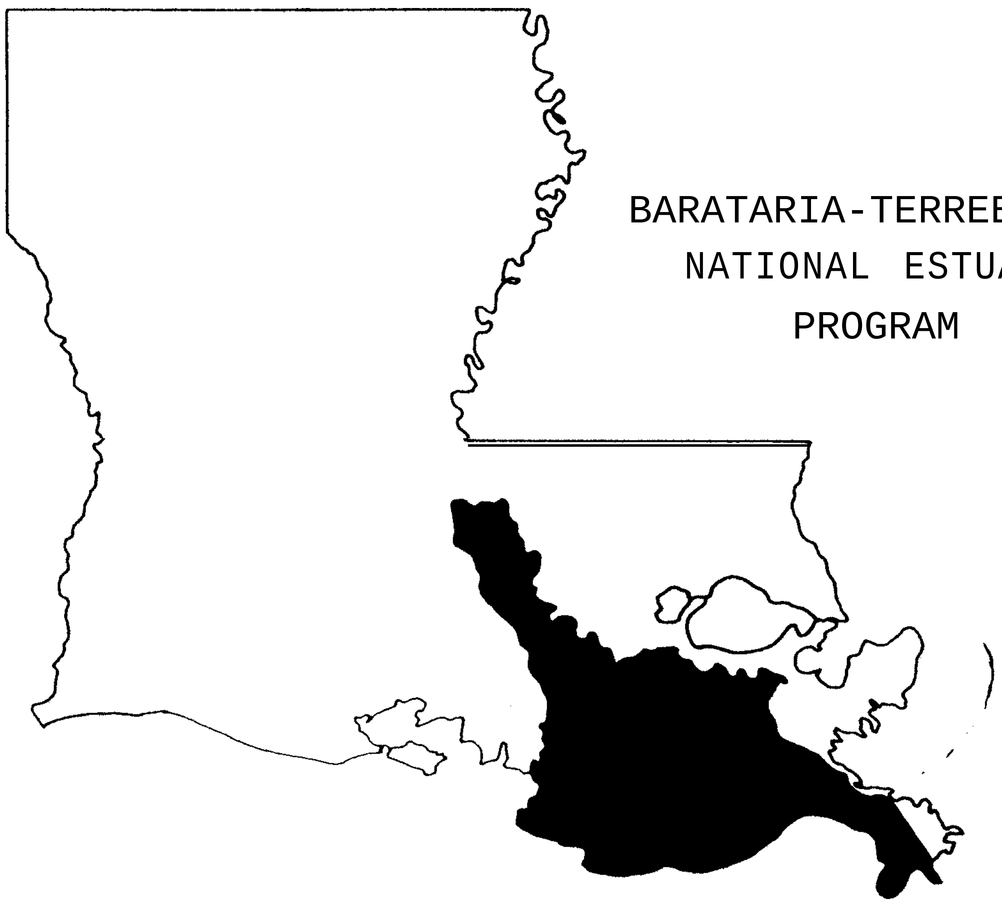
STATUS AND TRENDS OF HYDROLOGIC MODIFICATION, REDUCTION IN SEDIMENT AVAILABILITY, AND HABITAT/LOSS MODIFICATION IN THE BARATARIA-TERREBONNE ESTUARINE SYSTEM



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Status and Trends of Hydrologic Modification, Reduction in Sediment Availability, and Habitat Loss/Modification in the Barataria-Terrebonne Estuarine System

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PREFACE

In 1990, the U.S. Environmental Protection Agency (EPA) and the State of Louisiana agreed to work as partners to establish the Barataria-Terrebonne National Estuary Program (BTNEP). The overall mission of the BTNEP is to work with a wide variety of citizens and interest groups to develop a comprehensive, long-term management plan to preserve and protect the fragile environmental resources of both the Barataria and Terrebonne basins. This novel partnership is based on the premise that true change will take place only if the basins' stakeholders determine for themselves the problems and the solutions. The BTNEP is composed of representatives of not only federal, state, and local government, but also landowners, industry, fishermen, farmers, citizens groups, and academic institutions. The BTNEP is administered by the Louisiana Department of Environmental Quality and governed by a series of committees, each with varied representation and expertise. The committees are collectively referred to as the Management Conference. The final product of the five-year planning process is a Comprehensive Conservation and Management Plan (CCMP) which incorporates specific actions to enhance the quality of life in the Barataria and Terrebonne basins.

One of the many steps taken during the five-year planning process was the development of a series of four reports, which document the current status and the past trends of particular resources within the basins. Members of the report preparation teams were selected by the Management Conference based on their expertise in a particular subject, and with an eye toward ensuring that each subject was given accurate, fair, and balanced treatment. The entire Management Conference and a team of designated reviewers reviewed each draft report and provided comments to the preparation teams at day-long interactive review meetings. At that time the Management Conference also agreed upon needed modifications to each report.

The final step in the BTNEP planning process is the finalization of the CCMP. The information presented in this report will be instrumental in the development of all the management recommendations made in the final CCMP, which is scheduled for submission to EPA in the summer of 1996.

For information about this or other reports or the CCMP, please contact the BTNEP Office.

Steve Mathies
Program Director

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EXECUTIVE SUMMARY

Introduction

The Barataria-Terrebonne estuarine system (BTES) was selected in 1990 to be part of the U.S. Environmental Protection's National Estuary Program (NEP). The Management Conference set up as part of the NEP identified the principal environmental problems facing the estuary as hydrologic modification, habitat loss and modification, reduction in sediment availability, eutrophication, changes in living resources, toxic substances, and pathogen contamination. The purpose of this report is to evaluate the current status and recent trends in factors contributing to three of these priority problems: habitat loss and modification; hydrologic modification; and reduction in sediment availability.

Physical Setting

Over the past 10,000 years the Mississippi River has built the present southeastern coast of Louisiana as a series of overlapping delta lobes. As the transition from one delta lobe to another occurs, the marsh sediments compact and sink under their own weight, gradually losing surface elevation. Marsh vegetation becomes more and more deeply flooded and gradually loses vigor and dies. The marsh soils slowly break up, until finally the emergent delta lobe is replaced by the open waters of the estuary, and the stage is set for a repetition of the cycle. Barrier islands are also formed as part of this cycle of growth and decay. One of the most important implications of the delta lobe cycle for habitat change within the Barataria-Terrebonne estuary is the associated subsidence. Subsidence in the Mississippi River delta plain is complex and variable. Consolidation, settlement, geochemical processes, and faulting all affect and contribute to subsidence.

Vegetation and Habitat Modification

Status

The BTES is composed of a number of different vegetative communities that reflect gradients in salinity (the relative supply of fresh vs. marine water) and land elevation. The coastal marshes occur as adjacent bands of salt, brackish, intermediate, and freshwater vegetation lying parallel to the Gulf coast in a landward direction. These communities can be generally characterized by the following species associations: salt (*Spartina alterniflora*/*Distichlis spicata*), brackish (*Spartina patens*/*Spartina alterniflora*), intermediate (*Spartina patens*/*Vigna* spp./*Sagittaria lancifolia*/other spp.), and fresh (*Panicum hemitomon*/*Sagittaria* spp./*Eleocharis* spp./other species). Floating marshes are found primarily in fresh water areas, but also occur in intermediate and a few brackish areas. The dominant plant species in floating marshes are *Panicum hemitomon* and *Eleocharis* spp. Forests are found in the upper reaches of BTES and can be divided into three types: upland forests (nearly all are cleared for development); deepwater swamps dominated by cypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*); and seasonally flooded bottomland hardwood dominated by several species of oak (*Quercus* spp.). Coastal upland forests are limited to Cheniere Caminada. Barrier island vegetation is characterized by a number of species including *Sesuvium portulacastrum*, *Ipomoea stolonifera*, *Cakile geniculata*, and *Spartina patens*.

The most recent broad scale habitat data available (1988) cover approximately 3.5 million acres of the 4.1 million acres within the BTES area. Based on these data, and additional sources, for the 600,000 acres, there are approximately 909,000 acres of marsh (380,000 acres of fresh marsh and 531,000 acres of non-fresh marsh), 790,000 acres of forested wetland, and 1,500,00 acres of open water.

Trends

Land loss rates for the entire BTES were 18 mi^2 per year from 1956 to 1978 and 21 mi^2 per year for 1978 to 1988/90. About 294,000 acres of marsh were lost to open water from 1956 to 1978. Additional losses occurred due to conversion to development and to agricultural usage. From 1978 to 1988/90, nonfresh marsh alone was lost at a rate of 22 mi^2 per year. Nearly all of the non-fresh marsh was converted to open water.

Land loss for the Barataria basin was calculated from available habitat data to be 7.8 mi^2 per year (0.74% per year) for the period from 1958 to 1978. For the period from 1978 to 1988/90 the land loss rate was 11.1 mi^2 per year (1.3 to 1.5 % per year). In 1956 roughly 39% (429,000 acres) of the coastal area was classified as open water and 50% (528,000 acres) of the area was classified as marsh. The remaining land was classified as agriculture and pasture lands or was developed. In 1978 approximately 49% (538,000 acres) of the area was in open water. Marsh had decreased to 36% (388,000 acres) of the area with fresh marsh accounting for 5%, a loss of about 10 mi^2 per year, and non-fresh marsh about 31%. Other landcover categories remained approximately the same. In 1988/90 about 57% (623,000 acres) of the area was open water. Marsh decreased to about 28% (307,000 acres) of the area. Fresh marsh slightly increased in area to about 6%, an increase of 2.1 mi^2 per year, and non-fresh marsh decreased in area to 22%, a decrease of about 13 mi^2 per year.

The estimated land loss rate in the Terrebonne basin for the period from 1956 to 1978 based on available habitat data was 9.5 mi^2 per year (0.79% per year). From 1978 to 1988/90 the land loss rate was 10.4 mi^2 per year (1.1–1.2 % per year). In 1956 approximately 44% (607,000 acres) of the area was in open water, 50% (684,000 acres) in marsh, and 5% in forested wetlands. In 1978 open water area increased to 54% (741,000 acres) and marsh area decreased to 38% (529,000 acres) with 12% classified as fresh marsh, and 26% as non-fresh marsh. In 1988/90 the amount of open water increased to 59% (821,000 acres). Marsh area continued to decrease to about 33% (456,000 acres) with 12% classified as fresh marsh, a decrease of 0.2 mi^2 per year, and 21% classified as non-fresh marsh, a loss of 9 mi^2 per year.

Comparison of these loss rates with other studies (even though different methodologies were employed) all indicate high and mostly increasing land loss rates through the 1970s and early 1980s. Land loss does not occur uniformly over the Louisiana coastal zone and can be divided into two general types of loss: shoreline erosion and interior loss. Shoreline loss, due to erosion by storms, boat wakes, etc. represents about 31% of the total loss. Most of the rest is associated with interior land loss.

Mississippi River Sediments and their Role in Wetland Loss

Status

The average annual suspended load presently reaching the Gulf is approximately 60×10^6 m^3/yr. Artificial levees, which now line the entire length of the river, prevent sediment and water from being dispersed into the adjacent flood plain and wetlands by preventing overbank flow and crevasse splays from occurring. River sediments are now funneled to the mouth where they are discharged off the continental shelf edge. Although there are few direct avenues for the input of suspended sediment from the Mississippi and Atchafalaya rivers into the coastal wetlands of the BTES, some sediments do find their way into the marshes and swamps. The main source of suspended sediment to interior parts of BTES, isolated from the Mississippi and Atchafalaya rivers is reworking of sediments from the nearshore and coastal bays.

Trends

For over 100 years human modifications have disrupted or eliminated sediment and water pathways into the wetlands and have reduced and modified the amount and character of sediment carried by the Mississippi River. Since 1850, the suspended sediment load of the Mississippi River has declined by almost 80%. In conjunction with a decline in the amount of sediment carried in suspension, there has also been a decrease in the size of the suspended sediment load. Dams on such major tributaries as the Missouri and Arkansas rivers have impacted the river by decreasing the amount and size of sediments that the river transports.

Overbank flooding probably provided the most important source of sediment in terms of quantity, spatial extent of contribution, and period of time, after the interdistributary bays filled in and marine processes could no longer reach the upper portions of the basins. Suspended sediments are introduced into wetlands by overbank flooding when the levees are topped by the river's flow during flood periods. While a river overflows its banks on average of once every 1–2 years, the Lower Mississippi River floods seasonally, in the late winter and spring. Estimates of the pre-1900 accumulation rate of sediment for a 10,000 km² area below Baton Rouge are 1.2 mm/yr. Crevasse splays are important conduits for the transport of water and sediment into backswamps and interdistributary bays of flood basins. From 1849 to 1927, the Mississippi River below Baton Rouge experienced 23 flood years which produced crevasse splays. The number of crevasses per flood year was generally less than four, but as many as 20 were recorded in 1892.

A review of published sources of marsh accretion data showed two sites close to the Mississippi River at South Pass and Empire with relatively high rates of vertical accretion, and this was mirrored on the west side of BTES with most studies close to the Atchafalaya system showing short-term accretion rates in excess of 1 cm/yr. No clear pattern is apparent in the vertical accretion data for marshes isolated from riverine influences.

Hydrologic Modifications

Status

The magnitude of human impacts and hydrological modifications within the Louisiana coastal marshes is well documented. Creation of canals has directly impacted up to 2.59% and 3.45% of the Terrebonne and Barataria systems respectively. Indirect impacts on coastal marshes are of at least the same order of magnitude. In addition to dredge and fill activities related to navigation and mineral extraction, some alterations to natural hydrology have occurred as part of marsh management plans. Natural hydrology of the basins has also been disrupted by road railway construction which has frequently been associated with the construction of embankments across major portions of the estuaries with exchanges from one side of the embankment to the other restricted to culverts or bridges over controlled channels.

Trends

The natural bayous of the BTES systems are sinuous streams which terminate on the coast or in the coastal bays, typically into waters less than 10 feet deep. Many of these bayous have been dredged and deepened at various times to facilitate waterborne commerce and mineral exploration and extraction. The rapid expansion of the offshore oil and gas industry in the 1950s created a need for more direct access from coastal towns to the Gulf, and for the transportation of drilling structures and supplies through the coastal zone to the outer continental shelf. The impact of these channels on BTES include modification of basin circulation and salinity distributions. Studies show that under similar environmental conditions, saltwater penetrates further inland in large, deep channels (such as the Houma Navigation Canal) than in smaller, shallower channels (such as Bayou Petit Caillou). In addition, model simulations confirm that deepening and widening channels can increase saltwater penetration from the Gulf of Mexico.

Additional impacts of these channels are changes in shoreline configuration, interruption of longshore transport, and resultant erosion downdrift of jetties.

In addition to major navigation channels, dredging of smaller canals can severely impact coastal and estuarine systems. Potential indirect impacts of canal dredging can be associated with either the increased channelization of the marsh or the alterations to marsh surface hydrology caused by the dredged material levees. Increased channelization in marshes with previously low drainage densities may allow 1) the more efficient penetration of salt water into areas previously isolated from direct exchanges, and 2) increased tidal flow and enhanced erosion of some marsh types with highly organic soils. Marsh surface hydrology is altered by the placement of dredged material levees adjacent to canals. These levees impede the direct flow of water from the marsh surface to and from the canal. In addition, the high density of well-access canals in some oil and gas fields, and their intersection with dredged material levees associated with some pipeline canals, means that some areas of marsh have become semi-impounded or impounded by these levees. As well as impeding the flow of water onto and away from the marsh surface, dredged material levees may also impede the input of suspended sediment to the marsh surface. The vegetation response to these hydrologic alterations will vary with marsh type.

Structural marsh management in coastal Louisiana is usually designed to control both channel flow and marsh water levels, typically in areas that have experienced modifications to their natural hydrology. Hydrology is altered in order to achieve certain goals such as restoration, conservation or enhancement of emergent marsh or specific vegetation types, in some areas for the specific purpose of enhancing waterfowl habitat. Marsh management may be effective in promoting the growth of submerged aquatic vegetation. The effect of marsh management techniques on controlling salinity in coastal marshes is not consistent. Fixed-crest weirs can reduce the incursion of both saline and fresh waters to marsh areas. When saline waters penetrate into managed areas during storms, structures and levees can increase the residence time of high-salinity water. Increased use of variable structures can allow such water to escape the managed areas. Although drawdown can be used to alter species diversity, effective use of drawdown to increase the area of cover or vegetative vigor of emergent perennial species depends upon the intensity, efficiency, and responsiveness of drawdown. Passive management can reduce the amount of sediment deposition in managed areas compared to adjacent unmanaged areas. Flap-gated structures, a more active management approach, also reduce the amount of suspended material transported into managed areas, but if operated in response to natural cycles of sediment availability these effects could be minimized. Studies of marsh accretion show lower rates of material accumulation in managed compared to unmanaged areas. Flow-through marsh management strategies have potential for enhancing sediment deposition within managed areas but have not yet been broadly applied or quantitatively evaluated.

Trends in Water Levels and Salinities

Status

The BTES is a system characterized by a salinity structure which is determined by the balance between a source of higher salinity water from the gulf endpoint and the freshwater entering the system primarily from precipitation produced runoff. The salinity of the gulf endpoint is influenced by the freshwater plume of the Mississippi River. The precipitation produced runoff enters the system through a complex series of coastal swamps and wetlands, providing a mechanism for the slow release of fresh water over large wetland areas. Model results showed the upper basins to be important to generating and conserving fresh water flow. The natural system however, has had extensive hydrologic modification which has changed the way in which water (and salt) move through the system, causing problems such as impoundment and salt water intrusion, which can lead to vegetation loss.

The relationship between salinities in the marsh substrate and in adjacent open water bodies shows that, in general, the soil salinities (in brackish and salt) respond to variations on the order of several days, and reflect the mean of the open water salinity as opposed to the maximum or minimum. Thus, the soil salinity is moderated relative to the fluctuations in the adjacent water body.

Trends

The existing water level and salinity data bases show no coherent coastwide trends which can explain all of the land loss or change. The trends showed a mixture of both positive and negative trends depending upon location . The trends observed in the water level and salinity data are also very much dependent upon the length of record used in the analysis, the longer the record the better. There are very few records which cover the ~40-year time period over which the vegetation changes have been observed. In addition, the long-term trend signals are very difficult to find in the data due to the large amount of "noise" (natural variation).

The long-term (20+ year) water level records in BTES system showed relative sea level rises ranging from essentially zero to ~2.0 cm/year. Stations nearer to the coast tended to have more rapid rises than the inland stations (at least for Barataria). Analysis of long-term (20+ year) salinity stations indicated that there is no generalized coastwide increase in mean salinity for the estuarine waters, indicating that widespread salinity increases have not occurred. However, specific stations may show an increase which may be of local importance. For example, the salinities at Barataria and Lafitte, show an increase in the number of higher salinity "spikes" (>5 ppt) after about 1960. Possibly this is an effect of the Barataria Waterway.

Analysis of the salinity records by year class indicated that the increase in salinities were not the same over each time period. The most dramatic change was the 1969–1972 time period. The general trends are summarized below:

pre 1955:	no data
1955–1965:	small trends: 9 were positive, 2 were negative
1965–1969:	small trends: 5 were positive, 8 were negative
1969–1972:	large trends: 11 were positive, 4 were negative
1972–1985:	moderate trends: 17 were positive, 1 was negative
1985–1990:	small trends: 5 were positive, 6 were negative
1990–1994:	large trends: 1 was positive, 5 were negative

Analysis of the water level records by year class indicated that the increase in water levels were not the same over each time period. The most dramatic change was the 1969–1972 time period. The general trends are summarized below:

pre 1955:	no data
1955–1965:	small trends: 5 were positive, 4 were negative
1965–1969:	moderate trends: 7 were positive, 3 were negative
1969–1972:	large trends: 9 were positive, 1 was negative
1972–1985:	moderate trends: 9 were positive, 4 were negative
1985–1990:	moderate trends: 11 were positive, 2 were negative
1990–1994:	moderate trends: 5 were positive, 7 were negative

Causes of Wetland Loss

At a local scale, the fate of a marsh is determined by a complex interaction of plant species, local flooding regimes, local circulation patterns that determine mineral sediment inputs, and the extent of damage caused by waterfowl and mammalian herbivory. At the plant scale, remote events such as sea-level rise and canal construction are recorded simply as changes in depth, duration, and frequency of flooding, and as changes in mineral sediment and nutrient input, without regard to the cause. It is these local changes that determine whether a small parcel of marsh remains viable or degrades to an open water body. Thus, understanding the local processes is key to understanding and managing the basin system to minimize wetland loss and to restore lost marshes.

For salt marshes, dominated by *Spartina alterniflora*, a mineral sediment deficiency is the major factor leading to salt marsh degradation. Management strategies should optimize opportunities for sediment input by maintaining an open system without artificial barriers.

Brackish marshes are more complex. The dominant species, *Spartina patens,* is more sensitive than *S. alterniflora* to flooding and salt, but the plant requires mineral sediments to flourish. The key to effective management is to maximize sediment introduction without adverse salt and sulfide effects. Although burning as a management technique is reported to increase production, elimination of burning may be advantageous, since unburned *S. patens* makes a thick aboveground vegetation mat which traps mineral sediments efficiently and within which rooting occurs. Nutrient additions may enhance root growth and increase vertical accretion.

Fresh marshes, as characterized by *Panicum hemitomon*, are sensitive to salt and sulfate intrusion. Healthy mats are stable to most storms, but thin mat floating marshes are easily disrupted. They are sensitive to herbivore activity and probably to burning. Transformation of floating fresh marshes to more salt tolerant associations is problematic because salt tolerant species do not appear to be able to maintain a buoyant, sediment-free mat. Management actions should aim at maintaining a freshwater environment, control of nutria, careful use of burning, and perhaps the use of nutrient additions to enhance mat growth.

Vignettes

The vignette areas were chosen to represent different sections of the basins where loss had occurred. Of the four vignette study sites, three sites are in the Barataria basin (representing intermediate, brackish, and saline marshes) and one in Terrebonne basin (salt/brackish). Madison Bay site is in the salt/brackish marsh in Terrebonne basin; the Bayou Perot and Bayou L’Ours sites lie in the middle region of the Barataria basin; Leeville, in the lower Barataria basin, follows Bayou Lafourche on the west. The areas comprise marshes, open water, canal/spoil, natural levees and swamp-forests along bayous and their distributaries, and agricultural, urban, and industrial sites located on and adjacent to the bayou natural levees and on canal spoil. A close study of a time series of aerial photographs of each site taken between 1945 and 1990 brought home the complexity of the marsh, the number of different processes that can lead to marsh loss, and the complexity of the interaction of processes in space and time.

Changes in Bayous Perot and Rigolettes are primary examples of shoreline erosion. The change in configuration of these streams from the 19th century when they were narrow and sinuous, with dominant point bars, and the present configuration of wide lake-like water bodies with smooth shorelines or small cusps, suggests a major change in circulation from a flow-through riverine system to a tidal estuarine system. The Leeville and Bayou L'Ours sites are primary examples of the results of canal construction associated with oil field development. The canal network tends to increase circulation and accelerate salt intrusion by connecting salt sources such as Bayou Lafourche to interior marshes, and by providing deep, straight pathways of water flow where formerly there was over marsh sheet flow and shallow, sinuous natural bayous. Conversely, the spoil banks effectively isolate patches of marsh from the channels. These impoundments tend to prolong flood duration at deeper depths than normal, and reduce exchange. Damage from past hurricanes is difficult to document, but the timing of marsh losses at Bayou Perot, Bayou L'Ours, and Leeville suggest Hurricane Betsy in 1965 as a contributing factor, possibly exacerbating existing low level chronic stresses caused by impoundment in these areas. The large scale, rapid interior marsh collapse at Madison Bay is impossible to pin down with certainty from available evidence. However, the chronic effect of slow submergence on plant root productivity, which finally triggered a positive feedback loop leading to plant mortality, is a likely partial explanation.

In all case studies the history of the marsh appears to be of major importance. Bayou Perot, Bayou L'Ours, and much of Leeville were fresh marsh sites as recently as the 1940s. Some, perhaps all, supported floating marshes, and were therefore highly organic. The northern portion of Madison Bay may also have been fresher as recently as mid-century. In most of the case histories there is evidence from vegetation changes and/or salinity records of gradual salt intrusion over time. Increased marine influence, and the rate of change to a more marine environment may be critical for the fate of fresh marshes, and the possibility of transition of a fresh and/or floating marsh to a brackish marsh, and finally to a salt marsh. Madison Bay provides an excellent example. The southern portion is a typical salt marsh configuration, with sinuous bi-directional tidal streams supplying broad, stable marshes. Further north the vegetation was brackish in the 1960s and the soils more organic, with less mineral content. These brackish marshes have not had the same ability to cope with subsidence as the salt marshes, and over a period of about 15 years degraded rapidly.

Conclusions and Recommendations

Major Issues

The most striking trend identified in the Barataria and Terrebonne estuarine systems is the massive conversion of land to open water which has been documented in this report. It is clear that the problem results from combined influence of a number of factors (e.g., subsidence, reduced sediment availability, channelization of marshes, interruptions to tidal exchange, altered salinity regimes, increased water levels, etc.). Of these, subsidence is the most important and the most pervasive—a coastwide scale process—impacting all coastal wetlands in the estuaries.

The present BTES still maintains most of the features of typical natural estuaries. Even though the changes in hydrology, salinity and marshes documented in earlier sections have been severe, there is still a fresh to salt gradient, flow across many marshes, and an active fish and shellfish nursery—important aspects of estuarine function and integrity. However, the ramifications of the massive human modification of the estuarine system are of considerable concern as the integrity of estuarine system is threatened.

Management of the system should be guided by the following considerations:

1) A management action is a local action, but its impacts are basin-wide.
2) There are seldom single cause-single solutions to instances of marsh loss. Rather, there is commonly a complex interaction of processes and actions, resulting in chronic stress, leading to gradual and continuing marsh degradation and loss (although "triggers" may be responsible for sudden rapid changes to these stressed systems).

3) The accumulation of minor actions over time can cause major environmental changes. This suggests that any plan must specify limits on the total area of direct impact.

The cumulative effects of multiple interacting actions on local sites, and of accumulating actions over time over the whole BTES, are major management issues and must be addressed in any comprehensive management plan.

Management Recommendations

It is imperative to ensure that local plans enhance rather than detract from system integrity. The broad system-level goals of management might be described as: (1) to maintain and enhance estuarine system integrity; (2) to initiate delta building (the creation of new marshes); and (3) to slow or reverse degradation (wetland loss) of the estuary.

Specific management strategies should be designed to address local problems and not all of these strategies are appropriate in all marsh types or areas. The recommended process management strategies can be summarized as follows.

Offensive

Short-term: Beneficial use of maintenance dredged sediments (small scale);
Dedicated dredging to create new emergent marsh (small scale).
Long-term: Diversion of river sediments into open water areas (large scale);
Use pipelines to convey sediments from river source to areas of need (small or large scale).

Defensive

Short-term: More effective use of freshwater and sediments from the Mississippi and Atchafalaya rivers, including siphons (small or large scale);
Backfill pipeline canals and unused location canals (small scale);
Plug pipeline canals and unused location canals (small scale);
Remove dredged material levees and replace with natural levee elevation banks (small scale);
Control herbivory (small or large scale);
Prevent shoreline erosion of marshes (small scale).
Long-term: Freshwater diversions from Mississippi River (large scale).

In order to effectively management the BTES, scientific understanding of system processes and the interaction between system components must be increased. This report has documented the need for detailed study of two critical elements: the importance of tidal scour as a mechanism of marsh loss, and the role of barrier islands in maintaining the integrity of the estuarine system.

PART 1

INTRODUCTION

Denise J. Reed
Louisiana Universities Marine Consortium

INTRODUCTION

The Barataria-Terrebonne estuarine system (BTES) was selected in 1990 to be part of the U.S. Environmental Protection Agency's National Estuary Program (NEP). The NEP was established in 1987 to promote long-term planning and management of nationally significant estuaries threatened by pollution, development, or overuse. The Governor's Nomination (Roemer 1989) identified the principal environmental problems facing the estuary as hydrologic modification, habitat loss and modification, eutrophication, changes in living resources, toxic substances, and pathogen contamination. One of the first steps taken by the NEP, once established, was the setting up of a Management Conference involving volunteer members from federal, state, and local government agencies; commercial, recreational, and industrial users of the estuary; educational and scientific communities; and the general public. This Management Conference affirmed the original six problems and added a seventh: reduction in sediment availability. This additional problem recognizes the particular problems of subsidence facing the estuary as a result of its geologic history.

The purpose of this report is to evaluate the current status and recent trends in factors contributing to three of these priority problems:

(1) Habitat loss and modification,
(2) Hydrologic modification, and
(3) Reduction in sediment availability.

This evaluation will be used by the Management Conference in the development of the Comprehensive Conservation and Management Plan for the BTES. That plan will recommend priority corrective actions to balance the conflicting uses of the estuary while maintaining its natural ecological and geomorphic integrity.

Although it recognizes the broad array of problems facing the area, the Governor's Nomination (Roemer 1989) focuses on tidally influenced portions of the BTES. For the purposes of this report, therefore, the BTES includes those tidally influenced environments delimited by the west bank levees of the Mississippi River to the north and the west bank of South Pass to the east. The western boundaries are the Atchafalaya Bay, Atchafalaya River and the east guide levee of the Atchafalaya basin. The southern boundary is the Gulf of Mexico. The boundaries of BTES defined by the NEP encompass all land and water within these specified boundaries (Figure 1.1). This report, however, will focus on the tidal portion of the estuary as we believe these are the areas of most critical concern for the three priority problems to be addressed. Watershed issues will only be considered where they have a major influence on the tidal areas.

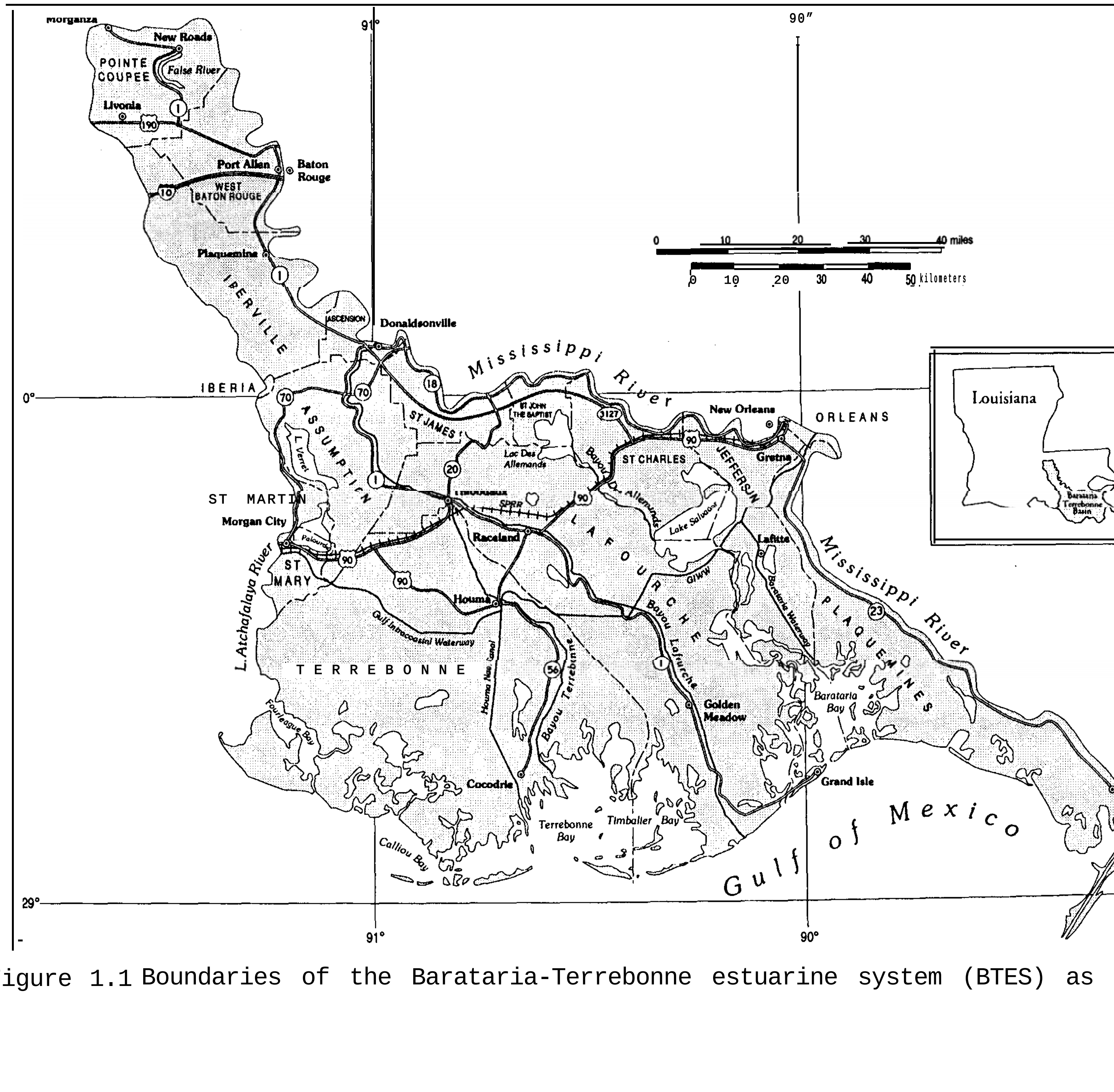

Figure 1.1 Boundaries of the Barataria-Terrebonne estuarine system (BTES) as

The approach adopted in this report is to amalgamate and evaluate previous assessments of issues related to the three priority problems. Where new data are available, they will be analyzed and reviewed in relation to existing data sets. In addition, new comparisons and syntheses of existing data sets may be necessary to elucidate particular trends within the estuary. To enumerate some aspects of the hydrologic modification priority problem is too monumental a task to be undertaken here. It has not been feasible to amalgamate details on all modifications that have been made to the estuary. Rather, the approach is to examine the way in which hydrologic modifications influence estuarine processes, providing illustrative examples where possible.

Similarly, to synthesize the details of priority problem impacts for the entire Terrebonne and Barataria estuaries, although recognized as a critical component of designing an effective management plan, was not feasible with currently available resources. The approach adopted in this report has been to select four small areas within the BTES which exemplify habitat types, sediment problems, and hydrologic modifications, and examine them in some detail. These evaluations are termed "vignettes" in this report. The consideration of vignettes illustrates the type of approach necessary to understand in detail the problems facing the estuary.

The report is structured to provide some contextual information regarding the geology and contemporary processes within the system, followed by new evaluations of habitat loss and change considered in comparison to previous studies, examination of changes in sediment availability and its movement into the coastal wetlands, review of hydrologic modifications and their impact on estuarine processes, detailed analysis of available water level and salinity data for the estuaries, and then an integrated approach to how the processes already described contribute to wetland loss. The vignettes section provides detailed assessment of selected areas. Each of these sections has been developed by teams of scientists. The conclusions and recommendations reflect the current views of the entire team working on the report, and are based upon the best available scientific information about the BTES.

The report reflects the level of scientific understanding of estuarine processes at the time of writing. As our information base and level of knowledge increase in the future, these recommendations may, and should, evolve to reflect the improved status of the science and more progress towards fully understanding the status of our estuary.

PART 2

PHYSICAL SETTING

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INTRODUCTION

The Louisiana coastal area can be divided into two distinct geomorphic zones: (1) the deltaic plain, which makes up the eastern portion of the Louisiana coastal zone, and (2) the chenier plain, west of the Atchafalaya River. The Barataria-Terrebonne estuarine system, which is the focus of this report, is located in the deltaic plain. This section reviews the geological history and present status of the delta plain.

GEOLOGICAL CONTEXT

Holocene Geology

Over the past 10,000 years the Mississippi River has built the southeastern coast of Louisiana as a series of overlapping delta lobes. This process has been described in many excellent reports (Fisk 1944, Fisk and McFarlan 1955, Frazier 1967, Coleman 1988, Wells and Coleman 1987, Penland et al. 1994) and will be summarized only briefly here. When the Mississippi River changes its course and its flow spreads out onto a new location on the shallow shelf of the Gulf of Mexico, the reduced velocity causes the river to deposit its sediment load and a delta lobe is built (Figure 2.1). This land is rapidly invaded by plants, forming freshwater intertidal marshes—fresh because the river is the dominant hydrologic force. As the new delta lobe grows, the pathways of water flow become longer and less efficient. Finally, the river breaks through its banks upstream and diverts to another location to build a new delta lobe, a process known as avulsion. During the transition from one delta lobe to another, river flow may occur down two distributaries simultaneously. Eventually, the abandoned lobe, deprived of its fluvial freshwater and sediment supply, becomes increasingly saline, starting at the seaward edges and moving inland. Marshes change from freshwater species to salt-tolerant species. As the transition occurs, the marsh sediments compact and sink under their own weight, losing surface elevation. Marsh vegetation becomes more deeply flooded and gradually loses vigor and dies. The marsh soils slowly break up, until finally the emergent delta lobe is replaced by the open waters of the estuary, and the stage is set for a repetition of the cycle.

The Barataria-Terrebonne estuary is fronted by a series of headlands and barrier islands, which have resulted from the delta lobe cycle. Penland et al. (1988) described the formation of an erosional headland with flanking barrier islands from an active distributary mouth after the distributary is abandoned. Sand deposits contained within the abandoned headland are reworked and dispersed longshore into flanking barriers enclosing interdistributary bays (Figure 2.2). Submergence of the delta plain separates the headland from the shoreline, creating a lagoon behind a barrier island. The landward-migrating island arc is unable to keep pace with relative sea level rise and

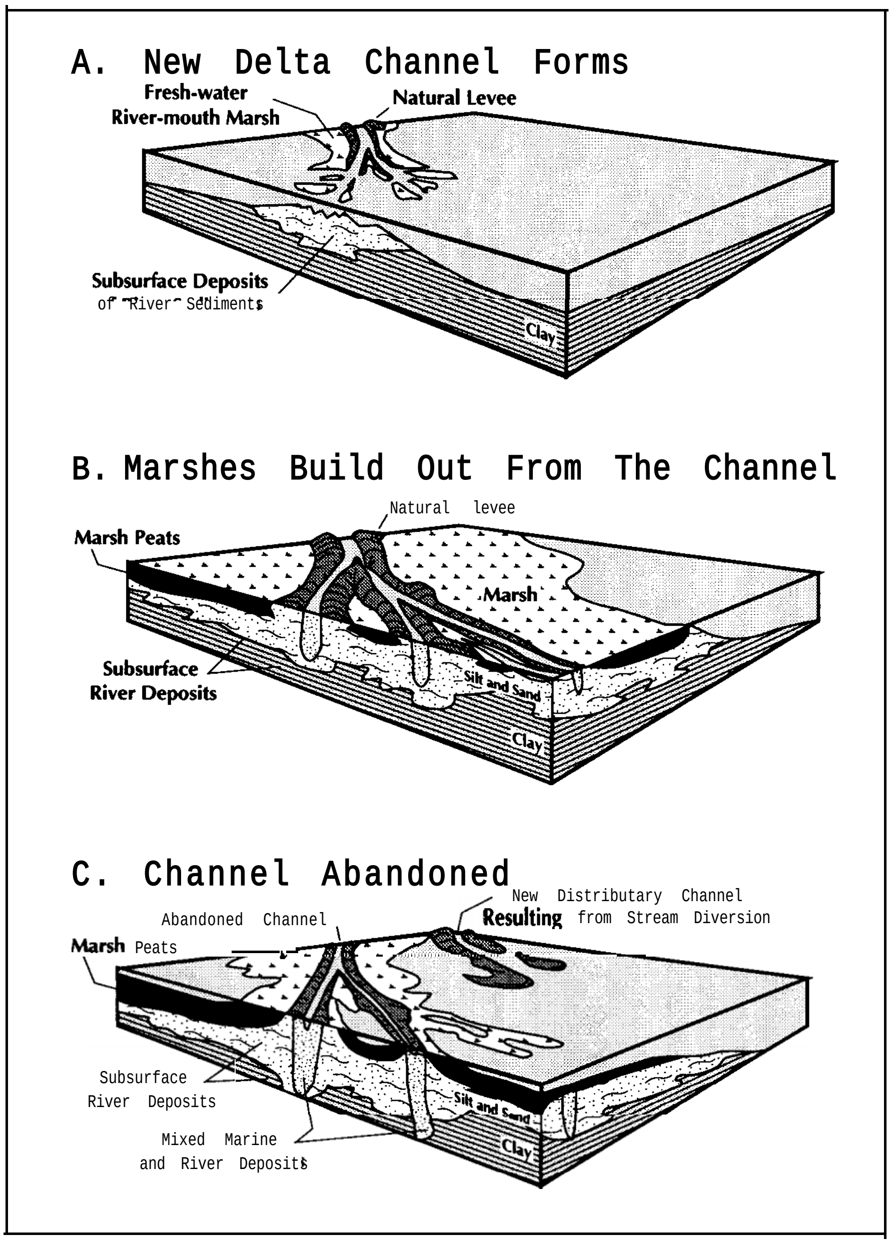

Figure 2.1. Idealized growth and decay of a delta lobe (Gosselink 1980).

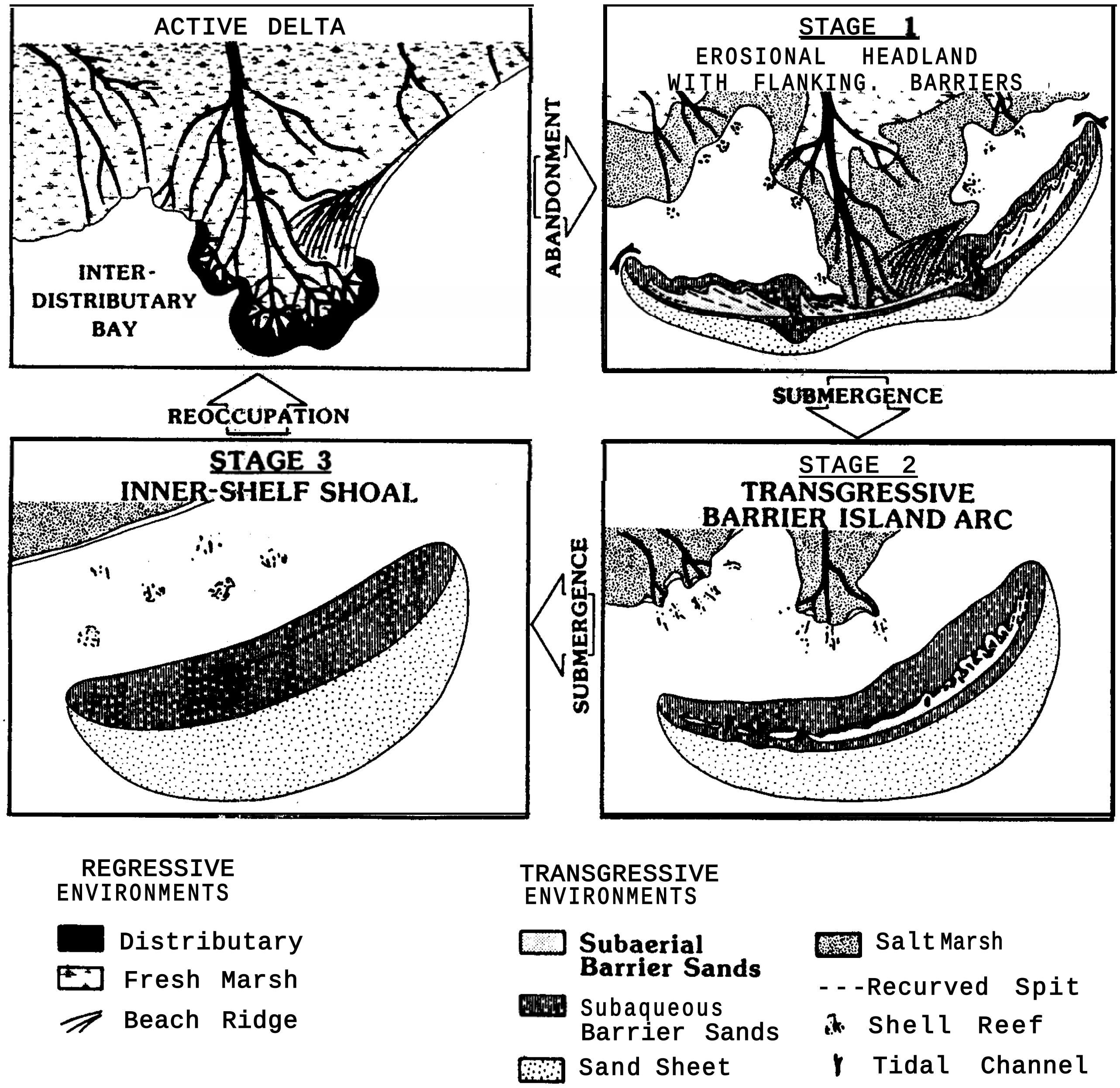

Figure 2.2 The genesis and evolution of transgressive depositional systems in the Mississippi River delta plain, summarized by this three-stage geomorphic model (Penland et al. 1988a), which begins with stage 1, erosional headland and flanking barriers. Next is stage 2, transgressive barrier island arc. The sequence ends with stage 3, inner-shelf shoals

the retreating mainland shoreline, resulting in submergence of the island and the formation of an inner shelf shoal (Penland et al. 1988a). Eventually, the island is leftfar from the mainland (e.g., the Chandeleur Islands), with further deterioration resulting in the formation of a shoal (e.g., Ship Shoal).

Since the last period of glaciation ended about 10,000 years ago, there have been a number of episodes of delta lobe growth. Figure 2.3 shows one reconstruction of the growth of the coast (Kolb and van Lopik 1958) with an outline of the Barataria-Terrebonne estuary superimposed. The estuary is underlain by parts of a number of delta lobes: on the west the Maringouin and Teche delta complexes, 4000-7000 years old; on the east the St. Bernard delta complex, 1000–4600 years old; in the center, the Lafourche delta complex, beginning about 3500 years ago and extending to the present; and on either flank, the modern, active Belize delta (east) and the Atchafalaya delta (west).

The natural cycle of growth and decay historically took about 5,000 years, with a rapid growth phase and a slow period of degradation. It is illustrated in Figure 2.4 from Gagliano and Van Beek (1975). Note the authors' speculation that biological production lags the evolution of the delta lobe, with maximum biological production during the middle of the decay phase. This is because the estuary becomes increasingly physically and biologically diverse after the river abandons it. As oceanic forces impose a strong salinity gradient, the landscape pattern becomes more complex, and the biota themselves mature.

All parts of the delta plain are in various stages of decay with the exception of the Atchafalaya which is active and expanding. Although the Belize delta is not prograding, some sediments move into adjacent areas. Thus, this estuarine system is composed of actively expanding flanks fed by the Mississippi River and its major distributary, the Atchafalaya River, and a large center section that is in various stages of deterioration and is fronted by a barrier island system. Geologically the estuary is extremely diverse. Those parts strongly influenced by river flow function much differently than the older delta lobes.

Subsidence

One of the most important implications of the delta lobe cycle for habitat change within the Barataria and Terrebonne estuaries is the associated subsidence. Subsidence in the Mississippi River delta plain is complex and variable. Consolidation, settlement, geochemical processes, and faulting all affect and contribute to subsidence (Penland et al. 1994).

