LOOP MARINE AND ESTUARINE MONITORING PROGRAM, 1978–95

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VOLUME 2: WATER CHEMISTRY

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ABBREVIATIONS USED

ANOVA	Analysis of Variance Modeling
BACI	Before-After, Control-Impact
Barrel of Oil	42 gallons
DIN	dissolved nitrate+nitrite+ammonia
ha	hectares
LDWF	Louisiana Department of Wildlife and Fisheries
mg/l	milligram per liter
NO2	nitrite
NO3	nitrate
NTU	national turbidity units
PDSI	Palmer Drought Severity Index
ppt	parts per thousand (usually referring to salinity in this text)
QA/QC	Quality assurance, quality control
SPM	single-point mooring
SS	suspended solids
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
TP	total Phosphorus
µg at/l	microgram atoms (of an element) per liter

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The data was collected and processed by the Marine Fisheries Division staff of the Louisiana Department of Wildlife and Fisheries. The following Chemistry Laboratory personnel, in particular, were of special assistance: Jerry Merrill, Kitty Henry, Patti Cheng, Raymond Tang, Lesa Orman, Marta Finalet and Marsha Strong.

EXECUTIVE SUMMARY

Introduction

The LOOP facility located off the Louisiana coast is the only Superport in the lower 48 states. The three single-point mooring (SPM) structures connected by pipelines to a platform mounted pumping station are located west of the Mississippi River delta, 30 kilometers (km) southeast of Belle Pass in the Gulf of Mexico, in 36 meters (m) of water, where the offshore depth contours fold landward. Pumping stations offshore and at the land-based Fourchon Booster Station move the off-loaded crude via subsurface pipeline to a storage facility located in the intermediate marsh zone of the northern Barataria Bay watershed (about 3 km east of Galliano, LA).

The proposed construction and use of these facilities in an environmentally sensitive area led to questions about various consequential environmental impacts arising from the following activities: (1) oil storage caverns were created by leaching out a salt dome at Clovelly. The water used to leach the cavern was sent, by pipeline, to the offshore disposal site (brine diffuser). This water therefore bypassed the usual route through the estuary; (2) the brine (average 200 parts per thousand (ppm)) and other leachates were disposed offshore into a major US fishing zone; (3) a pipeline corridor and subsequent activities resulted in direct and indirect wetland losses; (4) subsequent economic activities occurred during and after facility operations; (5) many small and a few large oil spills were reported. A water quality environmental sampling program was established by the State of Louisiana and operated by the Department of Wildlife and Fisheries from 1978 to 1995 to monitor the inshore and offshore area potentially impacted by the project. These are the water chemistry data that are analyzed herein.

The implicit specific objectives of this data analysis were:

(1) to determine if the seasonal and annual data obtained are useful for monitoring impacts;
(2) to determine if adverse or damaging environmental impacts occurred;
(3) to determine the cause of environmental damages or alterations;
(4) to evaluate long-and short-term impacts of the project.

Potential Impact Periods

The analyses were performed to evaluate construction, brine discharge, and oil spill impacts. Therefore the data was divided into portions that pertained to the appropriate impact: before construction, during construction, after construction, before the storage caverns were excavated, during continuous brine disposal, after continuous brine disposal, and when oil spills occurred. The nearly continuous offshore discharge of the excavated brine solution through a pipeline and a diffuser of 26 equally spaced ports began in May 1980, and lasted until December 1982, when discharge became intermittent, and lasted for several weeks at a time (Figure ES-1). Observations at the diffuser documented a maximum vertical height of the brine plume approximately five m off the bottom, and that the thickness was generally one to one and one-half meter off the bottom.

Seventy-eight percent of the brine discharged offshore occurred during 1980-82 when the caverns were being excavated with an average brine salinity of 201 ppt. The period from 1983 to 1994 had an annual release rate of 117 x 10^6 Barrels.

There were 1,882 barrels of oil (135 barrels/yr) spilled from May 1980 through December 1994 of which 95 percent was spilled offshore. In 1984 there were 2,306 pollution incidents involving 10,381 barrels of crude oil in the Gulf Coast, and there were 10,745 incidents involving 470,214 barrels in the US. The average of 135 barrels/yr at the LOOP site is thus equal to 1.3 percent and 0.3 percent of the GOM (Gulf of Mexico) and US amount spilled, respectively. Inshore, eight-seven percent of the oil amount released associated with LOOP operations occurred at the Clovelly storage area.

The Data Base

The LDWF LOOP water chemistry data base is comprised of the following general groups:

(1) Salinity
(2) Chlorophyll
(3) Dissolved Oxygen
(4) Nutrients and Solids

The data were collected at a series of monthly and quarterly sampling stations (about 40 stations) which were sampled from the LOOP Offshore Terminal to the upper portion of the Barataria Bay System (around Lake Salvador). Data were collected routinely from 1978 through 1995. There were also numerous (up to 40) shorter-term stations which were intensively sampled during the active phase of the LOOP construction (1978 through 1984).

The percent data return (number of times a sample depth was visited over the entire data set divided by the number of samples taken that are now in the data set) was greater than 95 percent in most cases. This is excellent performance for a monitoring project of this size.

Statistical Methods

All of the ANOVA and BACI statistical analyses were conducted using the data stations with the longest records (15 years or older; Figures ES- 2 and ES-3). Correlations among sample

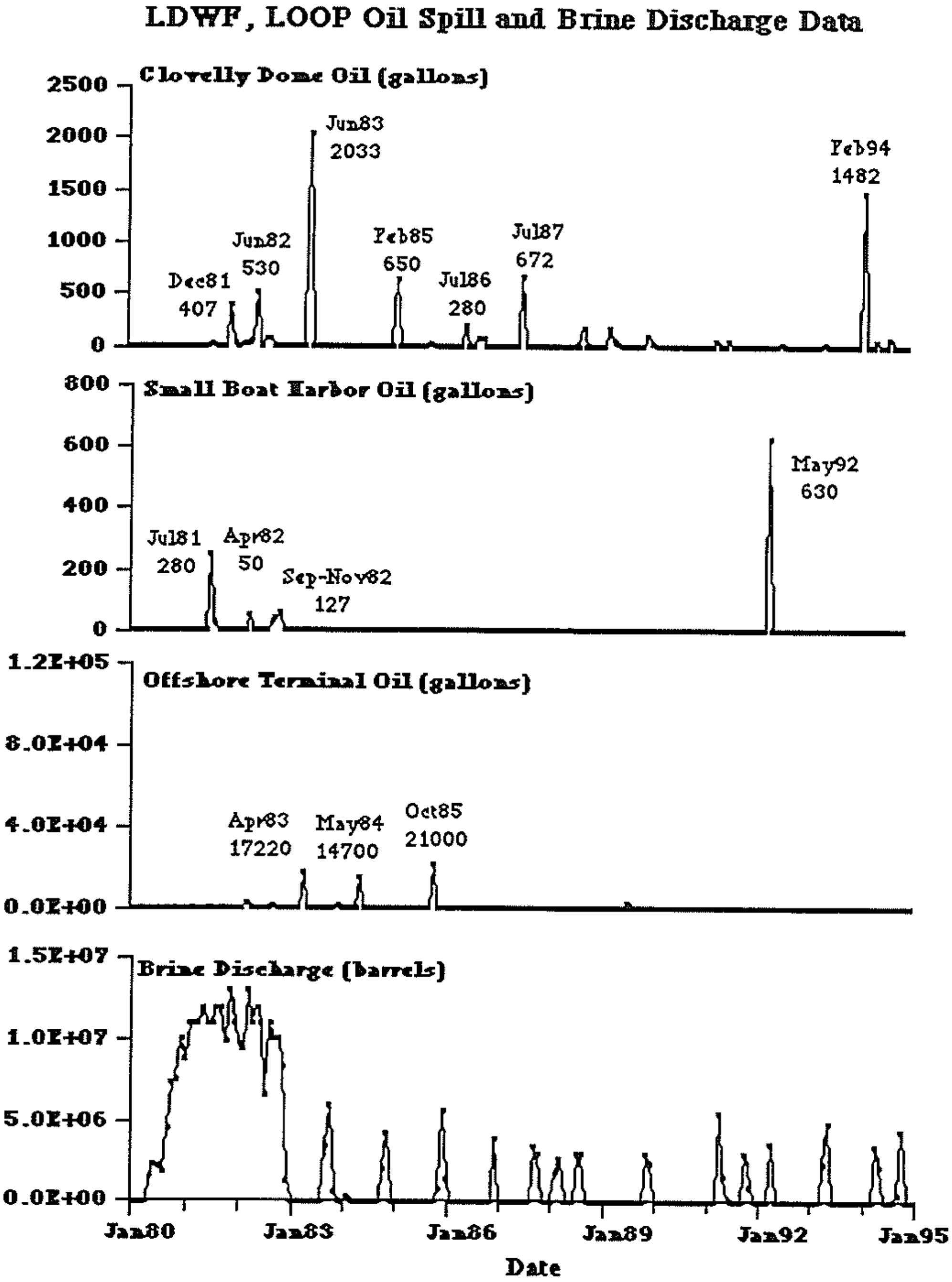

Figure ES-1. Time series plots of (top to bottom) gallons of oil spilled at the Clovelly Dome oil storage area, the Fourchon small boat harbor, the offshore terminal, and the barrels of brine discharged at the offshore diffuser. The dates and amount of oil spilled, for the more noticeable peaks on the plot, are listed.

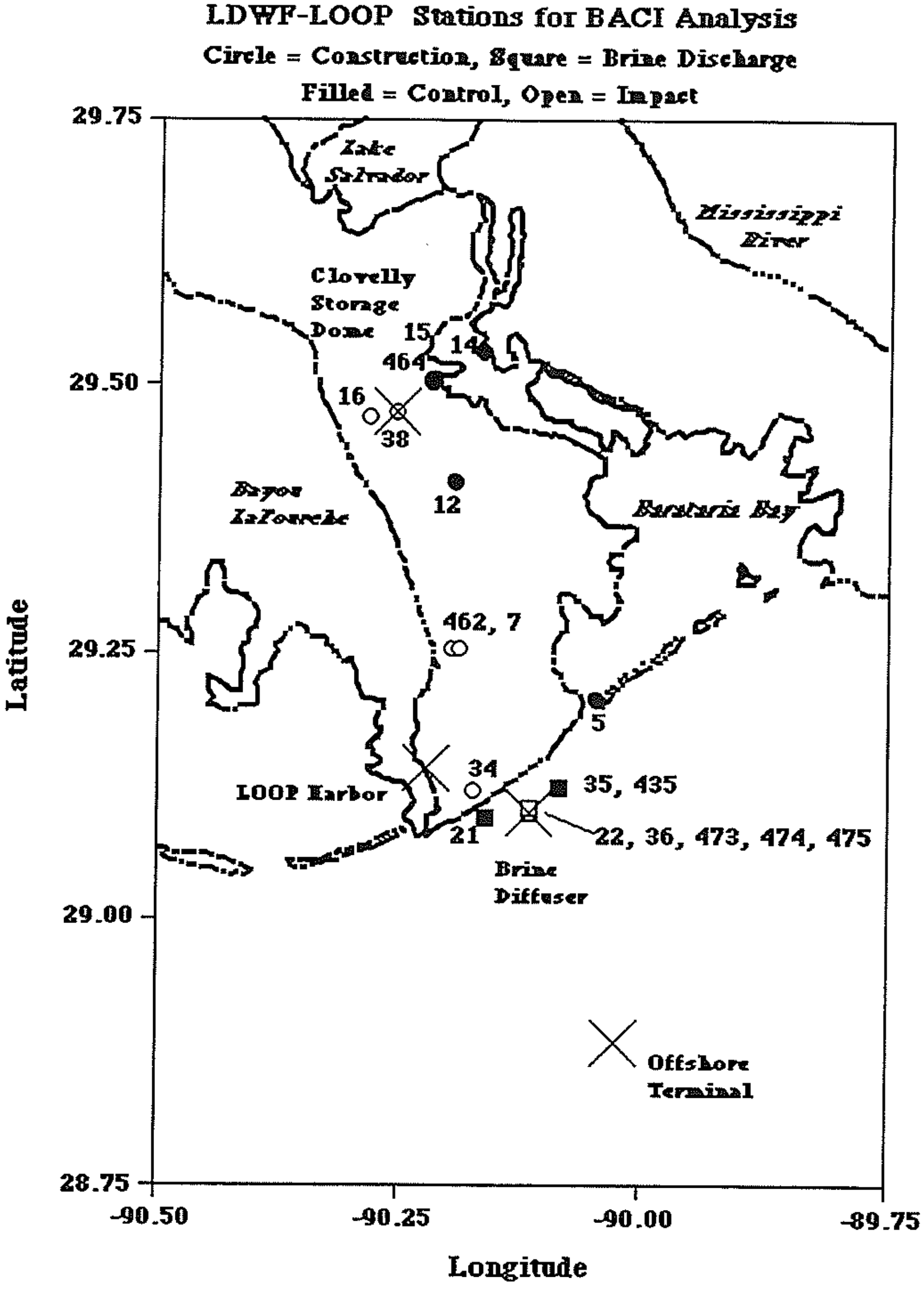

Figure ES-2. LDWF LOOP stations used in the BACI analysis for LOOP construction (circles) and brine discharge (squares). Filled symbols correspond to control stations and open symbols correspond to impact stations.

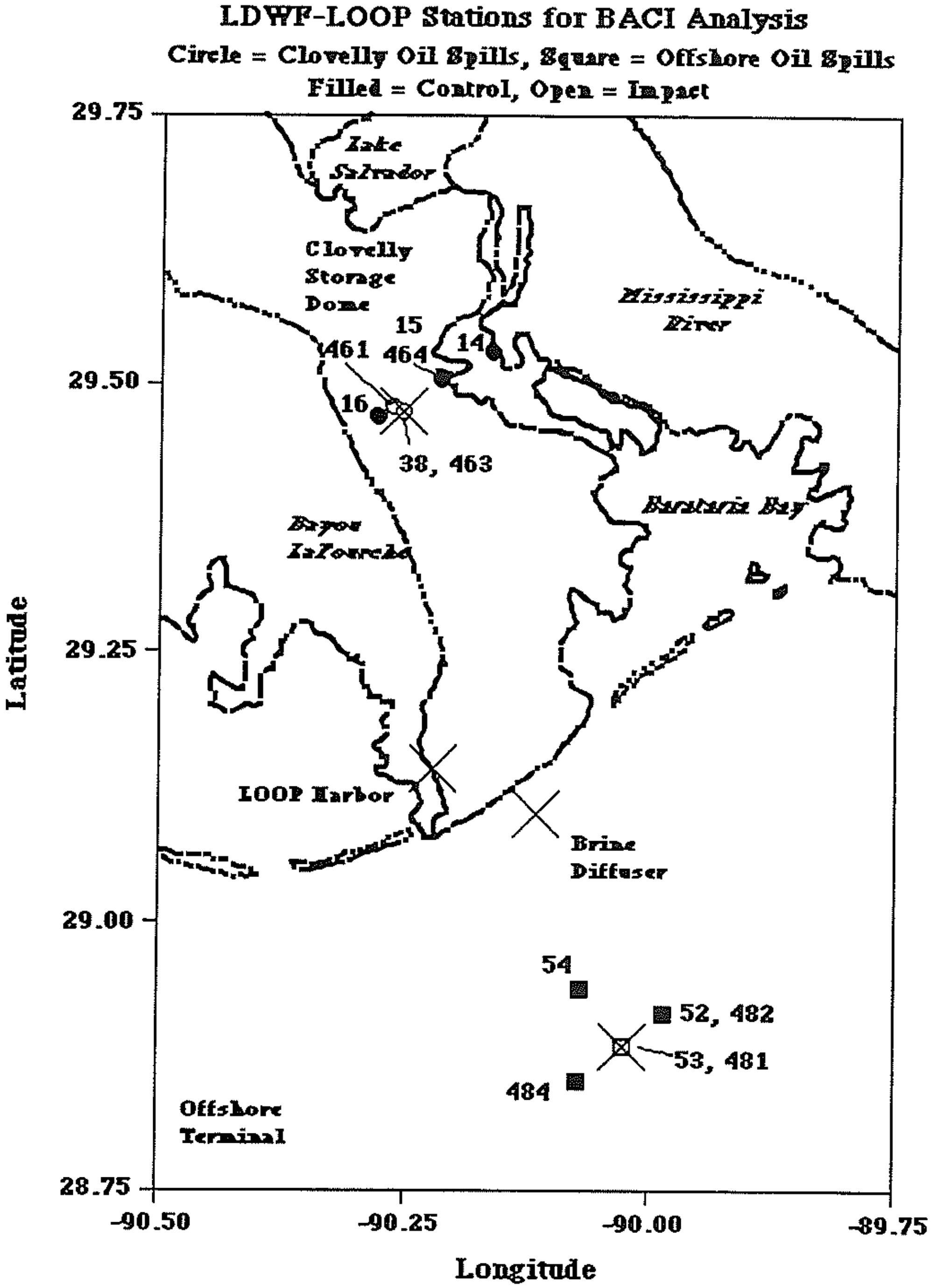

Figure ES-3. LDWF LOOP stations used in the BACI analysis for Clovelly Dome oil spills (circles) and offshore oil spills (squares). Filled symbols correspond to control stations and open symbols correspond to impact stations.

depths for each variable were also computed and more detailed statistical analyses done, including Analysis of Variance Modeling (ANOVA) Regression Analysis, Factor Analysis, and Before-After, Control-Impact (BACI).

Results and Discussion

Correlation Analyses

The results of the correlation between surface and bottom water chemistry variables indicate that the surface and bottom values are well correlated for all variables at the estuarine stations. The offshore stations exhibit weak correlations between surface and bottom for all variables except for sulfate, TKN (total Kjeldahl nitrogen), and TP (total phosphorus).

The results of the factor analysis indicated that the variance in the data can be explained by four or five factors in all cases (Table ES-1). The factors explain about 73 percent of the total variance for the estuarine stations and 60-65 percent of the total variance in the offshore stations. In all cases, the first (and most important factor) was a salinity grouping which explained 20-36 percent of the variation in all cases. The remaining factors were generally comprised of a turbidity factor (turbidity, TSS (total suspended solids), SS (suspended solids), TDS (total dissolved solids)), a nutrient factor (TKN, TP), an oxygen factor, and a chlorophyll factor.

Spatial Patterns

The general spatial patterns can be summarized as follows. Salinity shows an increase (from about 5 ppt to about 30 ppt) from the upper Barataria System to the offshore terminal. Most of the nutrients (ammonia, phosphate, silica, TKN, and TP) show a similar pattern of decreasing values from the upper part of the Barataria system to the offshore terminal. The exception in nitrate-nitrite which is lowest in the mid-portion of the Barataria system and higher in the upper portion of the Barataria system and at the offshore stations. Turbidity and suspended solids have a similar pattern to the nutrients, in that they decrease from the upper portion of the Barataria system to the offshore terminal. In addition, these variables also exhibit reduced variability in the offshore stations. Total dissolved solids and total solids follow the same general pattern as salinity, since they are highly correlated with salinity (the salt is a major component of the solids). Sulfate and Calcium both show increases in magnitude as well as variability from the upper part of the Barataria system to the offshore terminal. Alkalinity has the same value (about 100 milligrams per liter (mg/l)) throughout the whole system, however the offshore stations show reduced variability. Chlorophyll a also shows a decrease from upper Barataria to the offshore platform. Oxygen concentration exhibits a pronounced seasonal variation in the upper portion of the Barataria system, which was much more pronounced than at the offshore stations.

The brine diffuser began operations when bottom water oxygen concentrations began to decline in the general area (because of nutrient loading from the Mississippi River), but that change should not be attributable to the LOOP Superport operations. The salinity, dissolved inorganic nitrogen and chlorophyll a concentrations varied tremendously from year to year. These changes are observed over the whole shelf and are part of a regional phenomenon attributable to changes in the Mississippi River water quality.

Table ES-1. Results of a Factor Analysis of the LOOP water chemistry data. The percentage of the variance explained by each factor as well as the variables which make up the factor pattern are listed. Results are given for surface and bottom for both inshore and offshore stations.

Environment	Factor	Variance Explained	Variables in factor
Inshore, Surface	1	33.1	Salinity ,TDS, Calcium, Sulfate, Alkalinity
	2	13.9	Turbidity, SS, Phosphate, Silica
	3	9.8	TKN, TP
	4	9.2	Chlorophyll, Ammonia
	5	7.1	Oxygen
Inshore, Bottom	1	36.7	Salinity, TDS, Alkalinity, Calcium
	2	10.4	SS, Turbidity
	3	9.6	TKN, TP
	4	8.3	Oxygen
	5	8.0	Ammonia
Offshore, Surface	1	25.6	Salinity, TDS, Sulfate
	2	13.9	Turbidity, Ammonia
	3	9.8	TP, TKN
	4	7.2	Chlorophyll, Oxygen
Offshore, Bottom	1	21.9	Salinity, TDS, Calcium
	2	19.2	Silica, Phosphate, Ammonia, Oxygen
	3	9.5	TKN, TP
	4	8.6	SS, Turbidity
	5	6.7	NO3+NO2

Temporal Patterns

The mean trends for each area (inshore, offshore) were calculated using only the individual station trends that were significant at the 0.05 level. In general, only about a third of the water chemistry variables (there are a total of 16) showed statistically significant and consistent trends.

