OCS Study
MMS 91-0004

Fate and Effects of Nearshore Discharges of OCS Produced Waters

Volume I: Executive Summary

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U.S. Department of the Interior
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Volume I: Executive Summary

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COVER ILLUSTRATION

Aerial photograph of the East Timbalier Island study area with produced water treatment facilities. There are currently four active discharges and one discontinued discharge. Two discharges are generated on the Federal OCS. Black and white print of a color infrared photograph taken at 7000 feet by Wayne Grip of Aero Data Corporation. Orientation to the north.

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LIST OF ABBREVIATIONS

The following abbreviations may be used throughout this report:

AEC	acid-extractable compounds
Al	aluminum
Ba	barium
bbl	barrel
BR	Bayou Rigaud
COTR	Contracting Officer's Technical Representative
DBT	dibenzothiophene
DCM	dichloromethane
dpm	disintegrations per minute
EI	Eugene Island Block 18
EP	Emeline Pass
EPA	Environmental Protection Agency
EW	Empire Waterway
FFPI	Fossil Fuel Pollution Index
HC	hydrocarbons, usually total saturated hydrocarbons
LSU	Louisiana State University and A&M College, Baton Rouge
LUMCON	Louisiana Universities Marine Consortium
MMS	Minerals Management Service
Ni	nickel
nd	not detected
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
PAH	polynuclear aromatic hydrocarbons
Pb	lead
pCi	picocurie
PF	Pass Fourchon
ppb	parts per billion
ppm	parts per million
ppt	parts per thousand
Ra	radium
RP	Romere Pass
T	East Timbalier Island
TB	Tank Battery
Th	thorium
TOC	total organic carbon
tr	above background but below precision limit of method
TRI	Technical Resources, Inc.
VH	volatile hydrocarbons
VOA	volatile organic analysis
Zn	zinc

CONVERSIONS

1 bbl = 42 gallons = 159 liters

dpm ÷ 2.2 = pCi

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R. Hughes of LUMCON helped with data management and graphics. P. Swarzenski and S. Cenac of LUMCON drafted figures. D. Eschete, S. Cenac and L. Bonvillain prepared the manuscript.

EXECUTIVE SUMMARY

by

Nancy N. Rabalais
Program Manager

1 Introduction

During the production of crude oil, condensates, or natural 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 oil field brine. The water must be removed from the petroleum product as completely as possible in order to transport and use the product. This is conventionally done by pressurization and gravity separation. Water removal may also be enhanced by heat treatment or the use of demulsifiers. The separated produced water may be reinjected down a well, either for disposal or enhanced recovery of hydrocarbons, or as is the case of the vast majority of production from the northern Gulf of Mexico region, they may be discharged into surface waters of the ocean or coastal areas.

Approximately 95% of the oil and 98% of the gas produced on the Federal Outer Continental Shelf (OCS) comes from the central and western regions of the Gulf of Mexico. Much of the water produced in this process is separated and discharged from offshore production platforms. However, of the estimated 1 million barrels per day (1 barrel = 159 liters) of produced water generated on the Gulf OCS, a significant portion is piped ashore with the oil or gas streams and separated at shore-based facilities. While the number of facilities that discharge OCS produced waters into coastal environments of Louisiana are few in number, they account for large volumes, individually and collectively (Table 1). Our most current estimates (as of March 1991) indicate that 253,994 $bbl \cdot d^{-1}$ of produced waters originating on the Federal OCS are piped ashore for treatment and discharge in Louisiana State waters (Table 2). This represents 25% of the produced waters generated on the Federal OCS. These OCS-generated discharges represent 13% of all produced waters discharged into the State's waters (based on volumes reported as of 03/91 in Tables 1 - 3).

A previous Minerals Management Service (MMS) funded study (Boesch and Rabalais 1989) documented the general nature and extent of environmental contamination and biological effects at three areas of OCS-generated produced water discharges in Louisiana State waters. In general, this study found that sediment contamination and associated effects on the benthos extended beyond the region in which acutely lethal concentrations of contaminants would be expected to be found in waters receiving the dispersing plume. It also found that the limit of documentable contamination of the sediments was often set by an abrupt change in the depositional regime and sediment grain size. Because of the findings of the previous general study and the increasing need for information useful in the prudent regulation of OCS-related discharges, MMS provided funds for a follow-up study to provide information on more areas than investigated in the first study and to provide more resolution of the fate and effects of produced waters discharged from the previously examined and additional facilities.

The following goals of this study were identified:

1) Characterize the chemical composition of OCS produced waters discharged at coastal facilities in order to understand the variability.

2) Better define the spatial and possible temporal scale of impacts at the three areas previously studied (Boesch and Rabalais 1989).

3) Characterize the effects of produced water discharges from other OCS separation facilities located in different environments in the State's coastal environments (e.g., Mississippi River delta region, nearshore Gulf of Mexico).

4) Characterize the dispersion of contaminants in produced waters by field measurements of tracers of dissolved substances (e.g., salinity and radium).

5) Characterize the bioaccumulation of contaminants to marine organisms in the field.

2 Study Design

2.1 Study Areas

Of the 15 facilities which have been identified as discharging OCS-generated produced water into coastal environments of Louisiana (volumes reported as of 02/90 at the end of our field studies, Table 1), 10 facilities in seven areas were studied (Figure 1). Except for a few small volume discharges in Cameron Parish and another in Freshwater Bayou in southwestern Louisiana, most are found in the Mississippi River deltaic region from Atchafalaya Bay to the Mississippi River delta proper (Figure 1). Since identifying the discharges available for study, we have conferred with the operating company for verification or used existing permit applications from the Louisiana Department of Environmental Quality to determine the volume of produced waters discharged. The operators of the facilities that were designated for field studies provided estimates for volumes discharged at the time of the field collections and/or for a 25-month period from February 1988 - February 1990. These volumes are reported in Table 1. In addition, revised estimates as of March 1991 were provided by the operators for some of the discharges. Since completion of our field studies in February 1990, one of the OCS-generated discharges has been redirected offshore (T-1 in Table 1) and another has been completely directed to another facility (PF-1 OCS in Table 1). The discharge volumes of the OCS-generated produced water discharges range from approximately 3,000 to 106,000 $bbl \cdot d^{-1}$ (Table 1).

While the focus of this study was the discharge of OCS-generated produced waters in coastal Louisiana, the treatment facilities are very often located in close proximity to other OCS-source effluents and/or effluents from product streams generated in State waters. In addition to the OCS discharges, we also identified produced water discharges in the vicinity that were not generated on the Federally-controlled OCS (Table 3). Combination of the various volumes for each study site, both OCS- and State-generated, indicates there are large discharges of produced waters in any single receiving environment from one or as many as four facilities (see Table 5 in Section 3).

The receiving environments for these effluents are varied, but include the shallow, nearshore continental shelf; high energy, freshwater distributaries of the Mississippi River delta; and brackish to saline coastal environments with moderately to poorly flushed waters. All study areas are within the Mississippi River Deltaic Plain. This study expanded on the initial assessment of Boesch and Rabalais (1989) with increased temporal and spatial studies of three areas, additional study areas including an abandoned discharge, and additional analytical and field observations.

2.1.1 Primary Study Areas

Two locations were selected for seasonal and intense spatial sampling. These areas were sampled in the Boesch and Rabalais (1989) study on two occasions in 1987-1988 and displayed considerable sediment contamination. Sampling was conducted on four occasions--February,

May and October of 1989 and February 1990. These locations (Bayou Rigaud and Pass Fourchon) were also the areas selected for the bioaccumulation studies.

Bayou Rigaud is the location of two large discharges of OCS produced waters: the Conoco Grand Isle Shore Base and the Exxon Grand Isle Station (Table 1, Figures 1 and 2).

Pass Fourchon at the time of the field studies received two OCS produced water discharges (PF-1 OCS and PF-2 OCS) and a discharge generated in State waters (PF-2 State) (Tables 1 and 3, Figures 1 and 3). Changes in handling of product streams has occurred at all three facilities, but a large combined volume is still discharged at the location.

2.1.2 Secondary Study Areas

Additional locations were selected as secondary study areas because they represented the range of coastal environments receiving OCS produced waters and because of the size of the discharges. The secondary areas were sampled on one or two occasions:

East Timbalier Island is the location of several produced water discharges of significant volume (Figures 1 and 4). At the time of the field studies, two were discharging OCS-generated produced waters (T-1 and T-2 in Table 1, Figure 4). [One of these (T-1) has since been rerouted to the OCS (as of March 1991).] A third discharge, which had been generated on the OCS (TB 35 in Figure 4), was discontinued in 1988. In the general area for field studies, two additional discharges handle State-generated produced waters: Tank Battery 2 (TB 2) and Tank Battery 3 (TB 3) (see Table 3 and Figure 4). A large number of stations was sampled on one occasion in May 1989.

Eugene Island Block 18 is the location of a platform in the territorial sea just offshore of the remnant oyster reefs which demark the lower end of Atchafalaya Bay. The platform, situated in 2 to 3 m of water on the shallow continental shelf, is undoubtedly influenced by alternate deposition of sediments from the Atchafalaya River and wave scour of deposited sediments (Figure 1). Platform M, which discharges OCS-generated produced waters, also handles product streams from several wells in State waters (Table 1). This study area (Figure 5) was sampled twice: in May 1989 during high river flow and in November 1989 during low river flow.

Emeline Pass is one of the two study areas located in the Mississippi River delta proper (Figure 1). The study area is in a main distributary of the river. A single facility handles OCS produced waters (Table 1) and discharges into a marsh area next to the facility (Figure 6). On high river flow, which was the situation in April 1989 during sampling, the discharge may interchange with the waters of Emeline Pass. During low flow periods, as in the collections of October 1989 and as seen in the aerial photographs taken in November 1988, the discharge flows into the marsh away from the treatment facility.

Romere Pass is the second study area located in the Mississippi River delta proper (Figure 1). The study area is in a pass which connects to Main Pass, a major distributary of the river. There are two discharges of produced waters at the Romere Pass study area. One is generated on the Federally-controlled OCS (RP-1 OCS) and the second is generated within the State's territorial sea (RP-2 State) (Tables 1 and 3, Figure 7). The study area was sampled once in October 1989.

Empire Waterway is the location of a facility which currently discharges OCS-generated produced waters (Figure 1), as well as an abandoned discharge site (see below). The West Delta 30 Terminal is on an access canal which joins Empire Waterway. The final treatment process is a separation pond which empties through a discharge pipe into a slough in the marsh adjacent to the facility (Figure 8). The discharge is not located in the access canal where sample stations

were located. Drainage patterns from the slough and the marsh observed during the November 1989 field trip indicated that some of the effluent would possibly flow into the channel adjacent to the facility.

2.1.3 Abandoned Site

The Pelican Island Terminal was located on a dredged canal with access to Empire Waterway to the south of the West Delta Terminal described above (Figure 8). The facility is no longer in operation, and, at the time of the field studies in November 1989, was being dismantled. When discharging, the volume reported was an estimated 12,000 to 15,000 $bbl \cdot d^{-1}$; operations ceased in 1987. This site was selected as an abandoned discharge.

When we were developing this study, the Pelican Island Terminal was the only abandoned OCS discharge we were able to identify by comparisons with reported discharges by Gianessi and Arnold (1982) based on 1976 surveys. Since then, the OCS discharge at Chevron South Timbalier Block Tank Battery 35 (Figure 4) has ceased. In addition, since the end of our field studies, an OCS discharge at Tank Battery 21, 27, 28 in the East Timbalier Island study area (T-1 in Table 1, Figure 4) has been rerouted offshore, and the product stream for PF-1 OCS at Pass Fourchon has been routed to the PF-2 OCS facility (Figure 3). Other discharges from several of the study areas are scheduled for discontinuation.

2.2 Surveys of Contaminants and Biota

Within each of the study areas, a series of stations was designed for a general assessment of the fate and effects of the produced water discharge(s) in the receiving environment (see Figures 2 - 8). Detailed sample methodology is given in Chapter 3 of Volume II of this report.

The general characteristics of the water column in the study area were determined. Hydrographic profiles for standard water quality parameters were taken at each station. These included water depth, temperature, conductivity, salinity, pH and dissolved oxygen. Hydrogen sulfide (H_2S) was tested for in selected near-bottom waters of the receiving environment where any clear signal of elevated salinities and/or low dissolved oxygen levels were detected. In order to better characterize the receiving environments, water currents were measured at a station near a discharge point during the environmental assessment.

At each study area, produced waters and the near-bottom waters of the receiving water column were examined for contaminants. Produced waters generally have concentrations of dissolved salts much higher than sea water. In addition, they may contain elevated levels of inorganics (trace metals and sulfide) and organic (e.g., petroleum hydrocarbons) substances (Neff et al. 1989). Produced waters may also contain concentrations of radionuclides several times higher than typical coastal and marine waters (Reid 1983). Produced waters from the discharge points were sampled for salinity, hydrocarbons, trace metals, radionuclides and sulfides. The water column overlying the bottom near the discharge point and at selected stations along a gradient away from the discharge point were sampled for hydrocarbons and radionuclides.

Surficial sediments (10 cm) were sampled at all stations along a gradient away from the discharge for interstitial salinity, and hydrocarbon, trace metal and radionuclide (Pb-210) contaminants. At some stations, sediment cores were collected for vertical distribution of hydrocarbons, trace metals and radionuclides (Pb-210). Sulfides were not analyzed in sediments, since all sediments contain concentrations of sulfides under anaerobic conditions. Radium was not analyzed in sediments since it was expected to be soluble in the water column. Observations of high Ra-226 activities in sediments examined from stations near produced water discharges in brackish environments (St. Pé 1990) may be attributed to methodological

techniques in which the sediments were dried with interstitial waters intact prior to analysis for the radionuclide.

In order to properly characterize the receiving environments, to place the level of contaminants in context and to explain possible macroinfaunal distributions, general analyses of sedimentary characteristics were made. These included sediment total organic carbon (TOC), sediment grain size, and sedimentation rate measurements. Sediment grain size samples were analyzed from surface sediments at each station. Where vertical cores were taken, sediment grain size samples were taken for each 5-cm section down the core. Sediment TOC samples were taken for surface sediments, as well as a few blind replicates for quality control.

Bed sediments may serve as a temporary reservoir of particles available for resuspension into the water column and/or as a permanent burial site for particles (and associated contaminants). Selected radionuclides (Pb-210 and Th-234) can be used as tools to determine rates of sedimentary processes in bed sediments (Koide et al. 1973, Nittrouer et al. 1979). Pb-210 (22 year half-life) is useful in examining sedimentation rates over a 100-year time scale. This is accomplished by measuring the concentration profile of the radionuclide with depth in core, and calculating the time-averaged flux needed to maintain the observed concentration inventories in the seabed. By this method, the depth to which particles (and particle-reactive radionuclides) are buried at a site can be determined for 100-year time scales using Pb-210.

Bottom sediments were sampled for benthic macroinfauna along the same gradients as outlined above for sedimentary characteristics.

2.3 Bioaccumulation of Selected Contaminants

One of the objectives of this study was to examine the potential impacts of organic and inorganic contaminants associated with the discharges of produced waters into coastal environments, including any potential for extension of those impacts to man through the food chain. Many of the contaminants found in produced water discharges are toxic to aquatic organisms and to man, and many of the organic compounds are known or suspected mutagens or carcinogens. An aspect of this study, therefore, was to address the bioaccumulation potential of these contaminants. The approach used was to deploy an indigenous population of filter-feeding bivalves (the American oyster, *Crassostrea virginica*) at known distances from the discharge points for known periods of time. Two deployments were made at the Pass Fourchon and Bayou Rigaud study sites in April and May 1990 for 14 and 27 days, respectively.

2.4 Data Synthesis

The results of the field assessments were consolidated into a multi-component data base for characterizing the effects of produced waters on the water column, sediments and benthic biota. General hydrocarbon, trace metal and radionuclide data were combined with hydrographic data, sedimentological data and benthic community data. Standard benthic community parameters, including number of species, number of individuals and measures of species diversity were entered into the data base. The data provided the information needed to define the spatial and temporal scale of impacts. Differences in parameters (where replicated) were tested by analysis of variance and general linear model analyses. Simple correlations and multiple regression analyses were used to related species assemblage properties to location and environmental parameters.

An overall synthesis of the fates and effects of OCS produced waters discharged into coastal waters was based on the field assessments. The synthesis addressed the differences observed as related to the magnitude of the discharges, the total daily discharge rate in an area, the characteristics of the effluent and the characteristics of the receiving environment. A

synthesis team of all Principal Investigators (as listed in Table 4), as well as Donald F. Boesch and Thomas W. Duke, participated in the completion of the final synthesis product (Chapter 13 in Volume II). Much of the synthesis is reported in this volume; details of the study are given in Volumes II and III of this report.

3 Characterization of Produced Waters

Produced waters are one of a variety of wastes generated from oil and gas production wells (Neff et al. 1987). Produced waters are usually more concentrated in salinity than normal sea water (35 ppt) and range from 3 to 300 ppt (Rittenhouse et al. 1969). Produced waters analyzed in this study ranged between 43 and 192 ppt salinity. There was little variation in the salinity of the produced water discharge through time for those effluents sampled two or four times. Free sulfide may also be elevated in produced waters. Sulfide concentrations were high (120 μg-at $S \cdot l^{-1}$) in one of the discharges and elevated in several others (3.6 to 48 μg-at $S \cdot l^{-1}$). The remaining discharges were trace or not detected. Where elevated levels of sulfide were detected, the analyses were consistent across time for those discharges sampled more than once.

Produced waters contain high concentrations of organic compounds, primarily petroleum hydrocarbons but also partially oxidized organics. They also contain elevated levels of several metals. Radionuclides occur at elevated levels in produced water discharges, primarily as Ra-226, Ra-228 and Pb-210. The results detailed in Chapter 4 of Volume II provide the most detailed analyses to date for produced water effluents including a more thorough analysis of the semivolatile aromatic components.

Produced water discharges vary greatly in the amounts of organic and inorganic compounds. Similar compounds are found in each of the effluents, but the relative proportions differ with the facility and through time. Differences among facilities are related to the product streams which may come from multiple formations and to differences in treatment technologies. Temporal changes in concentrations of the various chemical constituents are related to changing chemistry of the product that is being treated, varying proportions of multiple and chemically different sources, changes in treatment technology, and efficiency of the separation. Concentrations of the hydrocarbon components varied the most among discharges and with time. Trace metal concentrations and Pb-210 and total radium activities also varied among discharges; trace metals and total radium activity were fairly consistent through time for a single effluent, while Pb-210 varied.

