ENVIRONMENTAL IMPACT OF PRODUCED WATER DISCHARGES IN COASTAL LOUISIANA

REPORT TO

THE LOUISIANA DIVISION OF THE

MID-CONTINENT OIL AND GAS ASSOCIATION

JULY, 1989

Prepared by the

Louisiana Universities Marine Consortium

in Collaboration with

Louisiana State University and A&M College

and Aero-Data Corporation

ENVIRONMENTAL IMPACT OF PRODUCED WATER DISCHARGES IN COASTAL LOUISIANA

Report Prepared for

The Louisiana Division of the

Mid-Continent Oil and Gas Association

Submitted by the

Louisiana Universities Marine Consortium

Chauvin, Louisiana 70344

In Collaboration with

Louisiana State University and A & M College

and

Aero-Data Corporation

Edited by

Donald F. Boesch and Nancy N. Rabalais

July, 1989

CONTRIBUTORS

Donald F. Boesch, Program Manager, Overall Management and Synthesis, Louisiana Universities Marine Consortium, Chauvin, LA 70344.

Kathryn M. Flynn, Vegetation Analysis, Laboratory for Wetland Soils and Sediments, Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803

Wayne Grip, Principal Investigator for Aerial Imagery Analysis, Aero-Data Corporation, 2351 Energy Drive, Suite 3010, Baton Rouge, LA 70808.

Nelson May, Aerial Imagery Analysis, Aero-Data Corporation, 2351 Energy Drive, Suite 3010, Baton Rouge, LA 70808.

Debra J. McMillin, Chemical Contaminants, Institute for Environmental Studies, Louisiana State University, Baton Rouge, LA 70803.

Jay C. Means, Principal Investigator for Chemical Contaminants, Institute for Environmental Studies, Louisiana State University, Baton Rouge, LA 70803.

Irving A. Mendelssohn, Principal Investigator for Vegetation Analysis, Laboratory for Wetland Soils and Sediments, Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803.

Charles S. Milan, Chemical Contaminants, Institute for Environmental Studies, Louisiana State University, Baton Rouge, LA 70803.

Nancy N. Rabalais, Principal Investigator, Principal Investigator for Field Hydrography and Benthos, Integration and Synthesis, Louisiana Universities Marine Consortium, Chauvin, LA 70344.

Lorene E. Smith, Benthos, Louisiana Universities Marine Consortium, Chauvin, LA 70344.

Erick M. Swenson, Hydrology Modelling, Coastal Ecology Institute, Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803.

Brian J. Wilsey, Vegetation Analysis, Laboratory for Wetland Soils and Sediments, Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803.

William J. Wiseman, Jr., Principal Investigator for Hydrology Modelling, Coastal Studies Institute and Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803.

TABLE OF CONTENTS

Title Page i
Contributors iii
Table of Contents v
Executive Summary xi
Chapter 1. Introduction 1
  1.1 Background 1
  1.2 Selection of Study Sites 3
  1.3 Description of Study Sites and Sampling Location 5
    1.3.1 Bayou Sale Site 5
    1.3.2 Lafitte Site 5
    1.3.3 Golden Meadow Site 15
Chapter 2. Modelling the Effects of Produced Water Discharges on Estuarine Salinity 23
  2.1 Introduction 23
  2.2 Data Used 23
    2.2.1 Estuarine Salinity 23
    2.2.2 Tides 24
    2.2.3 Freshwater Inputs 24
    2.2.4 Produced Water Emissions 24
  2.3 Salinity Statistics 24
  2.4 Refill Times Due to Produced Waters 38
  2.5 Tidal Prism Modelling 45
  2.6 Interpretation 52
Chapter 3. Effects of Produced Water Discharges on Wetland Vegetation 55

3.1 Introduction 55

3.2 Remote Sensing 55

3.2.1 Methods 55

3.2.1.1 Imagery 55

3.2.1.2 Sampling Strategy 56

3.2.1.3 Photointerpretation and Computer Mapping 56

3.2.1.4 Area Measurements 60

3.2.2 Bayou Sale Site 60

3.2.3 Lafitte and Golden Meadow Sites 68

3.3 Vegetation Field Assessments 68

3.3.1 Methods 68

3.3.1.1 Study Sites and Sampling Dates 68

3.3.1.2 Sampling Transects 68

3.3.1.3 Vegetation Samples 71

3.3.1.4 Interstitial Water Sample 71

3.3.1.5 Statistical Analysis 71

3.3.2 Vegetation Response 72

3.3.2.1 Plant Biomass 72

3.3.2.2 Plant Species Composition 77

3.3.3 Interstitial Salinity and pH 82

3.3.4 Relationship Between Plant Response and Interstitial Salinity and pH 82

3.4 Discussion 84

Chapter 4. Field Assessments: Hydrographic, Chemical and Biological Methods 87

4.1 Field Logistics 87

4.2 Hydrography 87

4.3 Sample Collection 87

4.4 Chemical Analyses 89

4.4.1 Organic Analytical Methods 89

4.4.1.1 Volatile Organic Analysis of Water 89

4.4.1.2 Extraction of Water for Semivolatile Organics 89

4.4.1.3 TOC and DOC Analysis of Water 90

4.4.1.4 Volatile Organic Analysis of Sediment 90

4.4.1.5 Extraction of Sediment for Semivolatile Neutral Organics 90

4.4.1.6 Biota Extraction Method 90

4.4.1.7 Semivolatile Instrumental Analysis 91

4.4.2 Trace Metal Analytical Methods 93

4.4.2.1 Instrumentation and Data Tabulation 93

4.4.2.2 Water Samples 93

4.4.2.3 Sediment Samples 93

4.4.2.4 Biota Samples 93

4.4.3 Other Analytical Methods 93

4.4.3.1 Interstitial Salinities 93

4.4.3.2 Particle Size Analysis 94

4.4.3.3 Organic Content 94

4.5 Analysis of Benthos 94

Chapter 5. Characterization of Produced Water 97

5.1 Introduction 97

5.2 Bulk Parameters 97

5.3 Organic Composition 97

5.3.1 Volatile Organics 97

5.3.2 Semivolatile Organics 100

5.3.3 Total Aliphatic Hydrocarbons 100

5.3.4 Aromatic Hydrocarbons 100

5.4 Trace Metals 100
5.5 Summary 110
Chapter 6. Bayou Sale Study Site 111
6.1 Hydrography 111
6.2 Organic Contaminants 111
6.2.1 Water 111
6.2.1.1 Bulk Parameters 111
6.2.1.2 Volatile Hydrocarbons 120
6.2.1.3 Semivolatile Hydrocarbons 120
6.2.2 Sediments 120
6.2.2.1 Bulk Parameters 120
6.2.2.2 Volatile Hydrocarbons 120
6.2.2.3 Semivolatile Hydrocarbons 127
6.3 Trace Major Elements 139
6.3.1 Water 139
6.3.2 Sediments 139
6.4 Benthic Communities 145
6.4.1 Dominants 145
6.4.2 Community Parameters 145
6.4.3 Marsh Stations 152
6.5 Synthesis 152
Chapter 7. Lafitte Study Site 161
7.1 Hydrography 161
7.2 Organic Compounds 168
7.2.1 Sediments 168
7.2.1.1 Bulk Parameters 168
7.2.1.2 Volatile Hydrocarbons 168

7.2.1.3 Semivolatile Hydrocarbons 168
7.3 Trace and Major Elements 178
7.3.1 Sediments 178
7.4 Benthic Communities 188
7.4.1 Dominants 188
7.4.2 Community Parameters 188
7.4.3 Marsh Stations 194
7.5 Synthesis 204
Chapter 8. Golden Meadow Study Site 209
8.1 Hydrography 209
8.2 Organic Contaminants 209
8.2.1 Sediments 209
8.2.1.1 Bulk Parameters 209
8.2.1.2 Volatile Hydrocarbons 218
8.2.1.3 Semivolatile Hydrocarbons 218
8.2.2 Bivalve Tissues 236
8.3 Trace and Major Elements 236
8.3.1 Sediments 236
8.3.2 Bivalve Tissues 244
8.4 Benthic Communities 253
8.4.1 Dominants 253
8.4.2 Community Parameters 253
8.4.3 Marsh Stations 258
8.5 Synthesis 258
Chapter 9. Synthesis and Conclusions 275
9.1 Scope and Limitations of Study 275
9.2 Effects of Produced Water Discharges on Estuarine Salinity 276

9.3 Effects of Produced Water Discharges on Wetland Vegetation 276

9.4 Chemical Contamination from Produced Water Discharges 277

9.5 Effects of Contamination on Estuarine Organisms 279

Literature Cited 285

EXECUTIVE SUMMARY

Background and Scope of Study

In response to concerns about the effects of the discharge of produced waters (oilfield brines) in estuarine and wetland environments of coastal Louisiana, the Louisiana Division of the Mid-Continent Oil and Gas Association contracted the Louisiana Universities Marine Consortium, in collaboration with Louisiana State University and Aero-Data Corporation, to conduct an assessment. The study had three components: 1) determination of the potential that the numerous brine discharges in the coastal zone have affected the salinity regime; 2) assessment of the effects of produced water discharges on wetlands based on analysis of aerial photographs; and 3) hydrological, chemical and biological field surveys.

For study components 2 and 3, three study sites were selected at which significant volumes of produced waters are discharged into receiving waters within tidal wetlands: a fresh marsh environment within the Bayou Sale oilfield in the Atchafalaya Basin; a brackish marsh environment within the Lafitte field in the Barataria Basin; and a brackish-saline transitional marsh within the Golden Meadow field in the Terrebonne-Timbalier Basin. At each study site, a major produced water discharge (3,000 to 4,000 barrels per day) was selected as the focal point of remote sensing analyses and field studies. A secondary discharge site was also examined in the Golden Meadow field. Analyses were based both on examination of changes with distance from the discharge points and comparison between discharge and reference areas, the latter consisting of areas within two to three kilometers distance which were physically similar to the discharge site but lacking produced water discharges.

Effects on Estuarine Salinity

Study component 1 examined the salinity distribution and trends, location and mass of brine emissions, and the flushing rates of the Barataria and Terrebonne-Timbalier Basins. The potential effects of produced water discharges on salinity within these estuaries were assessed through 1) estimation of the refill times, that is the time required for produced water discharges to refill the water or salt within delimited segments of the estuary, and 2) tidal prism modelling to predict the dilution of produced water introduced within a segment due to tidal flushing. Salinity within the two estuaries is naturally highly variable over time due to rainfall and runoff, water level variations, and the discharge of the Mississippi River, which influences the salinity of water entering the estuaries from the nearshore Gulf of Mexico. At present rates of discharge, it would take between 3 and 122 years to double the salinity of a particular estuarine segment, assuming a static system with no freshwater inputs or tidal exchange. The shortest replacement time is for the middle Barataria Basin. At the lowest flushing rates estimated (for the upper Barataria Basin), dissolved materials would be reduced to 10% of their starting concentrations within 1.75 months. When one couples the results of the refill analysis with those of the tidal prism modelling in a "worst case" analysis, it is apparent that it is unlikely that the mean salinity of any estuarine segment would increase more than a few percent due to presently occurring produced water discharges. Such changes are well within the range of seasonal or even tidal variation and, therefore, would be undetectable.

Effects on Wetland Vegetation

Based on the analysis of historical aerial photographs of the three study sites, there was extensive conversion of wetlands to open water habitats at the Lafitte and Golden Meadow study sites since the early 1950s. Approximately one half of the losses of wetlands was directly attributable to canal construction between 1952 and 1978. Wetland losses at the Bayou Sale site were less extensive and were mainly directly attributable to canal construction and widening. There were no differences in the amount or pattern of wetland losses not directly attributable to canal construction between discharge and reference areas within each of the study areas which could be attributed to produced water discharges. Rather, it appeared that the pattern of wetland loss not directly attributed to canals is related to hydrological modifications caused by canal construction, particularly semi-impoundment of marsh by spoil banks.

Live biomass of wetland vascular plants was not significantly different between discharge and reference areas except at the Golden Meadow site. However, the differences in plant biomass and species composition at Golden Meadow did not appear to be related to an increase of soil salinity due to produced water discharges. Observed contamination of marsh soils with petroleum hydrocarbons, possibly as a result of a spill, may have been a factor in the lowered plant biomass at the Golden Meadow discharge site. Three lines of evidence--historical photographic analysis, patterns of biomass and species composition of the vegetation, and the tendency of produced water to sink to the bottom in receiving waters and not significantly increase the salinity of the near-surface water which floods the marsh--all strongly suggest that there was no effect of produced water discharges on marsh loss at the three study sites or, at least, that this effect was very small in comparison to the effect of canal construction.

Chemical Contamination and Its Effects

The principal impacts uncovered in this study are related to the contamination of the estuarine environment with potentially toxic substances other than dissolved salts contained in discharged produced waters. These include petroleum hydrocarbons, hydrocarbon homologs, organic acids and other partially oxidized hydrocarbons, and trace metals. The concentrations of volatile aromatic, polynuclear aromatic, and saturated hydrocarbons and trace metals in produced waters sampled from the primary discharges within each of the three fields were generally similar and within the typical range reported in the literature. The total organic carbon content of the produced waters ranged from 250 to 540 ppm, most of which consists of poorly characterized, non-hydrocarbon organic compounds. Total volatile aromatic hydrocarbons--compounds including benzene and toluene which are of concern because of their acute toxicity--were present in concentrations of 2 to 4 parts per million (ppm). Several trace metals were also found in the produced water samples in concentrations much higher than in receiving waters. Barium, present at levels between 24 and 53 ppm, is particularly enriched in produced water.

Based on measurements of salinity in the vicinity of the discharges at the time of sampling, it is possible to develop a crude picture of the fate and dilution of the effluent, using salt as a conservative tracer. At all three sites an increase in salinity was observed in bottom waters near the point of discharge, but surface salinities showed little or no increase over ambient conditions. This reflects the sinking of the discharge plume which is much denser than the receiving waters because of the high concentration of dissolved solids. Dilution of the produced water upon its discharge into the receiving bayou or canal appeared to be rapid, with an approximately 20-fold dilution within the immediate mixing zone of the bottom-hugging dispersion plume. Salinity levels at the bottom were indistinguishable from background levels (necessitating at least a 100-fold dilution) within a maximum of 1000 meters of the discharge points.

Fine grained sediments within a kilometer of the discharges exhibited elevated concentrations of polynuclear aromatic and saturated hydrocarbons. Trace metals, except for barium, did not show a consistent pattern of enrichment in sediments near produced water discharges. Hydrocarbon contamination of bottom sediments was more extensive at the Lafitte and Bayou Sale sites, where it extended to at least 750 m and 500 m, respectively, than at Golden Meadow, where clearly elevated levels were only found within 100 m of the discharges. These differences seem to be related to the differences in tidal current velocities and bottom sediment type, with contamination being greater under more sluggish conditions where fine sediments accumulate.

Benthic (bottom dwelling) organisms were present in reduced densities and reduced diversity of species where there was high to moderate contamination of sediments by petroleum hydrocarbons (polynuclear aromatic hydrocarbon levels over 1,000 ppb). There were changes in species composition and population size structure in areas of moderate contamination (over 300 ppb PAH) when compared to uncontaminated sediments. The effects on benthos were greatest at the Lafitte site, where only very depauperate populations of brackish water polychaete worms were found within 250 to 300 m of the discharge. Effects on benthos in the freshwater habitat at Bayou Sale were less severe. Near the produced water discharge there, the diversity of the fauna was reduced but oligochaete worms were present in higher densities than were found in uncontaminated sediments. Increases in oligochaete population size have been characterized in the literature as benthic community changes in tidal freshwater and estuarine areas in response to physical disturbance and organic pollution. Because ambient salinity conditions at the Golden Meadow site were higher, more species of benthos occurred there than at the other two sites. Even under conditions of moderate sediment contamination near the discharges, no depressions in total faunal abundance or diversity were found.

Limited sampling of oysters and marsh mussels was conducted at the Golden Meadow site in order to assess the potential for uptake of contaminants by filter-feeding organisms. Concentrations of both polynuclear aromatic hydrocarbons (PAH) and total saturated hydrocarbons were greatly elevated near the two discharges studied compared to the reference area for both oysters and mussels. No consistent increases in trace metal concentrations were observed for either species. PAH concentrations were 10-20 times those from reference areas in oyster tissue and 4-14 times greater in mussel tissue. While the limited sampling conducted is insufficient to determine the extent of this effect, the potential for bioaccumulation of hydrophobic organic contaminants introduced by produced water discharges was demonstrated.

Chapter 1

INTRODUCTION

by

Donald F. Boesch and Nancy N. Rabalais

1.1 Background

In response to concerns raised within regulatory agencies and the Legislature of the State of Louisiana concerning the effects of the discharge of produced waters (oilfield brines) into coastal environments of the state, the Louisiana Division of the Mid-Continent Oil and Gas Association and the Louisiana Department of Environmental Quality began planning a series of coordinated assessments in 1987. In June 1988, Mid-Continent contracted with the Louisiana Universities Marine Consortium (LUMCON), in collaboration with the Louisiana State University and A & M College (LSU) and Aero-Data Corporation, for the conduct of a portion of these coordinated assessments, namely a study of the "Environmental Impact of Produced Water Discharges in Coastal Louisiana."

During the production of oil or gas, water that is trapped within permeable sedimentary rock may also be brought to the surface. This water is called formation water, produced water or oilfield brine. Such water is connate or fossil water that may have dissolved solids levels (salinity) in excess of that of sea water. In coastal Louisiana, formation waters range in salinity from 50 g/l (parts per thousand) to 150 g/l depending on the depth from which they are drawn and their proximity to salt diapirs (Hanor et al. 1986). In addition, produced waters often contain levels of various inorganic (e.g., trace metals, sulfide and elemental sulfur) and organic (petroleum hydrocarbons and partially oxidized organics) substances in excess of levels found in ambient sea water (Neff et al., 1987).

Water must be removed from the oil or gas as completely as possible in order to transport and use the petroleum. This is conventionally done by depressurization and gravity separation (Figure 1.1). This separation may be enhanced by the addition of demulsifiers. Following the initial separation, which is aimed at reducing the water content of the oil to acceptable levels, the produced water may be reinjected down a well, either for disposal or to enhance recovery of remaining hydrocarbons, or they may be discharged to surface waters. In the case of surface water discharges, further retention in holding tanks or ponds may be employed to reduce the oil and grease content of the effluent.

In a recently completed study conducted by LUMCON for the Minerals Management Service (Boesch and Rabalais, 1989), it was estimated from permit applications submitted to the Louisiana Department of Environmental Quality that a total of 2 million barrels of oil and gas produced waters are discharged into the state waters of Louisiana per day from nearly 700 sites. Of this amount, 23, 22, and 17 percent are discharged into fresh, brackish and saline wetland environments, respectively, with the remainder discharged into open embayments or nearshore Gulf waters. The focus of the study sponsored by Mid-Continent is on those discharges into fresh and brackish environments, because of the concern that the discharge of the briny produced waters results in increased salinity, effects on salt-intolerant wetland vegetation, and, consequently, wetland loss. It should be pointed out that recently completed and ongoing studies, sponsored by the American Petroleum Institute and the Minerals Management Service (Neff et al., 1989; Boesch and Rabalais, 1989) focus on the environmental effects of produced water discharges into higher salinity and open water environments.

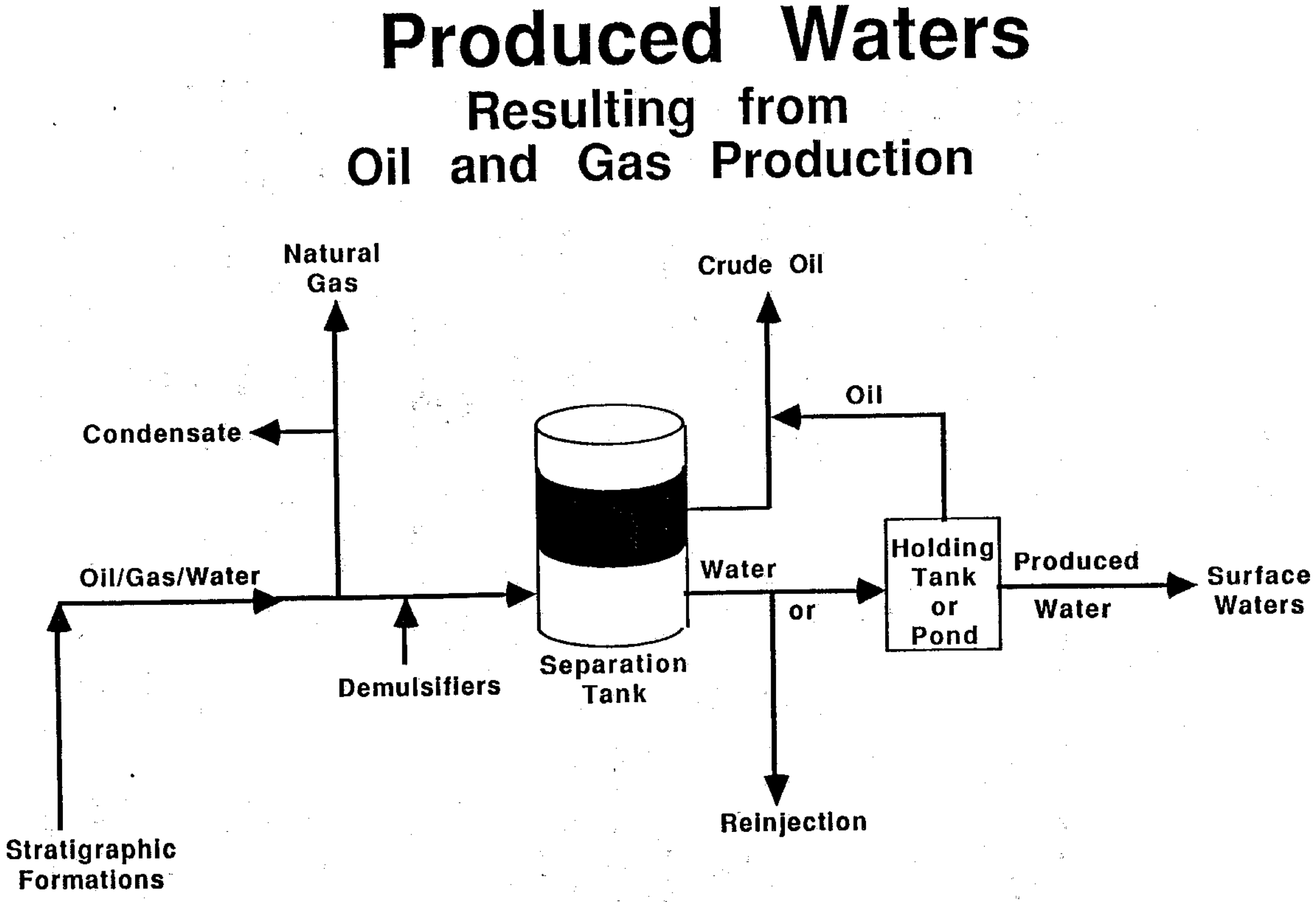


Figure 1.1. Procedures for separation, treatment, and disposal of produced waters.

This study consisted of three component tasks. Component 1 had as its objective the determination of the potential that the numerous discharges of oil and gas produced waters, which have a high concentration of dissolved salts, into Louisiana's estuaries has affected the salinity regime of these estuaries. It was based on a simplified numerical modeling approach which examined whether the input of salt with produced waters is sufficient to elevate salinity in the Barataria and Terrebonne estuarine basins. This component task was under the supervision of Dr. William Wiseman of Louisiana State University. Results of these analyses are presented in Chapter 2 of this report.

Component 2 consisted of an assessment of the effects of produced water discharges on wetlands in the vicinity of the discharges as deduced from analysis of historical and recent aerial photographs at selected sites. This component task was the responsibility of Aero-Data Corporation. Results of this assessment are presented in Chapter 3 of this report.

Component 3 consisted of field studies of the same sites selected for remote sensing analysis. In these studies, the chemical characteristics of produced waters discharged are analyzed and water quality, chemical contaminants in the environment, wetland vegetation and bottom-dwelling (benthic) organisms are sampled. These field studies were coordinated by Dr. Nancy N. Rabalais of LUMCON. Dr. Irving A. Mendelssohn of Louisiana State University was responsible for the wetland vegetation analyses and Dr. Jay Means of LSU was responsible for analyses of chemical contaminants. Dr. Rabalais conducted the hydrographic and benthic biological studies. The results of field studies of vegetation are included together with the results of the analyses of aerial photographs in Chapter 3. Characterization of the produced waters discharged at these sites is presented in Chapter 5 and descriptions of methods and results of the field assessments of water quality, contaminants and benthic organisms are presented in Chapters 4 through 8.

1.2 Selection of Study Sites

Studying every site at which produced waters are discharged in coastal Louisiana is clearly impossible, with nearly 700 known discharges from over 70 oil and gas fields. Rather than cover a large number of sites lightly, three sites were selected for intensive study. The selection of sites was made after careful consideration of the location of major volumes of produced water discharges and the potentially most sensitive environments, based on *a priori* criteria. A list of potential study sites was developed independently by LUMCON and the three study sites selected (Figure 1.2) based on consultation with Mid-Continent representatives, who were able to supply additional information about the characteristics and history of discharges.

One site was located in a tidally influenced, fresh marsh environment within the Bayou Sale oil field. This site is located west of Wax Lake Outlet, a distributary of the Atchafalaya River, and is thus influenced by Atchafalaya River flow. Unlike most other freshwater distributaries receiving produced water discharges, though, it is more of a backwater area and not a distributary channel experiencing large volume flows. Two sites were selected in brackish marsh environments, one within the Lafitte oil field in the Barataria estuarine basin (ambient salinity at time of sampling 6 to 7 ppt) and the other in the Golden Meadow oil field in the Terrebonne estuarine basin (ambient salinity 9 to 10 ppt). Within each study area, rectangular areas were selected for remote sensing analysis. These areas contained the site of a major produced water discharge and a "reference" area of similar wetland type and water:marsh ratio in which no discharges were located.

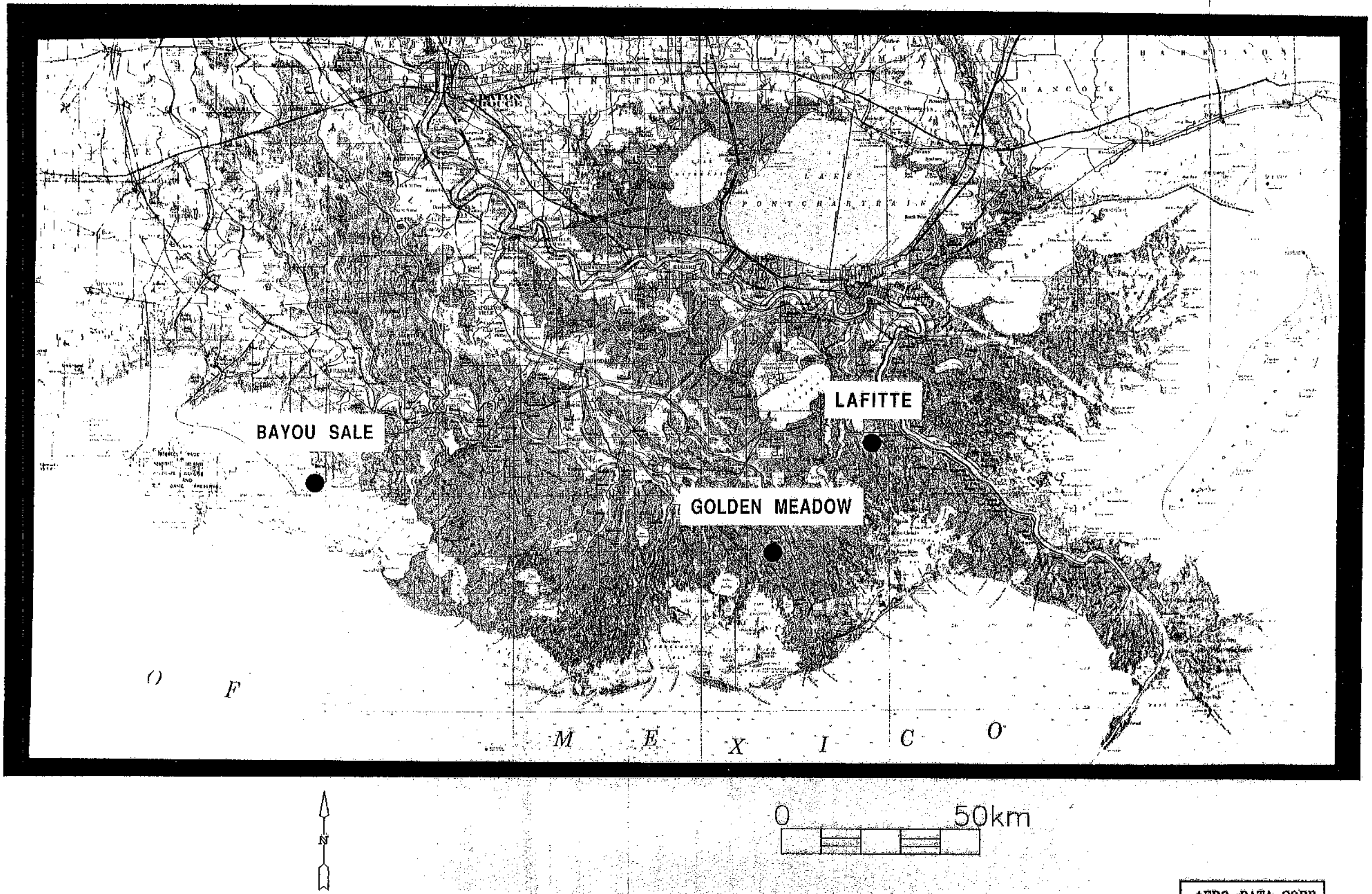


Figure 1.2. Locations of the Bayou Sale, Golden Meadow, and Lafitte study sites in southern Louisiana.

AERO-DATA CORP.
Baton Rouge, LA

1.3 Description of Study Sites and Sampling Locations

1.3.1 Bayou Sale Site

As mentioned above, the Bayou Sale site is located in a tidally influenced, fresh marsh environment west of Wax Lake Outlet, a distributary of the Atchafalaya River. During hydrographic sampling at this site, strong tidal currents were moving through the study area. The site is 6 km from the open waters of Atchafalaya Bay and 7 km from Wax Lake Outlet. Figure 1.3 illustrates the general study area.

The produced water discharge point which is the focus of our studies is the ARCO Salt Water Discharge #1 facility (SWD1) located on an east-west canal intersecting with Lone Oak Bayou (Figure 1.4). Several other produced water discharges are located within the study area. Along Lone Oak Bayou, there are two produced water discharges, one to the north of the station grid and one to the south. The one to the north is Exxon Tank Battery #9 (TB9), situated 700 m northwest of the most northerly station in the station grid (BS1500N). The discharge to the south is a Texaco facility, CF2, located 700 m south of the southernmost station in the station grid (BS1500S). On the eastern end of the station grid within 200 m of BS1500E, there are two well heads and ancillary facilities. These are owned by an independent operator, Samedan (SD in Figures 1.3 and 1.4). The reference stations are located in a canal intersecting Hog Bayou and along Hog Bayou (Figure 1.5). The location of vegetation transects and the area delimited for remote sensing analysis are shown on Figure 1.3. Details of the vegetation transects are given in Figures 1.6 and 1.7.

Produced water discharges from the ARCO facility SWD1 began in 1946. This facility has been in continuous operation since then, with shutdown only for repairs. Average daily discharge in September and August 1988 was 2,500 bbl/d with a chloride concentration of 62.5 ppt and an oil and grease content of 15 ppm. Over the last two years, discharge rates have averaged 2,684 bbl/d with a chloride concentration of 69.2 ppt and an oil and grease content between 15 and 25 ppm. The Exxon TB9 facility, which began operations in 1941, discharges 3,600 bbl/d, with a similar amount over the last couple of years. The chloride levels of this discharge are 47 ppt and the oil and grease content averaged 13 ppm during 1988. The Texaco CF2 facility has been discharging produced waters since 1953 with no known cessation. The average daily discharge for August and September 1988 was 1,860 bbl/d, The average chloride and oil and grease levels at that time were 43.1 ppt and 20 ppm, respectively. The Samedan operation began discharge of produced waters in 1972. During the period of sample collection, the discharge averaged 800 to 1,800 bbl/d, with an oil and grease content of 15 ppm. This discharge was stopped in October 1988; the produced waters are now piped to an ARCO facility located on the western side of Lone Oak Bayou for treatment and discharge.

1.3.2 Lafitte Site

The Lafitte study area is located within a tidally influenced, brackish marsh environment. The produced water discharge which is the focus of our studies is associated with Texaco Commingling Facility #8 (CF8) located on a north-south canal intersecting some natural open water areas which have been extensively channelized (Figure 1.8). The Barataria Bay Waterway runs northwest to southeast on the western edge of the discharge site. There are several produced water discharge points located 3 km north of the primary study site. There are no discharges within 1500 m of any the stations located around the discharge point of interest. The reference stations are located to the west of the Barataria Bay Waterway along dredged canals (Figure 1.9). The location of vegetation transects and the area delimited for remote sensing analysis are shown in Figure 1.8. Details of the vegetation transects are given in Figures1.10 and 1.11.

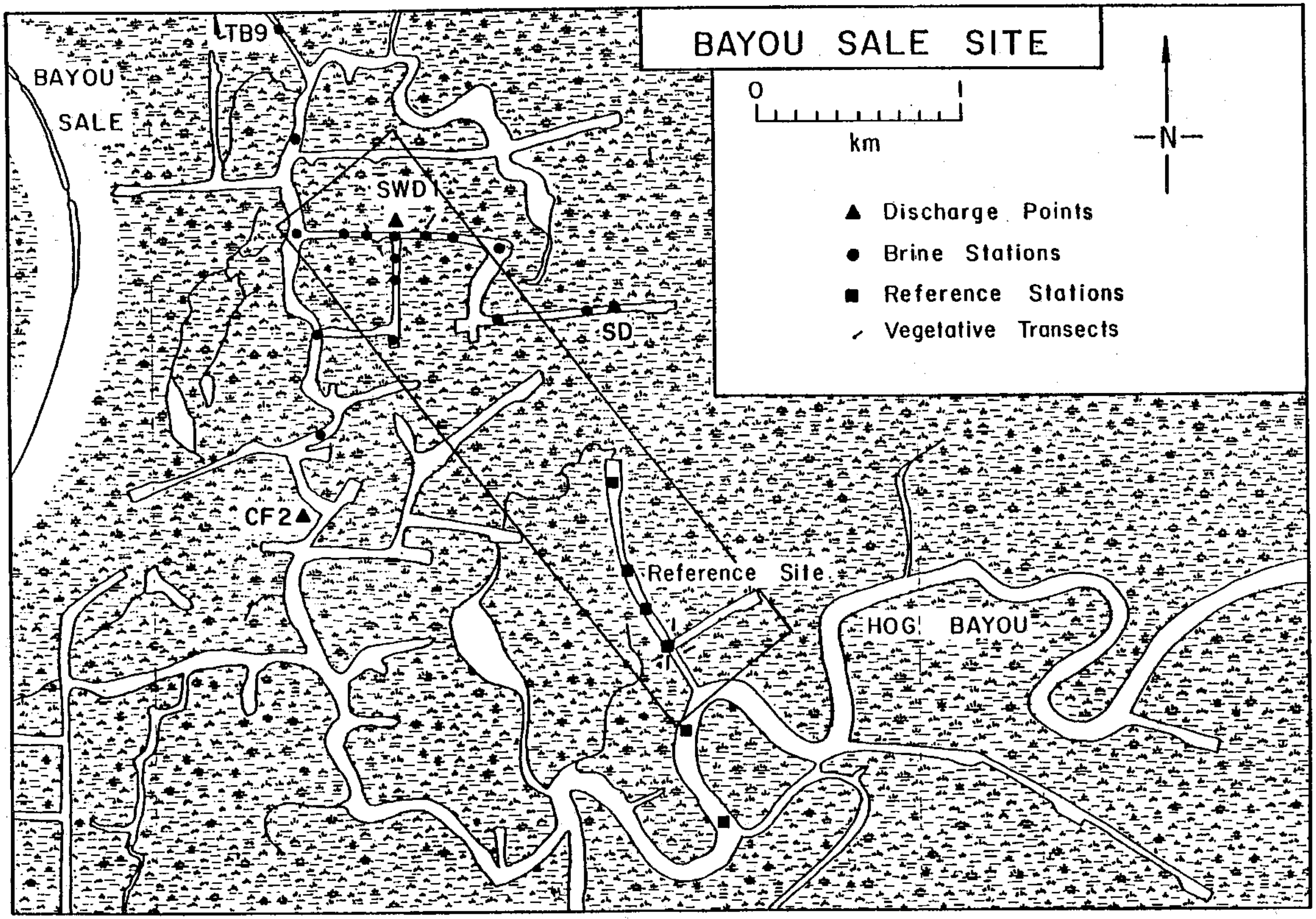


Figure 1.3. Bayou Sale study area. Rectangular area for remote sensing indicated.

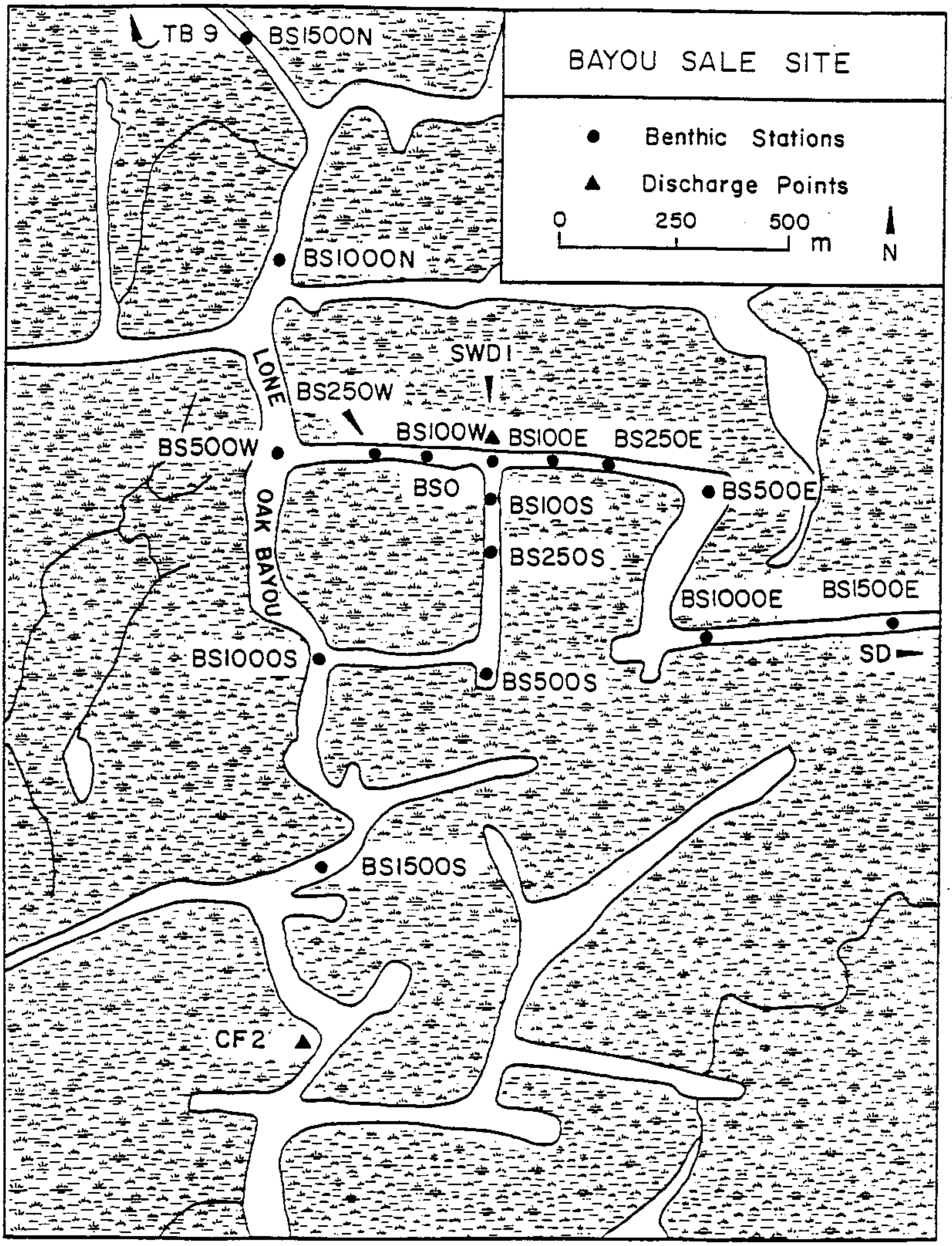


Figure 1.4. Location of stations around Bayou Sale SWD1 discharge site.

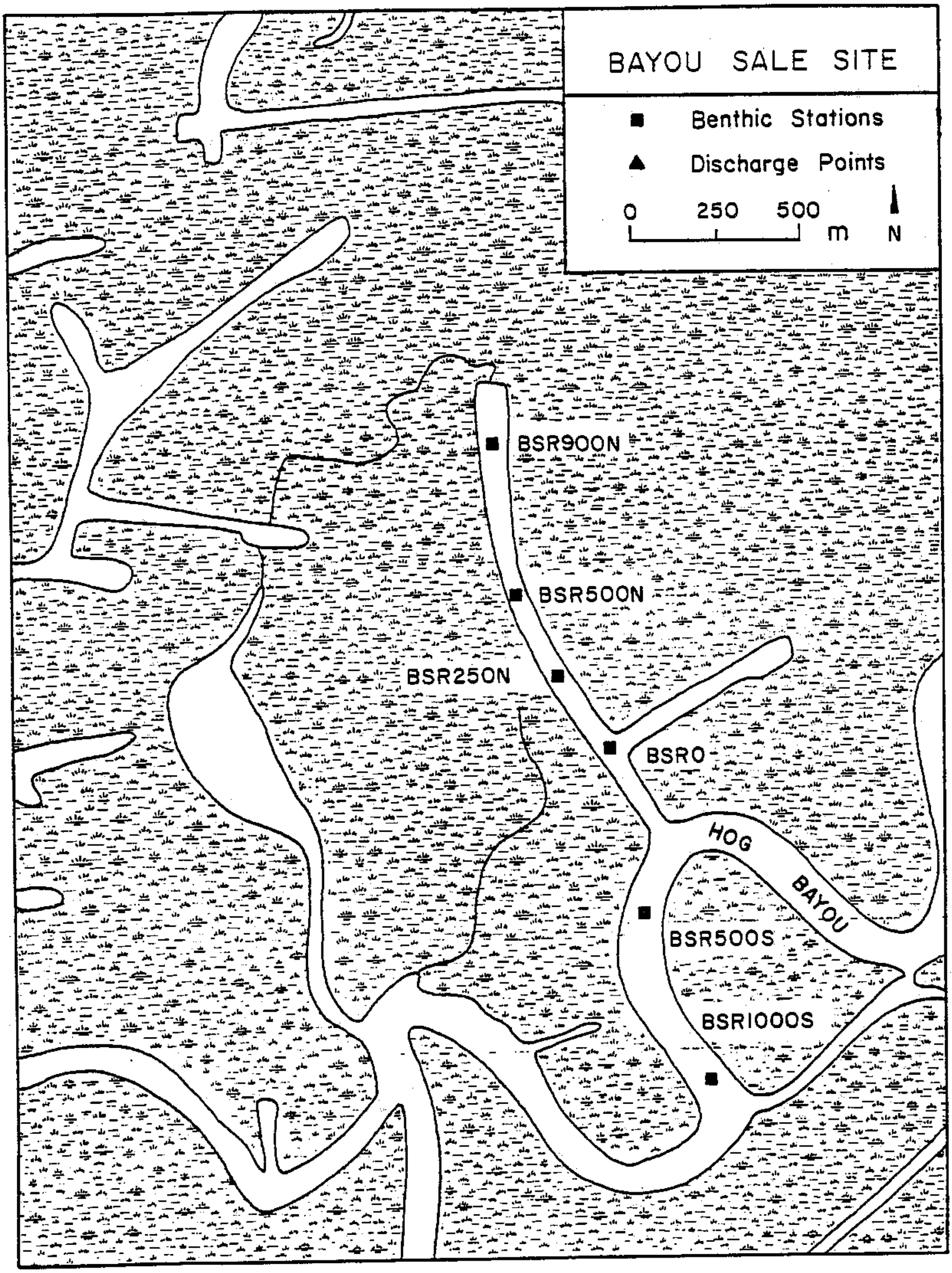


Figure 1.5. Location of reference stations for Bayou Sale site.

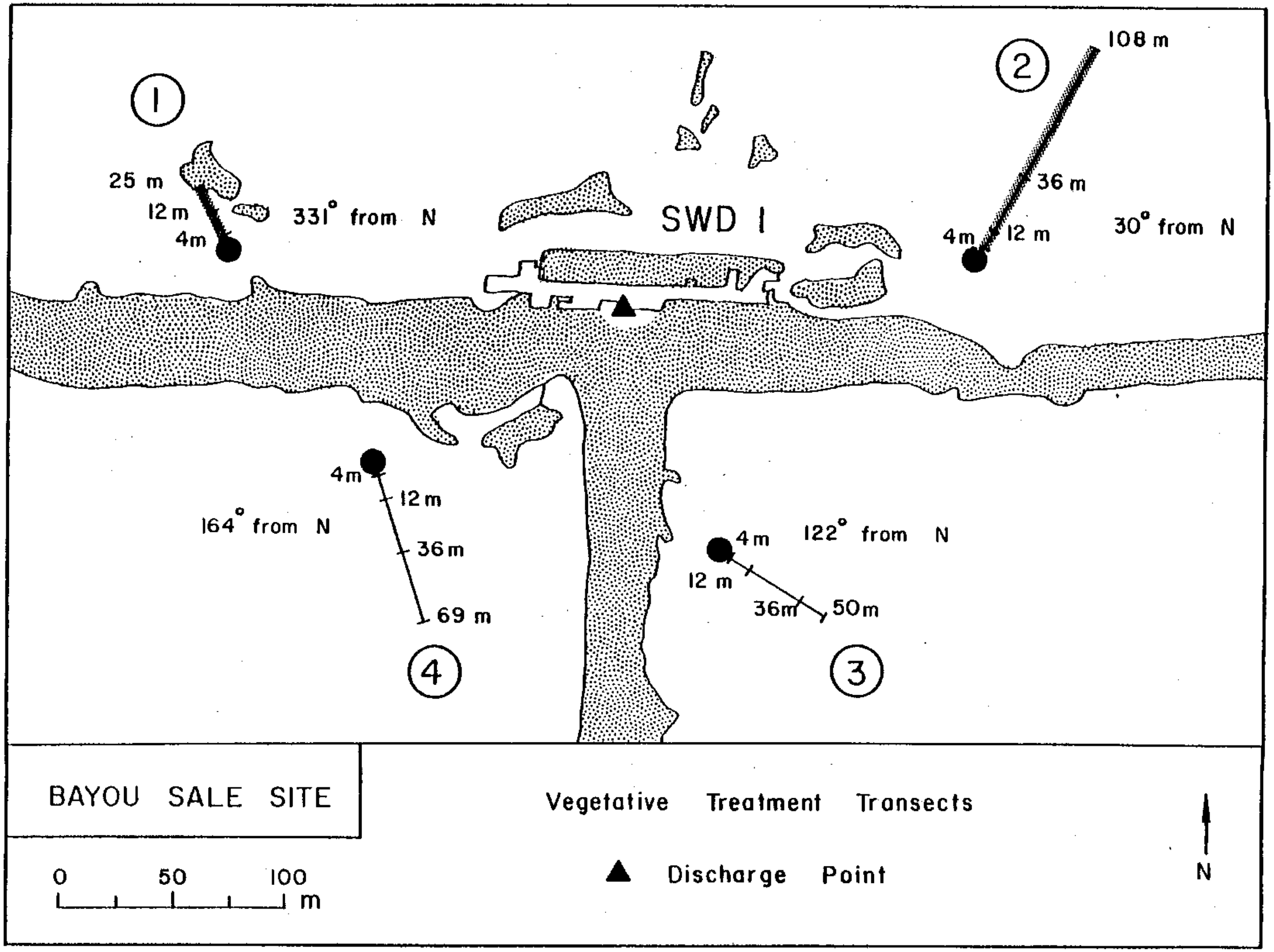


Figure 1.6. Location of vegetation transects as the Bayou Sale SWDI discharge site.

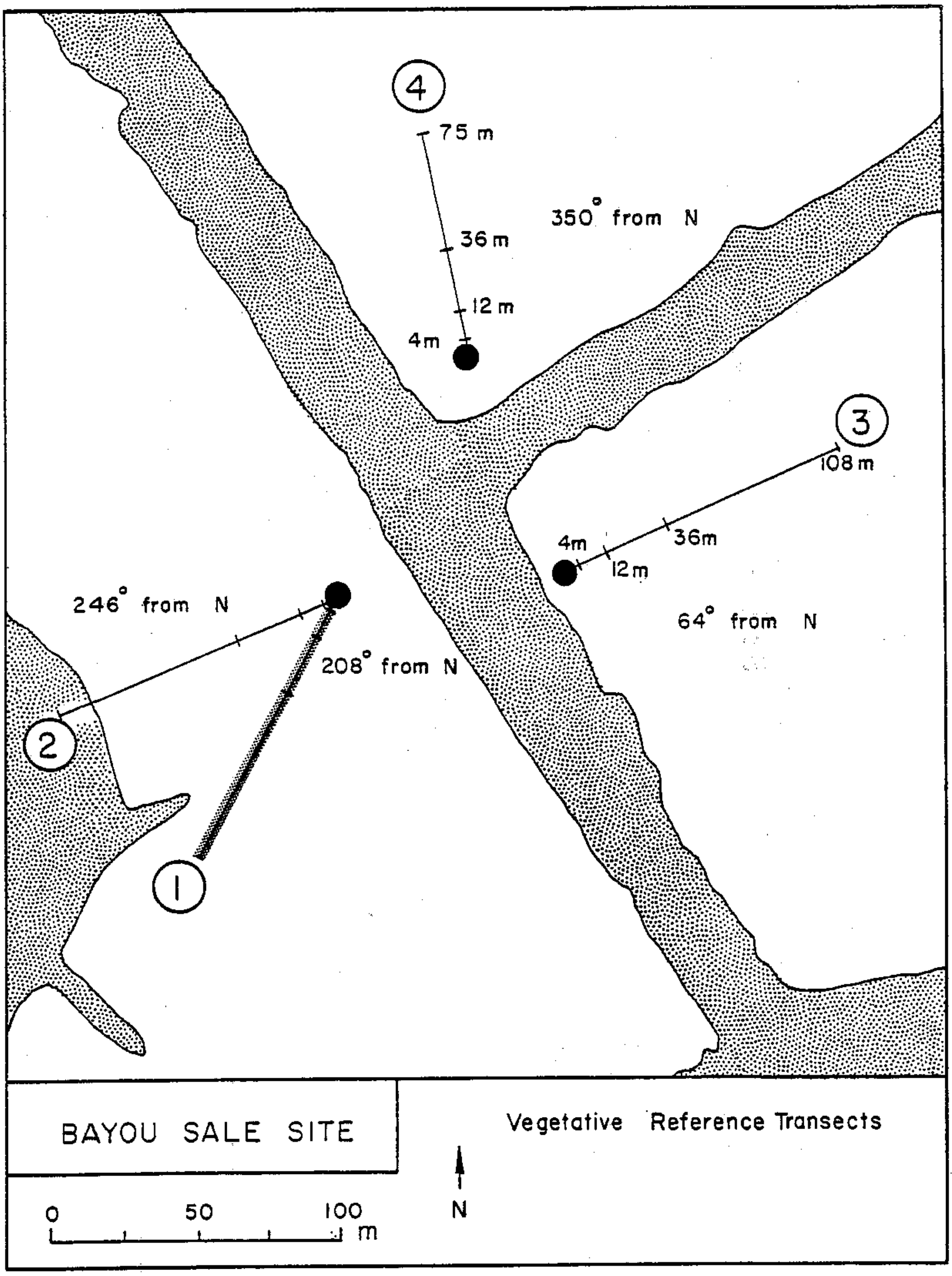


Figure 1.7. Location of vegetation transects for Bayou Sale reference area.

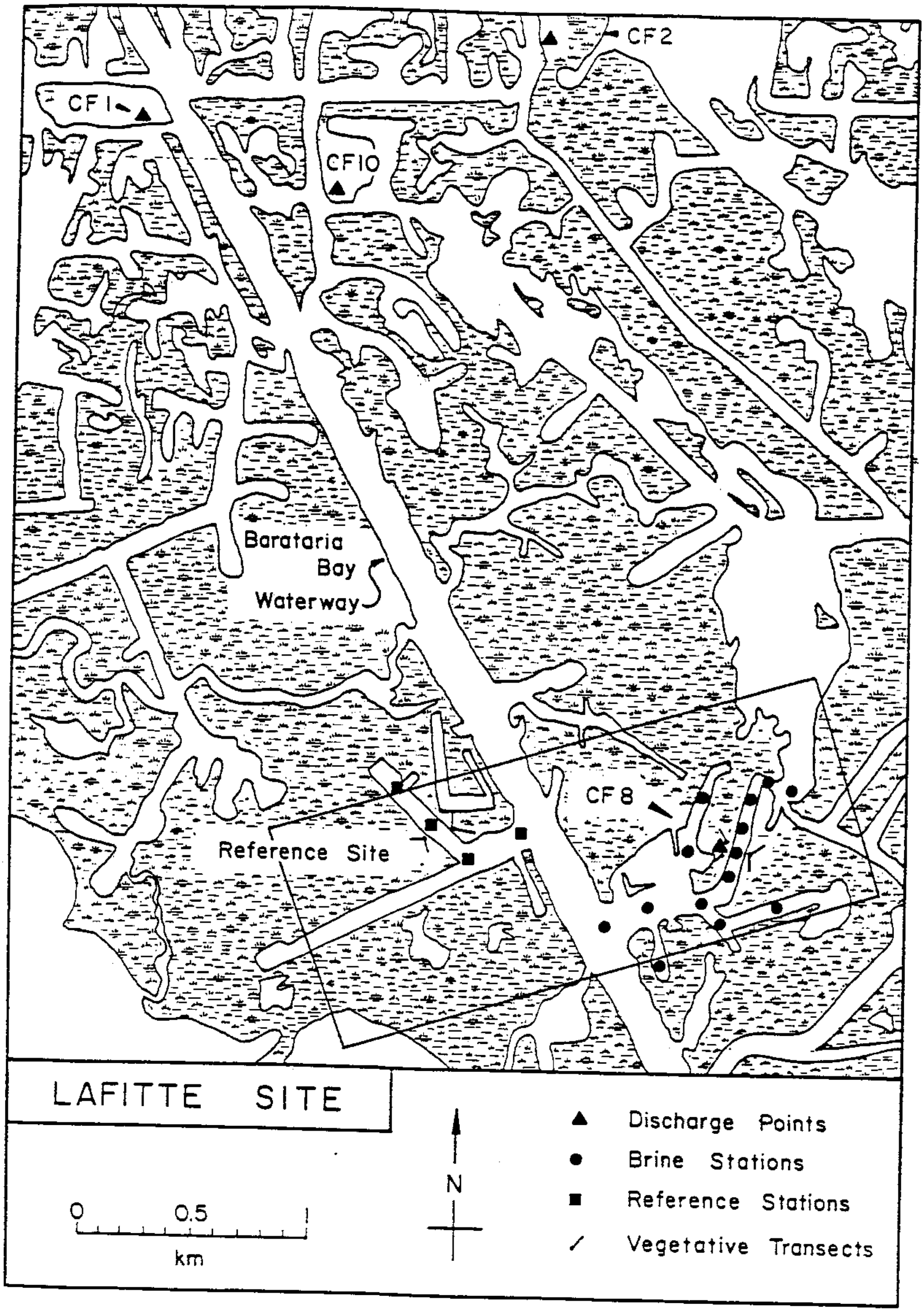


Figure 1.8. Lafitte study area. Rectangular area for remote sensing indicated.

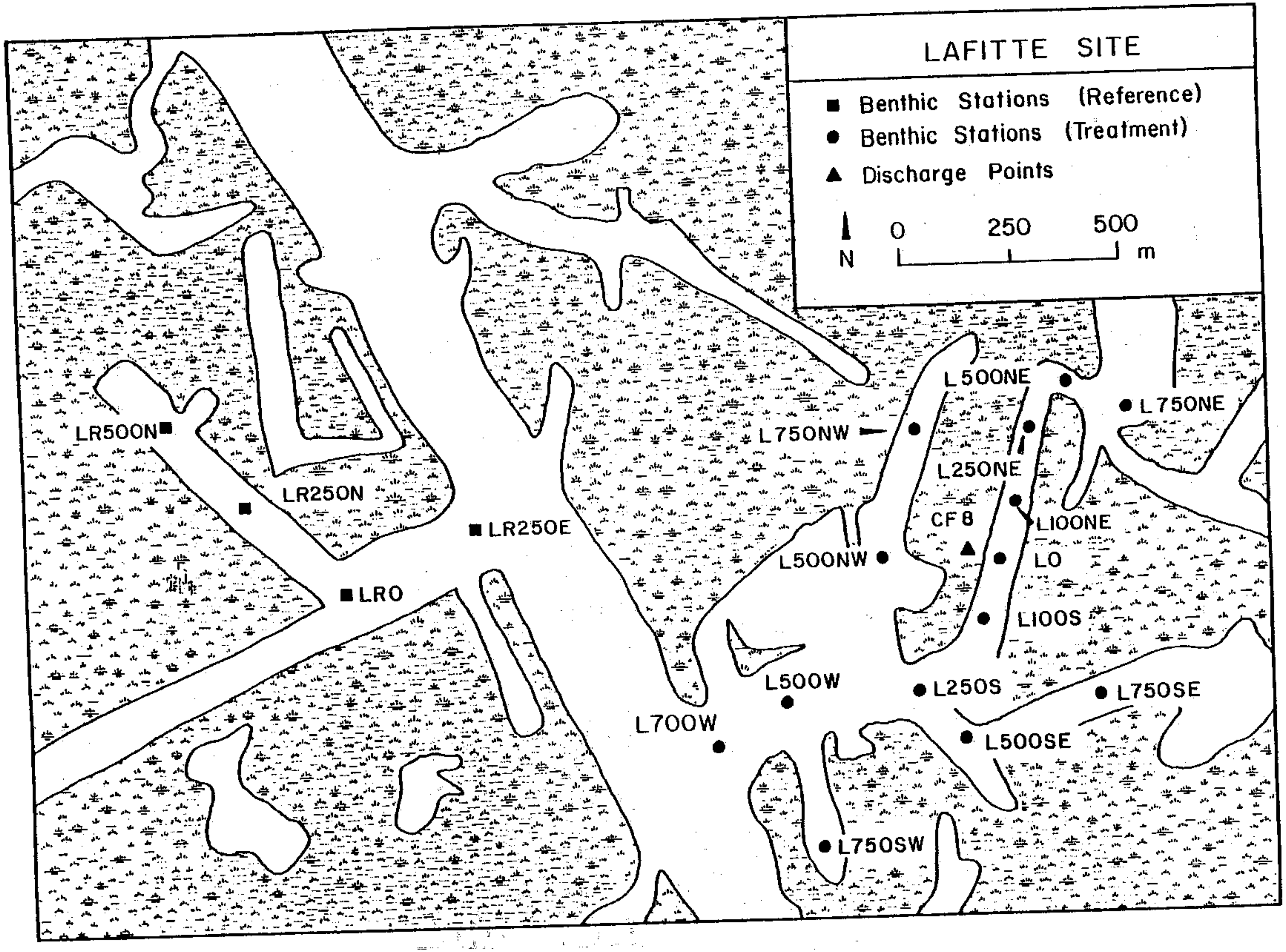


Figure 1.9. Location of stations around Lafitte CF8 discharge site and reference area.

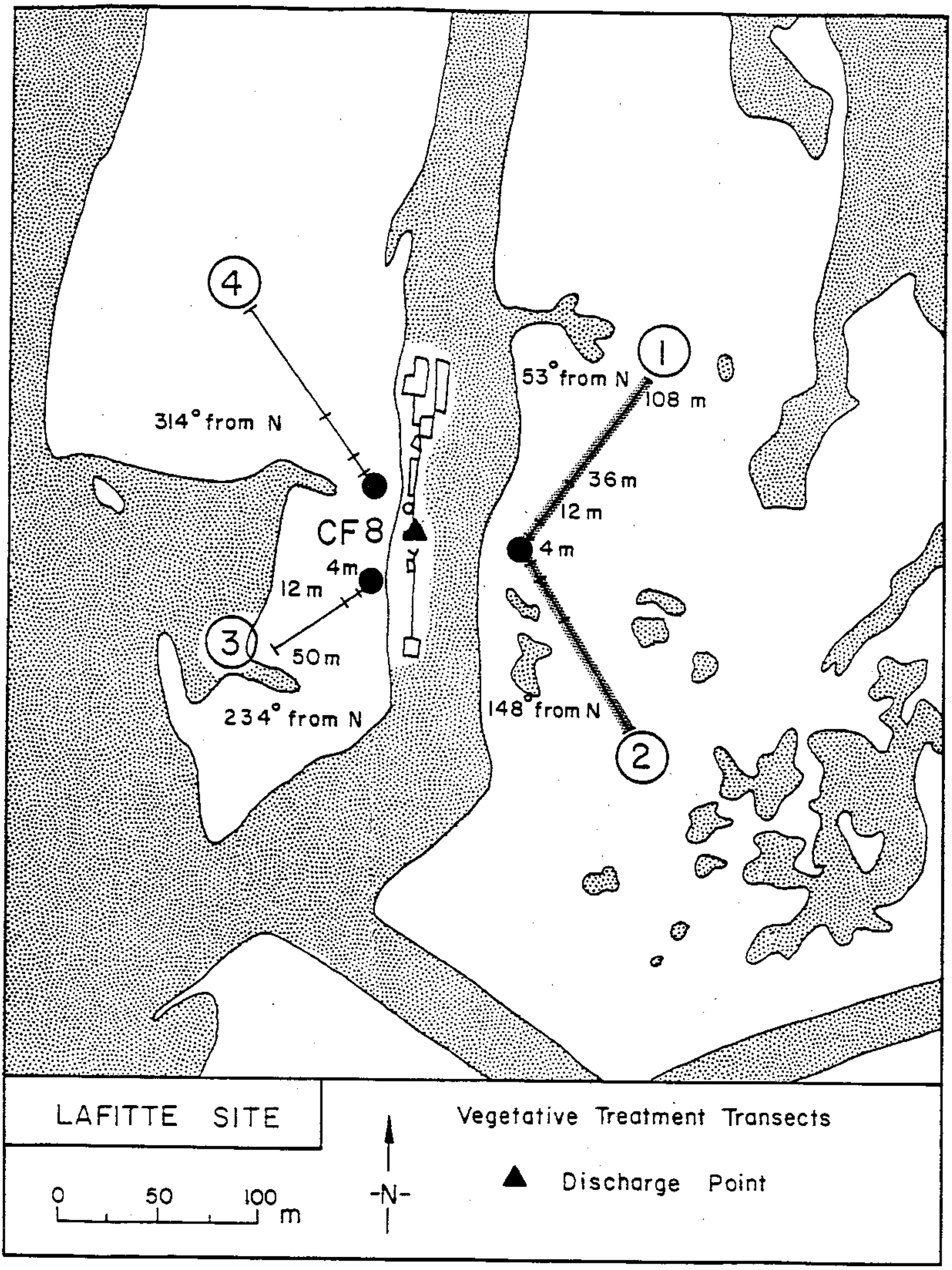


Figure 1.10. Location of vegetation transects for Lafitte CF8 discharge site.

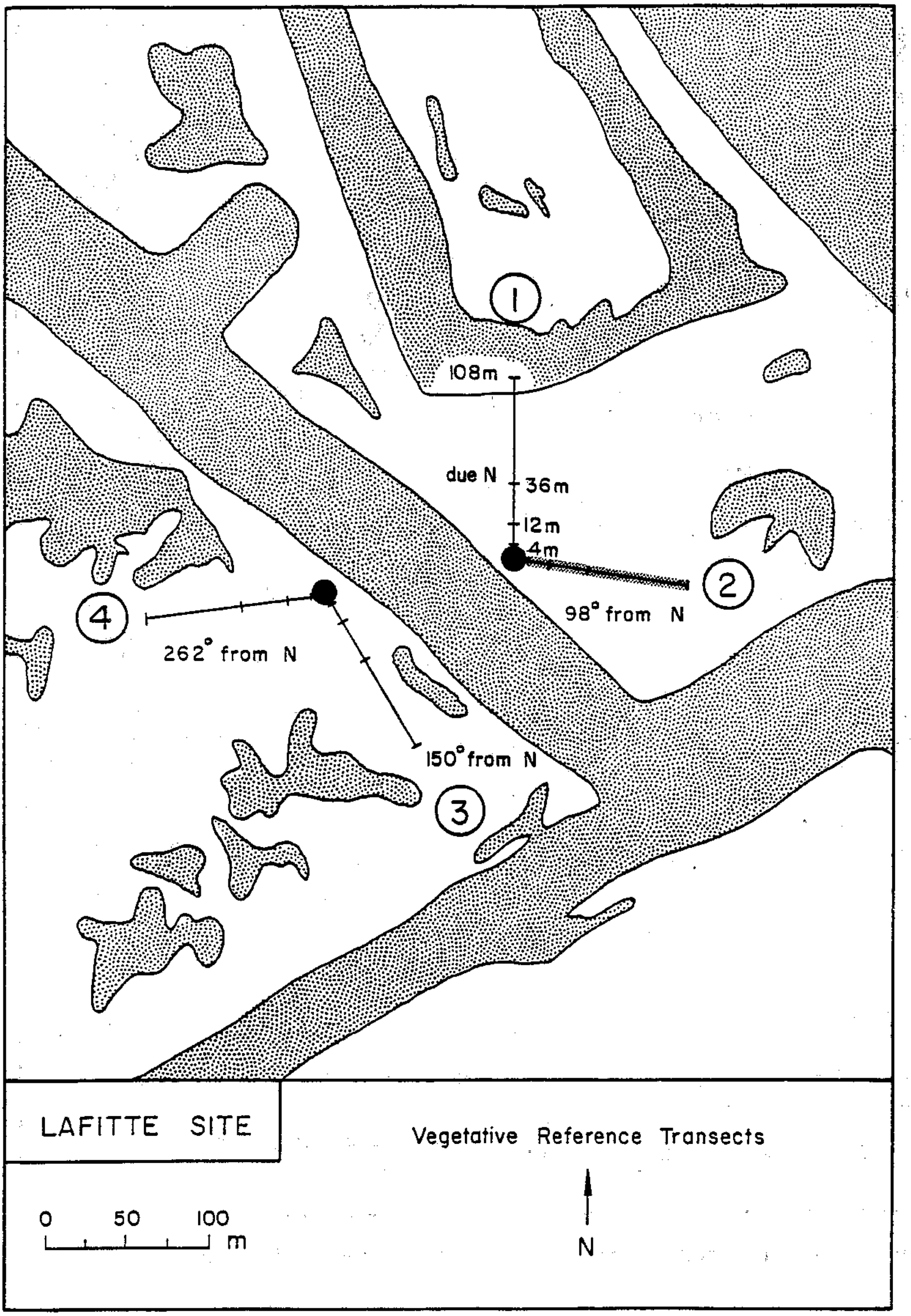


Figure 1.11. Location of vegetation transects for Lafitte reference area.

The Texaco CF8 facility was installed and discharge started in 1962. It has been in continuous operation since then. Average daily discharge in September 1988 was 3,676 bbl/d with an oil and grease concentration of 17 mg/l. Over the last two years, daily discharge rates have averaged 2,299 bbl/d with a steady increase in discharge from early 1987 to late 1988. Oil and grease concentration of the produced water discharge over the last two years has averaged 31 mg/l. No historic data were available from the operator on salinity or chloride levels for this discharge.

1.3.3 Golden Meadow Site

The Golden Meadow study area is located in a tidally influenced brackish marsh; the boundary between brackish and saline marshes (Wicker, 1980) lies just to the south of the study area. The area lies to the southwest of Catfish Lake and to the west of Grand Bayou Blue. The discharge points of interest are located on canals. The station grids are located on canals which intersect some natural water areas (Figure 1.12).

The produced water discharge points which are the foci of our studies are the Texaco Tank Battery #8 (TB8) to the south (primary site) (Figure 1.13) and Tank Battery #7 (TB7) to the north (secondary site) (Figure 1.14). Another facility (Texaco's Tank Battery #12) is located 1.1 km to the northwest of the station grid around TB7. The reference stations are located along a canal on the eastern edge of the study area between TB8 and TB7 (Figures 1.12 and 1.14). The location of vegetation transects and the area delimited for remote sensing analysis are shown on Figure 1.12. Details of the vegetation transects are given in Figures 1.15 - 1.17.

The produced water separator at TB7 was installed and discharge initiated in 1956 with no known cessation of operation since then. The average discharge during August and September 1988 was 2,845 bbl/d with an oil and grease content of 20 mg/l. Over the last two years, discharge rates have averaged 3,808 bbl/d, ranging from 2,800 to 5,100 bbl/d with an oil and grease content of 25 mg/l. TB8 was installed by Texaco and discharge initiated in 1962 with no known cessation of operation since then. The average discharge during August and September 1988 was 1,427 bbl/d with an oil and grease content of 23 mg/l. Over the last two years, discharge rates have averaged 1,408 bbl/d with an oil and grease content of 22 mg/l. TB12, to the northwest of the study area, was installed and discharge initiated in 1961. The average discharge rate over the last two years is 1,571 bbl/d with an oil and grease content of 27 mg/l. No historic data were available from the operator on salinity or chloride levels for any of the Golden Meadow study area discharges.

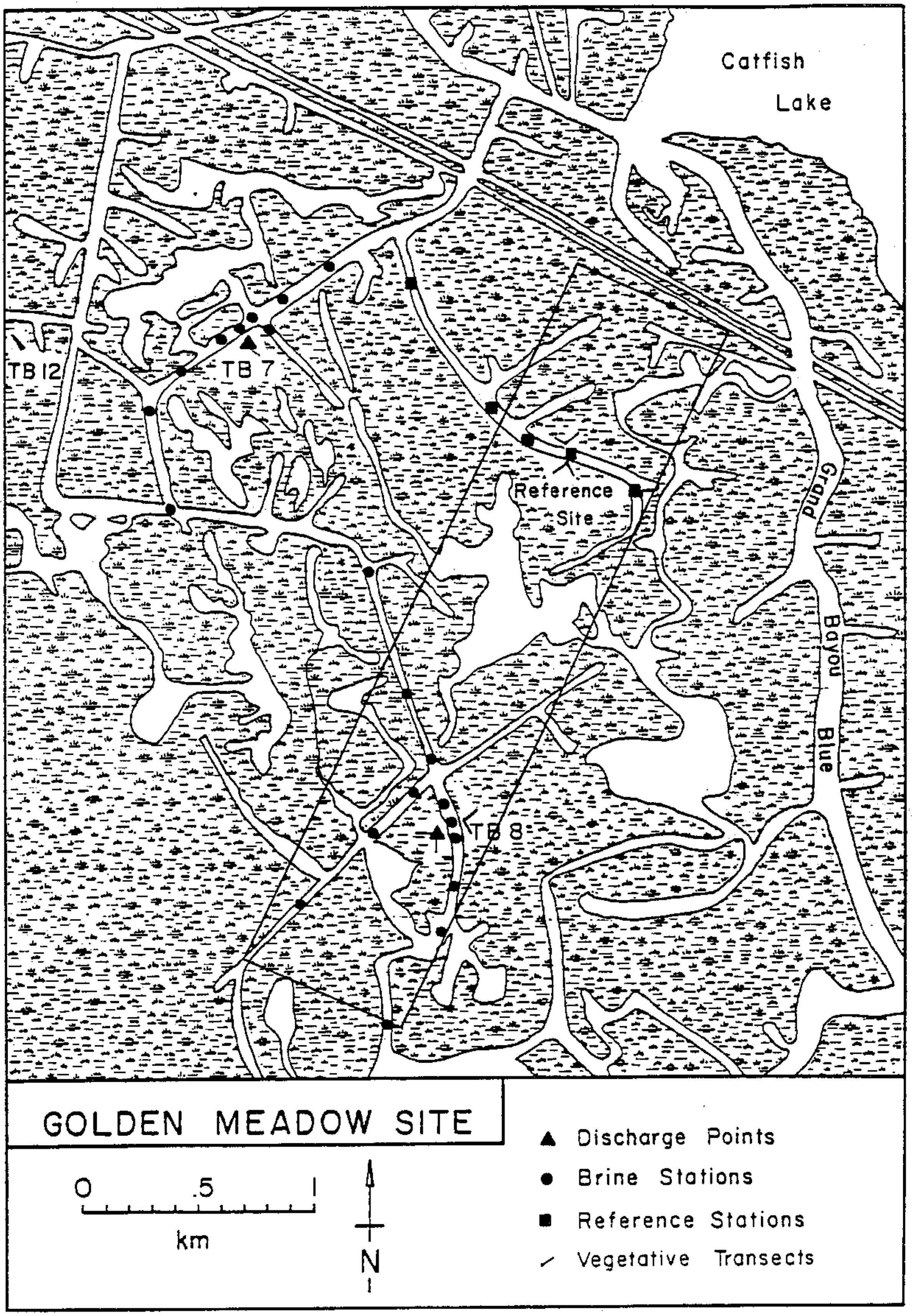


Figure 1.12. Golden Meadow study area. Rectangular area for remote sensing indicated.

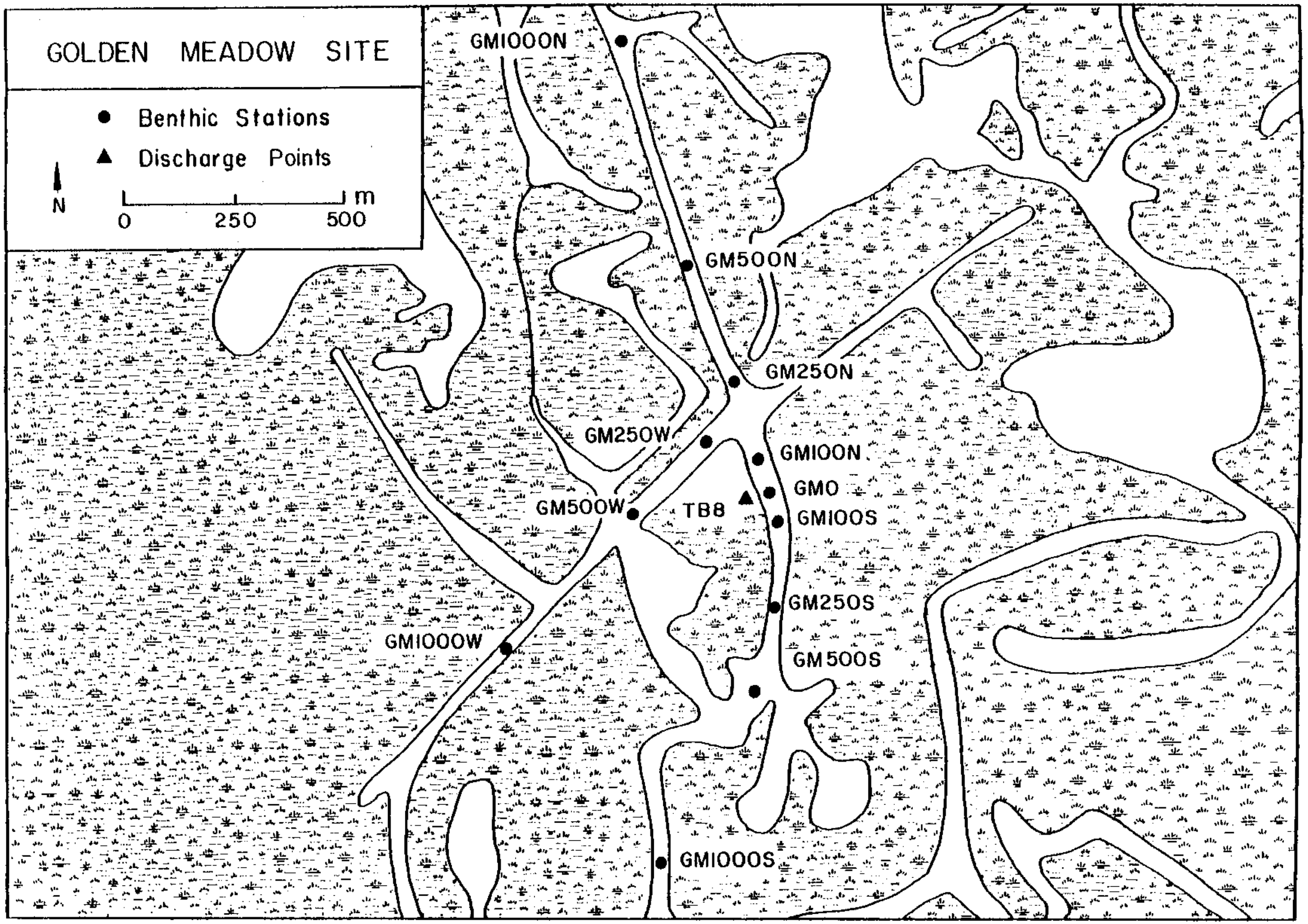


Figure 1.13. Location of stations around Golden Meadow TB8 primary discharge site.

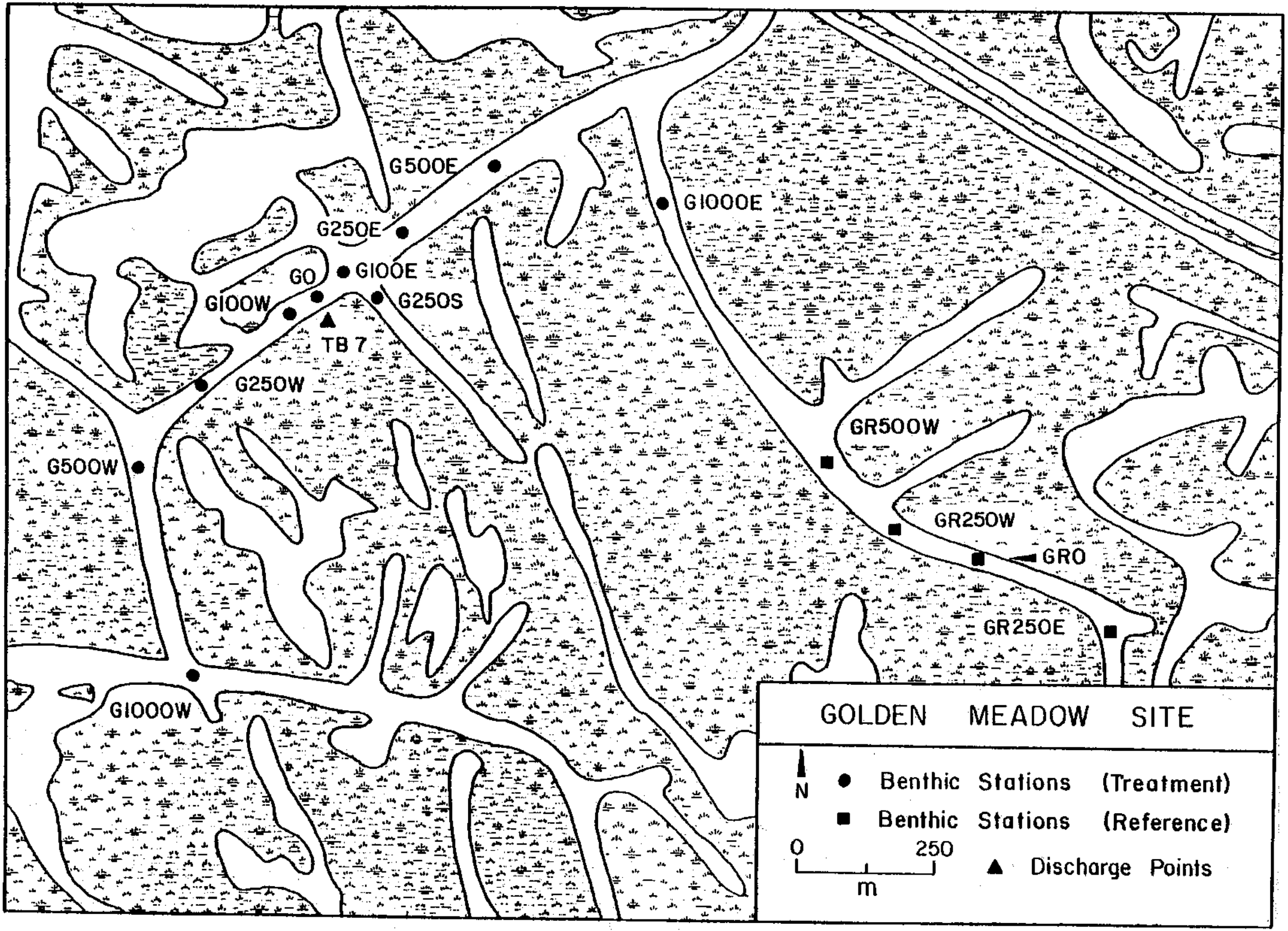


Figure 1.14. Location of stations around Golden Meadow TB7 secondary discharge site and at reference area.

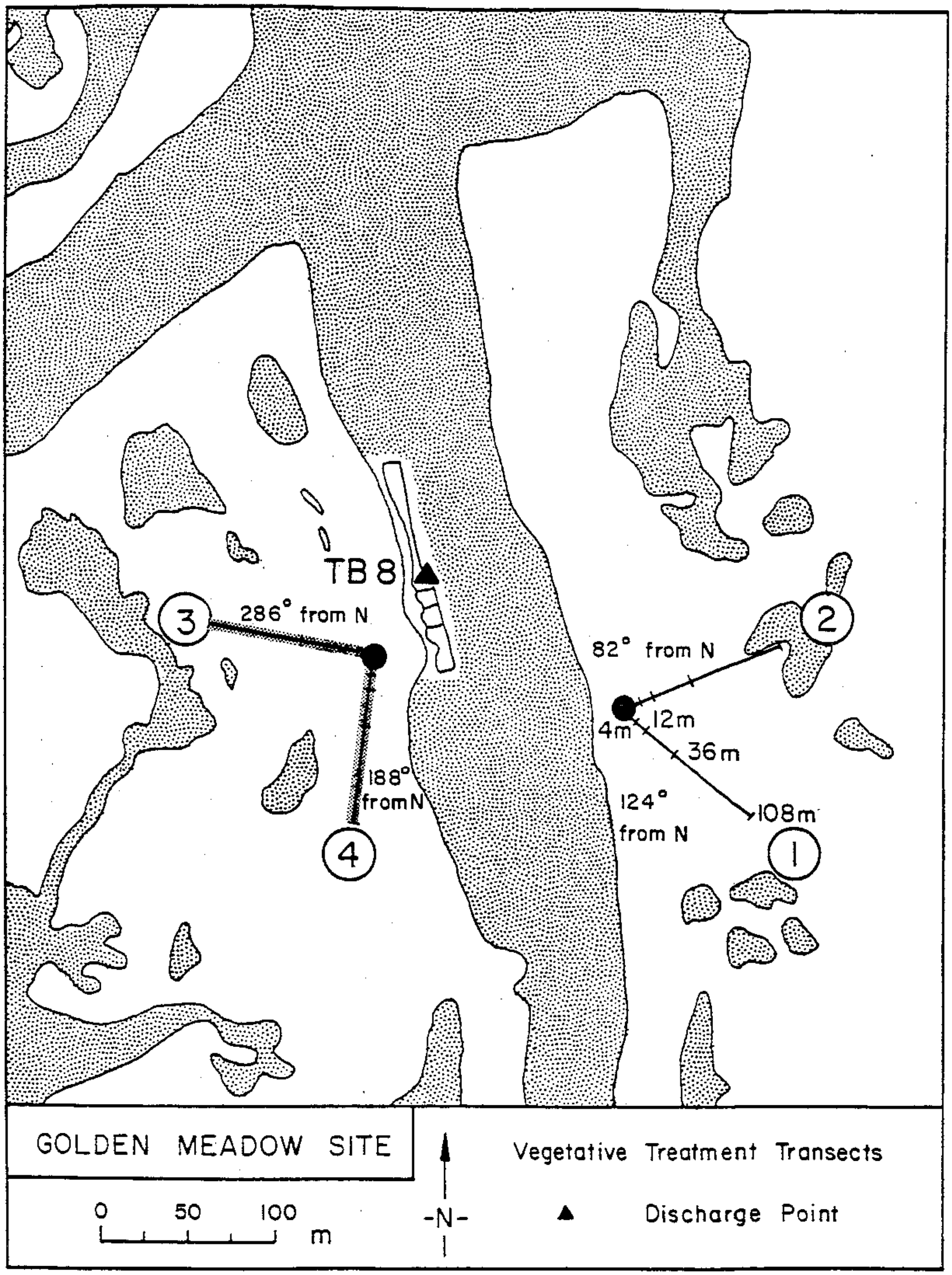


Figure 1.15. Location of vegetation transects for Golden Meadow TB8 primary discharge site.

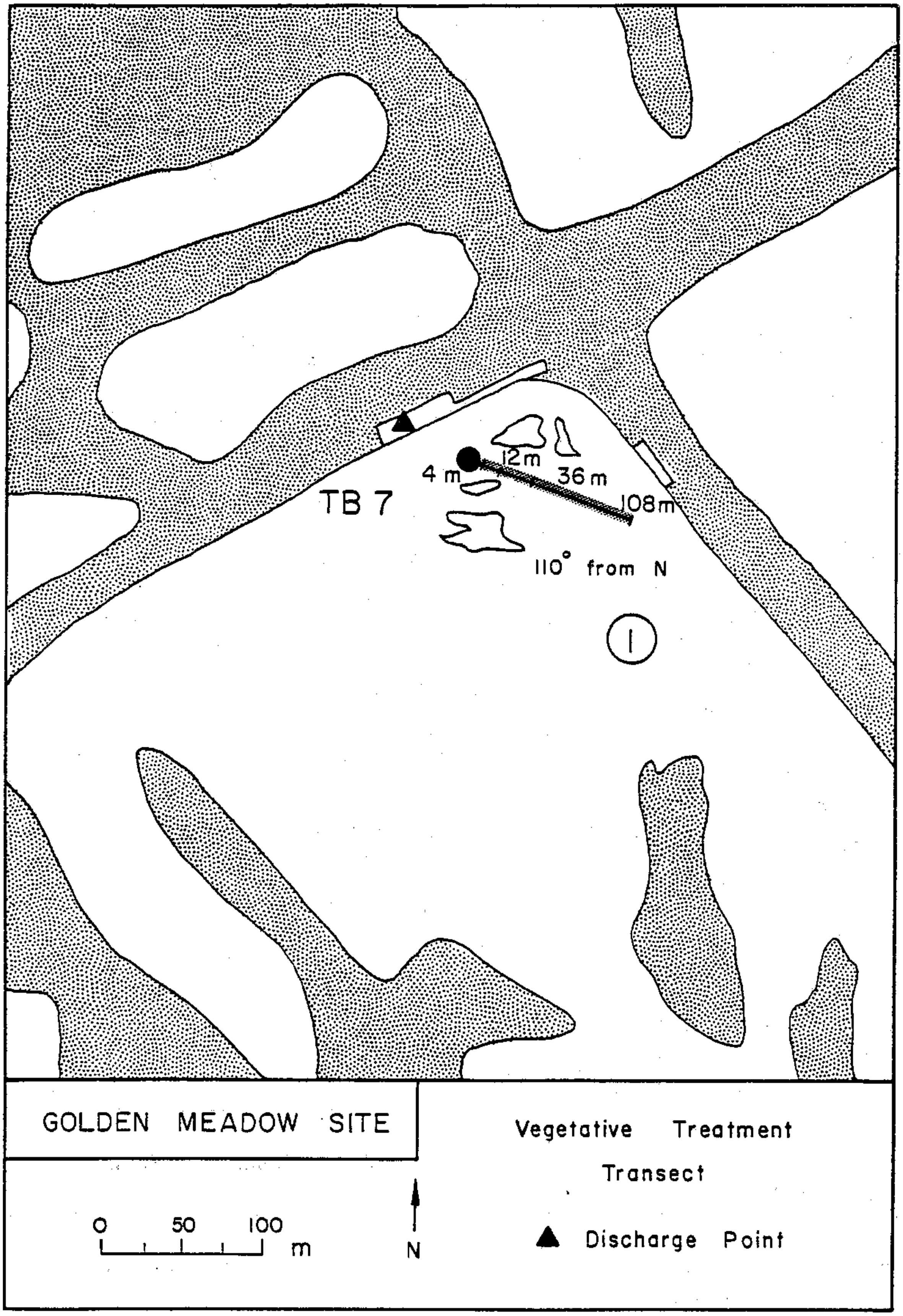


Figure 1.16. Location of vegetation transects for Golden Meadow TB7 secondary discharge site.

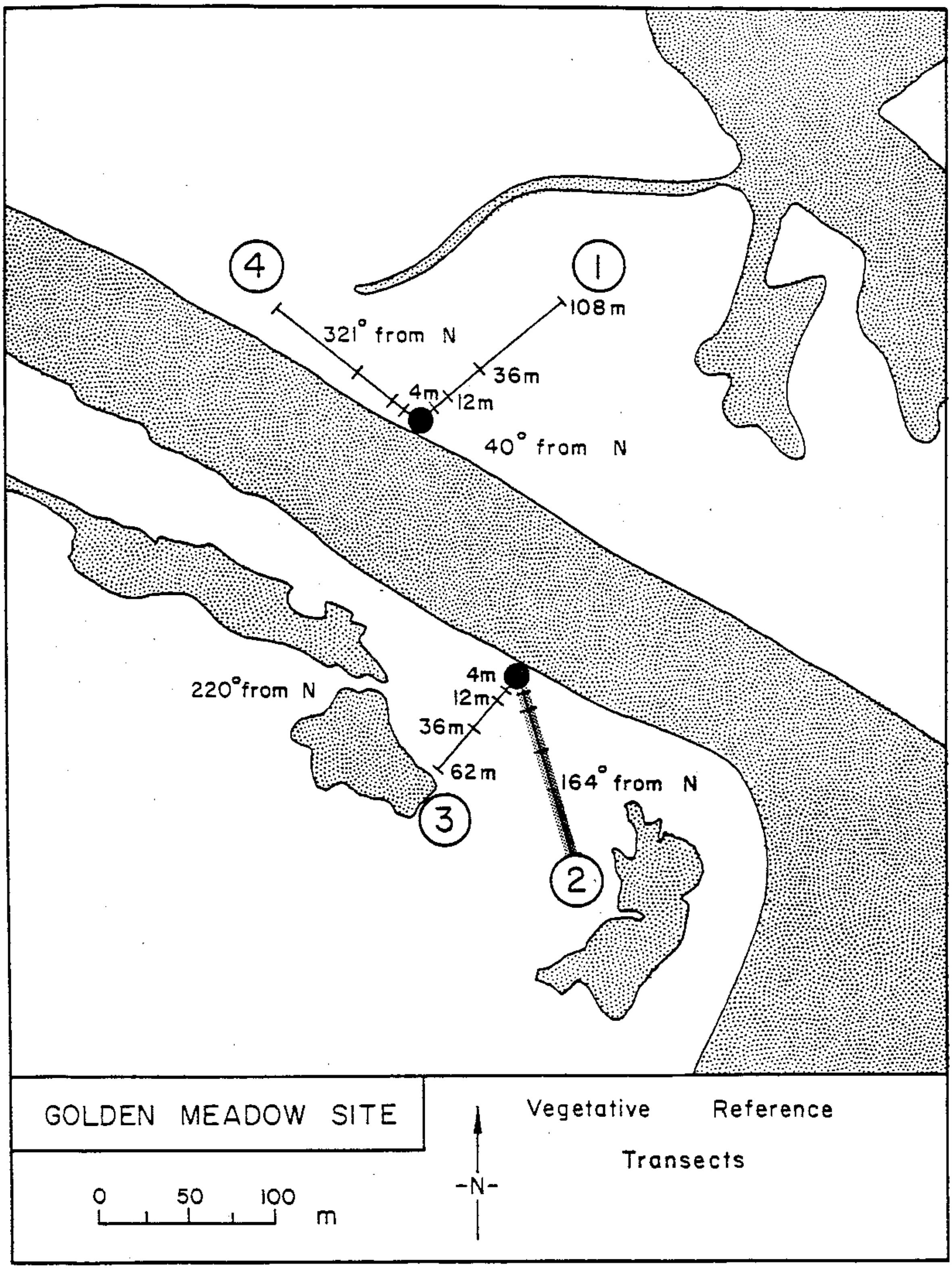


Figure 1.17. Location of vegetation transects for Golden Meadow reference area.

Chapter 2

MODELLING THE EFFECTS OF PRODUCED WATER DISCHARGES ON ESTUARINE SALINITY

by

Wm. J. Wiseman, Jr. and E. M. Swenson

2.1 Introduction

The purpose of this project component was to evaluate the degree to which extensive and voluminous discharges of produced waters in to Louisiana's estuaries could elevate salinity levels in the estuaries. Increasing salinity is widely cited in the popular press and news media as a factor contributing to the loss of coastal wetlands in Louisiana. Although generalization of a rising estuarine salinity cannot be made (Wiseman and Swenson, 1988), wetland deterioration, channelization and increased tidal exchange are thought to be the primary factors which could result in increased estuarine salinity. Produced waters from coastal Louisiana have a salinity of up to 4 times that of ocean water, and much higher than that of the estuarine receiving waters. Concern has been voiced that the large volumes of produced water discharged could also be responsible for increased estuarine salinity within large areas of an estuary.

We have approached this problem by compiling data on salinity patterns and variability and by evaluation of the potential that salt emissions from produced water could significantly alter salinity by application of simple tidal prism models. The physical hydrography of Louisiana's estuaries is complex and poorly known. Well calibrated models such as those which exist for many coastal plain estuaries are not available. Consequently, the modelling performed in this study should be considered as providing first order estimates only.

Two estuarine basins were investigated, Barataria Basin and Terrebonne-Timbalier Basin. These estuarine systems were selected because of the extensive produced water discharges they receive and because they included two of the three sites studied by other project components. Boesch and Rabalais (1989) estimated that 363,054 and 173,656 barrels per day of produced waters are discharged into the Barataria and Terrebonne basins, respectively. The volume, quality and coverage of available salinity and hydrological data from the two basins were extremely different. Furthermore, the morphology of the two systems presented additional problems. In the following sections, we will discuss the availability of data from the systems and statistics derived from the available data; compare observed salinities with estimates of the salinity input from produced waters; discuss the construction and results of tidal prism models; and finally present a discussion and interpretation of the results.

2.2 Data Used

2.2.1 Estuarine Salinity

Two types of salinity data were available. Long time series of salinity from stations maintained by the U. S. Army Corps of Engineers and the Louisiana Department of Wildlife and Fisheries were used to characterize the temporal variability of the salinity field at given stations within the two basins. The data quality and sampling techniques have been described elsewhere (Wiseman and Swenson, 1987). The best data were provided by hourly readings from the Louisiana Department of Wildlife and Fisheries gauges. Short, unbroken records were used to determine the high-frequency characteristics of the variance distribution. Further, whenever more than 75% of the data for a given day was present, these data were averaged to provide estimates of the daily mean salinity. For the sake of this study, these were assumed to be comparable with the daily samples acquired by the U. S. Army Corps of Engineers at their sampling sites.

Quasi-synoptic surveys of the two basins provided shorter time series of salinity (Barrett, 1971; Seaton, 1979; Eggler et al., 1961). The areal coverage, though, was sufficient to allow characterization of the spatial variability of the salinity field.

It should be noted that these data sets were collected after discharge of produced waters had begun within the two basins studied. Therefore, if there were any increase in salinity due to the discharge of produced waters, it is already present in the data set.

2.2.2 Tides

Tidal characterizations were determined from short (6-weeks to 2-months duration), continuous water level records of opportunity. These records were band-pass filtered to remove both high- and low-frequency variations (Figure 2.1). The filter had sharp cutoffs at 30 and 10 hours. The standard deviation of the resultant signal was used as an estimate of the mean tidal amplitude at the stations. National Ocean Service (NOS) characterizations of the mean diurnal tidal range were also used when available.

2.2.3 Freshwater Inputs

Runoff estimates were available from two sources, Muller (1975) and Butler (1975). Muller suggests that the total runoff to the Barataria Basin averages 12 x 10^6 m^3 per tidal cycle. Butler presents discharge records from Des Allemands that suggest that the annual mean discharge at this site is approximately 2 x $10^6 m^3$ per tidal cycle. Assuming that this discharge rate is due totally to local rainfall, this number can be prorated to give approximately half Muller's estimate for the runoff to the total basin. We chose to use the smaller of the two values in the subsequent modelling exercises. No adequate estimates of runoff to the Terrebonne-Timbalier estuary were available. We estimated the runoff by assuming that rainfall over the Terrebonne-Timbalier basin is similar to that over the Barataria Basin. We also allowed this rainfall to be significantly redistributed by the well-developed canal systems within the basin. All rainfall between Bayou Terrebonne, Bayou Lafourche and Bayou Blue was assumed to enter Bayou Terrebonne and Bayou Petit Caillou and subsequently to drain into Terrebonne Bay. Thus, river discharge has a significant effect where these two bayous connect with the main bay.

2.2.4 Produced Water Emissions

Boesch and Rabalais (1989) assembled data reported on produced water discharge permit applications submitted to the Louisiana Department of Environmental Quality. These data files were provided by LUMCON and included the discharge location, volumes and chlorinities. It is not clear whether the associated volumes and chlorinities reported on the permit applications are maxima, in which case all estimates of the impact of discharge would be conservative, or typical. Furthermore, certain values of chlorinity in the tables appear to be given in parts per million rather than parts per thousand. When such anomalies occurred, we took the liberal approach of correcting the salinities downward to the more realistic values.

2.3 Salinity Statistics

Salinity statistics, estimated from the longest time series available in the two basins, are presented in Table 2.1. The longest records demonstrate the presence of a significant longitudinal salinity gradient within Barataria Bay. Mean salinity at Grand Terre was 20.90 ppt, whereas it reached only 12.90 ppt at St. Mary's Point. The standard deviations obtained from the daily means at the two stations, though, are very similar (5.71 and 6.36 ppt, respectively).

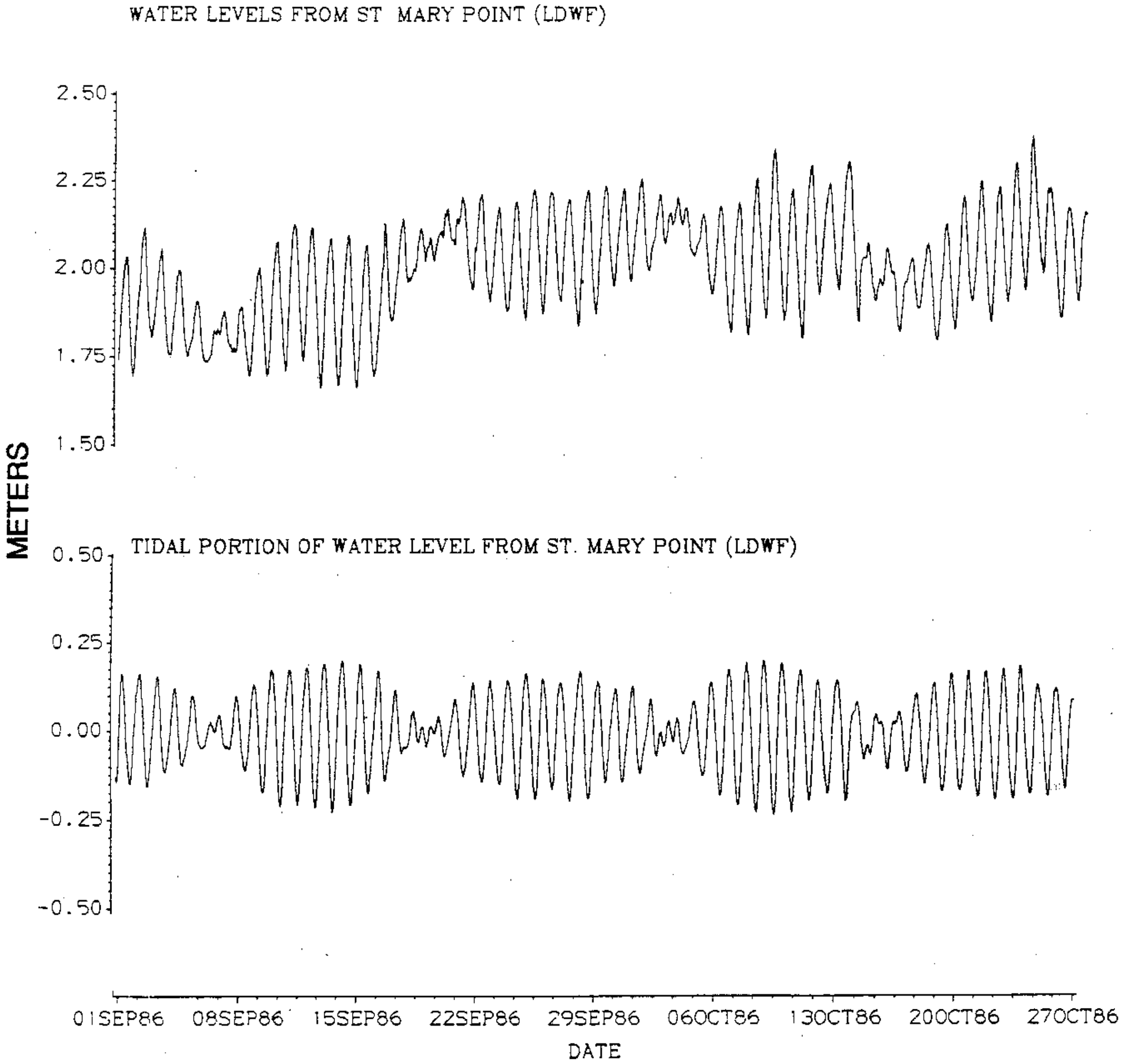


Figure 2.1. Time series of measured (top) and tidal portion (bottom) of hourly water level data from St. Mary's Point, from September 1, 1986 through October 27, 1986. The values are in meters relative to an arbitrary base level. Data was collected by the Louisiana Department of Wildlife and Fisheries.

Table 2.1. Statistical summary of long term salinity data sets from coastal Louisiana. Indicated are the station location, the time period of the record, the number of data points in the record, the mean salinity (PPT) and the standard deviation of the mean. These statistics are based on weekly means. Data is from the U. S. Army Corps of Engineers (COE) and the Louisiana Department of Wildlife and Fisheries (LDWF).

Station location	Agency	Dates covered by record	Number of data points	Mean salinity	Standard deviation
Cocodrie	LDWF	1967-1986	3370	9.44	5.49
Caillou Lake	LDWF	1967-1986	2763	10.76	5.14
Dulac	COE	1950-1982	11117	1.20	2.79
Bourg	COE	1963-1982	5854	0.62	1.60
Leeville	COE	1955-1978	7621	15.47	5.45
Galliano	COE	1962-1981	6527	1.72	3.17
Larose	COE	1950-1982	7951	0.56	1.19
Bayou Faleau	COE	1961-1973	235	10.04	5.33
Grand Terre	LDWF	1961-1987	7664	20.90	5.71
St. Mary's Point	LDWF	1973-1987	2984	12.90	6.36
Barataria	COE	1957-1973	380	2.19	1.75
Bay Lizette	COE	1962-1971	244	19.36	4.18
Barataria Waterway (mile 7.8)	COE	1962-1971	207	16.77	4.98
Barataria Waterway (mile 15)	COE	1962-1971	166	9.58	5.36
Barataria Waterway (mile ~mile 26)	COE	1962-1971	303	5.25	1.75

Table 2.2. Saliniy of various segments for the Barataria Basin System. Indicated are the basin section (see Figure 2.8) along with the mean salinity plus the standard deviation of that mean salinity, from three different data bases. The LDWF data is from unpublished weekly salinity samples collected by the Louisiana Department of Wildlife and Fisheries. The symbol nd indicates that there was no data for that segment.

SUB BASIN	SEGMENT	MAJOR WATER BODY	BARRETT, 1971	SEATON, 1976	LDWF, 1981-1988
NORTH	A	LAC DES ALLEMANDS	nd	0.0	nd
NORTH	B	BAYOU DES ALLEMANDS	nd	1.14±1.57	nd
NORTH	C	LAKE CATAOUATCHE	nd	0.57±1.13	nd
NORTH	C	BAYOU COUBA	nd	0.57±1.13	nd
NORTH	C	BAYOU BARDEAUX	nd	0.57±1.13	nd
NORTH	D	LAKE SALVADOR	nd	2.43±2.44	nd
MIDDLE	E	DELTA FARMS	nd	nd	nd
MIDDLE	F	BAYOU PEROT	nd	4.43±3.59	nd
MIDDLE	G	BAYOU RIGOLETTES	nd	3.21±3.46	nd
MIDDLE	H	LITTLE LAKE	nd	6.14±5.27	nd
MIDDLE	H	TURTLE BAY	nd	6.14±5.27	nd
MIDDLE	H	ROUND LAKE	nd	6.14±5.27	nd
MIDDLE	H	BAY L'OURS	nd	6.14±5.27	nd
MIDDLE	I	GRAND BAYOU CHANNEL	nd	nd	8.54±5.91
MIDDLE	I	GRAND BAYOU SHOALS	nd	nd	8.54±5.91
MIDDLE	J	MUD LAKE CHANNEL	nd	nd	nd
MIDDLE	J	MUD LAKE SHOALS	nd	nd	nd
MIDDLE	K	WILKINSON BAY	nd	nd	nd
SOUTH	L	GRAND BAYOU CHANNEL	9.92±5.16	nd	11.18±6.41
SOUTH	L	GRAND BAYOU SHOALS	9.92±5.15	nd	11.18±6.41
SOUTH	M	ST. MARY'S POINT	13.52±3.95	13.50±7.84	14.57±5.76
SOUTH	N	BAY BATISTE	15.02±3.03	nd	15.68±4.07
SOUTH	O	HACKBERRY BAY	nd	nd	11.66±5.77
SOUTH	P	CRANE ISLAND	nd	nd	17.37±3.90
SOUTH	Q	BAY RAMBO	nd	nd	nd
SOUTH	R	WEST CHAMPAGNE BAY	13.30±4.46	nd	14.26±6.15
SOUTH	S	PELICAN POINT	nd	nd	18.56±5.11
SOUTH	T	MID REEF	20.24±3.53	16.85±8.78	19.65±5.64
SOUTH	U	CAT BAY	18.33±3.36	nd	20.41±5.34
SOUTH	V	BAY RONQUILLE	19.46±3.93	nd	nd
SOUTH	W	CAMINADA BAY	19.47±4.02	nd	nd
SOUTH	X	BARATARIA PASS	21.49±4.56	22.00±5.51	21.75±5.52
SOUTH	X	BAY MELVILLE	21.49±4.56	22.00±5.51	21.75±5.52

Table 2.3. Estimated salt content of the Barataria Bay system, by segments (Figure 2.8). The salinity used for each segment is the mean of the salinities from the three seperate data bases listed in Table 2.2. In cases where there was no data, the salinities were estimated from the salinities of the surrounding segments.

