BRINE DISPOSAL IN THE GULF OF MEXICO:

Assessment and Analysis for West Hackberry

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U. S. Department of Commerce
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service


NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

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Assessment and Analysis for West Hackberry

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1.0 EXECUTIVE SUMMARY

1.1 Background

The international petroleum embargo of 1973-74 impressed upon the United States its dependence on foreign oil supplies and its national security vulnerability to disruptions in the flow of these supplies. In formulating contingency plans for minimizing the impacts of potential future disruptions in the international oil trade, Congress, through the Energy Policy and Conservation Act of 1975, mandated the establishment of a strategic petroleum reserve (SPR).

The Federal Energy Administration, precursor of the Department Of Energy (DOE), was given the task of having 150 million barrels of crude oil in storage by December 1978 and 500 million barrels in storage by December 1982. Amendments to the SPR plan in 1977, 1978 and 1979 accelerated the schedule and authorized an increase in the reserve. Subsequent revisions to the schedule currently call for completing oil fill of the 750 million barrel program in 1990.

The DOE concluded that the storage of crude oil in subterranean salt domes along the Gulf of Mexico was the most feasible strategy for storing such large amounts of oil. Development of these sites required solution mining on such a massive scale that ocean discharge was the only practicable alternative for brine disposal.

1.2 Purpose

The National Oceanic and Atmospheric Administration (NOAA) has the responsibility to provide DOE with an independent integration, synthesis and assessment of oceanographic monitoring studies relevant to the development of the Strategic Petroleum Reserve.

In fulfillment of that obligation, this report presents an analysis and assessment of marine environmental impacts related to the first 43 months of brine disposal at West Hackberry. This report draws upon pre-disposal and post-disposal monitoring data, analyses for Calcasieu Lake and for the West Hackberry discharge site, numerical models of brine diffusion characteristics and other pertinent NOAA and DOE marine environmental studies conducted to address concerns about offshore disposal of brine.

1.3 West Hackberry Site

The West Hackberry brine disposal site is located adjacent to the West Hackberry salt dome located in Cameron Parish of southwestern Louisiana, approximately 32 kilometers southwest of Lake Charles. The resultant brine from solution mining is transported via pipeline to a diffuser system 11 kilometers offshore at a depth of 9 meters. The Environmental Protection Agency (EPA) has approved discharge rates for the disposal of salt dome brine into the marine environment of approximately 1.1 million barrels per day. The brine has a salinity of 250-260 parts per thousand (ppt) and is roughly 7.5 times more concentrated than oceanic seawater and 9 times more concentrated than the Gulf of Mexico receiving waters.

Concerns for the potential impact of the discharge brine on the offshore marine environment stem from the following aspects of leaching and brine disposal operations:

1) rate of brine disposal,

2) concentration of the brine,

3) chemical composition of the brine (because dome salt has different ionic proportions than seawater, there was concern that brine-induced ionic imbalances would impact the biota, particularly the commercial shrimp) and

4) water quality characteristics of the leaching waters.

Another concern associated with the actual location of the West Hackberry brine diffuser was that with a high discharge rate in conjunction with a strong bottom current towards the northeast, the brine plume might reach Calcasieu Pass and affect the estuary.

1.4 Pre-disposal and Post-disposal Surveys

Pre-disposal baseline surveys were conducted intermittently at the offshore brine discharge site from September 1977 through April 1981. Meteorological, physical, chemical and biological variables were sampled. Sampling was monthly for the period of September 1977 - April 1978, quarterly for the period of June 1978 - May 1979, and then monthly for the period of February 1981 - April 1981. No surveys were conducted during the period of June 1979 - January 1981. NOAA has produced three synthesis reports that discuss the pre-disposal environment of the West Hackberry site.

Post-disposal monitoring studies began in May 1981 and have continued to the present. A field sampling program, that included not only marine stations but also estuarine stations in Calcasieu Lake, was conducted monthly (or with higher frequency) through the first year of brine discharge. Frequency of sampling has, since that time, been reduced, except during the summer. Physical oceanographic variables such as currents, temperature and salinity have been measured on a nearly continuous basis through the use of buoyed in situ instrument packages.

1.5 Results

Analysis of 39 monthly brine plume monitoring results for the period June 1981-November 1984 reveals that maximum deviation from ambient salinity in the bottom waters was less than 7 parts per thousand (ppt) in 95 percent of the cases and less than 5 ppt in 72 percent of the cases. Above-ambient salinity levels decrease exponentially with distance from the diffuser.

Initial concerns for potential movement of the brine plume into Calcasieu Pass or impingement on the Louisiana shoreline appear to be unsubstantiated. The furthest observed inshore incursion of the 1 ppt excess salinity level was only 4 km, while excess salinity levels of 4 ppt, or greater, never extended further than 0.9 km inshore of the diffuser.

The marine biota at the West Hackberry brine disposal site is typical of biota along the northwest Gulf of Mexico; thus, the brine disposal site is not situated in or near a unique or critical habitat. Characteristic of coastal temperate ecosystems, natural variability within the ecosystem at West Hackberry is high over small time and space scales. Seasonal variability of local biotic and abiotic factors is frequently an order of magnitude larger than variability between control and diffuser stations.

1.6 Conclusions

The only direct impact of brine disposal is an elevation of salinity in bottom waters and sediment pore waters in the vicinity of the brine diffuser. The elevated salinities will return to ambient (control) levels with cessation of brine discharge operations. Ionic imbalances, halite precipitation and elevated concentrations of pesticides, heavy metals and petrogenic hydrocarbons have not occurred as a result of discharge operations.

There is no reasonable evidence that brine disposal at West Hackberry has detrimentally impacted the biota during the first 43 months of brine discharge. This conclusion is supported by the results of a numerical model of the plume, and analysis and interpretation of results from sampling programs. Numerical abundances, number of species, diversity, community structure, and the composition of the plankton, nekton and benthos show no detrimental effects of brine discharge. Penaeid shrimp abundance, spawning, larval development and migration also show no detrimental effects of brine discharge. If detrimental effects on the biota have occurred, those effects are either not measurable or not separable from natural variability.

Naturally occurring hypoxia in bottom waters is common at intermittent intervals during summer in this region, and is likely to recur in the future. Hypoxia is not related to brine disposal. Detrimental effects of hypoxia are measurable and represent a potentially severe stress for the shelf ecosystem. However, the discharged brine is well oxygenated and we hypothesize hypoxia is ameliorated in the immediate vicinity of the diffuser, because increased abundance and diversity of the biota are sometimes measured at the diffuser during periods of hypoxia.

2.0 INTRODUCTION

2.1 Authorization

This report has been prepared in compliance with Article II, Task XVII of Interagency Agreement DE-AI01-78US07146 (hereafter referred to as the IA) between the Department of Energy (DOE) and the National Oceanic and Atmospheric Administration (NOAA). Under the terms of the IA, NOAA has responsibility to provide DOE with marine environmental analysis and assessment services relevant to the development of the Strategic Petroleum Reserve (SPR). Task XVII, added to Article II of the IA in 1983 under Amendment No. 19, gives NOAA additional responsibility for analyzing and assessing impacts of brine disposal operations on the marine ecology of the offshore disposal sites. It provides for the independent integration, synthesis and assessment of oceanographic monitoring data and analyses of brine disposal conducted by DOE contractors.

Specifically, this report presents an analysis and assessment of marine environmental impacts associated with the first 43 months of offshore disposal of brine from the West Hackberry, LA, salt dome. It draws upon pre-disposal and post-disposal monitoring data and data analyses for Calcasieu Lake and for the West Hackberry discharge site, numerical models of brine diffusion characteristics and other pertinent NOAA and DOE marine environmental studies conducted to address concerns about offshore disposal of brine from the West Hackberry salt dome. Submission of 20 copies of this report to the DOE Program Officer for the SPR is specified under Article III, Item 48, of the IA, Amendment No. 21 dated 15 August 1985.

2.2 The Strategic Petroleum Reserve: A Synopsis

The international petroleum imbargo of 1973-74 impressed upon the United States its dependence on foreign oil supplies and its national security vulnerability to disruptions in the flow of these supplies. In formulating contingency plans for minimizing the impacts of potential future disruptions in the international oil trade, Congress, through the Energy Policy and Conservation Act of 1975, mandated the establishment of an SPR.

The Federal Energy Administration, precursor of the DOE, was given the task of placing 150 million barrels of crude oil in storage by December 1978 and 500 million barrels in storage by December 1982. Amendments to the SPR plan in 1977, 1978 and 1979 accelerated the schedule, authorized an increase in the reserve from 500 to 1000 million barrels and described plans to store 750 million barrels. Subsequent revisions to the schedule currently call for completing oil fill of the 750 million barrel program in 1990. Decisions regarding development of storage for the final 250 million barrels have been deferred.

The DOE, in its evaluation of alternative approaches for implementing the SPR, concluded that the storage of crude oil in subterranean salt domes along the Gulf of Mexico was the most feasible strategy. The primary advantages of these salt domes as storage sites are their geological stability and their proximity to existing crude oil refining and distribution centers. Over 150 salt domes were screened from more than 500 salt domes that exist in the Gulf Coast states and nearshore Gulf of Mexico. From this number, six salt domes in Texas and Louisiana were selected. Development of three of these sites, Bryan Mound and Big Hill salt domes in Texas and West Hackberry salt dome in western Louisiana, required solution mining on such a massive scale that ocean discharge was the only practicable alternative for brine disposal (Figure 2-1). Between 4.2 and 4.8 billion barrels of brine will be discharged to the marine environment in the creation of 490 million barrels of net usable storage space. Ocean discharge of brine commenced at Bryan Mound in March 1980 and at West Hackberry in May 1981. Big Hill discharge is scheduled tentatively for some time in the future.

Leaching is accomplished by pumping fresh or brackish water from the Intracoastal Waterway (ICW) into the domes to dissolve the salt. The resultant brine solution is then pumped to a surface holding pond from which it is piped offshore and dispersed in the bottom water via an offshore pipeline ending in a 1000 meter long, multiple-port diffuser system which is designed for the rapid diffusion and dilution of the concentrated brine. As the leaching process creates storage volume, oil, which is lighter than water or brine, is pumped in to "blanket" the cavern from the top down, thereby preventing further undesired leaching. Removal of oil from the reserve will be accomplished by pumping water into the cavern at the bottom. This will force the less dense oil to flow from the cavern to the surface through a pipe at the top of the cavern. Figure 2-2 is a schematic of the leaching, filling and drawdown systems.

2.3 Background

On 14 August 1980, the Environmental Protection Agency (EPA) issued a National Pollutant Discharge Elimination System (NPDES) permit to the DOE for ocean discharge of 1.088 million barrels (MMB) per day of concentrated brine from the West Hackberry salt dome in development of the SPR. Conditions of the NPDES permit for West Hackberry required that DOE provide the following information to the EPA prior to brine discharge:

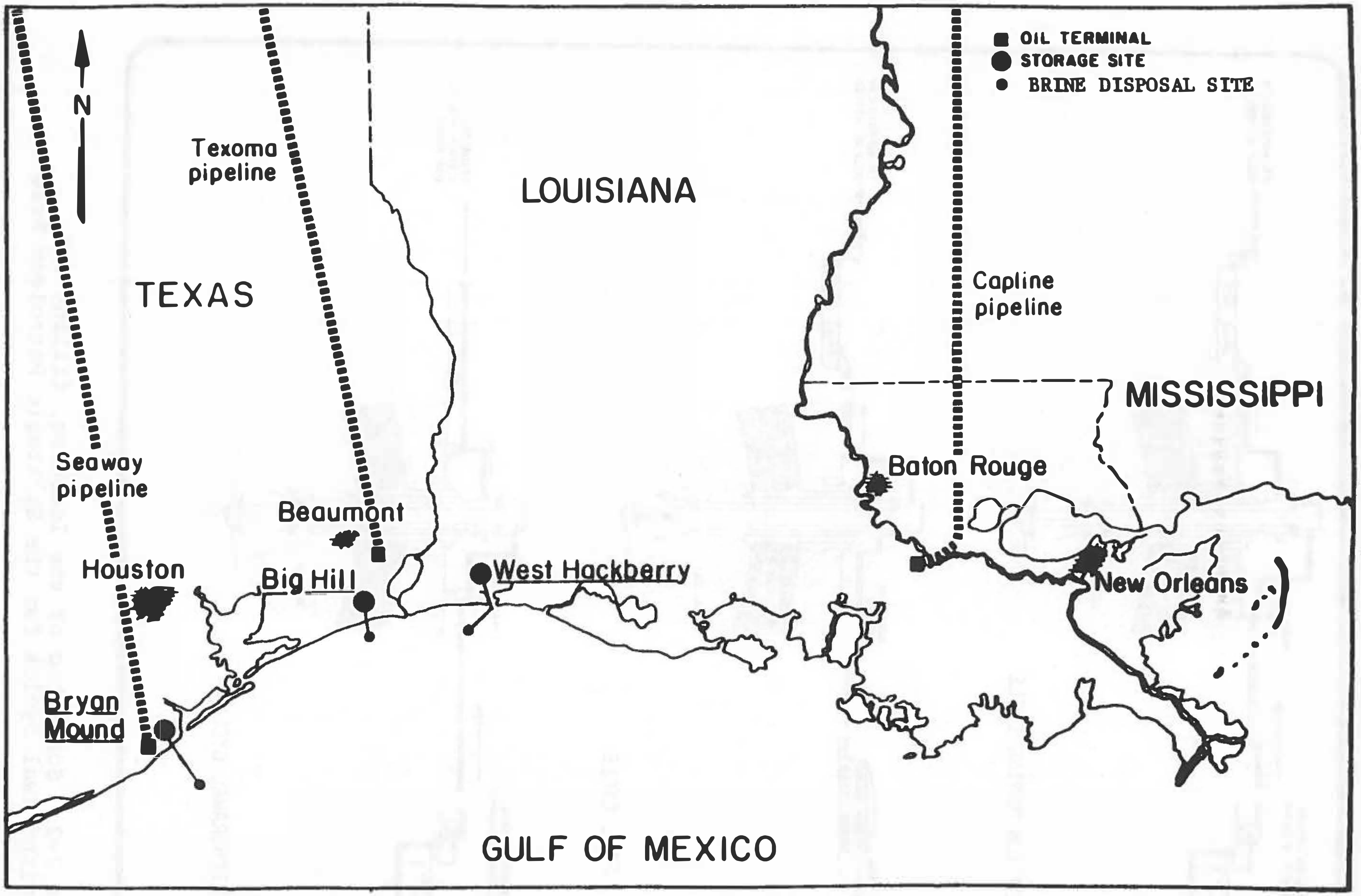


Figure 2-1. Location of salt dome sites for petroleum storage for the Strategic Petroleum Reserve and the offshore brine disposal sites.

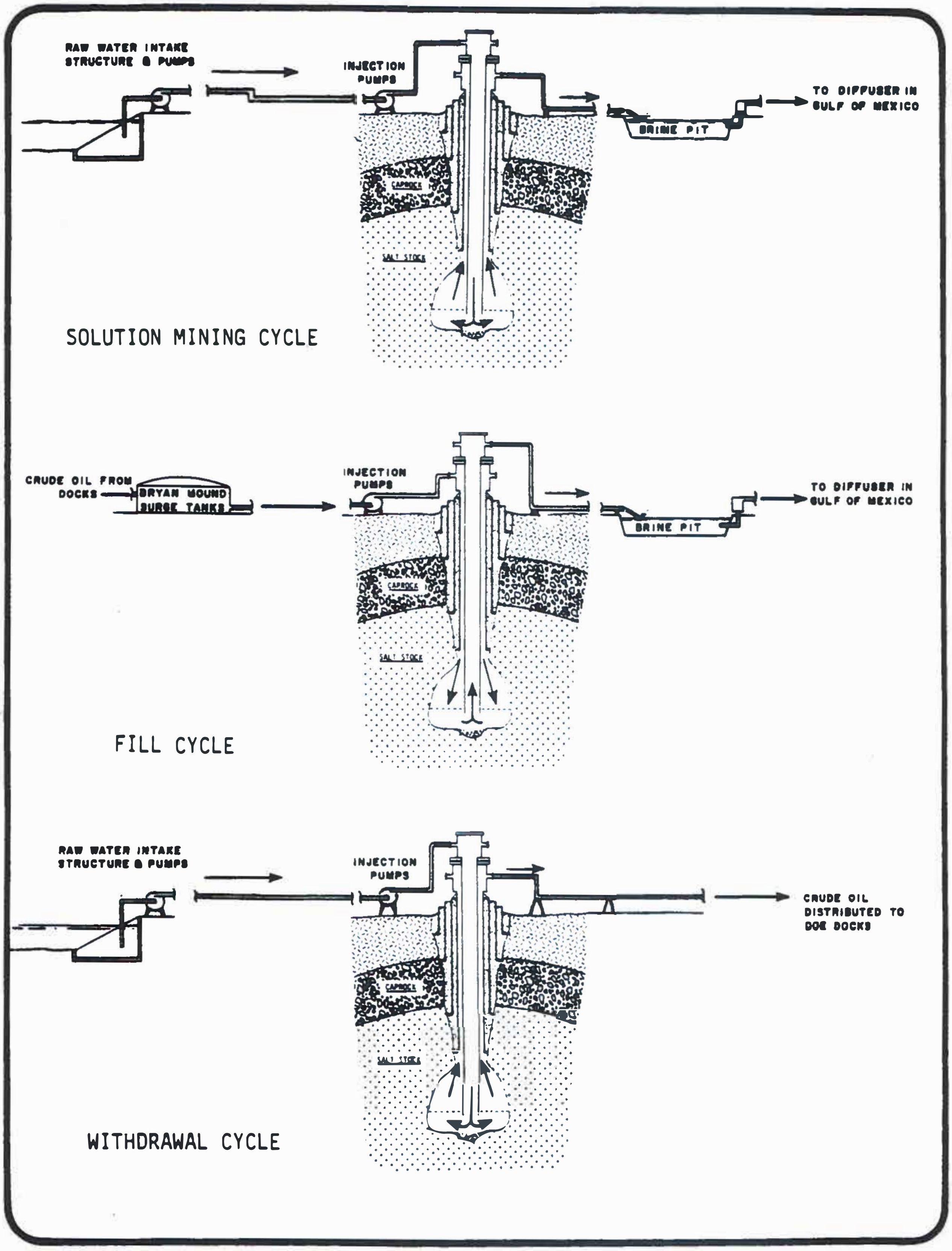


Figure 2-2. Schematic of the leaching, filling and withdrawal cycles for the Strategic Petroleum Reserve.

- o An updated brine dispersion prediction for West Hackberry based on actual dispersion information obtained at Bryan Mound.
- o An effects assessment of brine discharge at West Hackberry based on data obtained from the Bryan Mound Monitoring Plan.

NOAA, under terms of the IA, Article II, Task XIV, Amendment No. 15 dated 24 December 1980, provided the DOE with the required information in a report, "Brine Disposal in the Gulf of Mexico: Projected Impacts For West Hackberry Based on Bryan Mound Experience" (NOAA, 1981). Based on the first year of brine discharge experience for the Bryan Mound site and the results of brine dispersion modeling, the report presents the following conclusions for marine environmental impact of brine discharge from the West Hackberry site:

- o the brine plume will cover a bottom area greater than previously predicted;
- o brine concentrations near the diffuser will be higher than previously predicted;
- o the threshold of observed biological effects from elevated salinity has been shown to be higher than worst case discharge conditions; and
- o brine disposal will have minimal, if any, impact on the biota.

The present report provides an assessment based on actual monitoring data collected from the brine discharge site and Calcasieu Lake during the first 43 months of brine disposal operations at the West Hackberry site.

2.4 Brine Impact Concerns

2.4.1 Offshore Site

Concerns for the potential impact of the discharge brine on the offshore marine environment stem from the following aspects of leaching and brine disposal operations: 1) rate of brine disposal; 2) concentration of the brine; 3) chemical composition of the brine and 4) water quality characteristics of the leaching waters. The EPA has approved discharge rates for the disposal of salt dome brine into the marine environment that are approximately 1.1 million barrels per day per site. The brine has a salinity of 250-260 parts per thousand (ppt) and is roughly 7.5 times more concentrated than open ocean seawater and 9 times more concentrated than the Gulf of Mexico receiving waters. Brine disposal, over periods of up to 5 years, will introduce approximately 12.6 million metric tons of salt into the Gulf of Mexico. Thus, the potential for significant impacts, particularly on the benthic and demersal species and biotic assemblages, due to elevated salinities caused by continuous, high-volume disposal of concentrated brine is a serious concern.

This concern is not limited to the water column but extends to the bottom sediments as well. Because dome salt has different ionic proportions than seawater, there was also concern that brine-induced ionic imbalances would impact the biota. Lastly, there was concern that the use of ICW water as the leaching agent would result in the direct transmission of contaminants and pollutants into the offshore Gulf waters. While these concerns were directed to the marine ecosystem as a whole, specific interest was focused on potential negative impacts of brine disposal on the fisheries resources of the region. Of these, the shrimp fishery resources have received the most attention, and the possibility of indirect impacts on the fishery resources as a manifestation of complex ecosystem interactions has received close scrutiny.

2.4.2 Calcasieu Lake

Calcasieu Lake serves as a nursery area for important fishery species of which the white shrimp and brown shrimp are perhaps the most important. In addition, it supports a significant blue crab and oyster fisheries. The requirement for large volumes of water from the ICW for the leaching of the salt dome and the relative proximity of the offshore brine discharge site to the estuary elicited concerns that salt leaching and brine disposal operations might alter the salinity regime of the estuary and impact the estuarine-dependent fishery resources of the region.

Withdrawal of upwards of 1.1 million barrels of water per day from the ICW for leaching purposes represents a diversion of water which would normally flow into Calcasieu Lake. The primary concern associated with this diversion of freshwater from the estuary was that seawater intrusion would increase accordingly and result in elevated salinities through the estuary.

The Bryan Mound brine diffuser is located 11 nautical miles (nm) off the Texas coast. In comparison, the West Hackberry brine diffuser is situated just 6 nm off the Louisiana coast just to the southwest of Calcasieu Lake. The major concern associated with the location of the West Hackberry brine diffuser was that under long-term conditions of high discharge rates and strong bottom currents to the northeast, the brine plume might reach to Calcasieu Pass and be carried into the estuary during flood tide.

2.5 Summary of Pre- and Post-Disposal Environmental Study Reports

2.5.1 Pre-disposal Studies

Pre-disposal baseline surveys were conducted intermittently at the offshore brine discharge site from September 1977 through April 1981. Meteorological, physical, chemical and biological variables were sampled. Four prime contractors/agencies collected these data independently of each other and utilized different spatial and temporal sampling schemes. Sampling was monthly for the period of September 1977 - April 1978, quarterly (i.e., every three months) for the period of June 1978 - May 1979, and then monthly for the period of February 1981 - April 1981. No surveys were conducted during the period of June 1979 - January 1981. Results and findings of the pre-disposal baseline surveys are available in the following reports.

<u>September 1977 - April 1978 pre-disposal survey period</u>

Comiskey, C.E. and T.A. Farmer (eds.). 1981. Characterization of Baseline Oceanography for the Texoma Region Brine Disposal Sites: Volume I. SAI, Oak Ridge, TN, 302 pp.

Comiskey, C.E. and T.A. Farmer (eds.). 1981. Characterization of Baseline Oceanography for the Texoma Region Brine Disposal Sites: Volume II. SAI, Oak Ridge, TN, 532 pp.

<u>June 1978 - May 1979 pre-disposal survey period</u>

Boehm, P.D. and D.L. Feist. 1980. Determine hydrocarbons composition and concentration in major components of the marine ecosystem. Vol. VI. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978- 1979. NOAA Technical Memorandum NMFS-SEFC-30, 138 pp. Available from NTIS, Springfield, VA.

Brooks, J.M. 1980. Determine seasonal variations in inorganic nutrient composition of the water column. Vol. VIII. IN: Jackson, W.B. and G.M Faw (eds.). Biological/chemical survey of the Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-32, 31 pp. Available from NTIS, Springfield, VA.

Frey, H.R. and G.F. Appell (eds.). 1981. NOS Strategic Petroleum Reserve Support Project: Final Report. Volume Two - Measurements and Data Quality Assurance. NOS, National Oceanic and Atmospheric Administration, Rockville, MD, 182 pp and appendices.