Produced water samples and near-bottom water samples from the receiving environment were analyzed by a volatile organic analysis (VOA). Compounds quantified using this method are referred to as volatile hydrocarbons (VH). These waters and sediment samples were also analyzed for semivolatile hydrocarbons. Naphthalene is quantified as both a volatile and semivolatile because it displays appreciable volatility at room temperature making it difficult to quantify accurately by either method. Naphthalene is a part of both the totals graphed for volatiles and semivolatiles. When naphthalene and its alkylated analogs are discussed, naphthalene values are from semivolatile calculations.

The largest components of the organic load of the produced water effluents in this study were the aliphatic fatty acids and the aromatic acids (Figure 9). The acid-extractable compounds are very water soluble and not readily sorbed onto particulate matter (Boesch and Rabalais 1987). Therefore, these compounds are less likely to be deposited in sediments, but are more likely to be diluted in the water column. The saturated hydrocarbons were the next highest in concentration (Figure 9), but these compounds are the least toxic fraction of crude oil and very susceptible to microbial degradation when deposited in the environment (National Research Council 1985, Boesch and Rabalais 1987). The volatile hydrocarbons (VH) and phenols made

up the next largest component of the produced water effluents. Of the volatiles, benzene and toluene composed 75% to 95%. The volatiles and phenols are highly water soluble and are acutely toxic to organisms exposed to high concentrations (National Research Council 1985, Boesch and Rabalais 1987). Their long-term fate, however, is to be diluted and dispersed in the water column.

The polynuclear aromatic hydrocarbons (PAH) were the smallest component of the identifiable hydrocarbons. This fraction, however, is the heaviest, most toxic and environmentally stable fraction of crude oil. The toxicity of crude oil is a reflection of its aromatic content, primarily the alkyl-substituted naphthalenes and phenanthrenes (National Research Council 1985, Boesch and Rabalais 1987). PAH are the most likely components of produced water discharges to be incorporated into the sediments because of low water solubilities and high sorption coefficients (Boesch and Rabalais 1987). Figure 10 shows the distribution of PAH in the produced water samples analyzed in this study.

The produced water effluents generally had barium (Ba), vanadium (V) and nickel (Ni) in highest concentrations. Zinc (Zn), copper (Cu) and chromium (Cr) were also found in high concentrations in most of the discharges. Cadmium (Cd), mercury (Hg) and lead (Pb) were also detected in various effluents. [The data for aluminum (Al) and arsenic (As) were not reported, because the high salt background caused interference in the analyses.]

Water samples were analyzed for a variety of radionuclides: Pb-210, U-238, and Th-234. [For comparison to values of radioactivity reported in the literature as picocuries, the conversion from disintegrations per minute (dpm) to picocurie units (pCi) is dpm ÷ 2.2 = pCi.] In all water samples, both produced waters and near-bottom waters, U-238 and Th-234 activities were below detection levels (<0.5 and <0.8 $dpm \cdot l^{-1}$, respectively). This lack of enhanced uranium and thorium activity indicates strongly that the high radioactivity levels associated with produced waters originate with the radium isotopes and is not supported by radioactive parents of radium which are higher in the decay chain.

Produced waters from the sites examined had total radium radioactivities from 304 to 2312 $dpm \cdot l^{-1}$. Total radium is the sum of Ra-226 and Ra-228 activities. The ratio of Ra-226/total Ra varies from site to site for produced waters, but in most cases the Ra-226 activity constitutes more than two-thirds of the total radium activity. The total radium activities observed are approximately 150 to 1150 times higher than natural waters. All discharges sampled had total radium activities which were in excess of the 111 $dpm \cdot l^{-1}$ activity designated by the Environmental Protection Agency (EPA) as hazardous waste. Total radium activities of these produced waters correlated well with the salinity of the effluent.

Produced waters from the sites examined had Pb-210 radioactivities ranging from 0.21 to 25.4 $dpm \cdot l^{-1}$. These values are two to 254 times higher than natural waters. Differences in Pb-210 activities in produced water may be due to differences in the suspended sediment concentrations of these waters. Pb-210 is very particle-reactive, quickly sorbing onto particle surfaces; therefore, the settling out of particulate matter during treatment may change the total Pb-210 activity of the water sample.

Several factors determine the fate and effects of produced waters in coastal environments and organisms. These include the volume and composition of the discharge and the hydrologic and physical characteristics of the receiving environment. Comparisons of the produced water discharges can be approached by calculations of loadings of particular contaminants. Examples of PAH daily discharge rates for the individual effluents and totals for study areas with more than one discharge are shown in Figure 11. This comparison takes into account the daily discharge rate and concentration of the PAH in the effluent.

Similarly, the loadings of the PAH and other constituents can be combined for all discharge points in a single study area (Table 5). A lower volume discharge in a study area may be compensated for by a high concentration of a single constituent, e.g. volatile hydrocarbons or barium; or vice versa, a contaminant may not be particularly concentrated in the effluent, but the volume may be large and the total loading may be similarly large. These comparisons provide a context for the relative contribution of potentially traceable contaminants to a receiving environment.

The treatment of produced waters varies among facilities but may include heat treatment, gravity separation, aeration and settling ponds, and chemical additives. The purpose of the various treatments is to remove the particulate or dispersed oil in order to reduce the overall oil and grease content of the discharge. Comparison of variability among the discharges and through time with respect to treatment technologies was not possible because of limited information on the technologies employed. However, we were able to illustrate changes in the produced water effluent at two points in the treatment process for the Exxon discharge at Bayou Rigaud. The "Pre" and "Post" aeration pond samples indicated a reduction in the concentrations of volatile hydrocarbons, acid-extractable compounds, polynuclear aromatic hydrocarbons and Pb-210 activity, but not trace metals or total radium activity. These differences were attributed to aeration of volatile compounds and additional settling of particle-adsorbed contaminants in an open maze pond after gravity separation.

4 Comparison of Receiving Environments

As mentioned above, several factors determine the fate and effects of produced waters in coastal environments and on organisms, including, the volume and composition of the discharge and the hydrologic and physical characteristics of the receiving environment. An evaluation of the hydrological and sedimentological characteristics of each study area was made to determine the dilution potential of the environment. Dilution of water soluble contaminants would be influenced primarily by the volume of the receiving waters and the current velocity. With the exception of measurements taken on a high spring tide (Empire Waterway) and during a storm (Romere Pass and Eugene Island Block 18 in May 1989), current velocity measurements were assumed to be representative of similar conditions throughout the year.

Dispersion of sediment-adsorbed contaminants would be influenced by the bed shear stress which is proportional to the slope of the current velocity profile (i.e., potential for resuspension and transport), sedimentation rates, and the grain size distribution of the surface sediments. None of the Pb-210 vertical sediment profiles were acceptable for calculating sedimentation rates, because influx of Pb-210 greatly exceeded the natural decay rate for all the study sites. To calculate sedimentation rates, some decay in Pb-210 downcore must be observed. Accumulation of sediments was concluded from grain size distributions and/or surface sediment and downcore chemical contamination. Comparison of the receiving environments is shown in Table 6.

Two environments were characterized as having a high potential for dilution of contaminants: Emeline Pass (Figure 6) and Eugene Island Block 18 (Figure 5). Mean current velocities reach 9 $m \cdot s^{-1}$ in Emeline Pass, and the coarse-grained, low organic content sediments indicate active sediment transport close to the bed. Eugene Island Block 18 is located in open, shallow offshore waters adjacent to the Atchafalaya River delta (Figure 1). High freshwater flow influences the area. The high silt content of the surface sediments at this study area indicate the influence of sediment deposition from the Atchafalaya River plume; however, the shallow, inner continental shelf is expected to be subject to wind-induced events causing resuspension and rapid turnover of surface sediments.

On the other end of the continuum is the Pass Fourchon study area (Figure 3). Current velocities are consistently negligible (example in Figure 12); potential for sediment entrainment and transport is low. The sediments within the dead-end canal system are sandy muds or muddy sands. Abrupt transitions within the study area are apparent in increasing sand content at the station in closest proximity to the back of the sandy barrier shoreline and at those stations in the more tidally active Belle Pass. A notable change in the grain size distribution of the canal stations between two sample periods with a decrease in sand and an increase in silt indicates the potential for sediment accumulation but periodic shifts to sandier sediments probably related to storm events.

The remainder of the environments were characterized as having a medium potential for dilution of produced water contaminants. Current velocities were strong in Bayou Rigaud (Figure 2) and sufficient to resuspend and transport sediments during peak tidal flow (example given in Figure 13). The sedimentary regime, however, indicated periods of high silt content. Major shifts in sediment grain size composition between two sample periods would indicate periods of accumulation and periodic resuspension related to storms. Temporal variability in sediment-adsorbed hydrocarbon contaminants would also support periodic resuspension and accumulation of sediments.

A similar situation to Bayou Rigaud was found in Empire Waterway (Figure 8). Tidal currents were strong when measured (as noted above on a high spring tide) and indicated that the potential for sediment resuspension and transport was high. However, the high silt content of the sediments and the accumulation of contaminants near the abandoned discharge point indicated a depositional environment. Resuspension of sediments and shifts in sediment grain size distribution would be storm related as in Bayou Rigaud.

In Romere Pass sediments were sands, but fine-grained, and graded to silts on the northern end of the transect (Figure 7). Resuspension events in Romere Pass would be seasonal and related to the flow of the Mississippi River rather than storm related as in Bayou Rigaud and Empire Waterway. The influence of Mississippi River discharge along Romere Pass was seen in a north-south gradient in water column salinities.

Two hydrological and sedimentary environments were distinguished at the East Timbalier Island study area (Figure 4). The East Timbalier Island area was complex with regards to sedimentary, hydrological conditions and numerous produced water discharges (including one discontinued effluent). Current velocities, during the single sample period, indicated moderate flushing in the east-west canal parallel to the back side of the island along the southern end of Timbalier Bay where sediments were generally siltier but sands were coarser-grained. The access dead-end canal which was situated north-south in the study area was shallower, had sandier sediments typical of a back barrier washover area, and more sluggish tidal currents. The north-south canal was less well flushed and contained higher levels of sediment-adsorbed contaminants.

5 Dispersion of Brine Effluent

Because produced water effluents have salinity levels in excess of that of ambient sea water and may act as a dense plume upon discharge into receiving waters, the salt content of the bottom waters may be used as a conservative tracer of the brine plume. A clear density plume was identifiable only at the Pass Fourchon study site, and extended up to 800 m from the point of discharge (Table 6, Figure 14). Elevated salinity was found in the bottom water at a single station in the East Timbalier Island study site and was related to the produced water effluent (Table 6). Otherwise, no clear salinity signals were found that could be attributed to the produced water effluents (Table 6). Elevated interstitial water salinities of surface sediments

identified the same stations at Pass Fourchon and East Timbalier Island as being affected by the salinity plume (Figure 15).

Other tracers of the produced water effluent (VH, total Ra and sulfide) are water soluble and are not conservative, but their presence in near-bottom waters would indicate the extent of the produced water plume to at least the distance they were detected. In the case of VH, the extent of contamination of the water overlying the sediments by these chemicals was the same for Pass Fourchon (Figure 16) and East Timbalier Island as the salinity signal.

At Eugene Island Block 18, elevated VH in near-bottom waters was detected adjacent to the discharge and to some distance from the discharge whereas an elevated bottom water salinity was not. In a somewhat similar situation at Bayou Rigaud, elevated VH were detected in near-bottom waters near a discharge point and at uniformly low levels at several other stations even though a salinity plume was not detected in the bottom waters. Comparison of total loadings to a study site (Table 5) provides additional information concerning the dispersion of the brine effluent in the context of the receiving environment. For example, loadings of VH were large for Bayou Rigaud (primarily the result of the large volume) and Eugene Island Block 18 (primarily the result of high concentrations in the effluent). Detectable levels of VH were found in near-bottom waters at both of these study areas. In spite of a high dilution potential at Eugene Island Block 18 (Table 6), there were detectable levels of several VH at some distance from the discharge; the net loading of these constituents was important in their retention in the water column. Total loadings of VH were also high in the Pass Fourchon study area; this combined with a poorly flushed water column contributed to the retention of these contaminants in a density plume for some distance from the discharge. Loadings of VH were much lower for the remaining study areas. Of the five remaining areas, elevated levels of VH were found only at a single station at East Timbalier Island in a dead-end canal near the discharge point. The lack of flushing in this particular point compared to the moderately- to well-flushed characteristics of the other areas would account for VH contamination in spite of the relatively low loadings.

Sulfide levels were elevated in some of the near-bottom waters at Pass Fourchon; one of the effluents for the study area was high in sulfide. Elevated levels of sulfides in the near-bottom waters of some stations in the Romere Pass study area may be related to an effluent with a high sulfide content. Sulfides were not elevated in the remaining produced water discharges; but where an effluent contained high sulfides, there were indications that this constituent may be traced in the environment.

The levels of total radium activity in the near-bottom water potentially provide additional information to the salinity, VH or sulfide tracers concerning the dispersion of water column contaminants. At the Pass Fourchon study area, total radium activity was elevated above background level to a distance of 1000 m from the discharge point (Figure 17). VH and salinity signals were detectable only within 800 m of the discharge point. Elevated radium levels were detected at Bayou Rigaud, but there was no clear pattern to the distributions. At Eugene Island Block 18, higher total Ra activities paralleled the elevated levels of VH. In Romere Pass, total Ra three times above natural levels was detected at RP1000N (450 m from the discharge point) where there were no detectable levels of VH or elevated salinity. For both the East Timbalier Island and Empire Waterway study areas, total Ra activities were elevated well above background levels throughout the study areas. This indicates some level of water column contamination which was not indicated by the other tracers.

6 Sediment Contamination

6.1 Surface Sediments

Substantial contamination of fine-grained sediments with petroleum hydrocarbons of produced water origin was observed at all study areas with the exception of Emeline Pass and the active discharge facility at Empire Waterway. A comparison was made by study area of the distance from the discharge point where a sediment contaminant signal was identifiable (Table 7). Distance of contaminant effect was determined as the greatest distance where the concentration of the constituent was elevated above background levels or the FFPI (fossil fuel pollution index) indicated petrogenic origin hydrocarbons.

The extent to which sediment contamination was documented in distance from a discharge point is a function of the loadings of the contaminant (Table 5), the nature of the receiving environment (Table 6 and Section 4), and the partitioning of the chemical constituent in the environment. The fate of produced water source constituents were best determined from direct measurements of effluent-source hydrocarbons, particularly the alkylated PAH, rather than other constituents which are also associated with the discharge, e.g. barium and Pb-210. With the exception of the Bayou Rigaud study area, Ba was detected at least as far as or to greater distances from the discharge point than alkylated PAH and Pb-210 (Table 7). Because of inconsistent gradients of Ba with distance from the discharge (e.g., in Figure 18), characteristics of the geochemistry of Ba, or additional inputs to the systems from drilling fluids, Ba is not a particularly good tracer of sediment-borne hydrocarbon contaminants. With the exception of the Bayou Rigaud and Empire Waterway study areas, Pb-210 was found at elevated levels to equal to or less distances from the discharge point than elevated levels of PAH. Pb-210 is, therefore, not a particularly good tracer of sediment-borne hydrocarbon contaminants either. The concentration ratios of maximal Pb-210 concentrations to background levels were less than 10:1 compared to ratios of usually > 100:1 for alkylated PAH.

Elevated levels of alkylated PAH were found in the sediments at most of the study areas. Produced water origin PAH were found to the maximal distances of the study transects at both Bayou Rigaud and Pass Fourchon, 1300 and 1000 m, respectively (examples in Figures 19 and 20). More limited distances of effect were found for alkylated PAH at Romere Pass (450 m), East Timbalier Island (250 m), Eugene Island Block 18 (250 m) and the abandoned discharge at Empire Waterway (250 m).

Elevated levels of alkylated PAH were not found in surface sediments in the Emeline Pass study area and near the currently active discharge facility at Empire Waterway. The location of the discharge in both of these areas may account for lack of a contaminant signal in the receiving environment. The discharge point for the active treatment facility near Empire Waterway is next to a holding pond into a slough in the marsh adjacent to the facility. Drainage patterns from the slough and the marsh observed during field sampling indicated that some of the effluent would possibly flow into the access channel adjacent to the facility. The closest a sample station could be located to the discharge pipe was at 550 m. Drainage of the produced water effluent at Emeline Pass was not directly into the Pass but into a marsh area next to the facility. On high river flow, which was the situation in April 1989, the discharge may interchange with the waters of Emeline Pass. During low flow periods, as in the collections of October 1989 and as seen in the aerial photographs taken in November 1988, the discharge flows into the marsh away from the treatment facility. Emeline Pass has the added feature of being a high energy, river-dominated environment which would rapidly dilute any effluent which may enter the system.

6.2 Vertical Sediment Profiles

The concentration of hydrocarbons, trace metals and Pb-210 were analyzed for several vertical sediment cores at several of the study areas and for different time periods at some of them. Pb-210 activities in the vertical sediment profiles were not appropriate for calculation of sedimentation rates. Some decay in Pb-210 must be present with depth to calculate a sedimentation rate. The profiles obtained indicated either an increase in activity levels with depth or inconsistent variability with depth (Figure 21). We concluded that the profiles were due to several factors including varying input and disturbance of the sedimentary structure by dredging, boat traffic and/or natural events. This explanation is consistent with the hydrocarbon contamination seen in some of the vertical cores which indicates maxima in produced water origin hydrocarbons in both subsurface and/or with depth in the core. Such non-uniform distributions indicate varying inputs of contaminants to the sediments.

Hydrocarbon concentrations in vertical cores indicated 1) a decrease in overall concentrations with increasing distance from the produced water discharge point, 2) maximal concentrations in the upper sections of the cores at those stations closest to the discharge point, 3) subsurface maxima and additional peaks with depth in cores separated by lower concentrations in intervening sections, particularly in those closer to the discharge points, 4) very often a weathering of saturated hydrocarbons with depth in the core, and 5) elevated levels of hydrocarbons in the upper sections of vertical cores collected from the distal ends of study area transects usually indicative of pyrogenic hydrocarbon inputs. (See Figure 22 for example profiles from Pass Fourchon.) Changes in concentration of produced water hydrocarbons with depth in vertical cores are related to changes in mass loadings through time, variations in transport and deposition of contaminated sediments, resuspension and transport of contaminated sediments from the area during storm events, and transport of uncontaminated sediments into the area during storm events. The presence of high concentrations of produced water derived hydrocarbons to depths of 25 to 30 cm in a vertical sediment core in some of the study areas indicates the long-term accumulation of these contaminants and their resistance to degradation.