The monthly surface water chemistry variables which showed statistically significant trends were:

Silica	negative (-0.15 mg l^{-1} y^{-1})	all inshore stations
	negative (-4.07 mg l^{-1} y^{-1})	57 percent offshore stations
Sulfate	negative (-186.5 mg l^{-1} y^{-1})	64 percent inshore stations
	negative (-91.6 mg l^{-1} y^{-1})	all offshore stations
Suspended Solids	negative (-4.07 mg l^{-1} y^{-1})	82 percent inshore stations
	negative (-2.27 mg l^{-1} y^{-1})	all offshore stations
Total Kjeldahl Nitrogen	positive (8.14 µg-at l^{-1} y^{-1})	all inshore stations
	positive (5.00 µg-at l^{-1} y^{-1})	all offshore stations
Total Phosphorus (TP)	positive (0.03 µg-at l^{-1} y^{-1})	91 percent inshore stations
	positive (0.33 µg-at l^{-1} y^{-1})	all offshore stations
Turbidity	negative (-4.21 NTU y^{-1})	all inshore stations
	negative (-0.69 NTU y^{-1})	all offshore stations

The quarterly surface water chemistry variables which showed statistically significant trends were:

Phosphate	negative (-0.34 µg-at l^{-1} y^{-1}	75 percent inshore stations, 3 percent offshore stations
Sulfate	negative (-229.8 mg l^{-1} y^{-1})	all offshore stations, no inshore stations
Suspended Solids	negative (-2.62 mg l^{-1} y^{-1})	all offshore stations no inshore stations

Total Kjeldahl Nitrogen	positive (3.61 μg-at l^{-1} y^{-1})	all offshore stations
	positive (12.54 μg-at l^{-1} y^{-1})	50 percent inshore stations

The monthly bottom water chemistry variables which showed statistically significant trends were:

Alkalinity	positive (0.39 mg l^{-1} y^{-1})	71 percent offshore stations
	negative (0.94 mg l^{-1} y^{-1})	20 percent inshore stations
Nitrate-Nitrite	positive (0.38 mg-at l^{-1} y^{-1})	100 percent offshore stations
	negative (0.22 mg-at l^{-1} y^{-1})	40 percent inshore stations
Oxygen	negative (-0.13 mg l^{-1} y^{-1})	all offshore stations
	negative (-0.06 mg l^{-1} y^{-1})	40 percent inshore stations
Sulfate	negative (-36.7 mg l^{-1} y^{-1})	60 percent offshore stations
	negative (-38.4 mg l^{-1} y^{-1})	all inshore stations
Total Kjeldahl Nitrogen	positive (6.24 μg-at l^{-1} y^{-1})	all inshore stations
	positive (5.04 μg-at l^{-1} y^{-1})	all offshore stations
Total Phosphorus	positive (0.31 μg-at l^{-1} y^{-1})	all inshore stations
	positive (0.42 μg-at l^{-1} y^{-1})	all offshore stations

The quarterly bottom water chemistry variables which showed statistically significant trends at a majority of the stations were:

Silica	negative (0.17 μg-at l^{-1} y^{-1})	75 percent inshore stations
Sulfate	negative (-32.2 mg l^{-1} y^{-1})	25 percent inshore stations
	negative (-210.6 mg l^{-1} y^{-1})	86 percent offshore stations
Total Kjeldahl Nitrogen	positive (5.87 μg-at l^{-1} y^{-1})	all inshore stations

The only variables which showed consistent spatial and temporal trends were Total Kjeldahl nitrogen, total-phosphorus, and sulfate. These three variables exhibited trends at surface and bottom in both the inshore and offshore environment. A total of 20 statistically significant trends were detected in the monthly data. The quarterly data only detected seven statistically significant trends. This suggests that quarterly sampling is not sufficient to detect long-term trends.

BACI Analysis

Construction

The BACI analysis showed no statistically significant impacts that could be correlated with the construction for the variables analyzed.

Brine Discharge

There were some statistically differences before and after (surface ammonia, surface sulfate, surface TKN, surface turbidity, bottom sulfate, bottom TKN, and bottom turbidity). However, the Before-After, Control-Impact interaction was not significant, indicating that these differences were not correlated with the brine discharge for the variables analyzed.

Clovelly Dome Oil Spills

There were two statistically significant impacts that could be correlated with oil spills in the Clovelly Dome area: Surface ammonia and surface turbidity. The surface ammonia decreased from 4.04 μg-at/l (before) to 2.01 μg-at/l (after) for the control classes, and decreased from 4.95 μg-at/l (before) to 4.45 μg-at/l (after) for the impact classes. The surface turbidity decreased from 86.0 NTU (National Turbidity Units; before) to 17.5 NTU (after) for the control classes, and decreased from 93.4 NTU (before) to 10.1 NTU (after) for the impact classes. The bottom turbidity showed a statistically significant interaction without a statistically significant oil covariate term. This indicates that there was some sort of impact which is not correlated with oil spills. The bottom turbidity decreased from 86.0 NTU (before) to 28.1 NTU(after) for the control classes, and decreased from 108.6 NTU (before) to 18.9 NTU (after) for the impact classes. Although these changes were statistically significant they do not appear to be ecologically significant.

Offshore Terminal Oil Spills

There was a statistically significant difference before and after oil spills in surface turbidity, and a statistically significant difference between control and impact stations for bottom turbidity. However, the Before-After, Control-Impact interaction was not significant indicating that these differences were not correlated with the oil discharge for the variables analyzed. Offshore ammonia did have a statistically significant impact that was correlated with oil spills. The surface ammonia decreased from 1.87 μg-at/l (before) to 1.13 μg-at/l (after) for the control classes, and decreased from 1.41 µg-at/l (before) to 1.10 µg-at/l (after) for the impact classes. These changes are statistically significant, but not ecologically significant.

Discussion

Analysis of Brine Discharge

The Louisiana Department of Wildlife and Fisheries documented 32 brine plumes in bottom waters using a bottom sled equipped with dissolved oxygen, temperature and conductivity sensors. These results were used to plot the size of the plume vs. the discharge volume. The result was the observation that there is an increase in plume size with an increase in brine discharge. The intercept at zero discharge was not statistically different from zero. The range of values extended up to around 400 ha for the largest plume studied. Many times the monitoring stations were located out of the brine plume. The monitoring station most likely to detect changes among the four stations closest to the brine diffuser is the West station (no. 475).

The sampling station grid is close enough to detect the plume when it moves in the direction of the sampling station. However, the sampling stations are positioned so that the plume may pass between them. This is a common problem when constructing a sampling design for offshore stations, which has been partially addressed by placing sampling stations around the impact site so that they form an expanding spiral surrounding the impact site at least two times. The area impacted by the plume covers a large area (1600 ha), which is more than is covered by an individual plume on any one day. The plume is constantly changing directions, and therefore the bottom sampling is more likely to both preserve and experience the chronic impacts of fluctuating and stochastic event frequency. Finally, the variation in the plume may compromise sophisticated analytical techniques, including the BACI analyses.

Oil Spills

The total amount of oil reported spilled during the study interval amounted to less than 2,000 barrels (Figure ES-1) and almost all of it was spilled offshore. A recurrence interval analysis (Figure ES-4), using the 17 year long data record of oil spills, predicted that a maximum monthly oil spill between 1,000 and 10,000 barrels will occur once in 50 years. This result compares very well with a predicted return period for an individual spill predicted in the Environmental Impact Statement. That report estimated that a single spill of at least 10,000 barrels would occur once every 24 years (close to that predicted in Figure ES-4). Both the EIS

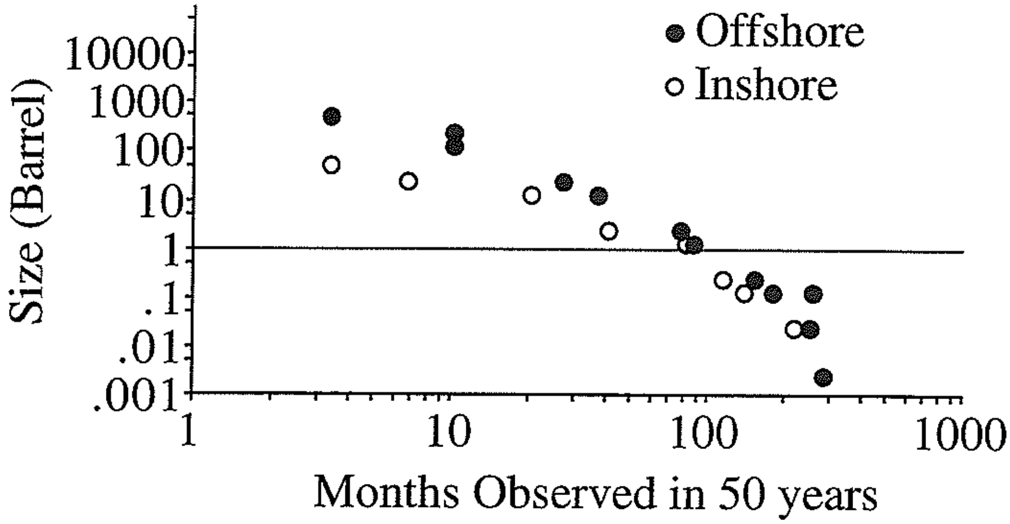

Figure ES-4. The recurrence frequency (calculated using the current oil spill record) of oil spill size for 50 years.

(DOT, USCG 1976) and the more recent Coast Guard study (DOT, USCG 1993) suggest that a larger spill than observed in the first 17 years of operations is possible (up to 240,000 barrels)[1]. That maximum credible spill is 500 times larger than observed to date, but within the predicted recurrence interval for an event of that infrequency (i.e., a large, but rare, spill).

Implications

The data sets we examined indicated that the current monitoring program, as identified in the original environmental management plan, worked (we were able to document spatial and temporal trends and some impacts).

Results from an analysis of the water quality parameters measured in this monitoring program showed limited evidence of extensive changes due to the brine disposal operations or the small (less than 100 barrels) oil spill. The variability introduced by the Mississippi River is a significant complication of the analysis because of its size and proximity to the monitoring stations. A change in the measured parameter values between a before-and-after impact analysis may not be due to the potential impact factor (brine), but actually be the result of long-term

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[1] The following information was added at the request of LOOP LLC. Because of OPA 90's separation of liabilities, the maximum credible accidental discharge for which LOOP itself would be liable is estimated to be 4,600 barrels. For a discussion of separation of liabilities in relation to accidental discharge of oil, see DOT, USCG (1993).

trends or events in environmental factors unrelated to the LOOP operations. The fixed location of the monitoring station network and sampling frequency are often too sparse to detect these impacts. Also, water masses are moving through the sampling area quickly. In other words, if an impact has occurred, it is likely that the water mass moved out of the area before the monthly sampling occurred. This does not preclude the necessity of monitoring (see below).

The bottom sled sampling by the State Department of Wildlife and Fisheries clearly located a brine plume whose position on the bottom moves among the stations, adding variability to the measured parameters, and perhaps compromising the results of the BACI sampling design. The variability in bottom salinity at station 473, for example (Figure 14), probably reflects these movements among and between sampling locations. The BACI analysis cannot, a priori, determine if the plume is over a station or not and a nearby station may be an adequate control station in one month, but an impact station in another month. Fixed control and impact stations cannot, therefore, be assigned.

Water chemistry monitoring measurements are necessary because they serve as ancillary measurements to interpret the background conditions, against which other impacts are measured. Including them in a monitoring program will contribute to the identification of "false positives", such as mis-identifying an increase or decrease as causally related to an oil spill, rather than to seasonal or long-term changes in the Mississippi River. However, experience brings better understanding and the opportunity to improve the existing monitoring network for water quality. It is quite natural that monitoring programs evolve with experience on site and from that gathered by other competent investigators. Federal and state governments have responsibility for the protection of natural resources, and monitoring is recognized as a useful instrument to prevent, minimize and mitigate various impacts, as well as the presumed or suggested impacts.

Oil Spill Size

The maximum "credible oil spill" estimated in the original EIS was 240,000 barrels, which is 127 times larger than that spilled through 1996. It is based on a pre-project spill recurrence interval that is substantiated by experience since 1978. In other words, the recurrence interval graph of the original projections in the EIS and the subsequent events are nearly coincidental. Fortunately the very large spill that was predicted to occur once in a period greater than 50 years has not happened in the first 17 years of operations.

Temporal Scales

The long-term nature of the monitoring effort has numerous invaluable benefits for the State, LOOP, LLC., and the various agencies involved. The LOOP facility is unique to the lower 48 states, and is of unprecedented economic significance in terms of tonnage and strategic economic positioning. It is located, however, directly in the middle of the finest and largest continental shelf fishing zones in the US and the infrastructure is aging. Improving our understanding of the long-term variations in continental shelf ecosystems (water column to benthos; zooplankton to fish) can only help renewable and non-renewable natural resource users manage this environment together, where necessary, and with informed judgment. The data sets we examined are useful for the intent of the monitoring program as identified in the original environmental management plan, but some readjustments are desirable based on the experience of the last 20 years. The Superport is still operating and all significant impacts have probably not occurred (the unrealized large oil spill).

Relationship of Water Chemistry to Biologic Components

Integrating an analysis of the water chemistry data and biological data sets on an ongoing basis will provide a useful perspective that is greater than analysis of each in isolation of the other. For example, the benthic community is the logical analytical subject for competent investigation of impacts near the brine disposal, and for oil spills (past and present). The benthic community is subject to a probable enhancement around the diffuser, if results from other studies are appropriate for this site. The immediate area of the brine plume (about 4 km^2 for a plume greater than 1 ppt) sweeps over an area of 16 km^2. The plume orientation is very responsive to currents, and the plume may move between the stations without detection by the present sampling grid. The benthic community is exposed to chronic conditions and some animals will remain for weeks and months within this brine plume shadow. The benthic data were not analyzed as part of this analysis, but there are several competent benthic ecologists who could check on the implications of the results in this report, including: the possibility of a brine plume "halo" or disturbance area around the brine diffuser; oil spills; the presence of brine or oil spill chemical markers in sediments and appearing coincidentally in time or space with changes in the water chemistry, nekton and plankton; and, detection of long-term trends in the benthic data that can be explained by the regional influences of the Mississippi River.

The water column turns over in a matter of days because of currents. The area is accumulating sediments, so dated cores might be useful to investigate the halo, if present, around the plume, and to retrospectively determine impacts near the brine diffuser. The sediments are also the best depository of information on the effects (if any) of a large oil spill (of presently experienced spill or future larger sized spill).

Technical Information for the LOOP Marine and Estuarine Monitoring Program Revision

Background

Experience brings better understanding and the opportunity to improve the existing monitoring network for water quality. It is quite natural that monitoring programs evolve with experience on site and from that gathered by other competent investigators. Federal and state governments have responsibility for the protection of natural resources, and monitoring is recognized as a useful instrument to prevent, minimize and mitigate various impacts, as well as the presumed or suggested impacts.

Station Locations

Eighty-seven percent of the inshore oil spills occurred at the Clovelly salt dome site (station no. 38). There are 24 stations with record lengths greater than ten years, but only one at Clovelly (station no. 38). Station 39 is within 1.5 km of station no. 38 (WSW), station no. 16 is within 2.5 km (WSW) but is isolated by a hurricane protection levee, and station no. 464 is within 4 km (NE). There are too few monitoring stations close to station no. 38.

The station locations offshore are set in a cross shaped pattern around the diffuser, but the plume appears to move between many of these. Some sort of adaptive sampling scheme (network of vertical profiles, towed vehicle) to collect data on the three-dimensional structure of the brine plume must be implemented if major brine discharges are to be detected in a systematic manner.

Background Conditions or 'False Positives'

The environmental conditions inshore and offshore are variable from year-to-year and month-to-month and from station to station. If water quality parameters are included in a monitoring program, then it should be possible to identify seasonal or long-term trends that complicate analyses, and be mis-identified as impacts.

Baseline Conditions for a LOOP Related Mega-oil Spill

Current speeds throughout the region suggest that water masses are replaced in days, not weeks or months. Events like a large (yet unobserved) oil spill similar to that predicted in the original environmental management plans, must be sampled within weeks of the event to establish reasonable baseline conditions against which to measure impacts. If the region were homogenous than they are and not near the Mississippi River, etc., then baseline conditions might be more safely predicted from less frequent sampling (quarterly). A second, related issue, is that a mega-oil spill may yet occur whose surface water and oil will be spread far beyond the

LOOP facility vicinity, and probably spread westward (assuming that is the dominant current direction). However, below the surface, there may be effects spreading in different directions from that in the surface layer.

Other Efforts

This monitoring program is an exceptionally valuable opportunity for science and management interests. Exploring ways to open up these efforts on an ongoing basis to provide data for other scientific efforts, and to publish analyses of the data arising from them would be useful.

Recommendations

We have made suggestions and recommendations regarding possible revisions to the LOOP Estuarine/Marine Monitoring Program based upon the analysis of the LOOP water chemistry data (Task 2). These recommendations are designed both to improve the sampling program and to reduce effort either by eliminating variables and/or sample stations, whenever possible.

Overall Recommendations

- The monitoring program will be improved simply by extending the data base; in other words, the monitoring should be continued.
- We recommend more frequent sampling be anticipated when a large spill occurs (sampling at more than four times/month) at the long-term monitoring stations.

Specific Sampling Recommendations

- We recommend sampling all present water quality variables except for Alkalinity, Calcium, Sulfate, Total Dissolved Solids, and Total Solids.
- We recommend monthly sampling of the water chemistry.
- We recommend surface sampling inshore, surface and bottom sampling offshore with occasional mid-depth samples to define important water column structure (e.g., oxygen minimum layer, halocline).
- The stations need to be distributed to cover the LOOP pipeline route, as well as other LOOP potential impact areas with sufficient impact and control stations in each area.

Other Recommendations

- The analysis of the water chemistry data should be integrated with the biological data sets, particularly with the benthic community analyses.
- The data from the bottom sled (brine) could be improved by sampling sufficiently in the field to go in all directions until a baseline value is found in all directions, and the salinity contours closed.
- The area is accumulating sediments, so dated cores might be useful to investigate the halo, if present, around the plume and to retrospectively determine impacts near the brine diffuser.
- It would be useful to explore ways to open up these efforts to serious scientific efforts and to publish analyses of the data arising from them.

DATA ANALYSIS
OF THE LOOP MARINE AND ESTUARINE MONITORING PROGRAM, 1978–95

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Louisiana Department of Wildlife and Fisheries

INTRODUCTION

The Louisiana Offshore Oil Port (LOOP) facility located off the Louisiana coast, is the only Superport in the lower 48 states. It was built, and is maintained, by a consortium of large US oil companies called LOOP, LLC., a private corporation owned by Shell Oil Company, Texaco Inc., Ashland Inc., Murphy Oil Corporation, and Marathon Pipeline company. LOOP, Inc. accepted the Federal and state licenses on August 1, 1977 (the US Department of Transportation and the Louisiana Offshore Terminal Authority (LOTA) licenses were jointly issued in January 1977). Its principal economic benefits arise from reducing crude oil transportation costs by as much as $1.50 per barrel when traveling the roughly 7,000 km long voyage between the Middle East to the US in large crude carriers (up to 250,000 deadweight (dwt). The three single-point mooring (SPM) structures connected by pipelines to a platform mounted pumping station are located west of the Mississippi River delta, 30 km southeast of Belle Pass in the Gulf of Mexico, in 36 m of water, where the offshore depth contours fold landward. Pumping stations offshore and at the land-based Fourchon Booster station move the off loaded crude via several subsurface pipelines to a storage facility located in the intermediate marsh zone of the Barataria Bay watershed (about three km east of Galliano, Louisiana). The crude is stored in eight caverns excavated from the Clovelly salt dome. The termination area was designed to be near a pipeline distribution system then serving 30 percent of the total US refining capacity. By 1983 the facility had a capacity to off load 1.4 million barrels/day from 200 ships/yr (Brossard 1984). The total movement of oil into the US in 1987 by sea was 6.3 million barrels/day (Kennish 1997, p 100), implying that the designed capacity of the LOOP facility represents a potential 22 percent of the annual transport of oil into the US. The first off loading of oil was on 5 May 1981 (1.5 million barrels of Saudi Light).

The proposed construction and use of these facilities in an environmentally sensitive area led to questions about various consequential environmental impacts, found elsewhere (Boesch and Rabalais 1987; Rabalais et al. 1991; Kennish 1997) arising from the following activities: (1) Oil storage caverns were created by leaching out a salt dome at Clovelly. The water used to leach the cavern was sent, by pipeline, to the offshore disposal site (brine diffuser). This water therefore bypassed the usual route through the estuary; (2) The brine (average 200 ppt) and other leachates were disposed offshore into a major US fishing zone; (3) A pipeline corridor and subsequent activities resulted in direct and indirect wetland losses, (4) subsequently economic activities during and after facility operations; (5) many small and a few large oil spills. An environmental monitoring program (EMP) to monitor the inshore and offshore area potentially impacted by the project was developed under mandate of the Superport Environmental Protection Plan (revised 1977) a regulation of the State of Louisiana implementing the Offshore

Terminal Act. Components of the monitoring program include: water chemistry, physical hydrography, brine discharge, zooplankton/ichthyoplankton, demersal nekton, benthos, and sediment quality. The Louisiana Department of Wildlife and Fisheries collected the data related to these components from 1978 to 1995. This report is the water chemistry component in a series of five reports that analyze the impacts of LOOP construction, operation, and maintenance on the estuarine/marine (inshore/offshore) environment.

OBJECTIVES

The objectives of this analysis are directly related to the objectives of the LOOP LLC Environmental Management Plan (EMP, section 3.1, page 8, March 1986), which are:

(1) to obtain seasonal environmental and ecological data so that conditions existing during operation can be related to historical baseline conditions;
(2) to detect during the operation of the project any adverse alterations or damages to the environment so that corrective action can be taken as soon as possible;
(3) to obtain sufficient data to determine the cause of environmental damages or alterations so that responsibility can be properly placed; and
(4) to provide information in order to evaluate long- and short-term impacts of the project.

The general objectives of this analysis are to evaluate the water quality data to determine if these are useful to meet these EMP objectives. The implicit specific objectives (using the water chemistry data only) are:

(1) to determine if the seasonal and annual data obtained thus far are useful for the purposes of monitoring impacts;
(2) to determine if adverse or damaging environmental impacts occurred;
(3) to determine the cause of environmental damages or alterations;
(4) to evaluate long-and short-term impacts of the project.

STUDY AREA DESCRIPTION

The LOOP facility is located near the terminus of the Mississippi River, which is one of the ten largest rivers in the world in terms of water discharge, length and sediment yield. The salinity regime, turbidity and nutrient concentrations at the brine discharge site are therefore strongly influenced by daily, monthly and annual changes in the river. This variability adds significant complexity to statistical analyses designed to detect change, and must be considered when evaluating the results. Several aspects of this variability are discussed here to frame the subsequent discussions about the interpretation of the impacts of brine releases and oil spills.

The average monthly discharge of the Mississippi River at Tarbert Landing, Louisiana. and an index of drought severity (the Palmer drought index) from 1980 to 1996 are shown in Figure 1. The maximum monthly discharge rate was six times the minimum rate, and there was a distinct seasonal cycle, but it was a cycle that was not symmetrical from year to year. The lowest flows occurred in the winter 1980, fall 1987, and summer 1988. The highest peak discharge months were in 1980, 1983-1986, 1989-1991 and in 1993-4. Moderate drought years occurred in 1982, 1987, and 1988 and 1990. Very moist years occurred in 1980, 1983, 1985, 1988, and 1991 - 1993.

Nutrients in the Mississippi River are often several orders of magnitude higher than the average concentration in the waters of the Gulf of Mexico that mix and dilute the river water. These nutrient concentrations also vary from year to year. Nitrate, an important nutrient limiting phytoplankton growth, has been increasing this century (Turner et al. 1991, 1994), whereas silicate has been decreasing (Figure 2). Silicate is required for diatom growth, and becomes limiting to coastal phytoplankton communities when it is lower than 1 µg at/l (=1 µ mole), or the DIN:Si atomic ratio (dissolved inorganic nitrogen and silicate) approaches 1:1 (DIN = $NO_3+NO_2+NH_4$). When diatoms, an important part of the coastal food web, are grazed by zooplankton, the fecal pellets sink to the bottom waters, and oxygen is consumed during the subsequent respiration (Rabalais et al. 1996; Sen Gupta et al. 1996). Thus, changes in the nutrients in the Mississippi River may affect the coastal nutrient chemistry and subsequent ecological events at the LOOP facility location. Separating out the effect of these external forcing functions from the effects of brine or oil is a significant challenge for statisticians.