The age and thickness of Holocene deposits have been identified on a regional basis as important factors contributing to subsidence. The thickest Holocene sediments are within the incised valley of the Mississippi River. Fisk (1944) identified the western boundary of the incised valley as trending from the Atchafalya basin near Morgan City through Point au Fer and offshore west of Ship Shoal. The eastern boundary of the incised valley trends offshore east of New Orleans. Consequently, most of the Terrebonne and Barataria basins lie directly over the incised valley and

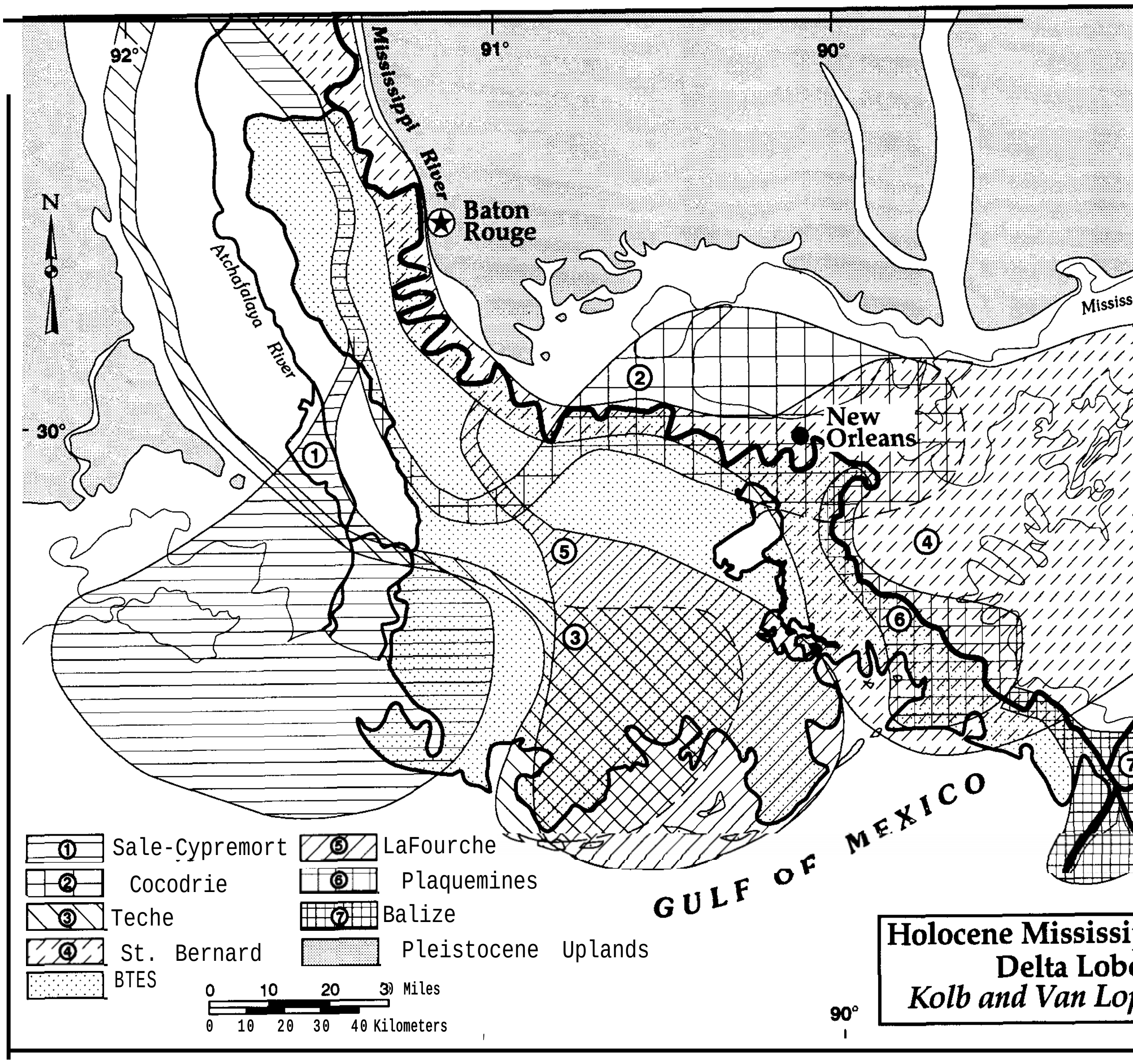

Figure 2.3 Major delta lobes that make up the active delta of the Mississippi

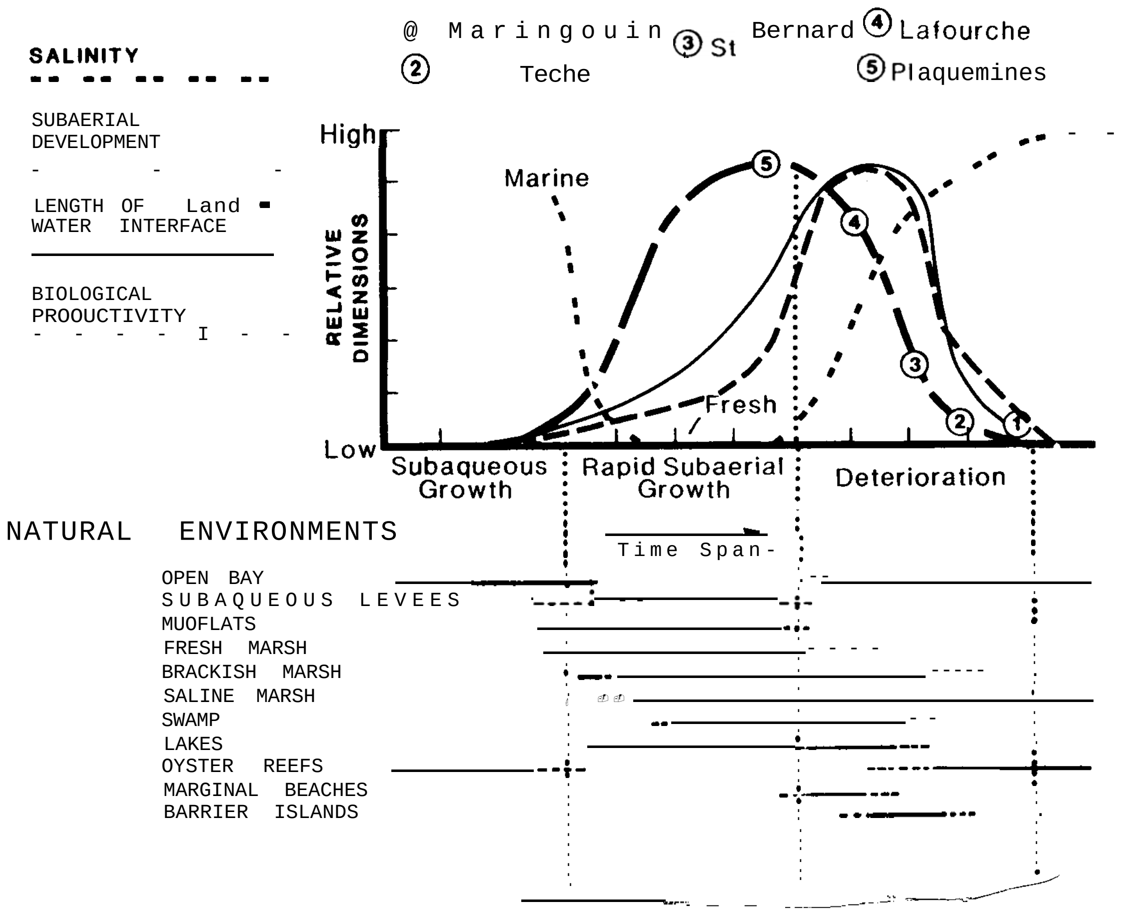

Figure 2.4 Graphical depiction of the growth and decay of a delta lobe (Gagliano and Van Beek 1975). Note that the major lobes making up the Barataria-Terrebonne estuary are all on the decay side of the cycle.

almost 100 m (330 ft.) of Holocene fluvial and deltaic sediments (Penland et al. 1994). Because the fill within the incised valley is composed of individual backstepping delta plains, the age of the deposits varies with location. Penland et al. (1994) present radiocarbon data from the Terrebonne basin that show that younger delta surfaces subside faster than older deltaic surfaces. The trend of diminishing subsidence with age reflects progressive consolidation of the delta deposits.

Kuecher et al. (1993) used geotechnical testing of the facies that compose a typical delta cycle to show that peats, organic rich sediments, prodelta clays and bay clays have the greatest consolidation potential. The distribution of such facies across the Barataria and Terrebonne estuaries is exemplified in Figure 2.5. Wherever the subsidence-prone facies are thickest, subsidence due to consolidation is greatest. In addition, position relative to active faults can locally control the rate of subsidence. Keucher (1994) documented that the downthrown sides of growth faults in the Mississippi River delta plain have a greater potential for subsidence. Higher rates of subsidence on the down throw side provide opportunity for preferential accumulation of subsidence-prone facies. A strong correlation is noted by Penland et al. (1994) between the down-thrown side of the Lake Hatch fault and land loss in the Lake DeCade area of the Terrebonne basin.

The highest rates of subsidence noted by Penland et al. (1994) using geodetic, tide gauge and radiocarbon data sets were 0.5–1.0 cm/yr (0.20–0.39 in/yr.) directly over the incised valley of the Mississippi River, the midst of the Terrebonne basin.

Barrier Islands

The coastal barrier islands of the Barataria-Terrebonne system represent the seaward limit of the estuarine system with exchange between the estuaries proper and the Gulf of Mexico taking place through tidal inlets between the islands. Shoreline change studies have recently been undertaken for Louisiana's barrier shorelines as part of a five-year cooperative agreement between the U.S. Geological Survey and the Louisiana Geological Survey. According to the terminology used in this study (e.g., McBride et al. 1991), the shorelines bordering the Barataria-Terrebonne estuary are the Isles Dernieres, the Timbalier Islands, the Caminada-Moreau Headland/Grand Isle complex, and the Plaquemines shoreline. These areas are all presently undergoing rapid erosion with long-term (>100 years) rates of gulfside erosion ranging between 22.9 m/yr (75.1 ft/yr) and 4.8 m/yr (15.8 ft/yr) for the islands of the Isles Dernieres chain (McBride et al. 1992). This dramatic shoreline retreat appears to be mainly the result of erosion during the passage of cold fronts (Dingler and Reiss 1990).

All of the BTES barrier islands are experiencing some degree of landward migration. While migration is common in barrier systems, it has been accompanied in the BTES by losses in land area, as a consequence more of island narrowing rather than of a reduction in length (Williams et al. 1992). The narrow islands are vulnerable as they are more easily overwashed and do not develop significant dune systems (Ritchie and Penland 1988). Shallow passes open up with storms that do not reseal after the return of fair weather (Levin 1993), although during fair weather

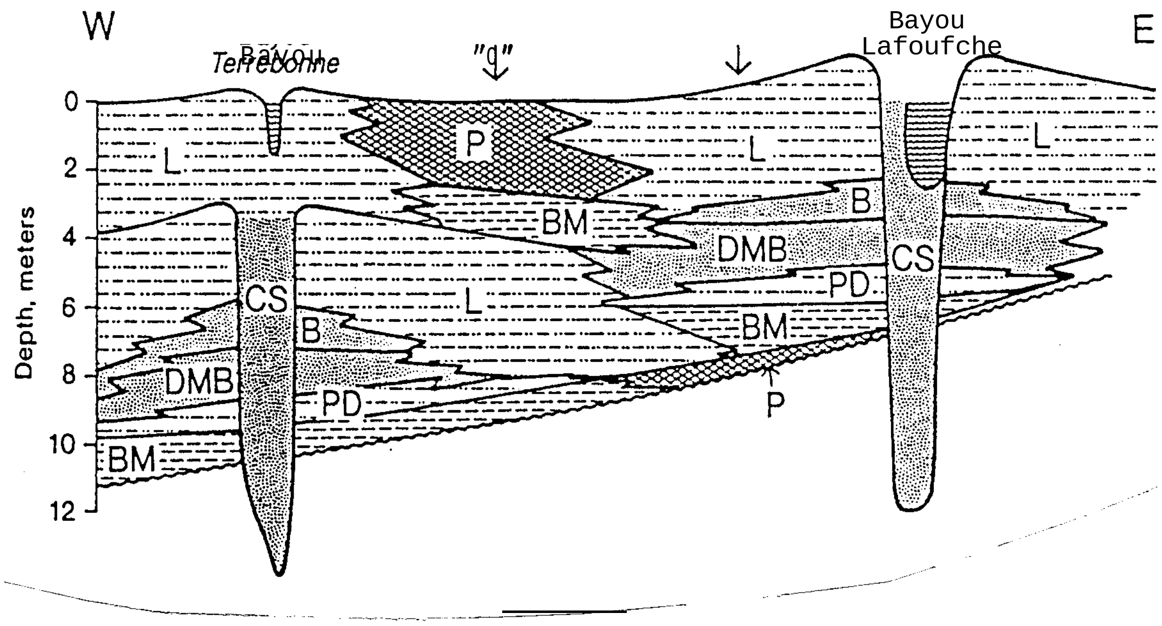

Figure 2.5 Schematic cross section on the eastern side of the Lafourche delta basin, illustrating the facies relationship that may exist. Legend: BM = bay mud; P = peat; PD = prodelta; DMB = distributary mouth ba = beach; CS = channel sand; and L = levee (Kuecher et al. 1993).

conditions there may be some short-term recovery from shoreline erosion. The Isles Dernieres and Timbalier chains decreased in area by70% from 5,209 ha (12,864 acres) in the 1890s to 1,551 ha (3,834 acres) in 1988 (Williams et al. 1992). McBride et al. (1992) showed a dramatic loss of wetlands behind parts of the Plaquemines barrier shoreline, from Bastion Bay to Bay Coquette, between 1973 and 1988. These changes resulted in detachment of the shoreline and the creation of islands.

Shoreline change analysis has also revealed that the bay shoreline of many barrier islands in the Barataria-Terrebonne system is also undergoing erosion. McBride et al. (1989) showed that between 1853 and 1988 shoreline change rates along the Whiskey Island section of the Isles Dernieres bayside shoreline reached 5.6 m/yr (18.4 ft/yr) in a seaward direction. Such rates were confirmed by field studies conducted by Reed (1989a) who measured erosion of almost 4 m (13.1 ft) between March 1987 and March 1988 on the bayside shoreline of the Isles Dernieres. Erosion of both gulfside and bayside shorelines of barrier systems in Louisiana, as well as tidal inlet expansion due to storm activity, has been incorporated into a conceptual model of barrier island erosion by McBride et al. (1991), which is summarized in Figure 2.6. Barrier islands gradually fragment and narrow and, according to the Penland et al. (1988a) model of shoreline development in Louisiana, in time they will gradually become shoals. Indeed, the detailed studies of the Isles Dernieres erosion, outlined above, have allowed predictions to be made of how long the islands will continue as discrete sub-aerial units. Estimates shown in Table 2.1 were originally made based upon long-term erosion rates (1880s–1980s) and short-term rates (1978–1988) (McBride et al. 1992). However, Penland et al. (in press) were able to examine the particular influence of Hurricane Andrew on short-term erosion rates for the islands, and, as shown in Table 2.1, the life-expectancy of the islands has decreased dramatically.

The examination of short-term loss rates is an important component of predicting barrier island disappearance and individual storm impacts may decrease island width to below a viable threshold for island recovery. These projections do not always incorporate the potential for short-term recovery from storm impacts may occur as shoreface equilibrium profiles are reestablished. Although some immediate recovery may occur, Dingler and Reiss (1990) found that such recovery was rarely enough for the beach face to regain profiles and forms present before the impact of cold fronts.

Changes in island area provide a limited perspective on how well the barriers function to protect mainland marshes from normal and storm-induced waves and how they affect circulation through back barrier bays and marshes. Narrower and lower profile barriers are more easily breached and overtopped, but any decrease in the linear Gulf frontage, or displacement of islands by passes affects estuarine hydraulics more directly. At the same time that the Terrebonne barriers decreased in area by 70%, they experienced a reduction in cumulative length of only 14%. The Barataria islands decreased in area by 47% but have seen a decrease in Gulf frontage of only 32%.

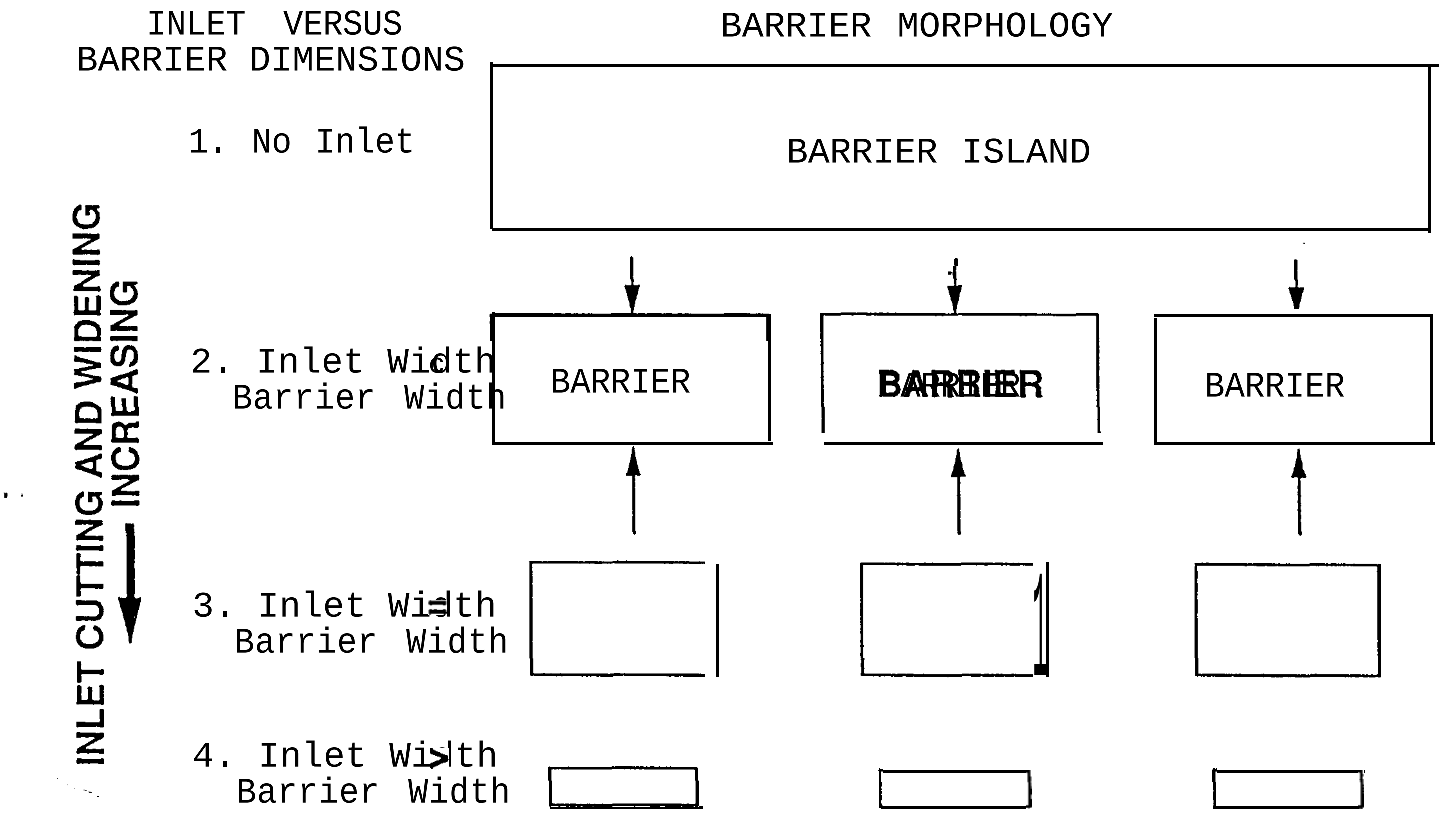

Figure 2.6 Model of changing barrier island morphology (after McBride et al. 1991).

Table 2.1 Predicted data of barrier island disappearance in Louisiana updated for the impact of Hurricane Andrew in 1992.

Barrier Island	Long-term Rate (LT)	Short-term Rate (ST)
Isles Dernieres	2015[1]/2011[2]	2004[1]/2002[2]
Timbalier Island	2046[1]/2028[2]	2000[1]/1999[2]
East Timbalier Island	NA/2002[2]	1997[1]/1996[2]
Grand Isle	>2100[1]/>2100[2]	>2100[1]/>2100[2]
Grand Terre	2033[1]/2008[2]	2008[1]/2002[2]

[1]McBride et al. (1992): LT 1880'S–1980'S/ST: 1978–1988.
[2]Penland, S., Westphal, K., and Zganjar, C. (in press). The Impact of Hurricane Andrew (1992) on Louisiana's Barrier Islands. U.S. Geological Survey, Miscellaneous Investigations Series Map I-0000.

CONTEMPORARY PROCESSES

Climate

The coastal regions within the northern Gulf of Mexico are part of the humid, subtropic climate region that includes the southeastern United States (Muller and Fielding 1988). This climate region is characterized by hot summers, relatively mild winters, and average precipitation that exceeds average evapotranspiration (Muller and Fielding 1988). The general climatology throughout the year is determined by the lower atmospheric circulation which produce the local weather. Muller (1977) used data from New Orleans to classify the weather into eight synoptic weather types. The general conditions associated with each of the synoptic weather types (based upon yearly means) are listed in Table 2.2.

The data in Table 2.2 indicate that the majority of the precipitation, on a regional scale, is explained by two weather types, the frontal overrunning and the frontal Gulf return. If the precipitation from tropical disturbances is included, one can conclude that 80% of the precipitation is associated with "stormy" weather types. The weather types have distinctive seasonal patterns. The occurrence of the "Pacific high" and the "coastal return" tend to be fairly evenly distributed throughout the year. The Gulf return and the frontal Gulf return have a generalized peak in the spring. The

Table 2.2. General conditions associated with each of the eight synoptic weather types, based upon data from New Orleans (adapted from Muller and Fielding 1988). The numbers represent annual means.

Type	Occurrence	Precipitation		Winds > 17 knots	
	% of hours	mm	%	hours	%
Pacific high	3	1	0	117	4
Continental high	23	3	0	465	14
Frontal overrunning	18	460	30	837	25
Coastal return	12	84	5	48	1
Gulf return	17	138	9	576	17
Frontal Gulf return	13	637	41	975	29
Gulf high	11	81	5	51	2
Tropical disturbance	3	150	10	282	8

continental high and the frontal overrunning types tend to have peak occurrences during the fall and winter. Both the Gulf high and the Gulf tropical disturbance have distinct peaks occurring from early summer through the fall. The seasonal rainfall among the types is also different, and when combined with the seasonal pattern of the synoptic types produces a distinct rainfall regime. During the winter, the frontal Gulf return and the frontal overrunning account for all of the rainfall. These same two types also account for 90% of the rainfall during the spring (Muller and Willis 1983). During the summer, all of the types are capable of producing light afternoon showers, however the continental high showers are usually insignificant and the types associated with maritime tropical air produce significant amounts of rainfall. The frontal Gulf return, however, is the most significant rainfall producer during the summer months of June through August (Muller and Willis 1983). The fall is a transitional period during which the frontal weather types again become dominant. This is also the time during which Gulf tropical disturbance rainfall becomes important.

Tropical storms and hurricanes are considered to be the most significant storm events along the Gulf Coast. Hurricanes generally occur between May and November with the peak frequencies occurring in September. Hurricanes have major impacts on the water exchange and hence the salinity distribution of Gulf Coast estuaries. A hurricane affects these systems both by the addition of fresh water through exceptionally heavy rainfall and through storm surges. These storm surges, which are associated with the long fetch of hurricane-induced onshore winds can cause massive flooding of the coastal wetlands. For example, the storm surge associated with Hurricane Camille in August 1969 caused massive flooding of Plaquemines Parish in Louisiana and a surge of 6.9 m (22.6 ft) at Pass Christian, Mississippi (Muller and Fielding 1988). Although hurricanes occur on a regular basis on the Gulf Coast, hurricane-induced winds and surges are actually quite uncommon at any given point along the coast (Muller and Fielding 1988).

Hydrology

The Barataria-Terrebonne estuary today is flanked by the two largest rivers in the United States. These rivers carry a combined average flow of 15,360 cumecs (542,756 cfs) (maximum flood flow of 57,900 cumecs (2,045,936 cfs)), and a daily sediment load of 1 to 1.5 million metric tons (0.98–1.48 million tons). The Mississippi River is leveed on its west bank so that the historical spring overbank flooding into the estuary no longer occurs. Most of the water and sediments are carried out of the mouth of the river into the deep water on the edge of the continental shelf where most of the sediment sinks and is lost from the coastal system. The fresh river water and the finest sediments, however, are usually carried by prevailing currents in a large gyre westward, curving back eastward along the shore of the Barataria basin. As a result, the offshore water, and consequently the tidal water entering the estuary is nearly always measurably diluted by river water. Salinity is depressed and nutrients are enriched by this dilution. On the west edge of the estuary, the Atchafalaya River is not leveed below the Avoca Island Cutoff (less than 16 km (10 miles) below Morgan City), so some of its water flows out through, and enriches with nutrients and sediments, the flanking marshes. During high river stages Atchafalaya River water may also flow northward up the Avoca Island Cutoff Channel to the Gulf Intracoastal Waterway (GIWW), and then eastward through the GIWW across the northern portion of the Terrebonne basin. Under these conditions, flows through the Avoca Island Cutoff may exceed 340 m^3s^{-1} (12,000 cfs). Measurements indicate that a substantial amount of this water reaches Houma, where up to 142 m^3s^{-1} (5,000 cfs) or more may flow down the Houma Navigation Channel (HNC) and up to 85 m^3s^{-1}(3,000 cfs)or more may flows eastward towards Bayou Lafourche (Paille, personal communication).

Fresh water draining from the Verret basin into the GIWW through Bayou Boeuf appears to dominate flows in the GIWW during moderate to low Atchafalaya River stages. The Verret discharge may range up to 198 m^3s^{-1} (7,000 cfs). However, under certain conditions, water may flow northward from the GIWW into the Verret basin. Depending on winds and tides, freshwater draining from the Verret basin may flow both to the east and west via the GIWW. Winds, tides, and Atchafalaya River stage determine how much of the water flows west to the Atchafalya River, and how much flows east to Houma. During moderate Atchafalya River discharge of 5,100 m^3s^{-1} (180,000 cfs), approximately 70 to 72% of the GIWW freshwater flows entering Houma flow southward down the Houma Navigation Channel. This percentage may vary depending upon winds, tides, and the volume of fresh water reaching Houma. Strong winds from the south overcome this and cause flow to the north in the Houma Navigation Channel. This is unlikely to occur during periods of high Atchafalaya River flow when the volume of fresh water entering the channel is larger. Much of the fresh water remaining in the GIWW flows to and beyond Bayou Lafourche, as confirmed by measurements in GIWW just west of Bayou Lafourche (R. Paille, personal communication).

Other flows of fresh water into the estuary occur through Bayou Lafourche, smaller streams, and a complex system of drainage canals that drain the land immediately north of the estuary and the fastlands along the distributary ridges. These flows are small in comparison to the two major rivers, but they empty directly into the estuary and, in combination with local rainfall, keep the upper portion of the estuary fresh. These freshwater sources are enriched in nutrients, and carry high loads of pesticides, other organic chemicals, and heavy metals, the consequences of which are poorly documented.

The magnitude of freshwater flows and the maintenance of salinity gradients in the estuary is controlled by a seasonal rainfall pattern (Figure 2.7). The average annual rainfall is about 150 cm (59.1 in), with about 50% evaporated each year. Therefore there is a surplus of about 75 cm (29.5 in), which infiltrates the soil or runs off through the estuary. Rainfall is fairly evenly distributed throughout the year, but evaporation is maximum during the hot summer months, as shown in Figure 2.7. The net result is a large rain surplus during the winter and spring, and very little surplus during the summer. In fact, a slight water deficit is likely even during summer rains but the pattern can vary considerably from year to year. Since this pattern of precipitation is typical for most of the Mississippi River valley, the river typically floods during the winter and spring and has low stages during the summer, magnifying the seasonal cycle of fresh water. As a consequence of the surplus rainfall, salinities in the estuary are almost always less than oceanic, a gradient of decreasing salinity is maintained from the coast inland, and impoundments in the coastal zone typically become increasingly fresh, even in the saline marsh area. Despite the freshwater surplus there may be short periods in the summer when evaporation exceeds precipitation. During these times, the saline water in marsh sediments can be concentrated enough to burn and sometimes kill local vegetation.

Marine tides and tidal flows are strongest along the central coast of the estuary, where river influence is weak. Tides enter the estuary through passes between the barrier islands and flow up-estuary through natural channels like Bayou Lafourche and Grand Bayou Blue. Several human-made channels also enhance tidal flows, both flood and ebb. These include the north-south trending Barataria Waterway and the Houma Navigation Canal. The GIWW traverses east-west across the estuarine system.

Tides along the coast are primarily diurnal, rather than the more common semi-diurnal pattern of the U.S. east coast. Tide range is only about 30 cm (1 ft), thus tidal energy is low. Nevertheless, tidal currents in the passes can be strong, and, because of the flat slope of the estuary, the tidal influence on water levels is felt as far as 80 km (50 km) inland. Water levels and tidal currents in the estuary can be greatly influenced by winds. Strong winds from the south tend to "pile" up water along the coast forcing water into the estuaries, raising water levels on the order of 0.3–0.5 m (1–1.5 ft) above normal. Conversely, winds from the north can force water out of the estuaries, depressing the water levels 0.3–0.5 m (1–1.5 ft) below normal.

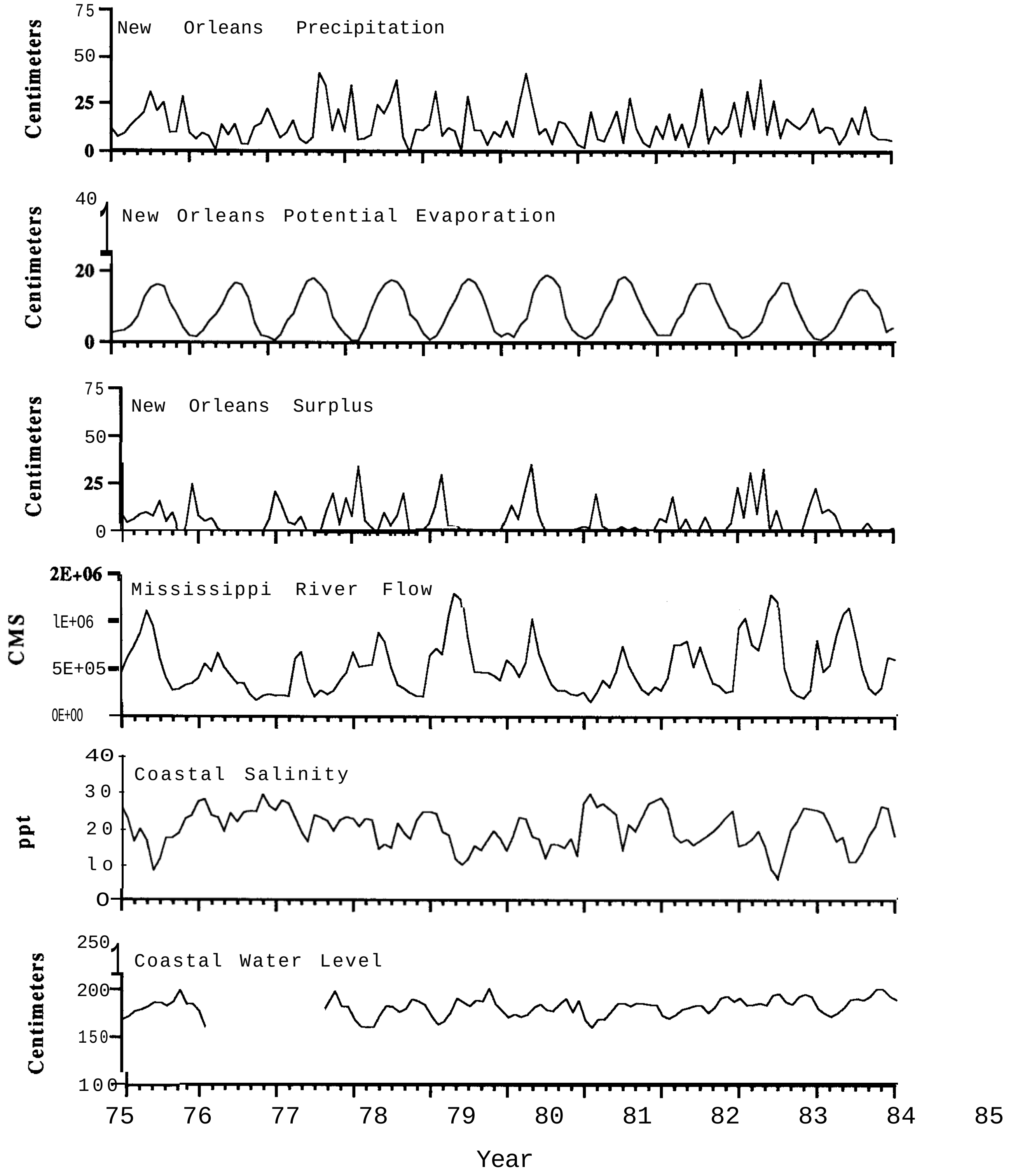

Figure 2.7Patterns of precipitation and evaporation measured at New Orleans (1975-1985) in comparison to Mississippi River discharge, showing the impact of these factors on coastal salinity and water levels.

PART 3

STATUS AND TRENDS IN VEGETATION AND HABITAT MODIFICATIONS

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INTRODUCTION

Perhaps the most important factor influencing the estuary is the rapid rate of wetland loss. While the factors contributing to this loss are complex and operate at many scales (as discussed below), the immediate cause of most wetland loss is submergence caused by subsidence of the land coupled with rising sea levels, both of which increase marsh flooding. Vertical aggradation, that is sediment deposition and production of organic peat, counteract submergence, raising marsh level. So the balance between these two sets of processes determines whether marshes will stay in the intertidal zone or will sink beneath the water. In the Barataria-Terrebonne estuary the submergence rate is about 1 cm/yr (3.25 ft per century), although the rate is variable from one location to the next. In river-influenced marshes with at least moderate mineral sediment supplies, accretion equals subsidence. However, most of the estuarine system is sediment-deficient in this respect, and these marshes are rapidly sinking and falling apart. Peat production is the major aggradational process in much of the freshwater marsh on the northern flank of the estuary. In these marshes the organic peat mass may begin to float, maintaining the marsh at the surface of the water in spite of subsidence.

VEGETATION

The first careful description of major marsh communities in Louisiana was made by Penfound and Hathaway (1938). They described the cypress-tupelo gum swamp; the fresh marsh dominated by cattails (*Typha spp.*), giant bulrush (*Scirpus californicus*), sawgrass (*Mariscus jamaicensis)*, and maidencane (*Panicum hemitomon*); the cane zone adjacent to levee areas dominated by Roseau cane (*Phragmites commmunis*) in the freshwater area and by hog cane (*Spartina cynosuroides*) in the more saline areas; salt marshes dominated by salt grass (*Distichlis spicata*) and oyster grass (*Spartina alterniflora*); and brackish marshes dominated by wire grass (*Spartina patens*), salt grass, and needle grass (*Juncus roemerianus*).

Marshes

In 1949, O'Neil (1949) published the first vegetation map of the Louisiana coast. His book was about muskrats and the vegetation zones reflect the vegetation most important as muskrat food. The map delimits fresh, intermediate, brackish, and saline marsh zones by the dominant plant species, and is the first (and until recently the only) map to identify floating fresh and brackish floating marshes (Figure 3.1). Because of

O'Neil's interest in vegetation important to muskrats, the vegetation communities described are not exactly equivalent to those described in more recent maps (e.g., Chabreck et al. 1968)).

Chabreck et al. (1968) surveyed the whole Louisiana coast by helicopter, and using Penfound and Hathaway's (1938) and O'Neil's (1949) classifications produced a detailed coastal vegetation map, which they updated in 1978 and 1988 (Chabreck and Linscombe 1988, Chabreck and Linscome 1978). Their maps show adjacent bands of salt, brackish, intermediate, and freshwater vegetation lying parallel to the Gulf Coastin a landward direction (Figure 3.2). Recently, the Southern Science Center (SSC), National Biological Service, generated landcover and wetland trend data from various data sets developed by the SSC and the Louisiana Department of Natural Resources based on the Cowardin et al. (1979) wetland classification system. Habitat data for 1956 and 1978 were developed by the U.S. Fish and Wildlife Service (FWS) (Wicker 1980) from photointerpreted aerial photography. The habitat data for 1988/90 are a merged data set produced by the SSC and based on 1988 FWS habitat data photointerpreted from aerial photography and 1990 classified Thematic Mapper Satellite water data (Appendix G). As with the Chabreck and Linscombe data, these data also depict adjacent bands of vegetation parallel to the Gulf, because Chabreck and Linscombe's data were used in delineating the boundaries between different habitat zones.

Two primary environmental factors control species distribution throughout the marsh—salinity and elevation. The broad vegetation bands reflect primarily salinity differences. Elevation is an important species determinant adjacent to the larger coastal streams where slightly elevated natural levees allow less flood-tolerant species to grow. The major elevated areas in the Barataria-Terrebonne basin are adjacent to the Mississippi River on the east, the Atchafalaya River on the west, the remaining distributary ridges (e.g., along Bayou Lafourche and Bayou Terrebonne), and some remnant coastal headlands just west of Grand Isle.

Floating Marshes

In 1994 Sasser and co-workers (1994) published a series of maps of the floating marshes in the Barataria-Terrebonne basin.[1] Floating marshes occur predominantly in the freshwater zone of the coast, although some intermediate and even a few brackish marshes do float (Sasser et al. 1994). They apparently develop in quiet freshwater environments where organic matter production in the absence of mineral sediment inputs make the marsh mat buoyant. As the underlying mineral substrate subsides, the

[1] Production of this map series was funded by the U.S. Environmental Protection Agency to support the Barataria-Terrebonne National Estuary Program. Summary maps will be available late in 1995.

buoyancy of the mat eventually leads to its separation from the substrate, and it subsequently floats on the water surface. Sasser et al. (1994) estimated that about 70% of the freshwater marshes in the Barataria-Terrebonne estuary are floating, a total of about 116,000 ha (286,528 acres).

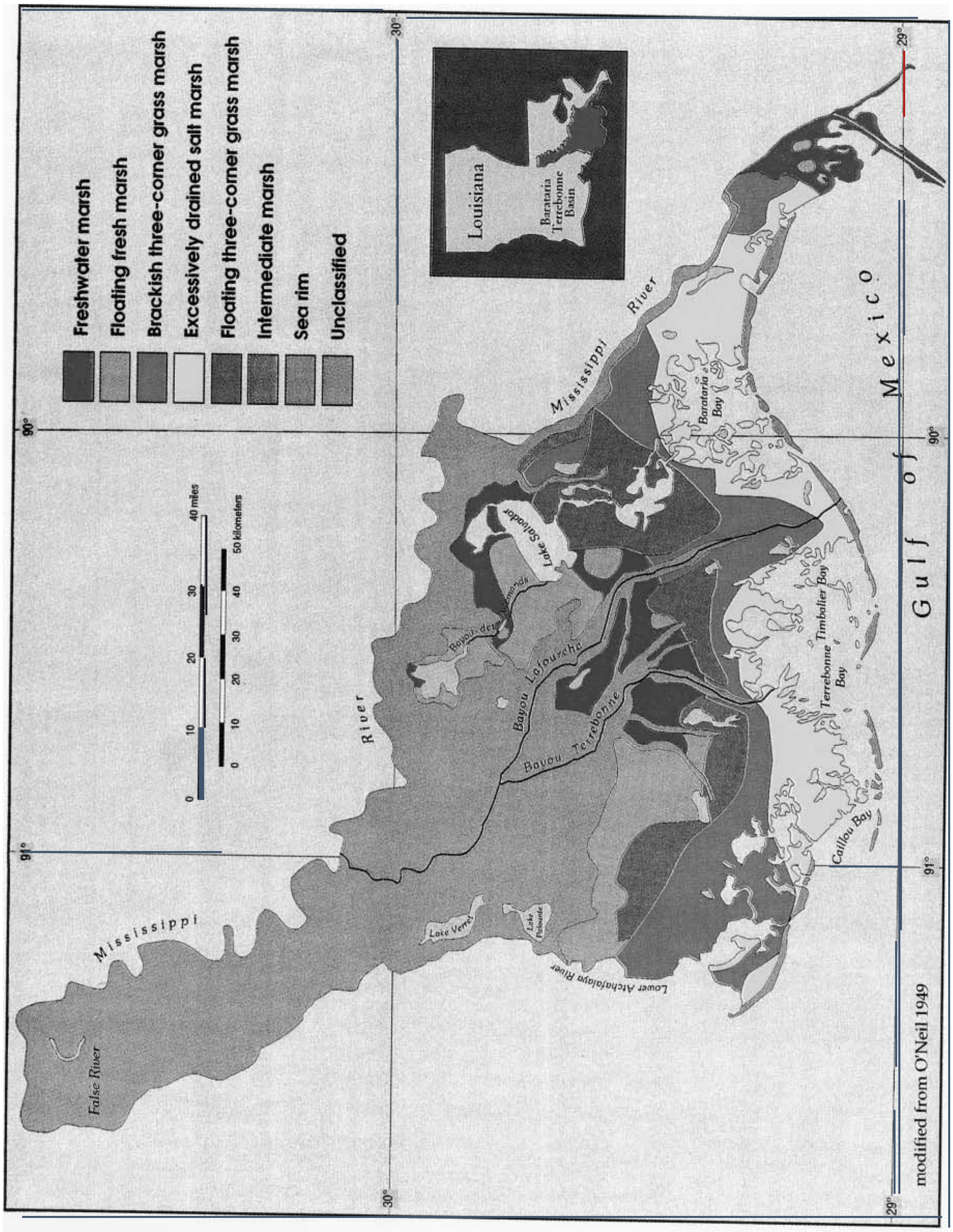


Figure 3.1. O'Neil's (1949) vegetation map of the Louisiana coast.

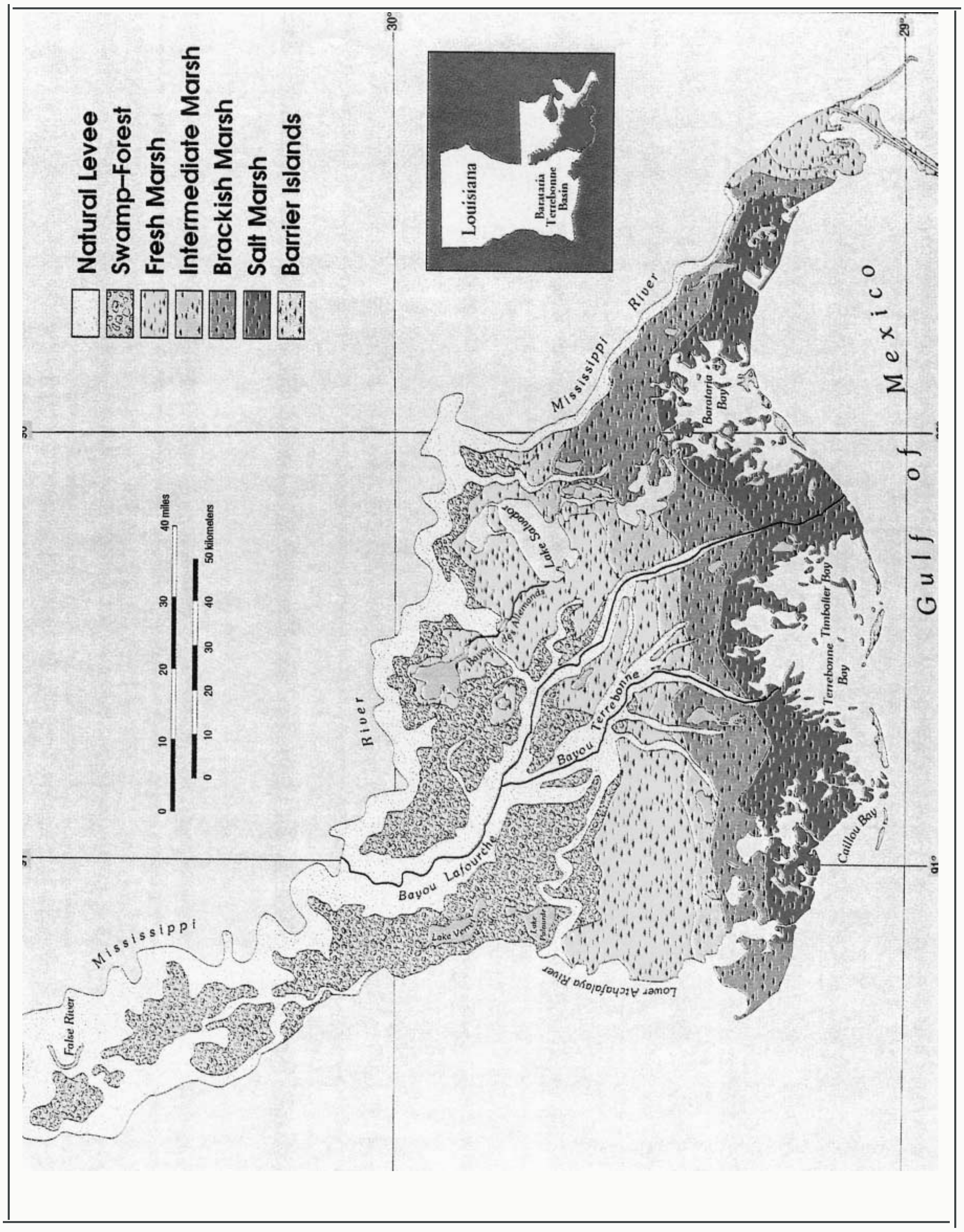


Figure 3.2. Vegetation of the Barataria-Terrebonne estuarine system as mapped by Chabreck and Linscombe (1988)

Other Habitat Types

Large areas of forested wetland, which Chabreck and co-workers did not map, lie landward of the freshwater marshes in the upper reaches of both subbasins. The highest ridges, especially in the Lake Verret subbasin in the extreme northwest of the BTES, support small areas of upland forest, although most of the area suitable for these terrestrial species has long since been cleared for agricultural production and industrial and urban use. The Gulf of Mexico is rimmed with beaches and a low dune/swale habitat that supports plant species adapted to dryer and harsher conditions. The reworked beach headlands east of Bayou Lafourche support the last remaining coastal forest on the Mississippi River delta plain. This forest is dying as the cheniers on which it is growing subside, as attested by the silhouettes of dead trees along its lower edges.

SPECIES COMPOSITION

Marshes

Relatively few wetland species dominate the flora of the coast. Species richness is extremely low in the salt marshes, increasing in an inland direction to the diverse fresh marshes and wetland forests. Major species, listed by salinity zone, are shown in Table 3.1. The only salt-tolerant tree species on the coast is the black mangrove, *Avicennia germinans*, which exists at the northern extreme of its range, and is kept as a shrub or small tree by periodic killing frosts. It is part of the saline marsh flora. Appendix A contains an extended list that includes most species found on the coast.

In a current study, Visser (unpublished data) is reanalyzing the vegetation data accumulated by Chabreck and Linscombe in their 1968, 1978, and 1988 surveys, as well as additional surveys they have made over smaller sections of the coast. Preliminary results of ordination of the species-by-plot matrices confirms the validity of the four vegetation zones used by Chabreck to classify marsh vegetation (Figure 3.3). It also subdivides the four zones into additional plant clusters. These include *Spartina alterniflora/Distichlis spicata* and *S. alterniflora/Juncus roemerianus* associations in the salt marsh, *S. patens/D. spicata* and *S. patens/Scirpus olneyi* associations in the brackish marsh, *S. patens/Vigna luteola* and *Paspalum sp.* associations in the intermediate marsh zone, and a number of associations dominated by *Sagittaria lancifolia, Eleocharis sp., Aeschynomene indica, Panicum hemitomon, Phragmites australis,* and *Scirpus californicus* in the fresh marsh zone.

Some of the fresh marsh associations identified above are probably usually floating marshes, especially the *Panicum hemitomon*–dominated association, and the *Eleocharis*–dominated association. The former dominates widespread floating marshes characterized by a thick, organic mat held together with live intertwined roots, that

floats year-around over a layer of clear water. The latter association is also widespread, forming a thin mat that will not usually support an individual's weight,

Table 3.1. Percentage cover of the dominant plant species in major marsh zones of the Louisiana coast (Chabreck 1972).

Species	Salt	Marsh zone Brackish	Intermediate	Fresh
Batis maritima	4.41	0	0	0
Distichlis spicata	14.27	13.32	0.36	0.13
Juncus roemerianus	10.10	3.93	0.72	0.60
Spartina alterniflora	62.14	4.77	0.86	0
Eleocharis parvula	0	2.46	0.49	0.54
Ruppia maritima	0	3.83	0.64	0
Scirpus olneyi	0	4.97	3.26	0.45
Scirpus robustus	0.66	1.78	0.68	0
Spartina patens	5.99	55.22	34.01	3.74
Bacopa monnieri	0	0.92	4.75	1.44
Cyperus odoratus	0	0.84	2.18	1.56
Echinochloa walteri	0	0.36	2.72	0.77
Paspalum vaginatum	0	1.38	4.46	0.35
Phragmites australis	0	0.31	6.63	2.54
Alternanthera philoxeroides	0	0	2.47	5.34
Eleocharis sp.	0	0.82	3.28	10.74
Hydrocotyl umbellata	0	0	0	1.93
Panicum hemitomon	0	0	0.76	25.62
Sagittaria falcata	0	0	6.47	15.15
Other species	2.43	5.09	25.06	29.10
Total	100.00	100.00	100.00	100.00
Total number of species	17	40	54	93

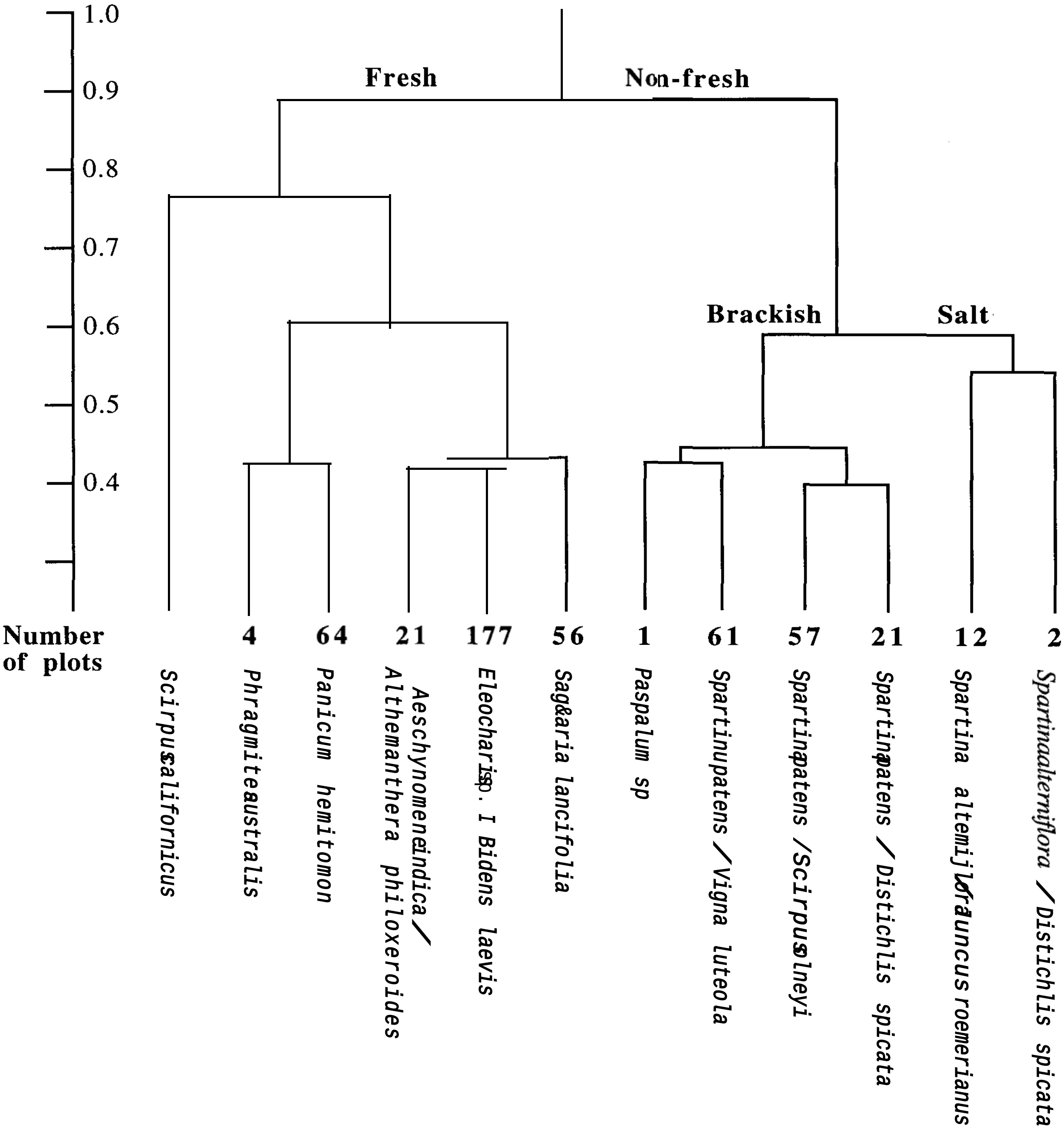


Figure 3.3. Twinspan analysis of marsh vegetation data collected by Chabreck and Linscombe (Visser, unpublished data).

and that is periodically submerged for months at a time. Sasser et al. (1994) identified additional floating marsh types that are less frequently found. Most of them appear to be developmentally related to the two described above.

