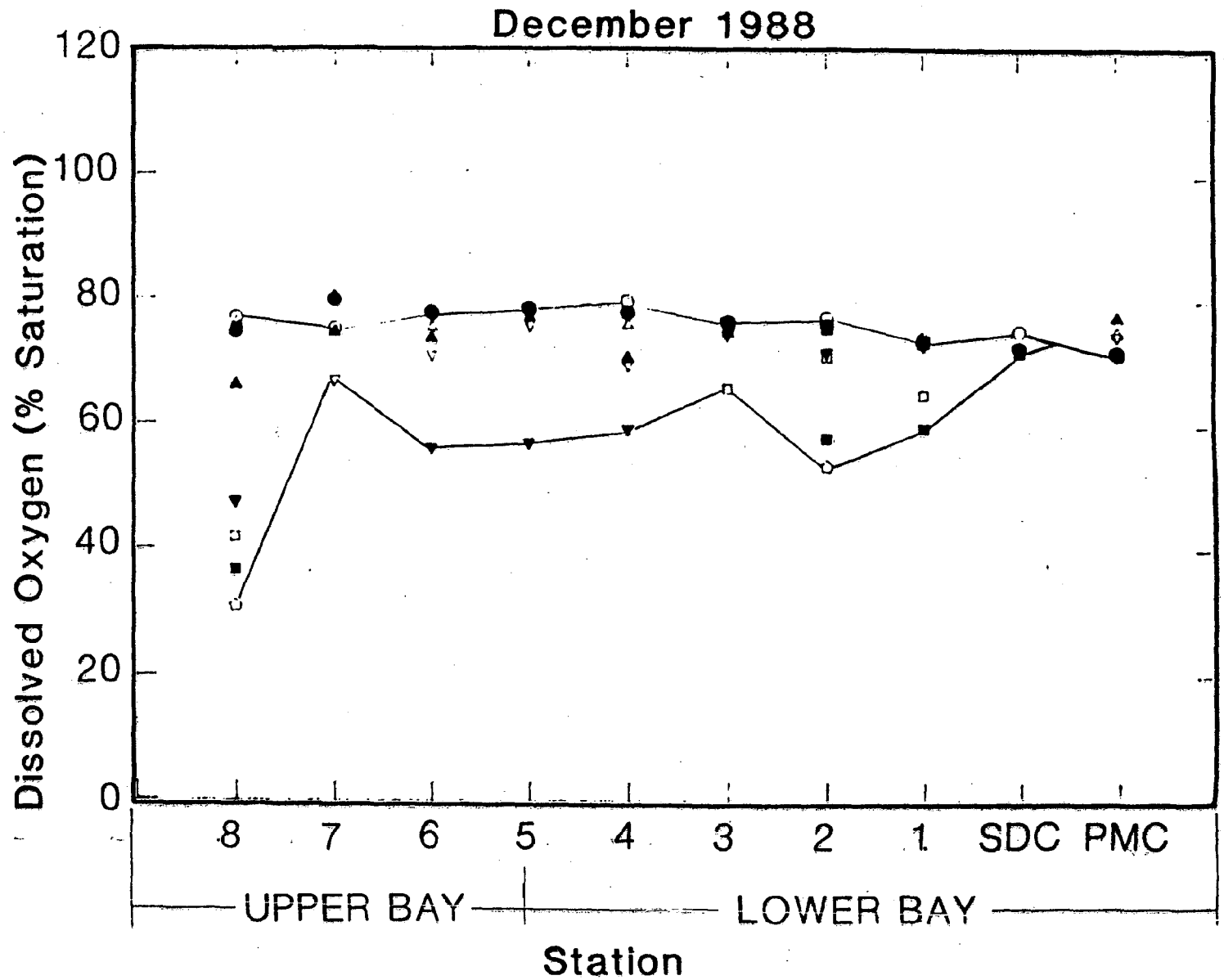

July 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

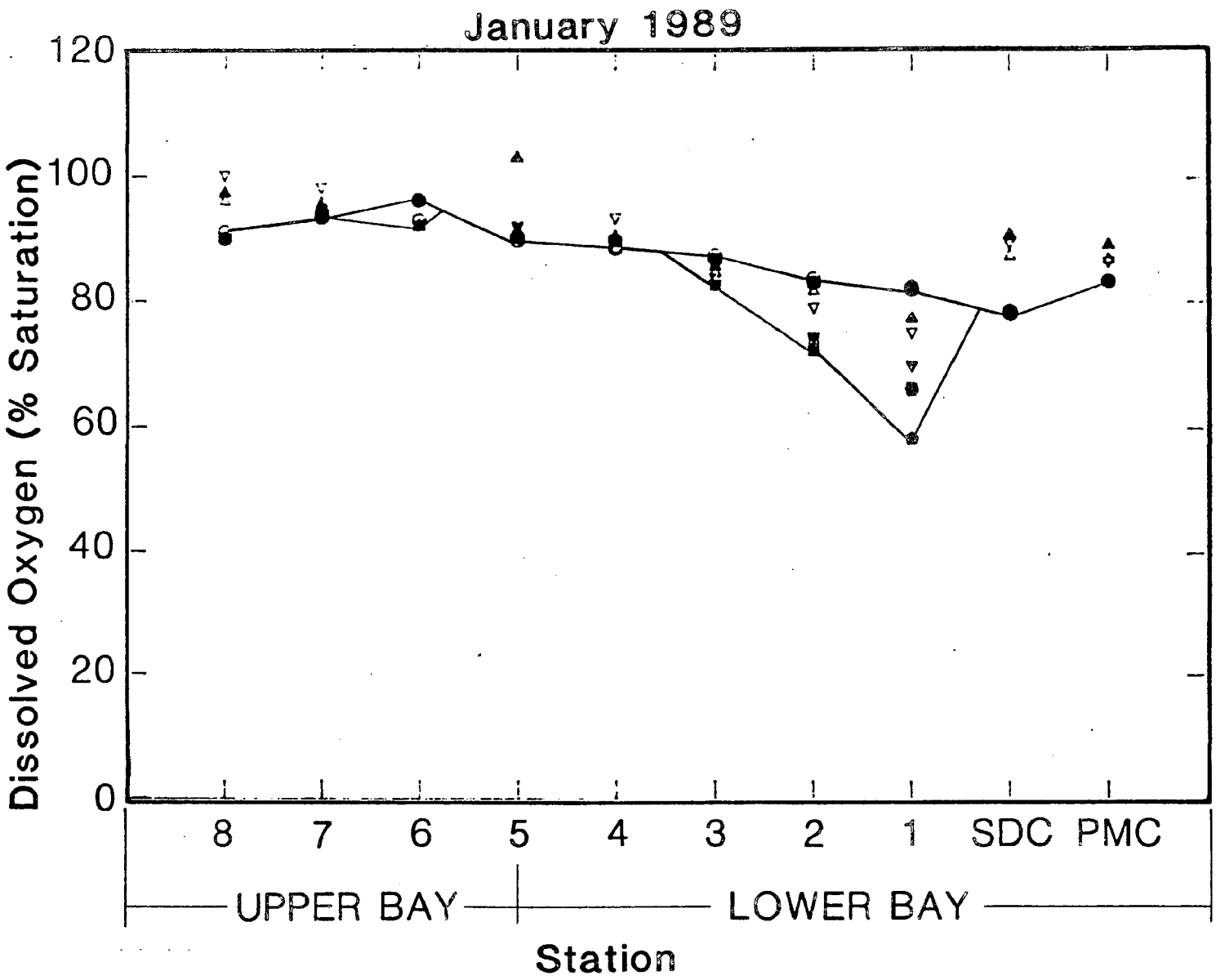

August 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