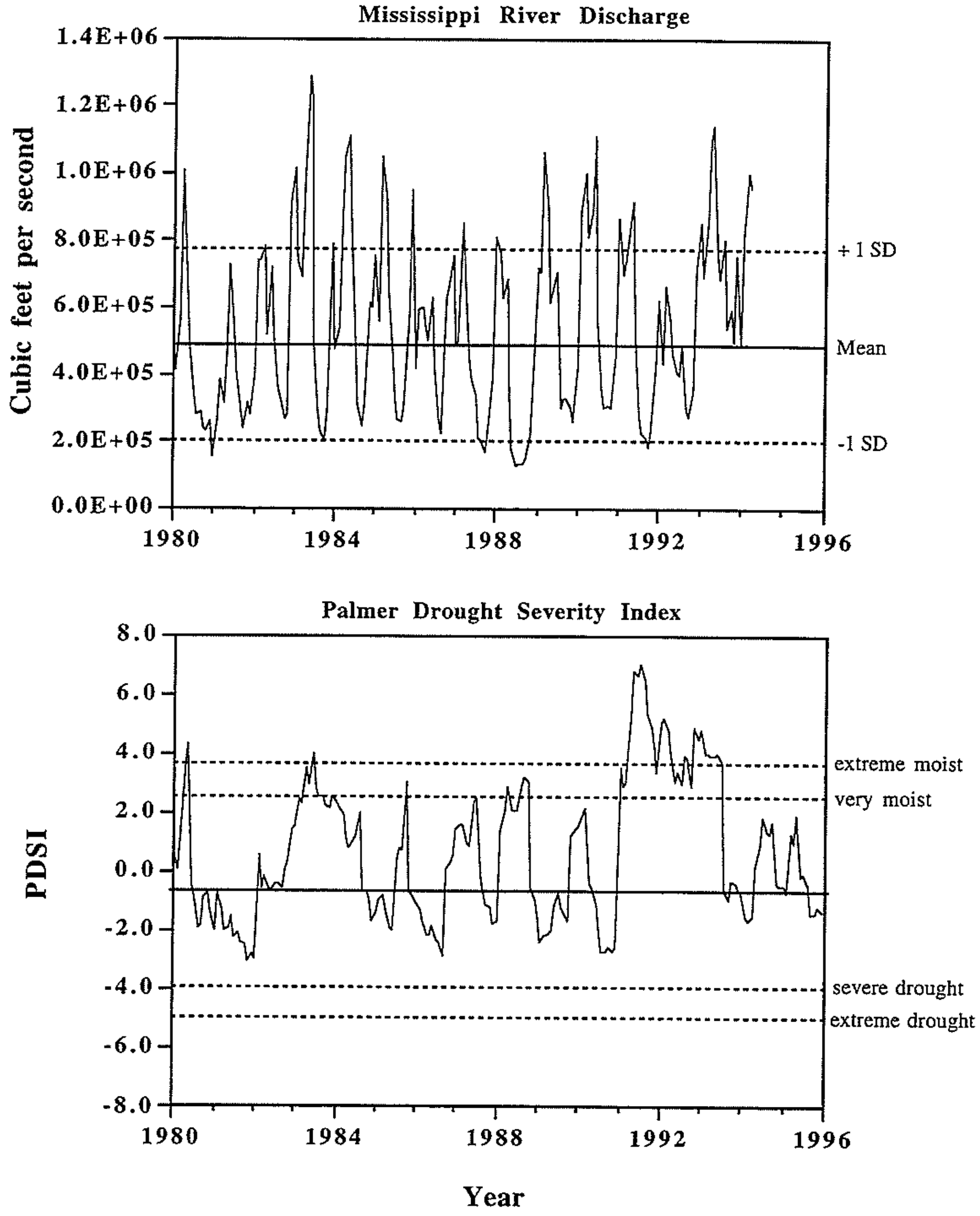


Figure 1. The average monthly discharge of the Mississippi River at Tarbert Landing, Louisiana. from 1980 to 1996. The dashed horizontal line indicates ±1 Standard Deviation of the mean. The Palmer Drought Severity Index (PDSI) is in the bottom panel. The PDSI is a relative index of water supply commonly use by climatologists. The dashed horizontal lines indicate high water supply (very moist, extreme moist) or low water supply (severe drought, extreme drought) levels.

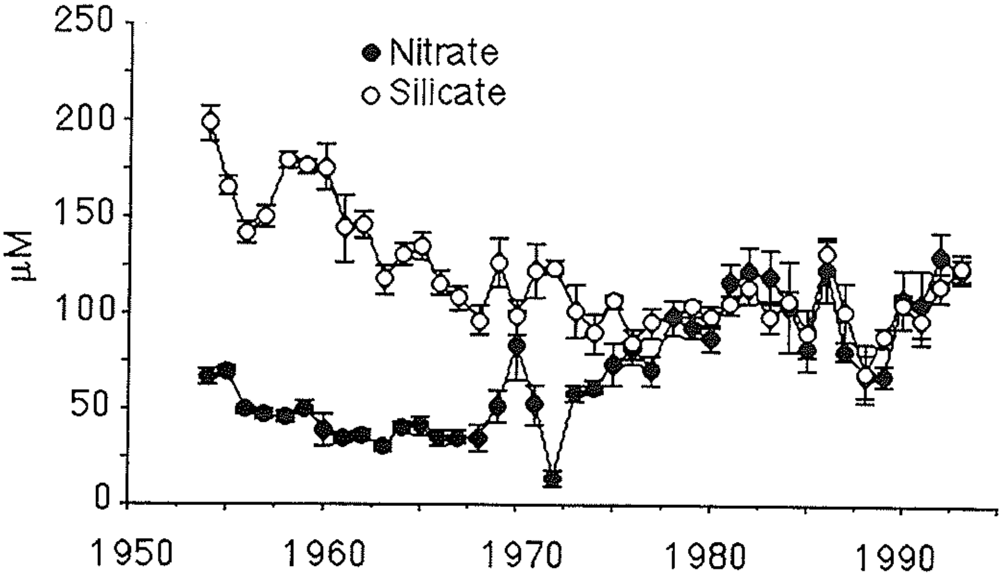


Figure 2. The average annual concentration (± 1 Standard Error) of nitrate and silicate in the Mississippi River at New Orleans. Note the uncoupled relationship between the two variables before 1980 and the coherent changes after 1980 (from Rabalais et al. 1996).

METHODS

The Data Base

Data Base Description

The LDWF LOOP water chemistry data base is comprised of the following general measurement groups:

(1) Salinity
(2) Chlorophyll a
(3) Dissolved Oxygen
(4) Nutrients and Solids

A listing of the variables measured (and the units) is presented in Table 1. The data were collected at a series of monthly and quarterly sampling stations (about 40 stations) which were sampled from the LOOP Offshore Terminal to the upper portion of the Barataria Bay System (near Lake Salvador). Data were collected routinely from 1978 through 1995. In addition to the long-term stations, there are numerous (up to 40) shorter-term stations which were intensively sampled during the active phase of the LOOP construction (1978 through 1984). Appendix F presents a plot showing the number of months of data collected each year from 1978 through 1995. The location (latitude and longitude), the total number of samples, the start and end year of sampling, the total years of record, the number of samples per year, and the depths sampled for each station is presented in Tables 2 and 3. Table 2 summarizes the monthly stations and Table 3 summarizes the quarterly stations. The long term (those with 15 or more years of data) monthly stations are plotted in Figure 3, and the long term quarterly stations are plotted in Figure 4. The number of months of data, for all water chemistry stations, for each year, is listed in Appendix A. Figure 5 shows the time history of the sampling effort (stations sampled per year and total months of data collected per year). The extensive sampling during the construction phase (~1979-1984) is quite evident, followed by continuous, routine sampling after about 1984.

Data Transfer and QA/QC Checks

The LDWF supplied LSU with the data in a SAS data library which contained the data from 1978 through 1995 as separate files. Creation of the final data base for analysis and checks for data quality was accomplished in Task 1, and are summarized here. Figure 6 presents an outline of the basic steps used in the data base creation and QA/QC checks.

Table 1. Listing of variables on the LDWF LOOP water chemistry data set. Listed, for each variable, is the variable name, a description of the variable, and the units of measurement.

Variable Name	Description	Units
STATION	Sample Station	
YEAR	Year	
SDEPTH	Station Depth	m
DEPTH1	Surface Sample Depth	m
DEPTH2	Mid-depth Sample Depth	m
DEPTH3	Bottom Sample Depth	m
SAL1	Surface Salinity	ppt
SAL2	Mid-depth Salinity	ppt
SAL3	Bottom Salinity	ppt
OXYGEN1	Surface oxygen	mg/l
OXYGEN2	Mid-depth oxygen	mg/l
OXYGEN3	Bottom oxygen	mg/l
TURBID1	Surface Turbidity	NTU
TURBID2	Mid-depth Turbidity	NTU
TURBID3	Bottom Turbidity	NTU
TDS1	Surface Total Dissolved Solids	mg/l
TDS2	Mid-depth Total Dissolved Solids	mg/l
TDS3	Bottom Total Dissolved Solids	mg/l
SS1	Surface Suspended Solids	mg/l
SS2	Mid-depth Suspended Solids	mg/l
SS3	Bottom Suspended Solids	mg/l
TS1	Surface Total Solids	mg/l
TS2	Mid-depth Total Solids	mg/l
TS3	Bottom Total Solids	mg/l
CHLOR_A1	Surface Chlorophyll-a	mg/m^3
CHLOR_A2	Mid-depth Chlorophyll-a	mg/m^3
CHLOR_A3	Bottom Chlorophyll-a	mg/m3
CL1	Surface Chlorinity	ppt
CL2	Mid-depth Chlorinity	ppt
CL3	Bottom Chlorinity	ppt
ALK1	Surface Alkalinity	mg/l
ALK2	Mid-depth Alkalinity	mg/l
ALK3	Bottom Alkalinity	mg/l
SULFATE1	Surface Sulfate	mg/l
SULFATE2	Mid-depth Sulfate	mg/l
SULFATE3	Bottom Sulfate	mg/l
AMMONIA1	Surface Ammonia	µg-at/l
AMMONIA2	Mid-depth Ammonia	µg-at/l
AMMONIA3	Bottom Ammonia	µg-at/l
CALCIUM1	Surface Calcium	mg/l
CALCIUM2	Mid-depth Calcium	mg/l
CALCIUM3	Bottom Calcium	mg/l
PHOSPHA1	Surface Phosphate	µg-at/l
PHOSPHA2	Mid-depth Phosphate	µg-at/l
T_PHOS1	Surface Total Phosphorus	µg-at/l
T_PHOS2	Mid-depth Total Phosphorus	µg-at/l
T_PHOS3	Bottom Total Phosphorus	µg-at/l
SILICA1	Surface Silicate	mg/l
SILICA2	Mid-depth Silicate	mg/l
SILICA3	Bottom Silicate	mg/l
NO3NO2_1	Surface Nitrate/nitrite	µg-at/l
NO3NO2_2	Mid-depth Nitrate/nitrite	µg-at/l
NO3_NO2_3	Bottom Nitrate/nitrite	µg-at/l
TKN1	Surface Total Nitrogen	µg-at/l
TKN2	Mid-depth Total Nitrogen	µg-at/l
TKN3	Bottom Total Nitrogen	µg-at/l

Table 2. Monthly sampling station summary. Listed, for each station is the station ID, the location (latitude and longitude), the total number of samples, the starting and ending years of sampling, the average number of samples per year, and the depths sampled (S = Surface, M = Mid-depth, and B = Bottom). **B** indicates that chlorophyll a was collected at the surface, and all other variables were collected at the bottom. The following variables were measured: alkalinity, ammonia, calcium, chlorophyll a, nitrate-nitrite, oxygen, phosphate, salinity, Silica, Suspended solids, sulfate, total dissolved solids, total Kjeldahl nitrogen, total solids, turbidity, and total phosphorus. The stations are sorted by series length.

Station	Latitude	Longitude	Samples	Start	End	Years	Samples/year	Depths
5	29.2058	90.0456	211	1978	1995	17	12	S, B
7	29.2550	90.1894	211	1978	1995	17	12	S
14	29.5297	90.1647	206	1978	1995	17	12	S
15	29.5036	90.2161	207	1978	1995	17	12	S
18	29.6594	90.2144	201	1978	1995	17	12	S, B
21	29.0950	90.1608	200	1978	1995	17	12	S, B
22	29.1044	90.1131	198	1978	1995	17	12	S, B
12	29.4094	90.1936	142	1978	1994	16	9	S
13	29.4233	90.1567	185	1978	1994	16	12	S
34	29.1206	90.1728	198	1979	1995	16	12	S
35	29.1228	90.0833	186	1979	1995	16	12	S, B
36	29.1000	90.1150	187	1979	1995	16	12	S, B
16	29.4694	90.2814	88	1978	1993	15	6	S
37	29.1417	90.2211	188	1980	1995	15	13	S, B
38	29.4744	90.2550	188	1980	1995	15	13	S, B
52	28.9133	89.9847	153	1980	1995	15	10	S, M, B
53	28.8850	90.0250	159	1980	1995	15	11	S, M, B
54	28.9367	90.0686	155	1980	1995	15	10	S, M, B
502	29.0972	90.1114	163	1981	1995	14	12	S, M, B
55	28.8633	90.0253	151	1982	1995	13	12	S, M, B
535	29.1228	90.0833	132	1982	1995	13	10	S, M, B
704	28.9961	90.0831	127	1984	1995	11	12	S, M, B
706	28.9417	90.0694	140	1984	1995	11	13	S, M, B
708	28.8842	90.0250	136	1984	1995	11	12	S, M, B
39	29.4731	90.2697	116	1985	1995	10	12	S
1	29.4197	89.9469	76	1978	1985	7	11	S
2	29.2894	89.9303	76	1978	1985	7	11	S
3	29.2717	89.9328	75	1978	1985	7	11	S
4	29.1833	89.9000	65	1978	1985	7	9	S, B
11	29.3347	90.2383	41	1978	1983	5	8	S
507	29.0894	90.1022	55	1981	1986	5	11	S, M, B
6	29.2103	90.1050	46	1978	1982	4	12	S
17	29.6658	90.1622	44	1978	1982	4	11	S
19	29.6908	90.2208	43	1978	1982	4	11	S
31	29.1239	90.1389	41	1978	1982	4	10	S
9	29.2700	90.0322	45	1978	1981	3	15	S
32	29.2256	90.2022	34	1979	1982	3	11	S
33	29.1481	90.2025	35	1979	1982	3	12	S
40	29.4072	90.1864	42	1988	1991	3	14	S
500	29.1039	90.1183	25	1981	1983	2	13	S, M, B
501	29.0964	90.1183	24	1981	1983	2	12	S, M, B
505	29.0956	90.0861	24	1981	1983	2	12	S, M, B
506	29.0872	90.1178	25	1981	1983	2	13	S, M, B

Table 3. Quarterly sampling station summary. Listed, for each station is the station ID, the location (latitude and longitude), the total number of samples, the starting and ending years of sampling, the average number of samples per year, and the depths sampled (S = Surface, M = Mid-depth, and B = Bottom). **B** indicates that chlorophyll a was collected at the surface, and all other variables were collected at the bottom. The following variables were measured: alkalinity, ammonia, calcium, chlorophyll a, nitrate+nitrite, oxygen, phosphate, salinity, silica, Suspended solids, sulfate, total dissolved solids, total Kjeldahl nitrogen, total solids, turbidity, and total phosphorus. The stations are sorted by series length.

Station	Latitude	Longitude	Samples	Start	End	Years	Samples/year	Depths
407	29.2550	90.1894	65	1979	1995	16	4	S, B
435	29.1228	90.0833	65	1979	1995	16	4	S, M, B
462	29.2547	90.1961	65	1979	1995	16	4	S, B
463	29.4756	90.2553	65	1979	1995	16	4	S, B
464	29.5019	90.2175	65	1979	1995	16	4	S, B
473	29.1003	90.1133	65	1979	1995	16	4	S, B
474	29.0978	90.1147	64	1979	1995	16	4	S, M, B
475	29.1003	90.1167	64	1979	1995	16	4	S, M, B
481	28.8850	90.0250	62	1979	1995	16	4	S, M, B
482	28.9133	89.9847	62	1979	1995	16	4	S, M, B
461	29.4781	90.2647	62	1980	1995	15	4	S, B
484	28.8511	90.0717	60	1980	1995	15	4	S, M, B
422	29.1044	90.1131	18	1979	1983	4	5	S, B
468	29.0997	90.1217	17	1979	1983	4	4	S, B
469	29.0964	90.1267	17	1979	1983	4	4	S, B
470	29.0906	90.1231	17	1979	1983	4	4	S, B
471	29.0872	90.1161	17	1979	1983	4	4	S, B
472	29.0967	90.1108	17	1979	1983	4	4	S, B
476	29.1031	90.1153	17	1979	1983	4	4	S, B
24	29.6922	90.4675	15	1978	1981	3	5	S
25	29.8300	90.6219	15	1978	1981	3	5	S
26	29.8319	90.6347	15	1978	1981	3	5	S
27	29.8531	90.6308	15	1978	1981	3	5	S
28	29.9300	90.7472	15	1978	1981	3	5	S
29	29.9136	90.7983	15	1978	1981	3	5	S
30	29.9711	90.8692	15	1978	1981	3	5	S
467	29.1047	90.1292	13	1979	1982	3	4	S, B
483	29.7658	90.6339	7	1980	1983	3	2	B
485	28.8661	90.0153	14	1980	1983	3	5	S, B
486	28.8792	90.0025	14	1980	1983	3	5	S, B
434	29.1206	90.1728	10	1979	1981	2	5	B
460	29.1297	90.1458	10	1979	1981	2	5	B
466	29.7739	90.6294	10	1979	1981	2	5	B
477	29.0358	90.0967	8	1979	1981	2	4	S, B
479	28.9367	90.0686	8	1979	1981	2	4	S, B
480	28.9361	90.0597	8	1979	1981	2	4	S, B
20	29.6983	90.1775	2	1978	1978	1	2	S
23	29.1550	90.0950	1	1978	1978	1	1	S
50	28.8089	90.0764	4	1978	1979	1	4	S, B
51	28.9450	90.0308	3	1979	1979	1	3	S, B
408			2	1995	1995	1	2	S, B
410			2	1995	1995	1	2	S, B
419	29.6908	90.2208	1	1979	1979	1	1	B
465	29.7783	90.6283	3	1979	1980	1	3	B
478	29.0358	90.0867	7	1980	1981	1	7	S, B
487	29.0903	90.1056	5	1982	1983	1	5	S, B

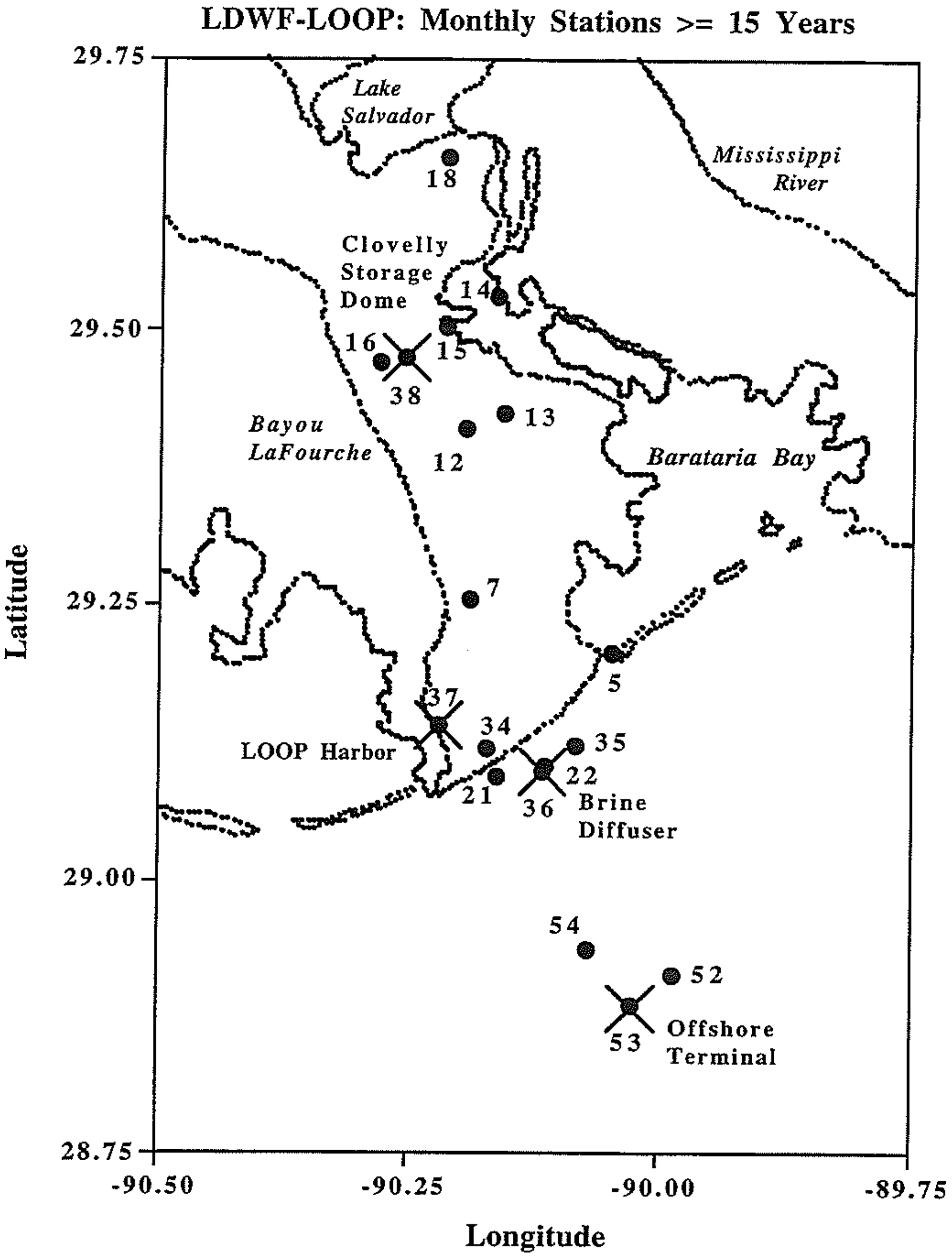


Figure 3. Location map showing monthly stations with long term data sets (greater than 15 years), the site of the Clovelly Storage Dome, the brine diffuser site, and the LOOP Terminal.