Wetland Forests

Wetland forests have an extremely diverse flora of trees, shrubs, and herbs (Conner et al. 1986). They can be roughly divided into deep-water swamps, dominated by bald cypress (*Taxodium distichum)* and tupelo gum (*Nyssa aquatic*), with a red maple (*Acer rubrum*) and buttonbush (*Cephalanthus occidentalis*) understory; and seasonally flooded bottomland hardwood forests dominated by several oak species (*Quercus* spp.), green ash (*Fraxinus pennsylvanica* var. *lanceolata*), and other hardwood species (Table 3.2). In the Barataria-Terrebonne basin the two types of forest occur about equally. In addition, there is considerable area characterized as scrub/shrub, which increasingly refers to the plant associations developing on elevated dredge deposits.

Coastal Upland Forests

A unique plant association on the Caminada chenier headland is all that remains of the coastal forests that used to fringe much of the coast, on the barrier islands and along the larger natural levees such as along Bayou Lafourche. Nearly all this association has been cleared for habitation, or as in the case of Caminada chenier, has subsided below the elevation that will support an upland forest. The remaining fragment is dominated by live oak (*Quercus virginiana*) and water oak (*Q. nigra*), with hackberry and other species. Buckbush (*Baccharis halmifolia*) and marsh elder (*Iva frutescens*) are the dominant shrubs, with considerable dwarf palmetto (*Sabal minor*) present.

Barrier Islands

The vegetation of the beaches fronting the Barataria-Terrebonne estuary is characterized by several "invaders" on the incipient dunes along the beach forefront, including beach purslane (*Sesuvium portulacastrum*), a recumbent succulent that grows and spreads as a dense mat; sea rocket (*Cakile geniculata*); and beach morning glory (*Ipomoea stolonifera*) (Ritchie and Westphal 1989) (Appendix B). Wiregrass (*Spartina patens*) is ubiquitous along the beach crest and in more protected environments between and behind the dunes, often accompanied by salt grass (*Distichlis spicata*) and sandrush (*Fimbristylis castanea*). In sandy areas behind the dunes, where salt often concentrates, a variety of succulents such as saltwort (*Batis maritima*) and glasswort (*Salicornia bigelovii*) are found. The marshes on the landward edge of the islands has typical salt and brackish vegetation, including oyster grass (*Spartina alterniflora*) and the black mangrove, *Avicennia germinans.*

Table 3.2.Dominant plant species of BTES swamps and bottomlands.

	Bottomland Forest [1]	Alluvial River Swamp [2]
Dominant Canopy Trees	***Quercus*** **spp. (oaks)**	***Taxodium distichum*** **(bald cypress)**
	Liquidambar styraciflua **(sweet gum)**	***Nyssa aquatica*** **(water tupelo)**
	Carya aquaticas **(water hickory)**	
	Celtis laevigata **(sugarberry)**	
Sub-dominant Trees	***Ulmus*** **spp. (elms)**	***Acer rubrum*** **var. *drummondii* (Drummond red maple)**
	Acer rubrum **(red maple)**	***Fraxinus tomentosa*** **(pumpkin ash)**
Shrubs	***Cornus drummondii*** **(rough-leaf dogwood)**	***Cephalanthus occidentalis*** **(buttonbush)**
	Planera aquatica **(water elm)**	***Salix nigra*** **(black willow)**
	Crataegus **spp. (hawthorn)**	
	Salix nigra **(black willow)**	
Herbs and Aquatic Vegetation		***Lemna minor*** **(duckweed)**
		Spirodella polyrhiza **(duckweed)**
		Riccia **sp.**
		Limnobium Spongia **(common frog's bit)**

[1]**After Clark and Benforado (1979).**
[2]**After Conner and Day (1976).**

HABITAT LOSS AND MODIFICATION

Methodology

The landcover and wetland trend data utilized by the Southern Science Center (SSC) for this project were generated from various data sets developed by the SSC and the Louisiana Department of Natural Resources. Three landcover data sets were used to examine habitat modification and loss for this study. Habitat data for 1956 and 1978 were based on data developed by the U.S. Fish and Wildlife Service (Wicker 1980). The habitat data for 1988/90 are a merged data set produced by the SSC and was based on 1988 Fish and Wildlife Service habitat data and 1990 classified Thematic Mapper (TM) Satellite water data.

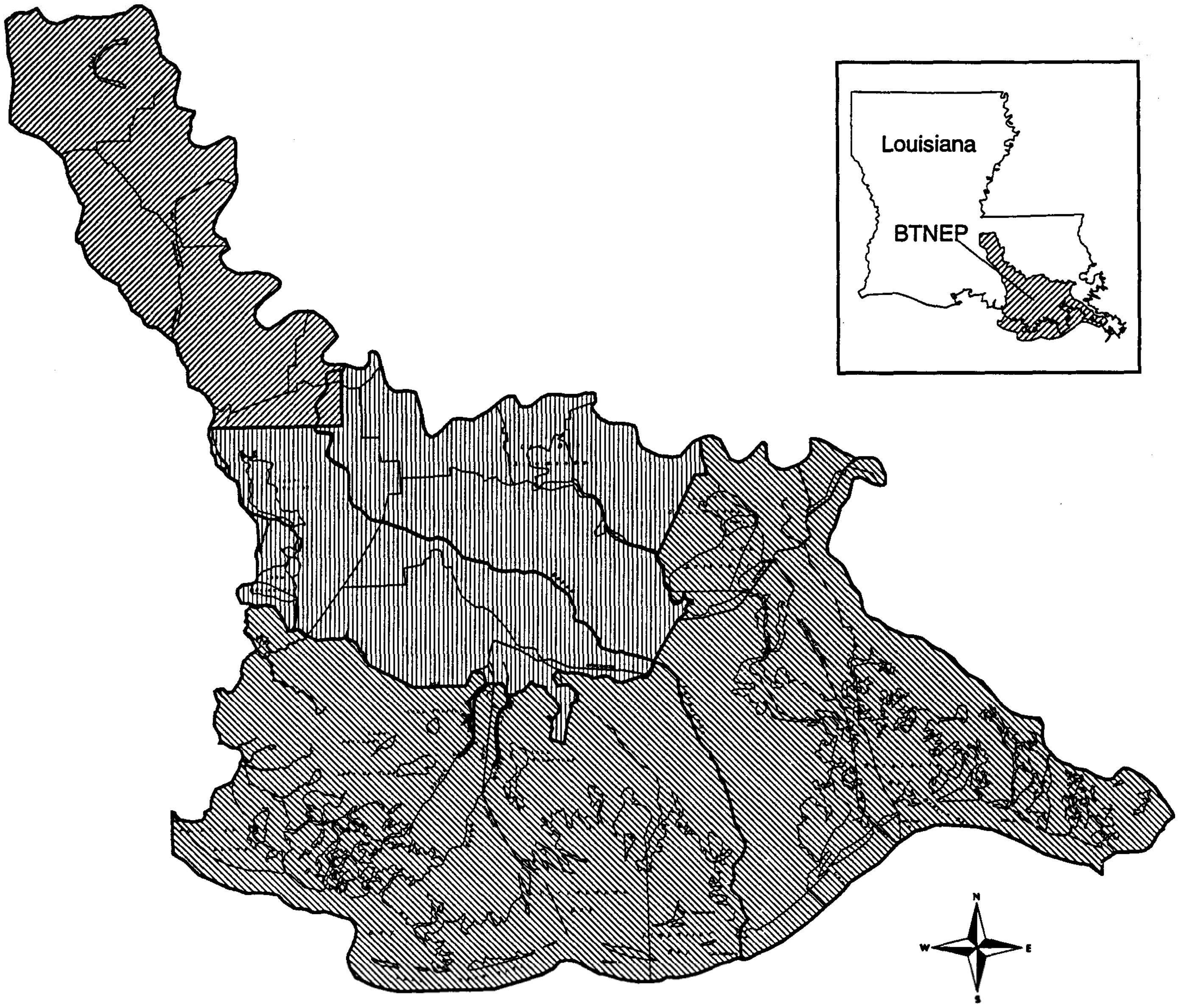
All BTES based landcover and wetland trend data generated for this study were extracted from the existing 1956, 1978, and 1988/90 data sets using the hydrologic basin boundaries as defined by the Louisiana Department of Environmental Quality. The 1956 and 1978 data are available only for that portion of the BTES that falls within the legislatively defined Louisiana coastal zone (covering approximately the lower one-third of the BTES) (Figure 3.4). The 1988/90 data also cover the coastal zone but extend farther north to Interstate 10 and encompass nearly all of the coastal area of the BTES (Figure 3.4).

Development of the Aggregated 1956 and 1978 Data Sets

The 1956 and 1978 habitat data sets were manually photointerpreted primarily from black and white, large scale (1:24,000) aerial photography (1955, 1956, 1958) and color infrared aerial photography at a scale of 1:24,000 (1978). The classification scheme used was based on Cowardin et al. (1979, Appendix C). The main data used to map the boundary between fresh and nonfresh marshes for the 1956 data were O'Neil's vegetation types (O'Neil 1949, Appendix D). Chabreck and Linscombe's (1978) data were used as the basis for delineating fresh and nonfresh marsh habitats for the 1978 data. All habitat data were referenced to existing 1:24,000 scale 7.5' USGS topographic quadrangle base of coastal Louisiana and digitized to produce vector format data. The Cowardin coding scheme was aggregated to a less complex Level One landcover classification to simplify data analyses and conversion (Appendix E). In order to use these data to analyze habitat trends on a regional and basin level the individual quads for 1956 and 1978 were rasterized at a 25-meter (82 ft) cell size. The quads were then mosaiced to form a contiguous coastwide habitat map.

Development of the Aggregated 1988/90 Data Sets

The 1988 habitat data set was developed by the SSC to update the existing 1956 and 1978 data sets. Color infrared aerial photography (scale 1:63,000) was acquired, photorectified to a 1:24,000 USGS quadrangle base map, photointerpreted using the Cowardin et al. (1979) classification, and digitized. The Cowardin classification was



- Area of Available 1956, 1978 and 1988190 Habitat Data
- Area of Available 1988/90 Habitat Data
- No Available Habitat Data

Figure 3.4 Coverage of available habitat data for 1956, 1978, and 1988/90 in the Barataria-Terrebonne estuary (SSC Map ID # 95-4-030).

aggregated to 19 landcover classes (Appendix F). Chabreck and Linscombe's (1988) data were used to delineate the fresh and nonfresh marsh habitat boundaries. The aggregated data set was rasterized to 25-meter (82 ft) resolution. Because the 1988 data covered a good deal more area than the 1956 and 1978 data, the 1988 data were clipped to match the area covered by the 1956 and 1978 data sets so that coastwide and basinwide landcover and wetland trend data comparing the three data sets would be based on identical areas. Initial analysis of the 1988 data indicated that wetland loss estimates were lower that expected, particularly in known high wetland loss areas. Further examination of the data revealed that the mapping conventions and classification methodologies used for this data tended to overestimate marsh in areas of "broken marsh." Thematic mapper satellite imagery, when classified to land and water categories, can be used to accurately identify broken marsh areas. The five Landsat scenes that comprise coastal Louisiana were rectified and then classified to identify land and water classes using techniques developed by SSC personnel. The scenes were then mosaiced to create a continuous land/water mosaic of coastal Louisiana. The 1990 data set was clipped to match the areal extent of the 1988 data set and merged with the 1988 data. The final product was a data set containing 1988 landcover classes with a 1990 water base which could be used to provide more accurate estimates of land loss. When rates of loss are calculated for specific habitat types they are calculated for both the 1978–88 time span and the 1978–90 time span.

Classification Methodologies

The appendixes contain the classification schemes used for each of the data sets used in these analyses. This includes the original Cowardin classification description (for a more detailed description see Cowardin et al. 1979), and the initial aggregations used to produce raster data sets (Appendixes C to F). Because the salinity modifiers for the 1956 data were based on O'Neil (1949) and the 1978 and 1988 salinity modifiers were based on Chabreck and Linscombe's data (1978, 1988), a table describing the relationship between the salinity classes for these data is contained in Appendix D. Examination of the species composition for O'Neil's classes revealed that a substantial portion of the 1956 habitat data classified as fresh marsh was really a nonfresh marsh (intermediate/brackish marsh). Therefore no designation between marsh types based on salinity was used for the 1956 habitat data. To minimize any other changes that resulted from classification methods, the habitat class statistics for these data sets were aggregated into seven general categories (Appendix G). Detailed habitat classes for the lower BTES, Barataria, and Terrebonne basins are included in Appendixes H, I, and J, respectively.

Development of the 1956–1978–1988/90 Wetland Trend Data

The final data set used for trend analysis consisted of habitat data covering the same area for 1956, 1978, and 1988/90. The development of a wetland trend data set depicting land loss/gain for the three time periods required two different methodologies due to differences in each of the data sets. Direct geographic information system (GIS) comparison of the 1956 and 1978 data sets can be made because they were photorectified using similar techniques. However, a direct comparison using GIS of the 1988/90 data with the 1956 and/or 1978 data cannot be made due to differences in the rectification techniques between the data sets. Conducting such comparisons would cause the appearance of false land loss and gain due to mis-registration. Two different techniques have been utilized to minimize the positional error problem. One technique uses GIS to visually depict the spatial distribution of wetland loss/gain over the entire data set. Spatial depiction of false loss or gain was minimized by filtering areas below several acres in size to produce maps depicting large areas of change. Accurate calculation of areal change in habitat classes was made by extracting area statistics for each data set using the GIS. The statistics are transferred to a spreadsheet which is used to calculate changes in habitat classes and to summarize total land loss or gain over the comparison interval, but the spatial distribution of habitat class changes cannot be depicted spatially. When used together, both analytical techniques allow for a reliable quantification and spatial depiction of wetland loss trends.

Wetland loss trends for the BTES were calculated using the methodology described above. Two different data sets were created for the 1988/90 data for the BTES and the Barataria and Terrebonne basins due to differences in overall coverage. Partial 1988/90 data were extracted to match the extent of the 1956 and 1978 data in order to calculate accurate landcover and land loss trends. Multi-date wetland trend data depicting hotspots of wetland loss and gain between 1956–1978–1988/90 were created from the master coastwide data set. All available 1988/90 data for the BTES were also extracted to provide maximum habitat area information and to provide an estimate of wetland status.

1988/90 Wetland Habitat Status and Recent Trends

There are no habitat data sets available that cover the entire BTES area. However the 1988/90 data do cover nearly all of the coastal area, approximately 1,427,600 ha (3.5 million acres) (Table 3.3, Figure 3.5). Excluded is the finger of land northwest of Morgan City in the extreme northwestern corner of the Terrebonne basin (the Verret subbasin). The available data allow a fairly accurate estimate of the 1988/90 status of selected coastal wetland habitats in the BTES. In the Barataria basin all of the marsh habitat is included in the habitat data (approximately 166,800 ha (412,000 acres)) and nearly all of the forested wetlands (approximately 131,600 ha (325,000 acres)). Approximately 70,000 ha (173,000 acres) of marsh in Barataria basin were categorized as fresh marsh, and approximately 97,200 ha (240,000 acres) were nonfresh marsh. In

Terrebonne basin the forested wetland habitats are not so completely covered as in Barataria. The nonfresh marshes are completely included and total approximately 117,800 ha (291,000 acres) (Table 3.3, Figure 3.5). There are approximately 83,400 ha (206,000 acres) of fresh marsh and 130,800 ha

Table 3.3. Wetland habitat area (mi^2) in Barataria-Terrebonne area for 1988/90 using available data.

	BTES	Terrebonne	Barataria
Water	2,385	1,360	1,024
Marsh	1,421	777	645
Fresh marsh	591	322	270
Nonfresh marsh	830	455	375
Forested wetlands[1]	1,013	505	508
Agriculture/pasture	498	225	273
Other[2]	195	82	114
Total	5,512	2,949	2,564

[1]Includes forest, swamp, shrub/scrub (Appendix G).

[2]Includes shore, inert, beach, upland, barren, developed, other.

(323,000 acres) of forested wetlands in Terrebonne based on these data, but this is an underestimation of the total.

None of these habitats is static through time. Even without the habitat deterioration and loss to open water that the coastal wetlands are experiencing (as discussed in the following section), the habitats are changing. As the coast subsides, marine influences move farther and farther up the estuary, and the marshes are gradually shifting to more salt-tolerant species. Chabreck and Linscombe (1982) documented the gradual shift of salinity zones between 1968 to 1978 (Table 3.4). This is seen as a gain in brackish and saline marsh at the expense of fresh and intermediate marsh. It is notable, however, that in some areas, especially along the eastern edges of Atchafalaya River, there was a freshening of the marsh. Thus, in the Terrebonne basin, while 544 km^2 (210 mi^2) of marsh became more saline, 210 km^2 (80.9 mi^2) became fresher. Even in the Barataria basin, which lacks a large freshwater supply, freshening was documented over 134 km^2 (51.7 mi^2), compared to 670 km^2 (258.8 mi^2) that became more saline (Chabreck and Linscombe 1982). In part this may be related to a change in the methodology used to determine the boundaries between marsh vegetation zones for the two time periods.

At a local scale, we have documented a change from fresh to nonfresh vegetation from 1978 to the present in a fresh/intermediate marsh near Clovelly in Barataria basin. During this period a transition occurred from freshwater species dominated by *Sagittaria lancifolia* to nonfresh species dominated by *Spartina patens* (Sasser, unpublished data). Although salinity data from continuous gauges in open water

locations, presented elsewhere in this report, do not show consistent upward trends, it is likely that the vegetation in interior marshes is responding to salinity variations.

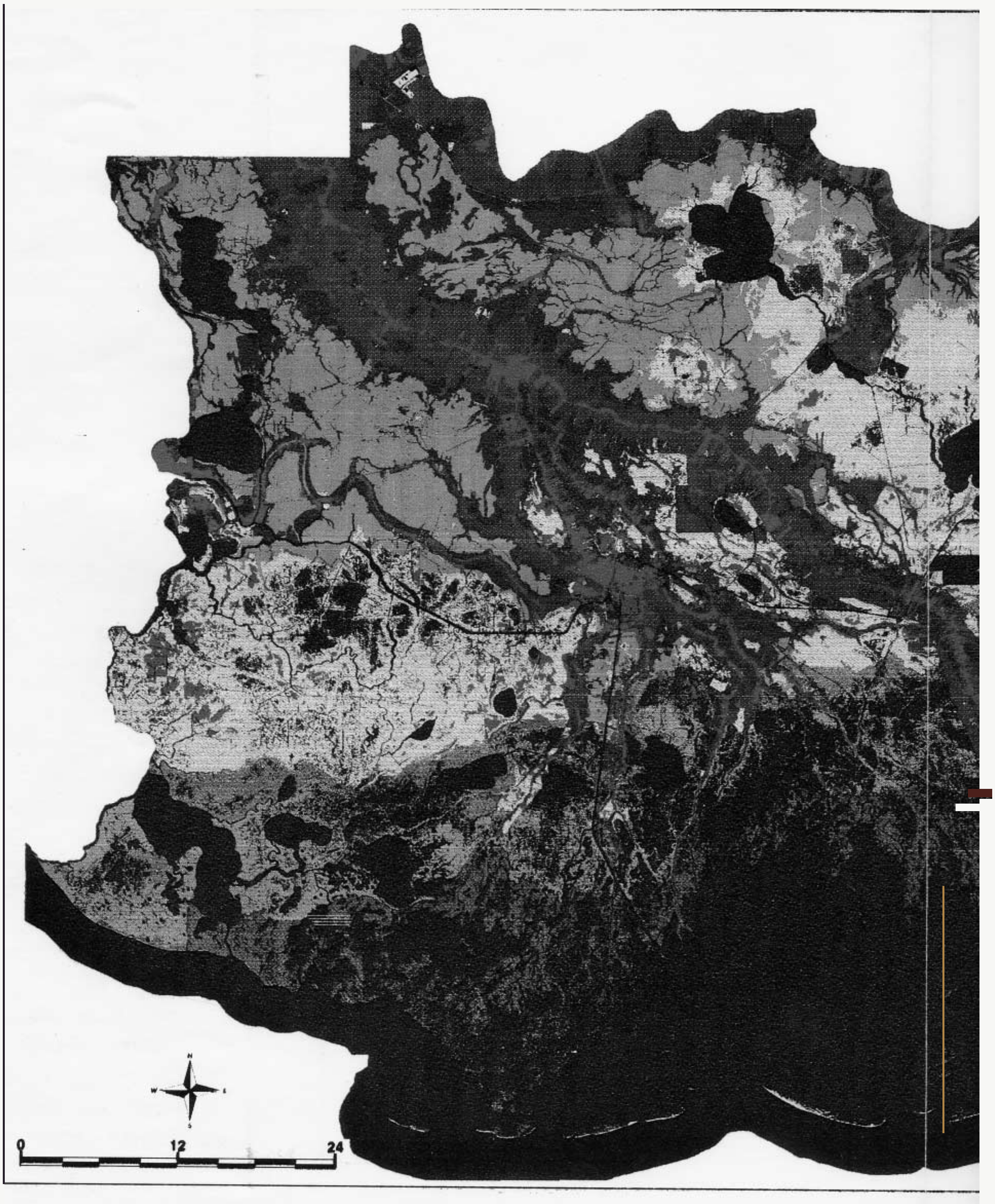


Figure 3.5 U.S. Fish and Wildlife Service 1988 habitat with 199 LandsatTM Water


Louisiana
Barataria - Terrebonne National Estuaries
Project Location
1 Water
2 Aquat. Bed Floating
3 Aquat. Bed Submerged
4 Fresh Marsh
5 Intermediate Marsh
6 Brackish Marsh
7 Saline Marsh
8 Estuarine Marsh
9 Cypress Forest
10 Bottomland Forest
11 Upland Forest
12 Dead Forest
13 Bottomland Shrub/Scrub
14 Upland Shrub/Scrub
15 Shore/Flat
16 Ag/Pasture
17 Upland Barren
18 Developed
19 Other Land
NBS SSC Map ID #95-4-016

Merge Data.

Table 3.4. Net change in the size of vegetative type in Louisiana coastal marsh from 1968 to 1978 (Chabreck and Linscombe 1982).

	Size of type[1] (sq. mi)		Change	
Vegetative types	1968[2]	1978	Sq. Mi.	Percent
Saline	1,455	1,585	+130	+8.9
Brackish	2,203	2,060	+37	+1.8
Intermediate	1,072	1,044	-28	-2.6
Fresh	2,031	1,892	-139	-6.8

[1]Includes natural marshes and associated water bodies.
[2]Data from Chabreck (1970).

With respect to forested wetlands, we were able to estimate with fair accuracy the forested wetland area in the northwest corner of Terrebonne basin that is not accounted for in the SSC data, from TM data generated by The Nature Conservancy (Mark Swan, personal communication). The area of forested wetland habitats shown in Table 3.5 was generated by SSC for the Barataria basin, but in the Terrebonne basin SSC data are supplemented for the missing section of the basin. The revised figure indicates a BTES total of about 319,800 ha (790,000 acres), with 121,500 ha (300,000 acres) in the Barataria basin and the rest in the Terrebonne basin. This is split about equally between cypress swamp and slightly less frequently flooded bottomland hardwood forest in Barataria. In the Terrebonne basin there is slightly more than twice as much bottomland hardwoods as cypress tupelo.

Because the data set is not complete, it has not been possible to determine trends of forested habitat change through time. However, data from the mid-1950s to mid-1970s for the Terrebonne basin parishes in the Lake Verret subbasin (which contains most of the forest) show a gradual loss of wetland forest (Figure 3.6) (Macdonald et al. 1979). This has occurred through clearing for agricultural production in the Terrebonne basin, and for industrial and urban development in the Barataria basin.

In addition to forest clearing, there is good evidence that subsidence is a serious problem in forested wetlands of the basin (Conner and Day 1988). This effect is difficult to detect on aerial photography because of the survival of mature trees that can withstand increasing flooding masks the fact that seed germination and seedling survival of wetland tree species is rare in flooded areas. Hence the regeneration of these forests is not occurring. Unless the accretion deficit can be reduced these areas are probably relict forests that will change to open water as the present stands die.

Table 3.5. Area of forested wetlands in the BTES in 1988/1992 (acres). Data from SSC and TNC[1].

	Terrebonne	Barataria	Total
Swamp	140,829	152,003	292,832
Bottomland hardwoods	312,516	125,008	437,524
Scrub-Shrub	38,735	21,472	60,207
Total	492,080	298,483	790,563

[1]The Nature Conservancy, Baton Rouge, Louisiana.

LAND LOSS

Habitat data covering approximately 1 million ha (2.5 million acres) of the BTES coastal area were available for the three time periods (Figure 3.4). In 1956 roughly 42% of the area was open water, 49% marsh, and 6% forested wetlands (Table 3.6). In 1978 the amount of open water increased to 52% and marsh decreased to 37% of the total area. Fresh marsh accounted for 9%, nonfresh marsh 28% of the area. Forested wetlands remained approximately the same. By 1988 open water accounted for 58%, fresh marsh 9%, nonfresh marsh 21%, and forested wetlands 6% of the BTES coastal area included in this data set (Table 3.6, Figure 3.5). Land loss rates for the entire BTES were 47 km^2 (18 mi^2) per year from 1956 to 1978 and 54 km^2 (21 mi^2) per year for 1978 to 1988/90 (Table 3.6). About 119,000 ha (294,000 acres) of marsh were lost during the period from 1956 to 1978 (Table 3.6). Some of this loss was conversion to development and agricultural usage and some loss was conversion to open water (Figure 3.7). From 1978 to 1988/90 nonfresh marsh underwent a loss of 57 km^2 (22 mi^2) per year (Table 3.6). Nearly all of the nonfresh marsh was converted to open water (Table 3.6, Figure 3.7).

Barataria Basin

Available habitat data for the Barataria basin during the three time periods included approximately 443,400 ha (1.1 million acres). Land loss for the Barataria basin was calculated to be 20.2 km^2 (7.8 mi^2) per year (0.74% per year) for the period from 1958 to 1978 (Table 3.7). For the period from 1978 to 1988/90 the land loss rate was 29 km^2 (11.1 mi^2) per year (1.3 to 1.5% per year). In 1956 roughly 39% (173,600 ha

Table 3.6. Area (mi²) and annual habitat change based on available data for Barataria-Terrebonne area for 1956, 1978, and 1988/90.

	YEAR			CHANGE	
HABITAT	**1956**	**1978**	**1988/90**	**56–78**	**78–88/90**
Water	1,619	1,999	2,257	17.72	21.40
Marsh	1,893	1,434	1,193	-20.91	-20.04
Fresh marsh		340	364		1.99
Nonfresh marsh		1,094	829		-22.02
Forested wetlands[1]	231	262	244	1.37	-1.43
Agriculture/pasture	73	80	89	0.30	0.81
Developed	40	89	83	2.22	-0.51
Other[2]	18	12	8	-0.29	-0.27
Total	3,874	3,876	3,874		

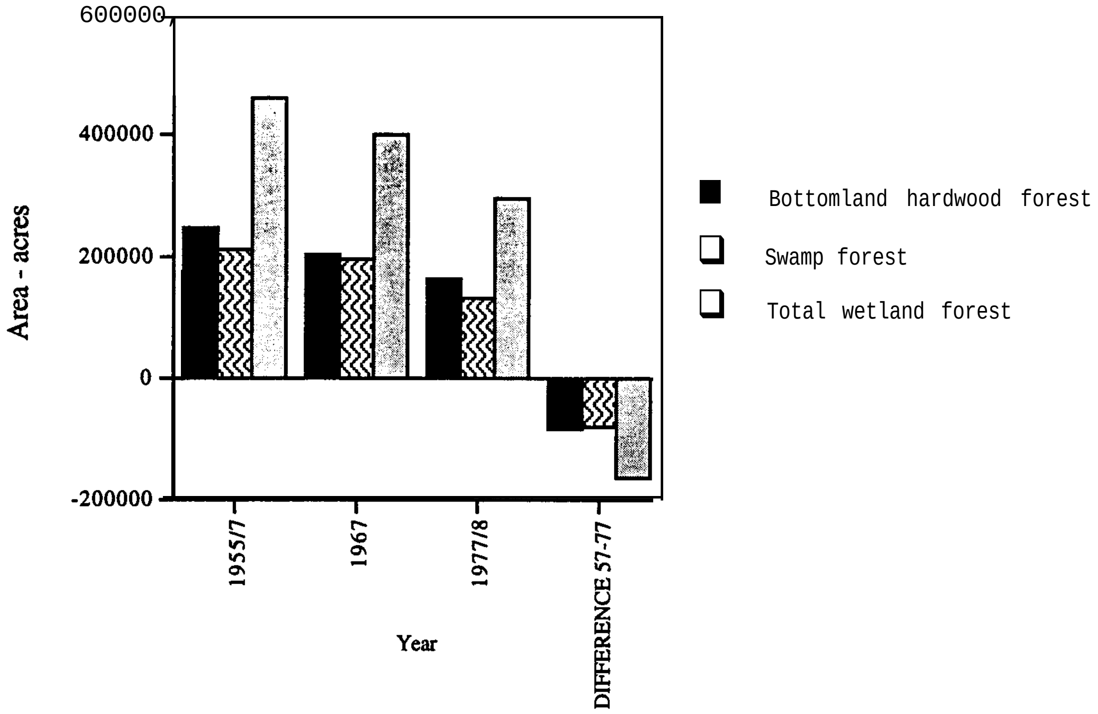
[1]Includes forest, swamp, shrub/scrub (Appendix G).
[2]Includes shore, inert, beach, upland, barren, other.

or 429,000 acres) of the coastal area was classified as open water and 48% (213,700 ha or 528,000 acres) of the area was classified as marsh (Table 3.7, Figure 3.8). The remaining land was classified as agriculture and pasture lands or was developed (Table 3.7). In 1978 approximately 49% (217,800 ha or 538,000 acres) of the area was in open water. Marsh had decreased to 36% (157,100 ha or 388,000 acres) of the area with fresh marsh accounting for 5%, a loss of about 26 km^2 (10 mi^2) per year, and nonfresh marsh about 31% (Table 3.7, Figure 3.9). Other landcover categories remained approximately the same. In 1988/90 about 57% (252,300 ha or 623,000 acres) of the area was open water. Marsh decreased to about 28% (124,300 ha or 307,000 acres) of the area. Fresh marsh slightly increased in area to about 6%, an increase of 5 km^2 (2.1 mi^2) per year, and nonfresh marsh decreased in area to 22%, a decrease of about 34 km^2 (13 mi^2) per year (Table 3.7, Figure 3.10). This increase in fresh marsh may indicate a trend of freshening reflected by changes in species composition, or it may be the result of interannual fluctuations in species abundance as documented in other studies (Evers et al. 1991).

The spatial distribution of land loss as shown in the habitat maps and accompanying statistics indicated that the marshes near the mouth of the Mississippi

River underwent extensive loss from 1956 to 1978 (Figure 3.11). Extensive loss also occurred in the Myrtle Grove and Bayous Perot and Rigolettes area during the same time. Wetland loss from 1978 to 1988/90 occurred in the marshes fringing Barataria Bay, particularly in the northwestern edges of the bay, from the Bayou L'Ours area

Terrebonne Basin Forested Wetland Area (MacDonald et al. 1979)



Barataria Basin Forested Wetland Area (Southern Science Center)

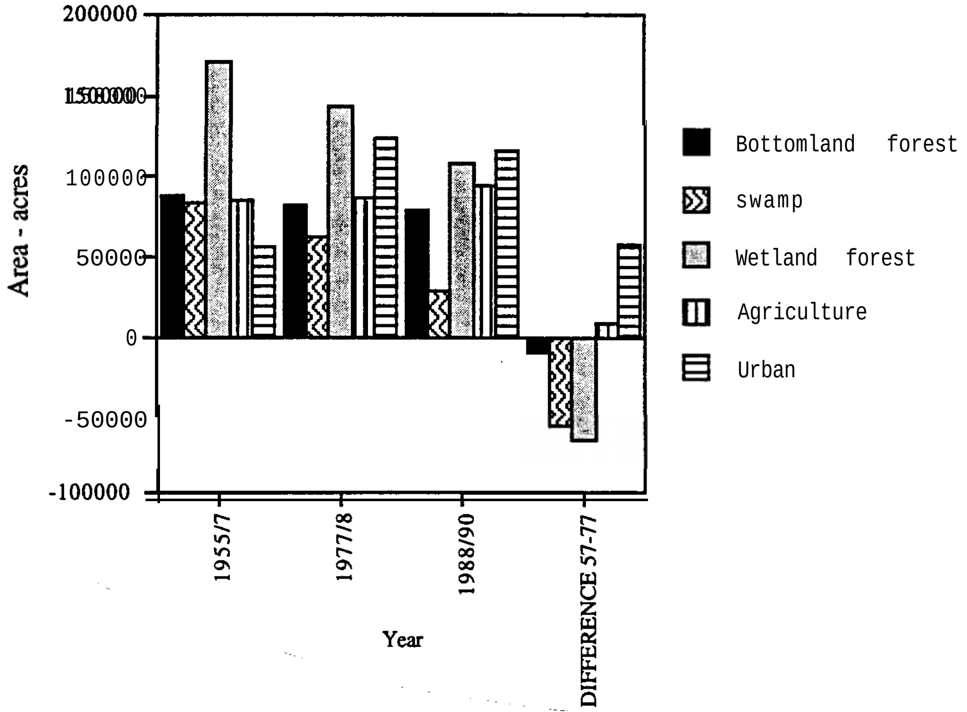


Figure 3.6 Estimates of the forested wetland area in the Barataria-Terrebonne estuarine system. Barataria estimates are from Southern Science Center Terrebonne estimates from MacDonald et al. (1979).

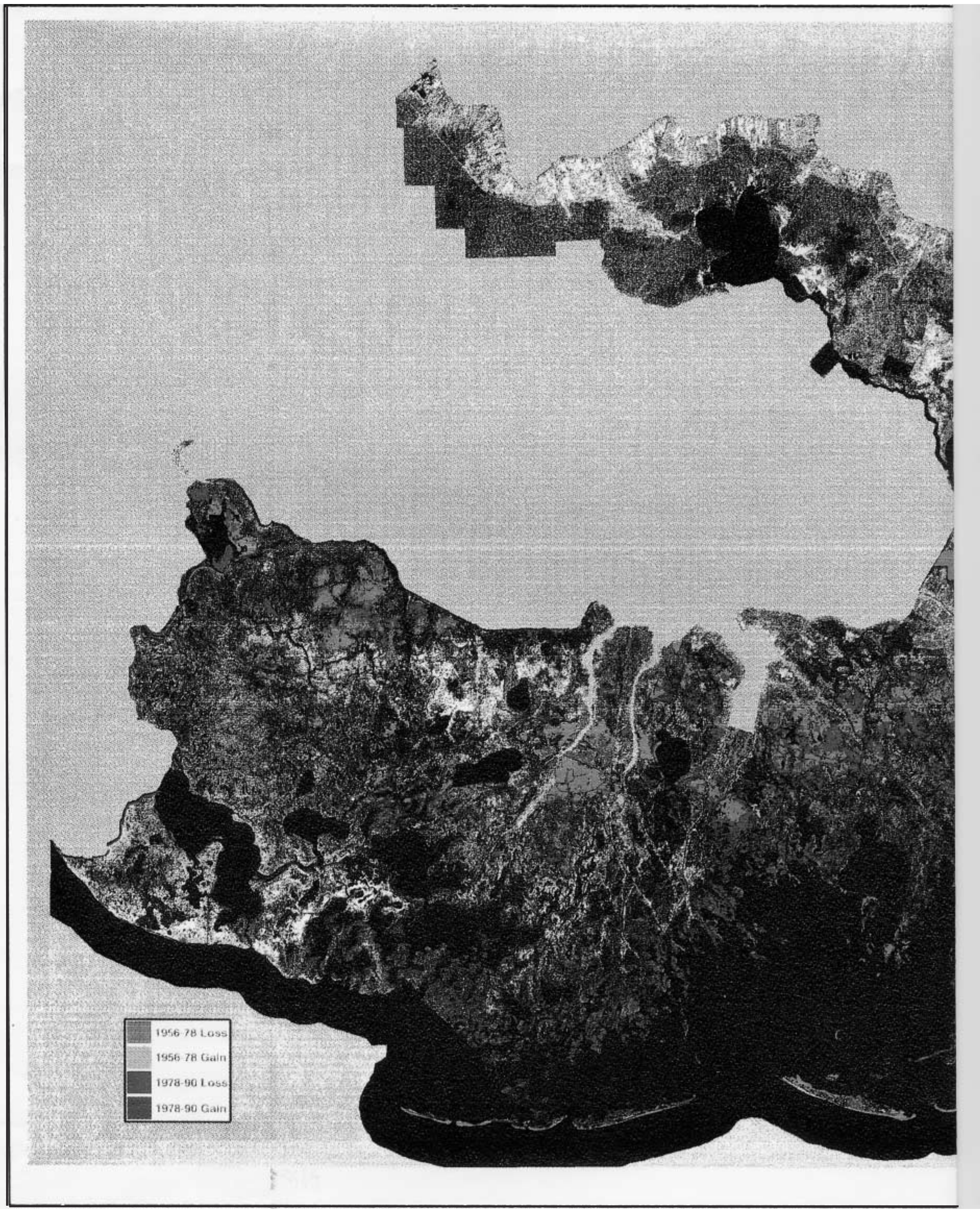


Figure 3.7. 1956-1978-1990 land loss data.

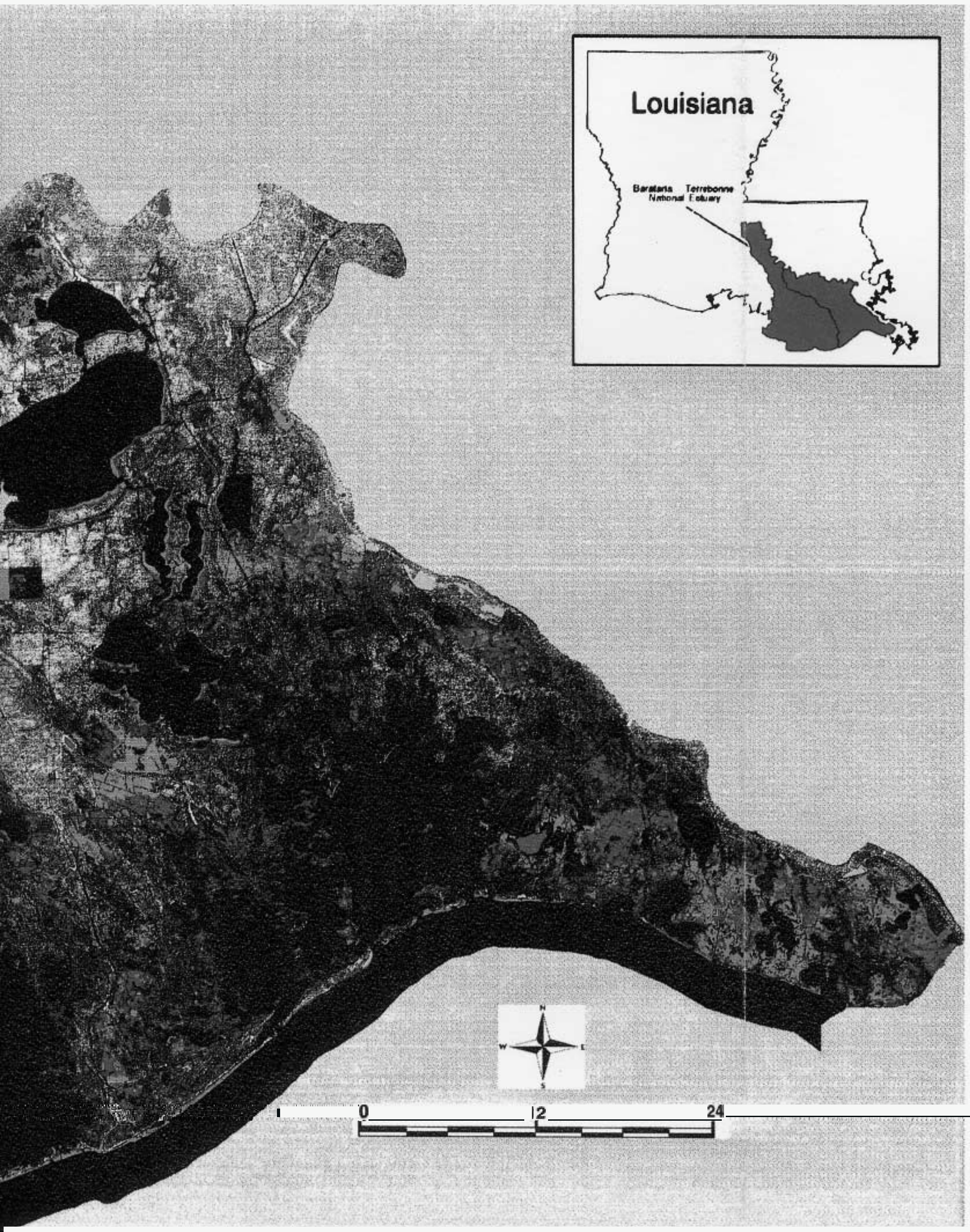


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Figure 3.8 U..S. Fish and Wildlife Service 1956 habitat data-Fk

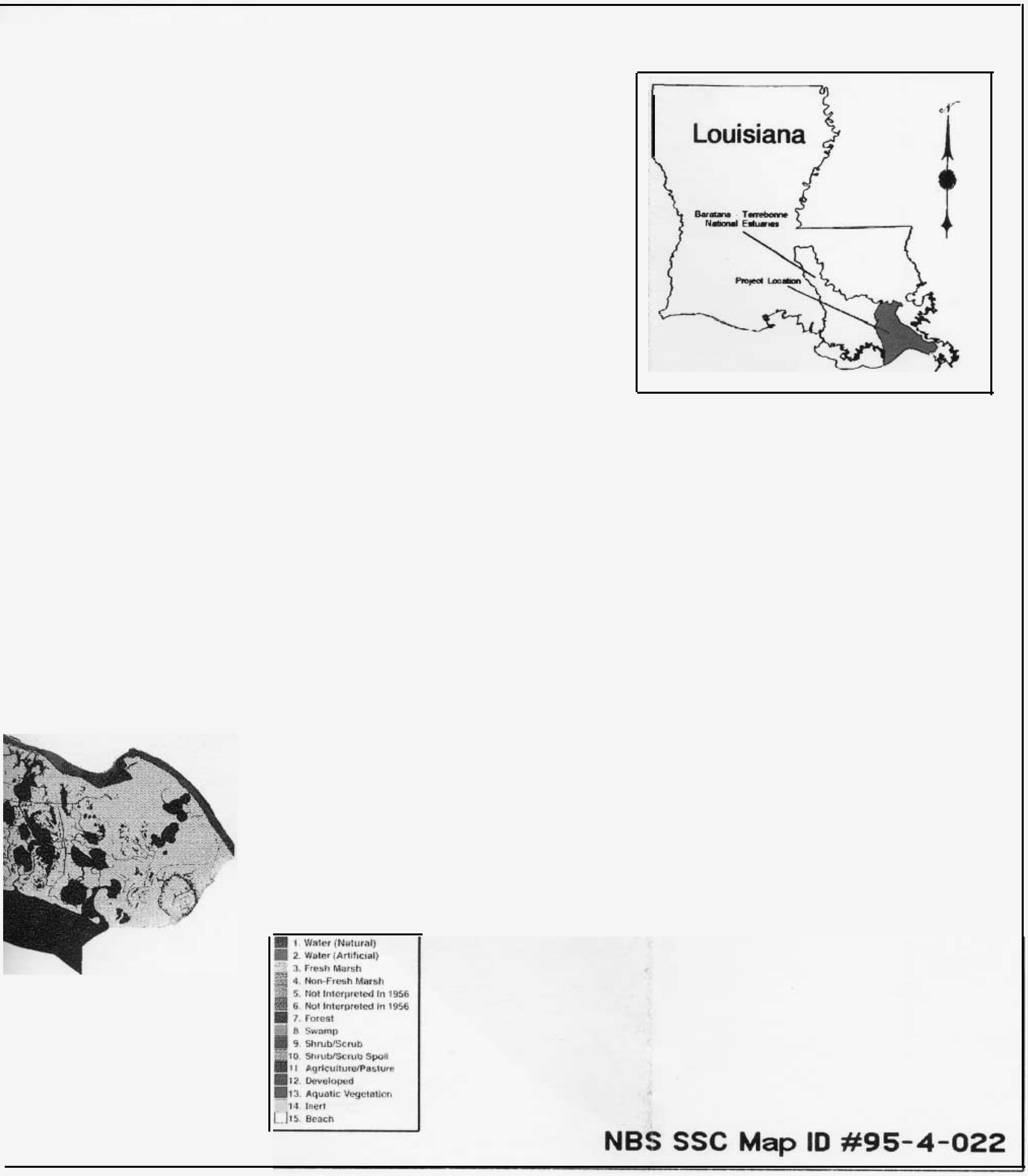

Louisiana
Barataria - Terrebonne National Estuaries
Project Location
1. Water (Natural)
2. Water (Artificial)
3. Fresh Marsh
4. Non-Fresh Marsh
5. Not Interpreted In 1956
6. Not Interpreted in 1956
7. Forest
8. Swamp
9. Shrub/Scrub
10. Shrub/Scrub Spoil
11. Agriculture/Pasture
12. Developed
13. Aquatic Vegetation
14. Inert
15. Beach
NBS SSC Map ID #95-4-022

Figure 3.9 U.S. Fish and Wildlife Service 1978 habitat data-Bar

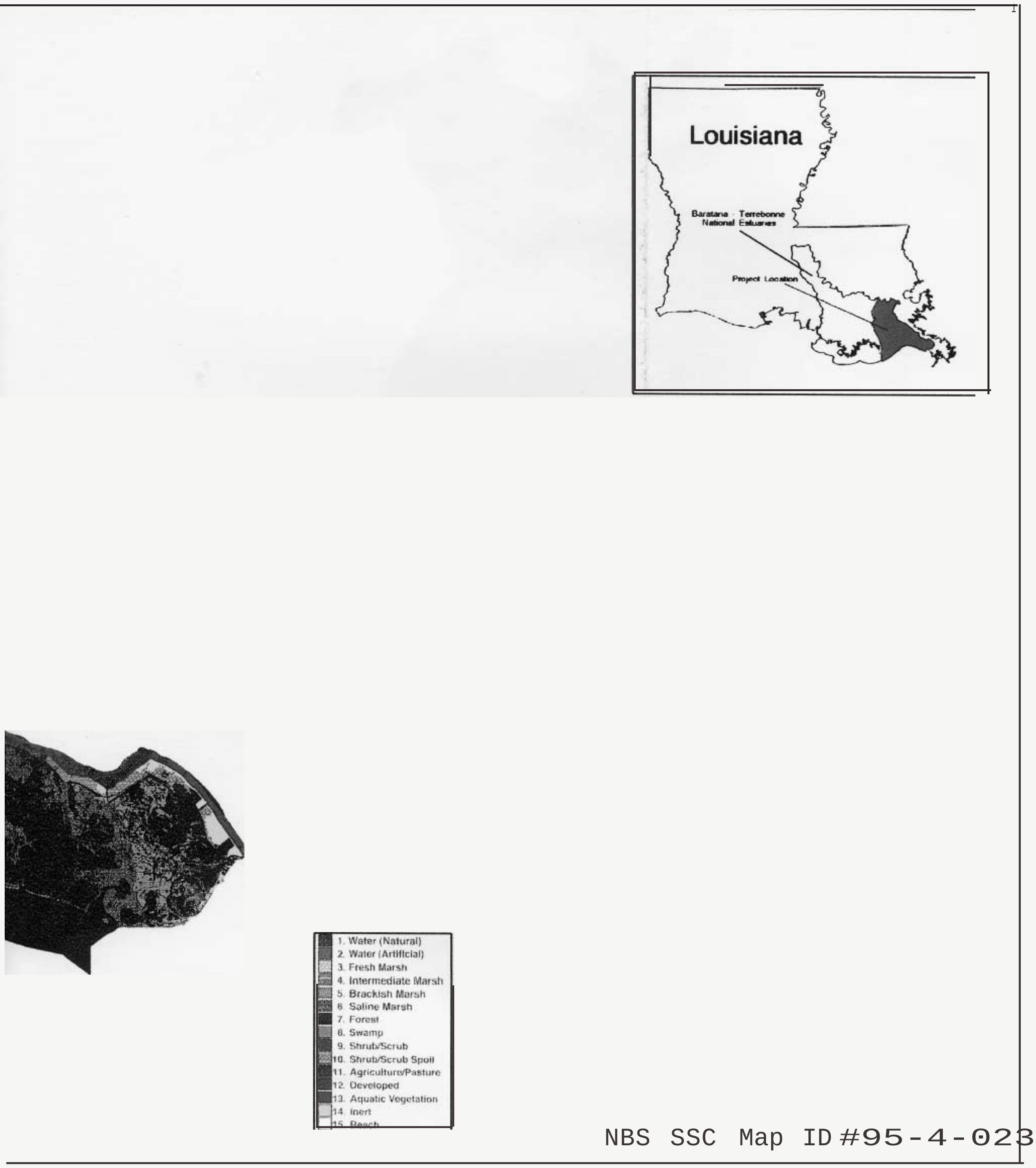
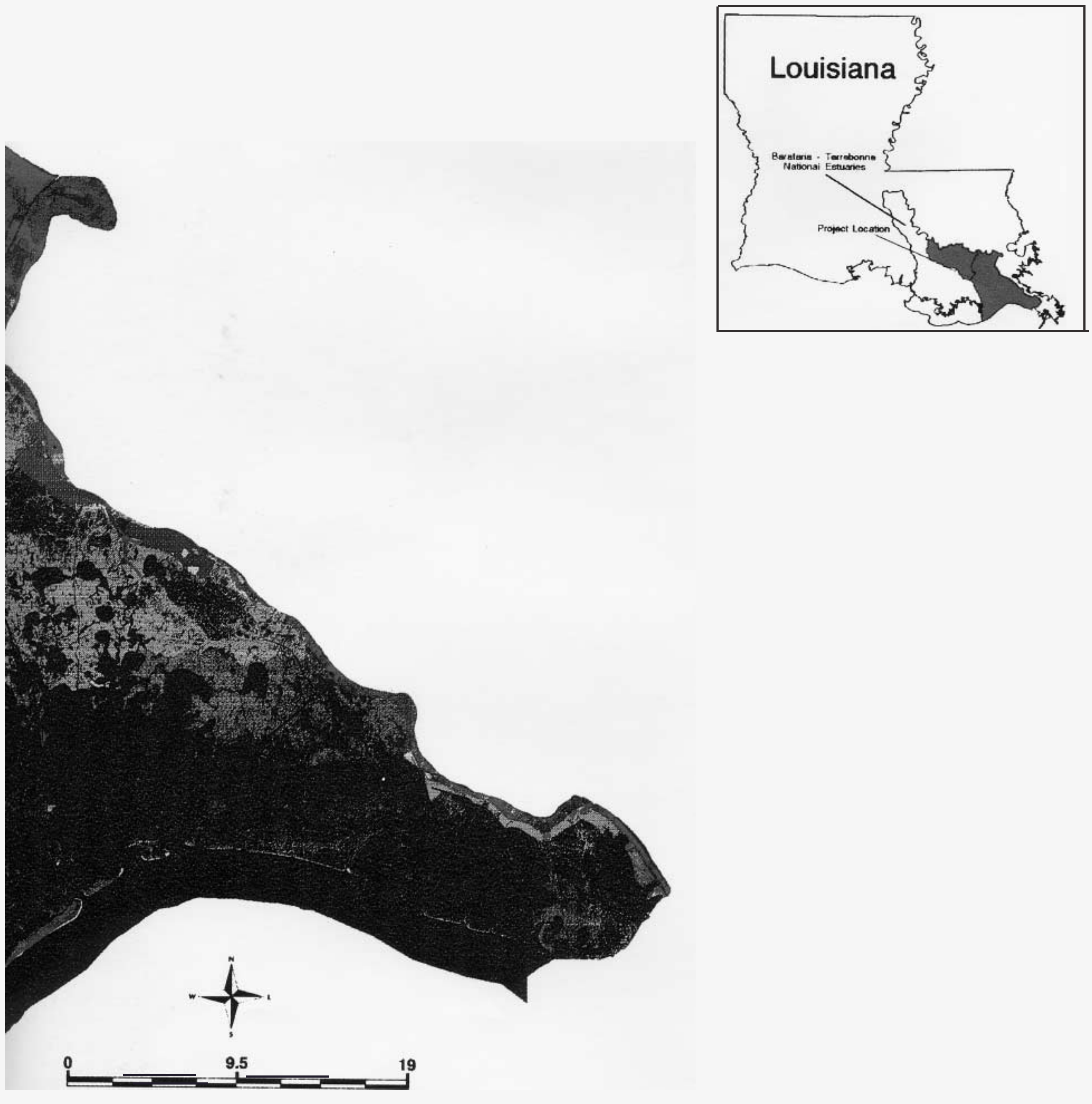

Louisiana
Barataria - Terrebonne National Estuaries
Project Location
1. Water (Natural)
2. Water (Artificial)
3. Fresh Marsh
4. Intermediate Marsh
5. Brackish Marsh
6. Saline Marsh
7. Forest
8. Swamp
9. Shrub/Scrub
10. Shrub/Scrub Spoil
11. Agriculture/Pasture
12. Developed
13. Aquatic Vegetation
14. Inert
NBS SSC Map ID #95-4-023

Figure 3.10. U.S. Fish and Wildlife Service 1988 habitat with LandsatTM



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Merge Data-Ehrataria basin.