BASIN	SEGMENT	MAJOR WATER BODY	SALINITY (PPT)	SALT CONTENT (G)
NORTH	A	LAC DES ALLEMANDS	0.00	0.00
NORTH	B	BAYOU DES ALLEMANDS	1.14	0.98E+11
NORTH	C	LAKE CATAOUATCHE	0.57	0.42E+11
NORTH	C	BAYOU COUBA	0.57	0.04E+11
NORTH	C	BAYOU BARDEAUX	0.57	0.06E+11
NORTH	D	LAKE SALVADOR	2.43	11.70E+11
MIDDLE	E	DELTA FARMS	ND	
MIDDLE	F	BAYOU PEROT	4.43	2.13E+11
MIDDLE	G	BAYOU RIGOLETTES	3.21	0.78E+11
MIDDLE	H	LITTLE LAKE	6.14	7.55E+11
MIDDLE	H	TURTLE BAY	6.14	1.26E+11
MIDDLE	H	ROUND LAKE	6.14	0.21E+11
MIDDLE	H	BAY L'OURS	6.14	0.64E+11
MIDDLE	I	GRAND BAYOU CHANNEL	8.54	0.94E+11
MIDDLE	I	GRAND BAYOU SHOALS	8.54	1.06E+11
MIDDLE	J	MUD LAKE CHANNEL	9.54 *	2.11E+11
MIDDLE	J	MUD LAKE SHOALS	9.54 *	1.32E+11
MIDDLE	K	WILKINSON BAY	9.54	1.93E+11
SOUTH	L	GRAND BAYOU CHANNEL	10.55	0.50E+11
SOUTH	L	GRAND BAYOU SHOALS	10.55	0.69E+11
SOUTH	M	ST. MARY'S POINT	13.93	19.50E+11
SOUTH	N	BAY BATISTE	15.35	5.39E+11
SOUTH	O	HACKBERRY BAY	11.66	2.35E+11
SOUTH	P	CRANE ISLAND	17.37	3.47E+11
SOUTH	Q	BAY RAMBO	15.00 *	4.35E+11
SOUTH	R	WEST CHAMPAGNE BAY	13.78	7.52E+11
SOUTH	S	PELICAN POINT	18.56	6.39E+11
SOUTH	T	MID REEF	18.91	7.77E+11
SOUTH	U	CAT BAY	19.37	5.92E+11
SOUTH	V	BAY RONQUILLE	19.46	8.68E+11
SOUTH	W	CAMINADA BAY	19.47	13.70E+11
SOUTH	X	BARATARIA PASS	21.75	2.96E+11
SOUTH	X	BAY MELVILLE	21.75	6.91E+11

---

* estimated

Table 2.4. Salinity of various segments for the Terrebonne-Timbalier System. Indicated are the basin section and segment designation (Figure 2.11) the name of the major water body comprising the segment, the measured salinity plus the standard deviation of the measurement for the section. Salinities from two data sources are given. The symbol nd indicates no data for the section.

SUB BASIN	SEGMENT	MAJOR WATER BODY	BARRETT, 1971	EGGLER, et al., 1961
NORTH	A	LAKE BOUDREAUX	3.16±1.76	nd
NORTH	A	LAKE QUITMAN	nd	nd
NORTH	A	OTHER	nd	nd
NORTH	B	LAKE TAMBOUR	17.28±2.62	nd
NORTH	B	MADISON BAY	nd	nd
NORTH	B	OTHER	nd	nd
NORTH	C	LAKE FELICITY	20.40±2.60	nd
MIDDLE	C	OLD LADY LAKE	nd	nd
MIDDLE	C	OTHER	nd	nd
NORTH	D	CATFISH LAKE	11.97±3.78	nd
NORTH	D	GRAND BAYOU BLUE	nd	13.77±8.26[a], 14.08±7.87[b]
NORTH	D	OTHER	nd	nd
MIDDLE	E	EAST PETIT CAILLOU	12.96±5.04	nd
MIDDLE	E	WEST PETIT CAILLOU	nd	nd
MIDDLE	E	HOUMA CHANNEL	nd	nd
MIDDLE	F	LAKE BARRE	18.82±2.88	nd
MIDDLE	F	PASS BARRE		nd
MIDDLE	F	BAYOU TERREBONNE		nd
MIDDLE	F	OTHER		nd
MIDDLE	G	LAKE RACCOURCI	nd	20.14
MIDDLE	G	TIMBALIER BAY, NW	22.57±2.24	23.43±3.63
MIDDLE	G	TIMBALIER BAY, NE	nd	nd
MIDDLE	G	OTHER	nd	nd
MIDDLE	H	LITTLE LAKE	15.61±3.34	16.01±4.23
MIDDLE	H	BAYOU BLUE	nd	nd
MIDDLE	H	GRAND BAYOU BLUE	nd	nd
MIDDLE	H	OTHER	nd	nd
MIDDLE	I	TERREBONNE BAY BASIN	nd	nd
MIDDLE	I	TERREBONNE BAY SHOALS	24.26±2.46	nd
MIDDLE	I	HOUMA CHANNEL	nd	nd
SOUTH	J	LAKE PELTO SHOALS	nd	nd
SOUTH	J	LAKE PELTO BASIN	nd	nd
SOUTH	J	PELICAN LAKE	nd	nd
SOUTH	J	CAT ISLAND PASS	26.01±3.35	nd
SOUTH	J	WINE ISLAND PASS	25.93±5.29	nd
SOUTH	J	WHISKEY PASS	26.29±3.26	nd
SOUTH	J	CAILLOU BOCA	nd	nd
SOUTH	K	TIMBALIER BAY	20.63±7.98	nd
SOUTH	K	LITTLE PASS TIMBALIER	26.61±3.35	nd
SOUTH	K	CAILLOU PASS	nd	nd

---

a. 4 miles south of Catfish Lake
b. at Catfish Lake

Table 2.5. Salinity of various locations in the Terrebonne-Timbalier System for stations from Eggler et al., 1961. Indicated are the sub-basin section and segment designation (See Figure 2.11), the name of the major water body and the measured salinities plus the standard deviation for that water body.

SUB BASIN	SEGMENT	WATER BODY	SALINITY
NORTH	A	BAYOU BLUE ~6 MILES N. OF CATFISH LAKE	3.54±6.29a
NORTH	A	LAKE BULLY CAMP	8.46±6.29a
NORTH	C	LAKE CHIEN	18.32±6.81a
NORTH	D	BAY COURANT, BAYOU TO LITTLE GRAND BAY	14.55±8.88a
NORTH	D	LAURIER BAY	14.11±7.67a
MIDDLE	G	LAKE RACCOURCI	19.26±3.47b
MIDDLE	G	LAKE RACCOURCI	19.99±3.92b
MIDDLE	G	LAKE RACCOURCI	20.65±3.17b
MIDDLE	G	LAKE RACCOURCI	20.65±3.17b
MIDDLE	G	TIMBALIER BAY, NW	23.43±3.63b
MIDDLE	G	TIMBALIER BAY, PELICAN ISLANDS	26.68±5.39b
MIDDLE	G	TIMBALIER BAY, CASSE TETE ISLANDS	24.90±4.80b
MIDDLE	H	LITTLE LAKE	16.01±4.23b
MIDDLE	H	GRAND BAYOU BLUE @ CATFISH LAKE	14.08±7.87a
MIDDLE	H	GRAND BAYOU BLUE ~4 MILES S OF CATFISH LAKE	13.77±8.26a
MIDDLE	H	BAYOU MONAIRE @ CATFISH LAKE	12.51±6.98a

---

a. Data from December 1954 thru October 1955
b. Data from January 1957 thru October 1957

Table 2.6. Estimated salt content of the Terrebonne-Timbalier system, by segments (Figure 2.11). The salinities used are those measured by Barrett, 1971 for stations within each of the segments.

SUB BASIN	SEGMENT	MAJOR WATER BODY	SALINITY (PPT)	SALT CONTENT (G)
NORTH	A	LAKE BOUDREAUX	3.16	0.76E±11
NORTH	A	LAKE QUITMAN	3.16	0.58E±11
NORTH	A	OTHER	3.16	0.04E±11
NORTH	B	LAKE TAMBOUR	17.28	1.98E±11
NORTH	B	MADISON BAY	17.28	2.79E±11
NORTH	B	OTHER	17.28	0.54E±11
NORTH	C	LAKE FELICITY	20.40	15.01E±11
MIDDLE	C	OLD LADY LAKE	20.40	5.11E±11
MIDDLE	C	OTHER	20.40	0.25E±11
NORTH	D	CATFISH LAKE	11.97	0.93E±11
NORTH	D	GRAND BAYOU BLUE	11.97	0.28E±11
NORTH	D	OTHER	11.97	1.00E±11
MIDDLE	E	EAST PETIT CAILLOU	12.96	0.84E±11
MIDDLE	E	WEST PETIT CAILLOU	12.96	9.56E±11
MIDDLE	E	HOUMA CHANNEL	12.96	2.03E±11
MIDDLE	F	LAKE BARRE	18.82	2.15E±11
MIDDLE	F	PASS BARRE	18.82	3.89E±11
MIDDLE	F	BAYOU TERREBONNE	18.82	0.37E±11
MIDDLE	F	OTHER	18.82	5.71E±11
MIDDLE	G	LAKE RACCOURCI	22.57	1.67E±11
MIDDLE	G	TIMBALIER BAY, NW	22.57	21.66E±11
MIDDLE	G	TIMBALIER BAY, NE	22.57	21.53E±11
MIDDLE	G	OTHER	22.57	1.55E±11
MIDDLE	H	LITTLE LAKE	15.61	1.44E±11
MIDDLE	H	BAYOU BLUE	15.61	0.54E±11
MIDDLE	H	GRAND BAYOU BLUE	15.61	0.65E±11
MIDDLE	H	OTHER	15.61	0.41E±11
MIDDLE	I	TERREBONNE BAY BASIN	24.26	50.64E±11
MIDDLE	I	TERREBONNE BAY SHOALS	24.26	56.47E±11
MIDDLE	I	HOUMA CHANNEL	24.26	0.96E±11
SOUTH	J	LAKE PELTO SHOALS	24.26	41.81E±11
SOUTH	J	LAKE PELTO BASIN	24.26	6.88E±11
SOUTH	J	PELICAN LAKE	24.26	1.83E±11
SOUTH	J	CAT ISLAND PASS AREA	26.01	6.36E±11
SOUTH	J	WINE ISLAND PASS AREA	25.93	12.39E±11
SOUTH	J	CAILLOU BOCA	26.29	2.65E±11
SOUTH	K	TIMBALIER BAY	20.63	38.01E±11
SOUTH	K	CAILLOU PASS	26.61	6.44E±11

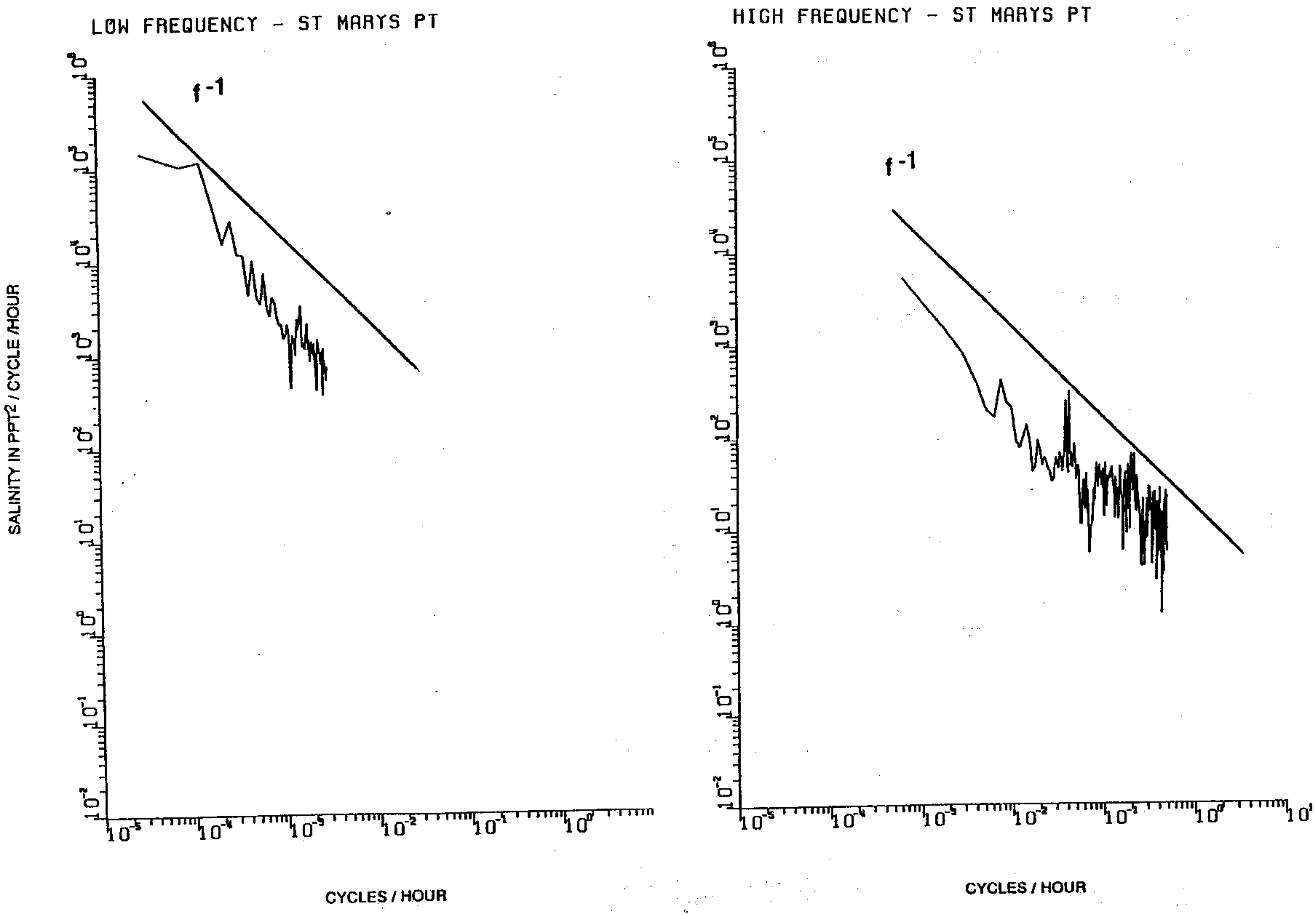


Figure 2.2. Spectral density estimates for salinity data from St. Mary's Point. The low frequency spectra on the left was calculated based on weekly means from August 1973 through March 1985. The high frequency spectra on the right was calculated based on hourly data from March 1981 through February 1982. Data was collected by the Louisiana Department of Wildlife and Fisheries.

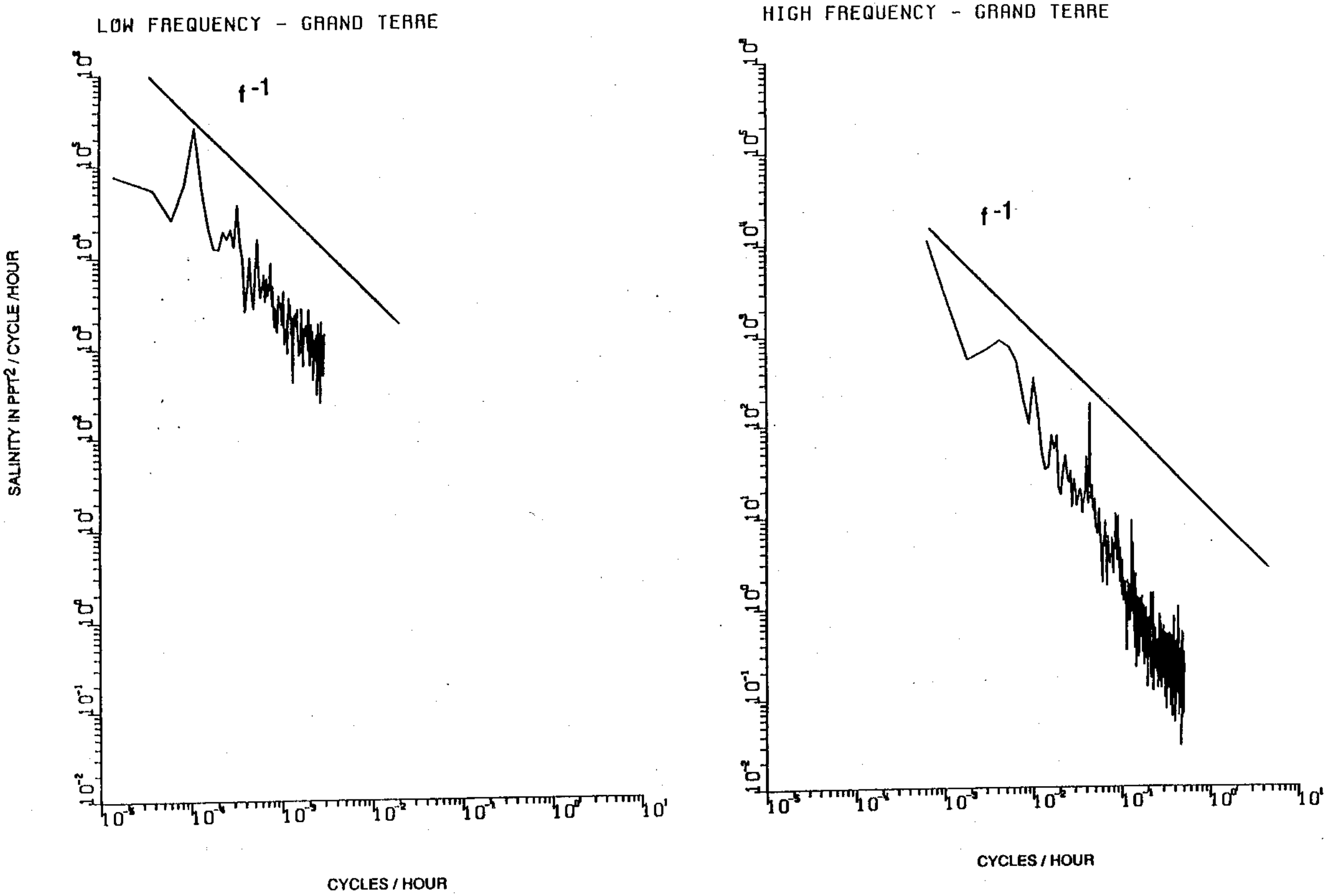


Figure 2.3. Spectral density estimates for salinity data from Grand Terre. The low frequency spectra on the left was calculated based on weekly means from April 1961 through March 1981. The high frequency spectra on the right was calculated based on hourly data from January 1978 through December 1978. Data was collected by the Louisiana Department of Wildlife and Fisheries.

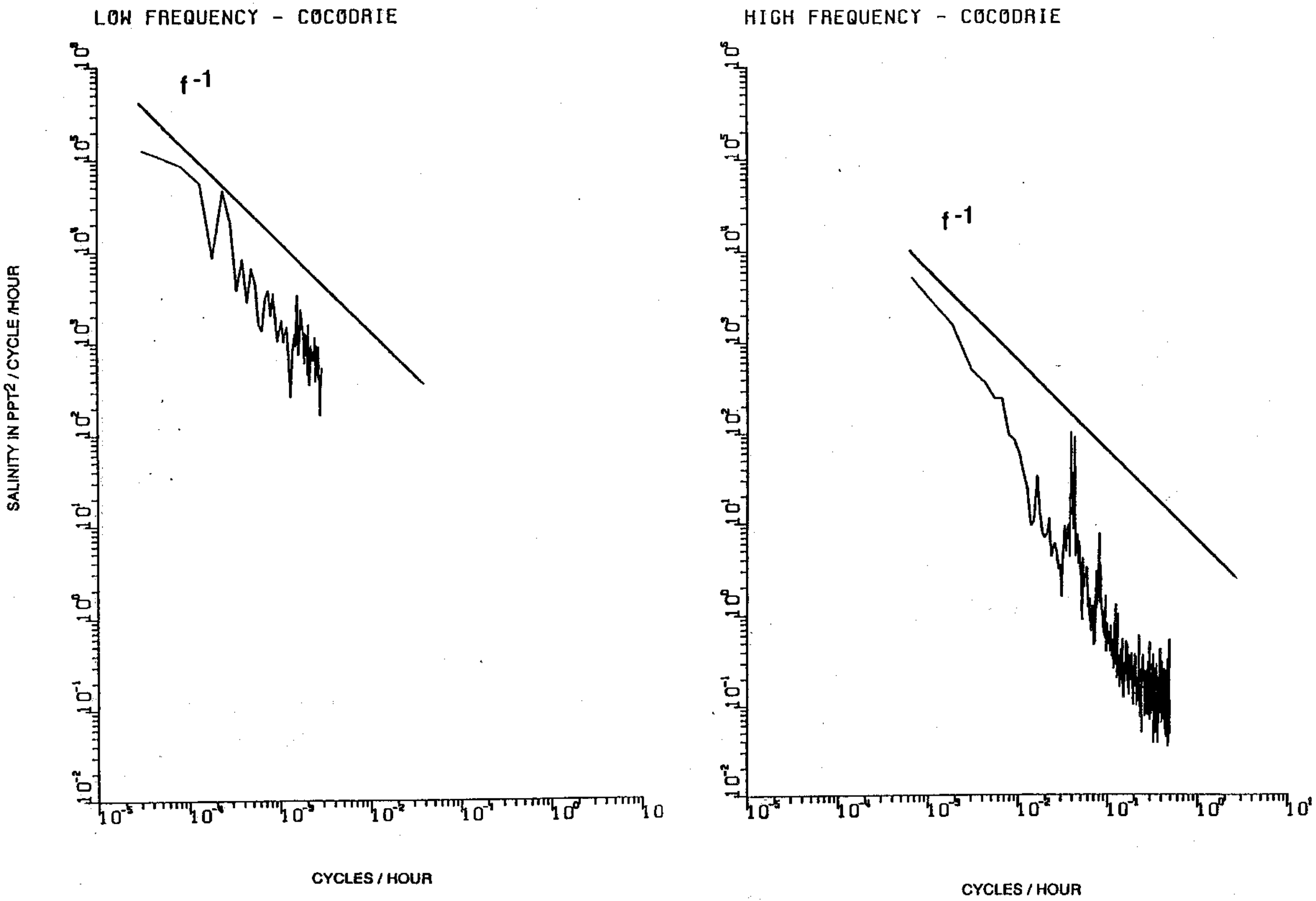


Figure 2.4. Spectral density estimates for salinity data from Cocodrie. The low frequency spectra on the left was calculated based on weekly means from July 1969 through August 1980. The high frequency spectra on the right was calculated based on hourly data from January 1978 through December 1978. Data was collected by the Louisiana Department of Wildlife and Fisheries.

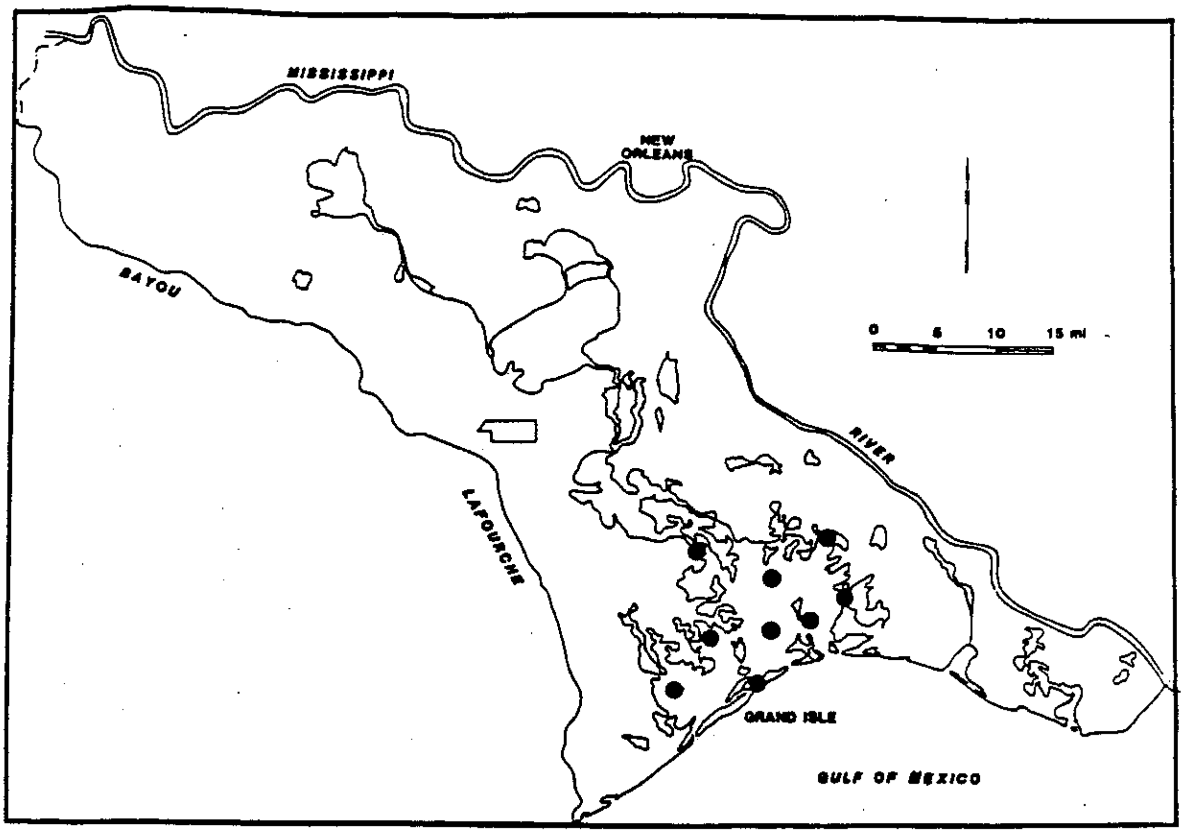


Figure 2.5. Base map of the Barataria Bay system showing the salinity sample stations occupied by Barrett (1971).

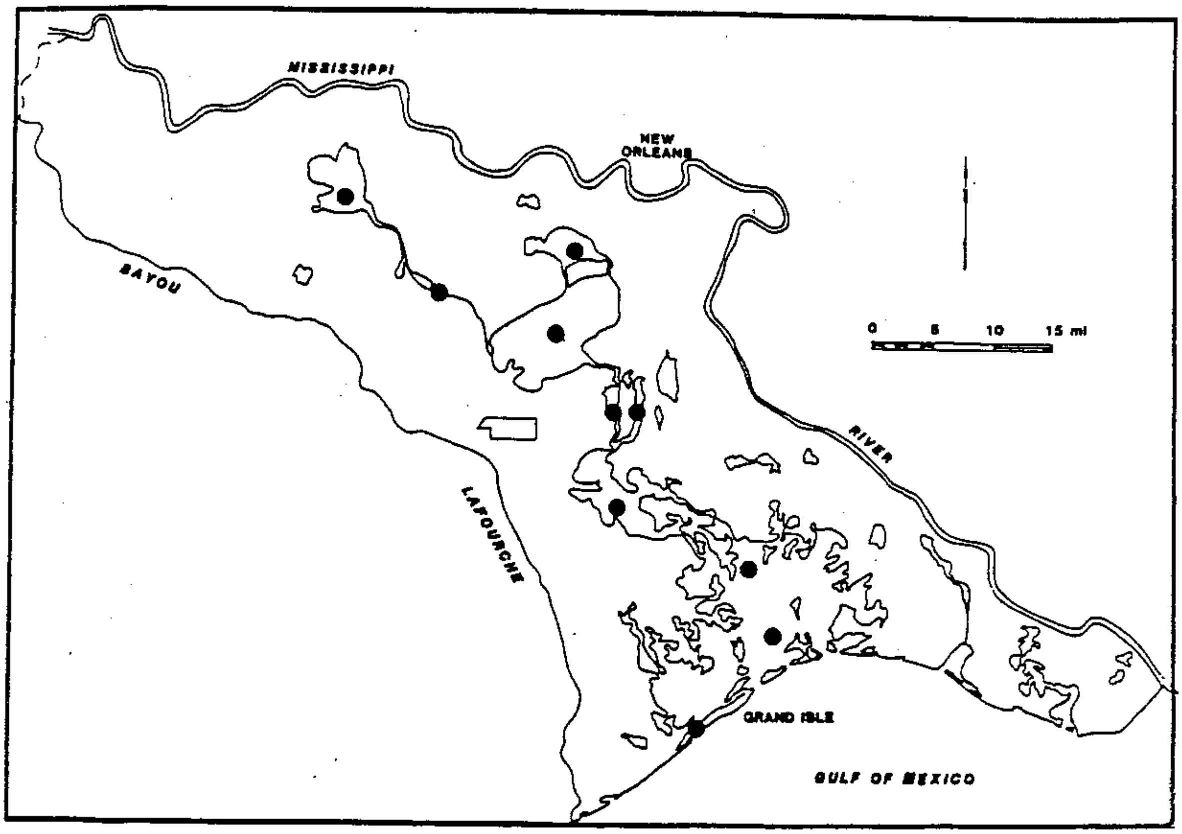


Figure 2.6. Base map of the Barataria Bay system showing the salinity sample stations occupied by Seaton (1976).

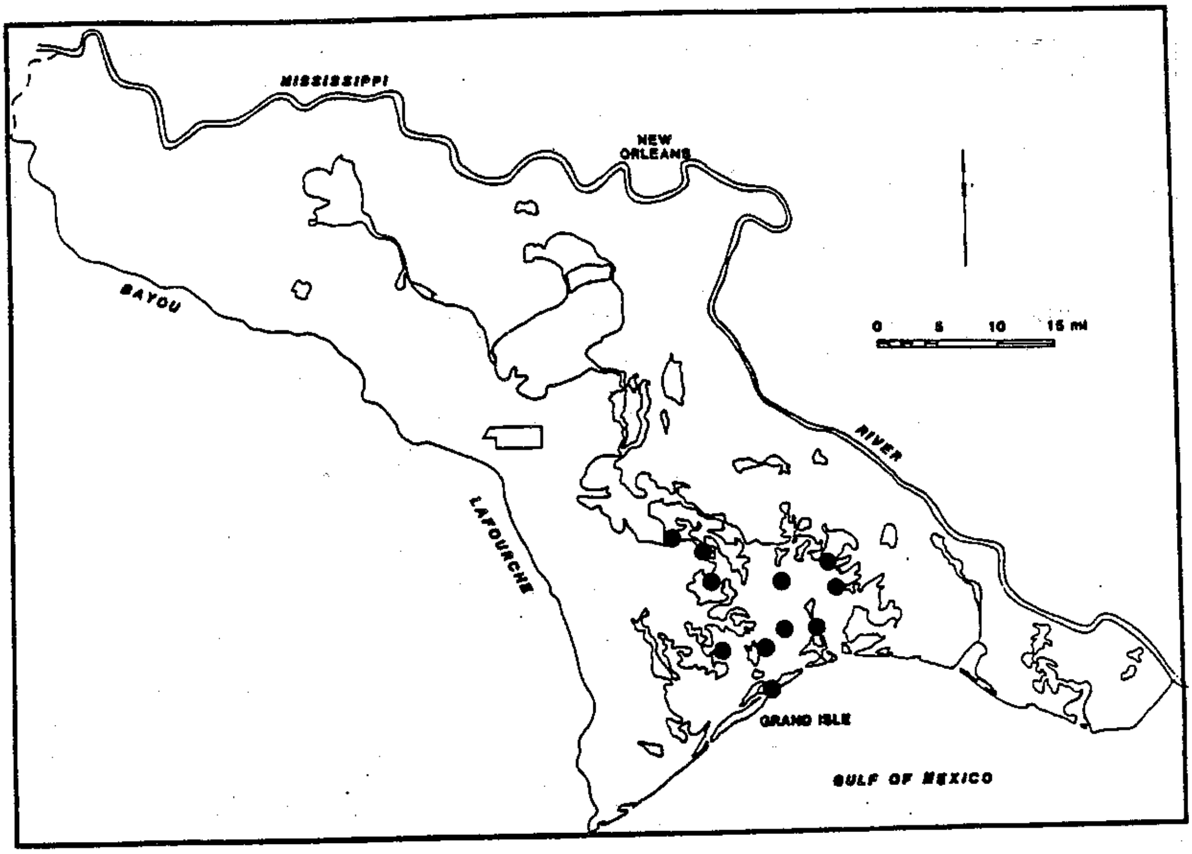


Figure 2.7. Base map of the Barataria Bay system showing the locations used by the Louisiana Department of Wildlife and Fisheries for their weekly sampling program.

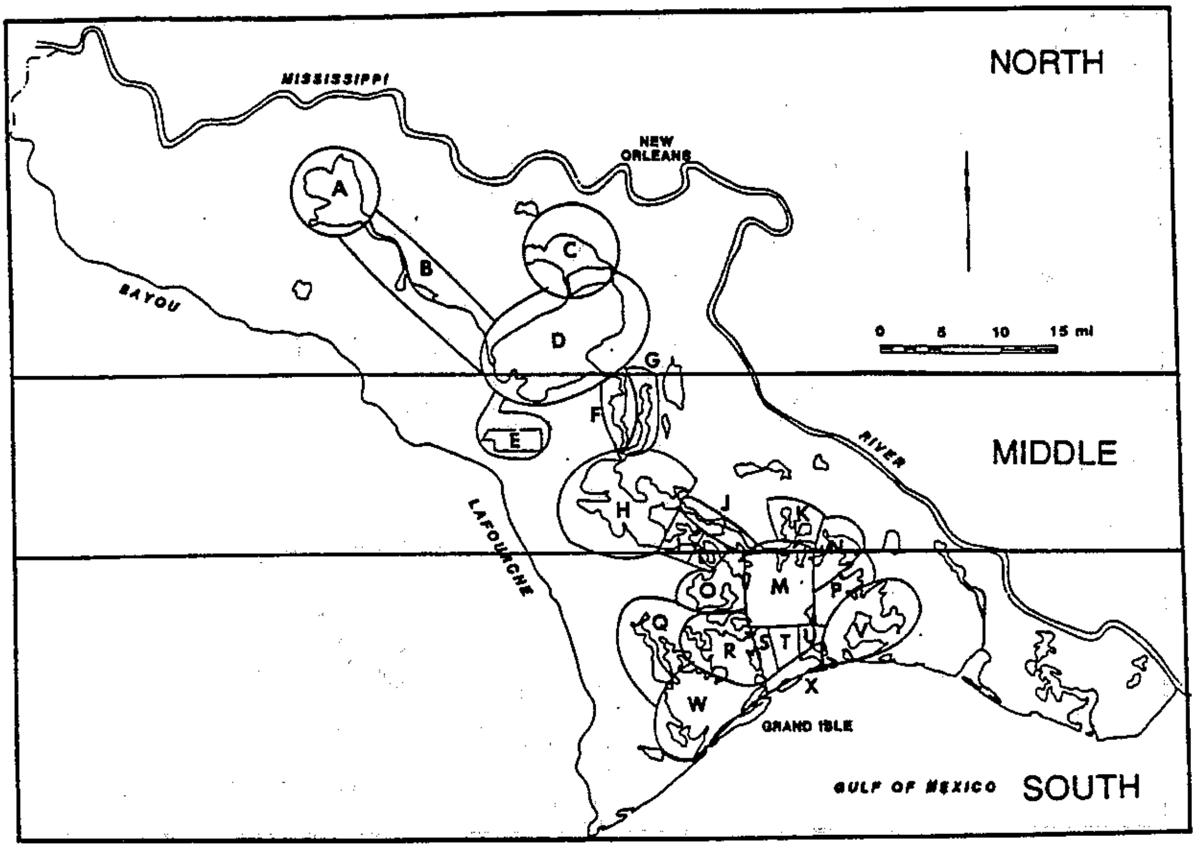


Figure 2.8. Base map of the Barataria Bay system showing the segments (A - X) used to estimate the salt content of the system as well as the latitudinal zones (north, middle, south) used to estimate the produced water inputs.

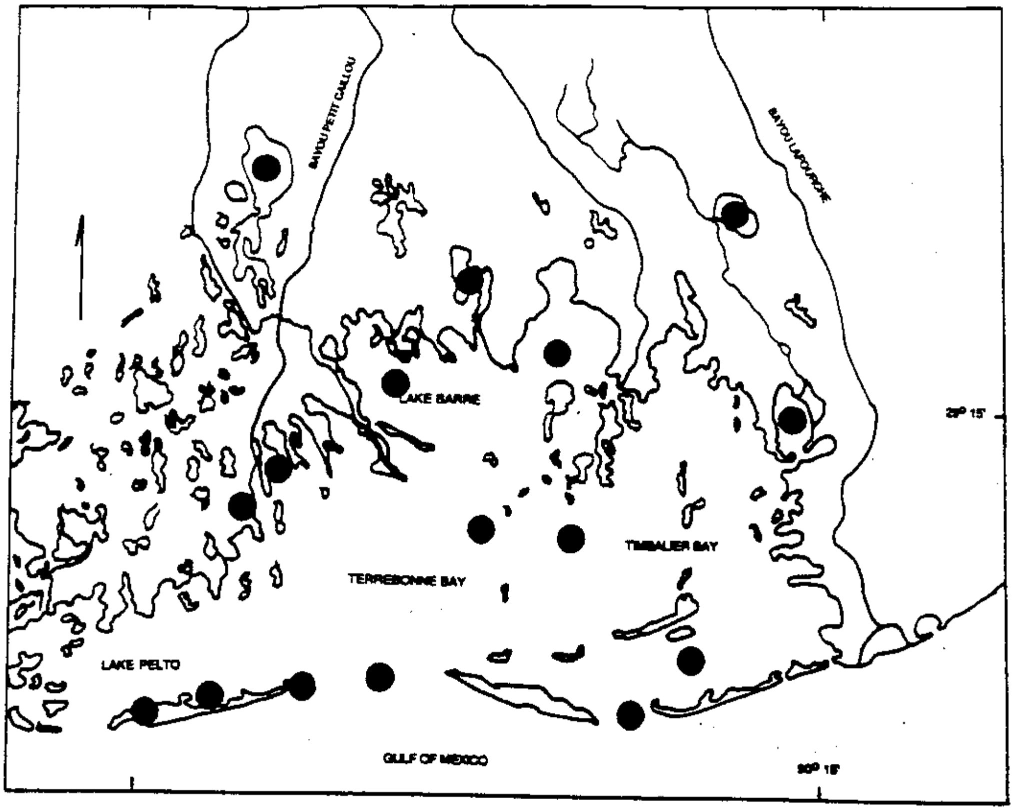


Figure 2.9. Base map of the Terrebonne-Timbalier system showing the salinity sample stations occupied by Barrett (1971).

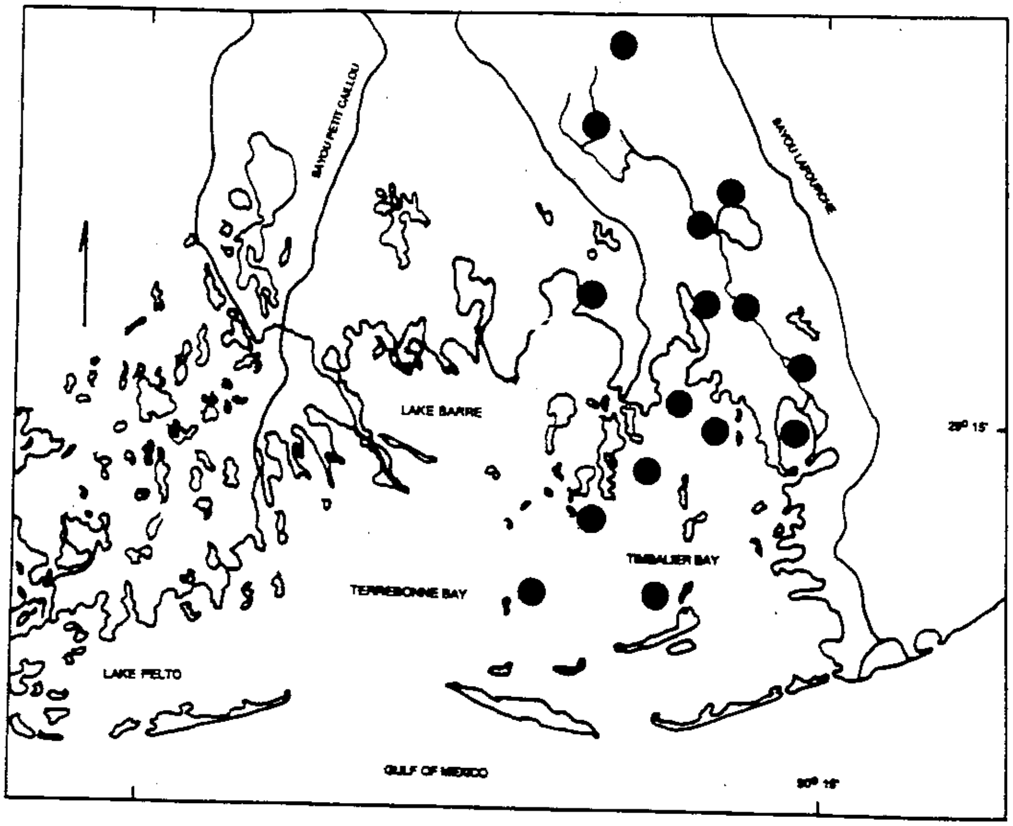


Figure 2.10. Base map of the Terrebonne-Timbalier system showing the salinity sample stations occupied by Eggler et al. (1961).

Biweekly and monthly salinity samples collected along the Barataria Waterway by both the Louisiana Department of Wildlife and Fisheries and the U. S. Army Corps of Engineers exhibit similar statistics. Mean salinities decreased consistently as one moves away from the coast, whereas the standard deviation of the data remained near 5 ppt until the station at Barataria proper is reached. At that point, the standard deviation dropped below 2 ppt. Salinity statistics from these and other shorter data sets are included in Tables 2.2 and 2.3.

In the Terrebonne-Timbalier Basin and in Bayou Lafourche (Tables 2.1, 2.4, 2.5 and 2.6), similar results are obtained using both daily mean salinities from the Louisiana Wildlife and Fisheries data set and daily samples from the U. S. Army Corps of Engineers data. The expected decrease of mean salinity with distance from the coast was observed. The standard deviation remained above 5 ppt until a mean salinity of approximately 10 ppt was reached. At stations where the mean salinity was lower than 2 ppt, though, the standard deviation was also greatly reduced.

We believe that the dependence of salinity variance on mean salinity reflects a change in process environment within the estuary. In the lower and middle regions of the estuary, salinity variance is dominated by the advection of a strong salinity gradient past the sampling site. Since we generally have been discussing daily mean samples, this advection is by subtidal, not tidal, currents. Closer to the head of the estuary, the longitudinal salinity gradient decreases. Salinity variance is dominated by the strongest wind-driven events and seasonal variations.

Thus, the variability of the salinity field is large. Much of this variability, at least in the open-water, lower reaches of the basins, can be accounted for by variations in the discharge of Mississippi River water into the coastal zone of the Gulf of Mexico (Wiseman et al., in review). This fresh water mixes with ambient water to form a low-salinity coastal water mass, which flows westward along the coast in front of the passes connecting the shelf with the estuaries. As water exchanges with the estuaries, the estuarine salinities respond to major variations in the salinity of coastal waters. The latter are controlled by Mississippi River discharge. This process appears to account for much of the longer period variability of the estuarine salinities. Cross-spectrum analysis between river discharge and salinity finds statistically significant coherence between the two signals only near the annual period.

Further information concerning the distribution of salinity variance with time scale is contained in the salinity spectra (Figures 2.2 through 2.4). These have been estimated using a fast Fourier transform algorithm and averaging over 10 independent estimates. The low-frequency estimates were made from time series of the weekly averages of the total data set. Because of gaps in the data records, hourly and daily data sets were not sufficiently continuous for such an analysis. The longest continuous records of hourly data were subsequently used to estimate the high frequency portion of the spectra.

A few points of interest about the spectra are noteworthy. A strong diurnal tidal signal and a weaker semi-diurnal signal are always present. The mean salinity gradient is obviously being advected through the system by the weak tidal currents. The spectra are red. That is, the largest spectral densities are present at the lowest frequencies. Because the data are plotted on log-log axes, the distribution of variance is not immediately apparent. In regions where the spectrum decreases faster than f^{-1}, the variance is larger at lower frequencies. There is often a break in slope between the lowest frequencies and the 0.001 to 0.01 cph band, i.e., periods between a few days and a few weeks.

2.4 Refill Times Due to Produced Waters

The total salt content was estimated for each basin by subdividing the basin into segments surrounding a sampling point (Figures 2.5 through 2.11). The resultant areas were planimetered and multiplied by a characteristic depth to obtain the volume of the segment (Tables 2.7 and 2.8). These volumes were then multiplied by the measured salinities to obtain an estimate of the mass of salt normally found in the basin at low tide (Tables 2.9 and 2.10). These results were then compared to estimates of the volume and salt content of the produced waters entering the basin. The data used and the results of the analyses are discussed below.

It should be noted that the water volumes we estimated for each segment were derived from bathymetric charts showing water depths at mean low water. As mentioned below, tidal variations, storm surges, and seasonal variations of water level may alter these volumes by a significant percentage. Tables 2.1 through 2.6 also indicate that the salinities at a given station are highly variable. Thus, these values of total salt content are probably correct in order of magnitude, but a significant variability around these values may be reasonably expected.

Three separates salinity databases were available for the Barataria Bay system: (1) Samples were collected by Barrett (1971) as part of a Louisiana Estuarine Inventory Program. These stations (Figure 2.5) were sampled on a monthly basis from December 1967 through June 1969. Comparison with other data sets suggests that the period sampled was very representative of the long-term mean conditions within the estuary. (2) Samples were collected by Seaton (1979) as part of a Master's degree research project on nutrient dynamics in the basin. Seaton's stations (Figure 2.6) were sampled on a quarterly basis from February 1976 through August 1977. (3) Weekly samples were collected by the Louisiana Department of Wildlife and Fisheries from 1981 through 1988 (Figure 2.7). The composite areal coverage of these databases was used to divide the Barataria basin into the segments. The basin was also divided into north, middle and south zones according to latitude (Figure 2.8). The area and volume for each of the segments are presented in Tables 2.7 and 2.9, and Tables 2.2 and 2.3 present the salinity data for the three data bases. In general, Barrett's 1971 data and the LDWF weekly data give excellent coverage in the lower portion of the basin, whereas Seaton's (1979) data give good coverage in the upper portion of the basin. The three databases were combined to obtain estimates of the salinity and mass of salt contained within each segment of the system.

The database for the Terrebonne-Timbalier system is not as extensive as the database for the Barataria system. We have used Barrett's (1971) data to estimate the salt content of the system. A second data set, presented by Eggler et al. (1961), provided excellent coverage for the northeastern portion of the basin (Timbalier Bay to Catfish Lake). The upper end of this coverage includes the Golden Meadow oil and gas field investigated in the remote sensing and field assessment components of this study. Although this data set was not used for estimating the salt content, it does supply data used for estimating general north-south salinity trends. Figures 2.9 and 2.10 present the sampling locations for Barrett's and Eggler et al.'s data, respectively. The segments used for estimating salt content are shown in Figure 2.11. The area and volume data are presented in Table 2.8. The salinity data for the system is presented in Tables 2.4, 2.5 and 2.6. In general, the system shows higher salinities in the open water areas, with a fairly rapid decrease in salinity as one moves to the north into the marsh. The decrease is particularly noticeable in Eggler et al.'s data set (Tables 2.4 and 2.5). The estimated mass of salt for the Terrebonne-Timbalier system is presented in Table 2.10.

The time required for the produced water discharges into each subsegment to refill the water and salt within the segment was estimated. The refill times of each basin and subsegments within each basin were estimated by dividing the volume of the basin by the discharge rate of produced waters into it. These calculations suggest that the produced waters provide a negligible volume of water (Tables 2.9 and 2.10). Similar refill times were estimated for salt by dividing the total mass of salt by the discharge rate at which salt is introduced into each basin or sub-basin by the discharge of produced waters. In Barataria Bay, these times were much shorter, of the order of a few years. In Terrebonne-Timbalier Bay, they were not as short as in the Barataria Bay system, principally because of the higher salinities normally found within the Basin. These

Table 2.7. Volumes of various segments for the Barataria Basin System. Indicated are the basin section and segment designation (See Figure 2.8), the name of the major water body comprising the segment, the area of the segment (at mean low water), the average depth of the segment (at mean low water) the calculated volume for the segment, and the mean tidal range.

SUB BASIN	SEGMENT	MAJOR WATER BODY	AREA (M^2)	DEPTH(M)	VOLUME (M^3)	TIDAL RANGE (M)
NORTH	A	LAC DES ALLEMANDS	64.31E+06[a]	2.0[b]	12.86E+7	
NORTH	B	BAYOU DES ALLEMANDS	24.49E+06[a]	3.5[b]	8.57E+7	0.03[b]
NORTH	C	LAKE CATAOUATCHE	37.27E+06[a]	2.0[b]	7.45E+7	
NORTH	C	BAYOU COUBA	2.22E+06[a]	3.5[b]	0.78E+7	
NORTH	C	BAYOU BARDEAUX	3.00E+06[a]	3.5[b]	1.05E+7	
NORTH	D	LAKE SALVADOR	192.72E+06[a]	2.5[b]	48.18E+7	0.02[d]
MIDDLE	E	DELTA FARMS	24.41E+06[a]	3.0[b]	7.32E+7	
MIDDLE	F	BAYOU PEROT	24.07E+06[a]	2.0[b]	4.81E+7	0.08[b]
MIDDLE	G	BAYOU RIGOLETTES	16.27E+06[a]	1.5[b]	2.44E+7	0.08[b] 0.06[d]
MIDDLE	H	LITTLE LAKE	61.53E+06[a]	2.0[b]	12.3E+7	0.12[d]
MIDDLE	H	TURTLE BAY	22.60E+06[a]	0.91[c]	2.06E+7	
MIDDLE	H	ROUND LAKE	3.83E+06[a]	0.91[c]	0.348E+7	
MIDDLE	H	BAY L'OURS	11.50E+06[a]	0.91[c]	1.05E+7	
MIDDLE	I	GRAND BAYOU CHANNEL	2.490E+06[c]	4.42[c]	1.10E+7	
MIDDLE	I	GRAND BAYOU SHOALS	4.742E+06[c]	1.60[c]	0.76E+7	
MIDDLE	J	MUD LAKE CHANNEL	4.08E+06[c]	5.43[c]	2.22E+7	
MIDDLE	J	MUD LAKE SHOALS	15.23E+06[c]	0.91[c]	1.39E+7	
MIDDLE	K	WILKINSON BAY	15.45E+06[c]	1.31[c]	2.02E+7	
SOUTH	L	GRAND BAYOU CHANNEL	1.54E+06[c]	3.05[c]	0.47E+7	
SOUTH	L	GRAND BAYOU SHOALS	7.24E+06[c]	0.91[c]	0.66E+7	
SOUTH	M	ST. MARY'S POINT	83.87E+06[c]	1.67[c]	14.01E+7	0.30[d]
SOUTH	N	BAY BATISTE	28.80E+06[c]	1.22[c]	3.51E+7	
SOUTH	O	HACKBERRY BAY	18.84E+06[c]	1.07[c]	2.02E+7	
SOUTH	P	CRANE ISLAND	21.95E+06[c]	0.91[c]	2.00E+7	
SOUTH	Q	BAY RAMBO	38.17E+06[c]	0.76[c]	2.90E+7	
SOUTH	R	WEST CHAMPAGNE BAY	50.99E+06[c]	1.07[c]	5.46E+7	

Table 2.7. (continued)

SUB BASIN	SEGMENT	MAJOR WATER BODY	AREA (M^2)	DEPTH(M)	VOLUME (M^3)	TIDAL RANGE (M)
SOUTH	S	PELICAN POINT	22.66E+06[c]	1.52[c]	3.44E+7	
SOUTH	T	MID REEF	24.50E+06[c]	1.68[c]	4.12E+7	
SOUTH	U	CAT BAY	25.06E+06[c]	1.22[c]	3.06E+7	
SOUTH	V	BAY RONQUILLE	49.03E+06[c]	0.91[c]	4.46E+7	
SOUTH	W	CAMINADA BAY	77.27E+06[c]	0.91[c]	7.03E+7	
SOUTH	X	BARATARIA PASS	2.23E+06[c]	6.10[c]	1.36E+7	0.32[b] 0.36[d]
SOUTH	X	BAY MELVILLE	17.52E+06[c]	1.83[c]	3.21E+7	

---

a. determined from USGS 1:100,000-scale metric topographic-bathymetric maps for New Orleans (map 29090-E1-TM-100) and Terrebonne Bay (map 29090-A1-TB-100).

b. data from Conner, W. H. and J. W. Day, Jr., 1987. "The Ecology of Barataria Basin, Louisiana: An Estuarine Profile". National Wetlands Research Center, U. S. Fish and Wildlife Service, U. S. Dept. of the Interior. Biological Report 85(7.13). 165 pp.

c. determined from Coast and Geodetic Survey Chart No.

d. Analysis of water level records from LDWF for this study.

Table 2.8. Volumes of various segments for the Terrebonne-Timbalier System. Indicated are the basin section and segment designation (See Figure 2.11), the name of the major water body comprising the segment, the area of the segment (at mean low water), the average depth of the segment (at mean low water) the calculated volume for the segment, and the mean tidal range.

SUB BASIN	SEGMENT	MAJOR WATER BODY	AREA (M^2)	DEPTH(M)	VOLUME (M^3)	TIDAL RANGE (M)
NORTH	A	LAKE BOUDREAUX	22.53E+06^{a}	1.07^{b}	2.41E+7	
NORTH	A	LAKE QUITMAN	17.30E+06^{a}	1.07^{b}	1.85E+7	
NORTH	A	OTHER	2.36E+06^{a}	0.61^{b}	0.14E+7	
NORTH	B	LAKE TAMBOUR	10.76E+06^{a}	1.07^{b}	1.15E+7	
NORTH	B	MADISON BAY	15.10E+06^{a}	1.07^{b}	1.62E+7	
NORTH	B	OTHER	5.17E+06^{a}	0.61^{b}	0.31E+7	
NORTH	C	LAKE FELICITY	40.20E+06^{b}	1.83^{c}	7.36E+7	
MIDDLE	C	OLD LADY LAKE	20.53E+06^{b}	1.22^{c}	2.50E+7	
MIDDLE	C	OTHER	2.36E+06^{b}	0.53^{c}	0.12E+7	
NORTH	D	CATFISH LAKE	7.31E+06^{a}	1.07^{c}	0.78E+7	0.120^{d}
NORTH	D	GRAND BAYOU BLUE	1.20E+06^{a}	2.00^{b}	0.24E+7	
NORTH	D	OTHER	11.98E+06^{a}	0.70^{b}	0.84E+7	
MIDDLE	E	EAST PETIT CAILLOU	7.11E+06^{b}	0.91^{b}	7.36E+7	
MIDDLE	E	WEST PETIT CAILLOU	120.60E+06^{b}	0.61^{b}	0.44E+7	0.240^{d}
MIDDLE	E	HOUMA CHANNEL	3.96E+06^{b}	3.96^{b}	1.57E+7	
MIDDLE	F	LAKE BARRE	75.34E+06^{b}	1.52^{b}	11.45E+7	
MIDDLE	F	PASS BARRE	4.09E+06^{b}	5.00^{b}	2.04E+7	
MIDDLE	F	BAYOU TERREBONNE	1.310E+06^{b}	1.52^{b}	0.20E+7	
MIDDLE	F	OTHER	33.320E+06^{b}	0.91^{b}	3.03E+7	
MIDDLE	G	LAKE RACCOURCI	60.62E+06^{b}	1.22^{b}	7.39E+7	
MIDDLE	G	TIMBALIER BAY, NE	62.77E+06^{b}	1.52^{b}	9.54E+7	
MIDDLE	G	TIMBALIER BAY, NW	78.65E+06^{b}	1.22^{b}	9.59E+7	
MIDDLE	G	OTHER	11.29E+06^{b}	0.91^{b}	0.69E+7	
MIDDLE	H	LITTLE LAKE	10.17E+06^{b}	0.91^{b}	0.92E+7	
MIDDLE	H	BAYOU BLUE	0.78E+06^{b}	4.50^{b}	0.35E+7	
MIDDLE	H	GRAND BAYOU BLUE	1.67E+06^{b}	2.50^{b}	0.42E+7	
MIDDLE	H	OTHER	4.29E+06^{b}	0.61^{b}	0.26E+7	
MIDDLE	I	TERREBONNE BAY BASIN	83.49E+06^{b}	2.50^{b}	20.87E+7	
MIDDLE	I	TERREBONNE BAY SHOALS	155.20E+06^{b}	1.50^{b}	23.28E+7	

TABLE 2.8. CONTINUED

SUB BASIN	SEGMENT	MAJOR WATER BODY	AREA (M^2)	DEPTH(M)	VOLUME (M^3)	TIDAL RANGE (M)
MIDDLE	I	HOUMA CHANNEL	1.00E+06[b]	3.96[b]	0.39E+7	
SOUTH	J	LAKE PELTO SHOALS	105.60E+06[b]	1.52[b]	16.05E+7	
SOUTH	J	LAKE PELTO BASIN	12.41E+06[b]	2.13[b]	2.64E+7	
SOUTH	J	PELICAN LAKE	11.52E+06[b]	0.61[b]	1.87E+7	
SOUTH	J	CAT ISLAND PASS	1.28E+6[b]	4.50[b]	0.57E+7	
SOUTH	J	CAILLOU BOCA	2.35E+6[b]	4.33[b]	1.02E+7	0.426[e]
SOUTH	K	TIMBALIER BAY	100.70E+6[b]	1.83[b]	18.43E+7	0.365[e]
SOUTH	K	CAILLOU PASS	17.06E+6[b]	1.83[b]	3.12E+7	

---

a. determined from USGS 1:100,000-scale metric topographic-bathymetric map for Terrebonne Bay, Map Number 29090-A1-TB-100.

b. determined from Coast and Geodetic Survey Chart No. 11357

c. determined from USGS 7.5' series topographic maps. (Lake Felicity, Lake Tambour, Dulac Quardrangles).

d. analysis of water level records from LDWF, NOS, USACOE for this study.

e. from NOAA tide tables.

Table 2.9. Estimated water volume, salt content, and produced water inputs (volume and salt) for sub-basins (Figure 2.8) within the Barataria system. Indicated are the total volume (liters) and total salt content (grams) along with the total produced water inputs, liters of fluid per day and grams of salt per day, for each sub basin. A replacement time for both volume and salt is also given.

	TOTAL CONTENTS		PRODUCED WATER INPUTS		REPLACEMENT TIMES	
SUB-BASIN	VOLUME LITERS	SALT GRAMS	VOLUME LITERS/DAY	SALT GRAMS/DAY	VOLUME YEARS	SALT YEARS
NORTH	78.89E+11	13.21E+11	4.09E+6	4.34E+8	528	8.3
MIDDLE	38.30E+10	19.96E+11	0.14E+6	20.25E+8	7495	2.7
SOUTH	57.70E+10	96.13E+11	37.53E+6	45.50E+8	42	5.8
TOTAL	174.90E+10	129.30E+11	41.76E+6	70.09E+8	115	5.0

Table 2.10. Estimated water volume, salt content, and produced water inputs (volume and salt) for sub-basins (Figure 2.11) within the Terrebonne-Timbalier system. Indicated are the total volume (liters) and total salt content (grams) along with the total produced water inputs, liters of fluid per day and grams of salt per day, for each sub basin. A replacement time for both volume and salt is also given.

	TOTAL CONTENTS		PRODUCED WATER INPUTS		REPLACEMENT TIMES	
SUB-BASIN	VOLUME LITERS	SALT GRAMS	VOLUME LITERS/DAY	SALT GRAMS/DAY	VOLUME YEARS	SALT YEARS
NORTH	1.67E+11	2.39E+12	8.16E+6	1.11E+9	56	5.9
MIDDLE	10.35E+11	22.33E+12	3.60E+6	0.50E+9	788	122.0
SOUTH	4.96E+11	11.73E+12	12.00E+6	2.06E+9	113	15.6
TOTAL	16.98E+11	36.45E+12	23.76E+6	3.67E+9	196	27.2

higher salinities are due, we believe, to the wider entrances to the system, which facilitate tidal exchange and the influx of coastal ocean salt.

2.5 Tidal Prism Modelling

Tidal prism models have been used for many years to estimate the flushing characteristics of tidal estuaries. Some notable success has been obtained using this methodology in large, single-channel, energetic systems such as the Mersey, the Raritan and the Thames. The formulation of the problem has been modified numerous times (Ketchum, 1951a,b; Dyer and Taylor, 1973; Wood, 1979; Brown and Arellano, 1980). We chose to use the formulation of Woods. A series of tidal ranges along the Barataria Basin were used to determine the local tidal excursion of a particle assuming linear shallow-water wave theory. These data and the continuity equation were then used to segment the estuary (Figure 2.12). Segment boundaries were modified slightly, as necessary, to ensure robustness of the model. The mean salinity data of Seaton (1979) was used to determine a mean salinity profile along the main axis of the bay. By modifying the mixing parameter of the model, a reasonably acceptable fit to the observed data was obtained (Figure 2.13).

The resultant model was then used to examine the fate of a contaminant introduced into specific segments. A unit concentration of contaminant was distributed throughout the *n*th segment and allowed to spread. The downstream boundary of the model was assumed to be absorbing. Contaminant spread both upstream and downstream. Ultimately, it was slowly flushed downstream by the river discharge. Concentrations changed as the contaminant dispersed because of the changes in neighboring segment size as well as because of the spreading of absolute mass of contaminant. Within a matter of 52 tidal cycles, or roughly 1.75 months, concentrations of contaminant released in segment 7 were reduced to below 10% of their initial concentrations (Figure 2.14), whereas similar concentrations for a release in segment 16 were obtained in less than one month (Figure 2.15). The lower portions of the estuary flushed more rapidly owing to the greater tidal range in this region of the system.

In Terrebonne-Timbalier Basin, the number of segments that could be generated was much smaller than in Barataria Basin (Figure 2.16). This was partially due to the higher tidal amplitudes observed within the system. Furthermore, the data set available was smaller and of poorer quality. For example, good tidal data were available only at the entrances to the bay system and near Cocodrie. Recent observations by the National Ocean Service have not yet been completely processed and were not available to us. We have been verbally informed, though, that the tidal amplitudes decrease dramatically as one enters the marsh. Thus, within the peripheral portions of the system, particularly the upstream section, the tidal excursion will be reduced, the number of segments necessary for an appropriate model increased, and the flushing time for the system probably increased. Nevertheless, the fit to available data was adequate (Figure 2.17). The results of similar analyses as performed for the Barataria system are shown in Figures 2.18, 2.19 and 2.20. The flushing times for releases in segments 3 through 5 are longer than those observed in Barataria Bay even though the tidal ranges are larger. This can probably be attributed to both the smaller freshwater discharge upstream of the release points and the rapid decrease of estuarine volume as one approaches the head of the estuary.

There are numerous problems in the application of such a model to the basins selected. The model was designed for a system where tidal forcing was dominant, the geometry was simple, and the data set available for defining the model parameters was appropriate. None of these is the case in coastal Louisiana.

Each system examined has multiple entries to the system, i.e., multiple tidal passes connecting the bays to the shelf. This will allow hydraulic current to develop within the basin,

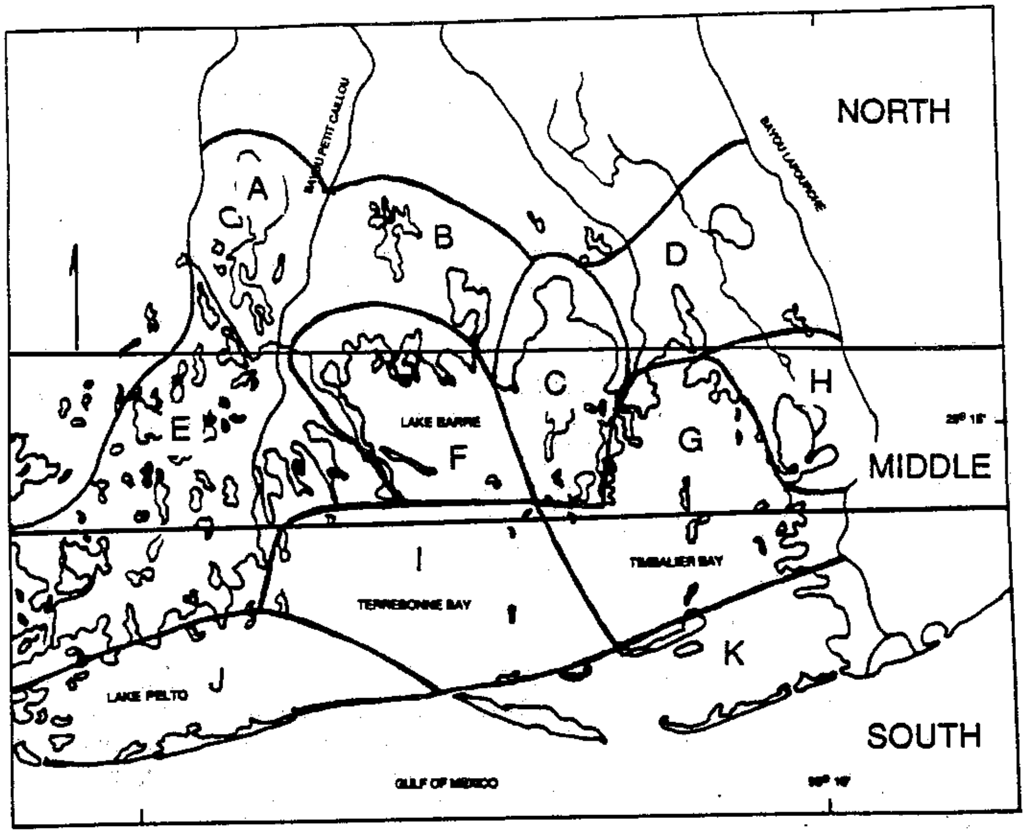


Figure 2.11. Base map of the Terrebonne-Timbalier Bay system showing the segments (A - K) used to estimate the salt content of the system as well as the latitudinal zones (north, middle, south) used to estimate the produced water inputs.

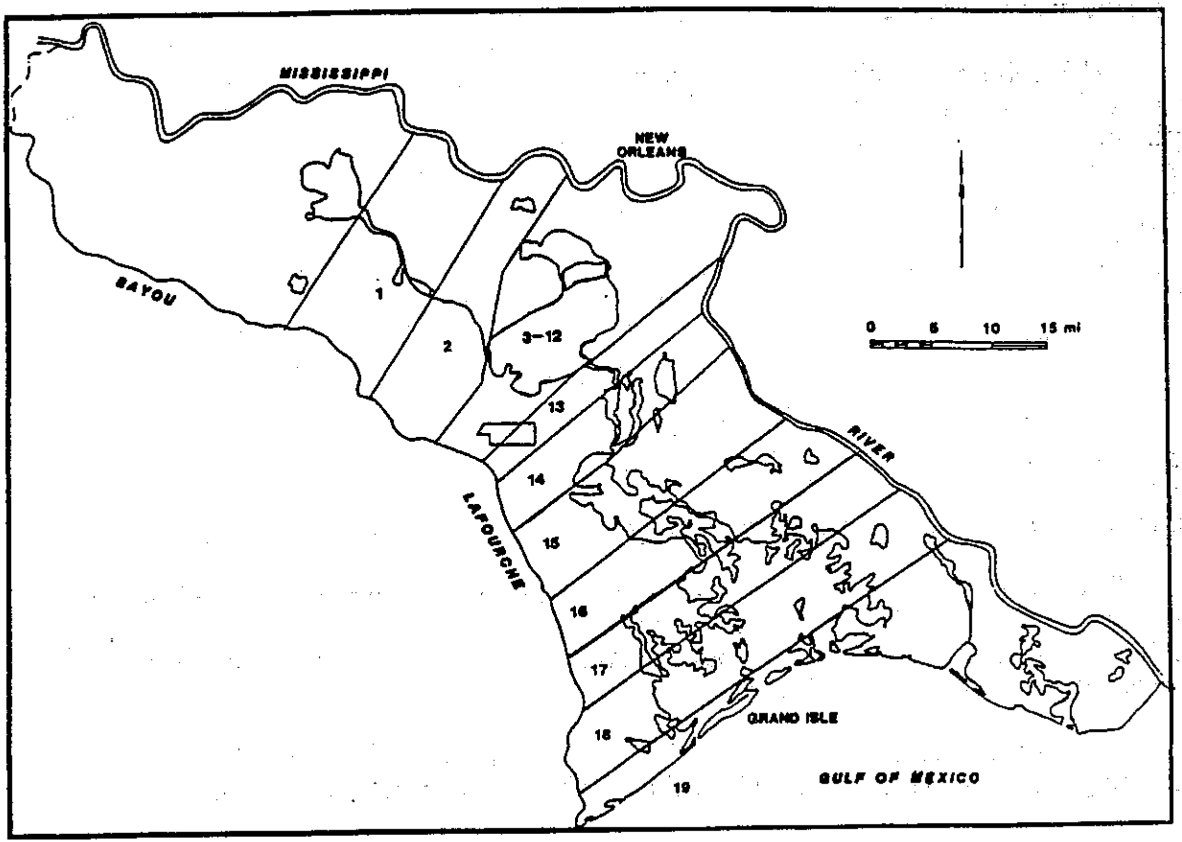


Figure 2.12. Base map of the Barataria Bay system showing the sections (1 - 19) used in formulating the tidal prism model.

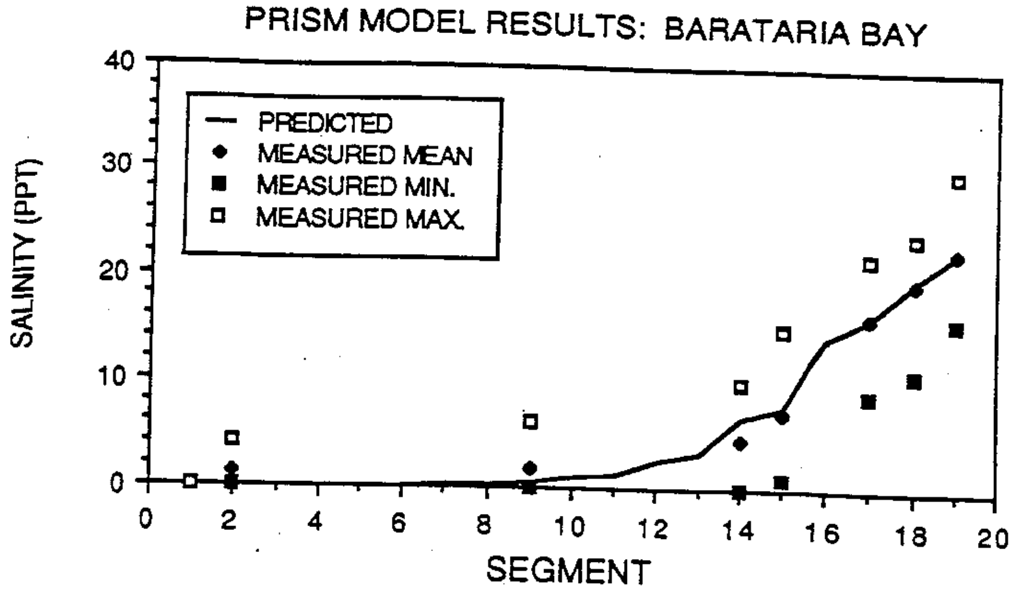


Figure 2.13. Results of the tidal prism modelling for the Baratatia Bay system. Shown is the predicted longitudinal salinity signal (solid line) along with the measured mean (solid diamond), minima (solid square) and maxima (open square) for the system.

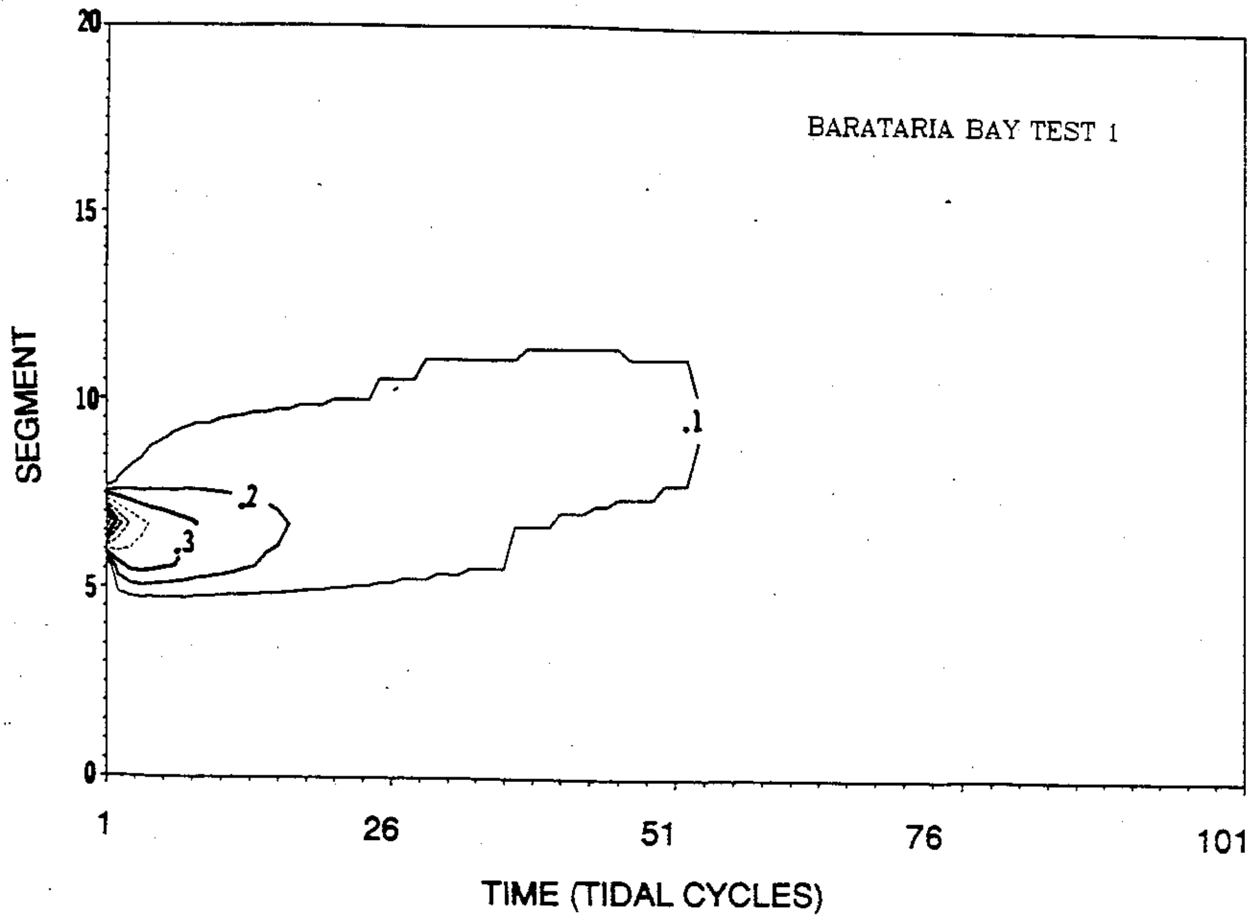


Figure 2.14. Contour plot of predicted concentrations as a function of time after release, at time t = 0, of a unit concentration in the upper portion of the Barataria Bay system. The horizontal axis is time, in tidal cycles and the vertical axis is segment number (proportional to distance downstream). The contour levels range from 0 to 1.0 and represent the relative concentration at a given time and segment.

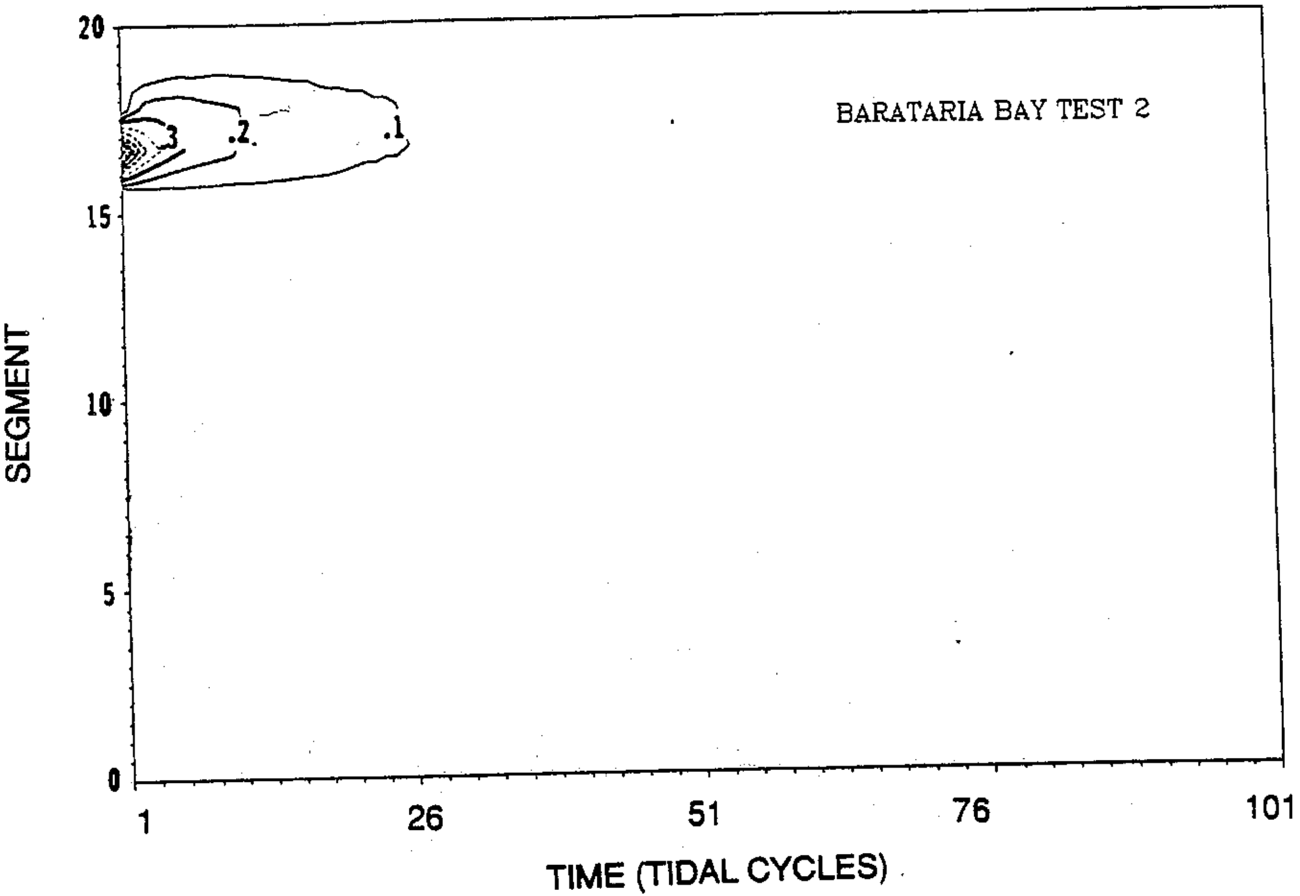


Figure 2.15. Contour plot of predicted concentrations as a function of time after release, at time t = 0, of a unit concentration in the lower portion of the Barataria Bay system. The horizontal axis is time, in tidal cycles and the vertical axis is segment number (proportional to distance downstream). The contour levels range from 0 to 1.0 and represent the relative concentration at a given time and segment.

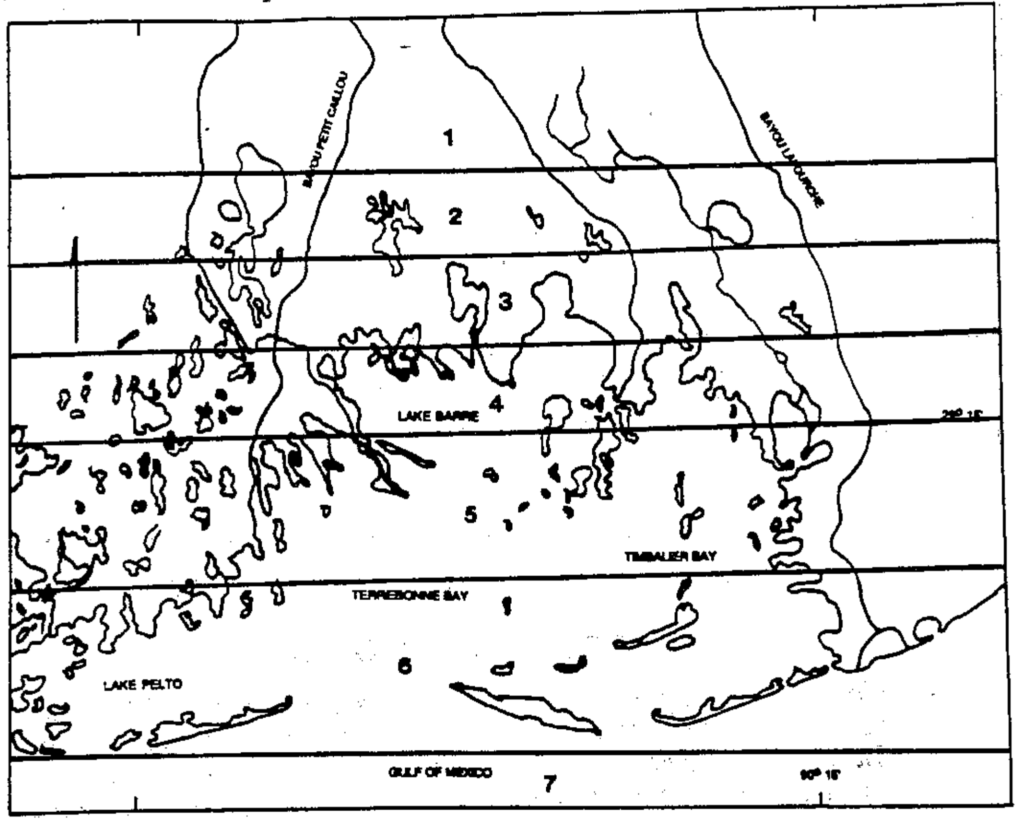


Figure 2.16. Base map of the Terrebonne-Timbalier Bay system showing the sections (1 - 7) used in formulating the tidal prism model.

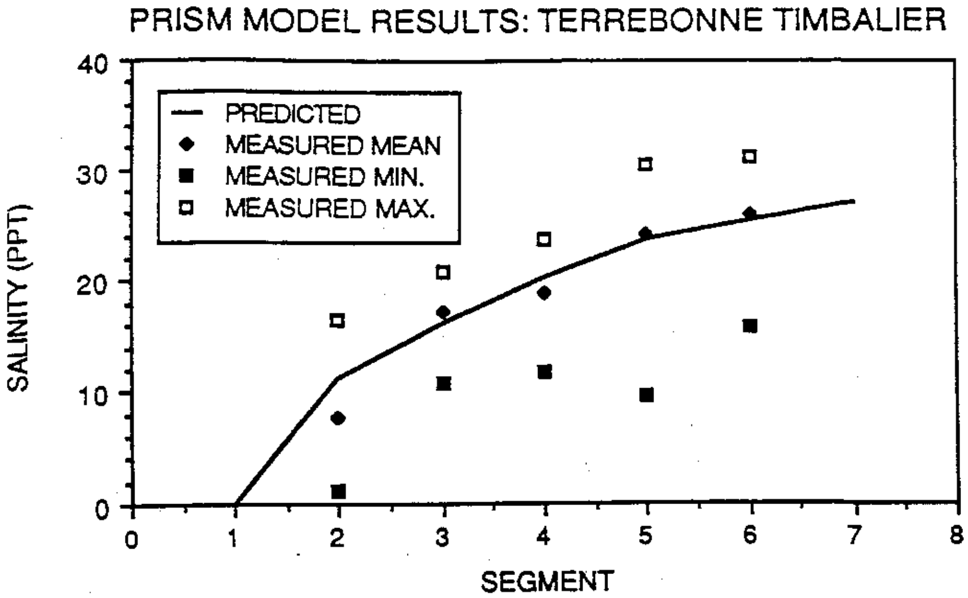


Figure 2.17. Results of the tidal prism modelling for the Terrebonne-Timbalier Bay system. Shown is the predicted longitudinal salinity signal (solid line) along with the measured mean (solid diamond), minima (solid square) and maxima (open square) for the system.

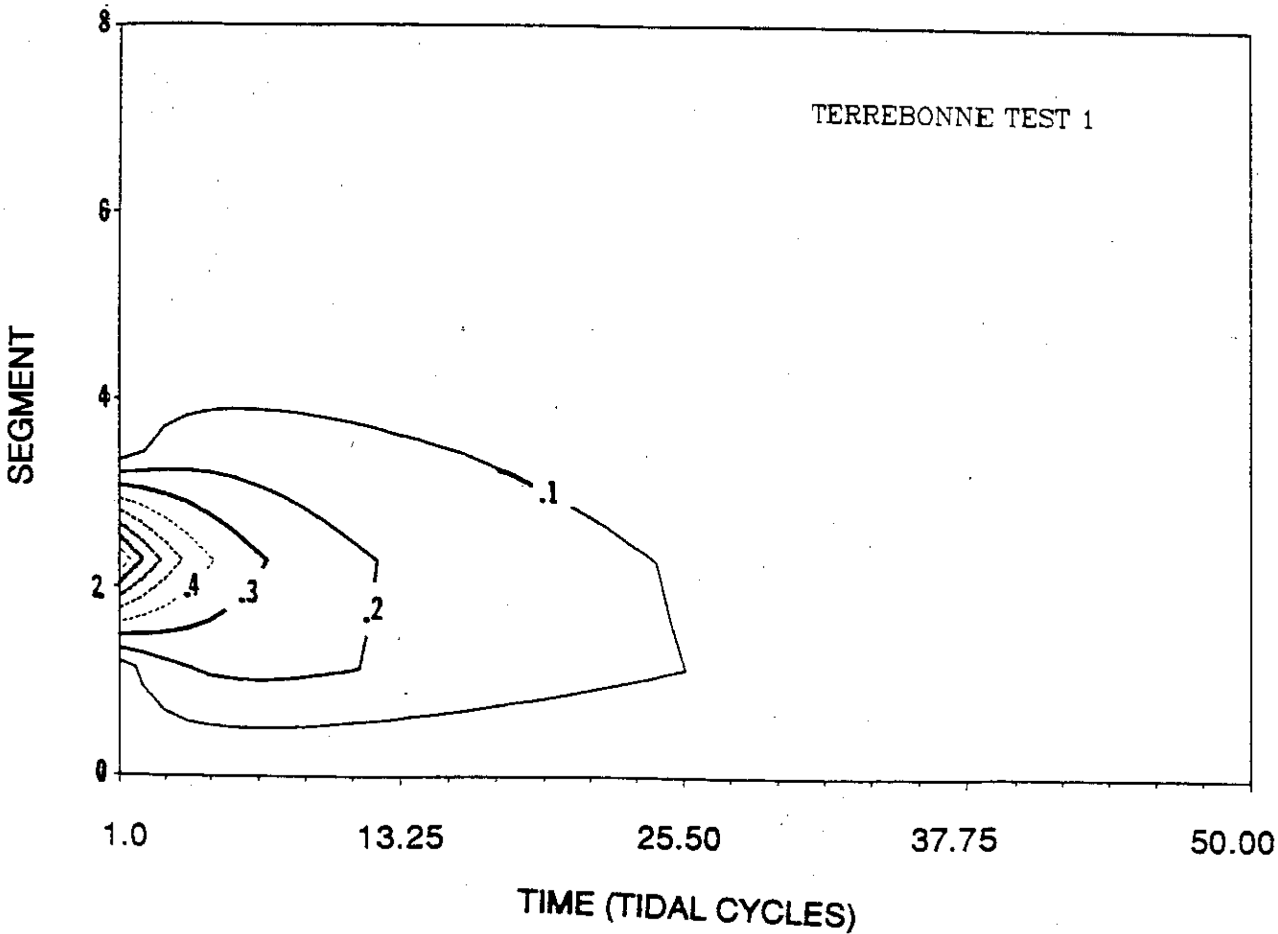


Figure 2.18. Contour plot of predicted concentrations as a function of time after release, at time t = 0, of a unit concentration in the upper portion of the Terrebonne-Timbalier Bay system. The horizontal axis is time, in tidal cycles and the vertical axis is segment number (proportional to distance downstream). The contour levels range from 0 to 1.0 and represent the relative concentration at a given time and segment.

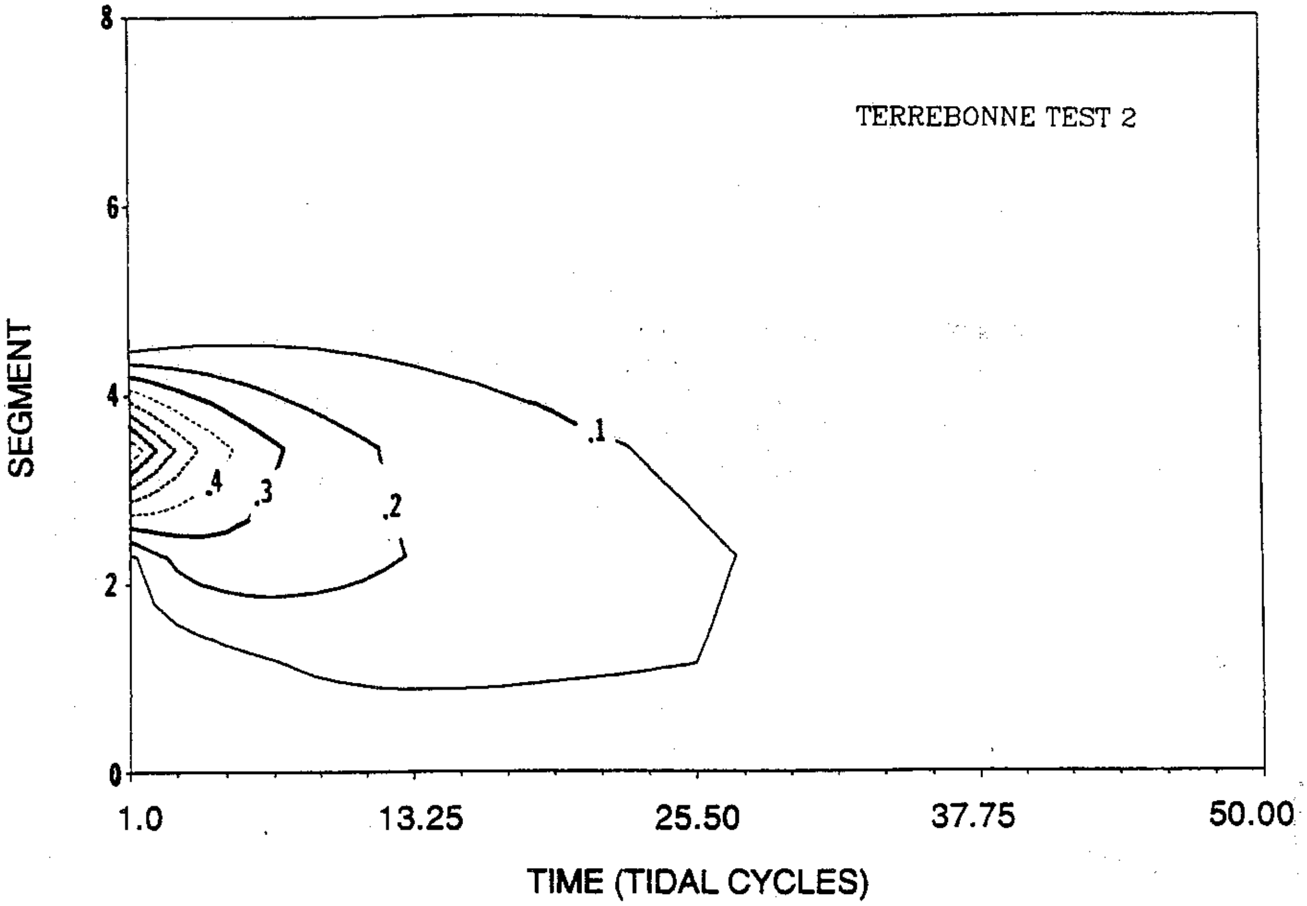


Figure 2.19. Contour plot of predicted concentrations as a function of time after the release, at time t = 0, of a unit concentration in the middle portion of the Terrebonne-Timbalier Bay system. The horizontal axis is time, in tidal cycles and the vertical axis is segment number (proportional to distance downstream). The contour levels range from 0 to 1.0 and represent the relative concentration at a given time and segment.

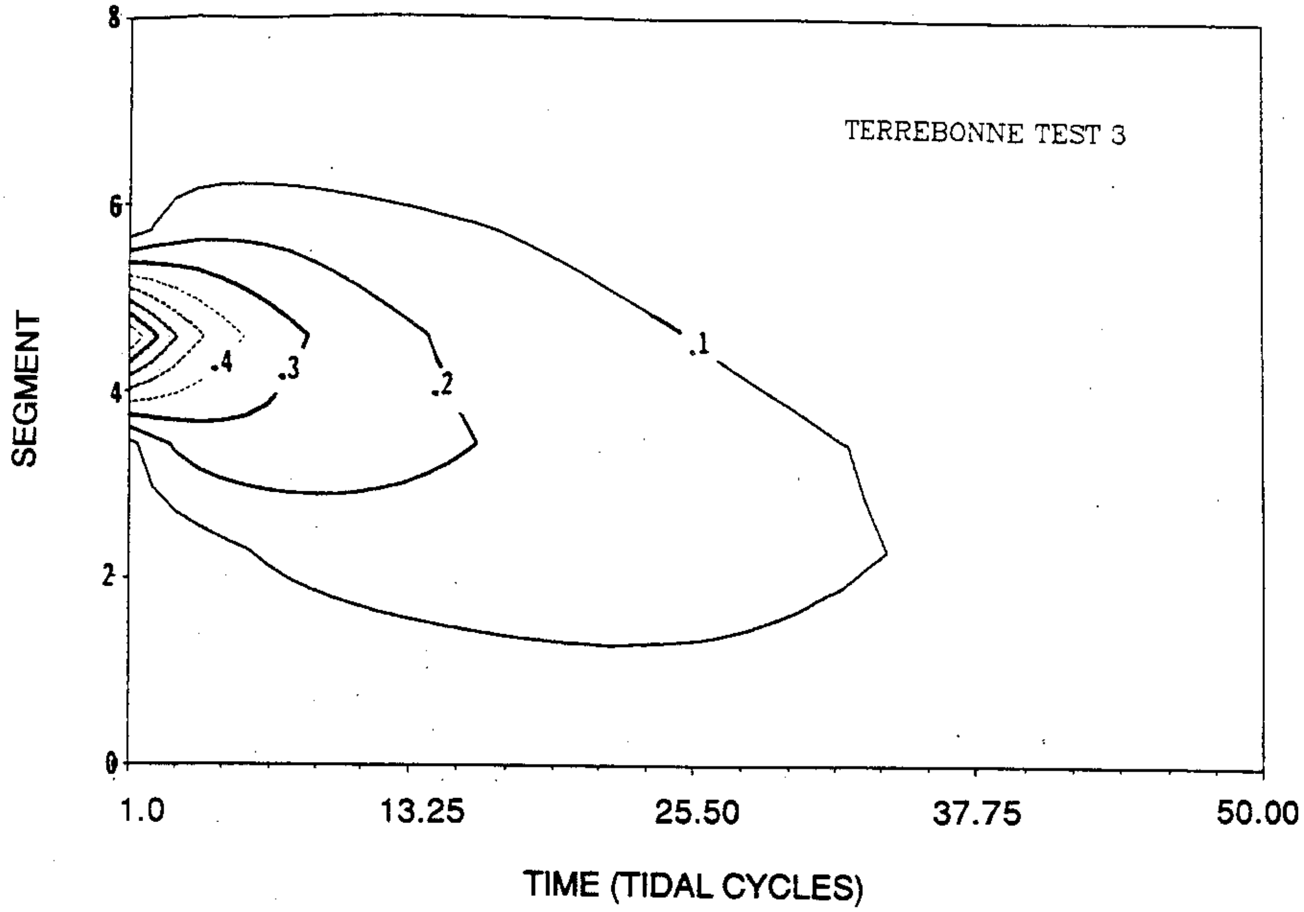


Figure 2.20. Contour plot of predicted concentrations as a function of time after release, at time t = 0, of a unit concentration in the lower portion of the Terrebonne-Timbalier Bay system. The horizontal axis is time, in tidal cycles and the vertical axis is segment number (proportional to distance downstream). The contour levels range from 0 to 1.0 and represent the relative concentration at a given time and segment.

driving anomalous cross-estuary flows (Kjerfve, 1973). Such flows are not accounted for by the simple segmentation process used in the model.

Each of the basins examined was fraught with multiple paths for the incoming waters to follow. Whereas the model was designed to handle a single channel system, the estuaries of south Louisiana contain numerous bayous, channels, and streams, all feeding into the same main bay. Some of these are broad channels that could be reasonably modelled given sufficient data. Others, such as the western regions of lower Terrebonne-Timbalier Basin, are so convoluted that the tidal prism model could only be conceived of as a lumped-parameter approximation to a complex, multiply-connected system. Some attempts have been made to construct tidal prism models of bifurcating systems (e.g., Brown and Arellano, 1980), but the success of these models has been marginal and data were not available for even an attempt at such a modification of the simplest system for the basins we examined.

Tidal range and water level varies on a variety of time scales in coastal Louisiana. The strongest tides, tropic tides, occur only part of the time. Through the course of a fortnight, tidal range may vary from 40 to 50 cm during tropic tides to near 0 cm during equatorial tides. We have used an approximation to the mean tidal range. Higher ranges will be associated with shorter flushing times and smaller ranges with longer flushing times. Mean water level changes on a semi-annual cycle by approximately 30 cm, or 10 - 20% of the total water depth throughout much of the Barataria Bay system. At low water level stands, the volume of water that must be exchanged with the shelf in order to flush the estuary is reduced. Furthermore, the tidal excursion of a particle is larger. Thus, one expects that the flushing times will be reduced during periods of low water.

Finally, the runoff to both systems investigated is very poorly known. We have made what appear to be reasonable assumptions concerning both the size and distribution of the runoff. Butler (1975) presents monthly runoff values at Des Allemands during the course of the year. These range from near 0 to nearly 4 x 10^6 m^3 per tidal cycle. A flood or massive rainfall could greatly increase the upstream runoff. This, in turn, would provide for rapid flushing of the upper system into the lower bay, where tidal flushing is most effective. This again will decrease the flushing time of the system.

2.6 Interpretation

The refill times for water and salt from produced waters suggest that the volume discharge of water is immaterial to the circulation within either system. The present estimates of the mass discharge of salt to Barataria Bay system is sufficiently large that it may be important to the total salt balance unless the mixing and non-tidal flushing are rapid enough to purge the system before a significant buildup occurs. This appears to be the case. The fact that the salinity signal is highly coherent with Mississippi River discharge on time scales of the order of a year implies a flushing time shorter than this period. The tidal prism modelling results (see below) also support this conclusion. In the Terrebonne-Timbalier system, the existing discharge of salt is less significant, both because the mass discharge rates are smaller than in the Barataria system and also because the ambient salt content of the system is greater.

The tidal prism model of the Barataria Bay system suggests that a contaminant (e.g., salt) discharge within the mid and lower bay will be reduced to 10% of its initial concentration level within less than 1.75 months. Within Terrebonne-Timbalier bays, this number increases to slightly over 2 months. Some of the caveats associated with this type of estimate have already been mentioned. This observation is only pertinent to the average concentration within the entire estuarine segment, not the dilution taking place in the vicinity of the produced water discharge. Field observations (see Chapters 6-8) have demonstrated a more than 20-fold dilution of produced water as a result of initial mixing. Furthermore, there are other sources of mixing and flushing present in the estuarine system besides simple tidal action. Wind mixing will be very effective during storms. The input of wind energy to the system is extremely effective in homogenizing these shallow systems (Schroeder et al., in press). The surge associated with a storm system can be as effective as the tides in exchanging waters with the coastal ocean (Schroeder and Wiseman, 1986). Water level variations over several days associated with frontal passage and wind shifts can result in water level changes of over 30 cm, representing an exchange of 10 to 20% of estuarine volume.

In the regions of restricted circulation, such as the western area of lower Terrebonne-Timbalier Basin, the multiple small bays, bayous and creeks contribute to an enhanced apparent longitudinal diffusion because of the storage of contaminant in small water bodies, from which it subsequently leaks (Okubo, 1973). Under similar tidal conditions, this would contribute to enhanced dispersion of an introduced contaminant. Unfortunately, it is not clear that the tidal wave propagates through this region without significantly enhanced dissipation. As mentioned above, NOS has indicated that tidal range is dramatically reduced within the small bayous within the marsh. Without hard data, though, we could not justify any particular methodology for incorporating this information into our modelling exercise. Thus, the net effect of weaker tidal flow and greater relative diffusion cannot be specified.

In a worst case scenario, one might still consider the results of our modelling to represent a box model of the system. Each box is not homogenized during a single tidal cycle, but general trends are represented by the output. Recognizing the problems mentioned above, the results of such a modelling exercise should provide order of magnitude estimates of the dispersion characteristics of the system. Our numbers do, in fact, agree with historical estimates of the flushing time of Barataria Bay. Kjerfve (1971) estimated a 50% renewal time for Airplane Lake (in the Barataria Basin) over 12 tidal cycles using a method developed by Pritchard. This implies a 90% renewal time, similar to what we have discussed, of 40 tidal cycles or about 1.3 months. Marmer (1948) estimated that 30% of the waters in Barataria Bay would be replenished each tidal cycle. He bases his estimate, though, on the assumption that there is no recirculation, i.e., that all water leaving the system on the ebb tide remains lost to the system. This is clearly not true. Much of the water leaving on the ebb cycle returns on the following flood tide. Thus Marmer's estimate is extremely liberal.

The analyses conducted in this project component do not address the degree to which salinity may be increased in the vicinity of produced water discharges because the time and space scales which can be studied using a tidal prism model are measured in days and kilometers, respectively. (As mentioned above, however, empirical evidence suggests that more than a 20-fold dilution takes place as a result of initial mixing, see Chapters 6-8). Nevertheless, a few important points deduced from these analyses should be stressed:

The water added to the estuaries studied by produced water discharges has a negligible effect on the circulation.

The salt added to the estuaries studied would double the present salinities only after a few years of discharge and, even then, only if there were no dispersion.

Assuming mean conditions, the concentration of any instantaneous discharge into the estuaries studied will be reduced to 10% of its initial value within less than two months.

The two month flushing time mentioned above is likely to be very conservative as it does not address the dispersion affected by floods, wind-driven mixing and wind-induced surges.

Even under worst case scenarios, it is unlikely that the mean salinities of any of the estuarine segments studied have increased more than a few per cent due to presently occurring produced water discharges.

These modelling efforts have been necessarily crude. It is unlikely that any great improvement in the reliability of the models will occur unless a very great effort is made to improve the data entering the model. Such an exercise does not appear to be warranted at this time. A far more productive effort might be spent on field measurements designed to characterize the dispersion environment in the sensitive regions of the system. In particular, the turbulent mixing and shear diffusion near the bottom of small bayous should be characterized.

Chapter 3

EFFECTS OF PRODUCED WATER DISCHARGES ON WETLAND VEGETATION

by

Irving A. Mendelssohn, Wayne Grip, Nelson May,
Kathryn M. Flynn and Brian J. Wilsey

3.1 Introduction

The influence of produced waters discharged from oil and gas production sites has recently been suggested as a major factor contributing to wetland loss. However, no data have existed to confirm or reject this assertion.

Produced water, the water separated from oil and gas reserves after their removal from the ground, generally contain high concentrations of dissolved salts, as well as hydrocarbons and heavy metals. In many coastal parishes in Louisiana, 95% of the oilfield produced water or brine is discharged into state waters (V. Van Sickle, quoted in the *Baton Rouge Morning Advocate*, December 29, 1987). The Department of Environmental Quality lists approximately 700 produced water discharges totalling 1.9 million barrels per day into Louisiana state waters (Boesch and Rabalais, 1989). Of this amount, approximately 1.2 million bbl/day are discharged into waters associated with coastal wetlands, including an estimated 887,850 bbl/day into brackish and freshwater wetlands. The effects of this addition of salt to brackish and freshwater wetland environments are undocumented.

The objectives of this study were to determine (1) if there were patterns of wetland loss apparent from historical comparisons of aerial photographs which could be attributed to produced water discharges; (2) if the marsh vegetation adjacent to sites of produced water discharge exhibit different biomass and species composition than nearby reference sites lacking produced water discharge; and (3) whether interstitial salinity and pH patterns relate to any observed differences in plant biomass and species composition.

3.2 Remote Sensing

3.2.1 Methods

The Remote Sensing Component involved the use of historical aerial photography, photointerpretation and computer mapping techniques to analyze temporal trends in the areal extent of wetlands and open water in the vicinity of produced water discharges and corresponding reference areas within each of the three study sites.

3.2.1.1 Imagery

A total of nine dates of historical aerial photography representing the period from 1940 to 1985 was obtained from government and private archives for the Bayou Sale and Golden Meadow sites. Similar coverage was obtained for the Lafitte site with the exception that 1952 was the earliest date of imagery obtained. In addition, high resolution color infrared photographs were taken in June, 1988, to provide current information on land cover and land use at the sites (Figure 3.1). These were most helpful in accurately locating discharge points and preparing accurate, contemporary maps for field studies. The dates, photo scales, and other characteristics of the aerial photography used in the study are listed in Table 3.1.

3.2.1.2 Sampling strategy

Aerial photographs were used for the selection of the rectangular study areas with "discharge" and "reference" comparison sections as described in Chapter 1. Large scale aerial photographs of the three study sites taken in December 1985 were used, each covering an area approximately 6,750 m N-S and 5,200 m E-W. The locations of produced water discharge facilities within these areas at the three sites were provided by ARCO, Exxon and Texaco. The approximate cumulative number of facilities operating at each site during the last four decades was estimated by using the locations of the discharge points and aerial photographs to follow the development of the fields. The estimated numbers of discharges operated within these three regions for the period 1941 to 1988 are shown in Table 3.2.

The study site rectangles selected for in-depth analysis of wetland changes and field studies (Chapter 1) encompassed approximately one square mile and included one or more produced water discharges and a reference area with approximately similar land-water ratio and configuration of canals and natural water bodies. Within both the discharge and reference areas, field sampling was concentrated within a 500-m radius of a discharge point or central point in a reference area. Thus, a similar scale of analysis of remote sensing imagery was chosen as most likely receiving heaviest contamination with salt and other contaminants which might adversely affect wetland vegetation. Because the 500-m sampling radii were not centered within the rectangular study site boundaries, some of the sampling stations were located outside of the area to be mapped. Within the 500-m radii, additional sampling radii were defined at 100-m intervals to track historical trends in waterbody sizes in relation to distance from the discharge point and center of reference area.

3.2.1.3 Photointerpretation and computer mapping

Photographic images were adjusted to the same scale and geographic coordinate system. Photography was co-registered to a Universal Transverse Mercator (UTM) using a four-step process. First, the 1978 color infrared photography was selected as a mapping base. The imagery was acquired during a high altitude NASA mission under near optimum atmospheric conditions and thus provided excellent planimetric control and resolution to serve as a mapping base. Second, four ground reference points were selected at each site that were visible in the historical imagery and on U.S. Geological Survey 7.5-min. topographic maps. The UTM coordinates of the ground reference points were determined from the topographic maps. Third, shorelines were delineated at each study site in the 1978 imagery using monoscopic and stereoscopic interpretation techniques and transferred to clear mylar overlays. Finally, the other dates of photography were interpreted and registered to the 1978 overlays, and mapped on separate layers of clear film. Spoil banks were also mapped from the 1988 imagery and transferred to clear film. The shoreline and spoil bank information was digitized and edited using AutoCAD software operating on a microcomputer-based digital mapping system. The system was equipped with a digitizing tablet, printer, color pen plotter, and three disk drives that provided a total of 70 Mb of storage space. Color maps showing shorelines, spoil banks, sampling radii, and the locations of field sampling stations were plotted on clear film.

Figure 3.1. Aerial photographs of the Bayou Sale, Golden Meadow, and Lafitte study sites and surrounding areas acquired in December 14, 1985. The boundaries of the mapped areas are delineated with black lines on the photographs.

AERO-DATA CORP.
Baton Rouge, LA

Table 3.1 Aerial photopgraphy used in the analysis of the Bayou Sale, Golden Meadow, and Lafitte study sites.

Date of acquisition	Film type	Photo scale	Source of of photography
January 15, 1940[a]	BW	1:20,000	U.S. Navy
May 14, 1941[b]	BW	1:18,000	U.S. Navy
February 27, 1952[b]	BW	1:20,000	Tobin
March 7, 1952[c,d]	BW	1:20,000	Tobin
March 8, 1952[a]	BW	1:20,000	Tobin
January 19, 1965	BW	1:78,000	Tobin
October 17, 1974[e]	CIR	1:120,000	EROS
October 1, 1978	CIR	1:65,000	EROS
December 14, 1985[e]	CIR	1:65,000	EROS
July 24, 1988	CIR	1:4,500	Aero-Data

[a] Overflight of the Golden Meadow study site.

[b] Overflight of the Bayou Sale study site.

[c] Overflight of the Lafitte study site.

[d] No coverage available for the Lafitte study site prior to 1952.

[e] Not mapped but used in conjunction with the other dates to aid in the photointerpretation analysis.

Table 3.2 Approximate cumulative number of produced water discharge points by year inferred from historical records and aerial photography for the three study sites.