Frey, H.R., M.W. Szabados, and L.F. Hickman. 1981. NOS Strategic Petroleum Reserve Support Project: Final Report. Volume One - Oceanography on the Louisiana Inner Continental Shelf. NOS, National Oceanic and Atmospheric Administration, Rockville, MD, 343 pp and appendices.

Hausknecht, K.A. 1980. Describe surficial sediments and suspended particulate matter. Vol. V. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/ chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-29, 56 pp. Available from NTIS, Springfield, VA.

Landry, A.M. and H.W. Armstrong. 1980. Determine seasonal abundance, distribution and community composition of demersal finfishes and macro- crustaceans. Vol. IV. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-28, 180 pp. Available from NTIS, Springfield, VA.

Margraf, F.J. 1980. Analysis of Variance of Gulf Coast shrimp data. Vol. IX. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978- 1979. NOAA Technical Memorandum NMFS-SEFC-33, 293 pp. Available from NTIS, Springfield, VA.

Parker, R.H., A.L. Crowe, and L.S. Bohme. 1980. Describe living and dead benthic (macro- and meio-) communities. Vol. I. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-25, 103 pp. Available from NTIS, Springfield, Virginia.

Reitsema, L.A. 1980. Determine seasonal abundance, distribution, and community composition of zooplankton. Vol. II. IN: Jackson, W.B. and G.M. Faw eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-26, 133 pp. Available from NTIS, Springfield, VA.

Schwarz, J.R., S.K. Alexander, A.J. Schropp, and V.L. Carpenter. 1980. Describe bacterial communities. Vol. III. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-27, 48 pp. Available from NTIS,Springfield, VA.

Tillery, J.B. 1980. Determine trace metal composition and concentration in major components of the marine ecosystem. Vol. VII. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/chemical survey of Texoma and Capline sector salt dome disposal sites off Louisiana, 1978 - 1979. NOAA Technical Memorandum NMFS-SEFC-31, 72 pp. Available from NTIS, Springfield, VA.

February 1981 - April 1981 pre-disposal survey period

DeRouen, L.R., R.W. Hann, D.M. Casserly, and C. Giammona. 1982. West Hackberry Brine Disposal Project: Pre-discharge Characterization. McNeese State University, Lake Charles, LA, 529 pp and appendices.

In addition, NOAA has produced three synthesis reports that discuss and describe the pre-disposal environment of the West Hackberry brine discharge site.

NOAA. 1981. Brine Disposal in the Gulf of Mexico: Projected Impacts for West Hackberry Based on Bryan Mound Experience. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., 51 pp.

Pechmann, K., K.W. Turgeon, I. Sheifer, and J .Foreman. 1985. Brine Disposal in the Gulf of Mexico: Annotated Inventory of the West Hackberry Site Pre- Disposal Data Sets, September 1977 - April 1981. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., 173 pp.

Turgeon, K.W. 1981. Synthesis of the Texoma/Capline Chemical and Biological Survey Results: June 1978 - May 1979. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., 87 pp.

2.5.2 Post-disposal Studies

Post-disposal monitoring studies began in May 1981 and have continued to the present. Over-the-side sampling, which includes estuarine stations in Calcasieu Lake, was conducted monthly (or with higher frequency) through the first year of brine discharge. Frequency of sampling has, since that time, been reduced, except during the summer. Physical oceanographic variables such as currents, temperature and salinity have been measured on a nearly continuous basis through the use of buoyed in situ instrument packages. McNeese State University, Lake Charles, Louisiana was responsible for the first year post-discharge monitoring; Texas AM University, College Station, Texas served as a coinvestigator. Texas AM University has been responsible for the post-disposal monitoring after the first year of discharge operations.

Three post-disposal monitoring reports have been produced and are listed below.

DeRouen, L.R., R.W. Hann, Jr., D.M. Casserly, and C.P. Giammona (eds.). 1982. West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year I Report: Final Report. Department of Energy. Available from NTIS, Springfield, VA; DOE-PO-10288-2.

Hann, R.W., Jr., C.P. Giammona, and R.E. Randall (eds.). 1984. Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Eighteen-month Report for the West Hackberry Site from May 1982 through November 1983. Department of Energy. Available from NTIS, Springfield, VA; DOE-PO10850-3.

Hann, R.W., Jr., C.P. Giammona, and R.E. Randall (eds.). 1985. Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy. Available from NTIS, Springfield, VA; DOE-PO10850-5.

3.0 THE WEST HACKBERRY BRINE DISPOSAL SITE

3.1 Site Location and Disposal Operations

The brine disposal site is located adjacent to the West Hackberry salt dome located in Cameron Parish of southwestern Louisiana, approximately 32 km southwest of Lake Charles (Figure 3-1). The resultant brine from solution mining at West Hackberry is transported via pipeline to a diffuser system 11.4 km offshore at a depth of 9.1 meters (m) (Figure 3-2). The diffuser is aligned perpendicular to the coast and consists of a 988 m diffuser with 55 brine discharge ports spaced 18 m apart.

The first year of brine discharge was characterized by intermittent hours of operation and variable flow rate and salinity. Operations began in May 1981 with a discharge of approximately 50,000 barrels per day (bbl/d) at 30 ppt. At the start of discharge operations, only 32 of the 55 ports were opened. Discharge rate and salinity were increased to 600,000 bbl/d and 220 ppt by mid-July. That level was maintained until late August, when discharge ceased until mid-September. Low volumes were then discharged intermittently until mid-October, when flow rates returned to July levels and remained stable for the rest of the year. Discharge was intermittent again in January 1982. During February discharge rates increased from 500,000 bbl/d to 750,000 bbl/d at salinities of 250 ppt. The number of open diffuser ports was increased to 50 on 18 March 1982 and then adjusted to 42 on 25 April 1982 to achieve optimum velocities for brine diffusion. During the first year, the average daily discharge rate was 529,000 bbl/d at an average salinity of 216 ppt.

During the second discharge assessment period, 1 May 1982 to 14 November 1983, brine discharge was almost continuous. In May 1982 the discharge rate was 750,000 bbl/d at 240-263 ppt, but in late June operations ceased because of pump malfunctions. By July, discharge rates had returned to the May level, although brine salinity was as low as 181 ppt. From August to October discharge rates were stable and salinity gradually increased to more than 240 ppt. From November 1982 to November 1983 discharge was almost continuous at rates from 800,000 to 1,000,000 bbl/d and salinities from 240 to 263 ppt.

During the third discharge assessment period, 15 November 1983 to 30 November 1984 operations were shut down for intermittent periods totaling 44 days. The discharge rate averaged 800,000 bbl/d at salinities above 250 ppt. The maximum pumping rate and salinity for the West Hackberry operation were 1,018,000 bbl/d and 270 ppt.

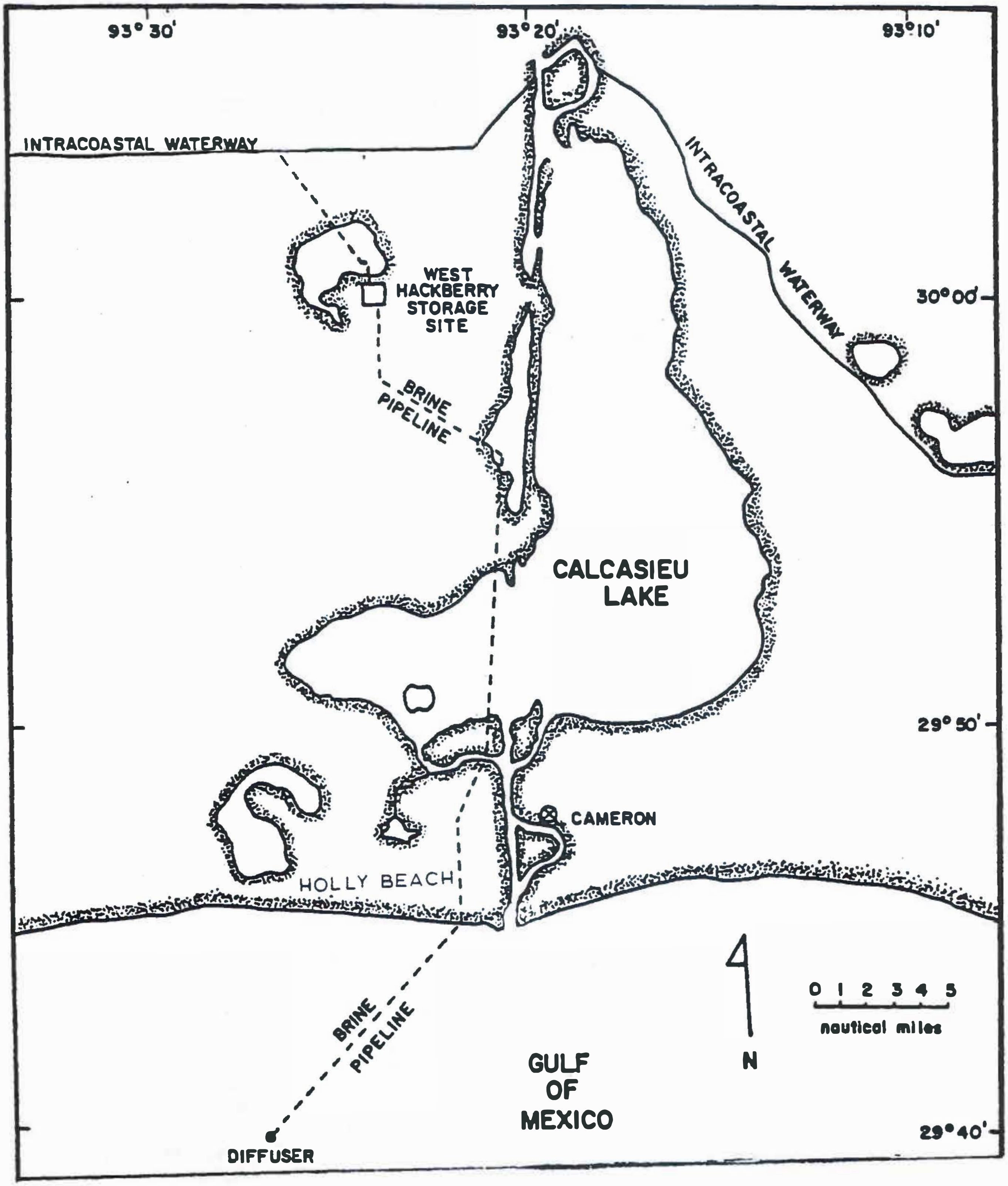


Figure 3-1. Map of West Hackberry area showing the onshore storage pipeline and offshore diffuser locations. Source: NOS.

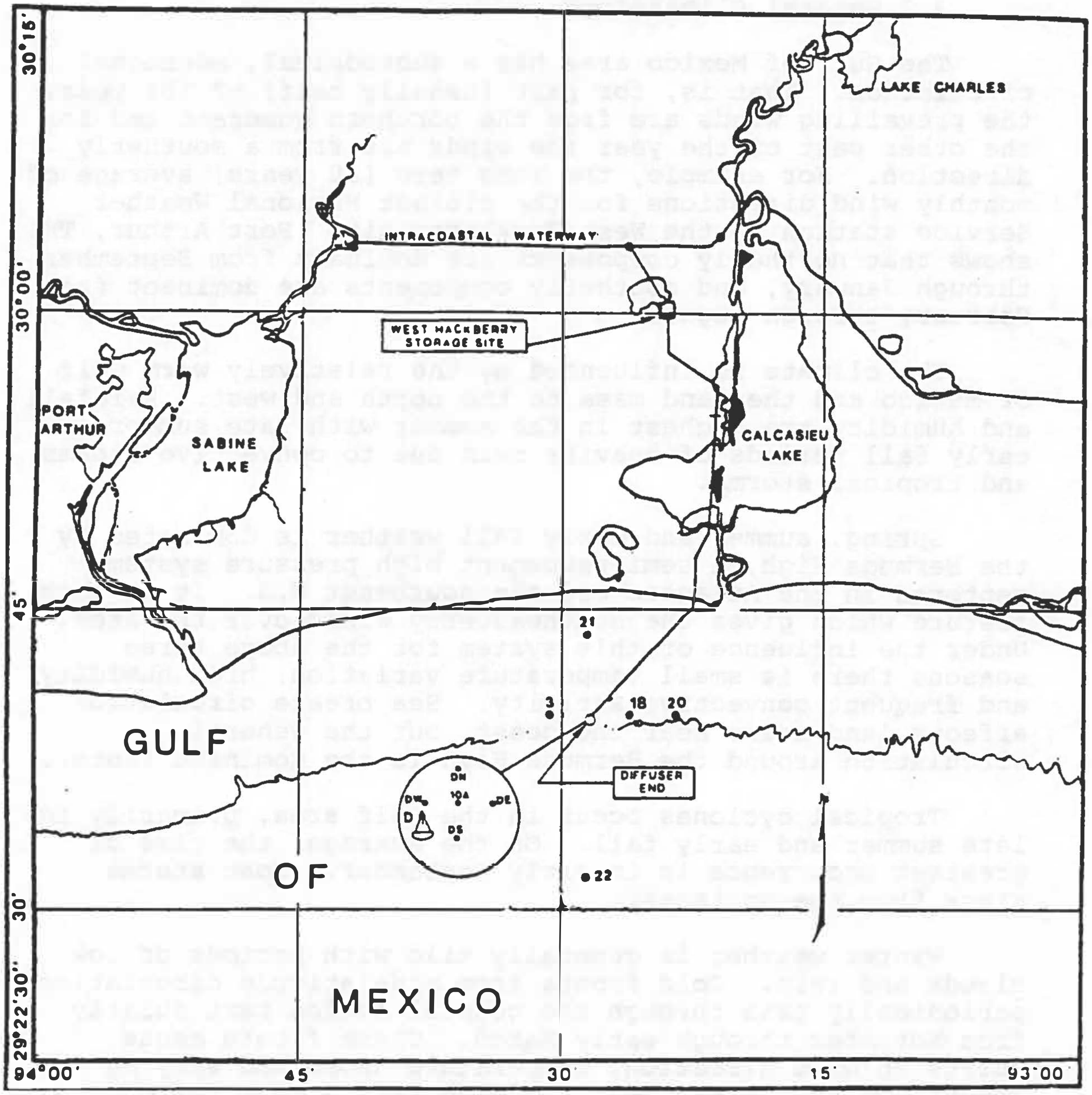


Figure 3-2. Map of West Hackberry offshore sampling stations.

3.2 General Climatology

The Gulf of Mexico area has a subtropical, monsoonal circulation. That is, for part (usually half) of the year, the prevailing winds are from the northern quadrant and for the other part of the year the winds are from a southerly direction. For example, the long term (30 years) average of monthly wind directions for the closest National Weather Service station to the West Hackberry site (Port Arthur, TX) shows that northerly components are dominant from September through January, and southerly components are dominant from February through August.

The climate is influenced by the relatively warm Gulf of Mexico and the land mass to the north and west. Rainfall and humidity are highest in the summer with late summer and early fall periods of heavier rain due to convective storms and tropical storms.

Spring, summer and early fall weather is dominated by the Bermuda High, a semi-permanent high pressure system centered in the Atlantic off the southeast U.S. It is this feature which gives the southeasterly winds over the area. Under the influence of this system for the above three seasons there is small temperature variation, high humidity and frequent convective activity. Sea breeze circulation affects land areas near the coast, but the general circulation around the Bermuda High is the dominant factor.

Tropical cyclones occur in the Gulf area, primarily in late summer and early fall. On the average, the time of greatest occurrence is in early September. Most storms track from the southeast.

Winter weather is generally mild with periods of low clouds and rain. Cold fronts from mid-latitude circulation periodically pass through the coastal region particularly from November through early March. These fronts cause shifts in wind direction, temperature drops and varying amounts of precipitation. The wind shifts last for one to three days bringing cooler, dryer air to the area. The duration of wind shift (and influx of cooler air) sometimes lasts for extended periods as it did in December 1983 (see Section 7.3 on severe winter conditions), and the colder air may be well below freezing for several days.

3.2.1 Air Temperature

Moderate temperatures occur most of the time because of the predominant southeasterly circulation and the influence of the Gulf water. Summers are warm and humid with maximum temperatures in the range of 25 to 35 degrees Celsius, winters are mild with relatively few days with temperatures below freezing. Winter temperatures are in the range of 10 to 20 degrees Celsius, but there is more variation around this climatic value because of the incursions of cold continental air.

3.2.2 Precipitation

The climatic averaged precipitation does not vary greatly in the area (monthly averages from about 8 centimeters (cm) in late winter to 15 cm in early fall). The type and frequency varies with season or month. Spring through early fall precipitation occurs from convective type showers. Winter precipitation occurs more frequently from frontal type circulation and is longer lasting. The largest amounts occur from thunderstorms, tropical storms and hurricanes. The number of days per month with thunderstorms varies from a minimum of 2 in December, January and February to 12 or 13 in July and August. The number of rainy days (0.0254 cm of precipitation) varies from about 6 in spring and fall to 12 in mid-summer. Snowfall is quite light, with a trace of it occurring in only about half the winters. Climatological annual average (30 years 1951-1980) precipitation amounts from nearby stations are Port Arthur 134 cm, Galveston 102 cm and Houston 114 cm.

3.2.3 Tropical Storms and Hurricanes

The Gulf is part of one of six regions of the earth in which tropical storms and hurricanes form. These storms generally form in the tropical Atlantic and track into the Gulf region. However, storms do originate in the Gulf area itself. In the period 1980 through 1984 of the nine tropical storms or hurricanes that tracked into or through the Gulf, five originated in the Gulf, and three tracked close to or over the West Hackberry site. In two of the years 1981 and 1984 no storms originated in or tracked into the Gulf area.

For the period 1886 through 1984 there were 251 tropical storms and hurricanes whose tracks went through the Gulf of Mexico. This is an average of 2 1/2 per year. Of these 124 had tracks through the area bounded by 90° W 25° N and the Texas - Louisiana coast line. Half of the storms that entered the Gulf passed in the vicinity of the West Hackberry area.

3.3 The Natural Marine Environment

3.3.1 Physical Oceanography

The dispersion and advection of brine is controlled principally by the ocean density-structure (salinity and temperature distribution) and by circulation. At the West Hackberry diffuser site the density-structure and circulation of shelf waters are most strongly influenced by three processes: wind stress, river runoff and, to a lesser extent, tidal processes. With the appropriate conditions, any one of these processes may dominate, but usually their influence is in concert with the others. The interplay of these processes causes the physical environment at West Hackberry to be highly variable. Because the shelf waters are shallow, they respond to high runoff or high wind stress within a few hours. Tidal processes appear to dominate the coastal boundary current only when both runoff and wind stress are low.

Winds are often the dominant factor in driving the local shelf circulation (Comiskey and Farmer, 1981). Currents in the vicinity of the diffuser are predominantly parallel to the shore and towards the west. Across-shelf currents are usually weak. Strong winds with a strong onshore or offshore component may produce transient, but significant, cross-shelf currents. The barotropic (sea surface slope) component of the local current is strong and coupled to wind stress. High wind stress also increases mixing, which decreases density gradients.

The circulation of the inner shelf region of Louisiana is strongly affected by river runoff. The Mississippi and Atchafalaya rivers account for an overwhelming majority of the total river discharge into the Gulf of Mexico. On the average these two rivers reach a maximum discharge in April and May and a minimum discharge in September. The mixing of Mississippi River discharge with ocean waters appears to be confined to the shelf region. Above-ambient salinities at the edge of the near-field zone of brine discharge are not as large as the natural spatial and temporal variation in salinity. Natural mixing processes are apparently strong.

3.3.2 Sediment Composition and Chemistry

The sediment composition of the shelf region of Louisiana is strongly influenced by the fine-grained sediments discharged by the Mississippi River. The Mississippi carries at least half of the total sediment load and water transported by all US rivers (Trefry et al., 1985). At West Hackberry, sediment particles range from clay to sand-silt-clay (Comiskey and Farmer, 1981). Recent studies have shown silty clay to be predominant except for a brief period during the summer and the fall of 1978, when sand-silt-clay was characteristic. Grain size decreases towards the west and across isobaths in the vicinity of the outflow from Calcasieu Pass. Shoreward of the diffuser site, sediments are predominantly clay with a typical grain size larger than 6 phi (0.0156 mm). For comparison, another brine diffuser site, Bryan Mound, has slightly coarser sediments with clayey sand and silty sand predominating (i.e., typical grain size less than 6 phi).

Throughout this region, relatively high trace metal concentrations are associated with these fine-grained sediments, because metal concentrations tend to increase with the increased surface area of finer sediments. Sediments from the same region typically have similiar ratios of trace metals unless perturbed by anomalous environmental factors. Recent studies also have shown that pollutant lead discharged by the Mississippi in 1982-1983 was 60 percent of the amount transported a decade earlier, in an apparent response to reductions in the use of leaded gasoline (Trefry et al., 1985).

Comiskey and Farmer (1981) compared sedimentary data among various sites in this region prior to brine disposal. They found percent clay to be highly correlated with total organic carbon and iron. Iron concentrations were very high, on the order of grams per kilogram. At those high concentrations, anthropogenic inputs of iron are trivial by comparison. High correlations (r) between iron and trace metals ranged from 0.88 for cadmium to 0.97 for both lead and zinc (Comiskey and Farmer, 1981). Variation among stations in regard to baseline concentrations of trace metals in the sediments was attributed to variation in sediment particle size, rather than to anthropogenic inputs. Consequently, trace metal concentrations in the water column at West Hackberry were higher than those at Bryan Mound, where concentrations were generally below detection levels.

Naturally-occurring hypoxic conditions arise periodically in this region. During hypoxic periods, adsorbed materials are chemically reduced, and their solubility in the overlying water column is enhanced. Thus, we should anticipate increased trace metal concentrations in the water column when hypoxic conditions arise.

The concentrations of hydrocarbons in the sediments vary more than metal concentrations. The hydrocarbons found at this site are primarily from weathered petroleum, sewage, urban runoff and combustion products (Boehm and Fiest, 1980). As with trace metals, the sediment hydrocarbon concentration at West Hackberry was higher than at Bryan Mound (Comiskey and Farmer, 1981). Hydrocarbons of biogenic origin vary with seasonal trends in river runoff and primary production.

Nutrients (ammonia, nitrate, nitrite, phosphate and silicate) dissolved or suspended in the water column at West Hackberry are highly variable and coupled to river runoff, turbulence, and climatological and biological trends (Comiskey and Farmer, 1981). Dissolved oxygen concentration is inversely correlated with ammonia, silicate and phosphate concentrations, suggesting that the concentrations of these nutrients may be controlled by bacterial regeneration of organic detritus. Nitrate is also inversely correlated with salinity, suggesting that local river discharge is the source (Brooks, 1980). An unusually large discharge from the Calcasieu River during January 1978 was concurrent with the highest nitrate concentration observed at West Hackberry (Comiskey and Farmer, 1981). This value was twice as high as the seasonal maximum observed in 1979 (Brooks, 1980). During January 1978 seasonally typical values of nitrate were found at Weeks Island and Chacahoula (Weissberg et al., 1980a and b), further supporting the hypothesis that nitrate levels at West Hackberry are strongly influenced by local river discharge. Slowey (1980) described a similiar pattern of nutrient distribution for Bryan Mound. However, he indicated the relation between nitrate and local runoff does not apply during flooding caused by tropical cyclones in late summer. This may be because soil nitrate is at the seasonal minimum in late summer or, because nitrate is massively diluted by the flood waters. While the Mississippi River discharge may dominate many coastal parameters (such as salinity) in the vicinity of West Hackberry, its influence on nitrate is not pronounced. This is at least partially the result of the high biological lability of nitrate.

Aside from high discharge events, such as from normal seasonal peaks of rainfall in winter and early spring, the coastal waters at West Hackberry are not especially rich in nutrients. Nitrate appears to be the limiting nutrient for phytoplankton production, except during high discharge of the local rivers, when phosphate may be limiting (Comiskey and Farmer, 1981). At West Hackberry, both nitrate and phosphate may be depleted on occasion (Slowey and Jeffrey, 1985).

Other factors of water quality, such as total suspended solids, oil and grease, and heavy metals, apparently are affected by local discharge in a manner similiar to nitrate (Comiskey and Farmer, 1981).