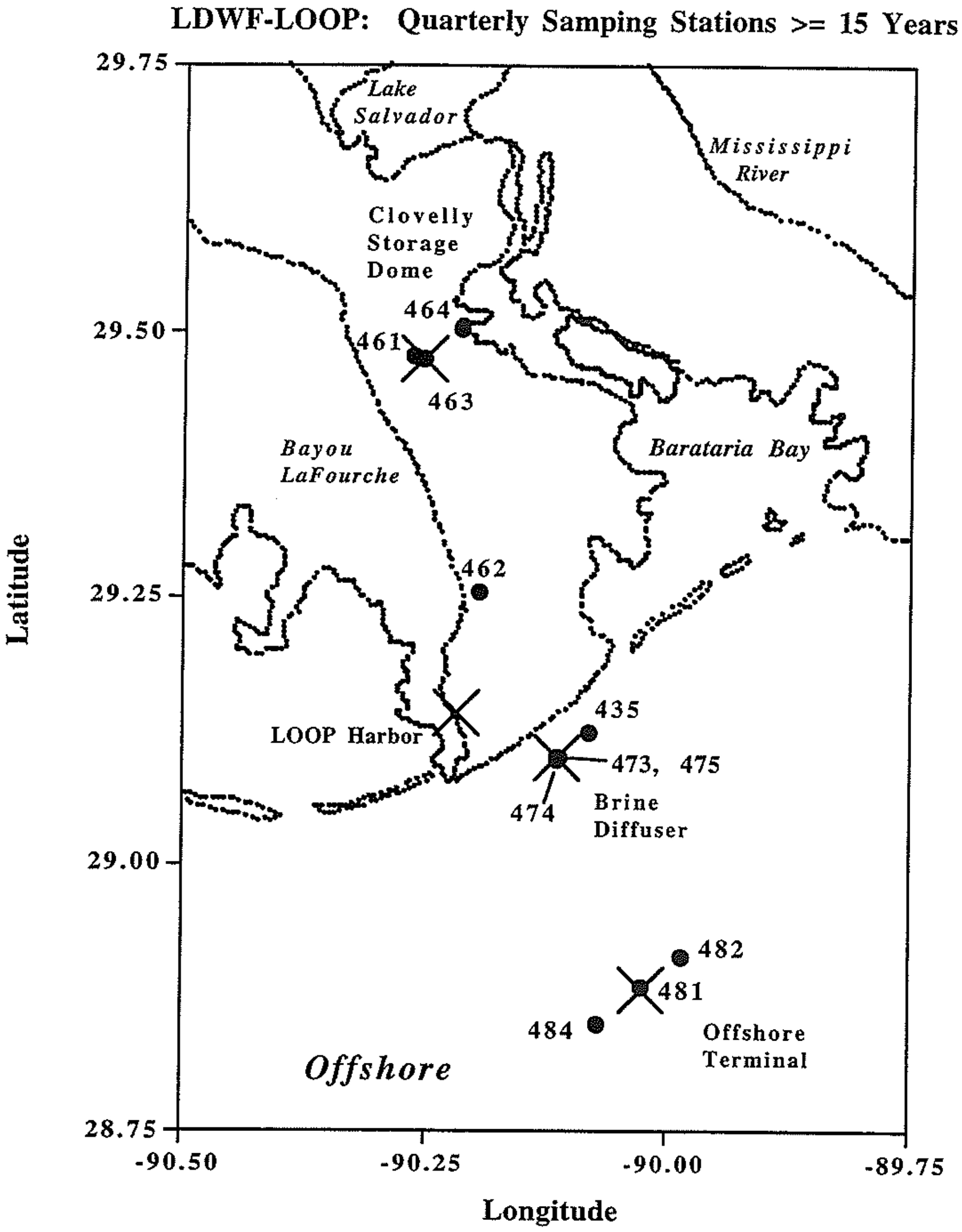


Figure 4. Location map showing quarterly stations with long term data sets (greater than 15 years), the site of the Clovelly Storage Dome, the brine diffuser site, and the LOOP Terminal.

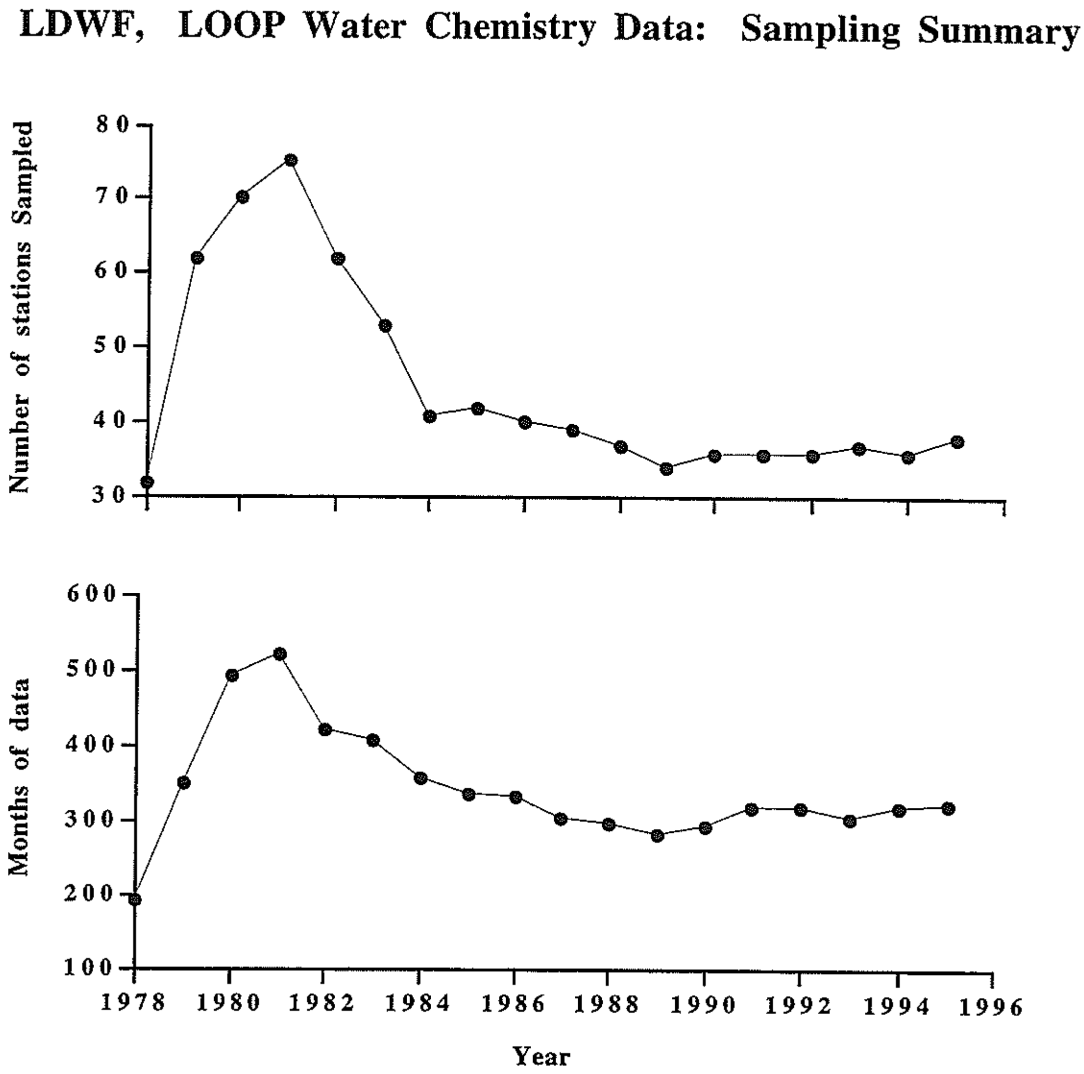


Figure 5. Sampling summary for the LDWF LOOP Water stations. The top panel shows the number of stations sampled each year, and the bottom panel shows the number of months of data collected each year. The data cover the period from 1978 through 1995.

The data inventory and QA/QC analysis (Task 1) consisted of the following:

(1) Data Inventories
    - Total Observations in data set
    - Total Observations by variable
    - Total Observations by station
    - Total Observations by year
    - Total Observations by variable, station, year combinations

(2) Descriptive Statistics (Mean, Standard Deviation, Minimum, Maximum)
    - For the entire data set.
    - For each variable
    - For each station
    - For variables and station by year

(3) QA/QC Information
    - Lists of potential outliers
    - Percent Data return for each variable
    - Plots of data distribution
        - Histograms
        - Stem and Leaf
        - Cumulative distribution
    - Data Distribution Tests
        - Skewness
        - Kurtosis
        - Test for Normality

The percent data return was calculated by dividing the number of times a sample depth was visited over the entire data set by the number of samples taken that are now in the data set. The percent data return for all variables is very high, being greater than 95 percent in most cases (the mean is 97 percent). This is excellent performance for a monitoring project of this size. An outlier list was created based upon a review of the data distribution along with discussions with experts in the field regarding what is believed to be the maximum reasonable values for the water chemistry variables. The number of outliers is quite small, being less than 0.5 percent in half of the cases. The outliers were not removed from the data set, but only identified. The percent data return and outlier list are presented in Appendix B.

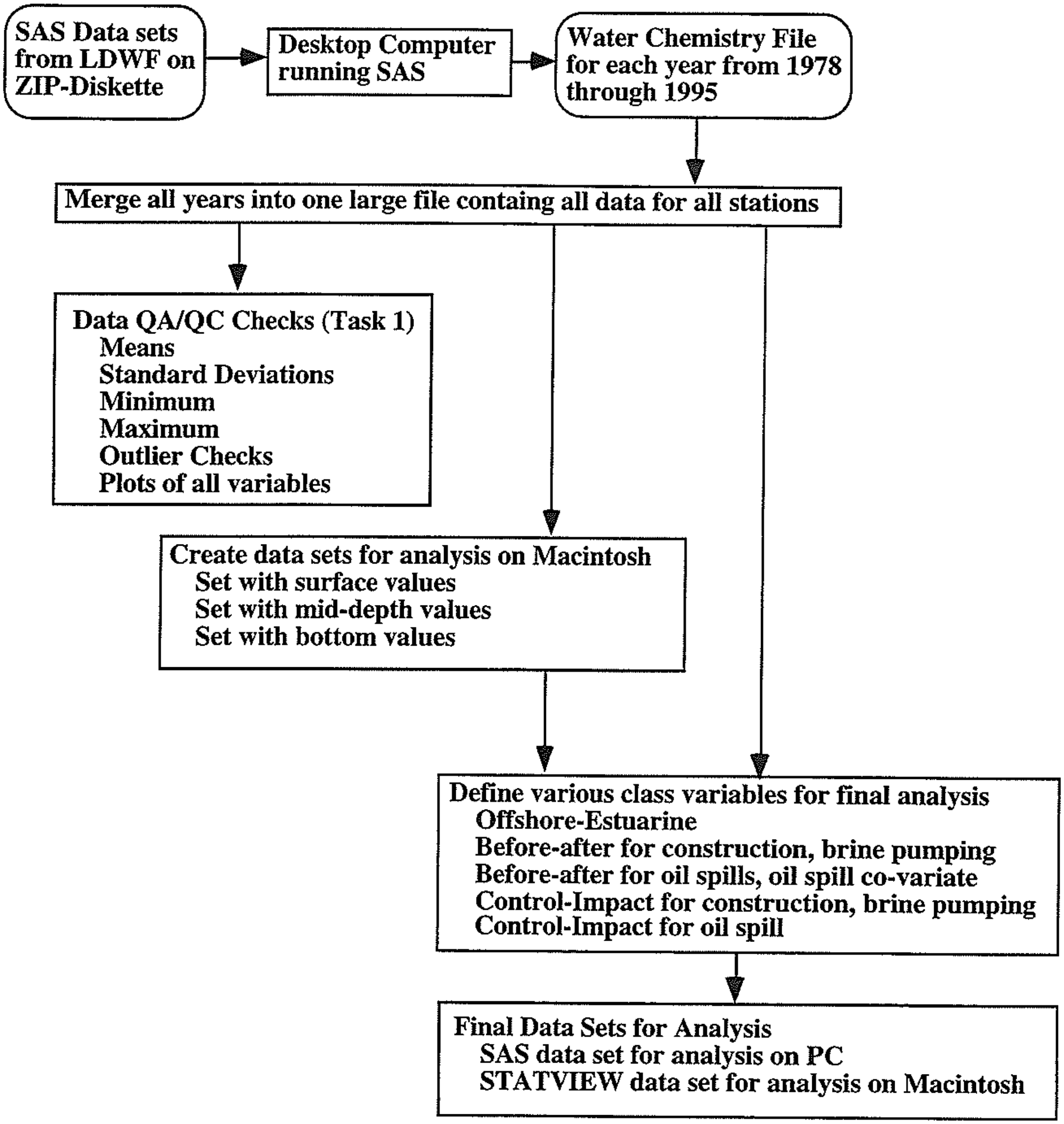


Figure 6. Outline of process used to merge data sets from LDWF into final data set for analysis. During merging the following sets of stations were combined since they had different station numbers but the same locations: stations 419 and 19 combined and numbered as 19, stations 422 and 22 combined and numbered as 22, and stations 407 and 7 combined and numbered as 7.

Data Collection

Field Sampling

All sampling trips followed a standard procedure, in order to ensure uniformity of data collection and to maximize efficiency. The following general sequence was used:

(1) Upon arrival at a station, all forward motion of the boat was allowed to stop.

(2) Environmental data were collected and recorded on a data sheet.

Air temperature
Wind Speed
Wind Direction
Cloud Cover
Wave Height
Secchi Depth

(3) Hydrographic profiles were collected using a Guildline/Rosette sampler multi-bottle array system for the offshore stations and a Hydrolab Surveyor II and Kemmerer sample for the inshore stations.

(4) The discrete water chemistry samples were collected. Dissolved oxygen was collected in a 250 ml glass bottle, salinity was collected in a 250 ml plastic bottle, nutrients were collected in 500 ml plastic bottles, offshore chlorophyll a was collected in 4.5 liter plastic bottle; the inshore chlorophyll a sample was collected in 1 liter plastic bottle. The samples were secured using the following guidelines:

Dissolved Oxygen: fixed according to Winkler titration method
Salinity: Cool to 4°C. in 500 ml bottle
Alkalinity: Cool to 4°C. in 500 ml bottle
Calcium: Cool to 4°C. in 500 ml bottle
Sulfate: Cool to 4°C. in 500 ml bottle
Turbidity: Cool to 4°C. in 500 ml bottle
Total Solids: Cool to 4°C. in 500 ml bottle
Nutrients: Cool to 4°C in 500 ml bottle
Chlorophyll: store in dark, filtered as soon as possible.

(5) The samples were returned to LDWF for chemical analysis.

Laboratory Analysis

The data were analyzed in the LDWF Chemistry laboratory using standard methods, as outlined below:

Dissolved Oxygen:	Azide modification of the Winkler Method APHHA (1985), Method 421B
Salinity:	Electrical Conductivity APHHA (1985), Method 210A
Alkalinity:	Potentiometric Titration to pre-selected pH APHHA (1985), Method 403
Calcium:	EDTA Titration method APHHA (1985), Method 311C
Sulfate:	Turbidimetric Method APHHA (1985), Method 426C
Turbidity:	Nephelometric Method APHHA (1985), Method 214A
Total Solids:	Dried at 103-105°C APHHA (1985), Method 209A
Ammonia:	Technicon Industrial Method Method 154-71 W
Nitrate-Nitrite:	Technicon Industrial Method Method 100-70 WB
Phosphate:	Technicon Industrial Method Method 155-71 W
Silica:	Technicon Industrial Method Method 186-72 WB
Total Phosphate:	EPA Ultra micro Semi-automated Method Method
Total Kjeldahl Nitrogen:	EPA Ultra micro Semi-automated Method Method
Chlorophyll:	Spectrophotometric Determination Strickland and Parsons (1972) Method IV.3.I

Potential Impact Periods

The analyses were performed to evaluate construction, brine discharge, and oil spill impacts. The data were therefore divided into portions that pertained to the appropriate impact: before construction, during construction, after construction, before the storage caverns were excavated, during continuous brine disposal, after continuous brine disposal, and when oil spills occurred.

Construction

Construction of the LOOP and LOCAP pipelines began in early 1979, and early 1980, respectively (Visser et al. 1996). Completion and backfilling of he LOOP pipeline was completed by mid-1980 and on the LOCAP pipeline later in 1980 (Visser et al., 1996).

Brine discharge

The nearly continuous offshore discharge of the excavated brine solution ran through a pipeline and a diffuser of 26 equally spaced ports began in May 1980 and lasted until December 1982, when discharge became intermittent, and lasting for several weeks at a time (Figure 7). An analysis of a new salt cavern was excavated in 1995 was not included in this analysis. Observations at the diffuser documented that the maximum vertical height of the brine plume was approximately 5 m off of the bottom, and that the thickness was generally 1 to 1.5 m off the bottom. The brine discharge volume and salinity data were used to estimate the potential area that might have been impacted by the brine. The discharge volume was converted to metric units and multiplied by the salt content to obtain the amount of salt (grams) being discharged at the diffuser. It was then assumed that this salt would be mixed into the bottom third of the 10 m deep water column. The resulting salinity increase above ambient was then calculated. The results were expressed as the surface area (square kilometers) that would have a 1 ppt increase above ambient.

The total amount of brine discharge, the brine salinity, and the potential area impacted are also shown in Figure 7. The minimum and maximum values for the individual daily discharge reported during the interval was 1,065 barrels/d (6 June 1991) and 602,696 barrels/d (4 March 1988), respectively. The range of values for salinity reported during the interval was 52.8 ppt (8 May 1980) and 368 ppt (10 October 1983) (Anon 1995).

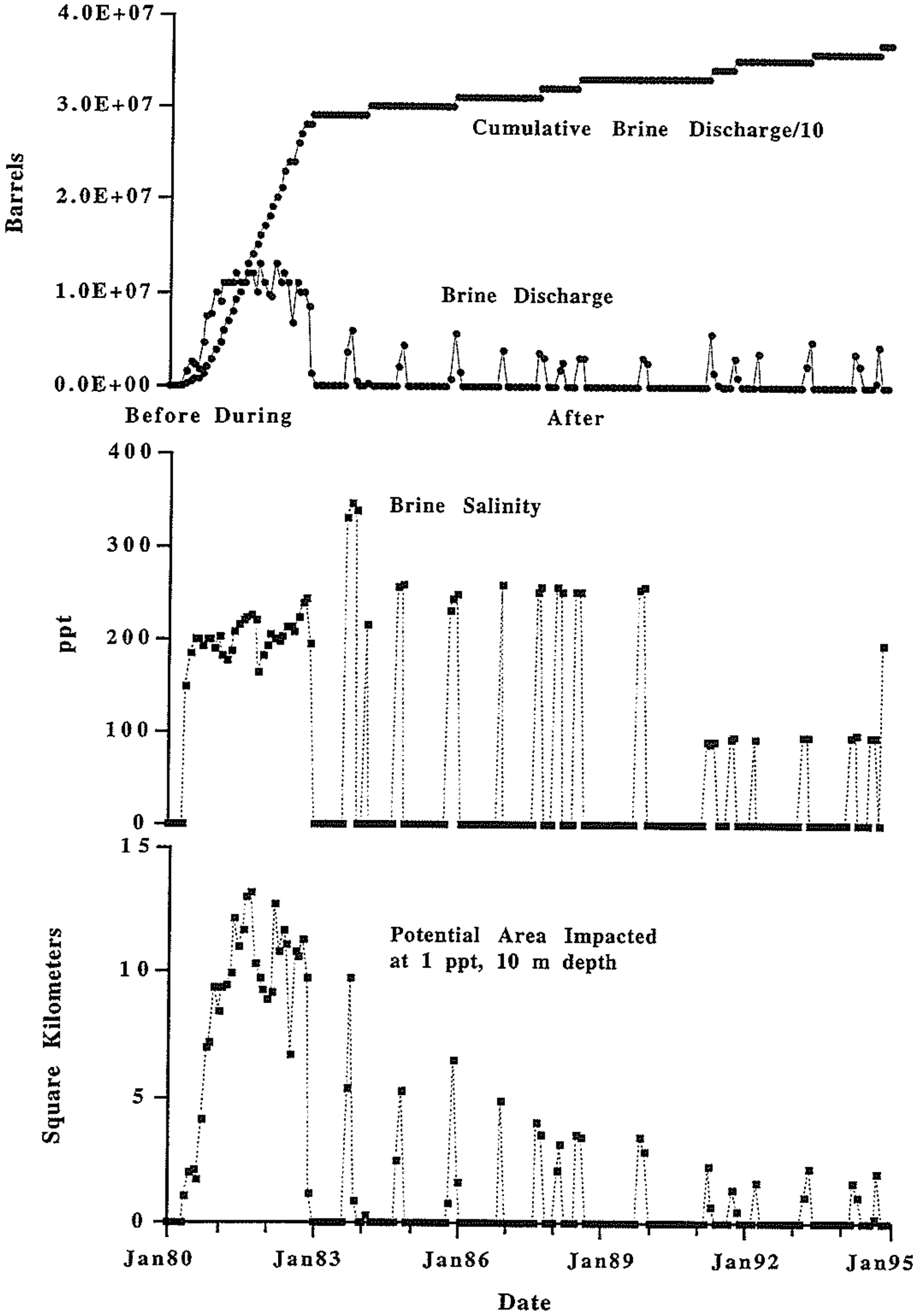


Figure 7. Brine discharge and salinity (ppt) at the offshore disposal site (monthly and cumulative values). The bar shows the before, during, and after time periods used in the data analysis. The potential area impacted, based on a 1 ppt increase in a 10 m water column is shown in the bottom panel.

Seventy-eight percent of the brine discharged offshore through 1995 occurred during 1980-82 when the caverns were being excavated. The average salinity of the brine solutions was 201 ppt. The period from 1983 to 1994 had an annual release rate of 117 x 10^6 barrels and an average concentration of 199 ppt.

Oil Spills

The date and amount of oil unintentionally released into the region by LOOP LLC. activities were recorded by regulatory agencies and provided to us by LOOP LLC The total oil spilled from May 1980 through December 1994 was 1,882 barrels of oil, (135 barrels/yr) of which 95 percent was spilled in offshore waters. This amount spilled is less than five percent of the pre-project estimated release of between 3,740 to 5,400 barrels/yr (DOT, USGS 1976). In 1984 the Gulf Coast had 2,306 pollution incidents involving 10,381 barrels of crude oil and in the US as a whole there were 10,745 incidents involving 470,214 barrels (Kennish 1997 p 107). The average of 135 barrels/yr at the LOOP site is thus equal to 1.3 percent and 0.3 percent of the amount spilled in the GOM (Gulf of Mexico) and US, respectively. Inshore, 87 percent of the amount released associated with LOOP operations occurred at the Clovelly storage area. The oil spill data are shown in Figure 8.

Statistical Methods

All of the ANOVA and BACI statistical analyses were conducted using the data stations with the longest records (15 years or older), to cover the entire time of the LOOP Operations. The stations used in the analysis are listed in Table 4. General Descriptive statistics (means, standard deviation, minimum, maximum) were computed for all variables, for all water quality stations. Correlations among sample depths for each variable were also computed. The more detailed statistical analyses are outlined below.

Regression Analysis

Regression analysis among various indicator variables was performed on a desktop computer (Macintosh® or DOS Machine) using commercial software products. Analyses on the Macintosh were accomplished using Statview II® (Abacus Concepts 1987); analyses on DOS machines were accomplished using PC SAS® (SAS 1990 a, b, c).