Study site	Cumulative number of discharge points by year				
	1940's	1952	1965	1978	1988
Bayou Sale	1	20	22	22	22[a]
Golden Meadow	1	3	8	8	8
Lafitte	(b)	8	9	10	10

[a] According to the records, a total of seven discharge facilities were in the process of being deactivated or had been abandoned by 1988.

[b] There was no aerial photography available for the Lafitte study site prior to 1952.

3.2.1.4 Area measurements

Open water was classified into natural waterbodies and dredged areas. Most dredged areas could be easily distinguished from natural waterbodies because of the presence of spoil banks nearby. However, there were several areas within the study sites where this distinction was not clear-cut, such as where channels traversed natural waterbodies. In these cases, the area of open water in the natural waterbody that was later traversed by a canal was classified as a natural waterbody.

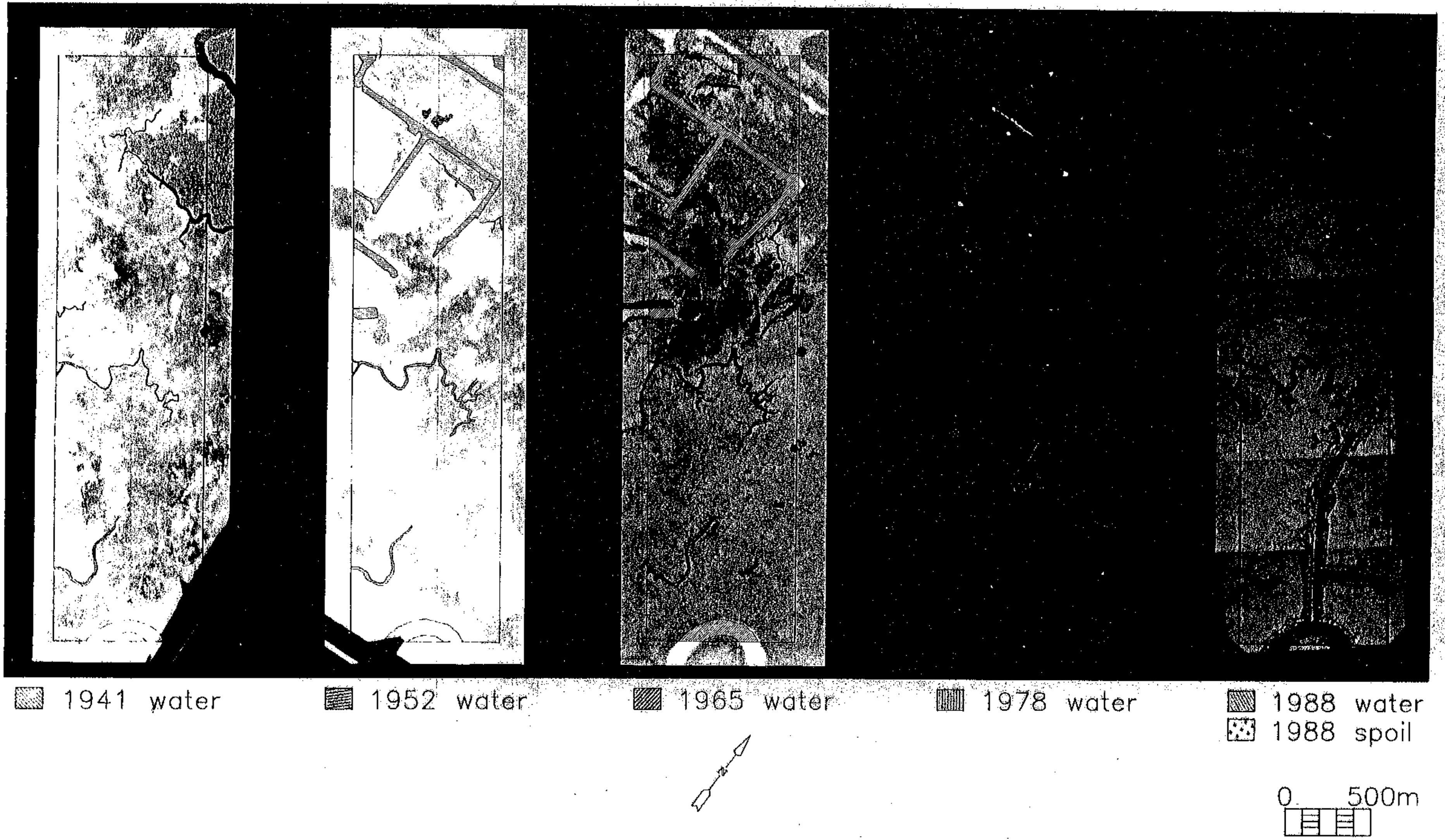
The potential long-term impacts of produced water discharges on wetland vegetation were evaluated by quantifying temporal changes in the areal extent of natural waterbodies and canals within sampling radii around each discharge point and comparing the tabulations with area measurements acquired with the same technique in the reference area. The area of natural waterbodies within a given sampling radius and the area of marsh which had been converted to a dredged canal was determined and expressed as percentages of the total area within each 100-m segment. This normalization was required because the area encompassed by within each sampling radius increased with distance from the center and because some circular sampling areas were truncated by the boundaries of the mapped areas. Figures 3.2 to 3.5 display the historical overlays for each study site and the cumulative changes.

3.2.2 Bayou Sale Site

The area of open water and canals for each sampling radius and each mapping period at the Bayou Sale site is presented in Table 3.3. Total marsh loss at the Bayou Sale site during the 1951 to 1985 period was less than half that at the Golden Meadow and Lafitte study sites (Figure 3.6). This is consistent with the broader trend of lower wetland loss in areas near the Atchafalaya River and its regular source of sediments, nutrients and freshwater. In fact there were signs of marsh expansion detected in the 1988 photography and, to a lesser extent, in the 1965 imagery. The presence of floating aquatic vegetation, such as common duckweed, *Lemna minor*, and water hyacinth, *Eichhornia crassipes*, in photographs taken during warmer months (1978 and 1988) presented some difficulties in interpreting the shorelines as this vegetation is virtually indistinguishable in the photographs from the surrounding marsh. Because there was less evidence of floating aquatic vegetation in the 1974 and 1985 imagery (winter time missions), these dates were used as collateral sources to facilitate the delineation of shorelines. Bayou Sale also differed from the other sites in that there was evidence of marsh regrowth detected in the 1988 photograph and, to a lesser extent, in the 1965 photograph.

Most of the development of the Bayou Sale field occurred between 1952 and 1974 as evidenced by the appearance of oil and gas access canals in the photographs. Most of the produced water discharges appeared to have begun operation in the early 1950s. There was very little difference in marsh loss between the discharge area and reference area and most of that was caused by canal dredging and spoil bank placement (Figures 3.6 and 3.7). The observed marsh loss not directly attributable to canals was generally well removed from canals and not hydrologically well connected with the canals receiving produced water effluents. The photographic evidence suggests that spoil banks created by canal construction created numerous obstructions to surface drainage and partial impoundments which may have eliminated wetland vegetation by submergemce.

Just to the north of the primary discharge point studied, a small area of marsh was lost during the 1941-52 period. A canal was dredged just to the south of this area during the same period. Although the effects of newly instituted produced water discharges cannot be definitively ruled out as a cause of this marsh loss, it appears likely that the spoil deposit from the canal blocked a natural marsh drainage channel and created an impoundment which caused a die back of the marsh vegetation.



Bayou Sale

Figure 3.2. Interpreted overlays registered to historical aerial photographs showing temporal changes in the areal extent of open water at the Bayou Sale study site.

AERO-DATA CORP.
Baton Rouge, LA

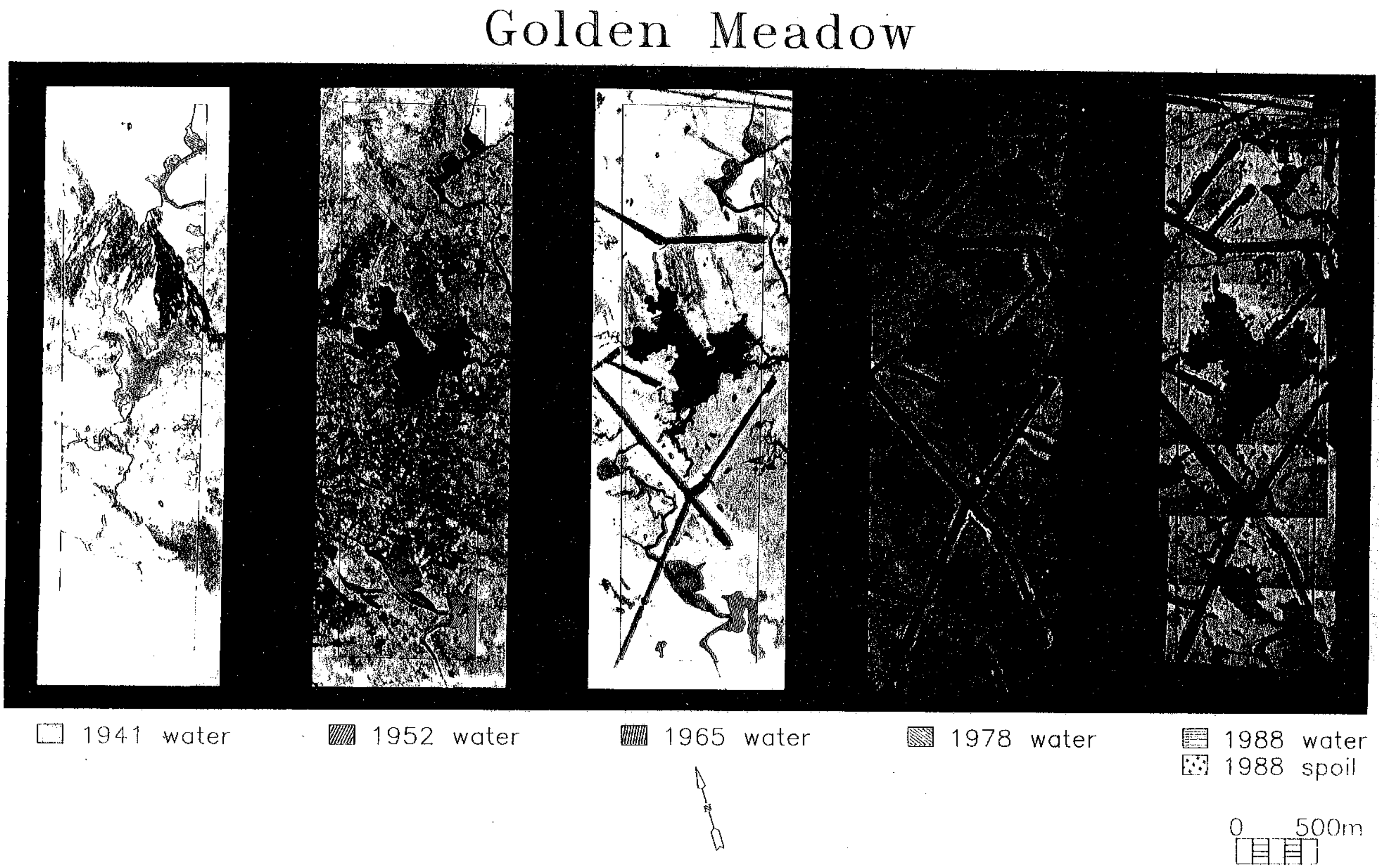


Figure 3.3. Interpreted overlays registered to historical aerial photographs showing temporal changes in the areal extent of open water at the Golden Meadow study site.

AERO-DATA CORP.

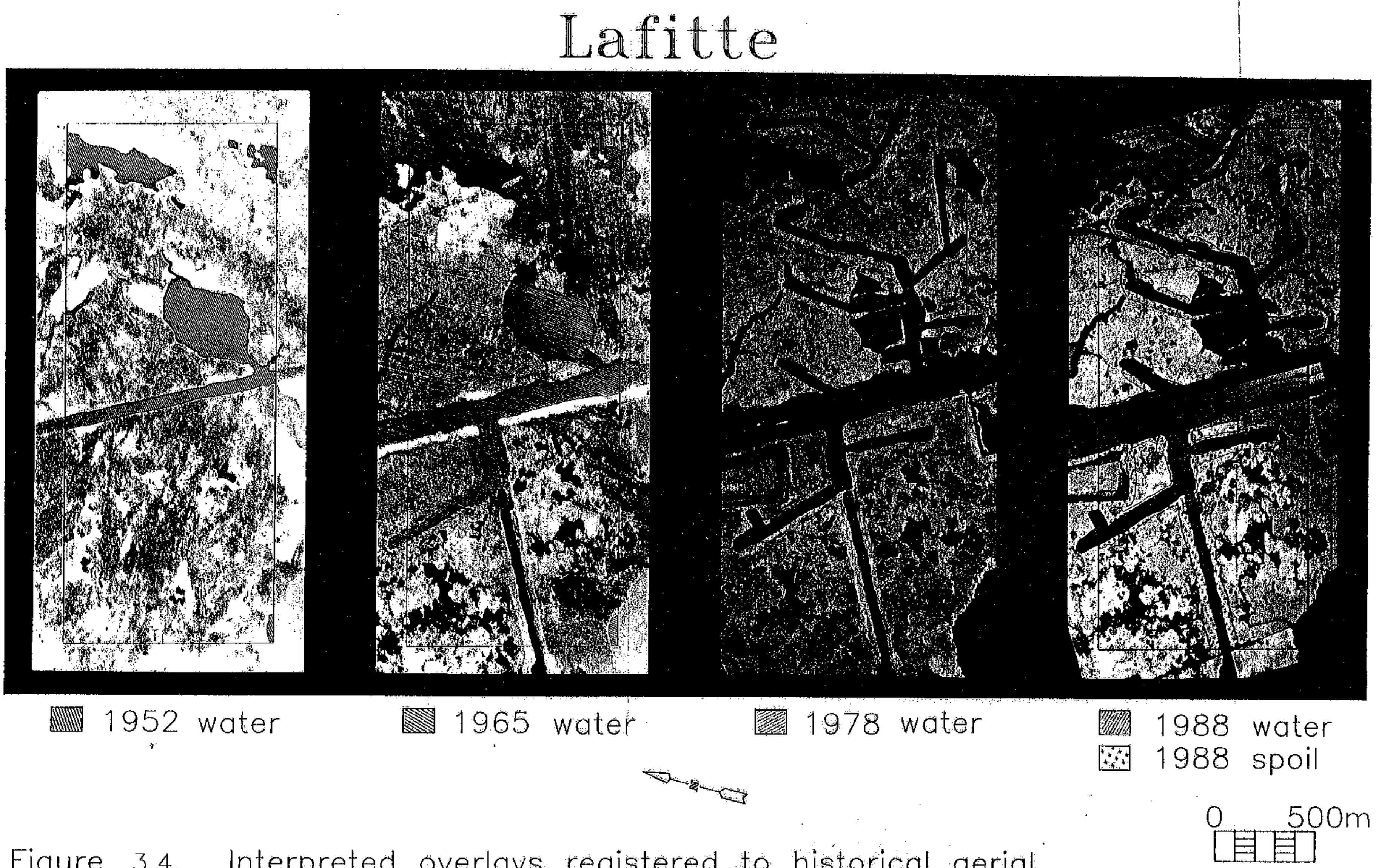


Figure 3.4. Interpreted overlays registered to historical aerial photographs showing temporal changes in the areal extent of open water at the Lafitte study site.

AERO-DATA CORP.
Baton Rouge, LA

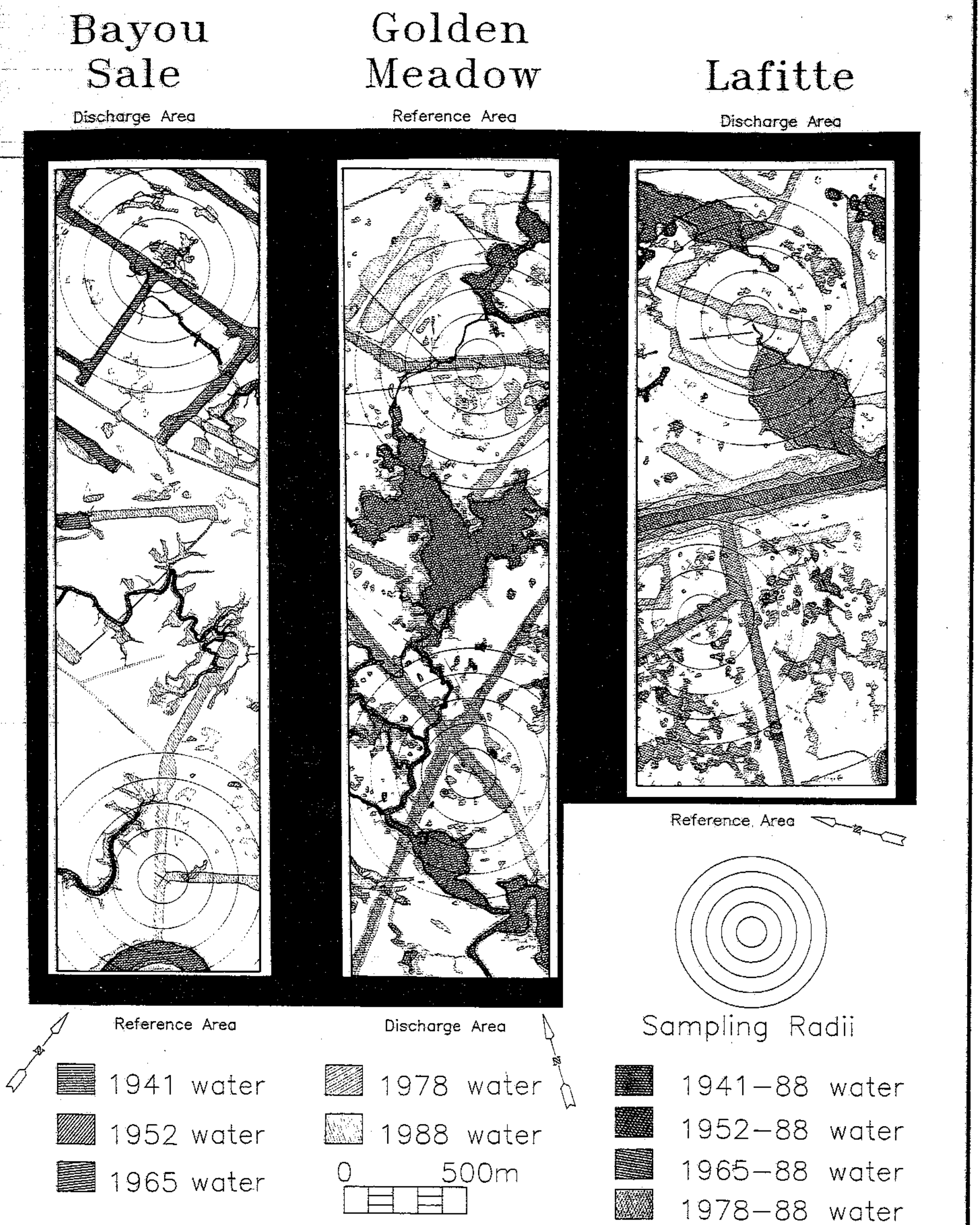
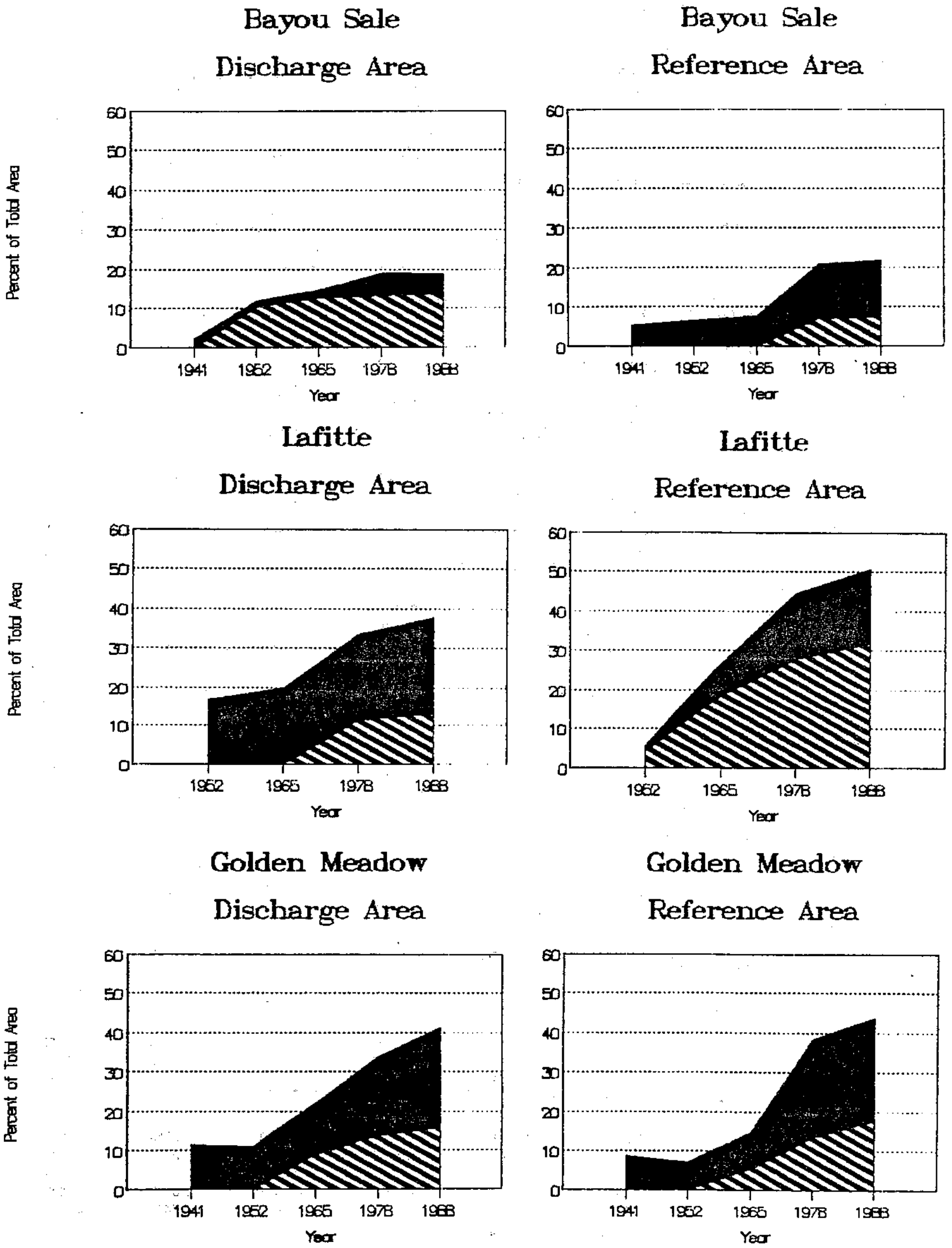


Figure 3.5. Interpreted and registered overlays showing cumulative changes in the areal extent of open water at the Bayou Sale, Golden Meadow, and Lafitte study sites.

Table 3.3. Area of open water and canals for each sampling radius and each mapping period at the Bayou Sale site.

Area	Date	Radii Segment	Radii Area (sq meters)	Water Area (sq meters)	Canal Area (sq meters)	Water Area	Canal Area
Discharge	5/15/41	100	31,416	4,809	0	15.31%	0.00%
		200	94,248	6,220	0	6.60%	0.00%
		300	157,079	945	0	0.60%	0.00%
		400	219,912	1,765	0	0.80%	0.00%
		500	170,863	1,514	0	0.89%	0.00%
	Total for 5/15/41:		673,518	15,253	0		
	2/22/52	100	31,416	3,861	9,523	12.29%	30.31%
		200	94,248	1,439	11,384	1.53%	12.08%
		300	157,079	857	9,415	0.55%	5.99%
		400	219,912	1,913	16,202	0.87%	7.37%
		500	170,863	1,149	22,510	0.67%	13.17%
	Total for 2/22/52:		673,518	9,219	69,034		
	1/24/65	100	31,416	0	10,607	0.00%	33.76%
		200	94,248	740	12,831	0.79%	13.61%
		300	157,079	3,905	10,550	2.49%	6.72%
		400	219,912	3,863	19,521	1.76%	8.88%
		500	170,863	4,103	31,116	2.40%	18.21%
	Total for 1/24/65:		673,518	12,611	84,625		
	10/1/78	100	31,416	6,894	10,893	21.94%	34.67%
		200	94,248	6,302	12,695	6.69%	13.47%
		300	157,079	10,676	11,130	6.80%	7.09%
		400	219,912	7,356	22,593	3.34%	10.27%
		500	170,863	7,898	31,220	4.62%	18.27%
	Total for 10/1/78:		673,518	39,126	88,531		
	7/24/88	100	31,416	6,713	10,712	21.37%	34.10%
		200	94,248	6,648	12,162	7.05%	12.90%
		300	157,079	7,590	11,153	4.83%	7.10%
		400	219,912	5,325	23,728	2.42%	10.79%
		500	170,863	7,525	34,392	4.40%	20.13%
	Total for 7/24/88:		673,518	33,801	92,147		
Reference	5/15/41*	100	31,416	0	0	0.00%	0.00%
		200	94,248	125	0	0.13%	0.00%
		300	157,079	11,537	0	7.34%	0.00%
		400	211,866	19,751	0	9.32%	0.00%
		500	146,295	2,405	0	1.64%	0.00%
	Total for 5/15/41:		640,904	33,818	0		
	2/22/52	100	31,416	0	0	0.00%	0.00%
		200	94,248	269	0	0.29%	0.00%
		300	157,079	12,031	0	7.66%	0.00%
		400	211,866	26,101	0	12.32%	0.00%
		500	146,295	2,730	0	1.87%	0.00%
	Total for 2/22/52:		640,904	41,131	0		
	1/24/65	100	31,416	502	0	1.60%	0.00%
		200	94,248	2,235	0	2.37%	0.00%
		300	157,079	14,679	0	9.34%	0.00%
		400	211,866	27,285	0	12.88%	0.00%
		500	146,295	3,841	0	2.63%	0.00%
	Total for 1/24/65:		640,904	48,542	0		
	10/1/78	100	31,416	0	10,329	0.00%	32.88%
		200	94,248	3,954	10,694	4.20%	11.35%
		300	157,079	32,387	9,402	20.62%	5.99%
		400	211,866	44,258	8,933	20.89%	4.22%
		500	146,295	6,939	5,925	4.74%	4.05%
	Total for 10/1/78:		640,904	87,538	45,283		
	7/24/88	100	31,416	0	9,386	0.00%	29.88%
		200	94,248	2,052	12,311	2.18%	13.06%
		300	157,079	30,704	10,539	19.55%	6.71%
		400	211,866	47,751	9,161	22.54%	4.32%
		500	146,295	11,006	6,230	7.52%	4.26%
	Total for 7/24/88:		640,904	91,513	47,627		



Bayou Sale Discharge Area

Bayou Sale Reference Area

Lafitte Discharge Area

Lafitte Reference Area

Golden Meadow Discharge Area

Golden Meadow Reference Area

Figure 3.6. Changes in the area of open water within the 500-m radius discharge and reference areas at each site as measured from aerial photographs (diagonally ruled: canals; solid: water bodies other than canals).

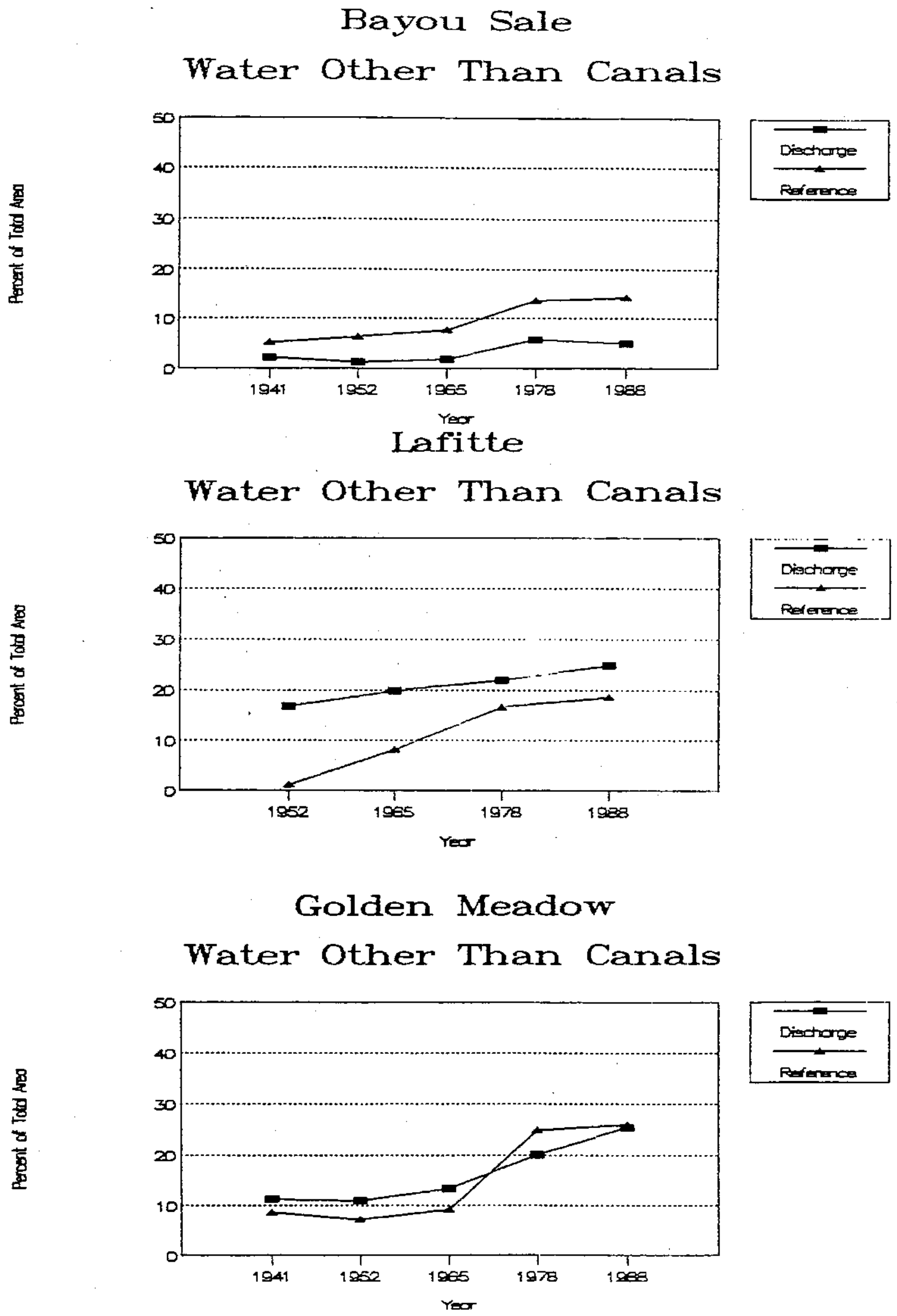


Figure 3.7. Changes in the area of water bodies other than canals within the 500-m radius discharge and reference areas at each site.

3.2.3 Lafitte and Golden Meadow Sites

The patterns and rates of marsh loss were similar in the Golden Meadow and Lafitte oil fields during the period from the early 1950s to the present (Tables 3.4 and 3.5, Figures 3.6 and 3.7). Mainly between 1952 and 1974, large amounts of solidly-vegetated marsh were converted to open water with highly reticulated shorelines. This was also a period characterized by active canal dredging associated with development of the fields. The resulting network of canals and adjacent spoil banks significantly altered the hydrology of the marsh. In addition, at the Lafitte site the widening and deepening of the Barataria Waterway resulted in large scale hydrological alterations.

The marsh losses observed which were not directly associated with canal construction or widening and spoil bank coverage were generally somewhat removed from the canals and are not hydrologically well connected to the receiving waters for produced water discharges. As in the case of Bayou Sale, these losses appeared to have resulted from the numerous partial impoundments created by spoil banks and consequent water logging of marsh vegetation. Corresponding with the reduction in the rate of new canal construction since 1978, there was a significant reduction in the rate of marsh loss. Assuming that produced water discharges in the area have probably increased since 1978 (as is the usual case in aging fields), this is further evidence that marsh loss has been much more affected by canal construction than produced water discharges.

The amount of marsh loss observed in discharge and reference areas was similar at the Golden Meadow site. At Lafitte, however, the loss was twice as great in the reference area as in the discharge area. This difference can be attributed to the presence of the Barataria Waterway which cuts portions of the sampling radii in the Lafitte reference area. Based on area measurements within 500 m of the discharge and reference points at both sites, there is no evidence of produced water effects on wetland loss.

3.3 Vegetation Field Assessments

3.3.1 Methods

3.3.1.1 Study Sites and Sampling Dates

The effects of produced waters upon marsh vegetation was investigated in three marshes in southern Louisiana (Figures 1.3, 1.8, and 1.12): Bayou Sale (fresh marsh), Lafitte (brackish marsh), and Golden Meadow (brackish marsh) [marsh types as determined by Chabreck and Linscombe (1978)]. Discharge (treatment) and reference sites were selected within each of these three marshes using color-infrared aerial photography generated by Aero-Data Corporation. At Golden Meadow a second treatment site was also chosen (Figure 1.12). The treatment and reference sites within each marsh were chosen such that the density and arrangement of canals and marsh areas were similar. Therefore, we attempted to ensure that the primary difference between the treatment and reference sites was the presence of the produced water discharge in the former. Of course, even with immediately adjacent treatment and reference sites this objective is very difficult, if not impossible, to completely achieve. Sampling was conducted at Golden Meadow on August 19, 1988 and September 8, 1988, Bayou Sale on August 23, 1988, and Lafitte on August 30, 1988. Details of the vegetation transects are given in Figures 1.6 through 1.7, 1.10 through 1.11 and 1.15 through 1.17.

3.3.1.2 Sampling Transects

Table 3.4. Area of open water and canals for each sampling radius and each sampling period at the Lafitte site.

Area	Date	Radii Segment	Radii Area (sq meters)	Water Area (sq meters)	Canal Area (sq meters)	Water Area	Canal Area
Discharge	3/7/52	100	31,416	654	0	2.08%	0.00%
		200	94,248	4,991	0	5.30%	0.00%
		300	157,079	19,585	0	12.47%	0.00%
		400	219,912	45,618	0	20.74%	0.00%
		500	268,512	58,755	0	21.88%	0.00%
	Total for 3/7/52:		771,167	129,603	0		
	1/19/65	100	31,416	0	0	0.00%	0.00%
		200	94,248	6,927	0	7.35%	0.00%
		300	157,079	22,956	0	14.61%	0.00%
		400	219,912	56,531	0	25.71%	0.00%
		500	268,512	66,496	0	24.76%	0.00%
	Total for 1/19/65:		771,167	152,910	0		
	10/15/78	100	31,416	343	10,257	1.09%	32.65%
		200	94,248	9,439	8,665	10.02%	9.19%
		300	157,079	22,459	24,264	14.30%	15.45%
		400	219,912	70,515	26,303	32.07%	11.96%
		500	268,512	66,851	18,151	24.90%	6.76%
	Total for 10/15/78:		771,167	169,607	87,640		
	7/24/88	100	31,416	818	11,818	2.60%	37.62%
		200	94,248	12,486	10,479	13.25%	11.12%
		300	157,079	24,967	29,026	15.89%	18.48%
		400	219,912	75,419	29,714	34.30%	13.51%
		500	268,512	76,703	18,124	28.57%	6.75%
	Total for 7/24/88:		771,167	190,393	99,161		
Reference	3/7/52	100	31,416	536	0	1.71%	0.00%
		200	94,248	355	0	0.38%	0.00%
		300	148,741	2,053	0	1.38%	0.00%
		400	160,338	2,260	594	1.41%	0.37%
		500	137,106	1,824	24,212	1.33%	17.66%
	Total for 3/7/52:		571,849	7,028	24,806		
	1/19/65	100	31,416	0	8,691	0.00%	27.66%
		200	94,248	3,237	12,693	3.43%	13.47%
		300	148,741	4,910	20,546	3.30%	13.81%
		400	160,338	16,644	18,808	10.38%	11.73%
		500	137,106	22,292	45,071	16.26%	32.87%
	Total for 1/19/65:		571,849	47,083	105,809		
	10/15/78	100	31,416	2,253	9,999	7.17%	31.83%
		200	94,248	7,069	20,405	7.50%	21.65%
		300	148,741	17,702	34,350	11.90%	23.09%
		400	160,338	30,417	36,414	18.97%	22.71%
		500	137,106	37,323	58,168	27.22%	42.43%
	Total for 10/15/78:		571,849	94,764	159,336		
	7/24/88	100	31,416	1,511	12,385	4.81%	39.42%
		200	94,248	9,761	25,351	10.36%	26.90%
		300	148,741	20,354	38,232	13.68%	25.70%
		400	160,338	34,704	45,554	21.64%	28.41%
		500	137,106	39,915	61,135	29.11%	44.59%
	Total for 7/24/88:		571,849	106,245	182,657		

Table 3.5. Area of open water and canals for each sampling radius and each sampling period at the Golden Meadow site.

Area	Date	Radii Segment	Radii Area (sq meters)	Water Area (sq meters)	Canal Area (sq meters)	Water Area	Canal Area
Discharge	1/15/40	100	31,416	0	0	0.00%	0.00%
		200	94,248	943	0	1.00%	0.00%
		300	157,079	10,490	0	6.68%	0.00%
		400	187,129	32,975	0	17.62%	0.00%
		500	174,958	28,749	0	16.43%	0.00%
	Total for 1/15/40:		644,830	73,157	0		
	3/8/52	100	31,416	0	0	0.00%	0.00%
		200	94,248	1,063	0	1.13%	0.00%
		300	157,079	10,271	0	6.54%	0.00%
		400	187,129	32,490	0	17.36%	0.00%
		500	174,958	27,418	0	15.67%	0.00%
	Total for 3/8/52:		644,830	71,242	0		
	1/19/65	100	31,416	169	7,062	0.54%	22.48%
		200	94,248	1,836	18,693	1.95%	19.83%
		300	157,079	13,322	12,456	8.48%	7.93%
		400	187,129	36,732	8,212	19.63%	4.39%
		500	174,958	34,317	9,913	19.61%	5.67%
	Total for 1/19/65:		644,830	86,376	56,336		
	10/15/78	100	31,416	930	9,135	2.96%	29.08%
		200	94,248	9,159	25,685	9.72%	27.25%
		300	157,079	22,681	21,747	14.44%	13.84%
		400	187,129	46,899	15,962	25.06%	8.53%
		500	174,958	49,109	15,936	28.07%	9.11%
	Total for 10/15/78:		644,830	128,778	88,465		
	7/24/88	100	31,416	1,406	11,360	4.48%	36.16%
		200	94,248	9,654	27,281	10.24%	28.95%
		300	157,079	30,258	25,006	19.26%	15.92%
		400	187,129	60,802	19,901	32.49%	10.63%
		500	174,958	61,512	18,261	35.16%	10.44%
	Total for 7/24/88:		644,830	163,632	101,809		
Reference	1/15/40	100	31,416	0	0	0.00%	0.00%
		200	94,248	0	0	0.00%	0.00%
		300	152,861	15,491	0	10.13%	0.00%
		400	169,300	12,358	0	7.30%	0.00%
		500	149,823	24,006	0	16.02%	0.00%
	Total for 1/15/40:		597,648	51,855	0		
	3/8/52	100	31,416	0	0	0.00%	0.00%
		200	94,248	4,136	0	4.39%	0.00%
		300	152,861	8,204	0	5.37%	0.00%
		400	169,300	9,663	0	5.71%	0.00%
		500	149,823	20,653	0	13.78%	0.00%
	Total for 3/8/52:		597,648	42,656	0		
	1/19/65	100	31,416	0	7,378	0.00%	23.48%
		200	94,248	1,748	7,855	1.85%	8.33%
		300	152,861	9,953	7,473	6.51%	4.89%
		400	169,300	16,123	5,560	9.52%	3.28%
		500	149,823	27,195	4,408	18.15%	2.94%
	Total for 1/19/65:		597,648	55,019	32,674		
	10/15/78	100	31,416	3,271	9,797	10.41%	31.18%
		200	94,248	17,644	10,791	18.72%	11.45%
		300	152,861	29,324	16,838	19.18%	11.02%
		400	169,300	21,857	29,785	12.91%	17.59%
		500	149,823	75,872	13,590	50.64%	9.07%
	Total for 10/15/78:		597,648	147,968	80,801		
	7/24/88	100	31,416	3,427	11,333	10.91%	36.07%
		200	94,248	18,815	12,078	19.96%	12.82%
		300	152,861	27,169	31,001	17.77%	20.28%
		400	169,300	24,954	37,303	14.74%	22.03%
		500	149,823	80,261	14,715	53.57%	9.82%
	Total for 7/24/88:		597,648	154,626	106,430		

Each treatment and reference site was divided into four 90^{o} quadrants starting from magnetic north. At the treatment sites, the discharge structure served as the center or pivot point of the four quadrants. At the reference sites, a point along the access canal served as the pivot point. Care was taken to choose each reference site so that it was physiognomically as similar as possible to the discharge site. Within each quadrant, a sampling transect was randomly established from a point immediately marshward of any natural or spoil levee (approximately 1-3 m marshward of a canal). At the second treatment site at Golden Meadow only one random transect was chosen. Location of transects was determined by selecting compass readings with a random numbers table. Sampling stations located at distances of 0, 4, 12, 36, and 108 meters from the starting point were marked along each transect, unless otherwise specified (e.g., Figure 1.6). Transect length was truncated on 6 of the 24 transects due to large areas of open water which made sample points inaccessible. In these cases, samples were collected at the last accessible point on the transect. However, all transects had 5 sampling stations with the exception of transect 1 at the treatment site of Bayou Sale (Figure 1.6) and transect 3 at the treatment site of Lafitte marsh which had four sampling stations (Figure 1.10). Thus, sample size was 40 (4 transects x 5 sampling stations/transect x 2 sampling plots/sampling station) for each site (treatment or reference) with the exception of the Lafitte and Bayou Sale treatment sites which each had a sample size of 38. The secondary treatment site at Golden Meadow had a sample size of 10 (1 transect x 5 stations x 2 sampling plots/station).

3.3.1.3 Vegetation Samples

Two sampling plots, located on either side of a transect, were randomly selected at each sampling station by tossing a circular wire quadrat of known area into the marsh. Since brackish and saline marshes have fewer plant species than fresh or intermediate marshes, a quadrat of 0.1 m^2 was used for the Golden Meadow and Lafitte marshes while a 0.25 m^2 quadrat was used for the Bayou Sale marsh. All vegetation (live and dead) within this quadrat was clipped to ground level, placed in plastic bags, transported to the laboratory and stored at 4^{o}C until sorted. Vegetation within each sample was identified to species, separated into live and dead categories and dried to a constant weight at 64^{o}C. In addition to species composition and above-ground biomass, species dominance values (SDV) were determined for treatment and reference sites. SDV = RF + RSC, where RF = relative frequency of species occurrence [(the number of times species A occurs/the number of times all species occur) x 100] and RSC = relative biomass of a species [(the mean biomass of species A/the sum of the mean biomass of all species] x 100). Since the RF and the RSC are percentages, the maximum SDV possible is 200 which will occur in monospecific stands.

3.3.1.4 Interstitial Water Samples

After vegetation samples were collected from the field plots, grab samples of soil were placed in zip-lock plastic bags, transported back to the lab and stored at 4^{o}C. Each soil sample was transferred to a centrifuge bottle and centrifuged at 5,000 rpm for 20 minutes in an RC-5B Refrigerated Superspeed Centrifuge to collect interstitial water. The pH and salinity of the interstitial water (supernatant) was determined using an Altex Model 3560 Digital pH Meter with a Corning General Purpose Combination Electrode and a Fisher Model 152 Conductivity Meter, respectively.

3.3.1.5 Statistical Analysis

The General Linear Model of the Statistical Analysis System (SAS, 1982) was used to analyze the data. The model was a factorial design with marsh location (Bayou Sale, Lafitte or Golden Meadow), treatment (produced water discharge or reference) and distance (0 to 108 m from the discharge or reference pivot points) as the main effects. The main effects and their interactions were tested using the Type I mean square for the Marsh x Treatment x Transect x

Distance interaction as the error term in the F-Test. Least squares means were used to identify statistically significant differences. Significant differences in the slope of the Treatment x Distance and Marsh x Distance interactions were determined with T-tests.

3.3.2 Vegetation Response

3.3.2.1 Plant biomass

Significant differences in live biomass occurred among marshes (Marsh main effect significant, $P<0.0001$) but not between treatments ($P > 0.07$). The brackish marshes, Lafitte and Golden Meadow, had significantly greater ($P < 0.0001$) live biomass (908 ± 65 g d wt m^{-2} and 822 ± 45 g d wt m^{-2}) than did the fresh marsh, Bayou Sale (334 ± 32 g d wt m^{-2}). Although the main effect of treatment on live biomass was not significant, individual marshes did exhibit a treatment effect (Treatment x Marsh interaction significant [$P < 0.02$]). Live biomass at the Golden Meadow marsh was significantly different ($P < 0.0002$) between the treatment and the references sites (Figure 3.8). The Golden Meadow treatment site , which received the produced water discharge, had 31% lower live biomass than its reference site (Figure 3.8). The secondary treatment site also had significantly lower ($P < 0.01$) live biomass than the reference site (Table 3.6). A significant Marsh x Distance interaction for live biomass ($P < 0.04$, Figure 3.9) indicated that regardless of the presence of produced water discharges, the trends in live biomass with distance were different with marsh sampled. Both Lafitte and Golden Meadow marshes exhibited significant increases ($P < 0.0001$ and $P < 0.003$, respectively) in live biomass with distance into the marsh (Figure 3.9). The rate of increase in live biomass with distance was significantly greater ($P < 0.05$) at Lafitte and Golden Meadow than that at Bayou Sale where live biomass did not increase with distance ($P > 0.93$) (Figure 3.9).

Averaged across all marshes, dead biomass was greater ($P < 0.006$) at the treatment sites (775 ± 75 g d wt m^{-2}) than the reference sites (471 ± 52 g d wt m^{-2}). In addition, when averaged over treatments, dead biomass at Lafitte (1118 ± 105 g d wt m^{-2}) was significantly ($P < 0.0001$) greater than at Golden Meadow (580 ± 37 g d wt m^{-2}) which in turn was greater ($P < 0.0001$) than at Bayou Sale (143 ± 20 g d wt m^{-2}). The treatment effect, however, differed with marsh (significant Treatment x Marsh interaction, $P < 0.006$). Dead biomass was significantly greater at both the Golden Meadow ($P < 0.03$) and Lafitte ($P < 0.0001$) treatment sites compared to their respective reference sites (Figure 3.10), but no significant difference was found between the Bayou Sale reference and treatment sites. The secondary site at Golden Meadow also had a higher dead biomass than the reference site (Table 3.6). Distance into the marsh was an important factor controlling dead biomass; however, the treatment effect influenced the response of dead biomass to distance (significant Distance x Treatment interaction, $P < 0.02$). Only at the reference site was the rate of increase in dead biomass with distance significant ($P < 0.0007$) (Figure 3.11). However, the reference site did not have a significantly greater rate of increase in dead biomass with distance than the treatment site ($P > 0.19$) (Figure 3.11).

When averaged over treatments, total (live plus dead) above-ground biomass was greatest at Lafitte (2027 ± 149 g d wt m^{-2}), lowest at Bayou Sale (477 ± 45 149 g d wt m^{-2}) and intermediate at Golden Meadow (1402 ± 67 149 g d wt m^{-2}) ($P < 0.0001$). The significant ($P < 0.009$) Marsh x Treatment interaction indicated that the response of total biomass to the treatment varied with marsh. Only at the Lafitte marsh was total biomass significantly different ($P < 0.0001$) at the treatment site compared to the reference site (Figure 3.12). Both Treatment and Marsh interacted significantly with Distance ($P < 0.05$). Total biomass increased significantly with distance into the marsh at both the reference and treatment sites ($P < 0.0001$ and $P < 0.05$, respectively), but the rate of increase was not significantly different ($P > 0.60$) between the sites (Figure 3.13). At the reference sites, total biomass increased slightly from 0 to 36 m and then almost doubled at 108 m (Figure 3.13). While at the treatment sites, total biomass decreased from 0 to 12 m and then increased at 36 and 108 m

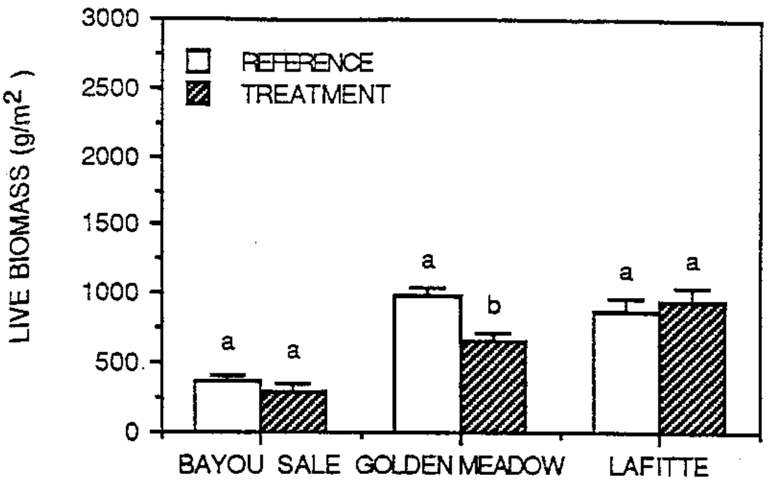


Figure 3.8. Comparison of aboveground live biomass between reference and treatment sites at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.). Different letters above bars within a marsh indicated significant differences (P<0.05).

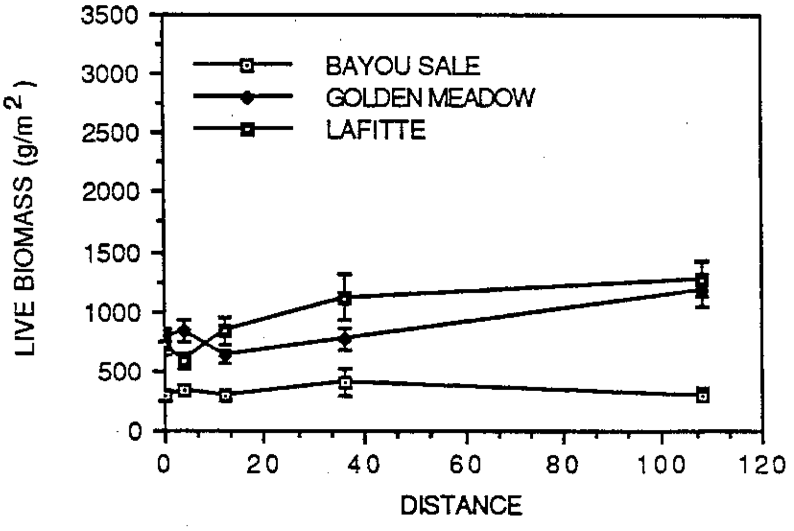


Figure 3.9. Aboveground live biomass as a function of distance into the marsh at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.)

Table 3.6. Comparison of plant and interstitial water variables at the three sampling sites at Golden Meadow marsh (different letters within a variable indicate significant differences at $P < 0.05$).

Variable	Primary Treatment Site (n = 39)	Secondary Treatment Site (n = 10)	Reference Site (n = 39)
Live biomass	653 ± 56a	652 ± 53a	986 ± 60b
Dead biomass	694 ± 58a	1107 ± 89b	469 ± 40c
Total biomass	1347 ± 105a	1759 ± 134a	1455 ± 86a
Salinity	126 ± 0.4a	11.8 ± 0.2ab	11.3 ± 0.4b
pH	5.64 ± 0.7a	5.17 ± 0.12b	6.48 ± 0.07c

Table 3.7 Species dominance values at Golden Meadow reference and treatment sites.

Species	N	Mean	Minimum Value	Maximum Value	STD Error of Mean
		REFERENCE			
Distichlis spicata	4	67.555	57.606	82.562	5.740
Spartina patens	4	33.467	29.354	43.257	3.277
Spartina alterniflora	4	43.821	34.942	58.069	5.086
Iva frutescens	4	16.985	16.695	17.257	0.153
Juncus sp.	4	18.269	16.667	21.926	1.226
Juncus roemerianus	4	17.403	16.667	18.462	0.378
		TREATMENT			
Distichlis spicata	4	14.867	9.822	20.200	2.310
Spartina patens	4	27.762	22.548	32.188	2.059
Spartina alterniflora	4	93.504	80.735	112.074	7.182
Iva frutescens	4	18.353	17.857	18.515	0.165
Juncus sp.	4	20.615	17.857	27.565	2.322
Juncus roemerianus	4	22.398	18.519	34.036	3.879

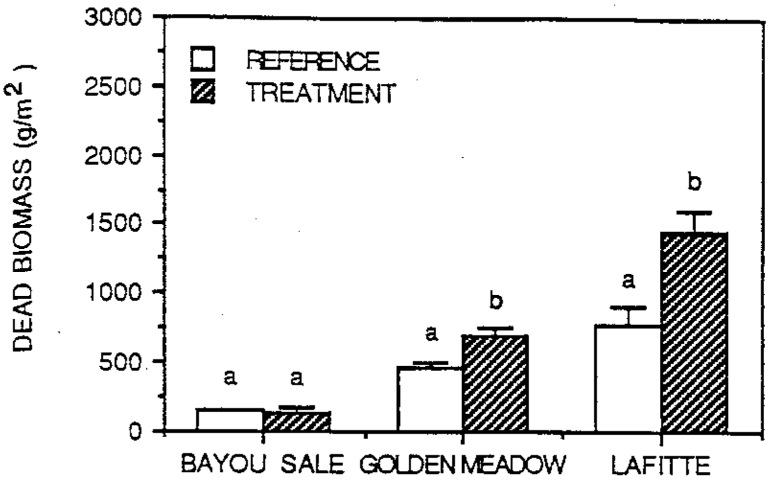


Figure 3.10. Comparison of aboveground dead biomass between reference and treatment sites at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.). Different letters above bars within a marsh indicate significant differences ($P<0.05$).

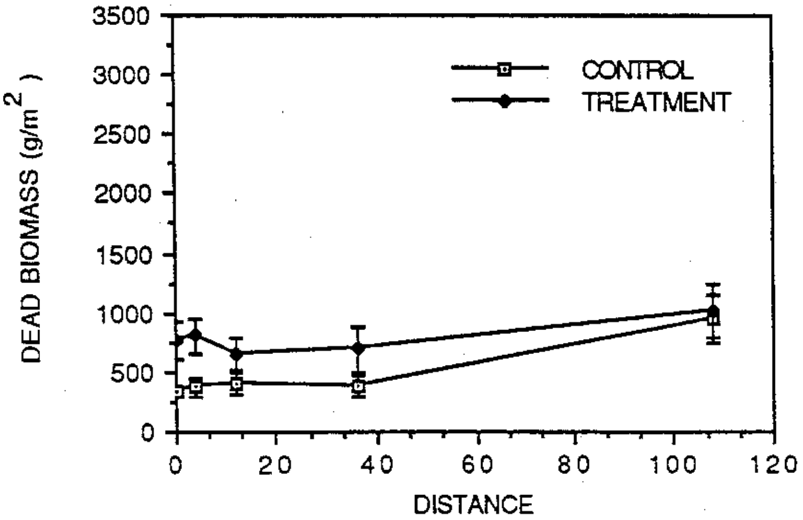


Figure 3.11. Aboveground dead biomass as a function of distance into the marsh at the reference and treatment sites (mean ± s.e.).

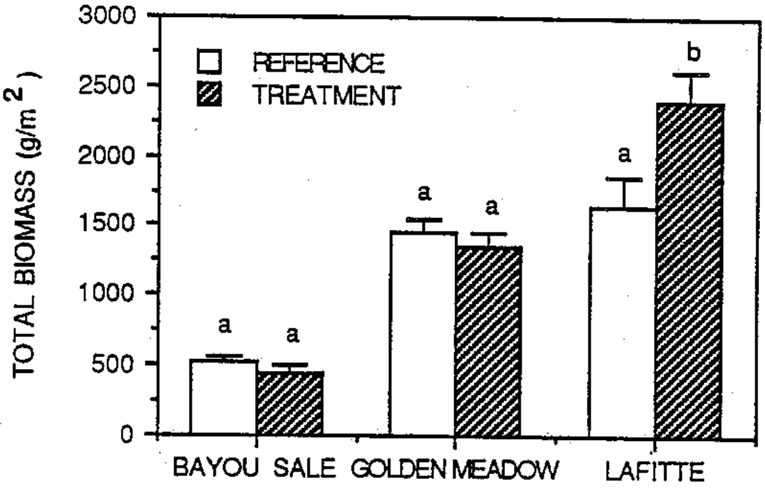


Figure 3.12. Comparison of aboveground total (live + dead) biomass between reference and treatment sites at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.). Different letters above bars indicate significant differences ($P<0.05$).

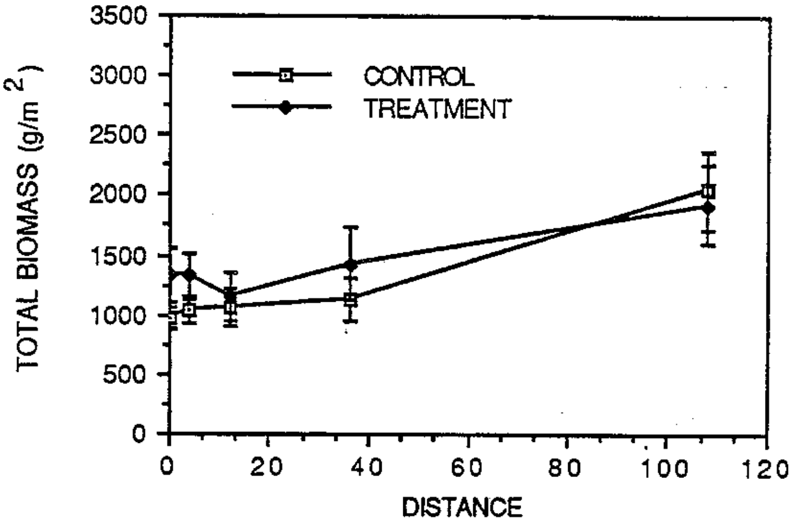


Figure 3.13. Aboveground total (live + dead) biomass as a function of distance into the marsh at the reference and treatment sites (mean ± s.e.).

(Figure 3.13). When averaged over treatments (Treatment main effect not significant, $P > 0.13$), total biomass at Golden Meadow and Lafitte increased with distance into the marsh, while that at Bayou Sale remained constant with distance (Figure 3.14). The rate of increase in total biomass with distance was significantly greater ($P < 0.06$) at Golden Meadow and Lafitte compared to Bayou Sale (Figure 3.14).

3.3.2.2 Plant species composition

The species composition of the three marshes reflected the salinities at each marsh as indicated by Chabreck and Linscombe (1978). The highest salinity marsh, Golden Meadow, contained the fewest vascular plant species (6) with *Spartina alterniflora* and *Distichlis spicata* dominant (Table 3.7). The medium salinity marsh, Lafitte, contained 18 species with *Spartina patens* and *Distichlis spicata* dominant (Table 3.8). Bayou Sale, the lowest salinity marsh, had the highest number of species (36) and was dominated by *Ludwigia leptocarpa*, *Sagittaria lancifolia*, *Alternanthera philoxeroides* and *Phyla nodilora* (Table 3.9).

At the Golden Meadow reference site, *Distichlis spicata*, *Spartina alterniflora* and *S. patens* were dominant with species dominance values (SDV) of 68, 44, and 33 respectively (Table 3.7). At the produced water discharge site, *S. alterniflora* and *S. patens* were dominant with SDVs of 94 and 28, respectively (Table 3.7). The SDV for *D. spicata* was significantly ($P < 0.0001$) lower and that for *S. alterniflora* was significantly ($P < 0.0009$) greater in the treatment site compared to the reference (Table 3.7). The secondary site also showed a dominance of *S. alterniflora* (SDV = 104) over *Distichlis* (SPV = 21) with *S. patens* a strong subdominant (SDV = 75) (note: since only one transect was sampled at the secondary site, an estimate of variation around the mean was not possible). This difference in species composition between the reference and treatment sites does not in itself support the conclusion of a produced water effect at the treatment site since *Distichlis* is more salt tolerant than is *S. alterniflora* (Parrondo et al., 1978). If there were a produced water effect at the treatment site, one would expect to find the more salt tolerant species dominating this habitat; this was not the case. Instead the highly flood tolerant *S. alterniflora* dominated the treatment site which indicates that the treatment site had experienced greater tidal inundation or duration of flooding than the reference site at Golden Meadow. This situation could be a response to a more altered hydrology caused by spoil banks at the treatment site compared to that at the reference site.

At Lafitte, the reference site was dominated by *Spartina patens* and *Distichlis spicata*, while *S. patens* dominated the treatment site (Table 3.8). The SDV for *S. patens* was significantly ($P < 0.05$) higher at the treatment site than the reference, while that for *D. spicata* was significantly ($P < 0.003$) lower at the treatment site (Table 3.8). As was observed for Golden Meadow, the species composition data in themselves do not suggest a brine effect at the treatment site at Lafitte. Instead, the dominance of *S. patens* relative to *D. spicata* at the treatment site would indicate more flooded conditions or a lower marsh surface elevation compared to the reference site where *S. patens* shared dominance with *D. spicata*. The majority of remaining species at Lafitte had SDVs of 5 and 6 (Table 3.8) and thus were of relatively minor importance.

Bayou Sale, the lowest salinity marsh, contained the greatest number of vascular plant species at 36 with 19 species common to the treatment and reference sites (Table 3.9). The reference and treatment sites contained 31 and 24 vascular plant species, respectively. *Ludwigia leptocarpa*, *Alternanthera philoxeroides* and *Phyla nodiflora* were dominant in the reference site, while *Ludwegia*, *Sagittaria lancifolia*, *Alternanthera* and *Phyla* were dominant in the treatment site (Table 3.9). The SDV for *S. lancifolia* was significantly ($P < 0.003$) higher in the treatment site than the reference site (Table 3.9). The difference in species composition between reference and treatment sites at Bayou Sale were relatively minor and do not immediately indicate a produced water discharge effect at the treatment site.

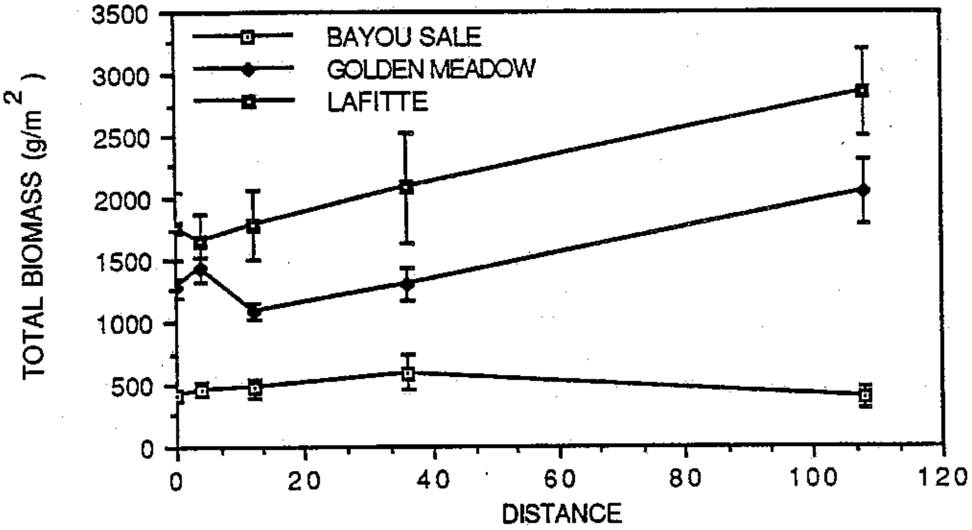


Figure 3.14. Aboveground total (live + dead) biomass as a function of distance into the marsh at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.).

Table 3.8. Species dominance values at Lafitte reference and treatment sites.

Species	N	Mean	Minimum Value	Maximum Value	STD Error of Mean
		REFERENCE			
Spartina patens	4	57.705	47.430	70.406	4.949
Distichlis spicata	4	37.196	27.315	48.604	5.094
Eleocharis spp.	4	5.606	5.556	5.682	0.027
Lythrum lineare	4	5.623	5.556	5.682	0.031
Baccharis halimifolia	4	5.822	5.587	6.295	0.160
Scirpus maritimus	4	6.419	5.587	8.029	0.565
Juncus roemerianus	4	13.603	5.556	5.751	6.588
Aster subulatus	4	5.644	5.556	5.738	0.045
Acnida sp.	4	5.640	5.556	5.738	0.042
Heleotropruim	4	5.630	5.587	5.681	0.025
Scirpus olneyi	4	6.832	5.587	9.767	0.996
Impomoea sagittata	4	5.613	5.587	5.681	0.023
Cyperus spp.	4	5.616	5.556	5.734	0.040
Aster sp.	4	5.640	5.556	5.830	0.064
Juncus sp.	4	5.603	5.556	5.682	0.027
Pluchea camphorata	4	5.603	5.556	5.682	0.027
Sagittaria lancifolia	4	5.603	5.556	5.682	0.027
Eleocharis parvula	4	5.603	5.556	5.682	0.027
		TREATMENT			
Spartina patens	4	86.253	55.289	101.694	10.489
Distichlis spicata	4	12.066	9.417	14.919	1.370
Eleocharis spp.	4	6.978	5.556	11.244	1.422
Lythrum lineare	4	5.980	5.556	7.254	0.425
Baccharis halimifolia	4	5.587	5.556	5.682	0.032
Scirpus maritimus	4	5.587	5.556	5.682	0.032
Juncus roemerianus	4	6.068	5.556	7.478	0.471
Aster subulatus	4	5.587	5.556	5.682	0.032
Acnida sp.	4	5.587	5.556	5.682	0.032
Heleotropruim	4	5.587	5.556	5.682	0.032
Scirpus olneyi	4	7.877	5.556	13.759	1.971
Impomoea sagittata	4	5.587	5.556	5.682	0.032
Cyperus spp.	4	5.587	5.556	5.682	0.032
Aster sp.	4	5.587	5.556	5.682	0.032
Juncus sp.	4	6.270	5.556	8.412	0.714
Pluchea camphorata	4	7.600	5.556	13.730	2.043
Sagittaria lancifolia	4	5.587	5.556	5.682	0.032
Eleocharis parvula	4	5.626	5.556	5.838	0.071

Table 3.9. Species dominance values at Bayou Sale reference and treatment sites.

Species	N	Mean	Minimum Value	Maximum Value	STD Error of Mean
REFERENCE					
Sagittaria lancifolia	4	8.661	3.345	17.196	2.980
Sagittaria graminea	4	0.000	0.000	0.000	0.000
Eichhorina crassipes	4	3.462	0.000	13.849	3.462
Aster spp.	4	0.555	0.000	2.219	0.555
Pluchea foetida	4	0.272	0.000	1.088	0.272
Juncus effusus	4	2.000	0.000	4.367	0.953
Bacopa sp.	4	2.782	0.000	8.254	1.866
Leersia sp.	4	1.540	0.000	3.211	0.665
Dichromena colorata	4	0.772	0.000	1.974	0.479
Hydrocotyle spp.	4	6.176	5.844	6.577	0.167
Cyperus spp.	4	10.022	8.307	12.179	0.804
Sesbania drummondii	4	1.607	0.000	5.372	1.279
Ludwigia leptocarpa	4	29.570	21.862	44.868	5.227
Polygonum sp.	4	11.274	8.014	12.709	1.103
Sagittaria latifolia	4	0.000	0.000	0.000	0.000
Ceratophyllum demersum	4	0.000	0.000	0.000	0.000
Cladium jamaicense	4	0.000	0.000	0.000	0.000
Saururus cernuus	4	0.000	0.000	0.000	0.000
Distichlis spicata	4	0.659	0.000	2.638	0.659
Habenaria repens	4	0.972	0.000	3.887	0.972
Eupatorium coelestinum	4	0.582	0.000	2.330	0.582
Miscellaneous	4	2.809	0.978	5.290	0.969
Unidentified grass	4	0.493	0.000	1.020	0.285
Eleocharis rostellata	4	3.569	0.000	8.240	2.109
Juncus roemerianus	4	2.199	0.000	5.537	1.182
Scirpus maritimus	4	1.704	0.000	2.726	0.618
Typha sp.	4	3.553	0.000	9.697	2.121
Eclipta alba	4	4.337	0.000	8.953	2.239
Galium sp.	4	1.213	0.000	2.934	0.730
Juncus sp.	4	1.691	0.000	3.096	0.662
Mikania scandens	4	5.984	0.000	10.437	2.220
Ipomoea sp.	4	1.086	0.000	2.321	0.630
Alternanthera philoxeroides	4	16.358	1.041	55.257	13.008
Vigna luteola	4	11.109	0.000	20.078	4.257
Phyla nodiflora	4	15.812	10.642	19.416	2.021
Spartina patens	4	11.055	4.281	16.883	2.601

Table 3.9. (continued)

Species	N	Mean	Minimum Value	Maximum Value	STD Error of Mean
		TREATMENT			
Sagittaria lancifolia	4	31.317	24.389	40.756	3.445
Sagittaria graminea	4	2.587	0.000	9.088	2.187
Eichhornia crassipes	4	6.494	0.000	9.796	2.220
Aster spp.	4	0.000	0.000	0.000	0.000
Pluchea foetida	4	0.000	0.000	0.000	0.000
Juncus effusus	4	0.000	0.000	0.000	0.000
Bacopa sp.	4	4.483	1.906	10.126	1.929
Leersia sp.	4	0.000	0.000	0.000	0.000
Dichromena colorata	4	0.000	0.000	0.000	0.000
Hydrocotyle sp.	4	9.697	2.085	14.829	2.710
Cyperus spp.	4	5.031	0.000	11.280	2.452
Sesbania drummondii	4	0.704	0.000	2.818	0.704
Ludwigia leptocarpa	4	32.191	22.875	52.688	7.010
Polygonum sp.	4	13.341	8.233	21.103	2.896
Sagittaria latifolia	4	1.431	0.000	4.288	1.011
Ceratophyllum demersum	4	0.417	0.000	1.668	0.417
Cladium jamaicense	4	0.650	0.000	2.600	0.650
Saururus cernuus	4	1.089	0.000	4.358	1.089
Distichlis spicata	4	0.000	0.000	0.000	0.000
Habenaria repens	4	0.000	0.000	0.000	0.000
Eupatorium coelestinum	4	0.000	0.000	0.000	0.000
Miscellaneous	4	4.640	2.758	6.261	0.759
Unidentified grass	4	2.083	0.000	3.929	0.858
Eleocharis rostellata	4	1.855	0.000	7.419	1.855
Juncus roemerianus	4	0.000	0.000	0.000	0.000
Scirpus maritimus	4	0.000	0.000	0.000	0.000
Typha sp.	4	0.000	0.000	0.000	0.000
Eclipta alba	4	6.029	4.081	9.049	1.120
Galium sp.	4	0.000	0.000	0.000	0.000
Juncus sp.	4	1.188	0.000	4.754	1.188
Mikania scandens	4	1.852	0.000	4.506	0.949
Ipomoea sp.	4	1.405	0.000	4.314	1.017
Alternanthera philoxeroides	4	22.988	0.000	49.965	10.265
Vigna luteola	4	2.604	0.000	8.274	1.956
Phyla nodiflora	4	21.452	1.942	40.231	6.357
Spartina patens	4	6.769	0.000	20.623	4.741

3.3.3 Interstitial Salinity and pH

Interstitial salinity was significantly different among marshes ($P < 0.0001$) and treatments ($P < 0.02$) with no significant interaction ($P > 0.18$) between these two main effects. Bayou Sale had the lowest salinity at 1.29 ± 0.09 ppt (range: 0 to 3), Golden Meadow the highest at 11.90 ± 0.28 ppt (range: 6 to 17) and Lafitte intermediate at 8.40 ± 0.18 ppt (range: 5 to 12) ($P < 0.0001$). Averaged over all marshes, the treatment sites had significantly higher salinity (7.53 ± 0.45 ppt, range: 1 to 17 ppt) than the reference sites (6.94 ± 0.43 ppt, range: 0 to 17). Although the Treatment x Marsh interaction was not significant ($P > 0.18$), Golden Meadow was the only marsh where a significant difference in salinity between the reference and treatment sites occurred, the treatment site being higher by 1.2 ppt (Figure 3.15). The salinity at the secondary site was not significantly greater ($P > 0.54$) than in the treatment site (Table 3.6). In addition, the minimum salinity at the treatment site (8 ppt) was 2 ppt higher than the reference site (6 ppt). The 50% greater salinity at the Bayou Sale treatment site (1.55 ppt) compared to the reference site (1.02 ppt) was not statistically different ($P > 0.39$) (Figure 3.15). Overall, there was a significant ($P < 0.02$) distance effect with salinity increasing from 0 (7.1 ppt) to 12 m (7.6 ppt), decreasing at 36 m (6.7 ppt) and increasing again at 108 m (7.2 ppt).

Although interstitial pH was significantly different between treatment and reference sites in the various marshes, the trends were not consistent among marshes (significant Marsh x Treatment interaction, $P < 0.0001$). At Golden Meadow both the primary and secondary treatment sites had a significantly ($P < 0.0001$) lower pH than the reference site (Figure 3.16). However, at Lafitte the opposite was true, i.e., the treatment site had a significantly ($P < 0.0001$) higher pH than the reference site (Figure 3.16). No significant pH difference ($P > 0.48$) between the treatment and reference site was observed at Bayou Sale. Averaging over all treatments (Marsh effect significant, [$P < 0.0001$]), Golden Meadow and Lafitte had the highest pHs at 6.07 ± 0.07 (range: 4.84 to 7.23) and 5.99 ± 0.05 (range: 4.90 to 7.02), respectively, and Bayou Sale the lowest pH at 5.23 ± 0.07 (range: 3.84 to 6.10). Averaging over all marshes (Treatment effect significant, [$P < 0.03$]), the treatment sites had a significantly ($P < 0.01$) lower pH (5.69) than the reference sites (5.85).

3.3.4 Relationship Between Plant Response and Interstitial Salinity and pH

A correlation analysis of the data collected demonstrated very similar relationships between plant response and interstitial salinity and pH within each marsh. All marshes exhibited significant negative correlations between live biomass and salinity (Golden Meadow: $r = -0.20$, $P < 0.09$; Lafitte: $r = -0.23$, $P < 0.04$; Bayou Sale: $r = -0.25$, $P < 0.03$). In addition, salinity was negatively correlated with pH in all marshes (Golden Meadow: $r = -0.30$, $P < 0.01$; Lafitte: $r = -0.16$, $P < .14$; Bayou Sale: $r = -0.71$, $P < 0.0001$), i.e., the higher the salinity the lower the pH. Normally, seawater salinities are associated with more alkaline conditions since sea water has an average pH of 8.6. Thus, if natural variation in interstitial salinity was the cause for its negative relationship with live biomass, we would expect to see a positive relationship between salinity and pH, rather than the observed negative relationship. Another explanation for the negative relationship between salinity and pH might involve the high chlorinity of produced waters which could cause greater acidic conditions. However, when separate correlation analyses were performed for each reference and treatment site within a marsh, we did not find evidence for a produced water effect at the treatment sites.

For example, at Bayou Sale the negative relationship between live biomass and salinity was not significant and occurred in both treatment and references sites (reference site: $r = -0.19$, $P > 0.25$; treatment site: $r = -0.25$, $P > 0.13$). When interstitial conductivity was correlated with live biomass, a significant negative relationship occurred, but only at the reference site ($r = -0.34$, $P < 0.04$). The positive relationship between pH and biomass at Bayou Sale was also only

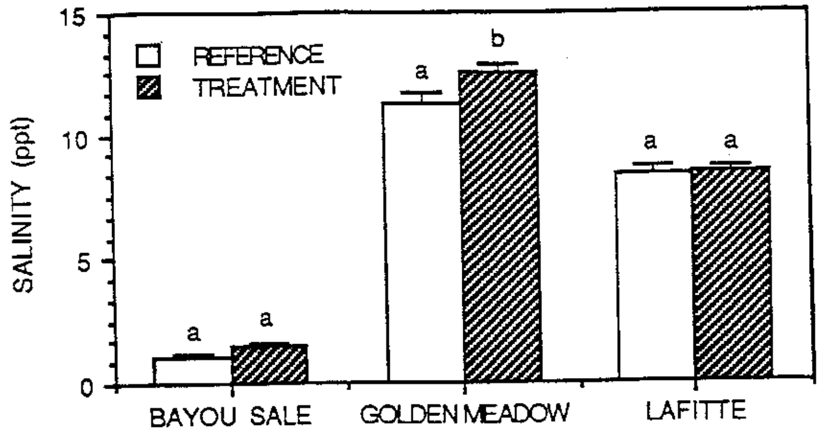


Figure 3.15. Comparison of salinity between reference and treatment sites at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.). Different letters above bars indicate significant differences (P<0.05).

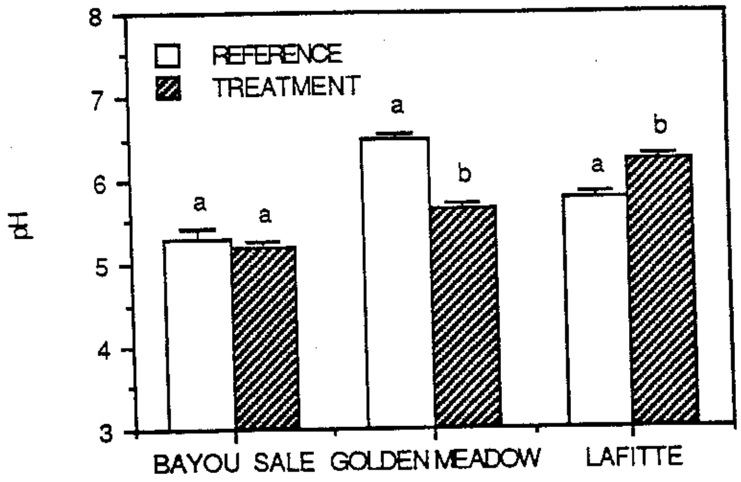


Figure 3.16. Comparison of pH between reference and treatment sites at Bayou Sale, Golden Meadow and Lafitte marshes (mean ± s.e.). Different letters above bars indicate significant differences (P<0.05).

significant at the reference site ($r = 0.33, P < 0.05$). In addition, the negative correlation between pH and salinity was significant at both the reference and treatment sites of Bayou Sale ($r = -0.76, P < 0.0001$; $r = -0.69, P < 0.0001$, respectively) indicating that the pH-salinity relationship found in this marsh was not related to the produced water discharge.

At Golden Meadow and Lafitte, the overall negative relationship between live biomass and salinity was primarily due to the significant correlation between these two variables in the reference site since no significant relationship was found at the treatment site (Golden Meadow reference: $r = -0.32, P < 0.05$; Golden Meadow treatment: $r = 0.19, P > 0.25$; Lafitte reference: $r = -0.40, P < .01$; Lafitte treatment: $r = -0.01, P > 0.93$). The negative pH-salinity relationship at Golden Meadow was primarily due to the reference site ($r = -0.37, P < 0.02$; treatment site: $r = 0.08, P > 0.65$). However, at Lafitte the negative relationship between pH and salinity was determined by the treatment site ($r = -0.37, P < 0.02$). These results do not support the hypothesis that the negative relationship seen in all marshes between salinity and biomass was a result of produced water.

In summary, the correlation analysis demonstrated that live biomass was negatively related to salinity and positively related to pH. Since these two environmental variables are highly correlated with each other, they may be controlled by the same factor. This factor could be the produced water since produced waters are high in salinity, but because of their high chlorinity, are also of high acidity, thereby resulting in the negative relationship between pH and salinity. However, when calculated separately for reference and treatment sites, correlations did not support the argument that the cause of the negative relationship between salinity and live biomass at the three marshes are due to the produced water.

3.4 Discussion

Assessment of the impacts of produced water discharges on wetland vegetation in this study was by two approaches and on different time scales. Remote sensing allowed the evaluation of large scale changes of wetlands to open water environments over decadal time scales. Field sampling allowed the evaluation of any more subtle patterns of plant species composition and biomass which may presently be evident on smaller spatial scales in association with produced water discharges.

Analyses of historical aerial imagery at the three study sites uncovered no suggestive evidence of wetland losses caused by produced water discharges. At each study site, dredging of canals in the marsh, the filling of marsh with dredge spoil, and indirect effects associated with impounding wetlands by spoil banks appeared to the principal causes of wetland loss since the early 1950s. Wetland loss not directly attributable to canal construction, widening and spoil banks was more rapid at the two brackish marsh sites (Lafitte and Golden Meadow) which are characterized by salt-tolerant vegetation than at the fresh marsh site (Bayou Sale) which is characterized by salt-intolerant vegetation. There was no localized loss of wetlands historically observed associated with the commencement of produced water discharges.

The goals of the vegetation sampling and analysis were two fold. Firstly, we sought to determine if the marsh vegetation adjacent to sites of produced water discharge exhibited different biomass and species composition than nearby reference sites. Secondly, we attempted to find relationships between interstitial water pH and salinity and these vegetation parameters in order to determine if any observed vegetational response was due to produced water discharge.

With respect to our first objective, only the Golden Meadow marsh showed significantly lower biomass at the treatment site compared to the reference site. Was this lower live biomass due to the produced water discharge? Since brine is a major component of produced waters, one might expect a higher interstitial water salinity at the treatment site compared to the reference if the lower live biomass at the former was due to the produced waters. Although we did find a significantly higher salinity in the treatment site at Golden Meadow than at the reference site, the salinity difference was only 1.5 ppt in a marsh with a mean salinity of 11.9 ppt. This salinity difference should have little to no effect on the biomass production of the dominant plant species in this marsh (Parrondo et al., 1987; Mendelssohn and McKee, 1987). Of course, these salinity values are based on a one time sampling in August. Whether the salinity difference between the sites becomes more extreme at other times of the year is unknown.

With respect to our second objective, we found an indication ($P<0.09$) of a negative correlation between interstitial salinity and live biomass in the Golden Meadow marsh, but this negative correlation was due to the salinity/live biomass relationship in the reference site ($r = -0.32$) rather than that in the treatment site ($r = 0.19$). Therefore, the lower live biomass at the treatment site could not have been due to a brine effect. Although interstitial pH was significantly lower at the Golden Meadow treatment site than the reference site, the pH-live biomass correlation showed that lower biomass was only associated with lower pH in the reference site. Could some other component of the produced water have caused the biomass reduction in the treatment site? Petroleum hydrocarbon concentrations were higher in soils in the treatment area, where plant biomass was less, than in the reference area. This correlation was, however, not significant ($r=-0.22$, $P>0.46$). A larger sample size is required to clarify the significance of this relationship. We conclude that there is no evidence that the lower live, above-ground biomass at the Golden Meadow treatment site compared to the reference site was due to produced water discharges, but may have been due to an oil release into this marsh at some time in the past and/or natural variation between sites.

Dead above-ground biomass, in addition, was significantly higher in the treatment sites at both Golden Meadow and Lafitte marshes. This may be indicative of a greater rate of plant mortality at these two treatment sites. Live biomasses in the treatment sites were lower or equal to that observed in the reference sites. Differences in dead biomass, therefore, were not likely caused by differences in live biomass. Another factor that could affect the amount of dead biomass is differential burning of treatment and reference sites. If the treatment sites were less frequently burned because of their close proximity to the tank batteries, the greater dead biomass at the treatment sites compared to the reference sites might be due to this burning factor. However, there was no field evidence that the reference marshes had undergone burning within a year of the sampling dates. In addition, the amount of dead biomass was substantial at the Golden Meadow and Lafitte reference sites (Figure 3.10), indicating the absence of any recent burning at these locations. These observations, however, do not rule out burning in previous years which could have influenced the observed biomass differences between reference and treatment sites.

Although species composition was relatively similar between treatment and reference sites, the relative dominance of various species did show significant differences between the sites. For example, at Golden Meadow *Spartina alterniflora* was significantly more dominant in the discharge site compared to the reference site, while *Distichlis spicata* was more dominant in the reference site. Since *S. alterniflora* is less salt tolerant, but more flood tolerant than *D. spicata*, these data suggest that the treatment site at Golden Meadow is generally more flooded and/or is more biochemically reduced (lower Eh) than the reference site. If a lower soil Eh does exist at the treatment site, this could be the result of the introduction of petroleum hydrocarbons which would provide a carbon source for bacteria, stimulating their metabolism and generating lower soil Eh. However, we have no direct data to confirm this hypothesis. It is interesting to note that the Golden Meadow secondary treatment site, which was also contaminated with petroleum hydrocarbons, exhibited a similar dominance of *S. alterniflora* over *D. spicata*. A significant difference in species dominance also occurred at the Lafitte marsh with *S. patens* more dominant and *D. spicata* less dominant in the treatment site compared to the reference site. The dominance of the more flood-tolerant *S. patens* suggests that the treatment site was of lower elevation and less frequently drained than the reference site. Since petroleum hydrocarbon contamination was not found in the Lafitte marsh, the dominance of *S. patens* over *D. spicata* could not have been due to a petroleum hydrocarbon generated lowering of the soil Eh. Hence, the difference in species dominance between the treatment and reference sites at Lafitte were probably due to natural variation rather than an effect of the produced water. The primary difference is species dominance at Bayou Sale was for *Sagittaria lancifolia* which was a dominant species at the treatment site but only a relatively minor species a the reference site. This difference is as yet unexplained.

Of the three marshes investigated only Golden Meadow exhibited a significant live above ground biomass reduction at the site receiving produced waters compared to the reference site. However, we have no evidence to support the contention that the observed biomass reduction at Golden Meadow was due to produced water discharge at this time. The elevated hydrocarbon concentrations at the treatment site suggests that a petroleum release may have been responsible for the lower live biomass found there. A produced waters effect on live above-ground biomass was not found at Bayou Sale or Lafitte marshes.

Our analyses are based on only three study sites, located in brackish to fresh conditions and at which significant discharges of produced waters occur. While it is possible that produced water discharges have resulted in damage to wetlands and increased loss rates, the observations made in this Chapter and elsewhere in this report suggest that such an effect is unlikely and would at most be localized. Produced waters which are discharged directly on or seep out onto the marsh surface could stress or kill wetland plants; however, the issue under examination here is the effects of discharges directly into water bodies. Two features reduce the exposure of the marsh vegetation to diluted brine in receiving waters. First, because it is denser than the estuarine receiving waters, the produced water dilution plume tends to be found along the bottom of the bayou or canal and represents very rapid dilution of the effluent upon discharge (Chapters 6, 7, and 8). It is the fresher surface water, not the bottom water, that enters the marsh via tidal inundation. Second, produced water discharges in wetland areas are essentially invariably associated with canal construction. As a consequence, the spoil banks which line the canals serve as an at least partially effective barrier to tidal inundation from the canal.

Chapter 4

FIELD ASSESSMENTS: HYDROGRAPHIC, CHEMICAL AND BIOLOGICAL METHODS

Jay C. Means and Nancy N. Rabalais

4.1 Field Logistics

Component 3 of the overall study consisted of field studies of the three marsh environments. In these studies, the chemical characteristics of produced waters discharged were analyzed, and water quality, chemical contaminants in the environment, wetland vegetation, and bottom-dwelling (benthic) organisms were sampled. Sampling was conducted at the three sites in a coordinated fashion. The sample design, including the station locations, was reviewed and approved by Mid-Continent following site visits by members of the research team and representatives of industry.

Detailed maps of each study site were given in Chapter 1. At each site a grid of stations was placed in water bodies around each discharge point in all directions at distances of 0, 100, 250, 500, 750, 1000, and 1500 m. In some cases, farthest distances sampled away from the discharge were 700, 750, or 1000 m, where restrictions were created by features of the environment or overlap with reference areas or other discharge points. Reference stations were located in as similar a nearby environment as possible at least 1 km away from the discharge. Where treatment sites included canals and natural waterways, the reference stations were situated as closely as possible in similar environments.

An attempt was made to collect chemical, benthic, and vegetative samples within the same day or week, but always within the same two-week period. Produced water discharges, chemical contaminants in water bodies and in the marsh, and benthic macroinfaunal samples in water bodies and in the marsh were taken on the same dates. Vegetation samples were often sampled on different dates. Table 4.1 provides the dates and types of samples taken at each of the study areas.

All collections from canals were taken from a small outboard boat. This sample platform provided ready access to shallow environments, but sometimes prohibited sampling in deeper channels, especially where currents were swift. Where the latter situation was encountered, stations were moved laterally until sediments could be reached with the various pieces of equipment that were used.

4.2 Hydrography

Water column hydrography measurements were made with a Hydrolab Surveyor II conductivity/temperature/depth (CTD) unit. The instrument was lowered to the bottom and a near-bottom measurement was made. Subsequent measurements were taken at 1-m intervals to the surface. The CTD was calibrated prior to field measurements and immediately thereafter according to the methods outlined in the manual (Hydrolab Corp., 1984). Corrections, based on the post calibration, were made to the data if necessary. The Hydrolab unit is maintained yearly by Hydrolab Corporation.

4.3 Sample Collection

Produced water discharges were collected either from the discharge pipe as it entered the receiving water environment, or from a spigot on the discharge pipe at the point nearest

Table 4.1. Dates and types of collections at each of the three study areas.

Study Area	Date	Sample Type
Bayou Sale	23 August	All vegetation samples Half chemical contaminants Half benthic macroinfauna
	24 August	Half chemical contaminants Half benthic macroinfauna Produced water discharge
Laffite	30 August	All vegetation samples
	1 September	All chemical contaminants All benthic macroinfauna Produced water discharge
Golden Meadow	19 August	Primary and reference vegetation transects
	7 September	Most chemical contaminants Most benthic macroinfauna Primary produced water discharge
	8 September	Part chemical contaminants Part benthic macroinfauna Secondary produced water discharge Secondary vegetation transect

discharge into the environment. Water column samples from the receiving environment were collected with a 1-l horizontally-mounted Alpha water sampler at a depth of 0.5 m below the surface of the water, so that water column samples consisted of "near surface" waters. Samples were pooled to obtain the volumes necessary for analyses. Water samples for volatile (VOA) and semivolatile organic analysis were placed in specially cleaned glass containers. Those for VOA were filled to the top in 15-ml sample bottles with a special plastic insert that prevented the inclusion of air bubbles. Water samples for semivolatile analysis were placed in 4-l sample bottles. Water samples for trace metal analysis and salinity determinations were placed in specially cleaned 500-ml plastic bottles. Water samples were stored on ice until return to the laboratory where they were stored at 4°C until analysis.

In the canals, sediment samples for chemical contaminants, total organic carbon (TOC) and sediment grain size analysis were collected in 7.5-cm core tubes mounted at the end of a long pole with a "core catching" device at its end. The cores were stored on ice until return to the laboratory where they were stored frozen until analysis. Two cores were collected, one for analysis, and one for archival. Subsamples of surface sediments (0-5 cm) from a third and fourth core were taken for TOC and sediment grain size samples. Canal sediments for benthic macroinfaunal analysis were collected with a 0.025-m^2 Peterson grab. On occasion when the Peterson grab would not collect an adequate sample, a 0.023-m^2 Ekman grab mounted on a pole was used. Both samplers penetrated the sediments to depths of 11-15 cm. Sediments were placed in 1-gal buckets, fixed with 10% buffered formalin stained with rose bengal, and transferred to the laboratory. Benthic samples were taken in triplicate.

Marsh sediments for chemical contaminants, total organic carbon, sediment grain size analysis, and benthic macroinfauna were taken with 7.5-cm core tubes inserted into the sediments to a depth of about 30 cm. Two cores were collected for chemical analysis (one served as an archive). The cores were stored on ice for transport to the laboratory where they were stored frozen until analysis. Three 7.5-cm cores were taken to a depth of 15 cm for benthic macroinfaunal analysis. The sediments were extruded into jars, fixed with 10% buffered formalin stained with rose bengal, and transferred to the laboratory.

4.4 Chemical Analyses

4.4.1 Organic Analytical Methods

4.4.1.1 Volatile organic analysis of water

Water samples for volatile organic analysis (VOA) were analyzed within 5 days of receipt by a purge and trap/gas chromatograph (GC) technique. The detector used was a flame ionization detector (FID). The instrumentation used was a Tekmar LS-2 purge and trap interfaced to a Hewlett Packard 5890 GC equipped with a 30 meter J&W 624 megabore capillary column. The initial GC temperature was 15°C for 2 min, then temperature programmed at 5°C/min to 135°C and held at the final temperature for 2 min. GC quantitative results are based on an external standard method using authentic standards and a 5-point standard curve.

4.4.1.2 Extraction of water for semivolatile organics

Samples were extracted by a liquid-liquid extraction method. Samples were adjusted to pH < 2 and extracted three times with dichloromethane (DCM). Hexamethylbenzene was added to each sample prior to extraction as a surrogate standard. Sample extracts were first reduced in volume using a rotary evaporator and then brought to their final volume under a stream of purified nitrogen. Sample extracts were then analyzed by gas chromatograph/mass spectrophotometer (GC/MS). Extraction blanks were analyzed to verify adequate glassware cleanliness and solvent purity. Duplicate and spiked samples were extracted to verify analytical recoveries and ensure reproducibility.

4.4.1.3 TOC and DOC analysis of water

Total organic carbon (TOC) was determined on 5 ml of water by wet combustion with a total carbon analyzer (Oceanography International, Inc.) using an infrared detector. Dissolved organic carbon (DOC) was determined in a similar manner using a water sample that had been filtered through a 0.4-µm membrane filter.

4.4.1.4 Volatile organic analysis of sediment

Volatiles in the upper 0-3 cm of sediments were determined by adding approximately 5 grams of sediment to a 14-ml culture tube along with enough organic-free water so that there was no head space when the tube was sealed. The samples were mixed with a vortex mixer, sonicated and equilibrated on a tumbler overnight (~20 h). The samples were centrifuged and a 5 ml aliquot of the water was analyzed by the water volatile method described previously.

4.4.1.5 Extraction of sediment for semivolatile neutral organics.

Approximately 25 g of wet sediment from the upper 0-3 cm of the core, excluding large rocks and shell fragments, was subsampled and then centrifuged to remove excess water. Samples were first sonicated in methanol, then centrifuged and the methanol poured off. Sodium sulfate was added in approximately equal weight with the sediment sample. The sample was extracted twice more by sonicating with hexane. All extracts were combined and added to a separatory funnel to separate the hexane from the methanol. The sample extracts were concentrated by rotary evaporation and a stream of purified nitrogen to a final volume of 200 µl. A deuterated internal standard consisting of six components was added to each of the samples prior to extraction as a surrogate standard. Extracts were separated into three fractions by silica gel chromatography. The F-1 fraction, containing the aliphatic hydrocarbons, was eluted with hexane, the F-2 fraction, containing the polynuclear aromatic hydrocarbons (PAH) and biogenic olefins, was eluted with DCM/hexane (1:1), and the F-3, containing polar compounds, was eluted with methanol. The fractions were reduced under a stream of purified nitrogen to a final volume of 200 µl. Duplicate and spiked samples were extracted to verify analytical recoveries and ensure reproducibility.

A 3-5 gram subsample of sediment was taken for dry weight determination. The wet sediment was dried in an oven at 90°C until a constant weight was obtained. The percent moisture value calculated was used to determine the dry weight of the sample for the wet weight that was extracted.

4.4.1.6 Biota extraction method

Tissue samples were removed from their shells, rinsed with deionized water and homogenized in a blender. The blender was washed, rinsed with water, acetone, hexane and dried in an oven at 160°C between samples. Ten grams of tissue were weighed in a 50-ml Teflon centrifuge tube to ± 0.01 g and a deuterated standard was added to each tube as an internal standard. Four grams of 4N NaOH was added to each sample after which the samples were heated in an oven at 90°C for 2 hrs to digest the sample. The samples were thoroughly shaken after the first hour. After heating, the samples were cooled to room temperature and then extracted three times with ethyl ether. All extracts were combined and reduced to 1 ml under a stream of purified nitrogen. Hexane (2 ml) was added and the volume was reduced to 1 ml prior to silica gel chromatography.

Extracts were fractionated using 8 g silica gel (activated at 170°C for 12 hrs) covered with 2 g alumina (activated at 170°C for 12 hrs) in a column 30 cm in length x 10.5 mm inside diameter (i.d.). Two 25-ml fractions were obtained: the F-1 fraction, containing the aliphatic hydrocarbons, was eluted with hexane and the F-2 fraction, containing the polynuclear aromatic hydrocarbons (PAH) and biogenic olefins, was eluted with DCM/hexane (1:1). The fractions were reduced under a stream of purified nitrogen to a final volume of 200 µl.

Quality control procedures were used throughout the entire analysis process. Procedural blanks were run to monitor the extraction and separation procedures. Internal standards were added to each sample to correct for any losses of components during the analysis. Laboratory duplicates were run to determine method reproducibility.

4.4.1.7 Semivolatile instrumental analysis

F-1 fractions for sediment and biota samples were analyzed with a Hewlett Packard 5890 GC equipped with a J&W 30 meter DB-5 capillary column, 0.25 mm i.d. and 0.25 micron film thickness, and a flame ionization detector (FID). An estimation of the total saturated hydrocarbons (aliphatics), total resolved saturated hydrocarbons, and total unresolved saturated hydrocarbons was determined by using a response factor based upon the average response of nC-15 and nC-25. Total resolved hydrocarbons were determined by a valley-to-valley integration technique, total saturated hydrocarbons by integrating the entire chromatogram (including the unresolved complex as a single peak) and the total unresolved saturated hydrocarbons were determined by subtracting the resolved saturated hydrocarbons from the total. The detection limits for the saturated aliphatics are approximately 12 µg/g (dry weight) for the total and resolved saturated hydrocarbons. Values reported as trace are detected but at less than the quantitative detection limit.

Water sample extracts and the F-2 fractions of the sediment and biota samples were analyzed with a Hewlett Packard 5890 GC equipped with a J&W 30 meter DB-5 capillary column, 0.25 mm i.d. and 0.25 µm film thickness, directly interfaced to a Hewlett Packard 5970B Mass Spectrometer. Quantifications were based on an internal standard technique compared to authentic standards where available and corrected for recoveries by the surrogate standard. To ensure reproducible instrument performance, the MS was tuned daily by the autotune program. Column performance was verified by the use of the Grob standard, internal standards, and standards of the analytes of interest.

Quantitative determination of the semivolatile target compounds listed in Table 4.2 was by an extraction ion/internal standard method similar to methods described in EPA Method 625. The target compounds were chosen because of: 1) their relative abundance in petroleum sources such as crude oil and production water; 2) their potential to rapidly partition into the sediment and accumulate due to their low water solubilities; and 3) their relative persistence in the environment. In addition to the petrogenic compounds, common pyrogenic compounds were qualitatively and quantitatively identified to aid in differentiating the contamination source. The surrogate standard hexamethylbenzene was used to correct for recovery in the water extracts, while the deuterated standard was used for sediment and biota samples. The homologous series components, C-1 naphthalenes, dibenzothiophenes and phenanthrenes, and C-2 naphthalenes were quantified with a standard mix of these alkylated homologs. The C-3 naphthalenes and C-2 phenanthrenes were estimated by extracted ions using the response factor of representative compounds. C-2 and C-3 dibenzothiophenes and C-3 phenanthrenes were estimated in water samples by extracted ions using the response factor of the unalkylated parent compound. These alkyl-substituted homologs are referred to in the data tables and figures as 'NDP Homologs' or 'NDP'. The minimum detection limit (MDL) was calculated for each sample. It is based upon

Table 4.2 Semivolatile neutral target compounds (PAH).

COMPOUND	QUANT. ION (m/z)
NAPHTHALENE	128
C-1 NAPHTHALENE	142
C-2 NAPHTHALENE	156
C-3 NAPHTHALENE	170
ACENAPHTHYLENE	152
ACENAPHTHENE	153
FLUORENE	166
DIBENZOTHIOPHENE	184
C-1 DIBENZOTHIOPHENE	198
PHENANTHRENE	178
C-1 PHENANTHRENE	192
C-2 PHENANTHRENE	206
ANTHRACENE	178
FLUORANTHENE	202
PYRENE	202
BENZO(a)ANTHRACENE	228
CHRYSENE	228
BENZO(b)FLUORANTHENE	252
BENZO(k)FLUORANTHENE	252
BENZO(a)PYRENE	252
INDENOPYRENE	276
DIBENZANTHRACENE	278
BENZOPERYLENE	276

QUANT. ION (m/z): the extracted ion used to quantify that particular compound.

the minumum detectable amount of phenanthrene, as determined from the standard curve, corrected for recovery of internal standards and dry weight of the sample.

4.4.2 Trace Metal Analytical Methods

4.4.2.1 Instrumentation and data tabulation

The instrument used for elemental analyses of water, tissue, and sediment samples was a Jarrell-Ash Model 855 AtomComp inductively coupled argon plasma emission spectrometer (ICP). The instrument was calibrated by a two-point calibration curve. The first point was a pure water sample (Standard 1) for the 0 µg/ml. The second calibration point was made with 10 mg/ml standards. Standard 2 contained 10.0 µg/ml of Cu, Zn, Cd, Pb, Ni, As, Fe, Mn, Ca, Mg, Mo, Al, K, V and Na. Standard 3 contained 10.0 g/m. of Cr, Si (typically not analyzed because of contamination problems with glass containers), and P. The above elements were measured by separate, fixed photomultiplier detectors operating with one fixed grating monochrometer. One additional detector was available with a variable wavelength grating for measuring elements other than those for which there were fixed detectors. This channel was used for Ba or V. It was calibrated with Standard 1 and Standard 4 (contained 10.0 µg/ml Ba). The linear range for the instrument was at least 100 mg/ml for all elements listed except for Zn (40 µg/ml), As (75 µg/ml), and Mg (50 µg/ml). When any element in a sample exceeded its linear range, the sample was diluted and analyzed again. For tissue and sediment samples, the sample weight was used for calculations along with final volume of sample after acid digestion/extraction and preliminary dilution.

4.4.2.2 Water samples

The water samples were shaken, and then a portion of each water sample was filtered through a 0.45-µm filter to obtain the water soluble fraction. The remaining sample would contain the original levels of suspended particulates. Filtered and whole water samples were analyzed on the ICP. Colloidal particulates associated with the water samples were swept into the plasma along with the fine mist of the aqueous portion of samples so that a reading was obtained on the total elemental concentration of the water sample (soluble + adsorbed to colloids).

4.4.2.3 Sediment samples

Sediment samples from the upper 0-3 cm of the core were dried at 60°C then ground and mixed to ensure a uniform sample. Approximately 0.7 g portions of dry sample were digested with 2 ml of nitric acid in Teflon digestion bombs in an oven at 130°C for 4 h. After cooling, the nitric acid solution was reduced to 0.5 to 1.0 ml in volume. Hydrofluoric acid (3 ml) was added and the digestion bombs heated in a oven at 130°C for 8 h. After cooling, the sample was transferred to polyethylene bottles and made to volume with a saturated boric acid solution. Metal analysis was performed by ICP using boric acid matrix-matched standards.

4.4.2.4 Biota samples

Tissue samples were removed from the shell, then blended in a high speed blender for about a minute. Aliquots of the blended samples were placed into 100-ml test tubes and dried at 105°C for 24 hours to get a dry weight of the samples. From this point, the sample processing was similar to that described above for sediment samples.

4.4.3 Other Analytical Methods

4.4.3.1 Interstitial salinities

Sediment samples from the upper 0-3 cm of the core were placed in centrifuge tubes and centrifuged at 5,000 rpm for 10 min. The interstitial water was decanted into 4 ml vials and stored at 5°C until analysis. The chloride ion concentration was determined with a Haake Buchler Digital Chloridometer. At least three replicates were analyzed and averaged for each sample. The chloride ion concentration (ppt) was multiplied by 1.80655 to obtain interstitial salinity (ppt).

4.4.3.2 Particle size analysis

Methods for particle size analysis followed those described by Gee and Bauder (1986) and Day (1955) with the exception of the pretreatment to remove organic matter. It was decided to determine the organic content of each sample by heating a separate aliquot in a muffle furnace. The resulting percentage was used as a correction factor to adjust the percent clay (calculated from the hydrometer reading) and the percent sand (calculated from the sieved weight of the sand). Data from a separate test for carbonates showed the pretreatment step to remove carbonates was unnecessary. The particle data is presented as percentages of the mineral weight of each sample.

4.4.3.3 Organic content

A subsample of a ground, air-dried sample was dried at 100 to 105°C for 24 h, then weighed to determine the dry weight. The samples were heated in a muffle furnace at 425°C for 16 hrs (overnight), cooled to 100-105°C and reweighed. This heat treatment also drives off carbonates, but separate testing of each sample showed that carbonate was not present. The percent organic matter content on a dry weight basis was calculated by multiplying the proportion of the weight loss upon heating by 100. Percent organic carbon was calculated by dividing the organic matter content by the constant, 1.67.

4.5 Analyses of Benthos

In the laboratory, sediments containing benthic macroinfauna were sieved through a 0.5-mm mesh screen. The retained animals and debris were preserved in 10% buffered formalin stained with rose bengal until further analysis. Subsequently, benthic infauna was sorted from debris, counted, and identified to lowest possible taxon.

Standard benthic community parameters were determined for each station and included number of species per replicate, number of individuals per replicate, diversity (H'), and evenness (J'). Diversity was calculated by the following formula:

$$H' = -\sum_{i=1}^{s} \left(\frac{n_i}{N}\right) \log \left(\frac{n_i}{N}\right)$$

where s = total number of species collected, n = number of individuals in each species, and N = total individuals. Evenness was calculated by the formula:

$$J' = \frac{H'}{\log 2s}$$

Basic statistics were computed using procedures of the Statistical Analysis System (SAS, 1982).

Infauna data were analyzed using the General Linear Models procedure for Analysis of Variance (ANOVA) of SAS (1982). Data were normalized by a square root or log transformation prior to analysis of variance, depending upon which transformation provided the best normalization of the data. Transformations are noted where appropriate. Data were not transformed if the sample size was too small to determine whether they were normally distributed. This was the case for all the marsh data. Where cell sizes were uneven, a note has been made. The level of significance was established at $P < 0.05$. Duncan's multiple range test was performed to identify significantly different stations within a group.

Chapter 5

CHARACTERIZATION OF PRODUCED WATER

Jay C. Means, Debra J. McMillin and Charles S. Milan

5.1 Introduction

Produced water samples from four sites, the oil separation facilities of ARCO at Bayou Sale, the Texaco facility at Bayou Lafitte and two Texaco facilities at Golden Meadow were characterized for: volatile organic compounds, extractable semivolatile organic hydrocarbons and metals.

5.2 Bulk Parameters

Geologic formation water produced from different strata and different petroleum reservoirs may differ significantly in chemical composition. Over short periods of time, the composition of a particular discharge may be relatively constant, however, large differences may be expected to occur as the field is depleted or as production practices are changed (e.g., application of secondary recovery techniques or changes in chemicals used to effect recovery). Because these formation waters have leached through many rock strata they may contain a wide variety of dissolved and particulate inorganic materials as well as a complex mixture of petroleum related hydrocarbons. The resulting brines are often hypersaline and contain a variable loading of trace elements. In the case of the specific produced waters collected for this study, the salinities (Table 5.1) ranged from 100 ppt for the Bayou Sale discharge to 140 ppt at the Lafitte discharge. The two Golden Meadow discharges (TB7 and TB8) were 120 and 130 ppt, respectively.

The total organic carbon (TOC) and dissolved organic carbon (DOC) (Table 5.1) contents of the produced waters are good indicators of the load of petroleum related organics being discharged in the particulate and dissolved phases. TOC valves ranged from 220 ppm at the Lafitte site to 540 ppm at the Bayou Sale site. The Golden Meadow produced waters contained 230 and 250 ppm TOC, respectively. The ratio of DOC to TOC is an indication of the amounts of materials in the discharge which are more soluble and therefore more likely to be transported longer distances away from the discharges as compared to those that are more likely to sediment out close to the discharge point on particles. At Bayou Sale the DOC/TOC ratio was 0.944 indicating that the vast majority of organics in this discharge are soluble. At the Lafitte site the ratio was 0.773, while at the Golden Meadow sites the ratios were 0.783 and 0.760, respectively. These latter three values suggest that, compared to Bayou Sale, a slightly larger proportion of the hydrocarbons in the Lafitte and Golden Meadow discharges are in suspension, as opposed to in solution.