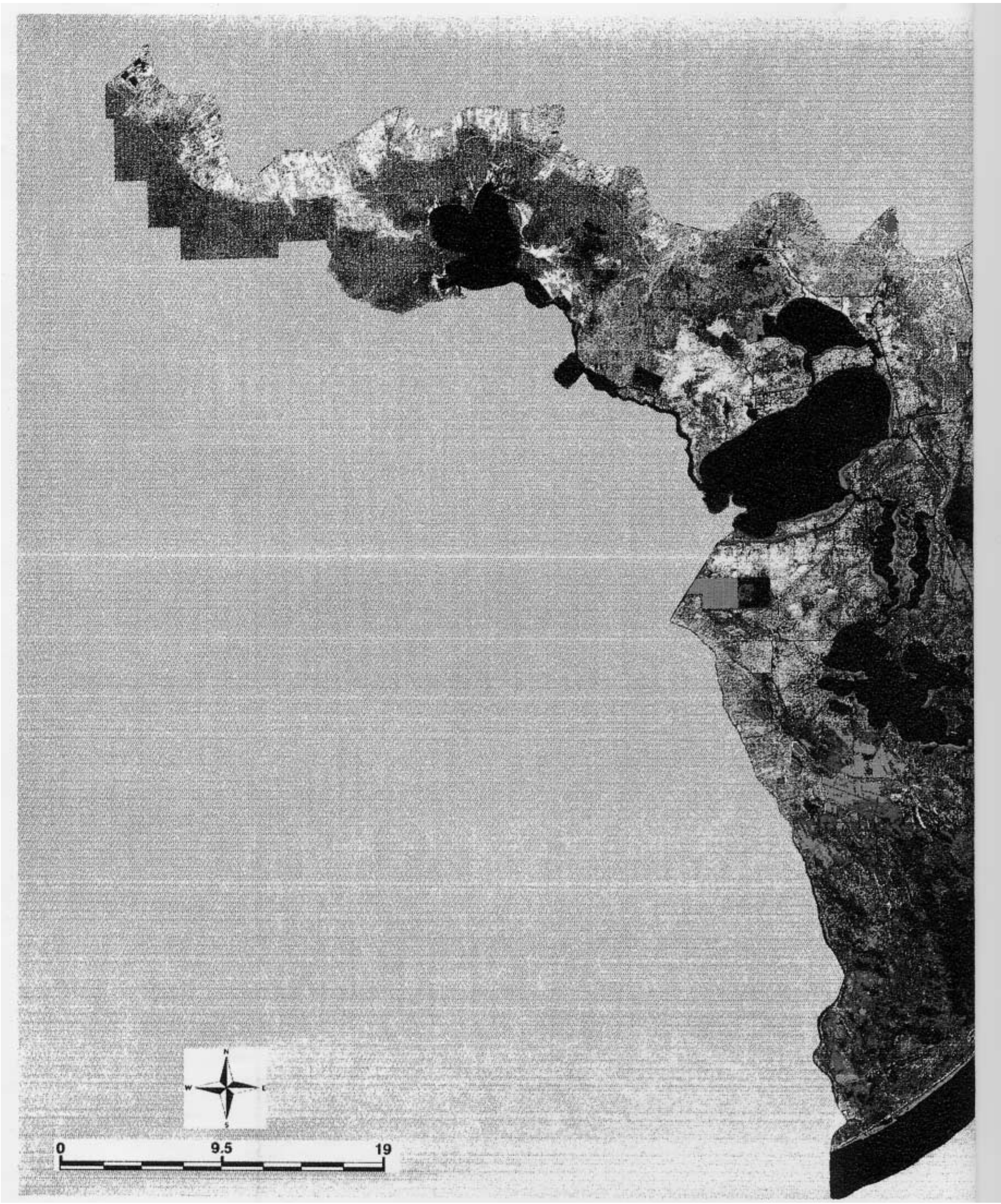

Figure3.11. 1956-1978-1988/90 land loss data-Barataria basin.

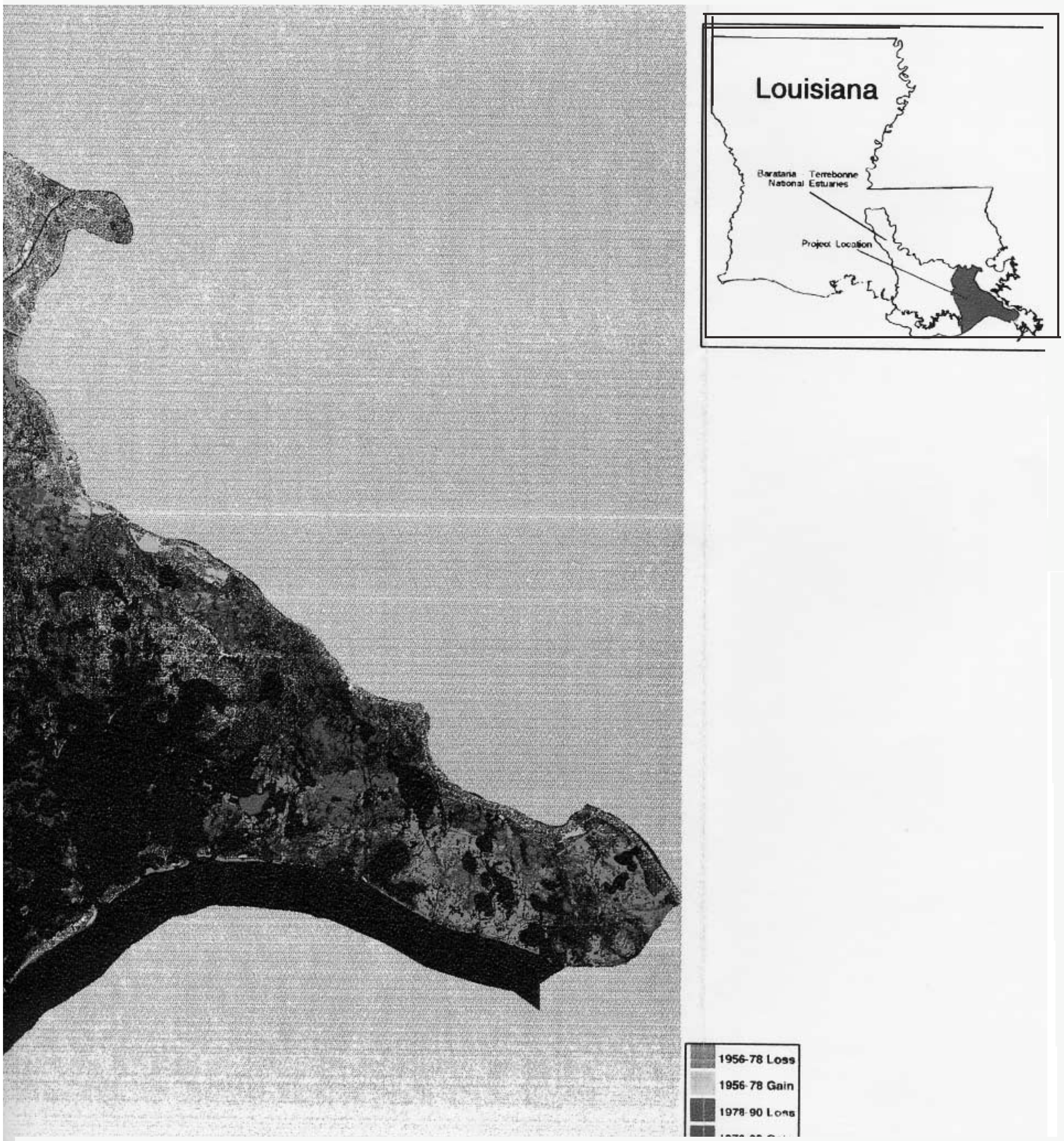

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Table 3.7. Area (mi^2) and annual habitat change based on available data for Barataria basin for 1956, 1978, 1988/90.

HABITAT	YEAR 1956	1978	1988/90	CHANGE 56–78	78–88/90
Water	670	841	974	7.75	11.11
Marsh	825	606	480	-9.94	-10.55
Fresh marsh		79	105		2.13
Nonfresh marsh		527	375		-12.68
Forested wetlands[1]	118	125	123	0.34	-0.23
Agriculture/pasture	53	55	59	0.07	0.38
Developed	36	78	72	1.91	-0.44
Other[2]	10	7	4	-0.12	-0.28
Total	1,712	1,712	1,712		

[1]Includes forest, swamp, shrub/scrub (Appendix G).
[2]Includes shore, inert, beach, upland, barren, other.

south along Bayou Lafourche to the Gulf. It is interesting to note that the marshes southeast of Myrtle Grove, at the northeastern edge of Barataria Bay have remained fairly stable from 1956 to 1988/90. One area of considerable loss obviously a result of agricultural practices occurred in the period from 1956 to 1978 in the Delta Farms area (Figure 3.11).

Terrebonne Basin

Available habitat data for the Terrebonne basin for the three time periods covered approximately 560,200 ha (1.4 million acres) of the coastal area (Table 3.8). The estimated land loss rate for the period from 1956 to 1978 was 25 km^2 (9.5 mi^2) per year (0.79% per year). From 1978 to 1988/90 the land loss rate was 27 km^2 (10.4 mi^2) per year (1.1–1.2 % per year) (Table 3.8). In 1956 approximately 44% (245,700 ha or 607,000 acres) of the area was in open water, 50% (276,900 ha or 684,000 acres) in marsh, and 5% in forested wetlands (Table 3.8, Figure 3.12). In 1978 open water area increased to 54% (300,000 ha or 741,000 acres) and marsh area decreased to 38% (214,200 ha or 529,000 acres) with 12% classified as fresh marsh, and 26% as nonfresh marsh (Table 3.8, Figure 3.13). In 1988/90 the amount of open water increased to 59% (332,300 ha or 821,000 acres). Marsh area continued to decrease to about 33% (184,900 ha or 456,300 acres) with 12% classified as fresh marsh, a

decrease of 0.5 km^2 (0.2 mi^2) per year, and 21% classified as nonfresh marsh, a loss of 23 km^2 (9 mi^2) per year (Table 3.8, Figure 3.14). The spatial distribution of land loss as shown in the habitat maps and accompanying statistics indicated that similar to

Table 3.8. Area (mi^2) and annual habitat change based on available data for Terrebonne basin for 1956, 1978, and 1988/90

	YEAR			CHANGE	
HABITAT	1956	1978	1988/90	56–78	78–88/90
Water	949	1,158	1,283	9.53	10.42
Marsh	1,069	827	714	-10.97	-9.49
Fresh marsh		260	259		-0.15
Nonfresh marsh		567	455		-9.33
Forested wetlands[1]	113	136	122	1.03	-1.20
Agriculture/pasture	20	25	30	0.23	0.42
Developed	4	11	11	0.31	-0.06
Other[2]	8	4	4	-0.17	0.01
Total	2,163	2,161	2,164		

[1]Includes forest, swamp, shrub/scrub (Appendix G).
[2]Includes shore, inert, beach, upland, barren, other.

Barataria basin, there were extensive areas of land loss fringing Terrebonne Bay and extending inland (Figure 3.15). As in Barataria Bay, there is a small area of marsh along the northeast edge of the bay that has remained fairly stable from 1956 to 1988/90. Another area of extensive loss occurred south of Lake DeCade from 1978–1988/90. The Turtle Bayou area underwent extensive loss from 1956 to 1978.

OTHER STUDIES

The Southern Science Center data are the most recent of a series of studies of Louisiana wetland loss reaching back to the 1970s (Gagliano et al. 1970). These studies provide a somewhat different estimates of absolute rates, but despite different methods employed, all show high, and mostly increasing loss rates. For the Louisiana coast as a whole the rate of land loss peaked in the 1970s and early 1980s and is now declining, in part because there is less marsh to lose. The Barataria-Terrebonne estuary, especially, has very high loss rates (with 33% of coastal area, this estuary has 50% (Britsch 1992) to 61% (Barras et al. 1994) of the wetland loss).

In the Barataria-Terrebonne estuary, the studies by Gagliano and co-workers (Gagliano 1981, Gagliano et al. 1970) give estimates of the earliest rates of loss (1900 to 1970s). They show wetland loss rates to be very low (0.13% yr^{-1}) during the early

part of the century, rising to 0.7%yr^{-1} in the 1970s. The U.S. Army Corps of Engineers' (USACE) set of reports on wetland loss in the Louisiana coastal

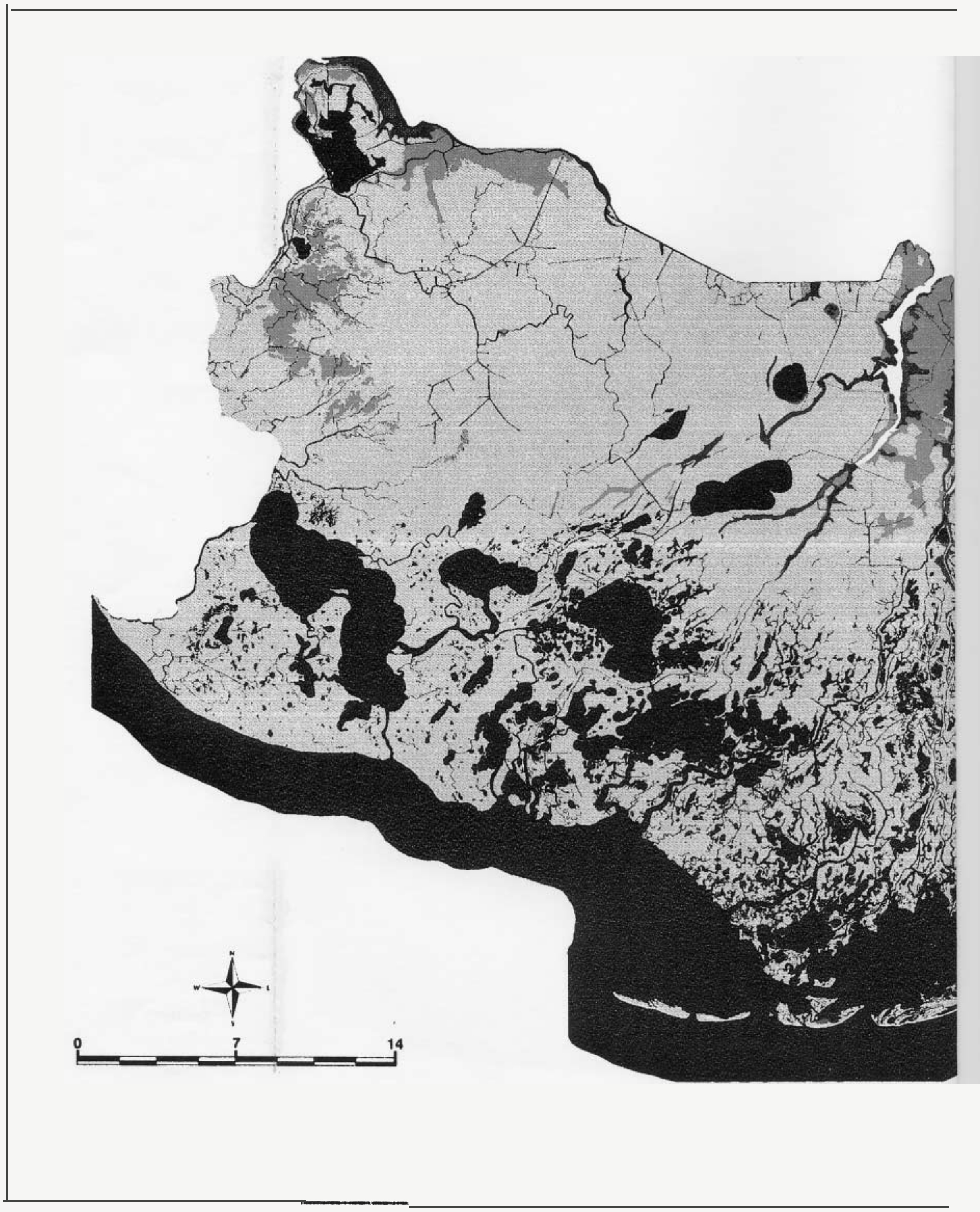
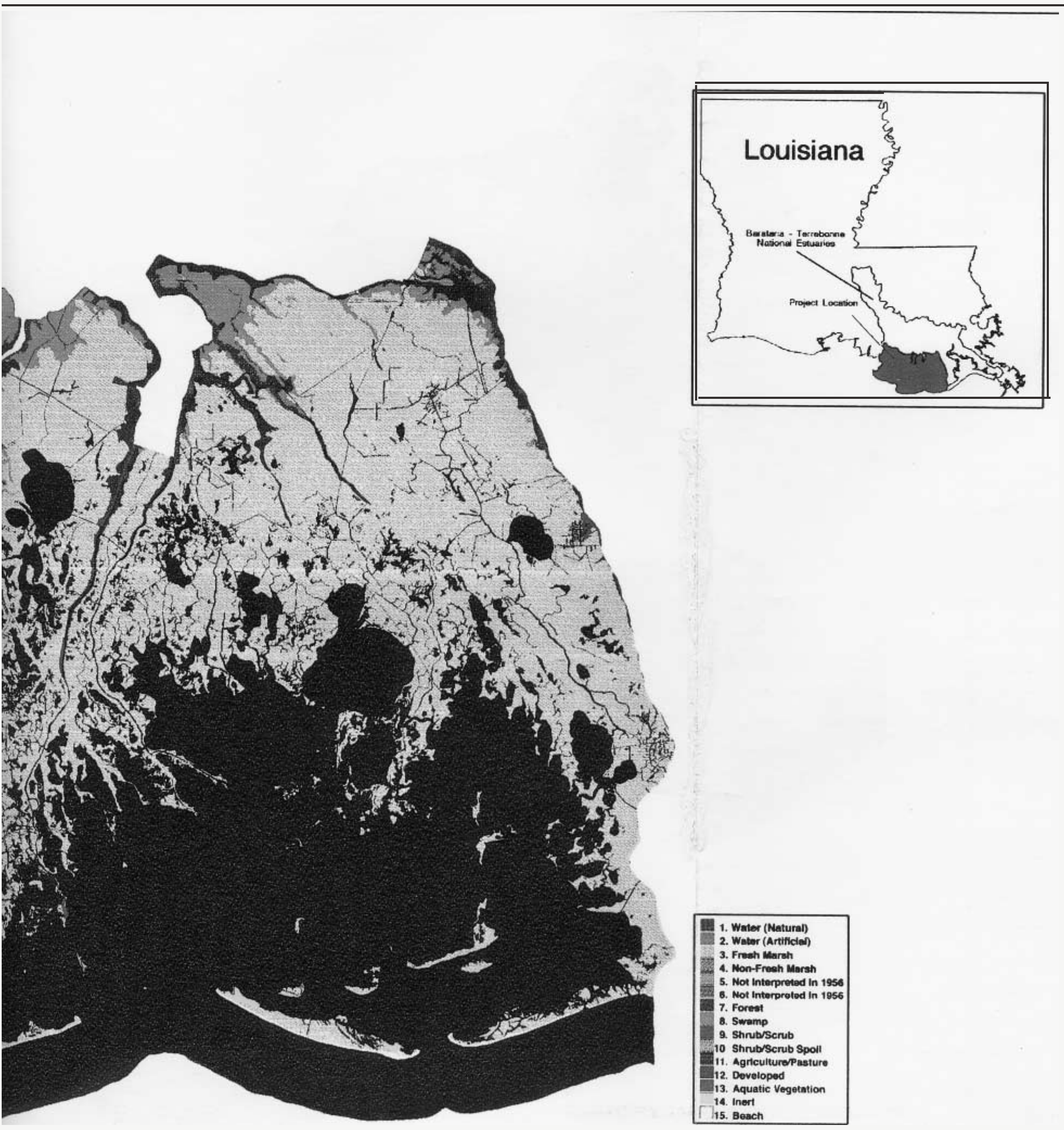


Figure 3.12. U.S. Fish and Wildlife Service 1956 habitat data-Te



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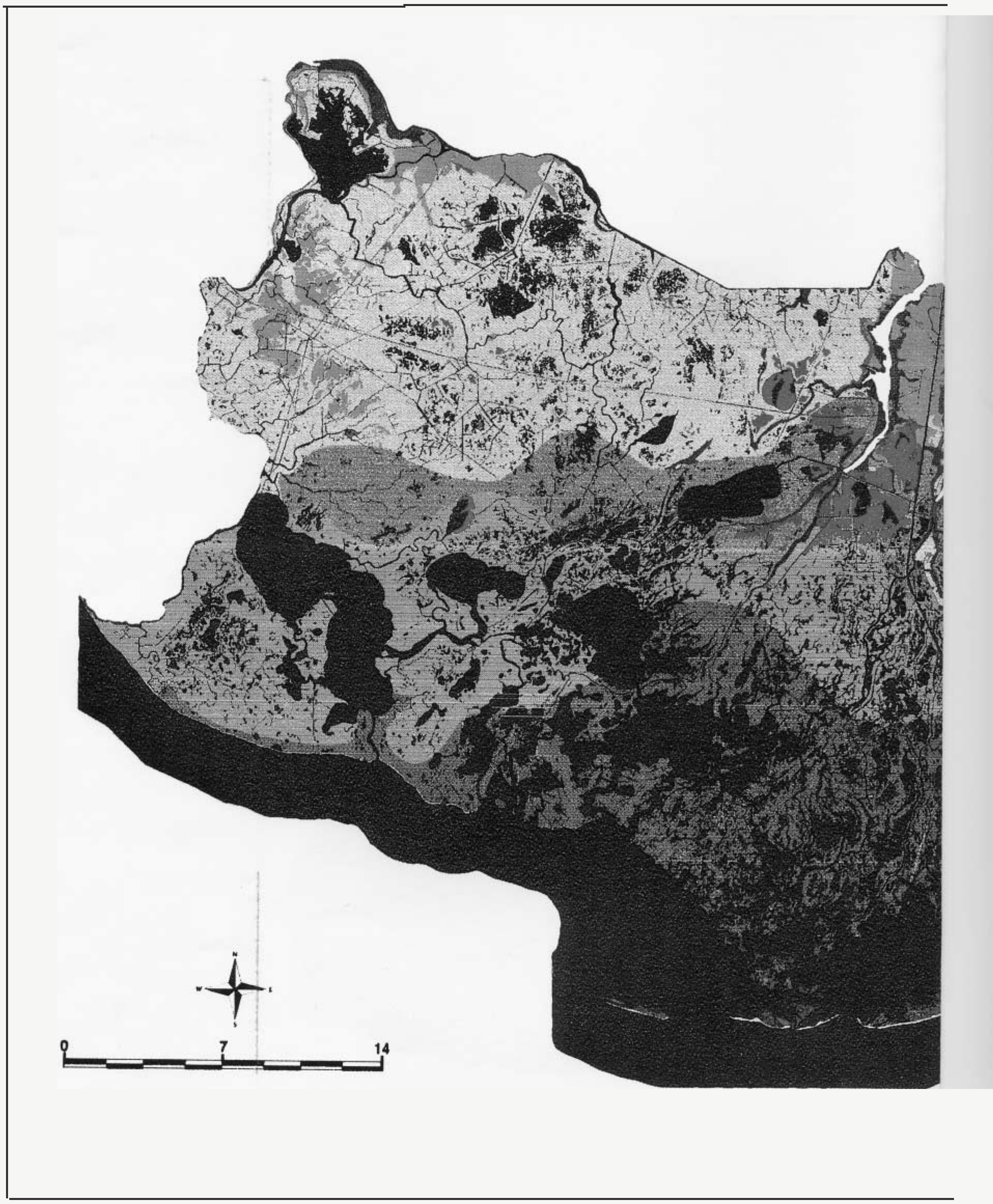
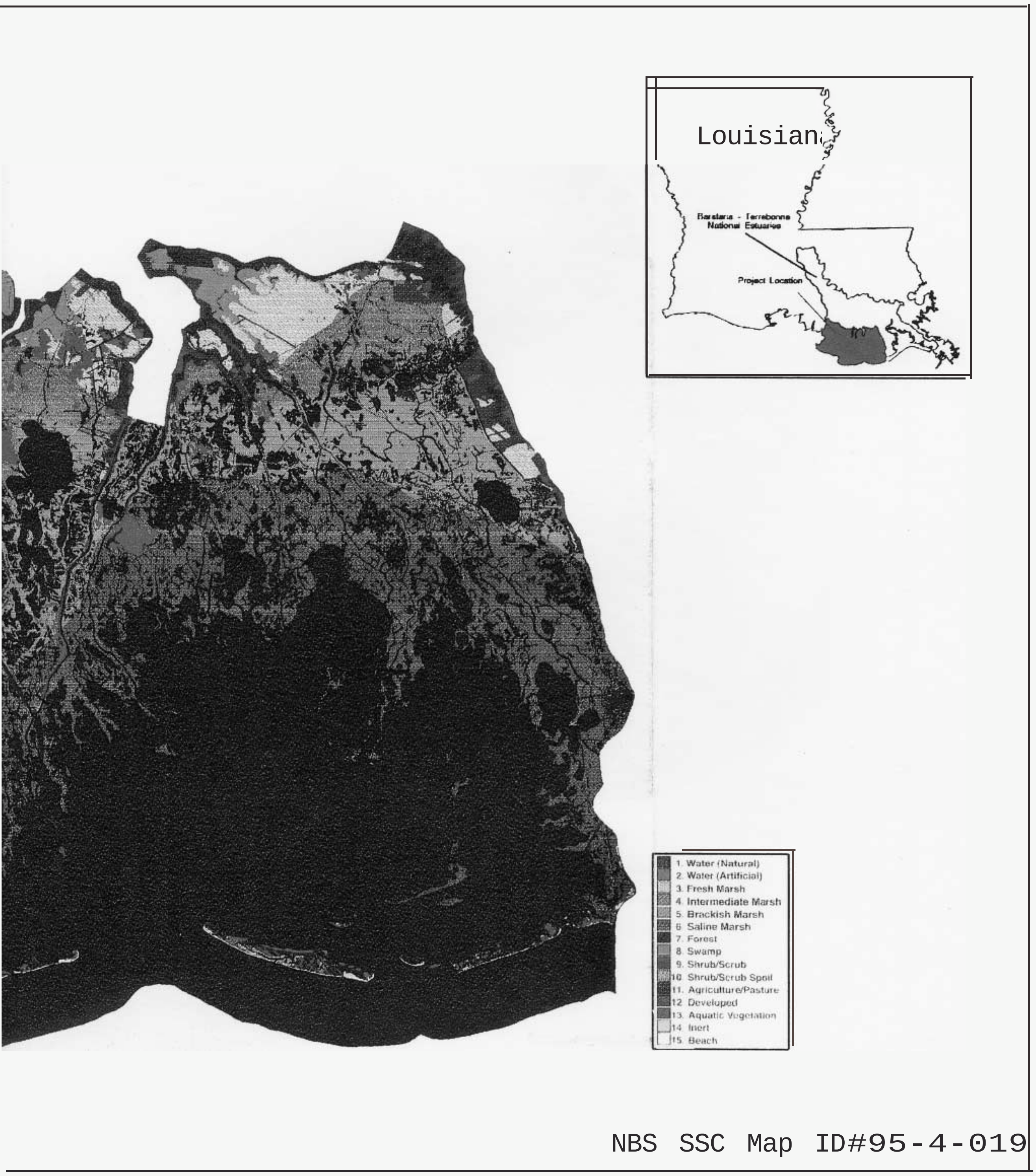


Figure 3.13 U.S. Fish and Wildlife Service 1978 habitat data-Te


Louisiana
Barataria - Terrebonne National Estuaries
Project Location
1. Water (Natural)
2. Water (Artificial)
3. Fresh Marsh
4. Intermediate Marsh
5. Brackish Marsh
6. Saline Marsh
7. Forest
8. Swamp
9. Shrub/Scrub
10. Shrub/Scrub Spoil
11. Agriculture/Pasture
12. Developed
13. Aquatic Vegetation
14. Inert
15. Beach
NBS SSC Map ID#95-4-019

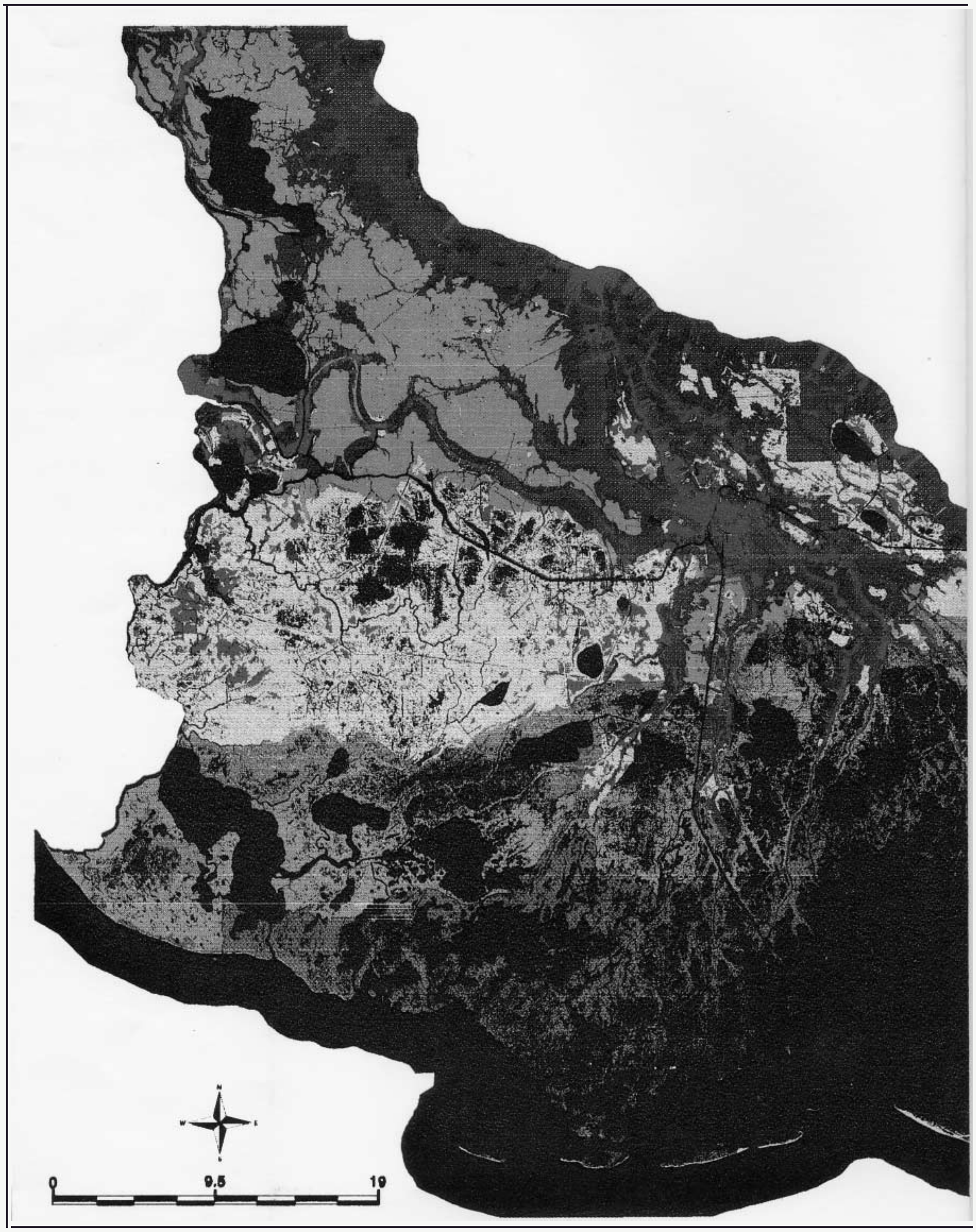
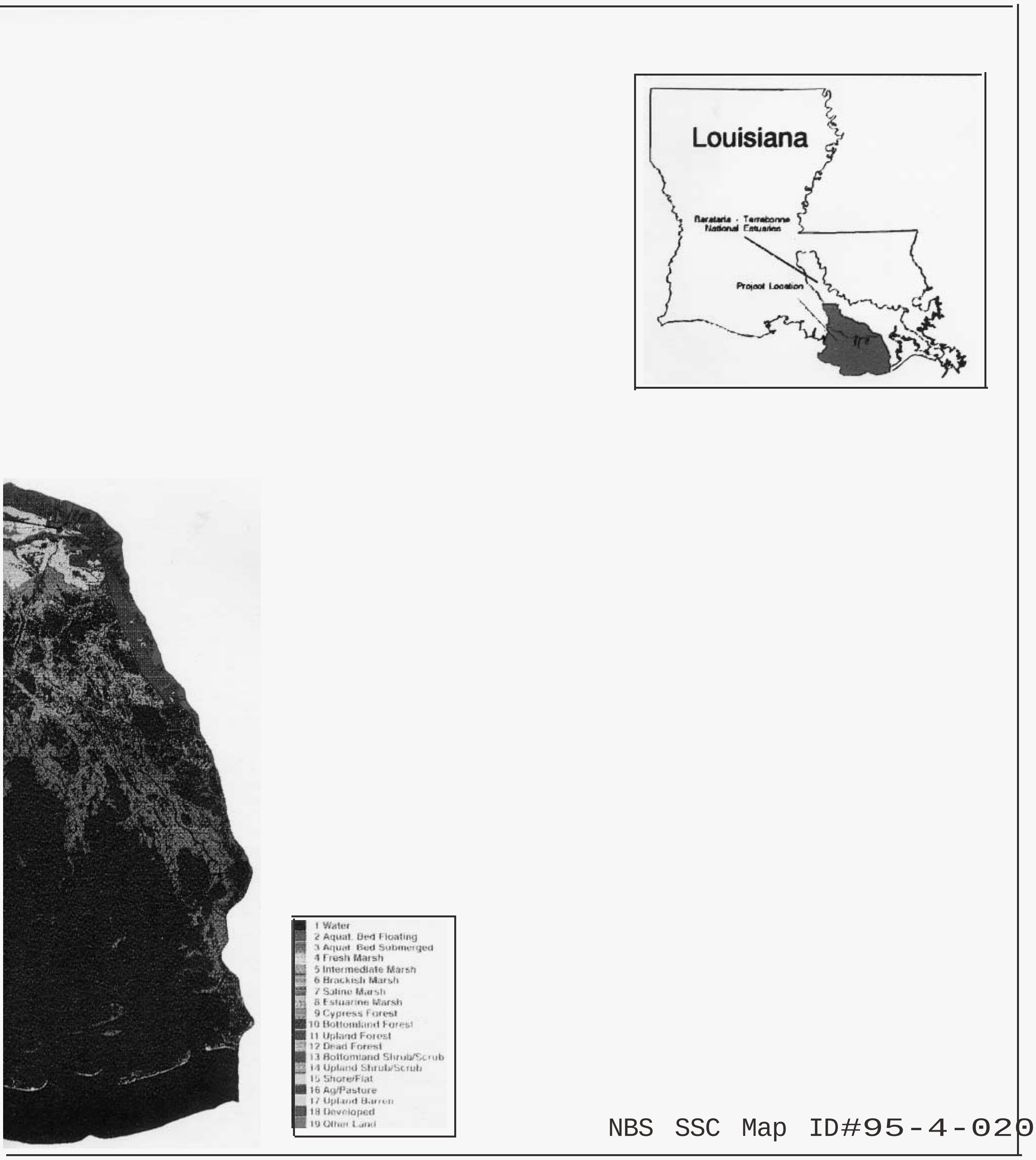


Figure 3.14 U.S. Fish and Wildlife Service 1988 habitat with Landsat TM W



er Merge Data-Terrebonne basin.

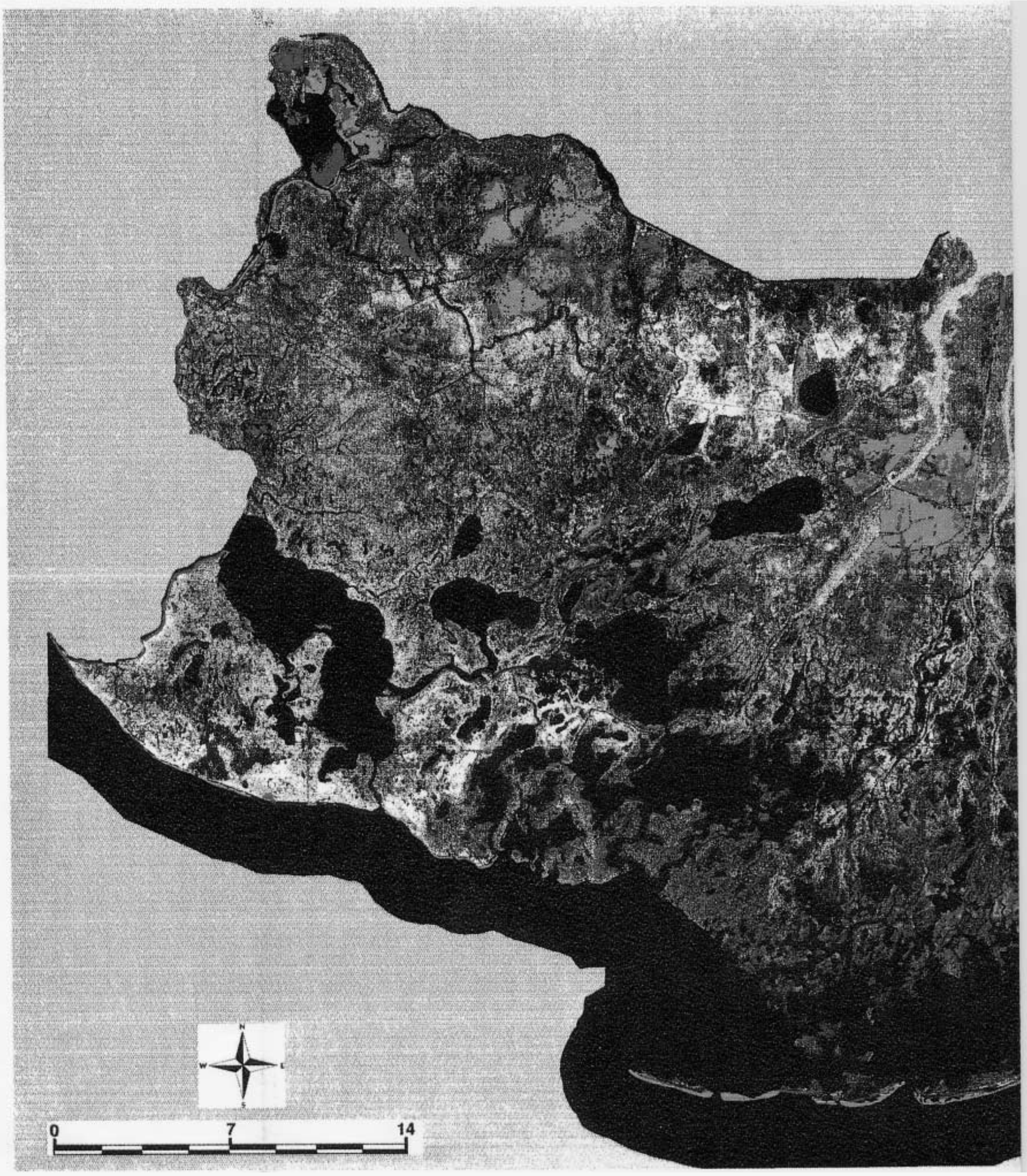
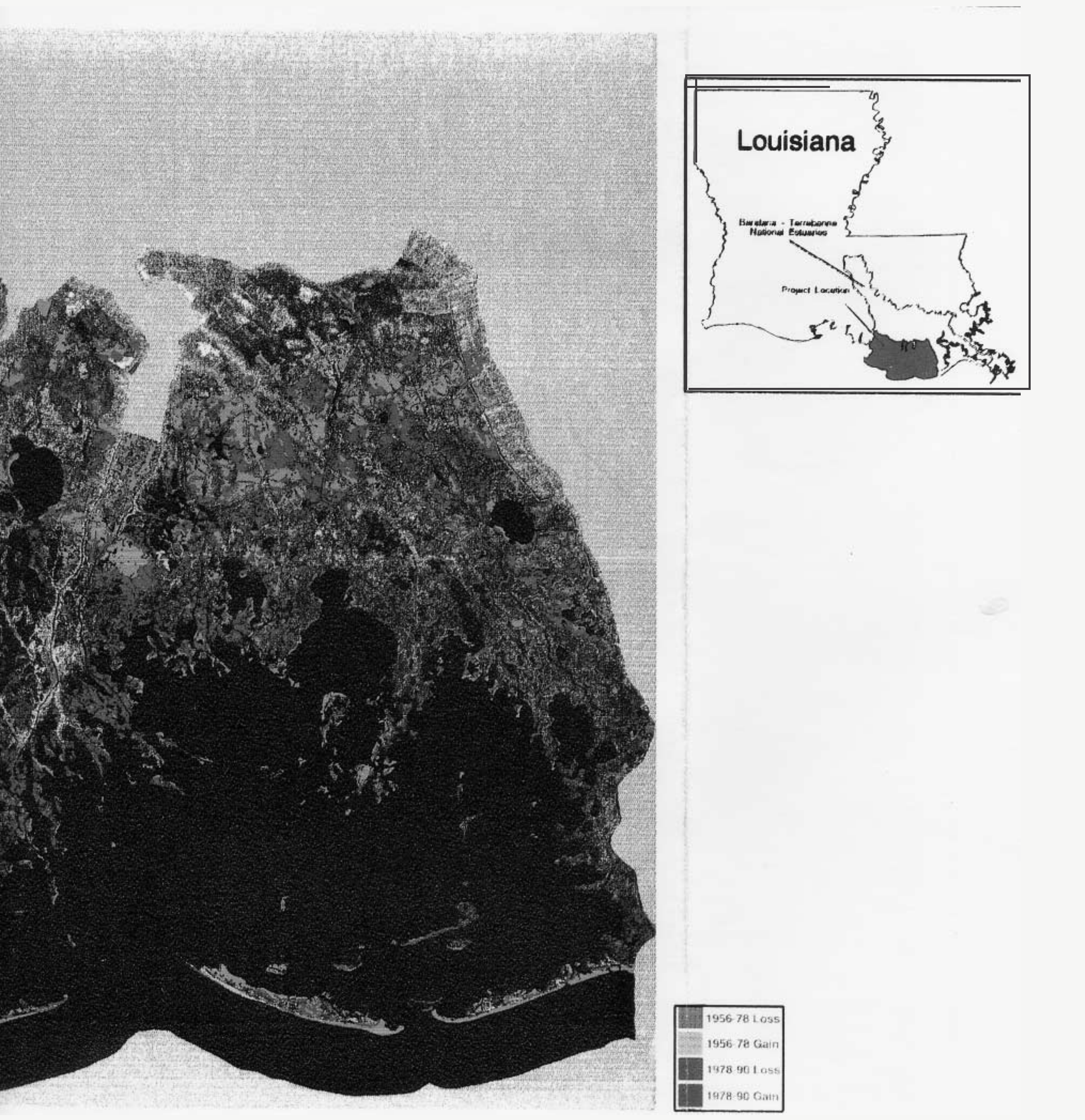


Figure 3.15 1956-1978-1988/90 land loss data-Terrebonne basin.