3.3.3 Biology

The biota of the Gulf of Mexico is characterized as transitional between temperate and tropical waters, but temperate forms predominant in the northern Gulf where the West Hackberry discharge site is located (Chittenden and McEachran, 1976). The physical environment is relatively variable and stressful, thus the species of this nearshore region of the Gulf have relatively short life spans and high reproductive potentials and are eurytopic (i.e., are tolerant of a relatively broad range of environmental conditions). Also, the spawning period of many local species is long relative to most temperate species. Because of this long spawning period, transient environmental perturbations are less likely to affect all the members of a year class, since there are differences in physiology and habitat selection among the various developmental stages. Many of the coastal species use estuaries for some stage of development. Thus, ecological relationships also must be interpreted in the context of estuary-shelf interactions (Hedgepeth, 1957). In an apparent relationship with both river discharge and nearshore currents, the distributions of most Gulf species show an alongshore trend (Comiskey and Farmer, 1981).

Plankton

The plankton in the vicinity of the West Hackberry diffuser is composed of forms typical of the coastal waters of the northwestern Gulf of Mexico. More than any other biological assemblage, the plankton community is not well defined geographically, but is associated with particular water masses and advective processes. The distribution of the plankton is controlled principally by the local circulation, including transient current reversals and, infrequently, eddies shed by the Loop Current. Thus, we commonly find oceanic and occasionally find estuarine forms mixed with the coastal plankton.

Phytoplankton

The majority of phytoplankton species collected during the pre-disposal studies are ubiquitous (Comiskey and Farmer, 1981). The standing crop of phytoplankton and the timing of the spring bloom are both related to the discharge of local rivers (ibid.). Phytoplankton at the West Hackberry site is characterized either by a mixture of neritic and oceanic forms during high river flows (spring) or by oceanic forms when river discharge is low (autumn). Dinoflagellates (Ceratium) dominate the assemblage in March and April, otherwise diatoms (Skeletonema, Chaetoceros, Rhizosolenia, Asterionella, Coscinodiscus and Nitzschia) are the dominant forms.

Zooplankton

The seasonal abundance of zooplankton follows a well-known and typical temperate pattern. There is a major peak in spring, followed by a low in summer, a minor peak in fall and another low in winter. The spring peak follows the peak for phytoplankton and is also coincident with the peak period of larval dispersal for many species. The dominant zooplankters are copepods; such as, Acartia tonsa, Paracalanus crassirostris and Oithona nana; the tunicate, Oikopleura; and the chaetognath, Saggita. The seasonal presence of many meroplanktonic forms, predominantly crustacean and fish larvae, also typifies coastal neritic waters.

Bacteria

Pre-disposal bacterial densities were highly variable (as much as one hundred fold) both between stations and replicates. This indicates that microenvironmental factors are highly variable at this site. Bacillus, Vibrio and Pseudomonas were the dominant aerobic-heterotrophic and halophilic genera isolated from the sediments (Schwarz et al., 1980). Pseudomonas (34 isolates) and Vibrio (1 isolate) were the only hydrocarbon- degrading genera collected (ibid.). There was no significant correlation between densities of hydrocarbon- degrading bacteria and hydrocarbon concentrations in sediments (ibid.). In the water column, Vibrio, Pseudomonas, Bacillus, Flavobacterium and Enterobacteriaceae were the most common heterotrophic bacteria (ibid.). Phytosynthetic bacteria were rare in the surficial sediments (Turgeon, 1981). Densities never exceeded 10 bacteria/ml-wet sediment, and photosynthetic bacteria were detected in only 13 percent of these samples (ibid.).

Sediment bacteria underwent temperature-dependent seasonal fluctuations in both abundance and diversity (Schwarz et al., 1980). Turgeon (1981) showed that sediment bacteria have peak abundance in spring and summer, then decline exponentially to a low in winter (Figure 3-3). Conversely, the mean abundance of water column bacteria peaked in winter. The phase differences may reflect the higher turbulence associated with winter storms, e.g., the resuspension of sediments transferring sediment bacteria to the water column. Alternatively, the large influx of riverine sediments in the fall, coupled with decreasing temperatures through the winter, may account for declines in bacterial abundance. Diversity of the sediment bacteria was relatively stable from summer to winter with a slight peak in fall, although spring values were significantly lower, only 37 percent of the autumn peak (Figure 3-3). Diversities of the water column bacteria followed a similiar cycle and were relatively low and stable from winter through summer with a significant peak in fall.

Benthos

Of the benthic meiofauna community, nematodes are the numerically dominant group with polychaetes, tintinnids, kinorhynchs, copepods, ostracods and amphipods also present (Comiskey and Farmer, 1981). The general seasonal trend is an increase in abundance from winter to spring. In the region of West Hackberry, total meiofaunal abundance is directly correlated with sediment particle size.

The benthic megafauna is composed mainly of polychaetes (Magelona sp., Paraprionospio pinnata, Neanthes succinea) and arthropods (Ampelisca sp.), (Table 3-1). The

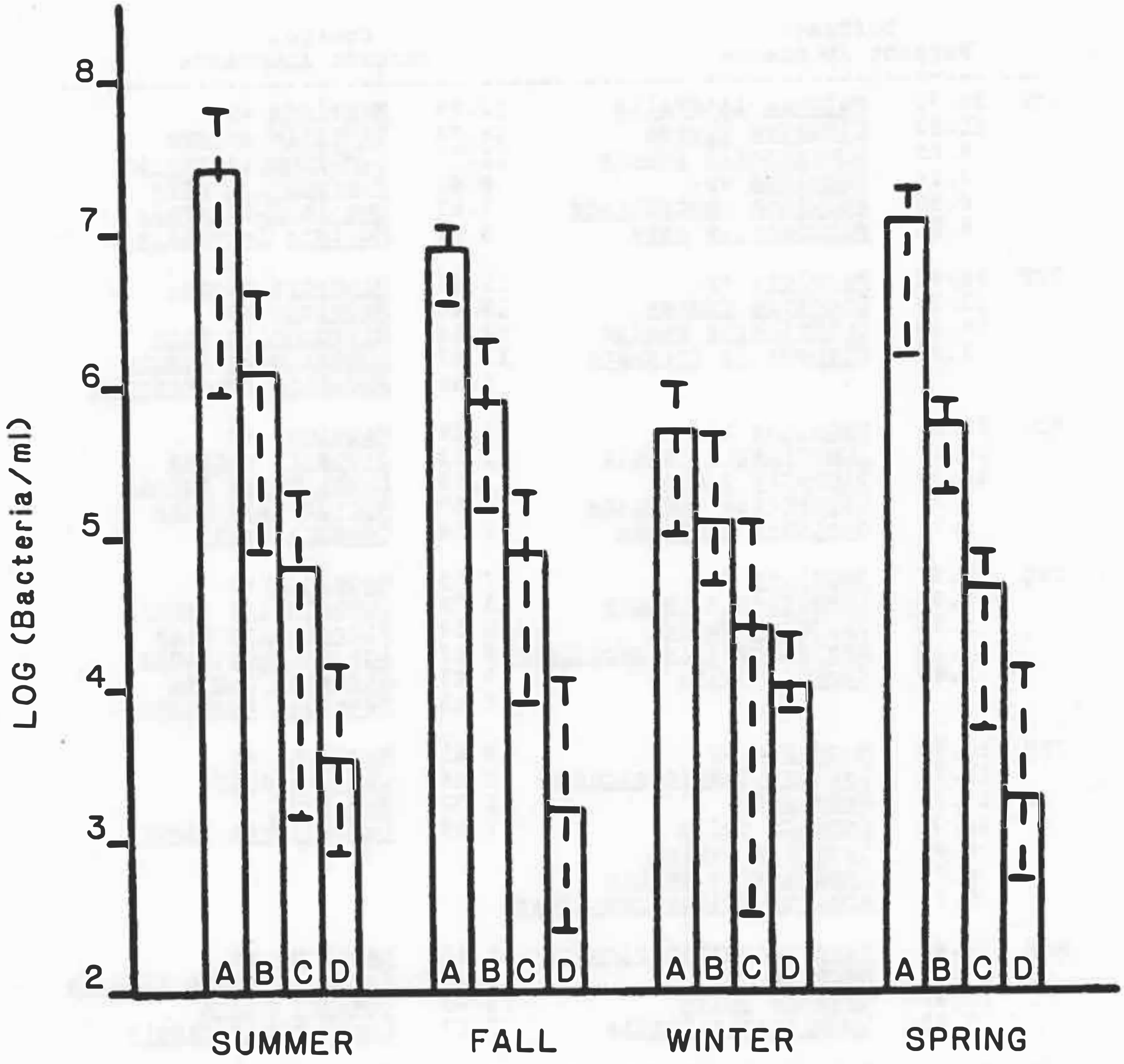


Figure 3-3. Mean population densities of sediment and water column bacteria at the West Hackberry survey site. Dashed vertical lines represent range of station means. A= Aerobic Heterotrophic Bacteria of Sediment, B= Halophilic Bacteria of Sediment, C= Hydrocarbon Degrading Bacteria of Sediment and D= Aerobic Heterotrophic Bacteria of Water Column. (from Turgeon, 1981).

Table 3-1. Seasonal patterns in dominance in the benthic megafaunal community at West Hackberry for the period September 1977 to May 1978. Only species accounting for greater than 5 percent of the community are shown. (adapted from Comiskey and Farmer, 1981).

	Diffuser Percent Abundance		Control Percent Abundance	
SEP	20.72	*Mulinia lateralis*	22.59	*Magelona* sp.
	11.93	*Diopatra cuprea*	14.74	*Diopatra cuprea*
	8.65	*Lumbrineris tenuis*	12.71	*Lumbrineris tenuis*
	7.24	*Magelona* sp.	8.81	*Micropholis atra*
	6.66	*Nuculana concentrica*	7.67	*Owenia fusiformis*
	6.51	*Micropholis atra*	5.99	*Mulinia lateralis*
OCT	38.42	*Magelona* sp.	15.67	*Diopatra cuprea*
	15.34	*Diopatra cuprea*	15.40	*Magelona* sp.
	14.29	*Lumbrineris tenuis*	14.54	*Micropholis atra*
	9.92	*Clymenella torquata*	13.67	*Lumbrineris tenuis*
			5.86	*Nuculana concentrica*
NOV	22.63	*Magelona* sp.	36.87	*Magelona* sp.
	20.15	*Lumbrineris tenuis*	15.32	*Diopatra cuprea*
	12.05	*Diopatra cuprea*	12.56	*Lumbrineris tenuis*
	9.21	*Clymenella torquata*	6.50	*Micropholis atra*
	6.03	*Neanthes succinea*	5.54	*Cossura delta*
DEC	32.57	*Magelona* sp.	27.35	*Magelona* sp.
	9.37	*Lumbrineris tenuis*	13.76	*Lumbrineris tenuis*
	9.36	*Diopatra cuprea*	10.13	*Micropholis atra*
	6.19	*Ancistrosyllis papillosa*	9.62	*Acetes americanus*
	5.69	*Cossura delta*	7.67	*Diopatra cuprea*
			7.18	*Neanthes succinea*
FEB	18.94	*Magelona* sp.	39.61	*Magelona* sp.
	13.87	*Paraprionospio pinnata*	13.66	*Cossura delta*
	13.70	*Nematoda*	11.32	*Nematoda*
	12.04	*Cossura delta*	7.59	*Lumbrineris tenuis*
	6.87	*Diopatra cuprea*		
	6.79	*Lumbrineris tenuis*		
	5.72	*Ancistrosyllis papillosa*		
MAR	34.47	*Paraprionospio pinnata*	21.40	*Magelona* sp.
	17.47	*Magelona* sp.	20.14	*Paraprionospio pinnata*
	10.49	*Cossura delta*	14.45	*Cossura delta*
	5.92	*Lumbrineris tenuis*	7.17	*Lumbrineris tenuis*
APR	31.23	*Paraprionospio pinnata*	19.98	*Paraprionospio pinnata*
	10.13	*Magelona* sp.	18.82	*Magelona* sp.
	7.83	*Sabellides oculata*	11.36	*Sabellides oculata*
	6.80	*Cossura delta*	8.50	*Cossura delta*
	6.75	*Paranthus rapiformis*		
	5.73	*Clymenella torquata*		
MAY	18.06	*Paraprionospio pinnata*	16.02	*Nematoda*
	15.06	*Nematoda*	12.67	*Magelona* sp.
	6.40	*Sabellides oculata*	9.89	*Paraprionospio pinnata*
	6.05	*Notomastus* sp.	9.06	*Cossura delta*
	5.45	*Clymenella torquata*	5.79	*Mulinia lateralis*

megabenthic community had lowest mean densities from September to October, corresponding to the season of lowest river discharge (Comiskey and Farmer, 1981). Recruitment to the megafauna occurs from December to March, and peak population densities occur from February to April (Harper, 1970).

Nekton

The demersal nekton assemblages in the vicinity of the West Hackberry diffuser are representative of the nearshore, fine-grained sediment habitat of the northwestern Gulf. The local fauna are commonly characterized by two dominant communities based on the distribution of the locally dominant species of shrimp, Penaeus setiferus and Penaeus aztecus (Hildebrand, 1954). The diffuser site is characterized by the white shrimp (P. setiferus) community and it's associated species of sciaenid finfish (Atlantic croaker, star drum, sand seatrout and silver seatrout). Gulf menhaden, Atlantic bumper and bay anchovy dominate the pelagic finfish. A few taxa (5-10) generally account for 75-90 percent of the biota, both by weight and number (Comiskey and Farmer, 1981). All of the common species are capable of accommodating localized adverse salinities, because they are tolerant of a wide range of salinities as well as highly motile. Shrimp and many of the associated demersal finfish are subject to heavy commercial exploitation of a single year class. Consequently, these fisheries typically experience large interannual fluctuations in catch.

In the initial stages of planning for the siting of the brine diffuser, potential impacts on the commercial shrimp were a major concern. The West Hackberry diffuser is located wholly within the faunal area typified by the adult white shrimp. The brown shrimp adults are generally found in waters deeper (22-46m) than the West Hackberry diffuser site (Comiskey and Farmer, 1981). However, the developmental stages of brown shrimp migrate to and from local estuaries, and some larvae or juveniles might encounter the brine plume during their migrations. The developmental stages of the white shrimp make a similiar migration, but their spawning grounds are inshore of the diffuser site. Thus, white shrimp larvae are not likely to encounter the brine plume.

4.0 CALCASIEU LAKE

4.1 Physical Description

Calcasieu Lake is located in the western part of Cameron Parish in the southeastern part of Louisiana. It is fed from the north by the Calcasieu River. The Calcasieu ship channel provides a direct connection between Calcasieu Lake and the Gulf. The Gulf Intracoastal Waterway (ICW), the primary manmade body of water in the area, is located near the northern end of the lake. Calcasieu Lake is the dominating open-water estuarine area in western Calcasieu Parish. Part of the Sabine National Wildlife Refuge lies within the lake.

Climate around the lake is classified as humid-subtropical with strong marine influences. Seasonal fluctuations are moderate. Winters are generally cool and clear with periods of overcast skies. During the summer, the days are generally warm and humid with little daily variation.

4.2 Biological Importance

Collections made in the region from April 1968 through March 1969 indicated that the most common vertebrate species found in the lake were menhaden, bay anchovy and Atlantic croaker. The most common invertebrate species were blue crabs and white shrimp. Trawl samples showed that spot, Atlantic threadfin and brown shrimp were also common (DOE, 1978).

Shellfish are of considerable economic importance to southern Louisiana. Calcasieu Lake contains the major shrimp fishing grounds of western Louisiana with over 1,000 vessels fishing during the spring shrimp season. Many of the brown shrimp in Calcasieu Lake are larger juveniles that have migrated from nursery areas in the wildlife refuge. Calcasieu Lake is a final staging area before migration to the Gulf. Oyster production in Calcasieu Lake was historically good, but productivity has declined in recent years in the northern and eastern parts of the lake due to causes unrelated to the SPR project.

The dominant estuarine fish species present are Gulf killifish, longnose killifish, variegated cyprinodea, common mosquito fish and sailfin molly (DOE, 1978). The most numerous zooplankter reported in the estuary was Acartia tonsa. Coelenterates, ctenophores, decapod larvae and copepods were also common in the lake. Most of the zooplankton were eurythermal and euryhaline (DOE, 1978).

4.3 Leaching and Water Operations

Monitoring studies to determine if significant adverse changes in ecosystem productivity or in the stability of the biological community as a result of leaching of the brine from West Hackberry were conducted from May 1981 through April 1983.

A major concern during this project was whether or not the removal of relatively large volumes of freshwater from the ICW would cause a significant increase in the salinity of the Calcasieu system and freshwater marshes nearby. Also of concern was whether the brine discharge would affect the estuary, if the plume reached the estuarine area.

Results from the post-disposal monitoring studies showed that the pumping of freshwater did not cause a significant change in salinity of the lake or the nearby marsh waters. Data collected during the period also showed that the brine plume never reached Calcasieu Pass. Although salinity fluctuations were observed during the monitoring period, they were a result of the yearly cycle of spring runoff.

5.0 ANALYSIS AND ASSESSMENT OF EXCESS SALINITY CONDITIONS

5.1 Brine Plume Monitoring

Analysis of 39 monthly brine plume monitoring results reported by Randall (1983) and Randall and Price (1984, 1985) for the period June 1981 - November 1984 reveals that maximum deviation from ambient salinity (i.e., elevations above ambient salinity attributable to brine disposal) in the bottom waters were less than 7 ppt in 95 percent of the cases and less than 5 ppt in 72 percent of the cases (Table 5-1 and Figure 5-1). Excess salinity levels greater than 8 ppt were observed only once (June 1982) and coincided with a period of low current speeds on the bottom (5.6 cm/sec) coupled with a low brine exit velocity (3.6 m/sec) from the diffuser ports. At that time, the highest observed excess salinity level was approximately 12.5 ppt.

Above-ambient salinity levels decreased rapidly with distance from the diffuser (Table 5-1), and the mean areal extent of excess salinity levels declined exponentially relative to the above-ambient concentration (Figure 5-2). Comparison of minimum and maximum areal extents of the 1-7 ppt excess salinity levels with those predicted by the MIT transient plume model for typical current conditions (NOAA,1981) demonstrates that the model, even with highly reduced vertical diffusion, underestimates the bottom area impacted by the brine plume (Figure 5-3). However, the calculated mean areal extent of the observed 1-7 ppt excess salinity levels fell within the upper limits of the MIT model's predicted maximum-minimum boundaries (Figure 5-4).

Initial concerns for potential movement of the brine plume into Calcasieu Pass or impingement on the Louisiana shoreline appear to be unsubstantiated. The furthest observed inshore incursion of the 1 ppt excess salinity level was only 4 km, while excess salinity levels of 4 ppt or greater never extended further than 0.9 km inshore of the diffuser. Computer simulations of excess salinity conditions, using NOAA's near-field and intermediate-field brine plume model (Appendix A), indicate that even under storm conditions with sustained onshore winds (tropical storm Chris), the maximum shoreward extension of the 1 ppt excess salinity level was only 6.3 km (Turgeon et al., 1984). Thus, brine plume monitoring and modeling data indicate that the 1 ppt excess salinity level has remained at least 4-5 km away from the Louisiana shoreline.

Allowing for operational variations in the number of diffuser ports open, brine plume exit velocities from the ports, brine concentration and discharge rates and for the large variations in bottom current speed and direction, it can be surmised that the brine diffuser meets the design

Table 5-1. Summary of brine plume monitoring data for the period of June 1981-November 1984.

	Excess Salinity Levels (ppt)										
	≥ 1	2	3	4	5	6	7	8	9	10	11
n	39	36	31	25	11	6	2	1	1	1	1
%	100	92.3	79.5	64.1	28.2	15.4	5.1	2.6	2.6	2.6	2.6
areal coverage (km^2; 1 km^2 = 247.1 acres)											
min	0.3	0.4	0.3	0.1	0.2	0.1	<0.1	0.9	0.6	0.3	0.1
max	43.5	28.4	16.4	7.5	2.5	1.7	1.2	---	---	---	---
$\bar{X}$	17.7	9.1	4.4	1.6	0.9	0.6	0.6	---	---	---	---
SD	11.8	6.6	3.8	1.7	0.8	0.6	0.8	---	---	---	---
longest observed distance inshore (km)											
	4.0	2.1	1.5	0.9	0.7	0.2	<0.2	....			
longest observed distance in any direction (km)											
	8.6	7.3	5.8	5.0	1.7	1.4	....				

n = number of observed occurrences; % = percentage of total observations; min = minimum observed; max = maximum observed; X = mean of observed occurrences; SD = 1 standard deviation.

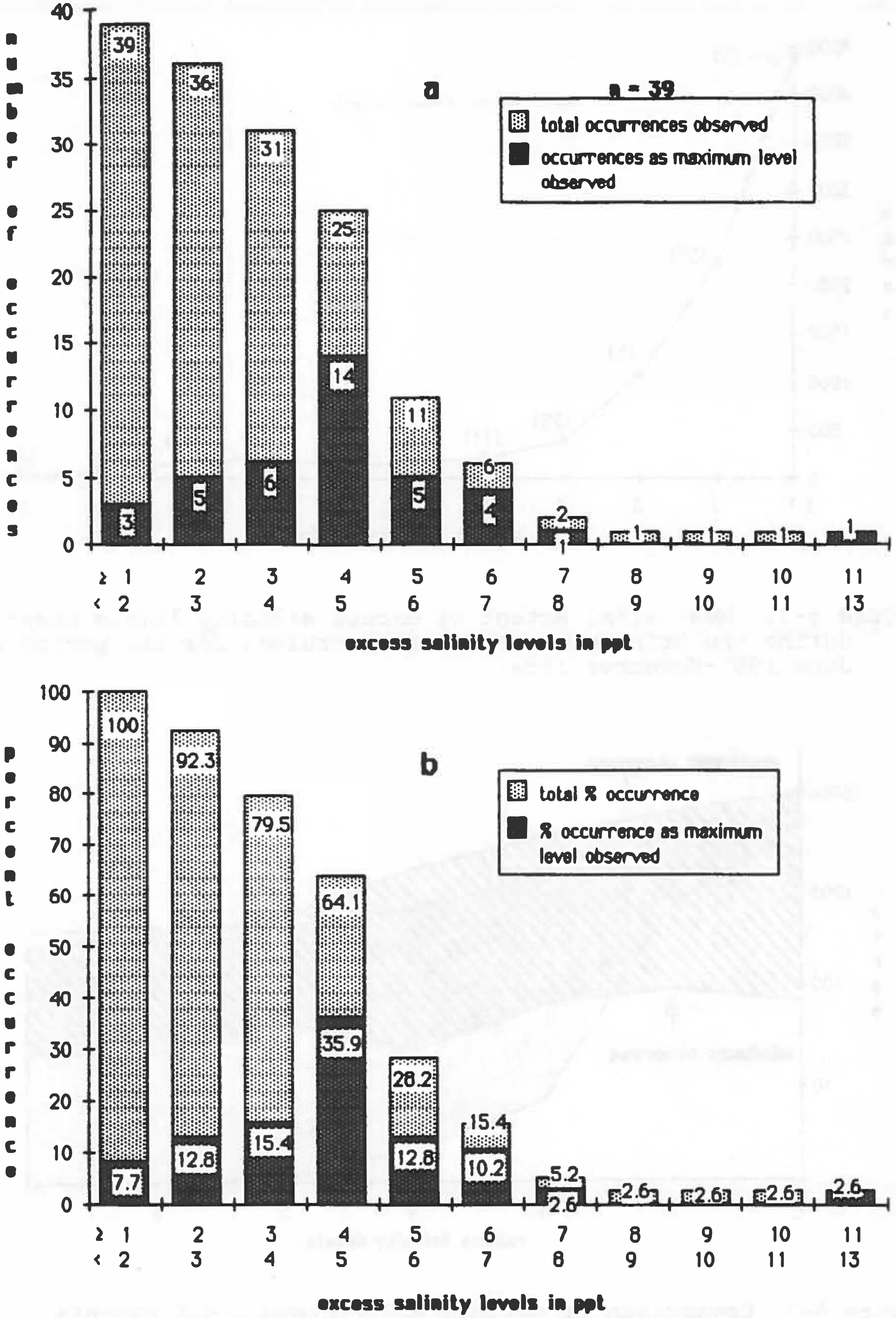


Figure 5-1. Absolute (a) and relative (b) occurrences of excess salinity levels observed during the brine plume monitoring cruises for the period of June 1981-November 1984.