5.3 Organic Composition

5.3.1 Volatile Organics

The produced waters were all found to contain relatively high concentrations of the volatile aromatic hydrocarbons benzene, toluene, ethylbenzene, xylene and cumene (Table 5.1), i.e., at levels at or above half the aqueous solubilities of these compounds. Benzene was the most abundant of these compounds in all of the discharges, ranging from 1100 mg/l in the Bayou Sale discharge to as high as 2000 mg/l in the TB8 discharge at Golden Meadow. Toluene was also found at concentrations as high as 1500 mg/l in the Golden Meadow discharge. Figure 5.1 shows the concentrations of the major detectable volatile hydrocarbons found in the produced

Table 5.1. Hydrocarbon concentrations and salinity in produced water samples.

Sample ID	Bayou Sale	Lafitte	GM-TB#7	GM-TB#8A	GM-TB#8B
SALINITY (ppt)	100	140	120	130	n/a
TOC (mgC/L)	540	220	230	250	n/a
DOC (mgC/L)	510	170	180	190	n/a
VOLATILES (µg/L) Detection Limit=2µg/L					
Benzene	1,100	1,400	1,600	2,000	1,900
Toluene	690	730	1,300	1,500	1,500
Ethylbenzene	36	40	79	92	83
Xylenes	290	270	520	620	560
Cumene	5	5	8	7	6
PAH (µg/L) Detection Limit=5µg/L					
Naphthalene	310	110	99	240	220
C-1 Naphthalenes	220	93	77	130	140
C-2 Naphthalenes	170	120	51	89	120
C-3 Naphthalenes	77	79	26	56	80
Acenaphthylene	tr	tr	tr	tr	tr
Acenaphthene	6	tr	tr	tr	tr
Fluorene	12	6	5	5	8
Dibenzothiophene	6	14	tr	tr	6
C-1 Dibenzothiophenes	11	14	6	14	24
C-2 Dibenzothiophenes	12	15	tr	7	17
C-3 Dibenzothiophenes	6	7	tr	tr	7
Phenanthrene	10	5	5	9	10
C-1 Phenanthrenes	23	31	10	23	26
C-2 Phenanthrenes	20	27	8	18	22
C-3 Phenanthrenes	10	12	tr	6	11
Anthracene	nd	nd	nd	nd	nd
Fluoranthene	nd	nd	nd	nd	nd
Pyrene	nd	nd	nd	nd	nd
Benzo(a)anthracene	nd	nd	nd	nd	nd
Chrysene	nd	nd	nd	nd	nd
Benzo(b)fluoranthene	nd	nd	nd	nd	nd
Benzo(k)fluoranthene	nd	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd	nd	nd
Indeno(1,2,3-cd)pyrene	nd	nd	nd	nd	nd
Dibenz(a,h)anthracene	nd	nd	nd	nd	nd
Benzo(g,h)perylene	nd	nd	nd	nd	nd
Total PAH	890	530	290	600	690
Saturated Hydrocarbons (µg/L) Detection Limit=5µg/L					
Resolved	2,300	2,400	2,000	2,700	3,400
Unresolved	2,500	2,500	1,700	2,200	3,200
Total	4,800	4,900	3,700	4,900	6,600

nd: not detected
tr: trace level, below detection limit
A&B: Field duplicates

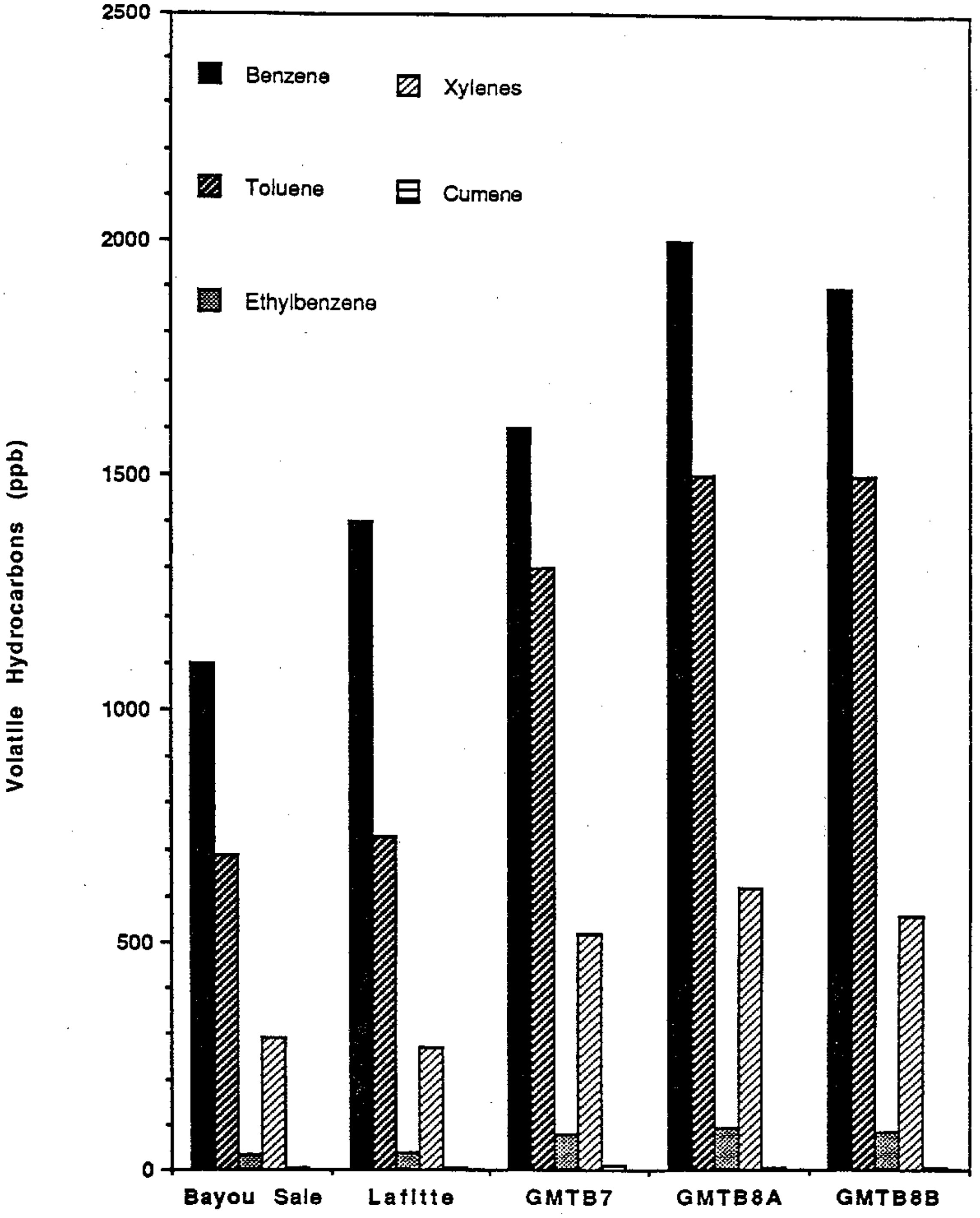


Figure 5.1. Major volatile organics detected in produced waters.

waters. Trace levels of several other compounds suspected to be short-chain normal alkanes, ketones and alcohols and cyclic alkanes were also detected in some samples but were not further characterized because they were present at such low concentrations (<1 µg/l) relative to the other constituents present. Examples of chromatograms obtained for the volatile hydrocarbons in produced waters are presented in Figure 5.2.

5.3.2 Semivolatile Organics

The produced waters were analyzed for normal polycyclic aromatic hydrocarbons, their C-1, C-2 and C-3 alkyl-substituted analogs and one class of heterocyclic aromatic hydrocarbons, the dibenzothiophenes, as well as the C-1, C-2 and C-3 alkyl-substituted dibenzothiophenes. In addition, each sample was also analyzed for total aliphatic hydrocarbons. Table 5.1 presents the individual concentrations of each of these chemical species in the four produced waters. The semivolatile fraction of the produced waters were all characterized by high levels of aliphatic hydrocarbons, naphthalene, dibenzothiophene and phenanthrene and their alkyl substituted analogs.

5.3.3 Total Aliphatic Hydrocarbons

Figure 5.3 shows the concentrations of the aliphatic hydrocarbons (HC) found in the four produced water samples. The histogram shows the relative amounts of resolved and unresolved aliphatic hydrocarbons detected. The total HC were relatively similar in all four discharges and ranged from 3,700 µg/l at Golden Meadow TB7 to 6,600 µg/l at the Golden Meadow TB 8 site. In all cases, the resolved hydrocarbons represented approximately 45 to 55% of the total aliphatics detected. Examples of chromatograms for these four produced waters are presented in Figure 5.4.

5.3.4 Aromatic Hydrocarbons

Naphthalene and its alkylated analogs were the most abundant PAH in all of the aromatic hydrocarbons present (Figure 5.5) ranging from 99 to 310 µg/l for naphthalene, 77 to 220 µg/l for C-1 methyl naphthalenes, 51 to 170 µg/l for C-2 naphthalenes and 26 to 80 µg/l for C-3 naphthalenes, respectively. The Bayou Sale discharge contained the highest total PAH (890 µg/l) while the Golden Meadow TB7 discharge was the lowest (290 µg/l). Intermediate values of 530 and 600 to 690 µg/l were observed at the Lafitte and Golden Meadow TB8 sites, respectively.

None of the four produced water samples were found to contain detectable levels of pyrogenic Pah with four rings or more. Anthracene, a tricyclic aromatic with the same molecular weight as phenanthrene, was also not detected.

5.4 Trace Metals

The four produced water samples contained a several trace elements at detectable levels in both filtered and unfiltered samples (Table 5.2, Figures 5.6-5.9). Copper was detected between 0.183 and 0.589 µg/ml in all four discharge waters, while zinc and lead were detected at concentrations between 0.035 to 0.087 µg/ml and 0 to 0.044 µg/ml, respectively. Cadmium was only detected in the Golden Meadow produced waters at 0.013 to 0.033 µg/ml. Nickel and mercury were not detected in any of the produced waters, while arsenic was found only in unfiltered Golden Meadow TB8 water. Iron was detected in all of the produced waters and was generally detected at higher levels in unfiltered samples. Barium was detected in all of the produced waters at levels between 24 and 53 ppm. The majority of the barium was in soluble form in the discharge water. Vanadium, another trace element associated with petroleum, was also detected in all of the samples at levels ranging from 0.3 to 1.8 ppm. In the Golden Meadow

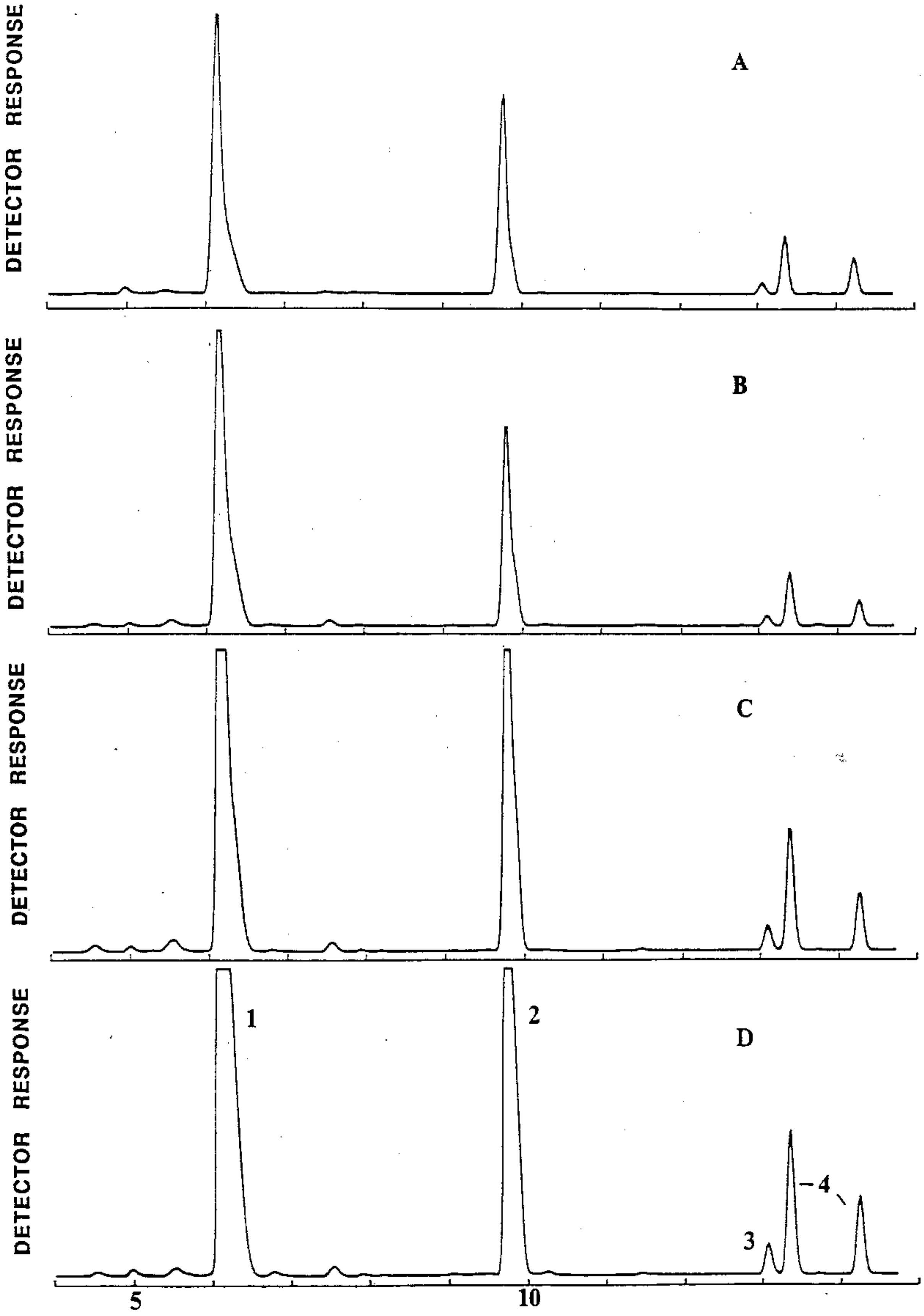


Figure 5.2. Chromatograms of volatile hydrocarbons in produced waters: A) Bayou Sale, B) Lafitte, C) Golden Meadow TB7, and D) Golden Meadow TB8; 1) benzene, 2) toluene, 3) ethylbenzene, and 4) xylenes.

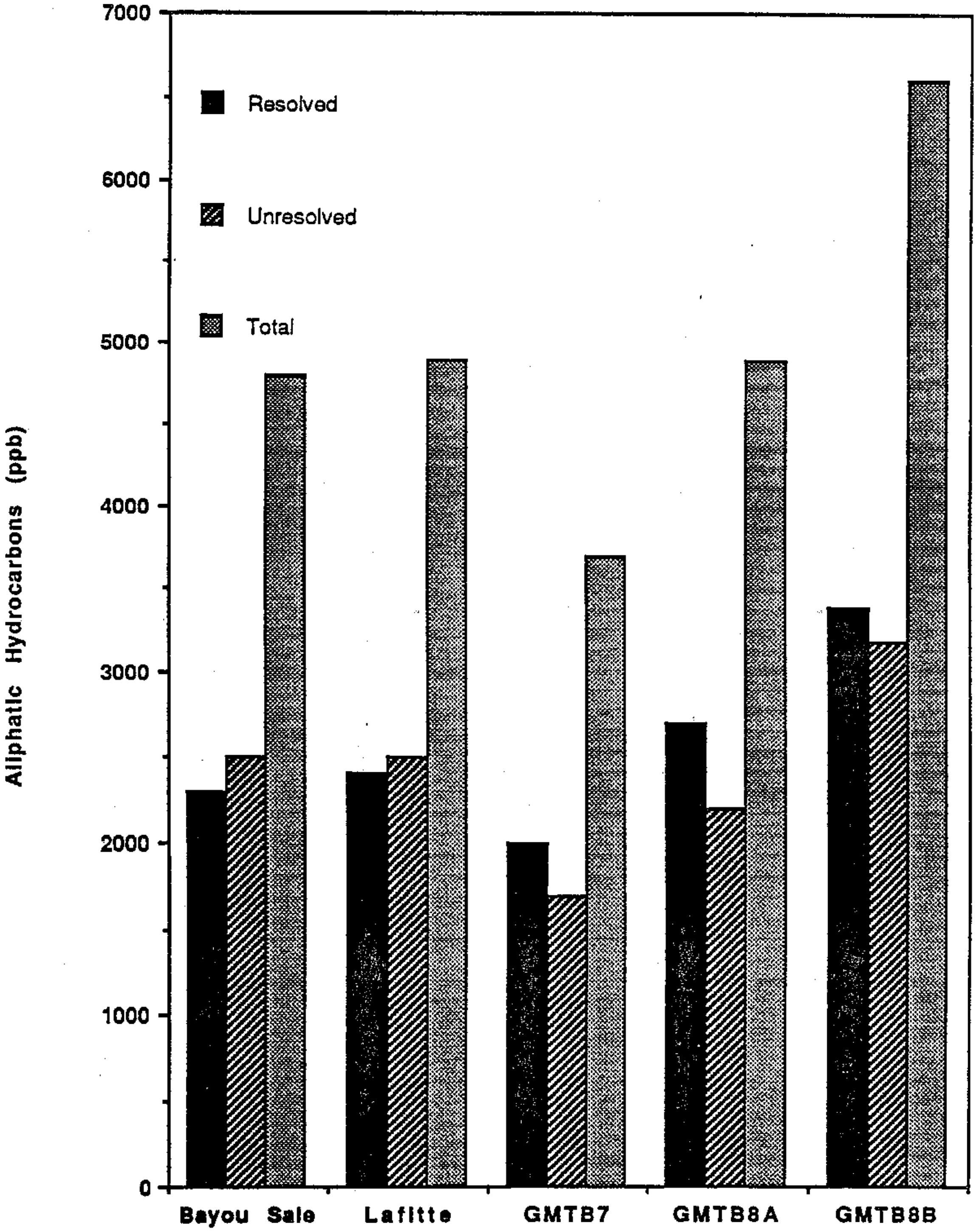


Figure 5.3. Aliphatic hydrocarbons detected in produced waters.

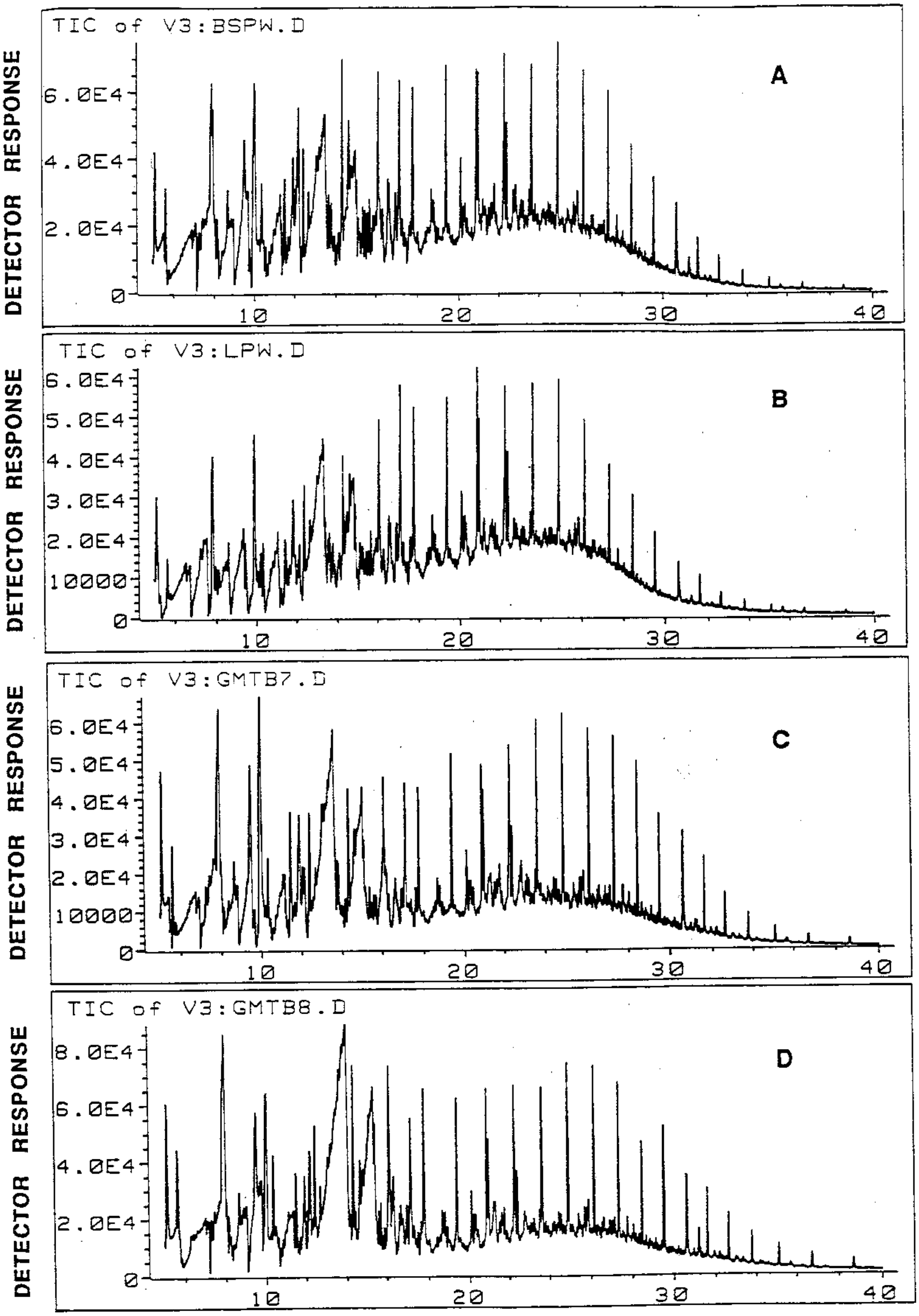


Figure 5.4. Total ion chromatograms (TIC) of produced water extracts: A) Bayou Sale, B) Lafitte, C) Golden Meadow TB7, and D) Golden Meadow TB8.

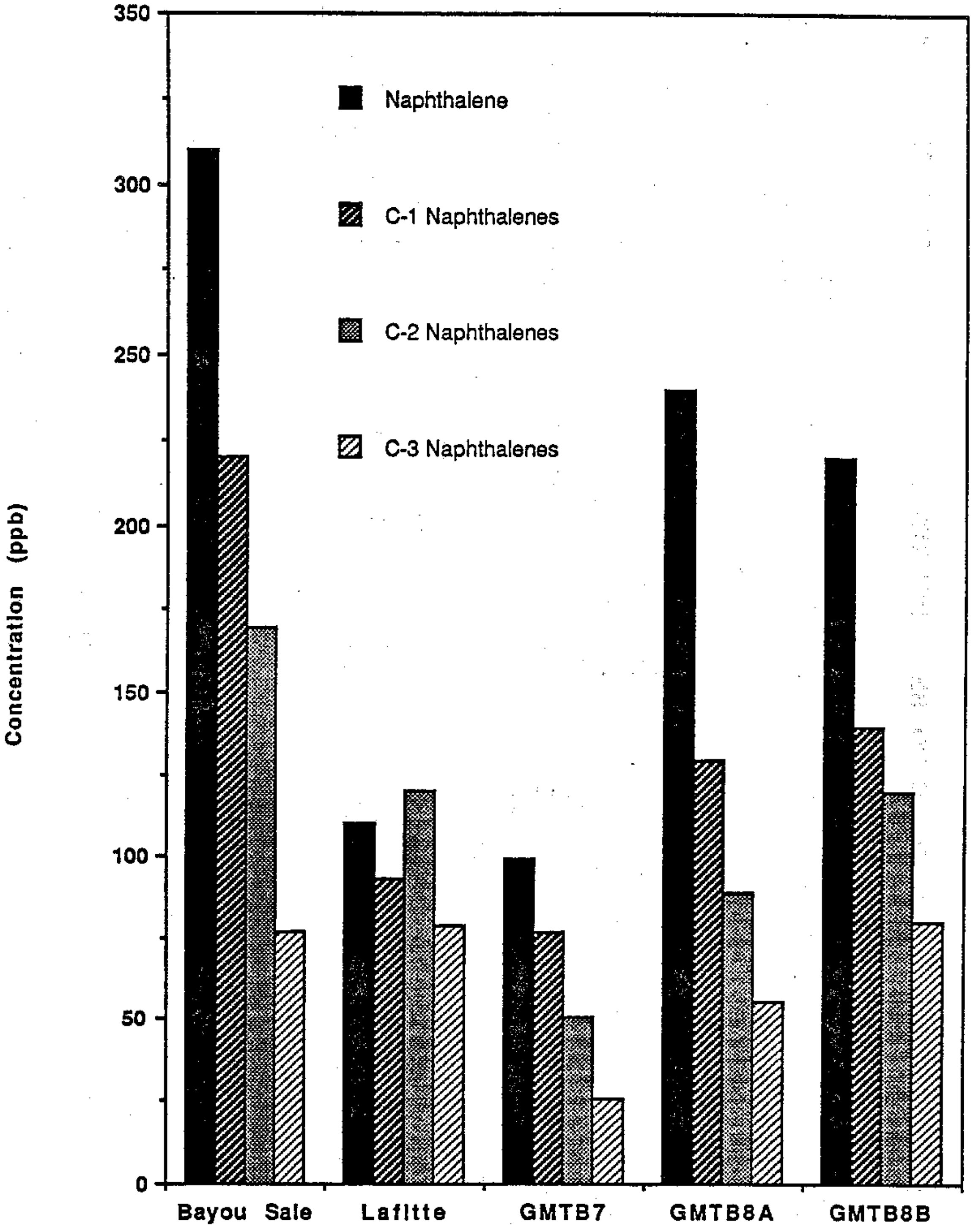


Figure 5.5. Naphthalene and C1-3 analogs in produced waters.

Table 5.2. Trace and major elements in produced water samples.

Sample ID	BS-filt	BS-unfilt	G-TB#7-filt	G-TB#7-unfilt	GM-TB#8-filt	GM-TB#8-unfilt	LAF-filt	LAF-Unfilt
Cu (µg/ml)	0.296	0.245	0.589	0.301	0.466	0.404	0.213	0.183
Zn	0.052	0.051	0.049	0.058	0.048	0.087	0.035	0.035
Cd	nd	nd	0.015	nd	0.013	0.033	nd	nd
Pb	0.039	nd	0.039	0.031	nd	0.039	nd	0.044
Cr	nd	nd	nd	0.010	nd	0.007	0.007	0.022
Ni	nd	nd	nd	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	0.098	nd	nd
Fe	0.233	2.03	2.04	8.14	0.151	4.86	5.01	10.1
Mn	4.07	4.03	0.830	0.785	1.69	1.63	0.957	0.910
Al	0.593	0.524	0.427	0.566	0.375	0.408	0.765	0.857
Na	32,800	29,900	37,800	39,300	39,900	43,800	49,500	42,400
Ba	24.9	23.7	52.7	52.6	46.9	45.3	35.4	33.8
V	0.420	1.80	0.356	0.395	0.335	0.310	0.637	0.655

nd: not detected

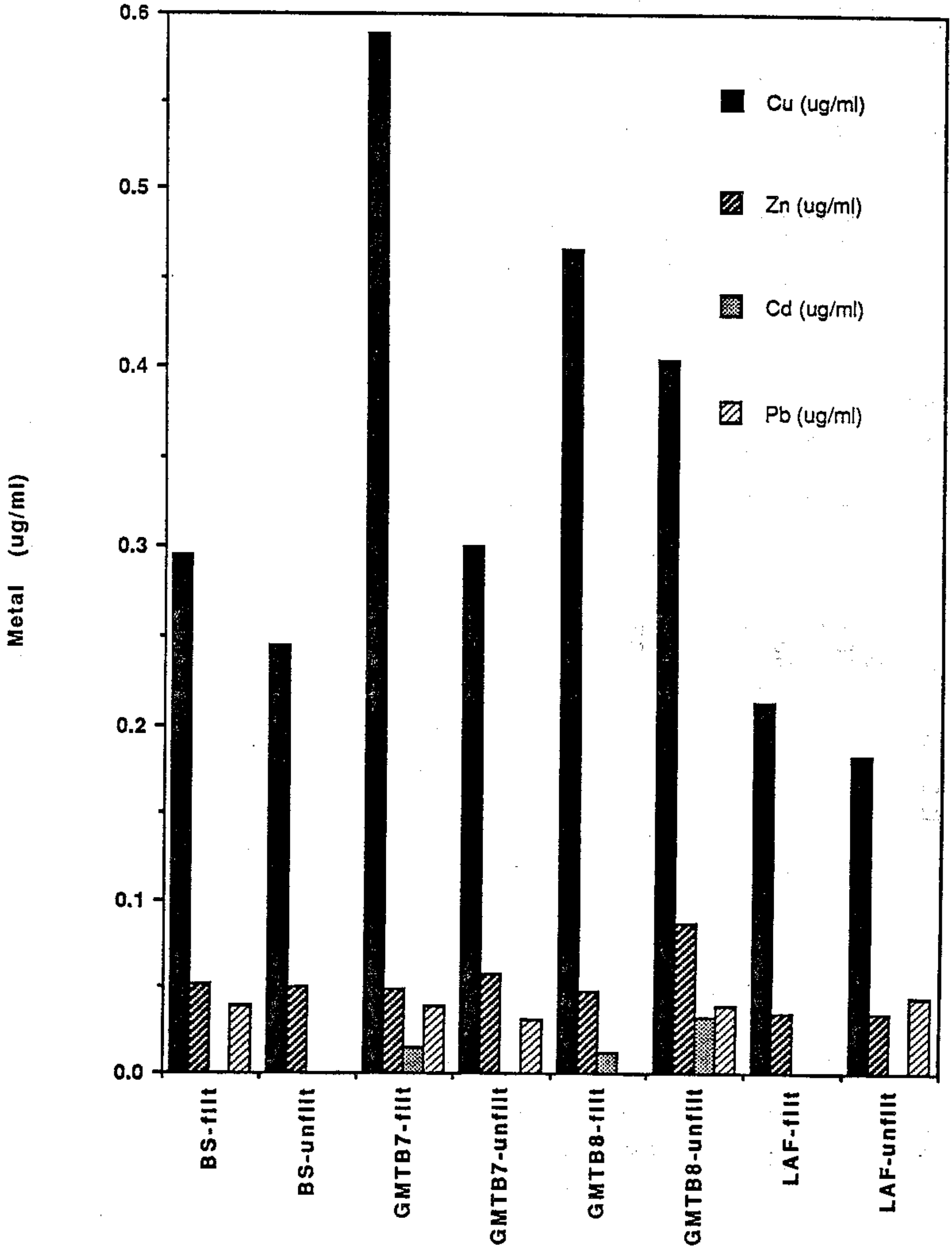


Figure 5.6. Copper, zinc, cadmium and lead concentrations in produced water samples.

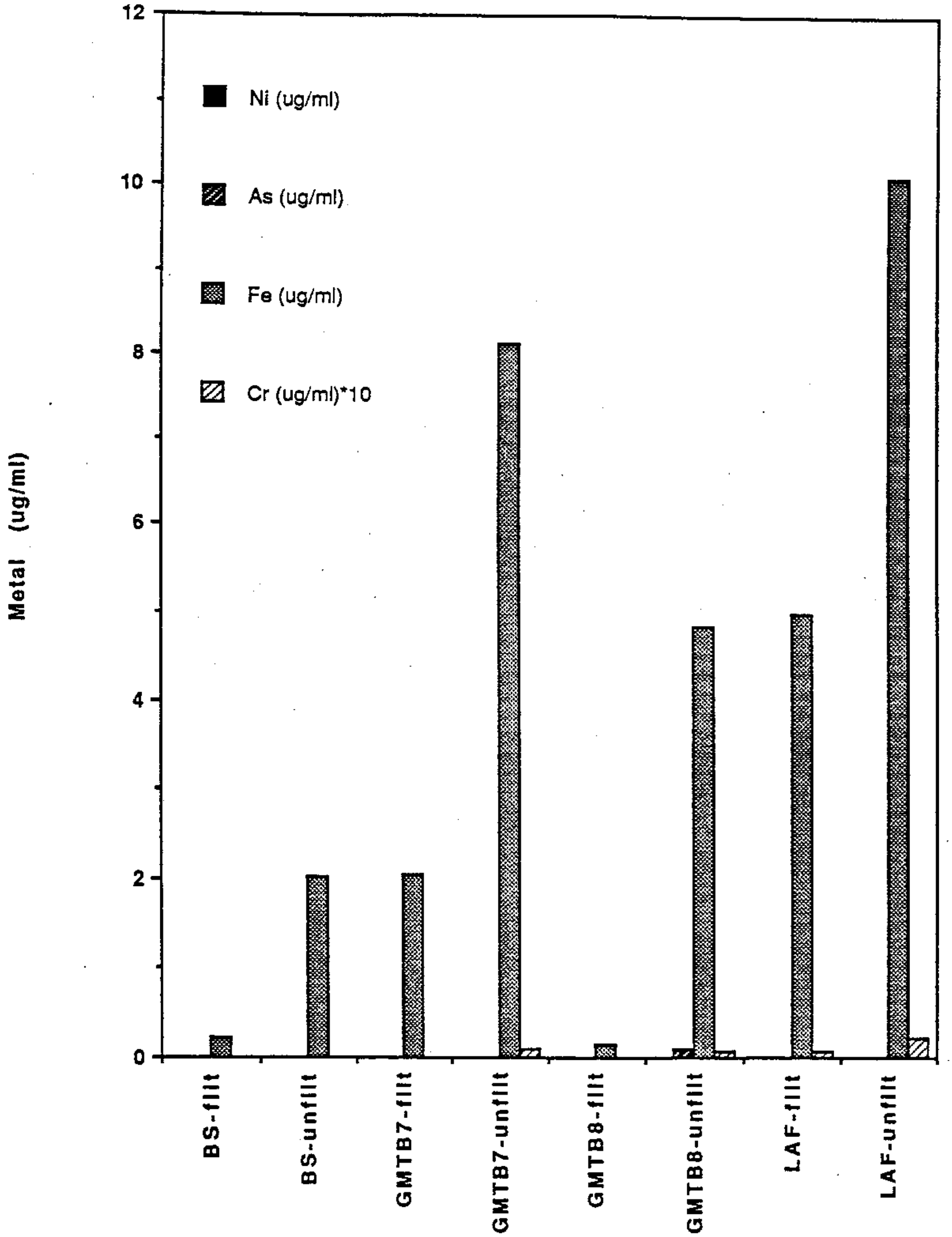


Figure 5.7. Nickel, arsenic, iron and chromium concentrations in produced water samples.

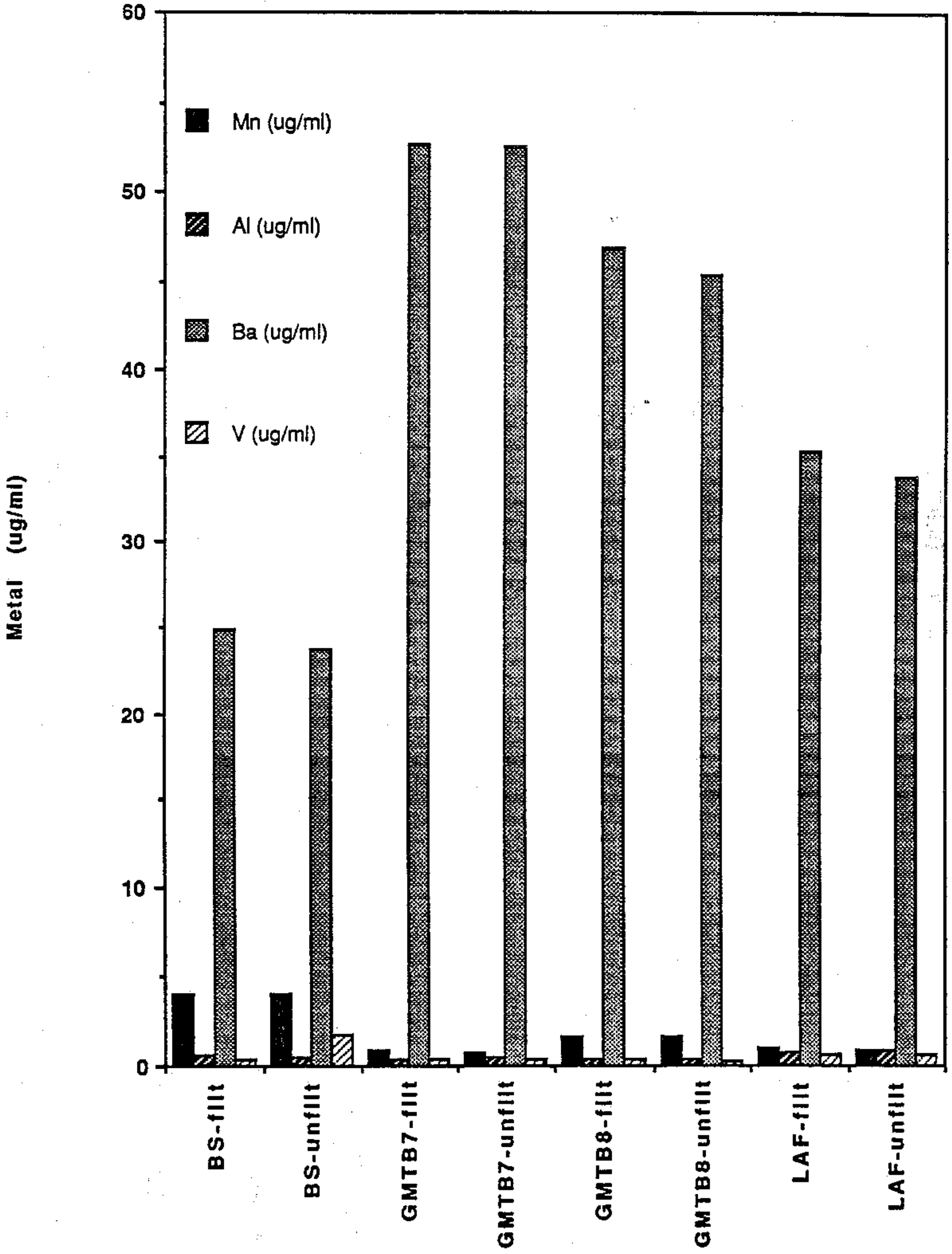


Figure 5.8 Manganese, aluminum, barium, and vanadium concentrations in produced water samples.

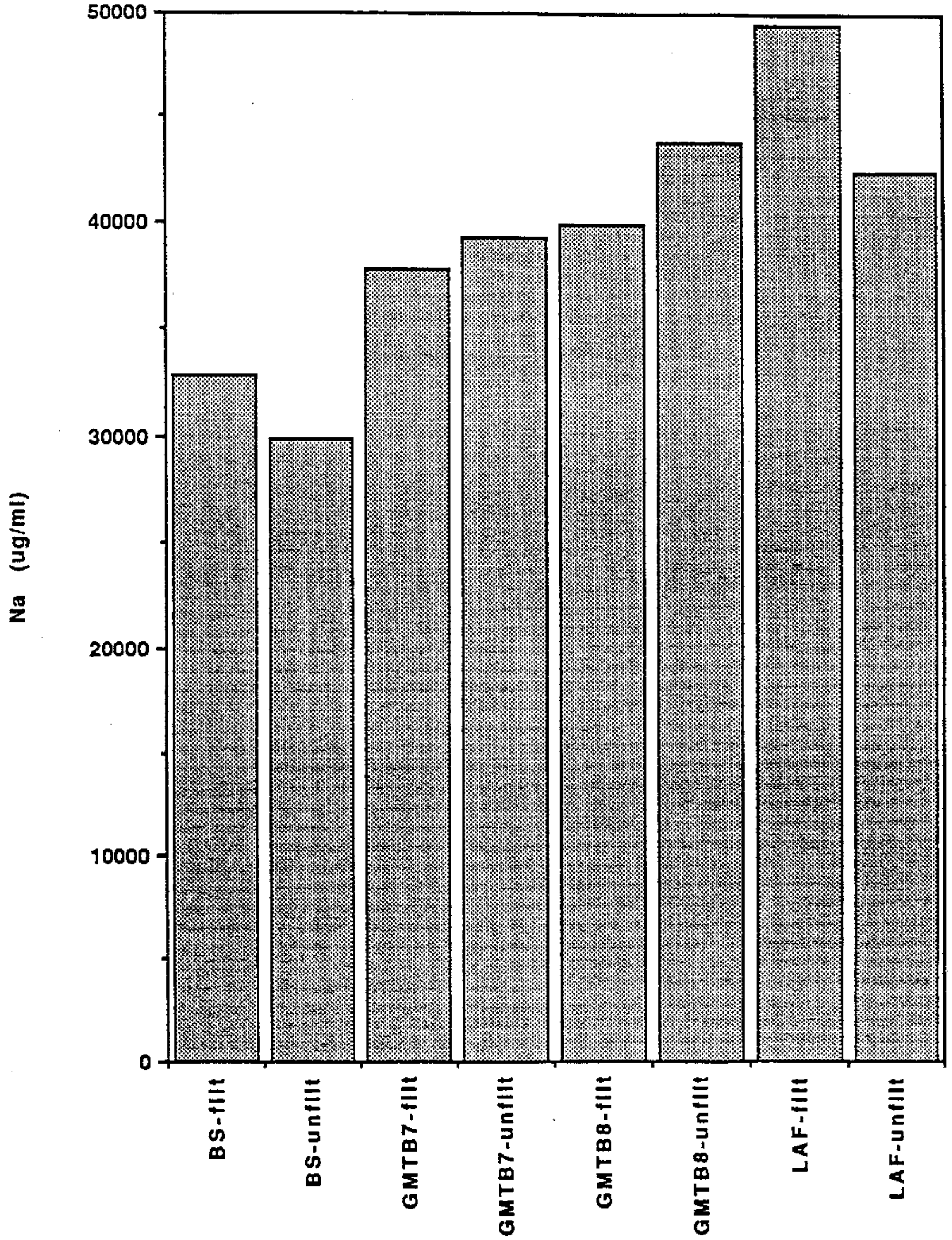


Figure 5.9. Sodium concentration in produced water samples.

and Lafitte discharges, the vanadium was primarily in soluble form while in the Bayou Sale discharge only 23% of the metal was found in the soluble fraction. Manganese and aluminum were detected in all of the discharges at levels from 0.78 to 1.7 µg/ml and 0.40 to 0.86 µg/ml, respectively. In both cases, the majority of the metals were in soluble form. Not surprisingly, sodium was detected at very high levels in all of the produced waters. Values ranged from 30,000 to 50,000 ppm Na, agreeing well with the salinity data presented earlier.

5.5 Summary

Produced waters were characterized by high salinities (three times as high as full strength sea water), dissolved sodium (three to five times), barium (one thousand times), manganese, vanadium (fifty times) and particulate iron. They also contain high TOC and DOC contents of which volatile aromatic hydrocarbons and aliphatic hydrocarbons made up the two largest identified groups along with certain petrogenic normal, alkylated and heterocyclic PAH. Aliphatic hydrocarbons are essentially saturated in produced waters. It should be noted, however, that all of the quantifiable hydrocarbons in the produced waters make up less than 2% of the total carbon detectable in the discharges. The chemical nature of the uncharacterized carbon is not known but may consist in part of short-chain acids, various pigments, and high molecular weight non-volatile compounds. This represents a major gap in our understanding of the nature of produce water discharges and their potential impacts on the environment.

Chapter 6

BAYOU SALE STUDY SITE

Nancy N. Rabalais, Jay C. Means, Charles S. Milan, Debra J. McMillin and Lorene Smith

6.1 Hydrography

The produced water discharge at the Bayou Sale site is the ARCO SWD1 facility located on an east-west canal intersecting with Lone Oak Bayou (Figure 1.3). On the dates of sampling, strong tidal currents were moving water north and south along Lone Oak Bayou. Some tidal influence was also observed at station BS500S on the second day of collections. Salinity of the produced water discharge collected was 100 ppt as determined by refractometer.

Salinity increases were detected up to 250 to 500 m from the discharge point (Figure 6.1, Table 6.1). Highest salinity values were 3.3 ppt (representing approximately 30-fold dilution of produced water) in the bottom water at the discharge point and reached ambient levels of 0 ppt at 500 or 1000 m from the discharge. Surface salinity values at the discharge point were 0.1 ppt (approximately 10^3 dilution of produced water) and reached ambient levels of 0 ppt at 500 or 1000 m from the discharge. Increased bottom water salinities extended greater distances from the discharge in the direction of canals (BS500S and BS500E) than in the direction of a natural water body (BS500W). Highest salinities were confined to the bottom or near-bottom waters (Figure 6.2). The appearance of a bottom density plume extended farther into the southern canal than into the eastern canal and even less into the western canal.

Because the level of detection for salinity (in ppt) was limited below 0.5 ppt, the conductivity values (in mmho/cm), which show greater detection at the low levels, are shown in Figure 6.3. Differences in bottom water conductivity can be detected up to 1000 m from the discharge point. Ambient levels were about 0.8-0.9 mmho/cm. A value of 1.1 at BS1500S may well have been an influence of the unstudied produced water discharge at TB7, 400 m to the south of this station (Figure 1.3).

Interstitial salinities of sediments along canals and waterways in the Bayou Sale area were higher at selected stations (BS250S, BS250W, BS500E, BS500W) near the discharge than near bottom waters (Figure 6.4). Stations immediate to the discharge (BS0, BS100E, BS100W), although higher than ambient salinities in near bottom waters, displayed interstitial salinities of 0 ppt.

Water quality parameters measured at the Bayou Sale stations were otherwise in the normal range to be expected in this environment except for considerably reduced dissolved oxygen levels near the bottom at the two stations to the east of the discharged and within 250 m of the discharge. Dissolved oxygen levels at or below 1 mg/l were found in the denser bottom waters below 2 m depth at BS100E and levels below 2 mg/l comparable depths at BS250E.

6.2 Organic Contaminants

6.2.1 Water

6.2.1.1 Bulk parameters

The data for volatile and semivolatile hydrocarbons detected in water samples collected adjacent to the discharge point and at distances out to 500 m from the discharge as well as three reference site water samples are presented in Tables 6.2 and 6.3, respectively.

Table. 6.1. Hydrographic data for Bayou Sale study area, 23-24 August 1988.

Stations (BS) in distance (m) away from SWD1
Reference stations (BSR) in distance (m) away from arbitrary "0" point

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (°C)	Dissolved Oxygen (mg/l)	pH
Station BS0 (10:05, 24 August 1988) (mid-channel, near discharge pipe)					
0.2	0.1	1.24	29.76	5.23	7.44
1.0	0.2	1.43	29.36	4.50	7.40
2.0	0.9	2.79	29.54	4.43	7.32
2.4	3.3	4.06	29.68	4.46	7.28
Station BS100E (10:40, 24 August 1988)					
0.2	0.1	1.27	29.83	5.58	7.43
1.0	0.2	1.34	29.44	4.62	7.38
1.5	0.2	1.66	29.61	4.24	7.37
2.0	0.8	2.37	29.43	0.88	7.22
2.4	0.9	2.63	29.46	1.01	7.20
Station BS250E (08:30, 24 August 1988)					
0.3	0.1	1.25	29.19	4.26	7.33
1.0	0.2	1.35	29.17	3.98	7.31
2.0	0.4	1.66	29.31	2.25	7.24
2.6	0.7	2.18	29.37	1.24	7.18
Station BS500E (08:20, 24 August 1988)					
0.3	0.1	1.13	29.17	3.47	7.18
1.0	0.1	1.14	29.09	3.46	7.16
1.5	0.1	1.13	29.04	3.46	7.16
Station BS1000E (08:15, 24 August 1988)					
0.3	0.0	0.65	28.67	3.37	7.08
1.0	0.0	0.65	28.68	3.38	7.06
2.0	0.0	0.64	28.64	3.44	7.07
2.6	0.0	0.63	28.59	3.60	7.11
Station BS1500E (08:00, 24 August 1988)					
0.3	0.0	0.48	28.78	4.52	7.20
1.0	0.0	0.48	28.78	4.43	7.19
2.8	0.0	0.53	28.54	2.91	7.16

Table 6.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (oC)	Dissolved Oxygen (mg/l)	pH
Station BS100S (10:55, 24 August 1988)					
0.2	0.1	1.38	30.11	5.38	7.45
1.0	0.3	1.64	29.55	5.04	7.41
1.5	0.6	1.96	29.41	4.54	7.38
2.0	1.2	3.04	29.48	4.01	7.30
Station BS250S (11:10, 24 August 1988)					
0.2	0.2	1.32	30.07	5.73	7.45
1.0	0.3	1.53	39.39	5.07	7.38
1.5	0.4	1.81	29.38	4.56	7.36
2.0	1.0	2.59	29.50	3.84	7.27
Station BS500S (12:20, 24 August 1988) (tide and wind pushing water from west to east along canal to the west of Station BS500S)					
0.2	0.1	1.29	30.22	5.71	7.45
1.0	0.1	1.30	29.99	5.70	7.42
2.2	0.5	1.85	29.41	4.04	7.32
Station BS1000S (15:20, 23 August 1988)) (water station at mid-channel, benthic and sediment samples from mouth of channel intersecting on eastern edge; strong tidal current to north)					
0.2	0.0	0.94	29.78	4.83	7.31
1.0	0.0	0.94	29.78	4.87	7.30
2.0	0.0	0.94	29.77	4.94	7.29
3.1	0.0	0.93	29.76	5.21	7.26
Station BS1500S (15:15, 23 August 1988) (water station at mid-channel, hard clay on bottom; benthic and sediment samples from side of channel, softer; strong tidal current to north)					
0.2	0.0	1.04	29.82	4.75	7.31
1.0	0.0	1.06	29.85	4.78	7.32
2.0	0.0	1.08	29.86	4.80	7.32
2.5	0.0	1.06	29.85	4.78	7.32
3.6	0.0	1.08	29.85	4.80	7.31
Station BS100W (09:50, 24 August 1988)					
0.3	0.0	1.05	29.86	5.34	7.42
1.0	0.2	1.32	29.34	5.32	7.39
2.2	0.4	1.79	29.17	5.17	7.34

Table 6.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (oC)	Dissolved Oxygen (mg/l)	pH
Station BS250W (09:45, 24 August 1988)					
0.2	0.1	1.26	29.19	5.48	7.41
1.0	0.2	1.42	29.35	5.46	7.38
2.0	0.4	1.68	29.16	5.26	7.32
Station BS500W (15:50, 23 August 1988) (water station mid-channel; benthic and sediment samples at mouth of channel intersecting to east; strong tidal current to north)					
0.3	0.0	0.84	29.76	4.91	7.30
1.0	0.0	0.84	29.75	4.91	7.29
2.0	0.0	0.85	29.75	4.96	7.28
3.0	0.0	0.85	29.75	5.26	7.27
Station BS1000N (16:20, 23 August 1988) (water station mid-channel where sediments were crumbly clay; benthic and sediment samples taken closer to eastern shore near St. Mary #6 wellhead where softer; strong tidal current to north)					
0.2	0.0	0.84	29.80	4.99	7.28
1.0	0.0	0.84	29.82	4.99	7.28
2.0	0.0	0.85	29.82	5.06	7.27
3.3	0.0	0.85	29.80	5.33	7.25
Station BS1500N (16:40, 23 August 1988) (tidal current to northwest)					
0.2	0.0	0.75	29.89	5.25	7.29
1.0	0.0	0.78	29.87	5.18	7.28
2.0	0.0	0.83	29.84	5.02	7.26
3.7	0.0	0.84	29.83	5.14	7.25
Station BSR0 (12:25, 23 August 1988)					
0.2	0.0	0.49	29.06	5.31	7.29
1.0	0.0	0.49	28.93	4.36	7.21
2.2	0.0	0.49	28.82	4.07	7.18
Station BSR250N (12:05, 23 August 1988)					
0.2	0.0	0.48	29.10	5.80	7.30
1.0	0.0	0.48	28.99	5.29	7.21
2.1	0.0	0.47	28.75	4.01	7.18

Table 6.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (°C)	Dissolved Oxygen (mg/l)	pH
Station BSR500N (11:30, 23 August 1988)					
0.2	0.0	0.48	29.12	5.23	7.18
0.6	0.0	0.48	29.04	4.46	7.10
1.3	0.0	0.48	28.84	3.70	7.07
Station BSR900N (11:02, 23 August 1988) (within area of floating aquatics, water hyacinths)					
0.3	0.0	0.48	28.72	2.70	6.91
0.6	0.0	0.49	28.69	2.48	6.90
1.5	0.0	0.49	28.64	2.34	6.90
Station BSR500S (12:55, 23 August 1988)					
0.3	0.0	0.49	29.38	6.97	7.81
1.0	0.0	0.50	29.38	6.84	7.74
2.0	0.0	0.50	29.21	6.07	7.63
3.3	0.0	0.50	29.22	5.75	7.56
Station BSR1000S (13:25, 23 August 1988) (Replicate #1 closer to shore, softer sediments; Replicates #2 and #3 in channel, sediments more compacted, less in grab)					
0.2	0.0	0.49	29.72	7.01	7.88
1.5	0.0	0.50	29.50	6.66	7.77
3.0	0.0	0.51	29.33	5.79	7.68
3.8	0.0	0.51	29.34	5.82	7.67

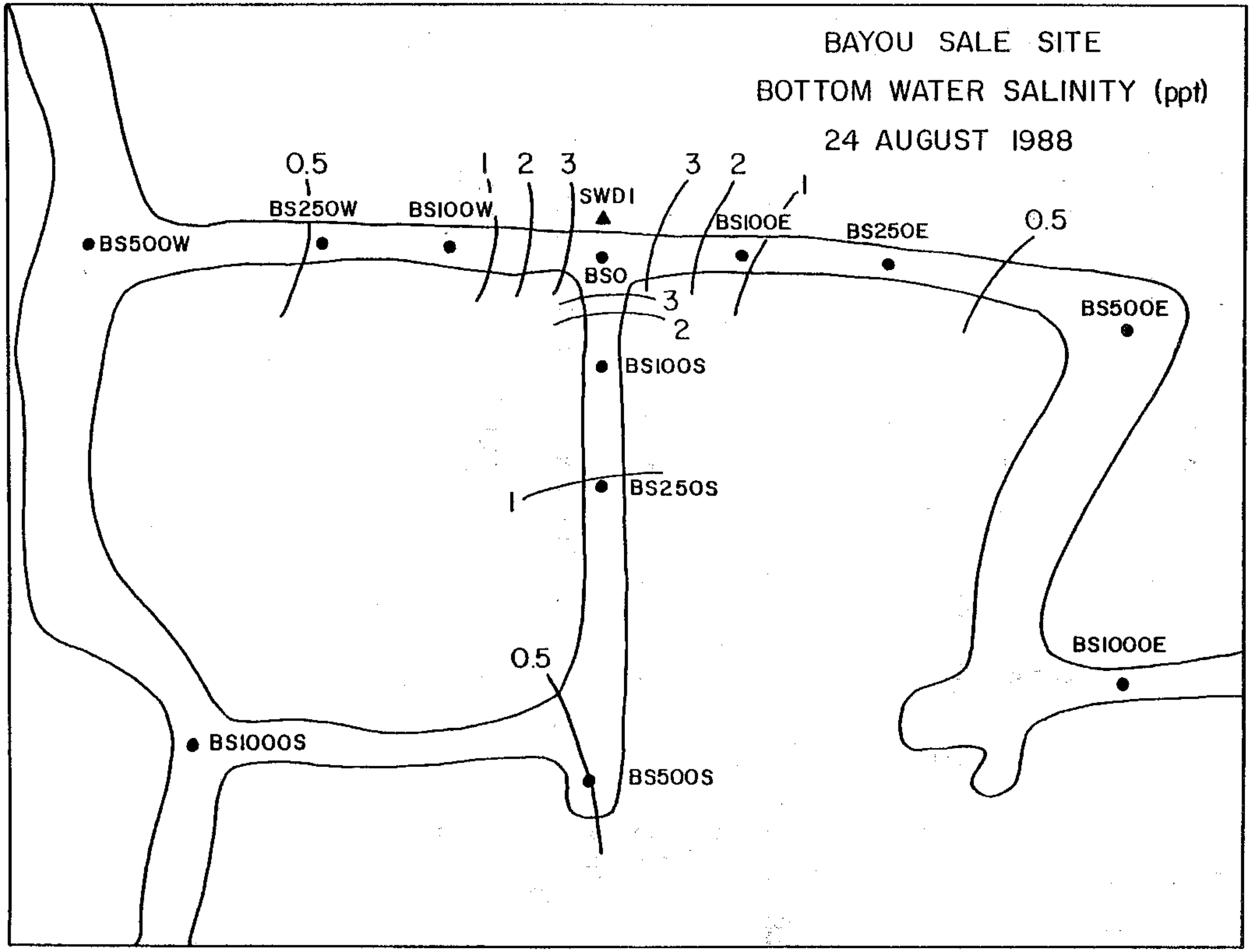


Figure 6.1. Bottom water salinity in discharge area at the Bayou Sale site.

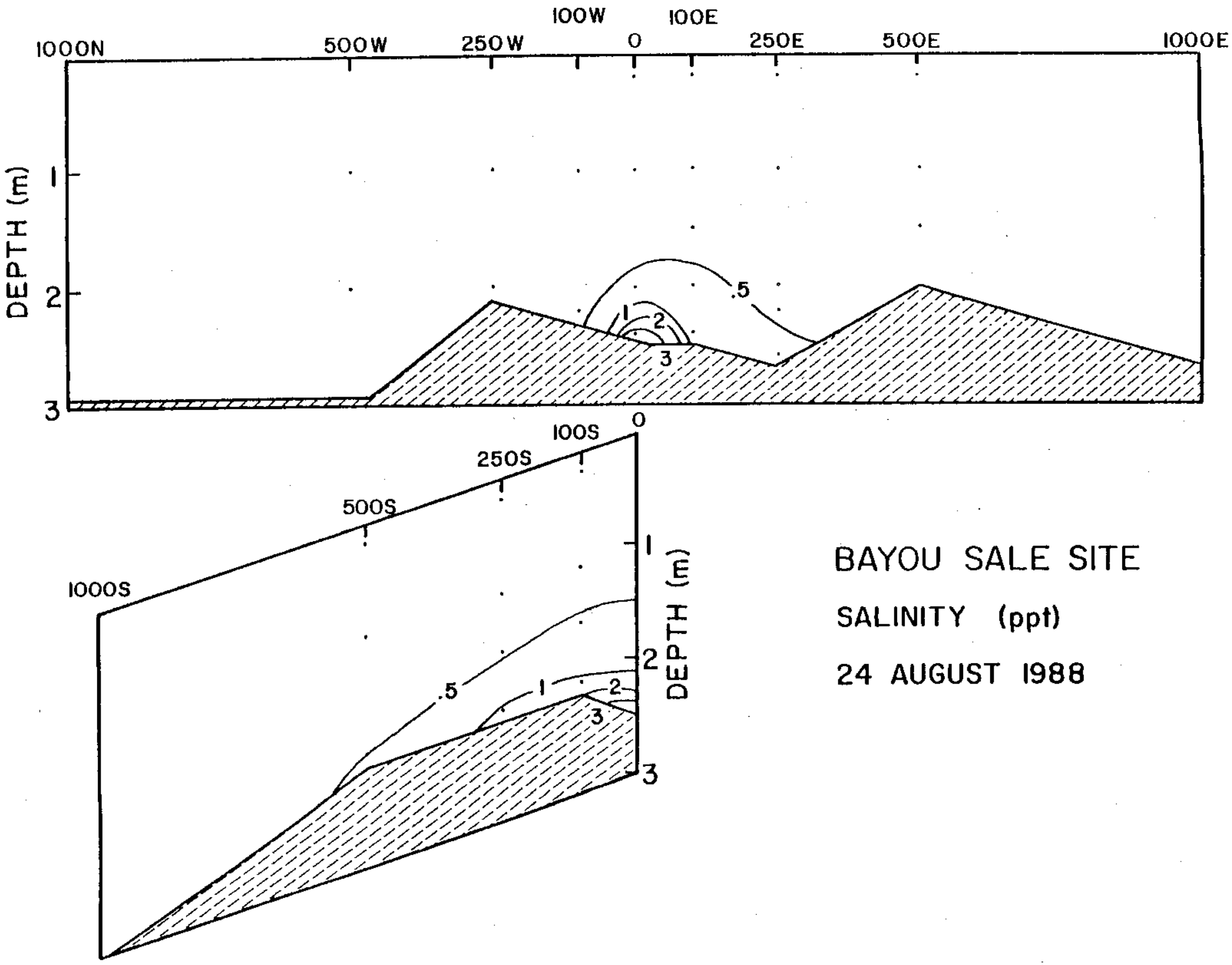


Figure 6.2. Salinity distribution in the water column in the discharge area at the Bayou Sale site.

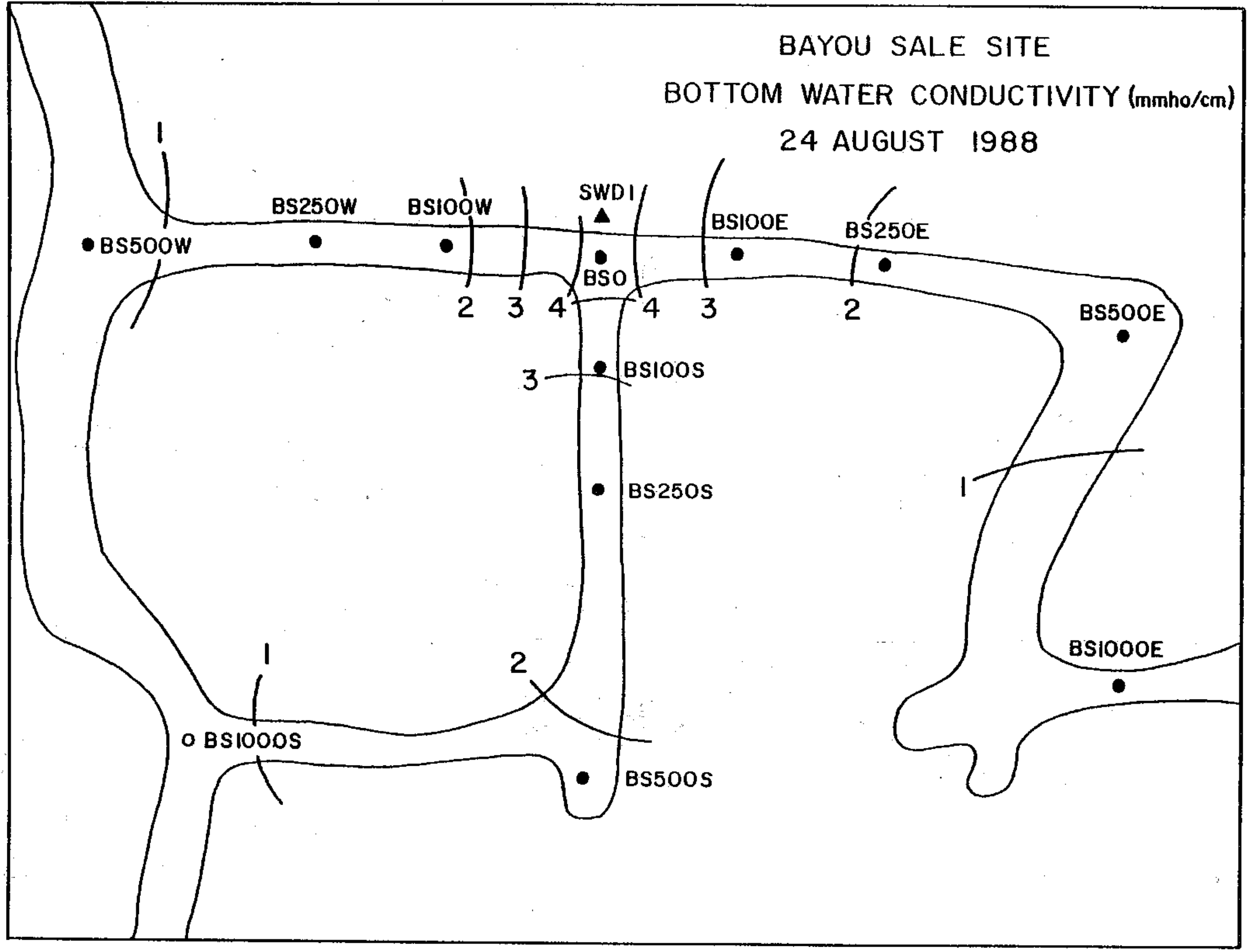


Figure 6.3. Bottom water conductivity in discharge area at the Bayou Sale site.

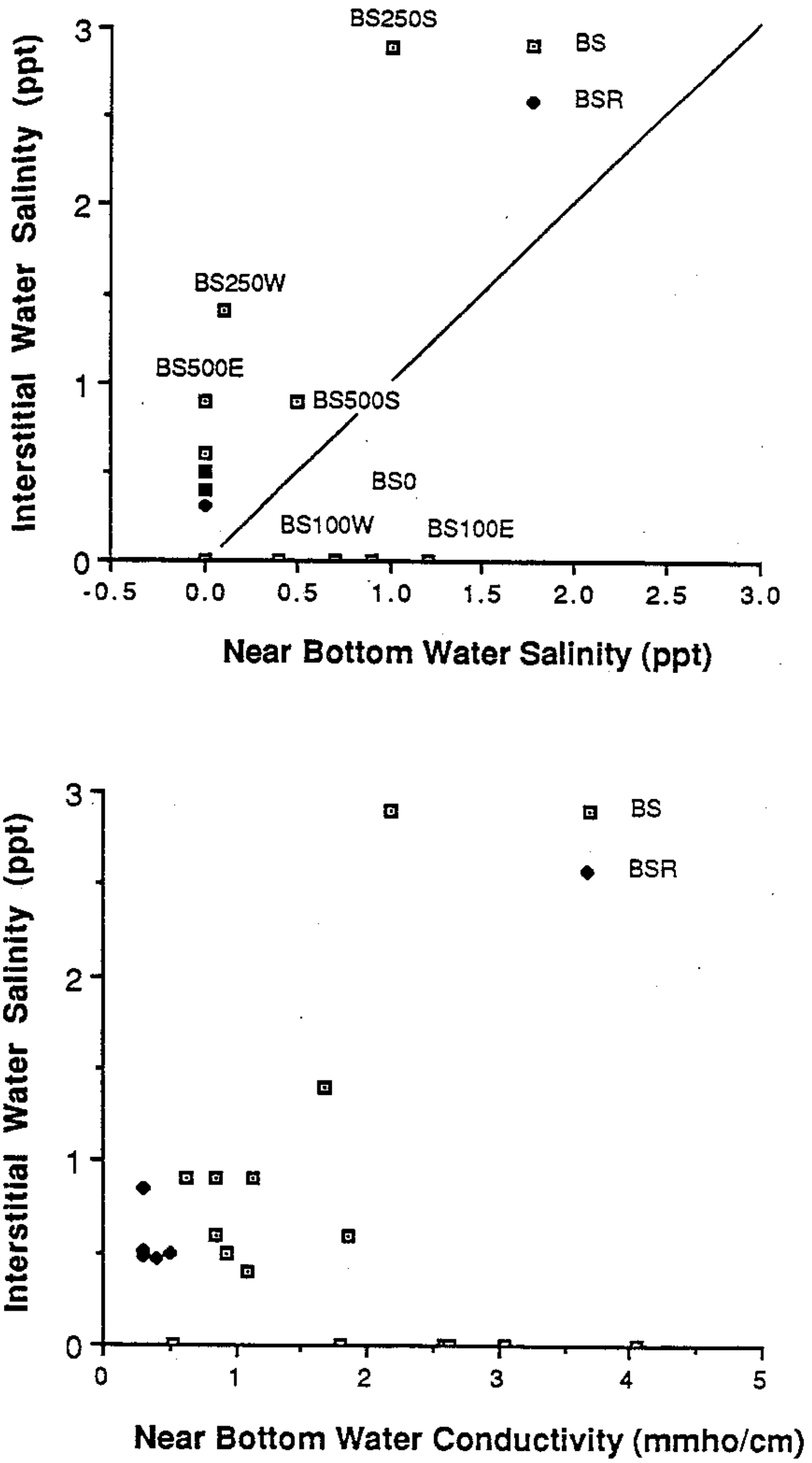


Figure 6.4. Comparison on interstitial water salinity from sediments of stations in waterways and channels of the Bayou Sale site to near bottom water salinity, above, and near botom water conductivity, below.

Organic carbon in the form of TOC and DOC was highly variable in the Bayou Sale system. At the reference site, TOC values ranged from 360 ppm at BSR0 to 4 ppm at BSR500N. In all cases, the carbon was mostly in dissolved form. At the discharge site, TOC values ranged from 45 ppm at BS0 to 5 ppm 500 m to the west of the discharge point. At these stations, a larger proportion (12-20%) of the TOC was in particulate form.

6.2.1.2 Volatile hydrocarbons

Determinations of volatile hydrocarbons (Tables 6.2 and 6.3) indicate that these substances were detected only as traces (1 ppb or less) at all of the stations near the discharge and at the reference site. This observation may be due in part to rapid volatilization of the aromatic hydrocarbons detected in the discharge water but may also be due to rapid dilution.

6.2.1.3 Semivolatile hydrocarbons

No aromatic hydrocarbons of either pyrogenic or petrogenic origin were found in any of the water samples from the Bayou Sale system (Table 6.2 and 6.3). This observation is consistent with the observation that the discharge is rapidly diluted by the water in the bayou system and suggests that semivolatile hydrocarbons being discharged into the bayou are rapidly entering sediments in the region since these materials are less likely to volatilize. The presence of low levels of chromatographically resolved aliphatic hydrocarbons in the water at the BS500W site (83 ppb) and at two of the reference sites (both 16 ppb) suggest an origin related to boat traffic in the area rather than the result of a produced water related discharge.

6.2.2 Sediments

6.2.2.1 Bulk parameters

General characteristics of the sediments are given in Table 6.4. Table 6.4 presents the data on sediment organic carbon content of the sediments in the Bayou Sale discharge site and the corresponding reference site. Figure 6.5 shows the spatial distribution of organic carbon in the sediments of the Bayou Sale system. Sediment organic carbon contents near the discharge site ranged from 3 to 11.5% while in the reference site they ranged from 1.3 to 8.9%. Sediment organic carbon values seemed to be elevated to the east of the discharge point but not in any other direction. As noted in Chapter 1 (Section 1.3.1) additional produced water discharges were occurring at the eastern end of the station grid. Elevated hydrocarbons in these sediments may also have been accompanied by higher organic carbon content. At the reference site a decreasing trend in sediment carbon content was seen from north to south.

6.2.2.2 Volatile hydrocarbons

Determinations of volatile hydrocarbons associated with sediment interstitial water and/or readily desorbable from sediments yielded little meaningful data. Table 6.5 presents a summary of the volatile hydrocarbon data at all of the sites in the Bayou Sale system including those located along marsh transects. Benzene, toluene and xylenes were detected at nominal concentrations at stations immediately adjacent to the discharge (e.g., BS0, BS100E, BS100W) Although the pattern of detected occurrences of each of the volatile hydrocarbons was discontinuous, Figure 6.6 shows that there was a general decreasing level of these substances leading away from the discharge in all directions. At the reference site, none of the volatile hydrocarbons was detectable at any of the sites except BSR1000S, which contained benzene, toluene, ethylbenzene and xylenes at nominal concentrations. This suggests some local origin for these compounds in the reference site.

Table 6.2. Hydrocarbon concentrations and salinity in Bayou Sale discharge site water.

Sample ID	BS-0	BS-500S	BS-500W	BS-500E
SALINITY (ppt)	3.6	3.7	4.2	3.6
TOC (mgC/L)	45	20	5	18
DOC (mgC/L)	36	17	4	14
VOLATILES (µg/L) Detection Limit=1µg/L				
Benzene	nd	nd	nd	nd
Toluene	tr	tr	tr	tr
Ethylbenzene	tr	nd	nd	tr
Xylenes	tr	tr	nd	tr
Cumene	nd	nd	nd	nd
PAH (µg/L) Detection Limit=5µg/L				
Naphthalene	nd	nd	nd	nd
C-1 Naphthalenes	nd	nd	nd	nd
C-2 Naphthalenes	nd	nd	nd	nd
C-3 Naphthalenes	nd	nd	nd	nd
Acenaphthylene	nd	nd	nd	nd
Acenaphthene	nd	nd	nd	nd
Fluorene	nd	nd	nd	nd
Dibenzothiophene	nd	nd	nd	nd
C-1 Dibenzothiophenes	nd	nd	nd	nd
C-2 Dibenzothiophenes	nd	nd	nd	nd
C-3 Dibenzothiophenes	nd	nd	nd	nd
Phenanthrene	nd	nd	nd	nd
C-1 Phenanthrenes	nd	nd	nd	nd
C-2 Phenanthrenes	nd	nd	nd	nd
C-3 Phenanthrenes	nd	nd	nd	nd
Anthracene	nd	nd	nd	nd
Fluoranthene	nd	nd	nd	nd
Pyrene	nd	nd	nd	nd
Benzo(a)anthracene	nd	nd	nd	nd
Chrysene	nd	nd	nd	nd
Benzo(b)fluoranthene	nd	nd	nd	nd
Benzo(k)fluoranthene	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd	nd
Indeno(1,2,3-cd)pyrene	nd	nd	nd	nd
Dibenz(a,h)anthracene	nd	nd	nd	nd
Benzo(g,h)perylene	nd	nd	nd	nd
Total PAH	nd	nd	nd	nd
Saturated Hydrocarbons (µg/L) Detection Limit=5µg/L				
Resolved	tr	tr	83	nd
Unresolved	nd	nd	nd	nd
Total	tr	tr	83	nd

nd: not detected
tr: trace level, below detection limit

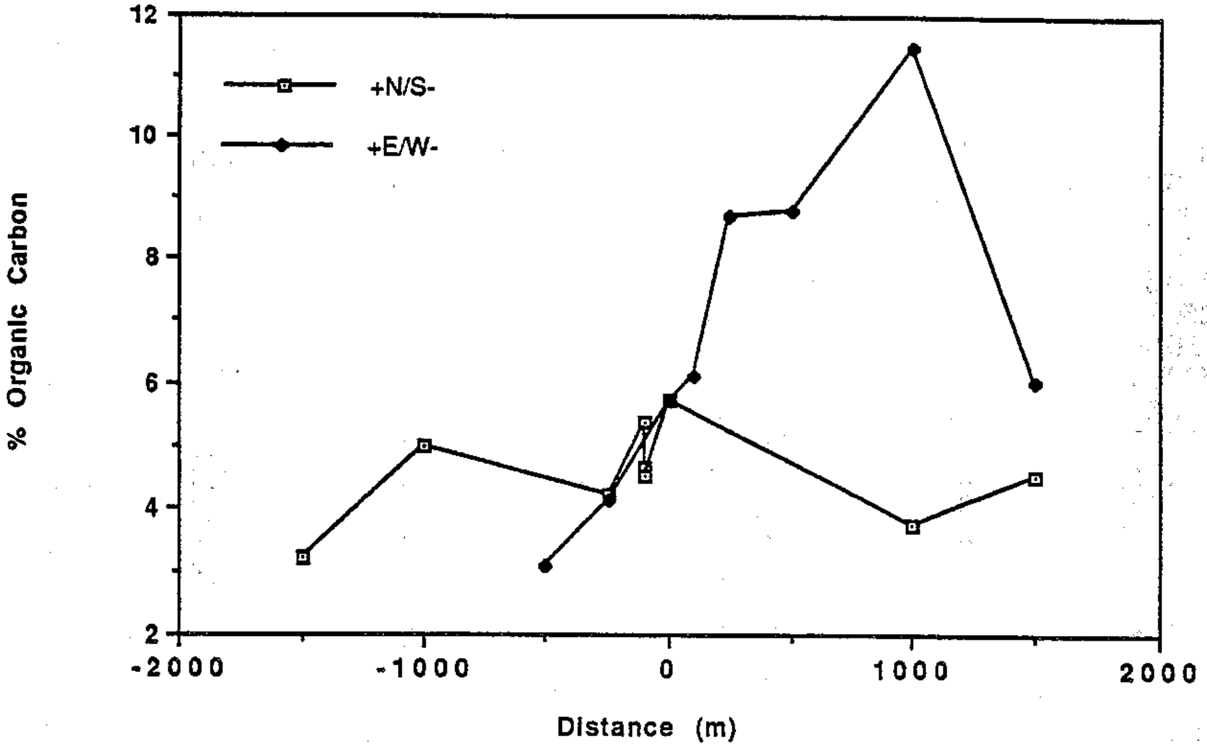
Table 6.3. Hydrocarbon concentrations and salinity in Bayou Sale reference site water.

Sample ID	BSR-0	BSR-500N	BSR-500S
SALINITY (ppt)	4.5	3.7	3.5
TOC (mgC/L)	360	4	110
DOC (mgC/L)	360	3	110
VOLATILES (µg/L) Detection Limit=1µg/L			
Benzene	1	tr	tr
Toluene	1	1	tr
Ethylbenzene	tr	tr	nd
Xylenes	1	tr	tr
Cumene	nd	nd	nd
PAH (µg/L) Detection Limit=5µg/L			
Naphthalene	nd	nd	nd
C-1 Naphthalenes	nd	nd	nd
C-2 Naphthalenes	nd	nd	nd
C-3 Naphthalenes	nd	nd	nd
Acenaphthylene	nd	nd	nd
Acenaphthene	nd	nd	nd
Fluorene	nd	nd	nd
Dibenzothiophene	nd	nd	nd
C-1 Dibenzothiophenes	nd	nd	nd
C-2 Dibenzothiophenes	nd	nd	nd
C-3 Dibenzothiophenes	nd	nd	nd
Phenanthrene	nd	nd	nd
C-1 Phenanthrenes	nd	nd	nd
C-2 Phenanthrenes	nd	nd	nd
C-3 Phenanthrenes	nd	nd	nd
Anthracene	nd	nd	nd
Fluoranthene	nd	nd	nd
Pyrene	nd	nd	nd
Benzo(a)anthracene	nd	nd	nd
Chrysene	nd	nd	nd
Benzo(b)fluoranthene	nd	nd	nd
Benzo(k)fluoranthene	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd
Indeno(1,2,3-cd)pyrene	nd	nd	nd
Dibenz(a,h)anthracene	nd	nd	nd
Benzo(g,h)perylene	nd	nd	nd
Total PAH	nd	nd	nd
Saturated Hydrocarbons (µg/L) Detection Limit=5µg/L			
Resolved	nd	16	16
Unresolved	nd	nd	nd
Total	nd	16	16

nd: not detected
tr: trace level, below detection limit

Table 6.4. Sediment characteristics for the Bayou Sale site.

Sample	%Organic Matter	%Organic Carbon	%$H_2$0	%Clay	%Sand	%Silt
BS0	9.5	5.71	64	29.7	6.8	63.5
BS100E	10.2	6.11	73	39.2	1.2	59.5
BS100S	7.5	4.51	67	38.4	0.5	61.0
BS100W	9.0	5.37	71	30.9	9.1	59.9
BS250E	14.6	8.73	78	34.2	2.9	63.0
BS250S	7.8	4.65	61	32.9	9.2	57.9
BS250W	7.0	4.19	74	36.7	3.2	60.1
BS500E	6.8	4.10	74	29.9	7.7	62.4
BS500S	14.7	8.78	66	37.8	4.2	57.9
BS500W	5.2	3.09	69	35.7	2.3	62.0
BS1000N	6.3	3.74	64	36.0	4.5	59.5
BS1000E	19.2	11.47	84	44.7	0.8	54.4
BS1000S	8.3	5.00	37	35.2	14.3	50.6
BS1500N	7.5	4.49	68	44.6	6.5	48.9
BS1500E	10.0	6.01	82	52.1	1.3	46.6
BS1500S	5.3	3.20	53	31.5	20.1	48.5
BSR0	5.7	3.38	55	43.0	1.1	55.9
BSR250N	6.8	4.05	71	43.2	3.1	53.7
BSR250N	7.0	4.17	-	-	-	-
BSR500N	14.3	8.59	72	37.6	11.6	50.7
BSR500S	2.1	1.27	38	28.4	1.5	70.1
BSR900N	14.9	8.91	69	42.4	8.4	49.2
BSR1000S	3.2	1.89	63	33.8	2.6	63.7
BS1-0	-	-	82	-	-	-
BS1-4	-	-	86	-	-	-
BS1-12	-	-	80	-	-	-
BS1-25	-	-	85	-	-	-
BSR1-0	-	-	91	-	-	-
BSR1-12	-	-	92	-	-	-
BSR1-108	-	-	88	-	-	-



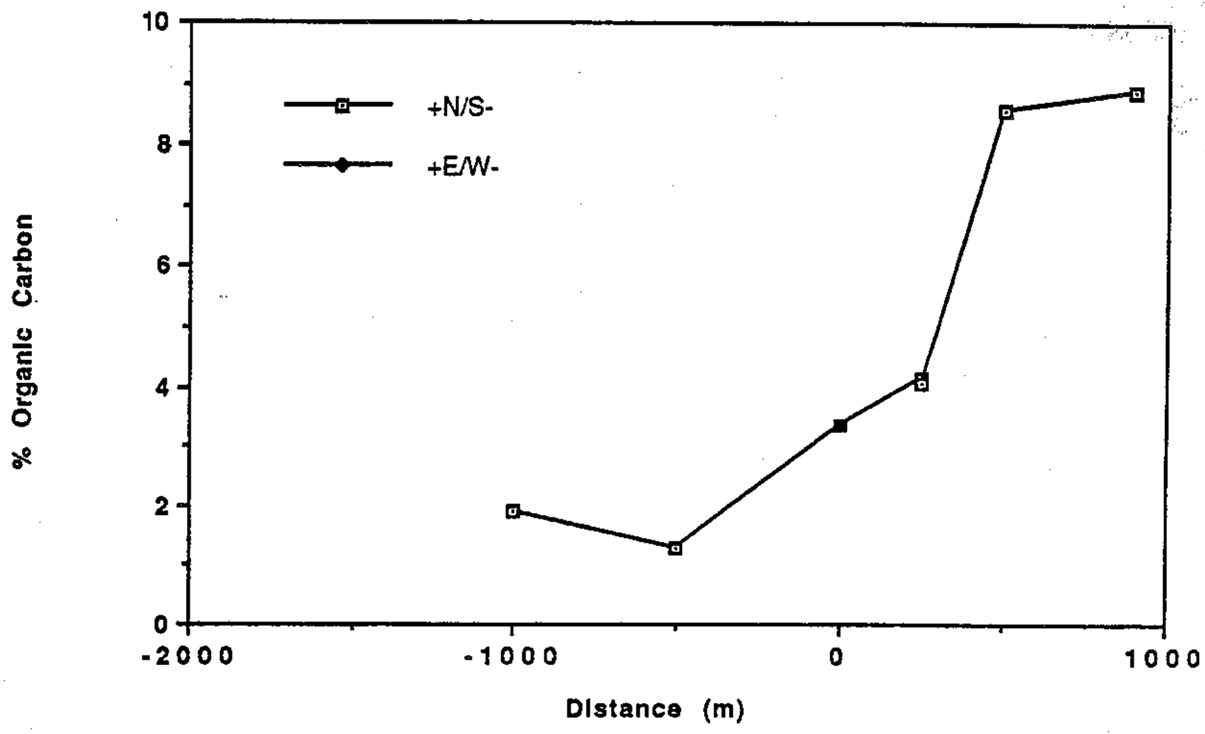


Figure 6.5 Spatial distribution of organic carbon content of Bayou Sale sediments; discharge site, above, reference site, below.

Table 6.5. Volatile hydrocarbons in interstitial waters of Bayou Sale sediments (concentrations in ppb, dry weight).

Sample ID	Benzene (ppb dry weight)	Toluene	Ethylbenzene	Xylenes	Cumene
BS-0	59	59	nd	140	nd
BS-100E	30	20	nd	110	nd
BS-100S	nd	nd	nd	nd	nd
BS-100W	14	tr	nd	16	nd
BS-250E	tr	16	nd	53	nd
BS-250S	nd	nd	nd	nd	nd
BS-250W	nd	19	nd	tr	nd
BS-500E	54	tr	nd	55	nd
BS-500S	11	nd	nd	nd	nd
BS-500W	nd	nd	nd	nd	nd
BS-1000N	nd	nd	nd	nd	nd
BS-1000E	tr	tr	nd	14	nd
BS-1000S	19	tr	tr	15	nd
BS-1500N	nd	nd	nd	nd	nd
BS-1500E	nd	nd	nd	nd	nd
BS-1500S	nd	nd	nd	nd	nd
BSR-0	nd	nd	nd	nd	nd
BSR-250N	nd	nd	nd	nd	nd
BSR-500N	nd	nd	nd	nd	nd
BSR-500S	nd	nd	nd	nd	nd
BSR-900N	nd	nd	nd	tr	nd
BSR-1000S	10	16	14	48	nd
BS1-0	nd	nd	nd	nd	nd
BS1-4	nd	nd	nd	nd	nd
BS1-12	nd	nd	nd	nd	nd
BS1-25	nd	nd	nd	nd	nd
BSR1-0	nd	nd	nd	nd	nd
BSR1-12	nd	nd	nd	nd	nd
BSR1-108	nd	nd	nd	nd	nd

Detection Limit = 10 ppb
Detection Limit = 15 ppb (Marsh samples)

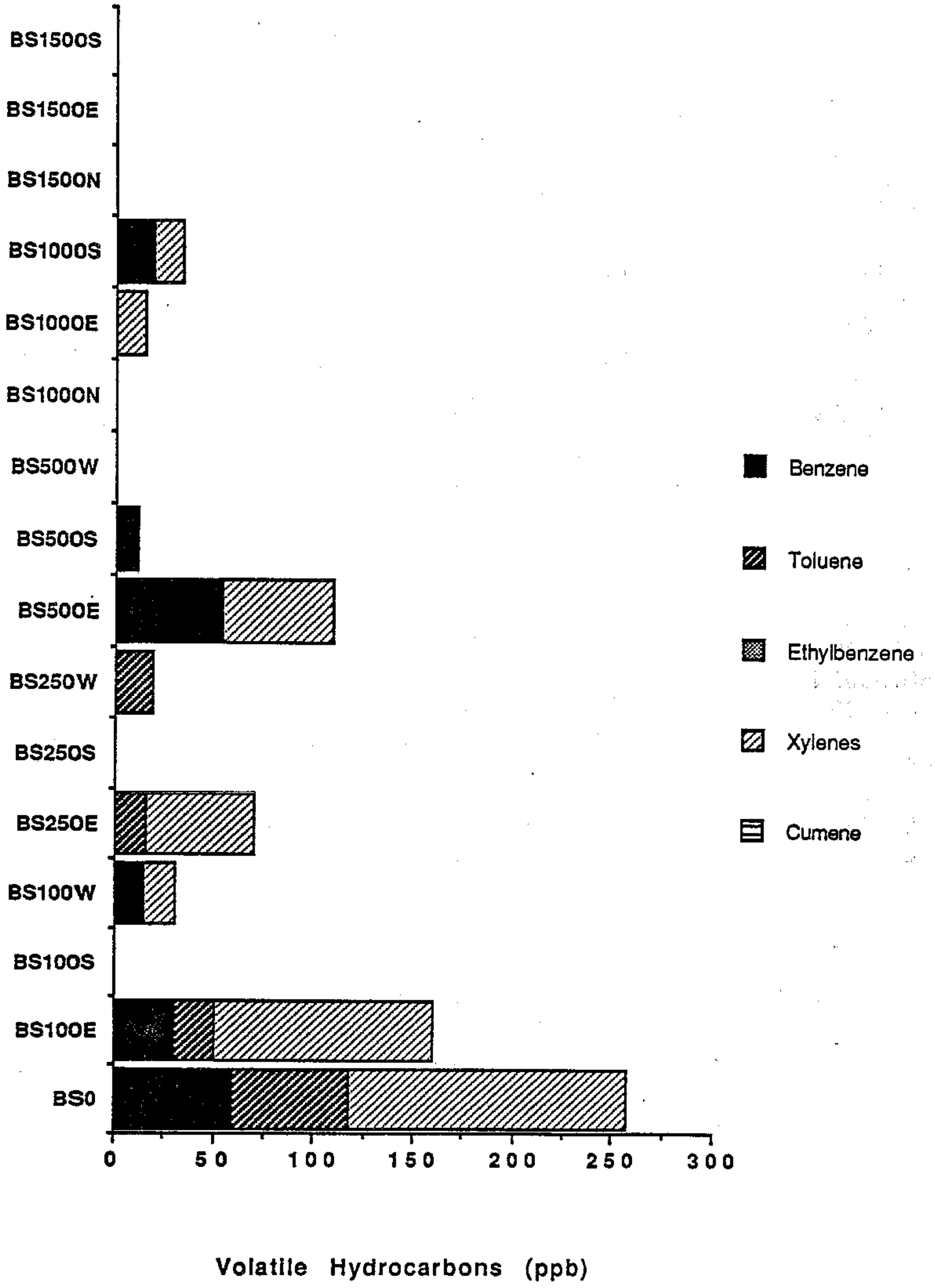


Figure 6.6. Volatile hydrocarbons in interstitial water of Bayou Sale sediments.

6.2.2.3 Semivolatile hydrocarbons

Tables 6.6 and 6.7 present a summary of all of the semivolatile hydrocarbon data for the Bayou Sale discharge site and the reference site, respectively.

Figure 6.7A shows the spatial distribution of normal aromatic PAH at various distances away from the discharge point. Total normal PAH are found maximally (3900 ppb) in the immediate area of the discharge and decline rapidly to 600 ppb or less within 500m of the discharge. Among the normal PAH, phenanthrene, naphthalene, fluorene, fluoranthene, and pyrene were found the most frequently in the region of the discharge. Figure 6.8 shows the spatial distribution of pyrene. The distribution pattern of pyrene parallels that of the total PAH very closely.

Figure 6.7 shows the spatial distribution of the sum of the normal PAH together with the alkylated and heterocyclic PAH. It is clear that the general pattern of the distribution is similar to that observed for the normal PAH alone, however, an examination of the amounts clearly shows that the alkylated PAH dominate the distribution. Figures 6.8 and 6.9 show the distributions of C-2 phenanthrenes, C-3 phenanthrenes and C-3 naphthalenes, respectively. Each of these compound groups exhibited the same general pattern with a maximum at BS0 and a sharp decline away from that site in all directions. Each of the compound groups as well as the total aromatics showed a secondary maximum at the BS500E site. This suggests that this region may be a depositional zone for hydrocarbons discharged at these sites.

The spatial distribution of PAH and PAH plus their alkylated and heterocyclic analogs is shown in Figure 6.10. In general the values are low relative to the discharge site. However, there appears to be some enrichment of all of the aromatic hydrocarbons toward the east of the zero point.

Aliphatic hydrocarbons were distributed in a similar pattern to the aromatics in the vicinity of the Bayou Sale discharge (Table 6.8). Figure 6.11 shows the spatial distribution of aliphatic hydrocarbons around the ARCO discharge. The pattern of hydrocarbon concentrations in sediments around the discharge is very similar to that for the more soluble aromatic compounds. As with the PAH there seems to be a secondary maximum at the BS500E site also suggesting that this is a depositional site. The aliphatic hydrocarbons at the reference site show a definite increase toward the east (Figure 6.12). Again, the discharges of an independent operator (Section 1.3.1) may have contributed to these elevated levels of contaminants. An example of an aliphatic hydrocarbon chromatogram for the BS0 site is presented in Appendix Figure 6.13.

Examination of the hydrocarbon data from the marsh sediments collected along transects into the Bayou Sale marsh adjacent to the discharge and at the reference site lead to a consistent picture (Table 6.9). These data show that normal PAH are found at relatively low and constant (8-18 ppb) concentrations in the reference marsh sediments but are much higher near the margins of the marsh adjacent to the discharge and decline to low levels 25 m into the marsh. When the petrogenic alkylated and heterocyclic PAH are included, the trend becomes even more pronounced. It should be noted that none of the petrogenic alkylated or heterocyclic PAH was found in the reference marsh, however, concentrations of these compounds in the marsh near the discharge ranged as high as 1500 ppb. This shows a clear pattern of contamination extending well into the marsh at this location.

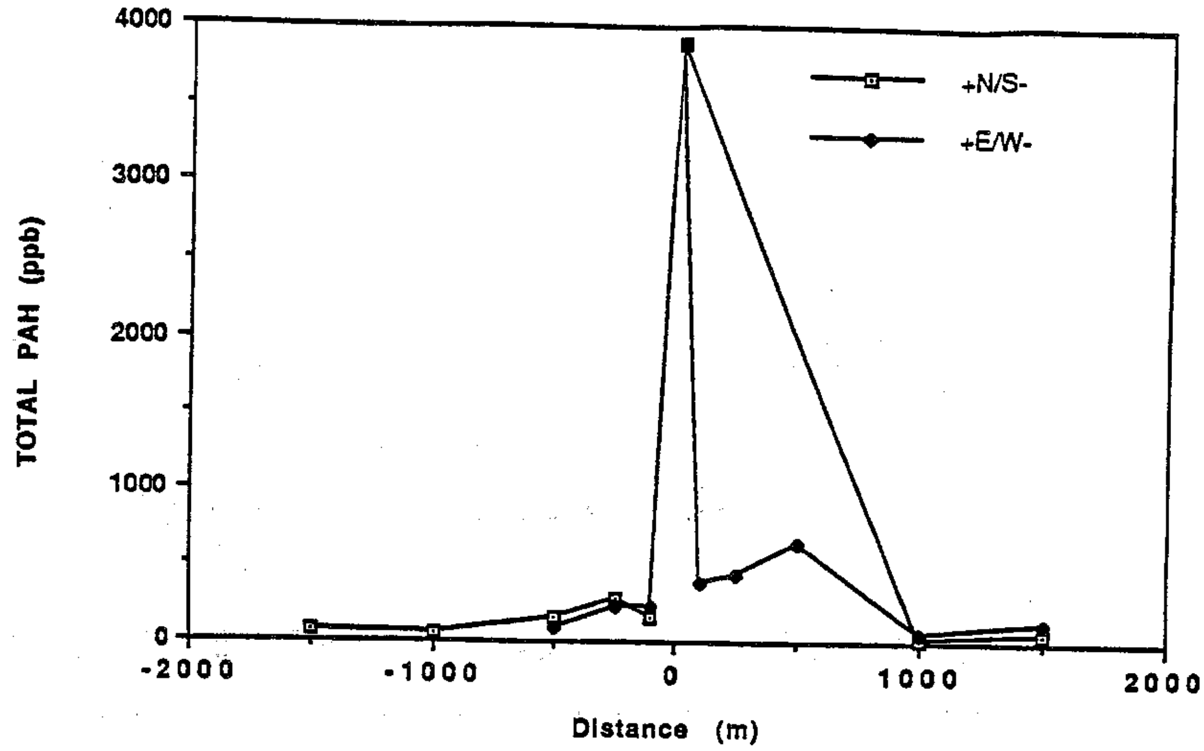
Aliphatic hydrocarbons in the marsh sediments show a similar pattern. Relatively low concentrations of hydrocarbons were observed in the zero point of reference marsh, while much higher concentrations were seen at the 12 m point. At 108 m into the reference marsh very low levels were observed. Relatively high levels of hydrocarbons were detected in Bayou Sale marsh sediments adjacent to the discharge (4 m) which declined with distance into the marsh.

Table 6.6. Semivolatile hydrocarbon concentrations in Bayou Sale discharge site sediments.

ANALYTE	BS-0	EAST					WEST			NORTH		SOUTH				
		100	250	500	1000	1500	100	250	500	1000	1500	100	250	500	1000	1500
MDL (ppb dry wt.)	14	8.1	64	5.0	18	17	3.8	6.2	8.1	9.7	4.7	3.9	4.9	5.9	5.4	3.4
Naphthalene	190	nd	nd	13	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthylene	nd	nd	trc	tr	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	47	trc	nd	54	tr	nd	trc	tr	nd	nd	nd	nd	nd	nd	nd	nd
Fluorene	420	41	trc	130	nd	trc	10	8.5	nd	nd	nd	4.8	9.2	nd	nd	nd
Dibenzothiophene	83	nd	nd	nd	nd	tr	tr	tr	nd	nd	nd	tr	nd	tr	tr	nd
Phenanthrene	1,300	96	86	130	tr	42	23	17	13	tr	tr	13	19	10	tr	6.4
Anthracene	72	tr	nd	18	nd	tr	4.1	tr	tr	nd	tr	6.7	7.7	tr	nd	tr
Fluoranthene	390	59	82	77	23	37	33	42	18	tr	21	29	46	29	12	15
Pyrene	420	81	130	92	35	42	41	50	28	10	34	45	72	38	19	21
Benzanthracene	210	41	tr	38	nd	nd	38	46	tr	nd	tr	14	36	35	nd	17
Chrysene	390	70	130	92	nd	nd	31	62	23	nd	tr	21	59	50	13	18
Benzo(b)fluorant.	180	nd	nd	nd	nd	nd	21	tr	nd	nd	nd	nd	26	nd	nd	nd
Benzo(k)fluorant.	nd	nd	nd	nd	nd	nd	18	tr	nd	nd	nd	29	5.6	nd	nd	tr
Benzo(a)pyrene	230	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd	tr	nd	tr	nd	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	na	nd	nd	nd	nd	nd	nd	nd	nd	nd	na	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Naph	2200	23	nd	7.7	nd	20	12	nd	nd	nd	nd	tr	tr	nd	nd	nd
C2-Naph	7200	200	tr	300	tr	42	76	tr	nd	nd	tr	13	30	tr	nd	nd
C3-Naph	31000	2200	1800	7300	230	940	340	50	nd	nd	260	160	460	35	10	tr
C1-DBT	680	110	96	220	tr	27	16	tr	nd	nd	13	12	40	tr	tr	tr
C1-Phen	3100	320	220	740	tr	130	56	8.9	tr	nd	62	33	69	15	tr	tr
C2-Phen	5600	930	1000	1600	140	280	180	92	22	tr	240	190	390	130	57	30
TOTAL PNA'S	3900	390	430	640	58	120	220	230	83	10	56	160	280	160	44	77
TOTAL PNA'S & NDP HOMOLOGS	54000	4200	3500	11000	430	1600	900	380	110	10	630	570	1300	340	110	110

Table 6.7. Semivolatile hydrocarbon concentrations in Bayou Sale reference site sediments.

ANALYTE	BSR-0	NORTH			SOUTH		
		250	500	900	500	500(d)	1000
MDL (ppb, dry wt.)	3.1	6.9	7.5	2.1	1.1	1.2	2.4
Naphthalene	nd	nd	nd	nd	nd	nd	nd
Acenaphthylene	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	nd	trc	tr	4.2	tr	tr	nd
Fluorene	trc	14	10	8.1	trc	trc	trc
Dibenzothiophene	tr	tr	tr	trc	nd	nd	nd
Phenanthrene	12	11	9.3	8.1	4.0	4.5	4.1
Anthracene	tr	tr	tr	tr	tr	tr	nd
Fluoranthene	19	26	26	22	8.2	8.2	4.9
Pyrene	24	41	33	23	10	11	4.6
Benzanthracene	15	22	nd	10	5.2	6.0	5.1
Chrysene	14	15	tr	13	7.6	7.4	3.0
Benzo(b)fluoranthene	16	nd	nd	8.7	4.8	6.5	4.6
Benzo(k)fluoranthene	8.7	nd	nd	9.4	8.4	8.7	nd
Benzo(a)pyrene	nd	nd	nd	nd	tr	1.8	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	na	nd	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd	nd	nd	nd
C1-Naph	tr	nd	nd	tr	tr	tr	tr
C2-Naph	tr	tr	tr	tr	nd	tr	nd
C3-Naph	nd	340	160	77	nd	nd	nd
C1-DBT	nd	tr	tr	tr	nd	nd	nd
C1-Phen	tr	6.9	tr	tr	tr	tr	tr
C2-Phen	tr	180	31	14	4.0	4.8	tr
TOTAL PNA'S	110	130	79	110	49	54	26
TOTAL PNA'S & NDP HOMOLOGS	110	660	270	200	53	59	26



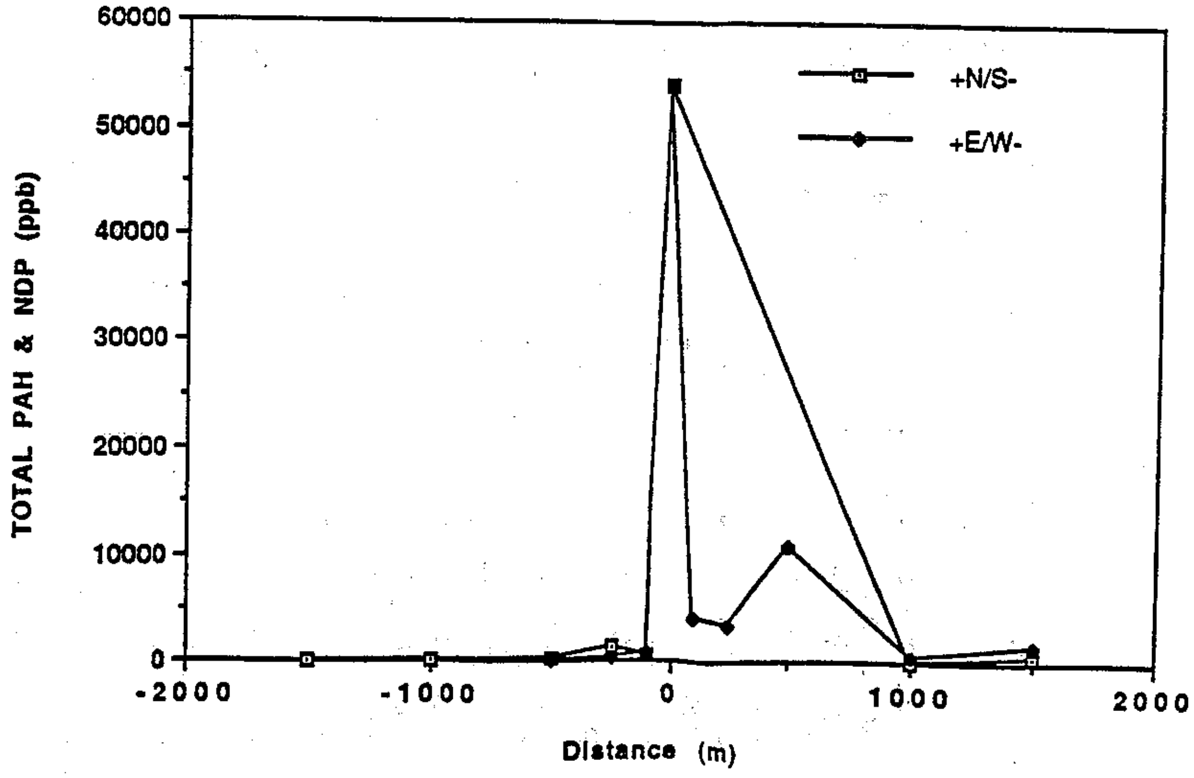
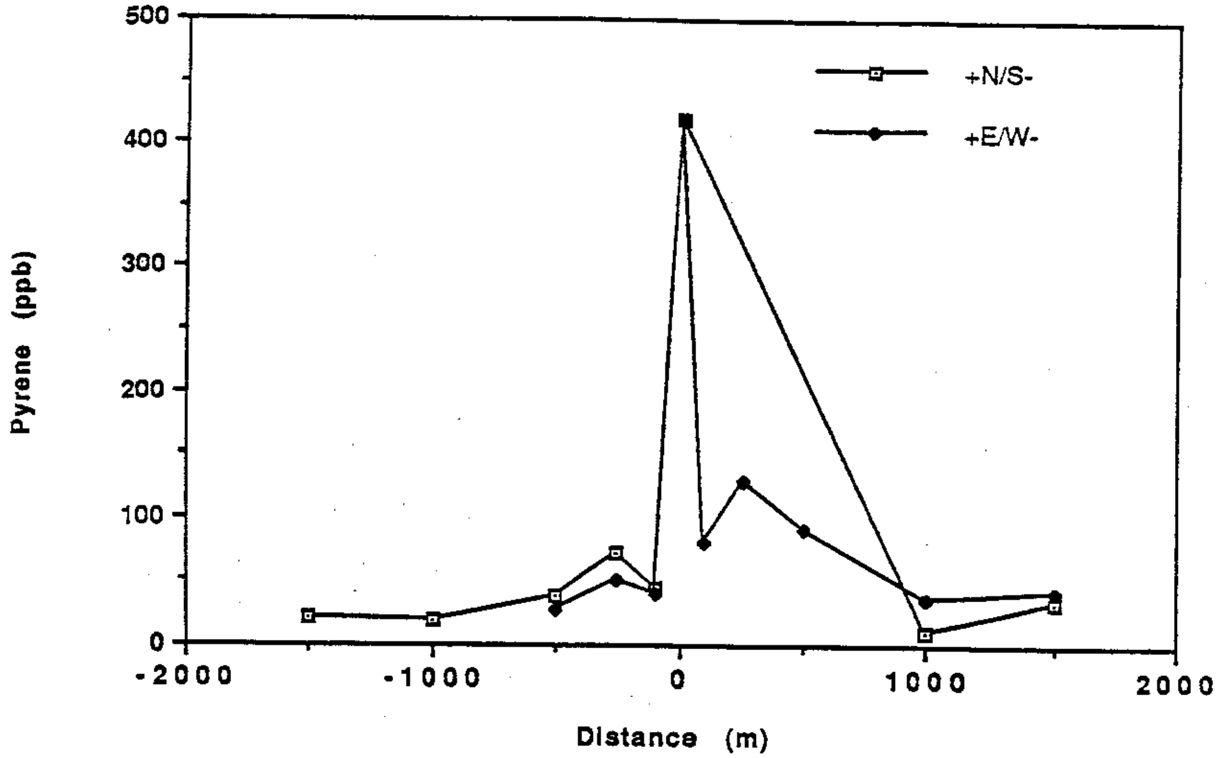


Figure 6.7. Spatial distribution of normal PAH, above, and total normal and alkylated PAH, below, in Bayou Sale sediments.