6.3 Abandoned Discharge

The study area at Empire Waterway included an abandoned discharge. The Pelican Island facility discontinued a discharge of approximately 12,000 to 15,000 $bbl \cdot d^{-1}$ in 1987. When the photomission was flown in November 1988, the facility was being dismantled; when sampled in November 1989, the marsh was being restored. Based on aerial photographs and communications with industry representatives, the point of the produced water discharge was determined to be near a pit along a slough in the marsh, somewhat removed from the dredged access canal. The distance from the discharge point to the closest station sampled was 250 m.

Alkylated PAH were detected at low concentrations at several stations along the transect adjacent to the abandoned discharge facility. In contrast, no significant levels of alkylated PAH were detected in any of the sediments along the transect near the active discharge. The maximum value was found at a station approximately 250 m from the discharge point at the Pelican Island facility, and concentrations decreased away from this point.

Vertical sediment cores analyzed from this study area showed maximal petrogenic contamination in surface sections, either 0-2 or 2-5 cm. In fact, the 2-5 cm section of the core from the station closest to the abandoned discharge point had the highest concentration of alkylated PAH for the entire Empire Waterway study area. Subsurface elevated levels of alkylated PAH of petrogenic origin were found in 20-25 cm sections of cores closest to the discharge point and to some distance from the discharge point. Despite the categorization of this study area as medium for dilution potential (Table 6), the sediments accumulate but are periodically resuspended and transported from the area (or into the area). The presence of

produced water origin hydrocarbons in relatively high concentrations with depth in the vertical sediment cores indicates the long-term accumulation of these constituents and their resistance to degradation.

7 Biological Assessments

Biological assessments of the impact of the produced water effluents were determined as changes in benthic communities along a gradient of distance from the discharge point(s) within each study area and by bioaccumulation studies of filter-feeding molluscs in a similar gradient at Pass Fourchon and Bayou Rigaud. The generalized results from these studies are shown in Table 8.

7.1 Benthic Communities

Benthic community parameters of mean number of species per replicate, mean number of individuals per replicate, mean diversity and mean evenness were calculated for each station along a transect away from the discharge or adjacent to the discharge. Analysis of variance indicated statistically significant differences among the station means of the number of species and number of individuals for most study areas. Results for diversity and evenness were ambiguous and were complicated by unequal sample sizes where the number of individuals in a replicate was zero. This discussion will be restricted to the parameters of number of species and number of individuals. Duncan's multiple range tests of the station means within each study area indicated that some groups of stations were distinct from others with regards to impacted fauna, but more often there was a gradient in impacts with distance from the discharge indicated by overlapping stations means in the analysis. Those station means that were distinctly different from other stations are labeled "Distinct" in Table 8; those with an overlap in the station means are labeled "Gradient." In three cases, the means for the benthic community parameters differed among stations, but these differences were not related to a gradient of distance or sediment contamination from the discharge point. These are labeled "No Effect" for both the Distinct and Gradient categories. Effects on benthic communities were generally negative in that they indicated loss of numbers of species and number of individuals compared to controls. It was not possible to determine from these studies ecological effects such as the manner in which the loss of biomass or specific organisms might adversely impact the structure of the ecosystem.

The most severely depressed benthic macroinfaunal communities were found within 500 to 800 m of the designated zero discharge point in Pass Fourchon (Figures 3 and 23). Benthic infauna was absent or substantially reduced at 400, 500, 600 and 800 m from the discharge point for most of the sample periods. Depending upon the positioning of the ship in the dead-end channel, benthic infauna was absent or reduced at PF600N and/or PF800N. Infauna was reduced in the deeper parts of the channel where the effluent density plume followed the bottom contours, but was present at higher topographic locations not impacted by the bottom-hugging effluent. The benthic fauna at PF600S and at distances of greater than 800 m to the north was not impacted by the discharges.

Impacts to the benthic communities were observed as far as 700 m in Bayou Rigaud, 300 m at Eugene Island Block 18, 100 m at East Timbalier Island, and within 550 m of the abandoned discharge at Empire Waterway. The impacts of accumulated and residual produced water contaminants adjacent to the abandoned discharge site indicate the persistent effects of these constituents on the benthic fauna and an unknown length of time for adequate recovery of the environment following cessation of effluents. It was not possible to estimate the time required for the affected benthic community to recover from the impact of the produced water, but evidently it exceeded the three years since the cessation of the discharge.

No effects on the benthic communities for the parameters analyzed were observed in the Emeline Pass and Romere Pass study areas. Both of these environments, however, were normally low in numbers of species and individuals. The depauperate fauna of Emeline Pass was a characteristic of the fine-grained, sandy, low organic sediments and the high energy river flow. The number of species and number of individuals were low in the Romere Pass study area, as expected in a brackish-to-fresh transition environment. Most species and individuals were found at the northernmost two stations on the transect where salinities were higher (Figure 7). The few number of stations in the Romere Pass study area limited the ability to find relationships with environmental parameters. There were positive relationships between the number of species and number of individuals with the primary chemical constituents of the sediments (i.e., parent PAH, alkylated PAH, total PAH, total HC, Al, Zn, Ni and Ba) but none of the relationships were strong or statistically significant.

Impacts on the benthic macroinfauna were consistent across season in the Pass Fourchon and Eugene Island Block 18 study sites (analysis of co-variance, $P < 0.05$). For the Bayou Rigaud and Emeline Pass study sites, there were significant differences among stations with regards to season.

Benthic community impacts were associated with levels of produced water chemical constituents in the sediments which generally decreased with distance from the discharge point(s). The threshold concentrations of contaminants at or above which the benthic community was affected varied among study areas. For example, the threshold level of alkylated PAH for East Timbalier Island was 5,000 ppb; Pass Fourchon 5,900 ppb; Bayou Rigaud, 7,700 ppb; and Eugene Island Block 18, 430 ppb. These differences are a function of the loadings to the environment, the sedimentary characteristics of the environment and the type of benthic community associated naturally with the environment.

7.2 Bioaccumulation

One of the objectives of this study was to examine the potential impacts of organic and inorganic contaminants associated with the discharges of produced waters into coastal environments, including any potential for extension of those impacts to man through the food chain. Many of the contaminants found in produced water discharges are toxic to aquatic organisms and to man, and many of the organic compounds are known or suspected mutagens or carcinogens. An aspect of this study, therefore, was to address the bioaccumulation potential of these contaminants. The approach used was to deploy an indigenous population of filter-feeding bivalves (the American oyster, *Crassostrea virginica*) at known distances from the discharge points for known periods of time. Two deployments were made at the Pass Fourchon and Bayou Rigaud study sites in April and May for 14 days (Deployment I) and 27 days (Deployment II), respectively. General methods for the bioaccumulation studies are given below but the details are in Chapter 13 of Volume II of this report.

Oysters were obtained the day before deployment from a local seafood supplier. The oysters for the first deployment came from an oyster lease near Casse-tete Island in Timbalier Bay, while the oysters for the second deployment came from West Champagne Bay, which is between Bayou Lafourche and Barataria Bay. A set of oysters equal in number to that deployed were retained as control oysters and returned to the laboratory for analysis. Oysters were deployed in cages in water depths of 1-2 m at a height of approximately 0.1 m above the sediment. Oyster cages were deployed adjacent to produced water discharges at Pass Fourchon and at Bayou Rigaud and at a series of stations representing a dilution series away from the discharges. Two reference sites where chosen in the Pass Fourchon area, far from oil-related activity. One was in Bayou Tartellon, PFR1, and the second, in a bayou off the northeast corner of Bay Champagne, PFR2. No reference site was used in Bayou Rigaud because no appropriate area was found.

A comparison of accumulation of produced water contaminants in oysters is shown in Table 8. The comparisons are based on Deployment I in April (as opposed to the one in May) as indicative of a predicted moderate level of accumulation compared to expected higher values in winter and the lower values found a month later when the oysters were presumed to be spawning and mobilizing lipids and associated hydrocarbons. There was higher mortality during the longer deployment period and at stations closer to the discharge for Pass Fourchon. Generally, mortality was higher in the Pass Fourchon area than in the Bayou Rigaud area. During the first deployment, oysters at stations PF0, PF200, PF400 and BR11 displayed significantly lower weight gain than the oysters at the reference stations. The lower weight gain for the oysters from Pass Fourchon was probably the result of the produced water discharges; with station BR11, this was not the case. The low weight gain may have resulted from stress induced during the deployment from potential burial of the tray with silts. Oysters from stations PF0 and PF200 again showed lower weight gains during the second deployment than oysters deployed at all other stations.

Oysters at Pass Fourchon and Bayou Rigaud accumulated significant levels of alkylated PAH and total hydrocarbons above background levels during the first deployment (Figure 24). Accumulations were higher for the Pass Fourchon study area. Both study areas demonstrated a rapid accumulation of produced water origin contaminants. The levels of accumulation during the second deployment were about half those of the first. These reductions are attributed to season and reproductive condition. Oysters accumulated levels of produced water origin hydrocarbons in excess of the concentrations of the contaminants found in ambient sediments in the region. Results for the trace metals were inconsistent with distance from the discharge point, and inconsistent with the values found in the sediments of the study areas. Total radium activity above the detection limit of 0.2 $dpm \cdot g^{-1}$ was measured in four of the 14 samples analyzed. These four elevated levels were in oysters deployed adjacent to a discharge (PF0 and BR4), or in one instance 200 m from a discharge (PF200). The bioaccumulation studies show the clear potential for uptake and accumulation of produced water origin contaminants by oysters, both in close proximity to the discharge and to great distances from the discharge.

Literature Cited

Boesch, D. F. and N. N. Rabalais, eds. 1987. Long-Term Environmental Effects of Offshore Oil and Gas Development. Elsevier Applied Science Publishers Ltd., London, 696 pp.

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

Gianessi, L. P. and F. D. ARnold. 1982. The Discharges of Water Pollutants from Oil and Gas Exploration and Production in the Gulf of Mexico Region. Report to Quality of the Environment Division, Resources for the Future, Washington, D.C., 104 pp.

Koide, M., A. Soutar and E. D. Goldberg. 1973. Marine geochronology with Pb-210. Earth and Planetary Science Letters 14:442-446.

National Research Council. 1985. Oil in the Sea. Inputs, Fates,and Effects. National Academy Press, Washington, D.C., 601 pp.

Neff, J. M., N. N. Rabalais and D. F. Boesch. 1987. Offshore oil and gas development activities potentially causing long-term environmental effects, pp. 149-173. In D. F. Boesch and N. N. Rabalais, eds. Long-Term Environmental Effects of Offshore Oil and Gas Development, Elsevier Applied Science Publishers, Ltd., London, 696 pp.

Neff, J. M., T. C. Sauer and N. Maciolek. 1989. Fate and Effects of Produced Water Discharges in Nearshore Marine Waters. API Publication No. 4472, American Petroleum Institute, Washington, D.D., 300 pp.

Nittrouer, C. A., R. W. Sternberg, R. Carpenter and J. T. Bennett. 1979. The use of lead-210 geochronology as a sedimentological tool: Application to the Washington continental shelf. Mar. Geol. 31:297-316.

Reid, D. F. 1983. Radium in formation waters: How much and is it of concern? pp. 187-191 In Proceedings, Fourth Annual Gulf of Mexico Information Transfer Meeting. OCS Report/MMS 84-0026, U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, Louisiana, 474 pp.

Rittenhouse, G., R. B. Fulton, III, R. J. Grabowski and J. L. Bernard. 1969. Minor elements in oil field waters. Chem. Geol. 4:189-209.

St. Pé, K. M., ed. 1990. An Assessment of Produced Water Impacts to Low-Energy, Brackish Water Systems in Southeast Louisiana. Louisiana Department of Environmental Quality, Water Pollution Control Division, Baton Rouge, Louisiana, 204 pp.

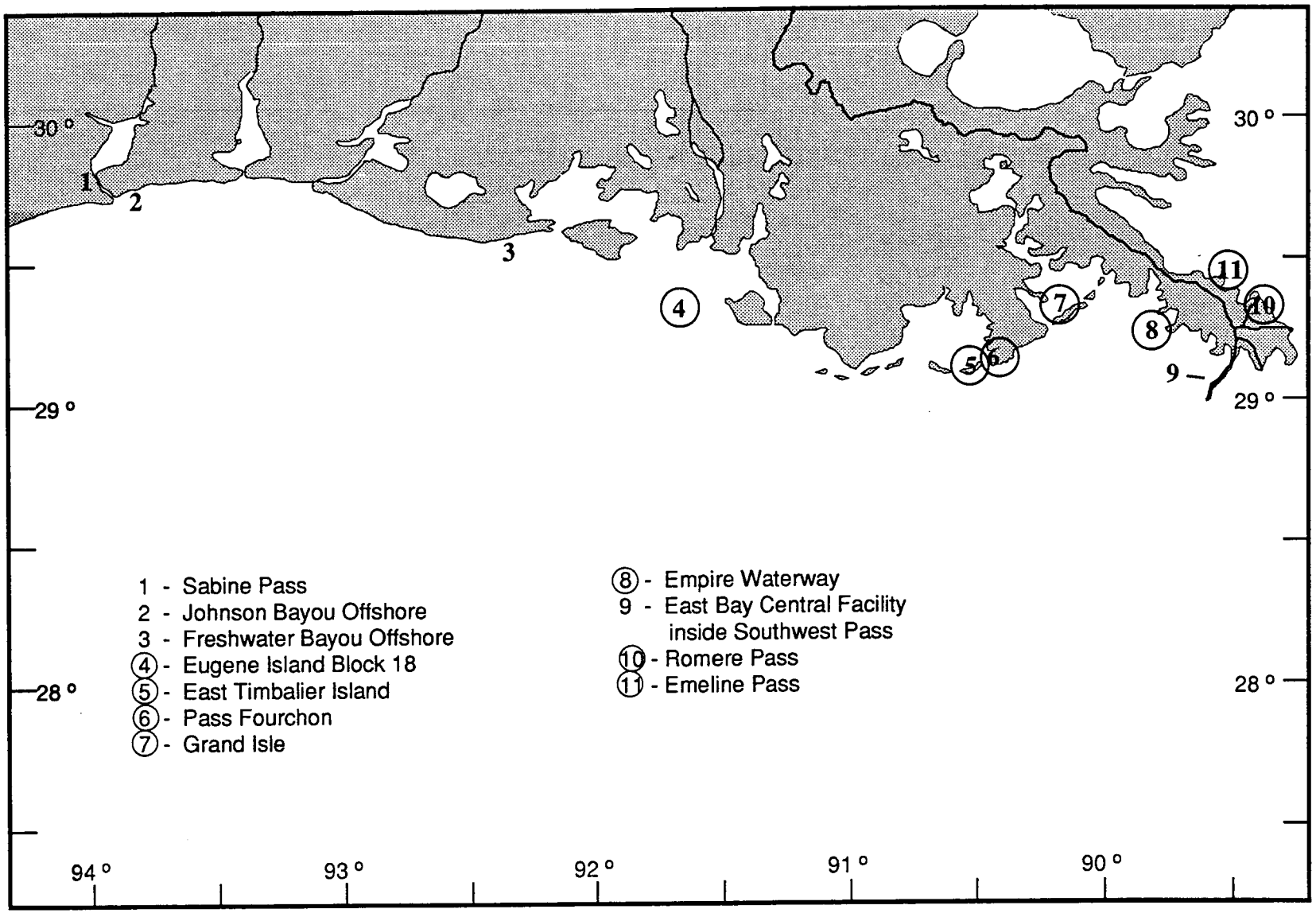


Figure 1. General location of OCS-generated produced water discharges in Louisiana State waters with circled numbers indicating areas studied.

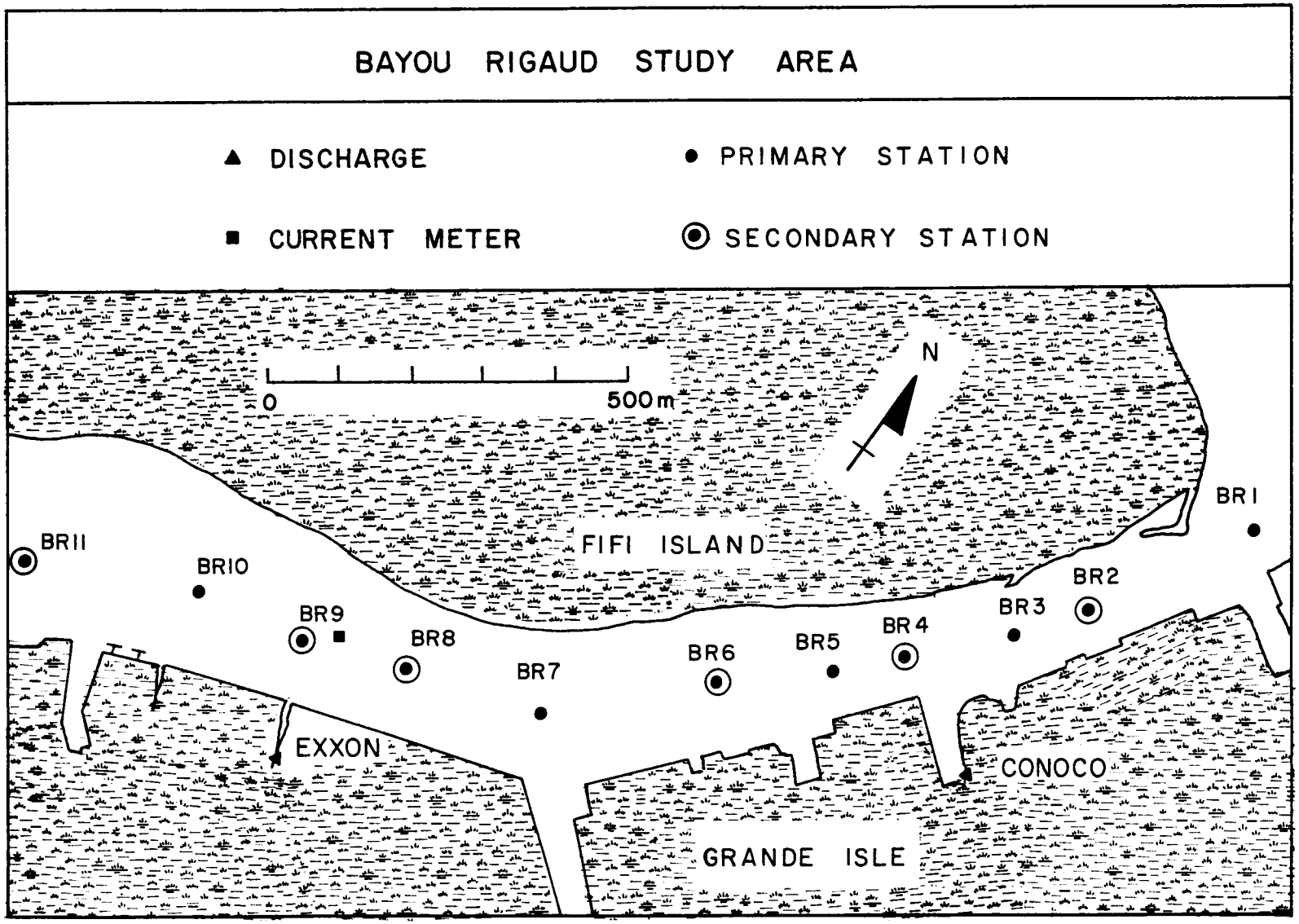


Figure 2. Bayou Rigaud study area for station coverage for February and October 1989, and February 1990.