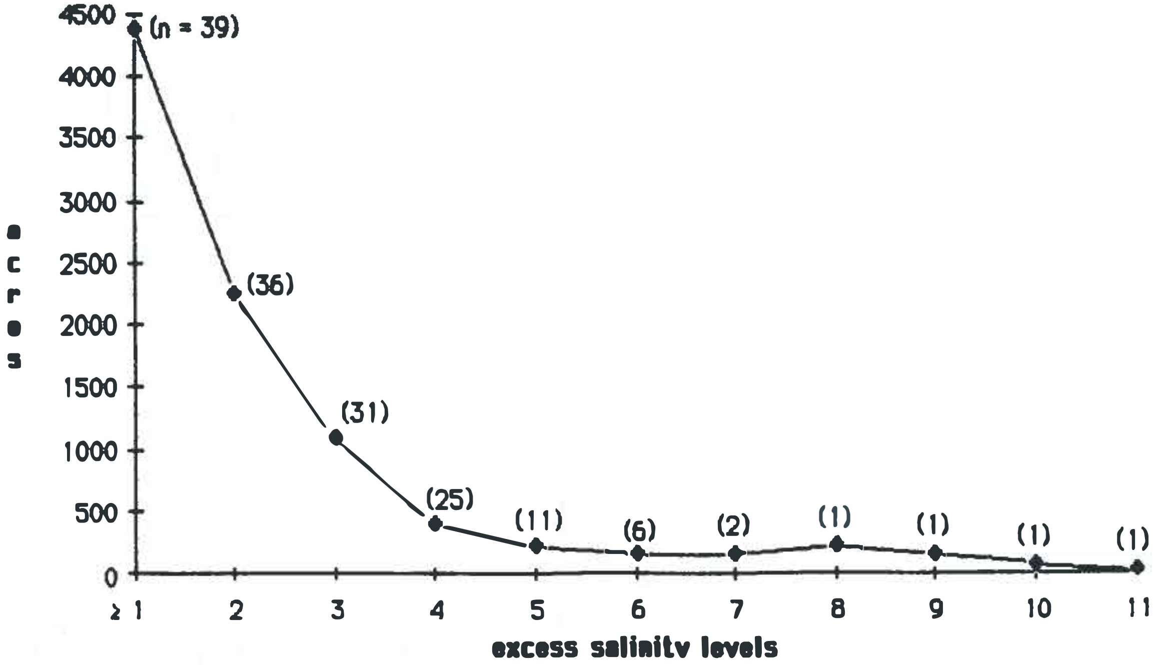


Figure 5-2. Mean areal extent of excess salinity levels observed during the brine plume monitoring cruises for the period of June 1981-November 1984.

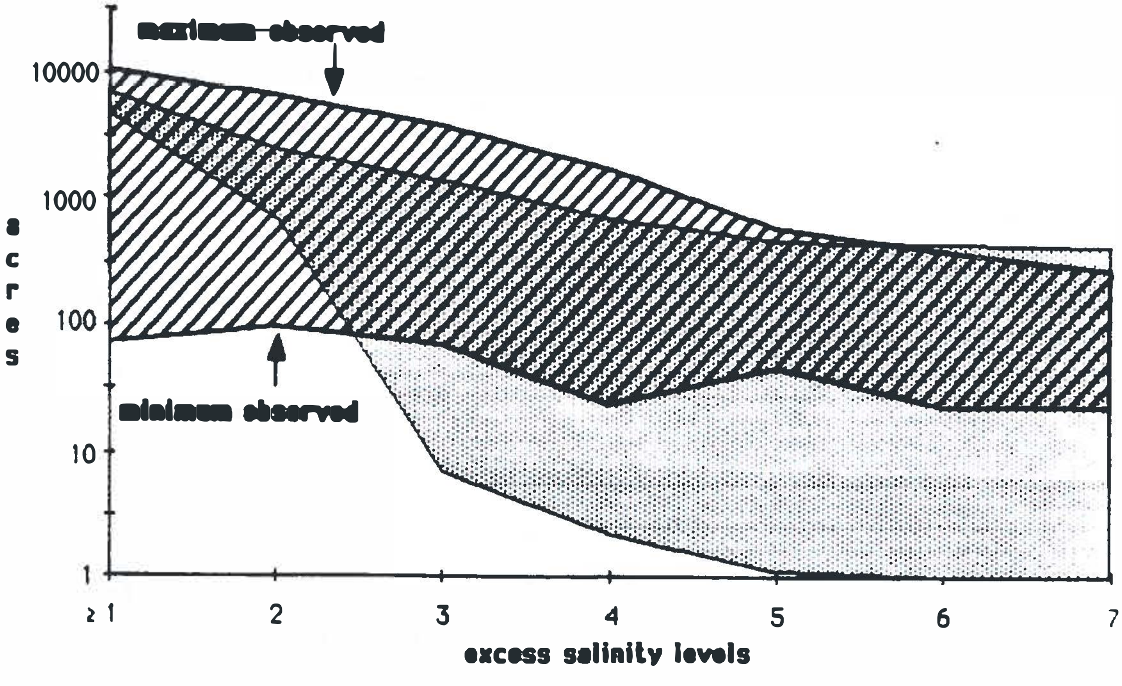


Figure 5-3. Comparison of maximum and minimum areal extents of excess salinity levels recorded during the brine plume modeling cruises for the period of June 1981-November 1984 with those predicted by the MIT transient plume model.

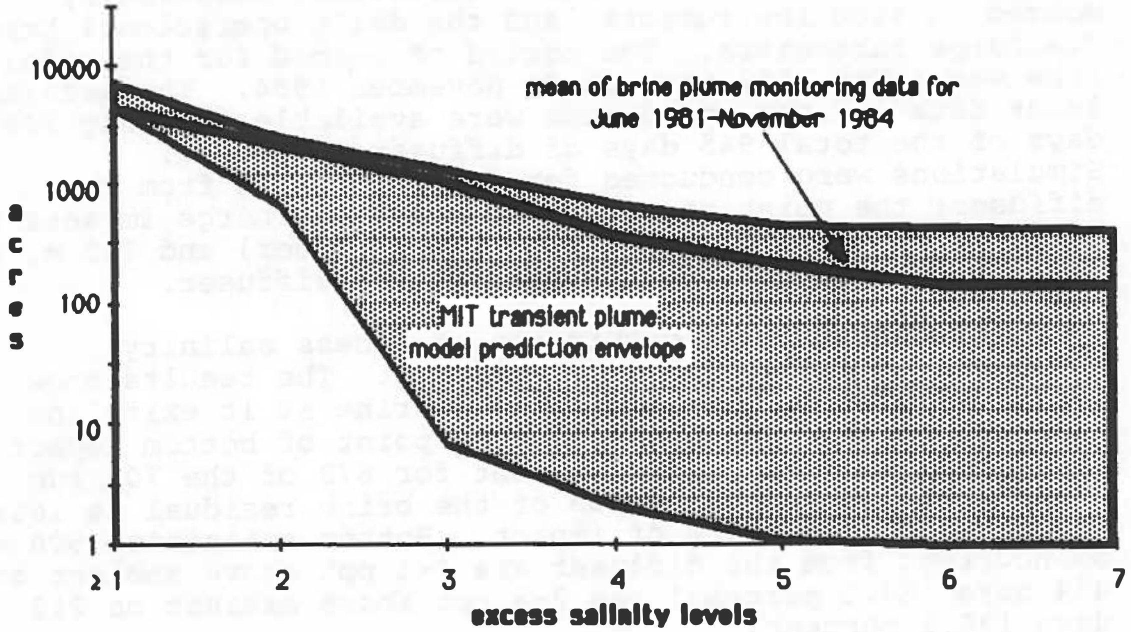


Figure 5-4. Comparison of the mean areal extents of excess salinity levels recorded during the brine plume monitoring cruises for the period of June 1981-November 1984 with the MIT transient plume excess salinity boundaries.

criteria for rapid dilution and dispersion of the brine plume.

5.2 Brine Plume Modeling

The temporal resolution of the brine plume monitoring data is too coarse to provide information about the long-term, day-to-day variability of brine-induced excess salinities over the broad range of operational discharge conditions and bottom current speeds and directions. Because of this, the NOAA near-field and intermediate-field brine plume model was run to simulate a continuous record of brine-induced excess salinities using the daily bottom current velocities and ambient salinities, measured by moored in situ instruments, and the daily operational brine discharge parameters. The period of record for the model runs was 1 May 1982 through 30 November 1984. The necessary input data for the model runs were available for only 704 days of the total 945 days of diffuser operation. Simulations were conducted for four distances from the diffuser: the point at which the brine discharge impacts the bottom (approximately 12 m from the diffuser) and 152 m, 304 m and 608 m directly downcurrent of the diffuser.

The frequency of occurrence of excess salinity intervals is summarized in Figure 5-5. The results show rapid dilution of the concentrated brine as it exits the diffuser ports. Salinities at the point of bottom impact are less than 6 ppt above ambient for 673 of the 704 run days (96 percent). Dilution of the brine residual is less rapid beyond the point of impact. Bottom salinities 608 m downcurrent from the diffuser are 3-4 ppt above ambient on 454 days (64.5 percent) and 2-3 ppt above ambient on 212 days (30.1 percent).

The time series of excess salinities at the four downcurrent distances are presented in Figures 5-6 through 5-9. These plots show that fluctuations in excess salinity levels decrease with distance from the diffuser. Thus, while evidence of brine-induced elevated salinities are consistently observed in the intermediate field, excess salinity levels are relatively low, and the above-ambient salinity environment is relatively stable.

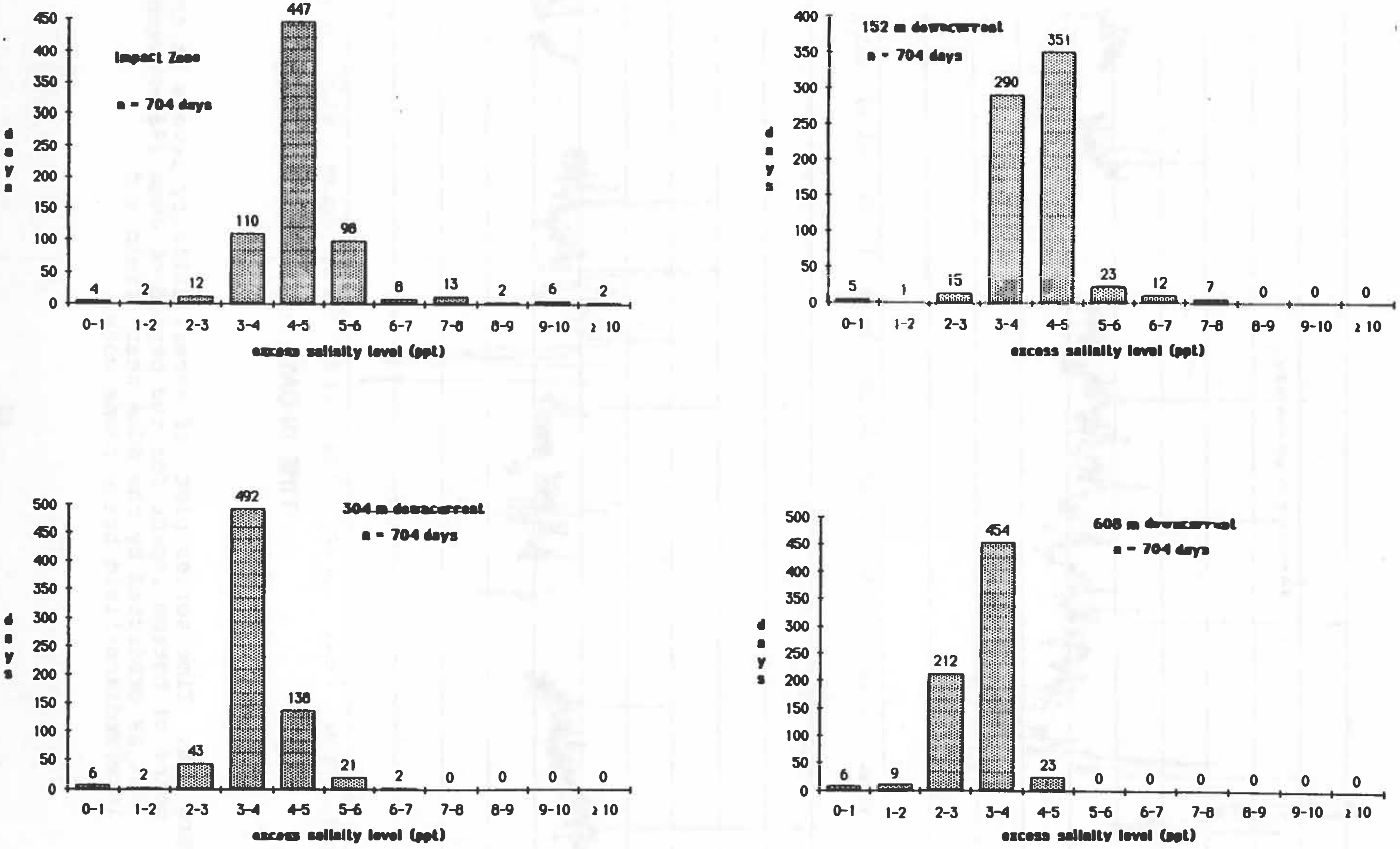


Figure 5-5. Model-derived absolute occurrences of excess salinity intervals for four distances directly downcurrent of the diffuser.

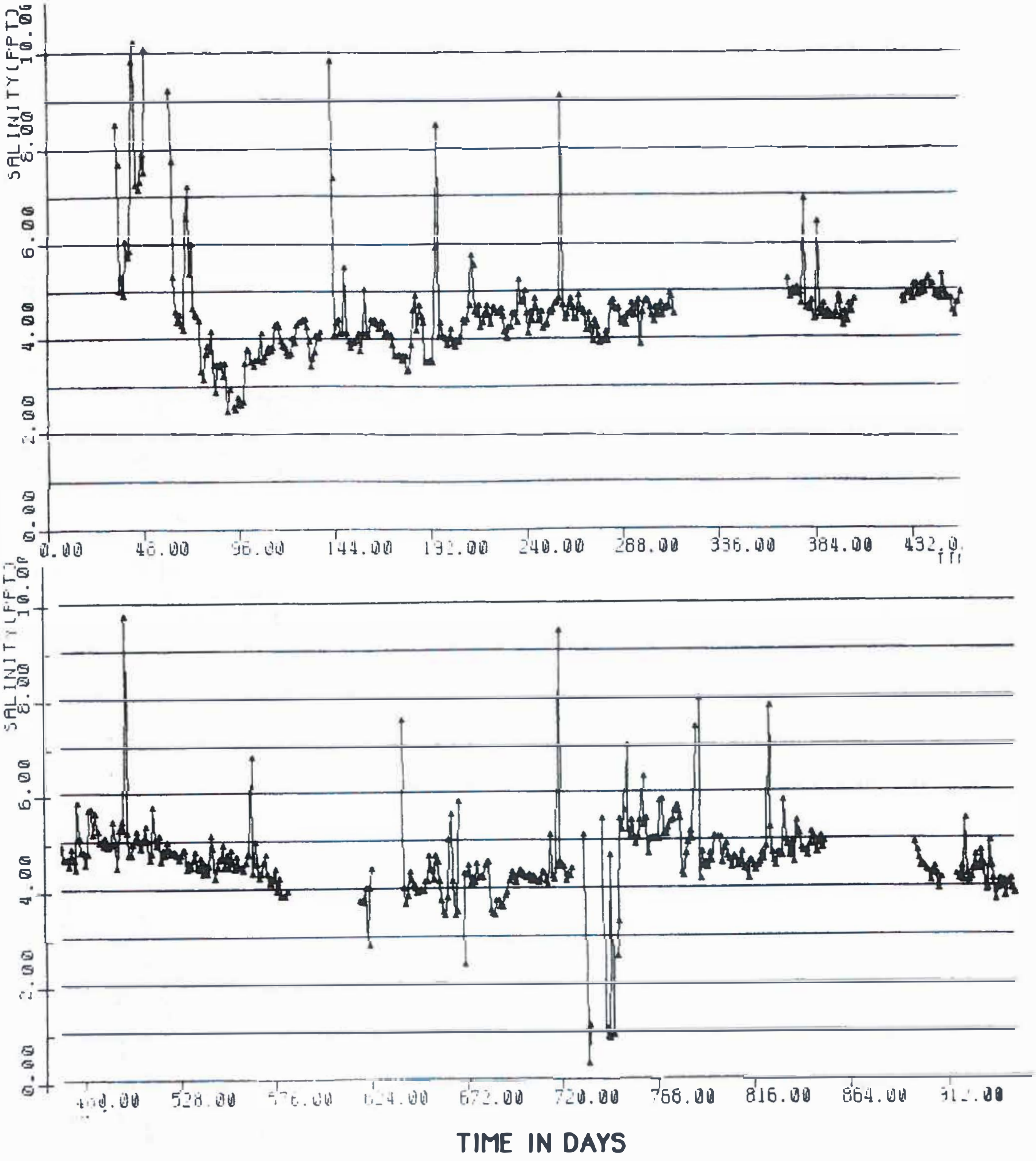


Figure 5-6. Time series plot of excess salinity levels at the point of bottom impact for the period of June 1982-November 1984 as predicted by the NOAA near- field and intermediate-field brine plume model.

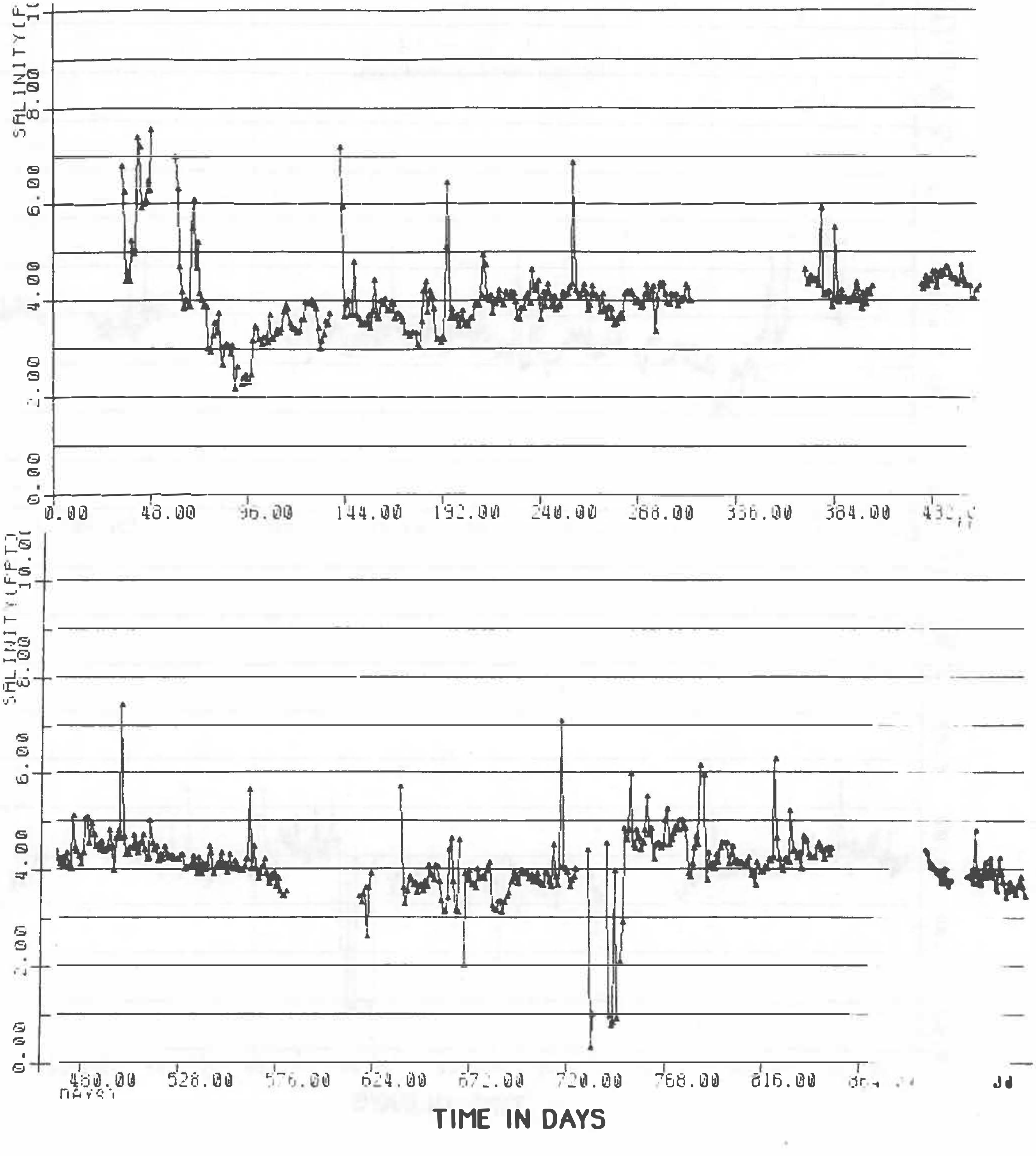


Figure 5-7. Time series plot of excess salinity levels at a point 152m downcurrent from the diffuser for the period of June 1982-November 1984 as predicted by the NOAA near-field and intermediate-field brine plume model.

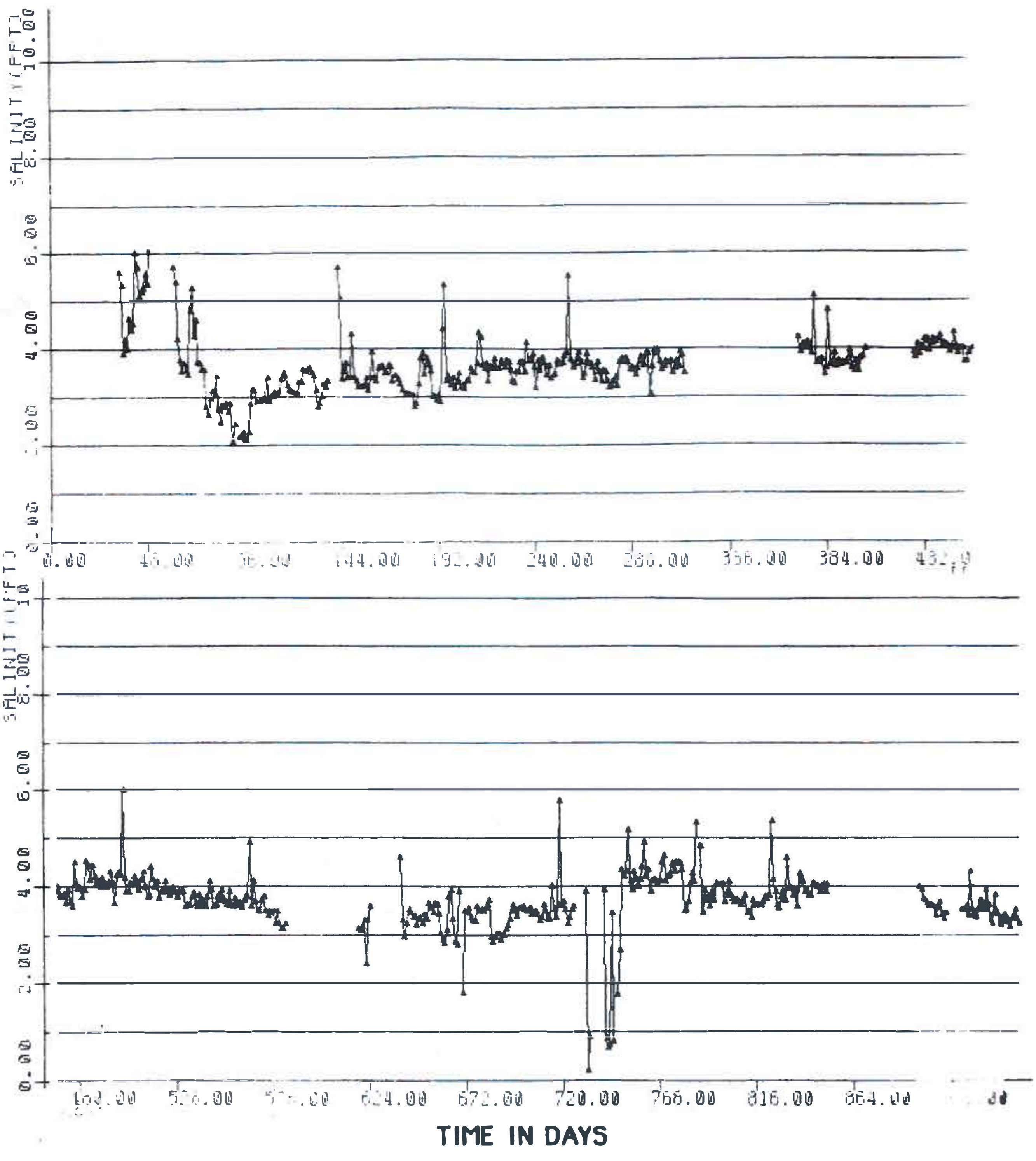


Figure 5-8. Time series plot of excess salinity levels at a point 304 m downcurrent from the diffuser for the period of June 1982-November 1984 as predicted by the NOAA near-field and intermediate-field brine plume model.