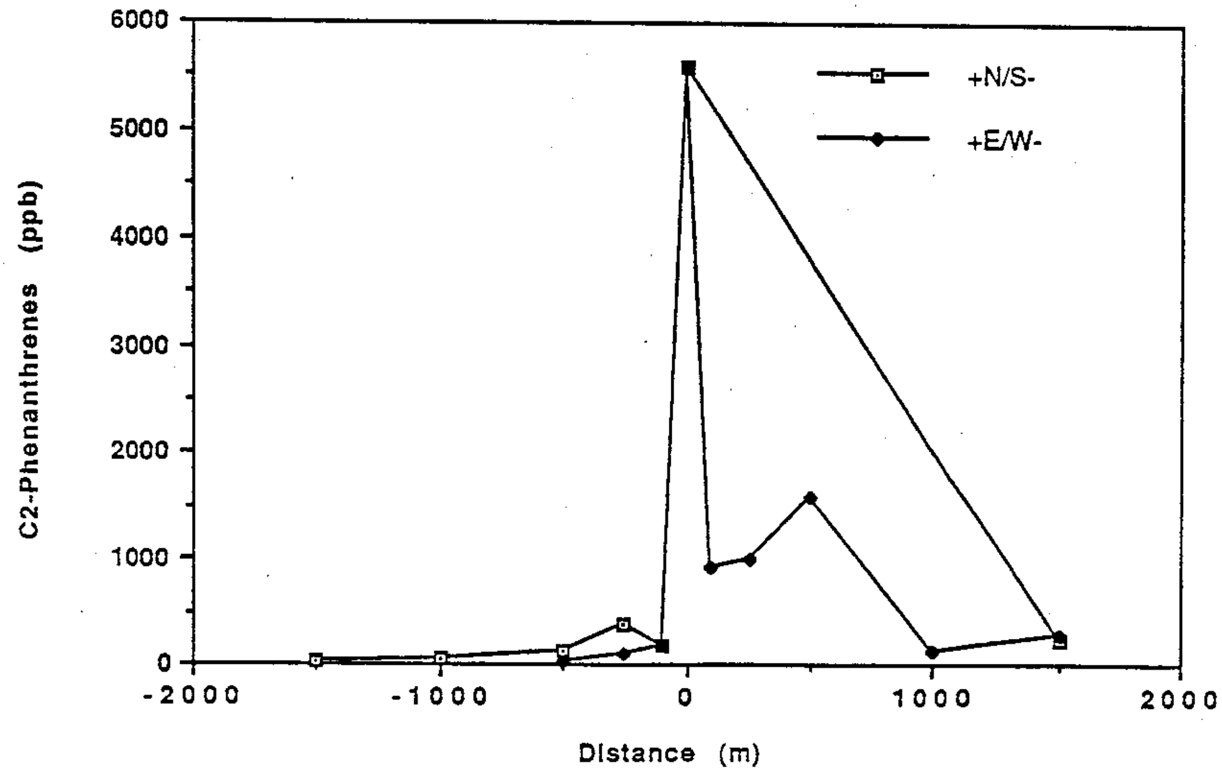
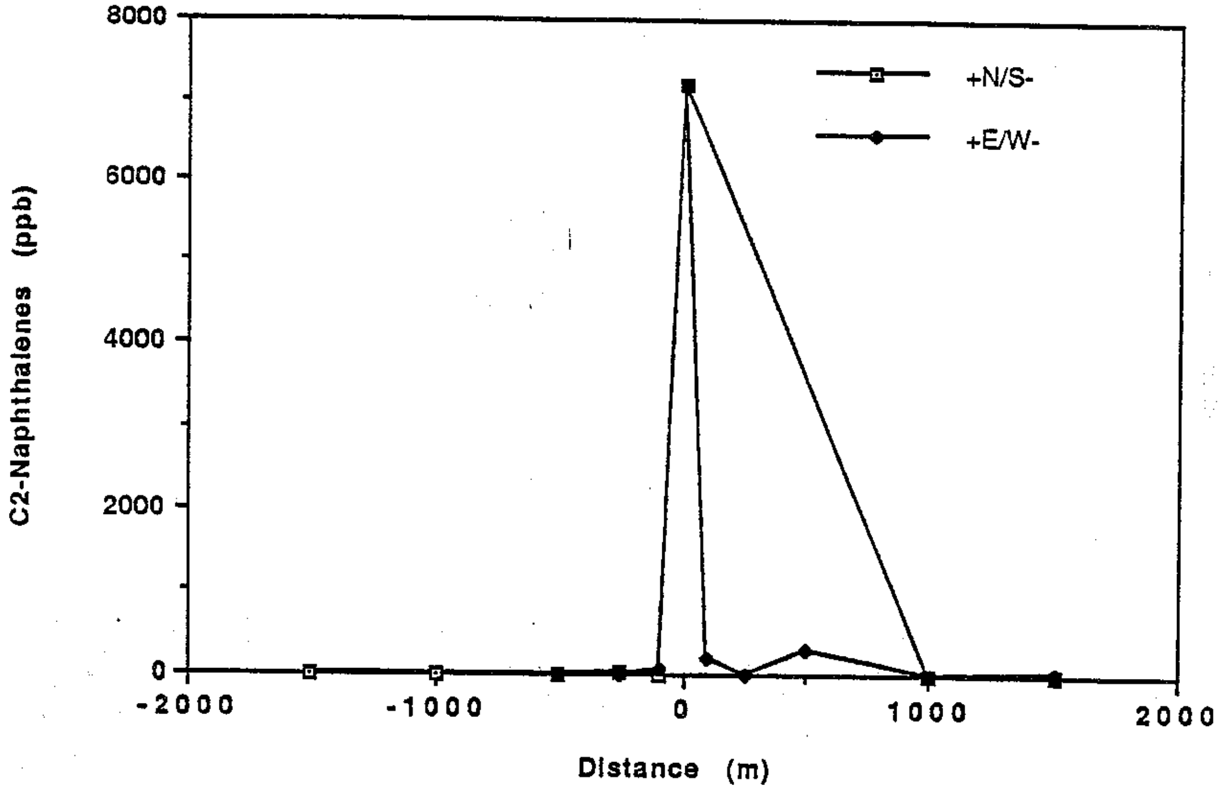


Figure 6.8. Spatial distribution of pyrene, above, and C-2 phenanthrenes, below, in Bayou Sale sediments.



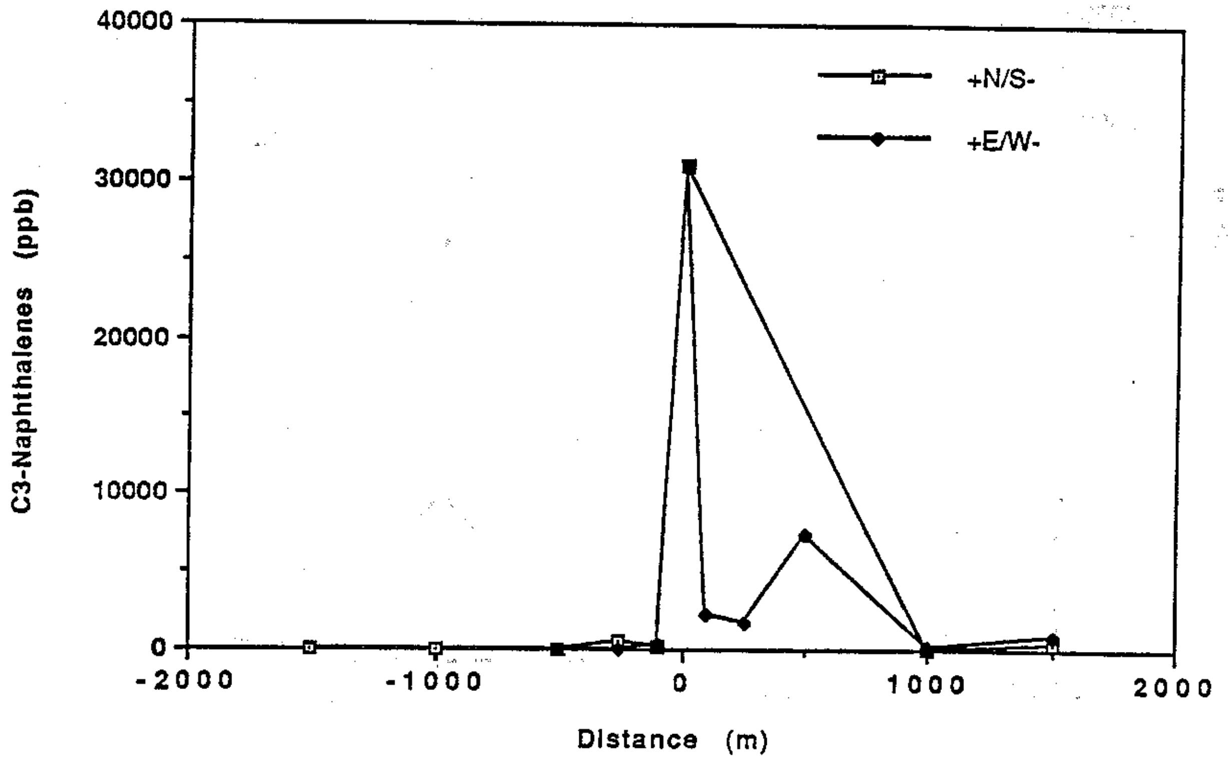
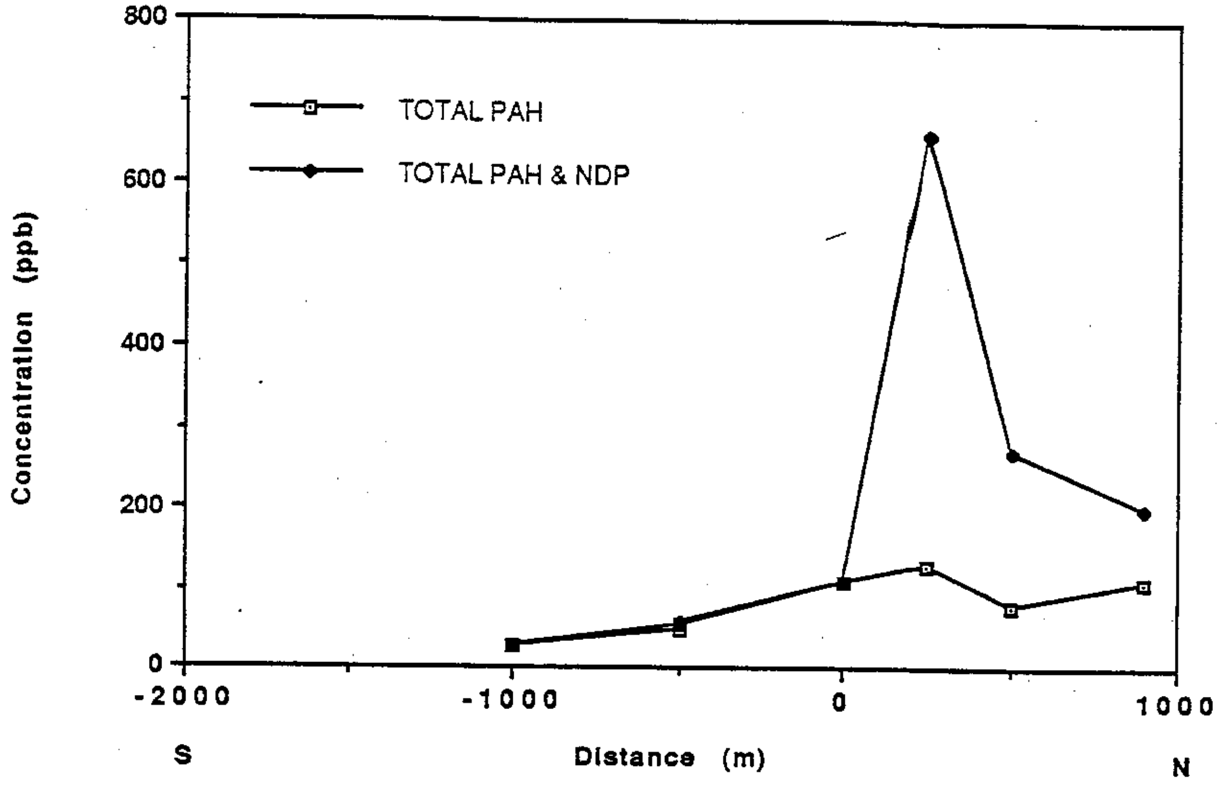


Figure 6.9. Spatial distribution of C-2 naphthalenes, above, and C-3 naphthalenes, below, in Bayou Sale sediments.



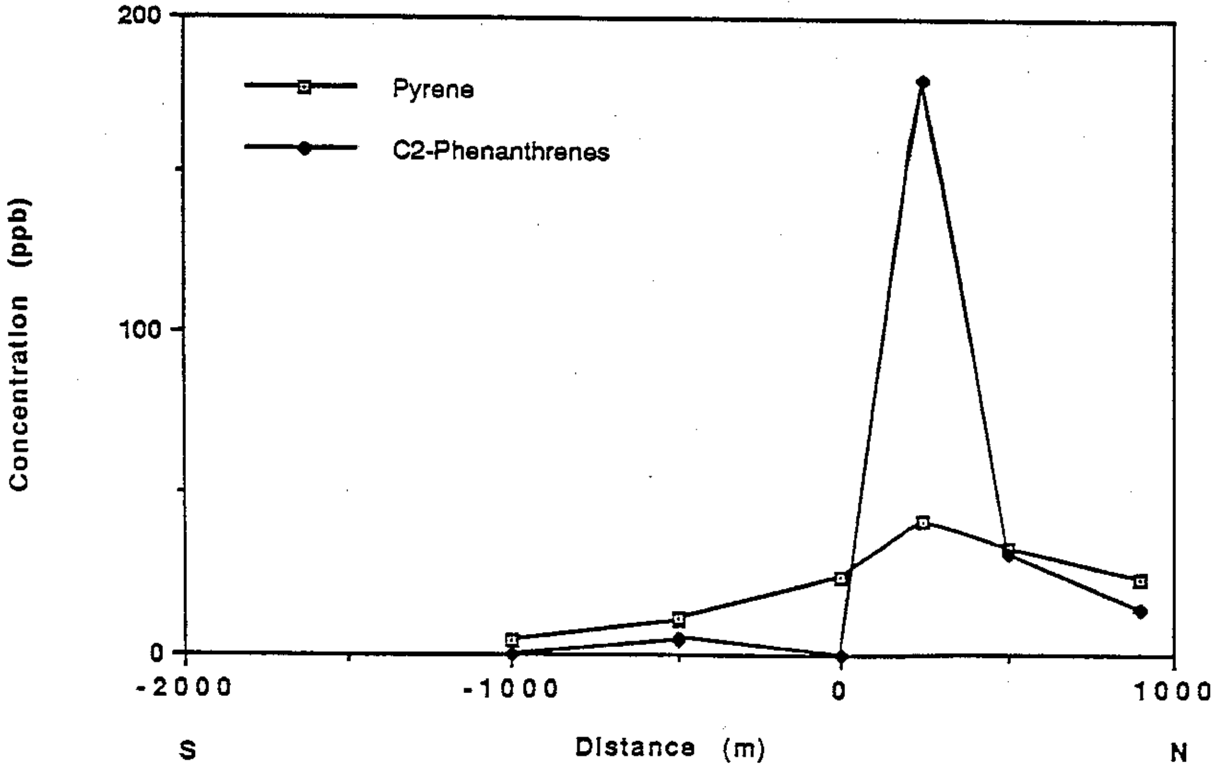


Figure 6.10. Spatial distribution of normal PAH, above, and total normal and alkylated PAH, below, in Bayou Sale reference site sediments.

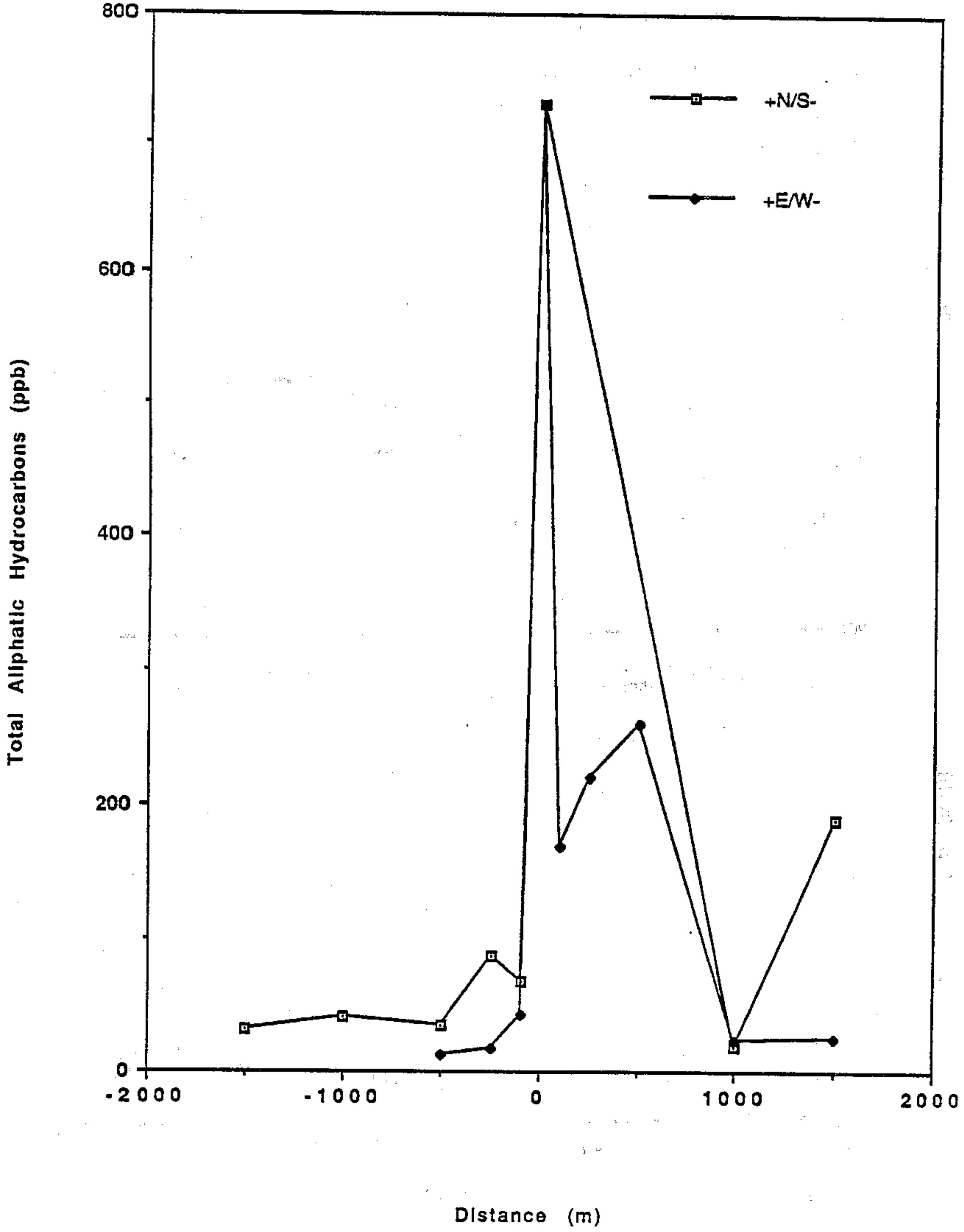


Figure 6.11. Spatial distribution of aliphatic hydrocarbons in sediments around the Bayou Sale discharge site.

Table 6.8. Saturated hydrocarbon concentrations in Bayou Sale sediments.

BAYOU SALE				
Distance (meters)	Resolved (ppb)	Unresolved (ppb)	TOTAL (ppb)	Resolved/ Total
0	240,000	940,000	1,200,000	0.18
NORTH				
1000	1,200	18,000	19,000	0.06
1500	24,000	170,000	190,000	0.12
EAST				
100	24,000	150,000	170,000	0.14
250	27,000	190,000	220,000	0.12
500	32,000	230,000	260,000	0.12
1000	2,200	22,000	24,000	0.09
1500	2,600	22,000	25,000	0.11
WEST				
100	5,600	37,000	43,000	0.13
250	1,500	15,000	17,000	0.09
500	1,000	11,000	12,000	0.08
SOUTH				
100	7,400	62,000	69,000	0.11
250	10,000	78,000	88,000	0.11
500	3,000	32,000	35,000	0.09
1000	2,400	40,000	42,000	0.06
1500	2,200	30,000	32,000	0.07

REFERENCE SITE				
Distance (meters)	Resolved (ppb)	Unresolved (ppb)	TOTAL (ppb)	Resolved/ Total
0	280	5,500	5,800	0.05
NORTH				
250	1,100	17,000	18,000	0.06
500	1,500	23,000	24,000	0.06
900	130	3,900	4,000	0.03
SOUTH				
500	180	4,400	4,600	0.04
1000	5,000	nd	5,000	1.00
MARSH SITES				
BS1				
0	1,800	8,000	9,800	0.18
4	3,200	46,000	49,000	0.07
12	320	7,500	7,800	0.04
25	3,800	18,000	22,000	0.17
BSR1				
0	730	1,200	1,900	0.38
12	66,000	nd	66,000	1.00
108	330	1,100	1,400	0.23

Resolved/Total = ppm resolved / (ppm resolved + ppm unresolved)
nd: not detected

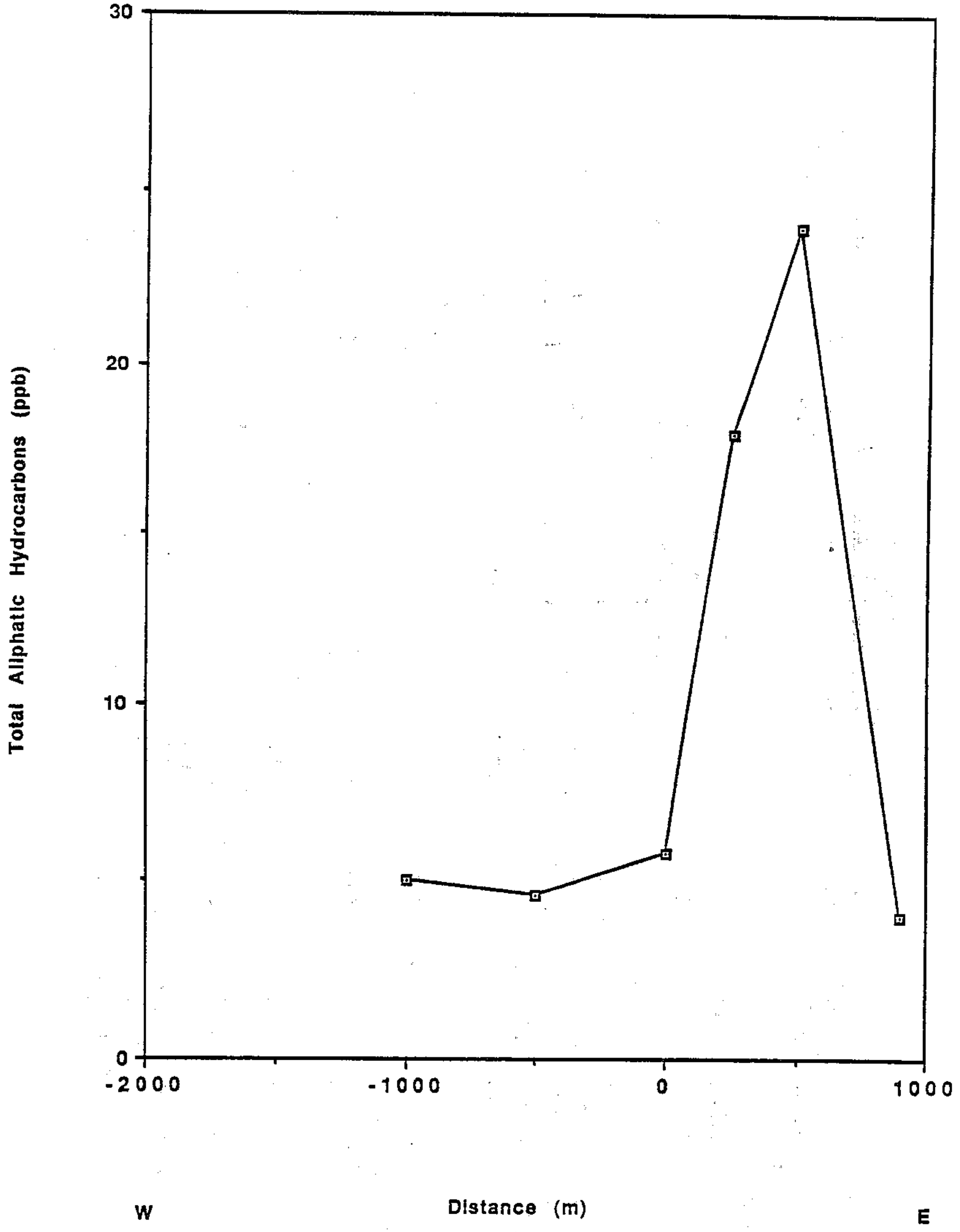


Figure 6.12. Spatial distribution of aliphatic hydrocarbons in Bayou Sale reference site sediments.

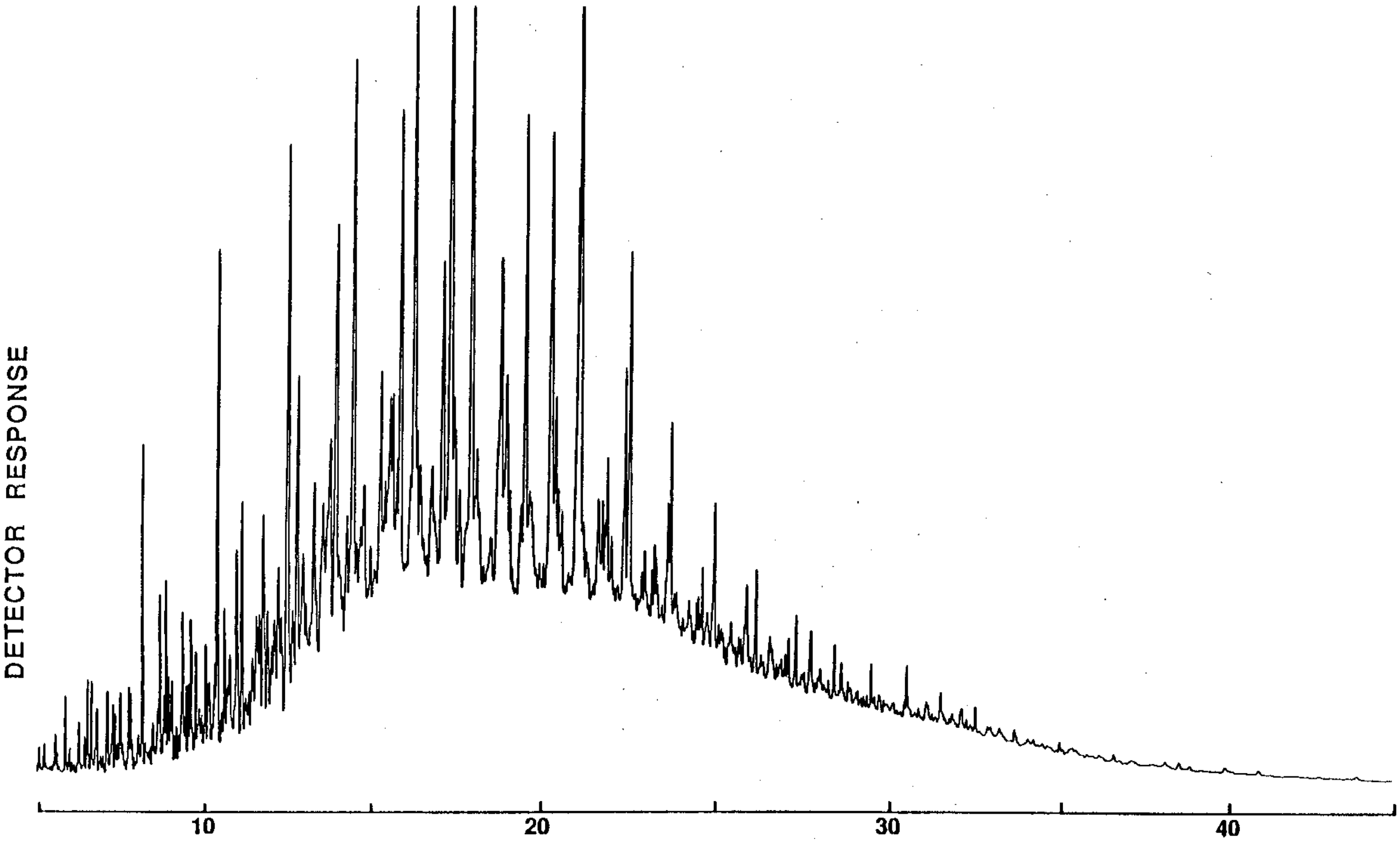


Figure 6.13. Chromatogram of the saturated hydrocarbon fraction (F-1) for sample station BS0 at the Bayou Sale study area.

Table 6.9. Semivolatile hydrocarbon concentrations in Bayou Sale marsh sediments.

ANALYTE	BS1					BSR1			
	0	4	12	12(d)	25	0	12	108	108(d)
MDL (ppb, dry wt.)	4.8	10	4.4	4.2	8.7	10	15	6.7	10
Naphthalene	nd	nd	10	nd	nd	nd	nd	nd	18
Acenaphthylene	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	nd	trc	nd	nd	trc	nd	15	nd	nd
Fluorene	tr	17	nd	nd	nd	nd	nd	nd	nd
Dibenzothiophene	nd	nd	nd	nd	nd	nd	nd	nd	nd
Phenanthrene	11	21	7.5	4.8	tr	12	tr	8.0	tr
Anthracene	nd	tr	nd	nd	nd	tr	nd	nd	nd
Fluoranthene	26	30	7.0	8.0	17	nd	tr	tr	tr
Pyrene	27	52	6.0	6.5	18	nd	tr	trc	tr
Benzanthracene	12	tr	8.5	13	9.3	tr	nd	tr	tr
Chrysene	36	trc	26	17	32	nd	nd	nd	tr
Benzo(b)fluoranthene	12	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(k)fluoranthene	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Naph	nd	nd	nd	nd	nd	nd	nd	nd	nd
C2-Naph	nd	nd	nd	nd	nd	nd	nd	nd	nd
C3-Naph	nd	790	nd	nd	nd	tr	nd	nd	nd
C1-DBT	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Phen	tr	170	tr	tr	tr	tr	nd	nd	nd
C2-Phen	8.3	570	tr	tr	32	tr	nd	nd	nd
TOTAL PNA'S	120	120	65	48	76	12	15	8.0	18
TOTAL PNA'S & NDP HOMOLOGS	130	1700	65	48	110	12	15	8.0	18

nd: not detected

tr: trace, extracted ion present, but below detection limit

trc: trace confirmed, extracted and confirming ions present, but below detection limit

Trace and Major Elements

6.3.1 Water

Concentrations of trace metals in water samples collected at various distances away from the discharge were uniformly very low or undetectable. Table 6.10 presents a summary of all of the trace and major element data for the Bayou Sale site as well as representing the produced water concentrations for the metals. An examination of these data shows that for every element except Cd, Cr, Ni, Hg and As which were not detected, there were elevated levels at the discharge point. However, all of the metals discharged are rapidly diluted out or sedimented out in the bayou system.

6.3.2 Sediments

As with any natural sediments, the concentrations of all elements must be considered in the context of the natural variability which exists as the result of variation in clay mineralogy and the geologic origins of the sediments in the system. For this reason, consideration of trace element concentrations may be normalized to some abundant element such as aluminum. Tables 6.11 and 6.12 present a summary of all of the data for trace and major elements determined in Bayou Sale sediments and the reference site sediments, respectively. When these data are plotted relative to the aluminum content of the sediments, those elements that are enriched in the sediments relative to the presumed source mineral material are be well above the hypothetical line, those in the expected range fall on or close to the line and those which are depleted fall below the line. Figure 6.14 shows examples of plots for several of the elements measured in sediments in the Bayou Sale system along with reference site data. Barium is very highly enriched at the discharge point and highly enriched at station as far as 1000 m away from the discharge. However, some sediment samples at intermediate distances (e.g., 100W, 250W, 250E, 250S) appear to have "normal" concentrations of this element. These data suggest that there are depositional and non-depositional zones within the bayou system for this soluble element. Chromium, copper, lead and vanadium are all also enriched within the Bayou Sale system, however, many of the sediments in the region appear to be depleted in zinc. When the discharge site sediments are compared to the reference site sediments, the ranges of values observed within the reference site are very similar to those near the discharge. Even for barium, the concentration at reference site BSR900N is similar to that at BS0. These data and those for the other elements suggest that there may be other sources of these metals other than the produced waters contributing to the sediment burdens in this region.

An examination of the spatial distribution of metals in the region of the discharges suggest some interesting patterns with respect to the fate of discharged metals. Figure 6.15 shows the spatial distributions for chromium, barium, lead and vanadium surrounding the discharge point. In the case of barium, as suggested earlier, the maximum level is seen at BS0 but there are secondary maxima at 1000E, 500S, 1000S and 500W with intervening minima. This suggests that there is an initial deposition of barium, perhaps in particulate form near the discharge. The resuspension and redeposition of fine particulates is a likely mode for the observed secondary maxima at greater distances from the discharge. Aspects of the solution chemistry for the soluble barium or discharges of drilling muds in the field may be other factors affecting barium levels.

Chromium, vanadium and lead distributions also showed some similarities to the barium distributions with a primary maximum at the BS0 site and secondary maxima away from the discharge with intervening minima. These differences in sediment distributions can partially be explained by sediment mineralogy but persist even when normalized for aluminum content. Therefore, some dynamic element chemistry is occurring in the vicinity of these sites, involving changes in salinity, particle interactions and trace element speciation.

Table 6.10. Trace and major elements in Bayou Sale water.

Metal (µg/ml)		Cu	Zn	Cd	Pb	Cr	Ni	As	Fe	Mn	Al	Na	Ba	V
Detection Limit (µg/ml)		0.020	0.010	0.010	0.025	0.005	0.025	0.060	0.020	0.010	0.150	0.080	0.100	0.005
Sample ID														
BS-PW	FIL	0.296	0.052	nd	0.039	nd	nd	nd	0.233	4.07	0.593	32,800	24.9	0.420
BS-PW	UNFIL	0.245	0.051	nd	nd	nd	nd	nd	2.03	4.03	0.524	29,900	23.7	1.80
BS-0	FIL	0.025	0.010	nd	nd	nd	nd	nd	0.034	0.015	nd	189	0.217	0.039
BS-0	UNFIL	nd	0.011	nd	nd	nd	nd	nd	0.341	0.020	0.478	194	0.170	0.005
BS-500E	FIL	nd	nd	nd	nd	nd	nd	nd	0.031	0.023	nd	159	0.192	0.011
BS-500E	UNFIL	nd	nd	nd	nd	nd	nd	nd	0.361	0.023	0.435	163	0.205	nd
BS-500S	FIL	nd	nd	nd	nd	nd	nd	nd	0.035	nd	nd	181	0.132	nd
BS-500S	UNFIL	nd	nd	nd	nd	nd	nd	nd	0.118	0.015	nd	185	0.143	nd
BS-500W	FIL	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	105	0.132	nd
BS-500W	UNFIL	nd	nd	nd	nd	nd	nd	nd	0.428	0.023	0.574	108	0.142	nd
BSR-0	FIL	nd	0.013	nd	nd	nd	nd	nd	nd	nd	nd	38.5	nd	0.005
BSR-0	UNFIL	nd	nd	nd	nd	nd	nd	0.064	0.210	0.014	0.300	42.5	nd	nd
BSR-500N	FIL	nd	nd	nd	nd	nd	nd	nd	0.036	0.015	nd	38.8	nd	0.011
BSR-500N	UNFIL	nd	nd	nd	nd	nd	nd	nd	0.245	0.017	0.309	39.6	nd	nd
BSR-500S	FIL	nd	0.015	nd	0.029	nd	nd	nd	0.042	nd	nd	39.1	nd	0.011
BSR-500S	UNFIL	nd	nd	nd	nd	nd	nd	nd	0.883	0.035	1.18	38.5	nd	nd

nd: not detected

Table .11. Trace and major elements in Bayou Sale discharge site sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Bayou Sale site												
BS-0	36	4.8	nd	193	101	38	31,271	342	65,339	8,069	1,529	142
BS-0 (dup)	37	18	nd	200	107	38	34,560	326	74,613	8,403	1,572	148
BS-100E	37	34	nd	173	86	37	30,030	370	33,720	2,668	459	135
BS-100S	38	23	nd	179	89	38	31,930	719	45,737	4,763	745	136
BS-100W	29	31	nd	137	71	29	27,593	430	25,697	1,493	125	138
BS-250E	34	34	nd	143	79	34	27,751	232	25,207	847	98	124
BS-250S	34	30	nd	169	79	33	27,853	389	28,530	2,775	222	120
BS-250W	33	30	nd	157	80	34	30,097	532	29,560	1,428	163	131
BS-500E	39	75	nd	156	97	35	26,993	212	19,129	356	132	125
BS-500S	39	22	nd	189	94	37	25,282	679	38,288	5,435	784	127
BS-500W	35	16	nd	150	89	36	33,843	1,108	52,660	7,414	822	137
BS-1000N	36	23	nd	148	84	35	32,621	800	49,921	5,624	665	140
BS-1000E	42	62	nd	140	98	40	31,143	368	33,958	2,135	709	138
BS-1000S	23	nd	nd	157	72	28	24,238	549	55,417	9,463	868	100
BS-1500N	29	21	nd	136	78	31	30,161	638	35,713	1,444	158	125
BS-1500N (dup)	32	24	nd	138	77	32	30,598	695	35,773	1,445	180	114
BS-1500E	35	56	nd	130	86	34	27,315	314	30,414	460	256	150
BS-1500S	31	15	nd	158	85	35	24,829	731	37,361	3,205	282	109

nd: not detected
n/a: not available

Table 6.12. Trace and major elements in Bayou Sale reference sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Bayou Sale Ref. Site												
BSR-0	39	24	nd	155	89	39	32,946	756	54,571	4,053	532	128
BSR-250N	34	97	nd	131	74	35	30,418	441	35,137	1,818	596	122
BSR-500N	38	84	nd	143	84	39	37,123	443	37,310	2,510	667	131
BSR-500S	28	nd	nd	152	74	27	21,941	631	50,166	8,562	539	97
BSR-900N	42	30	nd	191	102	43	31,538	567	62,665	4,033	1,563	144
BSR-1000S	35	2.4	nd	150	81	32	32,903	905	61,338	6,291	473	120

nd: not detected
n/a: not available

Table 6.13. Trace and major elements in Bayou Sale marsh sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Bayou Sale Marsh Site												
BS1-0	31	22	nd	105	69	31	24,569	126	32,341	452	55	118
BS1-4	28	21	nd	99	65	29	21,426	87	27,541	1,048	207	111
BS1-12	24	17	nd	91	60	28	19,139	100	25,846	1,454	231	108
BS1-25	31	35	nd	99	66	32	24,744	90	26,855	981	99	106
Bayou Sale Ref. Marsh Site												
BSR1-0	15	28	nd	57	37	21	14,402	108	17,879	161	124	55
BSR1-12	25	31	nd	87	60	28	22,682	101	24,805	542	157	105
BSR1-108	29	37	nd	88	62	32	27,206	506	24,615	379	54	114

nd: not detected
n/a: not available

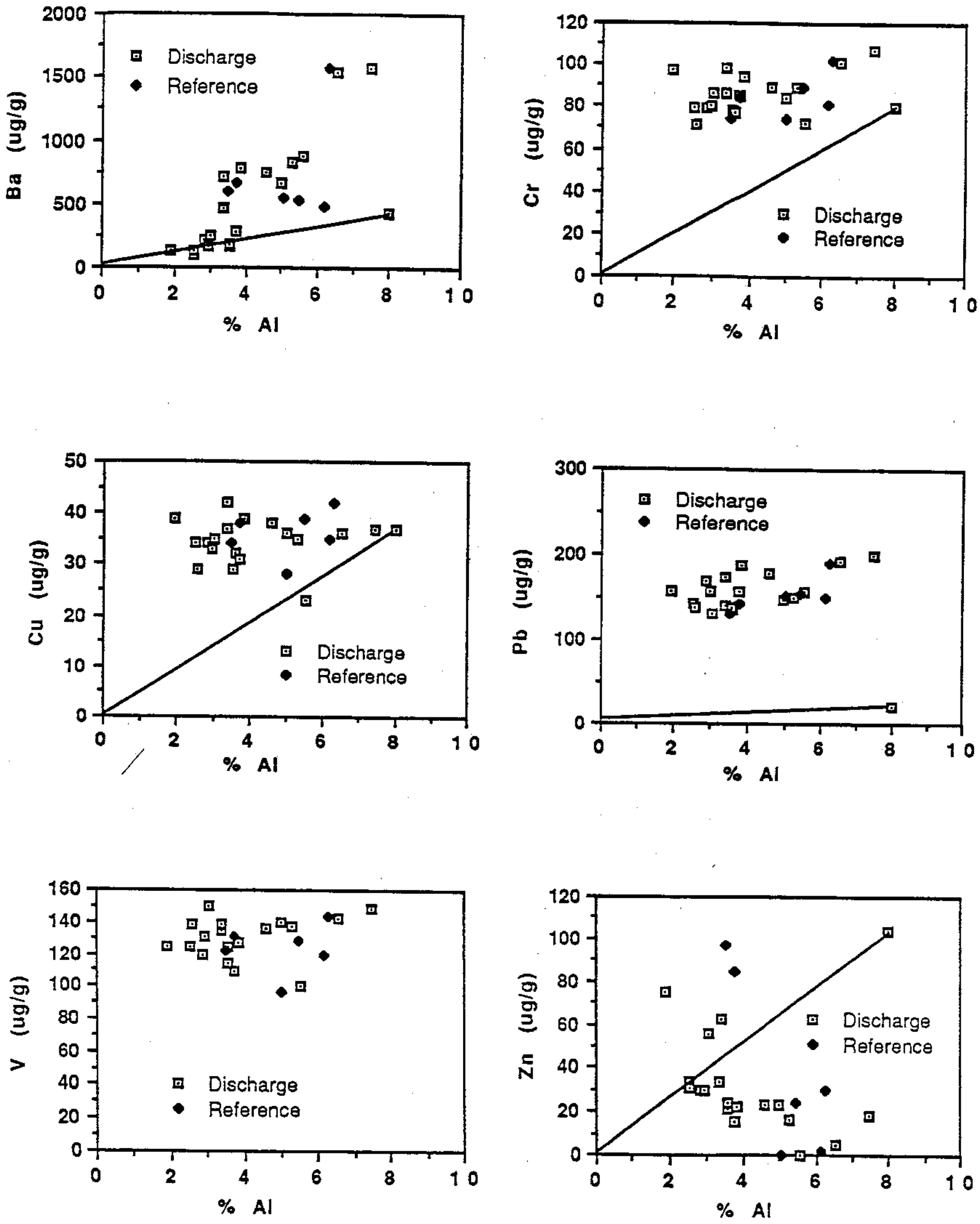


Figure 6.14. Concentrations of metals relative to aluminum for Bayou Sale discharge and reference site sediments.

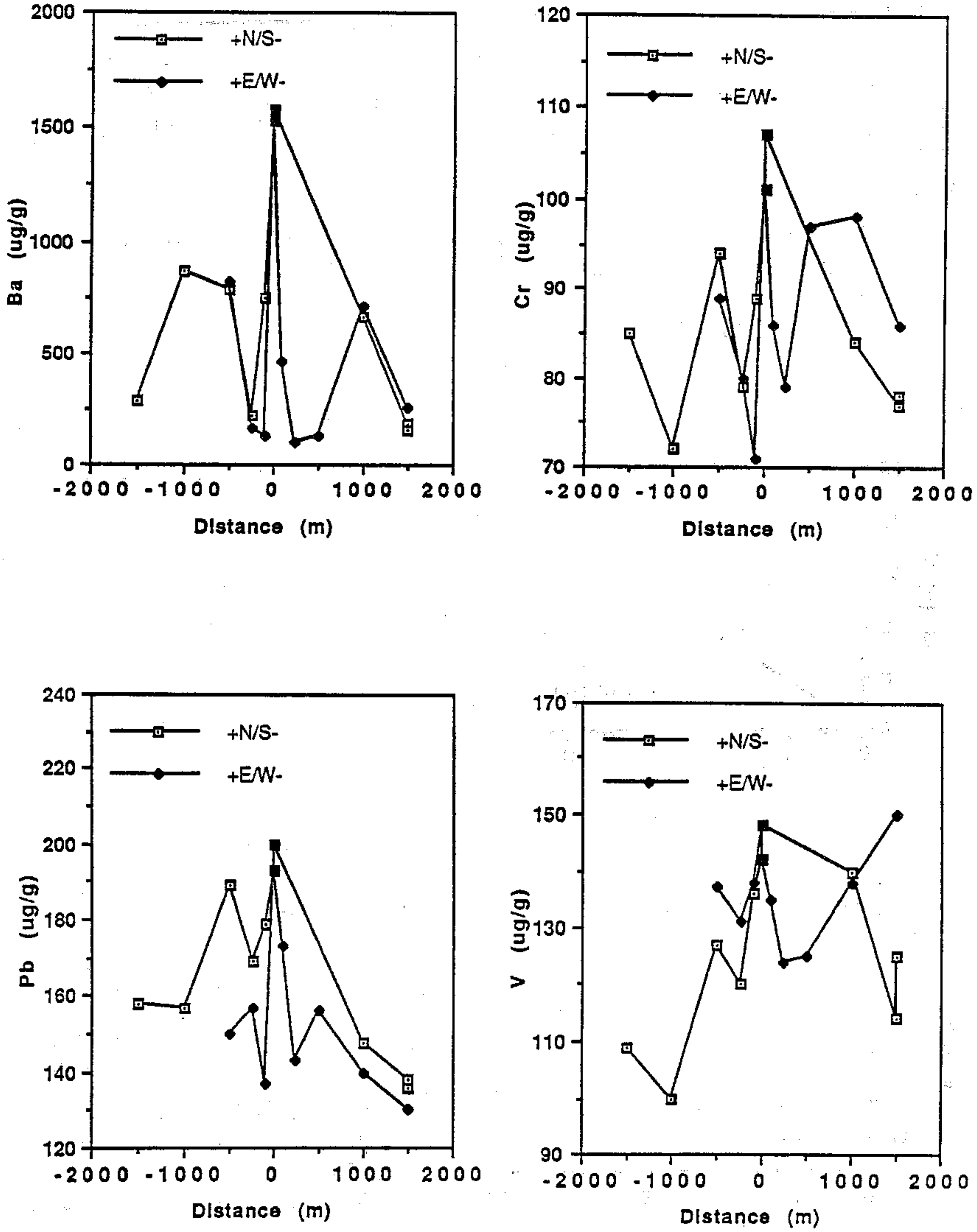


Figure 6.15. Spatial distribution of selected trace metals for Bayou Sale discharge site sediments.

Table 6.12 presents the trace and major element data for the reference site. Spatial distributions of the elements within this region showed some consistent trends which are not readily understood given the number of samples collected. All of the elements were found at concentrations similar in range to those at the discharge site but, except for manganese, there was a tendency for those sediments at the northerly stations in the reference area to have higher metals concentrations than those to the south. This might be related to the presence of sediments with a higher clay content to the north.

Table 6.13 presents a summary of the trace and major element data for the marsh sediments in the Bayou Sale system. In the case of barium, concentrations increased from the zero point into the marsh and then declined. For Pb and V, concentrations were highest near the discharge and generally decreased.into the marsh while at the reference site these two metals were lowest at the zero point and increased into the marsh. Zn and Cr deceased in concentration away from the discharge but then increased again, while at the reference site they were lowest at the zero point and increased into the reference marsh. Mn was fairly constant near the discharge but was observed to increase dramatically at the 108 m site in the reference site. This latter result may be due to redox phenomena occurring in the region.
Bayou Sale

6.4 Benthic Communities

6.4.1. Dominants

The benthic macroinfauna community at the Bayou Sale site is typical of tidal freshwater areas composed primarily of oligochaetes and chironomid insect larvae. The most numerous oligochaetes were *Limnodrilus* spp. Of the 58 total number of species collected at the Bayou Sale site, the most common species were *Limnodrilus* sp. made up 31% of the total occurrences. Occasional collections were made of the mysid shrimp *Mysidopsis almyra*, the gastropod *Probythenella louisianae*, the polychaete *Hobsonia florida*, and ostracods.

6.4.2 Community Parameters

A single replicate within the waterways and channels of the Bayou Sale study area has been analyzed for each station. For the discharge site, four stations along the southern transect have been analyzed in full (three replicates per station). For comparison three reference stations have been analyzed in full.

The number of species per station at the discharge site ranged from 1 to 12, compared to 6 to 13 at the reference stations (Table 6.14). The number of individuals per station ranged from 24 to 307 at the discharge site, compared to 56 to 159 at the reference stations. Measures of diversity (H') and evenness (J') for the reference stations were within the range for the same values at the discharge site (Table 6.15).

There were no clear trends in number of species or number of individuals with distance away from the discharge point (Figures 6.16-6.18) with the exception of anamolous values at the discharge point and at BS1500E. Differences were seen mainly in the community composition at the stations.

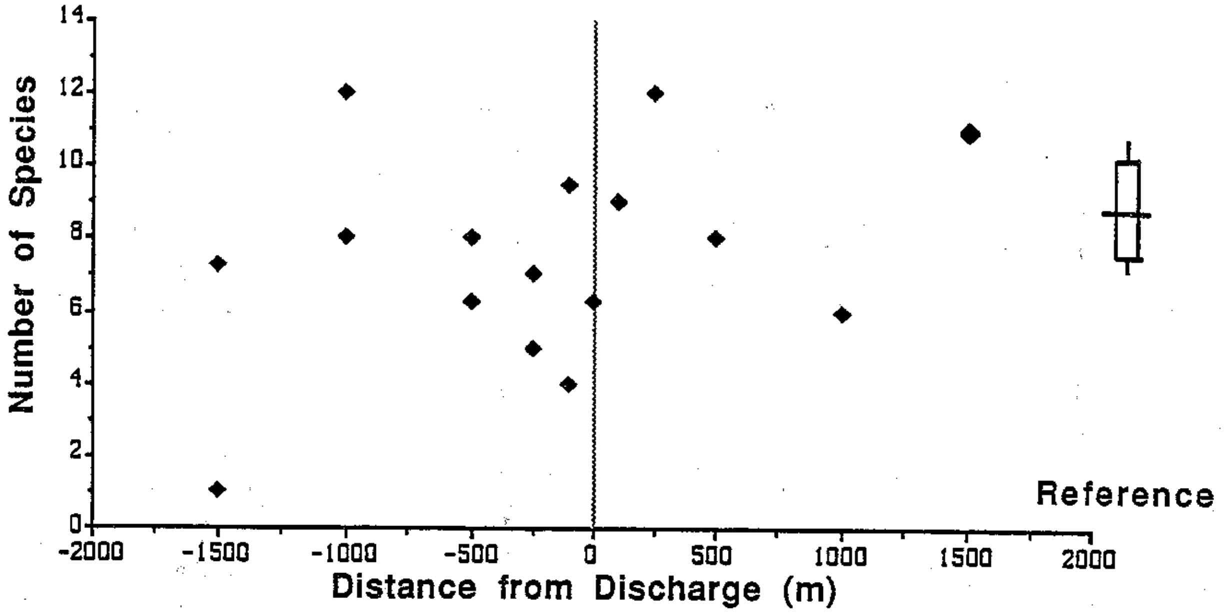
On the whole, the replicated group of discharge stations did not differ significantly from the replicated group of reference stations (Table 6.16). One should note, however, that cell sizes were unequal for the analysis and that statistically significant differences were found within each of the two station groupings (discharge vs. reference). Also, because of the sampling design, stations at greater distances from the discharge point were selected to determine a decrease in the

Table 6.14. Number of species per replicate and number of individuals per replicate for stations at the Bayou Sale site.

		Number of Species			Number of Individuals		
Stations	No. Repl.	Min.	Max.	$\bar{x}$ ± S.D.	Min.	Max.	$\bar{x}$ ± S.D.
BS0	3	5	9	6.3 ± 2.3	201	369	307 ± 92.2
BS100E	1			4			47
BS100S	2	9	10	9.5 ± 0.7	56	152	104.0 ± 67.9
BS100W	1			9			165
BS250E	1			7			136
BS250S	3	2	7	5.0 ± 2.6	12	129	54.3 ± 64.8
BS250W	1			12			106
BS500E	1			8			274
BS500S	3	5	9	6.3 ± 2.3	11	100	50.0 ± 45.5
BS500W	1			8			69
BS1000E	1			8			61
BS1000N	1			6			51
BS1000S	1			12			129
BS1500E	1			1			24
BS1500N	1			11			53
BS1500S	3	4	9	7.3 ± 2.9	21	70	51.3 ± 26.5
BSR0	3	5	9	6.3 ± 2.3	33	56	4.37 ± 11.6
BSR250N	3	11	14	12.7 ± 1.5	23	159	108.3 ± 74.3
BSR500S	3	5	9	7.3 ± 4.3	57	98	83.7 ± 23.1

Table 6.15. Benthic community parameters for stations at the Bayou Sale site.

Station	No. Calc.	Diversity (H') $\bar{x} \pm$ S.D.	No. Calc.	Evenness (J') $\bar{x} \pm$ S.D.
BS0	3	0.26 ± 0.07	3	0.10 ± 0.01
BS100E	1	0.17	1	0.08
BS100S	2	0.58 ± 0.12	2	0.18 ± 0.04
BS100W	1	0.47	1	0.14
BS250E	1	0.59	1	0.21
BS250S	3	0.41 ± 0.25	3	0.18 ± 0.04
BS250W	1	0.67	1	0.19
BS500E	1	0.54	1	0.18
BS500S	3	0.60 ± 0.16	3	0.23 ± 0.06
BS500W	1	0.61	1	0.20
BS1000E	1	0.71	1	0.24
BS1000N	1	0.56	1	0.22
BS1000S	1	0.62	1	0.17
BS1500E	1	0.00	0	-
BS1500N	1	0.23	1	0.21
BS1500S	3	0.47 ± 0.09	3	0.17
BSR0	3	0.66 ± 0.12	3	0.26
BSR250N	3	0.77 ± 0.22	3	0.21
BSR500S	3	0.41 ± 0.05	3	0.15



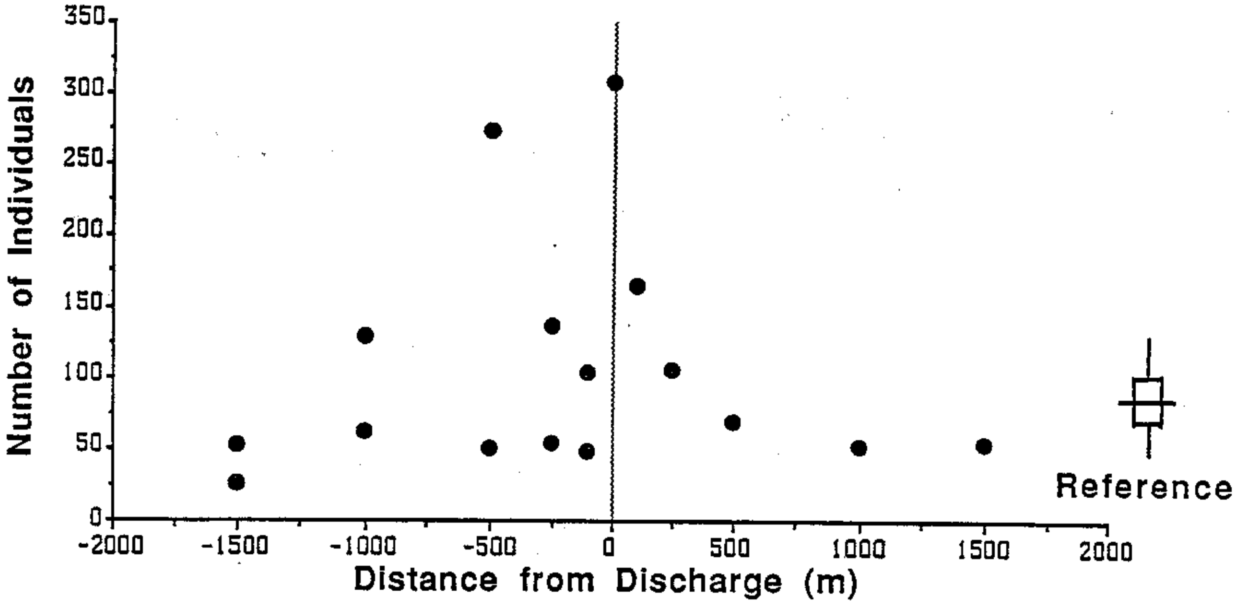


Figure 6.16. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna at all stations for the Bayou Sale discharge site. Mean, standard error and average minimum and maximum for reference stations shown to the right.

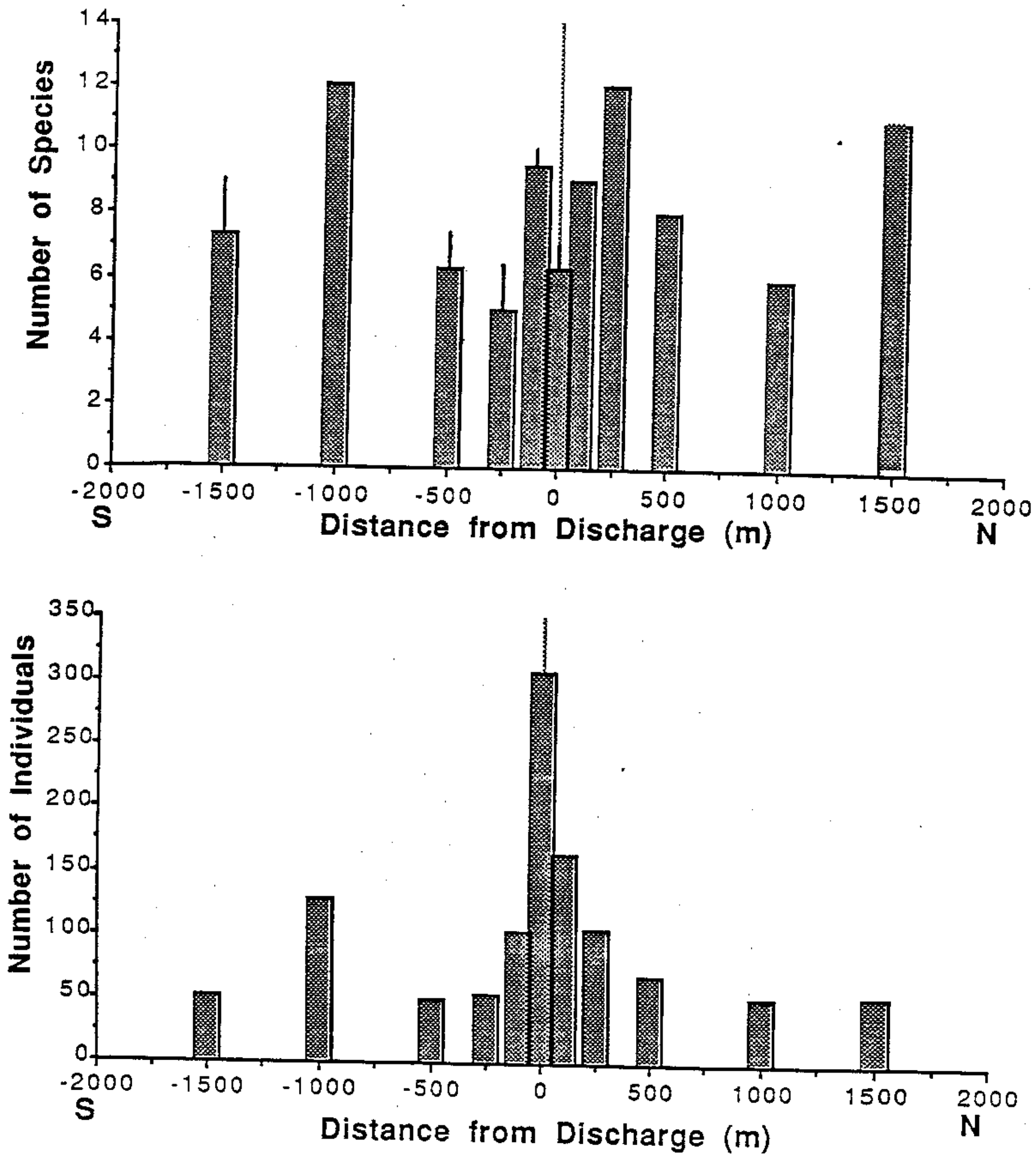


Figure 6.17. Number of species per replicate, above, and number of individuals per replicate below, for benthic macroinfauna along a north-south transect through the Bayou Sale discharge site (standard error bars shown at selected stations).

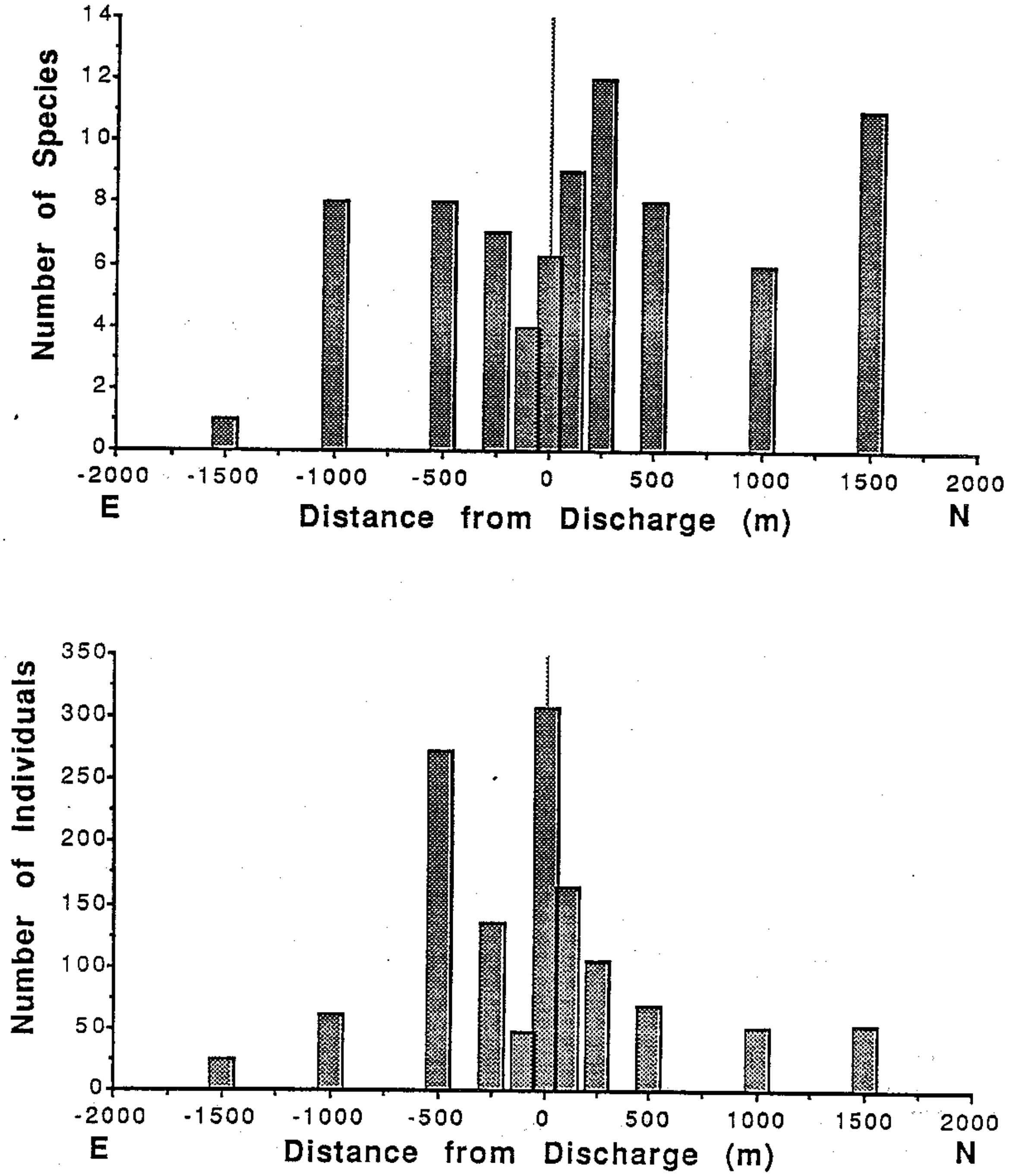


Figure 6.18. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna along a north-east transect through the Bayou Sale discharge site (standard error bars shown at selected stations).

Table 6.16. General linear model analysis of variance for Bayou Sale discharge stations versus reference stations.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	1	16.47	16.47	1.83	0.19
Error	22	198.49	9.02		
Corrected Total	23	214.96			
Number of individuals per replicate:					
Model	1	7471.11	7471.11	0.82	0.38
Error	22	201268.22	9148.56		
Corrected Total	23	208739.33			
Diversity H':					
Model	1	0.13	0.13	3.46	0.08
Error	22	0.80	0.36		
Corrected Total	23	0.93			
Evenness J':					
Model	1	0.01	0.01	2.15	0.16
Error	22	0.07	0.00		
Corrected Total	23	0.08			

effects of brine discharge (if this were the case) and were thus more similar to the reference stations than to stations nearer the discharge.

Within the grid of discharge stations for the Bayou Sale study area, there were statistically significant differences among the replicated stations for some of the benthic community parameters measured (Table 6.17) although these differences were limited (Table 6.18). The number of individuals was significantly higher at the discharge site than at the stations along the transect to the south away from the discharge (Table 6.18, Figure 6.17). Differences in evenness (J') combined with number of individuals indicates that a few species of oligochaetes made up these high numbers. This trend is consistent with reports in the literature that communities characterized by tubificid oligochaetes inhabiting tidal freshwater and estuarine areas respond to physical disturbance and organic pollution by increasing oligochaete population size rather than by major shifts in species composition (Diaz, 1980). Station BS1500E exhibited a reduced fauna of a single species of oligochaete. This station was excluded from the analysis of variance because of incomplete number of replicates, but the number of species and number of individuals is obviously reduced compared to the other stations in the area of the discharge (Table 6.14, Figure 6.18). This station was characterized by chemical contaminants (see below).

Within the grid of reference stations analyzed for the Bayou Sale site, there were statistically significant differences among the stations for only a single parameter, number of species per replicate (Table 6.19). The benthic community of station BSR250N was more diverse than the other two analyzed (Table 6.20). Note that these differences are based on only three sets of completed samples.

6.4.3 Marsh Stations

One set of replicates for marsh faunal analysis has been completed for each of BS1-0, a discharge site, and BSR1-0, a reference site; both of these stations are located at 0 m from either the discharge point or an arbitrary zero point at the reference stations. Number of individuals was significantly less at BS1-0 compared to BSR1-0 (Tables 6.21 and 6.22). Individuals at BS1-0 were primarily oligochaetes whereas bivalves dominated at BSR1-0.

6.5 Synthesis

Sediments for stations at the Bayou Sale site were predominantly muds, with only two stations having greater than 10% sand composition (BS1000S and BS1500S). Both of these stations were located at the southern end of the discharge station grid in Lone Oak Bayou where tidal currents were swift and accumulation of fine sediments less likely to occur. Similarly, total organic carbon content was uniformly less than 8%, with the exception of BS500S and stations along the transect to the east (BS250E, BS500E and BS1000E). The higher values to the east were not obviously related to differences in sediment grain size composition, but may have been related to the levels of chemical contaminants seen in the eastern transect. Because of the rather uniform environmental conditions with respect to sedimentary characteristics, benthic community parameters measured showed no correlations with sediment grain size distribution or sediment total organic carbon content.

As mentioned above (Section 6.2.2.3), concentrations of most chemical contaminants were maximal at the discharge point and decreased rapidly within 500 m of the discharge. There were increases in groups of hydrocarbons at several stations along the eastern transect. The benthic community parameters of number of species and number of individuals were examined in relationship to major groups of chemical contaminants in the sediments. There were no clear responses of these measures to the concentrations of total polynuclear aromatic hydrocarbons (PAH), total PAH and homologs of naphthalene, dibenzothiophene, and phenantherene (NDP

Table 6.17. General linear model analysis of variance for Bayou Sale site discharge stations (note: cell sizes unequal).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	5	52.43	10.49	1.80	0.21
Error	9	52.50	5.83		
Corrected Total	14	104.93			
Number of individuals per replicate:					
Model	5	146906.67	29381.33	7.43	0.00
Error	9	35583.33	3953.70		
Corrected Total	14	182490.00			
Diversity H':					
Model	5	0.23	0.47	1.96	0.18
Error	9	0.22	0.24		
Corrected Total	14	0.45			
Evenness J':					
Model	5	0.26	0.01	3.51	0.05
Error	9	0.01	0.00		
Corrected Total	14	0.39			

Table 6.18. Duncan's multiple range test for Bayou Sale discharge stations. Underlined stations are not significantly different from each other.

Number of individuals per replicate:

BS 0	BS 1000S	BS 100S	BS 250S	BS 1500S	BS 500S
———					
	———	———	———	———	———

Evenness J':

BS 500S	BS 100S	BS 250S	BS 1000S	BS 1500S	BS 0
———	———	———	———	———	
	———	———	———	———	———

Table 6.19. General linear model analysis of variance for Bayou Sale site reference stations.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	2	69.56	34.78	8.69	0.02
Error	6	24.00	4.00		
Corrected Total	8	93.56			
Number of individuals per replicate:					
Model	2	6390.22	3195.11	1.55	0.29
Error	6	12388.00	2064.67		
Corrected Total	8	18778.22			
Diversity H':					
Model	2	0.22	0.11	4.87	0.06
Error	6	0.13	0.02		
Corrected Total	8	0.35			
Evenness J':					
Model	2	0.02	0.01	4.22	0.07
Error	6	0.02	0.00		
Corrected Total	8	0.03			

Table 6.20. Duncan's multiple range test for Bayou Sale reference stations. Underlined stations are not significantly different from each other.

Number of species per replicate:

BSR 250N	BSR 500S	BSR 0
———	————————————	

Table 6.21. Benthic community parameters for marsh stations at the Bayou Sale Site.

		Number of Species			Number of Individuals		
Station	No. Repl.	Min.	Max.	$\bar{x}$ ± S.D.	Min.	Max.	$\bar{x}$ ± S.D.
BS1-0	3	3	7	5.3 ± 2.1	8	13	9.7 ± 2.9
BSR1-0	3	5	9	7.3 ± 2.1	16	33	26.0 ± 8.9

Station	No. Calc.	Diversity (H') $\bar{x}$ ± S.D.	No. Calc.	Evenness (J') $\bar{x}$ ± S.D.
BS1-0	3	0.66 ± 0.23	3	0.29 ± 0.02
BSR1-0	3	0.60 ± 0.33	3	0.20 ± 0.09

Table 6.22. General linear model analysis of variance for Bayou Sale marsh stations, discharge versus reference.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	1	6.00	6.00	1.38	0.30
Error	4	17.33	4.33		
Corrected Total	5	23.33			
Number of individuals per replicate:					
Model	1	400.17	400.17	9.16	0.04
Error	4	174.67	43.67		
Corrected Total	5	574.83			
Diversity H':					
Model	1	0.01	0.01	0.11	0.76
Error	4	0.32	0.08		
Corrected Total	5	0.33			
Evenness J':					
Model	1	0.01	0.01	2.51	0.19
Error	4	0.02	0.00		
Corrected Total	5	0.03			

homologs), and total resolved and unresolved aliphatic hydrocarbons in the sediments (Figures 6.19-6.21).

It would be premature to draw conclusions regarding the differences in marsh benthic communities at the discharge site and the reference site. In general, however, at the 0-m distance station analyzed, there were higher concentrations of total polynuclear aromatic hydrocarbons, selected PAH homologs, and total resolved and unresolved aliphatic hydrocarbons than at the reference site. The reduced number of individuals and different community composition at the marsh discharge site (BS1-0) may be related to these higher hydrocarbon concentrations. Total PAH and total PAH and NDP homolog concentrations were minimal at the reference marsh transects.

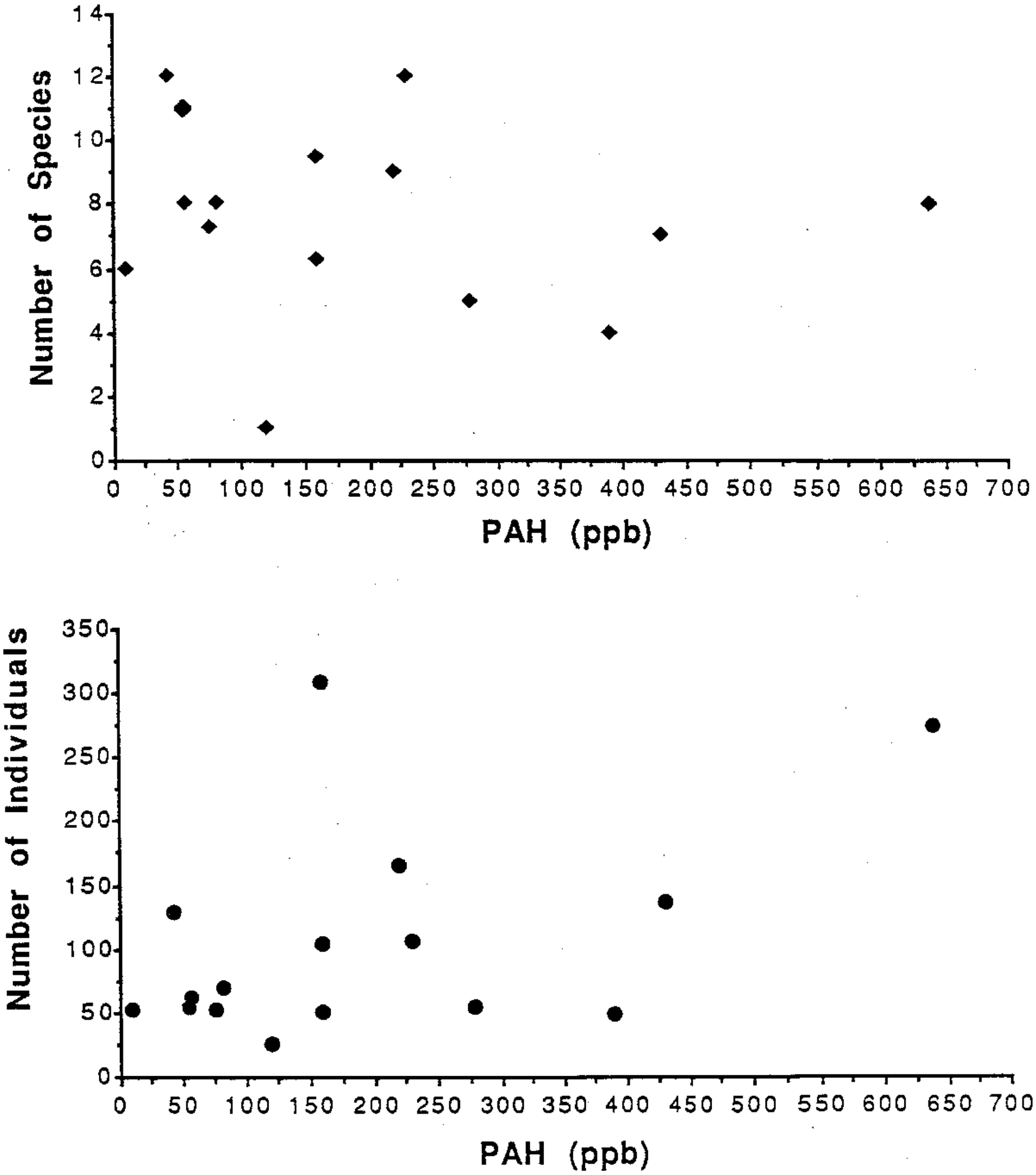


Figure 6.19. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) for the Bayou Sale discharge site.

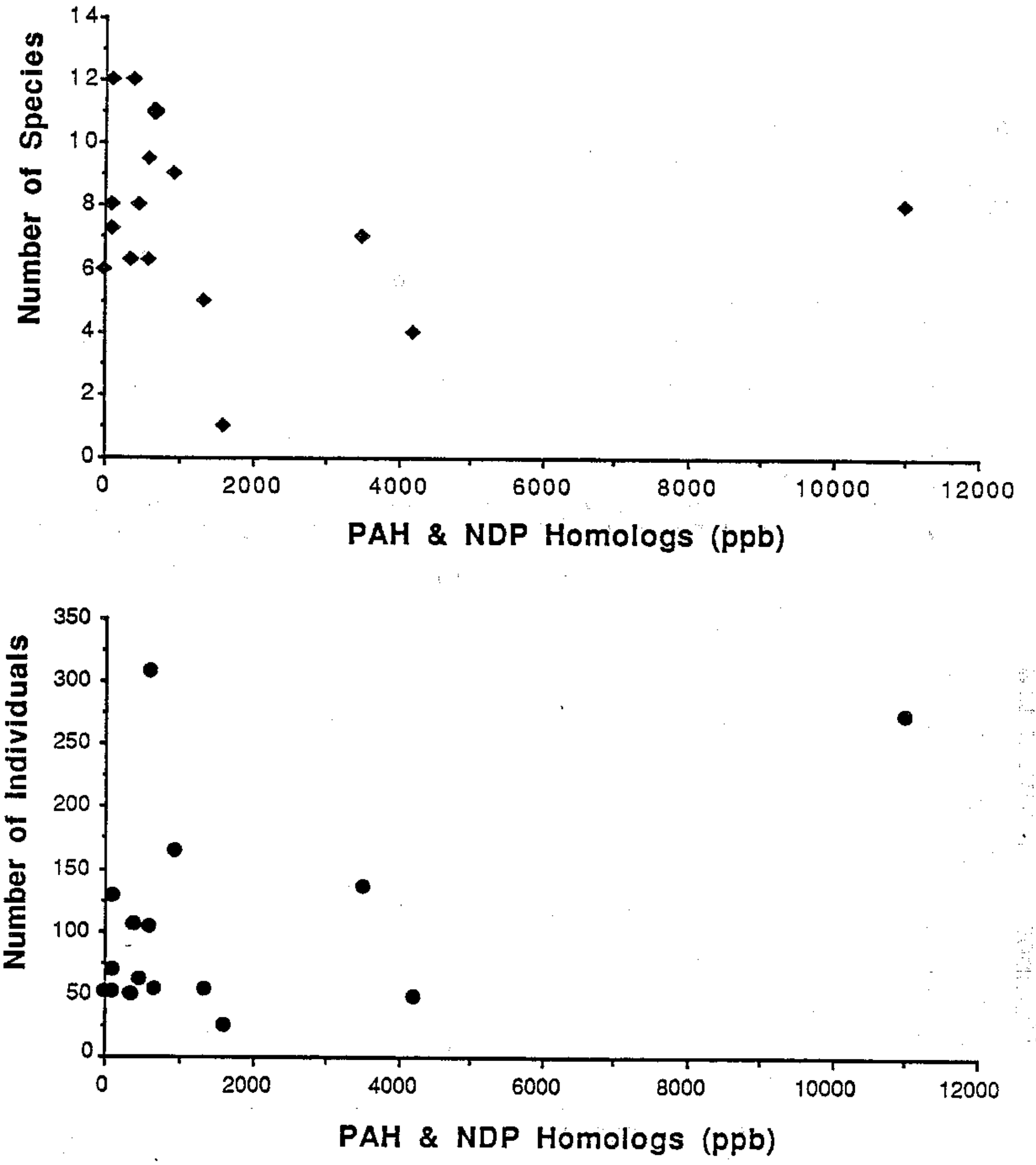
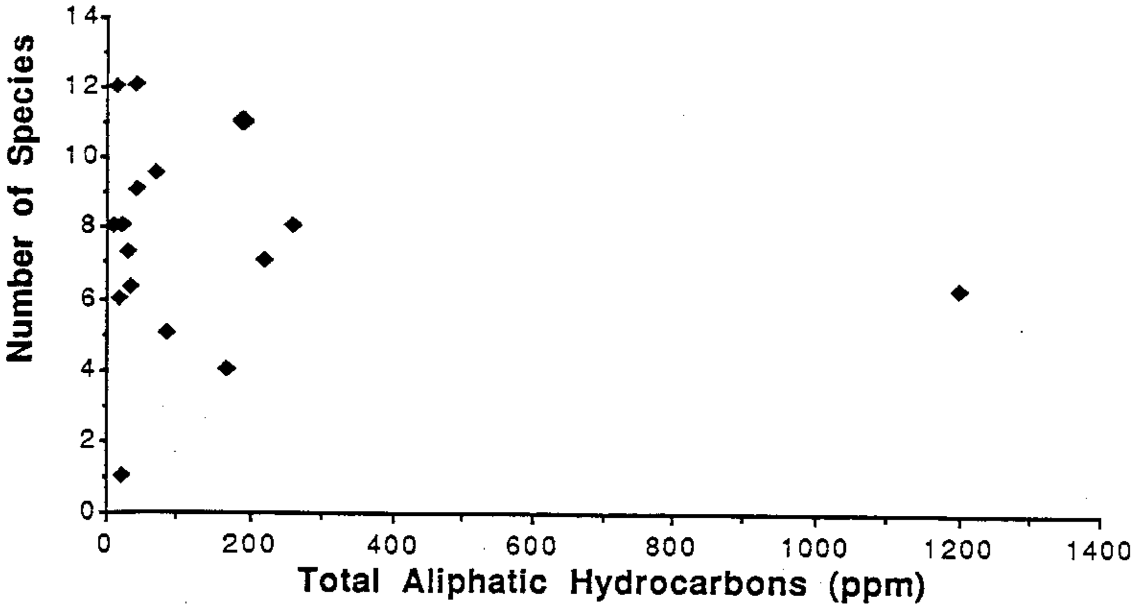


Figure 6.20. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) and total homologs of naphthalene, dibenzothiophene and phenanthrene (NDP) for the Bayou Sale discharge site.



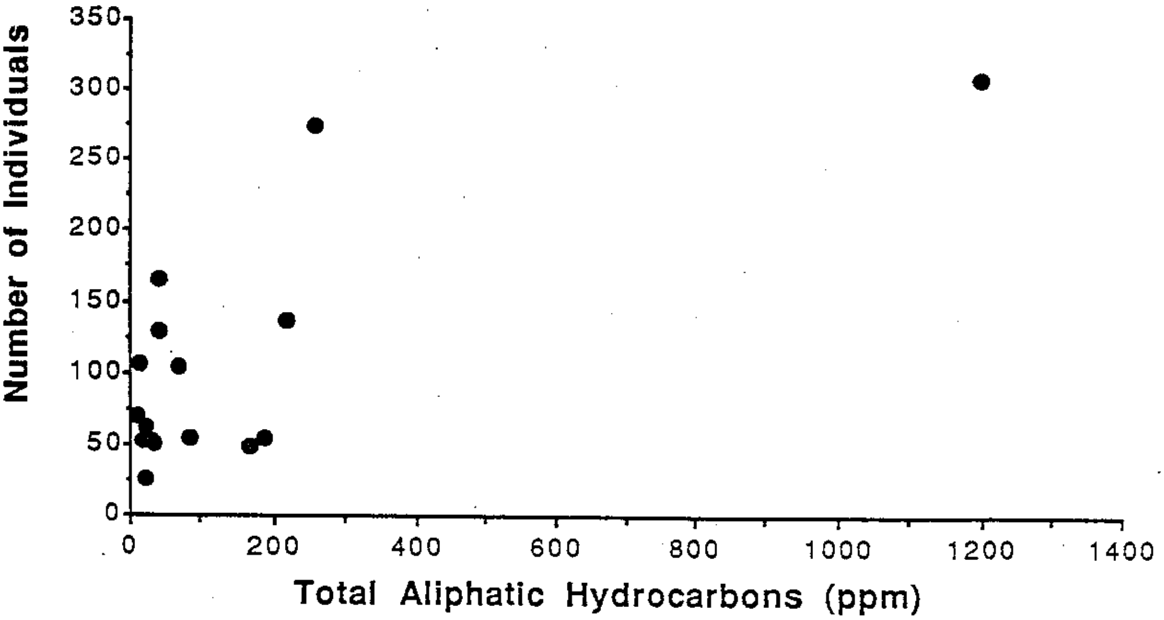


Figure 6.21. Comparison of number of species, above, and number of individuals, below, to total resolved and unresolved aliphatic hydrocarbons for the Bayou Sale discharge site.

Chapter 7

LAFITTE STUDY SITE

Nancy N. Rabalais, Jay C. Means, Charles S. Milan, Debra J. McMillin and Lorene Smith

7.1 Hydrography

The produced water discharge at the Lafitte site is the Texaco CF8 located on a north-south canal intersecting some natural open water areas which have been extensively channelized (Figure 1.8). The Barataria Waterway runs northwest to southeast on the western edge of the treatment site. The area includes tidally influenced brackish marsh. There are some east-west differences in the salinity field of the area. The Barataria Waterway may be a mechanism for intrusion of higher salinities seen along the western edge of the study area. Tidal flow from the northeast to the southwest through the study area on the day of data collection may have been an additional factor for lower ambient salinities observed along the northeastern part of the study area. Salinity of the produced water discharge at the time was 140 ppt as determined by refractometer.

Bottom water salinity at the discharge point was 6.5 ppt which was slightly above the ambient salinity (5.7-5.8 ppt) to the northeast (Figure 7.1, Table 7.1). The highest bottom water salinity value (10.9 ppt) was found at L250S. The denser bottom and near-bottom waters were displaced to the southwest from the actual discharge point (Figure 7.2). This is consistent with the direction of current flow observed during data collection at these stations. This observation suggests a nearfield dilution of greater than 20-fold. Bottom water salinities decreased away from L250S in all directions. Higher bottom water salinities could be detected up to 500 m from the discharge point (L0) or 250 m from the point of the greatest bottom water salinity value.

Along a transect from the northeastern edge of the study area (L750NE) to the western edge of the study area (L700W), there is a transition from a vertically well-mixed 5.6 ppt water column, through the area of the bottom and near-bottom density plume (L0 to L250S) to a vertically well mixed 7.1 to 7.4 ppt water column (L700W) (Figure 7.2). The water column at the reference stations was vertically stratified with values of 5.7-6.1 ppt on the surface and 7.5-9.3 ppt on the bottom. A higher than ambient bottom water salinity (8.5 ppt) at L750SW may be a function of either increased bottom water salinity due to the produced water discharge or the increased bottom water salinities along the western edge of the discharge study area resulting from saltwater intrusion up the deep and stratified Barataria Waterway.

Along the transect from L750NE to L700W, bottom water dissolved oxygen concentrations were considerably less than surface water values at L0, L100S, and L250S. At L250S where the bottom water salinity was the highest, the dissolved oxygen level was 0.75 mg/l. This low oxygen level was also accompanied by a low pH (6.91). At the reference stations where surface-to-bottom salinity differences were 2 to 3 ppt, bottom water dissolved oxygen levels were about 1 mg/l less than surface values, and no concentrations fell below 4 mg O_2/l.

Interstitial salinities of sediments along the canals and water bodies in the Lafitte study area were generally higher than the salinity of the near-bottom waters as measured by the Hydrolab CTD unit (Figure 7.3). This trend was consistent at the discharge site and at the reference stations.

Table 7.1. Hydrographic data for Lafitte study area, 1 September 1988.

Stations in distance away from CF8
Reference stations in distance away from arbitrary "0" point

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (oC)	Dissolved Oxygen (mg/l)	pH
Station L0 (14:20)					
0.2	5.9	10.90	28.75	6.72	7.58
1.0	5.9	10.92	28.75	6.72	7.55
1.9	6.5	11.87	28.76	6.50	7.38
Station L100NE (15:25)					
0.2	5.7	10.67	28.72	7.06	7.65
1.0	5.7	10.67	28.72	7.03	7.62
2.1	5.7	10.66	28.71	7.06	7.55
Station L250NE (15:40)					
0.2	5.7	10.57	28.69	7.19	7.69
1.0	5.7	10.56	28.69	7.17	7.67
1.9	5.7	10.56	28.68	7.21	7.61
Station L500NE (16:00)					
0.2	5.6	10.50	28.67	7.14	7.67
1.0	5.6	10.51	28.67	7.23	7.62
2.0	5.6	10.52	28.67	7.40	7.58
Station L750NE (16:35)					
0.2	5.8	10.77	28.73	7.66	7.74
0.8	5.8	10.84	28.72	8.20	7.71
Station L100S (13:50)					
0.2	5.8	10.84	28.69	6.49	7.51
1.0	5.9	10.94	28.67	6.33	7.43
1.9	8.0	14.26	28.72	4.34	7.18
Station L250S (13:20)					
0.2	5.8	10.85	28.66	6.35	7.48
1.0	6.0	11.19	28.60	5.77	7.34
2.0	7.1	12.88	28.57	3.57	7.14
2.2	10.9	18.90	28.54	0.75	6.91

Table 7.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (°C)	Dissolved Oxygen (mg/l)	pH
Station L500SE (17:05)					
0.2	5.9	10.90	28.53	6.29	7.31
0.8	5.9	10.90	28.53	6.37	7.26
1.3	5.9	10.91	28.53	6.63	7.22
Station L750SE (16:36)					
0.2	5.8	10.77	28.73	7.66	7.74
0.8	5.8	10.84	28.72	8.20	7.71
Station L500NW (12:10)					
0.2	5.4	10.18	28.44	4.86	7.05
0.7	5.5	10.24	28.41	4.73	7.04
1.5	7.1	12.85	28.18	4.99	6.97
Station L750NW (71:55)					
0.2	5.7	10.60	28.48	6.09	7.26
1.0	5.7	10.56	28.49	6.18	7.22
1.8	5.7	10.56	28.49	6.39	7.19
Station L500W (12:55)					
0.2	6.1	11.27	28.60	5.70	7.28
1.0	6.1	11.28	28.60	5.71	7.20
Station L700W (11:30) (used Eckman grab, consolidated sediments with clay)					
0.2	7.1	12.90	28.38	5.15	7.28
0.9	7.4	13.39	28.37	5.32	7.20
Station L750SW (11:45)					
0.2	7.1	12.90	28.67	6.04	7.33
1.0	7.7	13.79	28.42	5.27	7.22
1.6	8.5	15.00	28.55	3.95	7.12
Station LR0 (10:44)					
0.2	5.7	10.68	28.46	5.77	nd
0.8	6.1	11.28	28.61	5.58	nd
1.4	7.5	13.59	28.55	4.62	nd

Table 7.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (^oC)	Dissolved Oxygen (mg/l)	pH
Station LR250E (11:00)					
0.2	6.1	11.30	28.40	5.55	nd
1.0	8.7	15.60	28.41	4.78	nd
2.0	9.7	16.90	28.37	4.73	nd
Station LR250N (10:25)					
0.3	5.9	11.05	28.52	5.11	nd
1.0	6.4	11.81	28.38	4.77	nd
1.9	7.8	13.99	28.61	4.95	nd
Station LR500N (09:55)					
0.2	5.8	10.80	28.26	4.96	nd
1.0	5.9	11.00	28.31	4.79	nd
2.3	8.3	14.77	28.56	4.21	nd

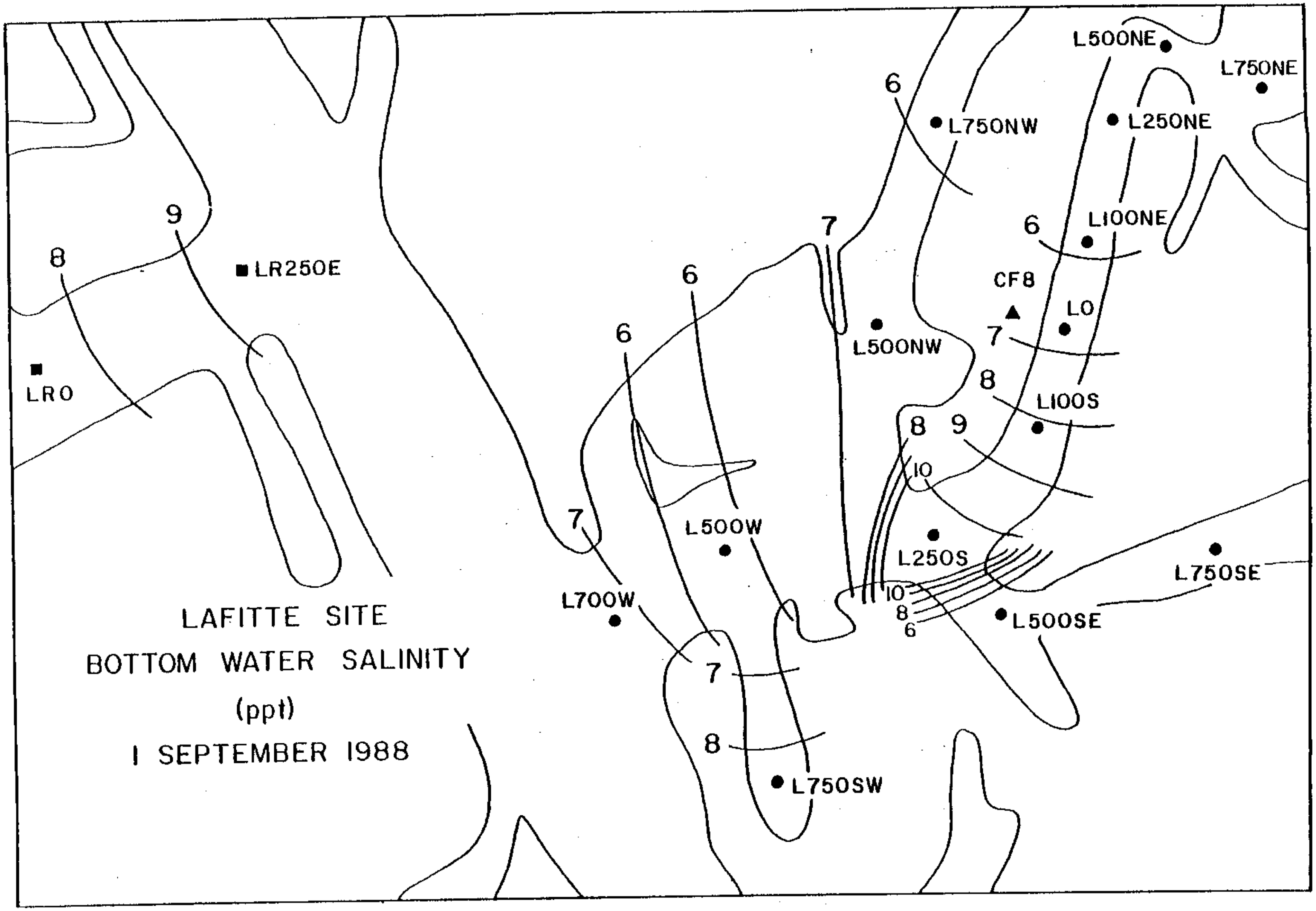


Figure 7.1. Bottom water salinity at the Lafitte site.

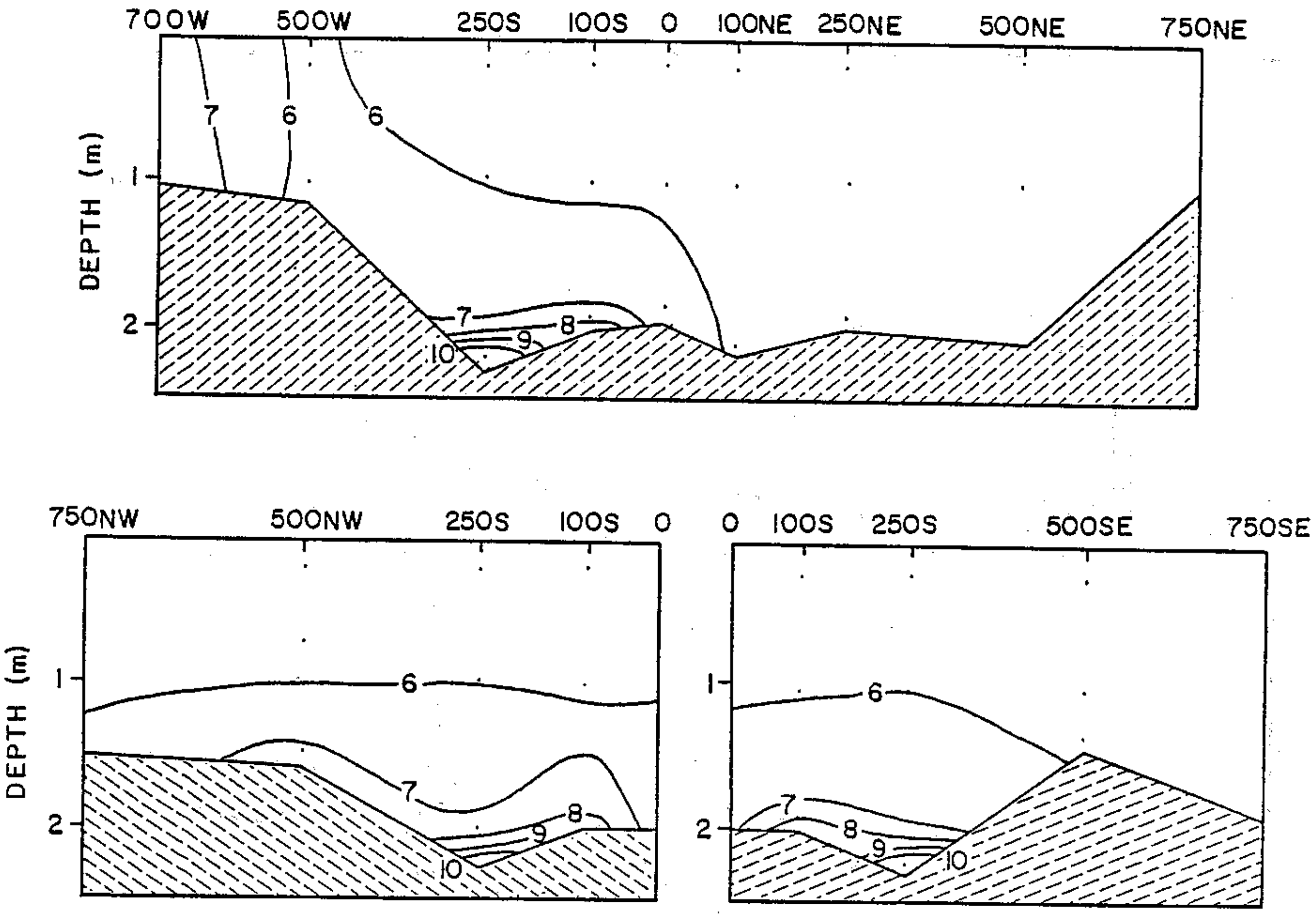


Figure 7.2. Salinity distribution in the water column in the discharge area at the Lafitte site.

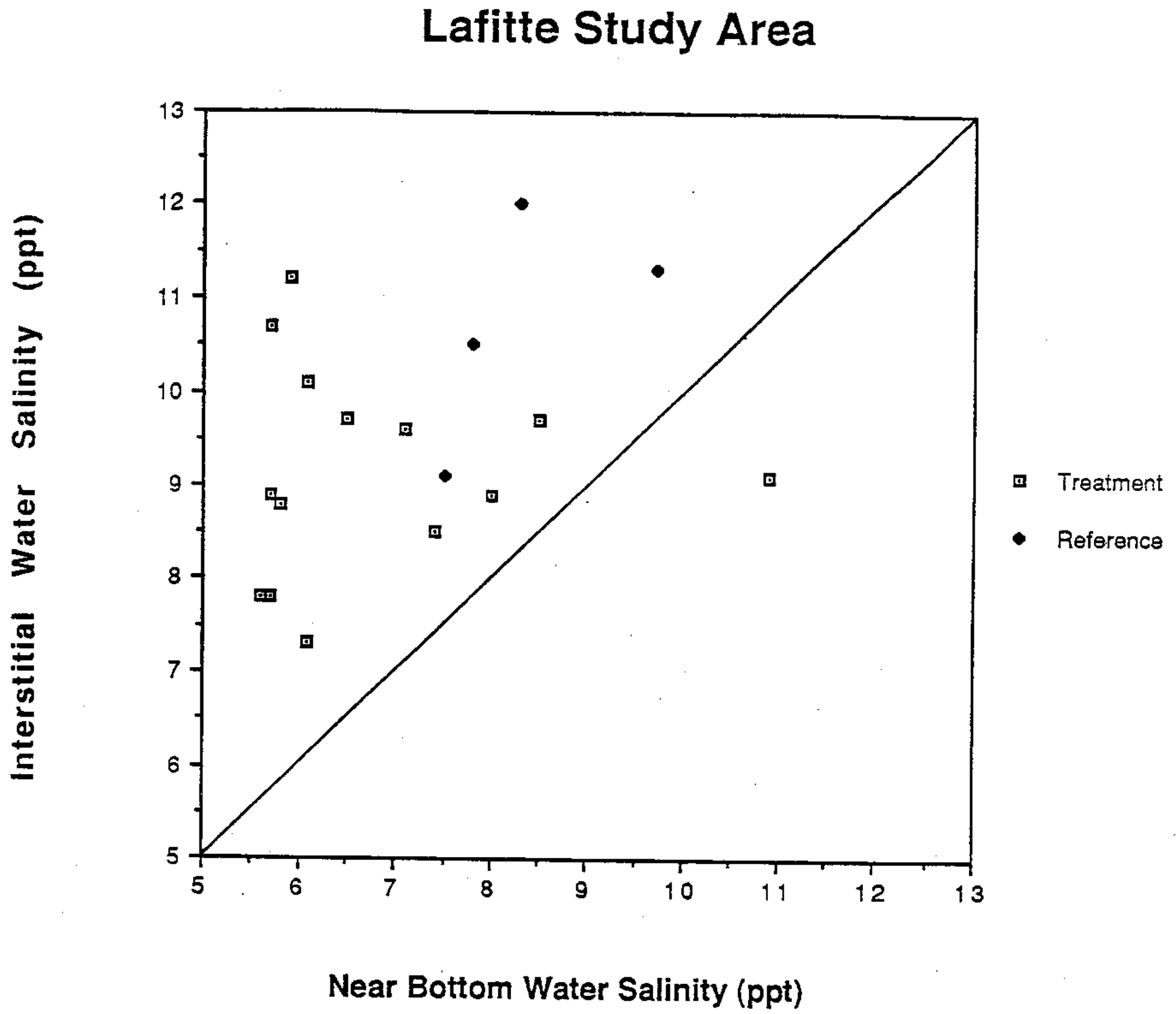


Figure 7.3. Comparison of interstitial water salinity from sediments of stations in waterways and channels of the Lafitte site to near bottom water salinity.

7.2 Organic Compounds

7.2.1 Sediments

7.2.1.1 Bulk parameters

Table 7.2 presents the data on sediment organic carbon content of the sediments in the Lafitte discharge site and the corresponding reference site. Figure 7.4 shows the spatial distribution of organic carbon in the sediments of the Lafitte system. The data are reported both as percent organic matter and percent organic carbon. Sediment organic carbon contents near the discharge site ranged from 5 to 15.4% while in the reference site they ranged only from 6.8 to 7.0%. Sediment organic carbon values seemed to be elevated to the northeast of the discharge point but not in any other direction. At the reference site, no spatial trends in sediment carbon content were seen.

7.2.1.2 Volatile hydrocarbons

Determinations of volatile hydrocarbons associated with sediment interstitial water and/or readily desorbable from sediments yielded little meaningful data. Table 7.3 presents a summary of the volatile hydrocarbon data at all of the sites in the Lafitte system, including those located along marsh transects. Benzene, toluene and xylenes were detected at nominal concentrations at the station immediately adjacent to the discharge but not in any of the other surrounding sites. The only other occurrence of volatile hydrocarbons was observed at 750m SW of the discharge, where benzene and xylenes were detected at concentrations near those at the L0 site. The pattern of detected occurrences of each of the volatile hydrocarbons was discontinuous. Figure 7.5 shows the levels of these substances leading away from the discharge in all directions. At the reference site, none of the volatile hydrocarbons was detectable at any of the sites except L0, which contained nominal concentrations of xylenes. This suggests some local origin for these compounds in the reference site.

7.2.1.3 Semivolatile hydrocarbons

Tables 7.4 and 7.5 present a summary of all of the semivolatile hydrocarbon data of the Lafitte discharge site (L) and the reference site (LR) and marsh sediments collected along transects near the discharge site (L1) and in the reference area (LR2), respectively.

Figure 7.6 shows the spatial distribution of normal aromatic PAH at various distances away from the Lafitte discharge point along with the reference site data. Total normal PAH were found maximally (1,500 ppb) in the immediate area of the discharge (250NE) and declined rapidly to 600 ppb or less within 500 m of the discharge in all directions. Among the normal PAH, phenanthrene, acenaphthene, fluorene, fluoranthene, benzanthrene, chrysene and pyrene were found the most frequently in the region of the discharge. Total PAH at the reference site were low and decreased from north to south or east. Figure 7.7 shows the spatial distribution of pyrene at the Lafitte site and reference site. The distribution pattern of pyrene parallels that of the total PAH very closely. Pyrene was one of the major PAH found at the reference site averaging approximately 25 ppb.

Figure 7.6 shows the spatial distribution of the sum of the normal PAH together with the alkylated and heterocyclic PAH at both the discharge and reference sites. It is clear that the general pattern of the distribution is similar to that observed for the normal PAH alone, however, the maximum is located at the LO site rather than the NE and an examination of the amounts clearly shows that the alkylated PAH dominate the distribution (as high as 80%). Figures 7.7 and 7.8 show the distributions of C-2 phenanthrenes, C-2 and C-3 naphthalenes, respectively.

Table 7.2. Sediment characteristics for the Lafitte site.

Sample	%Organic Matter	%Organic Carbon	%H_20	%Clay	%Sand	%Silt
L0	14.7	8.81	78	20.0	15.9	64.1
L100NE	18.2	10.92	81	17.1	27.6	55.3
L100S	14.2	8.48	65	28.3	2.8	68.9
L250NE	15.0	8.97	76	18.5	8.6	72.9
L250S	14.4	8.61	80	23.0	1.9	75.1
L500NE	25.7	15.37	77	-	-	-
L500SE	10.0	5.98	71	22.4	2.6	75.0
L500W	9.7	5.79	75	25.7	5.0	69.2
L500NW	12.1	7.25	78	32.9	0.9	66.3
L500NW	12.2	7.31	-	-	-	-
L700W	14.4	8.63	71	26.7	8.9	64.5
L750NE	16.7	10.02	78	25.1	6.1	68.8
L750SE	11.9	7.10	65	35.4	0.5	64.1
L750SW	8.3	4.98	-	30.0	12.0	58.0
L750SW	-	-	73	23.4	14.9	61.7
L750NW	16.0	9.61	75	31.3	0.7	68.0
LR0	11.5	6.92	74	38.9	1.5	59.6
LR250N	11.7	6.99	79	25.5	1.1	73.4
LR250E	11.4	6.80	76	18.7	0.4	80.9
LR500N	11.3	6.79	77	30.0	1.4	68.6
L1-0	-	-	92	-	-	-
L1-4	-	-	92	-	-	-
L1-12	-	-	91	-	-	-
L1-36	-	-	93	-	-	-
L1-108	-	-	92	-	-	-
LR2-0	-	-	74	-	-	-
LR2-12	-	-	82	-	-	-
LR2-108	-	-	86	-	-	-

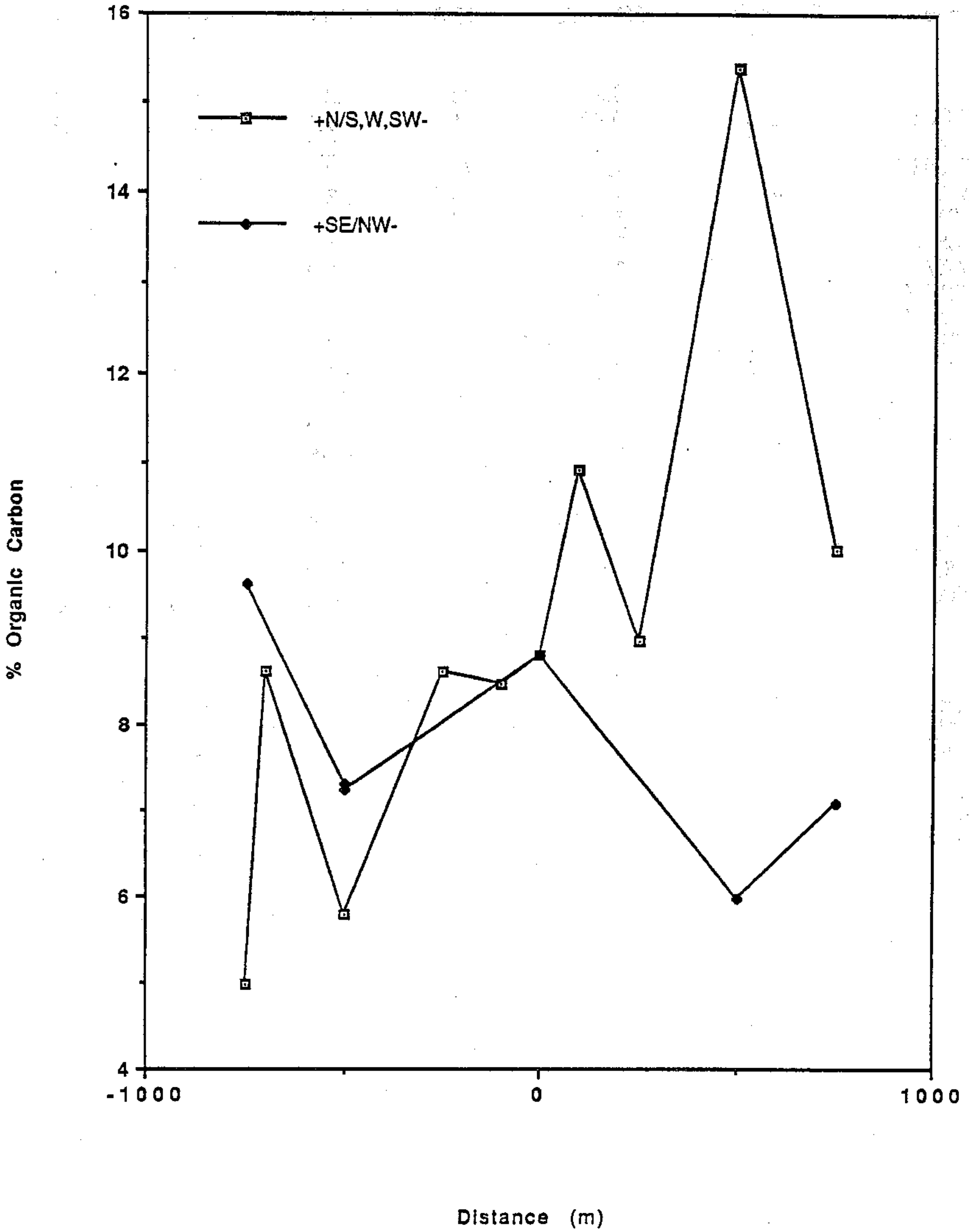


Figure 7.4 Spatial distribution of organic carbon content of Lafitte discharge site sediments.