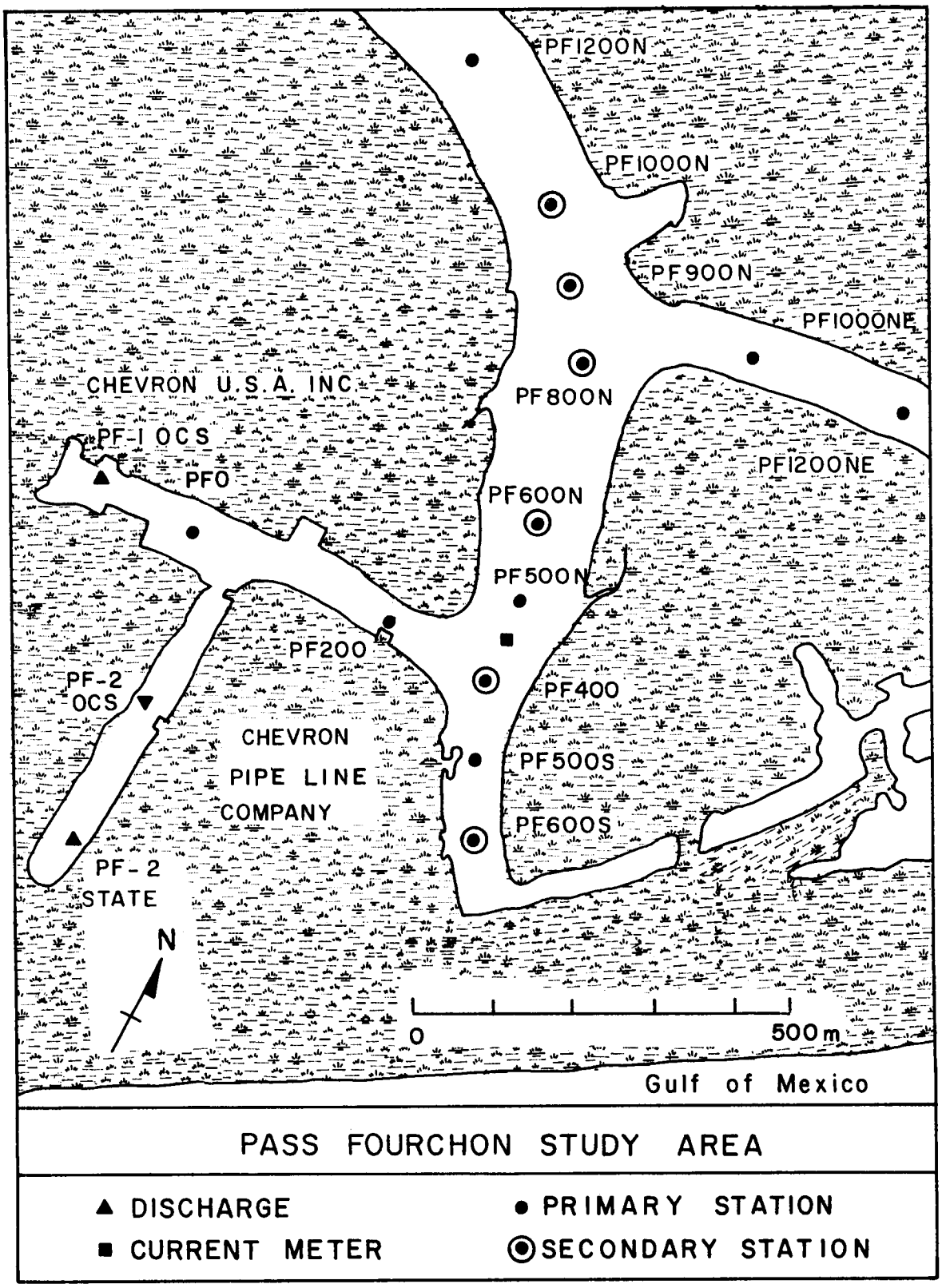


Figure 3. Pass Fourchon study area.

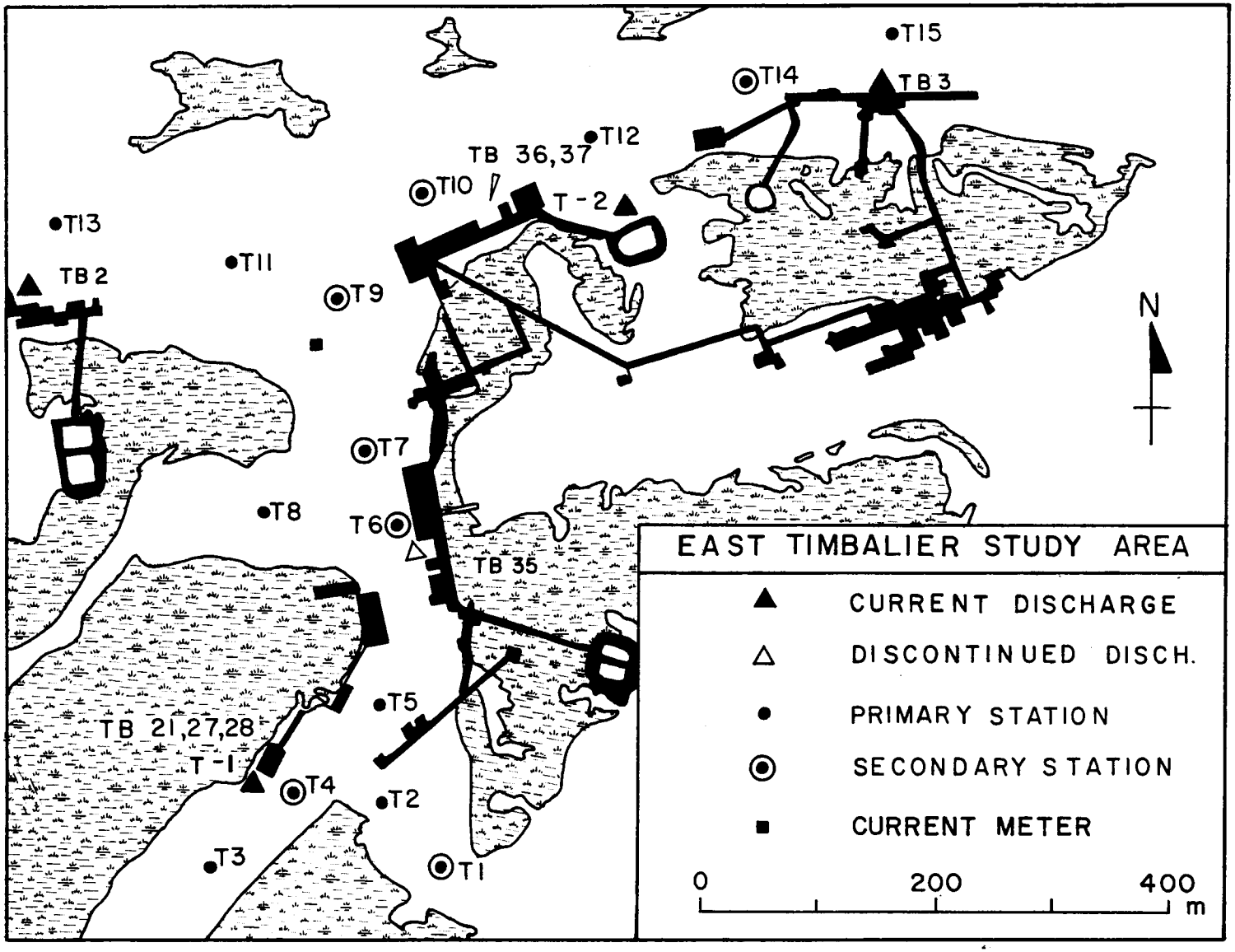


Figure 4. East Timbalier Island study area.

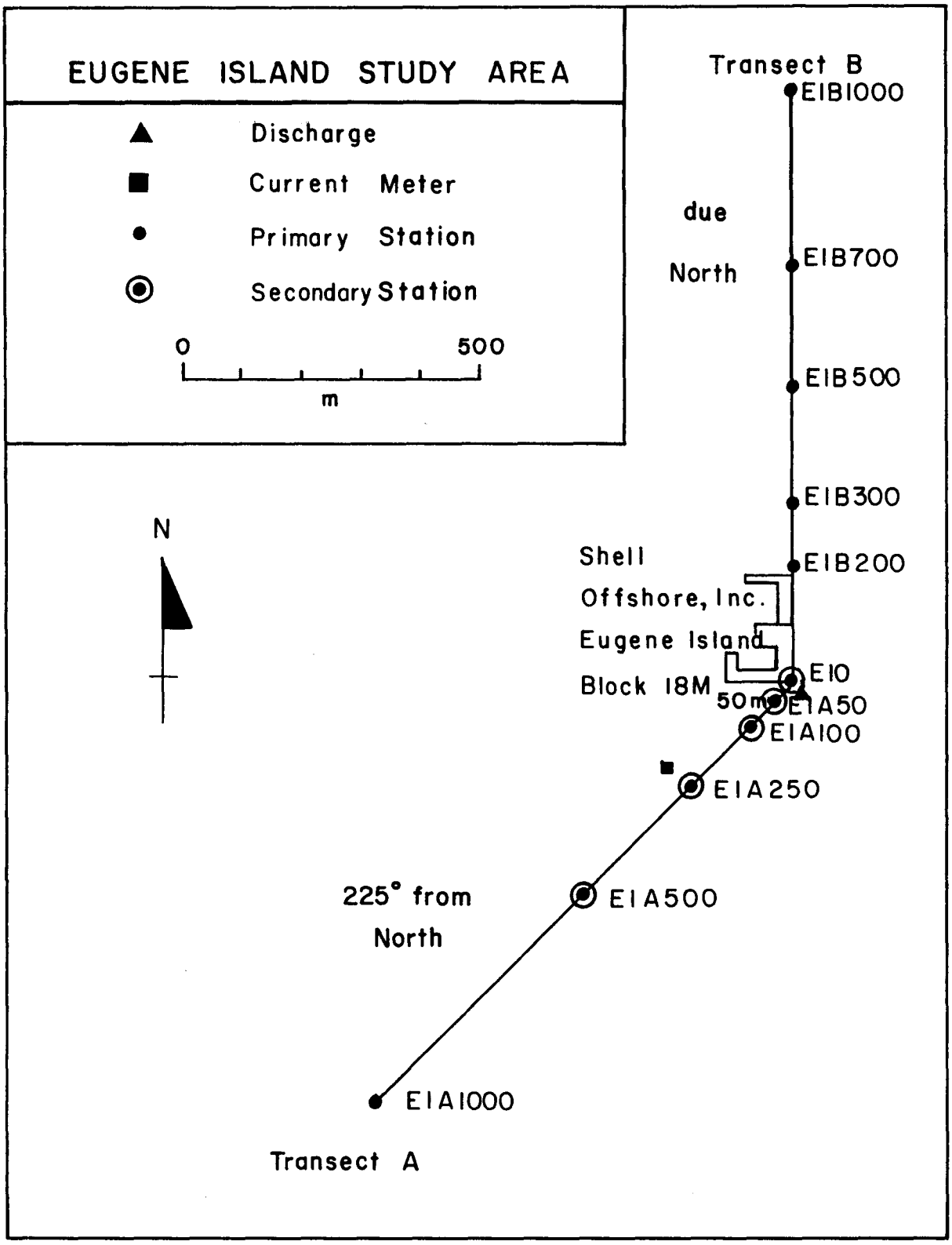


Figure 5. Eugene Island Block 18 study area.

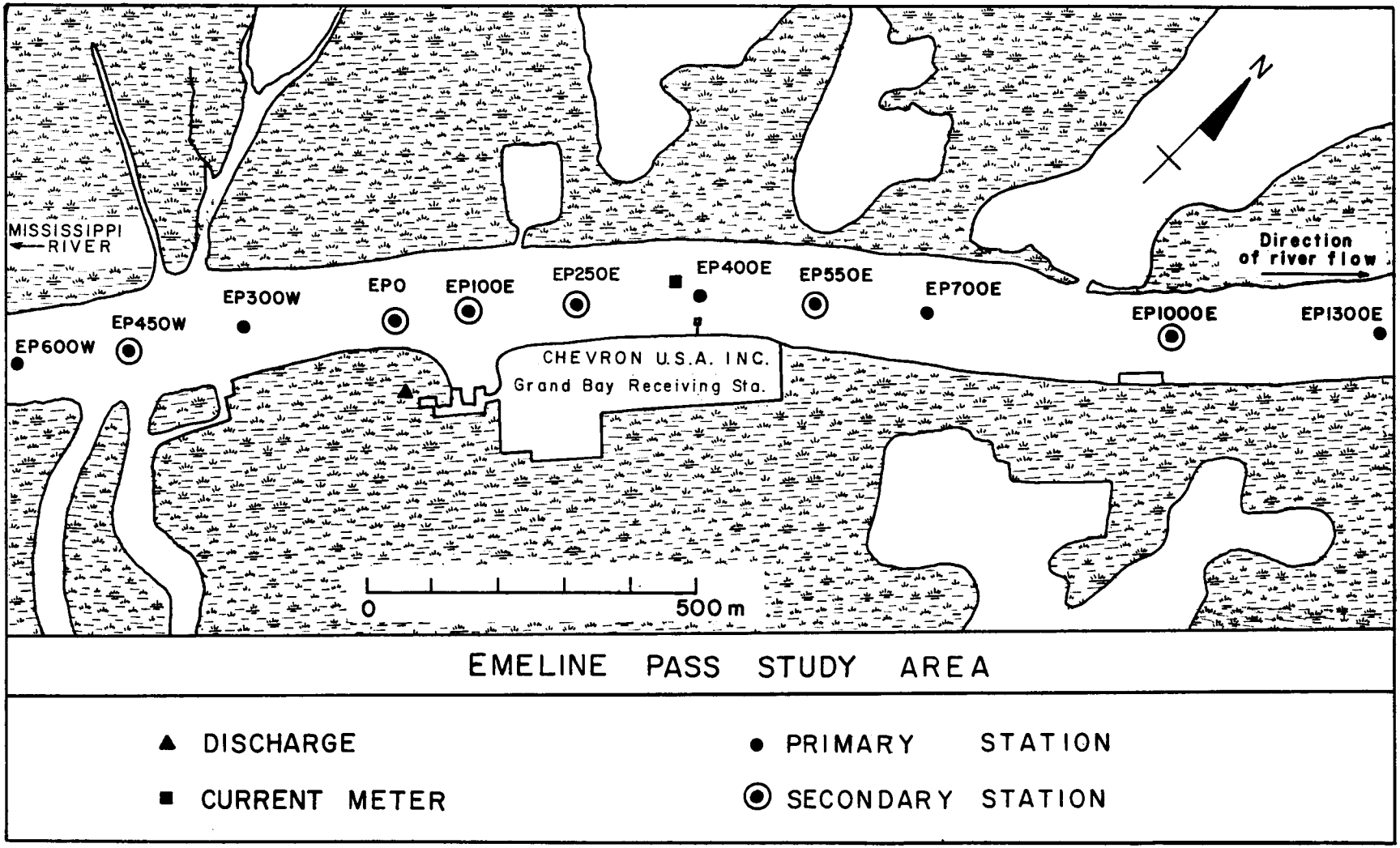


Figure 6. Emeline Pass study area.

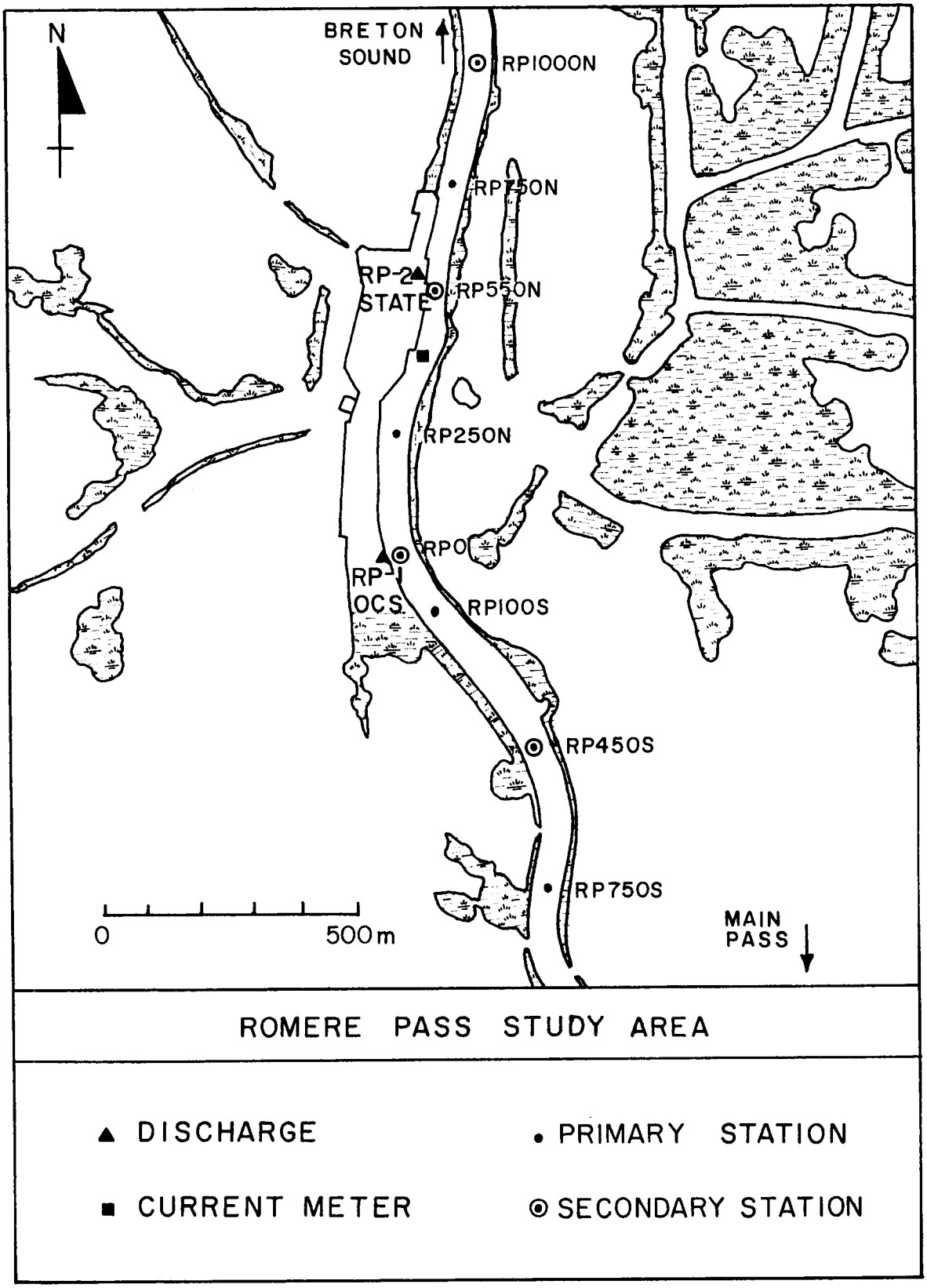


Figure 7. Romere Pass study area.