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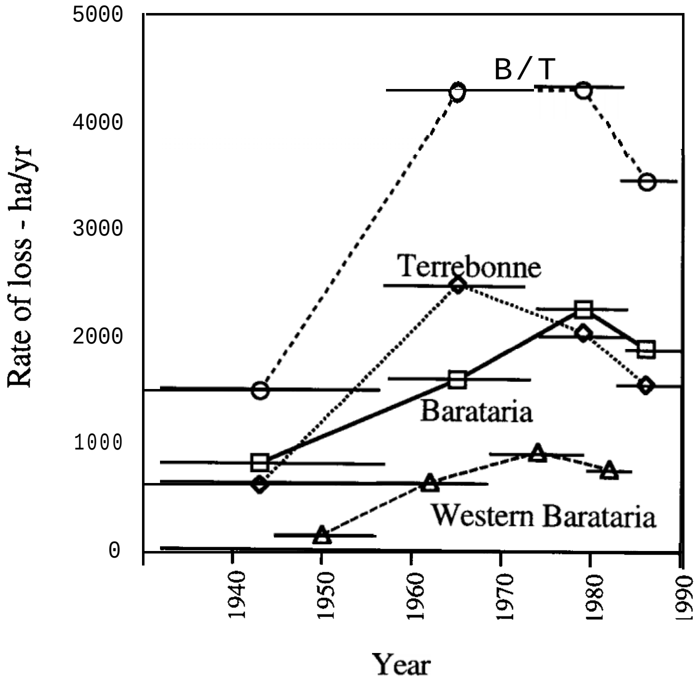
plain (Britsch and Kemp 1990, Dunbar 1990, Dunbar et al. 1992) has the most comprehensive coverage, both in terms of time (1932–1990) and space (entire Louisiana coast). The authors used aerial imagery to determine gross loss rates for four time intervals, by 15 minute quadrangle maps. Overall their calculations of loss rates for the Barataria-Terrebonne estuary are lower than those of the Southern Science Center, in part because the methodology is different.

The USACE studies show an increase in the wetland loss rate (changes of marsh to water) from the 1950s to the early 1980s, and a reduction of the absolute rate since 1983 (Figure 3.16). The peak rate of loss for the Barataria/Terrebonne estuary was 4300 ha (10,621 acres) yr^{-1} during 1974–83. The Barataria system peaked at 2264 ha (5,592 acres) yr^{-1} in the same period, but the Terrebonne system peaked earlier (1956–1974) at 2486 ha (6,140 acres) yr^{-1}. Perhaps this difference reflects the fact that the Terrebonne estuary is in a later stage of its delta cycle on a steeper part of the degradation curve (Figure 2.2). These results are in sharp contrast to the Southern Science Center data presented earlier, which shows rates increasing from 47 km^2 (18 mi^2) yr^{-1} in the 1956–78 period to 54 km^2 (21 mi^2) yr^{-1} from 1978 to 1990. In the two studies the time periods of most rapid loss overlap. Thus the peak rate for the USACE study was during 1974–83, while for the SSC study it was 1978–1990. High rates of loss in the late 1970s and early 1980s could explain some of the difference in these two data sets.

The relative rate of loss (the rate of loss relative to the wetland area at the beginning of the time interval, expressed as a percentage) is not yet dropping appreciably, because as the remaining wetland area decreases with time, the denominator of the loss ratio also decreases, inflating the rate (see Evers 1989 for comparison of and the implications of different ways of computing loss rates; the percentage loss rate is a way of normalizing data for comparison of different studies). The USACE rates are the most conservative (Figures 3.17 and 3.18). Gagliano et al. (1970), Adams et al. (1976) and an analysis of wetland loss in the western half of the Barataria basin done for the Louisiana Offshore Oil Port, Inc. (LOOP) (Evers et al. 1992, Sasser et al. 1986) all reported higher rates for the same 1960–1980s period. The LOOP data, exceptional for the most detailed analysis of 6 dates and 5 time intervals from 1945–1989, show much higher rates (% loss) than the other studies. In that study, the absolute areal loss began to decline in the 1980–1985 period, but the relative loss rate climbed to almost 2% yr^{-1}. These anomalous results can be traced to several factors: first, the western edge of the Barataria basin is an area of intense oil and gas exploration and drilling activity, and includes two "hotspots" of marsh loss, at the Leeville oil field in the south and the Clovelly area in the north. Leibowitz (1989) also showed exceedingly high loss rates in these hotspots; and the USACE data for the Leeville quadrangle has loss rates similar to LOOP's (Figure 3.17). Second, there is a significant difference in methods used in the LOOP study. The

USACE and SSC studies mapped land and water areas and determined land loss from the increase in water area. Thus, a canal shows as marsh loss, but the spoil bank formed in dredging the canal does not appear as marsh loss. The LOOP study, in contrast, mapped marshes as classes with different degrees of breakup



1, and Evers 1990).

Figure 3.16 Historical marsh loss rates in the Barataria-Terrebonne estuary (Britsch and Kemp 1990, Britsch 1991, and Evers 1990).

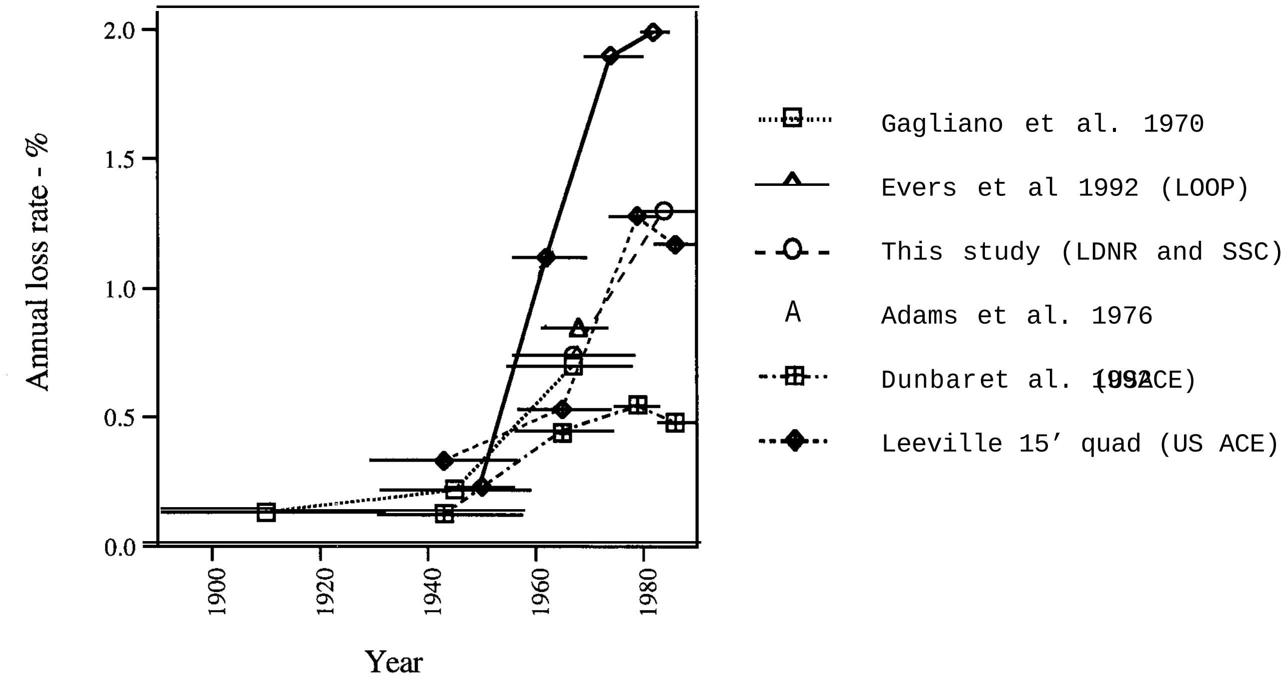


Figure 3.17 Comparison of marsh loss rates in the Barataria basin determined in a number of studies (Adams et al. 1976, this study,Dunbaret al. 1992, Evers et al. 1992, Gagliano 1981).

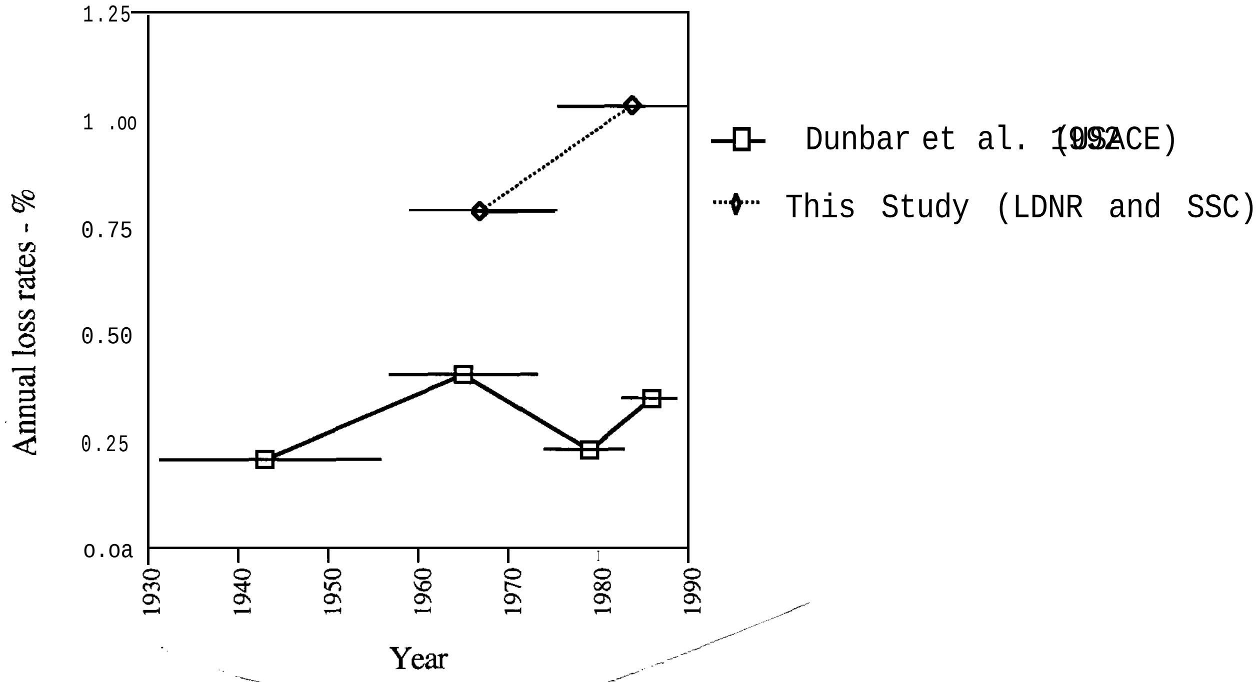


Figure 3.18. Comparison of marsh loss rates in the Terrebonne basin (this study and Dunbar et al. 1992).

(solid marsh, 0–10% water, 10–25% water, etc.), and called all areas with >60% water "water" and all areas with 40% or more marsh "marsh." Finally, the USACE rates are based on total land area, including fast lands, whereas the LOOP and SSC data are based on wetland area alone. Whatever the difference among studies, they all show low rates through the 1950s, increasing to exceedingly high wetland loss rates in the 1970s and 1980s, rates which threaten the integrity and resource productivity of the basin.

PATTERNS OF LAND LOSS

Several broad geographic areas of extensive habitat change are apparent in the BTES. One area occurs in Barataria basin at the southeastern tip near the mouth of the Mississippi River, extending northward in a narrow band along the river and extending westward through the Myrtle Grove area to the vicinity of Bayous Perot and Rigolettes (Figure 3.7). A second area is located southwest of Little Lake and extends southward in the marshes between Bayou LaFourche and Barataria Bay to the Gulf (Figure 3.7). In Terrebonne basin an area of extensive loss occurs south of the Catfish Lake area and extends north and then west. The marshes fringing western Terrebonne Bay are also areas of significant loss. Another area of extensive loss in the north western edge of the study area is the Turtle Bayou area (Figure 3.7). The southwestern parts of Terrebonne basin have undergone very little land loss from 1956 to 1988/90 presumably due to the influence of the Atchafalaya River.

Wetland loss does not occur uniformly across the Louisiana coast. Local loss rates are determined by an interaction of several processes, including the thickness of recent sediments, the pattern of distributaries of earlier delta lobes, the withdrawal of oil, gas, and other minerals, the type of marsh vegetation, the intrusion of marine waters into the estuary, and the size of water bodies as related to wind direction and fetch. Marsh loss can be classified into two major categories, shoreline loss and interior marsh loss (Wayne et al. 1993, 1994). Shoreline loss, due to erosion by storms, boat wakes, etc., represent only about 31% of the total loss. Nearly all the rest (67%) is associated with interior marsh loss. While the dredging of channels through marsh is a significant source of interior marsh loss (Craig et al. 1979, Turner et al. 1982, Scaife et al. 1983), most loss is associated with the development of small ponds that gradually coalesce into large shallow lakes (Wayne et al. 1994). At present the most rapid wetland loss rates are occurring in the brackish and intermediate interior marshes (Lee and Turner 1987), possibly because here the influence of subsidence and marine intrusion into previously low salinity marshes combine to stress the marsh vegetation beyond its ability to survive. The complexity of the loss pattern on the western edge of the Barataria basin is illustrative (Dozier 1983, Sasser et al. 1986, Evers 1989, Evers et al. 1992). In 1945 this area was largely solid marsh, with some areas of breakup in the southern, salt marshes. Through the years there was a gradual opening up of the

interior marshes, progressing from the salt marshes inland toward the fresh marshes. A second pattern was the progressive degradation of marshes adjacent to the natural levee of Bayou Lafourche. Figure 3.19 shows the overall spatial pattern of change over the period 1945 to 1985. The only solid marsh remaining is in the extreme north of the study area, a fresh marsh that has remained largely unchanged for the past 40 years. In contrast to other areas, the hydrology of this marsh has not been altered and it remains isolated from the central basin lakes. In addition, some supply of fresh water to the area was available for some time via a canal connection to Bayou Lafourche.

SUMMARY OF STATUS AND TRENDS

Status

The BTES is composed of a number of different vegetative communities which reflect gradients in salinity (the relative supply of fresh vs. marine water) and land elevation. The coastal marshes occur in adjacent bands of salt, brackish, intermediate and freshwater vegetation lying parallel to the Gulf Coast in landward direction. These communities can be generally characterized by the following species associations: salt (*Spartina alterniflora*/*Distichlis spicata*), brackish (*Spartina patens*/*Spartina alterniflora*), intermediate (*Spartina patens*/*Vigna* sp../*Sagittaria lancifolia*/other spp.), and fresh (*Panicum hemitomon*/*Sagittaria* spp./*Eleocharis* spp./other species). Floating marshes are found primarily in freshwater areas, but also occur in intermediate and a few brackish areas. The dominant plant species in floating marshes are *Panicum hemitomon* and *Eleocharis* spp. Forests are found in the upper reaches of BTES and can be divided into three types: upland forests (nearly all are cleared for development); deepwater swamps dominated by cypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*); and seasonally flooded bottomland hardwood dominated by several species of oak (*Quercus* spp.). Coastal upland forests are limited to Cheniere Caminada. Barrier island vegetation is characterized by a number of species including *Sesuvium portulacastrum, Ipomoea stolonifera, Cakile geniculata,* and *Spartina patens*.

The most recent broad scale habitat data available (1988) cover approximately 3.5 million acres of the 4.1 million acres within the BTES area. Based on these data, and additional sources, for the 600,000 acres, there are approximately 909,000 acres of marsh (380,000 acres of fresh marsh and 531,000 acres of nonfresh marsh), 790,000 acres of forested wetland, and 1,500,00 acres of open water.

Trends

Trends in the habitat data from 1956 to 1988 show a gradual shifting of marsh vegetation zones to more salt-tolerant species over time. This is generally seen as a

gain in salt and brackish environments at the expense of fresh and intermediate marshes. Loss rates based on available habitat data are estimated to be 18 square miles per year from 1956 to 1978 and 21.5 square miles per year from 1978 to 1988/90. Comparison of these loss rates with other studies (even though different methodologies were employed) all indicate high and mostly increasing land loss rates

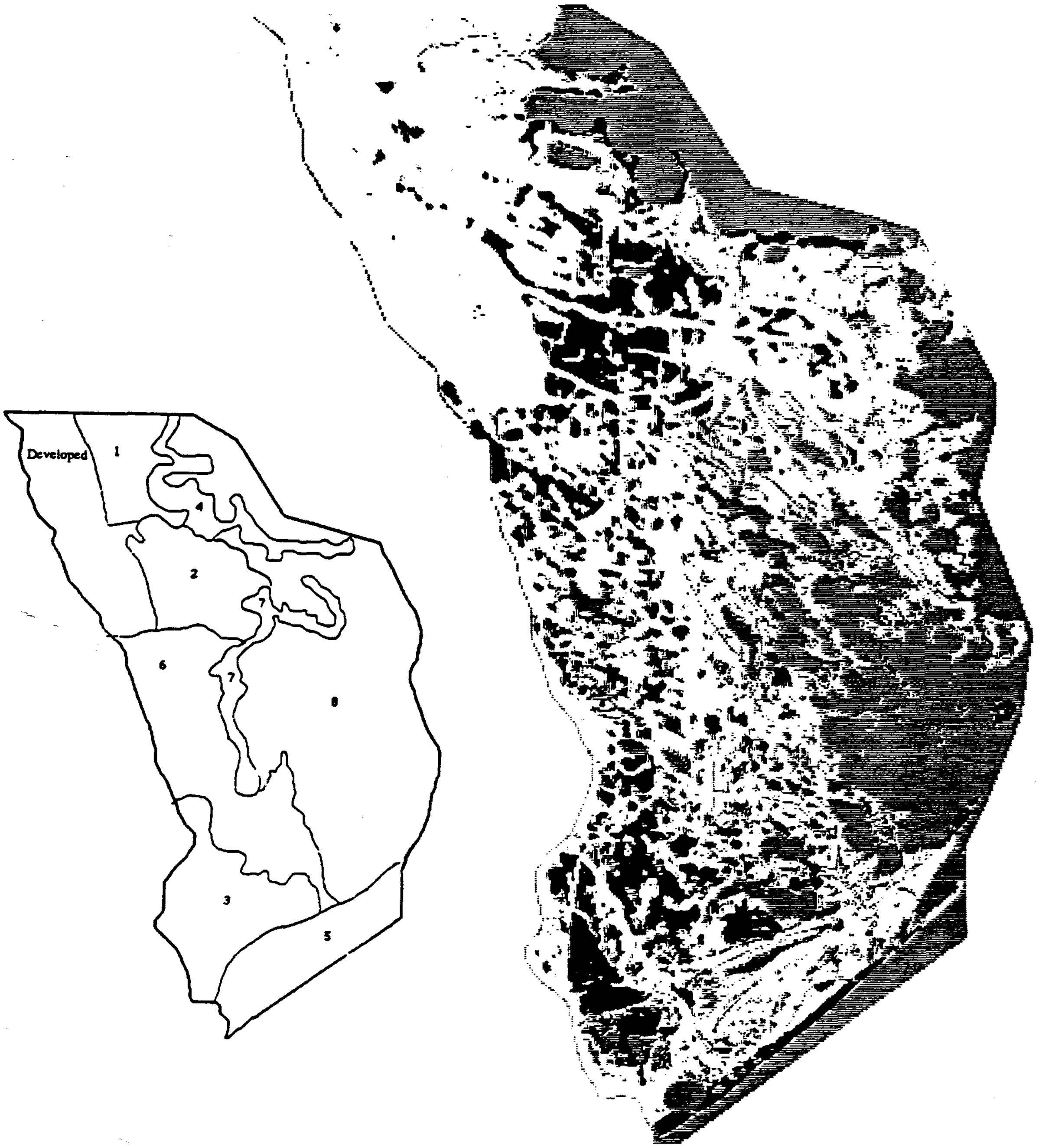


Figure 3.19 A change detection of the western Barataria area depicting in shades gray, pixels that were less than 60% water in 1945 and more than 60% water in 1985 (i.e., a change from “marsh” to “open water" The darker the pattern, the greater the density of water pixels in the area Horizontal stripes indicate areas that were more than 60% water in 1945. The white represents all other categories. The numbers of the outline of the study area depict eight different loss rate areas(Evers et al. 1991).

through the 1970s and early 1980s. Land loss does not occur uniformly over the Louisiana coastal zone and can be divided into two general types of loss: shoreline erosion and interior loss. Shoreline loss, due to erosion by storms, boat wakes, etc. represents about 31% of the total loss. Most of the rest is associated with interior land loss.

PART 4

STATUS AND TRENDS IN MISSISSIPPI RIVER SEDIMENT REGIME AND ITS ROLE IN LOUISIANA WETLAND DEVELOPMENT

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INTRODUCTION

The Mississippi River has provided the sediments that form the Louisiana coastal wetlands deposited directly as overbank and deltaic deposits or by reworking of riverine sediments by shallow marine processes. The discharge of the river includes sediments transported as suspended and bed load. The bed load, composed largely of fine sand (in Louisiana), provides sediment that makes up channel, point bar, distributary mouth bar, and coastal beach deposits. These deposits are the skeletal framework upon which the coastal plain wetlands have been built during the past 6,000 years (Kolb and Van Lopik 1958, Welder 1959). The silt, clay, and fine sand that make up the suspended load are carried into the wetlands during floods by way of interdistributary channels and overbank flow.

RIVER MODIFICATIONS

Since 1900, human modifications have disrupted or eliminated sediment and water pathways into the wetlands and have reduced and modified the amount and character of sediment carried by the Mississippi River. Figure 4.1 illustrates the magnitude and temporal aspects of the major modifications that have affected the behavior of the Lower Mississippi River. Dams on such major tributaries as the Missouri and Arkansas rivers have decreased the amount and size of sediments that the river transports. Land use changes appear to have initially been responsible for higher sediment loads in the fluvial system as the result of increased soil erosion, and after the introduction of agricultural conservation practices have reduced the amount of sediment supplied to the river from runoff (Keown et al. 1986, Kesel 1989). Artificial levees, which now line the entire length of the river, prevent sediment and water from being dispersed into the adjacent flood plain and wetlands by preventing overbank flow and crevasse splays from occurring (a crevasse is a break in the natural levee of the river). River sediments are now funneled to the mouth where they are discharged off the continental shelf edge. Revetments, concrete mattresses placed along the channel banks, have greatly reduced lateral migration and bank caving. It is estimated that bank caving was the main source of sediment for the Lower Mississippi River (Kesel et al. 1992). Thus, the introduction of revetments may have played a major role in altering the sediment regime of the river. Also, the length of the river has been shortened about 240 km (150 miles) by cutoffs in the central portion of the Lower Mississippi River (mainly from 650 to 1300 km (400 to 800 miles) below Cairo). This has caused an increase in the energy gradient, resulting in an adjustment of the channel thalweg, typically associated with channel degradation upstream and aggradation downstream (Ferguson 1940). Meander cutoffs may also be seen to significantly affect the sediment budget of the river. When a portion of the channel

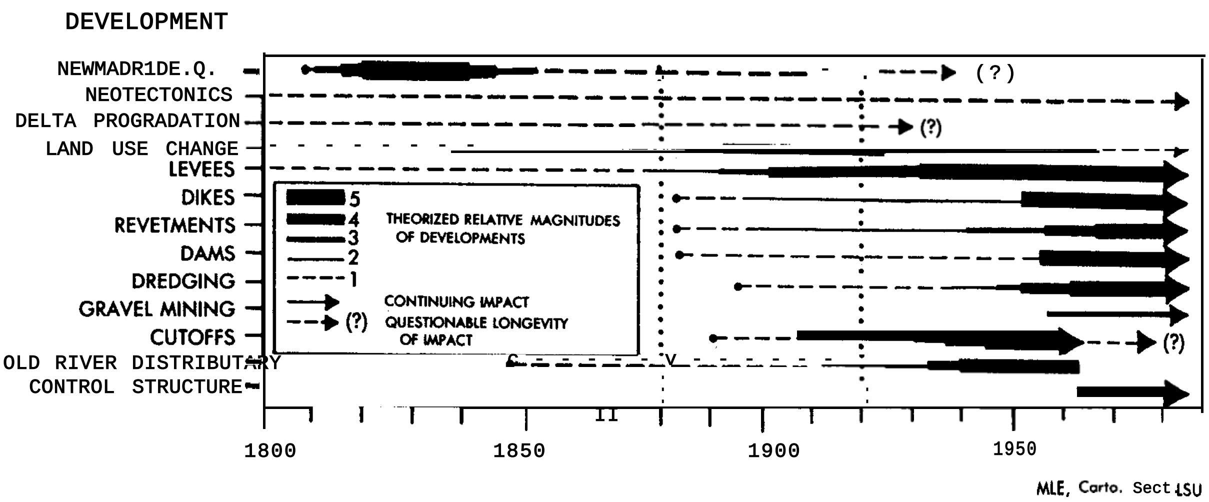


Figure 4.1 Qualitative estimates of the magnitude of events that may have caused changes in the sediment regime of the Lower Mississippi River (from Kesel 1988).

removed by cutoffs, the amount of sediment available for input into the system is reduced. This may be significant in the Lower Mississippi River considering the importance of bank failure as a mechanism of sediment input. Also, sediment stored in cutoffs on the channel bed and point-bars is no longer available to the system.

MISSISSIPPI RIVER SEDIMENT REGIME

Prior to modifications, the Lower Mississippi River was a classic meandering alluvial river that was aggrading its channel throughout much of its length. An estimate of the average annual sediment discharge reaching the Gulf included a suspended load of 270 x 10^6 m^3/yr (352 x 10^6 yd^3/yr) and bed load that may have been as much as 130 x 10^6 m^3/yr (170 x 10^6 yd^3/yr)(Kesel et al. 1992).

As a result of human modifications, the sediment regime of the Mississippi River has experienced significant changes (Keown et al. 1986, Kesel 1988, 1989, Kesel et al. 1992). Since 1850, the suspended sediment load of the Mississippi River has declined by almost 80%. Figure 4.2 shows the total annual suspended sediment load in the vicinity of New Orleans from 1850 to 1983. Although there are periods of missing data, a declining trend in the suspended sediment load is apparent. Kesel (1989) has characterized the sediment record of the Mississippi River into three periods; historic (prior to 1900), pre-dam (1930–1952), and post-dam (1963–1982). The suspended sediment load declined by 43% from the historic to the pre-dam period and by 51% from the pre-dam to the post-dam period.

In conjunction with a decline in the amount of sediment carried in suspension, there has also been a decrease in the size of the suspended sediment (Figure 4.3). At Tarbert Landing, 491 km above Head of Passes, the amount of sand declined by 50% from the late 1800s to 1982, while the amount of sand carried in suspension declined by 72% at Belle Chasse, 170 km above Head of Passes, from the late 1800s to 1983 (Kesel 1989). This means that there has been a proportionate increase in the silt-clay component of the sediment load, and may explain the increase in scatter between discharge and suspended sediment concentration for the 1963 to 1982 trend line (Figure 4.4). The relationship between sand and discharge is typically more linear than that between discharge and silt-clay (Knighton 1984). The declining trend in grain size compares well with a declining trend in bed load size. A comparison of bed load surveys completed in 1932 and 1989 shows a decline in the coarse faction of the bed load (Figure 4.5). From Cairo, Illinois, to the Old River Structure, 300 miles above Head of Passes, the bed load was finer in 1989. Downstream of mile 300 the mean grain size was about the same, although there was a more uniform distribution, with a decrease in the amount of very fine sand (Nordin and Queen 1992).

The average annual suspended load presently reaching the Gulf is approximately 60 x 10^6 m^3/yr (78 x 10^6 yd^3/yr) (Kesel 1989). Minimum concentrations of suspended sediment occur during the low flow months of August through November and maximum concentrations occur during high flow (January through June). Most of the sand that is carried as suspended load is transported during the periods of high river discharge. Several subjective estimates the bed load range from 1% of the

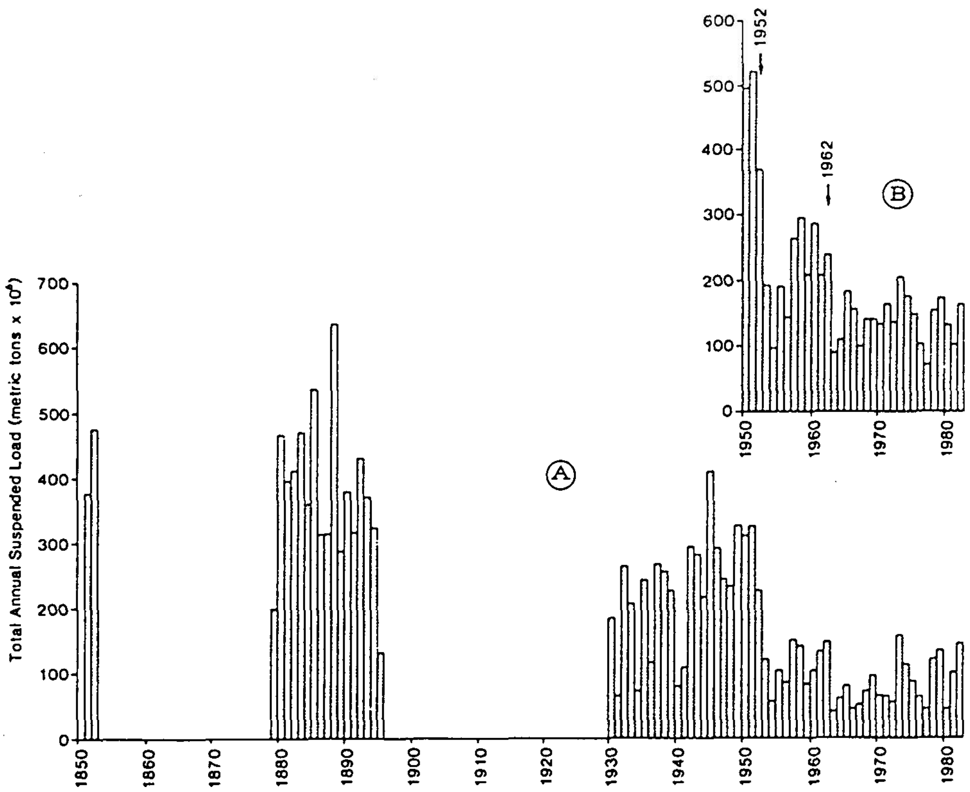


Figure 4.2 Total annual suspended sediment load for the Mississippi River (A) below new Orleans based on data from Humphreys and Abbot, 1851 to 1852; Quinn, 1879 to 1895; and New Orleans Water and Sewage Board, 1930 to 1982; (B) U.S. Corps of Engineers data for Baton Rouge, 1949 to 1958; Red River Landing, 1958 to 1963; and Tarbert Landing, 1963 to 1982 (from Kesel, 1989).

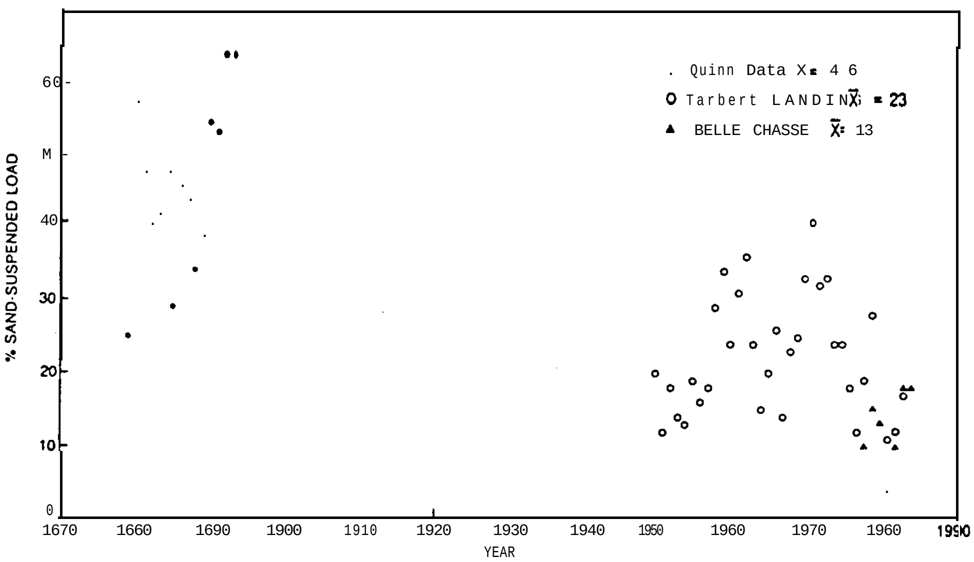


Figure 4.3 Changes in the percentage of sand carried as suspended lo data from Quinn (1894), Tarbert Landing (USCOE), and Belle Chasse (USGS) (from Kesel 1988).

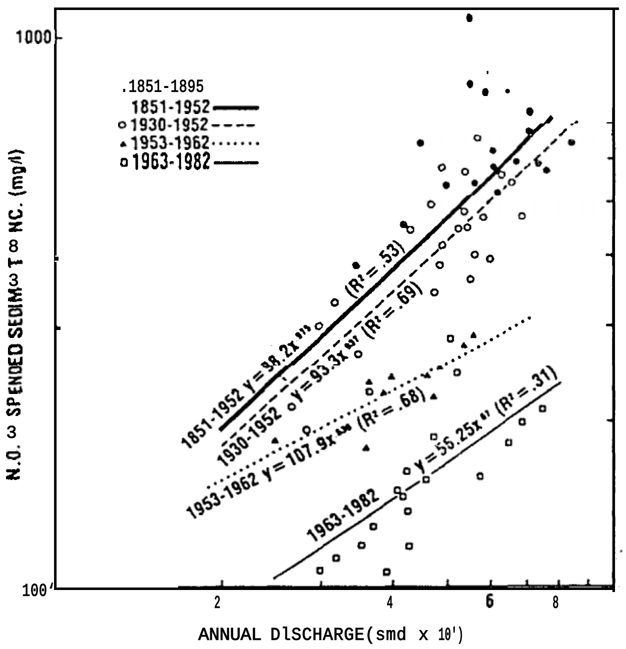


Figure 4.4 Relation between average annual sediment concentration and annual discharge at New Orleans. Three distinct groupings are evident in the data; 1851 to 1952 (historic); 1952 to 1962 (pre-dam); 1963 to 1982 (post-dam). Note the increase in scatter (R^2 = .31) associated with the post-dam trend (from Kesel 1988).

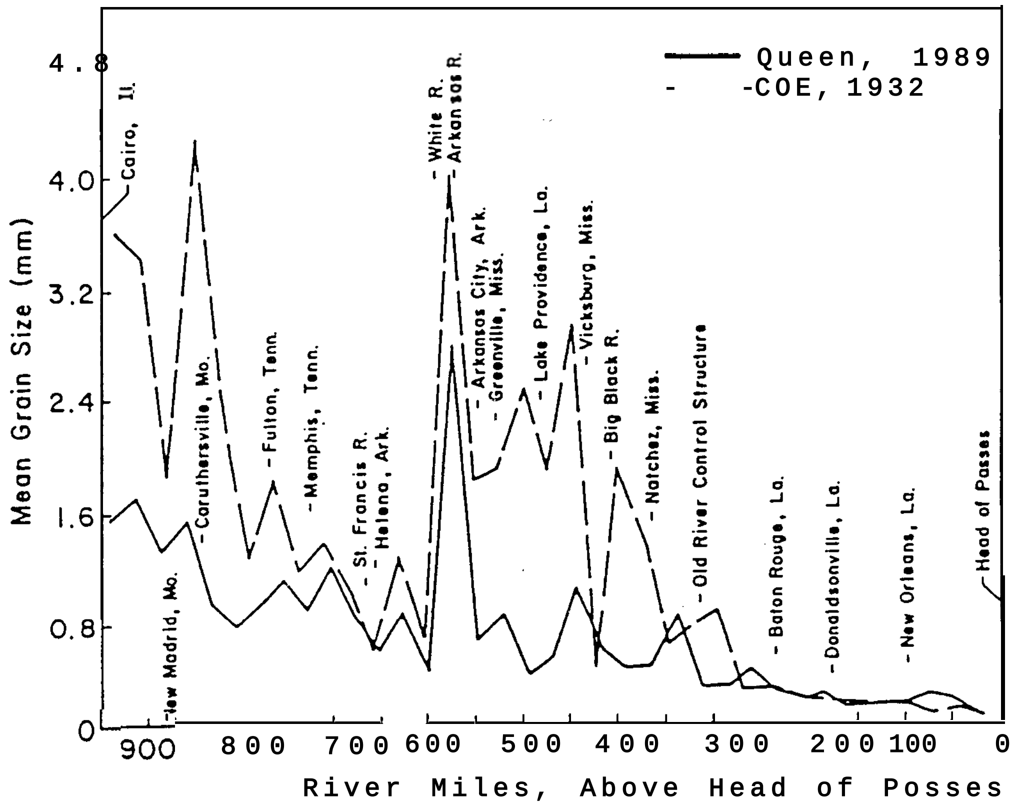


Figure 4.5 Comparison of the 1932 and 1988 bedload surveys by the U.S. Corps of Engineers. The 1988 survey shows a decrease in the mean grain size from Cairo to mile 300. Below Baton Rouge the mean grain size is similar for the two surveys (from Nordin and Queen 1992).

suspended load (Lane and Eden 1940) to 7–25% (Fisk, et al. 1954, Holle 1952) of the total sediment load.

SEDIMENT AND WATER DISCHARGE PATHWAYS INTO WETLANDS

Distributaries of the Mississippi River during the past several thousand years have provided major pathways for the dispersal of sediment and water into the Barataria and Terrebonne wetlands. Major distributaries include Bayous Lafourche, Terrebonne, Des Famillies, Barataria, and to a lesser degree, the Atchafalaya River. These distributaries have been active during different times and thus their importance in supplying sediment and discharge to the wetlands has varied temporally (Figure 4.6). While Bayous Terrebonne, Des Famillies, and Barataria never carried the full discharge of the Mississippi River, Bayou Lafourche, which follows a 107-mile course to the Gulf, functioned as the main channel of the Mississippi from the second century until the 12th century when the modern delta began actively prograding (Sasser et al. 1986). This switch of the Mississippi River's center of deposition relegated Bayou Lafourche to a minor distributary (Figure 4.7) until 1904 when the Army Corps of Engineers constructed a dam at the confluence of the Mississippi River at Donaldsonville to control downstream flooding. The dam, in effect, eliminated flow in the channel. Problems with stagnation and siltation of the channel led to the construction of a pumping station in 1955 which established an approximate average discharge of 11.2 m^3/s (400 cfs) (Doyle 1969).

Measurements of the suspended sediment discharge of Bayou Lafourche from 1959 to 1965 (Doyle 1969) provide some insight into how distributaries act as pathways for sediment. The average annual sediment load at the entrance of Bayou Lafourche at Donaldsonville during this pumping phase was 74,170 metric tons (73,000 tons). The sediment load 12.5 miles down the Bayou at Napoleonville was 48,463 metric tons/yr (47,700 tons/yr), indicating that over 35% of transported sediment was deposited in the first 10% of the channel length. The percentage of sand decreased from 43% to only 1% in the first 9,150 m (30,000 feet). The grain size as indicated by the D_{85} diameter decreased from 0.26 mm to 0.03 mm (.01 in to .001 in) in 12,200 m (40,000 feet).

The dispersal of water and sediment from the Mississippi River and other distributaries into adjacent wetlands occurred by overland flow during high water discharge periods. Discharge for the Mississippi is markedly seasonal, with highest flows occurring from February through May and lowest from September to November. Stage and discharge variations decrease towards Head of Passes due to lower gradients and the influence of the Gulf of Mexico. Tidal effects increase towards the Gulf of Mexico, and may be detected up to 35 mi above Baton Rouge during extreme low water (Mossa 1988). The mean annual discharge of the Mississippi River below Tarbert Landing is 12.8×10^3 m^3/s (4.5×10^5 cfs) with a bankfull discharge of 25.5×10^3 m^3/s (9.0×10^5 cfs). This represents a decrease by 1963 when the Old River Control Structure was completed, establishing that

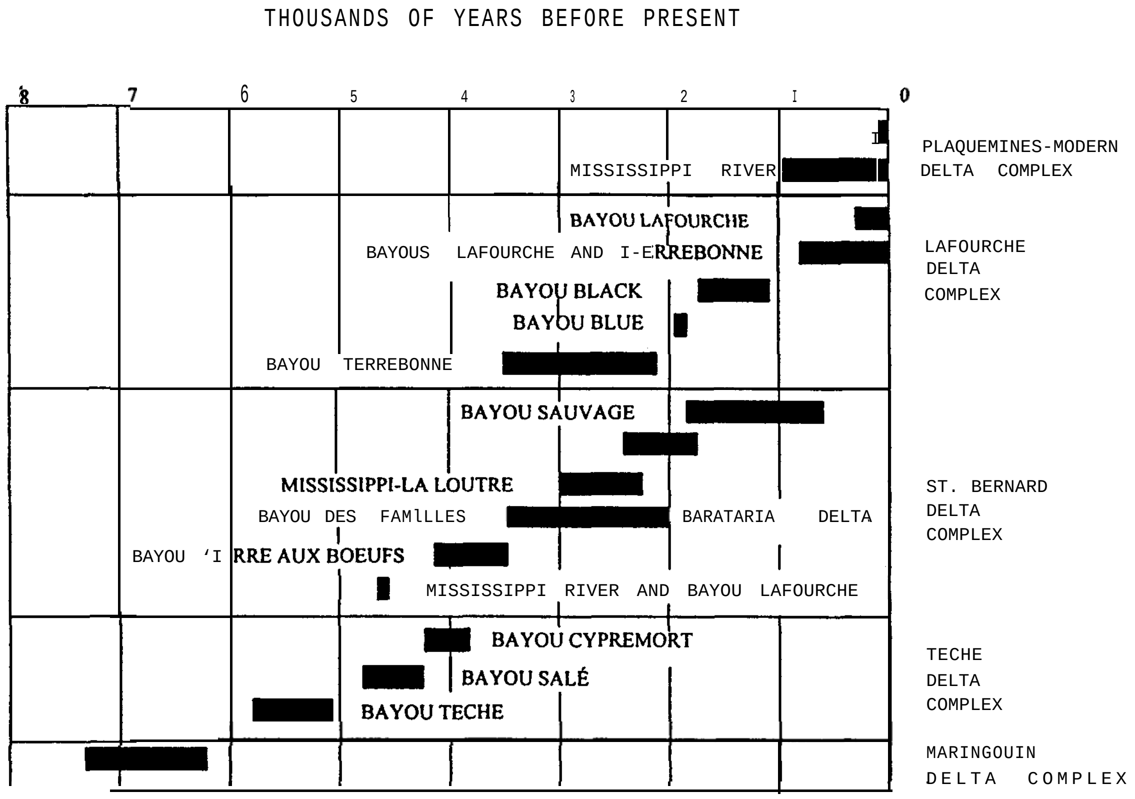
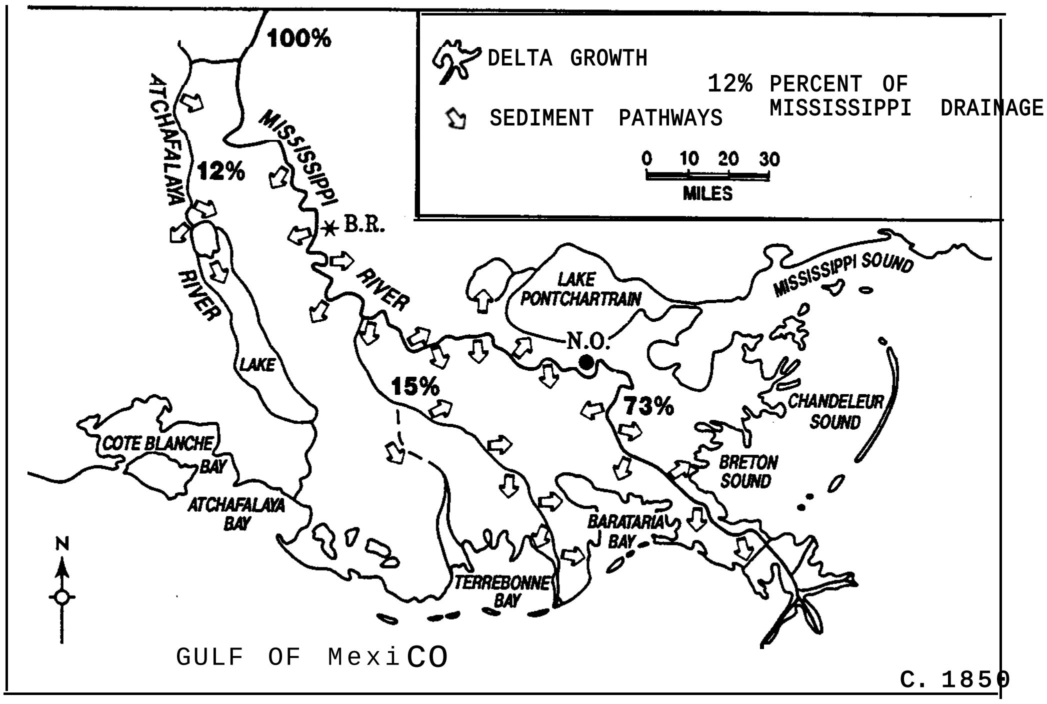


Figure 4.6 Chronology of delta lobes and time in which major channels were receiving discharge based on age of delta-plain peats (from Frazier 1967).



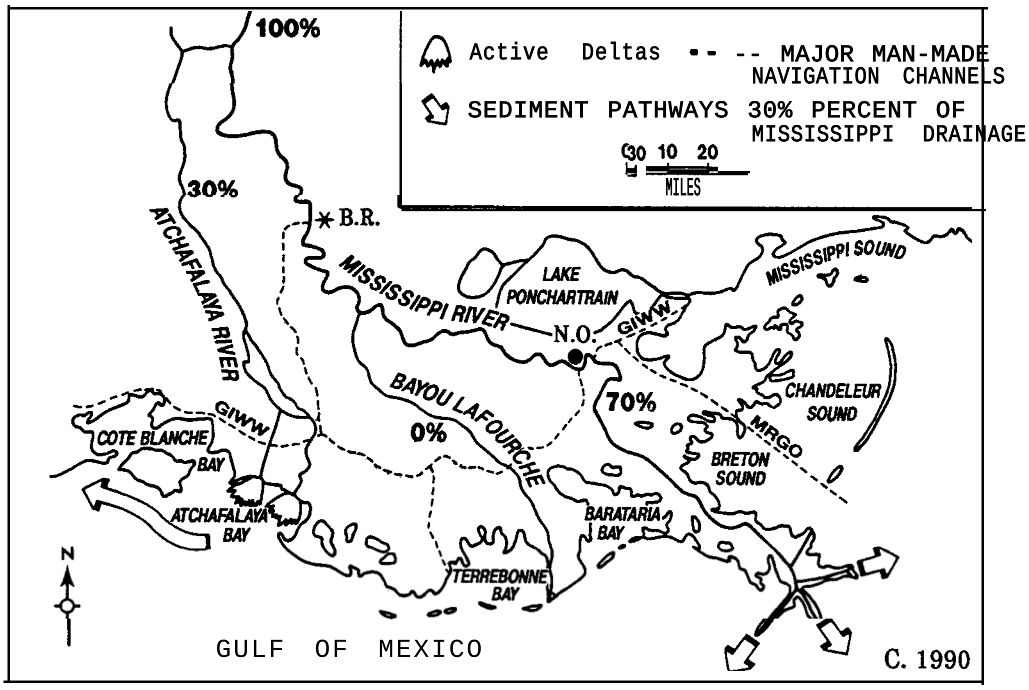


Figure 4.7 Comparison of the percentage of Mississippi discharge flowing down the Atchafalaya, Bayou Lafourche, and the Mississippi River for periods 1850 and 1990.

30% of the combined discharge of the Mississippi and Red Rivers would flow into the Atchafalaya River.

The Atchafalaya receives its discharge from the Red River and the Mississippi River via the Old River Diversion Structure. Since the early 1500s the Atchafalaya has been receiving discharge from the Mississippi (Roberts et al. 1980). Between 1850 and 1962 the proportion of discharge from the Mississippi River entering the Atchafalaya River had increased from 12% to 30%. The average annual flow between 1938 and 1972 at Simmesport, Louisiana, just below the confluence of the Red River and Old River, was 5,126 m^3/s (181,130 cfs) with an annual peak flow of 12,121 m^3/s (428,300 cfs) (Roberts et al. 1980). Fisk (1952) predicted that by 1975 the Mississippi River would have abandoned its present course for the Atchafalaya due to the slope advantage. The Atchafalaya's channel is 307 km (191 miles) shorter from the confluence of the two rivers to the Gulf of Mexico. Figure 4.7 shows the change in percentage of Mississippi discharge flowing down the Atchafalaya and Bayou Lafourche between 1850 and 1990.

Differences in the hydrology and basin characteristics between the Red River and the Mississippi River suggests that the discharge and sediment characteristics of the Atchafalaya may differ from that of the Mississippi. In the Red River basin precipitation is not as abundant and floods are more episodic, with shorter, more peaked events. However, overall the discharge regime of the Atchafalaya is dominated by Mississippi River discharge. Comparison of a 5-year moving average shows that the Atchafalaya tends to follow a similar discharge trend as the Mississippi River. From 1950 to 1985 69% of the discharge of the Atchafalaya came from the Mississippi (Mossa 1990). Discharge from the Atchafalaya flows into Atchafalaya Bay through two outlets, with approximately 30% of the discharge passing through Wax Lake Outlet, while 70% passes into eastern Atchafalaya Bay below Morgan City (van Heerden et al. 1983). Some modification to this flow occurred between 1987 and 1995 when the Wax Lake Weir was in operation.

In comparison to discharge, the proportion of sediment supplied to the Atchafalaya from the Red River and the Mississippi shows greater variation through time. The Mississippi contributes from 30% to 90% of the annual suspended sediment to the Atchafalaya at Simmesport, while the Red River contributes between 10% and 70% of the suspended sediment on a given year. From 1964 to 1986 the average contribution of the Mississippi and Red rivers to the Atchafalaya's suspended sediment load was 58% and 42%, respectively. The large amount of sediment supplied by the Red River to the Atchafalaya, relative to the amount of discharge, can probably be attributed to sediment yields in semi-arid basins being greater than in humid basins where vegetation may reduce runoff and soil erosion.