Table 7.3. Volatile hydrocarbons in Lafitte sediments.

Sample ID	Benzene (ppb, dry wt.)	Toluene	Ethylbenzene	Xylenes	Cumene
L-0	26	12	nd	11	tr
L-100NE	nd	nd	nd	nd	nd
L-100S	nd	nd	nd	nd	nd
L-250NE	nd	nd	nd	nd	nd
L-250S	nd	nd	nd	nd	nd
L-500NE	nd	nd	nd	nd	nd
L-500SE	nd	nd	nd	nd	nd
L-500W	nd	nd	nd	nd	nd
L-500NW	nd	nd	nd	nd	nd
L-750W	nd	nd	nd	nd	nd
L-750NE	nd	nd	nd	nd	nd
L-750SE	nd	nd	nd	nd	nd
L-750SW	21	tr	nd	20	nd
L-750NW	nd	nd	nd	nd	nd
LR-0	nd	nd	nd	15	nd
LR-250N	nd	nd	nd	nd	nd
LR-250E	nd	nd	nd	nd	nd
LR-500N	nd	nd	nd	nd	nd
L1-0	tr	15	19	90	nd
L1-4	nd	nd	nd	24	nd
L1-12	tr	tr	tr	62	nd
L1-36	nd	nd	nd	nd	nd
L1-108	nd	nd	nd	nd	nd
LR2-0	nd	nd	nd	nd	nd
LR2-12	nd	nd	nd	nd	nd
LR2-108	nd	nd	nd	nd	nd

Detection Limit = 10 ppb, dry wt.
Detection Limit marsh samples = 15 ppb, dry wt.
tr: trace, below detection limit

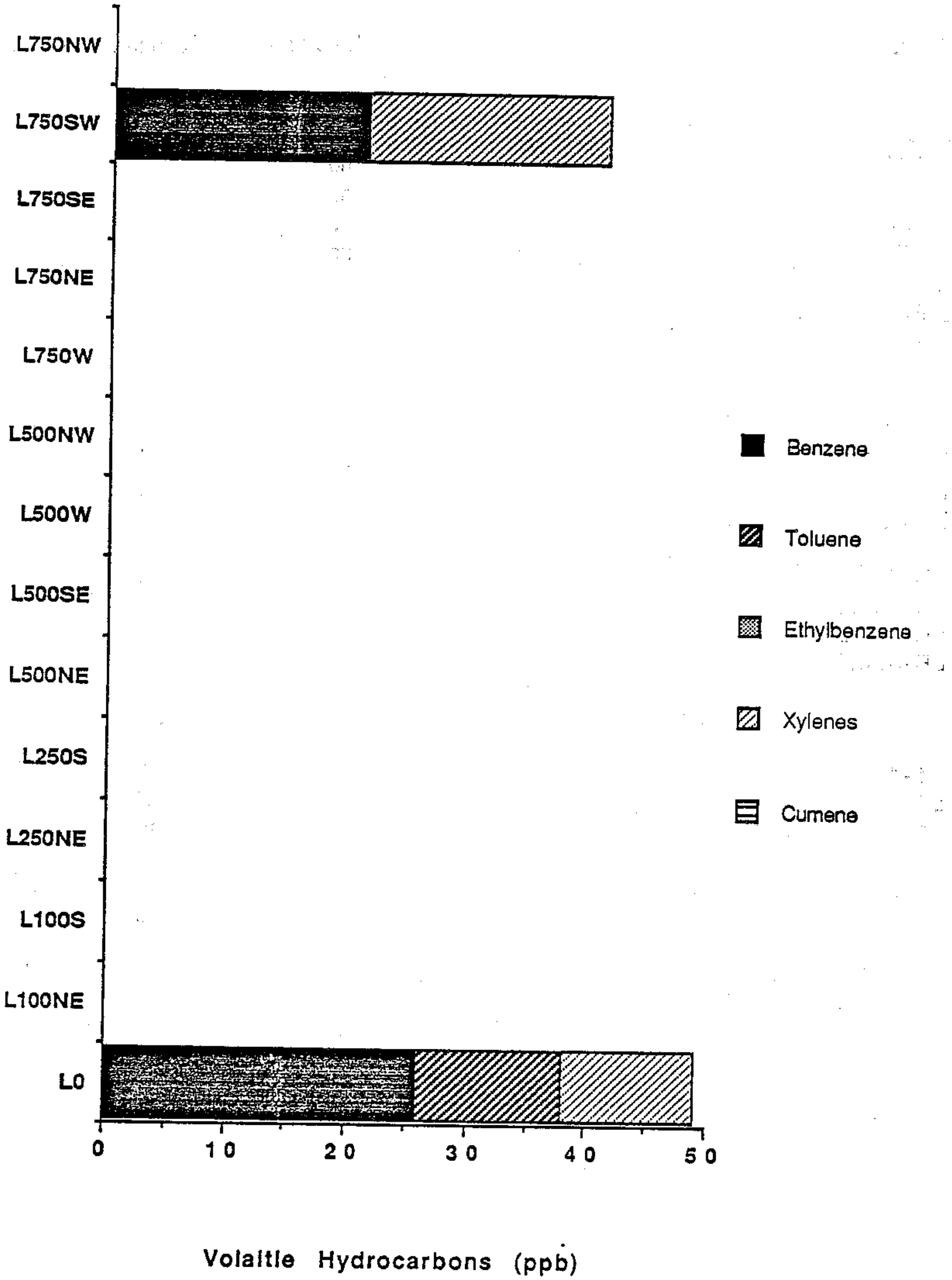


Figure 7.5. Volatile hydrocarbons in interstitial water of Lafitte discharge site sediments.

Table 7.4. Semivolatile hydrocarbon concentrations in Lafitte discharge site sediments.

ANALYTE	L	NORTHEAST				NORTHWEST		WEST		SOUTH		SOUTHEAST		SOUTHWEST	
	0	100	250	500	750	500	750	500	750	100	250	500	750	750	750(d)
MDL (ppb, dry wt.)	20	6.2	13	12	8.3	13	13	9.4	13	8.0	6.4	10	12	6.5	5.2
Naphthalene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthylene	nd	nd	nd	trc	nd	nd	nd	nd	nd	nd	nd	trc	nd	nd	nd
Acenaphthene	77	53	190	27	nd	27	nd	nd	nd	14	17	trc	nd	nd	nd
Fluorene	100	65	250	30	nd	26	nd	trc	trc	30	26	10	nd	trc	6.3
Dibenzothiophene	22	11	14	tr	nd	tr	nd	nd	nd	tr	tr	tr	nd	tr	tr
Phenanthrene	130	120	490	66	12	14	13	23	20	43	39	tr	tr	tr	9.0
Anthracene	62	57	78	18	tr	21	tr	tr	nd	14	18	tr	nd	tr	tr
Fluoranthene	230	230	200	74	39	110	48	55	28	110	140	53	38	29	40
Pyrene	220	210	180	88	48	130	64	80	49	120	120	68	48	36	40
Benzanthracene	160	130	141	18	nd	78	nd	nd	nd	tr	65	tr	nd	tr	12
Chrysene	160	230	nd	68	32	53	38	66	nd	21	100	46	37	24	27
Benzo(b)fluoranthene	nd	110	nd	nd	nd	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd
Benzo(k)fluoranthene	nd	79	nd	nd	nd	nd	nd	nd	nd	nd	49	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	na	nd	na	na	na	na	na	na	na	na	nd	na	na	na	na
Benzoperylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Naph	tr	15	tr	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C2-Naph	160	150	24	15	tr	tr	nd	tr	tr	11	22	nd	nd	nd	nd
C3-Naph	2500	1800	620	570	50	560	47	100	56	610	750	58	tr	tr	12
C1-DBT	49	20	15	tr	tr	29	tr	9.9	tr	14	6.4	tr	tr	tr	5.4
C1-Phen	310	210	140	79	tr	19	tr	34	30	110	110	tr	tr	tr	14
C2-Phen	920	680	410	220	74	370	170	190	94	630	600	190	150	42	73
TOTAL PNA'S	1200	1300	1500	390	130	460	160	220	97	350	570	180	120	89	130
TOTAL PNA'S & NDP HOMOLOGS	5100	4200	2800	1300	260	1200	380	560	280	1700	2100	430	270	130	240

nd: not detected

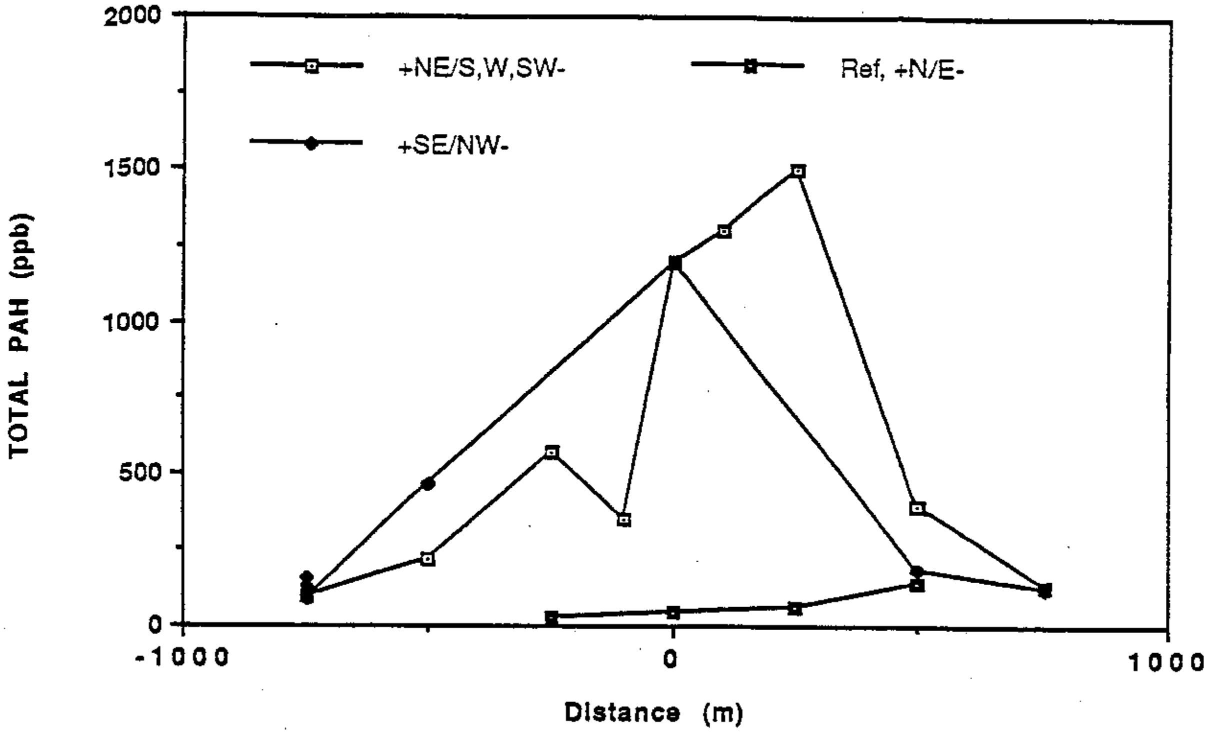
tr: trace, extracted ion present, but below detection limit

trc: trace confirmed, extracted and confirming ions present, but below detection limit

Table 7.5. Semivolatile hydrocarbons concentrations in Lafitte reference site and marsh sediments.

ANALYTE	REFERENCE SITE				MARSH SITES									
	LR	EAST	NORTH		L1						LR2			
	0	250	250	500	0	4	12	36	36(d)	108	0	0(d)	12	108
MDL (ppb, dry wt.)	10	20	11	8.8	13	29	30	53	43	37	12	14	19	20
Naphthalene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fluorene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzothiophene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Phenanthrene	tr	tr	tr	15	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Anthracene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fluoranthene	20	tr	24	32	tr	34	tr	tr	tr	tr	tr	tr	tr	tr
Pyrene	26	27	33	35	tr	tr	trc	nd	tr	tr	tr	tr	tr	tr
Benzanthracene	nd	nd	nd	33	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Chrysene	tr	nd	nd	25	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(b)fluoranthene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(k)fluoranthene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	na	na	na	na	na	na	nd	nd	nd	nd	na	na	na	na
Benzoperylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Naph	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C2-Naph	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C3-Naph	nd	nd	nd	36	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-DBT	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Phen	tr	tr	tr	19	nd	tr	nd	tr	tr	nd	nd	nd	nd	tr
C2-Phen	40	35	50	90	nd	tr	nd	nd	nd	nd	tr	nd	tr	tr
TOTAL PNA'S	46	27	57	140	tr	34	tr	tr	tr	tr	tr	tr	tr	tr
TOTAL PNA'S & NDP HOMOLOGS	86	62	110	290	tr	34	tr	tr	tr	tr	tr	tr	tr	tr

nd: not detected
tr: trace, extracted ion present, but below detection limit
trc: trace confirmed, extracted and confirming ions present, but below detection limit



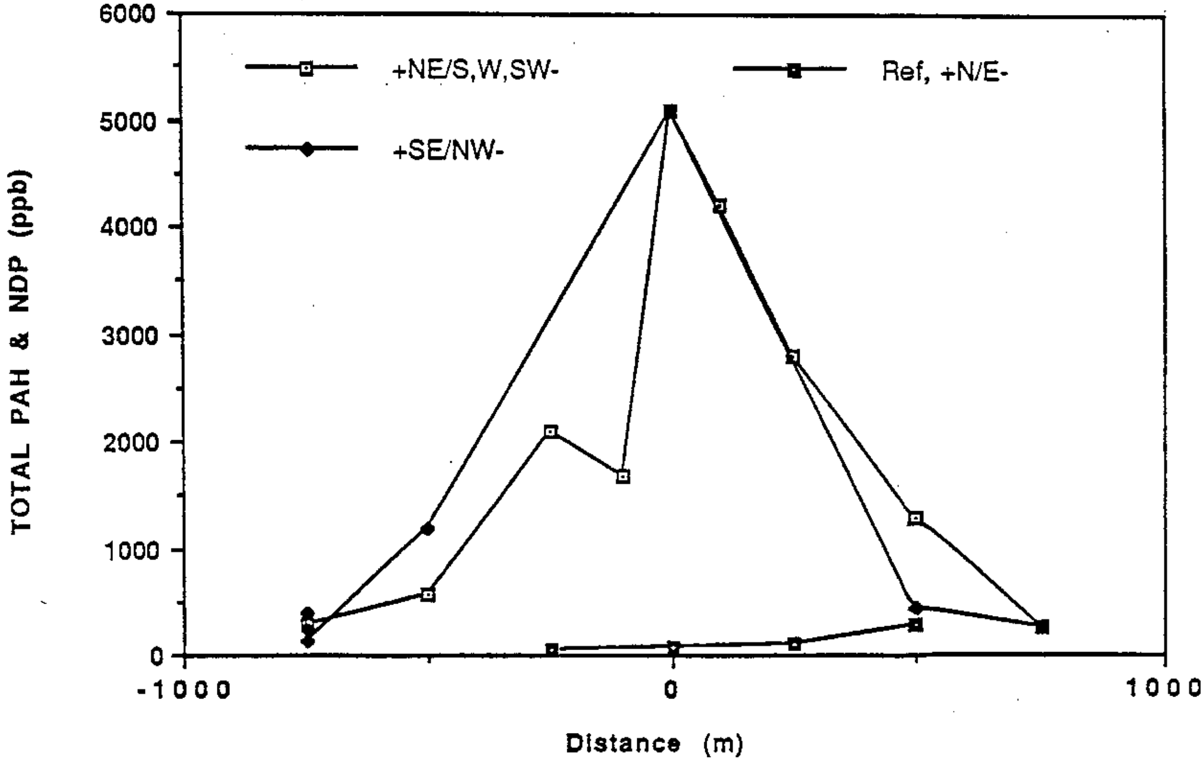
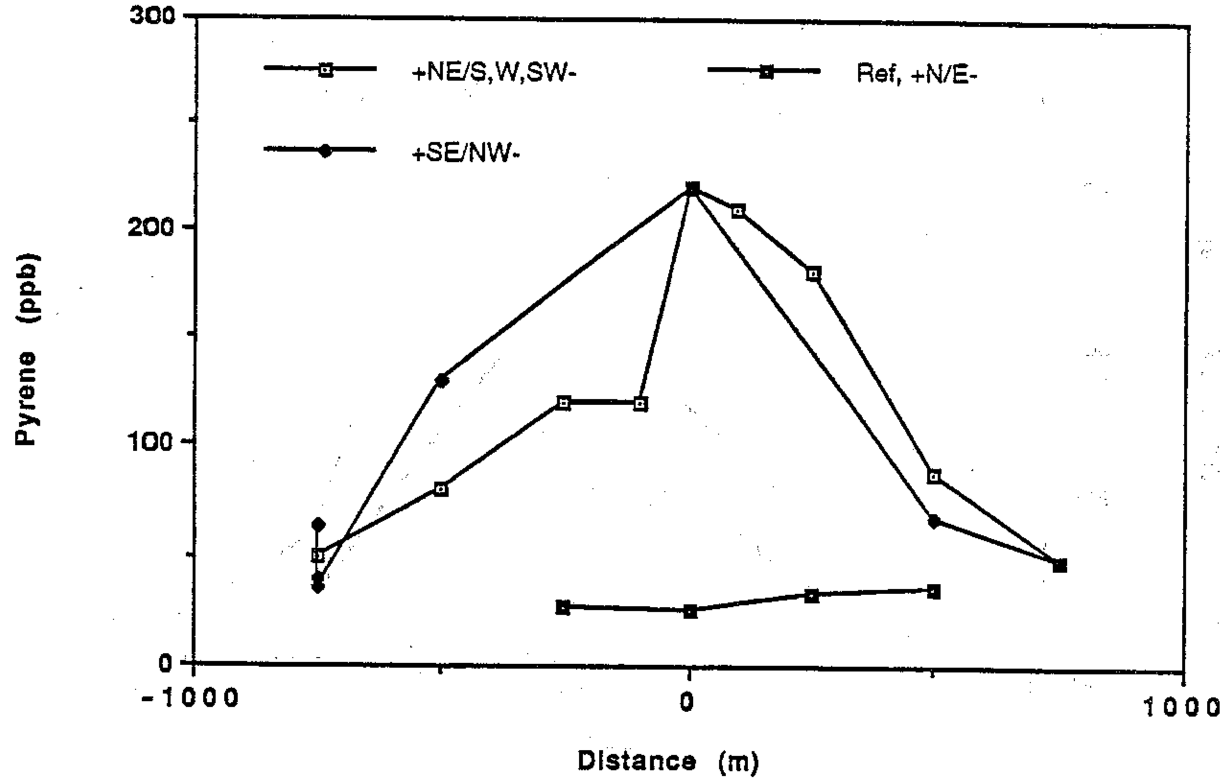


Figure 7.6. Spatial distribution of normal PAH, above, and total normal alkylated PAH, below, in Lafitte discharge site and reference site sediments.



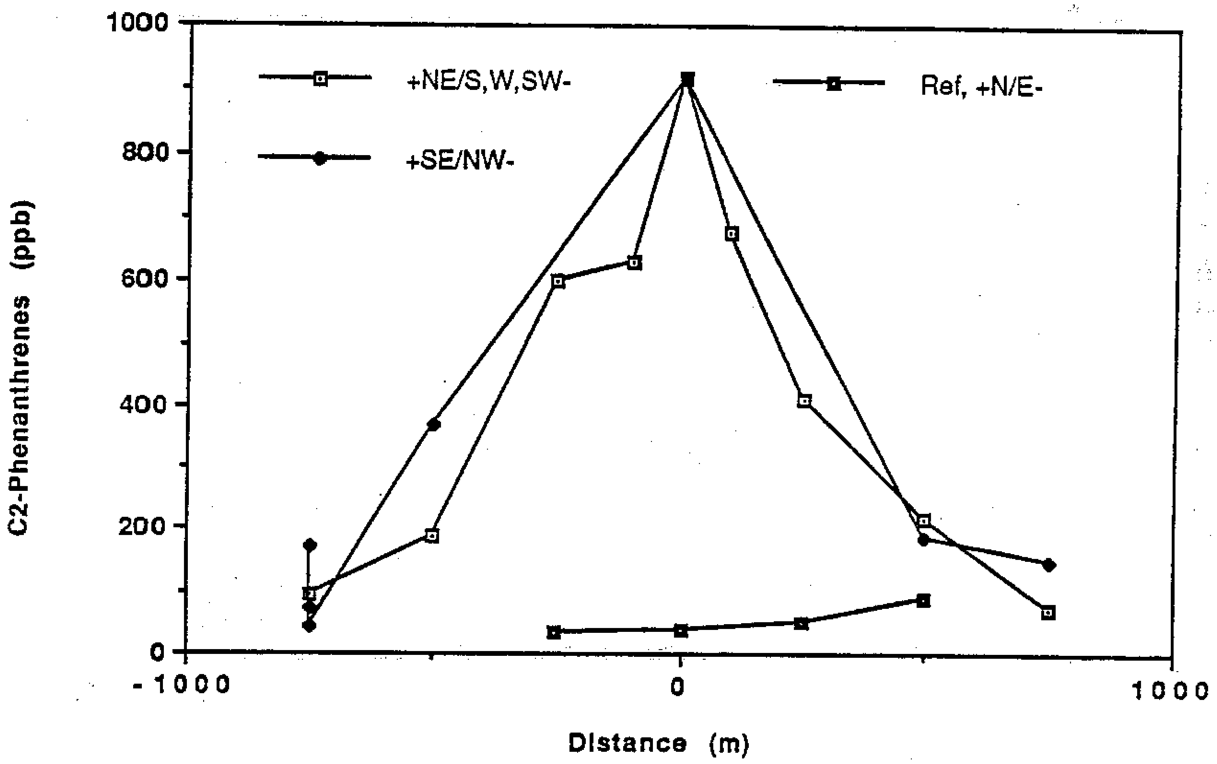


Figure 7.7. Spatial distribution of pyrene, above, and C-2 phenanthrenes, below, in Lafitte discharge site and reference site sediments.

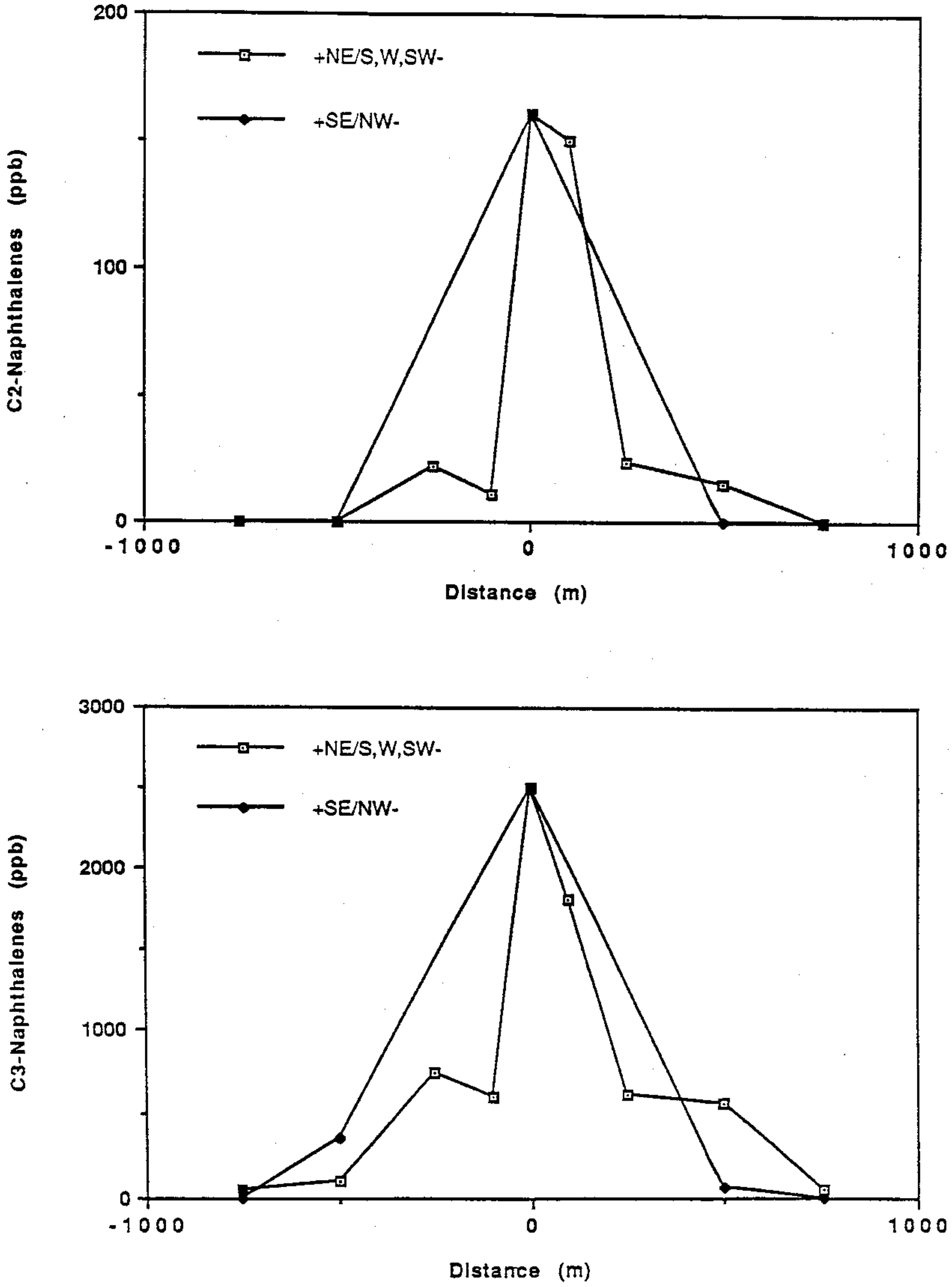


Figure 7.8. Spatial distribution of C-2 naphthalenes, above, and C-3 naphthalenes, below, in Lafitte discharge site and reference site sediments.

Each of these compound groups exhibited the same general pattern with a maximum at LO and a sharp decline away from that site in all directions.

Aliphatic hydrocarbons were distributed in a similar pattern to the aromatics in the vicinity of the Lafitte discharge (Table 7.6). Figure 7.9 shows the spatial distribution of aliphatic hydrocarbons around the discharge. The pattern of hydrocarbon concentrations in sediments around the discharge is very similar to that for the more soluble aromatic compounds. As with the PAH there was a maximum (350,000 ppb) at the L0 site and concentrations declined to much lower levels in all directions away from that point. The aliphatic hydrocarbons which averaged between 36,000 and 56,000 ppb at the reference site showed a slight increase toward the north (Figure 7.9). The reference site hydrocarbon concentrations were comparable to those observed at the 750NE and 750SW sites in the vicinity of the discharge (40,000 to 45,000 ppb). An example of an aliphatic hydrocarbon chromatogram for the L0 is presented in Figure 7.10.

Examination of the hydrocarbon data from the marsh sediments collected along transects into the Lafitte marsh adjacent to the discharge and at the reference site lead to a consistent picture (Table 7.34). These data show that normal PAH are found at trace levels and constant (< 5 ppb) concentrations in the reference marsh sediments but a single PAH, fluoranthene, was detected above trace levels near the margins of the marsh adjacent to the discharge and declined to trace levels 4 m into the marsh. None of the petrogenic alkylated or heterocyclic PAH were found in either the Lafitte site marsh nor the reference marsh.

Aliphatic hydrocarbons in the marsh sediments show a similar pattern. Relatively low concentrations of hydrocarbons were observed in the zero point of reference marsh (5,200 ppb), while higher concentrations were seen at the 12 m point. Moderate levels (7,000 to 10,000 ppb) of hydrocarbons were detected in Lafitte marsh sediments adjacent to the discharge. A maximum (21,000 ppb) was seen at 36 m, then levels declined with distance into the marsh, but then increased again to 19,000 ppb at the 108 m point.

7.3 Trace and Major Elements

7.3.1 Sediments

Tables 7.7 and 7.8 present a summary of all of the data for trace and major elements determined in Bayou Lafitte sediments and the reference site sediments, respectively. Figure 7.11 shows a plot for Ba measured in sediments in the Lafitte system along the reference site data. Barium is moderately enriched at the discharge point and highly enriched at stations to the west and southwest as far as 1000 m from the discharge. However, several sediment samples at intermediate distances (e.g., 100NE, 250NE, etc.) appear to have "normal" concentrations of this element. These data suggest that there are depositional and non-depositional zones within the bayou system for this soluble element. Figure 7.12 shows the enrichment pattern of six other elements in the Lafitte system. Chromium, copper, lead and vanadium are all also enriched within the Lafitte system, however, many of the sediments in the region appear to be depleted in zinc. When the discharge site sediments are compared to the reference site sediments, the ranges of values observed within the reference site are very similar to those near the discharge site. Even for barium, the concentration at reference site L0 is similar to that at L0. These data and those for the other elements suggest that there may be sources of these metals other than the produced waters contributing to the sediment burdens in this region.

An examination of the spatial distribution of metals in the region of the discharges suggests some interesting patterns with respect to the fate of discharged metals. Figures 7.13 and 7.14 show the spatial distributions for barium, copper, cadmium, chromium, manganese, nickel and lead, zinc and vanadium, respectively, surrounding the discharge point. In the case of barium, as suggested earlier, the maximum level is seen not at L0 but there are maxima at

Table 7.6. Saturated hydrocarbon concentrations in Lafitte sediments.

LAFITTE SITE Distance (meters)	Resolved (ppb)	Unresolved (ppb)	TOTAL (ppb)	Resolved/ Total
0	42,000	310,000	350,000	0.12
NORTHEAST				
100	15,000	130,000	150,000	0.10
250	18,000	170,000	190,000	0.10
500	16,000	97,000	110,000	0.14
750	7,700	33,000	41,000	0.19
SOUTHEAST				
500	13,000	130,000	140,000	0.09
750	6,400	70,000	77,000	0.08
SOUTH				
100	11,000	190,000	200,000	0.05
250	13,000	130,000	140,000	0.09
SOUTHWEST				
750	6,200	40,000	46,000	0.13
WEST				
500	9,500	80,000	89,000	0.11
700	11,000	58,000	69,000	0.16
NORTHWEST				
500	19,000	180,000	200,000	0.10
750	13,000	110,000	130,000	0.11

REFERENCE SITE Distance (meters)	Resolved (ppb)	Unresolved (ppb)	TOTAL (ppb)	Resolved/ Total
0	9,800	33,000	43,000	0.23
NORTH				
250	6,700	29,000	36,000	0.19
500	1,700	54,000	56,000	0.03
EAST				
250	7,200	37,000	44,000	0.16
MARSH SITES				
L1				
0	9,400	nd	9,400	1.00
4	10,000	nd	10,000	1.00
12	7,600	nd	7,600	1.00
36	17,000	nd	17,000	1.00
108	19,000	nd	19,000	1.00
LR2				
0	5,200	nd	5,200	1.00
12	8,500	nd	8,500	1.00
108	5,200	nd	5,200	1.00

Resolved/Total = ppm resolved / (ppm resolved + ppm unresolved)
nd: not detected

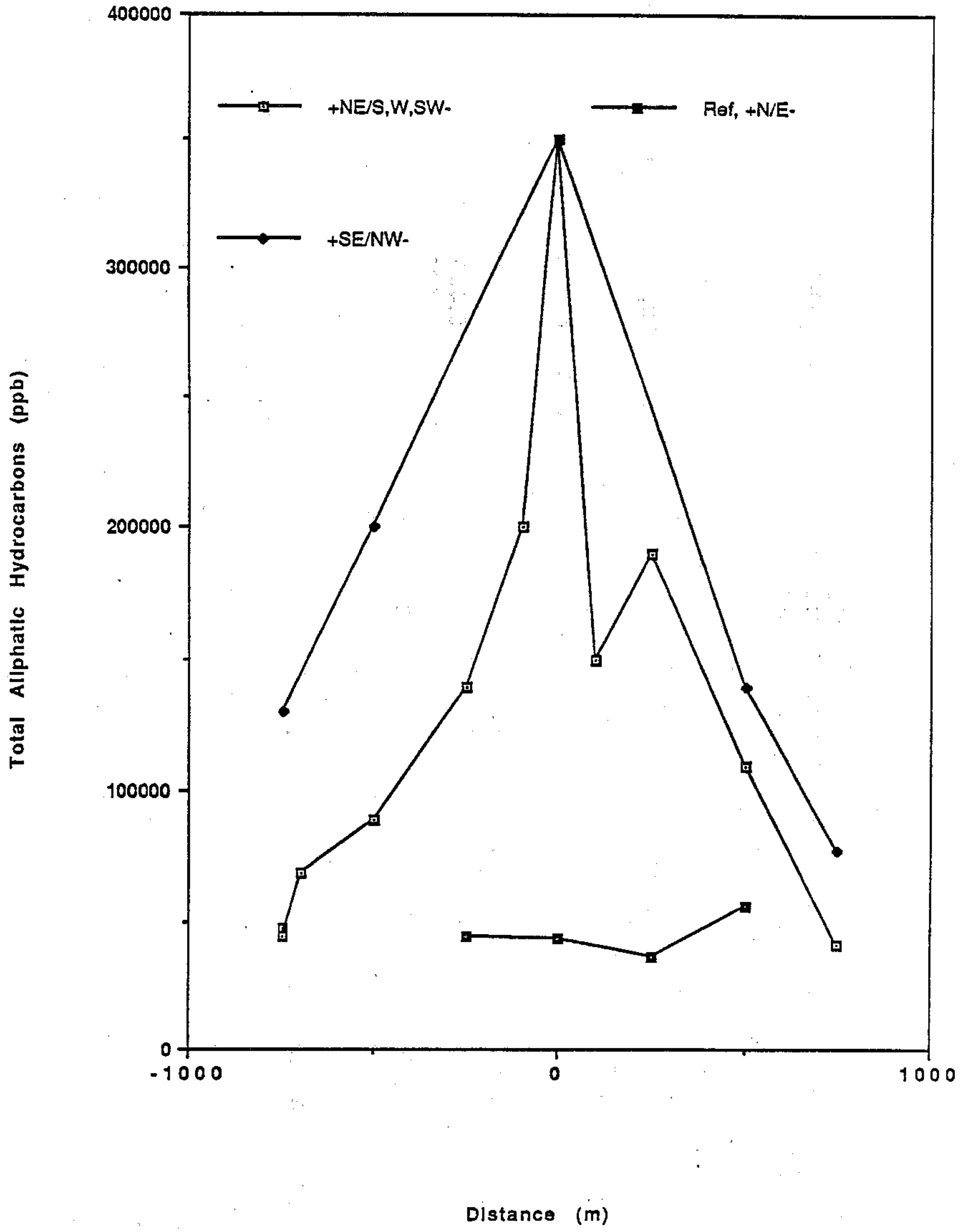


Figure 7.9. Spatial distribution of aliphatic hydrocarbons in Lafitte discharge site and reference site sediments.

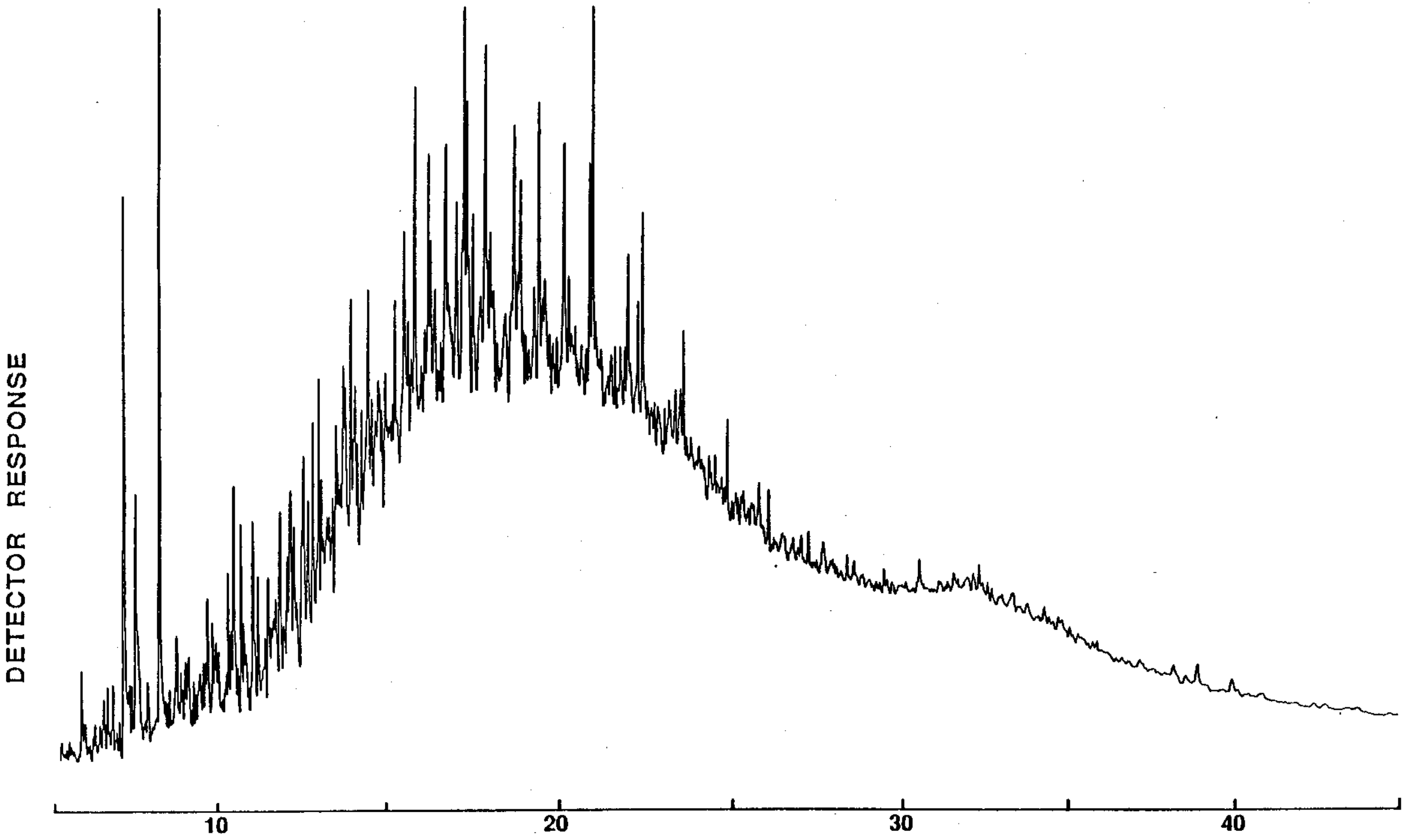


Figure 7.10. Chromatogram of the saturated hydrocarbon fraction (F-1) for sample station L0 Lafitte study area.

Table 7.7. Trace and major elements in Lafitte discharge site sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Bayou Lafitte Site												
L-0	30	60	1.3	106	65	31	25,052	178	10,739	11,722	220	122
L-100NE	28	31	0.55	106	63	29	22,980	180	17,327	8,286	74	116
L-100W	31	24	nd	145	78	31	30,125	328	56,935	13,918	851	130
L-250NE	30	30	nd	118	71	30	27,676	188	29,558	6,950	257	125
L-250S	32	32	nd	123	76	33	29,188	247	30,540	8,243	130	139
L-500NE	29	52	nd	109	69	30	26,166	223	17,810	9,273	27	120
L-500SE	34	52	nd	130	80	33	30,248	179	28,760	12,182	375	143
L-500W	33	33	nd	143	78	32	29,105	465	44,461	15,880	679	124
L-500W dup	29	26	nd	140	71	29	33,019	470	52,456	16,786	777	133
L-500NW	30	34	nd	127	78	31	29,264	221	41,045	15,371	250	134
L-700W	30	34	nd	122	61	29	28,565	469	28,709	12,855	182	120
L-750NE	26	27	nd	123	70	30	26,344	283	35,777	12,027	273	126
L-750SE	30	39	nd	121	75	31	27,013	157	29,050	11,724	157	136
L-750SW	26	32	nd	143	69	27	24,773	238	37,570	14,393	1,054	118
L-750NW	30	31	nd	127	77	31	29,015	196	39,819	12,877	230	137

nd: not detected
n/a: not available

Table 7.8. Trace and major elements in Lafitte reference site sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Bayou Lafitte Ref. Site												
LR-0	28	47	0.636	116	68	29	24,225	184	16,824	8,817	266	135
LR-0 dup	27	46	0.451	118	68	29	27,379	180	21,956	10,078	338	133
LR-250N	27	36	0.227	105	67	28	25,990	133	19,414	12,017	31	131
LR-250E	31	47	nd	124	74	32	24,327	739	24,154	14,085	270	149
LR-500N	27	38	0.513	95	60	25	23,760	119	14,287	10,429	40	126

nd: not detected
n/a: not available

Table 7.9. Trace and major elements in Lafitte marsh sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Bayou Lafitte Marsh Site												
L1-0	23	21	0.56	83	50	26	16,033	51	11,461	14,804	10	104
L1-4	11	1.9	nd	44	26	18	7,597	19	9,367	20,184	30	64
L1-12	19	4.9	nd	83	50	23	15,186	83	32,482	29,964	180	103
L1-36	9.1	6.7	nd	37	27	18	8,509	37	13,994	26,195	94	66
L1-108	12	6.8	nd	39	24	13	7,411	22	4,211	20,016	8.2	62
Bayou Lafitte Ref. Marsh Site												
LR2-0	22	18	nd	74	48	19	16,309	54	14,974	11,020	94	99
LR2-12	14	5.6	nd	55	36	16	14,632	30	17,654	6,165	9.2	89
LR2-108	22	23	0.35	69	44	20	15,383	34	11,540	8,621	2.3	89

nd: not detected
n/a: not available

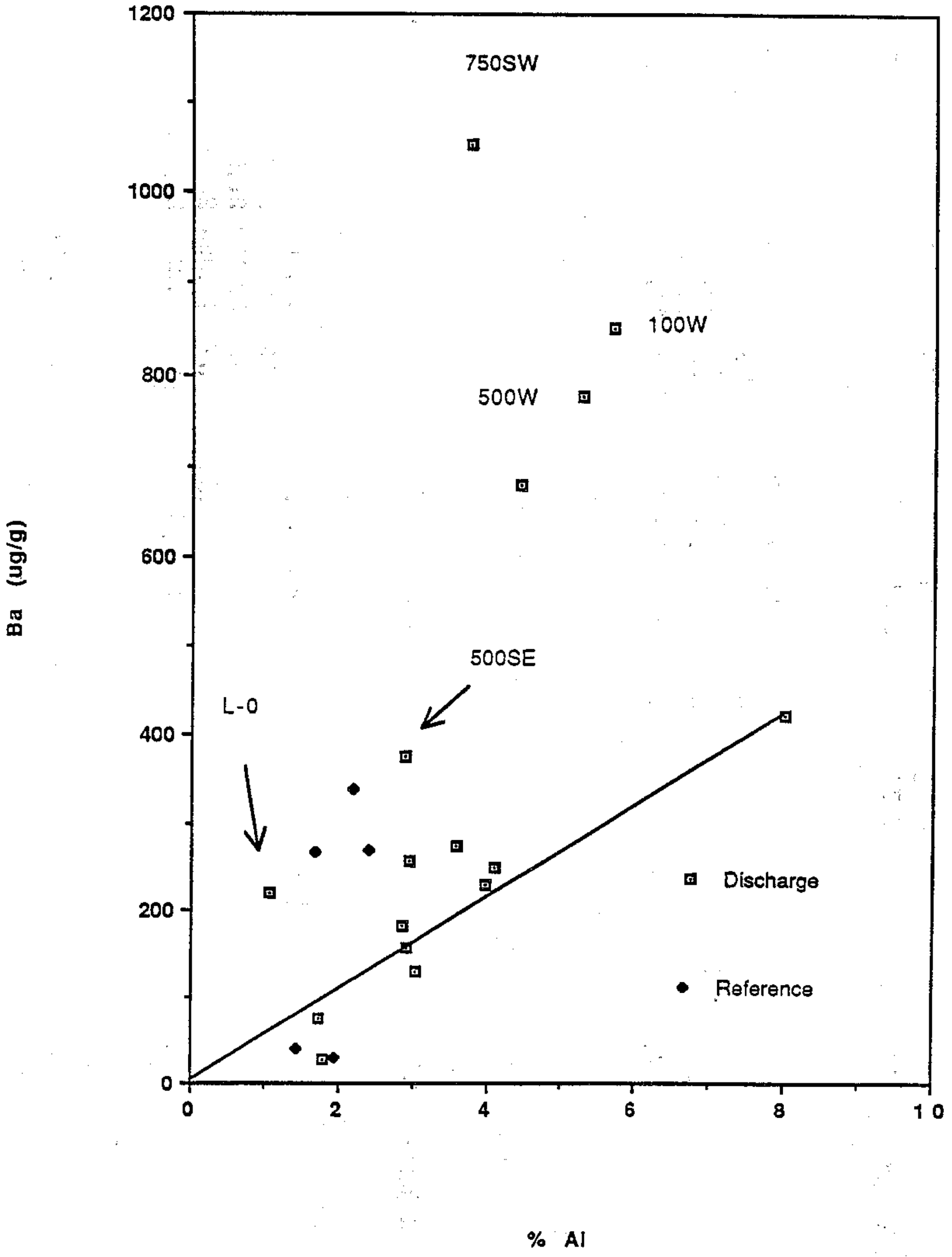


Figure 7.11. Concentration of barium relative to aluminum in sediments for Lafitte discharge and reference sites.

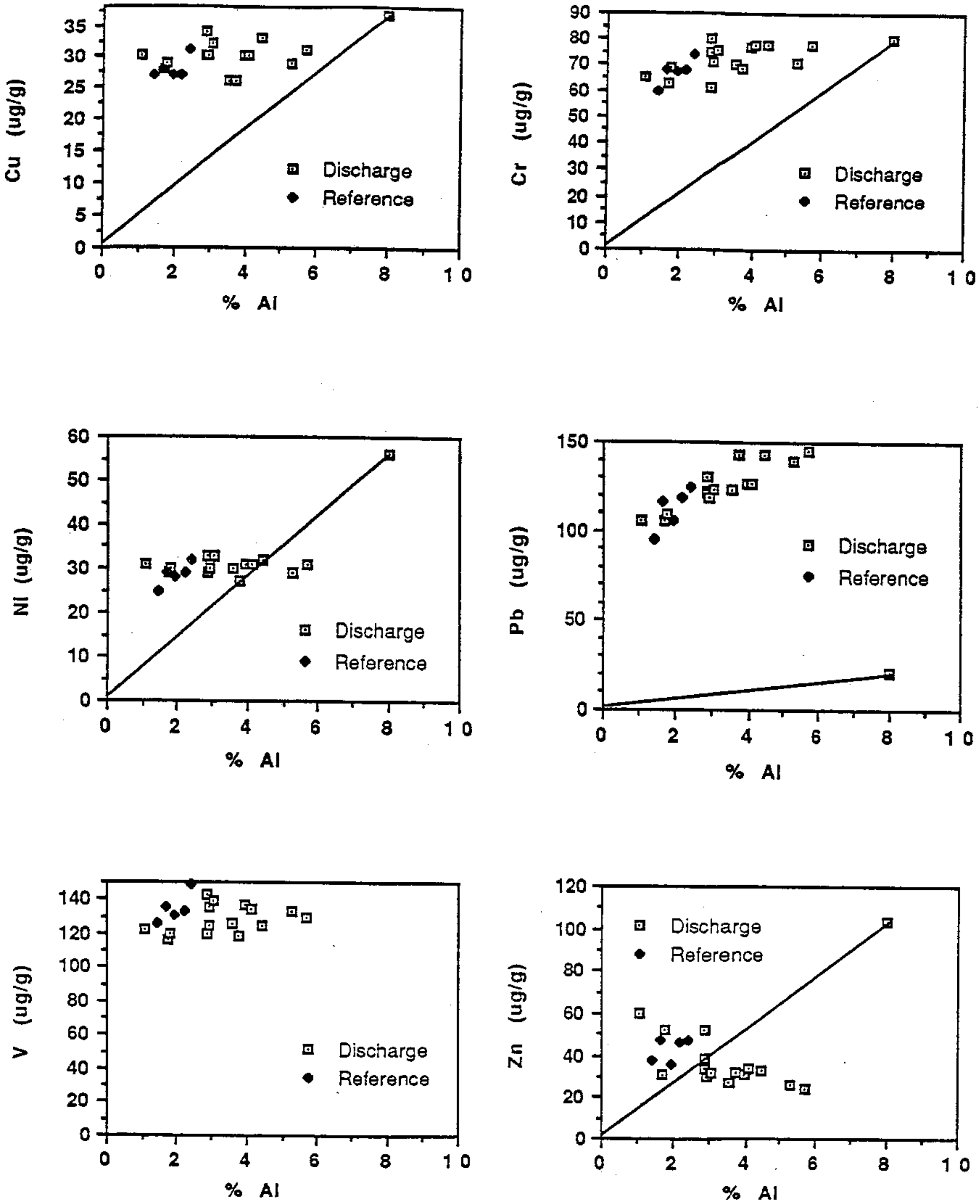


Figure 7.12. Concentrations of metals relative to aluminum for Lafitte discharge and reference sites.

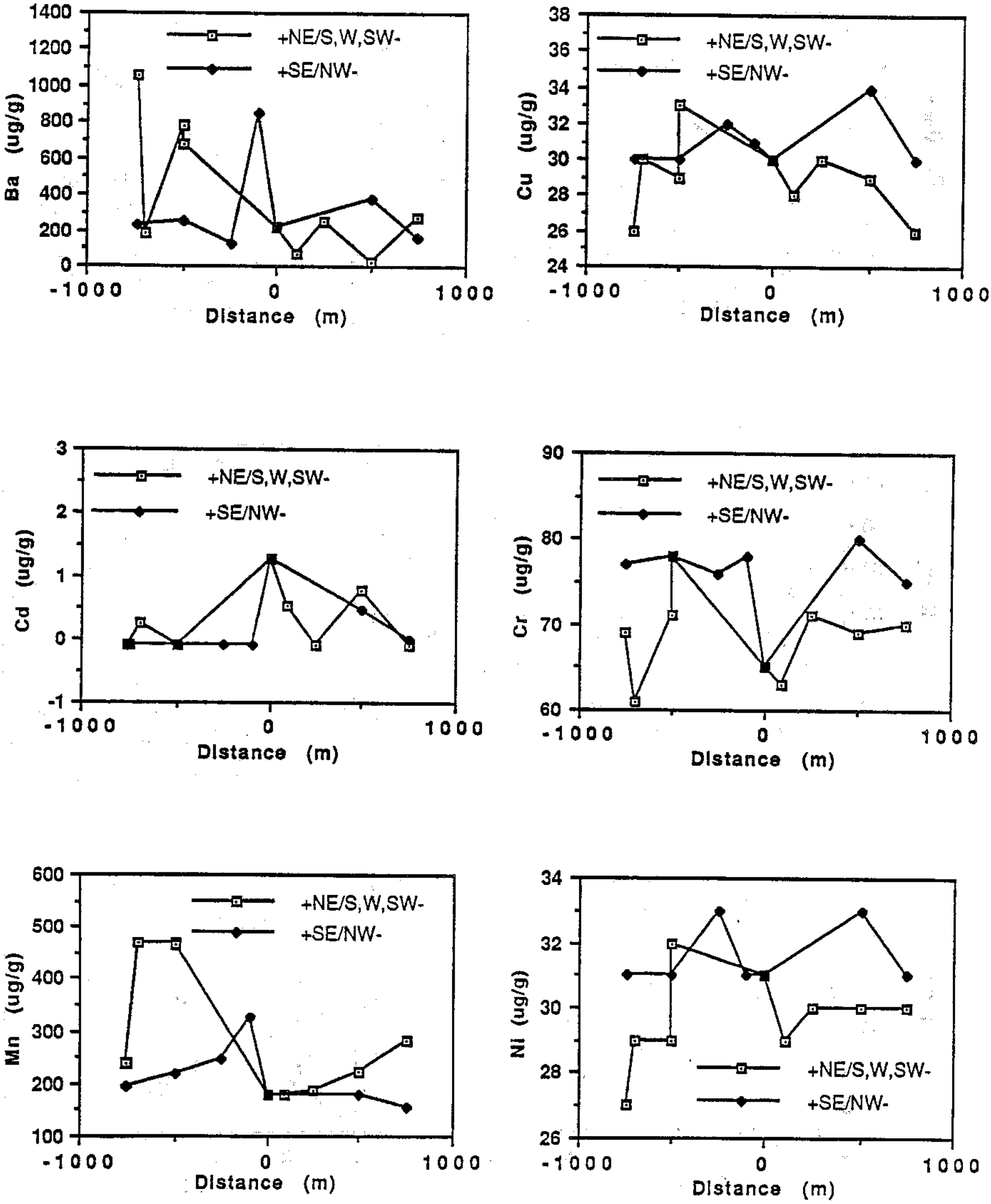


Figure 7.13. Spatial distribution of selected trace metals for Lafitte discharge site sediments.

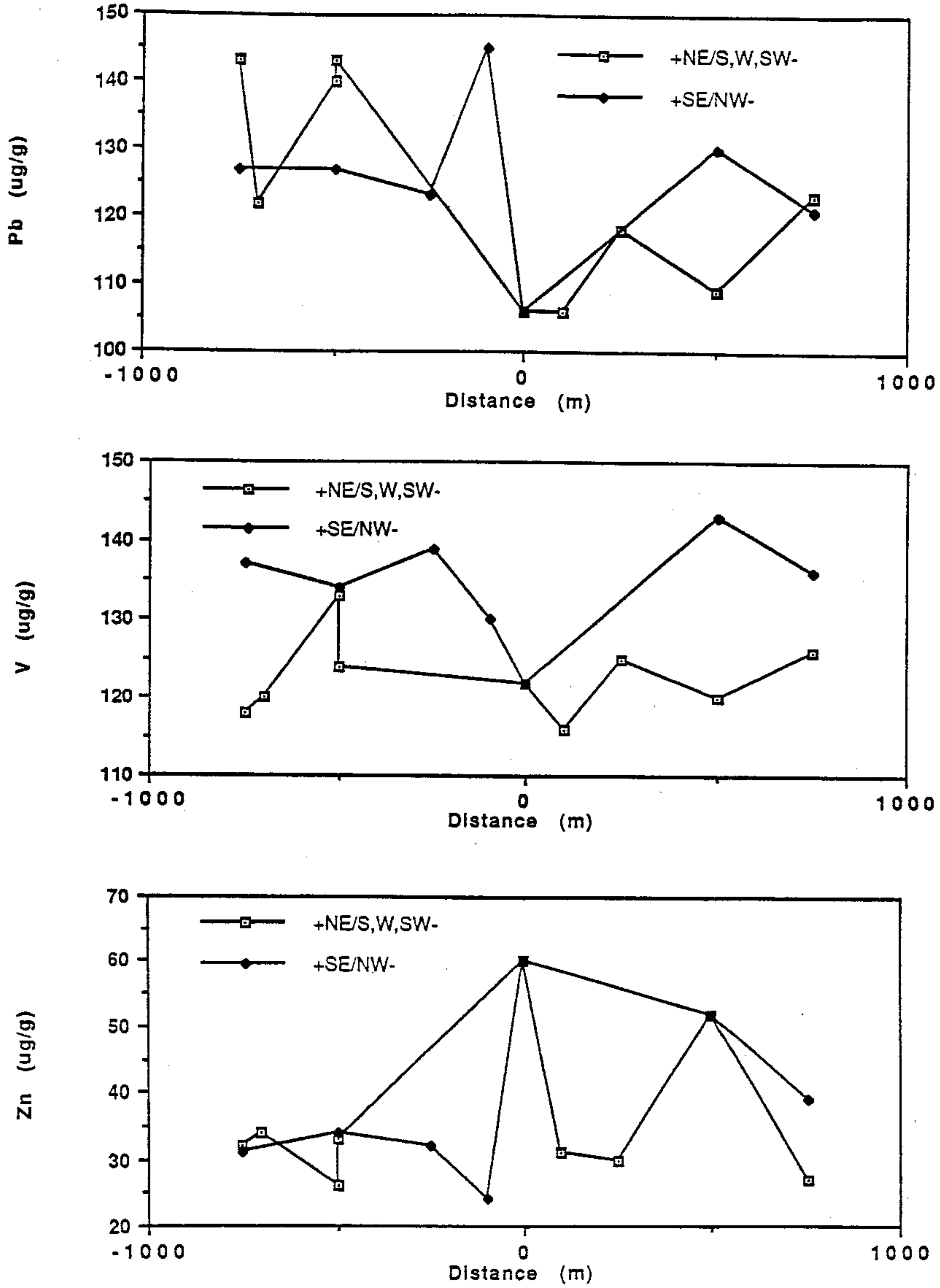


Figure 7.14. Spatial distribution of selected trace metals for Lafitte discharge site sediments.

L100S, L500W, and L750SW with intervening minima. Elevated levels to the south and west of the discharge point are consistent with the observed location of the near-bottom density plume. This suggests that there is a deposition of barium to the southwest of the discharge. The resuspension and redeposition of fine particulates is a likely mode for the observed secondary maxima at greater distances from the discharge. Aspects of the solution chemistry for the soluble barium or discharges of drilling muds in the field may be other factors affecting barium levels.

Distribution patterns for copper, chromium, nickel and manganese all have very complex structure. In many cases, there appears to be a general trend for these elements to increase in concentration from NE to S, W, or SW, with the discharge site representing an intermediate concentration. For cadmium the discharge point is the highest and levels of this metal decrease rapidly to undetectable within 100 to 250 m of the discharge. However, secondary maxima are observed at distances of 500 to 750 m. Vanadium and lead distributions also showed some similarities to the distributions just described for other metals with a multiple maxima away from the discharge with intervening minima. Zinc concentrations are highest at the discharge point and decrease in all directions. These very complex sediment distributions can partially be explained by sediment mineralogy but cannot readily be understood without further characterization of this highly modified hydrologic and sediment environment. Some very dynamic element chemistry is occurring in the vicinity of these sites, perhaps involving changes in salinity, particle interactions, resuspension and trace element speciation.

Table 7.8 shows the trace and major element data for the reference site. All of the elements were found at concentrations similar in range to those at the discharge site and there were no definite spatial patterns for all of the metals. The rather random distribution of metals at the reference site suggest that there are no localized inputs of metals into this region.

Table 7.9 presents a summary of the trace and major element data for the marsh sediments in the Bayou Lafitte system. Figures 7.15 and 7.16 show the spatial distribution along the marsh transects at the Lafitte site as contrasted to the reference marsh. In the case of barium, concentrations increased from the zero point into the marsh (12 m) and then declined. Barium levels were low in the reference marsh except at the zero point.

7.4 Benthic Communities

7.4.1 Dominants

Euryhaline polychaetes were the major community dominant at the Lafitte site, including the discharge and reference stations. The most numerous polychaetes were the opportunistic spionid, *Streblospio benedicti*, and opportunistic capitellid, *Mediomastus ambiseta*. Of the 38 total number of species collected at the Lafitte site, these two most common species made up 45% of the total occurrences. Other numerical dominants were nemertean worms, papillate tubificid oligochaetes (type 2), the bivalves *Mulinia lateralis* and *Rangia cuneata*, the isopod *Edotea sp.*, the mysid shrimp *Mysidopsis almyra*, and various amphipods and gastropod molluscs.

7.4.2 Community Parameters

All benthic stations (three replicates per each of 18 stations) within the waterways and channels of the Lafitte study area have been analyzed. Number of species per replicate and number of individuals per replicate were negligible or reduced at stations within 500 m or less of the discharge point (Table 7.10, Figure 7.17), with the exception of L750SW and L750SE. This trend was most obvious along the transect from L750NE to L700W and L750SW (Figure 7.18). Along transects away from the discharge point to the south and then to the northwest (L500NW

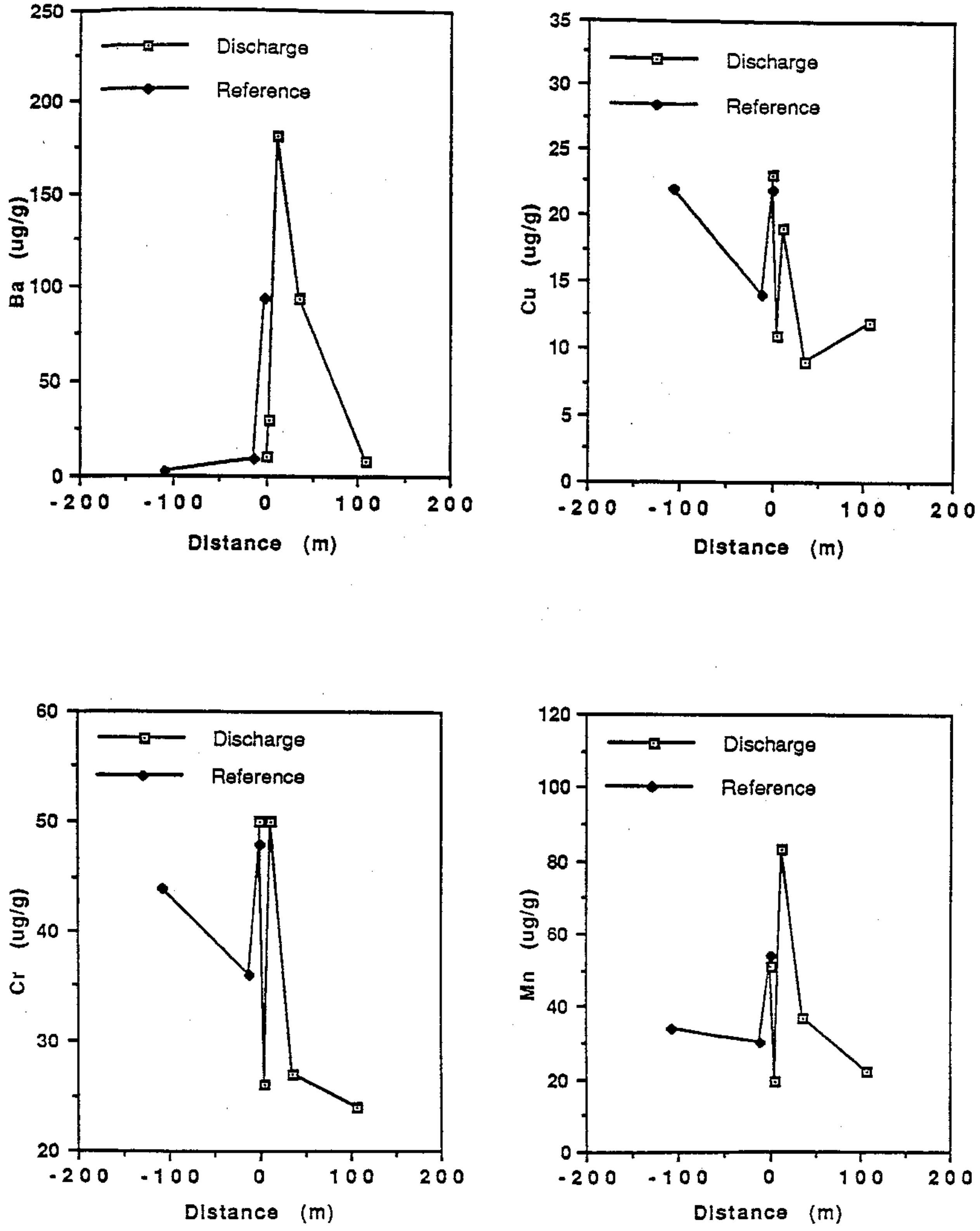


Figure 7.15. Spatial distribution of selected trace metals for Lafitte marsh sediments.

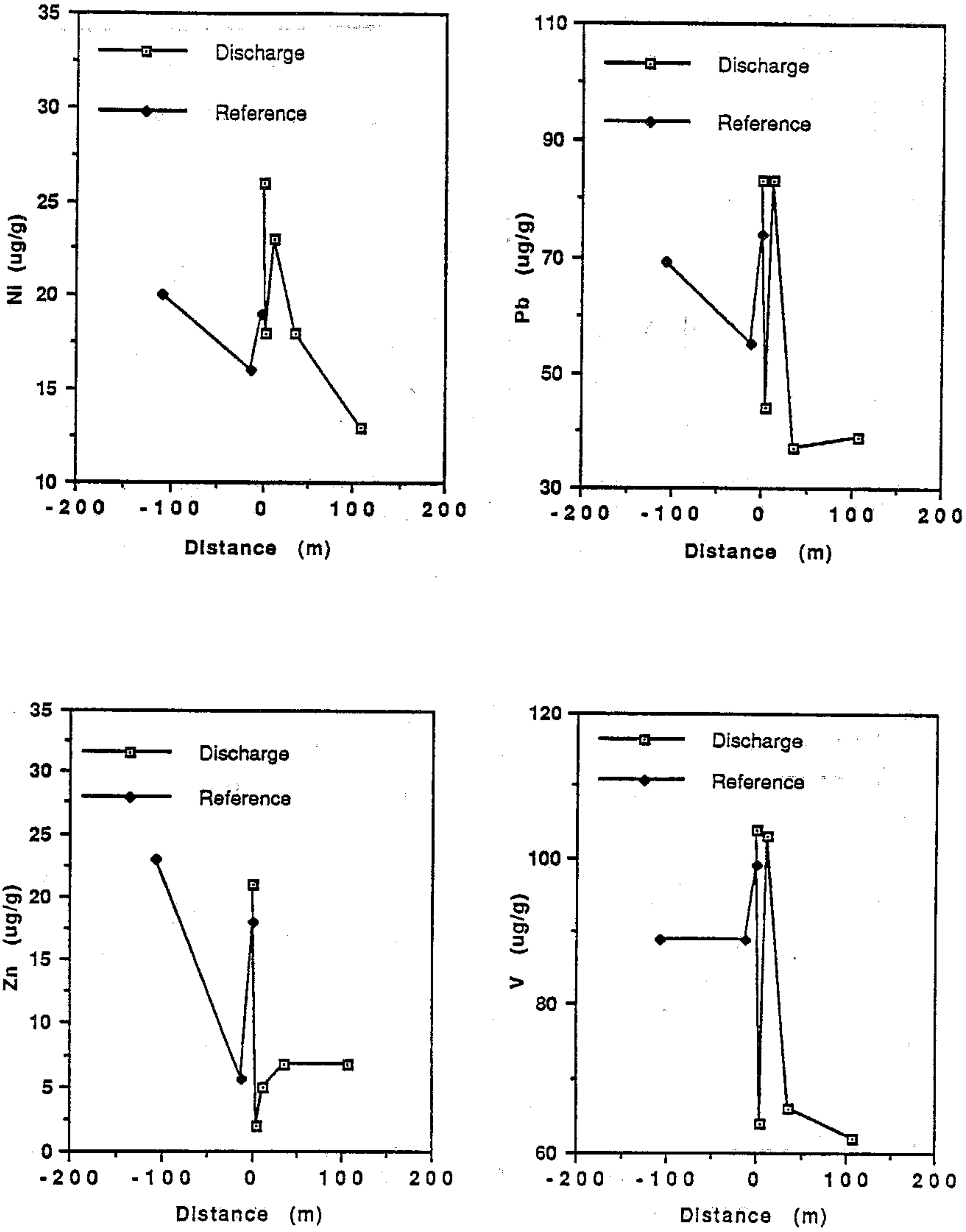


Figure 7.16. Spatial distribution of selected trace metals for Lafitte marsh sediments.

Table 7.10. Number of species per replicate and number of individuals per replicate for stations at the Lafitte site.

Station	No. Repl.	Number of Species			Number of Individuals		
		Min.	Max.	$\bar{x} \pm$ S.D.	Min.	Max.	$\bar{x} \pm$ S.D.
L0	3	1	2	1.7 ± 0.6	2	3	2.3 ± 0.6
L100S	3	0	3	2.0 ± 1.7	0	6	3.0 ± 3.0
L100NE	3	0	0	0.0 ± 0.0	0	0	0.0 ± 0.0
L250S	3	0	2	1.0 ± 1.0	0	2	1.0 ± 1.0
L250NE	3	0	3	1.7 ± 1.5	0	30	12.3 ± 15.7
L500W	3	6	11	9.0 ± 2.6	165	441	310.7 ± 138.7
L500NE	3	0	2	0.7 ± 1.2	0	3	1.0 ± 1.7
L500NW	3	3	4	3.3 ± 0.6	108	204	143.0 ± 53.0
L500SE	3	4	6	5.3 ± 1.2	336	442	374.7 ± 58.5
L700W	3	12	16	14.0 ± 2.0	49	308	161.7 ± 132.7
L750NE	3	8	16	13.0 ± 4.4	86	191	154.7 ± 59.5
L750NW	3	1	5	3.3 ± 2.1	22	152	96.7 ± 67.1
L750SE	3	1	3	2.3 ± 1.2	24	82	45.3 ± 31.9
L750SW	3	4	6	5.0 ± 1.0	132	297	188.0 ± 94.4
LR0	3	6	12	8.7 ± 3.1	260	685	412.3 ± 236.7
LR250E	3	3	6	4.3 ± 1.5	297	545	393.7 ± 132.7
LR250N	3	1	2	1.3 ± 0.6	9	55	25.0 ± 26.0
LR500N	3	0	1	0.3 ± 0.6	0	1	0.3 ± 0.6

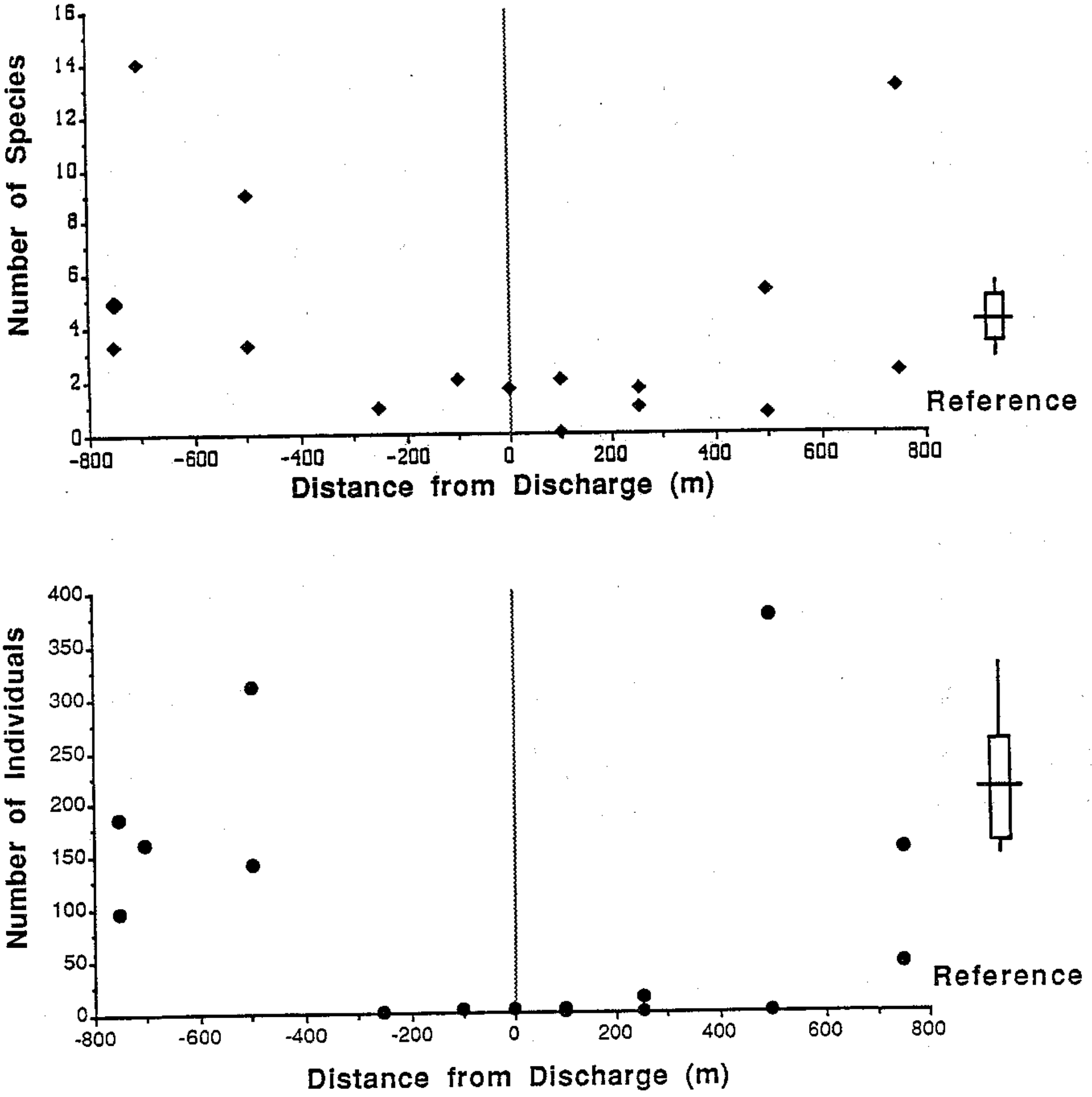
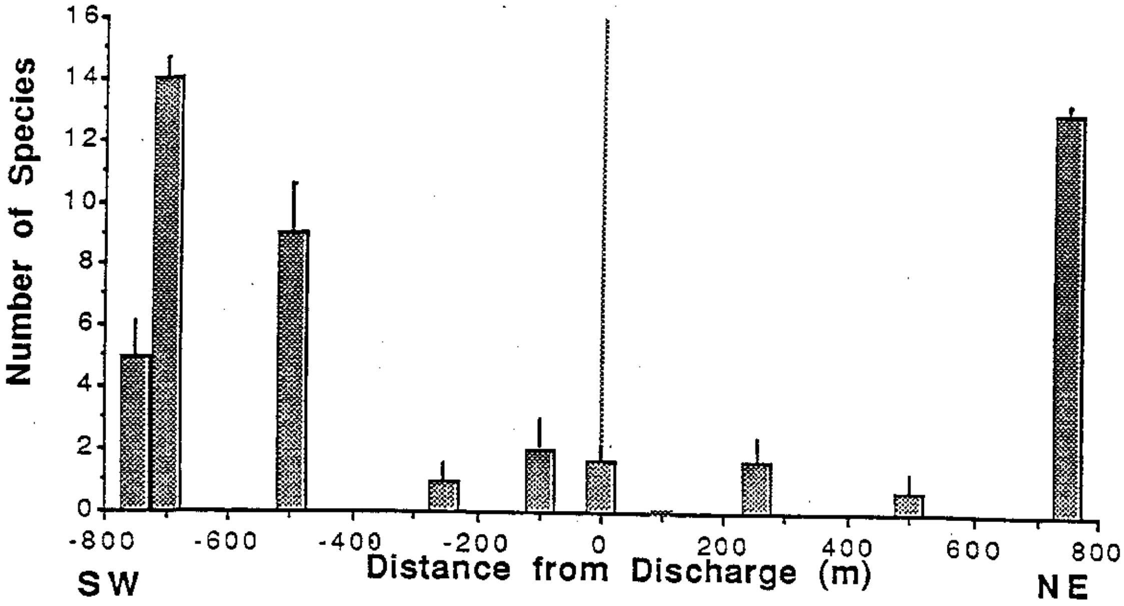


Figure 7.17. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna at all stations for the Lafitte discharge site. Mean, standard error and average minimum and maximum for reference stations shown to the right.



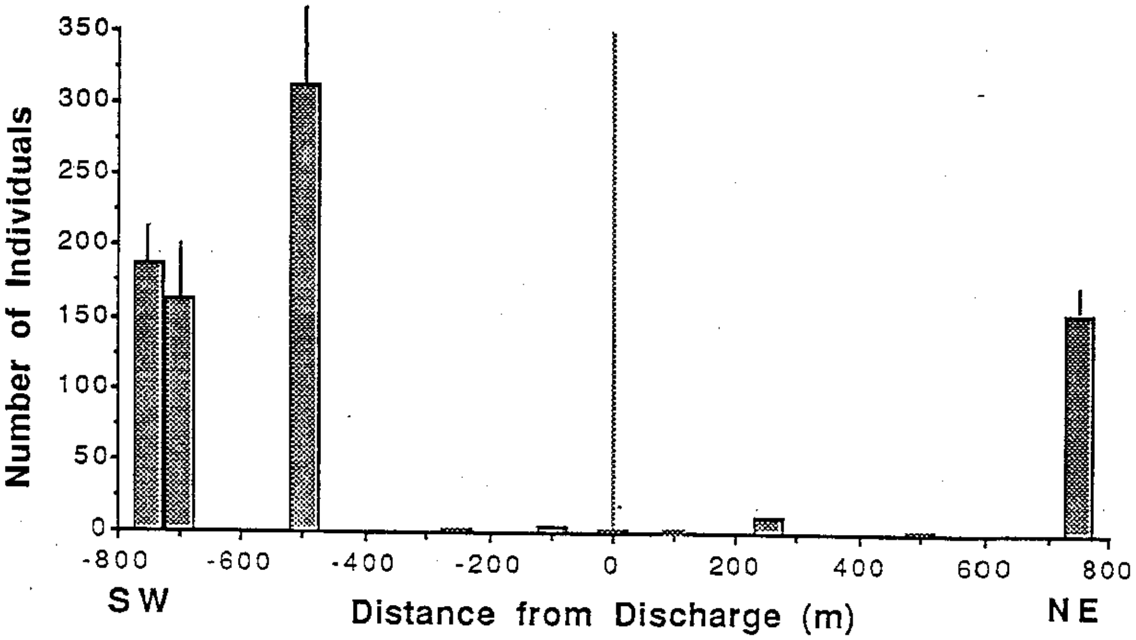


Figure 7.18. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna along a northeast to southwest transect through the Lafitte discharge site (standard error bars shown).

and L750NW) and to the southeast (L500SE and L750SE), reductions in species and numbers were restricted to stations within 250 m or less of the discharge, with the exception of L750SE (Figure 7.19). Measures of diversity (H') (Table 7.11) also showed general reductions near the discharge.

Trends in the benthic community parameters for the discharge stations must be placed in context of "natural" or background" levels. In the case of the Lafitte study area, the reference stations displayed benthic community measures similar to those found within the grid of stations around the discharge point, i.e., some of the reference stations were reduced in the number of species and number of individuals. In an analysis of variance of the benthic community parameters measured, the discharge stations were not significantly different from the reference stations (Table 7.12). We should note, however, that cell sizes were unequal for the analysis and that statistically significant differences were found within each of the major groupings (discharge vs. reference). These groupings will be dealt with separately.

Within the grid of discharge stations for the Lafitte study area, there were statistically significant differences among the stations for the full suite of benthic community parameters measured (Table 7.13). The groupings of stations based on Duncan's multiple range test (Table 7.14) showed that stations nearest the discharge were more similar to each other with respect to number of species and number of individuals. Stations removed in distance from the discharge (L700W, L750NE, and L500W) were the most diverse, in terms of number of species and diversity as measured by H' and also had high numbers of individuals. These stations could be considered the "background" stations for the discharge station grid. One station at a greater distance, L750SE, consistently grouped with those stations nearest the discharge in terms of number of species and number of individuals. Several stations at 500 to 750 m distance from the discharge point (L750SW, L750SE, 500NW and L750NW) had reduced numbers of species but increased numbers of individuals of the opportunistic polychaetes, *Streblospio benedicti* and *Mediomastus ambiseta*. These features of the benthic community are consistent with the "zone of stimulation" around produced water discharges in Texas inshore waters as noted by Harper (1986).

Within the grid of reference stations for the Lafitte study area, there were statistically significant differences among the stations for most of the benthic community parameters measured (Table 7.15), the exception being evenness (J'). Stations nearest the Barataria Waterway (LR0 and LR250E) were statistically different from stations (LR250N and LR500N) in the north-south canal adjacent to them (Table 7.16). The two former stations were high in diversity (number of species and H') and in number of individuals (Tables 7.10 and 7.11), while the two latter were the opposite, low in diversity and number of individuals.

Because there were such distinct differences within the reference station group, an additional analysis of variance and Duncan's multiple range test for the parameters of number of species and number of individuals was run on all stations combined. The results (Table 7.17 and 7.18) indicated statistical differences among all stations and that the reference stations LR250N and LR500N were more similar to stations near the discharge point than they were to the other reference stations. The reference stations, LR0 and LR250E, were more similar to the discharge stations that were considered "background" stations or in a "zone of stimulation."

7.4.3 Marsh Stations

One set of replicates for marsh faunal analysis has been completed for each of L1-0, a discharge site, and LR2-0, a reference site; both of these stations are at 0 m from either the discharge point or an arbitrary zero point at the reference stations. Number of species and individuals per sample replicate were reduced at L1-0 compared to LR2-0, but these differences were not significant at the $P < 0.05$ level (Tables 7.19 and 7.20, significant at the $P < 0.01$ level).

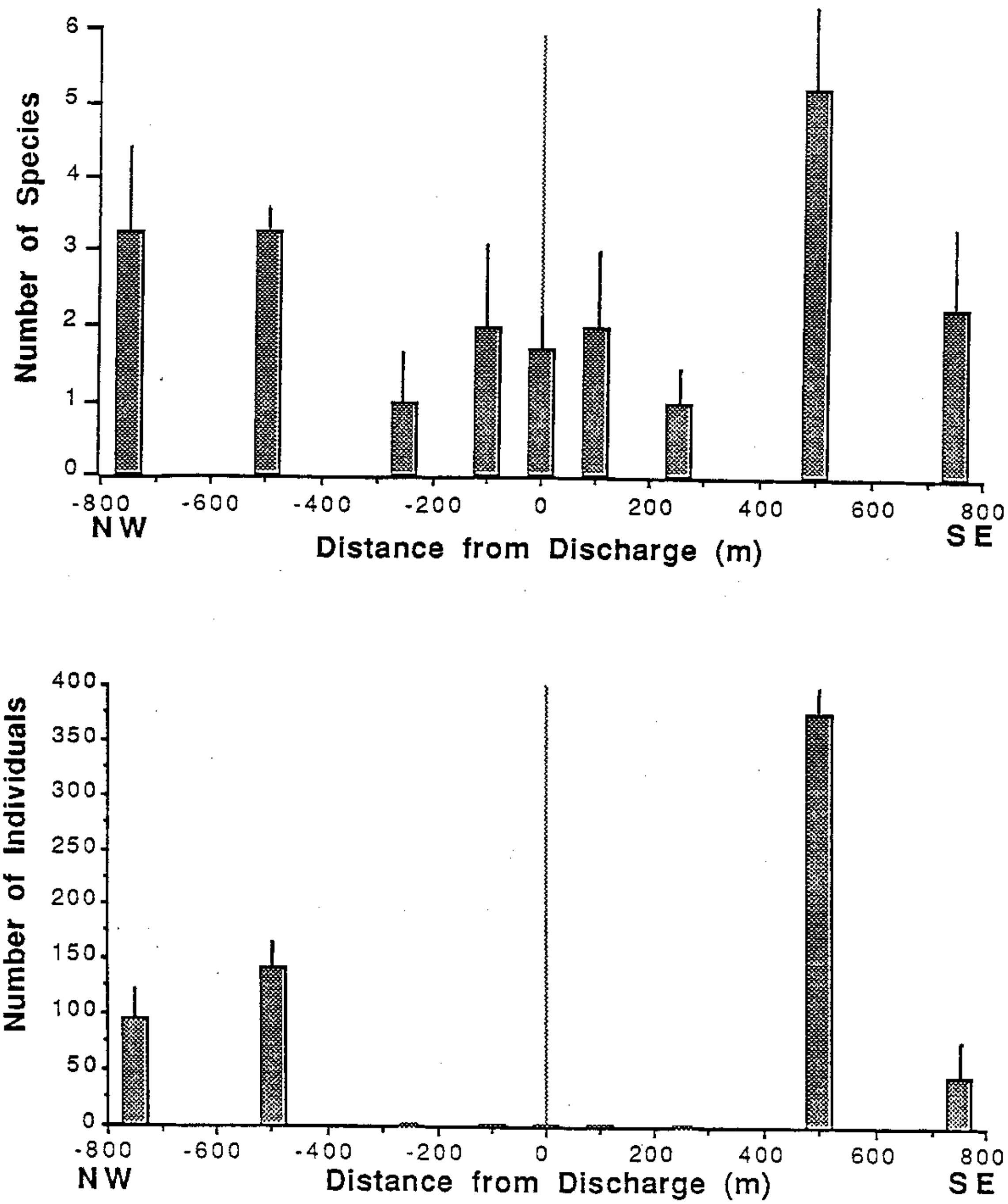


Figure 7.19. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna along a northwest to southeast transect through the Lafitte discharge site (standard error bars shown).

Table 7.11. Benthic community parameters for stations at the Lafitte site.

Station	No. Calc.	Diversity (H') $\bar{x} \pm$ S.D.	No. Calc.	Evenness (J') $\bar{x} \pm$ S.D.
L0	3	0.19 ± 0.17	2	0.29 ± 0.02
L100S	2	0.45 ± 0.03	2	0.29 ± 0.02
L100NE	0	-	0	-
L250S	2	0.15 ± 0.21	1	0.30
L250NE	2	0.27 ± 0.14	2	0.21 ± 0.04
L500W	3	0.24 ± 0.06	3	0.08 ± 0.01
L500NE	1	0.23	1	0.23
L500NW	3	0.38 ± 0.06	3	0.22 ± 0.01
L500SE	3	0.07 ± 0.02	3	0.03 ± 0.00
L700W	3	0.76 ± 0.13	3	0.20 ± 0.04
L750NE	3	0.66 ± 0.14	3	0.18 ± 0.01
L750NW	3	0.05 ± 0.04	2	0.03 ± 0.01
L750SE	3	0.12 ± 0.11	2	0.11 ± 0.02
L750SW	3	0.20 ± 0.03	3	0.09 ± 0.02
LR0	3	0.29 ± 0.05	3	0.10 ± 0.03
LR250E	3	0.32 ± 0.02	3	0.16 ± 0.03
LR250N	3	0.04 ± 0.08	1	0.13
LR500N	1	0.0 ± 0.0	0	-

Table 7.12. General linear model analysis of variance for Lafitte discharge stations versus reference stations, (note: unequal cell sizes).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate (square root transformed):					
Model	1	0.20	0.20	0.15	0.70
Error	52	69.98	1.35		
Corrected Total	53	70.18			
Number of individuals per station (square root transformed):					
Model	1	102.71	102.71	1.80	0.19
Error	52	2961.51	56.95		
Corrected Total	53	3064.22			
Diversity H' (log transformed):					
Model	1	0.04	0.04	1.33	0.26
Error	42	1.19	0.03		
Corrected Total	43	1.22			
Evenness J'					
Model	1	0.00	0.00	0.67	0.42
Error	35	0.26	0.01		
Corrected Total	36	0.26			

Table 7.13. General linear model analysis of variance for Lafitte discharge stations.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per station (square root transformed):					
Model	13	48.03592	3.69507	11.36	0.0001
Error	28	9.10557	0.32520		
Corrected Total	41	57.14149			
Number of individuals per station (square root transformed):					
Model	13	1741.23850	133.94142	18.50	0.0001
Error	28	202.76988	7.24178		
Corrected Total	41	1944.00838			
Diversity H' (log transformed):					
Model	12	0.89010	0.07417	10.54	0.001
Error	21	0.14783	0.00704		
Corrected Total	33	1.03793			
Evenness J':					
Model	12	0.23828	0.01986	38.06	0.0001
Error	17	0.00887	0.00052		
Corrected Total	29	0.24714			

Table 7.14. Duncan's multiple range test for Lafitte discharge stations. Underlined stations are not significantly different from each other.

Number of species per station (square root transformed):

700 W	750 NE	500 W	500 SE	750 SW	500 NW	750 NW	750 WE	0	100 S	250 NE	250 S	500 NE	100 NE
							———	———	———	———	———	———	
———	———	———	———	———	———	———	———	———			———	———	———
		———	———	———	———	———	———	———	———	———	———		

Number of individuals per station (square root transformed):

500 SE	500 W	750 SW	750 NE	700 W	500 NW	750 NW	750 SE	250 NE	0	100 S	250 S	500 NE	100 NE
———	———	———	———	———	———	———	———	———					
	———	———				———	———	———	———	———	———	———	———

Diversity H' (log transformed)

700 W	750 NE	100 S	500 NW	250 NE	500 W	500 NE	750 SW	0	250 S	750 SE	500 SE	750 NW
				———	———	———	———	———	———	———	———	
———	———	———	———	———	———	———						
					———	———	———	———	———	———	———	———
	———	———	———	———	———	———	———	———				

Evenness J'

250 S	0	100 S	500 NE	500 NW	250 NE	700 W	750 NE	750 SE	750 SW	500 W	750 NW	500 SE
———	———	———	———	———	———	———		———	———	———		
				———	———	———	———			———	———	———

Table 7.15. General linear model analysis of variance for Lafitte reference stations.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate (square root transformed):					
Model	3	11.27	3.76	19.14	0.0005
Error	8	1.57	0.20		
Corrected Total	11	12.84			
Number of individuals per station (square root transformed):					
Model	3	922.20	307.40	25.80	0.0002
Error	8	95.30	11.91		
Corrected Total	11	1017.51			
Diversity H' (log transformed):					
Model	3	0.13	0.04	19.73	0.002
Error	6	0.01	0.00		
Corrected Total	9	0.15			
Evenness J':					
Model	2	0.01	0.00	3.28	0.14
Error	4	0.00	0.00		
Corrected Total	6	0.01			

Table 7.16. Duncan's multiple range test for Lafitte reference stations. Underlined stations are not significantly different from each other.

Number of species per replicate (square root transformed):

LRO	LR250E	LR250N	LR500

Number of individuals per replicate (square root transformed):

LRO	LR250E	LR250N	LR500N

Diversity H':

LRO	LR250E	LR250N	LR500N

Table 7.17. General linear model analysis of variance for Lafitte study area, all stations combined.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate (square root transformed):					
Model	17	59.51	3.50	11.80	0.001
Error	36	10.68	0.30		
Corrected Total	53	70.18			
Number of individuals per replicate (square root transformed):					
Model	117	2766.15	162.71	19.65	0.0001
Error	36	298.07	8.28		
Corrected Total	53	3064.22			

Table 7.18. Duncan's multiple range test for Lafitte study area, all stations combined. Underlined stations are not significantly different from each other.

Number of species per replicate (square root transformed):

L 700 W	L 750 NE	L 500 W	LR 0	L 500 SE	L 750 SW	LR 250 E	L 500 NW	L 750 NW	L 750 SE	L 0	L 100 S	LR 250 N	L 250 NE	L 250 S	L 500 NE	LR 500 N	L 100 E
						———	———	———	———	———	———	———	———				
———	———	———		———	———	———	———	———	———	———				———	———	———	———
									———	———	———	———	———	———	———		
		———	———	———	———	———	———	———	———	———	———	———	———	———			
										———	———	———	———	———	———		

Number of individuals (square root transformed):

LR 0	LR 250 E	L 500 SE	L 500 W	L 750 SW	L 750 NE	L 700 W	L 500 NW	L 750 NW	L 750 SE	LR 250 N	L 250 NE	L 0	L 100 S	L 250 S	L 500 NE	LR 500 N	L 100 NE
										———	———	———	———	———	———	———	———
———	———	———		———	———	———	———	———	———	———	———	———	———				
			———	———				———	———	———							

Table 7.19. Benthic community parameters for marsh stations at the Lafitte site.

		Number of Species			Number of Individuals		
Station	No. Repl.	Min.	Max.	$\bar{x}$ ± S.D.	Min.	Max.	$\bar{x}$ ± S.D.
L1-0	3	1	1	1.0 ± 0.0	1	2	1.3 ± 0.6
LR2-0	3	2	6	4.3 ± 2.1	2	12	8.0 ± 5.3

Station	No. Calc.	Diversity (H') $\bar{x}$ ± S.D.	No. Calc.	Evenness (J') $\bar{x}$ ± S.D.
L1-0	3	0.00 ± 0.00	0	-
LR2-0	3	0.22 ± 0.05	3	0.29 ± 0.02

Table 7.20. General linear model analysis of variance for Lafitte marsh stations, discharge versus reference.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	1	16.67	16.67	7.69	0.05
Error	4	8.67	2.17		
Corrected Total	5	25.33			
Number of individuals per replicate:					
Model	1	66.67	66.67	4.71	0.10
Error	4	56.67	14.17		
Corrected Total	5	123.33			
Diversity H':					
Model	1	0.47	0.47	18.73	0.01
Error	4	0.10	0.03		
Corrected Total	5	0.57			

If data for the number of species were log transformed to normalize the data, then there would be statistically significant differences between the discharge station and the reference station. Transformation was not performed on the marsh data, however, because of the small sample size available to check for normality. Statistically significant differences were seen in diversity (H') for the discharge and reference stations analyzed.

7.5 Synthesis

Sediments for stations at the Lafitte site were predominantly muds, with only three stations having greater than 10% sand composition (L750SW, L0 and L100NE). Similarly, total organic content of the sediments was uniformly less than 10%, with the exception of three stations (L100NE, L500NE, and L750NE). Thus, there were rather uniform environmental conditions with respect to the sedimentary characteristics. The benthic community parameters measured showed no correlations with sediment grain size distribution or sediment total organic carbon content.

The numbers of species, as is consistent with the upper reaches of a mesohaline estuary is low. Differences in the numerical dominants controlled the response of the benthic community to water quality parameters or chemical contaminants. The benthic community parameters of numbers of species per replicate and number of individuals per replicate were examined in relationship to major groups of chemical contaminants in the sediments. There were distinct responses of these measures to the concentrations of total polynuclear aromatic hydrocarbons (PAH), total PAH and homologs of naphthalene, dibenzothiophene, and phenanthrene (NDP homologs), and total resolved and unresolved aliphatic hydrocarbons in the sediments. Numbers of species and individuals were negligible or reduced at total PAH concentrations greater than 300 ppb (Figure 7.20) and total PAH and NDP homologs concentrations greater than 1000 ppb (Figure 7.21). The trend was less abrupt for total aliphatics, but in general showed a decrease in number of species and individuals with an increase in aliphatic hydrocarbon concentration (Figure 7.22). Besides the station immediate to the discharge (L0), only one other stations (L750SW) had detectable levels of volatile aromatic hydrocarbons. This station also had a somewhat reduced number of species.

Based on the distribution of the near-bottom density plume (Figure 7.1) and the elevated contaminant levels at selected stations at greater distance from the discharge, it is possible that the dispersion of contaminated waters may reach greater distances periodically on stronger ebb tides that move these contaminants into dead-end canals. Subsequent flushing of these areas may be minimal, and these dead-end areas may be zones of contaminant accumulation.

While the levels of chemical contaminants at the reference stations were not as high as in the sediments of the discharge site, within the reference stations concentrations were higher at the two stations located in the dead-end canal (LR250N and LR500N) than at the terminus of the canals with Barataria Waterway (LR0 and LR250E). Most notable were the elevated levels of total PAH and NDP homologs at LR250N and LR500N. These two stations exhibited a reduced number of species and individuals compared to the other two reference stations. There are no other obvious differences among the reference stations with respect to sediment grain size distribution, sediment total organic carbon content or water quality.

It is premature to draw conclusions regarding the differences in marsh benthic communities at the discharge site and the reference site. In general, however, at the 0 m distance stations analyzed, there were higher concentrations of total resolved and unresolved aliphatic hydrocarbons at the discharge site than at the reference site. The reduced number of species and individuals at the marsh discharge site (L1-0) may be related to these higher hydrocarbon concentrations. Total PAH and total PAH and NDP homolog concentrations were trace at both the discharge and reference marsh transects.

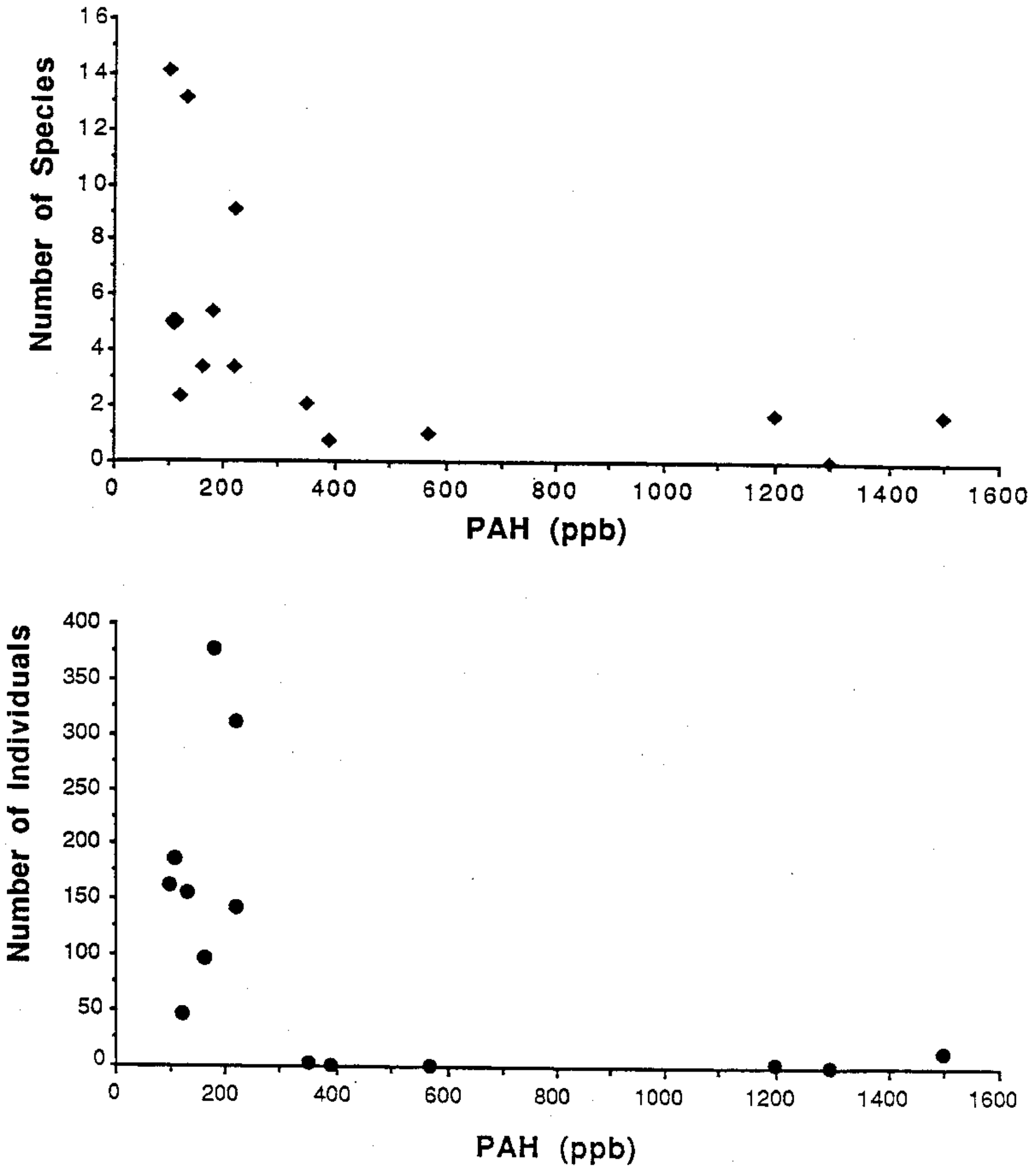


Figure 7.20. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) for the Lafitte discharge site.

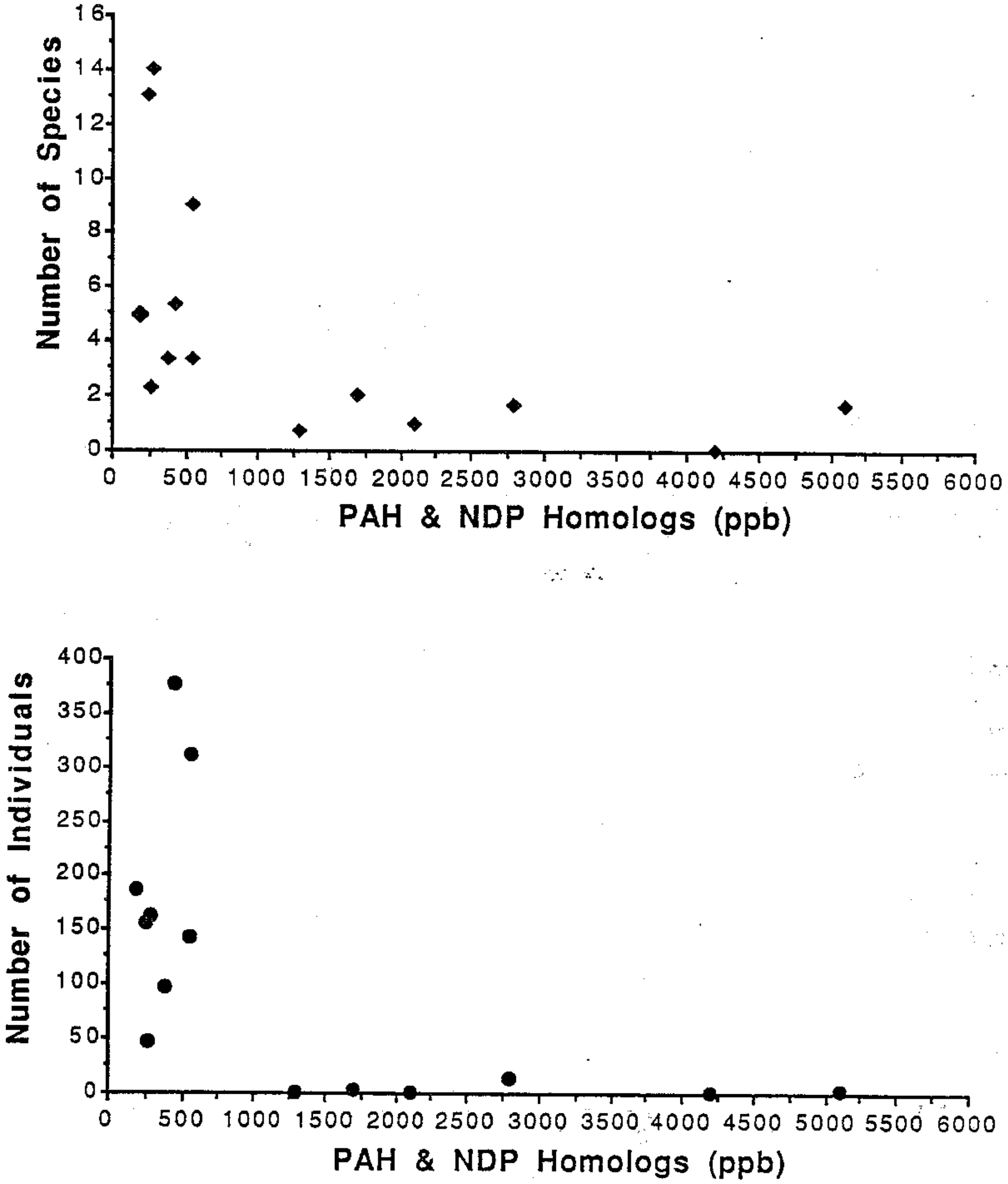


Figure 7.21. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) and total homologs of naphthelene, dibenzothiophene and phenanthrene (NDP) for the Lafitte discharge site.

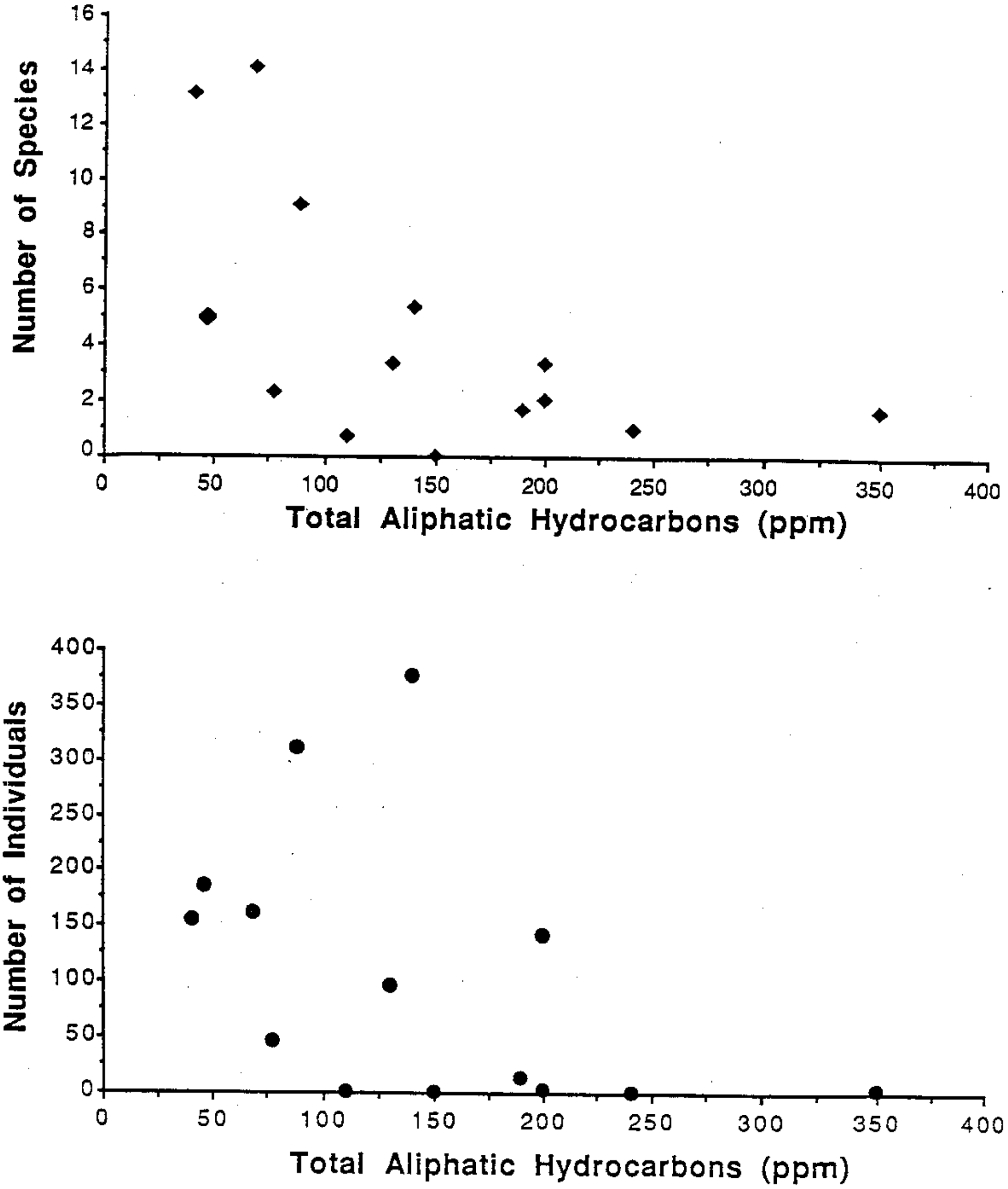


Figure 7.22. Comparison of number of species, above, and number of individuals, below, to total resolved and unresolved aliphatic hydrocarbons for the Lafitte discharge site.

Chapter 8

GOLDEN MEADOW STUDY SITE

Jay C. Means, Nancy N. Rabalais, Charles S. Milan, Debra J. McMillin and Lorene Smith

8.1 Hydrography

There are two produced water discharges at the Golden Meadow site: the Texaco facility TB8 to the south and the Texaco facility TB7 to the north (Figure 1.12). Both are located on canals which in some places intersect natural water bodies. There was a strong tidal current on the morning of September 7, 1988 moving to the north along the canal receiving produced waters from TB8. Currents were imperceptible at TB7 during collections there. Salinity of the produced water discharges at TB8 was 120 ppt and at TB7 on September 8 was 130 ppt as determined by refractometer.

There was no obvious salinity difference in the water column of stations arrayed away from GM0 at TB8 (Table 8.1). Currents were to the north at this time. At slack tide, a second reading was made of the bottom waters at GM0; in this case, bottom water was 10.7 ppt compared to an ambient salinity of 10.0 to 10.1 ppt.

A difference in bottom water salinity was only apparent at station G0 at TB 7 on a slack tide (September 7) (Table 8.1). Bottom water salinity was 11.3 ppt compared to a surface salinity of 9.4 ppt. A slight surface-to-bottom salinity difference was observed at G100E, G250E, and G250S but not at other stations. On September 8, when a current toward the east was observed at G0, there was no surface-to-bottom salinity difference noted.