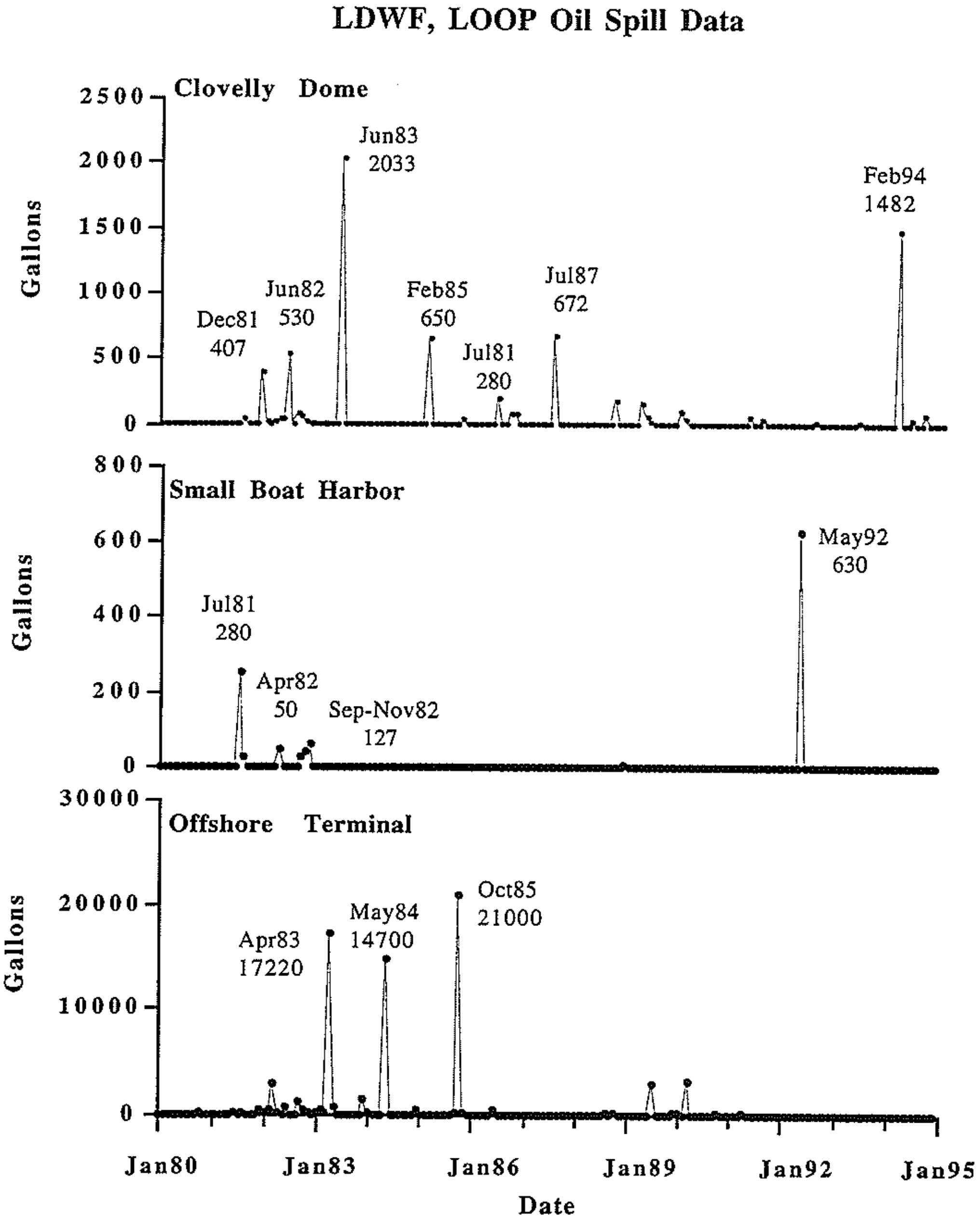


Figure 8. Time series plots of (top to bottom) gallons of oil spilled at the Clovelly Dome oil storage area, the Fourchon small boat harbor, and the offshore terminal,. The dates and amount of oil spilled, for the more noticeable peaks on the plot, are listed.

Factor Analysis

All factor analyses were conducted using the "Statistical Analysis System (SAS)", (SAS 1990a, b, c). The following discussion of the methods employed is based upon the description of the procedure found in the SAS/STAT users guide (SAS 1990 b).

Factor analysis is a statistical technique used to reduce the number of variables analyzed into a number of factors. These factors or "unobservable, latent" variables are used to explain the correlations or covariances among a set of variables. Generally, the factors are not linear combinations of the original variables, although it is assumed that the original variables are linearly related, but the relation is obscured by the random variation in the measured variables. In factor analysis, the linear relations and the amount of variation is estimated.

Factor analysis was used to reduce the number of chemistry variables into a series of factors, with each factor being comprised of one or more of the original chemical variables. The analysis was run on surface and bottom data for both the Estuary and the Offshore stations.

Analysis of Variance Modeling

All analysis of variance (ANOVA) modeling was conducted using the Statistical Analysis System (SAS) (SAS 1990 a, b, c). The following discussion of the method is based upon the description of the procedure found in the SAS/STAT Users guide (SAS 1990 b).

An ANOVA, using linear models, calculates the variance components from ratios using the expected mean square error. The general form of the linear model is:

$$\mathbf{Y} = \mathbf{XB} + \mathbf{e}$$

where $\mathbf{Y}$ represents the univariate data

$\mathbf{B}$ is an unknown vector of fixed effect parameters with a known model matrix $\mathbf{X}$

$\mathbf{e}$ is an unknown vector of independent random variables

The standard linear model is used to model the mean of $\mathbf{Y}$ using the fixed effects $\mathbf{B}$. The variance of each element of $\mathbf{e}$ is assumed to be constant. ANOVA modeling was used to investigate the possible impacts of oil spills.

Before-After, Control-Impact

LOOP activities (construction, brine discharge, oil spills) were analyzed for potential impacts on the Water Chemistry data using Before-After, Control-Impact (BACI) modeling with the General Linear Models (GLM) procedure in the Statistical Analysis System (SAS), (SAS 1990 a, b, c). BACI is an ANOVA technique, but differs from the standard linear model discussed above. The "Before" and "After "classes are based upon the timing of the events being studied and the "Control" and "Impact" classes are assigned based upon the distance between a given measurement station and the location where the event being studied occurred. The BACI model looks at the interaction of the Before-After and the Control-Impact statistical tests. If there is an effect, this term will be significant. A discussion of BACI analysis can be found in Underwood (1994). In using the model, the data are divided into "Before" and "After" and "Control" and "Impact" classes. The basic model is as follows:

Response Variable = BA YEAR(BA) CI STATION(CI)
BA*CI YEAR*BA*STATION(CI)

Where:

BA denotes Before/After class
YEAR denotes measurement over time
CI denotes Control/Impact class
* denotes an interaction term, a parenthesis denotes nesting

It is possible to have a difference between the Control and Impact stations (the CI term in the model would be significant) without an actual impact due to the event if the differences between stations is always present. Similarly, it is possible to have a difference between the Before and After samples (the BA term in the model would be significant) without an actual impact due to the event if all stations had the same response (i.e., all of the stations increased after the event). The BA*CI interaction term must be significant to show an impact. This means that the Impact stations are responding differently than the Control stations to the impact.

The standard BACI model was run to investigate the possible impact of (1) LOOP Construction, and (2) brine pumping. A modification of the standard BACI model was run to investigate the possible impact of oil spills. In this model the amount of oil spilled is added as a covariate in the model. The modified model is:

Response Variable = BA YEAR(BA) CI STATION(CI) OIL
BA*CI YEAR*BA*STATION(CI)

Where:

OIL denotes amount of oil spilled

(all other terms are the same)

The time periods for the construction were those suggested by LDWF, with pre-construction being before January 1979; construction covering the time period from January 1979 through December 1980; and after construction beginning in January 1980. The time periods for the brine discharge and the oil spills was based upon the data documenting these events. Figure 8 presents a plot of the oil spills at Clovelly Dome, the Fourchon small boat harbor, and the offshore terminal as well as the brine discharge. The actual amount of oil spilled was used in the model as a covariate with the before time period corresponding to the time before any oil was spilled and the after time period corresponding to the time after all oil was spilled. In the case of the brine pumping (Figure 7), the before time period corresponds to times before any pumping started (dates before 1 May 1980), the during corresponds to the time period during which major pumping occurred (1 May 1980 - 1 Dec 1982), and the after corresponds to the time period after major pumping stopped (dates after 1 Dec 1982).

In the case of the analysis of the construction phase, stations on or close to the LOOP inshore pipeline route were classified as "Impact" stations and those removed from the pipeline route, but still in the inshore area were classified as "Control" stations. In the case of the brine pumping, the stations very close to the brine diffuser were classified as "Impact" stations and the stations removed from the brine diffuser were classified as "Control" stations. Oil spills were analyzed for the Clovelly Dome and the offshore terminal only. The Fourchon small boat harbor did not have a suitable control station (there is not another Bayou LaFourche station), and the amount of oil spilled was quite small (Figure 9).

A second model, using a "High" and "Low" impact classification was also employed. In this model stations at the impact site (offshore terminal) were classified as "High" impact stations, stations close by were classified as "Low" impact stations, and stations further away were classified as "Control". The purpose of this model was to determine the extent of an impact, if one existed. The time periods used and the stations used for all analyses are summarized in Table 5 and shown in Figures 10 and 11.

Table 4. List of stations used for statistical analysis. The stations used were those with the longest records. Listed, for each station, is the number of samples per year for the time period from 1978 through 1995. Single and double digit numbers were monthly sampling stations, and three digit numbers were quarterly sampling stations.

	Year																	
Station	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
5	10	12	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12
7	9	12	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12
12	4	12	12	12	12	12	21	12	12	12	12	0	0	0	12	12	12	12
13	4	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	5	12
14	8	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12	12
15	7	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12	12
18	5	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12	12
21	5	12	12	12	12	12	21	10	12	12	12	12	12	10	12	12	12	12
22	8	12	12	12	12	12	21	10	12	12	12	12	12	9	12	12	12	12
34	0	10	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12	12
35	0	4	12	12	12	12	21	10	12	12	12	12	12	12	12	12	12	12
36	0	4	12	12	12	12	21	10	12	12	12	12	12	12	12	12	12	12
37	0	0	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12	12
38	0	0	12	12	12	12	21	12	12	12	12	10	12	12	12	12	12	12
52	0	0	3	4	12	12	21	12	12	12	12	12	12	12	12	12	12	12
53	0	0	3	4	12	12	21	12	12	12	12	12	12	12	12	12	12	12
54	0	0	3	4	12	12	21	12	12	12	12	12	12	12	12	12	12	12
435	0	2	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4
461	0	0	4	4	4	4	4	4	4	3	4	4	2	0	1	4	3	4
462	0	2	4	4	4	4	4	4	4	4	4	4	3	4	4	4	4	4
463	0	2	5	4	4	4	4	4	4	3	4	4	2	1	1	4	3	4
464	0	2	4	3	4	4	4	3	4	3	4	4	4	4	4	4	4	3
473	0	0	3	4	4	4	4	4	4	4	4	3	4	1	4	3	6	4
474	0	0	4	4	4	4	4	4	4	4	4	3	4	1	4	3	4	4
475	0	0	5	4	4	4	4	4	4	3	4	3	1	4	4	3	4	4
481	0	1	2	3	2	5	4	4	4	3	4	3	4	1	4	3	4	4
482	0	1	3	4	2	5	4	4	4	3	4	3	4	1	4	3	4	4
484	0	0	1	3	2	5	4	4	4	2	4	3	5	1	4	3	4	4

Table 5. Summary of Statistical Techniques to investigate possible Impacts of LOOP. Listed, for each potential impact type, is the time period over which the impact did (and did not) occur, the LDWF stations used in the analysis, and the type of analysis. The stations are classified as a control, a low impact or a high impact station.

Impact	Time Period Before	Time Period During	Time Period After	Stations Used Control	Stations Used Low Impact	Stations Used High Impact	Statistical Tests
Construction	Jan79	after Jan79 before or in Dec80	Dec80	5 12 15 14 464		7 16 34 38 462	BACI Model
Brine Pumping 1	May80	May80 before or in Dec82	Dec82	21 35 435		22 36 473 474 475	BACI Model
Oil Spills							
Clovelly Dome	Dec81	Dec81 before or in Feb94	Feb94	15 14 16 464		38 461 463	BACI Model with oil spilled as a covariate
Offshore Terminal 1	Apr83	after Apr83 before or in Apr90	Apr90*	52 54 482 484		53 481	BACI Model with Oil spilled as a covariate
Offshore Terminal 2	Apr83	after Apr83 before or in Apr90	Apr90	482 484	52 54	53 481	BACI Model with Oil spilled as a covariate

* April 1990 was used as the end date for the offshore spill period because following this month offshore spills exceeding 50 gallons did not occur.

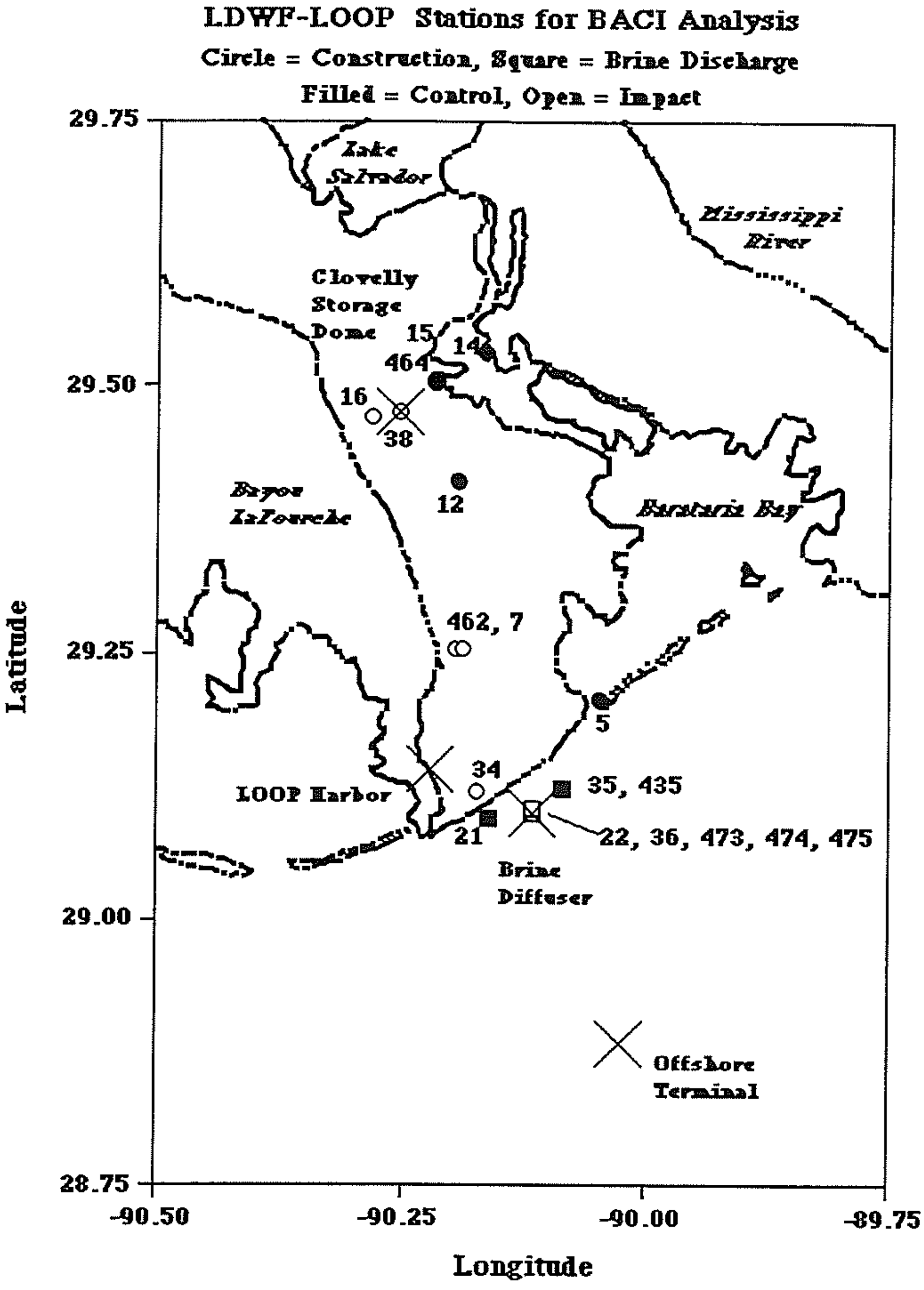


Figure 9. LDWF LOOP stations used in the BACI analysis for LOOP construction (circles) and brine discharge (squares). Filled symbols correspond to control stations and open symbols correspond to impact stations.

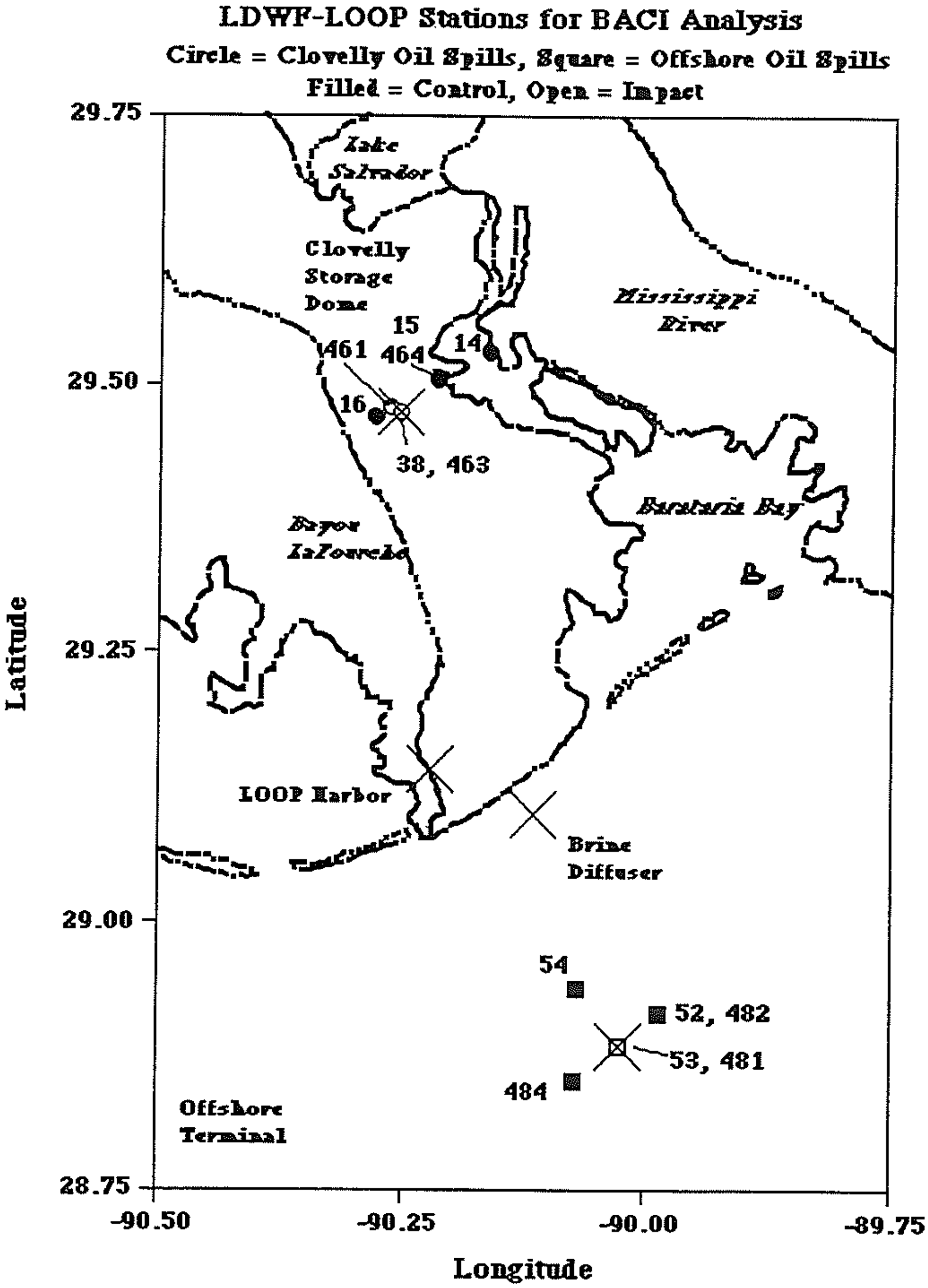


Figure 10. LDWF LOOP stations used in the BACI analysis for Clovelly Dome oil spills (circles) and offshore oil spills (squares). Filled symbols correspond to control stations and open symbols correspond to impact stations.

RESULTS AND DISCUSSION

Descriptive Statistics

The means, standard deviation, minimum and maximum values for all stations for all water chemistry variables are listed in Appendix C. Table 6 summaries the means for surface and bottom and for inshore and offshore stations for both the monthly and the quarterly data. These data indicate that the variability is quite high for all of the water chemistry variables. Both the monthly and the quarterly sampling give similar estimates of the mean values.

Correlation Analysis

The results of the correlation between surface and bottom water chemistry variables is presented in Table 7. The results indicate that the surface and bottom values are well correlated, for all variables, at the estuarine stations. The offshore stations exhibit weak correlations between surface and bottom for all variables except for sulfate, TKN, and TP.

Factor Analysis

The results of the factor analysis indicated that the variance in the data can be explained by four or five factors in all cases (Table 8). The factors explain about 73 percent of the total variance for the estuarine stations and 60 to 65 percent of the total variance in the offshore stations. In all cases, the first (and most important factor) was a salinity grouping which explained 20-36 percent of the variation in all cases. The remaining factors were generally comprised of a turbidity factor (turbidity, TSS, SS, TDS), a nutrient factor (TKN, TP), an oxygen factor, and a chlorophyll a factor.

Table 6. Summary statistics of all LDWF, LOOP water chemistry variables. The mean and standard deviation (SD) are listed for inshore and offshore environments based upon monthly and quarterly sampling.