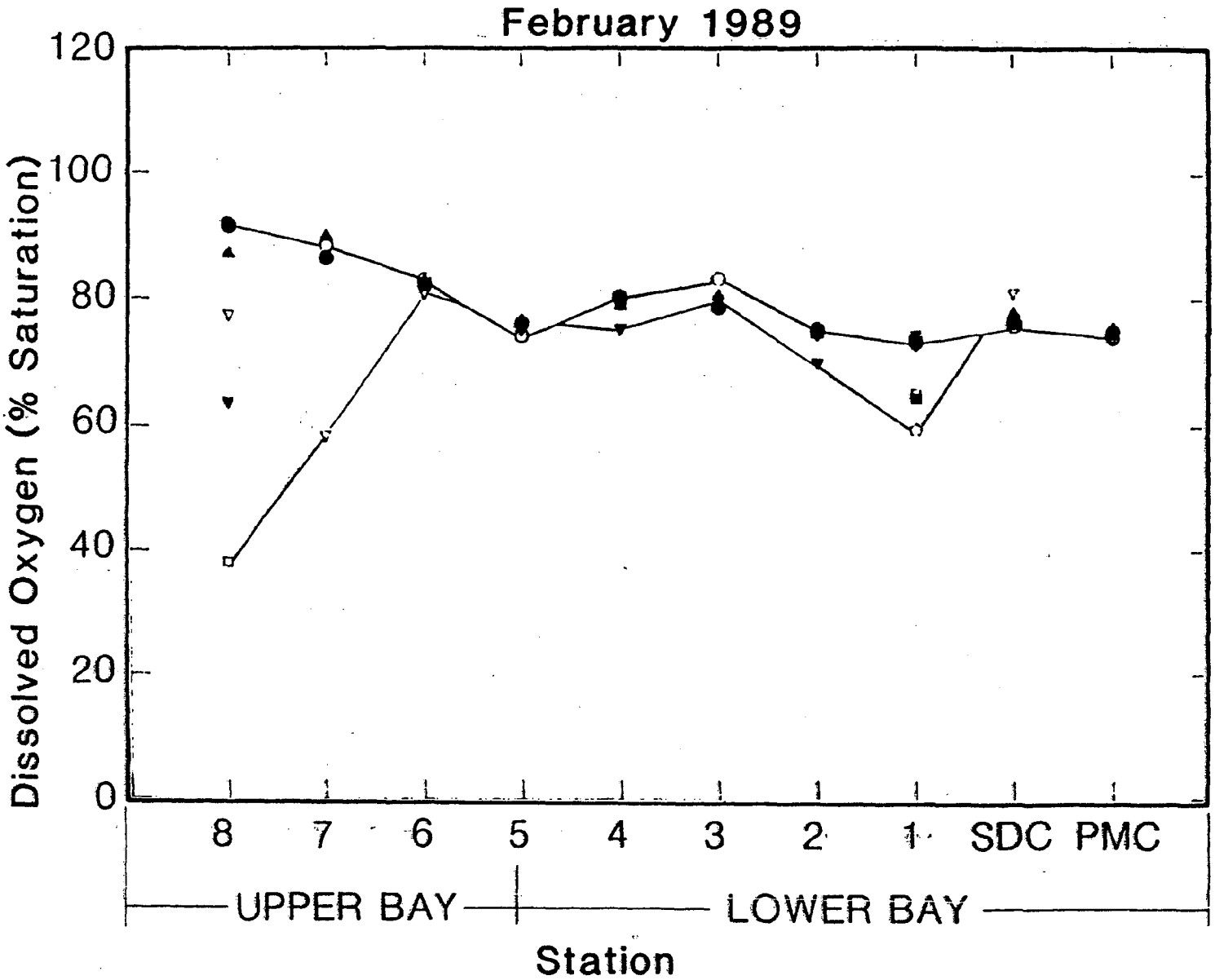

September 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

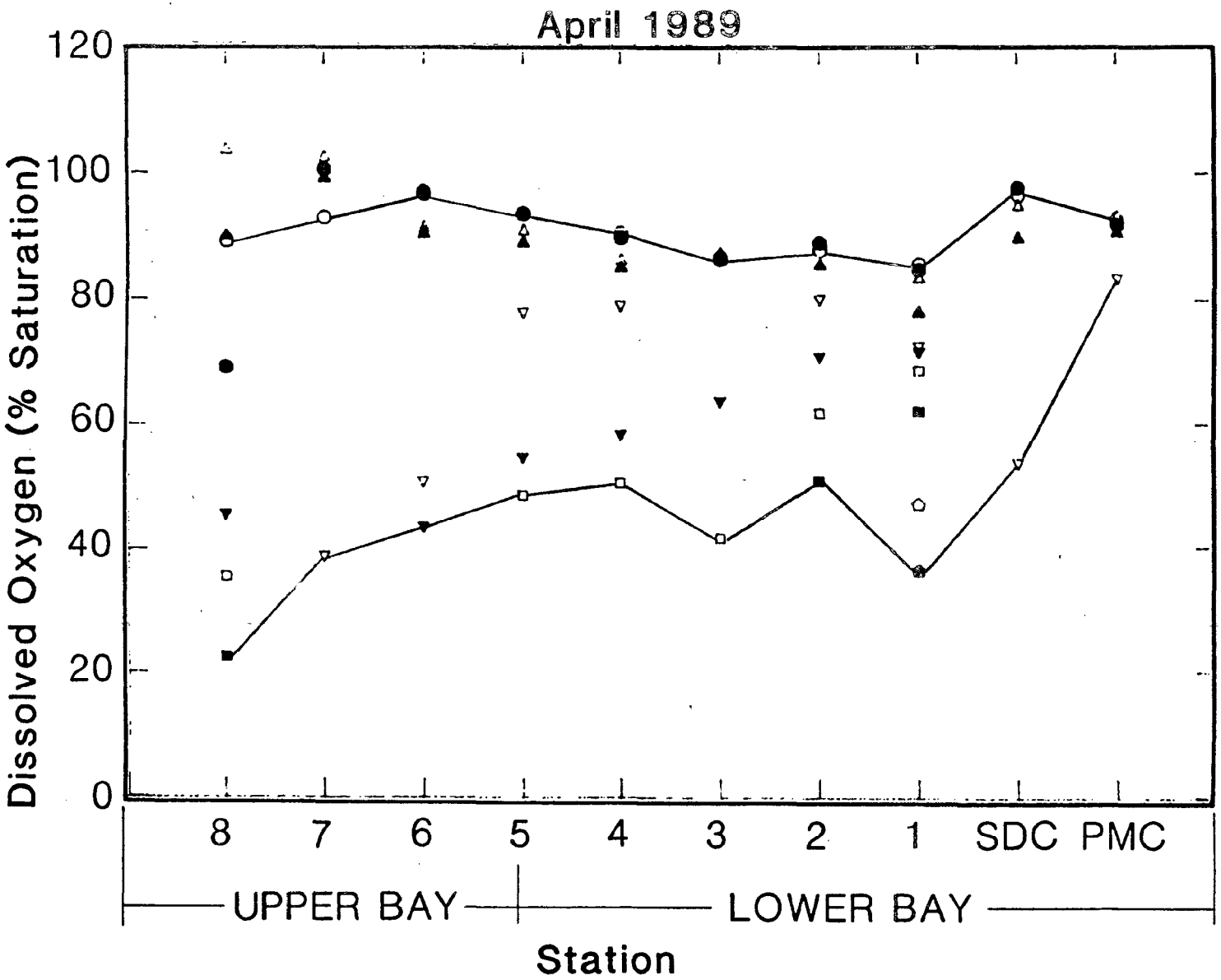