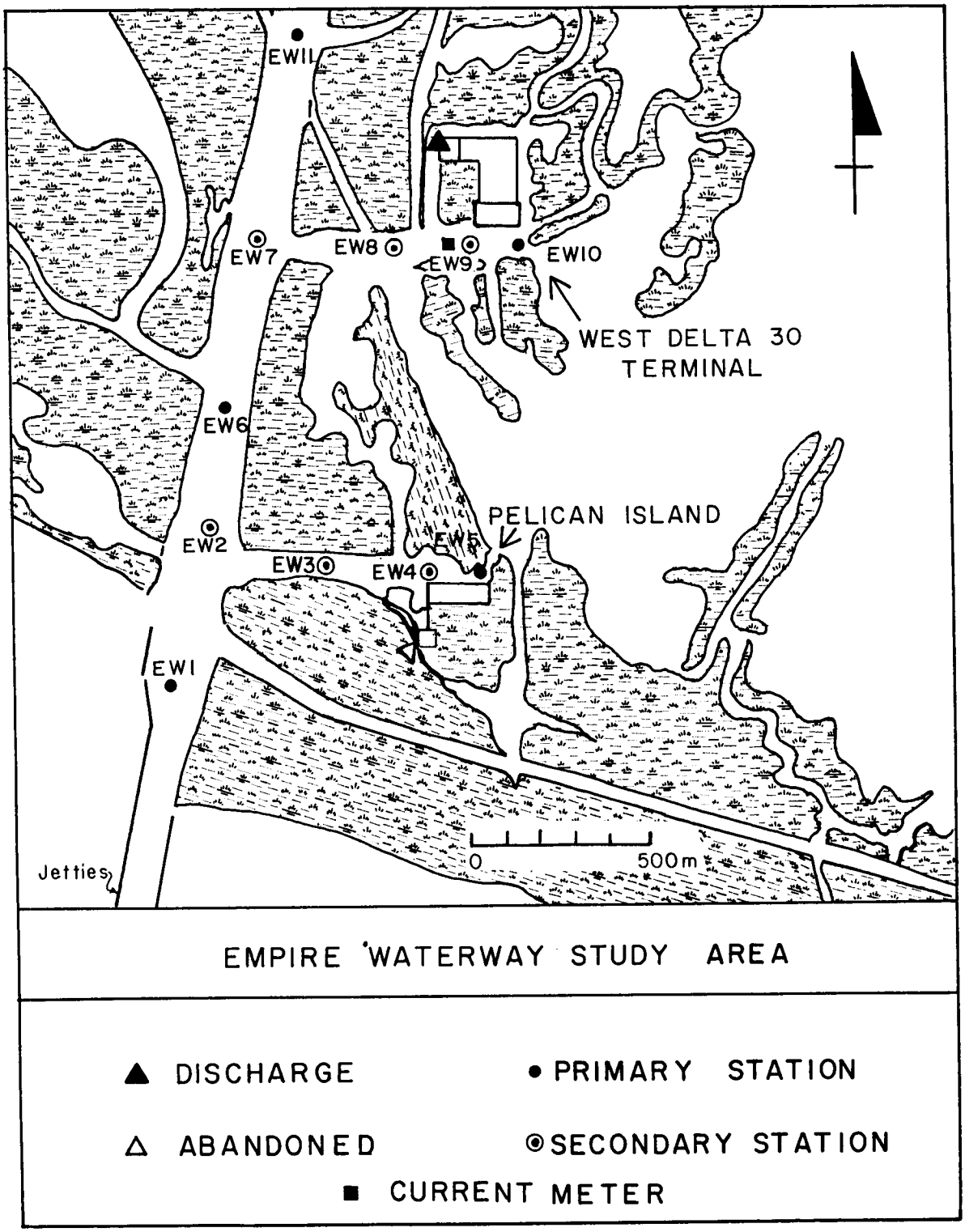


Figure 8. Empire Waterway study area.

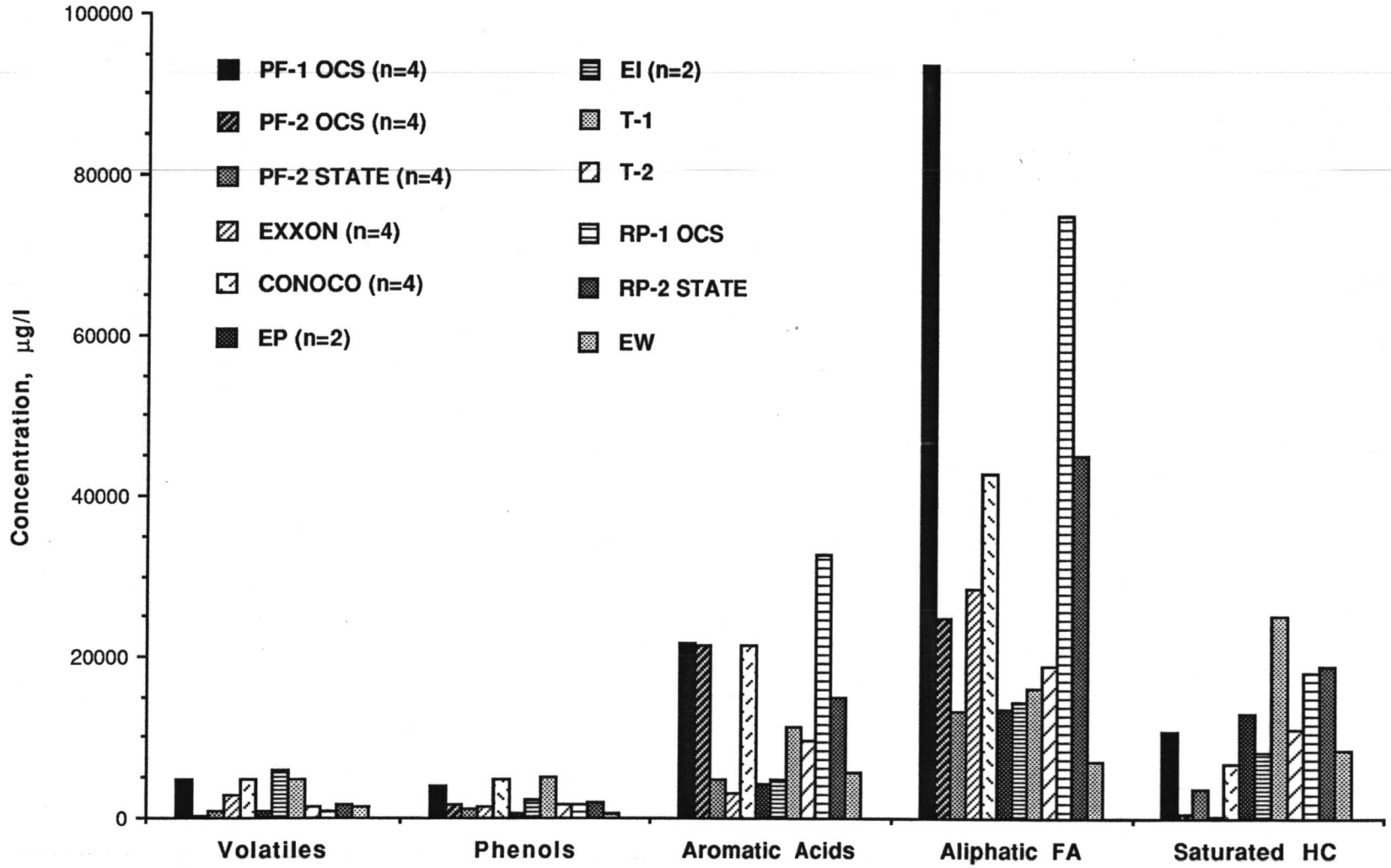


Figure 9. Comparison of volatiles, phenols, aromatic acids, aliphatic fatty acids and saturated hydrocarbons in 12 produced water discharges from this study. (n = number of discharge samples; FA=Fatty Acid, HC=hydrocarbon.)

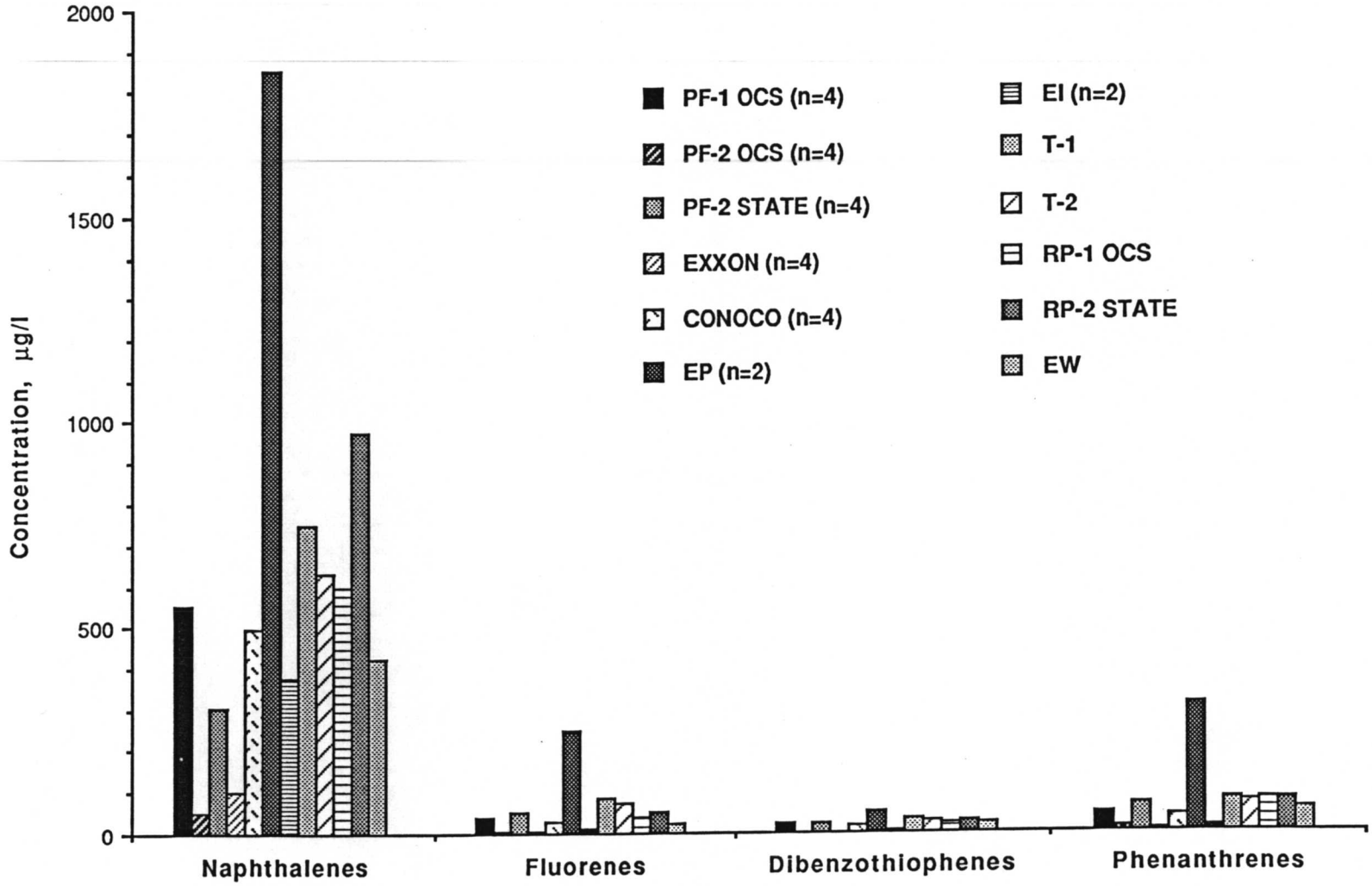


Figure 10. Comparison of polynuclear aromatic hydrocarbons in 12 produced water discharges from this study. (n = number of discharge samples.)

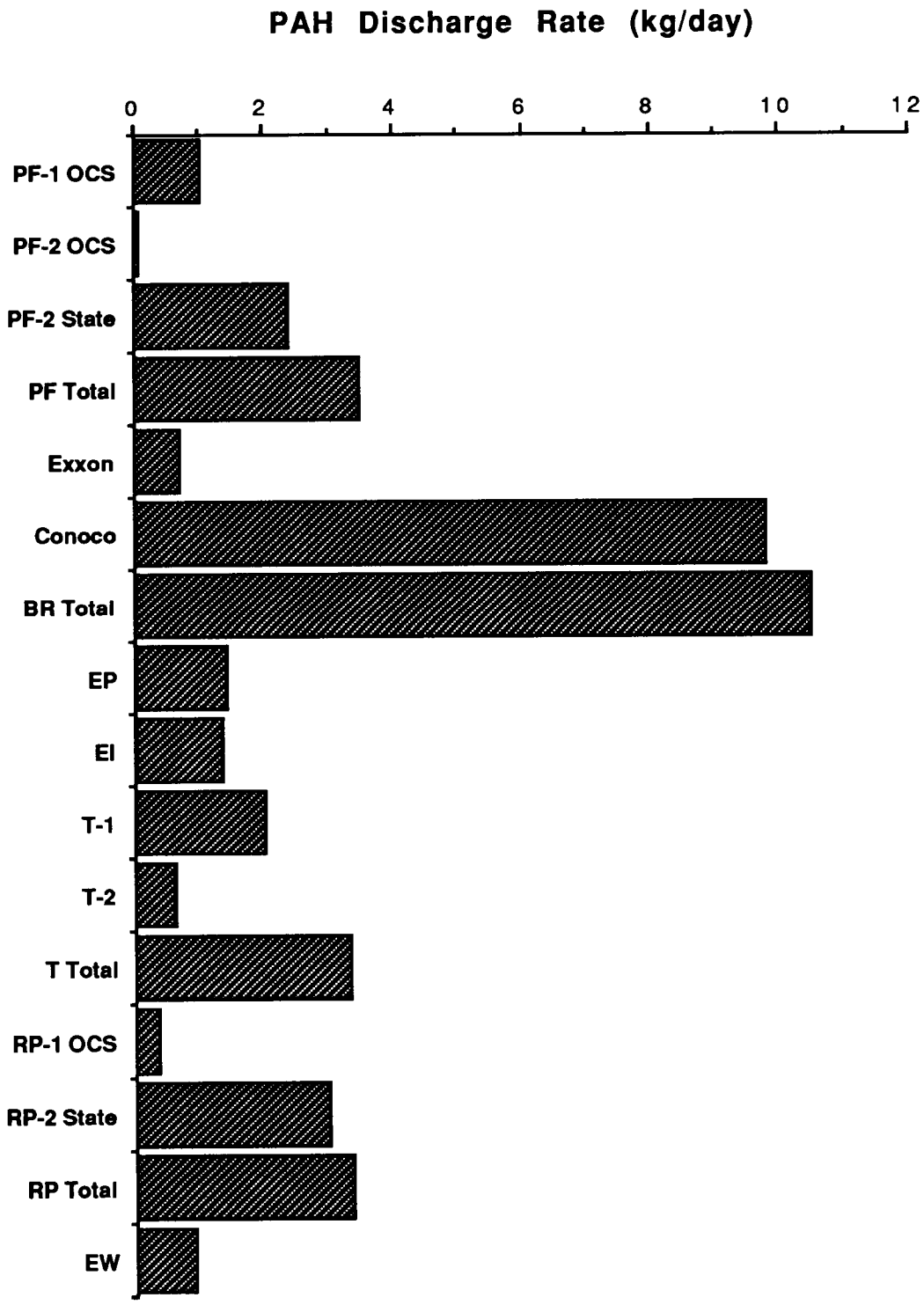
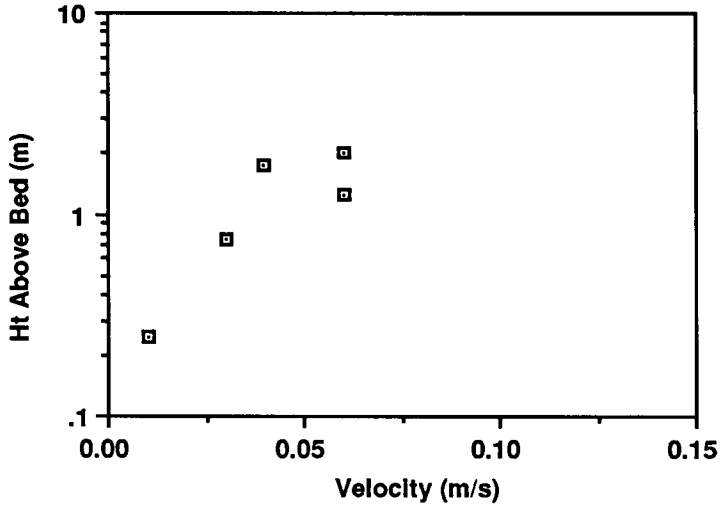


Figure 11. Comparison of PAH daily discharge rates for 12 produced water discharges in this study and the cumulative totals for Pass Fourchon (PR Total), Bayou Rigaud (BR Total), East Timbalier Island (T Total) and Romere Pass (RP Total).