	Inshore				Offshore			
	Monthly		Quarterly		Monthly		Quarterly	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Surface Alkalinity	94.5	24.1	82.5	16.7	112.5	11.3	110.7	10.3
Surface Ammonia	4.3	6.2	3.5	4.0	1.9	2.7	1.4	1.4
Surface Calcium	154.8	112.7	76.3	64.9	306.2	72.8	301.0	60.8
Surface Chlorophyll-a	15.5	13.1	24.8	25.2	6.9	10.4	7.6	10.2
Surface Nitrate-Nitrite	7.8	16.9	3.2	8.1	7.7	12.0	9.5	14.0
Surface Oxygen	7.4	2.0	7.3	2.0	8.3	2.1	9.0	1.6
Surface Phosphate	1.2	1.6	1.6	1.9	0.5	0.8	0.4	0.5
Surface Salinity	11.4	10.0	4.6	5.9	26.2	5.2	25.4	5.7
Surface Silica	1.8	1.8	1.8	1.0	0.5	0.9	0.5	0.5
Surface Sulfate	701.4	732.0	349.5	424.8	1744.1	678.2	1674	688
Surface Suspended Solids	49.3	58.6	64.1	80.9	28.5	38.9	25.2	29.3
Surface Total Dissolved Solids	12912.	11444	5891	7787	29642	6747	28630	6549
Surface Total Kjeldahl Nitrogen	85.5	63.2	144.7	90.4	44.8	37.5	43.0	33.5
Surface Total Phosphorus	5.2	4.1	8.2	3.1	2.9	3.1	3.3	6.9
Surface TS	12986	11454	5956	7773	29675	6743	28646	6562
Surface Turbidity	33.4	36.5	38.7	43.1	5.6	7.8	6.4	12.2
Bottom Alkalinity	98.8	20.8	97.1	21.2	117.6	8.9	117.2	16.6
Bottom Ammonia	4.5	5.9	4.5	8.0	3.9	6.3	3.5	4.6
Bottom Calcium	178.6	127.7	110.2	87.2	366.1	67.8	379.3	100.1
Bottom Chlorophyll-a	11.3	8.5	18.9	11.4	2.7	3.6	2.5	3.7
Bottom Nitrate-Nitrite	9.1	16.2	4.61	10.1	6.0	6.4	5.9	6.1
Bottom Oxygen	6.9	2.0	7.32	2.5	5.1	2.6	5.0	2.6
Bottom Phosphate	1.3	1.3	1.41	1.8	1.0	1.5	4.0	6.3
Bottom Salinity	13.8	11.4	7.1	7.5	32.4	3.8	33.0	3.9
Bottom Silica	1.6	1.6	1.8	1.0	0.6	0.8	0.6	0.6
Bottom Sulfate	898.2	830.0	441.7	526.0	2180.6	700.6	2142	700
Bottom Suspended Solids	71.3	83.7	55.7	61.1	39.7	48.0	37.3	35.9
Bottom Total Dissolved Solids	15637	13122	8242	8630	36644	5892	37137	5448
Bottom Total Kjeldahl Nitrogen	84.2	60.0	94.9	60.0	42.5	39.4	38.6	28.0
Bottom Total Phosphorus	6.0	4.6	6.6	5.0	3.8	4.1	4.0	6.3
Bottom Total Solids	15737	13107	8285	8612	36946	11427	37161	1714
Bottom Turbidity	38.8	41.6	33.6	34.8	11.2	14.0	9.8	12.1

Table 7. Correlation of surface and bottom variables for the LDWF-LOOP long term monitoring stations. Indicated for each variable is the Pearson Correlation Coefficient and the number of samples. The data are presented for both the estuarine and the offshore stations. All correlations were statistically significant at the 0.005 level.

Variable	Inshore Stations Correlation Coefficient	Inshore Stations Number of Samples	Offshore Stations Correlation Coefficient	Offshore Stations Number of Samples
Alkalinity	0.897	741	0.439	1231
Ammonia	0.895	742	0.416	1229
Calcium	0.968	746	0.550	1239
Chlorophyll-a	0.703	190	0.411	1121
NO3+NO2	0.989	739	0.456	1231
Oxygen	0.864	733	0.433	1212
Phosphate	0.840	741	0.319	1223
Salinity	0.993	731	0.318	1209
Silica	0.970	741	0.652	1238
SS	0.723	738	0.590	1229
Sulfate	0.969	736	0.817	1230
TDS	0.979	738	0.372	1228
TKN	0.908	730	0.878	1205
TS	0.978	741	0.150	1238
Turbidity	0.868	715	0.423	1173
TP	0.883	734	0.722	1224

Table 8. Results of a factor analysis of the LOOP water chemistry data. The percentage of the variance (individual and cumulative) explained by each factor as well as the factor pattern (variables, correlations) for each factor is listed. Results are given for surface and bottom for both inshore and offshore stations. Only the long-term stations were used in this analysis (Table 1).

		Variance Explained					
Data Used	Factor	Individual	Cumulative	Variables in factor	correlation		
Inshore Surface	1	33.1	33.1	Salinity	0.96	TDS	0.95
				Calcium	0.93	Sulfate	0.87
				Alkalinity	0.81		
	2	13.9	47.0	Turbidity	0.86	SS	0.68
				Phosphate	0.66	Silica	0.64
	3	9.8	56.8	TKN	0.84	TP	0.73
	4	9.2	66.0	Chlorophyll	0.80	Ammonia	-0.62
	5	7.1	73.2	Oxygen	0.85		
Inshore, Bottom	1	36.7	36.7	Salinity	0.95	TDS	0.91
				Alkalinity	0.80	Calcium	0.77
	2	10.4	47.2	SS	0.83	Turbidity	0.80
	3	9.6	56.7	TKN	0.86	TP	0.64
	4	8.3	65.0	Oxygen	0.77		
	5	8.0	73.0	Ammonia	0.76		
Offshore, Surface	1	25.6	25.6	Salinity	0.92	TDS	0.86
				Sulfate	0.65		
	2	13.9	39.5	Turbidity	0.64	Ammonia	0.62
	3	9.8	49.3	TP	-0.84	TKN	0.80
	4	7.2	56.6	Chlorophyll	0.80	Oxygen	0.77
Offshore, Bottom	1	21.9	21.9	Salinity	0.88	TDS	0.77
				Calcium	0.68		
	2	19.2	41.1	Silica	0.85	Phosphate	0.76
				Ammonia	0.72	Oxygen	-0.70
	3	9.5	50.6	TKN	0.84	TP	0.79
	4	8.6	59.2	SS	0.88	Turbidity	0.79
	5	6.7	65.9	NO3-NO2	0.90		

Spatial and Temporal Patterns

Times series plots of all of the surface water chemistry variable for a selected set of stations are presented in Appendix D, and the long term trend analysis results are presented in Appendix E.

Spatial Patterns

The general spatial patterns can be summarized as follows. Salinity shows an increase (from ~5 ppt to ~30 ppt) as one moves from the upper Barataria System to the offshore terminal. Most of the nutrients (ammonia, phosphate, silica, TKN, and TP) show a similar pattern of decreasing values from the upper part of the Barataria system to the offshore terminal. The exception is nitrate-nitrite which is lowest in the mid-portion of the Barataria system and higher in the upper portion of the Barataria system and at the offshore stations. Turbidity and suspended solids have a similar pattern to the nutrients, in that they decrease from the upper portion of the Barataria system to the offshore terminal. In addition, these variables also exhibit reduced variability in the offshore stations. Total dissolved solids and total solids follow the same general pattern as salinity, since they are highly correlated with salinity (the salt is a major component of the solids). Sulfate and calcium both show increases in magnitude as well as variability from the upper part of the Barataria system to the offshore terminal. Alkalinity has the same value (~100 mg/l) throughout the whole system, however the offshore stations show reduced variability. Chlorophyll a also shows a decrease from upper Barataria to the offshore platform. Oxygen exhibits a pronounced seasonal variation in the upper portion of the Barataria system, however this seasonal pattern is much less pronounced at the offshore stations.

The average oxygen concentration in offshore bottom and surface waters for the entire study area, and for summer months at two water depths is in Figures 12 and 13. The oxygen concentration is the average of May, June and July for 2 clusters (long-term stations less than 10 m and greater than 10 m water depth). The variability along a north-to-south transect is in Figure 12. There is a general decrease in oxygen concentration over the last 16 years, and for the shelf (Rabalais et al. 1996). The brine diffuser began operations during a period of decreasing oxygen in the general area, but that change should not be attributable to the LOOP facility operations. The salinity, dissolved inorganic nitrogen and chlorophyll a concentrations varied tremendously from year to year (Figure 13). These changes are observed over the whole shelf and are part of a regional phenomena attributable to changes in the Mississippi River water quality.

Temporal Patterns

The long term (temporal) trends were computed for all variables using the long-term (monthly and quarterly) stations listed in Table 4, and plotted in Figures 5 and 6. The mean inshore and offshore trends (slopes) for both surface and bottom values were calculated. The mean trends for each area (inshore, offshore) were calculated using only the individual station trends (Appendix E) that were significant at the 0.05 % level. In general, about one-third of the water chemistry variables (n = 16) showed statistically significant and consistent trends.

The monthly surface water chemistry variables which showed statistically significant trends at a majority of the stations for either inshore or offshore were:

Silica	negative (-0.15 mg l^{-1} y^{-1})	all inshore stations
	negative (-4.07 mg l^{-1} y^{-1})	57 percent offshore stations
Sulfate	negative (-186.5 mg l^{-1} y^{-1})	64 percent inshore stations
	negative (-91.6 mg l^{-1} y^{-1})	all offshore stations
Suspended Solids	negative (-4.07 mg l^{-1} y^{-1})	82 percent inshore stations
	negative (-2.27 mg l^{-1} y^{-1})	all offshore stations
Total Kjeldahl Nitrogen	positive (8.14 µg-at l^{-1} y^{-1})	all inshore stations
	positive (5.00 µg-at l^{-1} y^{-1})	all offshore stations
Total Phosphorus (TP)	positive (0.03 µg-at l^{-1} y^{-1})	91 percent inshore stations
	positive (0.33 µg-at l^{-1} y^{-1})	all offshore stations
Turbidity	negative (-4.21 NTU y^{-1})	all inshore stations
	negative (-0.69 NTU y^{-1})	all offshore stations

The quarterly surface water chemistry variables which showed statistically significant trends for either inshore or offshore were:

Phosphate	negative (-0.34 µg-at l^{-1} y^{-1})	75 percent inshore stations 3 percent offshore stations
Sulfate	negative (-229.8 mg l^{-1} y^{-1})	all offshore stations
Suspended Solids	negative (-2.62 mg l^{-1} y^{-1})	all offshore stations
Total Kjeldahl Nitrogen	positive (3.61 µg-at l^{-1} y^{-1})	all offshore stations
	positive (12.54 µg-at l^{-1} y^{-1})	50 percent inshore stations

The monthly bottom water chemistry variables which showed statistically significant trends for either inshore or offshore were:

Alkalinity	positive (0.39 mg l^{-1} y^{-1})	71 percent offshore stations
	negative (0.94 mg l^{-1} y^{-1})	20 percent inshore stations
Nitrate-Nitrite	positive (0.38 µg-at l^{-1} y^{-1})	100 percent offshore stations
	negative (0.22 µg-at l^{-1} y^{-1})	40 percent inshore stations
Oxygen	negative (-0.13 mg l^{-1} y^{-1})	all offshore stations
	negative (-0.06 mg l^{-1} y^{-1})	40 percent inshore stations
Sulfate	negative (-36.7 mg l^{-1} y^{-1})	60 percent offshore stations
	negative (-38.4 mg l^{-1} y^{-1})	all inshore stations
Total Kjeldahl Nitrogen	positive (6.24 µg-at l^{-1} y^{-1})	all inshore stations
	positive (5.04 µg-at l^{-1} y^{-1})	all offshore stations
Total Phosphorus	positive (0.31 µg-at l^{-1} y^{-1})	all inshore stations
	positive trend (0.42 µg-at l^{-1} y^{-1})	all offshore stations

The quarterly bottom water chemistry variables which showed statistically significant trends for either inshore or offshore were:

Silica	negative (0.17 µg-at l^{-1} y^{-1})	75 percent inshore stations
Sulfate	negative (-32.2 mg l^{-1} y^{-1})	25 percent inshore stations
	negative (-210.6 mg l^{-1} y^{-1})	86 percent offshore stations
Total Kjeldahl Nitrogen	positive (5.87 µg-at l^{-1} y^{-1})	all inshore stations

The only variables which showed consistent spatial and temporal trends were total Kjeldahl nitrogen, total phosphorus, and sulfate. These three variables exhibited trends at surface and bottom in both the inshore and offshore environment. A total of 20 statistically significant trends were detected in the monthly data. The quarterly data only detected seven statistically significant trends. This suggests that quarterly sampling is not sufficient to detect long-term trends.

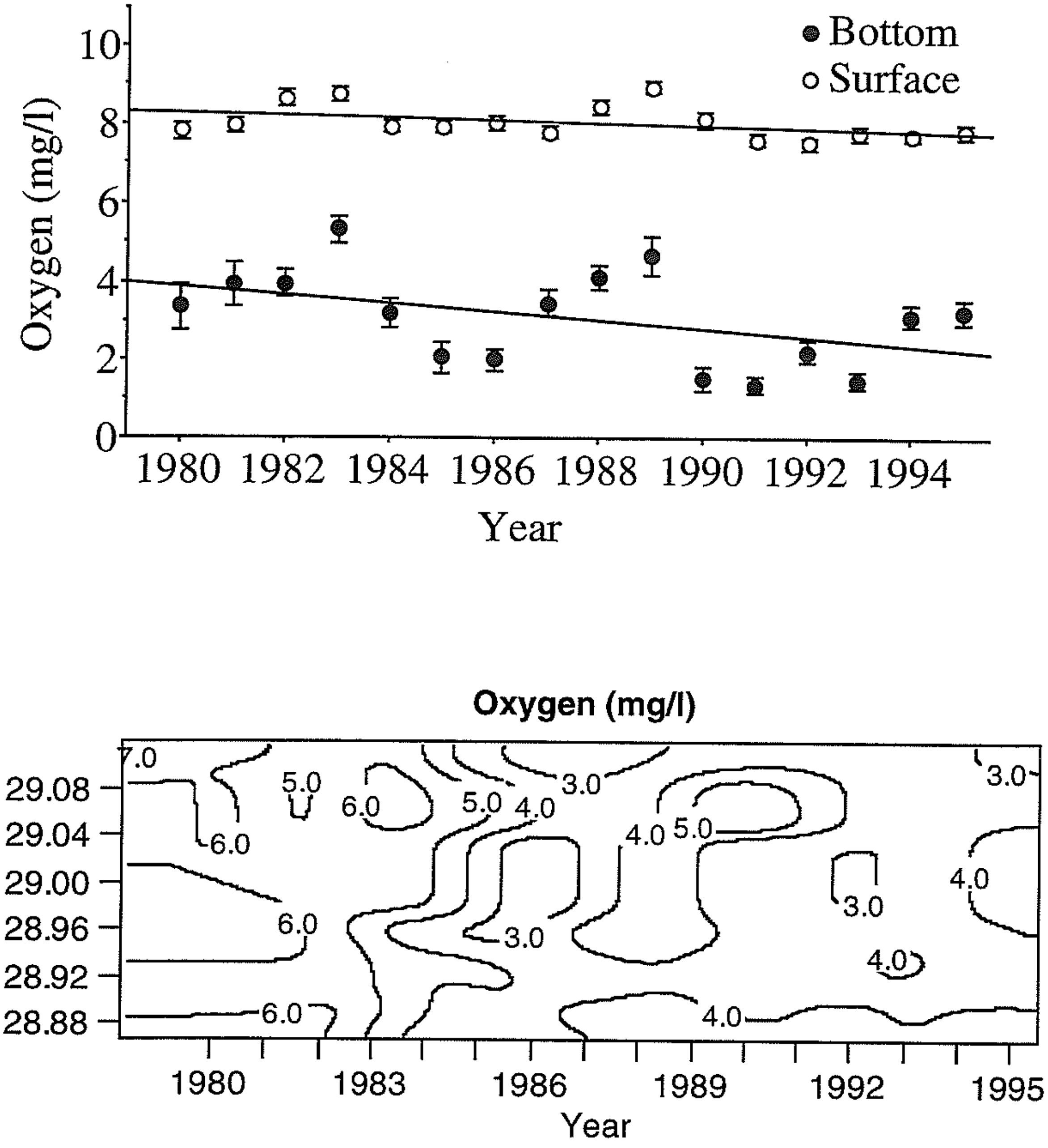
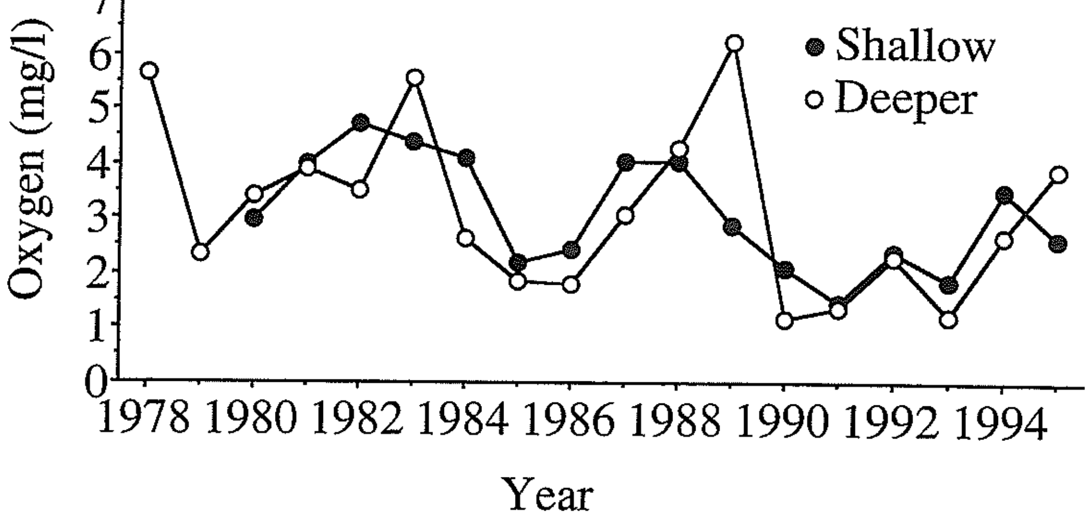


Figure 11. Top: The annual average monthly oxygen concentration offshore in surface and bottom waters (± 1 Std. Error) for records greater than ten years. The linear regression of the data is not statistically significant for either data set ($p = 0.19$ and 0.09, for top and bottom waters, respectively). Bottom: Oxygen concentration along a north to south transect offshore. A three month running average was used to smooth the data. The brine diffuser is at 29.1000° N and the LOOP offshore onloading port is at 28.8850° N.



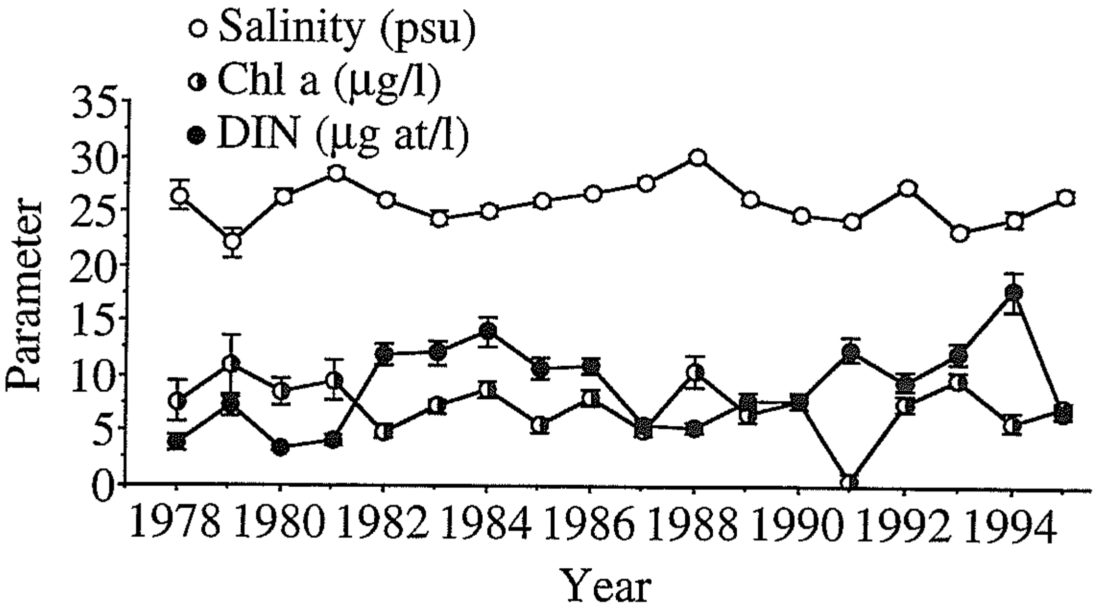


Figure 12. Top: The oxygen concentration during summer months for shallow and deep stations. Bottom: The annual dissolved inorganic nitrogen, chlorophyll a, and salinity for offshore monitoring stations. The mean ± 1 Std. Error is plotted.

BACI Analysis

The BACI analyses were conducted using the model outlined in Section 4.3.4 using a reduced number of variables as determined by the factor analysis. The following variables were used: ammonia, chlorophyll a, salinity, sulfate, TKN, and turbidity. BACI modeling was run on both surface and bottom values for each of these variables. The results for the surface values are in Table 9, and the results for the bottom values are in Table 10, and are statistically significant effects discussed below.

Construction

The BACI analysis showed no statistically significant impacts that could be correlated with the construction for the variables analyzed.

Brine Discharge

There were some statistically significant differences before and after (surface ammonia, surface sulfate, surface TKN, surface turbidity, bottom sulfate, bottom TKN, and bottom turbidity) however the Before-After, Control-Impact interaction was not significant indicating that these differences were not correlated with the brine discharge for the variables analyzed.

Clovelly Dome Oil Spills

There were two statistically significant impacts that could be correlated with oil spills in the Clovelly Dome area: Surface ammonia and surface turbidity. The surface ammonia decreased from 4.04 μg-at/l (before) to 2.01 μg-at/l (after) for the control classes, and decreased from 4.95 μg-at/l (before) to 4.45 μg-at/l (after) for the impact classes. The surface turbidity decreased from 86.0 NTU (before) to 17.5 NTU(after) for the control classes, and decreased from 93.4 NTU (before) to 10.1 NTU (after) for the impact classes. The bottom turbidity showed a statistically significant interaction without a statistically significant oil covariate term. This indicates that there was some sort of impact which is not correlated with oil spills. The bottom turbidity decreased from 86.0 NTU (before) to 28.1 NTU(after) for the control classes, and decreased from 108.6 NTU (before) to 18.9 NTU (after) for the impact classes. Although these changes were statistically significant they do not appear to be ecologically significant.

Offshore Terminal Oil Spills

There was a statistically-significant difference before and after in surface turbidity, and a statistically-significant difference between control and impact stations for bottom TKN However, the Before-After, Control-Impact interaction was not significant indicating that these differences were not correlated with the brine discharge for the variables analyzed. The BACI model with the oil spills as a covariate indicated that TKN did have a statistically significant impact that was correlated with oil spills. The surface TKN increased from 18.8 μg-at/l (before) to 73.1 μg-at/l (after) for the control classes, and increased from 9.5 μg-at/l (before) to 63.8 μg-at/l (after) for the impact classes. The before and after comparison was also significant, indicating that there was something else also occurring that may, or may not, have been due to the oil spills. Thus, the observed differences, although correlated with the oil, cannot be directly attributed to the oil spills.

Analysis of Brine Discharge

The Louisiana Department of Wildlife and Fisheries studied 32 brine plumes in bottom waters using a bottom sled equipped with dissolved oxygen, temperature and conductivity sensors (Anon 1995). Equipment failure and poor weather conditions prevented completion of some data collections. Contouring of the data were done to estimate the area of bottom waters in 1 ppt increments above the background levels. Ten cruises had sufficient data to map the brine plume (in the horizontal plain) around the diffuser to within 1 ppt of the background levels. These results were used to plot the size of the plume vs. the discharge volume (Figure 13). The result was the observation that there is an increase in plume size with brine discharge amounts. The intercept at zero discharge was not statistically different from zero. The range of values extended up to around 400 ha for the largest plume studied. The average discharge for the 1983-1994 brine discharge operations was 310,547 barrels/day and 200 ppt, which compares to the average of all of the LDWF data set (n=10) of 234,315 barrels/day and 204 ppt, respectively. At these average brine discharge rates, the average plume size (within 1 ppt of background) would be 165 ha (0.165 km^2). We can compare the average observed plume size (1 ppt above background) shown in Figure 13 with the area impacted estimated in Figure 7. The potential area impacted of all brine discharge periods estimated in Figure 7 was 1 to 13 km^2, and the average was 2.0 km^2.