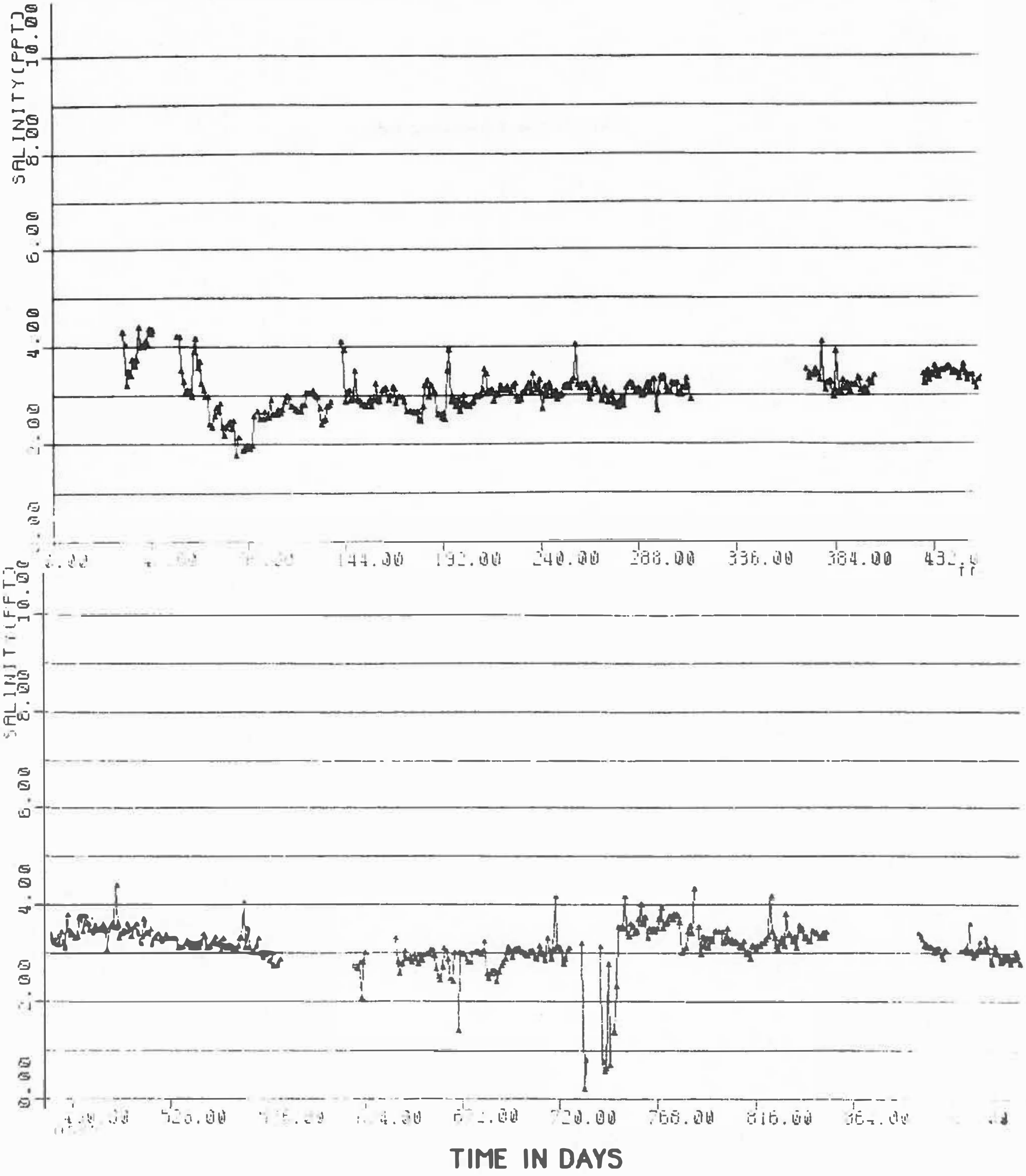


Figure 5-9. Time series plot of excess salinity levels at a point 608 m downcurrent from the diffuser for the period of June 1982-November 1984 as predicted by the NOAA near-field and intermediate-field brine plume model.

6.0 BRINE EFFECTS AT THE OFFSHORE BRINE DISPOSAL SITE

6.1 Water Quality and Sediment Chemistry

In the first assessment period (May 1981 through April 1982) no brine-related adverse changes were reported for the following water quality parameters: salinity, temperature, dissolved oxygen, pH, oil and grease, turbidity, nutrients (nitrate, nitrite, ammonia, nitrogen, orthophosphate, total phosphorous, silica) and major ions (Na+, Ca++, Cl-, Mg++, K+), (Jeffrey et al., 1983). A period of low dissolved oxygen was recorded in bottom waters at all stations in July 1981 (Figure 6-1), but this was related to recurring natural hypoxia rather than brine discharge. Levels of some major ions (Na+, Cl-) were elevated near the diffuser, but natural fluctuations in ion concentrations obscured any trend. Jeffrey et al. (1981) concluded that brine discharge had no adverse affect on major ion concentrations or ratios in either the water column or sediment pore water. Ambient salinities varied from 17.26 to 35.10 ppt during the first year of monitoring, reflecting the annual cycle of runoff.

In the second assessment period (May 1982 through November 1983), a hypoxic event was recorded in bottom waters during June 1982. Possibly in relation to this hypoxia, the highest nitrate values were observed in surface waters in May 1982 prior to the hypoxia and in bottom waters in August following hypoxia. The nutrient-nitrogen species sequence observed at West Hackberry followed a trend that is typical of a nitrate-fed phytoplankton bloom followed by microbial degradation of the excess production and regeneration of the nutrient-nitrogen in bottom waters (Slowey et al., 1984). This pattern was similiar to observed conditions during the 1981 hypoxic event and led to speculation that hypoxia is related to phytoplankton blooms resulting from the seasonal runoff of nitrate. Dissolved oxygen was generally undectable in bottom waters during June 1982. The hypoxic conditions were widespread and not related to brine discharge. During this reporting period, ambient salinities ranged from 16.6 to 36.2 ppt in response to the normal annual cycle of runoff. Changes in water quality parameters were related to runoff and no effect of brine discharge was discerned.

James (1977) discussed the possibility of a detrimental change in major ion ratios (e.g., the concentration of Na+ relative to the concentration of K+) in the vicinity of brine discharge, because the relative proportions of major ions in sea water differ from the brine solution. Slowey et al. (1984 and 1985) addressed this point. At the diffuser, Na+/K+ ratios were found to be higher than at control stations in half of the samples, but natural variability was found to be larger in both surface and bottom waters (Figures 6-2a and b). The results were similiar for the

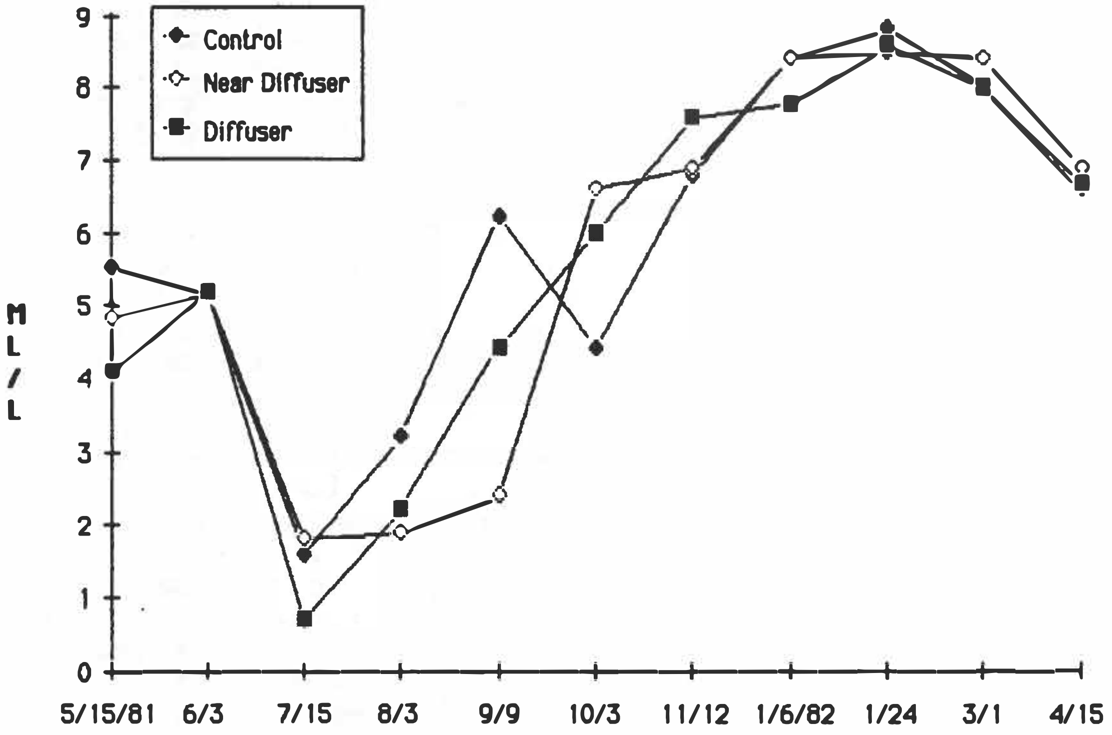


Figure 6-1. Changes in dissolved oxygen (DO) in bottom waters from May 1981 through April 1982.
Adapted from Jeffrey et al., 1983.

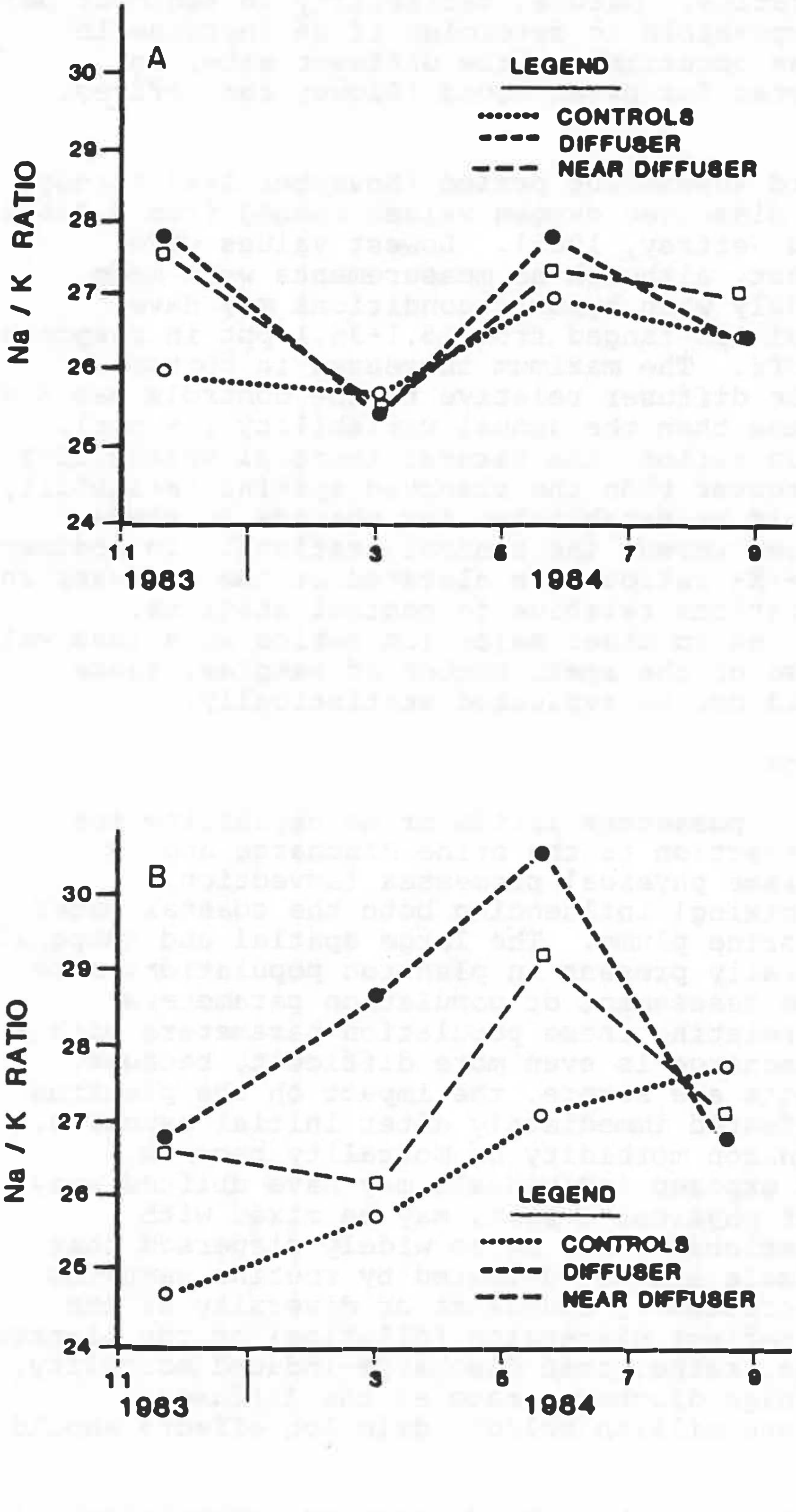


Figure 6-2a and b. Mean Na+/K+ ratios in (a) surface waters and (b) bottom waters. From Slowey et al., 1985.

other measured ratios. Natural variability in sediment pore water made it impossible to determine if an increase in Na+/K+ ratios was occurring at the diffuser site, as previously reported for Bryan Mound (Slowey and Jeffrey, 1983).

In the third assessment period (November 1983 through November 1984), dissolved oxygen values ranged from 2.0-6.2 ml/l (Slowey and Jeffrey, 1985). Lowest values were observed in August, although no measurements were made during June or July when hypoxic conditions may have occurred. Salinities ranged from 15.1-36.1 ppt in response to seasonal runoff. The maximum increases in bottom salinities at the diffuser relative to the controls was 6.6 ppt, which is less than the annual variability (16 ppt). For the major ion ratios, the natural temporal variability was also much greater than the observed spatial variability and no trend could be established for changes in these ratios at diffuser versus the control stations. In sediment pore waters, Na+/K+ ratios were elevated at the diffuser and near-diffuser stations relative to control stations. Spatial differences in other major ion ratios were less well defined. Because of the small number of samples, these differences could not be evaluated statistically.

6.2 Plankton

The plankton possesses little or no capability for avoidance or attraction to the brine discharge and is subject to the same physical processes (advection, dispersion and mixing) influencing both the coastal water masses and the brine plume. The large spatial and temporal variations naturally present in plankton populations make the quantitative assessment of population parameters difficult. Correlating these population parameters with a point source discharge is even more difficult, because, unless the effects are severe, the impact on the plankton may not be manifested immediately after initial exposure. By the time plankton morbidity or mortality becomes measurable, the exposed individuals may have drifted away from the zone of physical impact, may be mixed with unexposed populations or may be so widely dispersed that exposed individuals are not detected by routine sampling. Furthermore, decreases in abundance or diversity at the diffuser could reflect dispersion (dilution) of the plankton by the discharge, rather than discharge-induced mortality. Because of the high discharge rate at the diffuser (approximately one million bbl/d), dilution effects should be evaluated.

Biotic factors, such as predation and competition between exposed and unexposed populations, may also modify ecological parameters. The difficulty of measuring an impact is further aggravated when temporal variability is high, because physical, chemical and biological measurements in situ may not reflect the toxic exposure or biotic history of the plankton sample. Unless the effects on the plankton are acute, cover large areas or are physically confined (as in an embayment) clear impacts of brine discharge are not likely to be observed in the plankton.

6.2.1 Phytoplankton

Although occasional differences were observed, all phytoplankton sampling efforts found no clear pattern of differences in diversity between surface and bottom samples or between diffuser and control stations. In the most recent study, Fay and Schnitzen (1985) found phytoplankton species diversity, as measured by the Shannon-Weaver index, to be generally higher in 1984 relative to previous years. Species diversity calculated for surface samples at the diffuser (station M10A) was outside the range calculated for controls (stations M3 and M18) for all 8 cruises. The controls had higher diversity on 5 cruises. Similiar diversity calculations for bottom samples showed the diffuser station to have higher diversity on 2 cruises and lower diversity on 6 cruises. Abundances (cell concentrations) in 1984 were found to be within the range reported in earlier discharge assessments. From a total of 16 cases (8 cruises x 2 depths), the diffuser station was found to have significantly lower abundance values in 3 cases.

At intermittent periods during summer, hypoxic conditions were common during each year of discharge monitoring. When hypoxia occurred, it was frequently observed at all stations except the diffuser, as in June 1984, when hypoxic conditions were recorded at all stations except the diffuser (M10A) and 1 near-diffuser station (DE). Even during periods of combined brine discharge and hypoxia, diversity and abundance values for phytoplankton were not reported to be significantly different among stations.

With pigment concentration as an index of biomass, no pattern or effect on plant biomass was evident as a result of brine discharge. Pigment concentrations in the water column were routinely found to be significantly different between surface and bottom, but differences in light levels and water column stability could account for these differences. Fay and Schnitzen (1985) reported that such consistent differences between surface and bottom samples indicate that natural variation in the West Hackberry area is much larger than any variation attributable to brine discharge. They report natural variability of twofold to fourfold among stations and twentyfold or more among sampling periods. All phytoplankton sampling efforts to date have found no evidence that brine discharge is having any effect on phytoplankton populations.

6.2.2 Zooplankton

For the 10 most frequently occurring zooplankters, spatial variability among stations and between depths was from 1-3 orders of magnitude, and temporal variability was 1-4 orders of magnitude (Wolff et al., 1985). A report on the baseline sampling stated that natural variability was large prior to brine discharge, and even prior to brine discharge operations, statistically significant differences were common among stations near the diffuser site (Turgeon, 1983). Turgeon (1983) demonstrated that diffuser stations M10A and DW were significantly different from control stations M3 and M18 about as frequently (11 cases each) as the control stations differed from each other (12 cases). In this context, the contention of demonstrable brine impact on the zooplankton (Wolff et al., 1985) appears to be erroneous.

Wolff et al. (1985) based their conclusion of brine impact on a questionable and biased statistical approach. Spatial comparisons of seven abundant taxa were analyzed by pooling 5 stations between diffuser (M10A, DW and DE) and control (M3 and M18). At the 5 percent level, 18 of 98 comparisons were found to be statistically significant (Table 6-1). Of those 18 cases, the pooled diffuser stations had greater abundance in 6 cases, and in 12 cases the pooled controls had higher abundance. Wolff et al. (1985) proposed that the ratio of low diffuser abundance versus high control abundance has an expected probability of 0.0701 in a binomial distribution.

A binomial distribution explains the probability of outcomes when the number of trials (cases) is fixed, the probability of success is the same for each case and all the trials are independent (Freunde and Walpole, 1980). None of these conditions are met by the zooplankton data. First, all of the trials (18 cases) are not independent, because there are obvious temporal relationships among the cases (see cruise 8408, Table 6-1). Secondly, the probability of success (i.e., the probability that control abundance is higher than diffuser abundance) is the quantity that we are seeking to measure and is of course unknown. Furthermore, the pre-disposal data indicate that the probability of control abundance being higher than diffuser abundance is highly variable and, therefore, not the same for each case (Turgeon, 1983). Thirdly, the number of cases is not fixed, because it varies with the level of significance set in the ANOVA and Duncan's tests (e.g., a smaller alpha of 0.01 would reduce the number of significant cases, and a larger alpha of 0.10 would increase the number of cases). Because the above conditions are violated by the zooplankton data, the conclusions based upon this technique are not valid.

Table 6-1. Summary of ANOVA for within cruise between stations.
(From Wolff et al., 1985)

CRUISE	Depth	*A. tonsa*	*C. velificatus*	*Chaetognatha*	*L. aestiva*	*Paracalanus spp.*	*P. sayana(z)*	*A. lilljeborgii*
8311	B	D/C	ND	ND	ND	ND	C/D	ND
	S	C/D	ND	ND	ND	ND	ND	ND
8403	B	ND	ND	ND	ND	ND	ND	ND
	S	DC	ND	ND	ND	ND	ND	ND
8405	B	ND	ND	ND	ND	ND	ND	ND
	S	ND	ND	ND	ND	ND	ND	ND
8406	B	ND	ND	D/C	ND	ND	D/C	ND
	S	ND	ND	ND	ND	D/C	ND	ND
8407	B	C/D	ND	ND	ND	ND	ND	ND
	S	C/D	C/D	ND	C/D	ND	ND	C/D
8408	B	ND	ND	ND	ND	ND	ND	ND
	S	ND	C/D	C/D	ND	C/D	C/D	C/D
8411	B	ND	ND	ND	ND	ND	ND	ND
	S	D/C	ND	ND	N/D	ND	ND	ND

Various procedures used by Wolff et al. (1985) in their ANOVA calculations raise additional questions. In their previous report Wolff et al. (1984) showed that the data for many plankton species at West Hackberry violated one or more assumptions on which the ANOVA calculations are based. However, they concluded that the ANOVA was sufficiently robust to be used, anyway. These assumptions must be verified each time the ANOVA is performed, but this point is not addressed in the 1985 report. We do not attempt to validate the assumptions for the ANOVA here, because the analysis is also flawed in other respects.

When Wolff et al. (1985) performed their ANOVA on two pooled diffuser and three pooled control stations, they used only five of nine stations (Table 6-1). We performed a similiar ANOVA with pooled diffuser and control stations, retaining all nine stations in the analysis, because of the high variability among both control and diffuser stations (Turgeon, 1983). To be consistent with Wolff et al. (1985), we also used Duncan's new multiple range test to analyze the differences in station means, even though Duncan's method is not recommended (SAS, 1982). Duncan's method controls the comparison-wise error rate at the preselected alpha level; however, the experiment-wise error rate is not controlled and in this example approximately equals 0.99. Thus, the probability of making at least one type-one error is very high, and interpretations of statistical significance warrant extra caution.

For brevity and illustrative purposes, we present ANOVA results (Table 6-2) for only the 18 of 98 cases reported to be significant (Wolff et al., 1985). For each case we present the station means in descending order, followed by the results of the Duncan's test on the pooled diffuser and control stations. Two points are obvious: (1) there is no consistent trend of high or low abundance for any of the previously excluded stations; and (2) only 9 of the 18 previous cases have statistical significance, and in 5 of these 9 cases, the diffuser stations have greater abundance than the controls. Thus, the ANOVA does not demonstrate any trend in relative abundance, and the exclusion of stations obviously influences the results. Wolff et al. (1985) should have provided a strong justification for excluding stations. The conclusion of Wolff et al. (1985), that brine disposal had a significant non-random impact on the zooplankton, is based on an improper analysis and is invalid.

We conclude that brine discharge has no demonstrable impact on the zooplankton at West Hackberry. Given the precautions presented at the beginning of the plankton section, the plankton are the least likely biological assemblage to show an impact of brine discharge. If the brine discharge at West Hackberry does influence the

Table 6-2. Duncan's new multiple range test for mean abundance by cruise, species, depth and station. Numerical stations represent controls (e.g., 3= M3) and stations indicated by letters represent the diffuser (e.g., E= DE, A= M10A). Stations are listed from left to right in order of highest to lowest mean abundance. D/C=diffuser stations had a significantly larger mean abundance than controls. C/D= control mean abundance is larger. -- indicates not significant. Species codes: 1= _Acartia tonsa,_ 26= _C. velificatus,_ 27= _Chaetognatha,_ 66= _L. aestiva,_ 104= _Paracalanus_ spp., 115= _P. sayana_ (zoeae), 216= _A. lilljeborgii._

Cruise	Species	Depth	Stations									Signif.
8311	1	S	21	N	18	A	3	S	W	E	22	--
	1	B	21	N	E	S	W	3	A	22	18	--
	115	B	N	18	3	E	W	A	S	22	21	--
8403	1	S	E	S	A	N	W	3	21	18	22	D/C
8406	104	S	A	W	N	21	E	S	18	22	3	D/C
	27	B	E	22	S	A	N	21	W	18	3	D/C
	115	B	E	S	21	W	N	A	22	18	3	D/C
8407	1	S	18	22	3	E	N	W	S	A	21	--
	1	B	3	N	W	21	18	22	E	A	S	C/D
	26	S	18	22	N	W	3	E	21	S	A	--
	66	S	18	N	22	3	E	A	21	W	S	C/D
	216	S	18	3	E	N	W	22	S	A	21	--
8408	26	S	22	N	3	18	S	E	W	21	A	--
	27	S	22	21	N	S	3	18	W	A	E	C/D
	104	S	22	3	18	N	S	W	A	21	E	--
	115	S	22	3	21	N	S	18	W	A	E	C/D
	216	S	S	3	18	22	N	A	21	E	W	--
8411	1	S	E	S	A	W	18	N	21	22	3	D/C

zooplankton assemblage in any way, that impact is overshadowed by highly variable natural processes and is not quantifiable by present sampling efforts.