Like the Mississippi, the Atchafalaya has experienced a change in its sediment regime. Data from Simmesport show a decline in suspended sediment concentration of 14 mg/l per year from 1952 to 1985. This can be attributed to changes that have occurred within the basin, including dams and land use practices upstream (Mossa 1990). However, the volume of sediment reaching Atchafalaya Bay has increased from 88,643 x 10^3 metric tons/yr (87,247 X 10^3 tons/yr) between 1967 and 1971 to 150,581 x 10^3 metric tons/yr (148,210 X 10^3 tons/yr) between 1973 and 1975 (Roberts et al. 1980). The size of sediment has also increased, from dominantly silt and clay to silt and fine sand since 1960. This is due to the flow of the

Atchafalaya being concentrated in a single channel in the lower basin, resulting in scour and reentrainment of bed load during periods of high discharge.

The mechanisms that have historically been responsible for transporting sediment into the interdistributary bays and wetlands of the deltaic plain include seasonal overbank flooding, crevasse splays, and shallow marine coastal processes. The latter (not discussed here) is important in redistributing Mississippi and Atchafalaya River sediments. The relative importance of the other mechanisms in transporting sediment to the wetlands varies in terms of the quantity and size of sediment supplied, the duration of contribution, and the spatial extent of sediment deposition.

Overbank flooding probably provided the most important source of sediment in terms of quantity, spatial extent of contribution, and period of time. Suspended sediments are introduced into wetlands by overbank flooding when the levees are topped by the river's flow during flood periods (Figure 4.8). While many rivers overflow their banks on average of once every 1–2 years (Knighton 1984), the Lower Mississippi River floods seasonally, in the late winter and spring. Kesel (1989) estimated the pre-1900 accumulation rate of sediment for a 10,000 km^2 (3860 mi^2) area below Baton Rouge to have been 1.2 mm/yr (0.47 in/yr). In contrast, the accumulation rate, for the same area, of sediment from 1963 to 1983, had there not been levees to prevent overbank flooding, would have been 0.25 mm/yr (0.010 in/yr).

The sediment discharge carried by Bayou Lafourche prior to its closure can be estimated using the water discharge estimates from Figure 4.7 and those of Reed and Nyman (1995) and the average sediment concentration prior to 1900 for the Lower Mississippi River using data from Kesel (1988). The suspended load can be calculated using the equation:

$$Q_s = (Q_W) \times (C_S) \times (K)$$

Where:

Q_S is the suspended sediment discharge in tons/day (metric tons with conversion below)

Q_W is water discharge in cubic feet per second

C_s is sediment concentration in ppm

K is constant based on unit of measure of water discharge and that assumes a sp. gr. of 2.65 for sediment and converts to metric tons.

Thus:

$$Q_S = 81{,}300 \times 650 \times .00245$$

The suspended sediment discharge based on these figures would equal 129,000 metric tons/day or 47.3 x 10^6 metric tons/yr (126,963 and 46,553 x 10^6 tons, respectively). Assuming a density conversion of 1.4 tons = 1m^3 (Kesel 1988) this amount of sediment would translate into 33.8 x 10^6 m^3 (44 x 10^6 yd^3) carried annually by the bayou. This volume would be less today given the reduced amount of suspended load now carried by the Lower Mississippi River.

Crevasse splays are important conduits for the transport of water and sediment into backswamps and interdistributary bays of flood basins (Figure 4.8). The development of crevasses is related to stage levels, as they occur during overbank stages when concentrated flow scours a channel in the natural levee. Typically crevasses develop on the concave side of a meander bend and can be permanent or semi-permanent. Intermittent crevasses carry water only during high stage levels and result in a branching pattern of stream channels. Crevasses of longer duration may develop permanent channels which function up to several hundred years. Occasionally crevasses of long duration will result in an avulsion due to the slope advantage provided by the new channel (Gagliano and Van Beek 1970).

From 1849 to 1927, the Mississippi River below Baton Rouge experienced 23 flood years which produced crevasse splays. The number of crevasses per flood year was generally less than four, but as many as 20 were recorded in 1892 (Vogel 1930). During the same period Gunter (1950) estimated that a crevasse occurred once every two years in the vicinity of New Orleans. The average area covered by a crevasse splay was about 1675 km^2 (647 mi^2), with the largest covering 5,600 km^2 (2,162 m^{i2}) and the smallest 550 km^2 (212 mi^2) (Vogel 1930). Since crevasses function mainly during flood stage periods, the type of sediment transported into interdistributary bays and backswamps is related to the type of sediment transported in the main channel at high discharges. Although data on discharge and sediment transport during an active crevasse are scarce, data from the Bonnet Carre spillway, constructed approximately 30 km (19 miles) upstream of New Orleans in 1931 for flood protection, provide some comparative information. Figure 4.9 shows the relationship between discharge and suspended sediment discharge during openings of the spillway before and after dam and reservoir construction on major tributaries such as the Missouri and Arkansas rivers. A comparison of these data with the Bonnet Carre crevasse, located several km upstream of the spillway, provides a useful approximation for the differences in sedimentation rates for a diversion such as a crevasse or spillway during the historic (prior to human modifications), pre-dam and post-dam periods in the Lower Mississippi River. The average volume of sediment for each flow period that passed through the crevasse (historic) and that which passed through the spillway, had it remained open for the entire flood flow, during the pre-dam and post-dam periods was estimated as 61, 28, and 12 $m^3 \times 10^6$, respectively (82, 37 and 15 $\times 10^6$ yd^3) (Kesel 1989). Considering that the average crevasse covered an area of 1675 km^2 (647 mi^2), the average amount of deposition per flood event over the crevasse area during the historic, pre-dam and post-dam periods would have been 36, 16.8, and 7.2 mm, respectively (1.42, 0.66, and 0.28 inches).

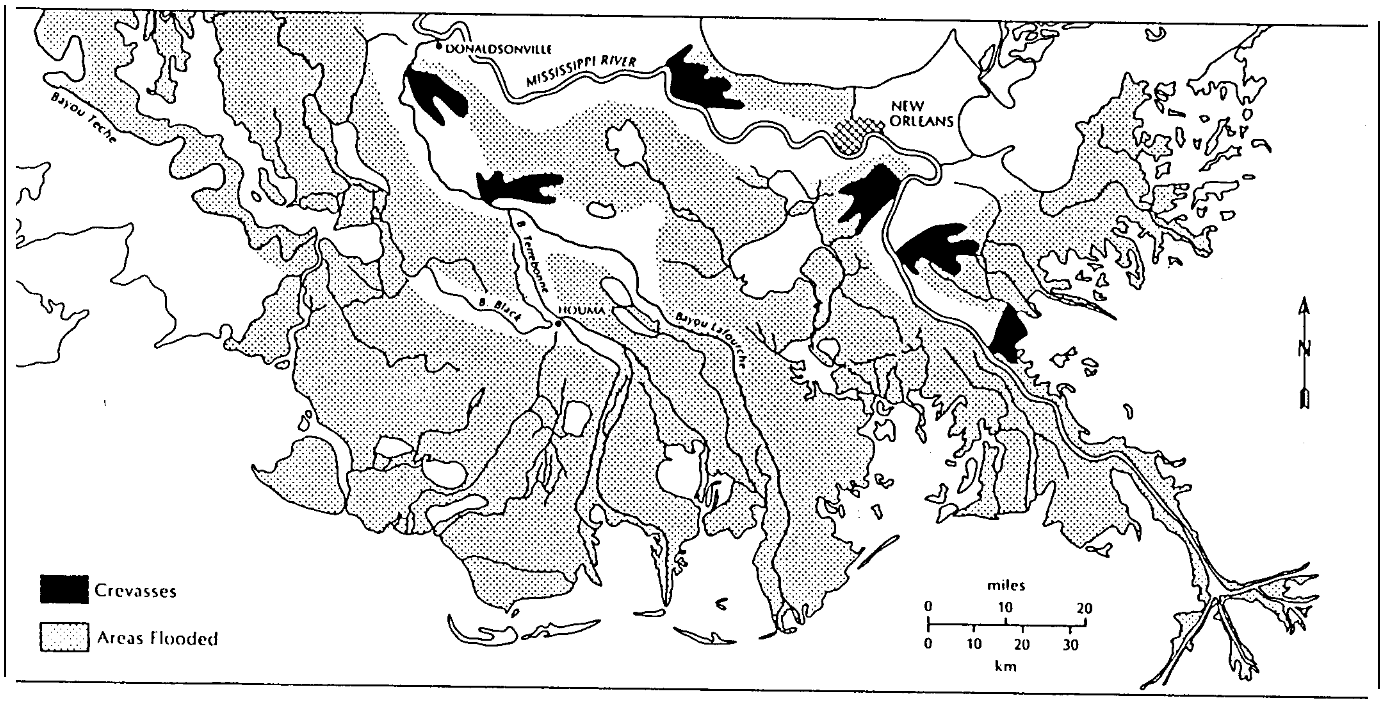


Figure 4.8. Area of deltaic plain that received sediment from overbank flooding and crevasse splays during the flood of 1874. Overbank flooding is responsible for a larger amount of sediment deposition than crevasse splays (from Hardee 1874).

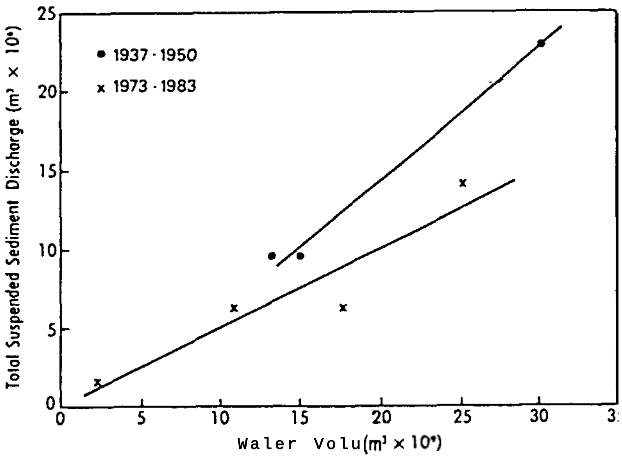


Figure 4.9 Relation between suspended load and water volume flowing through the Bonnet Carre spillway during the pre- and post-dam periods (from Kesel 1989).

Currently, artificial levees flanking the river prevent overbank flooding and crevasse splays from depositing sediments into the wetlands, thus in some ways the current Mississippi River may be seen as being in an inactive state in terms of supplying sediment by either process, although shallow marine processes continue to transport riverine sediments into the bays and estuaries.

SEDIMENTS WITHIN THE ESTUARY

There is little information concerning sediment exchange between the Gulf of Mexico and the coastal wetlands. Roberts et al. (1987) suggest that storm passage over the coastal boundary provides for accretion if there is a sediment supply offshore, but if there is no sediment supply, erosion is likely to occur. Estuaries with large openings to the Gulf contain higher percentages of sand and coarse silt than equally large bodies with no connection to the Gulf (Barrett 1971). The coarsest sediments occur in the vicinity of Barataria Bay where they are attributed to the large sand areas of the barrier islands. The finest sediments are found in the vicinity of the present delta and are derived from the Mississippi River. There is some indication that size and amount of sand deposited in some estuaries is decreasing. Krumbein and Aberdeen (1937) and Krumbein and Caldwell (1939) examined sediments from the floor of Barataria Bay. A comparison of their findings with those of Barrett (1971) almost 40 years later indicates that within the same area of the bay, the percentage of sand has decreased from 53% to 35%.

SEDIMENT ACCRETION IN COASTAL MARSHES

Although there are few direct avenues for the input of suspended sediment from the Mississippi and Atchafalaya rivers into the coastal wetlands of the BTES, some sediments do find their way into the marshes and swamps. The main source of suspended sediment to interior parts of BTES isolated from the Mississippi and Atchafalaya rivers is reworking of sediments from the nearshore and coastal bays. Reed (1989b) has described the role of cold fronts in delivering sediments to marshes on the margin of Terrebonne Bay, and the importance of hurricanes and tropical storms has been identified by a number of workers (Baumann et al. 1984, Rejmanek et al. 1988, Cahoon et al. 1995). Hurricane Andrew deposited as much as 9 cm of sediment in some coastal marshes (Nyman et al. in press). The impact of major storms on the coastal wetlands can be destructive in fragile organic soils (Guntenspergen et al. 1995) but in brackish and saline marshes, deposition of storm sediments can raise marsh elevation and stimulate vegetative growth.

Vertical accretion in coastal marshes results from the accumulation of both inorganic and organic matter. The relative contributions of these components for Louisiana marsh soils have been examined by Nyman et al. (1990). Few studies, however, identify the contributions of organic and inorganic components separately. Rather, the focus for most studies of accretion in Louisiana marshes is the vertical increment in soil development and its balance against the local rate of relative sea level rise. A number of techniques have been used to measure vertical accretion, e.g., accumulation over feldspar marker horizons, and ^{137}Cs and ^{210}Pb dating of soil cores, and direct comparison of data obtained using the different techniques is ill advised (Reed and Cahoon 1993). However, inspection of available data within BTES can assist in our evaluation of sediment delivery to the estuary in the light of major hydrologic modifications and reduced sediment availability from riverine sources.

A review of published sources of data was undertaken. The sites for which data were identified are shown in Figure 4.10a and b. The data have been standardized to cm/yr for the period of study and these are presented, with details of techniques and citations, in Appendix K. Two sites close to the Mississippi River at South Pass and Empire show relatively high rates of vertical accretion, and this is mirrored on the west side of BTES with most studies close to the Atchafalaya system showing short-term accretion rates in excess of 1 cm/yr (39 inches per century). Interestingly, the long-term measures (based on ^{210}Pb dating) close to the Atchafalaya show average rates lower than those based on an intermediate time period (about 30 years for ^{137}Cs), and highest rates are from the markers deployed for several years at the most, mostly during the 1980s. This reflects the changing pattern of sediment discharge into Atchafalaya Bay and its adjacent marshes shown in Figure 4.7.

No clear pattern is apparent in the vertical accretion data for marshes isolated from riverine influences. In general, ^{137}Cs techniques show rates less than 1 cm/yr (39 inches per century), but some short-term studies based on marker horizons show rates in excess of 2 cm/yr (79 inches per century). This indicates the episodic nature of sediment input to these coastal systems from cold fronts, tropical storms, and hurricanes. The frequency of these events is unpredictable.

Local patterns of sediment deposition are influenced by topographic and sediment supply factors such as the proximity to the nearest channel (e.g., stream side vs. backmarsh—see Hatton et al. 1983 and other references in Appendix K), barriers to sediment movement through channels (e.g., water control structures), barriers to sediment movements across the marsh surface (e.g., dredged material levees), and local topography (Cahoon and Reed, in press). Modifications to natural marsh hydrology impact not only water movement but the transport of suspended sediments (Reed 1992) and the potential effects of these factors on marsh sedimentation will be reviewed in subsequent sections.

SUMMARY OF STATUS AND TRENDS

Status

The average annual suspended load presently reaching the Gulf is approximately 60 x 10^6 m^3/yr (785 x 10^5 yd^3/yr). Artificial levees, which now line the entire length of the river, prevent sediment and water from being dispersed into the adjacent flood plain and wetlands by preventing overbank flow and crevasse splays from occurring. River sediments are now funneled to the mouth where they are discharged off the continental shelf edge. Although there are few direct avenues for the input of

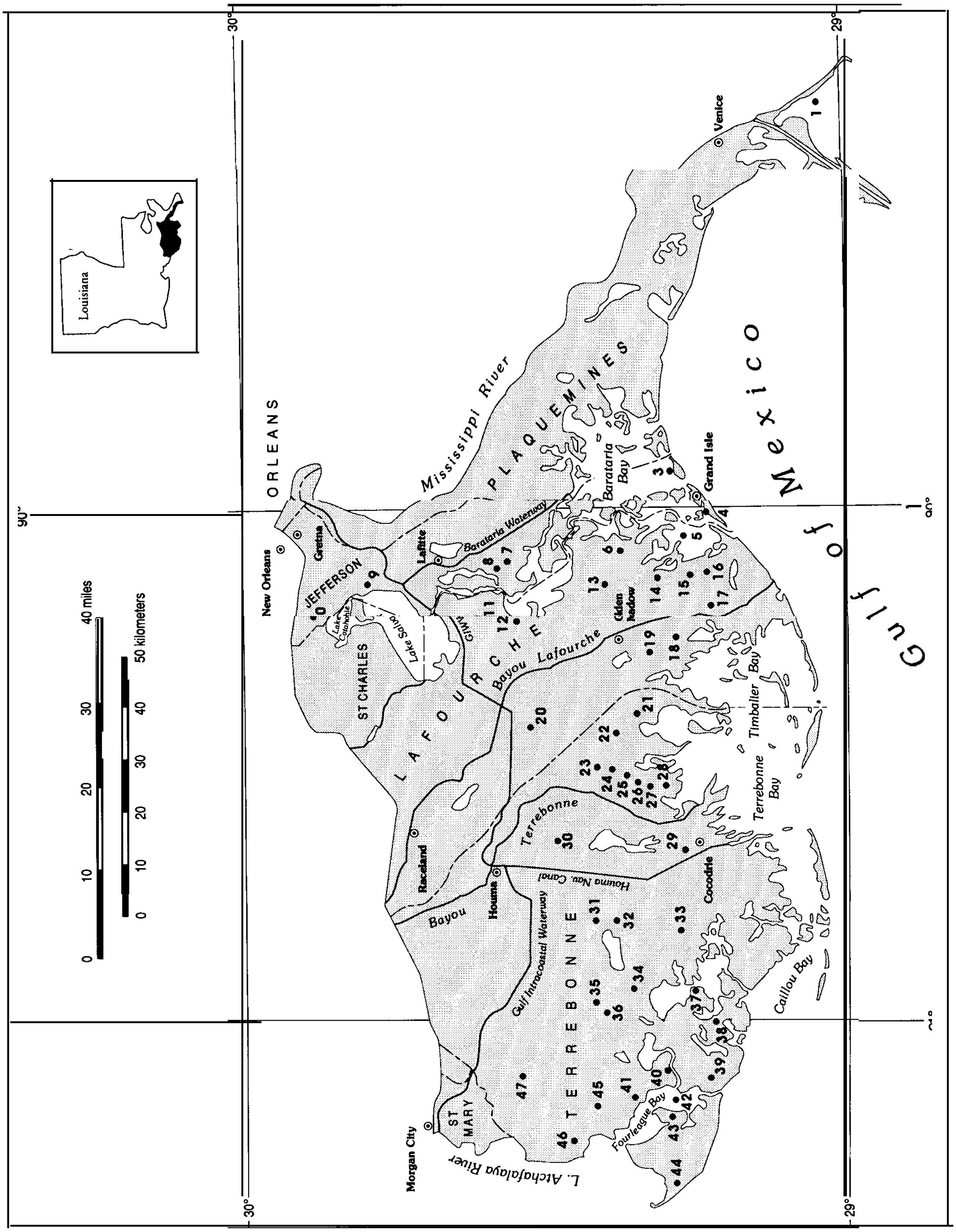


Figure 4.10a. Location of accretion study sites in the southern portion of BTES (summarized in Appendix K).

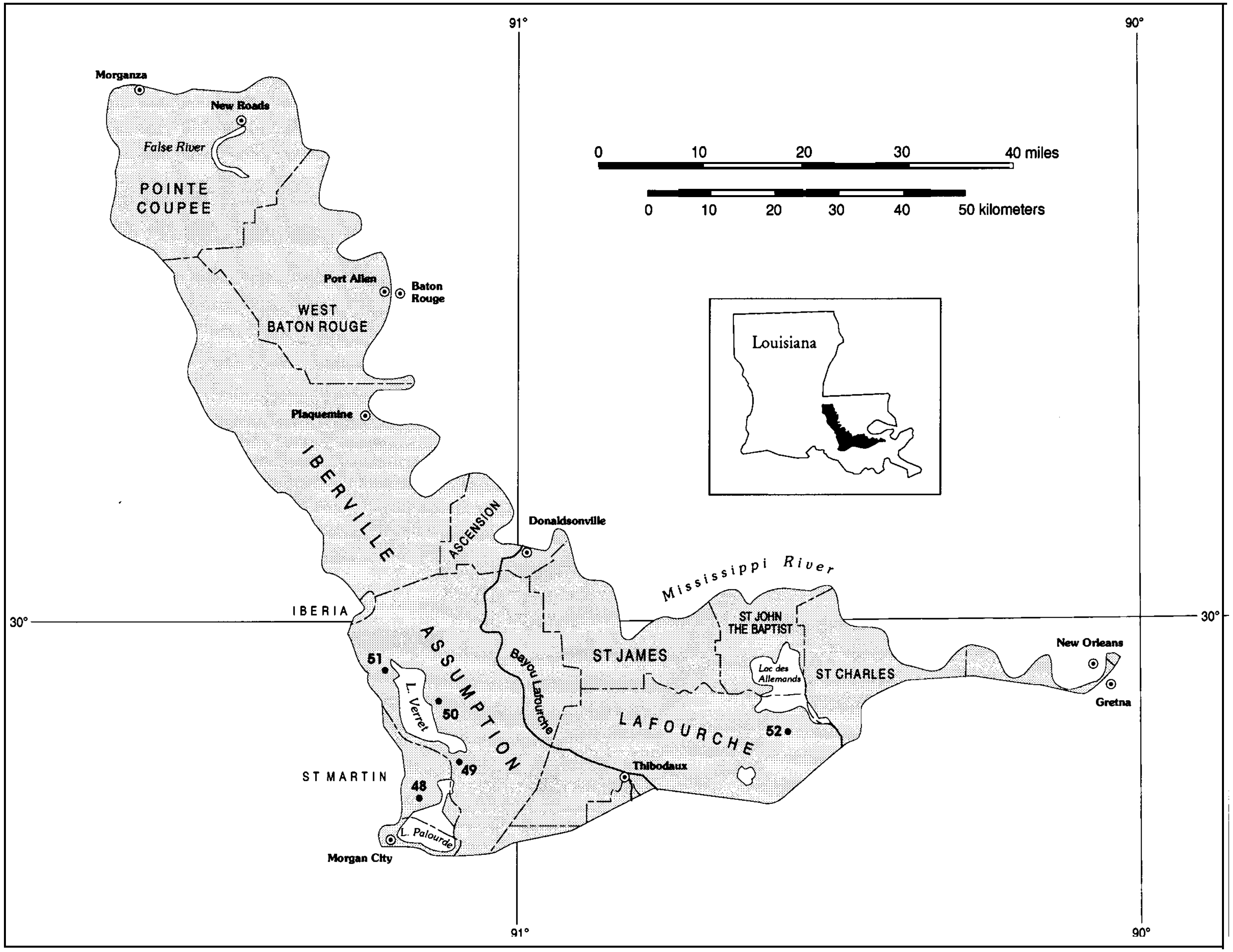


Figure 4.10b Location of accretion study sites in the northern portion of BTES (summarized in Appendix K).

suspended sediment from the Mississippi and Atchafalaya rivers into the coastal wetlands of the BTES, some sediments do find their way into the marshes and swamps. The main source of suspended sediment to interior parts of BTES that are isolated from the Mississippi and Atchafalaya rivers is reworking of sediments from the nearshore and coastal bays.

Trends

For over 100 years human modifications have disrupted or eliminated sediment and water pathways into the wetlands and have reduced and modified the amount and character of sediment carried by the Mississippi River. Since 1850, the suspended sediment load of the Mississippi River has declined by almost 80%. In conjunction with a decline in the amount of sediment carried in suspension, there has also been a decrease in the size of the suspended sediment load. Dams on such major tributaries as the Missouri and Arkansas rivers have impacted the river by decreasing the amount and size of sediments that the river transports.

Overbank flooding probably provided the most important source of sediment in terms of quantity, spatial extent of contribution, and period of time, after the interdistributary bays filled in and marine processes could no longer reach the upper portions of the wetlands. Suspended sediments are introduced into wetlands by overbank flooding when the levees are topped by the river's flow during flood periods. While a river overflows its banks on average of once every 1–2 years, the Lower Mississippi River floods seasonally, in the late winter and spring. Estimates of the pre-1900 accumulation rate of sediment for a 10,000 km^2 (3,860 mi^2) area below Baton Rouge are 1.2 mm/yr (0.05 in/yr). Crevasse splays are important conduits for the transport of water and sediment into backswamps and interdistributary bays of flood basins. From 1849 to 1927, the Mississippi River below Baton Rouge experienced 23 flood years which produced crevasse splays. The number of crevasses per flood year was generally less than four, but as many as 20 were recorded in 1892.

A review of published sources of marsh accretion data showed two sites close to the Mississippi River at South Pass and Empire with relatively high rates of vertical accretion, and this was mirrored on the west side of BTES with most studies close to the Atchafalaya system showing short-term accretion rates in excess of 1 cm/yr (39 inches per century). No clear pattern is apparent in the vertical accretion data for marshes isolated from riverine influences.

PART 5

IMPACT OF HYDROLOGIC MODIFICATION

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INTRODUCTION

The identification of hydrologic modification as a linchpin issue in the nomination of the Barataria-Terrebonne estuarine system (BTES) recognized the unique nature of the problems facing this area in comparison with other National Estuary programs. More conventional water quality issues were considered secondary to this major problem:

> Hydrologic modification of this shallow, sponge-like estuarine system has resulted from interruption of seasonal freshwater inputs from the Mississippi and Atchafalaya rivers, from the extensive construction of linear canals, many of which are deeper than natural water bodies, and from impoundments by spoil banks and dikes (Roemer 1989).

Changes that have impacted the distribution of water and sediments from the Mississippi and Atchafalaya rivers have already been documented in this report. The magnitude of human impacts and hydrological modifications within the Louisiana coastal marshes has been summarized in several major studies (e.g., Turner and Cahoon 1988, Wicker et al. 1989). Turner et al. (1982) identify a positive correlation between the density of canals and the rate of coastal land loss for hydrologic units of coastal Louisiana. In the same paper, data from Wicker (1980) show that 0.9% and 1.58% of the land area in Terrebonne/Timbalier Bay and Barataria Bay, respectively, was taken up by canals. These figures increased to 2.59% and 3.45%, respectively, in 1978. These numbers only reflect the direct impacts of the canals. Indirect impacts on coastal marshes can be of at least the same order of magnitude (Turner 1987). In addition to dredge and fill activities related to navigation and mineral extraction, some alterations to natural hydrology have occurred as part of marsh management plans (Cahoon and Groat 1990). Natural hydrology of the basins has also been disrupted by road railway construction, which has frequently been associated with the construction of embankments across major portions of the estuaries with exchanges from one side to the other restricted to culverts or bridges over controlled channels.

To detail the specifics of each hydrological modification within the BTES is beyond the scope of this report. Rather, the focus will be to review how hydrologic modifications within the estuary systems can affect habitat modification and loss, and to assess, in general terms, the relative spatial and temporal magnitudes of these impacts. The discussion will examine modifications to hydrology related to navigation channels, pipeline and location canals associated with mineral exploitation, and levees and water control structures associated with marsh management. Some examples will be examined in detail to illustrate the nature of these hydrologic modifications and their potential impacts on coastal habitats. More detailed evaluation of specific features on temporal and spatial patterns of habitat change and modification will be provided in the vignettes section.

RIVER WATER INFLOW

The largest scale hydrological modification to the BTES, in terms of both time and space, was the virtual elimination of freshwater inputs from the Mississippi River, Atchafalaya River, and Bayou Lafourche. When Europeans arrived, Bayou Lafourche and the Mississippi River appeared equal in size (DuRu 1934, cited in van Heerden 1994) and a strong current still flowed through Barataria Bay in 1785 (Condrey 1993). Levees were largely ineffective until 1931 (Davis 1991) and major floods occurred roughly every 2.8 years between 1799 and 1931 (Gagliano and van Beek 1970). These floods covered wide areas with relatively shallow water flowing at about 0.8 feet/second (0.24 m/s) (Gagliano and van Beek 1970). The flood of 1874 (Figure 4.8) was considered a typical major flood of this period. That flood covered southeastern Louisiana from Bayou Teche west of the Atchafalaya River, to Breton Sound east of the Mississippi River (Gagliano and van Beek 1970). Federal interest in flood control began in 1879, but attempts to keep the Mississippi River in its banks were not successful until new initiatives taken after the flood of 1927 (Davis 1991). The major affect of those flood control activities on the freshwater budget of the BTES occurred in 1904 when a dam was constructed on Bayou Lafourche at Donaldsonville. Assuming a mean annual discharge of 15,360 m^3/s (542,400 ft^3/s) on the Mississippi River and 15% of that discharge entered Bayou Lafourche prior to damming (see Figure 4.7), damming Bayou Lafourche in 1904 decreased freshwater inflow into the BTES by 2,304 m^3/s (81,365 ft^3/s). When Bayou Lafourche was connected to the Mississippi River, flow occurred primarily during spring floods and crevasses often developed on Bayou Lafourche. Crevasses from Bayou Lafourche were noteworthy in 1854, 1858, and 1874; the 1854 crevasse, which occurred at Lockport, is known to have remained open for 5 months (see contemporary newspaper reports cited in Davis 1991). The 2,304 m^3/s (81,365 ft^3/s) of fresh water that Bayou Lafourche delivered to the BTES is 2.5 times greater than the 859 m^3/s (30,341 ft^3/s) of fresh water currently entering the BTES in the form of local rainfall (based on 4.9 feet (1.49 m) of rainfall/yr and 4.5 million acres (18,210 km^2) in BTES). The pumping station constructed on Bayou Lafourche at Donaldsonville in 1955 restored 11.2 m3/s (400 ft^3/s) of the former flow.

Bayou Lafourche was not the only avenue by which river water entered the BTES. As noted earlier in this report, some crevasses on the Mississippi River on the west bank of the river south of Donaldsonville thereby discharged into Barataria Bay for months (Gagliano and van Beek 1970). Few descriptions of these crevasses are available, but Humphrey and Abbot (1861, cited in Davis 1991) reported that a crevasse on the Mississippi River inundated upper Barataria basin with 1.2 meters (3.94 ft) of water in 1849. The last major crevasse from the Mississippi River into Barataria Bay occurred in 1912 at Hymelia (Gagliano and van Beek 1970). We do not know how frequently crevasses from the Mississippi River discharged into the BTES, but 12 of the 32 crevasses occurring between 1849 and 1927 within roughly 100 miles (160 km) of New Orleans discharged into the BTES (Gagliano and van Beek 1970:66). From these data we can conservatively estimate one crevasse discharged fresh water from the Mississippi

River into Barataria Bay every 6 years. Average maximum flow of crevasses was about 1,840 m^3/s (65,000 ft^3/s) (Gagliano and van Beek 1970), but we do not know how this relates to total discharge over the 3–5 month life of a crevasse. Assuming a total discharge over the 3–5 month life of the crevasse equal to one month of peak flow, we can conservatively estimate that until 1931 Barataria Bay was flushed with an additional 141 m^3 (185 yd^3) of fresh water at least every six years. This is roughly 30% of the current freshwater input into Barataria basin of 461 m^3/yr (16,290 ft^3/yr) from local rainfall each year (based on 4.9 feet (1.49 m) of rainfall/yr and 2.4 million acres (9,713 km^2) in Barataria basin).

The Atchafalaya River also discharged fresh water into the BTES, but no data are available to estimate how much of this water flowed through Terrebonne basin before entering the Gulf of Mexico. Of the three sources of river water to the BTES operating in 1900, only the Atchafalaya currently contributes fresh water. However, it is not known how much fresh water enters the BTES from that Atchafalaya River today, or if this input differs from that occurring earlier in this century.

In summary, we can conservatively estimate that freshwater inputs into the BTES exceeded 3163 m^3/yr (111,767 ft^3/yr) until 1904. Construction of a dam across Bayou Lafourche combined with systematic levee construction on the Mississippi River reduced freshwater inputs into the BTES over 70% by 1930. Because of these modifications, Barataria basin is now almost completely dependent on local rainfall for fresh water. The coastal wetlands of the Terrebonne basin still receives fresh water from the Atchafalaya River and from Bayou Boeuf at Amelia, but the historical and current inputs are largely unquantified. It is interesting to note that most fresh water previously entered the BTES during late spring and early summer, which is the time of the year currently experiencing a freshwater deficit (see Figure 2.7).

BARRIER ISLAND EFFECTS ON HYDROLOGY

Changes in barrier island physiography have been described in previous sections. Islands move and shrink, but are also displaced by passes. The three main passes present in the Terrebonne system in 1891, for example, had coalesced into Cat Island Pass by 1974, part of which now occupies the former locations of Caillou and Wine Islands (Suter and Penland 1987). This pass, partly dredged and partly natural, continues to dominate estuarine hydraulics despite the opening of numerous shallow storm channels through the deteriorating islands. Barataria Pass has always been the dominant pass in the Barataria system, but three others that were not important in the 1890s are quite significant now (Levin 1993, Howard 1983).

Inlet cross-sectional area was first related to the diurnal tidal prism by O'Brien (1931) and has since been developed into an empirical correlation for use on the Gulf Coast by Jarrett (1976). The theoretical basis for this relationship is that of a balance between ebb tidal velocities that scour passes and the wave-induced and flood tidal currents that will tend to push sand into the inlets and reduce cross-section. This relationship is found to hold well on coasts which are adequately supplied with sand. Inlet cross-sections have increased over the past century from (31,000 to 57,000 m^2 (37,100 to 68,200 yd^2) in Terrebonne and from 4,400 to 16,100 m^2 (5250 to 19,250 yd^2) in the Barataria system, increases of 84% and 270%, respectively (List et al. 1994). In the Terrebonne system, 42% of the present inlet cross-section consists of shallow tidal flats less than 3m (10 ft) deep that tend to be dominated by flood tidal currents (Levin 1993, Howard 1983). Less than 28% of the Barataria inlets are shallower than 3 m (10 ft), but much of this estuary does not really have a barrier/inlet shoreline.

The diurnal tidal prism estimate of Wiseman and Swenson (1989) for the Terrebonne system can be used to calculate the inlet cross-section necessary to accommodate this prism (5.2×10^8 m^3 or 6.7×10^8 yd^3) using the method of Jarrett (1976). The resulting value, 19,500 m^2 (23,300 yd^3), is 34% of the total 1988 cross-section and 59% of the ebb-dominant channel cross-section (>3 m or 10 ft). A value of 9,837 m^2 (11,765 yd^2) is similarly calculated for the Barataria system using the Wiseman and Swenson (1989) estimate of tidal prism for this system of 2.3×10^8 m^3 (2.75×10^8 yd^3). This theoretical cross-section is 61% of the total 1988 cross-section and 85% of the ebb-dominant channel cross-section (>3 m). In both cases, the available cross-section far exceeds that necessary to accommodate the diurnal tidal prism calculated in the manner recommended for this analysis. Indeed, it would appear that these estuaries have had oversized openings to the Gulf since at least the 1890s.

The recent history of breakup of the BTES barrier islands indicates that these islands and the inlets they flank are affected at least as much by sediment deprivation and subsidence as by tidal prism. At some point, the term "inlet" loses meaning as bay mouths open up and the relationship between inlet dimensions and tidal prism breaks down. It has been noted that the maximum depths of the major inlets continue to increase, suggesting that ebb tidal velocities are also increasing (Shamban and Moslow 1991). This suggests that while these inlets may be out of equilibrium with the diurnal tide, they are continuing to be shaped by less frequent storm tides that introduce much greater than normal volumes of water into the BTES across the flood tidal flats and through new overwash points. This water moves out predominantly through the ebb tidal channels and these channels enlarge. Because sediment supply associated with littoral transport is so small, both the flood tidal flats and the ebb tidal channels tend not to fill in under fair weather conditions (Howard 1983).

A numerical model was recently used to explore the effects of changes in circulation that result from losing islands and increasing pass dimensions beyond that needed for tidal prism (J.N. Suhayda, Louisiana State University, personal communication). Model results from the Terrebonne system confirm that the Terrebonne bay/barrier system is currently so open that the primary effect of the islands is not on tidal prism but on other aspects of flow dynamics that affect the movement of tides through the entire estuary. For example, when the Isles Dernieres group was removed experimentally, this change did not affect tidal prism but resulted in changes in the period of marsh inundation.

Some areas were predicted to see a reduced period of inundation while other areas would experience more. The net result basin-wide was that removal of islands and shoals or, alternatively, expansion of inlets, caused most marsh areas to experience an increased period of inundation. Removal of the Isles Dernieres alone resulted in a predicted increase in the period of normal inundation of greater than an hour per day for approximately 6,500 ha (16,00 acres) of marsh. Removal of all islands increased this value to more than 36,000 ha (88,900 acres). The ecological consequences of these changes in inundation period are as yet unclear. Removal of the Timbalier Islands, relative to the Isles Dernieres, produced a greater effect on estuarine circulation.

NAVIGATION CHANNELS

The natural bayous of the BTES systems are sinuous, meandering streams that terminate on the coast or in the coastal bays, typically into waters less than 3 m (10 ft) deep. Many of these bayous have been dredged and deepened at various times to facilitate waterborne commerce. However, the rapid expansion of the offshore oil and gas industry in the 1950s (Lindstedt et al. 1991) (Figure 5.1) created a need for more direct access from coastal towns to the Gulf, and for the transportation of drilling structures and supplies through the coastal zone to the outer continental shelf. The impact of these channels on sensitive coastal habitats has been documented by Wicker et al. (1989) with a focus on impacts at the shoreline. Such impacts include changes in shoreline configuration and resultant erosion associated with jetties, but these channels may have additional impacts further inland as they modify basin circulation and salinity distributions.

Within the BTES the only major bayou connecting the Gulf Intracoastal Waterway (GIWW) with the Gulf of Mexico was Bayou Lafourche and it continues to provide a major link between commercial activity on the GIWW and the Gulf. In 1935, the Rivers and Harbors Act authorized a 2 m x 18 m (6 ft by 60 ft) channel from Larose to the Gulf with a set of 61 m (200 ft) jetties at the mouth, and these were completed in 1939. The problem with building jetties to maintain a channel across a shoreline eroding as rapidly as that of the Caminada-Moreau headland, is that shoreline retreat eventually isolates the jetties in open water. Consequently, by 1945 the jetties needed to be extended an additional 60 m (200 ft). Additional modifications were required in the 1950s and the channel between the jetties was widened to over 91 m (300 ft). In 1968, the Greater Lafourche Port Commission assumed maintenance of the navigation channel and it is currently maintained at 6.1 m (20 ft) deep and 91 m (300 ft) wide. The jetties have been extended periodically to maintain contact with the retreating shoreline. Wicker et al. (1989) documented the changes in jetty configuration and shoreline retreat for the period 1934 to 1985 (Figure 5.2). They found that prior to channel enlargement and jetty construction the shoreline retreated in a relatively straight line but the jetties have interrupted longshore sediment movements (east to west in this area)

(Mossa et al. 1985) and the result is a pronounced "offset" in shoreline erosion on either side of the jetties. This interruption to sediment movements along the shoreline has also resulted in enhanced erosion of East Timbalier Island (McBride et al. 1992).

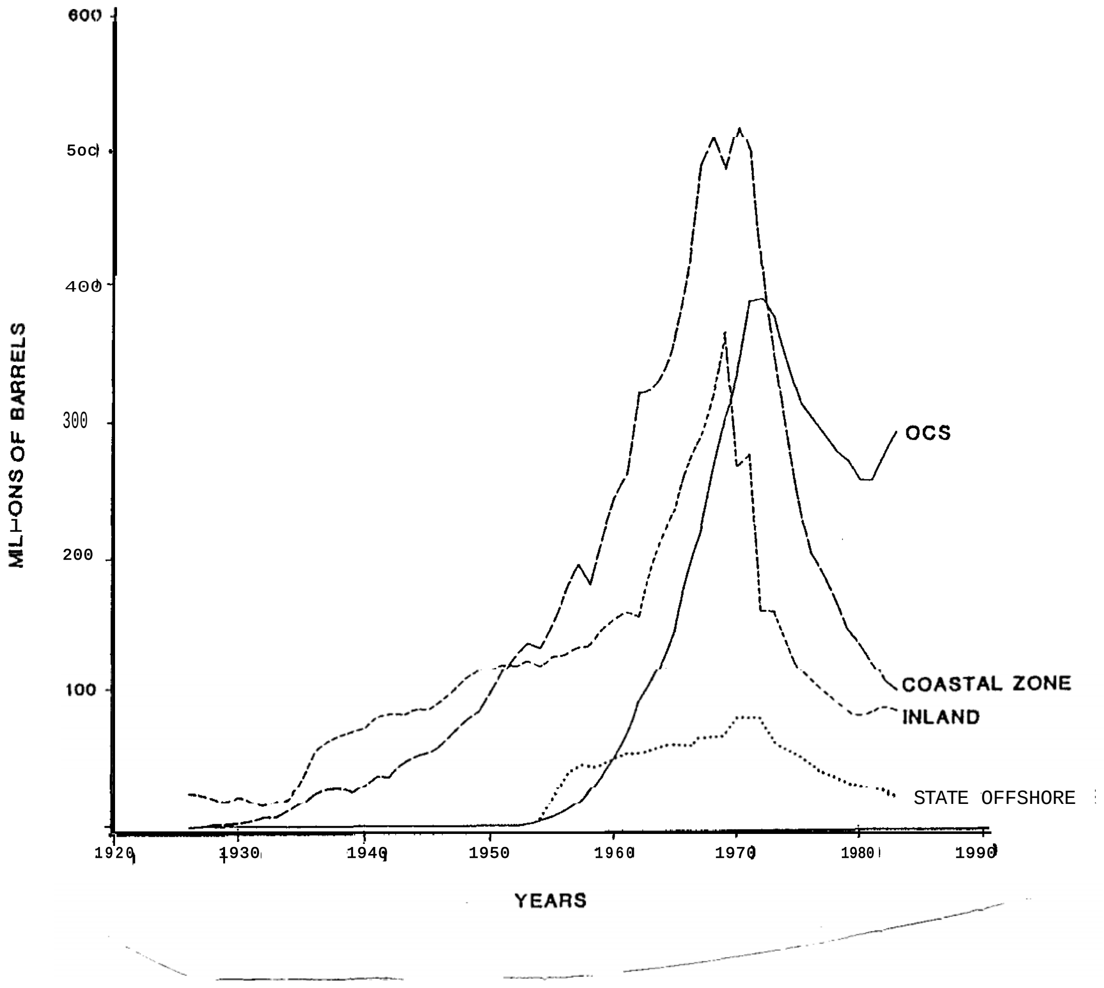

Figure 5.1 Oil production in Louisiana for each area, 1926-1983 (Lindstedt et 1991).

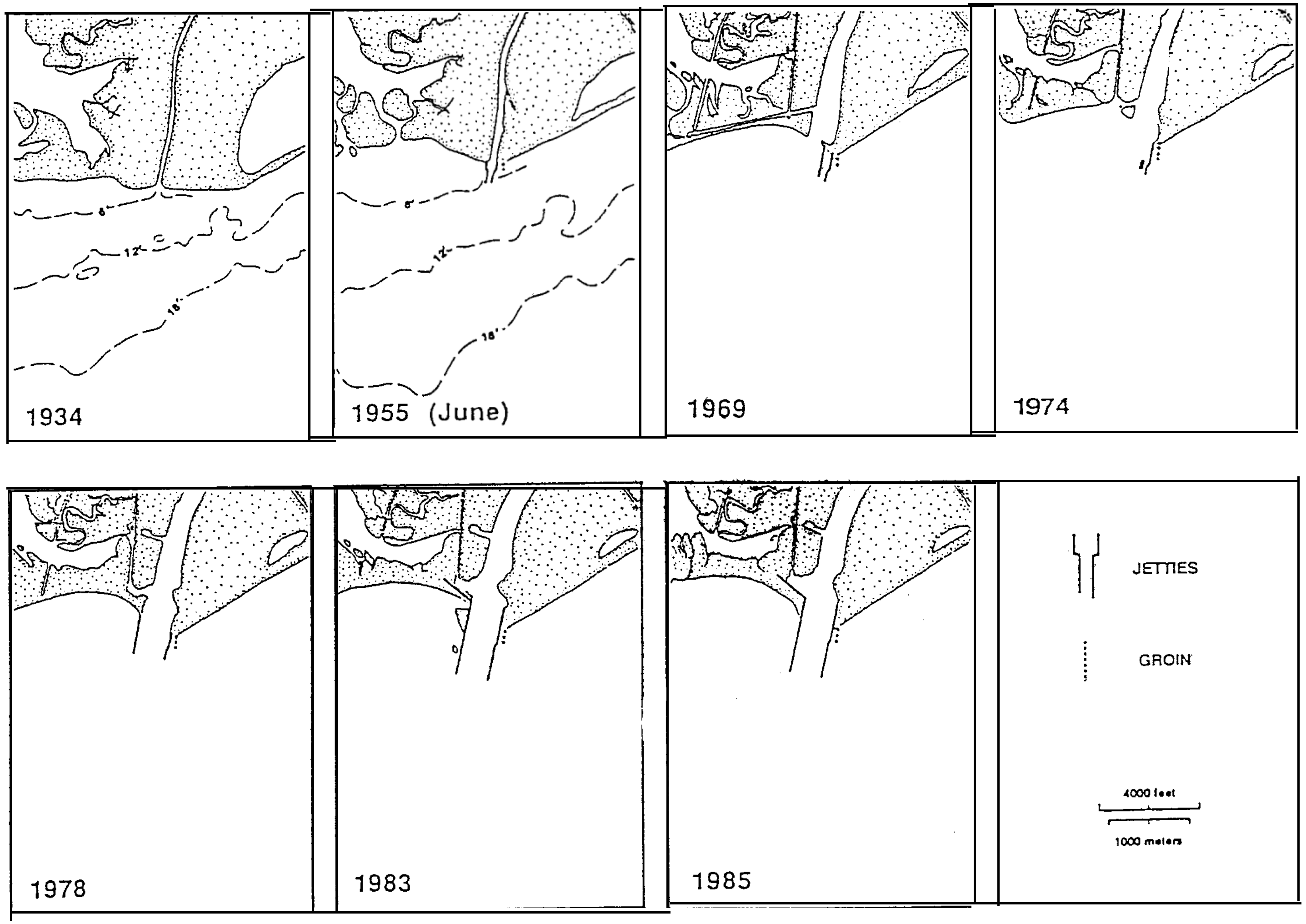

Figure 5.2. Comparison of shoreline position and configuration and size of the Belle Pass navigation channel and jetties at various times between 1934 and 1985 (Wicker et al. 1989).

In areas where natural channels of the desired size did not exist or could not be modified, channels were dredged specifically for commercial traffic. The Houma Navigation Canal (HNC) was dredged as a shortcut between the commercial center of Terrebonne Parish in Houma and the Gulf (Wicker et al. 1989). The HNC traverses the fresh, brackish, and saline marshes of the Terrebonne estuary and continues through Terrebonne Bay to enter the Gulf through Cat Island Pass. No jetties were required because the channel utilizes a natural tidal inlet in the barrier shoreline.

The construction of the canal was funded by Terrebonne Parish government and was supported by a bond sale in 1955 (P. Prejean, personal communication). Falgout Canal, connecting the HNC with Bayou DuLarge, was constructed at the same time with dredged material being placed on the south side of the canal to provide for a road bed. The HNC was opened in 1962 and responsibility passed to the Corps of Engineers under the Rivers and Harbors Act. The original dimensions of the channel were 91 m (300 ft) top width with a bottom depth of 4.9 m (16 ft) across the center 46 m (150 ft) of channel. The channel is currently maintained by the USACE to a depth of 4.6 m (15 ft). In 1973, Cat Island Pass channel, was authorized to 91 m (300 ft) wide and 5.5 m (18 ft) deep and this was completed in 1974 (Wicker et al. 1989).

Wang (1987, 1988) compared the salinity distribution and stratification along the HNC with Bayou Petit Caillou, a natural bayou located about 10 km (6.2 miles) east of the HNC but intersecting with the HNC in Cocodrie. The depth of Bayou Petit Caillou, typical of most natural bayous, is only about 3 m (10 ft). In September 1986, Wang documented that the 5 ptt isohaline in HNC reached north of Houma, 40–50 km (25 to 31 mi) from the channel entrance, while in October 1986 the 1 ppt isohaline reached to only 25 km (15.5 mi) from the channel entrance. Wang (1987, 1988) also presents data to show that the HNC can be well stratified under low discharge conditions (Figure 5.3). These data demonstrate the temporal and spatial variability in the penetration of salt water along the HNC. Wang concludes that under similar environmental conditions, salt water penetrates farther inland in large, deep channels (such as the HNC) than in smaller, shallower channels (such as Bayou Petit Caillou). In addition, her model simulations confirm that deepening and widening channels can increase saltwater penetration from the Gulf of Mexico.

PIPELINE/LOCATION CANALS

For the entire coast of Louisiana approximately 16% (over 46,000 ha or 113,600 acres) of wetland loss for the period 1955/56 to 1978 was directly caused by dredging of canals (Baumann et al. 1987), with 18,110 ha (44,700 acres) of wetland converted to open canal and 28,245 ha (69,760 acres) covered with the associated dredged material. Turner et al. (1982) use data from Wicker (1980) to show that the Barataria and Terrebonne hydrologic units rank below only the Mississippi River delta and the Atchafalaya delta in canal impacts as a percentage of total land area.