Location:	**Port Fourchon**
Date:	**9 May 1989**
Time:	**0900**
Shear Velocity:	**0.88 cm/s**
Roughness Length:	**15.68 cm**
R-squared:	**.773**

Figure 12. Profile of current velocities through the water column at the Pass Fourchon study area for 9 May 1989 at 0900.

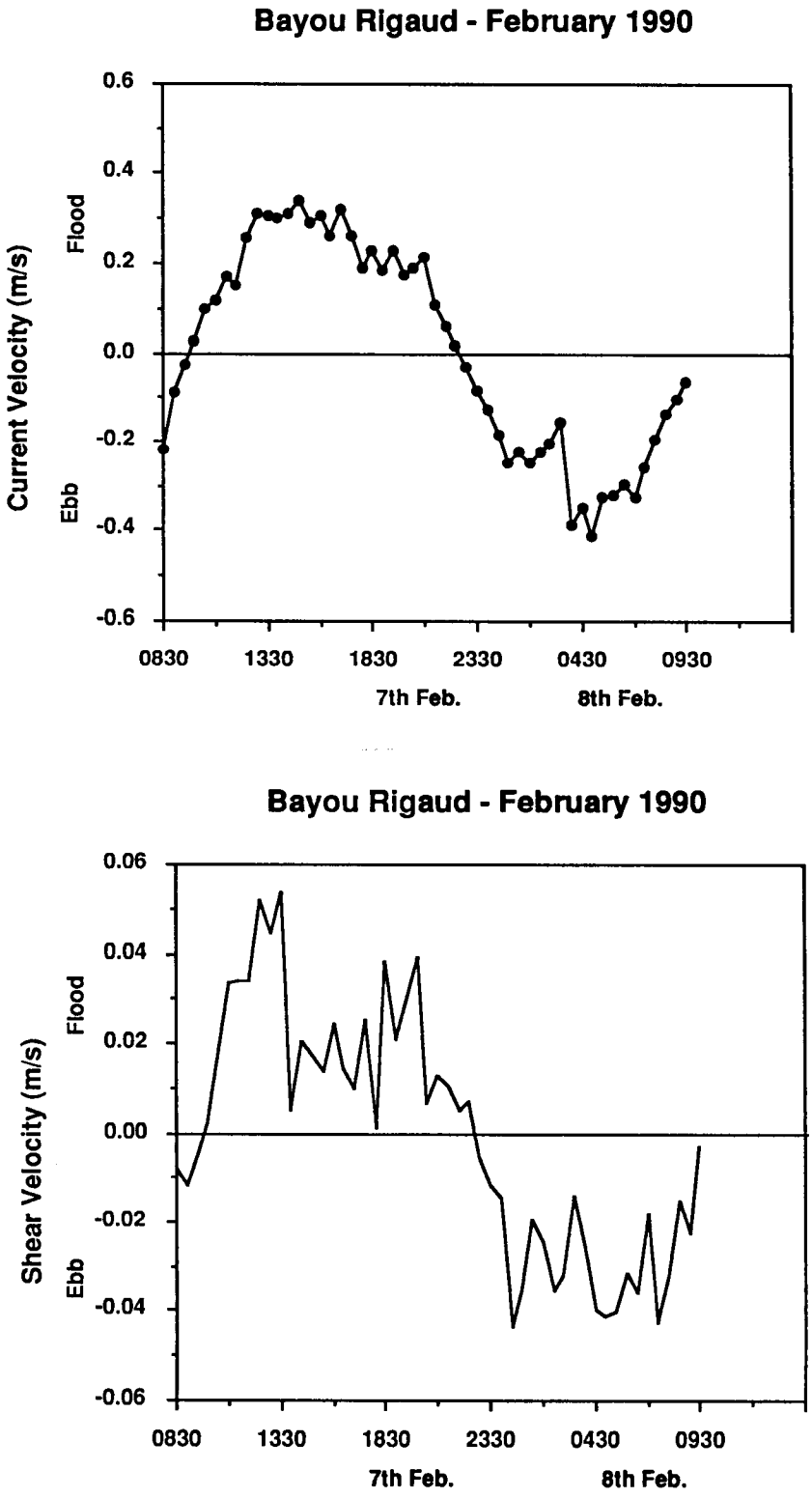


Figure 13. Mean tidal current velocity variation and calculated shear velocities for Bayou Rigaud, February 1990.

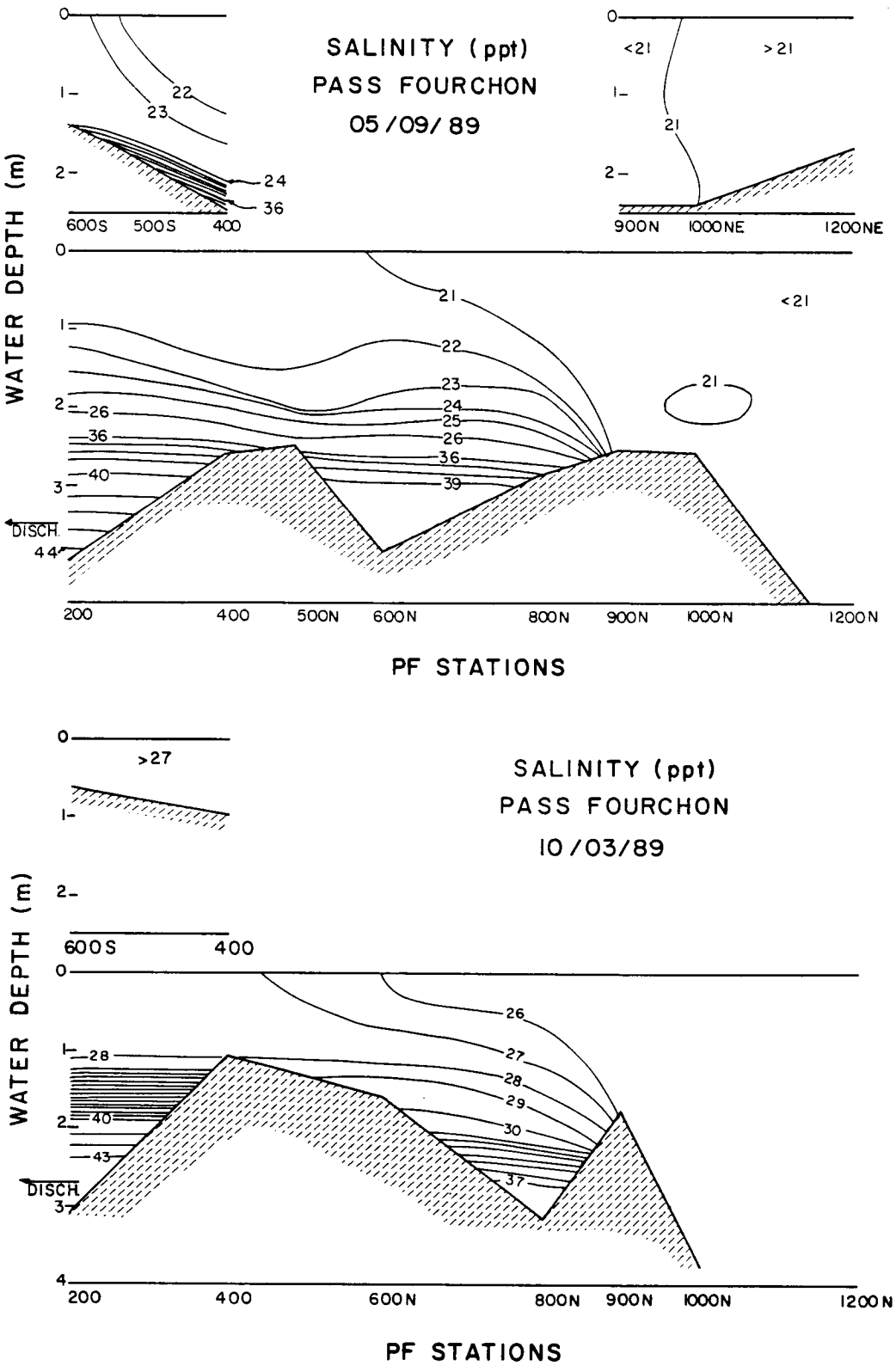


Figure 14. Salinity distribution through the water column at the Pass Fourchon study area, May and October 1989. DISCH. = direction of discharges.

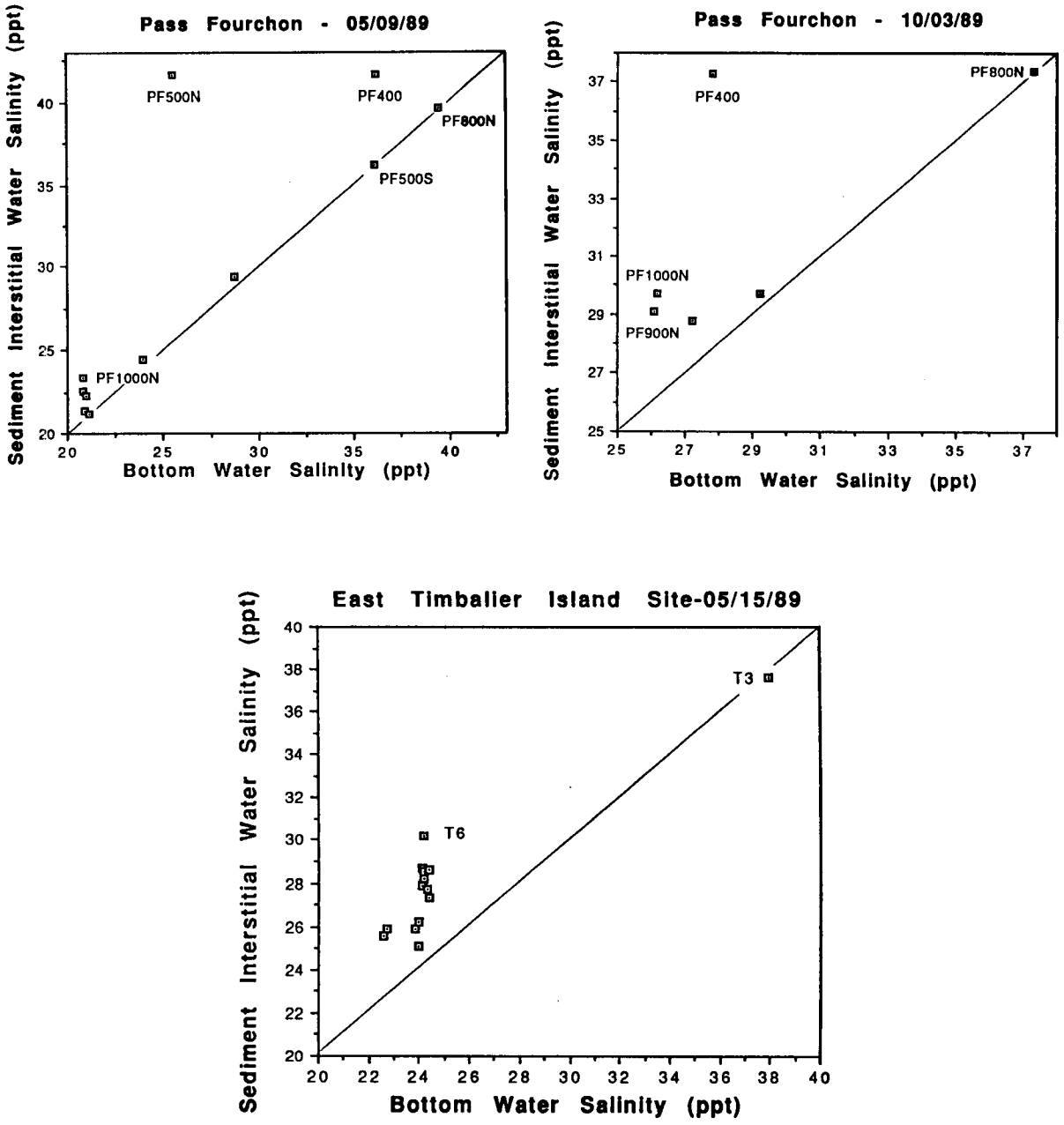


Figure 15. Comparisons of interstitial water salinity from surface sediments and near-bottom water salinity in the Pass Fourchon and East Timbalier Island study areas. Station numbers given for values most different from a 1:1 relationship (indicated by diagonal line) and/or for stations affected by the density plume.

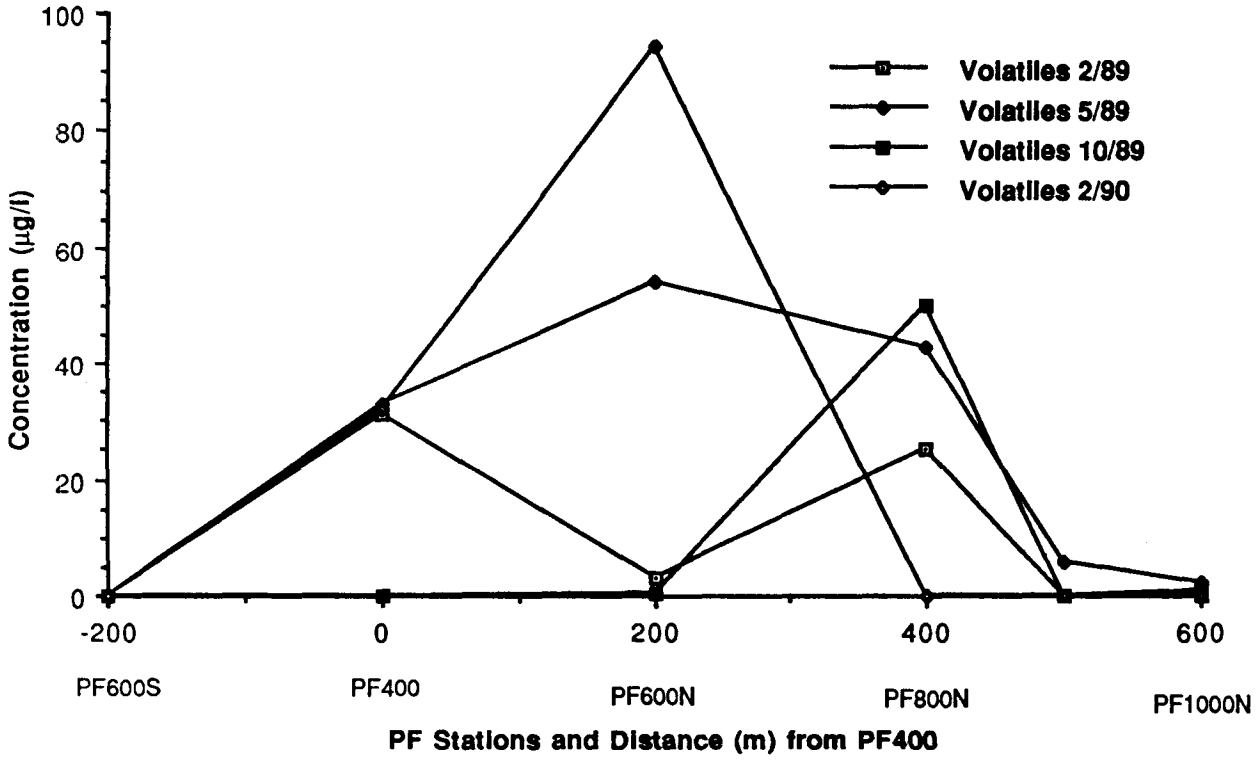


Figure 16. Spatial distribution of volatile hydrocrabons in Pass Fourchon near-bottom waters for four sample periods.

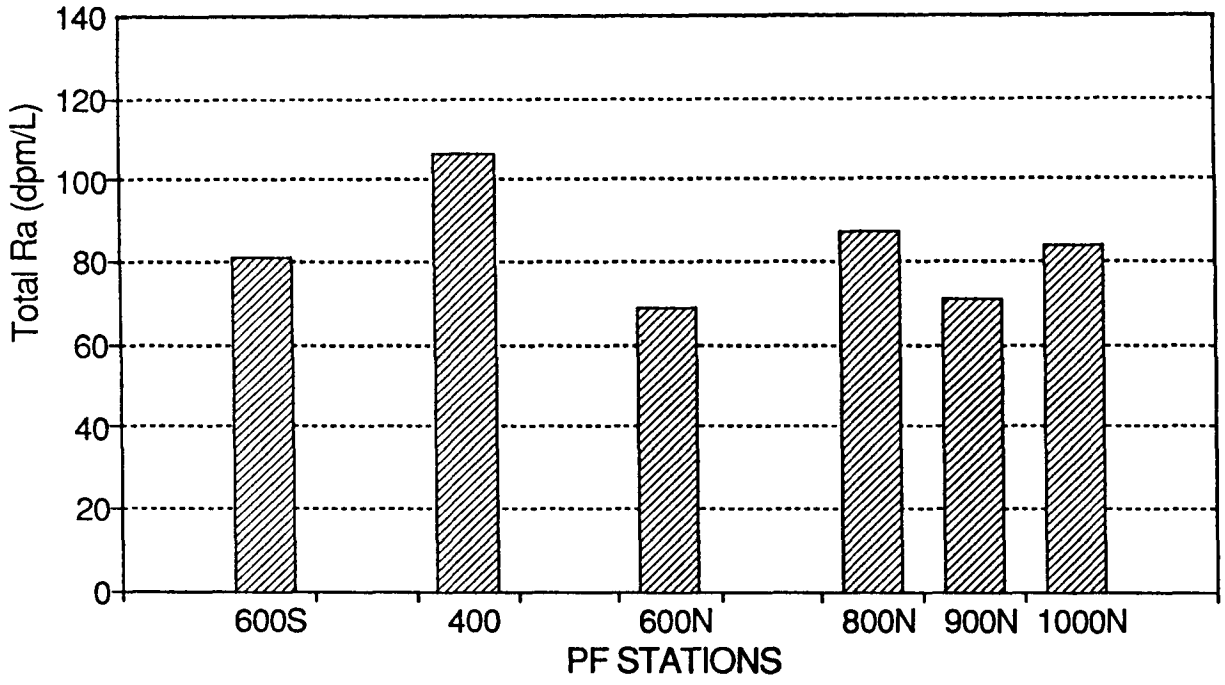


Figure 17. Spatial distribution of total radium activities in Pass Fourchon near-bottom waters, February 1989.