6.3 Nekton

No morbidity or mortality of the nekton was observed during the discharge monitoring program from 1981-1984, and likewise, no aberrant behavior of the nekton was observed (Ilg et al., 1983; Landry et al., 1984, 1985). In addition, no trend of decreasing species weight or abundance was noted in the vicinity of the diffuser or brine plume (Ilg et al., 1983; Landry et al., 1984, 1985). An analysis of spatial trends indicated that abundance was highest at a near-diffuser station (DE) and lowest at a control station (M20), (Landry et al., 1985). However, temporal variability in nekton abundance was larger than spatial variability by an order of magnitude (Table 6-3).

During the third discharge survey, nekton catches were largest in late spring and summer (Landry et al., 1985). Previous discharge surveys reported peak catches from late summer and early fall 1981 (Ilg et al., 1983), late summer 1982 and early summer 1983 (Landry et al.,1984). The timing of peak catch was apparently influenced by the onset and timing of hypoxia, but large catches were generally reported for those late spring and summer months that were not severely impacted by hypoxia (Landry et al., 1985).

Peak catches in July and August 1984 coincided with the highest average bottom salinities recorded during brine discharge. However, mean abundance was very low in November, when similiar bottom salinities occurred. Conversely, summer hypoxic conditions did appear to influence species numbers, particularly at control stations. In general, months with lowest dissolved oxygen values coincided with smaller catches.

During the three reporting periods of the discharge monitoring program, a temporal comparison of the number of dominant species showed a slight decline from 15 to 11 (Ilg et al., 1983; Landry et al., 1984, 1985). There are two causes of this slight trend. (1) In the third discharge assessment, several previously dominant invertebrate taxa were not as common (Landry et al., 1985). (2) The Atlantic bumper, Chloroscombrus chrysurus, was the dominant species both by weight and numbers from May 1981 to April 1982, but from May 1982 to November 1984 the croaker, Micropogonias undulatus was the dominant species (Ilg et al., 1983; Landry et al., 1984, 1985). The relative contributions by other dominant species was diminished because of the increases in croaker.

Table 6-3 R-squared values from analysis of variance tests. Adapted from (Landry et al., 1985). N/A= not available.

		r**2 Abundance	Biomass
Nov 1983-Nov 1984	time	.571	.610
	stations	.073	.070
	interaction (TxS)	.338	.265
	random error	.018	.055
May 1982-Nov 1983	time	.767	.640
	stations	.023	.018
	interaction (TxS)	.187	.266
	random error	.024	.076
May 1981-May 1982	N/A		

Partly because of increases in croaker, the dominance of white shrimp and brown shrimp (*Penaeus* spp.), relative to other dominant members of the nekton, declined during the three discharge monitoring surveys, even though the catch for both species increased during the second and third monitoring surveys. The low and variable catch of shrimp precluded any interpretation of station preference by either species of shrimp during the third discharge monitoring survey (Landry et al., 1985). Table 6-4 shows the commercial catch of shrimp for Louisiana and the entire US catch from the Gulf of Mexico during the discharge period (1981-1984). In Louisiana waters, commercial shrimp catches declined from 1981 through 1983, then increased during 1984. Gulf of Mexico catches followed a similiar trend. Thus, declines in shrimp abundance and biomass at West Hackberry between 1981 and 1983 reflect coastwide trends.

During the first two monitoring periods, no species indicated a preference for control or diffuser stations. However, during the third discharge monitoring period the catch of the overall dominant species, *Micropogonias undulatus*, was highly variable relative to other dominant species. The smallest relative catch of croaker occurred at the diffuser (station M10A), but this trend is not statistically significant (Landry et al., 1985).

Overall catch rates for the nekton indicate a different pattern of abundance with respect to station location. The diffuser stations collectively yielded a higher catch than the control stations. Catch was highest at two near-diffuser stations (DN and DE) and lowest at a control station (M20). During hypoxic periods, highest and lowest catches were recorded, respectively, at the diffuser and control stations (Landry et al., 1985). Nekton biomass was the highest ever recorded at West Hackberry during July and August 1984, when dissolved oxygen was low, and salinities were elevated. Prolonged hypoxia during the summers of 1982 and 1983 severely impacted nekton abundance; however, the hypoxic conditions during 1984 were less severe, and nekton abundance was less affected.

A discriminant analysis of the relationship of abiotic parameters to nekton abundance indicated that bottom temperatures and bottom dissolved-oxygen levels were strongly associated with nekton abundance. Landry et al. (1985) found salinity to be slightly more important in defining group separations than in previous analyses, but salinity was nevertheless relatively unimportant when compared to temperature and dissolved oxygen.

Table 6-4. Annual U.S. commercial catch of shrimp for Louisiana and Gulf of Mexico, 1980-1984. Data from Current Fisheries Statistics 1981-1984 (NMFS, Fisheries Statistics Program, 1985).

	YEAR	CATCH (millions of lbs)
Louisiana	81	110.2
	82	90.5
	83	77.0
	84	106.4
Gulf of Mexico	81	268.2
	82	209.9
	83	198.5
	84	254.3

6.4 Benthos

There were no reported effects of brine discharge on the benthos during the first year of discharge (Gaston and Weston, 1983), but effects of brine discharge were reported for the second discharge period. Like the nekton, the benthos at the diffuser station (M10A) was reported to have greater diversity than control stations, however abundance at the diffuser was generally not higher than at other stations (McKinney et al., 1984). Based on 7 cruises in the third discharge period, McKinney et al. (1985) reported higher abundances and diversity in the discharge area (Figures 6-3 and 6-4). Only 1 brine station of 1 cruise (1 of 42 cases) was reported to have significantly lower abundance than a control, and diversity was reported to be significantly higher at the diffuser in 4 of 7 cruises. Only in one case were both abundance and diversity significantly higher at the diffuser at the same time, and on that cruise bottom salinities were similiar at control and diffuser stations.

Two species, *Paraprionospio pinnata* and *Mulinia lateralis,* accounted for the majority of the diversity difference between diffuser and control stations (McKinney et al., 1985). McKinney et al. (1985) concluded both that the distribution of *M. lateralis* was influenced by brine discharge, and that their meroplanktonic larvae preferentially settled near the diffuser. No data or observations were presented to support the latter conclusion, and the conclusion that brine discharge influenced the distribution of *M. lateralis* was contrary to their published data (Figure 6-5). That conclusion is questionable because 38 percent of the total catch (see M18 in February) was deleted from the analysis. When all of the data are considered, the distribution of *M. lateralis* is not significantly different between diffuser and control stations. In the pre-discharge study, Comiskey and Farmer (1981) found the abundance of *M. lateralis* to be highly variable between both cruises and sites, and their ANOVA indicated a significant interaction term, i.e., variation among stations was not uniform with time. Thus, any interpretations of statistical differences of *M. lateralis* abundance would have to take into account this non-uniform (not homoscedastic) variability.

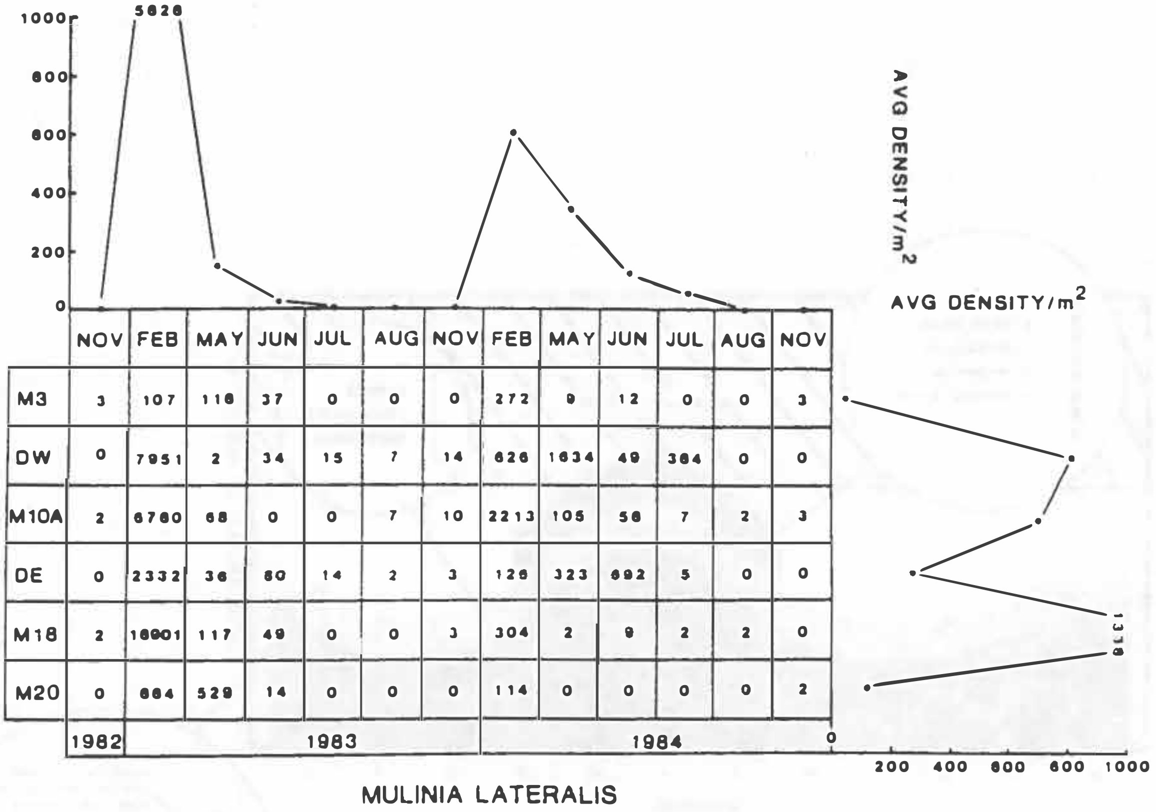
Summer hypoxia in bottom waters was a major source of variation in the benthic studies. McKinney et al. (1985) report the major significance of the hypoxia as a synergistic stress with brine discharge (Figure 6-6). Because they have not demonstrated clearly that brine discharge either adversely impacts the benthos or might intensify a hypoxic stress, their graphic depiction of brine-induced impact superimposed on hypoxic stress is not supportable (Figure 6-6). It contradicts data showing

	STATIONS					
MONTHS	M3	DW	M10A	DE	M18	M20
FEB 84			X			
MAY 84		X	X	X		
JUN 84	X	X		X	X	X
JUL 84	X	X	X	X	X	

Figure 6-3. Comparisons of benthos abundance by station. Stations comprising the group with the highest abundance (alpha= 0.05) are indicated by an "X". Three cruises (Nov 83, Aug 84, Nov 84) showed no significant difference and are not shown. Adapted from McKinney et al., 1985.

	STATIONS					
MONTH	M3	DW	M10A	DE	M18	M20
NOV 83	X	X	X	X	X	
FEB 84	X	X		X	X	X
MAY 84			X			
JUN 84	X		X		X	
JUL 84			X			
AUG 84			X			
NOV 84			X			

Figure 6-4. Comparison of benthos diversity by station. Stations comprising the group with the highest diversity (alpha= 0.05) are indicated by an "X". Adapted from McKinney et al., 1985.



	NOV	FEB	MAY	JUN	JUL	AUG	NOV	FEB	MAY	JUN	JUL	AUG	NOV
M3	3	107	118	37	0	0	0	272	9	12	0	0	3
DW	0	7951	2	34	15	7	14	626	1634	49	384	0	0
M10A	2	6760	68	0	0	7	10	2213	105	56	7	2	3
DE	0	2332	36	80	14	2	3	128	323	692	5	0	0
M18	2	16901	117	49	0	0	3	304	2	9	2	2	0
M20	0	664	529	14	0	0	0	114	0	0	0	0	2
	1982	1983						1984					

Figure 6-5. Distribution of <u>Mulinia lateralis</u>. Horizontal graph represents column averages, vertical graph represents row averages. Adapted from McKinney et al., 1985.

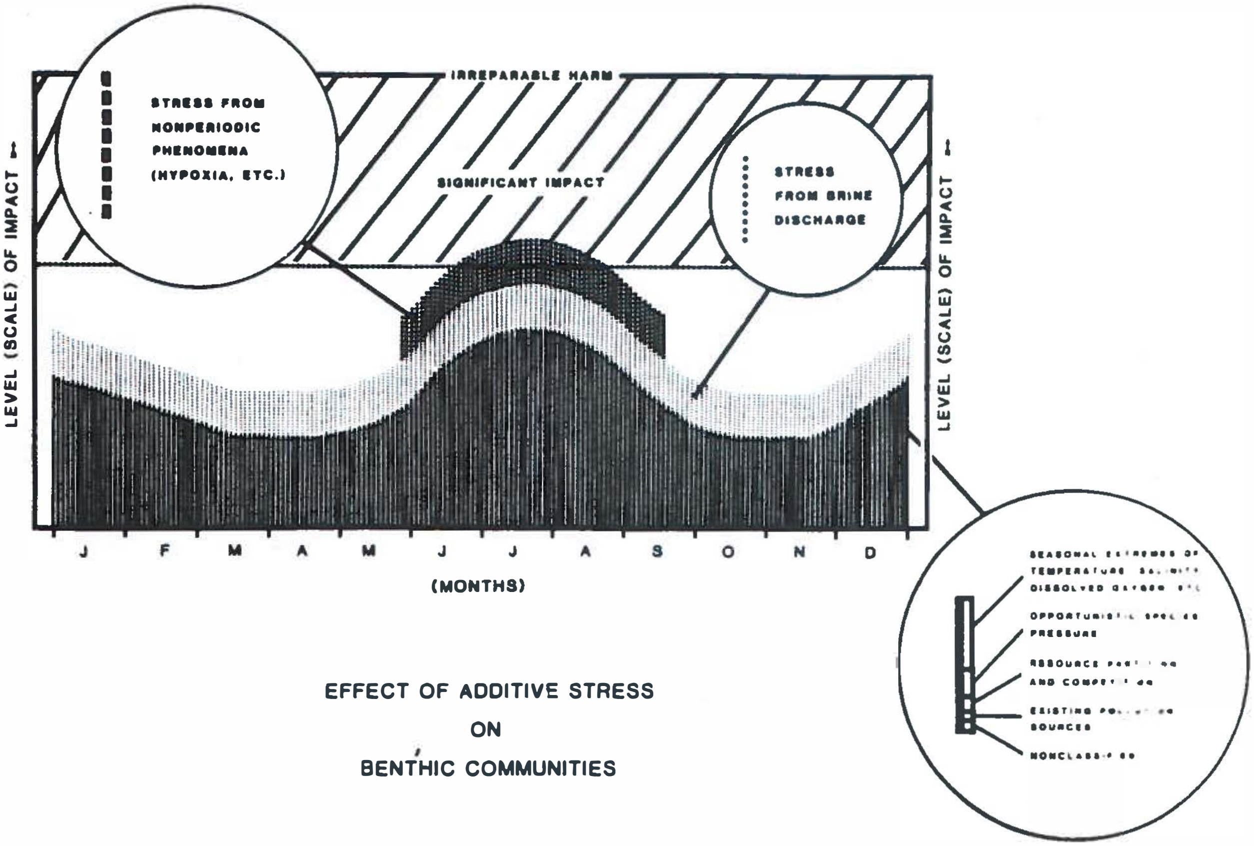


Figure 6-6. Graphic representation of cumulative stress. Note that Dissolved Oxygen is added to the cumulative stress twice: in both the hypoxia and nonperiodic phenomena curves. Reproduced from McKinney et al., 1985.

enhanced biological assemblages at the diffuser and does not realistically portray the magnitude and phase of seasonal variability of stress.

Abiotic stress is often characterized by rapid changes or extremes in physical or chemical conditions. As represented conceptually in Figure 6-7, natural stress reflects physical and chemical conditions at West Hackberry; hypoxia is treated separately. In that regard, summer is not a particularly stressful period.

A more realistic, but also simplistic, hypothesis of the interaction of brine discharge and hypoxia is that brine discharge serves to ameliorate hypoxia in the vicinity of the brine diffuser, thus lowering environmental stress (Figure 6-7). This explanation accounts for the observed increases in diversity and abundance at the diffuser, and does not assume brine-related environmental degradation, when none is indicated by the results of the sampling program.

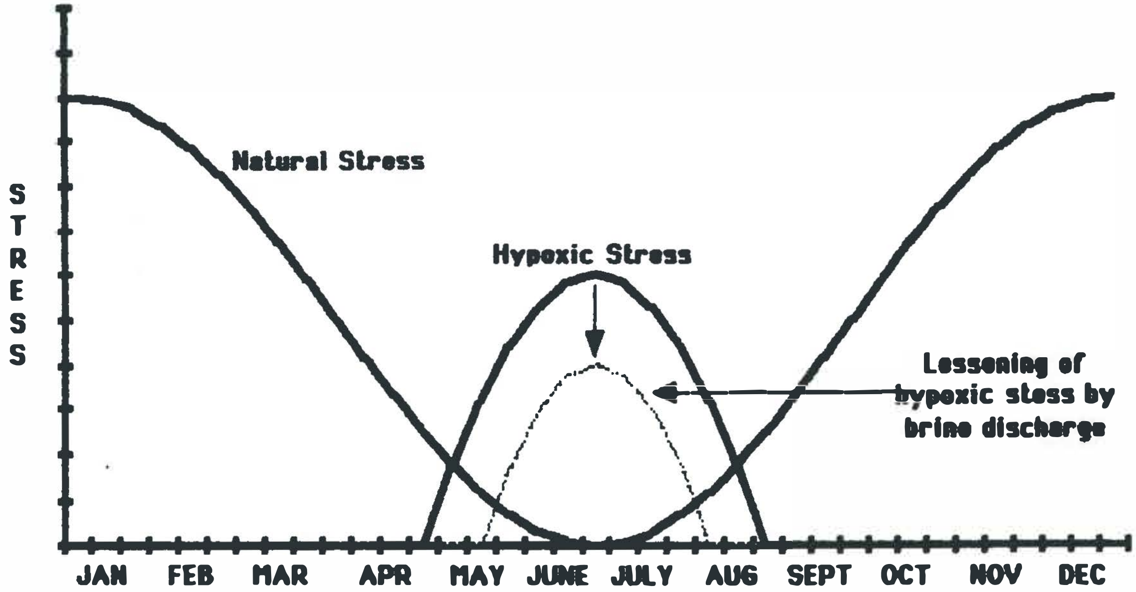


Figure 6-7. A more realistic, though still simplistic, representation of ecosystem stress in the vicinity of West Hackberry, compare with Figure 6-6. As shown by field sampling, (a)seasonal stress is lowest in summer and (b) brine discharge serves to ameliorate the stress of hypoxia.

7.0 ENVIRONMENTAL IMPACTS OF NATURALLY - OCCURRING STRESSES

Naturally-occurring stresses are major factors to consider when evaluating environmental impacts. Although these physical conditions can cause immediate and obvious impacts, they also can have long-term adverse effects on the environment.

7.1 Hypoxia and Anoxia of Bottom Waters

Natural depletion of dissolved oxygen to hypoxic levels (measurements less than 2.0 parts per million, ppm) in bottom waters of the continental shelf of the northwestern Gulf of Mexico has been recognized since the 1930's (Pavella et al., 1983). Hypoxia or anoxia, a condition in which the dissolved oxygen concentration approaches 0 ppm, occurs in the summer when there is a combination of a large influx of low salinity surface water, calm weather and a high level of organic decay (Fotheringham and Weissberg, 1979). The low salinity surface water and calm weather cause the water column to be strongly stratified. Therefore, the surface waters, which are oxygenated by the air-sea interaction and photosynthesis, do not mix with bottom waters that become progressively depleted of oxygen probably by organic decay and respiration (Comiskey and Farmer, 1981).

Studies of the benthos are of particular importance in assessing the health of this ecosystem in the northwestern Gulf of Mexico, because these animals are an important food source for many commercially important species. The species composition and abundance of benthic fauna from the Louisiana coastal waters appear to be affected by season, storm surges and, in summer, low dissolved oxygen in the bottom water. Since the benthos have limited mobility, prolonged periods of low dissolved oxygen can cause widespread mortalities (Parker et al., 1980).

A case of hypoxia was observed during the quarterly baseline study conducted at West Hackberry from June 1978 to April 1979. Parker et al. (1980) measured low dissolved oxygen during the summer 1978 cruise and described the following: " A large area of the nearshore Gulf off the Louisiana coast, especially near Calcasieu Pass, is characterized by critically low dissolved oxygen values during the summer. The very low dissolved oxygen values at West Hackberry may control larval settlement and survival. However, most of the predominant benthic animals in the area have larval planktonic stages that settle out in the fall and winter. This would allow repopulation of areas that were subjected to environmental stresses--such as low dissolved oxygen levels or storm surges." The temporal resolution of the quarterly sampling of the field operations precluded determining the duration of the low dissolved oxygen values and any definitive subsequent effects on the benthic population.

Another confirmed case of hypoxia occurred from May to July 1979 at two study sites off Freeport, TX. Monthly benthic sampling revealed that this event altered the bottom community. The number of species declined drastically, and low population densities were evident as many organisms were killed. A cross-shelf transect between the two study areas in late June 1979 passed over an area containing a rocky structure known as East Bank, where this event dramatically altered the reef assemblage. Several species appeared to be eradicated, and the populations of others were drastically lowered. The normal reef fish community was also affected. Scientists observed only a few fish of a single species in what had been a healthy community, as the fish apparently avoided the hypoxic region. After the hypoxic conditions were disrupted, the number of species increased through March 1980 (Harper and McKinney, 1980).

7.2 Storms

During the winter as many as 30 continental polar air masses move southward toward the Gulf, causing occassional sudden drops in temperature. When these cold fronts reach the Gulf, maritime tropical air flowing northward causes the fronts to abate and become stationary. The majority of these fronts spill out over the Gulf and produce surface winds from 28-37 kilometers per hour (km/hr). Approximately one-third of these cold outbreaks have winds over 62 km/hr, with about one-half of these having winds reaching 89 km/hr (US Dept. of Interior, 1983).

Tropical storms occur most frequently in this region in the late summer and early fall and approach the Gulf in a northwesterly direction from the equatorial Atlantic Ocean. More than half of the tropical storms develop into hurricanes. Extreme drops in pressure and high winds are commonly associated with the passage of these tropical storms. The very shallow shelf in the West Hackberry region of the Gulf, the frequent inundation of low-lying coastal areas by normal precipitation events, and the high water table in coastal areas make the region susceptible to severe storm surge and wind damage by these storms (Comiskey and Farmer, 1981).

Hurricane Debra hit the Louisiana coast on 28 August 1978. The storm caused the deposit of 1.5 m of clay and silt at the brine diffuser, burying the benthic population. The accompanying storm surge generated currents that broke current meter moorings and swept the meters away (Everdale, 1985).

7.3 Abnormally Severe Winter Conditions

The shallow waters of the shelf and the estuaries are particularly susceptible to prolonged periods of extreme cold. It is hypothesized that juvenile finfish and immature white shrimp spend the winter in the estuaries. Water temperatures below 5 degrees Centigrade can kill these species and other organisms. In December 1983 a prolonged cold spell hit the Gulf coast and brought freezing air temperatures to the area from Galveston, TX, to New Orleans, LA. An estimated 15.2 million fish, crabs and shrimp were killed in the shallow bay waters of Texas (Baxter, 1984).

High precipitation and the subsequent high runoff and river discharge that can be associated with winter storms affect the shallow shrimp-nursery areas. The nursery area salinities may be reduced below the tolerence limits of many juveniles causing mortalities (Larson et al., 1980).