Table 9. Results of Before:After, Control:Impact (BACI) analyses of LOOP surface water chemistry data. Listed, for each BACI model, and selected variables, is the F value and the probability for (1) the Before:After, (2) the Control:Impact, and (3) the interaction of the Before:After and Control:Impact portions of the model. In the case of the oil spills, the F value and the probability is also given for the oil spill covariate used in the model. Details of the parameters used in the BACI model are listed in Table 1. The symbol 'nd' indicates that there were not enough data points to run the model, and the symbol 'na' indicates the model term was not applicable. **Bold face** indicates a result significant at the 0.05 level.

		Before:After		Control:Impact		Interaction		Oil Spill Covariate	
Variable	Type of Impact	F	P>F	F	P>F	F	P>F	F	P>F
Ammonia	Construction	0.082	0.922	2.024	0.169	0.180	0.836	.na	.na
Ammonia	Brine	**6.154**	**0.006**	0.345	0.566	0.064	0.938	.na	.na
Ammonia	Clovelly Oil	0.549	0.583	1.926	0.186	1.782	0.170	**4.199**	**0.041**
Ammonia	Offshore Oil	0.978	0.395	1.590	0.259	0.338	0.714	1.995	0.158
Chlorophyll-a	Construction	1.406	0.267	0.079	0.782	1.994	0.137	.na	.na
Chlorophyll-a	Brine	2.105	0.137	0.033	0.856	0.486	0.616	.na	.na
Chlorophyll-a	Clovelly Oil	2.966	0.074	13.852	0.006	1.684	0.188	2.630	0.105
Chlorophyll-a	Offshore Oil	0.083	0.921	0.044	0.841	0.289	0.749	0.560	0.454
Salinity	Construction	0.647	0.537	0.344	0.573	0.576	0.563	.na	.na
Salinity	Brine	0.140	0.870	0.498	0.491	0.002	0.998	.na	.na
Salinity	Clovelly Oil	1.176	0.329	0.002	0.963	0.512	0.599	0.763	0.383
Salinity	Offshore Oil	1.786	0.197	0.034	0.859	0.543	0.582	2.821	0.094
Sulfate	Construction	2.273	0.136	0.188	0.676	1.869	0.158	.na	.na
Sulfate	Brine	**10.414**	**0.001**	0.006	0.939	0.117	0.889	.na	.na
Sulfate	Clovelly Oil	1.138	0.340	0.188	0.667	0.511	0.600	3.083	0.080
Sulfate	Offshore Oil	2.204	0.144	0.008	0.932	0.114	0.892	3.011	0.083
TKN	Construction	2.753	0.096	0.083	0.777	0.133	0.876	.na	.na
TKN	Brine	**4.894**	**0.021**	1.231	0.275	0.561	0.571	.na	.na
TKN	Clovelly Oil	**10.003**	**0.001**	0.238	0.634	0.115	0.892	0.938	0.322
TKN	Offshore Oil	**13.630**	**0.000**	0.456	0.517	0.090	0.914	0.332	0.565
Turbidity	Construction	1.689	0.215	0.126	0.736	0.146	0.703	.na	.na
Turbidity	Brine	**19.98**	**0.000**	0.180	0.677	3.012	0.051	.na	.na
Turbidity	Clovelly Oil	**9.842**	**0.001**	0.106	0.753	2.084	0.126	**4.332**	**0.038**
Turbidity	Offshore Oil	**5.792**	**0.013**	0.077	0.793	0.131	0.877	0.012	0.913

Table 10. Results of Before:After, Control:Impact (BACI) analyses of LOOP bottom water chemistry data. Listed, for each BACI model and selected variables, is the F value and the probability for (1) the Before:After, (2) the Control:Impact, and (3) the interaction of the Before:After and Control:Impact portions of the model. In the case of the oil spills, the F value and the probability is also given for the oil spill covariate used in the model. Details of the parameters used in the BACI model are listed in Table 1. The symbol 'nd' indicates that there were not enough data points to run the model, and the symbol 'na' indicates the model term was not applicable. **Bold face** indicates a result significant at the 0.05 level.

		Before:After		Control:Impact		Interaction		Oil Spill Covariate	
Variable	Type of Impact	F	P>F	F	P>F	F	P>F	F	P>F
Ammonia	Construction	0.082	0.922	2.024	0.169	0.180	0.836	.na	.na
Ammonia	Brine	0.503	0.614	0.830	0.364	0.694	0.500	.na	.na
Ammonia	Clovelly Oil	1.092	0.357	0.021	0.889	0.567	0.570	0.240	0.625
Ammonia	Offshore Oil	1.487	0.261	0.461	0.530	1.613	0.202	0.504	0.478
Chlorophyll-a	Construction	.nd	.nd	.nd	.nd	.nd	.nd	.na	.na
Chlorophyll-a	Brine	1.716	0.206	0.083	0.777	0.582	0.447	.na	.na
Chlorophyll-a	Clovelly Oil	.nd	.nd	.nd	.nd	.nd	.nd	.na	.na
Chlorophyll-a	Offshore Oil	2.507	0.103	1.352	0.256	0.544	0.581	0.007	0.931
Salinity	Construction	1.162	0.328	0.002	0.968	0.033	0.856	.na	.na
Salinity	Brine	0.798	0.464	1.959	0.187	1.129	0.324	.na	.na
Salinity	Clovelly Oil	1.406	0.272	3.582	0.123	0.517	0.597	0.471	0.493
Salinity	Offshore Oil	0.000	0.999	0.354	0.576	0.266	0.767	1.777	0.183
Sulfate	Construction	3.119	0.062	0.014	0.911	0.077	0.782	.na	.na
Sulfate	Brine	**16.420**	**0.000**	0.069	0.795	1.257	0.286	.na	.na
Sulfate	Clovelly Oil	0.907	0.422	0.831	0.406	0.378	0.687	1.824	0.178
Sulfate	Offshore Oil	**5.197**	**0.018**	2.990	0.128	0.512	0.600	0.271	0.603
TKN	Construction	1.689	0.215	0.126	0.736	0.146	0.703	.na	.na
TKN	Brine	**5.360**	**0.015**	0.666	0.423	0.264	0.768	.na	.na
TKN	Clovelly Oil	**7.911**	**0.004**	0.065	0.806	0.724	0.488	0.122	0.723
TKN	Offshore Oil	**25.094**	**0.000**	0.129	0.726	0.576	0.563	**4.49**	**0.034**
Turbidity	Construction	0.778	0.476	0.261	0.612	0.633	0.428	.na	.na
Turbidity	Brine	**12.520**	**0.000**	0.534	0.473	1.367	0.256	.na	.na
Turbidity	Clovelly Oil	**12.618**	**0.000**	1.763	0.257	**3.917**	**0.024**	0.646	0.422
Turbidity	Offshore Oil	2.315	0.118	**5.161**	**0.026**	0.143	0.867	0.131	0.718

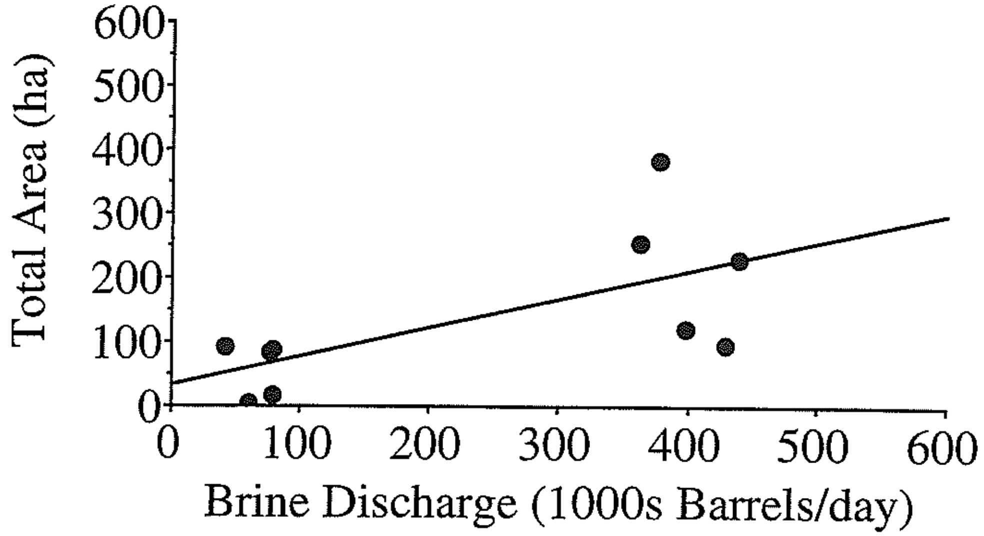


Figure 13. The size of the brine plume on the bottom layer vs. the brine discharge amount. The data are from a draft Louisiana Department of Wildlife and Fisheries (LDWF) report (Anon 1995) which mapped the area with a benthic sled. Only data with closed salinity contours within 1 ppt of ambient salinities were used.

This number must be reduced by the amount of mixing occurring in the area, which can be estimated from the current speeds. An average bottom water current speed for the area is around ten cm/sec (Anon 1995). Therefore, the water turnover rate is every 27 hours, and the area impacted by the 1 ppt increase is 1.79 km^2 on an average day. This average size compares well with the observed brine plume size (at 1 ppt or higher) of 1.65 km^2.

The relationship between the area of the plume at greater than 1 ppt and higher salinities is shown in Figure 14. The area of the plume at each increment above 1 ppt was divided by the area of the plume for greater than 1 ppt to normalize the data for comparison from one cruise to another. The average area of the plume at +2 ppt and +10 ppt is about 60 and 20 percent, respectively, of the area at greater than 1 ppt. The LDWF contours of the salinity zone (Anon 1995) showed a general maximum 2000 m extension of the plume in any direction over the sampling events (for the plume of greater than 1 ppt above background), equivalent to a brine plume shadow of 16 km^2.

The average brine plume is thus theoretically large enough (50 to 400 ha) to be measured at the 4 monitoring stations located within 150 m of the brine diffuser (stations 473, 474, 475 and 476). The bottom current direction and long axis of the brine plume during these studies ran parallel to the coast in a generally east and west direction (Figure 15). However, the westward bottom currents are centered at 270 degrees, and the eastward currents are offset to the northeast

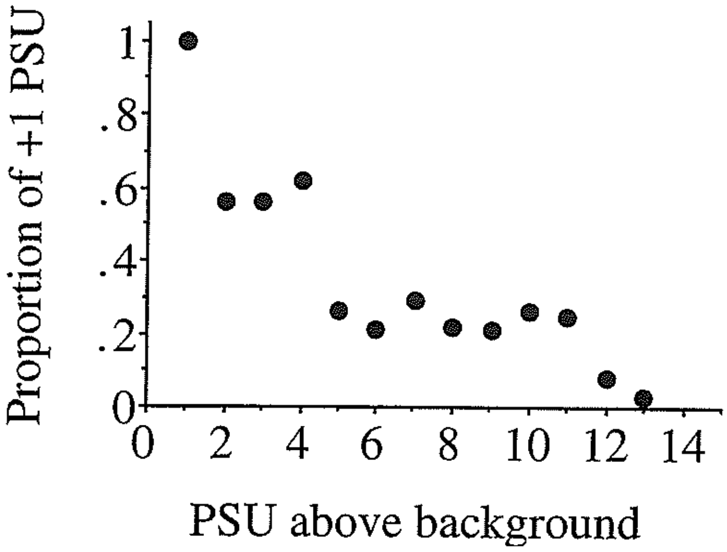


Figure 14. The relationship between the proportion of the plume area at salinities above 1 ppt above background compared to the area covered by the plume within +1 ppt of background salinity.

(45 degrees), rather than at 90 degrees (Figure 15). An examination of the plotted data (Anon 1995) shows that many times the monitoring stations were located out of the brine plume. The monitoring station most likely to detect changes among the four closest to the brine diffuser is the West station (no. 475).

We examined variability in bottom water salinity by computing the ratio of the bottom water salinity at the eastern station to other stations near the brine diffuser site. Equipment monitoring salinity at station 468, which is several km away from the diffuser, presumably would not detect a plume of 200 ha (equal to a rectangle of 2000 m X 1000 m). Furthermore, the plume is oriented in the general direction of the bottom currents, frequently moving between the four closest monitoring stations. The result shows that the variability was higher at station 475 (west of the diffuser) during the continuous brine disposal operations (1980 to 1982), but then was less variable after brine diffuser operations became more irregular (beginning in 1983) (Figure 16). A summary of the coefficient of variance for the ratio of salinity station no. 47x : salinity of station no. 473 is shown in Figure 17 (where 47x represents station 468, 474, 475 or 476). The anticipated result was observed: salinity and dissolved oxygen variations (the diffuser acts as an aerator) were greater when the brine diffuser was in operation, than not in operation.

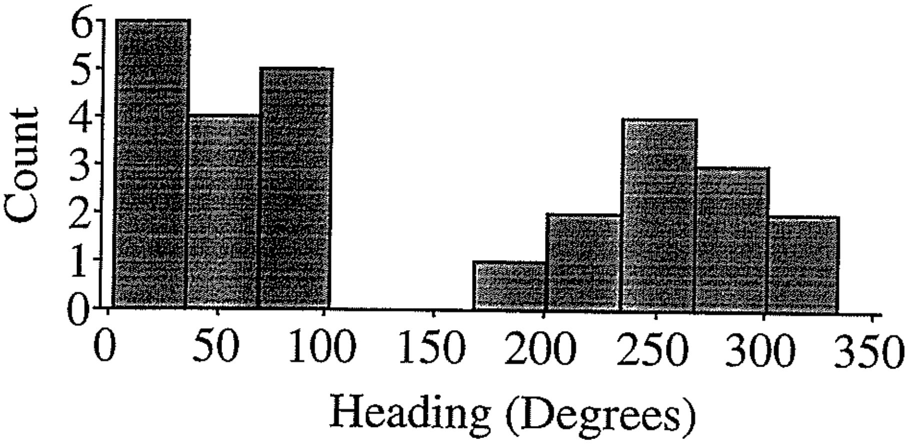


Figure 15. The frequency of the current headings at the sea bottom layer observed by the Louisiana Department of Wildlife and Fisheries during the brine plume dispersal studies (Anon 1995).

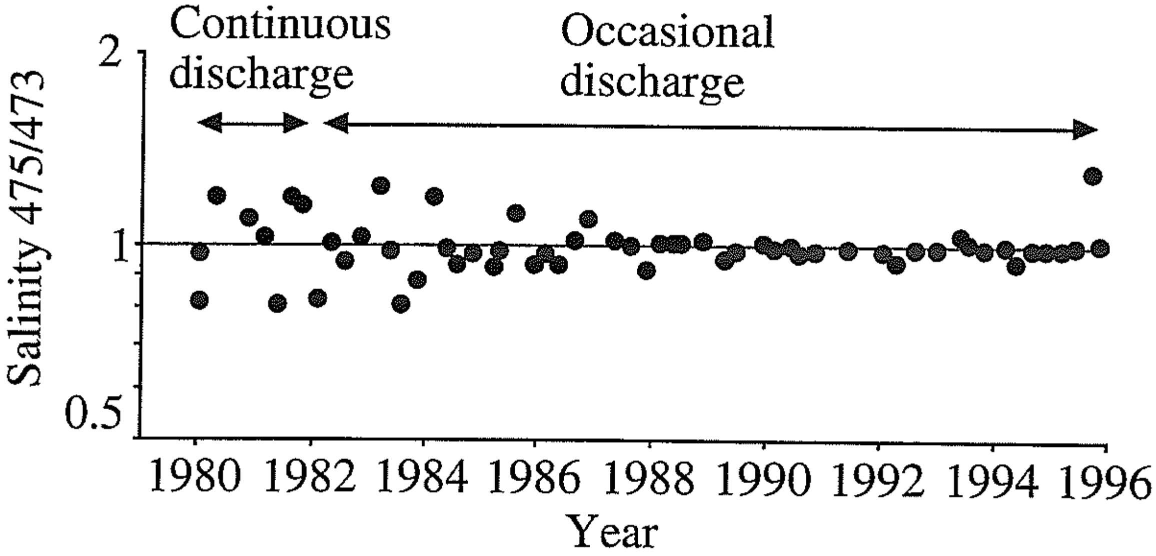


Figure 16. The average annual salinity in bottom water at stations near the brine disposal site, normalized to the salinity at station 473. Normalization was done by dividing the salinity at station 475 by the salinity at station 473 for the sampling day.

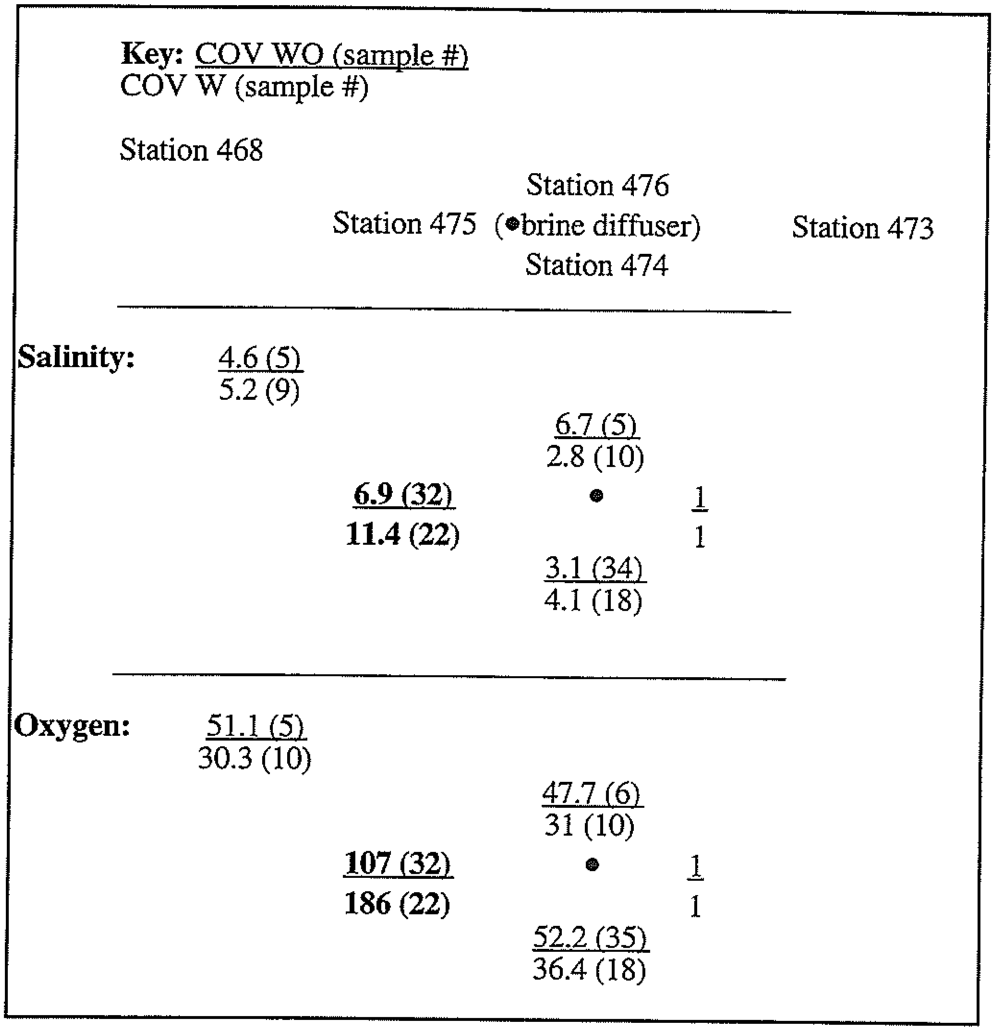


Figure 17. The Coefficient of Variance (COV) of either salinity or dissolved oxygen during periods with (W) and without (WO) brine disposal. Normalization of the data was done by dividing the observed salinity (or dissolved oxygen) at station 47x by the salinity (or dissolved oxygen) at station 473 for the sampling day. A COV was then determined for the normalized data (a ratio) for each station set. Stations 473, 474, 475 are 150 m east, south, west and north of the diffuser. Station 468 is approximately 0.9 km northwest of station 473. Stations in **bold** have a much higher COV with the diffuser in operation, than when not in operation.

There are several important consequence of these observations. First, a plume does exist, it covers a large area (16 km^2), and the sampling station grid is close enough to detect the plume when it moves in the direction of the sampling station. Second, the sampling stations are positioned so that the plume may pass between them. This is a common problem when constructing a sampling design for offshore stations, which has been partially addressed by placing sampling stations around the impact site so that they form an expanding spiral surrounding the impact site at least two times. Third, the area impacted by the plume covers more than is covered by an individual plume on any one day. The orientation of the plume is constantly changing directions. Because of this, the benthic sampling is more likely to both preserve and experience the chronic impacts of fluctuating and stochastic event frequency. Finally, this variation in plume direction may compromise the sensitivity of the BACI analyses.

Stone (1977) reported that the estimated maximum freshwater removal rates for the dissolution of the Clovelly brine cavern amounted to 1.7 to 3.3 percent of the excess freshwater (total rainfall-evaporation) in the drainage basin. Based on the observed relationship between the average salinity and distance to the coast (0.6 ppt per 1000 m), Stone (1977; based on Light 1975, which is cited therein) predicted an estimated saltwater gradient increase landward of 425 to 850 m across a broad front. This movement would be for all salinity ranges. Changes of this size would probably be regionally insignificant because of the normal daily and seasonal mixing and movements of different water masses through the estuarine zone. However, they might be locally important if the intake structure was from an intake channel linked directly to the coast and lined by spoil banks. This does not seem to be the case for the Clovelly salt dome. We expect, therefore, that naturally-occurring large variations in salinity will mask any slight change in salinity resulting from removal of freshwater from the area during leaching operations.

Frequency and Size of Oil Spills

The total amount of oil reported spilled during the study interval amounted to less than 2,000 barrels (Figure 4) and almost all of it was spilled offshore. A recurrence interval analysis that used the 17 year long data record of oil spills predicted that a maximum monthly oil spill between 1,000 and 10,000 barrels will occur once in 50 years (Figure 18). This result compares very well with a predicted return period for an individual spill predicted in the Environmental Impact Statement (DOT, USGS 1976). That report estimated that a single spill of at least 10,000 barrels should occur once every 24 years (close to that predicted in Figure 18).