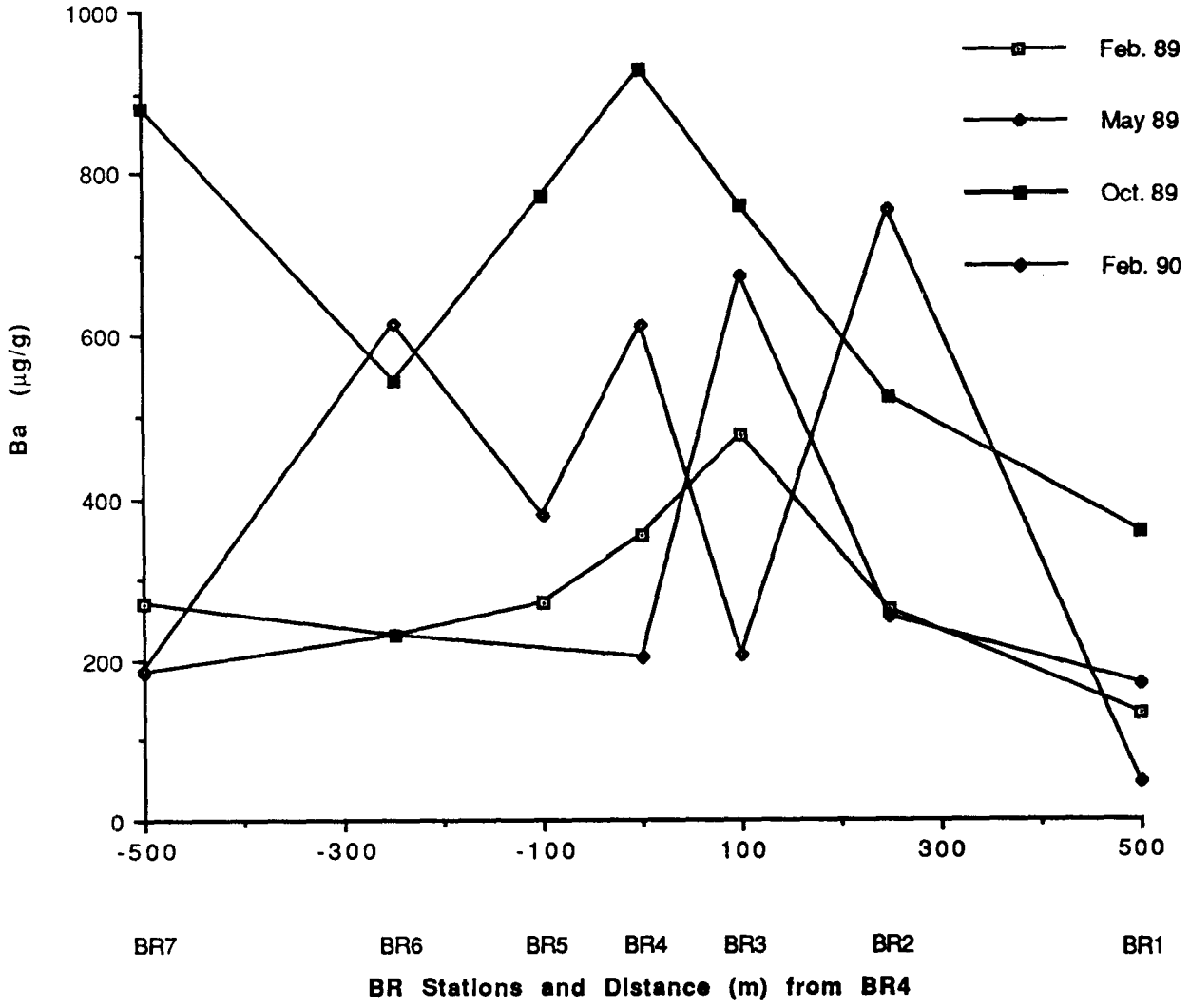


Figure 18. Spatial distribution of Ba concentrations in surface sediments from transect 2 in Bayou Rigaud for four sample periods.

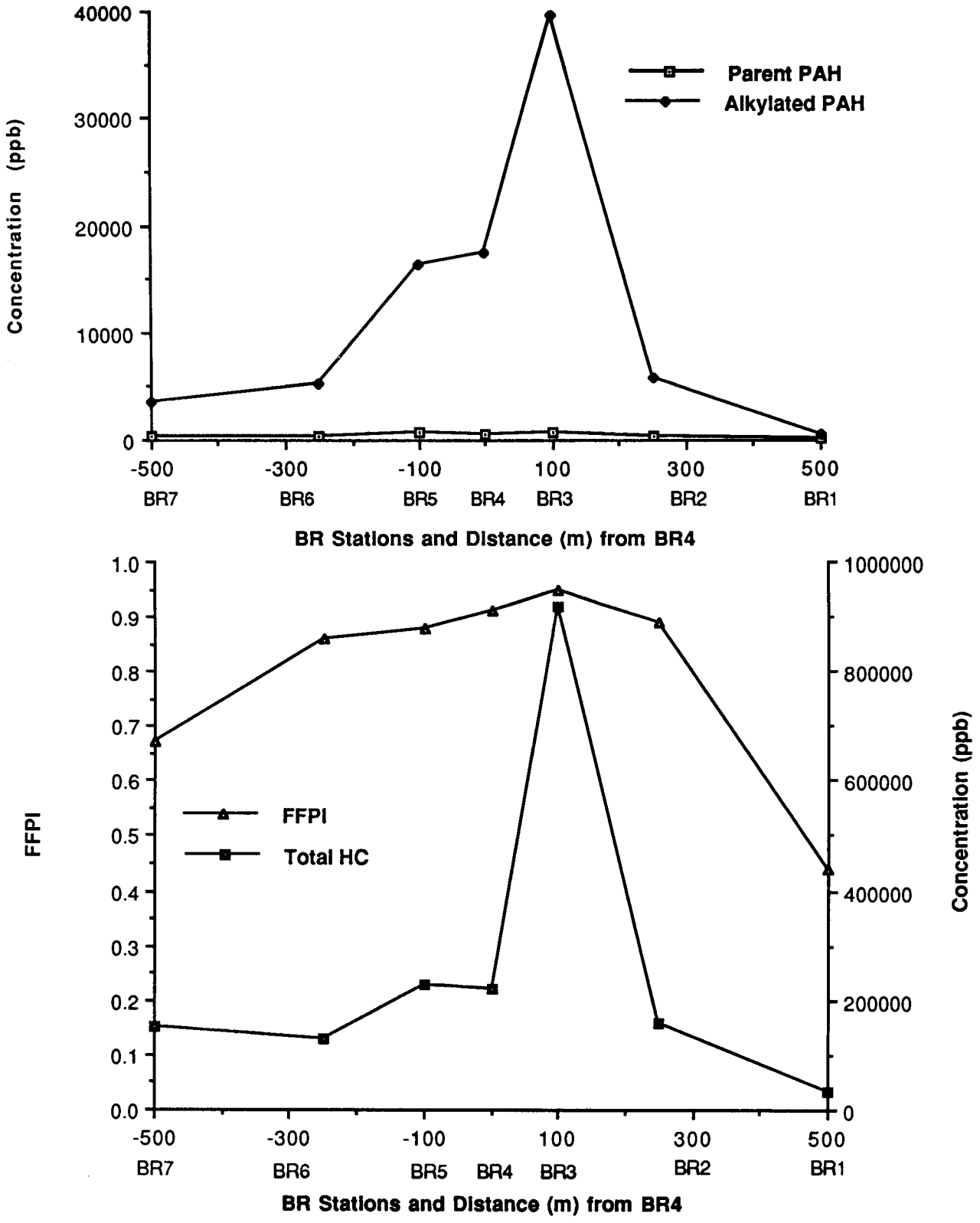


Figure 19. Spatial distribution of PAH and total HC concentrations and FFPI in surface sediments from transect 2, Bayou Rigaud, February 1989.

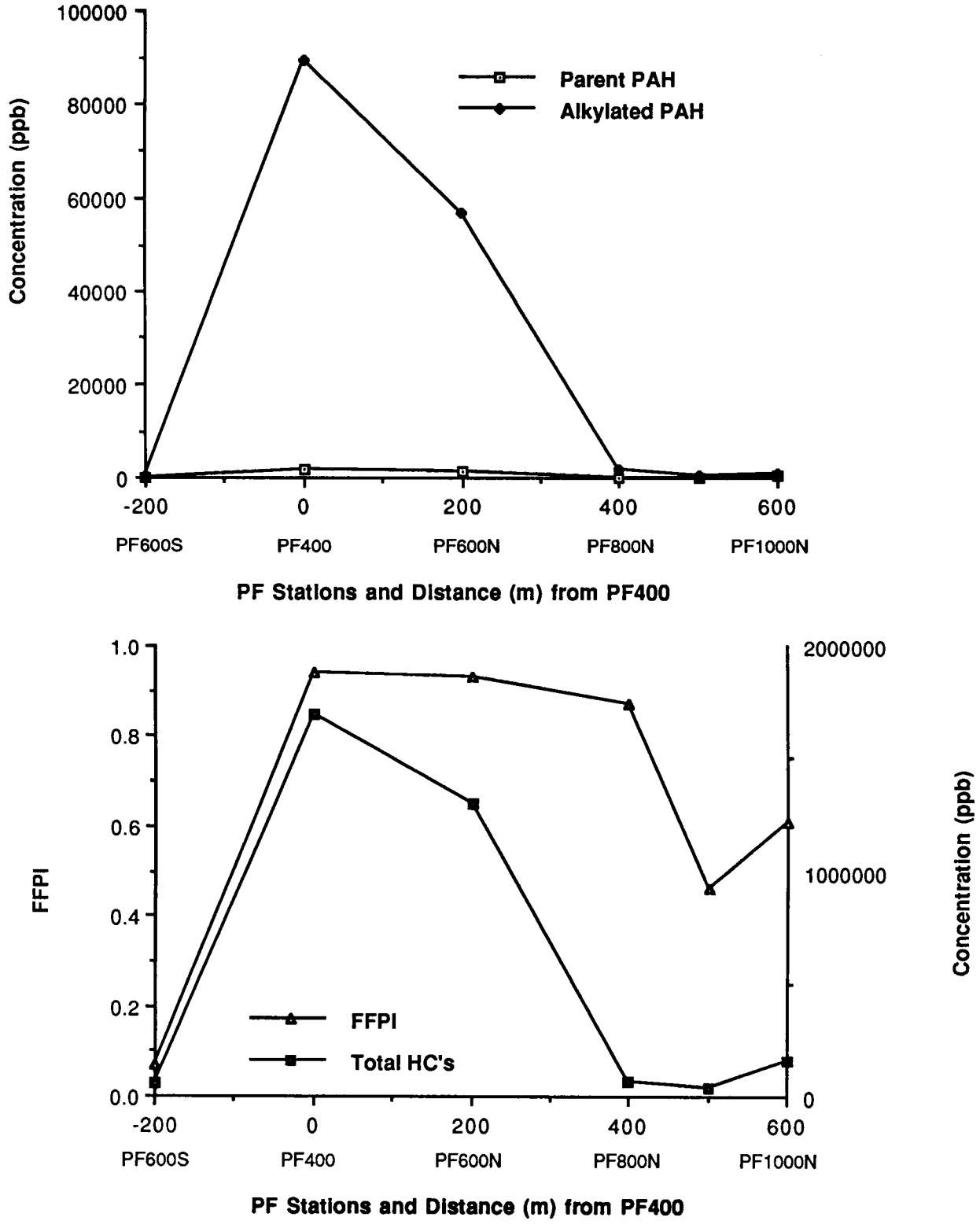


Figure 20. Spatial distribution of PAH and total HC concentrations and FFPI in surface sediments from Pass Fourchon, February 1990.

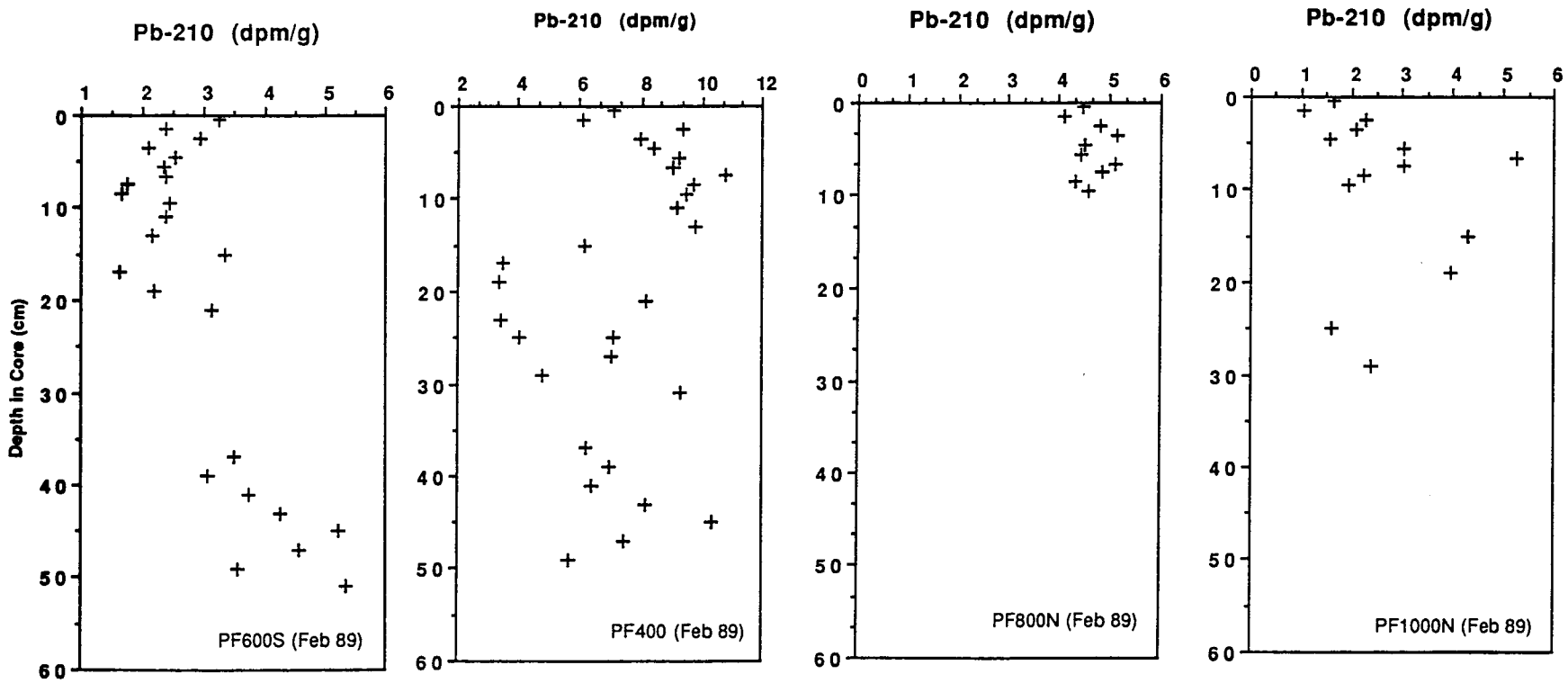


Figure 21. Pb-210 activities in vertical sediment core sections from selected stations in Pass Fourchon, February 1989. (Value for each core section is plotted at the top of that section; for example, the value for 15-20 cm is plotted at 15 cm.)

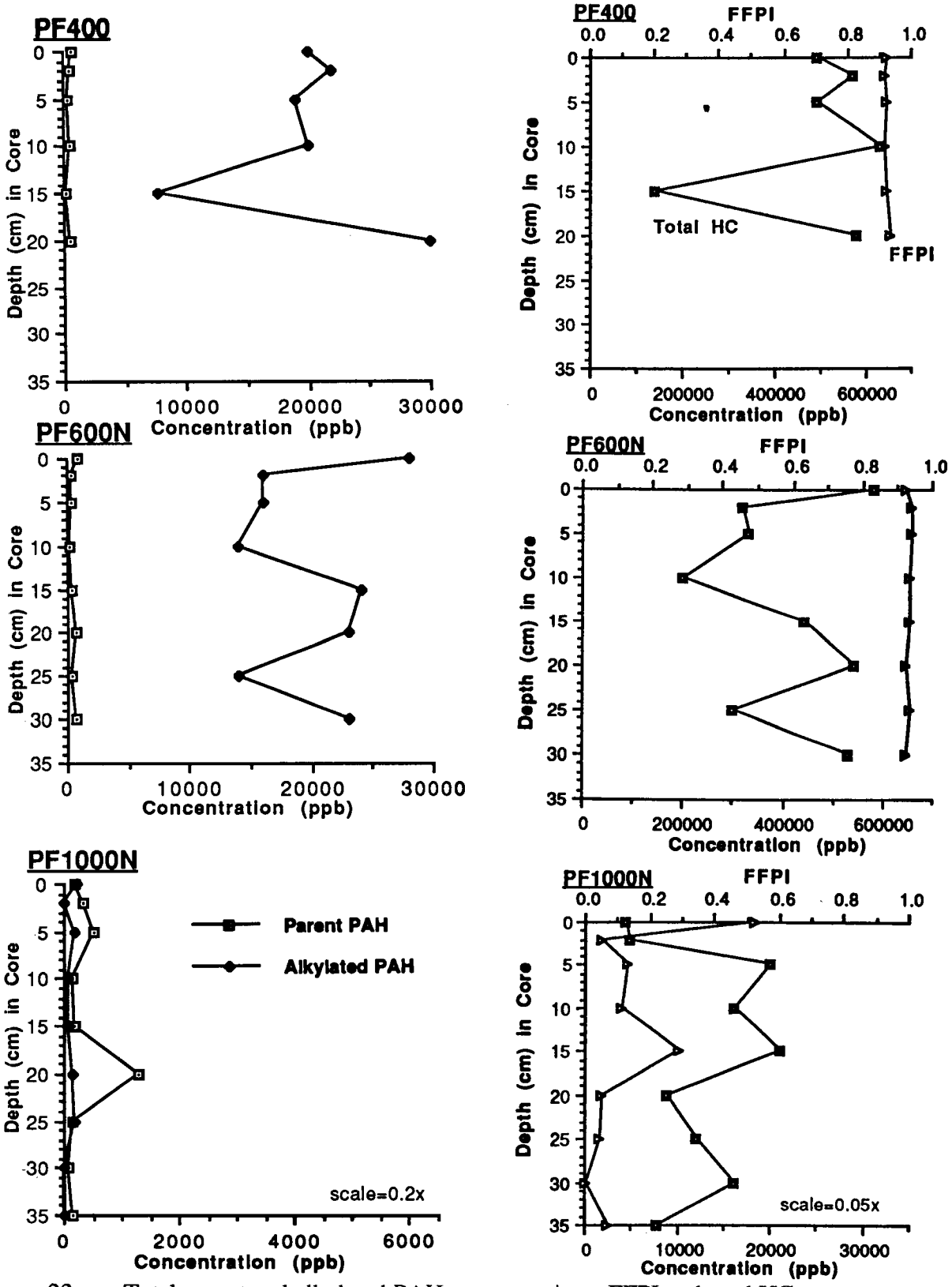


Figure 22. Total parent and alkylated PAH concentrations, FFPI and total HC concentrations in vertical sediment core sections from selected stations at Pass Fourchon, February 1989. (Value for each core section is plotted at the top of that section; for example, the value for 15-20 cm is plotted at 15 cm.)