Ambient salinities (9.2 to 9.5 ppt) at the reference stations were generally lower than ambient salinities at TB7 (9.8 to 10.0 ppt) and TB8 (10.0 to 10.7 ppt) indicating a general increase in salinities from east to west and from north to south through the study area. All waters were well oxygenated at the time of sampling.

Interstitial salinities of sediments along canals and waterways in the Golden Meadow study area were generally higher than the salinity of the near-bottom waters as measured by the Hydrolab CTD unit (Figure 8.1). This trend was consistent at both discharge sites and at the reference stations. Figure 8.1 also shows the general trend in near-bottom water salinities through the study area.

8.2 Organic Contaminants

8.2.1 Sediments

8.2.1.1 Bulk parameters

Table 8.2 presents the data on sediment organic carbon content of the sediments in the vicinity of the Golden Meadow discharge sites and the corresponding reference site. Stations associated with primary discharge site at TB8 are designated as GM sites, while those associated with the secondary discharge site TB7 as designated simply G. The reference site is designated GR. The data are reported both as percent organic matter and percent organic carbon. Figure 8.2 shows the spatial distribution of organic carbon in the sediments of the Golden Meadow system. Sediment organic carbon contents near the primary discharge site ranged from 0.3 to 2.5% and from 0.95 to 5.9% near the secondary discharge site, while in the reference site they ranged from 7.1 to 7.9%. Sediment organic carbon values seemed to be elevated near the

Table 8.1. Hydrographic data for Golden Meadow study area, 7-8 September 1988

Primary site (GM), stations in distance (m) away from TB8
Secondary site (G), stations in distance (m) away from TB7
Reference stations (GR) in distance (m) away from arbitrary "0" point

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (°C)	Dissolved Oxygen (mg/l)	pH
Station GM0 (10:20, 7 September 1988)) (weak current towards north)					
0.2	10.0	17.3	24.30	7.08	7.55
1.0	10.1	17.4	24.27	7.05	7.53
2.1	10.1	17.4	24.22	7.16	7.51
Station GM0 (13:45, 7 September 1988) (slack tide)					
2.1	10.7				
Station GM100S (09:55, 7 September 1988) (weak current towards north)					
0.2	10.1	17.5	24.25	6.99	7.51
1.0	10.1	17.5	24.23	7.01	7.49
1.5	10.0	17.4	24.17	7.09	7.46
Station GM250S (09:35, 7 September 1988) (weak current towards north)					
0.2	10.0	17.5	24.19	6.87	7.50
1.0	10.1	17.5	24.18	6.84	7.49
2.2	10.1	17.5	24.11	7.01	7.48
Station GM500S (09:15, 7 September 1988) (strong current towards north)					
0.2	10.1	17.5	24.12	6.85	7.40
0.9	10.0	17.4	24.12	7.01	7.37
Station GM1000S (08:40, 7 September 1988) (strong current towards north)					
0.2	10.1	17.6	24.12	6.74	7.42
1.0	10.1	17.5	24.13	6.75	7.41
2.0	10.1	17.6	24.12	6.72	7.38
2.9	10.1	17.6	24.08	6.75	7.36

Table 8.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (oC)	Dissolved Oxygen (mg/l)	pH
Station GM100N (10:40, 7 September 1988)					
0.2	10.1	17.6	24.38	7.23	7.58
1.0	10.2	17.6	24.33	7.17	7.57
1.5	10.2	17.6	24.33	7.17	7.56
2.0	10.2	17.7	24.33	7.17	7.54
2.4	10.3	17.8	24.31	7.32	7.45
Station GM250N (12:40, 7 September 1988) (current towards north on bottom) (sandy, low volume benthic grabs)					
0.2	10.5	18.1	24.99	8.12	7.75
1.0	10.5	18.1	24.95	8.08	7.71
1.6	10.5	18.2	24.92	8.30	7.65
Station GM500N (13:00, 7 September 1988)					
0.2	10.4	18.1	24.97	8.02	7.76
1.0	10.5	18.1	24.94	7.99	7.75
2.0	10.5	18.1	24.92	7.95	7.73
3.0	10.4	18.1	24.88	7.95	7.72
3.7	10.5	18.1	24.87	8.00	7.70
Station GM1000N (13:25, 7 Septembmer 1988)					
0.2	10.4	18.0	25.13	8.30	7.78
1.0	10.3	17.9	25.12	8.29	7.77
1.8	10.3	17.9	25.08	8.83	7.64
Station GM250W (11:05, 7 September 1988) (currents towards west on surface and towards east on bottom) (sandy sediments, less volume in benthic grabs)					
0.2	10.3	17.9	24.50	7.41	7.63
1.0	10.3	17.9	24.46	7.34	7.62
2.0	10.3	17.9	24.43	7.31	7.60
2.6	10.4	17.9	24.38	7.48	7.48
Station GM500W (11:30, 7 September 1988) (current towards west on surface and towards east on bottom) (benthic replicate #1 with more sediment volume; benthic replicates #2 and #3 with less sediment volume than station GM250W)					
0.2	10.2	17.7	24.81	7.77	7.68
1.0	10.2	17.8	24.75	7.69	7.67
2.0	10.4	18.1	24.53	7.52	7.63
2.9	10.5	18.2	24.50	7.77	7.58

Table 8.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (oC)	Dissolved Oxygen (mg/l)	pH
Station GM1000W (12:00, 7 September 1988) (current towards east on bottom)					
0.2	10.7	18.5	24.76	7.83	7.74
1.0	10.7	18.5	24.75	7.83	7.73
2.0	10.7	18.5	24.73	7.80	7.72
3.0	10.7	18.5	24.71	7.81	7.71
3.7	10.7	18.4	24.71	7.90	7.67
Station G0 (17:40, 7 September 1988)					
0.2	9.4	16.4	25.88	8.81	7.90
1.0	9.5	16.6	25.87	8.74	7.89
1.5	9.5	16.7	25.84	8.70	7.88
2.0	9.8	17.1	25.75	8.49	7.83
2.3	11.3	19.2	25.75	8.54	7.76
Station G0 (10:55, 8 September 1988) (current towards east)					
0.2	9.9	17.3	24.38	7.26	7.67
1.0	9.9	17.2	24.34	7.27	7.66
2.0	9.9	17.3	24.31	7.27	7.65
2.7	10.0	17.3	24.29	7.35	7.65
Station G100E (17:25, 7 September 1988))					
0.2	9.4	16.5	25.92	8.92	7.91
1.0	9.5	16.6	25.86	8.85	7.89
2.0	9.8	17.2	25.66	8.66	7.83
2.8	9.9	17.3	25.67	8.75	7.81
Station G250E (16:45, 7 September 1988))					
0.2	9.8	17.0	25.73	8.85	7.88
1.0	9.8	17.0	25.69	8.79	7.87
2.0	9.8	17.0	25.60	8.69	7.81
3.1	10.1	17.6	25.51	8.48	7.75
Station G500E (16:20, 7 September 1988)					
0.2	9.9	17.2	25.60	8.57	7.83
1.0	9.9	17.2	25.58	8.53	7.82
2.0	10.0	17.3	25.56	8.50	7.80
2.5	10.0	17.4	25.53	8.44	7.75

Table 8.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (oC)	Dissolved Oxygen (mg/l)	pH
Station G1000E (16:00, 7 September 1988)					
0.2	9.4	16.4	25.71	8.83	7.83
1.0	9.4	16.4	25.64	8.67	7.80
1.8	9.5	16.6	25.12	8.32	7.68
Station G250S (17:00, 7 September 1988)					
0.2	8.5	15.0	26.32	9.38	8.01
1.0	9.9	17.3	25.66	8.51	7.80
2.1	10.1	17.6	25.33	8.01	7.70
Station G100W (15:35, 7 September 1988)					
0.2	10.2	17.7	25.56	8.55	7.83
1.0	10.2	17.7	25.52	8.54	7.81
2.0	10.2	17.7	25.38	8.46	7.79
2.6	10.3	17.8	25.35	8.52	7.75
Station G250W (15:15, 7 September 1988)					
0.2	10.2	17.7	25.57	8.63	7.83
1.0	10.2	17.7	25.54	8.59	7.81
2.0	10.3	17.8	25.34	8.40	7.77
2.7	10.3	17.8	25.28	8.45	7.72
Station G500W (14:55, 7 September 1988)					
0.2	10.2	17.7	25.45	8.51	7.83
1.0	10.2	17.7	25.38	8.41	7.81
2.0	10.3	17.9	25.18	8.22	7.77
3.0	10.4	17.9	25.16	8.22	7.73
3.5	10.4	17.9	25.15	8.36	7.67
Station G1000W (14:35, 7 September 1988)					
0.2	10.2	17.7	25.37	8.41	7.76
1.0	10.3	17.8	25.23	8.38	7.71
2.0	10.4	17.9	25.17	8.35	7.56
Station GR0 (09:25, 8 September 1988)					
0.3	9.4	16.5	23.58	6.59	7.49
1.0	9.3	16.3	23.50	6.65	7.49
2.4	9.3	16.3	23.49	6.83	7.47

Table 8.1. Continued.

Depth (m)	Salinity (ppt)	Conductivity (mmho/cm)	Temperature (°C)	Dissolved Oxygen (mg/l)	pH
Station GR250E (09:40, 8 September 1988)					
0.3	9.4	16.5	23.51	6.87	7.54
1.0	9.4	16.4	23.50	6.98	7.54
2.2	9.5	16.5	23.36	7.22	7.57
Station GR250W (09:05, 8 September 1988)					
0.3	9.4	16.4	23.43	6.48	7.47
1.0	9.4	16.4	23.43	6.57	7.48
2.2	9.4	16.4	23.43	6.83	7.50
Station GR500W (08:45, 8 September 1988)					
0.3	9.2	16.2	23.38	6.44	7.45
1.0	9.2	16.2	23.37	6.46	7.44
2.0	9.2	16.2	23.35	6.44	7.43
2.5	9.3	16.2	23.35	6.51	7.42

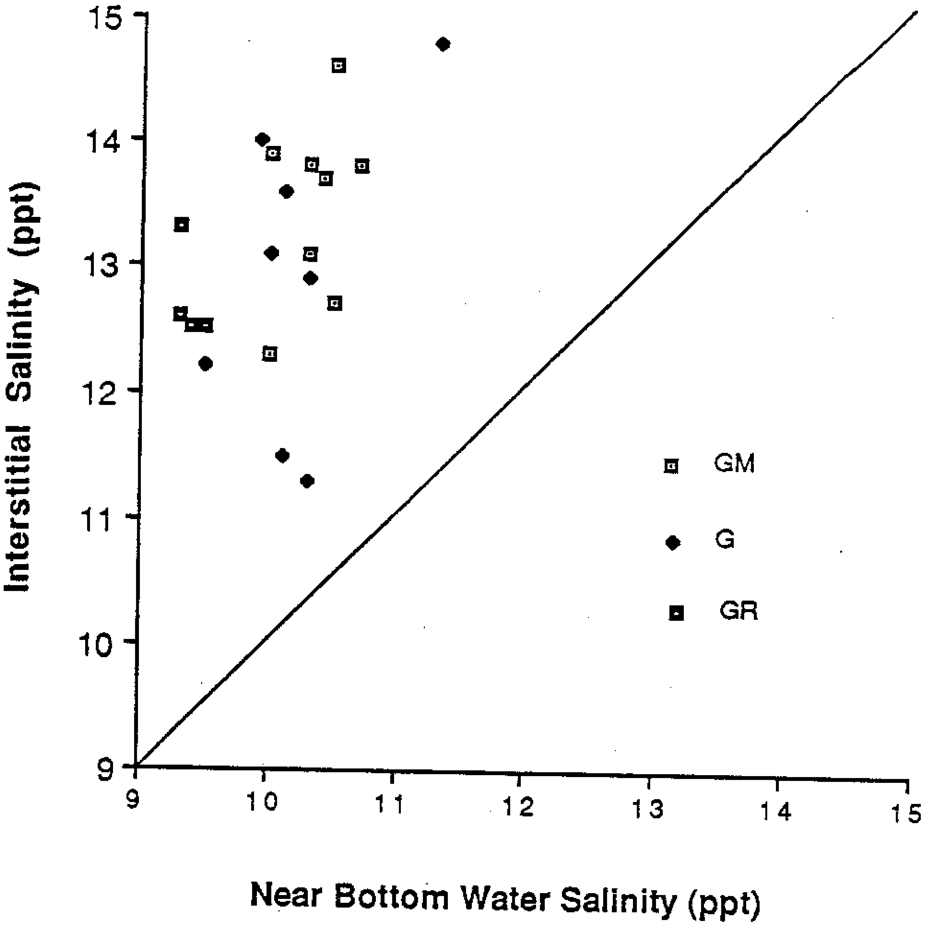
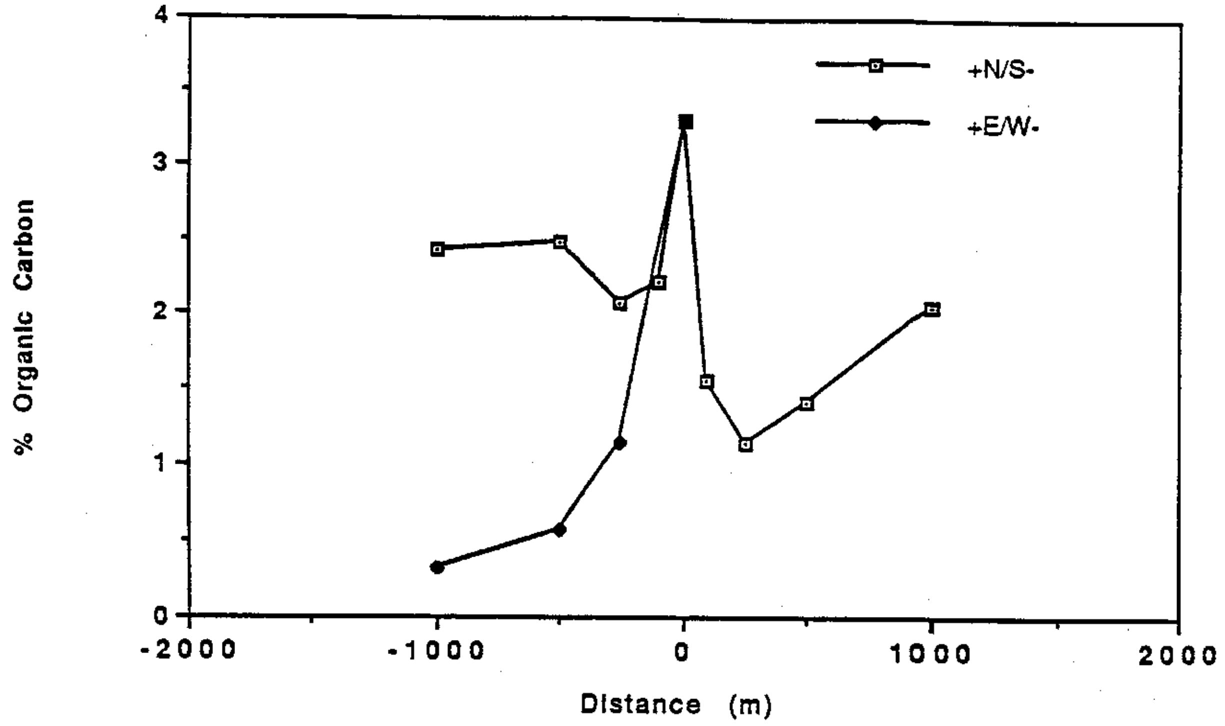


Figure 8.1. Comparison of interstitial water salinity from sediments of stations in waterways and channels of the Lafitte site to near bottom water salinity.

Table 8.2. Sediment characteristics for the Golden Meadow site.

Sample	% Organic Matter	% Organic Carbon	%$H_2$0	%Clay	%Sand	%Silt
GM0	5.5	3.30	49	11.3	39.4	49.2
GM100N	2.6	1.55	33	5.6	55.5	38.9
GM100S	3.7	2.22	52	13.2	45.5	41.4
GM250N	1.9	1.14	30	15.0	52.3	32.7
GM250S	3.5	2.08	47	6.0	51.5	42.4
GM250W	1.9	1.14	31	3.1	78.5	18.3
GM500N	2.3	1.41	44	19.4	38.3	42.3
GM500S	4.2	2.49	53	15.5	43.2	41.3
GM500W	1.0	0.58	25	5.4	85.7	8.9
GM1000N	3.4	2.05	41	20.4	46.6	33.0
GM1000S	4.0	2.42	39	16.5	65.9	17.6
GM1000W	0.6	0.33	22	1.9	95.2	3.0
GM1000W	-	-	-	4.1	92.3	3.6
G0	6.8	4.05	56	19.6	22.9	57.5
G100E	8.2	4.92	65	27.3	15.4	57.4
G100W	5.8	3.48	36	19.5	27.5	53.0
G250E	6.8	4.06	46	19.1	31.0	49.9
G250S	8.3	4.96	72	21.5	15.3	63.2
G250W	4.4	2.65	31	10.4	38.6	51.0
G500E	9.8	5.88	47	12.2	28.3	59.4
G500W	1.6	0.95	22	3.1	81.7	15.2
G1000E	14.2	8.53	69	15.3	14.9	69.9
G1000W	7.2	4.34	42	26.9	20.9	52.2
G1000W	5.8	3.48				
GR0	12.0	7.16	-	24.5	0.8	74.7
GR250E	13.1	7.86	-	28.4	0.3	71.3
GR250W	13.2	7.89	-	17.5	7.1	75.4
GR500W	12.6	7.56	-	29.9	11.5	58.6
GMR0	-	-	73	-	-	-
GMR250E	-	-	78	-	-	-
GM250W	-	-	69	-	-	-
GMR500W	-	-	71	-	-	-
GM4-0	-	-	79	-	-	-
GM4-4	-	-	81	-	-	-
GM4-12	-	-	86	-	-	-
GM4-36	-	-	90	-	-	-
GM4-108	-	-	88	-	-	-
G1-0	-	-	87	-	-	-
G1-4	-	-	87	-	-	-
G1-12	-	-	89	-	-	-
G1-36	-	-	90	-	-	-
G1-108	-	-	89	-	-	-
GR2-0	-	-	72	-	-	-
GR2-12	-	-	69	-	-	-
GR2-108	-	-	69	-	-	-


GOLDEN MEADOW PRIMARY SITE

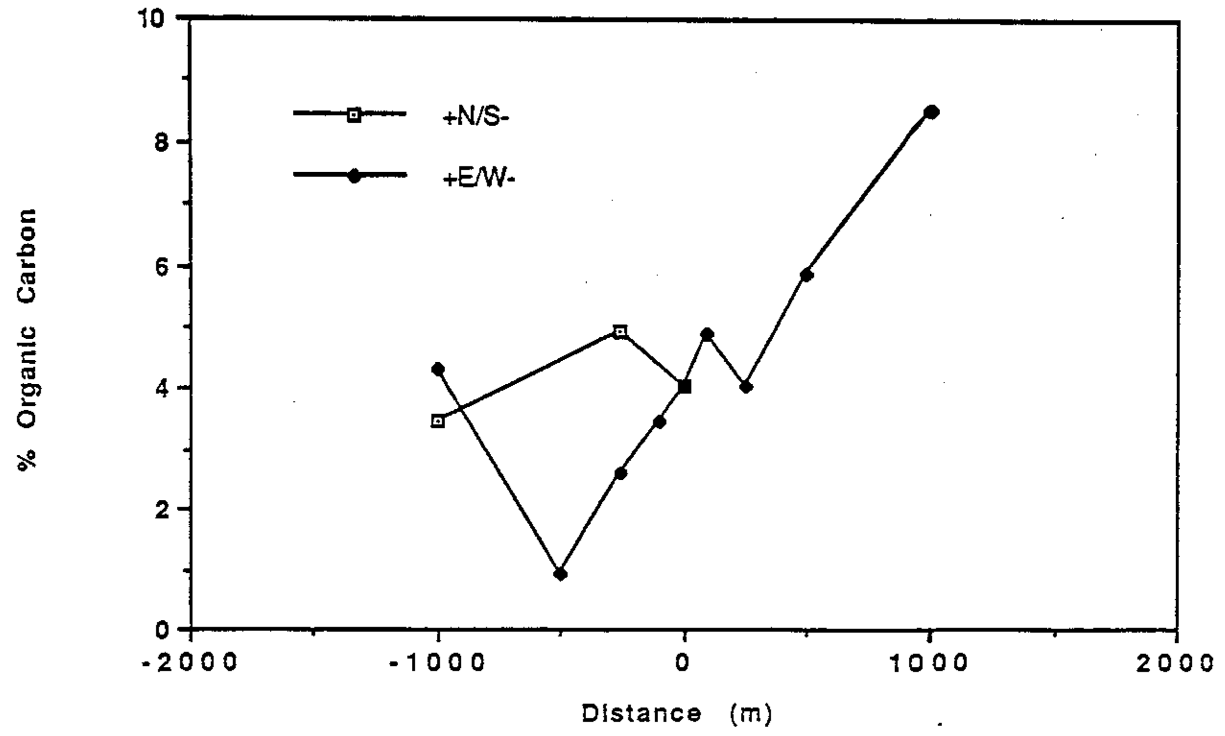

GOLDEN MEADOW SECONDARY SITE

Figure 8.2. Spatial distribution of organic carbon content of Golden Meadow primary site, above, and Golden Meadow secondary site, below, sediments.

primary discharge and decrease in all directions away from that point, while at the secondary discharge site organic carbon values seem to be elevated to the east of the discharge point but not toward the west. At the reference site, no trend in sediment carbon content was observed from east to west.

8.2.1.2 Volatile hydrocarbons

Determinations of volatile hydrocarbons associated with sediment interstitial water and/or readily desorbable from sediments yielded little meaningful data. Table 8.3 presents a summary of the volatile hydrocarbon data at all of the primary and secondary sites in the Golden Meadow system and reference area, including those located along marsh transects. Benzene, toluene and xylenes were detected at nominal concentrations at stations near to the secondary discharge (e.g., G100W) but only xylenes were detected at the G0 point (Figure 8.3). At the primary site, benzene was detected at the GM250W site and xylenes were detected at the GM500S site. However, neither were detected at the GM0 site near the primary discharge (Figure 8.4). At the reference site, none of the volatile hydrocarbons were detectable at any of the sites. One very anomalous finding was observed at the GM4-36 site in the marsh. This sample contained 2300 ppb of xylenes and 120 ppb ethylbenzene. This suggests some local origin for these compounds in the marsh site. These data were paralleled by data on semivolatile hydrocarbons at this same station, suggesting perhaps a spill at this site.

8.2.1.3 Semivolatile hydrocarbons

Tables 8.4 and 8.5 present a summary of all of the semivolatile hydrocarbon data for the Golden Meadow primary and secondary discharge sites, respectively and the reference site data are presented in Table 8.6.

Figure 8.5 shows the spatial distribution of normal aromatic PAH at various distances away from the Golden Meadow primary discharge point along with the reference site data. Total normal PAH were found maximally (300 ppb) in the immediate area of the discharge and decline rapidly to 210 ppb (GM100S) or less within 100 m of the discharge. Among the normal PAH, phenanthrene, fluorene, fluoranthene, pyrene and benzanthracene were found the most frequently in the region of the discharge. It should be noted that the total concentrations at the reference site were present at approximately 50% of the maximum at the discharge point, suggesting that normal PAH may be high in the reference site. Figure 8.6 shows the distribution of normal PAH around the secondary discharge point. Phenanthrene, fluorene, fluoranthene, pyrene and benzanthracene were found the most frequently in the region of the secondary discharge. Concentrations of normal PAH were (610 ppb) just south of the discharge and decreased rapidly to 200 ppb or less within 250 m of the discharge point. Total PAH in the reference site ranged from 100 to 180 ppb throughout, with the same four compounds dominating the distribution.

Figure 8.7 shows the spatial distribution of pyrene near the primary site, while Figure 8.8 shows the distribution of pyrene at the secondary site. The distribution pattern of pyrene at both sites closely paralleled that of the total PAH.

Figure 8.5B shows the spatial distribution of the sum of the normal PAH together with the alkylated and heterocyclic PAH for the Golden Meadow primary site as well as those occurring at the reference sites. It is clear that the general pattern of the distribution was similar to that observed for the normal PAH alone, however, an examination of the amounts clearly shows that the alkylated PAH contributed approximately 50% of the distribution. Figure 8.6B shows the sum of the normal and alkylated and heterocyclic PAH at the secondary discharge site. The alkylated and heterocyclic PAH represented a higher proportion of the total at this site (as

Table 8.3. Volatile hydrocarbons in Golden Meadow sediments.

Sample ID	Benzene (ppb, dry wt.)	Toluene	Ethylbenzene	Xylenes	Cumene
GM-0	nd	nd	nd	nd	nd
GM-100N	tr	nd	nd	nd	nd
GM-100S	nd	nd	nd	nd	nd
GM-250N	tr	nd	nd	nd	nd
GM-250S	nd	nd	nd	nd	nd
GM-250W	13	nd	nd	nd	nd
GM-500N	nd	nd	nd	nd	nd
GM-500S	tr	nd	nd	18	nd
GM-500W	tr	nd	nd	tr	nd
GM-1000N	nd	nd	nd	nd	nd
GM-1000S	nd	nd	nd	nd	nd
GM-1000W	nd	nd	nd	nd	nd
G-0	tr	nd	nd	10	nd
G-100E	nd	nd	nd	nd	nd
G-100W	19	10	tr	32	nd
G-250E	nd	nd	nd	nd	nd
G-250S	nd	nd	nd	nd	nd
G-250W	nd	nd	nd	nd	nd
G-500E	11	nd	nd	tr	nd
G-500W	nd	nd	nd	nd	nd
G-1000E	nd	nd	nd	nd	nd
G-1000W	nd	nd	nd	nd	nd
GMR-0	nd	nd	nd	nd	nd
GMR-250E	nd	nd	nd	nd	nd
GMR-250W	nd	nd	nd	nd	nd
GMR-500W	nd	nd	nd	nd	nd
GM4-0	nd	nd	nd	nd	nd
GM4-4	nd	nd	nd	nd	nd
GM4-12	nd	nd	nd	nd	nd
GM4-36	nd	nd	120	2,300	nd
GM4-108	nd	nd	nd	nd	nd
G1-0	nd	nd	nd	nd	nd
G1-4	nd	nd	nd	nd	nd
G1-12	nd	nd	nd	nd	nd
G1-36	nd	nd	nd	nd	nd
G1-108	nd	nd	nd	nd	nd
GR2-0	nd	nd	nd	nd	nd
GR2-12	nd	nd	nd	nd	nd
GR2-108	nd	nd	nd	nd	nd

Detection Limit = 10 ppb, dry wt.
Detection Limit marsh samples = 15 ppb, dry wt.
tr: trace, below detection limit

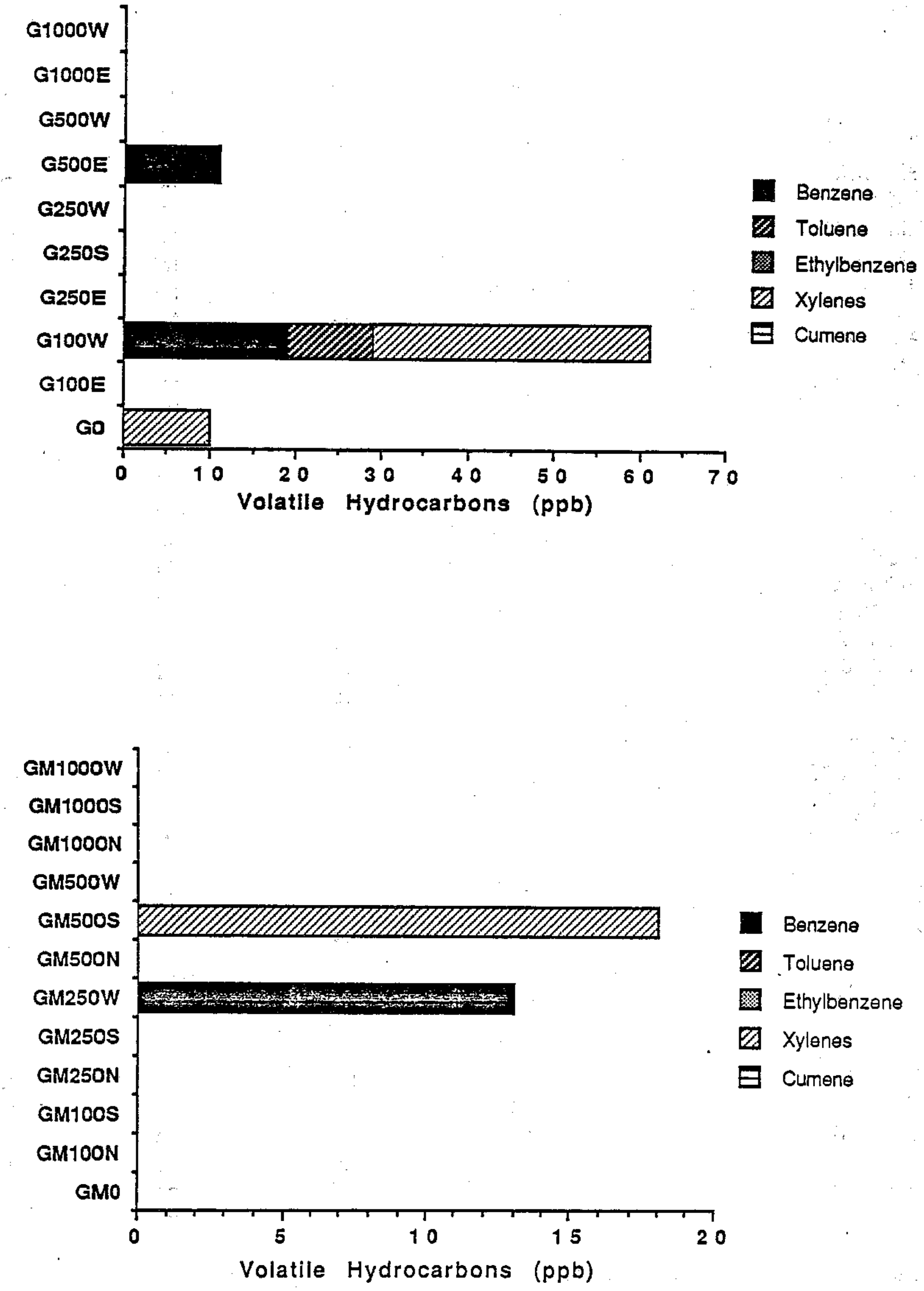


Figure 8.4. Volatile hydrocarbons in interstitial water of Golden Meadow, secondary, above, and primary, below, site sediments.

Table 8.4. Semivolatile hydrocarbon concentrations in Golden Meadow primary discharge site sediments.

ANALYTE	GM	WEST				NORTH					SOUTH			
	0	250	500	1000	1000D	100	250	250D	500	1000	100	250	500	1000
MDL (ppb, dry wt.)	2.5	0.90	1.2	0.71	0.96	2.1	0.96	0.99	0.93	1.3	1.8	1.1	1.4	0.80
Naphthalene	nd	nd	nd	nd	nd	nd	nd	1.4	nd	nd	nd	nd	nd	nd
Acenaphthylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	tr	nd	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd	nd	tr
Fluorene	trc	nd	nd	trc	tr	tr	nd	nd	nd	trc	6.3	trc	nd	tr
Dibenzothiophene	nd	nd	nd	nd	nd	nd	nd	nd	nd	trc	nd	nd	nd	tr
Phenanthrene	16	2.8	2.5	0.99	1.3	6.1	2.0	2.1	1.8	4.1	17	3.8	1.9	4.9
Anthracene	3.9	tr	nd	nd	1.1	tr	tr	nd	tr	trc	5.4	tr	nd	1.1
Fluoranthene	78	7.5	5.1	0.90	1.4	24	3.9	4.3	5.5	9.3	48	16	7.7	10
Pyrene	73	9.6	4.9	1.2	1.3	22	5.3	6.1	8.0	11	44	17	8.3	10
Benzanthracene	25	5.4	4.7	1.2	1.4	14	3.9	4.3	nd	4.7	23	7.7	6.2	4.8
Chrysene	39	8.4	3.9	tr	tr	13	3.1	3.4	8.6	5.6	23	10	5.5	6.2
Benzo(b)fluoranthene	25	2.6	tr	nd	nd	3.1	nd	1.4	nd	3.6	17	15	nd	3.4
Benzo(k)fluoranthene	39	2.8	tr	nd	nd	2.8	nd	nd	nd	tr	16	2.6	nd	1.3
Benzo(a)pyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	7.1	nd	nd	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	na	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Naph	nd	tr	nd	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd	nd
C2-Naph	nd	tr	nd	tr	tr	nd	tr	tr	tr	tr	tr	tr	nd	tr
C3-Naph	9.6	1.4	nd	tr	tr	nd	1.9	2.4	2.9	5.4	83	6.2	tr	1.1
C1-DBT	tr	tr	tr	tr	tr	nd	nd	nd	nd	tr	3.5	tr	nd	1.4
C1-Phen	8	4.6	tr	tr	tr	tr	2.8	2.9	3.8	4.5	25	7.4	tr	5.7
C2-Phen	65	16	3.6	2.3	1.7	16	16	14	20	32	120	36	3.8	18
TOTAL PNA'S	300	39	21	4.3	6.5	85	18	23	24	38	210	72	30	42
TOTAL PNA'S & NDP HOMOLOGS	380	61	25	6.6	8.2	100	39	42	51	80	440	120	33	68

nd: not detected

tr: trace, extracted ion present, but below detection limit

trc: trace confirmed, extracted and confirming ions present, but below detection limit

Table 8.5. Semivolatile hydrocarbon concentrations in Golden Meadow secondary discharge site sediments.

ANALYTE	G	EAST					WEST				SOUTH
	0	100	100(d)	250	500	1000	100	250	500	1000	250
MDL (ppb, dry wt.)	3.6	2.0	2.4	1.7	2.1	2.0	1.6	0.99	0.87	0.95	3.1
Naphthalene	nd	4.0	nd	nd	2.1	4.5	nd	2.5	1.8	2.6	nd
Acenaphthylene	nd	trc	nd	nd	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	12	6.9	3.1	nd	nd	nd	4.7	tr	trc	1.4	nd
Fluorene	21	8.6	7.1	2.0	trc	2.8	3.9	trc	trc	4.7	trc
Dibenzothiophene	11	nd	nd	trc	nd	tr	trc	tr	nd	nd	nd
Phenanthrene	10	7.4	7.1	13	8.3	8.4	83	6.8	7.2	16	8.6
Anthracene	4.1	4.0	tr	2	2.6	tr	6.7	4.3	trc	nd	6.1
Fluoranthene	50	37	40	46	34	35	190	23	10	19	61
Pyrene	45	37	40	41	34	32	130	28	10	28	54
Benzanthracene	18	22	19	15	23	30	30	16	5.5	7.4	31
Chrysene	30	37	28	28	30	35	44	23	5.1	13	46
Benzo(b)fluoranthene	30	16	10	28	8.1	35	81	12	6.2	14	7.9
Benzo(k)fluoranthene	6.6	nd	4.9	11	17	10	nd	7.2	2.3	nd	3.2
Benzo(a)pyrene	nd	nd	7.4	nd	nd	nd	41	7.4	0.95	4.5	nd
Indenopyrene	nd	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd
Dibenzanthracene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd
C1-Naph	tr	trc	nd	nd	tr	tr	tr	tr	nd	1.9	nd
C2-Naph	51	2.8	5.7	nd	tr	tr	tr	tr	nd	1.2	nd
C3-Naph	1200	510	540	nd	2.3	tr	tr	2.8	nd	170	6.1
C1-DBT	24	3.4	12	nd	tr	tr	nd	1.6	nd	8.8	tr
C1-Phen	70	46	41	5.2	6.2	12	20	5.7	tr	60	18
C2-Phen	450	270	340	43	34	84	52	38	1.9	240	140
TOTAL PNA'S	240	180	170	190	160	190	610	130	49	110	220
TOTAL PNA'S & NDP HOMOLOGS	2000	1000	1100	230	200	290	690	180	51	600	380

nd: not detected

tr: trace, extracted ion present, but below detection limit

trc: trace confirmed, extracted and confirming ions present, but below detection limit

Table 8. Semivolatile hydrocarbon concentrations in Golden Meadow reference site sediments.

ANALYTE	GMR 0	EAST 250	WEST 250	500
MDL (ppb, dry wt.)	5.2	5.5	3.2	4.1
Naphthalene	nd	nd	nd	nd
Acenaphthylene	nd	nd	nd	nd
Acenaphthene	tr	tr	nd	nd
Fluorene	tr	trc	trc	trc
Dibenzothiophene	trc	trc	tr	trc
Phenanthrene	11	12	9.7	17
Anthracene	trc	9.5	tr	6.6
Fluoranthene	37	36.0	45	45
Pyrene	36	32	45	41
Benzanthracene	tr	12	28	16
Chrysene	13	29	39	55
Benzo(b)fluoranthene	nd	nd	8.4	nd
Benzo(k)fluoranthene	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	nd	nd
Indenopyrene	nd	nd	nd	nd
Dibenzanthracene	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd
C1-Naph	nd	tr	nd	tr
C2-Naph	nd	tr	nd	tr
C3-Naph	nd	nd	nd	tr
C1-DBT	5.9	10	6.8	7.9
C1-Phen	12	24	8.4	11
C2-Phen	59	43	84	59
TOTAL PNA'S	98	130	180	180
TOTAL PNA'S & NDP HOMOLOGS	150	180	220	230

nd: not detected
tr: trace, extracted ion present, but below detection limit
trc: trace confirmed, extracted and confirming ions present, but below detection limit

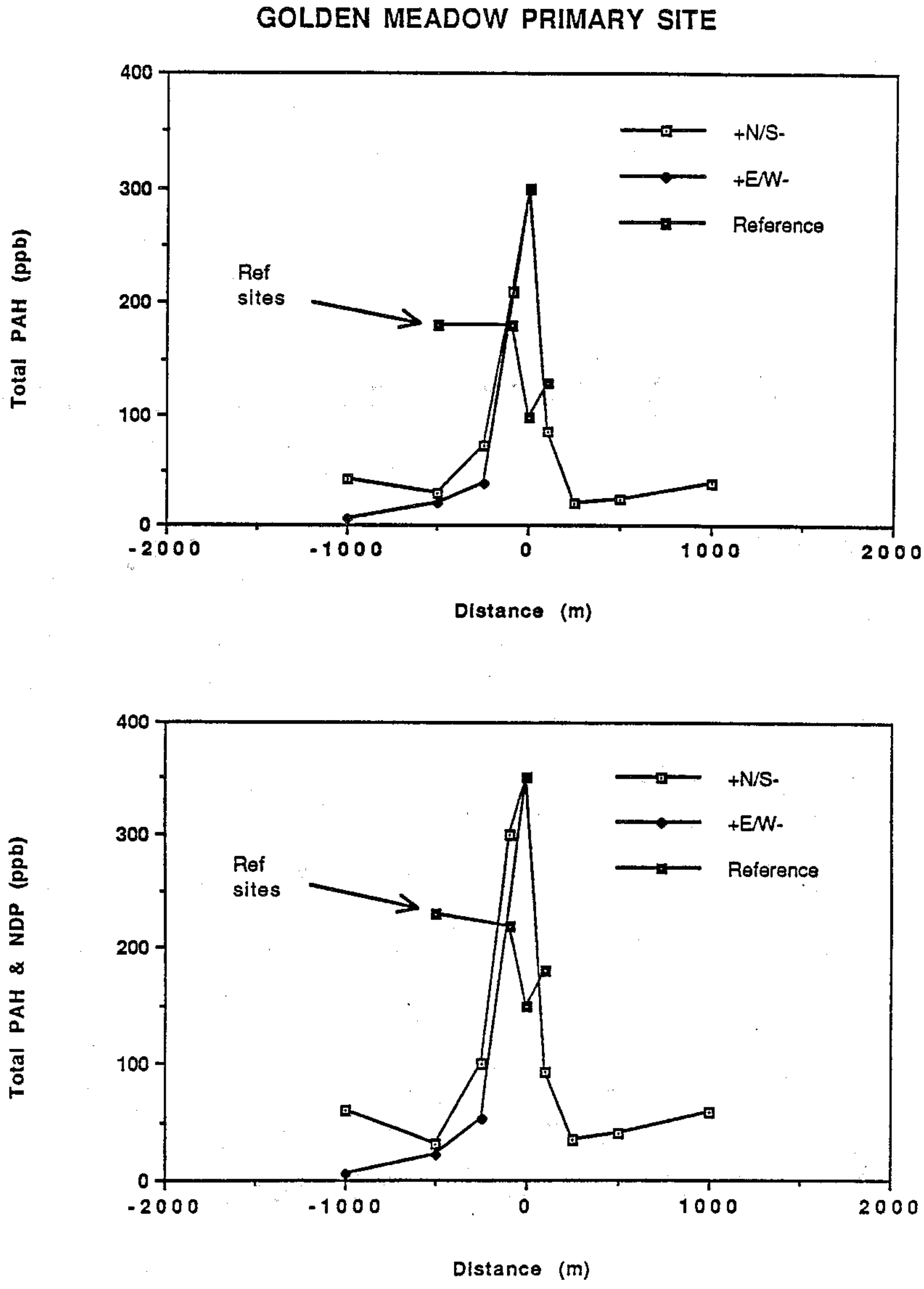


Figure 8.5. Spatial distribution of normal PAH, above, and total normal and alkylated PAH, below, in Golden Meadow primary site and reference sediments.

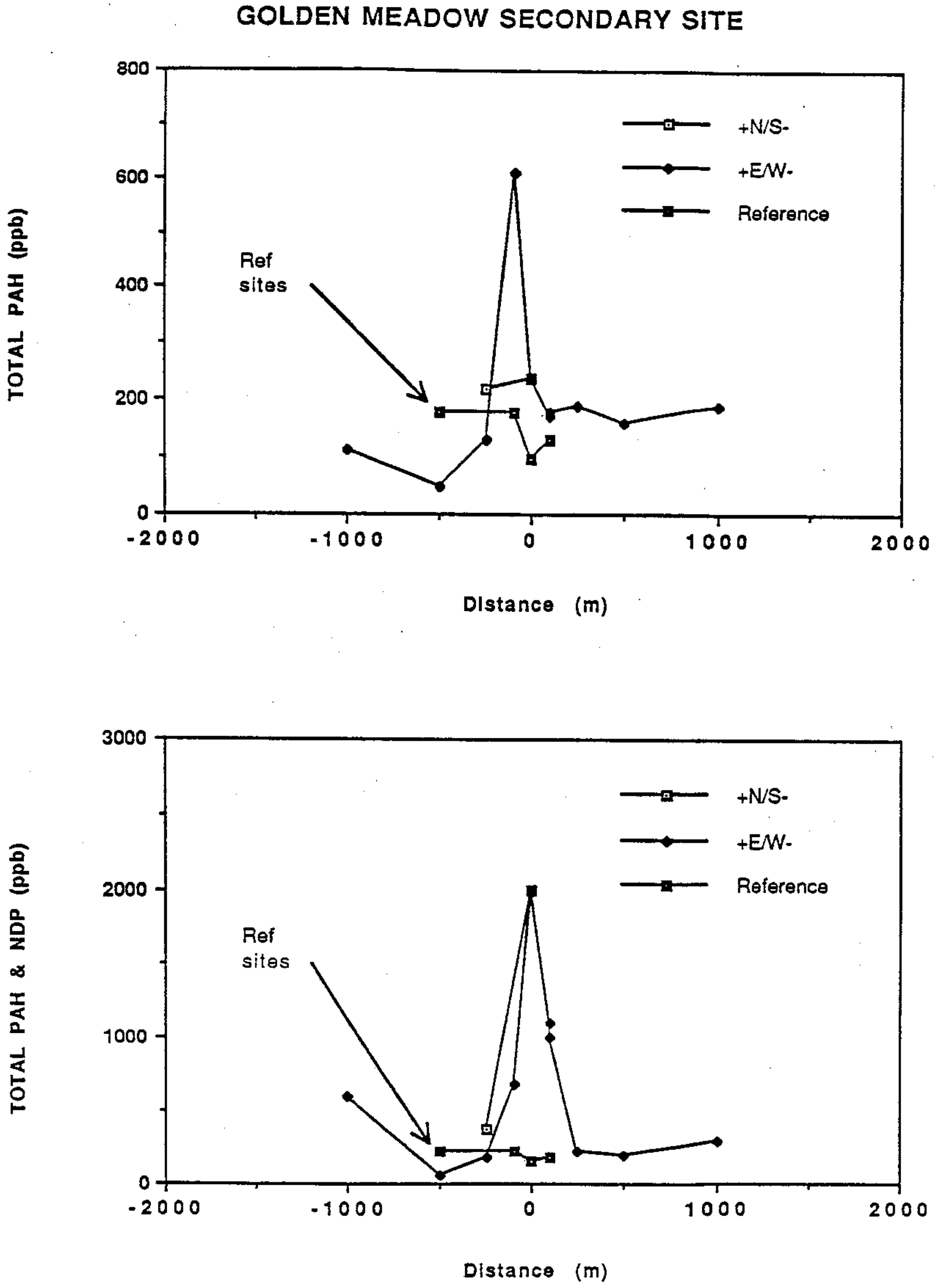
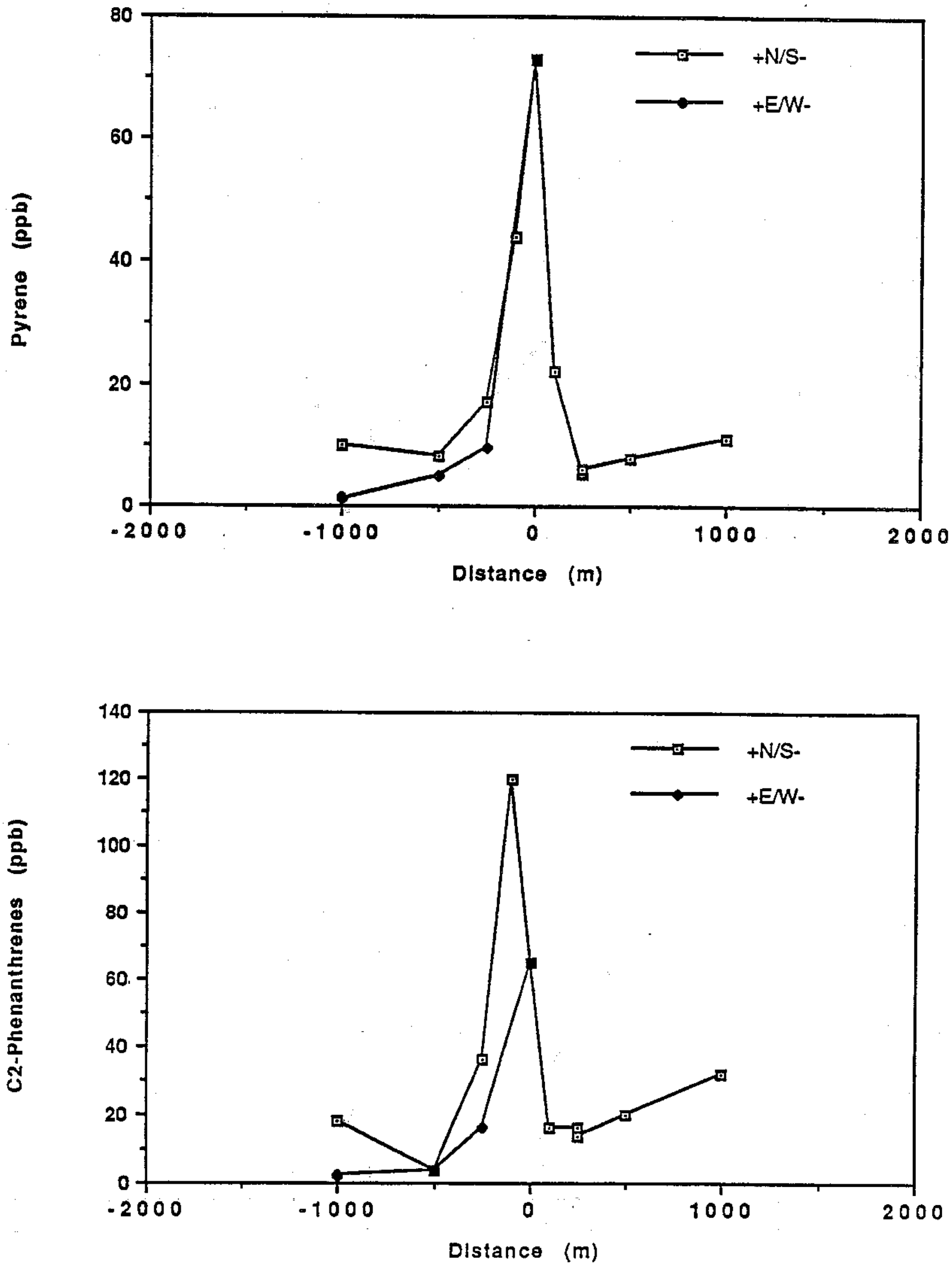


Figure 8.6. Spatial distribution of normal PAH, above, and total normal and alkylated PAH, below, in Golden Meadow secondary site sediments.



GOLDEN MEADOW PRIMARY SITE

Figure 8.7. Spatial distribution of pyrene, above, and C-2 phenanthrenes in Golden Meadow primary site sediments.

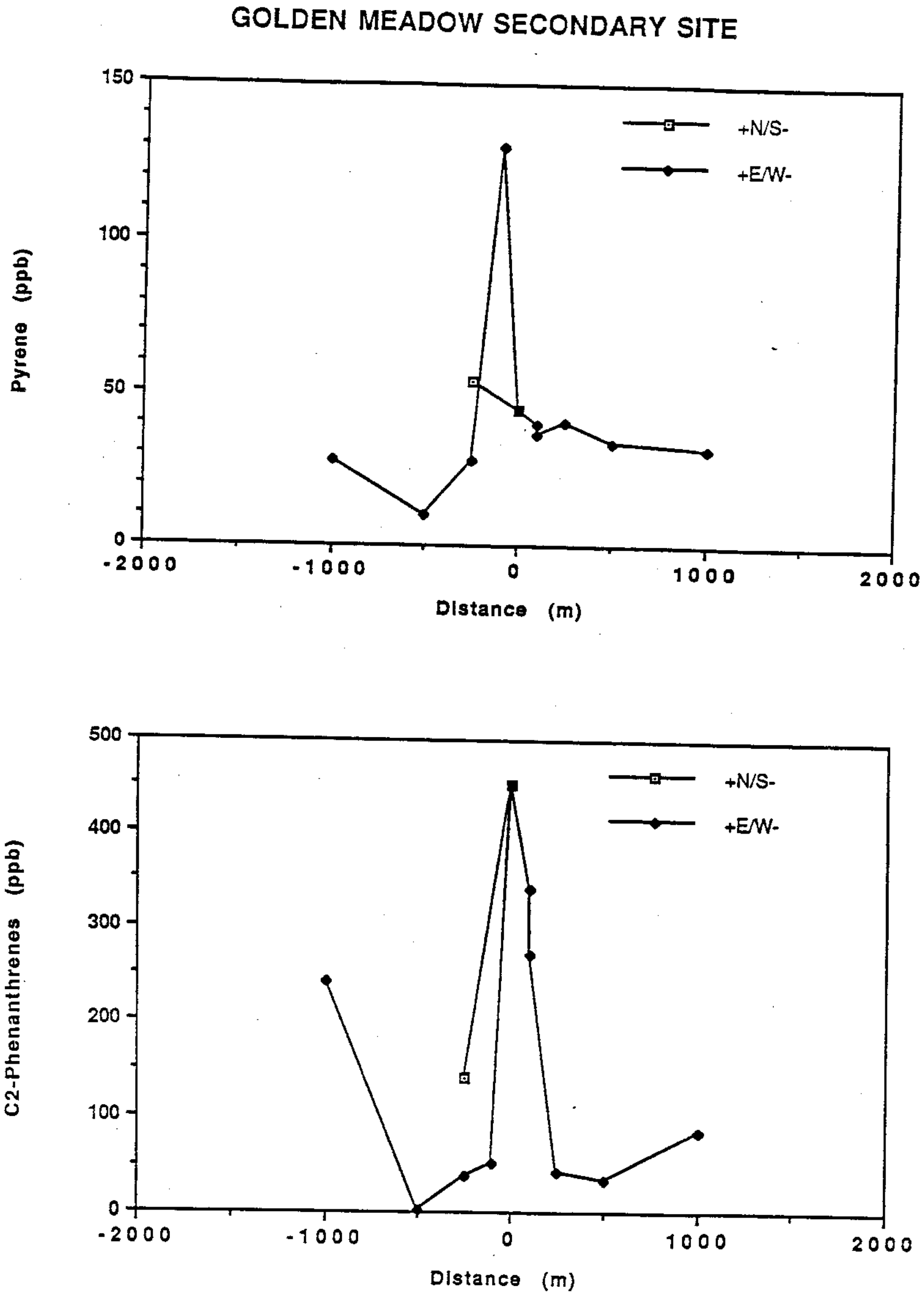


Figure 8.8. Spatial distribution of pyrene, above, and C-2 phenanthrenes, below, in Golden Meadow secondary site sediments.

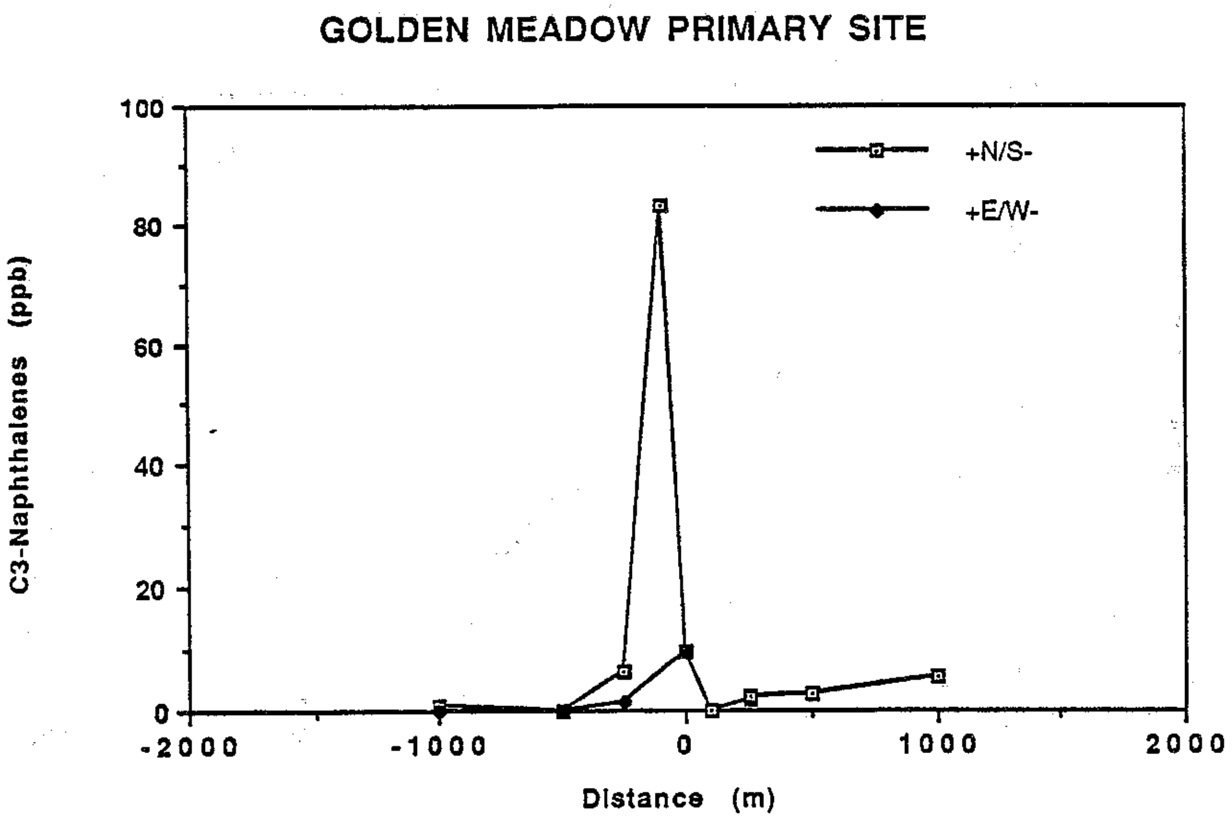


Figure 8.9. Spatial distribution of C-3 naphthalenes in Golden Meadow primary site sediments.

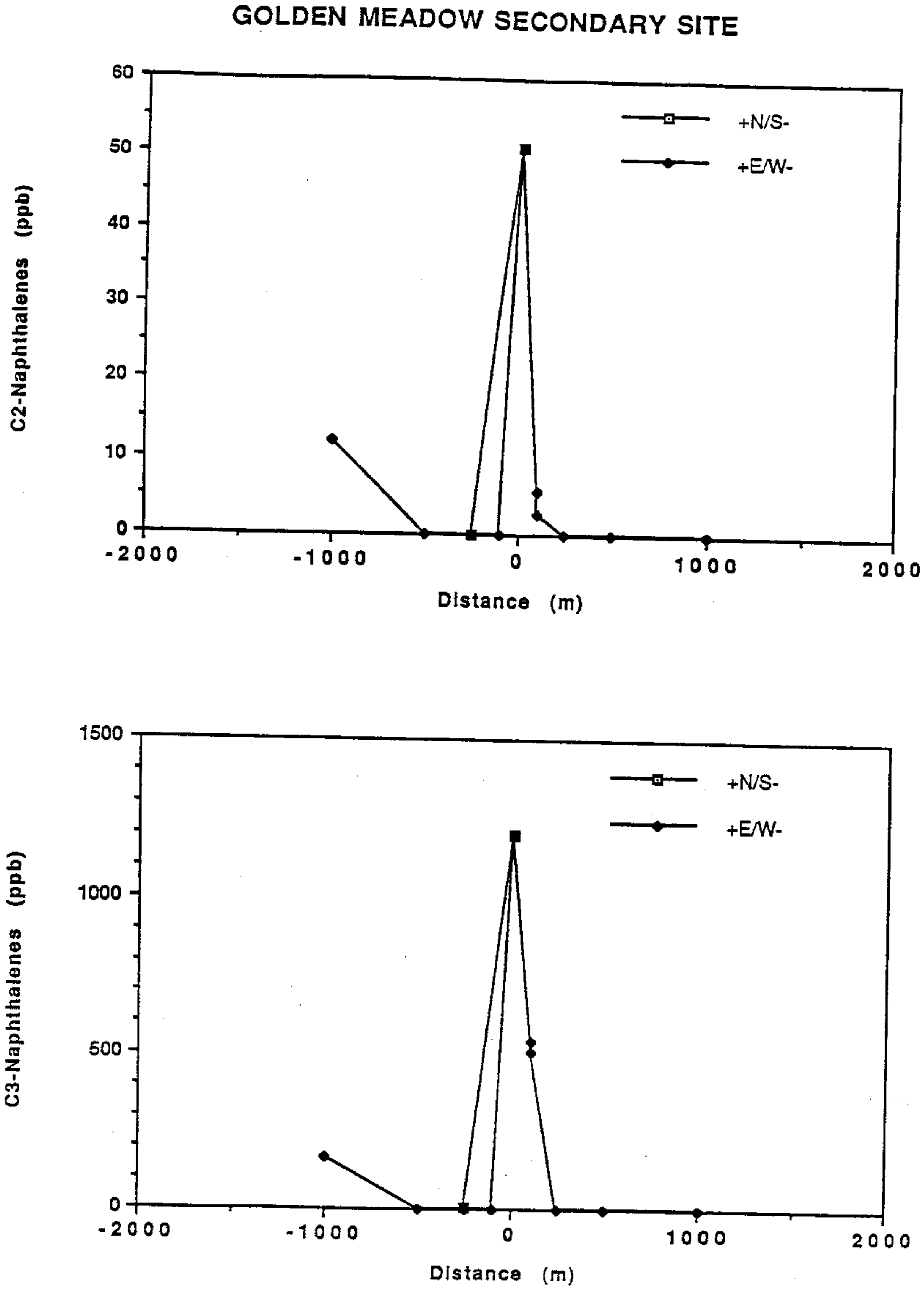


Figure 8.10. Spatial distribution of C-2 naphthalenes, above, and C-3 naphthalenes, below, in Golden Meadow secondary site sediments.

much as 80%). The concentrations of PAH at the reference site were low relative to the total PAH observed within 250 m the secondary discharge site.

Figures 8.7B and 8.8B show the distributions C-2 phenanthrenes near the primary and secondary sites, while Figures 8.9 and 8.10 show the spatial distributions of C-2 naphthalenes and C-3 naphthalenes, respectively, near the primary and secondary sites. Each of these compound groups were major components of the sediment extracts and exhibited the same general concentration patterns with a maximum at GM0 or G0, and a sharp decline away from those sites in all directions, except for the C-2 naphthalenes, which were not detected at the primary discharge site. Each of the compound groups, as well as the total aromatics, showed a secondary maximum at the 1000N site adjacent to the primary discharge. This suggests that this region may be a depositional zone for hydrocarbons discharged at this site.

Aliphatic hydrocarbons were distributed in a similar pattern to the aromatics in the vicinity of the Golden Meadow primary discharge (Table 8.7). Figure 8.11 shows the spatial distribution of aliphatic hydrocarbons around the Texaco primary discharge as well as the distribution at the reference site. The pattern of hydrocarbon concentrations in sediments around the discharge is very similar to that for the more soluble aromatic compounds. A maximum of 110,000 ppb was observed at the GM0 site, however, values decreased to 20,000 ppb or less within 100 m of the discharge point. The concentrations of aliphatic hydrocarbons at the reference sites ranged from 22,000 to just under 60,000 ppb. The minimum value was observed at GMR0. At the secondary site, aliphatic hydrocarbons were detected at concentrations as high as 400,000 ppb at G0 (Figure 8.12). Hydrocarbon concentrations declined rapidly to levels below 50,000 ppb within 250 m of the discharge point. When these values were compared to those at the reference site, it is clear that aliphatic hydrocarbons were enriched by nearly a factor of ten at the G0 site. Examples of aliphatic hydrocarbon chromatograms at each Golden Meadow site are presented in Figure 8.13.

Examination of the hydrocarbon data from the marsh sediments collected along the transects into the Golden Meadow marsh adjacent to the primary discharge, adjacent to the secondary site, and at the reference site provided an inconsistent picture (Table 8.8). These data show that normal PAH are found at relatively low and constant (23-100 ppb) concentrations in the reference marsh sediments but are much higher (190 ppb) near the margins of the marsh adjacent to the discharge, increase to a maximum 5,600 ppb at 36 m into the marsh and then decline to nondetectable 108 m into the marsh. When the petrogenic alkylated and heterocyclic PAH are included, the trend becomes even more pronounced. At the margin of the marsh, alkylated and heterocyclic PAH were ~60% of the total of 510 ppb but at 36 m they represented over 80% of the total aromatics in these sediments. It should be noted that none of the petrogenic alkylated or heterocyclic PAH were found in the reference marsh. This showed a clear pattern of contamination extending well into the marsh at this location. At the secondary discharge marsh transect the petrogenic alkylated and heterocyclic PAH contributed less than 15% of the total aromatics suggested that petroleum-related discharges were primary or recent source.

Aliphatic hydrocarbons in the marsh sediments show a similar pattern (Table 8.7). Relatively low concentrations of hydrocarbons were observed in the reference marsh sediments, while much higher concentrations were seen in marsh sediments adjacent to both the primary and secondary discharges. In the case of the primary site, concentrations ranged from 100,000 to 200,000 ppb at the edge of the marsh to a maximum of 5-8 million ppb at the 36 m point in the marsh and then declined to levels comparable to reference sediments at the 108 m site (~6,000 ppb). These data together with the aromatic hydrocarbon data suggest that a large discharge of petroleum materials impacted an area 36 m into the primary site marsh. It is unknown whether this was the result of produced water discharges into the marsh, leakage from facilities or an oil spill.

Table 8.7. Saturated hydrocarbon concentrations in Golden Meadow sediments.

GOLDEN MEADOW PRIMARY SITE (GM)				
Distance (meters)	Resolved (ppb)	Unresolved (ppb)	TOTAL (ppb)	Resolved/ Total
0	8,800	79,000	88,000	0.10
NORTH				
100	8,800	62,000	71,000	0.12
250	3,250	17,500	21,000	0.16
500	2,500	16,000	18,000	0.14
1000	2,000	15,000	17,000	0.12
WEST				
250	3,700	19,000	23,000	0.16
500	2,400	7,800	10,000	0.24
1000	1,800	1,270	3,100	0.59
SOUTH				
100	8,300	100,000	110,000	0.08
250	4,500	27,000	32,000	0.14
500	2,700	7,300	10,000	0.27
1000	1,600	12,000	14,000	0.12
GOLDEN MEADOW SECONDARY SITE (G)				
0	34,000	380,000	420,000	0.08
EAST				
100	15,500	185,000	200,000	0.08
250	5,400	43,000	49,000	0.11
500	4,600	31,000	35,000	0.13
1000	9,000	54,000	63,000	0.14
WEST				
100	7,100	62,000	69,000	0.10
250	4,600	36,000	40,000	0.11
500	2,500	7,300	9,800	0.26
1000	12,000	88,000	100,000	0.12
SOUTH				
250	10,000	140,000	150,000	0.07

REFERENCE SITE				
Distance (meters)	Resolved (ppb)	Unresolved (ppb)	TOTAL (ppb)	Resolved/ Total
0	1,700	24,000	25,000	0.07
EAST				
250	12,000	47,000	59,000	0.20
SOUTH	WEST			
250	5,400	46,000	52,000	0.11
500	6,800	41,000	47,000	0.14
MARSH SITES				
GM4				
0	14,000	300,000	320,000	0.04
4	3,300	70,000	73,000	0.05
12	4,200	120,000	130,000	0.03
36	485,000	5,900,000	6,350,000	0.08
108	6,400	nd	6,400	1.00
G1				
0	24,000	510,000	540,000	0.04
4	17,000	340,000	360,000	0.05
12	11,000	150,000	170,000	0.07
36	14,000	120,000	130,000	0.10
108	6,000	94,000	100,000	0.06
GR2				
0	3,700	13,000	17,000	0.22
12	2,500	4,900	7,400	0.34
106	970	5,300	6,300	0.15

Resolved/Total = ppm resolved / (ppm resolved + ppm unresolved)
nd: not detected

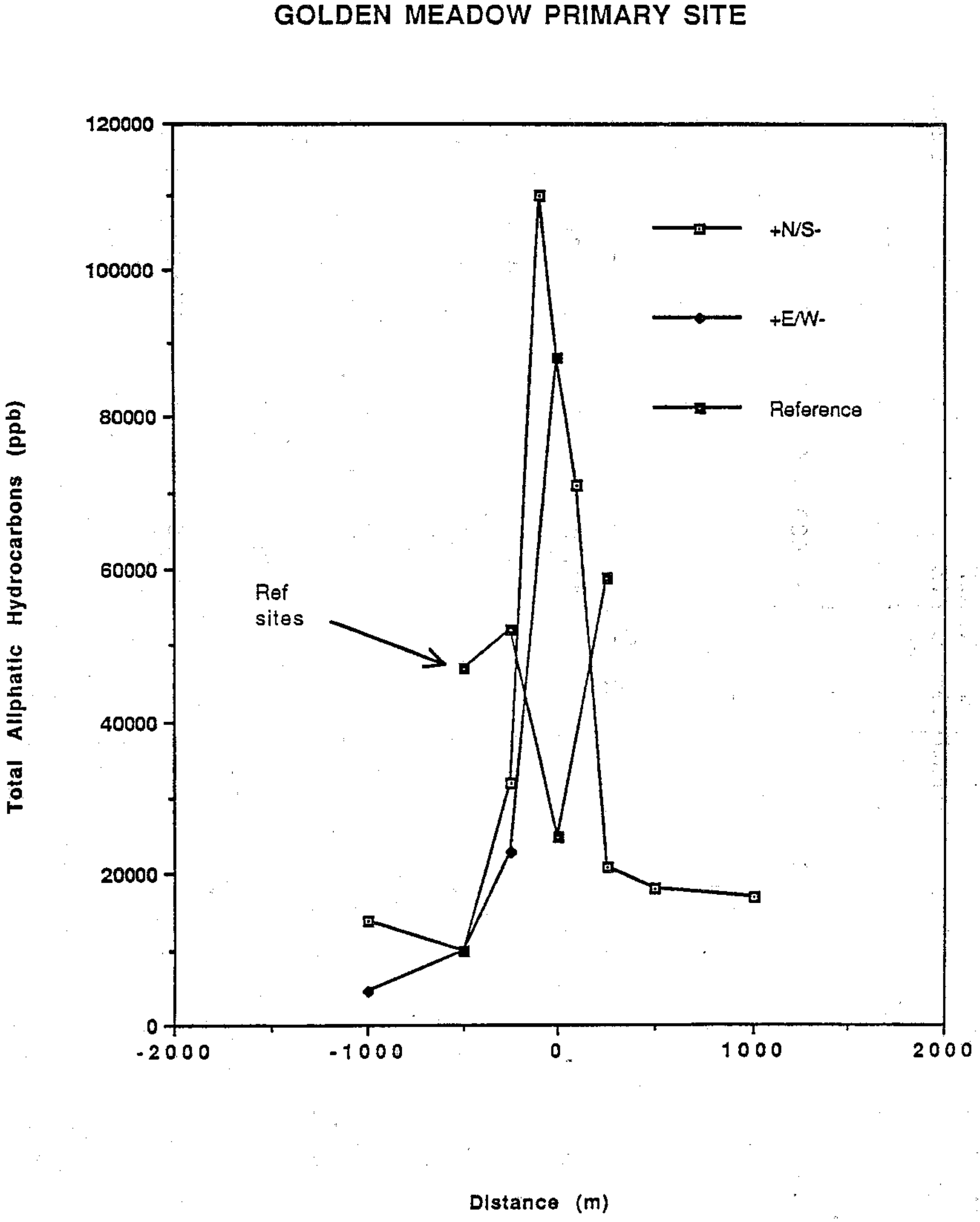


Figure 8.11. Spatial distribution of aliphatic hydrocarbons in Golden Meadow primary site sediments.

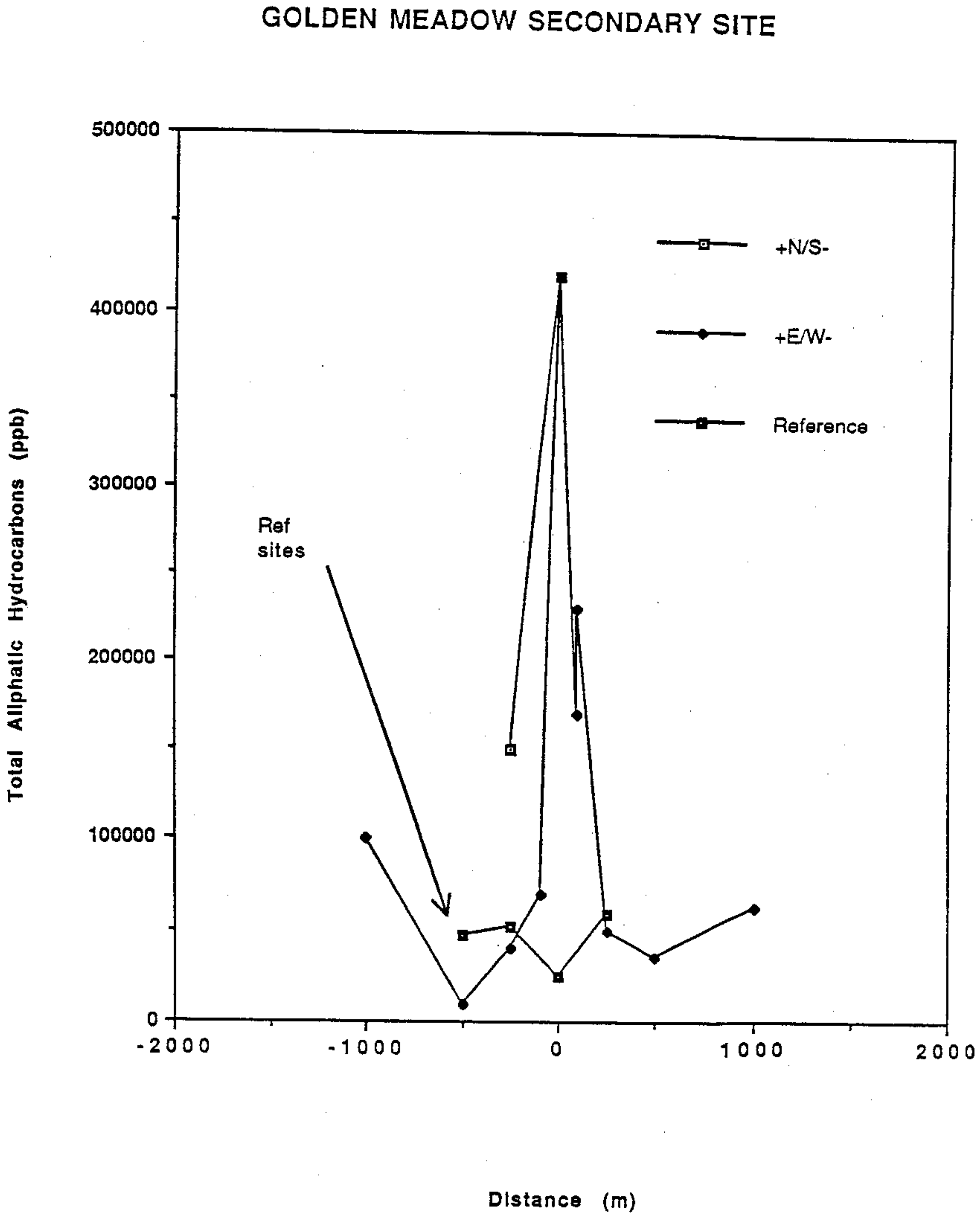


Figure 8.12. Spatial distribution of aliphatic hydrocarbons in Golden Meadow secondary site sediments.

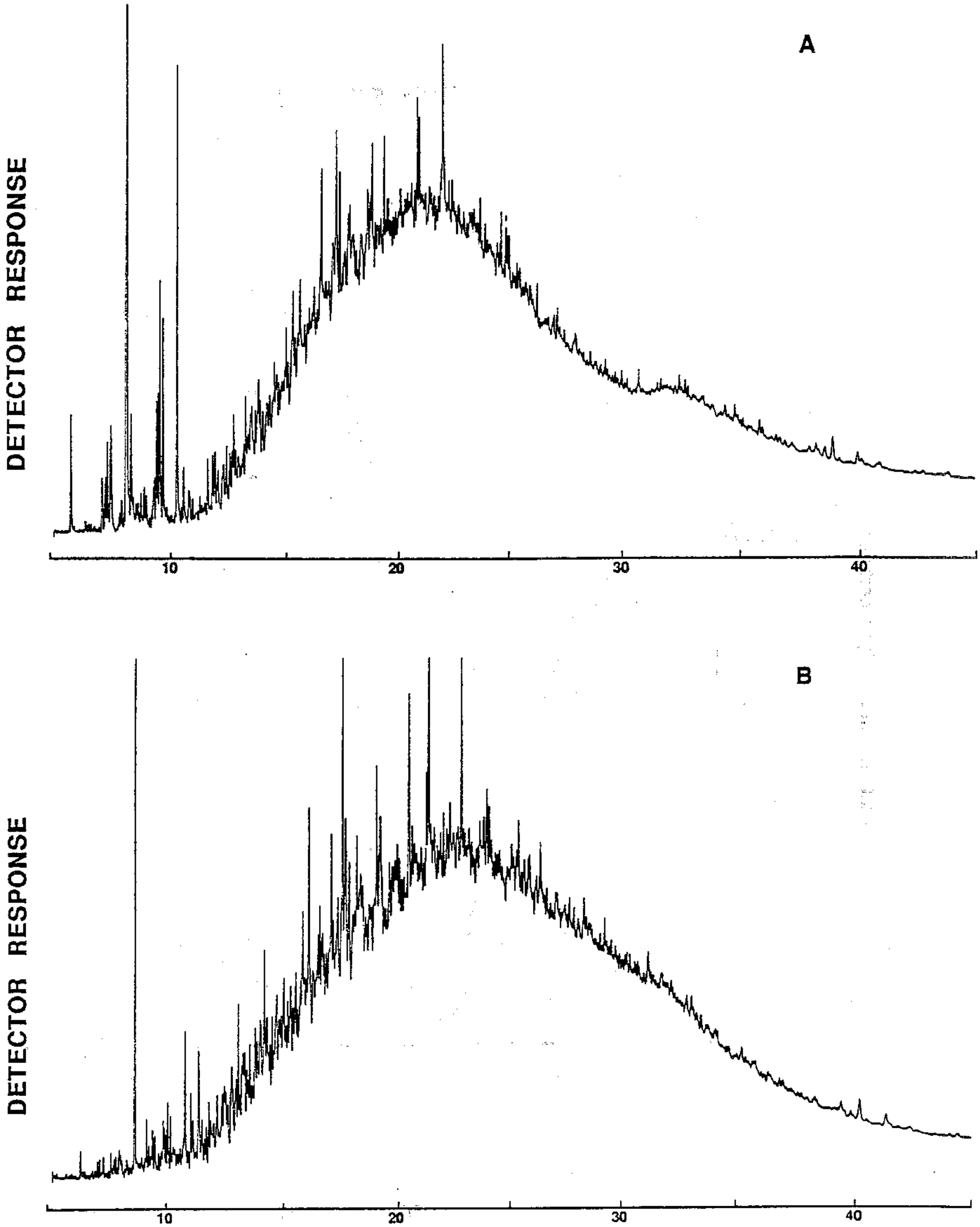


Figure 8.13. Chromatograms of the saturated hydrocarbon fraction (F-1) for sample stations: a) GM0 (Golden Meadow primary site) and B) G0 (secondary site).

Table 8.8. Semivolatile hydrocarbon concentrations in Golden Meadow marsh sediments.

ANALYTE	G1					GR2			GM4					
	0	4	12	36	108	0	12	108	0	4	12	36	36(d)	108
MDL (ppb, dry wt.)	31	45	6.7	10	8.3	1.9	2.6	2.5	5.7	6.8	13	190	48	19
Naphthalene	nd	nd	nd	nd	18	8.9	nd	4.8	nd	nd	nd	tr	160	nd
Acenaphthylene	nd	nd	nd	nd	nd	nd	tr	nd	nd	nd	nd	nd	nd	nd
Acenaphthene	nd	nd	370	trc	nd	nd	nd	nd	tr	trc	nd	890	600	nd
Fluorene	nd	nd	55	trc	trc	nd	nd	nd	9.0	trc	nd	nd	nd	nd
Dibenzothiophene	nd	nd	52	nd	tr	tr	nd	nd	trc	nd	nd	nd	nd	nd
Phenanthrene	35	55	410	17	19	11	11	3.0	20	15	19	nd	nd	tr
Anthracene	nd	tr	670	tr	tr	tr	tr	nd	tr	trc	nd	nd	320	nd
Fluoranthene	180	310	4500	120	80	20	9.0	5.8	38	48	38	nd	nd	tr
Pyrene	370	410	3100	130	150	17	6.1	4.2	35	35	33	960	nd	tr
Benzanthracene	nd	240	1200	61	46	19	4.5	2.7	19	18	19	nd	nd	nd
Chrysene	470	710	1200	160	210	20	4.5	2.7	71	44	43	3700	2500	nd
Benzo(b)fluorant.	nd	nd	3500	130	120	6.8	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(k)fluorant.	nd	nd	nd	72	120	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzo(a)pyrene	nd	nd	1200	nd	nd	tr	nd	nd	nd	nd	nd	nd	nd	nd
Indenopyrene	nd	nd	470	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dibenzanthracene	nd	na	tr	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	360	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C1-Naph	nd	nd	tr	nd	tr	tr	nd	tr	nd	nd	nd	tr	130	nd
C2-Naph	nd	nd	tr	nd	nd	tr	nd	nd	tr	nd	nd	tr	870	nd
C3-Naph	nd	nd	54	nd	nd	nd	nd	nd	120	nd	nd	27000	22000	nd
C1-DBT	nd	nd	32	tr	tr	tr	nd	nd	18	nd	nd	nd	250	nd
C1-Phen	nd	nd	660	tr	9.1	tr	nd	nd	14	tr	tr	nd	nd	nd
C2-Phen	220	140	420	100	210	61	nd	nd	170	13	25	1500	2800	nd
TOTAL PNA'S	1100	1700	17000	690	760	100	35	23	190	160	150	5600	3600	nd
TOTAL PNA'S & NDP HOMOLOGS	1300	1900	18000	790	980	110	35	23	510	170	180	34000	30000	nd

nd: not detected

tr: trace, extracted ion present, but below detection limit

trc: trace confirmed, extracted and confirming ions present, but below detection limit

8.2.2 Bivalve Tissues

Samples of oysters, *Crassostrea virginica*, and mussels, *Geukensia demissa*, were collected near the two discharge sites in the Golden Meadow system and at the reference site. Analyses of these tissue samples for aliphatic and normal, alkylated and heterocyclic PAH yielded some limited information on the bioaccumulation potential of some of the PAH discharged into the system. Tables 8.9 and 8.10 present a summary of the data for mussels and oysters, respectively. Both aliphatic and aromatic hydrocarbons were found to accumulate in mussels near both the primary and secondary discharge sites and to a lesser degree at the reference site. Figure 8.14 shows the relative accumulations of PAH and total PAH and total aromatic in mussels. At the reference site, all of the PAH (26 ppb) accumulated were normal pyrogenic PAH. Fluorene and chrysene were the two most abundant compounds accumulated. At the secondary discharge site, normal PAH including fluorene, pyrene, phenanthrene, fluoranthene, benzanthracene, and chrysene were accumulated along with some C-2 phenanthrenes to a total of 180-220 ppb. At the TB8 site, mussels accumulated a more extensive suite of PAH including benzo(a)pyrene, benzofluoranthenes and C-1 and C-2 phenanthrenes to a total of 430 ppb. Total aliphatic hydrocarbons (Figure 8.15) accumulated to concentrations of 12,000 ppb, 41,000-47,000 ppb and 45,000 ppb in mussels at the reference, TB7 and TB8 sites, respectively.

Table 8.10 summarizes the bioaccumulation data for oysters. Figure 8.16 shows the relative amounts of PAH accumulated in oyster tissues. PAH in reference site oyster were very low (5 ppb) or at trace levels. Phenanthrene was the only compound detected and was barely above detection limits. At the TB7 site, oysters accumulated 53 ppb of normal PAH, including fluoranthene, pyrene, phenanthrene, chrysene, benzanthracene and benzofluoranthenes. In addition, a broad spectrum of petrogenic alkylated PAH was accumulated to a total of 110 ppb. Oysters at the TB8 site accumulated approximately twice the amounts of both normal and alkylated PAH. Aliphatic hydrocarbons were also accumulated to significant levels in oysters. Figure 8.17 shows the levels of aliphatic hydrocarbons at the reference and discharge sites. At the reference site hydrocarbons totaled 8,000 to 15,000 ppb, while at the primary and secondary discharges the levels were 67,000 ppb and 62,000 ppb, respectively.

Both organisms showed the ability to accumulate hydrocarbons from the surrounding environment. If it can be assumed that the two species were exposed to similar amounts of contaminants, then some conclusions can be drawn concerning their relative bioaccumulation potential. In general, oysters accumulated less aromatic hydrocarbons, but more of the aliphatic hydrocarbons from the environment (when the data are reported on a wet weight basis) than did mussels exposed in the same environments. These differences may be due to different lipid contents in the organism, different abilities to metabolize accumulated residues, or different sources of the contaminants (e.g., water, sediment, food).

8.3 Trace and Major Elements

8.3.1 Sediments

As with Bayou Sale sediments, the concentrations of all elements were normalized to the abundant element aluminum. Tables 8.11 through 8.13 present a summary of all of the data for trace and major elements determined in primary and secondary discharge site sediments and the reference site sediments, respectively. Barium (Figure 8.18) was highly enriched at the secondary discharge point and highly enriched at several of the primary stations as far as 1000 m away from the discharge. However, some sediment samples at intermediate distances (e.g., 100N and 500N) appeared to have "normal" concentrations of this element. These data suggest that there are depositional and non-depositional zones within the bayou system for this soluble

Table 8.9. Semivolatile hydrocarbon concentrations in Golden Meadow mussels.

ANALYTE	GM Mussels Ref	GM Mussels TB#7	GM Mussels TB#7 (Dup)	GM Mussels TB#8
MDL (µg/g, wet wt.)	5.9	4.4	4.0	4.7
Naphthalene	nd	nd	nd	nd
Acenaphthylene	tr	nd	nd	nd
Acenaphthene	trc	tr	nd	tr
Fluorene	5.9	trc	trc	trc
Dibenzothiophene	nd	tr	tr	tr
Phenanthrene	11	6.7	6.8	31
Anthracene	tr	nd	nd	tr
Fluoranthene	tr	12	16	60
Pyrene	tr	29	43	83
Benzanthracene	tr	18	11	34
Chrysene	9.1	41	32	60
Benzo(b)fluoranthene	tr	tr	tr	27
Benzo(k)fluoranthene	tr	tr	tr	51
Benzo(a)pyrene	nd	nd	nd	5.2
Indenopyrene	nd	nd	nd	nd
Dibenzanthracene	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd
C1-Naph	tr	tr	tr	tr
C2-Naph	nd	nd	nd	tr
C3-Naph	nd	tr	nd	nd
C1-DBT	nd	tr	tr	tr
C1-Phen	tr	tr	tr	14
C2-Phen	tr	74	110	68
TOTAL PNA'S	26	110	110	350
TOTAL PNA'S & NDP HOMOLOGS, ppb wet	26	180	220	430
TOTAL SATURATED HC	12,000	41,000	67,000	45,000
TOTAL RESOLVED HC	2,100	1,900	4,200	4,300
TOTAL UNRESOLVED HC	10,000	39,000	63,000	41,000

nd: not detected
tr: trace, extracted ion present, but below detection limit
trc: trace confirmed, extracted and confirming ions present, but below detection limit

Table 6.10. Semivolatile hydrocarbons concentrations in Golden Meadow oysters.

ANALYTE	GM Oysters Ref	GM Oysters Ref (Dup)	GM Oysters TB#7	GM Oysters TB#8	GM Oysters TB#8 (Dup)
MDL (µg/g, wet wt.)	4.5	4.6	1.4	4.1	4.4
Naphthalene	nd	nd	nd	nd	nd
Acenaphthylene	nd	nd	tr	nd	nd
Acenaphthene	nd	nd	2.4	tr	nd
Fluorene	nd	nd	3	trc	trc
Dibenzothiophene	nd	nd	tr	tr	trc
Phenanthrene	5.2	tr	9.3	17	16
Anthracene	nd	nd	tr	tr	tr
Fluoranthene	tr	tr	8.1	36	38
Pyrene	trc	tr	9.0	28	31
Benzanthracene	nd	nd	5.0	7.6	8.1
Chrysene	nd	nd	6.0	19	17
Benzo(b)fluoranthene	nd	nd	3.9	8.9	7.3
Benzo(k)fluoranthene	nd	nd	6.1	9.9	4.4
Benzo(a)pyrene	nd	nd	nd	nd	nd
Indenopyrene	nd	nd	nd	nd	nd
Dibenzanthracene	nd	nd	nd	nd	nd
Benzoperylene	nd	nd	nd	nd	nd
C1-Naph	tr	tr	7.7	tr	tr
C2-Naph	nd	nd	1.5	nd	nd
C3-Naph	nd	nd	7.4	nd	nd
C1-DBT	nd	nd	1.9	tr	tr
C1-Phen	nd	nd	2.1	9.3	trc
C2-Phen	nd	nd	36	86	85
TOTAL PNA'S	5.2	tr	53	130	120
TOTAL PNA'S & NDP HOMOLOGS, ppb wet	5.2	tr	110	220	210
TOTAL SATURATED HC	15,000	8,600	62,000	n/a	67,000
TOTAL RESOLVED HC	1,000	230	3,600	n/a	4,400
TOTAL UNRESOLVED HC	14,000	8,400	58,000	n/a	63,000

nd: not detected
tr: trace, extracted ion present, but below detection limit
trc: trace confirmed, extracted and confirming ions present, but below detection limit
n/a: not analyzed

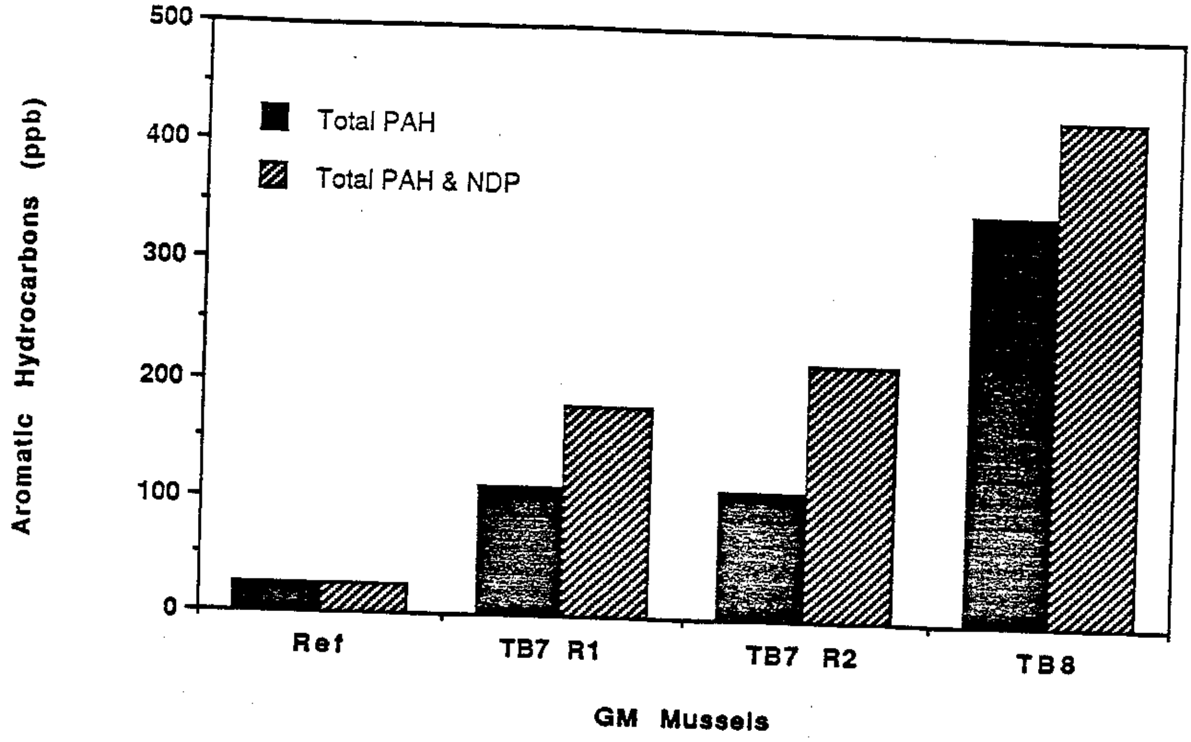


Figure 8.14. Normal PAH and total normal and alkylated PAH in Golden Meadow mussels.

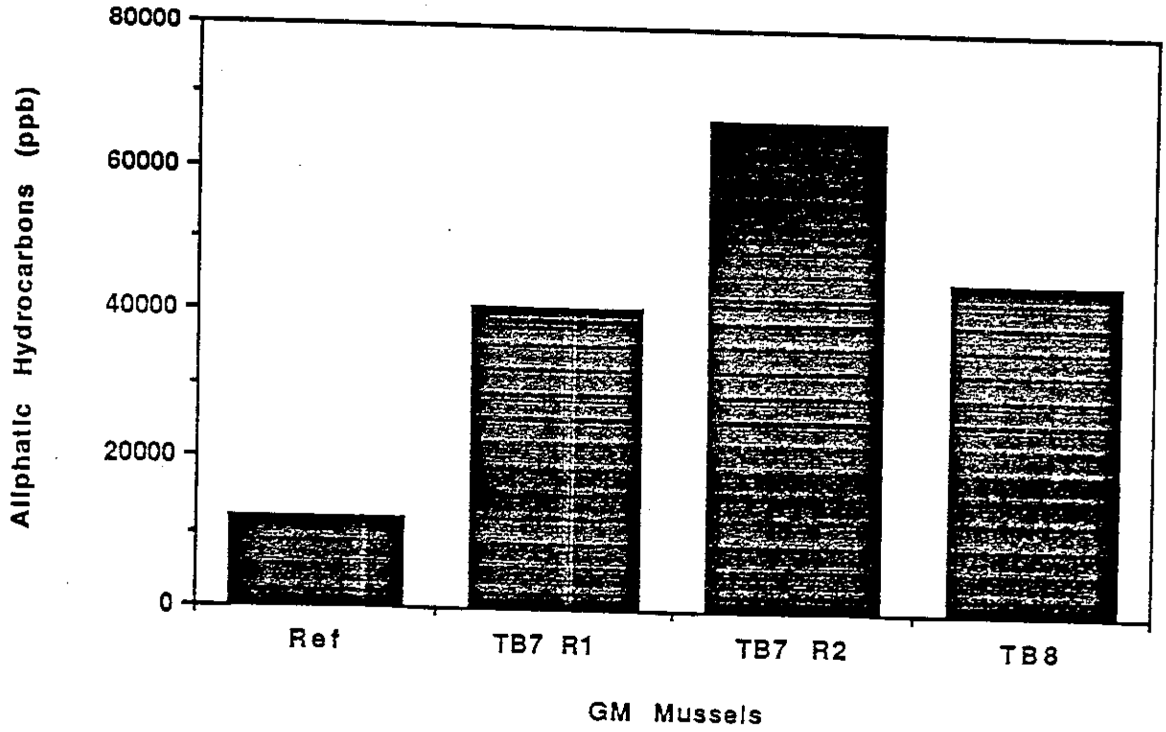


Figure 8.15. Total aliphatic hydrocarbons in Golden Meadow mussels.

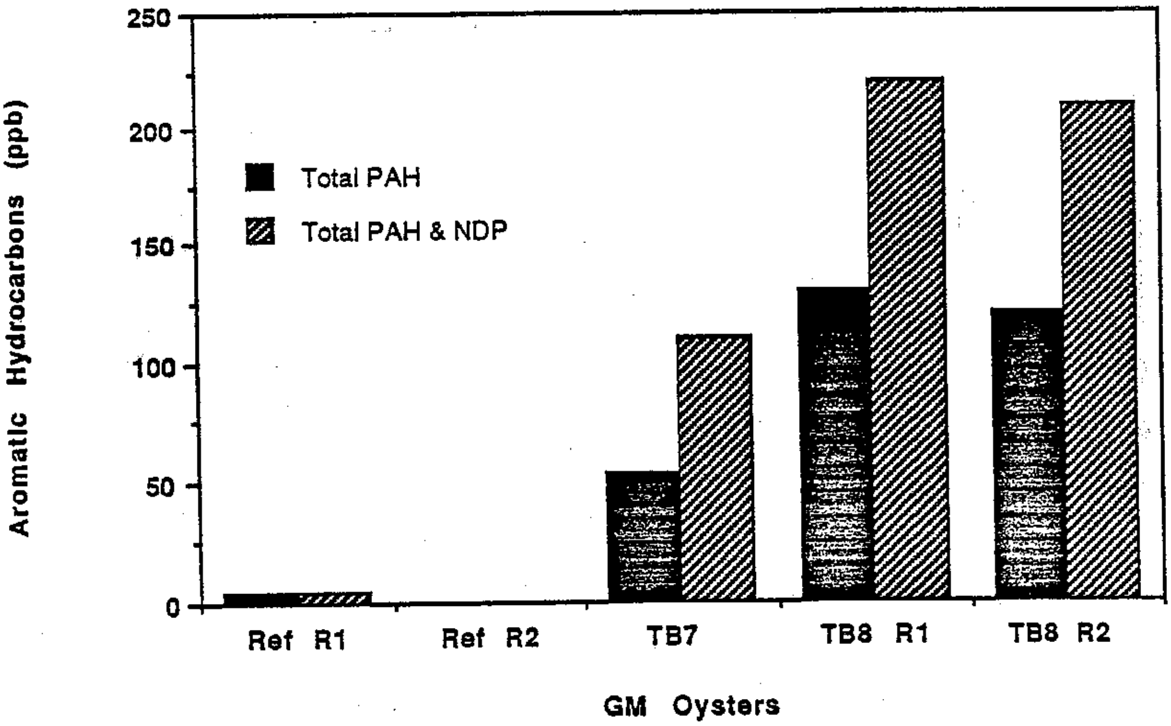


Figure 8.16. Normal PAH and total normal and alkylated PAH in Golden Meadow oysters.

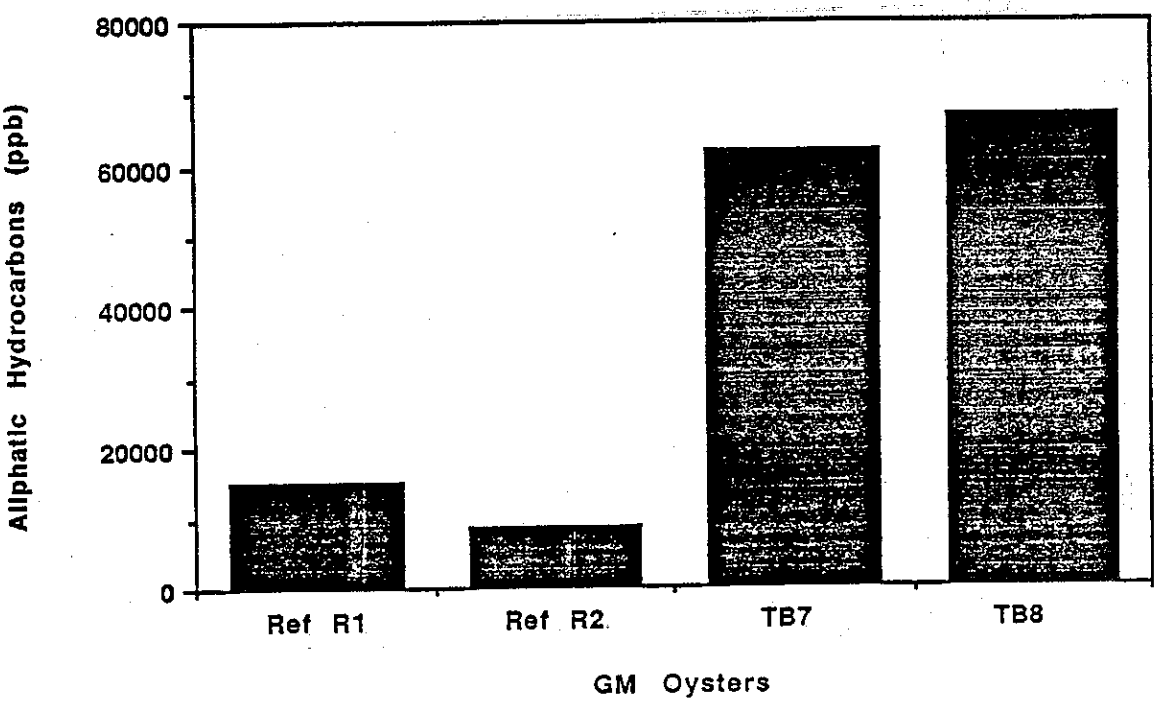


Figure 8.17. Total aliphatic hydrocarbons in Golden Meadow oysters.

Table 8.11. Trace and major elements in Golden Meadow primary discharge site sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Golden Meadow Primary Site												
GM-0	17	nd	nd	141	56	21	19,797	267	48,721	14,519	605	81
GM-100N	18	15	nd	107	323	17	16,758	140	50,203	13,194	428	64
GM-100N (dup)	15	nd	nd	58	43	16	13,810	141	25,905	9,142	90	74
GM-100S	22	nd	nd	143	60	24	22,007	310	32,006	10,851	648	105
GM-250N	8.8	nd	nd	141	45	17	14,563	202	41,189	12,935	560	63
GM-250S	15	nd	nd	146	53	20	15,208	307	43,141	13,717	555	75
GM-250W	13	nd	nd	149	58	21	17,106	285	42,149	13,989	676	80
GM-500N	12	nd	nd	145	49	19	14,552	151	25,949	10,243	380	64
GM-500S	18	nd	nd	147	58	21	20,164	321	49,408	15,419	503	78
GM-500W	7.7	nd	nd	142	37	15	11,107	233	27,405	10,102	461	47
GM-1000N	12	nd	nd	143	48	18	14,218	172	33,876	10,731	467	65
GM-1000S	11	nd	nd	144	49	17	15,989	209	43,876	14,129	586	69
GM-1000W	6.2	nd	nd	149	39	20	13,164	230	32,491	12,117	546	51

nd: not detected
n/a: not available

Table 8.12. Trace and major elements in Golden Meadow secondary discharge site sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Golden Meadow Secondary Site												
G-0	20	4.0	nd	162	70	25	20,272	291	48,975	14,893	1,191	93
G-100E	26	0.19	nd	162	77	28	22,900	311	50,937	16,984	1,599	101
G-100E (dup)	24	3.7	nd	150	72	27	22,114	300	46,062	16,159	868	104
G-100W	11	nd	nd	145	44	17	13,147	235	34,171	11,791	766	42
G-250E	20	nd	nd	139	59	21	18,181	270	46,039	13,776	1,056	76
G-250S	27	48	0.48	128	67	241	26,610	430	23,482	13,654	386	113
G-250W	18	nd	nd	161	60	21	13,816	273	37,331	12,413	1,159	64
G-500E	18	nd	nd	144	60	22	17,787	318	44,503	15,091	1,142	77
G-500W	16	nd	nd	161	50	18	13,779	204	41,364	14,522	521	55
G-1000E	24	9.2	nd	149	68	27	21,722	413	44,067	18,179	769	98
G-1000W	27	10	nd	156	72	28	22,725	541	40,144	12,205	646	96

nd: not detected
n/a: not available

Table 8.13. Trace and major elements in Golden Meadow reference sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Golden Meadow Ref. Site												
GR-0	25	34	0.58	117	64	26	25,929	341	21,925	11,799	446	118
GR-250E	28	37	0.55	118	70	30	28,038	377	22,797	11,438	355	127
GR-250W	21	35	0.24	120	57	23	21,244	367	20,790	12,051	641	95
GR-500W	24	31	0.46	118	60	25	22,539	306	21,017	10,676	476	112

nd: not detected
n/a: not available

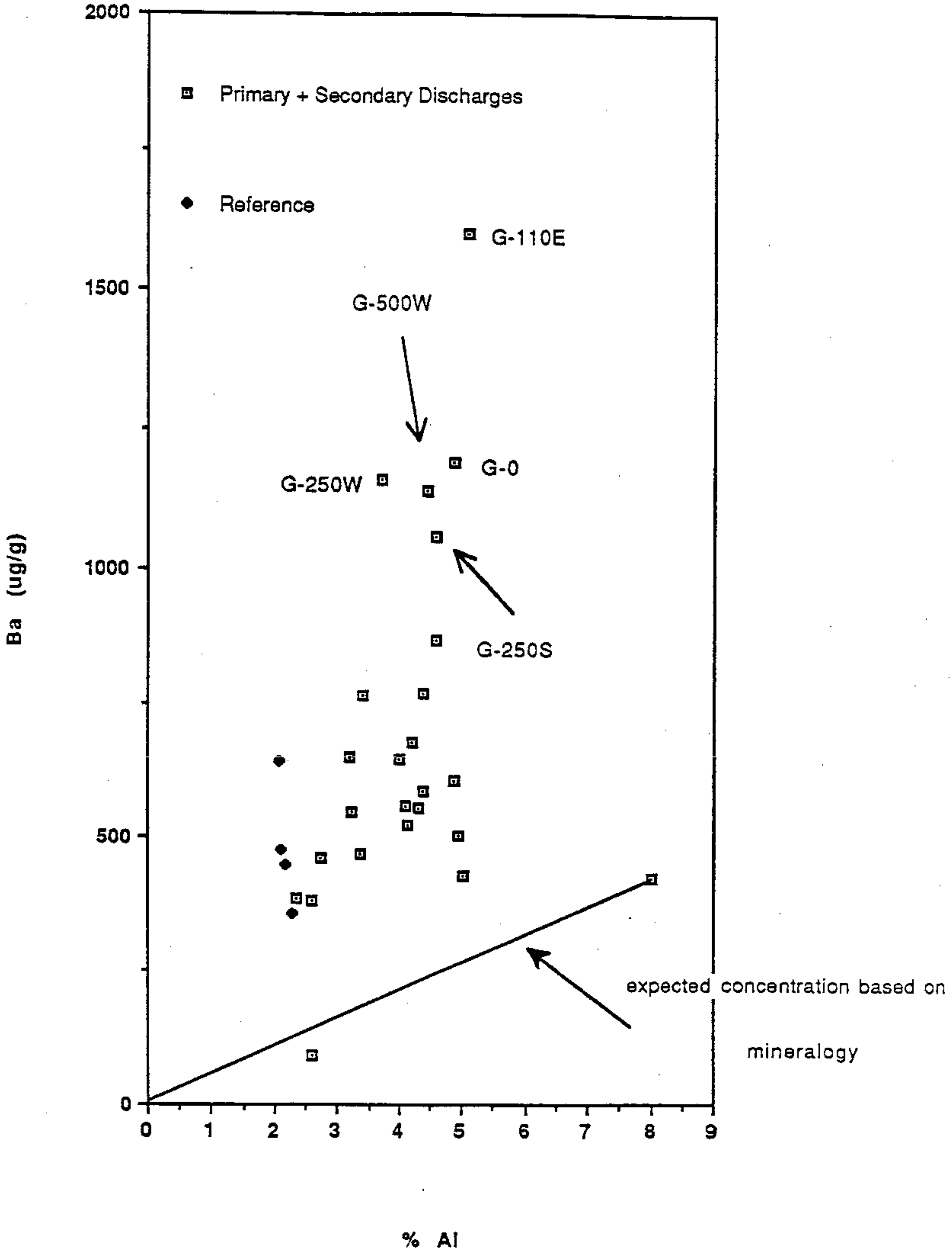


Figure 8.18. Concentration of barium relative to aluminum in sediments for Golden Meadow primary, secondary and reference sites.

element. Figure 8.19 shows examples for several of the elements measured in sediments at the Golden Meadow site along with reference site data. Chromium, copper, zinc and manganese are all non-enriched within the Golden Meadow system, in fact, many of the sediments in the region appear to be depleted in both manganese and zinc. Lead appears to be highly enriched throughout the Golden Meadow system. When the discharge site sediments are compared to the reference site sediments, the ranges of values observed within the reference site are very similar to those near the discharge. Even for barium, the concentration at reference sites were similar to that within either the primary or secondary sites.

An examination of the spatial distribution of metals in the region of the discharges suggested some interesting patterns with respect to the fate of discharge metals. Figures 8.20 and 8.21 show the spatial distributions for chromium, barium, copper, lead, nickel, manganese and vanadium surrounding the primary and secondary discharge points, respectively. In the case of barium, as suggested earlier, the maximum level is seen at GM0, but there are secondary maxima at 1000E, 1000N, 1000S and 250N. This may indicate that there is an initial deposition of barium, perhaps in particulate form near the discharge and secondary depositional zones at greater distances for the soluble barium which result from changes in solution chemistry or particulate distributions. A similar maximum at G0, with secondary maxima at 500E and 500W were observed near the secondary discharge point.

Chromium, copper, nickel, vanadium and lead distributions also showed some similarities to the barium distributions with a primary maximum at the GM0 or G0 sites and secondary maxima away from the discharges with intervening minima. These differences in sediment distributions can partially be explained by sediment mineralogy, but persist even when normalized for aluminum content. Therefore, some dynamic element chemistry is occurring in the vicinity of these sites, involving changes in salinity, particle interactions and trace element speciation.

Spatial distributions of the elements within the reference area (Table 8.13) showed some consistent trends which are not readily understood given the number of samples collected.

Table 8.4 presents a summary of the trace and major element data for the marsh sediments in the Golden Meadow system. In the case of barium, concentrations at both sites decreased from the zero point into the marsh.