A recent Coast Guard analysis (DOT, USCG 1993) involves an analysis of predicted spills at the deepwater port operated by LOOP LLC. It provides estimates of the relative risks of transporting crude oil, not of the absolute risk. In other words, it provides representation of the risks associated with each mode relative to the other modes, which includes spills resulting

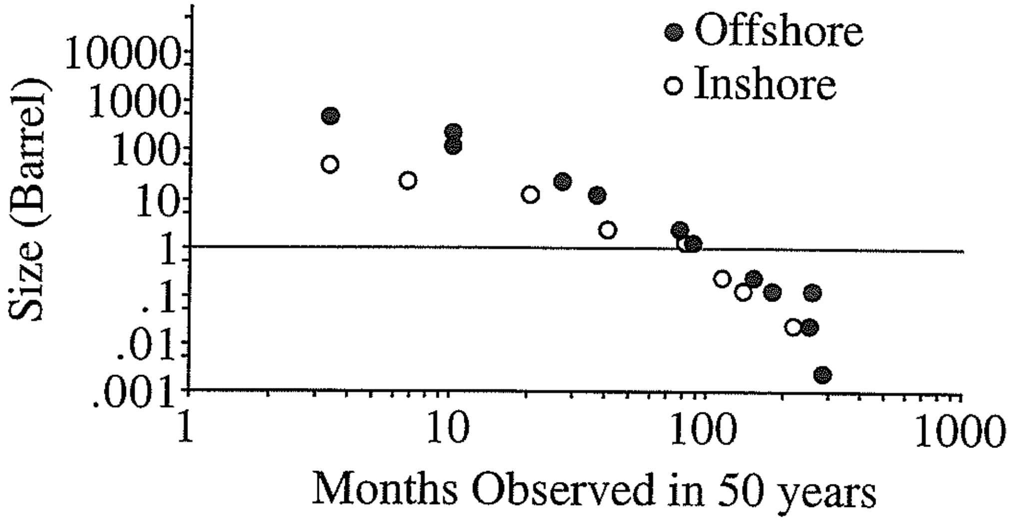


Figure 18. The observed recurrence frequency of oil spill size. The vertical axis is the oil spill size observed since 1980, prorated over 50 years. Example: an offshore spill of about 500 barrels was observed to occur at a rate of 3 months every 50 years.

Table 11. Statistically significant results from a multiple regression model used to test for the significance of several variables, including whether there was a large oil spill that month, on either dissolved oxygen or chlorophyll a concentrations. Only data from 1985 to 1995, and March through July were used.

A. Surface dissolved oxygen
R^2 0.20, F = 35.71 p = 0.0001 n = 548

Variable	Coefficient	Probability
Intercept	14.46	
Spill month	-1.90	0.0012
Alkalinity	-0.028	0.0018
Chl a	0.069	0.0001
NO_3+NO_2	0.0267	0.0007

B. Surface Chl a
$R^2 = 0.20$, F = 35.2 p = 0.0001 n = 550

Variable	Coefficient	Probability
Intercept	-8.72	
Spill month	9.24	0.0064
Oxygen	0.069	0.0001
NO_3+NO_2	-0.274	0.0001
Salinity	-0.589	0.0001

during transit (navigation-related accidents), transfer casualties (cargo transfer/discharge operations), and intrinsic casualties (i.e., from accidents, fire, explosions). The worst case scenario for a LOOP pipeline rupture is estimated at 4,600 barrels. Both the EIS (DOT, USCG 1976) and the more recent Coast Guard study (DOT, USCG 1993) suggest that a larger spill than observed in the first 17 years of operations is possible (up to 240,000 barrels)[1]. The recurrence interval graph (Figure 18) based on the data from actual spills resulting from LOOP LLC facility operations as provided to us by LOOP LLC shows that a large spill (1,000 to 10,000 barrels) has a probability of occurring once every 50 years.

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[1] The following information was added at the request of LOOP LLC. Because of OPA 90's separation of liabilities, the maximum credible accidental discharge for which LOOP itself would be liable is estimated to be 4,600 barrels. For a discussion of separation of liabilities in relation to accidental discharge of oil, see DOT, USCG (1993).

SUMMARY AND CONCLUSIONS

The data sets we examined indicated that the current monitoring program, as identified in the original environmental management plan, worked (we were able to document spatial and temporal trends and some impacts).

Results from an analysis of the water quality parameters measured in this monitoring program showed limited evidence of extensive changes due to the brine disposal operations or the small (less than 100 barrels) oil spill. The variability introduced by the Mississippi River is a significant complication of the analysis because of its size and proximity to the monitoring stations. A change in the measured parameter values between a before-and-after impact analysis may not be due to the potential impact factor (brine), but actually be the result of long-term trends or events in environmental factors unrelated to the LOOP operations. The fixed location of the monitoring station network and sampling frequency are often too sparse to detect these impacts. Also, water masses are moving through the sampling area quickly. In other words, if an impact has occurred, it is likely that the water mass moved out of the area before the monthly sampling occurred.

The bottom sled sampling by the State Department of Wildlife and Fisheries clearly located a brine plume whose position on the bottom moves among the stations, adding variability to the measured parameters, and perhaps compromising the results of the BACI sampling design. The variability in bottom salinity at station 473, for example (Figure 14), probably reflects these movements among and between sampling locations. The BACI analysis cannot, a priori, determine if the plume is over a station or not and a nearby station may be an adequate control station in one month, but an impact station in another month. Fixed control and impact stations cannot, therefore, be assigned.

Water chemistry monitoring measurements are necessary because they serve as ancillary measurements to interpret the background conditions, against which other impacts are measured. Including them in a monitoring program will contribute to the identification of "false positives", such as mis-identifying an increase or decrease as causally related to an oil spill, rather than to seasonal or long-term changes in the Mississippi River. However, experience brings better understanding and the opportunity to improve the existing monitoring network for water quality. It is quite natural that monitoring programs evolve with experience on site and from that gathered by other competent investigators. Federal and state governments have responsibility for the protection of natural resources, and monitoring is recognized as a useful instrument to prevent, minimize and mitigate various impacts, as well as the presumed or suggested impacts.

Oil Spill Size

The maximum "credible oil spill" estimated in the original EIS was 240,000 barrels, which is 127 times larger than that spilled through 1996. It is based on a pre-project spill recurrence interval that is substantiated by experience since 1978. In other words, the recurrence interval graph of the original projections in the EIS and the subsequent events are nearly coincidental. Fortunately the very large spill that was predicted to occur once in a period greater than 50 years has not happened in the first 17 years of operations.

Station Locations

Eighty-seven percent of the inshore oil spills occurred at the Clovelly salt dome site (station no. 38). There are 24 stations with record lengths greater than ten years, but only one at Clovelly (station no. 38). Station 39 is within 1.5 km of station no. 38 (WSW), station no. 16 is within 2.5 km (WSW) but is isolated by a hurricane protection levee, and station no. 464 is within 4 km (NE). There are too few monitoring stations close to station no. 38.

The station locations offshore are set in a cross shaped pattern around the diffuser, but the plume appears to move between many of these. Some sort of adaptive sampling scheme (network of vertical profiles, towed vehicle) to collect data on the three-dimensional structure of the brine plume must be implemented if major brine discharges are to be detected in a systematic manner.

Background Conditions or 'False Positives'

The environmental conditions inshore and offshore are variable from year-to-year and month-to-month and from station to station. If water quality parameters are included in a monitoring program, then it should be possible to identify seasonal or long-term trends that complicate analyses, and be mis-identified as impacts.

Baseline Conditions for a LOOP Related Mega-oil Spill

Current speeds throughout the region suggest that water masses are replaced in days, not weeks or months. Events like a large (yet unobserved) oil spill similar to that predicted in the original environmental management plans, must be sampled within weeks of the event to establish reasonable baseline conditions against which to measure impacts. If the region were homogenous than they are and not near the Mississippi River, etc., then baseline conditions might be more safely predicted from less frequent sampling (quarterly). A second, related issue, is that a mega-oil spill may yet occur whose surface water and oil will be spread far beyond the LOOP facility vicinity, and probably spread westward (assuming that is the dominant current direction). However, below the surface, there may be effects spreading in different directions from that in the surface layer.

Relationship of Water Chemistry to Biologic Components

Integrating an analysis of the water chemistry data and biological data sets on an ongoing basis will provide a useful perspective that is greater than analysis of each in isolation of the other. For example, the benthic community is the logical analytical subject for competent investigation of impacts near the brine disposal, and for oil spills (past and present). The benthic community is subject to a probable enhancement around the diffuser, if results from other studies are appropriate for this site. The immediate area of the brine plume (about 4 km^2 for a plume greater than 1 ppt) sweeps over an area of 16 km^2. The plume orientation is very responsive to currents, and the plume may move between the stations without detection by the present sampling grid. The benthic community is exposed to chronic conditions and some animals will remain for weeks and months within this brine plume shadow. The benthic data were not analyzed as part of this analysis, but there are several competent benthic ecologists who could check on the implications of the results in this report, including: the possibility of a brine plume "halo" or disturbance area around the brine diffuser; oil spills; the presence of brine or oil spill chemical markers in sediments and appearing coincidentally in time or space with changes in the water chemistry, nekton and plankton; and, detection of long-term trends in the benthic data that can be explained by the regional influences of the Mississippi River.

The water column turns over in a matter of days because of currents. The area is accumulating sediments, so dated cores might be useful to investigate the halo, if present, around the plume, and to retrospectively determine impacts near the brine diffuser. The sediments are also the best depository of information on the effects (if any) of a large oil spill (of presently experienced spill or future larger sized spill).

Temporal Scales

The long-term nature of the monitoring effort has numerous invaluable benefits for the State, LOOP, LLC., and the various agencies involved. The LOOP facility is unique to the lower 48 states, and is of unprecedented economic significance in terms of tonnage and strategic economic positioning. It is located, however, directly in the middle of the finest and largest continental shelf fishing zones in the US and the infrastructure is aging. Improving our understanding of the long-term variations in continental shelf ecosystems (water column to benthos; zooplankton to fish) can only help renewable and non-renewable natural resource users manage this environment together, where necessary, and with informed judgment. The data sets we examined are useful for the intent of the monitoring program as identified in the original environmental management plan, but some readjustments are desirable based on the experience of the last 20 years. The Superport is still operating and all significant impacts have probably not occurred (the unrealized large oil spill). The responsibilities for management have not diminished with time.

Other Efforts

This monitoring program is an exceptionally valuable opportunity for science and management interests. Exploring ways to open up these efforts on an ongoing basis to provide data for other scientific efforts, and to publish analyses of the data arising from them would be useful.

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TECHNICAL INFORMATION FOR THE LOOP MARINE AND ESTUARINE MONITORING PROGRAM REVISION:

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INTRODUCTION

The overall goal of Task 3 is to provide LOTA and the PRC the technical information needed for revising the LOOP Estuarine/Marine Monitoring Program. The specific objectives of this data monitoring program (EMP) are:

(1) to obtain seasonal environmental and ecological data so that conditions existing during operation can be compared to the historical (baseline) conditions
(2) to detect during the operation of the project any adverse alterations or damages to the environment so that corrective action can be taken
(3) to obtain sufficient data to determine the cause or causes of environmental damages or alterations so that responsibility can be properly placed; and
(4) to provide information in order to evaluate long and short-term impacts of the project

We have made suggestions and recommendations regarding possible revisions to the LOOP Estuarine/Marine Monitoring Program based upon the analysis of the LOOP water chemistry data (Task 2). These recommendations are designed both to improve the sampling program and to reduce effort either by eliminating variables and/or sample stations, whenever possible. We have attempted to formulate recommendations that are based upon the four objectives stated above. We briefly summarized the pertinent findings from the Task 2 to support these recommendations when appropriate. In some instances the recommendations are based upon professional judgment.

We have organized our recommendations into three basic categories:

(1) overall recommendations
(2) specific sampling recommendations
    (a) variables to be measured
    (b) frequency and depth of sampling
    (c) station distribution
(3) other recommendations

OVERALL RECOMMENDATIONS

- **The monitoring program will be improved simply by extending the data base; in other words, the monitoring should be continued.**

The long-term nature of the monitoring effort has numerous invaluable benefits for the State, LOOP, LLC., and the various agencies involved. The LOOP facility is unique to the lower 48 states, and is of unprecedented economic significance in terms of tonnage handled and its strategic economic positioning. It is located, however, directly in the middle of the finest and largest continental shelf fishing zones in the US. The water chemistry data sets we examined are useful for the intent of the monitoring program as identified in the original environmental management plan. The Superport is still operating and all significant impacts have probably not occurred (e.g., the unrealized large oil spill). The responsibilities for management have not diminished with time. Rather, these responsibilities have increased in the last 2 decades as our knowledge of how human use affects living resources has expanded.

The variability introduced by the Mississippi River is a significant complication of the analysis because of its size and proximity to the monitoring stations. A change in the measured parameter values between a before-and-after impact analysis may not be due to the potential impact factor (e.g., brine), but actually be the result of long-term trends or events in environmental factors unrelated to the LOOP facility use. Adequate monitoring of these long-term trends and events is required to determine responsibility for an impact (EMP Objective 3).

The maximum 'credible oil spill' estimated in the original EIS was 240,000 barrels, which is 500 times larger than that spilled through 1996. It is based on a pre-project spill recurrence interval that is substantiated by experience since 1978, and which includes a total spill volume of about 1,883 barrels. In other words, the recurrence interval graph of the original projections in the EIS and the subsequent events are nearly coincidental. Fortunately, this very large spill has not happened (yet). These results and observations suggest that a credible monitoring program should take into account the information needs of this larger, yet unrealized oil spill.

- **We recommend more frequent sampling be anticipated when a large spill occurs (sampling at more than four times/month) at the long-term monitoring stations.**

Current speeds throughout the region suggest that water masses are replaced in days, not weeks or months. Events like a large (yet unobserved) oil spill similar to that predicted in the original environmental management plans, must be sampled within weeks of the event to establish reasonable baseline conditions against which to measure impacts (EMP Objective 1). If the region were homogeneous, not near the Mississippi River, etc., then baseline conditions might be more safely predicted from less frequent sampling (e.g., quarterly). A second related issue is that the monitoring program should be prepared to mobilize for a Mega-oil spill. The dispersal of surface water and oil will be spread far beyond the LOOP Superport vicinity, and probably spread westward (assuming that is the dominant current direction). However, below the surface, there may be effects spreading in different directions from that in the surface layer.

SPECIFIC SAMPLING RECOMMENDATIONS

Table 1 Summarizes the trend analysis and the impact analyses (BACI) from Task 2. This table presents the results (both significant and non-significant) for each of the water chemistry variables. The trends are presented for inshore and offshore environments for surface and bottom values, and the impacts are presented by impact type (construction, brine discharge, oil spills).

Variables to be measured

- **We recommend sampling all present water quality variables except for Alkalinity, Calcium, Sulfate, Total Dissolved Solids, and Total Solids.**

(1) Alkalinity: This variable shows very little spatial variation and no temporal trends. Therefore it is probably insensitive to any impacts.
(2) Calcium: This variable showed no temporal trends, and was not considered to be an important covariate, Therefore it is probably not useful in the determination of impacts.
(3) Sulfate: This variable is highly correlated with salinity (R=0.86 for surface values and R=0.84 for bottom values).
(4) Total Dissolved Solids This variable is highly correlated with salinity (R=0.97 for surface values and R=0.87 for bottom values).
(5) Total Solids: This variable is highly correlated with salinity (R=0.96 for surface and bottom values).

Table 12. Summary of results (significant and non-significant) from Task 2 water chemistry analysis. Indicated for each water chemistry variable is the trend (positive, negative, not significant) for the inshore and offshore environment, whether an impact (presented by impact type, construction, brine discharge, oil spills) was significant or not significant, and an indication of whether or not a water chemistry variable is considered to be an important covariable. Trends are listed as significant if 70% or more stations in the environment (inshore or offshore) exhibited a statistically significant trend at the 0.05 level. Bold type trends indicate all stations exhibited a statistically significant trend.

I. Surface Variables

	Temporal Trends		Impact Analysis (BACI)				Important
Variable	Inshore	Offshore	Construction.	Brine	Clovelly Oil	Offshore Oil	Co-variable
Alkalinity	No	No	na	na	na	na	No
Ammonia	No	No	No	No	Yes	Yes	Yes
Calcium	No	No	na	na	na	na	No
Chlorophyll-a	No	No	No	No	No	No	Yes
Nitrate-Nitrite	No	No	na	na	na	na	Yes
Oxygen	No	No	na	na	na	na	Yes
Phosphorus	No	No	na	na	na	na	Yes
Salinity	No	No	No	No	No	No	Yes
Silica	**Negative**	No	na	na	na	na	Yes
Sulfate	No	**Negative**	No	No	No	No	No
Suspended Solids	Negative	**Negative**	na	na	na	na	Yes
Total Dissolved Solids	No	No	na	na	na	na	No
Total Kjeldahl Nitrogen	**Positive**	**Positive**	No	No	No	No	Yes
Total Phosphorus	Positive	**Positive**	na	na	na	na	Yes
Total Solids	No	No	na	na	na	na	No
Turbidity	**Negative**	**Negative**	No	No	Yes	No	Yes

II. Bottom Variables

	Temporal Trends		Impact Analysis (BACI)				Important
Variable	Inshore	Offshore	Construction.	Brine	Clovelly Oil	Offshore Oil	Co-variable
Alkalinity	No	Positive	na	na	na	na	No
Ammonia	No	No					Yes
Calcium	No	Positive	na	na	na	na	No
Chlorophyll-a	No	No					Yes
Nitrate-Nitrite	No	**Positive**	na	na	na	na	Yes
Oxygen	No	**Negative**	na	na	na	na	Yes
Phosphorus	No	No	na	na	na	na	Yes
Salinity	No	No					Yes
Silica	No	No	na	na	na	na	Yes
Sulfate	Negative	**Negative**					No
Suspended Solids	No	No	na	na	na	na	Yes
Total Dissolved Solids	No	No	na	na	na	na	No
Total Kjeldahl Nitrogen	**Positive**	**Positive**					Yes
Total Phosphorus	**Positive**	**Positive**	na	na	na	na	Yes
Total Solids	No	No	na	na	na	na	No
Turbidity	No	No					Yes

Frequency and depth of sampling

- **We recommend monthly sampling of the water chemistry.**

Temporal trends were calculated for two cases (1) using the monthly data, and (2) using the quarterly data. Trends were calculated for surface and bottom variables and for both the inshore and offshore environments. Using the monthly data, a total of 20 (8 inshore trends, 12 offshore) trends were detected. Using the quarterly samples, only 7 (2 inshore, 5 offshore) trends were detected. Clearly, quarterly sampling is not sufficient to detect the long-term trends needed to evaluate possible impacts of LOOP (EMP Objective 4).

- **We recommend surface sampling inshore, surface and bottom sampling offshore with occasional mid-depth samples to define important water column structure (e.g., oxygen minimum layer, halocline).**

Correlation analysis indicated a high degree of correlation (correlation coefficients of ~0.9 for 13 variable, >0.7 and <0.9 for 3 variables) between surface and bottom for all the inshore water chemistry variables.

The offshore variables had much lower correlation coefficients (only 2 variables had correlation coefficients >0.8; 9 variables had correlation coefficients <0.5) between surface and bottom.

The mid-depth data did not add much information because it did not define the structure of the water column. A possible modification to the mid-depth sampling would be to use this sample to identify major structures (*e.g.*, low oxygen layer) in the water column. This sample would only be collected when such structure is detected by profile sampling.

Station distribution

- **The stations need to be distributed to cover the LOOP pipeline route, as well as other LOOP potential impact areas with sufficient impact and control stations in each area.**

The general station distribution that we recommend has a total of 28 stations, and is described below. This distribution would have enough stations to monitor the LOOP pipeline, the Clovelly Dome, the brine diffuser, and the offshore terminal. The existing stations can be used in a majority of the cases. The actual number could be less since some of the Clovelly dome stations may also be part of the upper Barataria system pipeline route stations.

The station distribution should have two controls and two impact stations in the following inshore areas along the pipeline route:

(1) The upper portion of the Barataria Bay System (four station total)
(2) The middle portion of the Barataria Bay System (four station total)
(3) The lower portion of the Barataria Bay System (four station total)

Eighty-seven percent of the inshore oil spills occurred at the Clovelly salt dome site (Station no. 38). There are 24 stations with record lengths > or = 10 years, but only one at Clovelly (no. 38). Station 39 is within 1.5 km of no. 38 (WSW), no. 16 is within 2.5 km (WSW), and no. 464 is within 4 km (NE). At least one more impact station should be added at the Clovelly Dome and a second station added within 1.0 km of the Clovelly Dome, resulting in a total of six stations near the Clovelly dome.

The station distribution should have two controls and two impact stations in the following offshore areas:

(1) The brine diffuser (four station total)
(2) The offshore terminal (four station total)

Two controls at a point midway between the brine diffuser and the offshore terminal.

OTHER RECOMMENDATIONS

- **The analysis of the water chemistry data should be integrated with the biological data sets, particularly with the benthic community analyses.**

The benthic community is the logical analytical subject for competent investigation of impacts near the brine disposal and for oil spills (past and present). The benthic community is subject to a probable enhancement around the diffuser if results from other studies are appropriate for this site. The immediate area of the brine plume (about 4 km^2 for a 1+ ppt plume) sweeps over an area of 16 km^2. The plume orientation is very responsive to currents, and the plume may move between the stations without detection by the present sampling grid. The benthic community is exposed to chronic conditions and some animals will remain for weeks and months within this brine plume shadow. The benthic data were not analyzed as part of this analysis and requires, as far as we can tell, annotations to make it usable. This data should be analyzed by independent benthic ecologists to check on the implications of the results in this report, including: (1) the possibility of a brine plume 'halo' or disturbance area around the brine diffuser; (2) the presence of brine or oil spill chemical markers in sediments and appearing coincidentally in time or space with changes in the water chemistry, nekton and plankton; and, (3) detection of long-term trends in the benthic data that may be explained by the regional influences of the Mississippi River.

- **The data from the bottom sled (brine) could be improved by sampling sufficiently in the field to go in all directions until a baseline value is found in all directions, and the salinity contours closed.**

The bottom (brine) sled surveys are an excellent addition to the monitoring, but the contouring is frequently incomplete.

The sled sampling by the State Department of Wildlife and Fisheries clearly located a brine plume whose position on the bottom moves among the stations, adding variability to the measured parameters, and perhaps compromising the results of the BACI sampling design. The variability in bottom salinity at station 473, for example, probably reflects these movements among and between sampling locations (see Figure 15). The BACI analysis cannot, a priori, determine if the plume is over a station or not, and a nearby station may be an adequate control station in one month but an impact station in another month. Fixed control and impact stations cannot, therefore, be assigned.

Some sort of adaptive sampling scheme (network of vertical profiles, towed vehicle) to collect data on the three-dimensional structure of the brine plume should be implemented if major brine discharges occur. This will supply data that can be used to more adequately determine any short-term impacts of brine discharge (EMP Objective 4) and to close the contour profiles outlining the plume in both horizontal and vertical directions.

- **The area is accumulating sediments, so dated cores might be useful to investigate the halo, if present, around the plume and to retrospectively determine impacts near the brine diffuser.**

The water column turns over in a matter of days because of currents. The sediments are also the best depository of information on the effects (if any) of a large oil spill (of presently experienced spill or future larger sized spill).

- **It would be useful to explore ways to open up these efforts to serious scientific efforts and to publish analyses of the data arising from them.**

This monitoring program is an exceptionally valuable opportunity for science and management interests. It would be useful to explore ways to open up these efforts on an ongoing basis to provide data for other scientific efforts, and to publish analyses of the data arising from them.