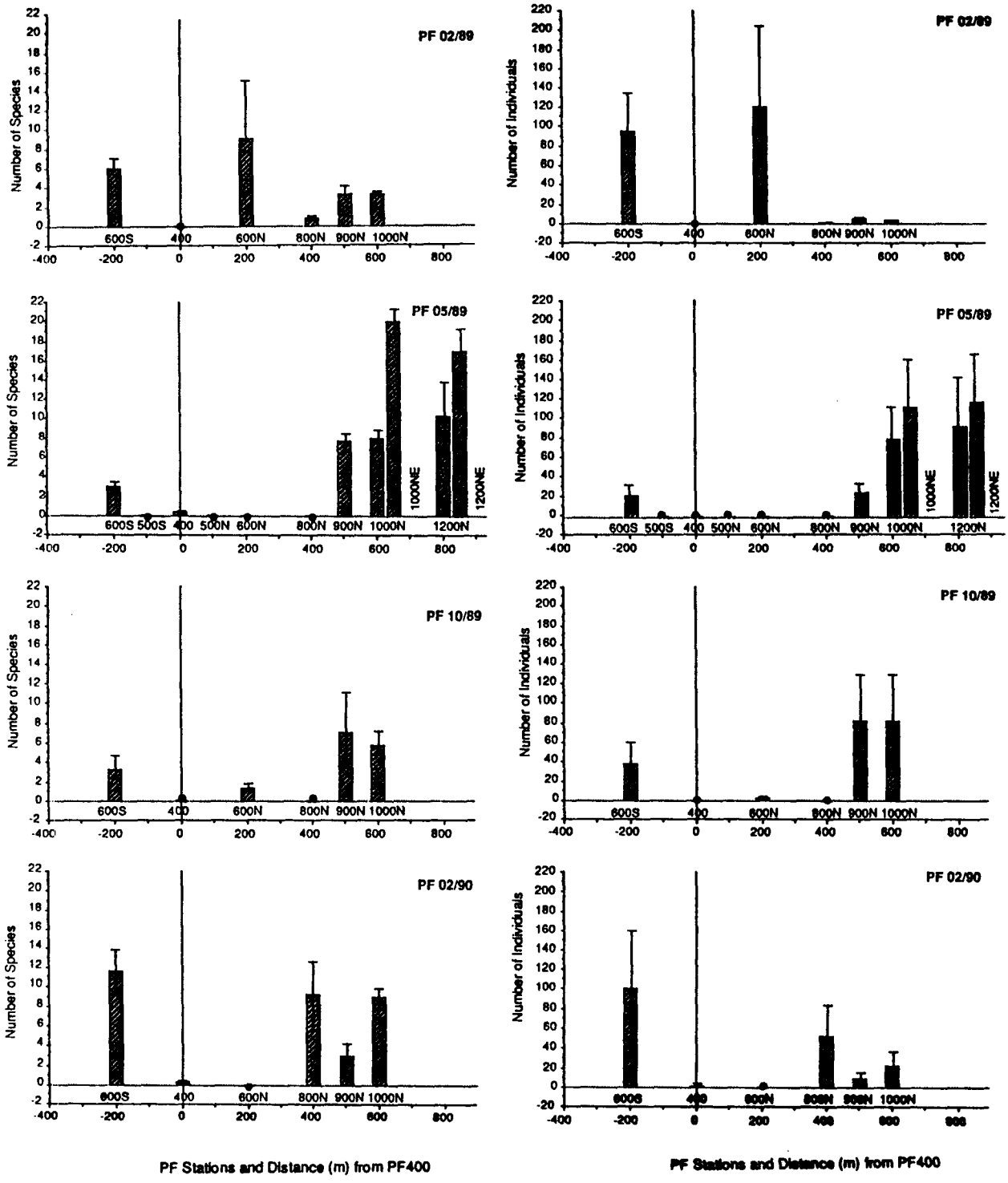


Figure 23. Spatial distribution of number of species per replicate (mean ± standard error) and number of individuals per replicate (mean ± standard error) for Pass Fourchon for four sample periods.

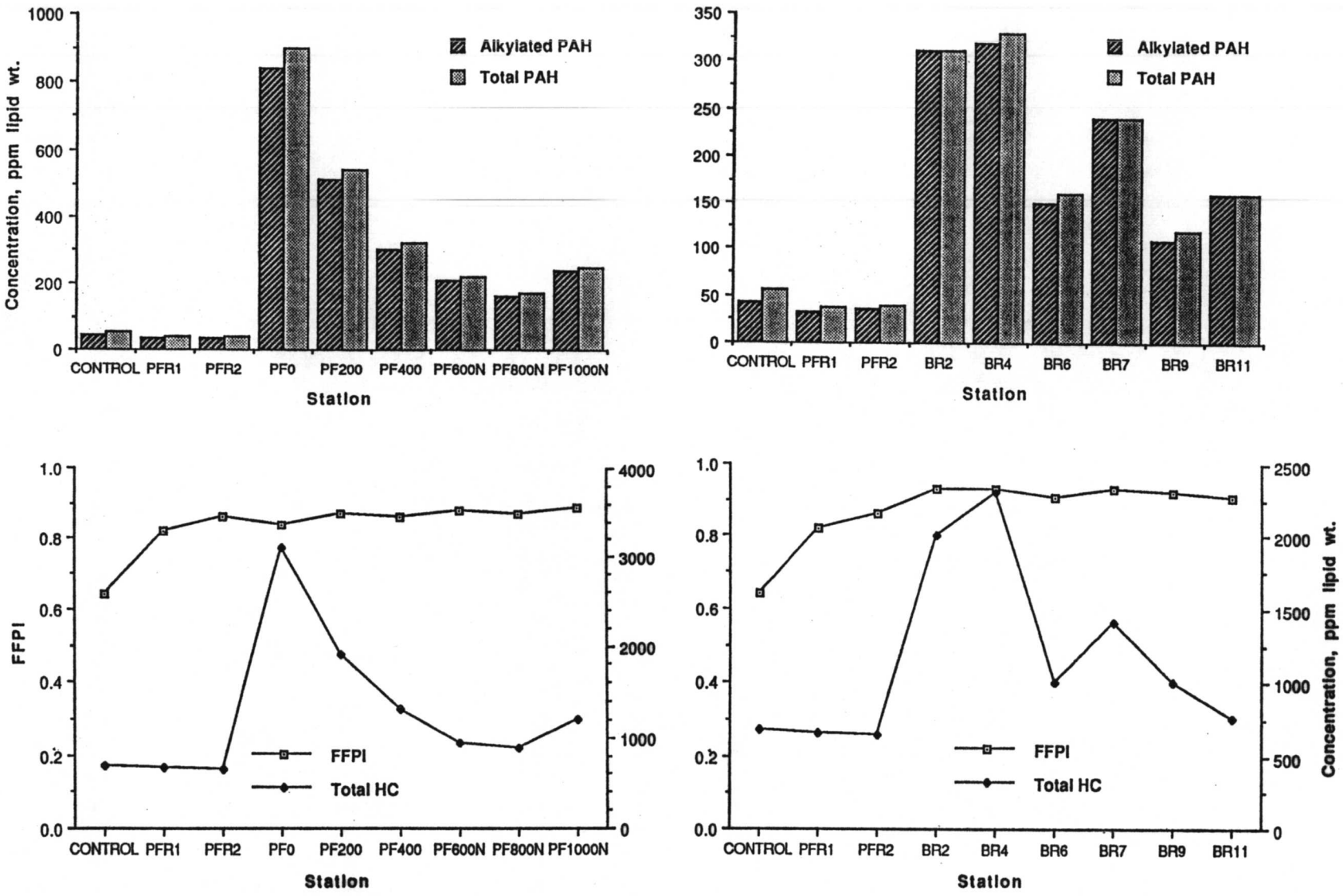


Figure 24. Bioaccumulation of PAH and total HC and calculated values of FFPI for oysters deployed in Pass Fourchon and Bayou Rigaud for 14 days in April 1990 (Deployment I). Station locations shown in Figures 2 and 3; locations of CONTROL, PFR1 and PFR2 described in Section 7.2.

Table 1. Facilities in the Louisiana coastal zone which discharge produced waters emanating from the Federally-controlled outer continental shelf (as of 02/90). Number in left margin keyed to general location in map in Figure 1. Location names in (parentheses) refer to discharge labels used in subsequent sections. [A barrel = 42 gallons = 159 liters.] (Modified from Boesch and Rabalais 1989.)

	Facility	Location	Company	Discharge ($bbl \cdot d^{-1}$)
1	Sabine Terminal	Sabine Pass	Chevron U.S.A. Inc.	288** (OCS = 24)
2	Johnson Bayou Tank Battery	Cameron Parish	Chevron U.S.A. Inc.	500
2	West Cameron Block 45	Johnson Bayou Cameron Parish	Phillips	2,100**
3	Texas Gas Sales	Freshwater Bayou	Union	10
4	Eugene Island Block 18	Platform M	Shell Offshore, Inc.	21,000* (OCS = 100)
5	Tank Battery 21,27,28	East Timbalier Island (T-1)	Chevron U.S.A. Inc.	13,258* 0**
5	Tank Battery 36,37	East Timbalier Island (T-2)	Chevron U.S.A. Inc.	5,005* 8,500**
6	Fourchon Terminal	Pass Fourchon (PF-2 OCS)	Chevron Pipe Line Co.	4,768* 32,500**
6	Bay Marchand Barge	Pass Fourchon (PF-1 OCS)	Chevron U.S.A. Inc.	9,645* 0**
7	Grand Isle Station	Bayou Rigaud	Exxon Pipeline Co.	40,000*
7	Grand Isle Shore Base	Bayou Rigaud	Conoco	105,760*
8	West Delta Block 30 Terminal	Empire Waterway	Chevron Pipe Line Co.	10,959* 15,000**
9	East Bay Central Facility	Southwest Pass/ Mississippi River	Shell Offshore, Inc.	185,000** (OCS = 38,000)
10	Main Pass Block 41 Terminal	Romere Pass/Main Pass (RP-1 OCS)	Chevron Pipe Line Co. Chevron U.S.A. Inc.	3,021* 5,000**
11	Grand Bay Receiving Station	Emeline Pass	Chevron U.S.A. Inc.	3,693* 6,500**

* Volume discharged is an average of monthly discharge rates for period 02/88 - 02/90 (data from operator).

** Volume discharged as of 03/91 (data provided by operator).

OCS = volume discharged of total volume that is generated on the OCS.

Table 2. Comparisons of estimates of produced water discharges ($bbl \cdot d^{-1}$) from this study and that of Boesch and Rabalais (1989).

		OCS-Generated		State-Generated		
		OCS Disposal	Louisiana State Coastal Disposal	Louisiana State Coastal Disposal	Texas State Coastal Disposal	Total
Boesch and Rabalais (1989)	Volume	745,228	434,772	1,524,962	735,854	3,440,816
	Percentage	22%	13%	44%	21%	
This Study (as of 02/90)	Volume	750,900	236,843	1,698,448	735,854*	3,422,045
	Percentage	22%	7%	50%	21%	
This Study (as of 03/91)	Volume	764,158	253,994	1,700,055	735,854*	3,454,061
	Percentage	22%	8%	49%	21%	

* No new estimates.

Table 3. Facilities in the Louisiana coastal zone with discharges of produced waters emanating from State waters but which were located near or in the vicinity of those discharging produced waters generated on the Federal OCS (as listed in Table 1). Number in left margin keyed to general location in map in Figure 1. Discharge names in (parentheses) refer to labels used in subsequent sections.

	Facility	Location	Company	Discharge ($bbl \cdot d^{-1}$)
5	Tank Battery 2	East Timbalier Island	Chevron U.S.A. Inc.***	4,866
5	Tank Battery 3	East Timbalier Island	Chevron U.S.A. Inc.***	2,429*
6	Fourchon Terminal	Pass Fourchon (PF-2 State)	Chevron Pipe Line Co.	33,756* 32,500**
10	Romere Pass State	Romere Pass/Main Pass (RP-2 State)	Chevron U.S.A. Inc.	17,137* 20,000**

* Volume discharged is an average of monthly discharge rates for period 02/88 - 02/90 (data provided by operator).
** Volume discharged as of 03/91 (data provided by operator).
*** Sold to another oil and gas operator since initiation of this study.

Table 4. Study component participants.

Investigator (Institution)	Study Component
Nancy N. Rabalais (LUMCON)	Program Manager Principal Investigator for Hydrography and Benthos Sulfides Interstitial Salinity Synthesis
Denise J. Reed (LUMCON)	Principal Investigator for Currents and Sediments Current Velocity Profiles Sediment Total Organic Carbon Sediment Grain Size Synthesis Team
Brent A. McKee (LUMCON)	Principal Investigator for Radionuclides Sedimentation Rates Synthesis Team
Jay C. Means (LSU)	Principal Investigator for Chemical Contaminants Hydrocarbon Analyses Trace Metals Synthesis Bioaccumulation Synthesis Team
Ken Jenkins (CS-LB)	Trace Metal Analyses
Donald F. Boesch (CEES)	Study Design, Synthesis Team
Thomas A. Duke (TRI)	Synthesis Team

LUMCON - Louisiana Universities Marine Consortium
LSU - Louisiana State University, Institute for Environmental Studies
CS-LB - California State University, Long Beach
CEES - University of Maryland, Center for Estuarine and Environmental Studies, formerly LUMCON
TRI - Technical Resources, Inc.

Table 5. Comparison of produced water discharge volumes and loadings by study area. Study areas arranged in order of decreasing total daily discharges of both OCS- and State-generated produced waters.

Study Area	Daily Discharge[a] ($bbl \cdot d^{-1}$)	Number of Current Discharges	Mass Loadings[b]			
			VH ($kg \cdot d^{-1}$)	PAH ($kg \cdot d^{-1}$)	Ba ($kg \cdot d^{-1}$)	Pb-210 ($dpm \cdot d^{-1}$)
Bayou Rigaud	145,760	2	98.8	10.5	1,030.1	1.02
Pass Fourchon	48,169	3	11.2	3.5	207.2	0.07
East Timbalier Island	25,558	4	1.2	3.6	934.6	0.03
Eugene Island Block 18	21,000	1	19.4	1.4	634.4	0.01
Romere Pass	20,158	2	5.1	3.4	25.7	0.01
Empire Waterway (Current discharge)	10,959	1	2.6	0.9	4.1	<0.01
Emeline Pass	3,693	1	0.5	1.4	14.4	<0.01

[a]Total for study area (from current discharges listed in Tables 1 and 3 for period 02/89 - 02/90).
[b]Calculated from average concentrations in effluents, average daily discharges, and conversion of 1 barrel = 159 liters.

Table 6. Comparison of study areas with respect to dilution potential of the receiving environment. Study areas arranged in order of decreasing total daily discharges (listed in Table 5).

Study Area	Dilution Potential of Environment[a]			Dilution of Plume and Extent[b]
	High	Medium	Low	
Bayou Rigaud		Depositional environment Periodic resuspension (storm related)		No plume observed Limited in previous study
Pass Fourchon			Depositional environment	3 to 6:1 initially 800 m on bottom
East Timbalier Island		Depositional environment/ Erosional environment		3:1 initially 100 m on bottom
Eugene Island Block 18	Depositional environment Periodic resuspension (wind related)			No plume observed
Romere Pass		Depositional environment Seasonal resuspension (river flow related)		No plume observed
Empire Waterway		Depositional environment Periodic resuspension (storm related)		No plume observed
Emeline Pass	Erosional			No plume observed

[a]Based on current velocity profiles and sedimentary characteristics.
[b]Based on bottom water salinity.

Table 7. Comparison of study areas with respect to distance of elevated contaminants from discharge points. Study areas arranged in order of decreasing total daily discharges (listed in Table 5).

Study Area	Extent of Sediment Contamination (in m from discharge)		
	Ba	Alkylated PAH	Pb-210
Bayou Rigaud	1,000	1,300	1,000
Pass Fourchon	1,000	1,000	1,000
East Timbalier Island	580	360	<100
Eugene Island Block 18	250	250	<50
Romere Pass	450	450	<250
Empire Waterway			
(Current discharge)	1,000	NA	<300
(Abandoned discharge)	1,000	250	<450
Emeline Pass	<100	<100	<100

NA - not applicable, because only trace levels detected.

Table 8. Comparison of study areas with respect to biological effects; extent of effect given in meters from discharge point. Study areas arranged in order of decreasing total daily discharges (listed in Table 5).

Study Area	Type of Effect	Benthic Community Differences: Species Effect	Species Extent (m)	Individuals Effect	Individuals Extent (m)	Bioaccumulation* Effect	Bioaccumulation* Extent (m)
Bayou Rigaud	Distinct	Yes	150	No	---	High	200
	Gradient	Yes	500	Yes	700	Moderate	1,000
Pass Fourchon	Distinct	Yes	500	Yes	500	High	350
	Gradient	Yes	800	Yes	800	Moderate	300
East Timbalier Island	Distinct	Yes	100	Yes	100		
	Gradient	No	---	No	---		
Eugene Island	Distinct	No	---	Yes	<50		
	Gradient	Yes	300	Yes	300		
Romere Pass	Distinct	No	---	No	---		
	Gradient	No	---	No	---		
Empire Waterway (Current)	Distinct	No	---	No	---		
	Gradient	No	---	No	---		
(Abandoned)	Distinct	No	---	No	---		
	Gradient	Yes	250	Yes	<550		
Emeline Pass	Distinct	No	---	No	---		
	Gradient	No	---	No	---		

*Based on Deployment I (see Section 7.2).

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interest of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.