8.3.2 Bivalve Tissues

Trace metals were determined in the tissues of both mussels and oysters at both discharge sites. Table 8.15 presents a summary of these data. Figures 8.22-8.24 present the data obtained on bivalve tissue samples located near the two Golden Meadow discharges and at the reference site. Figure 8.22 shows the data for copper and zinc in mussels and oysters. Copper was observed at ~1.5 ppm in mussels at the reference site and at the TB8 discharge site, while at the TB7 site it was found at ~5 ppm. In oysters a similar pattern of concentrations was observed, however, oysters accumulated five times the amount of copper as the mussels. For zinc in mussels no differences were seen between the reference or discharge sites. In oysters, more zinc was accumulated at the two discharge sites than at the reference site, but the differences were not large. Oysters accumulated ~30 to 40 times the amount of zinc as compared to mussels at the same sites.

Figure 8.23 shows the data for cadmium and chromium in mussels and oysters. For cadmium in mussels, higher levels were seen at both discharge sites relative to the reference site. Chromium in mussels at the reference site was higher than at the TB8 site but lower than at the TB7 discharge site. In the oyster, cadmium was not different between the reference and TB8

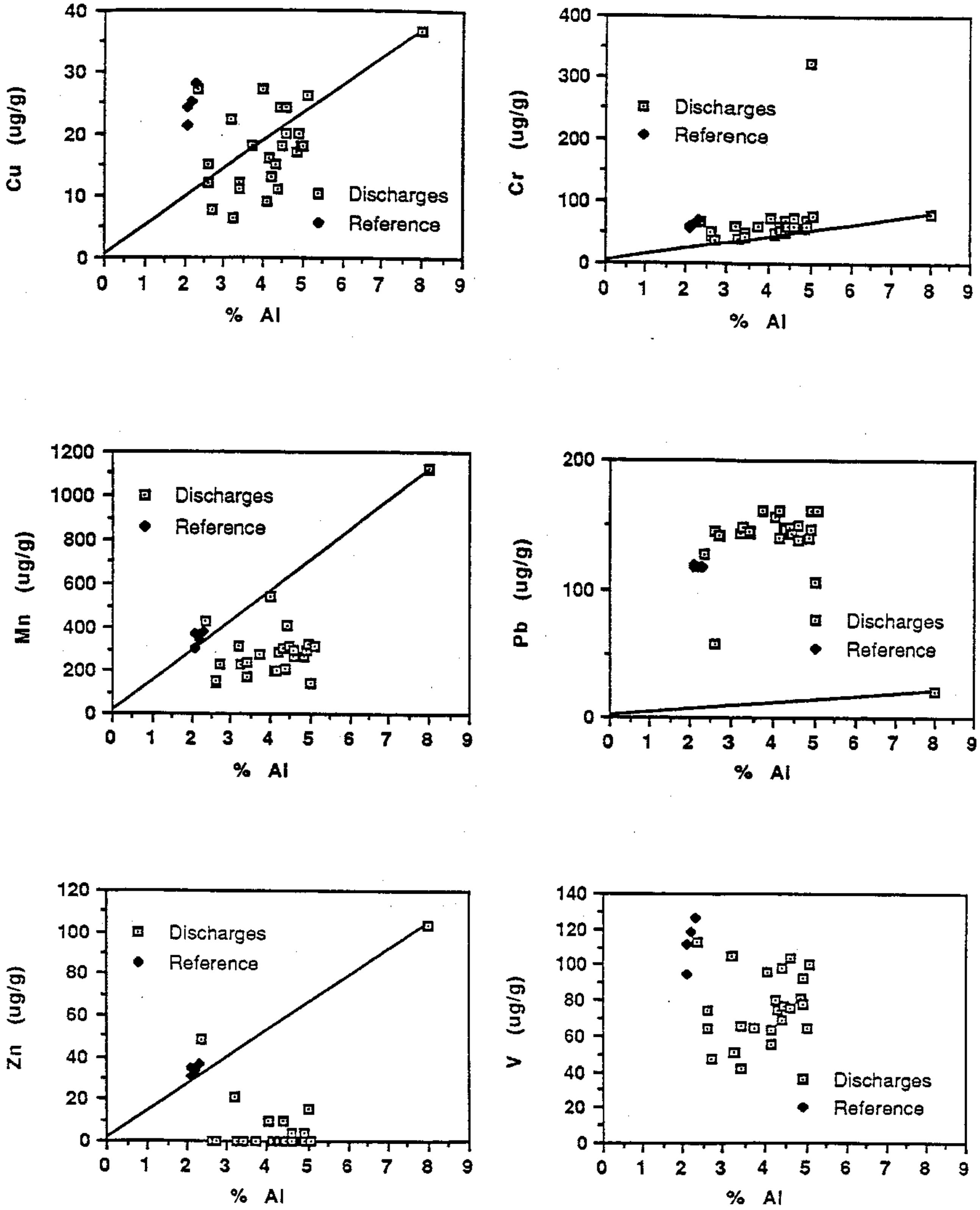


Figure 8.19. Concentrations of metals relative to aluminum for Golden Meadow primary, secondary and reference sites.

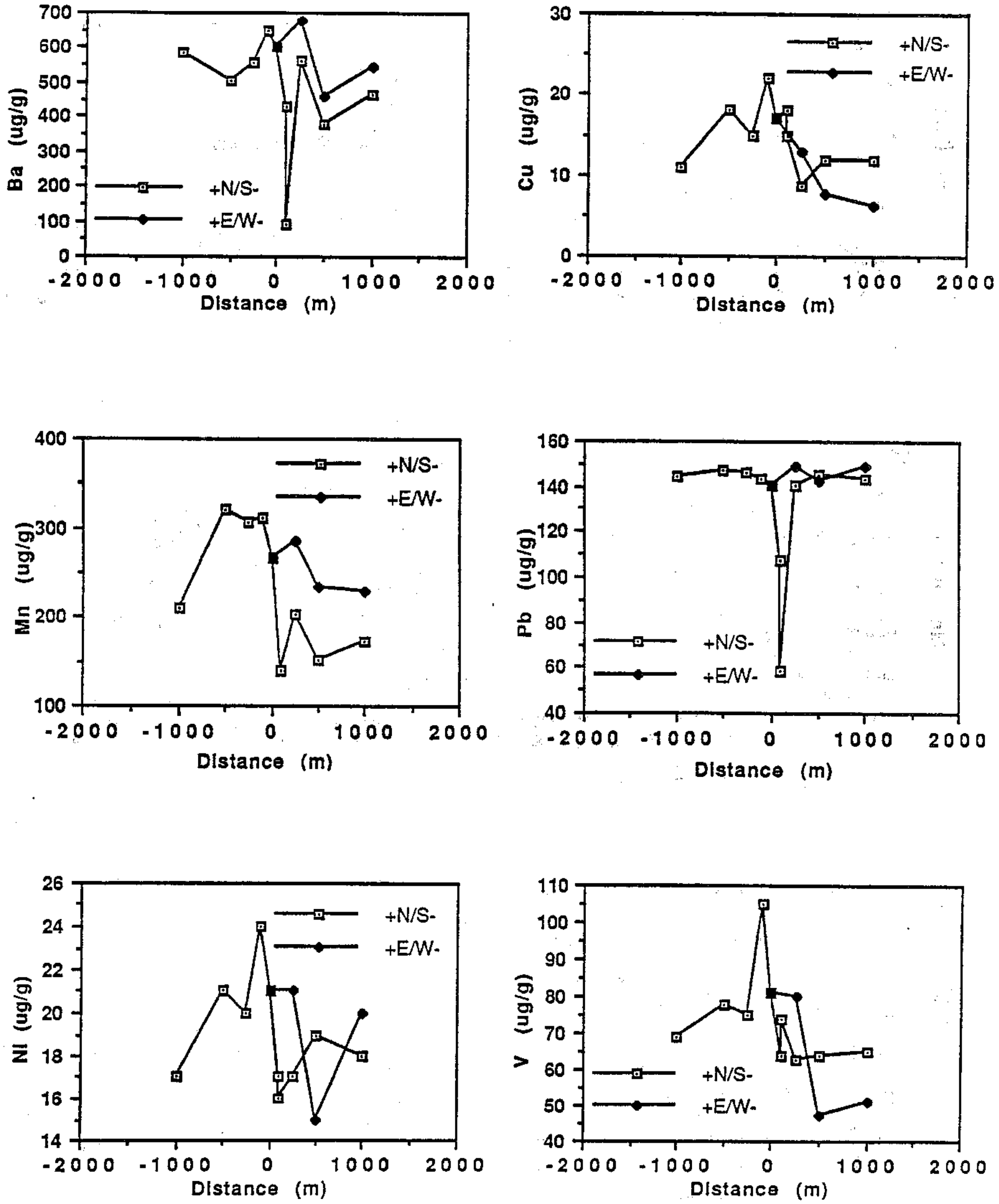


Figure 8.20. Spatial distribution of selected trace metals for Golden Meadow primary site sediments.

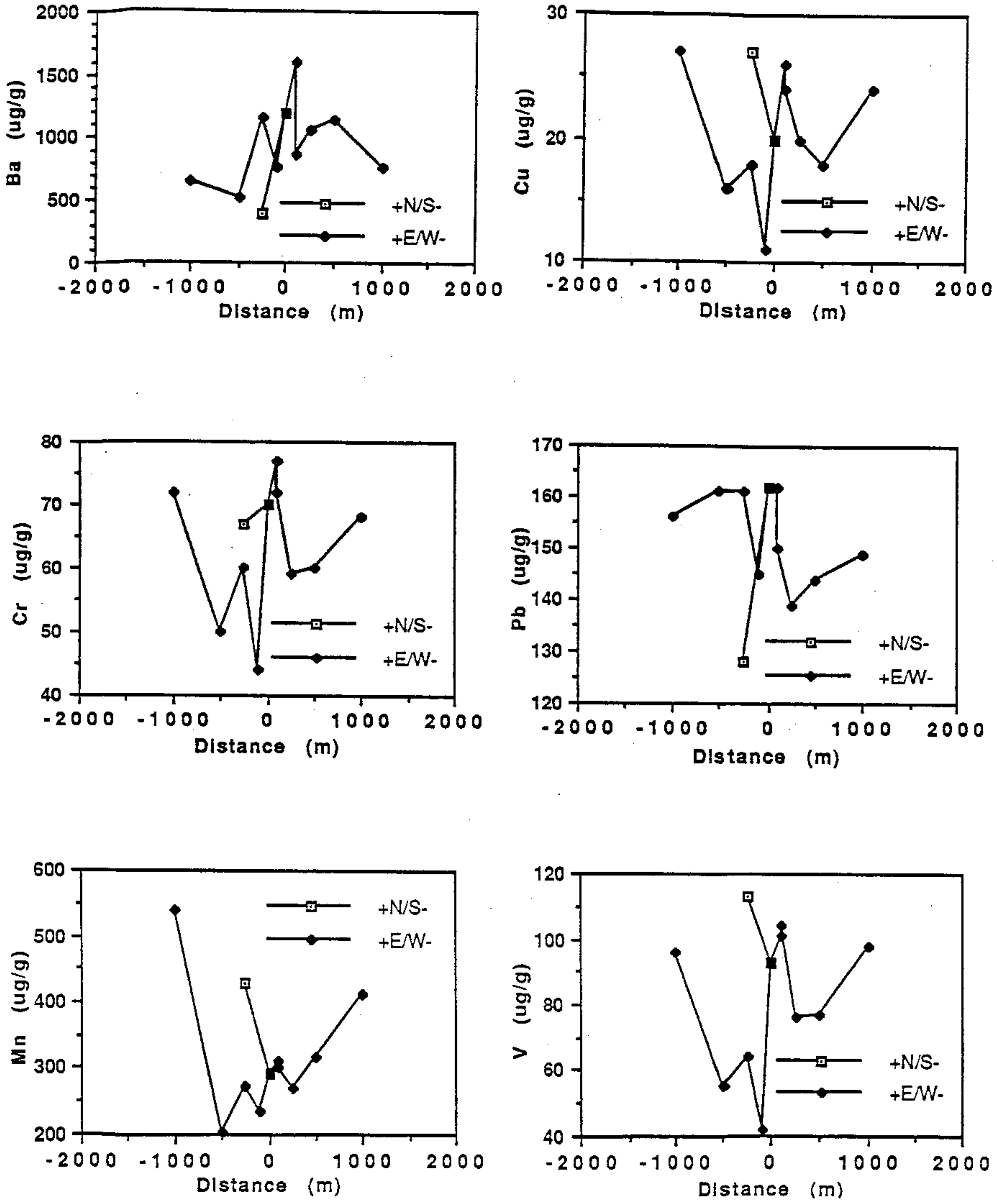


Figure 8.21. Spatial distribution of selected trace metals for Golden Meadow secondary site sediments.

Table 8.14. Trace and major elements in Golden Meadow marsh sediments.

Metal (ug/g)	Cu	Zn	Cd	Pb	Cr	Ni	Fe	Mn	Al	Na	Ba	V
Detection Limit (ug/g)	0.57	0.29	0.29	0.71	0.14	0.71	0.57	0.29	4.3	2.3	n/a	n/a
Sample ID												
Golden Meadow Primary Marsh Site												
GM4-0	16	14	0.08	85	44	18	13,927	43	13,066	12,038	19	86
GM4-4	20	18	0.23	90	49	20	14,954	48	12,461	14,166	16	95
GM4-12	20	18	0.39	80	44	19	15,573	62	12,269	12,526	11	73
GM4-36	20	25	0.65	67	38	20	13,491	60	6,585	15,347	6.0	81
GM4-108	23	25	0.34	79	45	25	15,734	49	11,088	11,149	1.2	94
Golden Meadow Secondary Marsh Site												
G1-0	22	21	0.34	82	49	24	18,548	55	14,309	16,701	9.3	103
G1-4	18	16	0.26	68	42	20	14,529	44	10,265	16,627	1.7	83
G1-12	14	14	0.49	55	30	18	10,577	26	4,648	27,240	1.6	64
G1-36	18	23	0.65	65	35	21	15,489	49	5,808	23,119	1.7	82
G1-108	21	23	0.03	72	39	21	13,771	42	12,132	14,778	1.6	79
Golden Meadow Marsh Ref. Site												
GR2-0	21	31	0.34	109	57	20	18,816	62	14,275	11,828	5.8	103
GR2-0 (dup)	23	36	0.59	103	59	21	18,369	66	11,503	12,285	163	108
GR2-12	31	35	0.81	95	66	25	24,285	61	13,043	9,857	21	136
GR2-108	19	33	0.42	58	28	21	13,684	1,442	5,533	22,957	21	70

nd: not detected
n/a: not available

Table 8.15. Concentrations of metals in Golden Meadow discharge and reference biota.

Metal (µg/g, wet wt.)	Cu	Zn	Cd	Pb	Cr	Ni	Ba
Sample ID							
Mussels							
GM Ref.	1.6	6.6	0.06	nd	0.19	0.42	6.8
GM Ref. (Dup)	1.3	6.5	0.06	nd	0.21	0.27	6.7
G TB#7	5.0	7.3	0.08	nd	0.25	0.41	9.0
GM TB#8	1.6	6.9	0.11	nd	0.16	0.18	5.8
Oysters							
GM Ref.	7.4	180	0.21	nd	0.30	0.35	6.7
GM Ref. (Dup)	7.1	180	0.20	nd	0.25	0.35	6.7
G TB#7	9.9	200	0.26	nd	0.19	0.36	2.2
GM TB#8	7.6	250	0.22	nd	0.12	0.28	5.0

nd: not detected

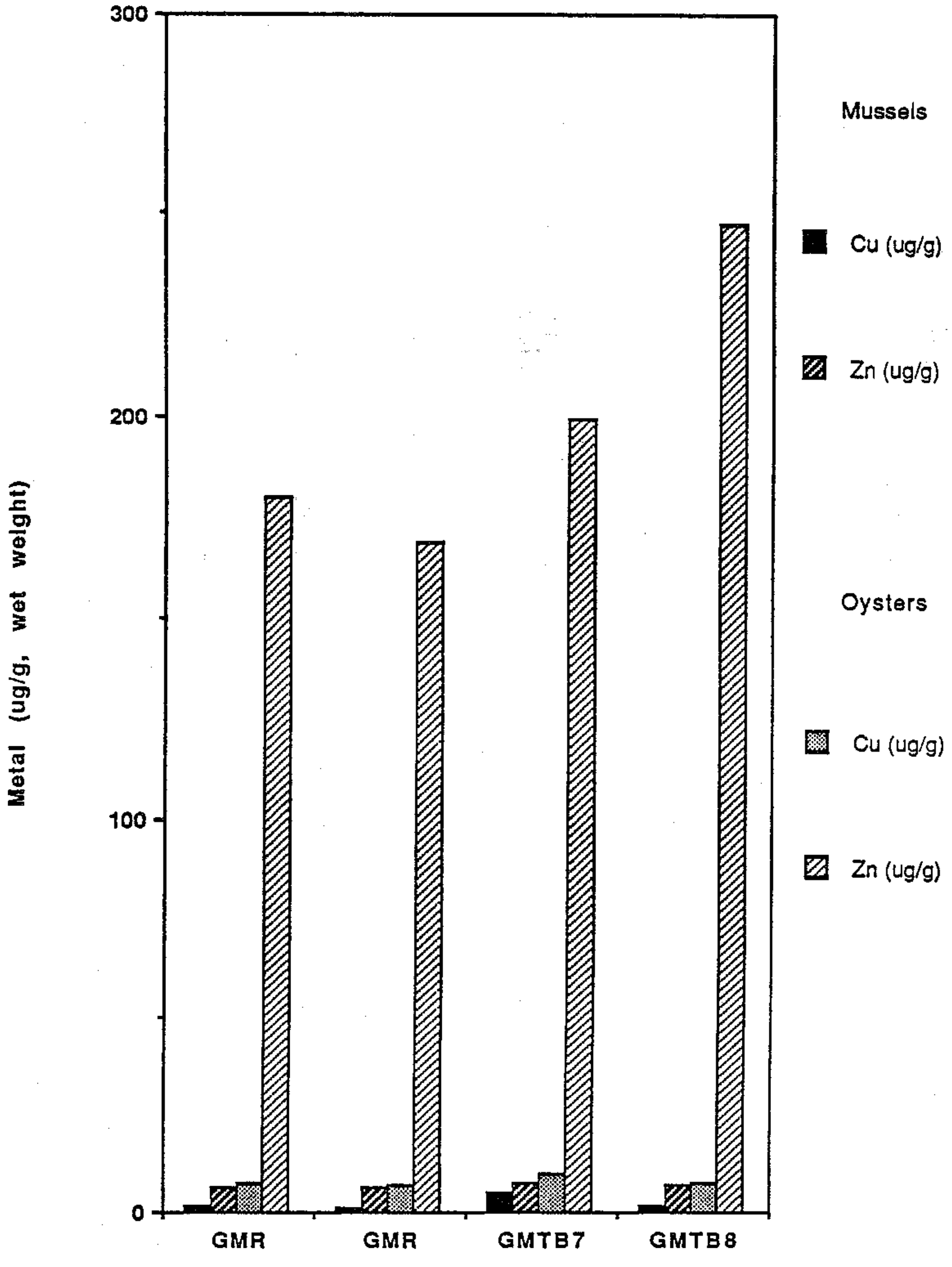


Figure 8.22. Comparison of copper and zinc levels in oysters and mussels from Golden Meadow discharge sites and reference site.

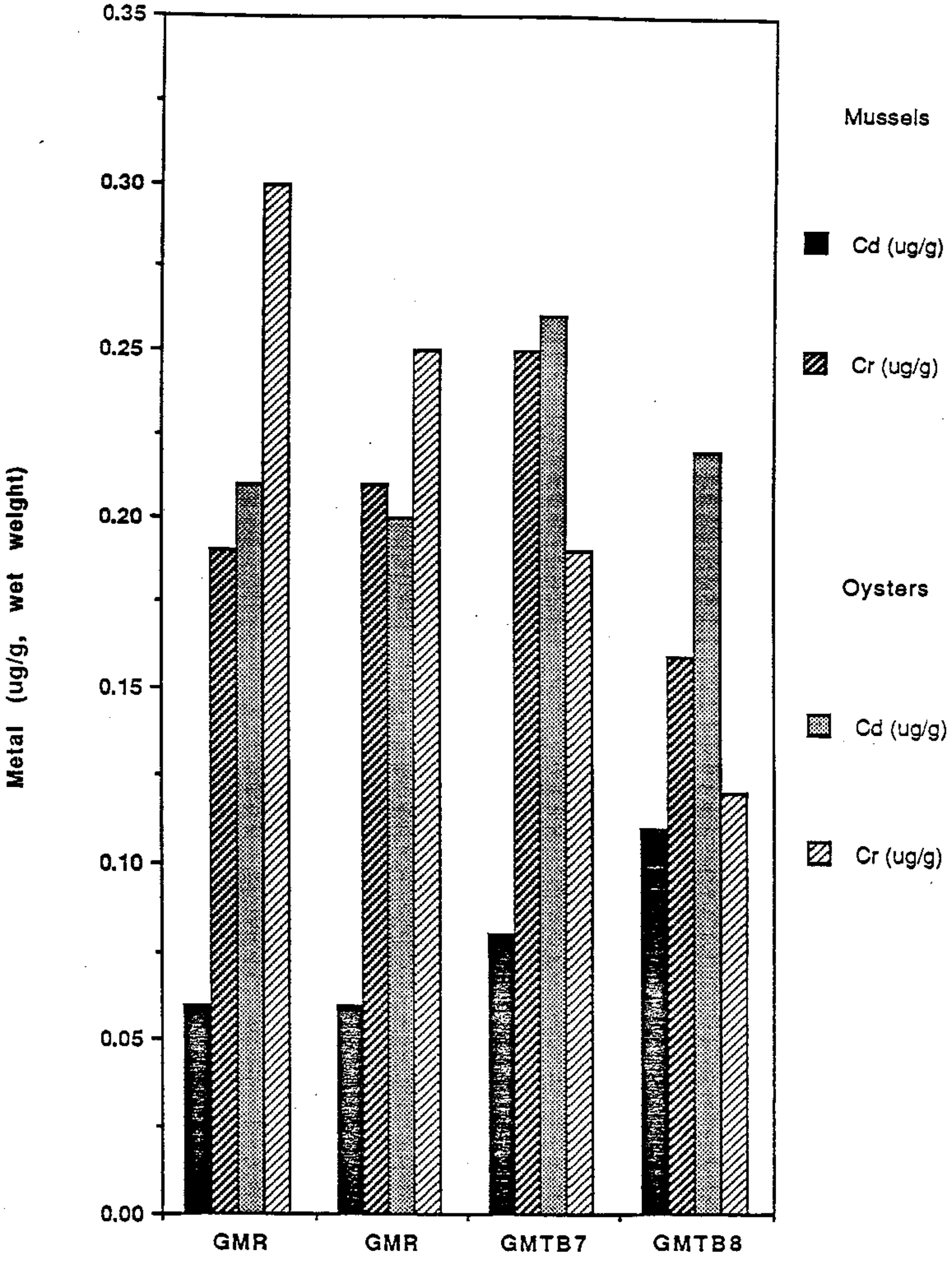


Figure 8.23. Comparison of cadmium and chromium levels in oysters and mussels from Golden Meadow discharge sites and reference site.

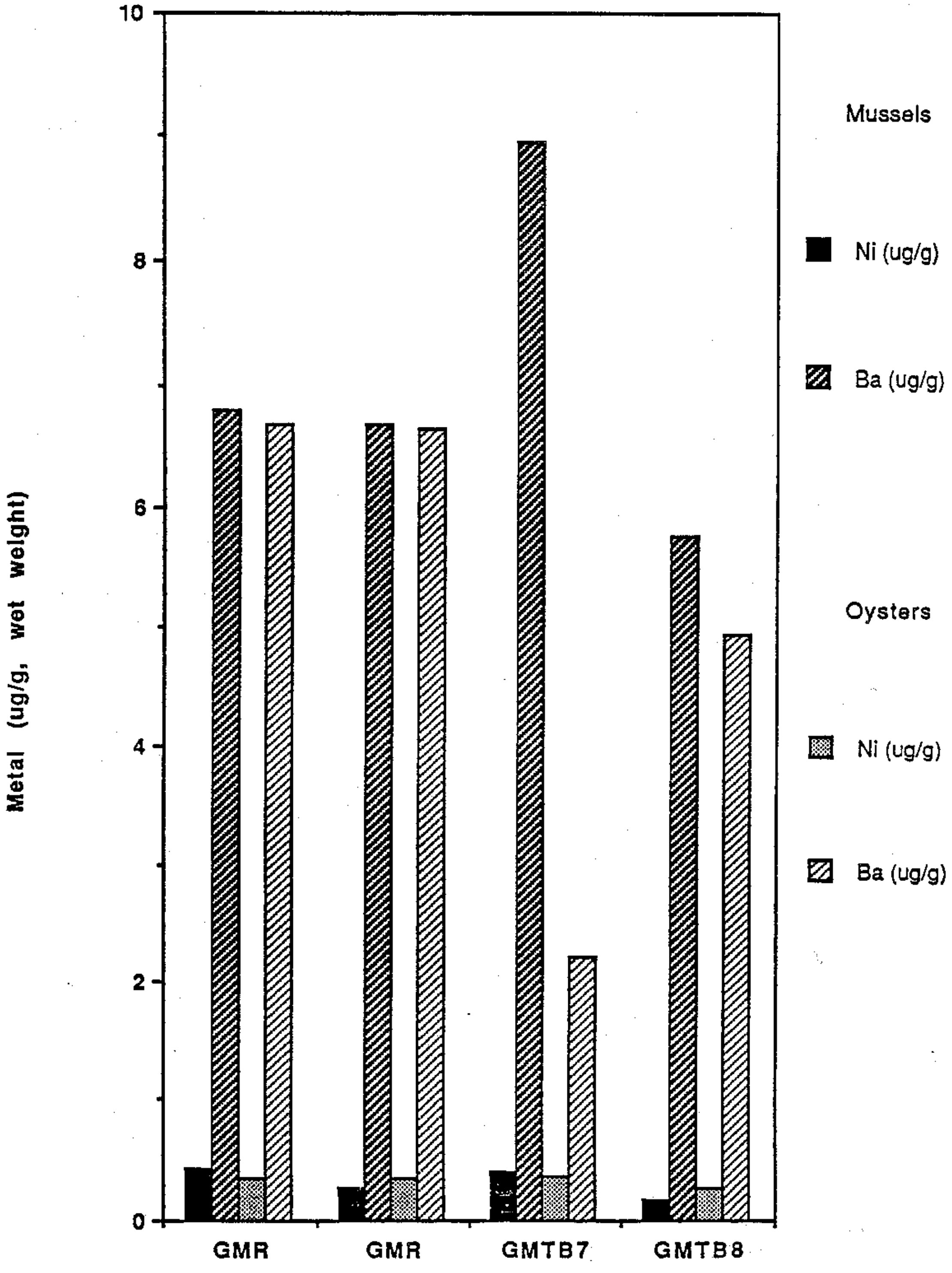


Figure 8.24. Comparison of nickel and barium levels in oyster and mussels from Golden Meadow discharge sites and reference site.

sites but was higher at the TB7 site. For chromium in oysters, the reference site levels were higher than was observed at either discharge site.

Figure 8.24 shows the data for nickel and barium in mussels and oysters. Nickel was observed at levels between 0.2 and 0.4 ppm. No differences were observed between sites in either the mussel or oyster. Barium, a non-essential element, was accumulated to levels between 5.7 to 9.0 ppm in the mussel. At the TB7 site, Ba was higher than at the reference site but no different than the reference at the TB8 site. For oysters, barium was found at lower concentrations at both discharge sites than at the reference site.

8.4 Benthic Communities

8.4.1 Dominants

The benthic macroinfauna community at the Golden Meadow sites is a combination of euryhaline and more marine infaunal invertebrates, and is, therefore, very diverse. Polychaetes were the numerically dominant fauna, with the capitellid *Mediomastus ambiseta* being the most common. Of the 65 total number of species collected at Golden Meadow, the most frequently collected species were the cumacean *Cyclaspis varians*, the isopod *Edotea* sp., the papillate tubificid oligochaete (type 1), and the polychaete *Mediomastus ambiseta* and made up 25% of the total occurrences. Other numerical dominants were the polychaetes *Neanthes succinea*, *Sigambra* cf. *bassi*, *Glycinde solitaria*, *Heteromastus filiformis*, *Parandalia* sp., and *Leitoscoloplos fragilis*, nemerteans, the amphipods *Ampelisca abdita*, *Cerapus* sp. and *Corophium* sp., the gastropods *Acteocina canaliculata* and gastropod sp. A, the bivalves *Tellina versicolor*, *Mulinia lateralis*, and Mytilidae spp., and the cumacean Leuconidae sp.

8.4.2 Community Parameters

All benthic stations (three replicates per each) for the 12 stations within the waterways and channels of the Golden Meadow primary discharge study area have been analyzed. A single replicate for each of the 10 stations associated with the secondary discharge site has been analyzed. All replicates for the reference stations have been completed. Thus, statistical analyses could be completed for the primary discharge site and the reference area.

The number of species per replicate and the number of individuals for stations at both discharge sites and the reference area were similar in that there was considerable variability within each of the areas (Table 8.16). The number of species at the primary discharge site ranged from 5 to 20, at the secondary discharge site from 8 to 21, and at the reference area from 8 to 13. The number of individuals at the primary discharge site ranged from 27 to 171, at the secondary discharge site from 43 to 146, and at the reference area from 44 to 343. Similarly measures of diversity within each area were variable and similar between areas (Table 8.17). The measure of evenness showed less variability.

There were no clear trends in number of species or number of individuals with distance away from the discharge point (Figure 8.25). When discharge points were considered separately, some differences were noted. At the primary discharge site, there was a trend in increasing numbers of species with distance along a north-south transect (Figure 8.26). This trend was not consistent with hydrocarbon concentrations in the sediments. There was a change in habitat type from man-made canals in the northern part of the station grid to natural channels in the southern part. The number of individuals along the same north-south transect decreased to the immediate north of the discharge point. There was one station (GM1000S) with considerably higher numbers at the extreme southern end of the transect (Figure 8.26). These trends were not correlated with similar trends in sediment contaminants.

Table 8.16. Number of species per replicate and number of individuals per replicate for stations at the Golden Meadow site.

		Number of Species			Number of Individuals		
Stations	No. Repl.	Min.	Max.	$\bar{x}$ ± S.D.	Min.	Max.	$\bar{x}$ ± S.D.
G0	1			8			121
G100E	1			15			76
G100W	1			15			146
G250E	1			21			81
G250S	1			9			138
G250W	1			19			132
G500E	1			17			176
G500W	1			11			153
G1000E	1			9			64
G1000W	1			13			43
GM0	3	14	14	14.7 ± 0.6	120	235	171.0 ± 58.6
GM100N	3	12	15	13.7 ± 1.5	93	119	104.3 ± 13.3
GM100S	3	13	23	19.0 ± 5.3	84	204	158.3 ± 64.9
GM250N	3	9	11	10.0 ± 1.0	21	32	25.3 ± 5.9
GM250S	3	17	22	19.0 ± 2.6	78	159	111.3 ± 42.4
GM250W	3	10	14	11.3 ± 2.3	33	74	55.7 ± 20.8
GM500N	3	11	16	14.0 ± 2.6	28	100	67.7 ± 36.6
GM500S	3	17	24	20.3 ± 3.5	71	110	94.0 ± 20.4
GM500W	3	14	21	18.0 ± 3.6	42	346	143.7 ± 175.3
GM1000N	3	12	14	13.0 ± 1.0	47	214	109.7 ± 91.0
GM1000S	3	17	20	18.0 ± 1.7	79	139	103.3 ± 31.6
GM1000W	3	3	8	5.0 ± 2.6	19	31	27.0 ± 6.9
GR0	3	12	13	12.7 ± 0.6	307	401	343.3 ± 50.5
GR250E	3	6	10	8.3 ± 2.1	47	68	57.0 ± 10.5
GR250W	3	7	13	10.3 ± 3.1	12	93	60.3 ± 42.7
GR500W	3	9	11	9.7 ± 1.2	25	55	44.3 ± 16.8

Table 8.17. Benthic community parameters for stations at the Golden Meadow site.

Station	No. Calc.	Diversity (H') $\bar{x}$ ± S.D.	Evennes (J') $\bar{x}$ ± S.D.
G0	1	0.76	0.25
G100E	1	0.84	0.22
G100W	1	0.91	0.23
G250E	1	1.12	0.25
G250S	1	0.44	0.14
G250W	1	0.91	0.21
G500E	1	0.88	0.21
G500W	1	0.57	0.16
G1000E	1	0.74	0.23
G1000W	1	1.08	0.29
GM0	3	0.81 ± 0.06	0.21 ± 0.02
GM100N	3	0.73 ± 0.10	0.20 ± 0.03
GM100S	3	0.91 ± 0.23	0.22 ± 0.03
GM250N	3	0.86 ± 0.09	0.26 ± 0.02
GM250S	3	0.92 ± 0.03	0.22 ± 0.02
GM250W	3	0.81 ± 0.04	0.23 ± 0.02
GM500N	3	0.98 ± 0.02	0.26 ± 0.02
GM500S	3	1.16 ± 0.12	0.26 ± 0.01
GM500W	3	0.91 ± 0.38	0.22 ± 0.09
GM1000N	3	0.94 ± 0.04	0.25 ± 0.01
GM1000S	3	0.87 ± 0.07	0.21 ± 0.01
GM1000W	3	0.37 ± 0.21	0.16 ± 0.04
GR0	3	0.69 ± 0.10	0.19 ± 0.02
GR250E	3	0.71 ± 0.09	0.23 ± 0.01
GR250W	3	0.89 ± 0.14	0.27 ± 0.04
GR500W	3	0.82 ± 0.09	0.25 ± 0.02

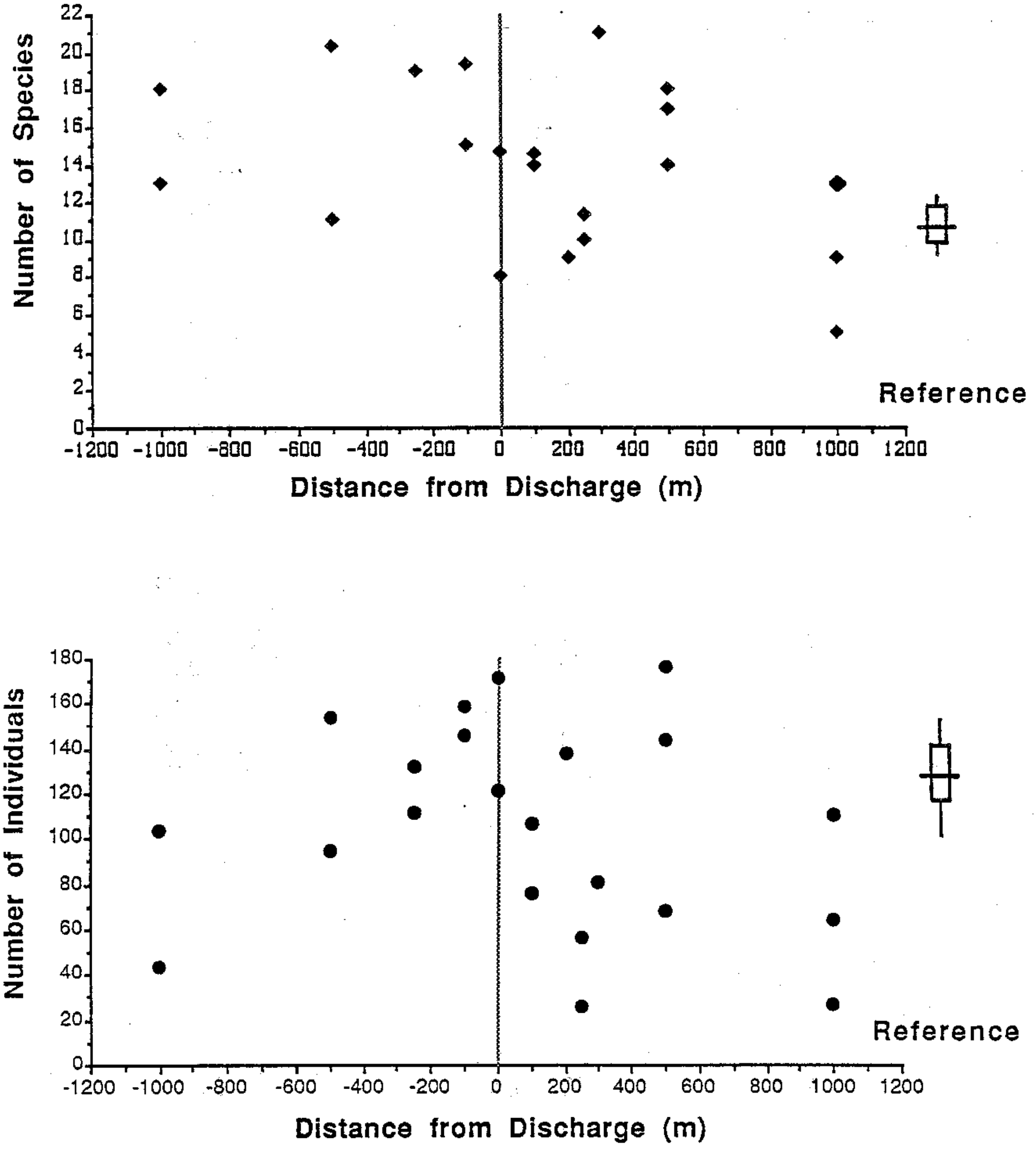


Figure 8.25. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna at all stations for the Golden Meadow discharge sites. Mean, standard error and average minimum and maximum for reference stations shown to the right.

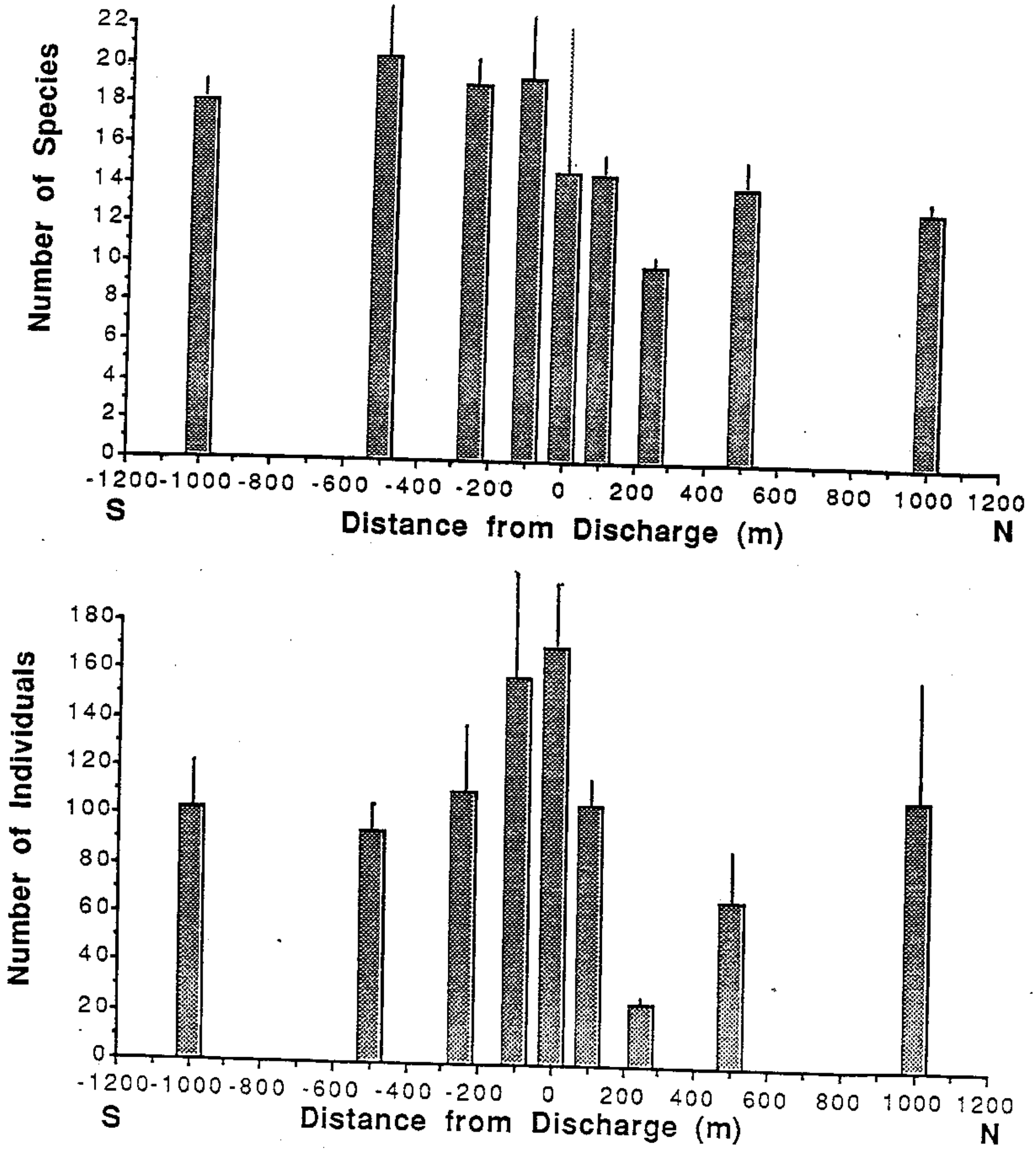


Figure 8.26. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna along a north-south transect through the Golden Meadow primary discharge site (standard error bars shown).

At the secondary discharge site, there was a depression in the number of species immediately at the discharge site and within 100 m in either direction (Figure 8.27). Numbers of individuals were depressed at the discharge point and within 250 m to the east (Figure 8.27).

When compared to the reference area, the stations at the primary discharge site differed with regards to having fewer number of species per replicate (Table 8.18), but were similar with regards to the other community parameters analyzed. Similar analyses were not possible for the secondary discharge site (unreplicated numbers). Statistically significant differences were found within each of the two station groupings (primary discharge versus reference) (Tables 8.19-8.22). There were significant differences among stations at the primary discharge site for all community parameters (Table 8.19), but these differences were not related to distance away from the discharge point (Table 8.19). There was also considerable overlap among the stations with regards to the community parameters (Table 8.20). Within the reference area, the stations were more similar (Table 8.21), with statistically significant differences among stations being confined to number of individuals and evenness (Table 8.22).

When all replicated stations at the Golden Meadow site are considered together for the variables of number of species and number of individuals, there were significant differences among all stations (Table 8.23), however, there was considerable overlap among the stations and those stations of the reference area were not clearly distinguishable from those of the primary discharge site (Table 8.24).

8.4.3. Marsh Stations

One set of replicates for marsh faunal analysis has been completed for the primary discharge site (GM4-0), but only a single sample for the reference marsh (GR1-0). Both of these stations are at 0 m from either the discharge point or an arbitrary zero point at the reference stations. Based on the limited numbers available, the marsh at the discharge point appears to be reduced in numbers of species and numbers of individuals (Table 8.25). Chemical contaminant levels are greater in the marsh at the discharge point than in the marsh at the reference area.

8.5 Synthesis

Sediments for stations at the Golden Meadow site were predominantly clayey silts, with several stations having a high sand content. Sediments at the reference stations were generally composed of less sand than stations associated with the two discharge sites. Thus, there was considerable variability in the sediment composition throughout the study area. The total organic carbon content of the sediments was generally less than 5%, but exceeded this at a few stations primarily those of the reference area. This distribution was not unexpected given the correlation of organic content with sediment grain size (Figure 8.28). Despite the variability in environmental parameters measured across the study area, there were no strong correlations of community parameters, such as number of species or number of individuals, with sediment grain size composition or total organic carbon content.

Chemical contaminants in the sediments at the Golden Meadow site were elevated at the point of discharge for both the primary and secondary discharge sites. There was a rapid decrease in these contaminants away from the discharge point at 100 m for the primary discharge site and at 250 m for the secondary discharge site. Levels were generally higher for the secondary discharge site than for the primary. The benthic community parameters of number of species and number of individuals were examined in relationship to major groups of chemical contaminants in the sediments. At the primary discharge where concentrations were generally lower and decreased more rapidly, there were no clear correlations of numbers of species or numbers of individuals to the concentrations of total polynuclear aromatic hydrocarbons (PAH), total PAH and homologs of naphthalene, dibenzothiphene, and phenanthrene (NDP homologs),

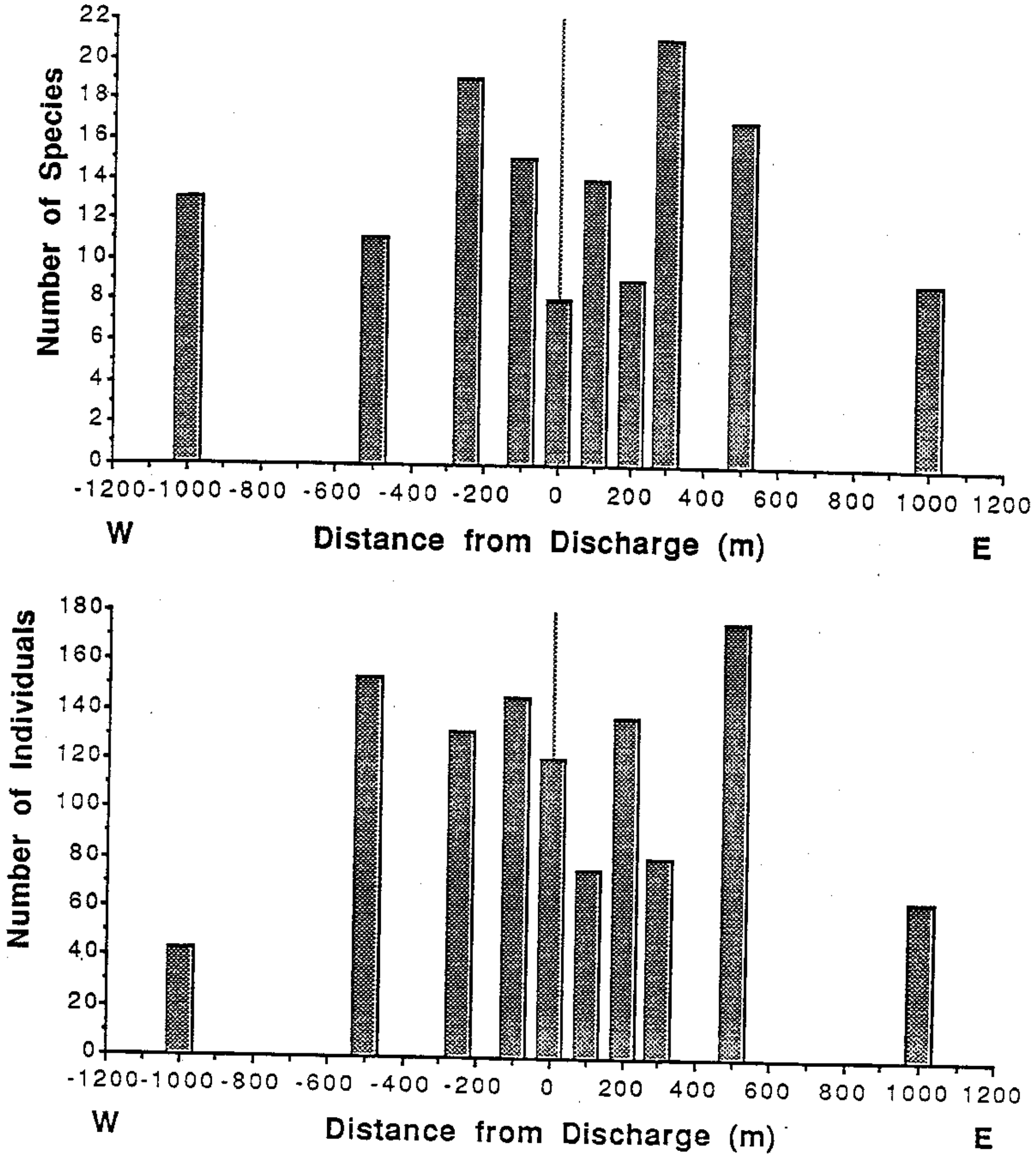


Figure 8.27. Number of species per replicate, above, and number of individuals per replicate, below, for benthic macroinfauna along an east-west transect through the Golden Meadow secondary discharge site.

Table 8.18. General linear model analysis of variance for Golden Meadow discharge stations (primary site) versus reference stations.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	1	175.56	175.56	8.95	0.004
Error	46	902.25	19.61		
Corrected Total	47	1077.81			
Number of individuals per replicate (log transformed):					
Model	1	0.00	0.00	0.00	0.96
Error	46	29.87	0.65		
Corrected Total	47	29.88			
Diversity H':					
Model	1	0.06	0.06	1.39	0.24
Error	46	1.91	0.04		
Corrected Total	47	1.96			
Evenness J':					
Model	1	0.00	0.00	0.58	0.45
Error	46	0.08	0.00		
Corrected Total	47	0.08			

Table 8.19. General linear model analysis of variance for Golden Meadow discharge stations (primary site).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	11	677.33	60.67	8.34	0.001
Error	24	174.67	7.28		
Corrected Total	35	842.00			
Number of individuals per replicate (log transformed):					
Model	11	11.44	1.04	3.68	0.004
Error	24	6.79	0.28		
Corrected Total	35	18.23			
Diversity H':					
Model	11	1.16	0.11	4.40	0.012
Error	24	0.58	0.02		
Correted Total	35	1.74			
Evenness J':					
Model	11	0.03	0.00	2.39	0.036
Error	24	0.03	0.00		
Corrected Total	35	0.06			

Table 8.20. Duncan's multiple range test for Golden Meadow discharge stations. Underlined stations are not significantly different from each other.

Number of species per replicate:

500 S	250 S	100 S	500 W	1000 S	0	500 N	100 N	1000 N	250 W	250 N	1000 W
			—	—	—	—	—	—			
—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—					

Number of individuals per replicate (log transformed):

0	100 S	250 S	100 N	1000 S	500 S	1000 N	500 W	500 N	250 W	1000 W	250 N
								—	—	—	—
—	—	—	—	—	—	—	—	—			
	—	—	—	—	—	—	—	—	—		

Diversity H':

500 S	500 N	1000 N	250 S	100 S	500 W	1000 S	250 N	0	250 W	100 N	1000 W
—	—	—	—	—	—	—					—
	—	—	—	—	—	—	—	—	—	—	

Evenness J':

500 S	500 N	250 N	1000 N	250 W	500 W	250 S	100 S	0	1000 S	100 N	1000 W
					—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—		
	—	—	—	—	—	—	—	—	—	—	

Table 8.21. General linear model analysis of variance for Golden Meadow reference stations.

Source	DF	Squares of Means	Mean Square	F Value	Pr > F
Number of species per replicate:					
Model	3	29.58	9.86	2.57	0.13
Error	8	30.67	3.83		
Corrected Total	11	60.25			
Number of individuals per replicate (log transformed):					
Model	3	8.79	2.93	8.21	0.01
Error	8	2.85	0.36		
Corrected Total	11	11.64			
Diversity H':					
Model	3	0.08	0.03	2.50	0.13
Error	8	0.09	0.01		
Corrected Total	11	0.17			
Evenness J':					
Model	3	0.01	0.00	5.03	0.03
Error	8	0.06	0.00		
Corrected Total	11	0.02			

Table 8.22. Duncan's multiple range test for Golden Meadow reference stations. Underlined stations are not significantly different from each other.

Number of individuals per replicate (log transformed):

GR0 GR250E GR250W GR500W

Evenness J':

GR0 GR250E GR250W GR500W

Table 8.23. General linear model analysis of variance for Golden Meadow study area, all stations combined.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Number of species:					
Model	15	872.48	58.17	9.06	0.0001
Error	32	205.33	6.42		
Corrected Total	47	1077.81			
Number of individuals (log transformed):					
Model	15	20.23	1.35	4.47	0.002
Error	32	9.65	0.30		
Corrected Total	47	29.88			

Table 8.24. Duncan's multiple range test for Golden Meadow study area, all stations combined. Underlined stations are not significantly different from each other.

Number of species:

GM 500 S	GM 250 S	GM 100 S	GM 500 W	GM 1000 S	GM 0	GM 500 N	GM 100 N	GM 1000 N	GR 0	GM 250 W	GR 250 W	GM 250 N	GR 500 W	GR 250 E	GM 1000 W
			—	—	—	—	—	—	—	—	—	—	—	—	
—	—	—	—	—	—	—	—	—	—	—				—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—		

Number of individuals (log transformed):

GR 0	GM 0	GM 100 S	GM 250 S	GM 100 N	GM 1000 S	GM 500 S	GM 1000 N	GM 500 W	GM 500 N	GR 250 E	GM 250 W	GR 250 W	GR 500 W	GM 1000 W	GM 250 N
		—	—	—	—	—	—	—	—	—	—				
—	—	—	—	—	—	—	—	—	—	—	—	—	—		
									—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—					

Table 8.25. Benthic community parameters for marsh stations at the Golden Meadow site.

Station	No. Repl.	Number of Species Min.	Number of Species Max.	Number of Species $\bar{x} \pm$ S.D.	Number of Individuals Min.	Number of Individuals Max.	Number of Individuals $\bar{x} \pm$ S.D.
GM4-0	3	3	4	3.3 ± 0.6	3	9	5.3 ± 3.2
GR2-0	1			7			35

Station	No. Calc.	Diversity (H') $\bar{x} \pm$ S.D.	No. Calc.	Evenness (J') $\bar{x} \pm$ S.D.
GM4-0	3	0.49 ± 0.05	3	0.29 ± 0.01
GR2-0	1	0.69	1	0.25

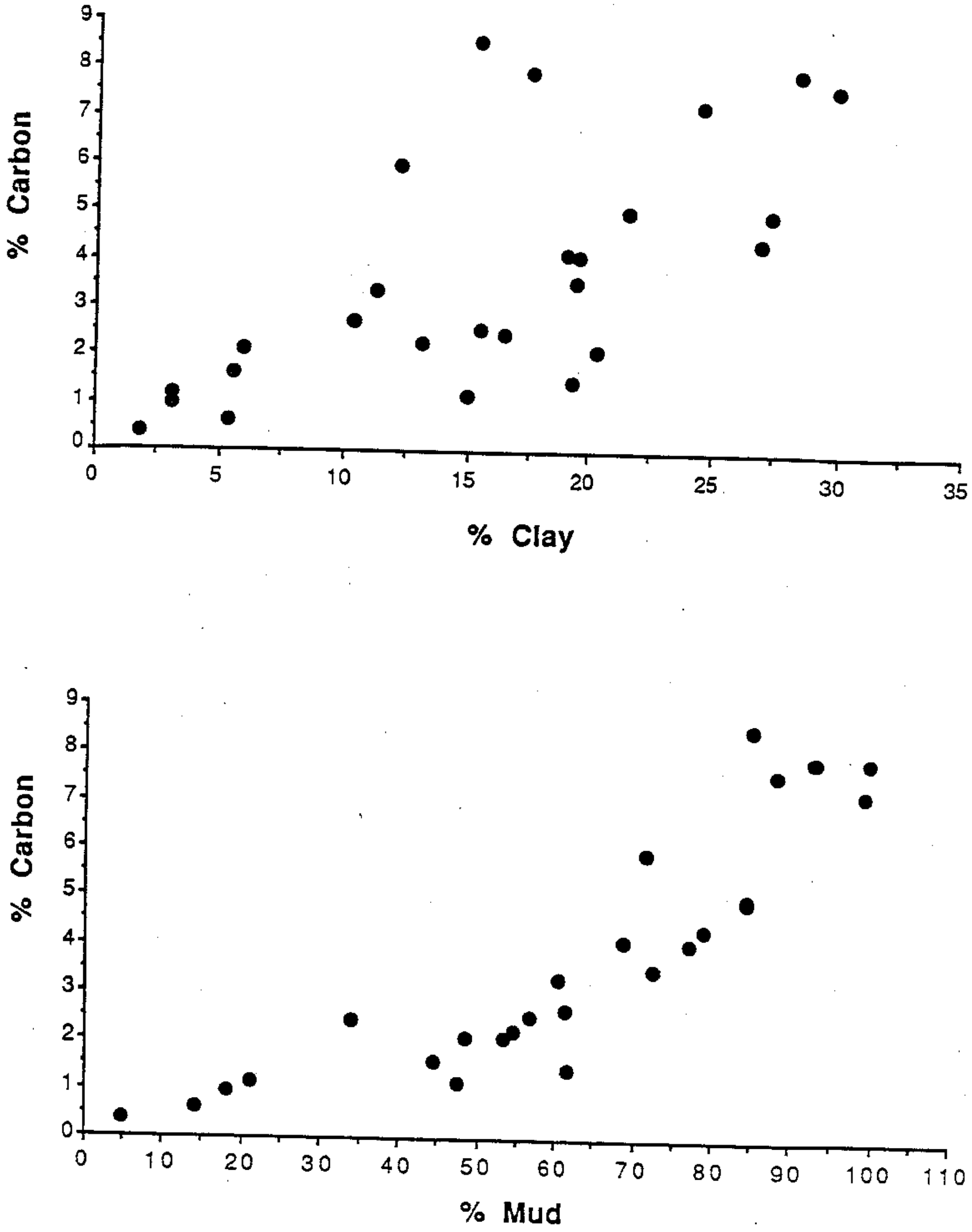


Figure 8.28. Comparison of total organic carbon content to %clay, above, and %mud, below, in Golden Meadow study area stations.

and total resolved and unresolved aliphatic hydrocarbons in the sediments (Figures 8.29 through 8.31). At the secondary discharge site where concentrations were generally higher and decreased at 250 m as compared to 100 m at the primary discharge site, there was only a depression in the number of species at the discharge point in relationship to total PAH and NDP homologs and total resolved and unresolved aliphatic hydrocarbons, but not total PAH (Figures 8.32 through 8.35).

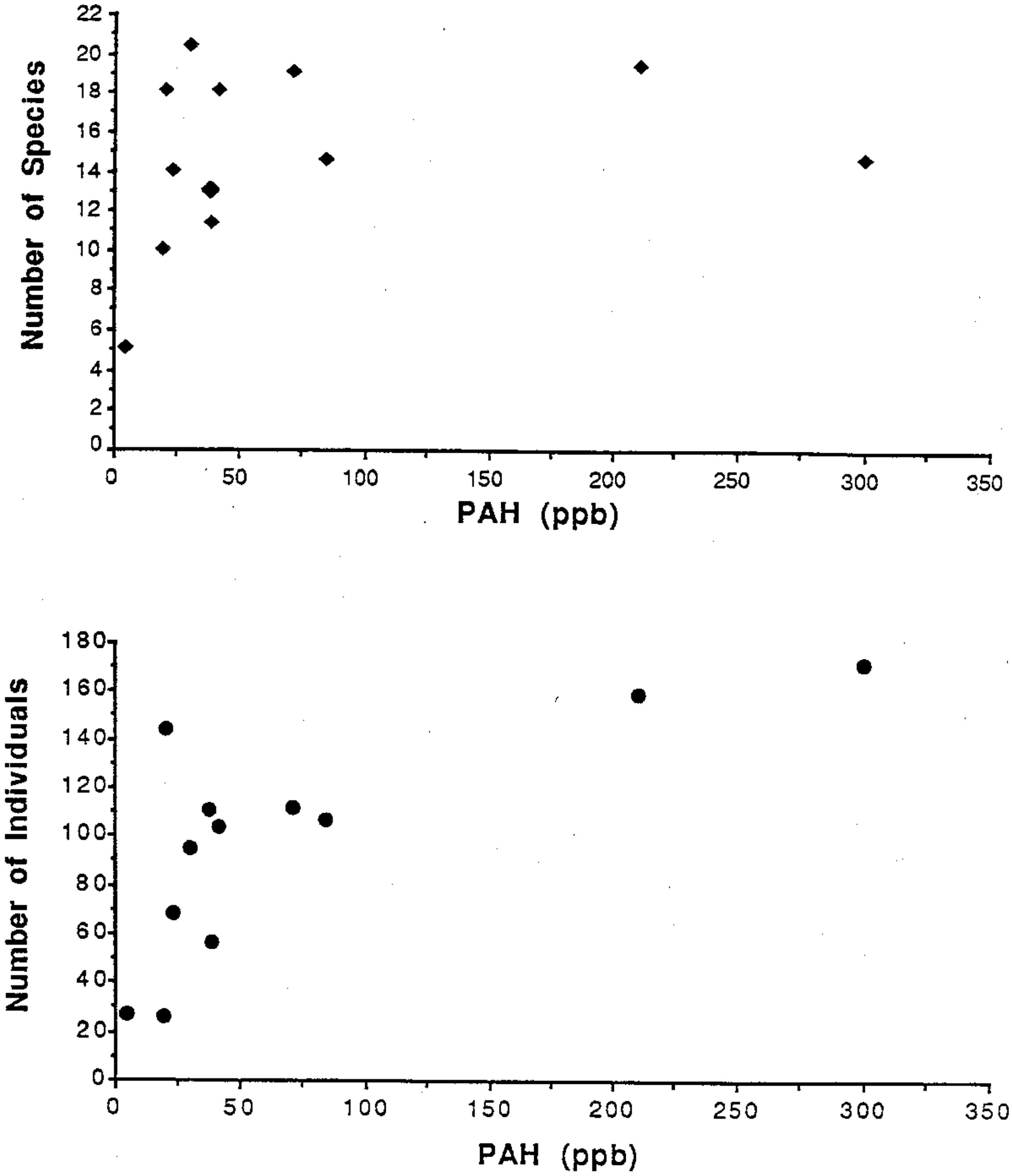
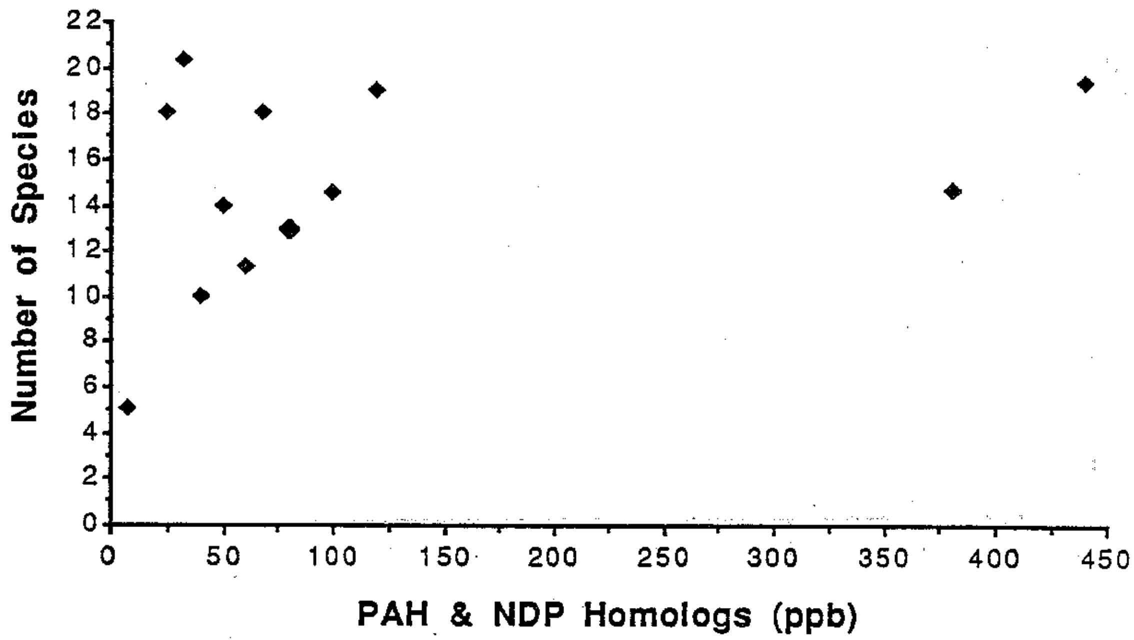


Figure 8.29. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) for the Golden Meadow primary site.



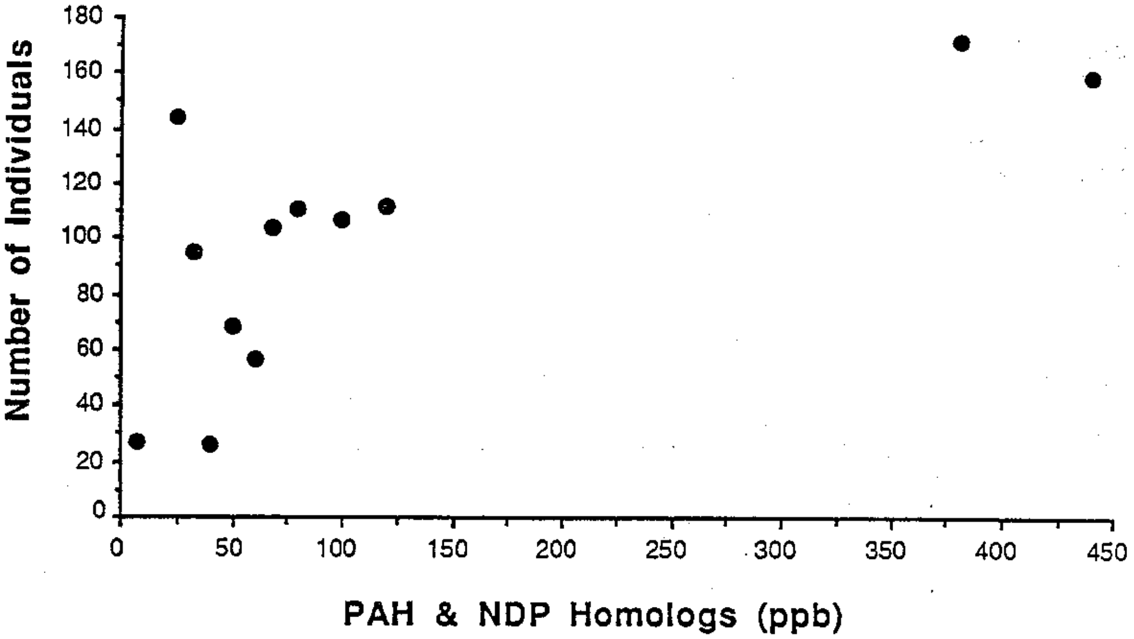


Figure 8.30. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) and total homologs of naphthalene, dibenzothiophene and phenanthrene (NDP) for the Golden Meadow primary site.

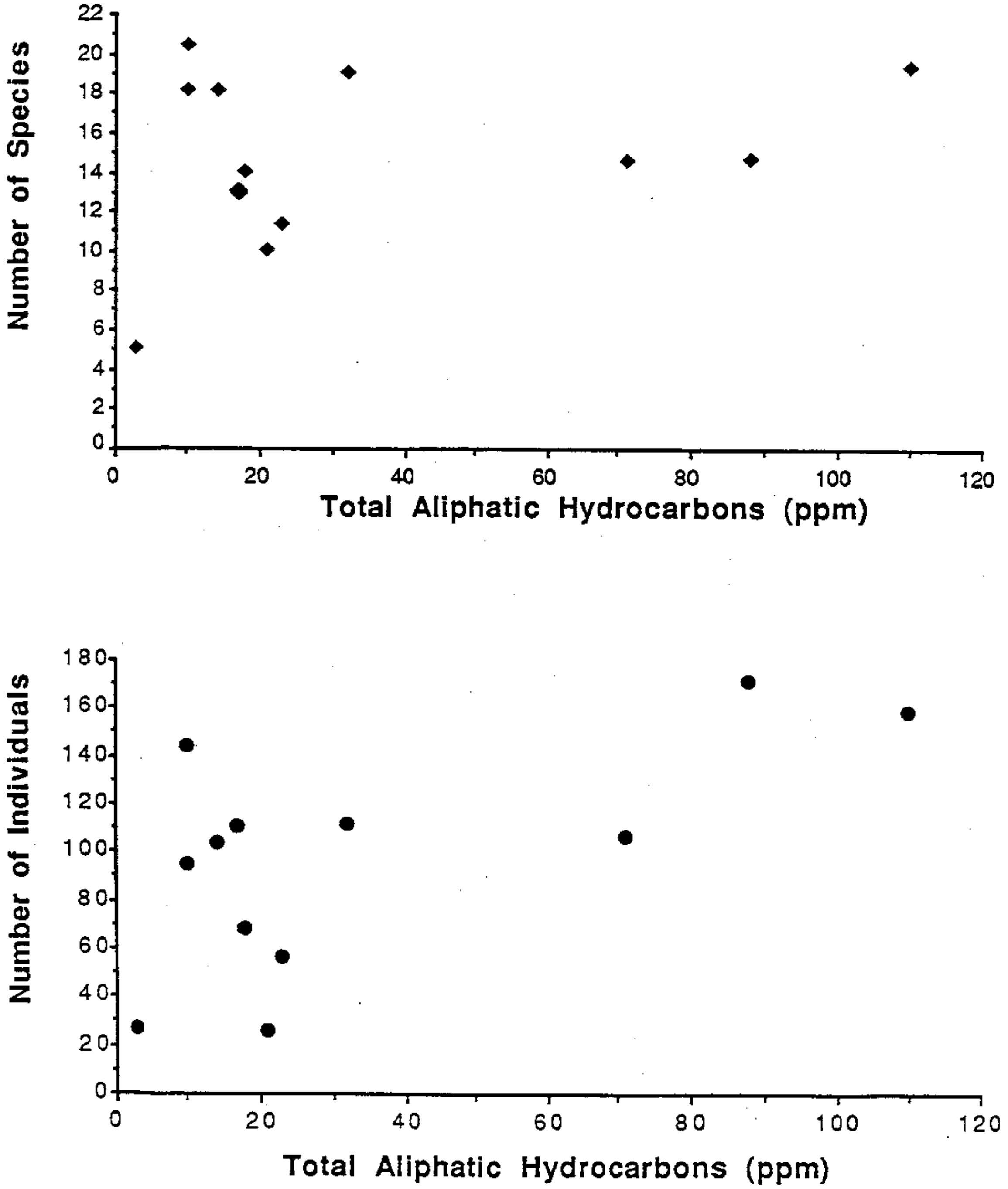


Figure 8.31. Comparison of number of species, above, and number of individuals, below, to total resolved and unresolved aliphatic hydrocarbons for the Golden Meadow primary site.

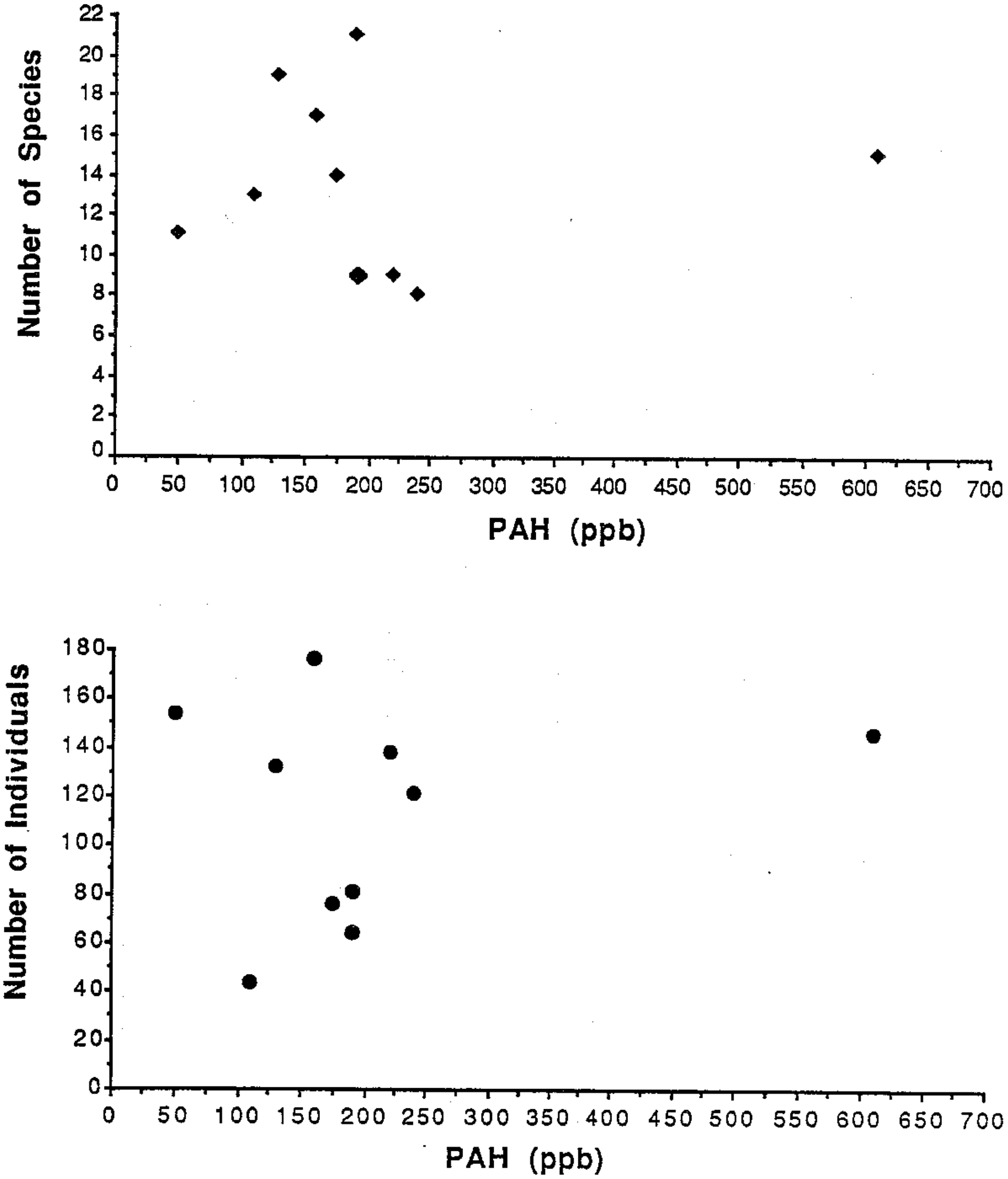


Figure 8.32. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons (PAH) for the Golden Meadow secondary site.

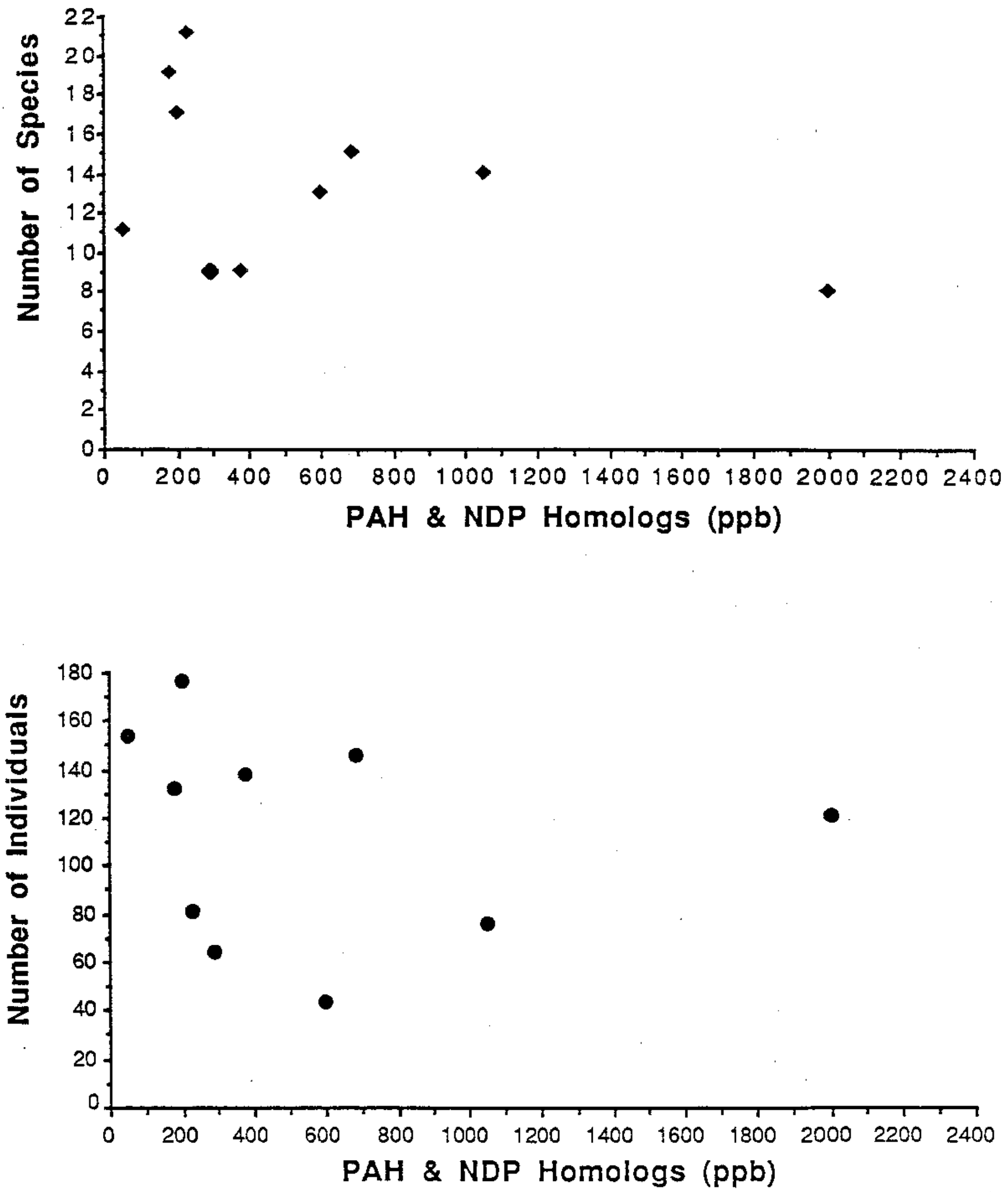


Figure 8.33. Comparison of number of species, above, and number of individuals, below, to total polynuclear aromatic hydrocarbons and total homologs of naphthalene, dibenzothiophene and phenanthrene (NDP) for the Golden Meadow secondary site.

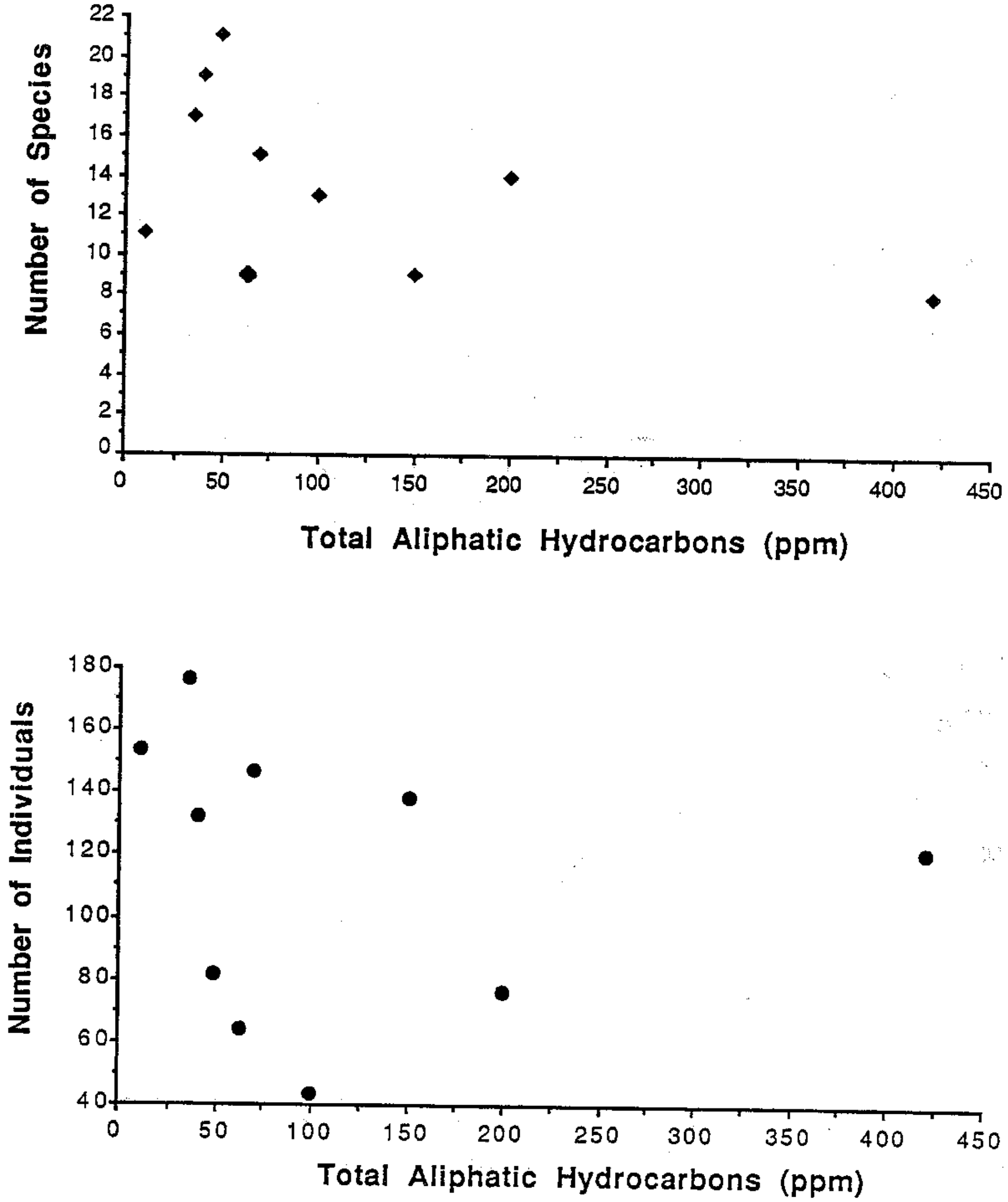


Figure 8.34. Comparison of number of species, above, and number of individuals, below, to total aliphatic resolved and unresolved aromatic hydrocarbons.

Chapter 9

SYNTHESIS AND CONCLUSIONS

by

Donald F. Boesch and Nancy N. Rabalais

9.1 Scope and Limitations of Study

This study included a modeling component which examined the effects of produced water discharges on salinity patterns within the Bararatia and Terrebonne estuarine basins and field and remote sensing components which focused on only three of the over 200 oil and gas fields in coastal Louisiana where produced waters are discharged. Generalizations from the study results, therefore, depend on the degree to which the two estuarine basins and the three study sites represent conditions which are at least typical, and preferably are subject to larger impacts than the norm, for estuarine produced water discharges in Louisiana.

The Barataria estuary receives the largest volume of produced water discharges of any well enclosed estuarine basin in Louisiana (Boesch and Rabalais, 1989). Larger volumes are discharged into the Vermilion and Chandeleur basins, but those are dominated by large volume discharges into open bay waters. Much more produced water is discharged into wetland habitats in the Barataria estuary than in any other estuarine basin. Based on the volume of discharges and the more enclosed nature of the estuary, the Barataria basin represents the greatest potential that estuarine salinity would be affected on large scales by produced water discharges. The Terrebonne estuarine basin receives about one half of the volume of produced water as the Barataria Basin. The majority of the discharges in the Terrebonne system is into open bays (Terrebonne and Timbalier Bays and Lake Pelto).

The Mid-Continent Oil and Gas Association decided to limit this study to fresh and brackish marsh environments for two reasons: 1) several studies had already investigated the effects of produced water discharges into higher salinity environments and open bays; and 2) produced water discharges were alleged to be causing loss of wetlands less tolerant of salty conditions which might result from these discharges. The three study sites were selected by the LUMCON team based on an examination of the oil and gas fields in brackish and fresh environments at which fairly large quantities of produced waters were discharged in close proximity to wetlands. Fields which had only very small discharges and at which discharges were made into extensive open waters were not considered. All three fields had several discharges of over 1,000 bbl/day. The vast majority of discharges in coastal Louisiana are of less than 500 bbl/day; only 10% are over 5,000 bbl/day and most of those release their effluents into open waters.

All oil and gas fields within wetland habitats in coastal Louisiana are characterized by extensive canal development which confounds the effects produced waters may have on wetland vegetation in two ways. First, spoil banks tend to partially isolate the marsh surface from the waters of canals or bayous which receive the produced water effluents. Second, the direct and indirect effects of canal development tend to be the overwhelming cause of wetland losses within the field. These two factors are likely to be equally important in any other field which could have been selected.

This study made no attempt to assess the effects of produced water discharges which are released directly onto the marsh surface, either from the end of a pipe, a leak or by seepage from a containment pit. In such cases, the high salinity produced water will locally stress wetland vegetation and may be a cause of marsh loss. The effects of these practices were not examined because the sponsor wished to investigate the potential impacts of only these discharges that the state would reasonably be expected to continue to permit. Rather, this study focussed on discharges which are made directly into tidal waters.

Finally, it should be noted that this study was a short-term investigation involving a single sampling effort for each study site. We were not able to evaluate seasonal and other temporal trends nor the effects of different hydrological conditions on the distribution of contaminants.

9.2 Effects of Produced Water Discharges on Estuarine Salinity

Two lines of evidence are available from this study from which to evaluate the notion that produced water discharges increase estuarine salinity: localized field hydrographic and water quality measurements and whole-basin modeling of estuarine salinity patterns. Field hydrographic measurements showed that a bottom-hugging plume of diluted produced waters was typically found down-current of the discharge. Initial dilution of the effluent, as deduced from salinity measurements taken proximal to the discharge, was of the order of 20-fold under the current conditions which prevailed at the time of sampling. Discharges into dead end canals or during slack tidal conditions are probably less rapidly diluted initially. Moreover, the extent of initial dilution should be a function of the rate of produced water discharge. For example, an order of magnitude larger discharge into a dead-end canal system at Pass Fourchon was not diluted 20-fold until 800 m from the actual discharge point (Boesch and Rabalais, 1989).

The bottom plume of diluted produced water is transported along with the current and is gradually mixed by turbulent processes, such that, for the sites and times studied here, no increases of salinity over ambient levels were observed beyond 1,000 m of the discharges at the three sites. Importantly, although increases in salinity of up to 4 ppt were observed 2 to 3 meters deep just above the bottom, the increase in salinity in surface waters was observed to be less than 1 ppt, even in the immediate vicinity of the discharge. This is an important consideration in evaluating the effects of increased salinity on wetland vegetation. The water which floods onto the wetland surface and comes in contact with the plants is surface water.

The modeling study component provided a basis for evaluating the effects of brine discharge on estuarine salinity on larger scales. Comparisons of the estimated mass of salt dissolved in estuarine water within segments of the Barataria and Terrebonne basins with the mass emission of salt into those sedments from produced water discharges showed that it would take at least 2.7 years for the estuarine segment with the largest volume of discharges (middle Barataria basin) for the salinity level to double assuming no tidal or wind-forced exchange or freshwater input whatsoever. However, as a result of freshwater input and tidal mixing, 90% of the volume of middle and lower Barataria Bay is exchanged every 1.75 months, a period during which salinity would have increased by only 5% assuming the segment had remained static. As one can see, the situation is analagous to trying to fill a leaky bucket which is able to drain out much faster that it can be filled.

When one combines the results of estuarine basin-scale modeling and field hydrographic measurements, it becomes clear that present produced water discharges result in only localized (several km at most) increases in salinity, mainly in bottom waters, and that the effect on salinity within major segements of the estuaries is negligible.

9.3 Effects of Produced Water Discharges on Wetland Vegetation

The availability of historical aerial photography allowed us to carefully document the changes in the aerial extent of wetlands within the three fields studied from before produced water discharges began in these regions to the present. Contemporary field studies provided insight into differences in plant species composition and biomass as a function of proximity to produced water discharges.

The analysis of historical aerial imagery clearly demonstrated the major effect construction of a dense network of canals for access to well sites and pipeline transportation has on wetland loss. This study did not compare wetland loss rates in channelized and non-channelized reference areas, but compared loss rates between similarly channelized areas which either received or did not receive produced water discharges. Consequently, it is not designed to assess the impact of channelization. Nonetheless, a large portion of the losses observed since the 1940's in these fields (10 to 30%) were directly attributable to canals and associated spoil banks. Much of the remainder of the losses were within marsh areas which were partially impounded by the spoil bank system and are presumed to be an indirect effect of canal construction. In any case, the rate of wetland loss not directly attributed to canal construction within the areas receiving produced water discharges was equal to or less than the rate within similarly channelized, reference areas.

This suggests that there was no effect of produced water discharges on marsh loss or, at least, that this effect was very small (and hard to separate) in comparison to the effect of canal construction. The alternate hypothesis that produced water discharges contributed equally to the losses not directly attributed to canals in both discharge and reference areas is not plausible based on the observed rate of dilution of produced waters and the distance of reference sites from discharges.

The field studies of wetland vegetation showed that there was no significant difference in plant biomass between discharge and reference areas except at the Golden Meadow primary and secondary sites. The sampling plots which yielded lower biomass at Golden Meadow were also characterized by much higher soil hydrocarbon levels, suggesting that a spill or leakage of oil or produced water onto the marsh surface may have been the cause of lower plant biomass. Although there were differences in relative abundance of plant species at the Golden Meadow and Lafitte sites, these differences were not consistent with the possible occurrence of higher salinity at the discharge site. The more salt-tolerant species were, in fact less abundant near the discharge. At the Golden Meadow site, altered hydrology likely created conditions in which the highly flood tolerant *Spartina alterniflora* dominated the treatment site.

As discussed in section 9.2, it is unlikely that the salinity of water flooding the marsh could be elevated sufficiently (i.e. by greater than 2 ppt) to cause death to brackish or tidal freshwater marsh plants or to affect species replacement, except where the discharges are directly onto the marsh surface or into very shallow ditches. Produced waters may affect marshes by chronic contamination from a thin sheen of floating oil which is frequently observed in association with the discharges. The presence of spoil banks in the vicinity of many discharges may reduce the direct exposure of the adjacent marsh to any contaminants concentrated at the air-water interface. Nonetheless, many of the marsh soil samples in the vicinity of discharges contained slightly elevated levels of petroleum hydrocarbons, possibly from this source or from spills. However no significant reductions in plant biomass or species composition were noted, except at Golden Meadow.

9.4 Chemical Contamination from Produced Water Discharges

In addition to high concentrations of dissolved salts, produced waters contain elevated levels of petroleum hydrocarbons (particularly aromatic hydrocarbons), hydrocarbon homologs, organic acids and other partially oxidized hydrocarbons, and some trace metals. Table 9.1 shows that the levels of major hydrocarbon types and selected trace metals in the discharges at sites studied here are similar to those in the large volume OCS-related discharges at Bayou Rigaud, Pass Fourchon and East Timbalier Island studied by Boesch and Rabalais (1989).

Table 9.1. Comparison of hydrocarbon and metals concentrations in produced waters discharged at sites included in this study with those measured for OCS produced waters discharged at coastal Louisiana sites by Boesch and Rabalais (1989).

	Bayou Sale	Lafitte	Golden Meadow		Bayou Rigaud		Pass Fourchon	East Timbalier
			TB7	TB8	Conoco	Exxon		
Hydrocarbons (mg/l)								
Volatiles	2,116	2,446	3,446	4,137	4,545	2,392	2,804	2,085
PAH	890	530	290	645	1,326	88	520	880
Saturated	4,800	4,900	3,700	5,750	45,000	6,400	16,400	13,000
Selected Metals (mg/l)								
Cu	0.25	0.18	0.30	0.40	0.05	0.36		
Zn	0.05	0.04	0.06	0.09	0.01	0.04		
Fe	2.03	10.1	8.14	4.86	3.14	5.53		
Ba	23.7	33.8	52.6	45.3	39.2	20.0		

The principal impacts uncovered in this study are related to the contamination of the estuarine environment with organic compounds and metals contained in the produced waters. Measurements of contaminants in surface receiving waters are reported here only for Bayou Sale. At Bayou Sale, only the receiving water immediately at the discharge site showed elevated levels of organic and metal contaminants, however these samples were taken from surface waters rather than bottom waters. Volatile aromatic hydrocarbons, such as benzene and toluene, which are relatively toxic but ephemeral in the environment, probably constitute the most likely cause of any effects in the water column. Several observations suggest this: 1) they are present in high concentrations in produced water; 2) the dispersion of the salinity plume along the bottom indicates that toxic concentrations may be found within several hundred meters of a discharge; 3) volatile aromatic hydrocarbons were detected in some bottom sediment samples, indicating their presence in overlying waters; and 4) measurable concentrations were detected in bottom waters in a previous study (Boesch and Rabalais, 1989).

More dramatic is the contamination of fine-grained bottom sediments which is evident at virtually every produced water discharge which has been studied. This is a result of the more intimate exposure of bottom sediments to the dense produced water plume, the sorption of hydrophobic organic compounds onto fine-grained sediments, and the precipitation of some inorganic components, such as barium. Trace metals, in general, seem less prone to this accumulation in the sediments in the vicinity of discharges than organic compounds. Among the organic compounds, only the hydrocarbons have been measured; although accumulation is also possible for other organic compounds, these compounds are generally more soluble and have less affinity for sediments than hydrocarbons.

Table 9.2 compares levels of hydrocarbons found in bottom sediments at the three sites studied here with those found by other studies in estuarine environments in Louisiana and Texas. There is considerable variation in the level and extent of bottom sediment contamination at these sites which seem largely a function of the volumes discharged and the hydrodynamic and sedimentologic features of the sites. The heaviest contamination and the most extensive impacts were seen where the discharge volumes are extremely large (Bayou Rigaud) or where the tidal flushing rates are low (the dead end canal system at Pass Fourchon). Given comparable discharges, less contamination is witnessed in regions with vigorous tidal flushing, such as Golden Meadow, compared to less flushed sites, such as Lafitte.

Although the zone of distinguishable contamination of bottom sediments by petroleum hydrocarbons was limited to within hundreds of meters from the point of discharge, there are many unanswered questions regarding the ultimate fate and potential far-field effects of sediment-borne contaminants in these shallow estuarine sediments. Sediment resuspension by tidal currents, wind waves and vessels is frequent. This brings into question the fate and effects of contaminated suspended sediments within the estuarine system.

9.5 Effects of Contamination on Estuarine Organisms

The more acutely toxic components of produced waters, such as the volatile aromatic hydrocarbons, may result in mortality or sublethal effects on estuarine biota within the mixing zone of the discharge (generally within 1 km). Bioassays of produced waters have shown that most crustaceans tested had LC_{50}s less than 10% produced water. LC_{50}s for brown shrimp larvae were approximately 1% produced water (Rose and Ward, 1981).

The results of the benthic community analyses should be placed in the context of the environments sampled and the design of the station arrays. As mentioned in Section 9.1, the three study sites were limited to tidal freshwater and brackish marsh environments. As with all oil and gas fields in wetland habitats in coastal Louisiana, extensive canal development

Table 9.2. Comparison of hydrocarbon levels in bottom sediments in relationship to distance from produced water sources for eight estuarine discharge sites.

Location	Station	Distance from nearest discharge (m)	Total Alkanes (ppm)	PAH (ppm)
Bayou Sale (this study) (2,500 bbl/day)				
Proximate to Discharge	BS0	10	1,200	3.9
Moderate Contamination	BS500E	500	260	0.64
Background	BS1000E	1,000	24	0.06
Lafitte (this study) (3,676 bbl/day)				
Proximate to Discharge	L0	10	350	1.2
Moderate Contamination	L500NE	500	110	0.39
Background	L750NE	750	41	0.13
Golden Meadow (this study) (2,845 bbl/day)				
Proximate to Discharge	GM0	10	88	0.30
Moderate Contamination	GM100S	100	110	0.21
Background	GM1000S	1,000	14	0.4
Bayou Rigaud (Boesch and Rabalais, 1989) (105,000 bbl/day)				
Proximate to Discharge	BR1, Oct	200	1,300	27
Moderate Contamination	BR3, Oct	800	98	0.2
Background	BR4, Oct	1,300	38	<0.1
Pass Fourchon (Boesch and Rabalais, 1989) (45,000 bbl/day)				
Proximate to Discharge	PF2, Jan	400	650	43
Moderate Contamination	PF7, Jan	600	5.2	0.2
Background	PF11	2,800	37	2.2
East Timbalier Island (Boesch and Rabalais, 1989) (20,000 bbl/day)				
Proximate to Discharge	T1, Jan	10	57	2.3
Moderate Contamination	T4, Jan	50	16	1.3

Table 9.2. Continued.

Location	Station	Distance from nearest discharge (m)	Total Alkanes (ppm)	PAH (ppm)
Lake Pelto (Neff et al., 1989) (3,700 bbl/day)				
Proximate to Discharge	1,5,9,13	20	163	5
Moderate Contamination	2,6,10,14	100	44	4
Background	3,5,7,11,15	300	27	0.3
Trinity Bay (Armstrong et al., 1979) (4,000-10,000 bbl/day)				
Proximate to Discharge	--	--	62	34

characterizes the environment. Within each of the study areas, most stations were located within canals or a natural water body that had been channelized. Oilfield service boat traffic in each area was active. Other stations were located in more shallow water not accessible to larger boat traffic or were located in natural bayous and waterways. Within each study area, station locations ranged from those in which fine sediments might accumulate but might also be resuspended periodically to those in which strong tidal flushing prevented the accumulation of sediments. Stations within the reference areas for each study site were situated as similarly as possible to those within the treatment area. The station array within each treatment area was also designed so that a gradient effect, if present, could be determined. Thus, many of the stations within the treatment areas at the greatest distance from the discharge point were more similar to those in the reference areas than to those near the discharge point. Given the one-time field sampling effort, we were not able to determine any seasonal or temporal trends nor variations due to different hydrological conditions and the effect those differences might have on the distribution of contaminants.

Two of the study areas, Bayou Sale and Lafitte, were relatively uniform in the environmental parameters most affecting the benthic communities, i.e., sedimentary characteristics. The Golden Meadow study area, on the other hand, was quite diverse in the range of environmental parameters associated with the benthos. Despite the heterogeneity of the study area, there were few apparent trends in benthic community parameters associated with environmental parameters measured. Differences, where seen, could be attributed often to the level of hydrocarbon contamination. The most diverse benthic community, in terms of number of species and in the measure of diversity (H') was the Golden Meadow site, where euryhaline and more marine organisms were both found. The second most diverse site was the tidal freshwater habitats of the Bayou Sale area. The Lafitte area was lower in species diversity.

The range of effects seen within the study areas were (1) low densities of organisms and few species under conditions of high to moderate hydrocarbon contamination of sediments, (2) changes in the species composition and population structure in areas of moderate contamination, or (3) no obvious effects in areas of low hydrocarbon contamination. The levels of contamination reported for the three areas in this study were generally an order of magnitude less than those reported for more saline environments with larger volumes of produced water discharges (Boesch and Rabalais, 1989) (Table 9.2).

The Lafitte study area had the highest levels of PAH (1,200-1,500 ppb) and total PAH and NDP homologs (1,000-5,000 ppb) and was also the area where the benthic communities were the most affected. Total aliphatic hydrocarbon levels were similar to most of the other study areas. Numbers of species and numbers of individuals were negligible or reduced within 250 to 500 m of the discharge point. Two stations at greater distances (750 m) were also reduced and had moderate hydrocarbon contamination. Even within the reference area at the Lafitte site, where there were reduced numbers of individuals and species, there were moderate levels of hydrocarbon contamination, the source of which is unknown.

Moderate contamination levels of PAH (600-650 ppb) and total PAH and NDP homologs (1,000-2,000 ppb) were found near the discharge point at the Golden Meadow secondary site and near the discharge point and surrounding stations at the Bayou Sale site. Numbers of individuals and species were reduced at the discharge point and nearby stations at the Golden Meadow secondary site. In the case of Bayou Sale, however, the number of species was reduced at the discharge point but the number of individuals was greater than any other station. In this case, a few species of oligochaetes made up these high numbers. Tubificid oligochaetes inhabiting tital freshwater and estuarine areas respond to physical disturbance and organic pollution by increasing population size (Diaz, 1980). Stations at the eastern end of the station grid at the Bayou Sale discharge site were low in number of individuals and/or species; these stations had moderate hydrocarbon contamination.

There were no trends in benthic community parameters with distance from the discharge point at the Golden Meadow primary site. The hydrocarbon contamination levels were also lowest among the discharge sites studied. The long-term average volume of produced water discharged at the primary site was also lower than that of the secondary site (2,300 bbl/d compared to 3,800 bbl/d). Where hydrocarbon contaminant levels were low at this study site and at stations within other study sites, the numbers of individuals and numbers of species were variable and not obviously related to any hydrocarbon parameters measured.

While the analyses of contaminants in bivalve tissues conducted here and by Boesch and Rabalais (1989) involved comparing specimens collected very close to discharges to those far removed, with no intermediate sampling, there was a similar pattern of bioaccumulation of petroleum hydrocarbons near the discharge apparently from produced waters. While the question of bioaccumulation and biomagnification has been addressed, to a degree, in the literature (Neff, 1988), the significance and mechanisms of bioaccumulation deserve more in-depth study in order to properly investigate the potential for human health and ecological effects resulting from the uptake of produced water-associated contaminants by estuarine organisms.

LITERATURE CITED

Armstrong, H. W., K. Fucik, J. W. Anderson and J. M. Neff. 1979. Effects of oilfield brine effluent on sediments and benthic organisms in Trinity Bay, Texas. Mar. Environ. Res. 2:55-69.

Barrett, B. B. 1971. Cooperative Gulf of Mexico Estuarine Inventory and Study, Louisiana. Phase II, Hydrology and Phase III, Sedimentology. Louisiana Wildlife and Fisheries Commission, New Orleans, Louisiana, 191 p.

Boesch, D. F. and N. N. Rabalais, editors. 1989. Produced Waters in Sensitive Coastal Habitats: An Analysis of Impacts, Central Gulf of Mexico. OCS Report/MMS 89-0031, U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, Louisiana, 157 p.

Brown, W. S. and E. Arellano. 1980. The application of a segmented tidal mixing model to the Great Bay Estuary, N. H. Estuaries 3:248-257.

Butler, T. J. 1975. Aquatic Metabolism and Nutrient Flux in a South Louisiana Swamp and Lake System. Unpublished M.S. Thesis, Louisiana State University, Baton Rouge, Louisiana, 58 p.

Chabreck, R. H. and G. Linscombe. 1978. Vegetative type map of the coastal Louisiana marshes. Louis. Dept. Wildl. and Fish., New Orleans, Louisiana.

Day, P. R. 1954 - 1955. Report of the Committee on Physical Analysis. Soil Science Society of America.

Diaz, R. J. 1980. Ecology of tidal freshwater and estuarine Tubificidae (Oligochaeta). Pages 319-329 in R. O. Brinkhurst and D. G. Cook, eds., Aquatic Oligochaete Biology. Proceedings, First International Symposium on Aquatic Oligochaete Biology, Sidney, British Columbia, Canada. Plenum Press, New York, 529 p.

Dyer, K. R. and P. A. Taylor. 1973. A simple, segmented prism model of tidal mixing in well-mixed estuaries. Estuarine and Coastal Marine Science 1:411-418.

Eggler, W. A., A. K. Ekker, R. T. Gregg, E. Haden, A. Novak, R. Walden, H. Williams and R. J. Russell, eds. 1961. Louisiana Coastal Marsh Ecology. Technical Report No. 14. Coastal Studies Institute, LSU, Baton Rouge, Louisiana. Office of Naval Research Project Number NONR 1575 (03), Task order No. NR388 002, 273 p.

Gee, G. W. and Bauder, J. W. 1986 (2nd edition). Particle size analysis. Pages 383-441 in A. Klute (ed.) Methods of Soil Analysis, Part 1-Physical and Mineralogical Methods, American Society of Agronomy, Madison, Wisconsin.

Hanor, J. S., J. E. Bailey, M. C. Rogers and L. R. Milner. 1986. Regional variations in physical and chemical properties of south Louisiana oil field brines. Trans. Gulf Coast Assoc. Geol. Societies 36: 143-149.

Harper, D. E., Jr. 1986. A Review and Synthesis of Unpublished and Obscure Published Literature Concerning Produced Water Fate and Effects. Report to Offshore Operators Committee by D. E. Harper, Jr., Texas A&M University Laboratory, Galveston, Texas.

Hydrolab Corp. 1984 (Rev. 1985). Operation and maintenance manual for Hydrolab Surveyor II. Hydrolab Corp., Austin, Texas, 59 p.

Ketchum, B. H. 1951a. The exchanges of fresh and salt water in tidal estuaries. J. Mar. Res. 10:18-38.

Ketchum, B. H. 1951b. The flushing of tidal estuaries. Sewage and Industrial Wastes 23:198-209.

Kjerfve, B. 1971. A field study of Airplane Lake, Lake Palourde and Lake Laurier area of coastal Louisiana. Unpublished manuscript, Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana, 31 p.

Kjerfve, B. 1973, Dynamics of the Water Surface in a Bar-Built Estuary. Unpublished Ph.D. Thesis. Louisiana State University, Baton Rouge, Louisiana, 91 p.

Marmer, H. A. 1948. The Currents in Barataria Bay. Publication of the Texas A&M Research Foundation. Project No. 9., College Station, Texas.

Mendelssohn, I. A. and K. L. McKee. 1987. Experimental field and greenhouse verification of the influence of saltwater intrusion and submergence on marsh deterioration: Mechanisms of action. Chapter 8, Pages 145-180 in R.E. Turner and D.R. Cahoon (eds.), Causes of Wetland Loss in the Coastal Central Gulf of Mexico. Volume II: Technical Narrative. Final report submitted to Minerals Management Sevice, New Orleans, Louisiana. Contract No. 14-12-0001-30252. OCS Study/MMS 87-0120, 400 p.

Muller, R. A. 1975. Freshwater potential in the Louisiana coastal marshes and estuaries. Geoscience and Man 12:1-7

Neff, J.M. 1988. Bioaccumulation and Biomagnification of Chemicals from Oil Well Drilling and Production Wastes in Marine Food Webs: A Review. Final Report to American Petroleum Institute, Washington, D.C., 54 p.

Neff, J.M., N.N. Rabalais and D.F. Boesch. 1987. Offshore oil and gas development activities potentially causing long-term environmental effects. Pages 149-173 in D.F. Boesch and N.N. Rabalais (eds.), Long-Term Environmental Effects of Offshore Oil and Gas Development. Elsevier Applied Science, London, 708 p.

Neff, J. M., T. C. Sauer and N. Maciolek. 1989. Fate and Effects of Produced Water Discharges in Nearshore Marine Waters. American Petroleum Inst. Publ. No. 4472, American Petroleum Institute, Washington, D.C., 338 p.

Okubo, A. 1973. Effect of shoreline irregularities on streamwise dispersion in estuaries and other embayments. Netherlands J. of Sea Res. 6:213-224.

Parrondo, R. T., J. G. Gosselink and C. S. Hopkinson. 1978. The effect of salinity and drainage on the growth of three salt marsh grasses. Bot. Gaz. 139:102-107.

Rose, C. D. and T. J. Ward. 1981. Acute toxicity and aquatic hazard associated with discharge formation water. Pages 301-328 in B. S. Middleditch (ed.), Environmental Effects of Offshore Oil Production. The Buccaneer Gas and Oil Field Study. Plenum Press, New York.

SAS Institute, Inc. 1982. SAS User's Guide. SAS Institute, Inc., Cary, North Carolina.

Schroeder, W. W., S. P. Dinnel and Wm. J. Wiseman, Jr. (in press) Stratification-destratification in a river-dominated estuary. Estuaries.

Schroeder, W. W. and Wm. J. Wiseman, Jr. 1986. Low-frequency shelf-estuarine exchange processes in Mobile bay and other estuarine systems on the northern Gulf of Mexico. In D. A. Wolfe, ed., Estuarine Variability. Academic Press, Inc., Orlando, Florida, 509 p..

Seaton, A. M. 1979. Nutrient Chemistry and the Barataria Basin - A Multivariate Approach. M.S. Thesis, Louisiana State University, Baton Rouge, Louisiana, 124 p.

Wicker, K. M. 1980. Mississippi Deltaic Plain Region Ecological Characterization: A Habitat Mapping Study. A User's Guide to the Habitat Maps. U.S. Fish Wildl. Serv., Off. Biol. Serv., Publ. No. FWS/OBS - 79.07, Washington, D.C.

Wiseman, Wm. J., Jr. and E. M. Swenson. 1988. Long-term salinity trends in Louisiana estuaries, Chapter 6 in Turner, R. E. and D. R. Cahoon (eds.), Causes of Wetland Loss in the Coastal Central Gulf of Mexico. Volume II, Technical Narrative. Final Report Submitted to Minerals Management Service, New Orleans, Louisiana. Contract No. 14-12-0001-30252. OCS Study/MMS 87-0120, 400 p.

Wiseman, Wm. J., Jr., E. M. Swenson and F. J. Kelly. (in review) Coastal ocean controls on estuarine salinities. In R. Cheng (ed.), Physics of Shallow Seas and Bays.

Wood, T. 1979. A modification of existing simple segmented tidal prism models of mixing in estuaries. Estuarine and Coastal Marine Science, 8:339-347.