8.0 SUMMARY AND CONCLUSIONS

The marine environment at the West Hackberry brine disposal site is typical of shelf habitats along the northwest Gulf of Mexico; thus, the brine disposal site is not situated in or near a unique or critical habitat. Characteristic of coastal temperate ecosystems, natural variability within the ecosystem at West Hackberry is high over small time and space scales. Seasonal variability of local biotic and abiotic factors is frequently an order of magnitude larger than variability among stations.

There is no substantiated evidence that brine disposal at West Hackberry has detrimentally impacted the biota during the first 43 months of brine discharge. This conclusion is supported by the results of a numerical model of the brine plume, and analysis and interpretation of results from pre-discharge and discharge sampling programs. Numerical abundances, number of species, diversity, community structure and composition of the plankton, nekton and benthos show no detrimental effects of brine discharge. Penaeid shrimp abundance, spawning, larval development and migration also show no detrimental effects of brine discharge.

The only direct impact of brine disposal is an elevation of salinity in bottom waters and sediment pore waters in the vicinity of the brine diffuser. The elevated salinities will return to ambient levels with cessation of brine discharge operations. Ionic imbalances, halite precipitation and elevated concentrations of pesticides, heavy metals and petrogenic hydrocarbons have not occurred as a result of discharge operations.

Naturally occurring hypoxia in bottom waters is common at intermittent intervals during summer in this region, and is likely to recur in the future. Hypoxia is not related to brine disposal. Detrimental effects of hypoxia are measurable and represent a potentially severe stress for the shelf ecosystem. However, the discharged brine is well oxygenated and we hypothesize hypoxia is ameliorated in the immediate vicinity of the diffuser. During periods of hypoxia, brine discharge may influence the biota near the diffuser, because, relative to control stations, increased species abundance and diversity are sometimes measured there.

In conclusion:

1) brine disposal has not adversely impacted the biota in the vicinity of the West Hackberry diffuser site;

2) measurable ecosystem variability in the vicinity of the West Hackberry brine diffuser is a result of natural environmental factors, not brine disposal and

3) hypoxia occurs naturally at the West Hackberry site with severe and measurable impact, but is not related to brine disposal operations. In fact, brine discharge operations may lessen the impact of hypoxia near the diffuser.

References

Baxter, D. (ed.). 1984. Redfish, trout limits reduced by commission, Texas Parks and Wildlife. p. 33.

Boehm, P.D. and D.L. Fiest. 1980. Determine Hydrocarbons Composition and Concentration in Major Components of the Marine Ecosystem. Vol. 6. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/Chemical survey of Texoma and Capline Sector Salt Dome Brine Disposal Sites off Louisiana, 1978-1979. NOAA Technical Memorandum NMFS-SEFC-27, 48p. Available from NTIS, Springfield, VA.

Brooks, J.M. 1980. Determine Seasonal Variations in Inorganic Nutrient Composition of the Water Column. Vol. 8 IN: Jackson, W.B. and G.M. Faw (eds.). Biological/Chemical Survey of Texoma and Capline Sector Salt Dome Brine Disposal Sites off Louisiana, 1978-1979. NOAA Technical Memorandum NMFS-SEFC-27, 48p. Available from NTIS, Springfield, VA.

Comiskey, C.E. and T.A. Farmer (eds.). 1981. Characterization of Baseline Oceanography for the Texoma Region Brine Disposal Sites. Volumes I and II. Final report to U.S. Department of Energy, Strategic Petroleum Reserve Office, Washington, D.C. Contract No. DEAC 01-77US08788.

Chittenden, M.E., Jr. and J.D. McEachran. 1976. Composition, Ecology and Dynamics of Demersal Fish Communities on the Northwestern Gulf of Mexico Continental Shelf, with a Similiar Synopsis for the Entire Gulf. Sea Grant Publ. No. TAMU-SG-76-208. 104p.

Dennis, G.D., T.J. Bright, and C.A. Shalan (eds.). 1984. Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annotated Bibliography of Hypoxia and Other Oxygen-Depleted Literature on the Marine Environment. Final Report. Contract No. DE-AC96-83P010850. Available from NTIS, Springfield, VA.

Department of Energy. 1978. Final Environmental Impact Statement--Strategic Petroleum Reserve Texoma Group Salt Domes. Vol. I and Appendix A. Available from NTIS, Springfield, VA. FEA-DES-77-8.

Everdale, F.G. 1985. Personal communication. Oceanographer, Assessment and Information Services Center, Washington, D.C

Fay, R. and M. Schnitzer. 1985. Phytoplankton. Vol. 1, Chapt 7., 51p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy, 1985. Available from

NTIS, Springfield, VA; DOE-P010850-5.

Fay, R. and M. Schnitzer. 1984. Phytoplankton Vol. 1, Chapt 7., 50p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from May 1982 through November 1983. Department of Energy, 1984. Available from NTIS, Springfield, VA; DOE-P010850-3.

Fotheringham, N. and G.H. Weissberg. 1979. Some Causes, Consequences and Potential Environmental Impacts of Oxygen Depletion in the Northern Gulf of Mexico. Offshore Tech. Conf. Proc. OTC, 3611:2205-2208.

Freund, J.E. and R.E. Walpole. 1980. Mathematical Statistics. Prentice Hall, Inc., Englewood Cliffs, New Jersey. 548p.

Gaston, G.R. and D.P. Weston. 1983. Benthos. Vol. 3, Chapt. 6, 154p. IN: Derouen, L.R., R.W. Hann, D.M. Casserly, C. Giammona, and V.J. Lascara. (eds.). West Hackberry Strategic Petroleum Rreserve Site Brine Disposal Monitoring, Year 1 Report. Department of Energy, 1983. Available from NTIS, Springfield, VA. DE-AC96-80P010288.

Hann Jr., Roy W. 1983. Description of the Study Area. Vol II. Chapt. 4, 19 p. IN: Field and Laboratory Procedures Manual for the West Hackberry Site of the Strategic petroleum Reserve Program. Department of Energy. Conract No. DE-AC-96-80P010288.

Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.) 1985. Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy. Available from NTIS, Springfield, VA; DOE-P010850-5.

Hann, R.W., Jr., C.P. Giammona, and R.E. Randall, (Eds.). 1984. Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from May 1982 through November 1983 Department of Energy. Available from NTIS Springfield, VA. Conract No. DOE-P010850-5.

Harper, D.E., Jr. 1970. Ecological studies of selected level-bottom macro-invertebrates off Galveston, Texas. Ph.D. Thesis, Texas AM Univ., College Station, TX.

Harper, D.E., Jr. and L.D. McKinney. 1980. Benthos. Chapt. 5. 79 p. IN: Hann, R.W., Jr. and R.E. Randall (eds.). Evaluation of Brine Disposal from the Bryan Mound Site of the Strategic Petroleum Reserve Program; Final Report of Predisposal Studies to the Department of Energy. Volume 1.

Contract No. DE-FC96-79P010114. Available from NTIS, Springfield, VA.

Harper, D.E., Jr. and L.D. McKinney. 1981. Benthos. Chapt. 5. 30 p. IN: Hann, R.W., Jr. and R.E. Randall (eds.). Evaluation of Brine Disposal from the Bryan Mound Site of the Strategic Petroleum Reserve Program; Final Report of Postdisposal Intensive Studies to the Department of Energy. Contract No. DE-FC96-79P010114. Available from NTIS, Springfield, VA.

Hedgepeth, J.W. 1957. Estuaries and Lagoons. II Biological Aspects. IN: J.W. Hedgepeth (ed.). Treatise on Marine Ecology and Paleoecology, Vol. 1, Ecology, Geol. Soc. Am. Mem. 67:693-729.

Hildebrand, S.F., 1954. A study of the fauna of the brown shrimp (Penaeus aztecus Ives) grounds in the Western Gulf of Mexico. Publ. Inst. Mar. Sci. Univ. Texas 4:169-232.

Ilg, R.J., T.L. Kirby, and G. Stacy,III. 1983. Nekton. Vol. 3, Chapt. 7, 111p. IN: Derouen, L.R., R.W. Hann, D.M. Casserly, C. Giammona, and V.J. Lascara. (eds.). West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year 1 Report. Department of Energy, 1983. Available from NTIS, Springfield, VA. DE-AC96-80P010288.

James, W.P. (ed.). 1977. Proceedings of the Strategic Petroleum Reserve Workshop on Environmental Considerations of Brine Disposal Near Freeport, Texas. Center for Resources, Texas A and M Univ., College Station, TX.

James, Wesley P. and Robert E. Randall. 1983. Estuarine Hydrology and Hydrography. Vol. II, Chapt. 3, 39 p. IN: DeRouen, L.R., R.W. Hann, D.M. Casserly, C.P. Giammona and V.J. Lascara (eds.). West Hackberry Strategic Petroleum Reserve Site Brine Monitoring, Year I report. Department of Energy, 1983. Available from NTIS, Springfield, VA. Contract No. DE-AC96-80P010288.

Jeffrey, L.M., H.E. Murry, J.F. Slowey, J. Beck, C. Webre and G. Grout. 1981. Water and Sediment Quality. Vol. 2, Chapt. 5, 77 p. IN: Derouen, L.R., R.W. Hann, D.M. Casserly, C. Giammona, and V.J. Lascara. (eds.). West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year 1 Report. Department of Energy, 1983. Available from NTIS, Springfield, VA. DE-AC96-80P010288.

Landry, A.M., Jr., D.E. Pitts, Jr., T.L. Kirby. 1985. Nekton. Vol. 1, Chapt. 5, 107 p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic

Petroleum Reserve: Annual report for the West Hackberry Site from November 1983 through November 1984. Department of Energy, 1985. Available from NTIS, Springfield, VA; DOE-P010850-5.

Landry, A.M., Jr., D.E. Pitts, Jr., T.L. Kirby. 1984. Nekton. Vol. 1, Chapt. 5, 98 p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from May 1982 through November 1983. Department of Energy, 1984. Available from NTIS, Springfield, VA; DOE-P010850-3.

Larson, D.K., D. Davis, R. Detro, P. Dumond, E. Liebow, R. Motschall, D. Sorensen, and W. Guidroz. 1980. Mississippi Deltaic Plain Region Ecological Characterization: A Socioeconomic Study. Vol. 1. Synthesis papers. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-79/ 05.

Maples, R. 1983. Phytoplankton. Vol. 3, Chapt. 8, 78p. IN: Derouen, L.R., R.W. Hann, D.M. Casserly, C. Giammona, and V.J. Lascara. (eds.). West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year 1 Report. Department of Energy, 1983. Available from NTIS, Springfield, VA. DE-AC96-80P010288.

McKinney, L.D., J.M. Nance and D.E. Harper. 1985. Benthos. Vol. 1, Chapt. 6, 98p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy, 1985. Available from NTIS, Springfield, VA; DOE-P010850-5.

McKinney, L.D., D.E. Harper and J.M. Nance. 1984. Benthos. Vol. 1, Chapt. 6, 126p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry site from May 1982 through November 1983. Department of Energy, 1984. Available from NTIS, Springfield, VA; DOE-P010850-3.

National Marine Fisheries Service. 1985. Fisheries of the United States 1984. Current Fisheries Statistics No. 8360 121 p. National Fisheries Statistics Program, NMFS/NOAA Washington, DC. Available from NTIS, Springfield, VA.

Parker, R.H., A.L. Crowe, and L.S. Bohme 1980. Describe Living and Dead (Macro- and Meio-)Communities. Vol. I. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/Chemical Survey of Texoma and Capline Sector Salt Dome Brine Disposal Sites Off Louisiana, 1978-1979. NOAA Technical Memorandum NMFS-SEFC-26, 123 pages. Available from NTIS, Springfield, VA.

Pavela, J.S., J.L. Ross, and M.E. Chittenden, Jr. 1983. Sharp Reduction in Abundance of Fishes and Benthic Macroinvertebrates in the Gulf of Mexico Off Texas Associated With Hypoxia. Northeast Gulf Sci., 6(2): 167-173.

Randall, R.E. and P.W. Price. 1985. Brine Plume. Vol. 1, Chapt. 2, 120p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy, 1985. Available from NTIS, Springfield, VA; DOE-P010850-5.

Randall, R.E. and P.W. Price. 1984. Brine Plume. Vol. 2, Chapt. 2, IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry site from May 1982 through November 1983. Department of Energy, 1984. Available from NTIS, Springfield, VA; DOE-P010850-3.

Randall, R.E. 1983. Brine Plume Measurements. Vol. 2, Chapt. 4, 105p. IN: Derouen, L.R., R.W. Hann, D.M. Casserly, C. Giammona, and V.J. Lascara. (eds.). West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year 1 Report. Department of Energy. Available from NTIS, Springfield, VA. DE-AC96-80P010288.

SAS Institute. 1982. SAS Users Guide: Statistics. SAS Institute, Inc. Cary, NC. 584p.

Schwarz, J.R., S.K. Alexander, A.J. Schropp and V.L. Carpenter. 1980. Describe bacterial communities. Vol. 3. IN: Jackson, W.B. and G.M. Faw (eds.). Biological/Chemical survey of Texoma and Capline Sector Salt Dome Brine Disposal Sites off Louisiana, 1978-1979. NOAA Technical Memorandum NMFS-SEFC-27, 48p. Available from NTIS, Springfield, VA.

Slowey, J.F., L.M. Jeffrey and H.E. Murry 1984. Water and Sediment Quality. Vol. 1, Chapt. 3, 32 p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West

Hackberry site from May 1982 through November 1983. Department of Energy, 1984. Available from NTIS, Springfield, VA; DOE-P010850-3.

Slowey, J.F. and L.M. Jeffrey 1985. Water and Sediment Quality. Vol. 1, Chapt 3. 26p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy, 1985. Available from NTIS, Springfield, VA; DOE-P010850-5.

Slowey, F.J. 1980. Sediment and Water Quality. Chapt. 3. IN: Hann, R.W., Jr., and R.E. Randall (eds.). Evaluation of Brine Disposal from the Bryan Mound Site of the Strategic Petroleum Reserve Program. Final Report of Predisposal Studies. Texas A and M University, College Station, TX.

Trefry, J.H., S. Metz, R.P. Trocine and T.A. Nelson 1985. A decline in lead transport by the Mississippi River. Science 230:371 and 439-441.

Turgeon, K. 1983. A Review and Assessment of West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year I Report: Zooplankton. Preface to Chapt. 9, 22p. IN: DeRouen, L.R., R.W. Hann, D.M. Casserly, C. Giammona and V.J. Lascara. West Hackberry Strategic Petroleum Reserve Site Brine Disposal Monitoring, Year I Report. Depart. of Energy 1983. DOE Contract No. DE-AC96-80P010288. Available from NTIS, Springfield, VA.

Turgeon, K. 1981. Synthesis of the Texoma/Capline Chemical and Biological survey results: June 1978-May 1979. NOAA, Department of Commerce. Available from NTIS, Springfield, VA.

U.S. Dept. of the Interior. Minerals Management Service. 1983. Final Regional Environmental Impact Statement, Gulf of Mexico. Vol. I. Prepared by the Minerals Management Service Gulf of Mexico OCS Region. Metairie, LA: Minerals Management Service, Gulf of Mexico OCS Region; 527 pages. Available from NTIS, Springfield, VA.

Weissberg, G.H., D.G. McGrath, W.M. Levitan and S.H. Blood. 1980a. Weeks Island Brine Diffuser Study: Baseline Conditions and Environmental Assessment. Dames and Moore Report to DOE, Contract No. AC01-77US08781.

Weissberg, G.H., D.G. McGrath, W.M. Levitan and S.H. Blood. 1980b. Chacahoula Brine Diffuser Study: Baseline Conditions and Environmental Assessment. Dames and Moore Report to DOE, Contract No. AC01-77US08781.

Wolff, G.A., J.H. Wormuth and S.P. Berkowitz. 1985. Zooplankton. Vol. 1, Chapt. 8, 53 p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from November 1983 through November 1984. Department of Energy, 1985. Available from NTIS, Springfield, VA; DOE-P010850-5.

Wolff, G.A., B.L. Andryszak, J.H. Wormuth and S.P. Berkowitz. 1984. Zooplankton Vol. 1, Chapt. 8, 46 p. IN: Hann, R.W., Jr., C.P. Giammona and R.E. Randall (eds.). Offshore Oceanographic and Environmental Monitoring Services for the Strategic Petroleum Reserve: Annual Report for the West Hackberry Site from May 1982 through November 1983. Department of Energy, 1984. Available from NTIS, Springfield, VA; DOE-P010850-3.

Brine Dispersion Modeling in Near and Intermediate-Fields

1. Introduction

Numerical modeling of brine waste dispersion at offshore disposal sites of the Strategic Petroleum Reserve (SPR) Development Program has been conducted using a Transient Plume (TP) model developed at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics at the Massachusetts Institute of Technology (Adams et. al, 1975). Experience with results from the Transient Plume model and on-site surveys have shown that critical levels of salinity are not likely to be found in the far-field region of diffusion where the model provides accurate results (NOAA, 1980 and 1981). Estimates of near and intermediate-field dilution are made by the TP model using empirical relationships without grid point orientation. Because of the likely occurrence of significant increases in salinity in the immediate area of the brine diffuser during low ambient current, development of improved near and intermediate-field diffusion models was initiated (NOAA, 1981).

This report presents the characteristics of the near and intermediate-field models (produced by T.S. Associates of Columbia, MD), provides examples of results from these models which are run on NOAA computers, and examines the results with respect to information about brine concentrations which were measured during monitoring cruises at the diffuser sites. In addition, results from Transient Plume model runs during the period of application of the near and intermediate-field models are included for comparison.

At each offshore disposal site, waste brine is pumped vertically from a diffuser on the bottom. The diffuser consists of a transfer pipe with diffuser ports which are elevated about three to five feet above the bottom.

2. Near Field Modeling

Vertically rising brine plumes from the ports are carried downstream by the ambient current. Because of velocity differences between a plume and the ambient water, entrainment of seawater into each plume produces dilution of the waste brine and increased plume diameter. Under present operating conditions, the rate of entrainment is not sufficient to bring plume, brine density to the density of the ambient sea water by the time a plume reaches its maximum height of rise. Since plume density remains greater than the ambient sea water density, plumes fall to the bottom where the impacting plumes spread along the bottom.

Near-field processes considered by the model are entrainment into vertically rising and falling plumes, down stream advection of plumes, and impact of falling plumes on the bottom.

The near-field model is, essentially, a simple plume trajectory mapping model which produces a plume center line trajectory from an exit port on the submerged brine diffuser (NOAA, 1980) where the ambient current is U_a. Assuming a "top hat" distribution of brine salinity and velocity in a brine plume, the plume radius, r, the vertical plume velocity, W, and the plume center- line height, z, above an exit port may be computed as afunction of distance, x, from the diffuser by step-wise integration of the following equations:

$$r^2(U_a^2+W^2)^{1/2}W = r_0^2(U_a^2+W_0^2)^{1/2}W_0\left[1-\frac{1}{RF_j^2}\cdot\frac{x}{d_0}\right] \tag{1}$$

$$r^2(U_a^2+W^2)^{1/2} = r_0^2(U_a^2+W_0^2)^{1/2}+\frac{2\alpha}{U_a}\int_0^x r\left|W\right|(U_a^2+W^2)^{1/2}\,dx \tag{2}$$

where the jet Froude number F_j is given by

$$F_j = \frac{W_0}{\left(g\frac{\Delta\rho_0}{\rho}d_0\right)^{1/2}}$$

and the cross-flow velocity ratio R by

$$R = \frac{U_a}{W_0}$$

Height z may be computed from equation (3) where z_0 is the height of the discharged port above the ocean floor.

$$z = z_0 + \frac{1}{U_a}\int_0^x W\cdot dx \tag{3}$$

The maximum height of rise of the brine plume may be approximated by:

$$z_{max} \simeq 2 d_0 F_j$$

and dilution, S, of brine along the plume center-line may be computed at any displacement downstream, x, from equation (4).

$$S = \left(\frac{r}{r_0}\right)^2 \cdot \left(\frac{U_a^2 + W^2}{U_a^2 + W_0^2}\right)^{1/2} \qquad (4)$$

d_0 is the exit port diameter $(r_0 = d_0/2)$ where subscript o designates initial magnitudes of variables. $\Delta\rho$ is the difference between plume and ambient water density ρ_a, and g is the gravitational acceleration. α, the plume horizontal entrainment constant was set equal to 0.07, based on laboratory tests (Tong and Stolzenbach, 1979). The distribution of dilution amount laterally may be approximated by a Gaussian distribution.

2.1 Results From Near Field Modeling

Figure 1 shows a model produced brine plume vertical cross section under the ambient current and water density conditions of October 1, 1980. The brine diffuser port is estimated to be about 5 feet above the sea floor in the immediate vicinity of the diffuser. The cross section shows the brine dilution distribution from the plume center line (dashed) concentration, based on a gaussion model of distribution. The isolines of dilution are drawn around the plume center line starting at dilution equal 10:1 and the outer contour is 40:1 dilution. At the sea floor (model estimated at 3.6 feet down stream from the diffuser), a dilution of 44.2:1 is estimated. Jet rise above the diffuser port was estimated to be 7.8 feet.

Model produced estimates of excess salinity distribution around the diffuser is shown in figure 2 for the October 1, 1980 case. In present computational procedure, the near-field model results initiate the intermediate-field model with production of combined computer graphics. The down-stream extent of the near field is beyond the bottom impact, where the plumes merge on the bottom, with maximum salinity excess expected at the impact location i.e., 4.5 ppt above ambient. It is interesting to note that the largest salinity excess found during the Texas A&M monitoring cruise of October 1 was 4.8 ppt.

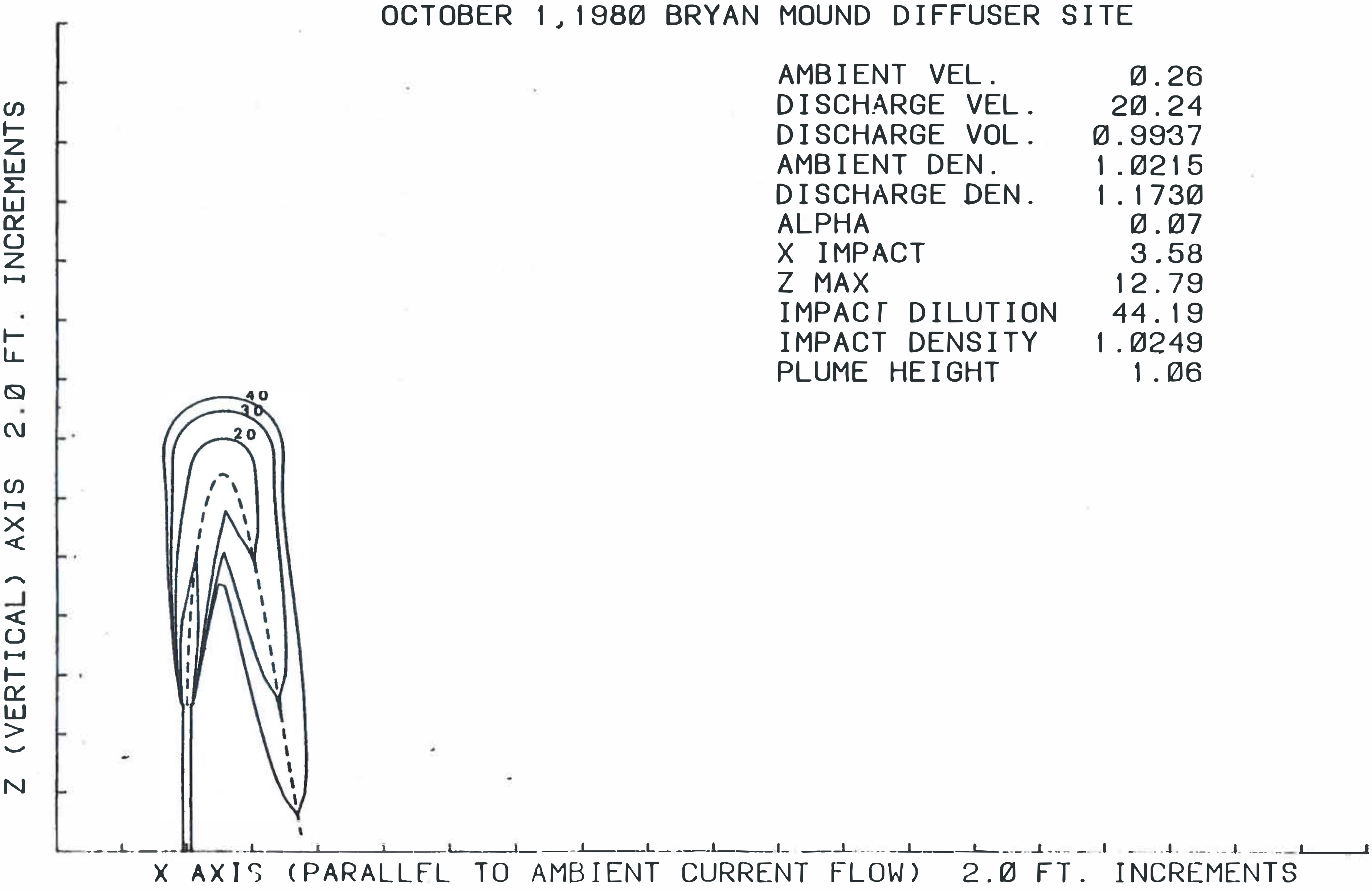


Figure 1. Model brine plume trajectory and near-field isopleths of dilution. 10:1, 20:1, 30:1 and 40:1.