October 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

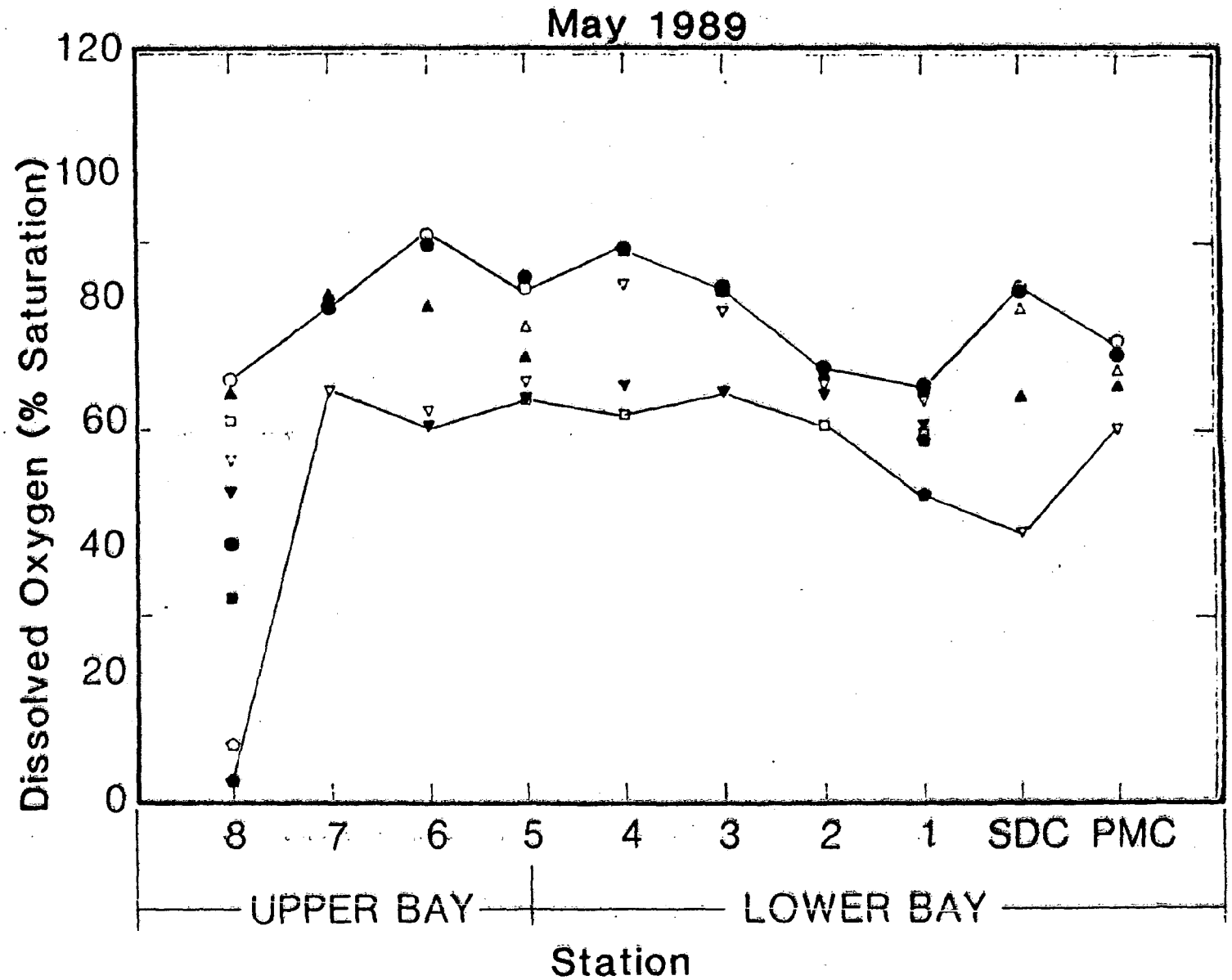

November 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

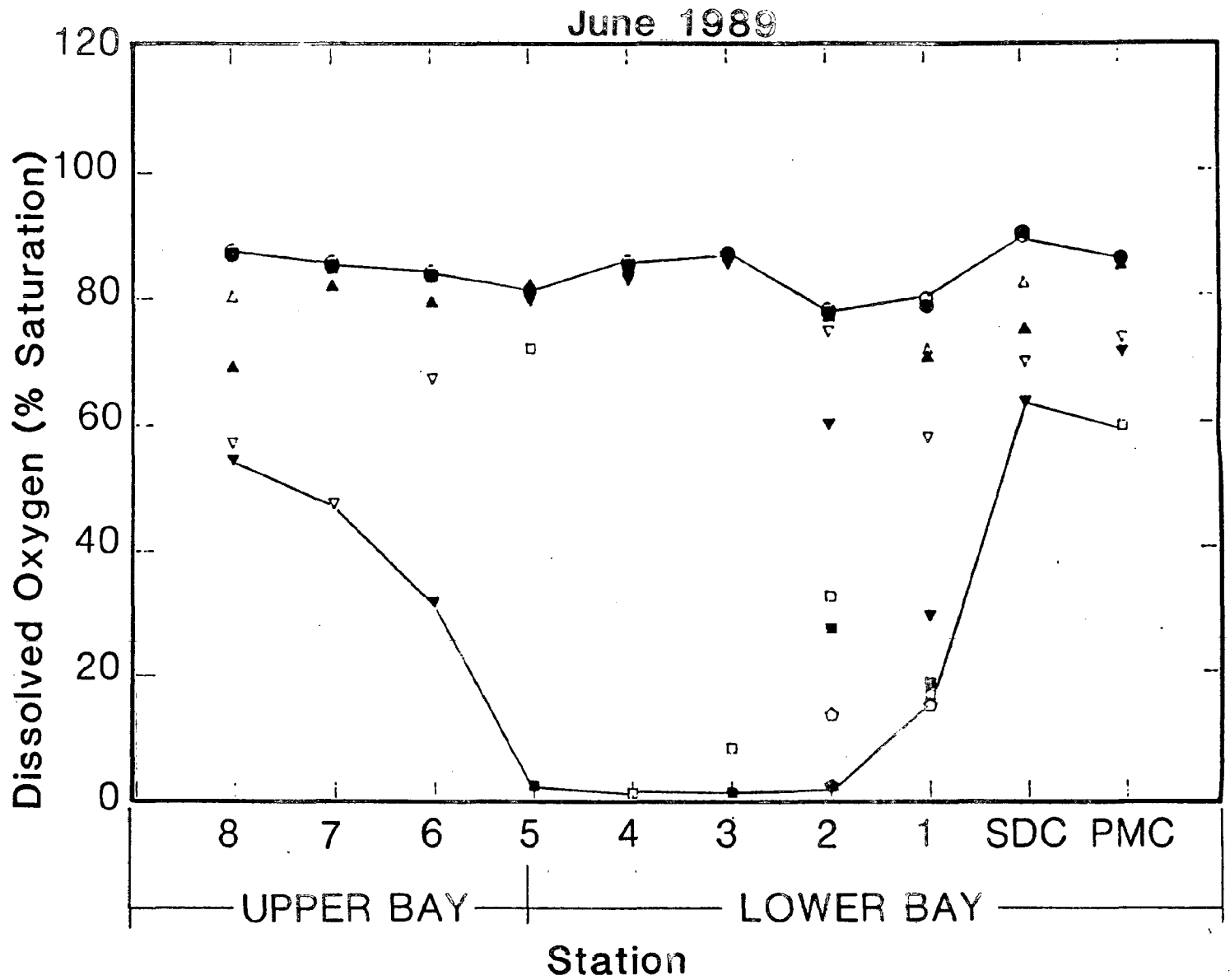

December 1988
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station


January 1989
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station


February 1989
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station


April 1989
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station


May 1989
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station


June 1989
Dissolved Oxygen (% Saturation)
120
100
80
60
40
20
0
8
7
6
5
4
3
2
1
SDC
PMC
UPPER BAY
LOWER BAY
Station

NOAA COASTAL SERVICES CTR LIBRARY
3 6668 14111356 5