The direct impacts at the time of construction are relatively easy to quantify for these canal impacts. More important in identifying their role in longer term habitat change is the rate of recovery of the impacted area and any indirect effects associated

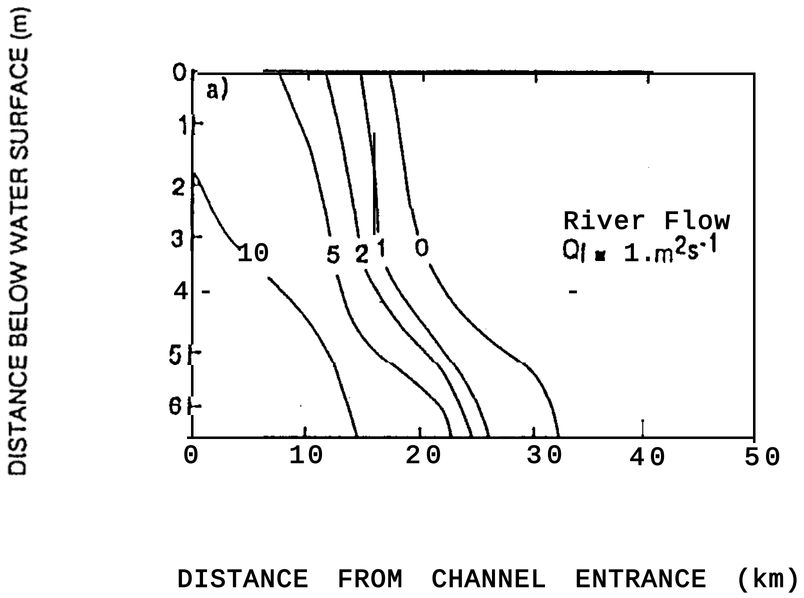

Figure 5.3 Time-averaged salinity distribution derived from field measurements at the Houma Navigation Canal, October 17-18, 1986.

with canal placement. These factors vary according to the purpose of the canal and its utilization after construction. Several types of canals will be discussed in this section:

- Pipeline canals are constructed specifically to lay pipelines through wetlands. Several different construction techniques have been used. These canals are usually long, many extending across the entire coastal zone, and a single canal may traverse several different habitat types. These canals are commonly plugged at their intersection with other waterways.

- Oil field navigation canals are dredged to permit ready access for watercraft to oil and gas fields located within the coastal wetlands. The vessels are usually smaller than those supporting the offshore oil and gas industry. The canals usually link major water bodies within the coastal zone where natural bayous are not readily navigable or do not exist.

- Well-access canals are dredged from navigable water bodies to the specific location where drilling will occur. Boat traffic along these canals is limited to that supporting the activities at the well.

Indirect Impacts

Potential indirect impacts of canal dredging can be associated with either the increased channelization of the marsh or the alterations to marsh surface hydrology caused by the dredged material levees. Increased channelization in marshes with previously low drainage densities may allow 1) the more efficient penetration of salt water into areas previously isolated from direct exchanges, and 2) increased tidal flows which are thought by some workers to enhance erosion of some marsh types (Gagliano and Wicker 1989).

An additional indirect effect of this channelization is further loss of marsh by erosion of canal banks subsequent to dredging. Johnson and Gosselink (1982) examined canal widening at two locations within BTES. The Southwestern Louisiana canal, presently an oil field navigation canal, was dredged in 1880 and connects Caminada Bay and Little Lake. Its original width was approximately 9 m (30 ft) but by 1978 it had widened to over 100 m (330 ft) at many locations. Johnson and Gosselink (1982) show an exponential increase in canal width and this may be explained by an initially low rate of widening as the dredged material levees originally adjacent to the canal provided a firmer substrate. Within the Leeville oil field, Johnson and Gosselink (1982) also examined widening rates for various types of well-access canals. The amount and type of boat traffic greatly influenced that rate of widening. Well-access canals linked to major navigation waterways widened fastest (2.25m/yr or 7.4 ft/yr) than those connected to oil field navigation canals (1.12m/yr or 3.7 ft/yr). Non-major canals removed from frequent boat traffic widened only at 0.95 m/yr (3.1 ft/yr). Thus, the long-term impact of canals on land loss can include a significant contribution from shoreline erosion.

Marsh surface hydrology is altered by the placement of dredged material levees adjacent to canals. These levees impede the direct flow of water from the marsh surface to and from the canal. In addition, the high density of well-access canals in some oil and gas fields, and their intersection with dredged material levees associated with some pipeline canals, means that some areas of marsh have become semi-impounded or impounded by these levees. Turner and Rao (1990) examined the relationship between marsh ponds and the distance to canals and their associated dredged material levees. Their study area encompassed a large part of the BTES and included fresh through saline marshes. The study found that many ponds were either parallel to canals and/or their levees, or had an apparent hydrologic connection leading to a canal. Turner and Rao (1990) conclude that canals and their dredged material levees are directly related to wetland-to-water conversion and that the association is evident up to 2 km (1.2 mi) away from the canals. Swenson and Turner (1987) examined the effect of semi-impoundment by dredged material levees on the flooding regime of impacted brackish marshes. They found that semi-impounded marshes had few flooding events that marshes with unaltered hydrology (4.5 events vs. 12.9 events), but that the average duration flooding events was significantly longer (149.9 hrs. vs. 29.7 hrs.). The dredged material levees prevented the marsh flooding regularly but once when water elevations were sufficiently high to overtop the levees, for instance during the passage of a cold front, marsh flooded and the levees impeded drainage of the flood waters. Such an increase in marsh hydroperiod can result in plant deterioration (Reed and Cahoon 1992) and may be one of the factors contributing to the pattern of marsh pond formation identified by Turner and Rao (1990). However, it may be expected that the response of the vegetation and soil substrate to such hydrologic changes will vary with marsh type. Floating marshes, for example, may be able to adapt to increased hydroperiod and maintain a healthy vegetative mat.

As well as impeding the flow of water onto and away from the marsh surface, dredged material levees may also impede the input of suspended sediment to the marsh surface. Studies of marsh accretion in such hydrologically isolated areas have found similar results. Taylor et al. (1989) in their study of Jean Lafitte National Park note that marsh sites which have free communication with natural waterways experienced significantly greater rates of marsh accretion than in areas isolated from tidal exchange by spoil banks. Similarly, Cahoon and Turner (1989) reported that two hydrologically restricted brackish marshes influenced by a major levee system in southwestern Louisiana showed significantly lower accretion rates when compared to adjacent marshes experiencing direct hydrologic exchange.

Increased channelization of marshes caused by canal dredging may result in more efficient exchange of tidal waters which could increase salinities and the magnitude of tidal flows. Tabberer et al. (1985) examined salinities in their study of push-pull ditches with two sites in BTES and found no consistent difference in salinity between pipelines and their control sites. Adkins and Bowman (1976) compared salinities in open water areas with plugged canals at two locations in the Terrebonne basin. They found that salinities fluctuated more at the open water control sites and were more stable in the enclosed canals. There are few studies of flows through tidal channels in Louisiana coastal marshes, and even fewer which include measurements in canals. Kjerfve's (1976) study of tidal flows and salinities in the lower Barataria basin close to Airplane Lake includes one site, of 25 total, in a canal. The depth-averaged salinity in the canal conforms to the natural gradient in salinities away from Caminada Bay identified in the study. Kjerfve notes lower salinities in the canal (Williams Canal) in comparison to the rest of the study area but does not identify any particular impact of the canal on tidal flow regime in the area. Wang et al.'s (1994) study of tidal flows through a natural bayou and an intersecting pipeline canal shows similar flow velocities through the two channels but they suggest that the canal is capturing flow from the natural bayou. This alteration in local circulation may result in enhanced sedimentation in some reaches of the natural bayou (Wang et al. 1994). The isolation of parts of the natural drainage system by canals has also been identified by Turner and Rao (1990).

Some workers have suggested that increased channelization of previously intact marshes can increase the potential for a process known as "tidal scour" (Cahoon and Day 1991), possibly the same process termed "dynamic tidal flux" by Broussard (1991). This process involves the physical entrainment and removal of soil particulates by a tidally-induced flow and there are three situations where it may occur: particulate removal by sheetflow across vegetated surfaces; channelized flows; and flows through open ponds.

Physical erosion of sediment from the vegetated marsh surface by sheetflow, as opposed to erosion of subsoil after vegetation deterioration (Gagliano and Wicker 1989) is unlikely to be a factor of importance in coastal Louisiana marshes. Wang et al. (1993) measured tidal currents on the marsh surface and noted values only 10 to 20% of currents measured in adjacent bayous. In addition, Wang et al. conclude that maximum shear stresses reached for overmarsh flows are considerably less than those required to erode marsh surface sediments. The erosion of exposed substrate following the removal or death of emergent vegetation has been observed in Louisiana coastal marshes but rarely quantified.

Scour of channel banks and the extension of first-order drainage networks by tidal flows may be important local mechanisms of particulate removal from marsh substrates. The well documented expansion of canals subjected to high boat traffic (Johnson and Gosselink 1982) suggests that on some channels any removal by tidal flows may be exacerbated by boat wakes or wave activity. However, measurements of tidal flows in natural channels in salt marshes by Murray et al. (1993) show that velocities can exceed 50 cm/s (1.64 ft/s). These channelized velocities may well be adequate to remove sediment from channel banks. However, these flows were measured in Bayou Chitigue, a saline marsh with cohesive sediments in channel banks requiring considerable energy to resuspend. Areas with more organic soils in brackish and fresh marshes are unlikely to experience such high flow rates under normal tidal conditions but sediments may be more readily detached. The relationship between soil type and flow velocity required for erosion needs to quantified in more detail before the impact of "tidal scour" in marsh channels can be accurately assessed.

Nyman et al. (1994) note the importance of undercutting as a process contributing to marsh loss on Marsh Island. The undercutting appears to be important in areas open to normal tidal flow, as well as those with flows restricted by fixed-crest weirs (Nyman et al. 1990) and consequently the marsh loss cannot be attributed to normal tidal action. The lack of "tidal scour" around the margins of marsh ponds has been confirmed by Day et al. (1994) who conclude that there is insufficient energy within ponds under normal tidal and wind conditions, from either waves or tidal flows, to erode the marsh edge.

Our present understanding of tidal scour problems in Louisiana coastal marshes is largely based upon indirect or undocumented observations. Many workers consider tidal scour an important contributor to wetland loss but there is little information on the nature of the detachment and transport processes. Process studies are required to document the importance and extent of tidal scour and to enable effective restoration in affected areas.

Recovery from Direct Impacts

The type of pipeline placement or canal construction technique used and the extent to which the area can be restored to pre-construction conditions determine the long-term impact of the activity on the adjacent habitat. The type of environment in which the dredging activity takes place is also an important determinant of future conditions. Wicker et al. (1989) identified three major pipeline emplacement techniques which have been used in coastal areas. The features of these techniques are summarized in Table 5.1. Post-construction closure methods associated with these placement techniques are shown in Table 5.2.

Upland trenching is the technique usually used in upland areas and it can be used in dry firm soils within the coastal zone, e.g., on barrier islands. The pipe needs to be buried to protect it from vandalism and other hazards, but the removed sediment is placed back on top of the pipe and should be contoured to mimic preconstruction topography. Pipelines which cross the BTES may use this technique as they cross ridges and fastlands. The right of way (ROW) is normally kept clear of trees and tall vegetation to facilitate regular aerial inspection for leaks and other damage.

Flotation canals are excavated waterways that allow the passage of barges to excavate the canal and lay the pipe. Typical canal dimensions are shown in Table 5.1. Historically, the dredged material was placed in parallel levees adjacent to the canal, although this practice is rare today. The placement of the dredged material back in the canal after pipeline placement was rarely required and studies have suggested that it is rarely possible to recover sufficient material from the levees to refill the canal completely (Abernethy and Gosselink 1988). This is because of oxidation and dewatering of the sediments while they are in the levee, as well as lack of efficiency of the second dredging process. Rather than filling the canal so that emergent vegetation could be reestablished, shallow water bodies less than 1 m in depth remain after

Table 5.1. Physical parameters characterizing three of the major pipeline techniques (after Wicker et al. 1989).

VARIATION IN EMPLACEMENT CHARACTERISTICS BY EMPLACEMENT TECHNIQUES

Emplacement Feature	Upland Trenching	Flotation Canal	Push-Pull Ditch
Associated environment	Stable, well-drained soils.	Unstable soils, shallow water bodies.	Moderately firm, but wet soils.
Construction ROW	30.5 to 38.1 m	45.7 to 91.4 m	30.5 to 61.0 m
Maintenance ROW	9.1 to 30.5 m	30.5 to 61.0 m	15.2 to 30.5 m
Canal depth (base)	1.2 to 2.4 m	1.8 to 3.0 m	1.2 to 2.4 m
Canal width (base)[2]	0.9 to 2.4 m	12.8 to 15.2 m	2.4 to 3.0 m
Lay barge size: (onshore to -3.7 m) 30.5x9.1x2.0 m 41.4x10.9x2.4 m 48.8x12.2x1.7 m	N.A.	Lays pipe in canal.	Pushes pipe along canal from push-point.
Lay barge size: (offshore -5.5 m out) 41.4x12.2x2.6 m 76.2x15.2x3.5 m 106.6x18.2x7.0 m	N.A.	N.A.	N.A.
Pipe barge size: 30.5x9.1x1.8 m 41.4x10.9x2.4 m	N.A.	Brings pipe along canal to lay barge.	Delivers pipe to push-point.
Installation segment length	Indefinite	Indefinite	Approx. 24 km/30-in. line
Construction spoil condition	One side of trench 0.9 to 1.5 m high; 3.0 to 6.1 m base.	One or both sides of trench; continuous or broken; 0.9 to 1.5 m high; 15.2 to 25.9 m base.	One or both sides of trench; continuous or broken; 0.3 to 0.9 m high; 6.1 to 15.2 m base.
Post-construction condition	Back fill.	Leave in place or backfill.	Leave in place or backfill.
Post-construction ROW	Cleared of tall vegetation.	Deep open water; or shallow open water.	Shallow open water; or marsh vegetation.
Equipment utilized on pipeline	Cars/trucks; backhoe or ditcher; bulldozer.	Marsh buggies, small boats; tug boats, barge-mounted dredge, helicopters; lay barges; crew/supply boats; jet barge; pipe barge.	Marsh buggies, marsh buggy or track-mounted draglines with timber mats; lay barge; small boats; crew/supply boats.
Mitigation	Reestablish construction contours; place top soil on top; plant/seed; implement erosion control measures for topsoil.	Isolate canal hydrologically from tidal flow; backfill canal to create shallow water, aquatic beds; deposit spoil so as not to interfere with natural drainage; incorporate canal in wetland management plan.	Double ditch spoil and place top soil on top when backfilling; replant/reseed if necessary; bulkhead filled canal at waterway intersections.

[1]Flotation canal has pipe ditch (0.9–1.5 m wide x 0.9–1.8 m deep) in bottom to receive pipe from lay barge.

[2]Canal slope is dredged at 1:2 or 1:3 thereby giving a canal surface width larger than bottom width. Slumping of sides in unstable soils can further enlarge surface canal width during and after construction.

Table 5.2. Possible project closures associated with the major pipeline emplacement techniques ("X" denotes when techniques used) (after Wicker et al. 1989).

PROJECT CLOSURE TECHNIQUES	EMPLACEMENT TECHNIQUE *Upland Trenching*	*Flotation Canal*	*Push-Pull Ditch*
Leave Canal Unfilled			
1. Continuous spoil both sides canal; no breaks.		X	X
2. Continuous spoil both sides canal; 15.2 m breaks every 152.4 m.		X	X
3. Alternating spoil deposits.		X	X
4. Continuous spoil one side of canal; no breaks.		X	X
5. Continuous spoil one side of canal; 15.2 m breaks every 152.4 m.		X	X
Backfill Canal			
1. Single ditch spoil deposits; backfill; no remaining spoil deposits.	X	X	X
2. Double ditch spoil deposits; backfill; no remaining spoil deposits.	X	X	X
3. Remove spoil deposits to canal; pump in fill material.		X	
4. Leave spoil deposits adjacent to canal; pump in fill material.		X	
Right-of-Way Restoration			
1. Backfill and allow to revegetate naturally.	X	X	X
2. Do not backfill and allow to revegetate naturally.		X	X
3. Backfill; recontour; plant; fertilize; water for set period.	X		X
Shoreline Erosion Retardation			
1. Dams/bulkheads at or near beach crossings.		X	X
2. Dams/bulkheads at all channel crossings.		X	X
3. Dams/bulkheads at regular intervals along open canal.		X	X
4. Plug beach crossing with sand/shell.		X	X
5. Install erosion mats at beach crossing.		X	X

backfilling of the LOOP Inc. pipeline in Lafourche Parish (Abernethy and Gosselink 1988).

As continuous water access is not required through the canal after pipe placement, these canals are usually plugged with shell dams or bulkheads at their junction with natural bayous or other waterbodies. Reed and Rozas (in press) examined the cross-sectional area of both plugged and unplugged OCS pipeline canals in the Terrebonne basin, and they found no difference between the two types. This suggests that plugs, even though they may minimize boat traffic and tidal exchange, do not impact bank erosion (as suggested by Wicker et al. 1989 and implied by Johnson and Gosselink 1982) or canal infilling However, increased water clarity in plugged canals (Adkins and Bowman 1976), especially in brackish marsh areas, may encourage the growth of submerged aquatic vegetation and increase the value of these canals as habitat for juvenile fishes and macrocrustaceans (Rozas and Reed 1994).

Push-pull ditches are normally infilled soon after pipe placement and according to Wicker et al. (1989) regulatory agencies frequently require double ditching so that top soil can be kept separate and replaced at the surface to encourage revegetation of these areas. As this technique allows pipe to be laid more rapidly than the flotation canal technique there is usually little time for oxidation and dewatering of sediments. However, the efficiency of the infilling process is still limited by the efficiency of the re-filling process where material has to be scraped back into the ditch without gouging holes in the adjacent marsh surface underlying the material to be moved. Tabberer et al. (1985) examined vegetation cover adjacent to five push-pull canals in coastal Louisiana, including two within the BTES, compared to adjacent control sites. They found that the percentage of canopy cover at 0 to 20 m (65 ft) away from the pipeline was lower than on transects 100 m (330 ft) from the pipeline and the impacts were greatest closest to the pipelines. These data suggest that even though no significant levees are left after infilling push-pull ditches, that there is still incomplete recovery of the vegetation.

Impact of Backfilling

Backfilling canals has been suggested as an effective tool to minimize the indirect impacts of levee placement adjacent to canals. Neill and Turner (1987) examined backfilled well-access canals and found that there was rarely sufficient material in the levees to refill the canals completely. The well-access canals were only backfilled after the well had been abandoned and so the time for oxidation and dewatering of levee material was greater than that for a push-pull ditch. However, the results of Neill and Turner (1987) and Abernethy and Gosselink (1988), who examined a push-pull ditch, are remarkably similar as both studies identify the open water bodies less than 1 m (3.2 ft) deep remaining after backfilling. Reed and Rozas (in press) used survey techniques to evaluate the potential for backfilling OCS pipeline canals in the Terrebonne basin. They found that although there is less material available in the levees of older canals, less material is required to infill older canals. It appears that some natural infilling occurs through time, perhaps as the canals are usually deeper than natural bayou and provide quiescent loci for the preferential deposition of suspended sediments and organic debris. Most canals examined in the Reed and Rozas study would convert to shallow open water bodies, less than 1 m (3.2 ft) deep after backfilling, assuming a certain efficiency in the backfilling process.

Turner et al. (1994) revisited backfilled canals evaluated 10 years earlier by Neill and Turner (1987) to examine progressive changes in backfill success and the stability of any restoration achieved. They determined that the most important factors influencing vegetation re-establishment were canal length and the percentage of dredged material returned to the canal during backfilling. Many canals examined by Turner et al. (1994) showed meandering channels within the backfilled areas, and other indications of a return to more natural hydrology.

MARSH MANAGEMENT

Structural marsh management in coastal Louisiana is usually designed to control both channel flow and marsh water levels. Hydrology is altered in order to achieve certain goals such as restoration, conservation or enhancement of emergent marsh or specific vegetation types, in some areas for the specific purpose of enhancing waterfowl habitat. Marsh management is frequently implemented to address hydrologic changes which have resulted from prior alterations to the natural system, such as canal dredging. Plans may seek to achieve such goals through the control of salinity and/or water levels using systems of control structures and levees (Cowan et al. 1988) which can be used to passively or actively control marsh hydrology. The types and purposes of structures and levees used in marsh management are reviewed in detail by Clark and Hartman (1990). However, marsh management is an evolving science as our knowledge of marsh function increases. Passive management is presently rarely practiced on its own, but many active management regimes include a period when structures are operated as fixed-crest weirs and so examination of fixed-crest weir management can contribute to our understanding of the implications of active management. New technologies and approaches are being developed (Clark and Lehto 1991), and the benefits and impacts of marsh management in the future may change from those in the present and the past. However, marsh management has been implemented in many areas within BTES and the examination of these areas, and others across the coast, can provide information on the nature of this type of hydrologic modification.

Very few studies have examined the impact of such structural alteration on marsh hydrology in detail. Hydrologic monitoring of existing management areas required by the State of Louisiana for a Coastal Use Permit is usually limited to measurements of water level and salinity (Wilkins 1990). Conclusions regarding the specific impacts of hydrologic alterations associated with marsh management on vegetation, accretion, or fisheries productivity within the managed area can best be drawn from areas where observations have been quantified, results have been published, and the managed area has been compared to a suitable control site. This discussion will draw upon such studies, focusing on examples from within the BTES, as well as current scientific understanding of fundamental wetland processes.

The Impact of Marsh Management on Vegetative Growth

Marsh management can influence marsh hydrology through passive measures, where permanently set structures are used to control water flows, or actively, where more sophisticated water control structures and levees are used to manipulate marsh hydrology (Cowan et al. 1988).

Passive Management

The use of fixed-crest or Wakefield weirs (Cowan et al. 1988, Clark and Hartman 1990) is the most popular form of passive marsh management practiced in coastal Louisiana. The original motivation of the installation of the weirs was usually to reduce water level fluctuation, stabilize water salinity, minimize water turbidity and reduce the rate of tidal exchange (Chabreck and Hoffpauir 1962) with the overall objective of improving habitat for waterfowl and wildlife. These alterations in hydrology can be effective in promoting the growth of submerged aquatic vegetation. However, they have also been viewed as effective in preventing emergent marsh loss through the prevention of saltwater intrusion (Chabreck and Nyman 1989).

Several studies have examined the effect of fixed-crest weirs on salinity in Louisiana coastal marshes (Table 5.3). Scientific studies have indicated that fresh and intermediate marsh vegetation may be more susceptible to rapid increases in salinity of several parts per thousand, rather than gradual changes of small magnitude (Pezeshki et al. 1987a, 1987b, Mendelssohn and McKee 1987). Consequently, it is the role of fixed-crest weirs in stabilizing salinities which might benefit the vegetation. It appears that fixed-crest weirs can be effective in preventing the intrusion of some pulses of more saline waters, but when events of sufficient magnitude (e.g., hurricanes or tropical storms) overcome the weirs and introduce higher salinity waters, drainage is impaired and the weired marshes can be subjected to elevated salinities for prolonged periods (Meeder 1987, Simmering et al. 1989). Overall, the effect of weirs appears to be to slow the rate of change in salinity relative to open water bodies and this can mean extending periods of both high and low salinities.

The overall impact of passive management on marsh vegetation has been examined in many of the studies summarized in Table 5.3. The change in species composition noted at some sites controlled by weirs is generally a transition to more flood-tolerant vegetation. However, species composition was thought by Meeder (1989) to be more dependent upon factors such as burning and grazing, rather than weir management. Fixed-crest weirs are normally positioned 15 cm below marsh surface level (Cowan et al. 1988) and thus prevent drainage of the marsh water bodies and soil below that level. The increase in inundation period and reduced drainage noted by Meeder (1989) may result in more reduced soil conditions as identified by Hoar (1975). Two studies of emergent vegetation cover in areas managed by weirs, and which include comparison to unmanaged areas, are summarized in Table 5.3 (Nyman et al. 1990, Larrick 1975) and neither provides conclusive evidence that weir management increases the cover of emergent vegetation. Nyman et al. (1994) also show that marshes are suffering from undercutting and loss in both managed and unmanaged marshes at Marsh Island.

Table 5.3. Summary findings of studies of passive marsh management on soils and vegetation.

Study	Type of Management	Location	Observations within Managed Area	Observations in Control Area	Comments
Chabreck and Hoffpauir (1962)	Fixed-crest weirs	Terrebonne-Lafourche	Av. salinity 10.5 ppt	Av. salinity 11.1 ppt	No difference in vegetation types
Chabreck and Hoffpauir (1962)	Fixed-crest weirs	Marsh Island	Av. salinity 2.9 ppt Higher water levels cf. control	Av. salinity 2.9 ppt	Influenced by Atchafalaya River. High variability between sampling dates. Change in elevation of low tides as drainage prevented. No difference in vegetation types.
Chabreck (1968)	Fixed-crest weirs	Marsh Island	*Eleocharis* sp. replaced much of *Juncus roemerianus* found in 1962 study.		
Meeder (1987)	Fixed-crest weirs	Rainey Wildlife Sanctuary	High salinities after Hurricane Danny did not drain—killed *Scirpus olneyi*		Control area salinities generally lower than in weired marshes
Meeder (1989)	Fixed-crest weirs	Rainey Wildlife Sanctuary	Weir prevents drainage of low marsh areas, increases marsh hydroperiod. Dominated by *Spartine patens* and *Scirpus olneyi*		Storm flood waters took longer to drain from weired marshes. Managed areas did not show inc. standing crop of *S. olneyi*.
Craft and Kleinpeter (1989)	Fixed-crest weir	Avery Island	Sept. 1982 - 3.5 ppt Oct. 1984 - 10 ppt Decline in woody plants, inc. in *Eleocharis* sp. and *Scirpus robustus*	Sept. 1982 - 16.7 ppt Oct. 1984 - 5.5 ppt	Salinity less upstream of weir than downstream in 73% of samples. Vegetation changes 5 years after weir installation.

Table 5.3. (cont.)

Study	Type of Management	Location	Observations within Managed Area	Observations in Control Area	Comments
Larrick (1975) reported in Chabreck and Nyman (1989)	Fixed-crest weir	Marsh Island (MI), Lafourche Parish (LP), Jefferson & Plaquemines Parishes (JP)	89.7% emergent cover MI 42.4% emergent cover LP 75.3% emergent cover JP	86.8% cover MI 64.6% cover LP 80.2% cover JP	In all areas free-soil-water salinities lower in managed than unmanaged
Nyman et al. (1990)	Fixed-crest weir	Marsh Island	1957–1983 marsh loss 0.38%/yr.	1957–1983 marsh loss 0.35%/yr.	No significant difference
Simmering et al. (1989)	Active with fixed-crest weirs	Tenneco LaTerre	Higher salinity than control area in 1988		Attributed to low rainfall and trapping of Hurricane Juan salt water
Hoar (1975) reported in Turner et al. (1989)	Fixed-crest weirs	Coastal Louisiana	Soil Eh lower than in marshes without weirs		

Active Management

The combined use of levees and water control structures allows managers to actively manipulate marsh hydrology on a seasonal basis. One aspect of this manipulation which is thought to have significant impacts on the growth of emergent vegetation is the use of drawdown. This requires structures which can eliminate the inflow of water to the managed area while allowing drainage, and a system of levees to prevent exchange of water across the marsh surface. Drawdown is practiced in freshwater marshes to promote the growth of annual plants which grow in moist soils, such as *Echinochloa walteri*, which is also an important duckfood (Chabreck and Junkin 1989). In brackish marshes such a drawdown might be used by managers wishing to promote the growth of plants such as *Scirpus maritima*. When marsh areas subjected to active management are not in their drawdown phase, they are frequently managed to maintain water levels at or near fixed-crest weir levels (Clark and Hartman 1990).

Structures will be used to gradually increase water levels after drawdown in drawdown years, with water levels maintained no more than 15 cm (6 in) below marsh level during the winter and fall for waterfowl use and trapping access. During non-drawdown years, this type of regime is maintained throughout the year (Clark and Hartman 1990), and the consequences for vegetation are the same as those described above for passive marsh management.

Drawdowns are used to revegetate open-water areas on the premise that many emergent wetland plants require bare mudflats for successful germination. This technique has been effectively used to control vegetation coverage and succession in freshwater prairie wetlands for many years (e.g., Kadlec 1962, Harris and Marshall 1963). The morphology and hydrology of these wetlands are very different from that of the Louisiana coastal zone but the response of some plant species to drawdown will likely be similar.

The application of this established wetland management technique to coastal Louisiana is complicated by salinity influences, and the more complex natural hydrology of tidal marshes. In some areas, the use of drawdowns has increased the number of emergent plant species within managed marshes. Kadlec and Wentz (1974) note that for most wetland plants which are favored by drawdowns, the optimum condition for germination and establishment is either wet soil or very shallow water, indicating that drying and desiccation of marsh soils is not necessarily beneficial to vegetation establishment. Variations in the response of vegetation between managed areas may be caused by slight variations in management practice or efficiency. In coastal Louisiana the impact of many drawdowns on increasing emergent species has been dependent upon maintaining delicate balances between drying to promote germination of seeds and rooting in firm substrate, and overdrying of saline soils. The impact of weather conditions while drawdown is in progress is clear in some studies (e.g., Lehto and Murphy 1989), with drawdown under drought conditions frequently resulting in extreme soil salinities. Prevost (1987) advocates continued water circulation during drawdown in South Carolina brackish marshes to enhance salinity management. This is effected by allowing controlled water inflow to managed areas during daily high tides and discharges during low tides. Although the types of structures used to manipulate water levels on South Carolina managed marshes, known as trunks, are similar to many used in Louisiana (Clark and Hartman 1990), this type of responsive management strategy is rarely used in coastal Louisiana.

The impact of drawdown on the growth and vigor of existing vegetation has rarely been examined. The one-year comparative study of Flynn et al. (1990) at two managed areas, one of which was in BTES, demonstrates that active management can either increase or decrease the primary productivity of *Spartina patens* depending on the success of drawdown. Sweeney et al. (1990) did not examine the impact of drawdown *per se*, but they found that between 1985 and 1988 half of their study sites established more marsh or lost less marsh than their unmanaged controls. The response of vegetation cover within actively managed areas appears to be related to the intensity and responsiveness of management practice, but the Sweeney et al. study does not allow the identification of specific cause-effect relationships between management practice (e.g., drawdown) and marsh response.

Impact of Marsh Management on Accretionary Processes

Marsh management affects accretionary processes through 1) the alteration of direct exchanges of suspended material between managed marshes and adjacent uncontrolled areas, and 2) changes in soil characteristics that can affect processes of organic matter production and decomposition.

Passive Management

The goal of marsh management using fixed-crest weirs is to reduce water level fluctuation, stabilize water salinity, minimize water turbidity and reduce the rate of tidal exchange (Chabreck and Hoffpauir 1962). Clearly, a reduction in water turbidity will result in less sediment available for deposition on the marsh surface within the managed area during normal tidal conditions, although sediments may accumulate in pond bottoms. Similarly, reduced rates of tidal exchange are not conducive to the continued supply of suspended sediment from sources outside of the managed areas. However, as organic accumulation is also an important component of marsh vertical accretion, the overall impact of passive management must be examined through its effects on both sediments and vegetation.

Table 5.4 summarizes several studies that have documented the effects of altered marsh hydrology on sediment deposition and marsh accretion, including two which specifically examine fixed-crest weirs. Some workers argue that reductions in the input of inorganic sediment to fresh and brackish marshes caused by marsh management does not necessarily result in decreased marsh accretion, as increased vegetative production will compensate for the lack of inorganic sediments. However, the preceding discussion of the impact of passive management on vegetative growth did not indicate that altered hydrology results in enhanced productivity of emergent vegetation. If marsh accretion is in balance with relative sea level rise before management is implemented, an imbalance may occur after implementation as sediment supply is reduced. Organic accumulation must increase to compensate for the lack of inorganic accumulation or waterlogging and submergence will occur.

Table 5.4. Summary findings of published studies concerning sediment deposition and marsh accretion in hydrologically altered systems.

Study	Alteration to Hydrology	Location or Marsh Type	Observation of Altered vs. Unaltered Marsh	Comments
Reed (1992)	Fixed-crest weirs	Fresh-intermediate	Lower sediment deposition within weir managed marsh	Marsh surface sediment deposition only
		Brackish	Variations between sampling dates	
		Saline	Lower sediment deposition within weir managed marsh	
Taylor et al. (1989)	Dredged material levees	Jean Lafitte National Park	Greater accretion in areas with free access to natural channels compared to marshes isolated by levees	Feldspar marker technique
Cahoon and Turner (1989)	Dredged material levees	Southwest Louisiana. Brackish	Greater accretion in areas with direct hydrologic exchange compared to areas isolated by levees	Feldspar marker technique
Meeder (1987)	Fixed-crest weirs	Rainey Wildlife Sanctuary	No differences between sediment deposited by storms in managed and adjacent unmanaged marshes	Hurricanes Danny and Juan. Large events override effect of weirs
Boumans and Day (1990)	Active management	Rockefeller Refuge	Greater short-term sediment deposition in unmanaged marshes compared to control	Marsh surface sediment deposition only
		Fina LaTerre	No significant difference between managed and control marshes	
Cahoon (1994)	Active management	Rockefeller Refuge	Greater organic and inorganic accumulation in unmanaged marshes	Rockefeller significantly different at $p=0.01$
		Fina LaTerre	Greater organic and inorganic accumulation in unmanaged marshes	Fina organic significantly diff. at $p=0.05$

If soil drainage is reduced by retention of water behind weirs, this may decrease decomposition of soil organic matter, leading to increased organic matter accumulation, but such mechanisms have yet to be quantified. Organic matter accumulation would also increase if management stimulated plant productivity, although the above discussion indicated there was little evidence that this would occur. Any such increases in organic matter accumulation should be reflected in equivalent or higher rates of marsh accretion but this does not appear to be the case in areas that are hydrologically isolated by levees (Table 5.4). While marsh management may be effective in reducing salinity fluctuations and tidal exchange, the results of these few available studies of sediment deposition and marsh accretion in areas of limited tidal exchange suggest that marsh management using fixed-crest weirs may have a detrimental impact on marsh vertical accretion. The importance of such impacts on marsh sustainability will vary with marsh types, being less significant in dominantly organic fresh marshes. In addition, improvements in technology and more responsive management of structures may minimize these impacts in the future.

Active Management

The use of culverts and variable crested structures to control tidal exchanges may be expected to allow greater flux of suspended sediments into managed areas than the use of fixed-crest weirs. Tidal exchange can occur through a greater depth of the water column with most of these structures allowing more potential for sediment transport. However, the use of flap-gates on these structures to prevent any import of suspended sediment during certain management regimes, and their use in conjunction with levee systems which prevent any exchange of water and suspended sediments across the marsh surface except under extreme storm conditions, means that although there is potential for suspended sediment transport into actively managed marshes, this may not always be realized. In addition, the water management schedule for most managed marshes is determined by the life cycles of the plant and animal species targeted for management, and this schedule does not necessarily coincide with the sediment dynamics of the wetland system (Cahoon 1991).

Marsh management strategies could be adopted to allow for sediment introduction to managed areas while minimizing interruption of other management goals (Cahoon 1991). One approach to management which allows for the periodic introduction of sediment-laden waters is the use of a flow-through phase into the management schedule (Clark and Hartman 1990). Inflow structures allow water to move into the managed areas at times of low salinities and high suspended sediment concentrations, and outflow structures are used to prevent ponding within the managed area. This technique may be particularly useful in parts of coastal Louisiana close to natural deltas or freshwater and sediment diversions where high sediment availability usually coincides with high levels of fresh water during spring floods on the Mississippi River (Cahoon 1991, Mossa 1991). However, for much of coastal Louisiana, isolated from riverine inputs of sediment and fresh water, the maximum availability of suspended sediment coincides with the passage of winter cold fronts (Reed 1989B) and tropical storms (Baumann et al. 1984) which also introduce higher salinity waters to coastal marshes. As yet there is no published quantitative evaluation of the use of flow through management strategies and their impact on sediment deposition and vertical accretion.

A one-year evaluation of the effect of marsh management, including drawdown, on materials flux was conducted by Boumans and Day (1994). Results at their Fina LaTerre study site within BTES show net import of suspended material into unmanaged areas during periods when there was essentially no import or export into the managed areas. The reduced flux in the managed areas was primarily caused by the reduction in water flux caused by the management structures. Boumans and Day (1994) also observed strong export of material from managed areas at Rockefeller Refuge study sites in the chenier plain during northerly winds.

Similar studies of longer-term marsh accretion by Cahoon (1994) examined accretion during both drawdown and flooding (structures operated as fixed-crest weirs) phases of management at both Fina LaTerre and Rockefeller study sites. Results showed that vertical accretion in the managed marsh was less than vertical accretion in the unmanaged marsh, especially during the flooding phase. At Rockefeller, accretion was lower in the managed marsh than the unmanaged marsh during the drawdown phase and was essentially zero in the managed area during the flooding phase. Cahoon (1994) concludes that the source of accreted matter to the Fina LaTerre managed area study sites is primarily from pond bottoms within the managed area with minor inputs through the control structures in the southern part of the management unit.

SUMMARY OF STATUS AND TRENDS

Status

The magnitude of human impacts and hydrological modifications within the Louisiana coastal marshes is well documented. Creation of canals has directly impacted up to 2.59% and 3.45% of the Terrebonne and Barataria systems, respectively. Indirect impacts on coastal marshes can be at least the same order of magnitude. In addition to dredge and fill activities related to navigation and mineral extraction, some alterations to natural hydrology have occurred as part of marsh management plans. Natural hydrology of the basins has also been disrupted by road railway construction which has frequently been associated with the construction of embankments across major portions of the estuaries with exchanges from one side of the embankment to the other restricted to culverts or bridges over controlled channels.

Trends

Specific trends in hydrologic modifications have not been addressed in this report. The nature of the changes which have occurred have been described with some examples to provide a time-scale for the modifications.

The natural bayous of the BTES systems are sinuous streams which terminate on the coast or in the coastal bays, typically into waters less than 3 m (10 ft) deep. Many of these bayous have been dredged and deepened at various times to facilitate waterborne commerce and mineral exploration and extraction. The rapid expansion of the offshore oil and gas industry in the 1950s created a need for more direct access from coastal towns to the Gulf, and for the transportation of drilling structures and supplies through the coastal zone to the outer continental shelf. The impact of these channels on BTES include modification of basin circulation and salinity distributions. Studies show that under similar environmental conditions, salt water penetrates further inland in large, deep channels (such as the Houma Navigation Canal) than in smaller, shallower channels (such as Bayou Petit Caillou). In addition, model simulations confirm that deepening and widening channels can increase saltwater penetration from the Gulf of Mexico. Additional impacts of these channels are changes in shoreline configuration and resultant erosion associated with jetties.

In addition to major navigation channels, dredging of smaller canals has severely impacted BTES. Potential indirect impacts of canal dredging can be associated with either the increased channelization of the marsh or the alterations to marsh surface hydrology caused by the dredged material levees. Increased channelization in marshes with previously low drainage densities may allow 1) the more efficient penetration of salt water into areas previously isolated from direct exchanges, and 2) increased tidal flow and enhanced erosion of some marsh types with highly organic soils. Marsh surface hydrology is altered by the placement of dredged material levees adjacent to canals. These levees impede the direct flow of water from the marsh surface to and from the canal. In addition, the high density of well-access canals in some oil and gas fields, and their intersection with dredged material levees associated with some pipeline canals, means that some areas of marsh have become semi-impounded or impounded by these levees. As well as impeding the flow of water onto and away from the marsh surface, dredged material levees may also impede the input of suspended sediment to the marsh surface.

Structural marsh management in coastal Louisiana is usually designed to control both channel flow and marsh water levels. Marsh management techniques, their effectiveness, as well as their benefits and impacts to coastal marshes have been the subject of debate in coastal Louisiana for more than 10 years. Hydrology is altered in order to achieve certain goals such as restoration, conservation or enhancement of emergent marsh or specific vegetation types, in some areas for the specific purpose of enhancing waterfowl habitat. The effect of marsh management techniques on controlling salinity in coastal marshes is not consistent. Fixed-crest weirs can reduce the incursion of both saline and fresh waters to marsh areas. When saline waters penetrate into managed areas during storms, structures and levees can increase the resident time of high salinity water. Although drawdown can be used to alter species diversity, effective use of drawdown to increase the area of cover or vegetative vigor of emergent perennial species depends upon the intensity, efficiency, and responsiveness of drawdown. Passive management can reduce the amount of sediment deposition in managed areas compared to adjacent unmanaged areas. Flap-gated structures, a more active management approach, also reduce the amount of suspended material transported into managed areas.

Studies of marsh accretion show lower rates of material accumulation in managed compared to unmanaged areas. Flow-through marsh management strategies have potential for enhancing sediment deposition within managed areas but have yet to be broadly applied and have not yet been quantitatively evaluated. New approaches and technologies are being developed to ensure that marsh management projects can be responsive to natural variability in the estuarine system.

PART 6

WATER LEVELS AND SALINITY IN THE BARATARIA-TERREBONNE ESTUARINE SYSTEM

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INTRODUCTION

The Barataria-Terrebonne estuarine system (BTES) consists of a series of lakes and bays surrounded by low-lying marshes. The marsh systems are characterized hydrologically by many interconnecting lakes, channels, and bayous that constitute the "blood vessels" of the marshlands (Murray 1976). Flows through these channels are coupled with extensive overland flooding, thus exchanging water between the marsh surface and the surrounding water bodies. The circulation patterns and salinity structure in these estuaries are controlled internally by a combination of tidal dynamics, riverine input, and local wind forcing. The estuaries in turn exchange water with the adjacent shelf. The Mississippi River, which drains about 41% of the United States (Turner 1990), serves as an indirect (at the coastal endpoint) input of fresh water to the BTES.

This report examines the general hydrologic character of the BTES and trends in both water levels and salinities. A regional overview, based upon a literature review, which describes the features of the Gulf of Mexico circulation and the coupling of the coastal waters with the estuaries, is presented first. This sets the stage for the more detailed discussion of the hydrologic characteristics of the BTES. This discussion (using literature review and limited data analysis) presents both the spatial characteristics of and trends in water levels and salinity in the BTES. Examples of the time series data analyzed, methods used, and a discussion of the major characteristics observed, are presented. Because the data set is quite large, only selected examples of the data are shown, but those shown are typical of each system. Time series plots of all the long-term water level and salinity data are in Appendixes L–P.

OVERVIEW OF REGIONAL ENVIRONMENT

Gulf of Mexico Circulation

The general circulation within the Gulf of Mexico is dominated by two large scale systems: the "loop current" in the eastern portion and an anticyclonic gyre in the west (Behringer et al. 1977, Leipper 1970). The loop current enters the Gulf through the Yucatan Straits and exits through the Florida Straits (Molinari et al. 1977). The path of the loop current is variable, usually forming an anticyclonic loop (Behringer et al. 1977). In general, it follows a pattern in which there is growth of the loop northward into the Gulf to a maximum penetration which coincides with the separation of an eddy, followed by the westward drift of this eddy which leaves behind a loop current with reduced penetration into the Gulf (Behringer et al. 1977). The offshore waters mix with the nearshore waters forming a "coastal boundary layer." It is this coastal boundary layer that exchanges water with the estuaries.

Tides

The tides in the northern Gulf of Mexico are of the diurnal type with a mean astronomical range of about 0.5 m (1.6 ft) (Marmer 1954). The tides in the Gulf are affected by several cycles: biweekly, seasonal, and an 18.6-year cycle (Baumann 1979). These cycles have a significant contribution to the observed water level at any given station and must be considered in any interpretation of water level data. The biweekly cycle is due to the changing declination of the moon's orbit relative to the earth and is characterized by maximum tidal range when the moon is over the tropics and minimum tidal range when it is over the equator. These changes are referred to as tropic-equatorial tides, and are the analog of spring-neap tides (which are caused by changes in the phase of the moon) found along the East Coast of North America. This variation in range between tropic and equatorial tides represents the greatest change that occurs in the astronomical tidal amplitude. This is typical for areas dominated by diurnal tides (Marmer 1954). The seasonal change in the tides for stations around the Gulf can be seen in Figure 6.1. In general the stations in the northern Gulf exhibit a bi-modal pattern with peaks in the spring and fall. It is postulated that this monthly variation is due to changes in monthly water density (steric effect), most likely temperature related, and atmospheric pressure changes due to cold front passages (Whittaker 1971). The tides within the Gulf also exhibit the effect of the 18.6-year lunar epoch. This change in tidal range is due to the change of the inclination of the moon's orbit relative to the earth's equator. Baumann (1979) noted that for Barataria basin, this change is greater than the seasonal change but much less than the biweekly change. He also noted that marsh inundation frequency is positively related to this 18.6-year cycle.

Mean sea level (MSL) is defined as the average of the hourly values of water levels measured over a 19-year tidal datum epoch (Hicks 1989). In practice mean tide level (MTL), a plane midway between high and low water that is computed by averaging high and low water levels over a 19-year period (Swanson 1974), is often used in place of MSL since it is easier to compute. MSL and MTL approximate each other along the open coast (Swanson 1974). The National Geodetic Vertical Datum (NGVD)—a fixed (relative to the center of the earth) datum based upon the best fit over a large area—does not take into account local variations or changing stands in sea level and should not be confused with MSL (Hicks 1989). The relationship between MTL (MSL) and NGVD is not consistent from one location to another in either time or space (Swanson 1974). Thus, in order to standardize MSL estimates, local tide data are tied into a specified National Tidal Datum Epoch, which is a specific 19-year period over which observations are to be averaged to compute means (Hicks 1989). It is possible, however, to compute means based upon short-term data sets. Such a short-term mean may or may not be an accurate representation of the accepted value of MTL, depending upon location. Swanson (1974) compared MSL from short-term records to MTL calculated from a 19-year record. His results indicate that for the Gulf Coast, with one month of observations, the accuracy of the

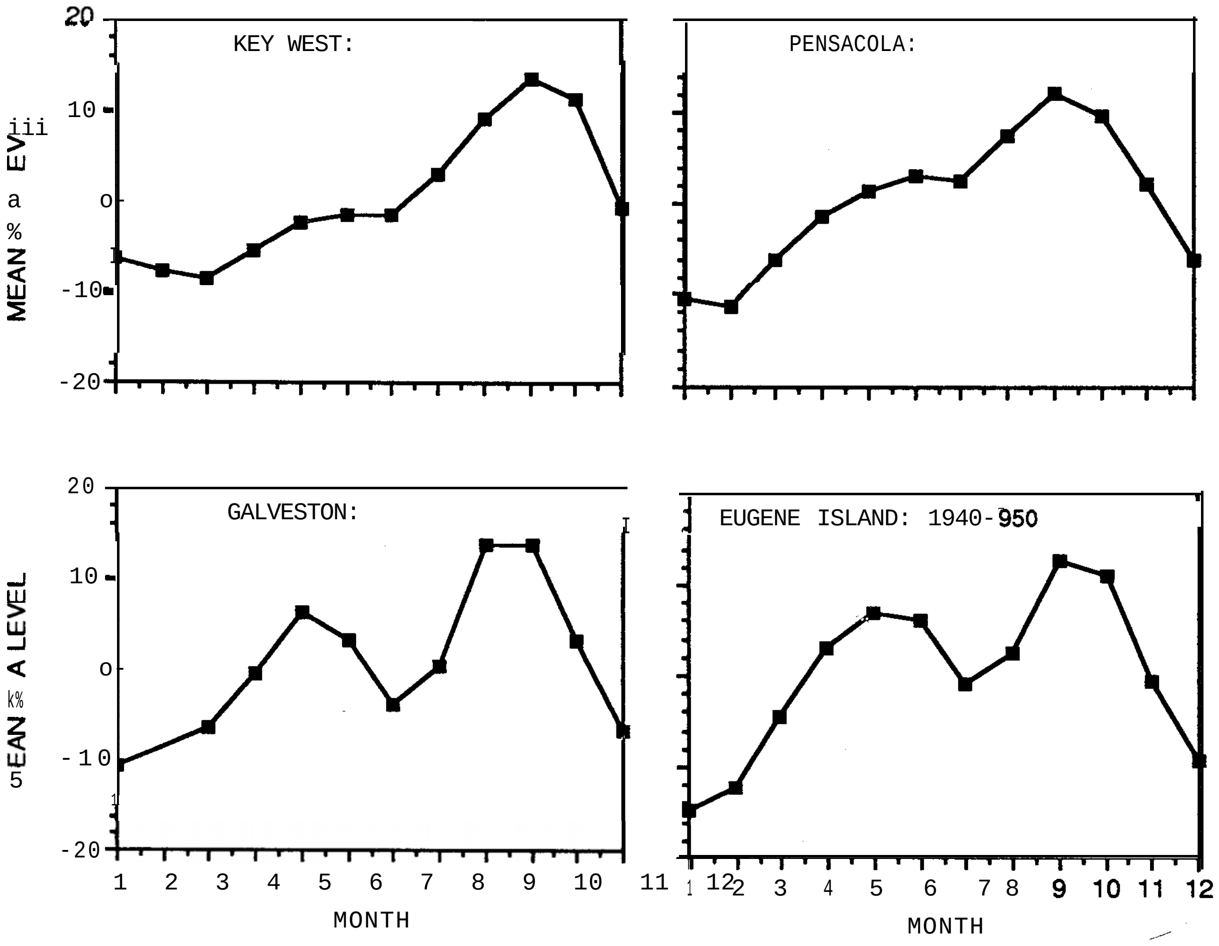


Figure 6.1 Plot of monthly mean water levels for stations around the Gulf of Mexico.

estimate of MTL is ~5.5 cm (2.17 in). The accuracy improves to ~3 cm (1.18 in) with 12 months of observations.