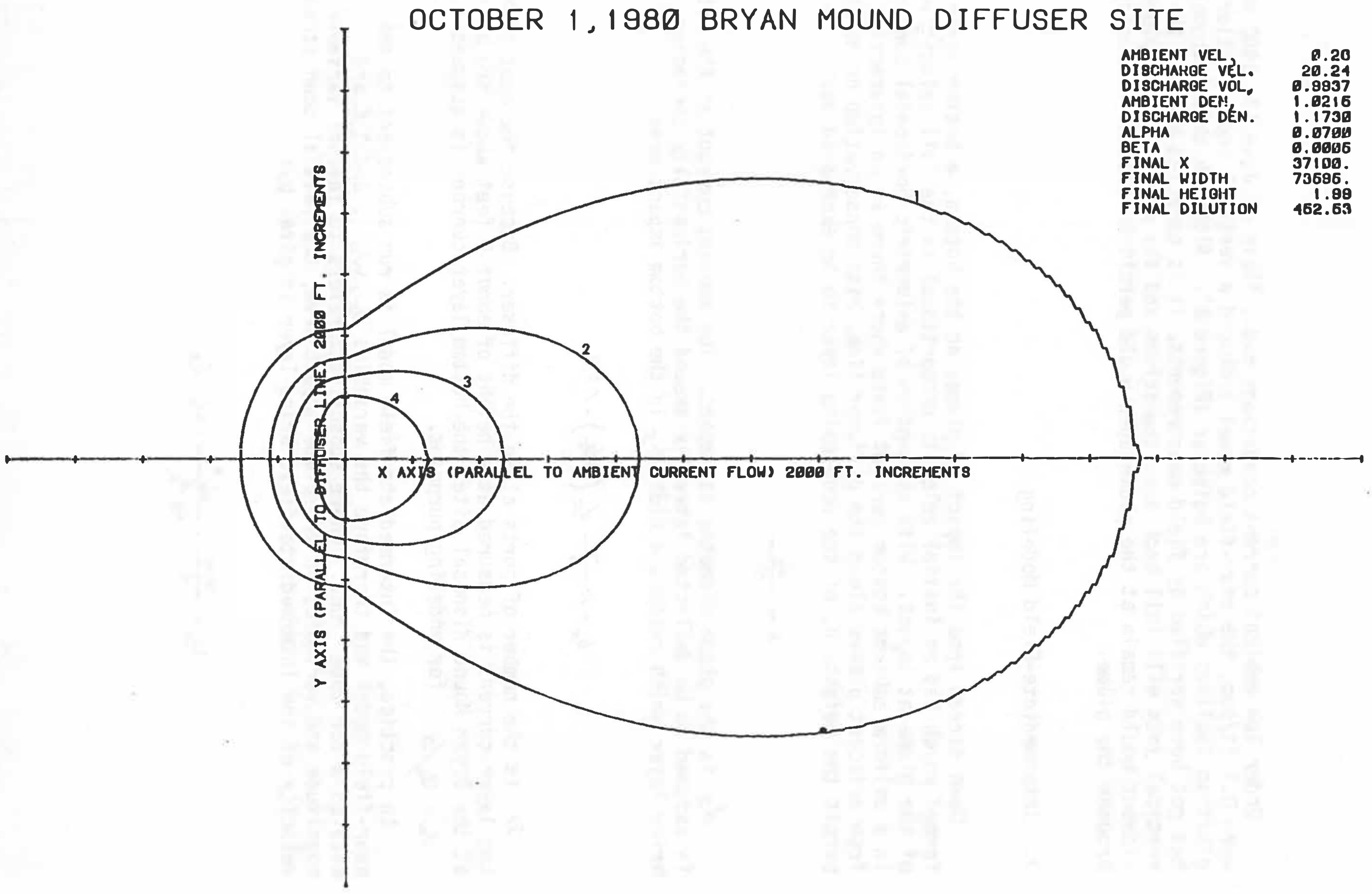


Figure 2. Model estimates of salinity (ppt) above ambient on the bottom at Bryan Mound.

Under low ambient current conditions e.g., those of June 13, 1980 which were 0.1 ft/sec, the near-field model produced a vertical cross section of dilution isolines which are bulbular (Figure 3). Although this phenomenon has not been verified by field measurements, it is expected because the vertical jets will fall back over themselves and the period that a plume element would remain at the plume apex would permit horizontal diffusion to broaden the plume.

3. Intermediate-Field Modeling

Down stream from the impact of plumes on the bottom, a bottom layer is formed which has an initial velocity proportional to the fall velocity W_I, of the plume at impact. With assumption of axiometric horizontal spreading in a uniform ambient bottom current field where there is no interaction from adjacent plumes along the diffuser line, mass conservation principles permit the height, h, of the developing layer to be expressed as:

$$h = \frac{d_I}{4} \tag{5}$$

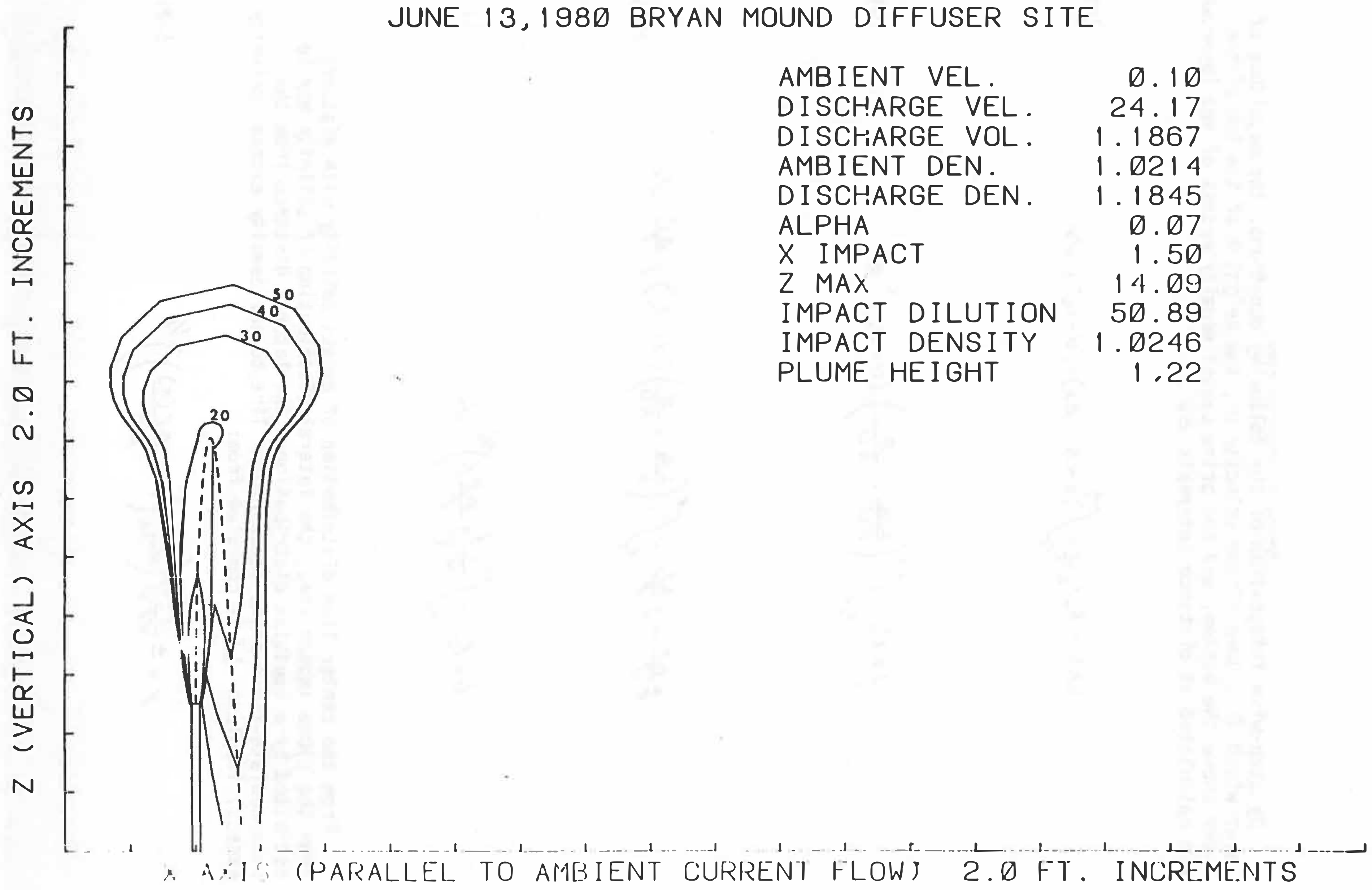
d_I is the plume diameter at impact. The ambient current at the bottom is assumed to be deflected laterally around the horizontally spreading brine layer which reaches a width b_I in the bottom impact area:

$$b_I = n \frac{\pi}{2} d_I \left(\frac{W_I}{U_a'} \right) \cdot 1.74 \tag{6}$$

n is the number of ports along the diffuser. Because the ambient bottom layer current is measured at a height of about 6 feet above the bottom at the Bryan Mound disposal site, the bottom layer current is assumed to be $U_a' = U_a/3$ for modeling purposes.

In practice, the intermediate-field model is run subsequent to the near-field model and therefore the variables S_I, W_o, and $\Delta \rho_I$ are available for model runs. Where subscript I refers to initial variable magnitude and variables in the plume impact area, the initial down stream velocity of the intermediate-field brine layer is given by:

$$U_I = \frac{\pi n}{4} \cdot \frac{d_o^2}{b_I h_I} \cdot W_o \cdot S_I$$



AMBIENT VEL.	0.10
DISCHARGE VEL.	24.17
DISCHARGE VOL.	1.1867
AMBIENT DEN.	1.0214
DISCHARGE DEN.	1.1845
ALPHA	0.07
X IMPACT	1.50
Z MAX	14.09
IMPACT DILUTION	50.89
IMPACT DENSITY	1.0246
PLUME HEIGHT	1.22

Figure 3. Model brine plume trajectory and near field isopleths of dilution 10:1, 20:1, 30:1, 40:1 and 50:1.

By step-wise integration of the following equations, the magnitude of layer width b, down stream velocity U, the height h of the top of the layer above the bottom, and the brine caused density excess of the layer $\Delta\rho$ are calculated at distance intervals Δx.

$$bhU = b_I h_I U_I + \int_{x_I}^{x} (2\alpha h + \beta b)\cdot(U - U_a') \, dx \tag{8}$$

$$U = U_I - \int_{x_I}^{x} \left(\frac{2\alpha}{bU} + \frac{\beta}{hU} \right) (U - U_a')^2 \, dx \tag{9}$$

$$g\frac{\Delta\rho}{\rho} = g\frac{\Delta\rho_I}{\rho} - \int_{x_I}^{x} \left(\frac{2\alpha}{bU} + \frac{\beta}{hU} \right) (U - U_a') \, g\frac{\Delta\rho}{\rho} \, dx \tag{10}$$

$$b = b_I + \int_{x_I}^{x} \frac{1}{U} \left(g\frac{\Delta\rho}{\rho} h \right)^{1/2} dx \tag{11}$$

From the center line distribution of excess salinity with distance x from the plume impact area, the lateral distribution of salinity may be estimated by a Gaussian distribution. the lateral distance from the intermediate-field brine layer center line to any density excess (salinity excess) isopleth $\Delta\rho$ is computed from:

$$y = \pm \frac{b(x)}{\sqrt{2\pi}} \left(\log_e \left(\sqrt{2} \, \frac{\Delta\rho(x)}{\Delta\tilde{\rho}} \right) \right)^{1/2} \tag{12}$$

The vertical entrainment constant, β is set equal to 0.0005 for the model runs. The end of the intermediate-field is reached when the down stream bottom layer plume velocity is 10% above the ambient current or at 2000 feet, the boundary for the far-field model.

The maximum upstream intrusion X_s of the bottom brine layer which is produced by the horizontal momentum imparted to the plume at bottom impact, is estimated by equation 13.

$$\frac{2\pi}{m} U_a' + \frac{1}{X_s} + \sum_{n=1}^{N} \frac{2X_s}{X_s^2 + n^2 \ell^2} = 0 \tag{13}$$

n is the number of diffuser ports, $N = (n-1)/2$, ℓ is the port spacing along the diffuser, and $m = 1.74\,\pi\, d_I W_I$. Since $\ell << X_s$, 13 reduces for approximations to;

$$x_s \simeq -nm/2\pi U_a' \tag{14}$$

In present model applications, the shape of upstream isopleths of salinity excess are estimated by computing ellipses from the relationship;

$$\frac{x^2}{X_s^2} + \frac{4y^2}{b_I^2} = 1 \tag{15}$$

3.1 Results From Intermediate-Field Modeling

Isopleths of excess salinity upstream from the diffuser were drawn by the computer graphics routines and are shown on Figure 2 for the October 1, 1980 case. The connection of the ellipses with intermediate-field downstream isopleths is a little irregular but sufficiently smooth for present modeling purposes.

The intermediate-field isopleths in Figure 2 are drawn beyond the distance considered for intermediate-field processes. Operationally, estimates of the distribution of excess salinity beyond about 2000 feet are produced by the Transient Plume far-field model.

Table 1 lists results from intermediate and near-field modeling on a number of dates which correspond to dates of monitoring cruises to the Bryan Mound brine disposal area. TP model intermediate-field salinity excess calculations are based on empirical equations (based on test data) which have been modified to incorporate variation from the normal brine discharge

Table 1. Near, intermediate and far-field modeling results for the Bryan Mound disposal site with observations from Texas A&M brine plume monitoring cruises.

date	ambient current (cm/sec)	plume rise (ft)	impact distance (ft)	salinity excess at impact (ppt)	measured max. salinity (ppt)	TP model, end of intermediate field excess (ppt)	intermediate-field model estimate (ppt)	observed salinit excess distribut (ppt)
3/22/80	14	12.2	6	4.6	3.6	3.3 at 1721 ft	4.0 at 1800 ft 3.0 at 3300 ft	
3/30/80	25	12.4	11	4.3	3.4	2.5 at 2341 ft	3.0 at 2800 ft 2.0 at 5100 ft	3.0 at 800 ft 2.0 at 2700 ft
3/31/80	16	12.4	7	4.5	5.9	3.1 at 1877 ft	4.0 at 1800 ft 3.0 at 3200 ft	
4/10/80	13	16.5	7.6	3.6	5.5	3.6 at 2408 ft	3.0 at 3200 ft	
5/22/80	9	14.7	4.6	4.3	4.2	4.0 at 1758 ft	4.0 at 2000 ft	4.0 at 2600 ft
6/13/80	3	14.1	1.5	4.3	6.1	4.9 at 1016 ft	4.0 at 2100 ft	5.0 at 1700 ft 4.0 at 3200 ft
7/21/80	11	14.6	7.7	2.3	1.2	2.4 at 2479 ft	2.0 at 2600 ft	
7/30/80	13	17.5	12.2	1.6	1.4	1.9 at 3205 ft	1.0 at 7300 ft	1.0 at 3400 ft
8/01/80	4	21.1	4.8	1.2	2.2	2.5 at 2441 ft	1.0 at 6500 ft	2.0 at 3200 ft 1.0 at 6400 ft
08/02/80	13	17.7	10.6	2.2	3.1	2.4 at 3590 ft	2.0 at 2600 ft	3.0 at 2700 ft 2.0 at 8600 ft
08/26/80	27	15.8	16.3	3.1	3.9	2.3 at 4891 ft	3.0 at 2200 ft 2.0 at 5700 ft	2.0 at 4700 ft
09/10/80	13	13.4	6.4	4.0	4.3	3.2 at 2811 ft	3.0 at 3600 ft	3.0 at 500 ft
10/01/80	8	12.8	3.6	4.5	4.8	3.8 at 2214 ft	4.0 at 2500 ft 3.0 at 4700 ft	4.0 at 4000 ft 3.0 at 6200 ft
10/22/80	15	16.9	10	2.9	4.7	2.8 at 3965 ft	2.0 at 5700 ft	3.0 at 3200 ft 2.0 at 6200 ft
11/06/80	20	16.3	12.2	3.3	3.8	2.7 at 4460	3.0 at 2000 ft 2.0 at 6600 ft	3.0 at 6400 ft 2.0 at 1200 ft
12/29/80	14	14.8	7.2	4.0	6.0	3.6 at 3455 ft	3.0 at 4364 ft	4.0 at 5400 ft 3.0 at 8000 ft
01/28/81	8	13.3	3.7	4.4	5.2	4.1 at 2356 ft	4.0 at 2454 ft	4.0 at 3400 ft 5.0 at 2000 ft

velocity, 25 ft/sec. In computational practice, these calculations may be be used as boundary conditions to initiate the TP far-field model. The boundary conditions estimated by the intermediate-field model may also be used to initiate the far-field model.

4.0 Conclusions

The recently developed near and intermediate-field models produce suitable estimates of excess salinity for the present requirements of the DOE Strategic Petroleum Reserve Development Program. As shown on Table 1, there is good agreement between observed maximum bottom layer excess salinity and estimated salinity excess in the plume impact areas. In addition, comparison of the estimates of salinity excess at the end of the intermediate-field from the Transient Plume model with distribution of salinity excess estimated by the intermediate-field model indicate that the results of the two independent models are compatible. Therefore, the model development goal, develop near and intermediate-field models to augment the modeling capability of the Transient Plume model in the near and intermediate-field areas, has been achieved.

Future modeling requirements may necessitate modifications to the present models. Preliminary model runs in areas where there is a bottom slope have indicated that an upward sloping bottom can have a significant effect on the bottom layer plume spread. It is recommended that research be initiated to include bottom slope in the models. In addition, because the near and intermediate-field models assume no interaction between the individual plume spreads along the bottom, these models are not expected to produce accurate results during the periods when the ambient current is along the line of diffuser ports.

REFERENCES

Adams, E.E., K.D. Stolzenbach and D.R.F. Harleman, 1975. Near and far-field analyses of buoyant surface discharge into large bodies of water. Report No. 205, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, MIT, Cambridge, MA.

NOAA, 1980. Comparison of observed and modeled brine discharges for the Bryan Mound site. Environmental Data and Information Service, U.S. Department of Commerce, Washington, DC.

NOAA, 1981. Brine disposal in the Gulf of Mexico: projected impacts for West Hackberry based on Bryan Mound experience. Environmental Data and Information Service, U.S. Department of Commerce, Washington, DC.

Tong, S.S. and K.D. Stolzenbach, 1979. Submerged discharges of dense effluent. Report No. 243. R.M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, MIT, Cambridge, MA.

Appendix A Computational Procedure

NOAA has implemented the near and intermediate field models on a PDP-11 computer, however, the nature of the model related mathematics permit the use of a limited-storage computational device to run the model. Necessarily it is impractical to run the model for output of great detail without the use of the larger machine but for initial estimates of impact point and center line dilution the limited device will serve. A program in computer language follows.

Near-Field Modeling

diameter of a diffuse port, $D_o = 0.25\ \text{ft} = D(1)$

jet exit velocity, $W_o \simeq 25\ \text{ft/sec} = W(1)$

gravity constant, $G = 32.179\ \text{ft/sec}^2$

ambient current, U_a

ambient density, ρ_a

brine density, ρ_o

height of diffuser, $Z_o \simeq 5\ \text{ft} = Z(1)$

horizontal entrainment constant, $\alpha = 0.07$, ALPHA

vertical entrainment constant, $\beta = 0.0005$, BETA

$$F_j = W_o / SQRT(G * ((\rho_o - \rho_a)/\rho_a) * D_o)$$

```
   DELX = 0.1
   X(1) = 0.0
   DO 10 I = 2,K
   X(I) = X(I-1) + DELX
   A(I) = D(I-1) **2 * SQRT(Ua**2 + W(I-1) **2) *
          (1.0 + 4.0 *ALPHA * ABS(W(I-1) * DELX/
          (Ua * D(I-1)
   B(I) = D(1) **2 * SQRT(Ua **2 + W(1) **2) * W(1) *
          (1.0 - W(1) * X(I)/(Fj **2 * Ua * D(1))
   W(I) = B(I)/A(I)
   D(I) = SQRT(B(I)/(W(I)* SQRT(Ua**2+W(I)**2)))
   Z(I) = Z(I-1) + (W(I) + W(I-1)) * DELX/(2.0 * Ua)
   IF(Z(I).LE. 0.0)  GOTO 20
10 CONTINUE
```

W(I) is the vertical plume velocity at a distance X(I) from the diffuser, Z(I) is the height of the plume and D(I) is the plume diameter.

Compute dilution of brine at impact point.

```
20 CONTINUE
   DILIMP =1.74*SQRT((Ua**2 + W(I)**2)/
      (Ua**2 + W(1)**2))*(D(I)/D(1))**2
```

Compute angle of impact

```
ANGIMP = ATAN(ABS(W(I))/Ua)
```

Compute height of brine layer on the bottom at impact

```
H(1) = D(I)/4.0
```

Compute mass flow from impact of a single plume.

```
Q = (π*D(1)**2/4.0)*W(1)
QIMP=DILIMP*Q*SIN(ANGIMP)
```

Intermediate-Field Modeling

Since the current is measured 6 feet off the bottom, the ambient current of the brine layer on the sea floor is:

```
U = Ua/3.0
```

```
UF = 1.1*Ua
```

N = number of active diffuser port

Compute the initial width of the intermediate-field

```
B(1) = N*QIMP/(2.0*H(1)*U)
```

Compute the plume density at impact point

```
ρ(1) = ρa + (ρI - ρa)/DILIMP
```

Equations 8, 9, 10, and 11 are solved by step-wise integration where Δx of 100 feet may be used with small calculators. Initial values of variables are indicated above.

```
      GPRIME(1) = G*(ρ(1)-ρa)/ρa
      X(1) = 0.0
      DELX = 100.0
      DO 50 I=2,K
      X(I) = X(I-1) + DELX
      ALBETA(I) = 2.0*ALPHA+BETA*(B(I-1)/H(I-1))
      GPRIME(I) = GPRIME(I-1)*(1-ALBETA(I))*
           (U(I-1)-Ua)*DELX/(B(I-1)*U(I-1))
      B(I) = B(I-1) + SQRT(GPRIME(I-1)*H(I-1)*
           DELX/U(I-1))
      U(I) = U(I-1)-(ALBETA(I)*(U(I-1)-Ua)**2*
           DELX)/(B(I-1)*U(I-1))
      H(I) = (B(I-1)*H(I-1)*U(I-1)+ALBETA(I)*
           H(I-1)*(U(I-1)-Ua)*DELX)/(B(I)*U(I))
     IF(U(I).LE.UF) GO TO 70
 50   CONTINUE
 70   CONTINUE
```

$B(I)$ is the intermediate-field plume width, $U(I)$ is the plume speed and $H(I)$ is the plume height. Compute the lateral distance y to any isopleth of salinity.

$$y = \pm \frac{b(x)}{\sqrt{2\pi}} \left(\log_e \left(\sqrt{2}\, \frac{\Delta\rho(x)}{\Delta\tilde{\rho}} \right) \right)^{1/2}$$

$\Delta\tilde{\rho}$ is the brine layer excess density related to a specified salinity, level at the lateral distance y and b is the top-hat layer width and $\Delta\rho$ is the layer density at a distance x from the diffuser.