The water levels in the Gulf of Mexico also exhibit longer term trends which are due to larger scale processes (global sea level rise, regional subsidence). The sea level trends (over the period 1855–1986) for the United State were summarized by Lyles et al. (1988). Their analysis of stations in the Gulf of Mexico showed relatively stable conditions at the Florida stations with long-term-trends ranging from 2 to 3 mm / yr (0.08 to 0.12 in / yr). The Louisiana and northern Texas stations showed long-term trends ranging from 6 to 14 mm / yr (0.24 to 0.55 in / yr). The southern Texas stations (south of Rockport) again showed stable conditions with trends ranging from 3 to 4 mm / yr (0.12 to 0.16 in / yr).

Coastal-Estuarine Coupling

Estuarine gravitational circulation is in many cases influenced by flows occurring as a result of other processes, with wind being dominant. Estuarine-coastal exchange processes resulting from wind forcing result in the formation of buoyant effluent plumes, which in turn influence shelf chemistry and biology as well as physics (Wiseman 1986). These exchanges are bi-directional with significant transfers of mass and momentum as well as chemical and geological constituents also occurring between the shelf and the estuary (Wiseman 1986). Meteorological forcing in estuaries along the northern Gulf of Mexico can be considered in terms of (1) exchange between the estuarine waters and the waters in the coastal zone; and (2) local forcing occurring within the estuary proper. Flows in estuaries along the northern Gulf Coast respond to the subtidal (low frequency) wind stresses. Schroeder and Wiseman (1986) summarized the wind forcing characteristics of Gulf of Mexico estuaries. They indicated that at long time scales (several days), the alongshore wind stress sets up an Eckman convergence / divergence along the coast that drives the estuarine flows. At shorter time scales, the cross-shelf winds frictionally drive the flows by "pushing" water into the estuaries. Strong winds from the south "pile" up water along the coast forcing water into the estuaries, raising water levels on the order of 0.3–0.5 m (1.0 to 1.7 ft) above normal. Conversely, winds from the north force water out of the estuaries depressing the water levels 0.3–0.5 m (1.0 to 1.7 ft) below normal. The "set up" of water usually occurs as a front approaches the area from the west and the southerly winds pile water along the coast. After the front passes the winds shift to a more northerly direction, resulting in a rapid drop in the estuarine water levels. Hart and Murray (1978) describe this type of situation in Chandeleur-Breton Sound. These events result in substantial fluxes of water in and out of the estuarine systems, and can have dramatic effects on the salinity distribution within an estuarine system. The shelf exchange characteristics for several estuaries along the northern Gulf are summarized in Table 6.1. Work by

Kjerfve (1975) in Caminada Bay, Louisiana, demonstrated that the diurnal tidal influence in addition to the wind forcing can be important in controlling the internal dynamics of these systems, depending upon the time scales involved.

Table 6.1. Major water level and salinity time series data sets for the BTES. Shown are the start date, end date, sampling interval (hours), expected number of observations, actual number of observations, and the percentage of data missing.

Station Name	Location	Start Date	End Date	Samp. Int.	Exp. Obs.	Act. Obs.	Percent Missing
		USACOE Daily Salinity					
S03780	Atch. River at Morgan City	1-Aug-46	1-Oct-81	24	12845	6134	52.2
S52800	B. Boeuf at Amelia	1-Jan-55	16-Nov-87	168	1715	1569	8.5
S52880	B. Black at Greenwood	21-Jan-90	13-Mar-91	24	416	410	1.4
S76303	B. Petite Caillou at Cocodrie	1-Jan-70	30-Sep-84	24	5386	4469	17.0
S76320	GIWW at Houma	1-Sep-46	15-Dec-88	24	15446	12689	17.8
S76323	B. Grand Caillou at Dulac	1-Jul-48	24-Sep-84	24	13234	12045	9.0
S76343	HNC at Crozier	1-Sep-61	29-Dec-88	24	9981	7585	24.0
S76403	B. Terrebonne at Bourg	1-Dec-62	1-Jan-82	24	6971	5854	16.0
S82203	B. LaFourche at Larose	6-Jan-70	28-Jul-88	24	6778	5695	16.0
S82300	B. LaFourche at Galliano	1-May-61	17-Jul-84	24	8478	7784	8.2
S82350	B. LaFourche at Leeville	1-Oct-55	12-Jul-77	24	7955	7659	3.7
S82700	Bayou des Allemands	23-Jan-78	29-Jan-81	24	1102	61	94.5
S82750	Barataria	1-Jun-57	29-Jan-81	168	1235	339	72.5
S82875	Lafitte	15-Oct-55	28-Oct-88	24	12067	15120	-25.3
S88600	Eugene Island	1-Jun-48	1-Sep-57	24	3379	3119	7.7
		LDWF Hourly Salinity					
S315	Grand Terre	5-Aug-75	1-Dec-93	1	160632	147380	8.2
S317	St. Mary's Point	10-May-73	9-Aug-93	1	177504	135471	23.7
S323	Lake Palourde	10-May-88	6-Feb-92	1	32808	30535	6.9
S325	Tenn. Gas Canal	18-Mar-82	2-Dec-93	1	102648	72565	29.3
S326	Little Lake	28-Jul-82	2-Dec-93	1	99480	44871	54.9
S416	Cocodrie	1-Oct-74	14-May-85	1	93072	49618	46.7
S518	Sister Lake (L. Mechant)	18-Dec-73	2-Jul-85	1	101136	52367	48.2

Table 6.1 (cont.)

			USACOE Daily Stage				
S03780	Atch. River at Morgan City	1-Jan-35	29-Aug-94	24	21790	21699	0.4
S03850	Round Bayou at Deer Island	9-Mar-74	10-Aug-94	24	7459	7104	4.8
S52800	B. Boeuf at Amelia	12-Jan-55	9-Nov-94	24	14546	13154	9.6
S52880	B. Black at Greenwood	6-Jan-64	16-Nov-92	24	10542	8161	22.6
S76320	GIWW at Houma	1-Jan-59	18-Nov-94	24	13105	11226	14.3
S82301	B. Blue at Catfish Lake	1-Jan-76	20-Dec-92	24	6198	5931	4.3
S82350	B. LaFourche at Leeville	19-Jan-56	24-Dec-94	24	14219	13387	5.9
S82700	Bayou des Allemands	1-Jan-55	20-Nov-92	24	13838	12310	11.0
S82750	Barataria	1-Jan-59	20-Nov-92	24	12377	11668	5.7
S82875	Lafitte	19-Oct-58	8-Nov-92	24	12439	11465	7.8
S88350	West Bay (Miss. River Delta)	26-Jan-74	15-Dec-92	24	6898	5135	25.6
S88600	Eugene Island	1-Jan-45	5-Aug-94	24	18113	16214	10.5
			NOS Hourly Water Levels				
2928	Cocodrie	1-Nov-86	31-Dec-90	1	36504	35496	2.8
3731	Grand Isle	1-Jan-55	31-Dec-90	1	315552	286569	9.2
2084	Leeville	1-Nov-86	31-Dec-90	1	36504	35496	2.8

Barrett (1971) and Gagliano et al. (1973) noted the relationship between Mississippi River flow and coastal salinities in Louisiana. Gagliano et al. (1973) analyzed monthly salinities using multiple linear regression (with multiple lags) to model the effect of the Mississippi River on salinity. Their results also showed an increase in the effect of the Mississippi River on salinities closer to the Gulf. Their study also showed that the variations in Mississippi River discharge can explain 50% of the variation in salinity within Barataria Bay. Wiseman et al. (1990) analyzed the relationship between weekly discharge of the Mississippi River and Louisiana coastal salinities based upon long-term records, using auto-regressive moving average (ARMA) time series modelling. This type of analysis assumes that the present state of a system is a function of the present and past values of its inputs. Thus, the model is able to account for lags in the system, with the larger lags having less effect then the more recent. The total models were able to account for 70 to 86% of the observed variance in the salinity signal. The direct river portion of the model accounted for 30 to 50% of the variance of Louisiana coastal salinities, the remainder (the auto-regressive portion) described processes not directly related to the river flow (tidal dispersion, wind-driven estuarine-shelf exchange). The data also indicate an increase in the lag between the Mississippi River flow and coastal salinity as one moved either into the estuary or westward along the coast. Although the models were statistical, they are consistent with a model of westward dispersion (by the Louisiana Coastal Current) of waters discharged from the Mississippi coupled with an upstream dispersion within the estuaries.

DATABASE DESCRIPTION

In order to characterize the basic hydrology of the BTES as well as the trends in both water levels and salinities, several data bases were analyzed. The data bases used in this study can be grouped into four basic categories:

(1) Long-term (20+ years) high frequency sampling (daily, and in some cases hourly) data from monitoring stations run by various state and federal agencies.

(2) Short-term (usually less than 2 years), high frequency sampling (hourly data) from specific studies within the system.

(3) Long-term (20 years), low sampling frequency (monthly) from monitoring stations run by various state and federal agencies.

(4) Short-term (usually less than 2 years), low sampling frequency (monthly) data from specific projects (i.e., a project for a thesis or dissertation).

Trends in water levels and salinities were determined by using the data from the first category. The primary data for these analyses came from the Corps of Engineers (COE) coastal monitoring stations, the National Ocean Survey (NOS), tide gages and the Louisiana Department of Wildlife and Fisheries (LDWF) coastal monitoring stations. The station distribution is shown in Figure 6.2. Table 6.1 lists the locations and period of record for the data sets from this category that were used for the long-term trend analysis.

Data from categories 1 and 2 were used to address spatial patterns of water levels (including marsh inundation) and salinities within the BTES. These data were collected in conjunction with several studies:

- The USACOE study of Barataria Bay for the Davis Pond Diversion. The station distribution is shown in Figure 6.3.

- Continuous recording gages from the Louisiana Department of Wildlife and Fisheries (LDWF). The station distribution is shown in Figure 6.2.

- A study of the fresh and intermediate marshes of Barataria and Terrebonne conducted by the Coastal Ecology Institute at Louisiana State University for Region 6 of the U.S. Environmental Protection Agency. The station distribution is shown in Figure 6.4.

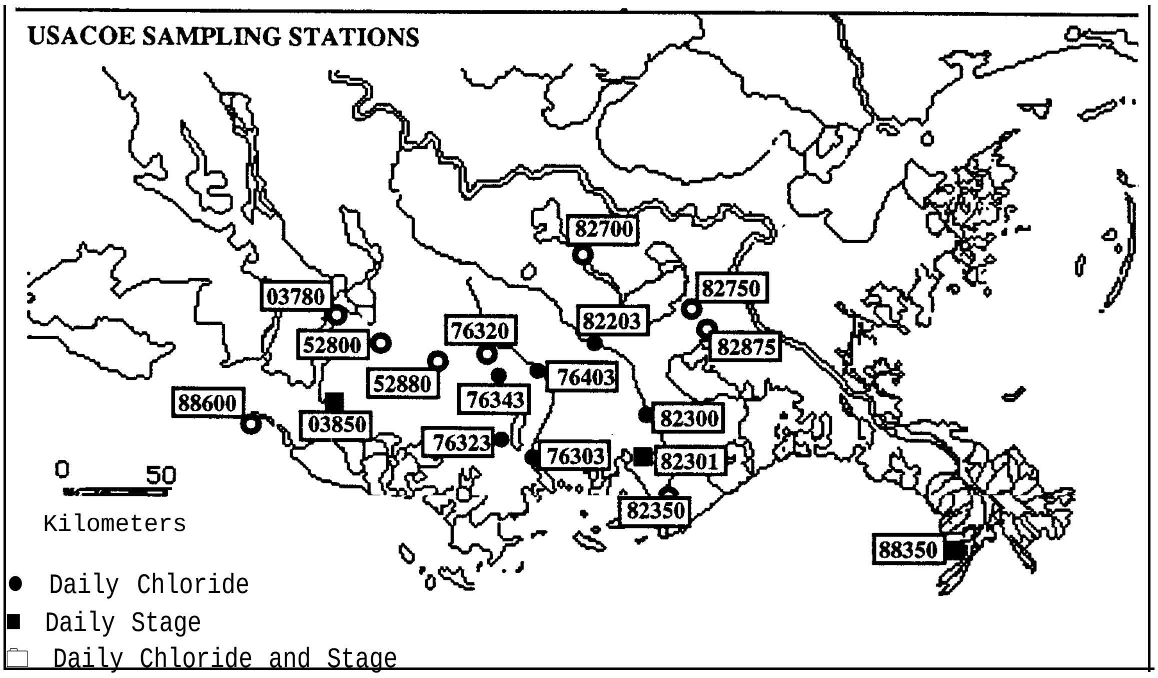
- Various marsh water level research projects conducted by the Coastal Ecology Institute at LSU. The station distribution is shown in Figure 6.4.

Data from categories 3 and 4 were used mainly in a descriptive fashion to characterize the BTES. A majority of the data were summarized in Wiseman and Swenson (1989). These data came from several sources:

- The Louisiana Cooperative Estuarine Inventory and Study (Barrett 1971). The station distribution is shown in Figure 6.5. The LDWF monthly biological sampling stations are located at a sub-set of these stations, with a few additional sampling locations.

- A vegetation study conducted by Eggler et al. (1961) along the Bayou Blue watershed in the eastern portion of the Terrebonne estuary. The station distribution is shown in Figure 6.5.

- A thesis by Seaton (1979) investigating nutrient dynamics along an inland-to-coast gradient in the Barataria system. The station distribution is shown in Figure 6.5.



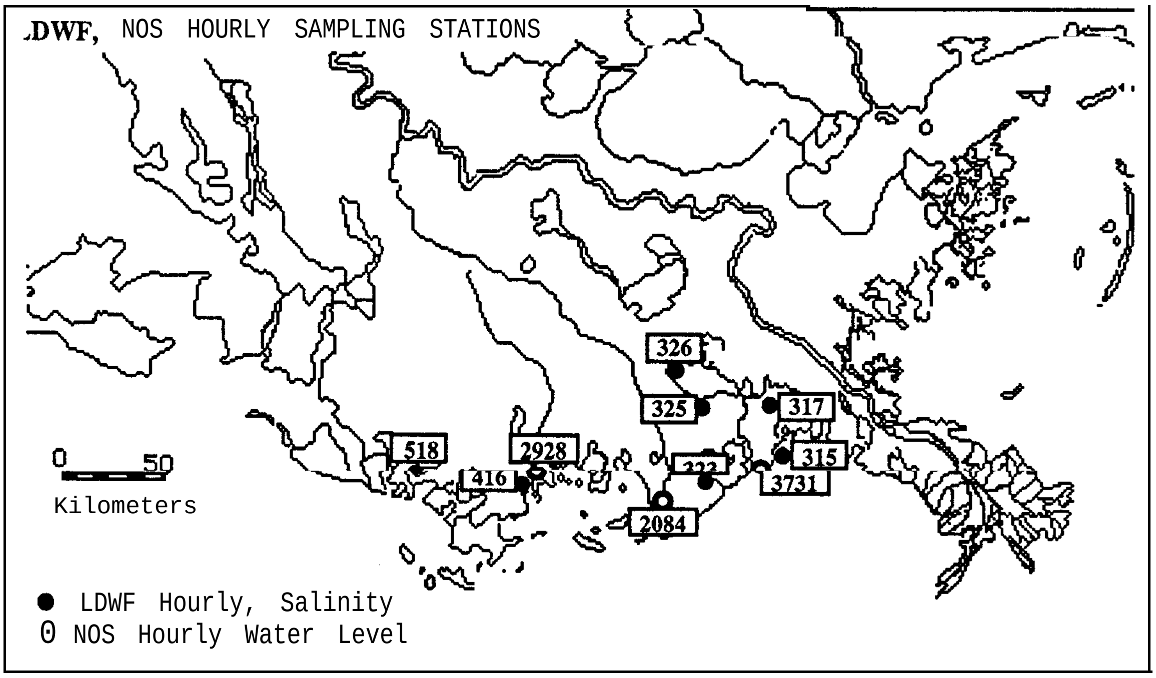


Figure 6.2. Sampling station distribution for the U.S. Army Corps of Engineers (COE) coastal monitoring stations, the National Ocean Survey(NOS) tide gages and the Louisiana Department of Wildlife and Fisheries (LDWF) coastal monitoring stations.

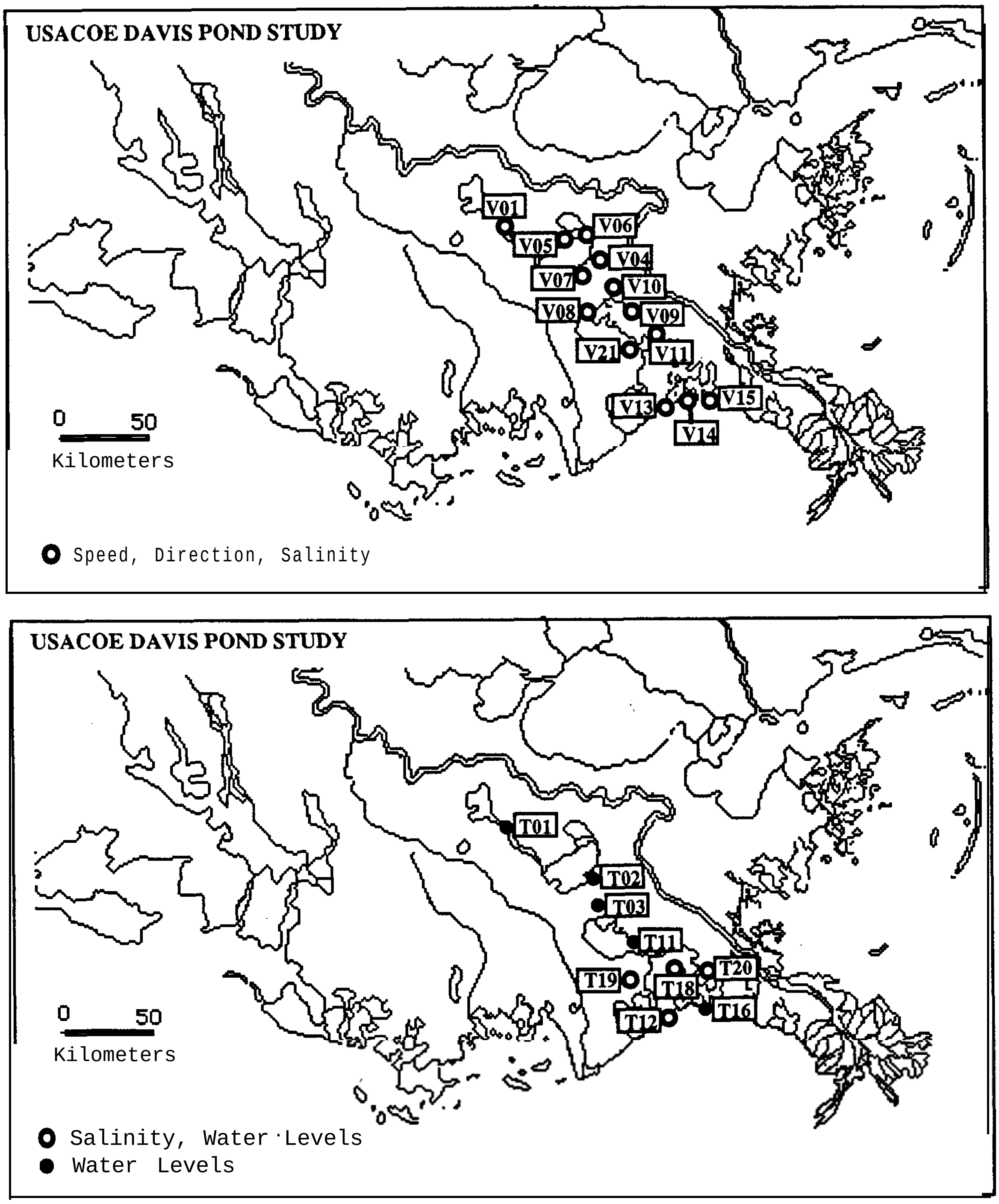


Figure 6.3 Sampling station distribution for the U.S. Army Corps of Engineers study of Barataria Bay for the Davis Pond Diversion.

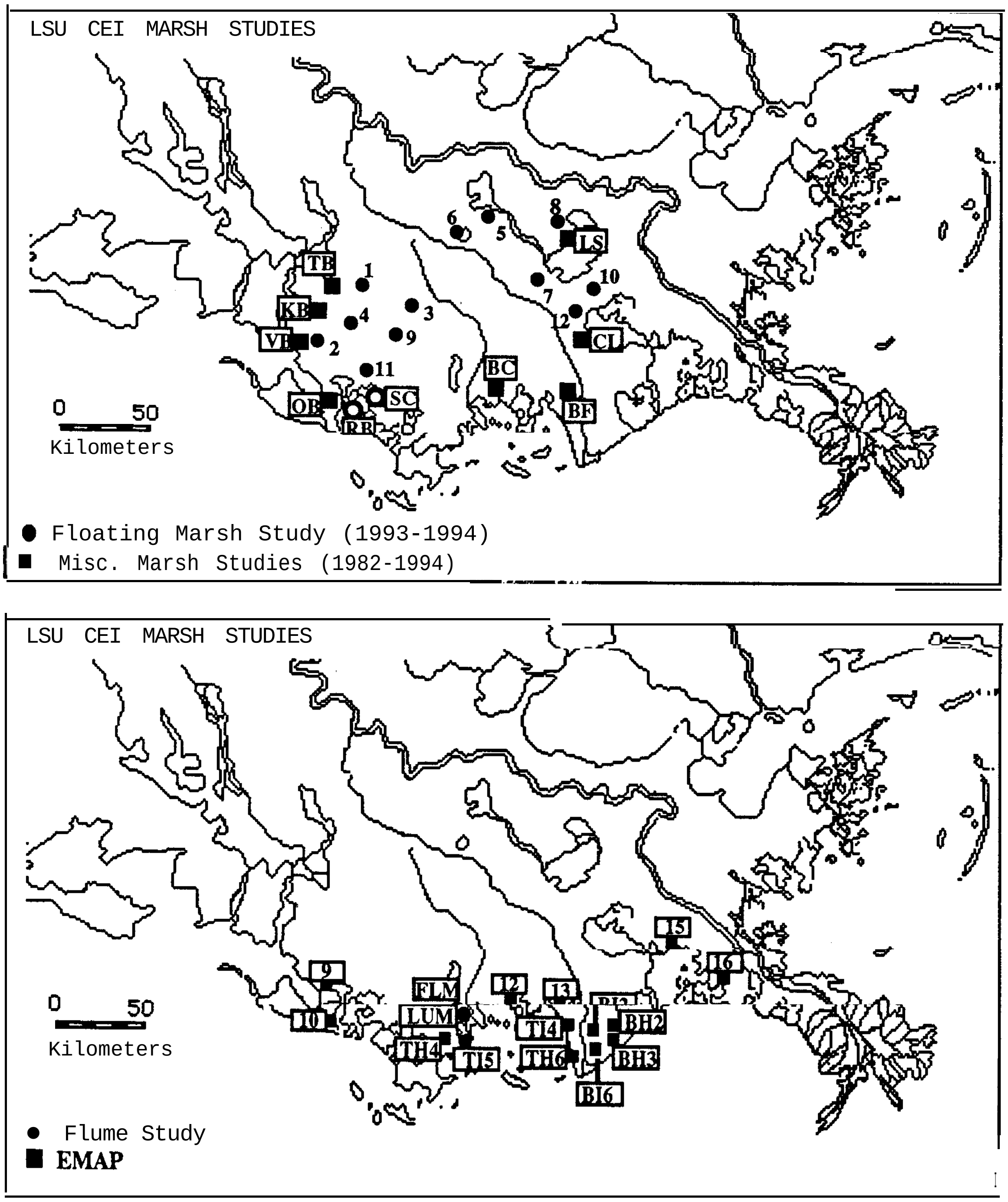


Figure 6.4. Sampling station distribution for various marsh water level research projects conducted by the Coastal Ecology Institute at Louisiana State University.

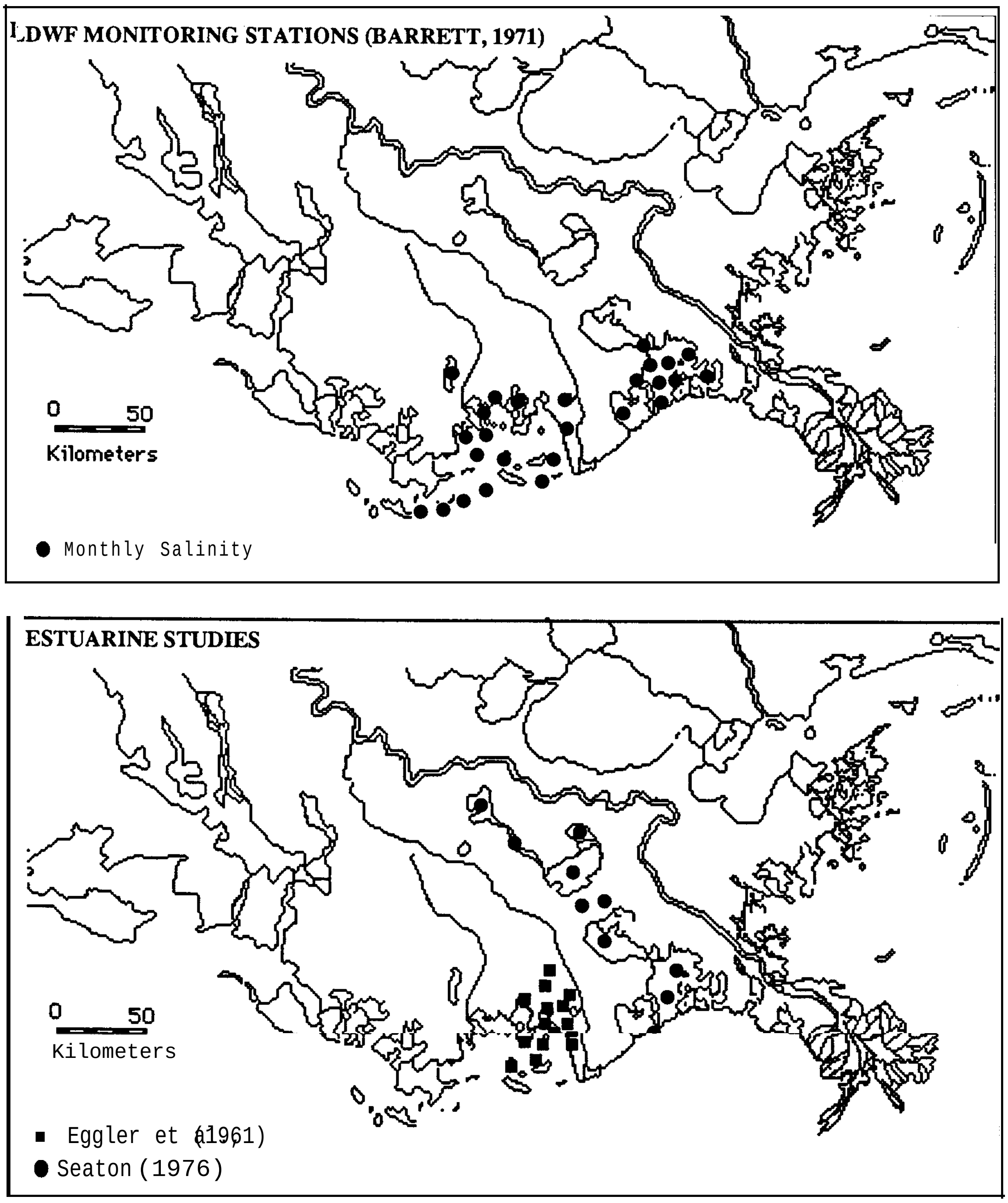


Figure 6.5. Sampling station distribution for the Louisiana Cooperative Estuarine Inventory and Study (Barrett 1971), a vegetation study conducted by Eggler et al. (1961), and a thesis by Seaton (1979).

ANALYTICAL METHODS

The only data used for detailed analysis were those time series data sets that were readily available in a computer compatible format (usually an ASCII file). The time series data files were transferred to the Louisiana State University mainframe computer for analysis using Statistical Analysis System (SAS 1990a, b, c, d, e). Since all of the data were in time series format, the same basic techniques were used for all sites. After the data were transferred, a preliminary analysis to check the data for missing data points and / or outliers was performed. During this check any needed correction factors (for conversion to metric units, calculation of salinity from chloride or conductivity) were applied. The data were then ready for final analysis. The hourly data sets were summarized as daily means. One concern was whether or not the daily 8 am data were adequate to characterize the system. This was tested by sub-sampling the hourly data at 8 am to create an 8 am data set. The daily means were then calculated from the hourly data and compared to the daily 8 am subset. The comparison (Table 6.2) indicated that the daily 8 am readings give the same results as the daily means. This also applies to the computation of the monthly means using either the hourly or the daily 8 am (Table 6.2). Byrne et al. (1976) reported similar results from a comparison of the daily mean to the three-hour mean water level in Barataria Bay.

Monthly means were computed from the daily data. The main goal of the water level and salinity analysis was to investigate the trends in the data and their possible relationship to habitat changes. In this regard, we were interested in the fluctuations occurring on time scales of months to years as opposed to hourly. Thus, we used the monthly mean values for the trend analysis.

The final analysis consisted of:

1) Time series plots of the data
   a) Daily means for the entire record for each station (Appendix L)
   b) Monthly means for the entire record for each station (Appendix M)
   c) Hourly means of selected stations and time periods to characterize the system at small time scales
2) Spatial patterns of salinity and water levels
3) Characterization of the mean seasonal patterns of water levels and salinities (Appendix N)
4) Long-term trends in salinity and water levels
   a) Trends in the mean
   b) Trends in the minimum
   c) Trends in the maximum

5) Trends in salinity and water levels by year; classes to correspond with the time periods covered by the aerial photos used to develop the vignettes presented in Part 8 of this document.

Table 6.2.Comparison of (I) daily mean water level and salinity (calculated from hourly values) versus daily 8 am salinity and water level readings, and (II) monthly mean water levels and salinities estimated from the daily mean (based upon hourly data) versus the monthly mean estimated from the daily 8 am readings. The results of a regression analysis are presented.

I. Daily 8 AM reading Versus Daily mean estimated from hourly data.

	Water Levels				Salinity			
Station	n	Intercept	Slope	r-square	n	Intercept	Slope	r-square
3731	11949	-21.59	1.12	0.71				
2084	1479	-32.35	1.32	0.74				
2928	1479	-33.08	1.32	0.65				
315	6167	5.52	0.98	0.97	5800	-0.16	1.00	0.95
317	1306	-3.03	1.01	0.92	5460	-0.21	1.01	0.95
323					1271	-0.21	1.01	0.97
325	1108	-15.20	1.00	0.96	3004	-0.01	0.99	0.98
326					1874	-0.08	1.05	0.97
416	253	0.16	0.89	0.93	2065	0.00	1.00	0.96
518	237	0.21	0.93	0.95	2180	-0.16	1.00	0.95

II. Monthly mean estimated from Daily 8 AM reading versus monthly mean estimated from Daily Mean (based on hourly data).

	Water Levels				Salinity			
Station	n	Intercept	Slope	r-square	n	Intercept	Slope	r-square
3731	406	-22.43	1.13	0.77				
2084	49	-44.55	1.45	0.84				
2928	50	-44.70	1.44	0.73				
315	53	5.80	0.98	0.98	215	0.02	0.99	0.99
317	54	-8.90	1.03	0.92	210	-0.06	0.99	0.98
323					46	-0.30	1.02	0.99
325	52	-20.20	1.00	0.99	120	0.07	0.98	0.99
326					65	-0.06	1.03	0.99
416	13	0.28	0.82	0.97	83	-0.02	1.01	0.99
518	12	0.24	0.92	0.96	85	-0.11	1.00	0.99

Trends were analyzed using a linear model with date (time) as the independent variable and monthly water level and salinity as the dependent variable. The model was run using the SAS GLM procedure and the SAS REG procedure (SAS 1990b). Two forms of the model were used: (1) a seasonal interaction term was incorporated to account for the seasonal pattern in the data, and (2) no seasonal interaction term was used.

SYSTEM WIDE CHARACTERISTICS

Freshwater Inflow

The BTES is a series of bar-built systems in which fresh water is generally dispersed throughout the system by numerous small channels or bayous. The details of the freshwater input into these systems is not well known, although it is known to be related to precipitation. Gagliano et al. (1973), in a preliminary study, modeled (using multiple regression techniques) the relationship between streamflow, precipitation surplus and deficits, and salinity. They concluded that there is a definite and predictable relationship between fluctuations in salinity and freshwater input. Levees along Bayou Lafourche and the Mississippi River form hydrological boundaries for the Barataria basin, and only precipitation from the uplands enters the headwater areas. Discharge from the Atchafalaya can enter the marshes in Terrebonne basin directly from the headwaters and move through the basin. This is not possible in Barataria basin. The mean annual precipitation in coastal Louisiana is about 160 cm (5.25 ft) (Baumann 1979). Wax et al. (1978) produced a water budget based upon climatic conditions to estimate periods of surplus and deficit for Barataria basin. They found a surplus in winter and spring when precipitation was high and evapotransporation was low, and deficits in summer and autumn. Sklar (1983) produced an average annual water budget from upper Barataria (Figure 6.6) based upon data from 1914 through 1978. Sklar's data show that most of the surplus occurs in winter, with deficits most likely to occur during the summer (June–July), although the autumn did not show a deficit, the surplus was quite low. Sklar (1983) also noted that deficits (dry-downs) should not be expected to occur regularly, since precipitation is greater than evaporation on the average. It is likely that a similar seasonal trend in the water budget also exists in the Terrebonne system. Sklar (1983) also found that of the total annual precipitation, ~61 cm (24 in) was available for surface runoff and groundwater discharge. Butler (1975) indicated freshwater inflow into Lake des Allemandes (from the des Allemandes drainage basin) of 42–54 m^3s^{-1} (1,484–1908 cfs) under average flows and ~80 m^3s^{-1} (2,827 cfs) under peak flow conditions. Wiseman and Swenson (1989) prorated this number to give a total runoff into the basin of ~150 m^3s-1 (5,300 cfs). Muller (1975) estimated the freshwater input to the Barataria basin system to be 12 x 10^6 m3 (400 x 10^6 ft^3) per tidal cycle (266 m^3s-1 or 9,400 cfs). Howard (1982) estimated the total precipitation over the Barataria basin to be 21 x 10^6 m3 (700 x 10^6 ft^3) per tidal cycle. Using Sklar's (1983) estimate of 40% of the precipitation being available for runoff, this gives a freshwater input of

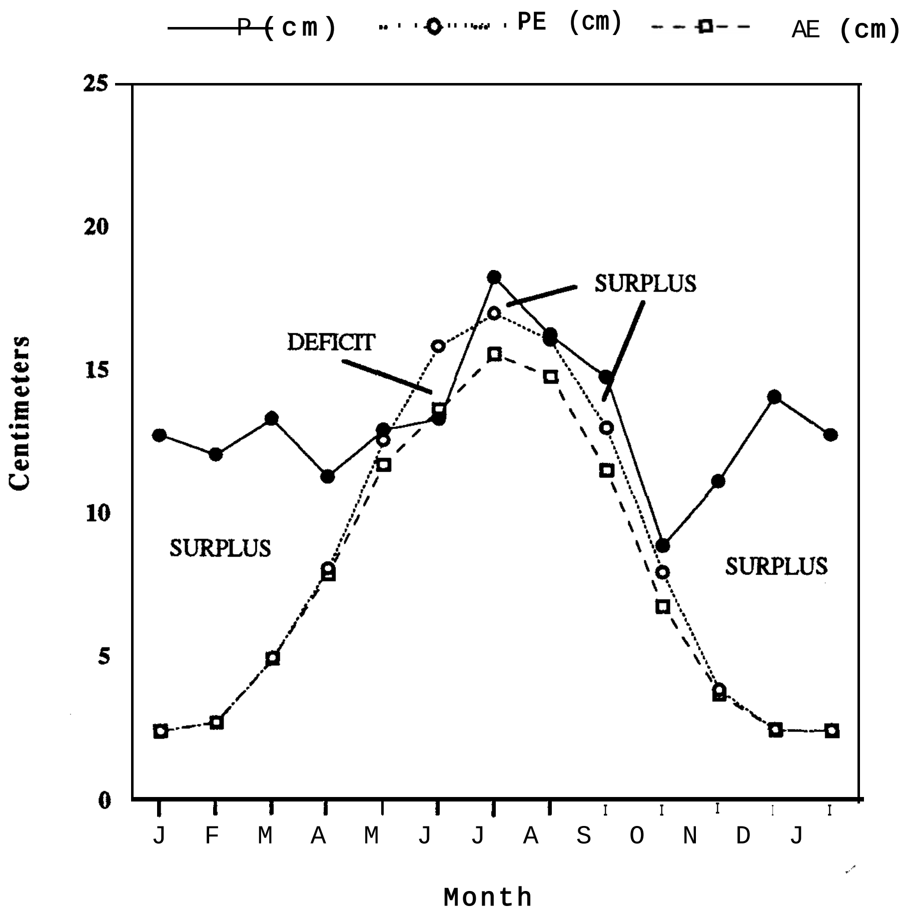


Figure 6.6 Water budget from upper Barataria (adapted from Sklar 1983).

~186 m^3s-1 (6,572 cfs). Based upon the above estimates, it appears that a reasonable value for the runoff into the Barataria system is ~200 m^3s-1 (7,067 cfs). Wang (1988) indicated that the "riverine" inputs into the Terrebonne-Timbalier Bay system are on the order of 20 to 50 m^3s^{-1} (700 to 1750 cfs) and are important indicators of gravitational circulation within the system.

Spatial Patterns of Water Levels and Salinities within the Basins

The long-term means, minima, and maxima are summarized in Table 6.3. These data are presented in graphical form in Appendix O. The longitudinal salinity distribution for the BTES is shown in Figure 6.7. The Barataria System shows a rapid decrease from the coast through Barataria Bay proper to ~30 km (18 mi) inland (Little Lake). Salinities then decrease gradually through the upper part of the basin to about 1.3 ppt at des Allemandes. The Terrebonne system shows a rapid decrease across Terrebonne Bay, with a sharp depression in salinity about 20 km (12.5 mi) inland (Cocodrie), reaching a minimum of about 1.5 ppt around 30 km (18 mi) inland. This depression in salinity around Cocodrie corresponds to the large input of fresh water (from Bayou Terrebonne, Bayou Petite Caillou) to the system at this point. The low salinity endpoint in the Terrebonne system occurs over a large longitudinal range (40 to 65 km (25 to 40 mi) inland), in contrast to Barataria which has a "fixed" low salinity endpoint about 80 km (50 mi) inland (des Allemandes).

The seasonal patterns of water levels and salinities are summarized in Table 6.4 and 6.5. Table 6.4 indicates the month during which the maxima occur and Table 6.5 indicates the month in which the minima occur. Plots of the long-term monthly means, which show the seasonal pattern for each station are in Appendix O.

Winter months were periods of absolute low water in both basins. Away from direct influence of river discharge, high water occurred in spring and late summer. At those stations close to river discharge, water levels were highest in the spring, and decreased throughout the rest of the year, with a slight attenuation during September. Annual water level fluctuations were also higher at these latter stations, reaching about 30 to 35 cm (12 to 14 in).

There were not enough stations spatially spread out in Terrebonne basin to show intrabasin variability in water levels. It is clear that the Atchafalaya River stage dominates water levels in the western portions of the basin, with only a single peak in spring. Moving easterly and southerly, a second peak in the fall could reasonably be expected.

The three stations away from direct river influence show a bimodal pattern of elevated water levels. In a landward direction, the spring peak is accentuated. The flat topography of the basin, together with its triangular shape and apex towards the headwaters causes water levels in the basin interior and towards the uplands to be especially sensitive to variations in precipitation and sea level. Gagliano et al. (1973) and Gosselink (1985) pointed out the significance of the marsh system for freshwater retention and slow release of fresh water over large wetland areas. Model

Table 6.3. Summary of monthly maximum water level and salinity patterns. The month of the major peak is indicated by a large X, the month of the secondary peak is indicated by a small x.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
USACOE Month of Maximum Salinity												
S03780									X	X		
S52800									X			
S52880						x					X	
S76303					x					X	X	
S76320				x						X	X	
S76323					x					X	X	
S76343					x				X	X		
S76403				X						X		
S82203				X						X	X	
S82300				X						X	X	
S82350							x				X	
S82700							x		X			
S82750						x					X	
S82875					x					X		
LDWF Month of Maximum Salinity												
S315										X	X	
S317										X	X	
S323							x				X	
S325			X				X				X	
S326					x						X	
S416				x						X	X	
S518			x	x							X	
USACOE Month of Maximum Stage												
S03780												
S03850						X						
S52800					X				x			
S52880					X				x			
S76320					X				X			
S82301						x			X	X		
S82350						x			X	X		
S82700					X				X			
S82750					X				X			
S82875					X				X			
S88350					X	X	X	X	X			
S88600	X											X
NOS Month of Maximum Water Level												
3731					x	x			X	X		

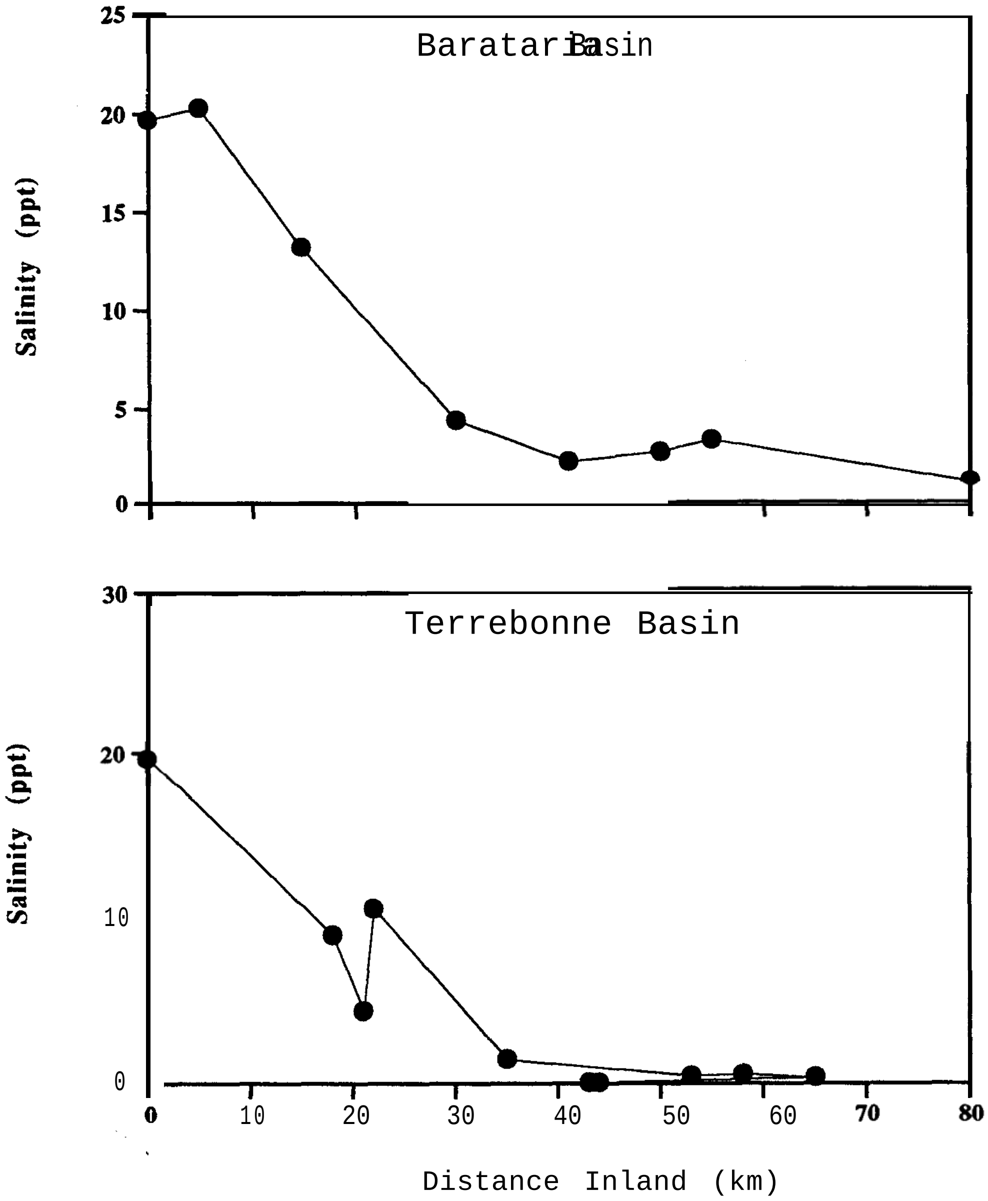


Figure 6.7. Mean salinity versus distance inland.

Table 6.4. Summary of monthly minimum water level and salinity patterns. The month of the major peak is indicated by a large X, the month of the secondary peak is indicated by a small x.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
USACOE Month of Minimum Salinity												
S03780				X								
S52800			X	X	X	X						
S52880			X	X								
S76303		X										
S76320						X	X					
S76323		X	X									
S76343		X					X					
S76403							X					
S82203		X	X				X					
S82300		X					X					
S82350			X									
S82700		X										
S82750			X									
S82875		X	X									
LDWF Month of Minimum Salinity												
S315						X						
S317						X						
S323				X								
S325		X		X					X			
S326		X					X					
S416	X											
S518							X					
USACOE Month of Minimum Stage												
S03780												
S03850												X
S52800								x			X	
S52880								X			X	
S76320	X	X					x					
S82301	X	X					x					
S82350	X	X					x					
S82700	X						x					
S82750	X						x					
S82875	X						x					
S88350	X							x				
S88600						X			x			
NOS Month of Minimum Water Level												
3731	X						x					

Table 6.5.Summary statistics of the water level and salinity records.

Station Name	n	Mean (ppt)	Std. Dev.	Max. (ppt)	Min. (ppt)	Range (ppt)
			USACOE Daily Salinity			
S03780	6134	0.1	0.05	1.6	0.0	1.6
S52800	1569	0.1	0.12	2.6	0.0	2.6
S52880	410	0.2	0.07	0.8	0.1	0.7
S76303	4469	4.4	3.69	21.1	0.0	21.1
S76320	12688	0.4	1.06	18.4	0.0	18.4
S76323	12045	1.5	3.14	39.9	0.0	39.9
S76343	7585	0.5	1.72	25.3	0.0	25.3
S76403	5854	0.6	1.59	17.5	0.0	17.5
S82203	5695	0.6	1.48	19.8	0.0	19.8
S82300	7784	2.0	3.53	25.4	0.0	25.4
S82350	7659	15.7	5.45	31.0	0.3	30.8
S82700	61	1.3	2.46	17.2	0.0	17.2
S82750	339	3.4	4.16	33.6	0.2	33.4
S82875	5974	2.8	3.00	24.6	0.0	24.6
			LDWF Hourly Salinity			
S315	139179	19.7	5.55	33.7	1.9	31.8
S317	131023	13.2	6.45	32.6	0.0	32.6
S323	30533	20.3	5.53	34.6	3.8	30.8
S325	71839	4.4	3.27	34.9	-0.1	35.0
S326	44868	2.3	2.73	26.1	0.1	26.0
S416	49618	8.9	5.23	27.9	0.0	27.9
S518	52367	10.5	5.01	28.7	0.2	28.5

Station Name	n	Mean (cm)	Std. Dev.	Max. (cm)	Min. (cm)	Range (cm)
			USACOE Daily Stage			
S03780	21699	64.0	48.46	317.0	-88.4	405.4
S03850	7104	43.2	21.27	222.5	-36.9	259.4
S52800	13154	55.1	21.26	144.2	-30.8	175.0
S52880	8161	65.3	23.76	146.9	-35.1	182.0
S76320	11226	56.7	18.64	156.3	-22.9	179.2
S82301	5931	42.9	14.98	160.0	-17.7	177.7
S82350	13387	36.3	19.80	174.0	-43.3	217.3
S82700	12310	42.0	15.18	117.6	-9.1	126.7
S82750	11688	40.9	14.74	127.1	-10.1	137.2
S82875	11465	40.0	15.39	146.0	-28.9	174.9
S88350	5135	52.2	22.42	142.9	-23.8	166.7

S88600	16214	10.2	29.70	228.9	-92.0	320.9
			NOS Hourly Water Levels			
2928	35496	99.4	18.76	168.6	3.1	165.6
3731	286569	171.7	21.10	312.7	91.4	221.3
2084	35496	96.7	16.14	152.7	19.5	133.2

results from Light et al. (1973) showed the upper basins to be important to generating and conserving freshwater flow. It is in these upper basins that management can most effectively influence estuarine conditions. A limited amount of fresh water can build up enough of a head gradient to prevent the inland flow of water from the Gulf. Conversely, when droughts occur during times of seasonally elevated sea level, and the normal head of fresh water is absent, inland flow of saline Gulf waters can be rapid.

With the exception of the Leeville station, peak salinities occurred in the fall. In most stations, there was a second, usually slightly smaller peak in spring or early summer. In general, salinities were at their absolute lowest during the late winter months. The station at Grand Terre, however, had lowest salinities in spring, coinciding with peak Mississippi River discharge. Sister Lake had lowest salinities during early summer. Differences in monthly means were greatest at the latter two stations, varying by as much as 8 to 10 parts per thousand over the year.

Examples of three-hourly water level and salinity patterns for the salt and brackish areas of the Barataria Bay system are presented in Figures 6.8 through 6.13. These figures present examples of three-hour means (from March 1992 through 1993) of water levels, salinities, and temperatures. In addition to the time series plots, spectral density plots are also presented. Time series data from the coast (Grand Terre) and the spectral density plots for the coast are presented in Figures 6.8 and 6.9. Time series data from the approximate middle of the Barataria Bay system (St. Mary's Pt.) and the spectral density plots for the middle of the system are presented in Figures 6.10 and 6.11. Time series data from the northern part of the Barataria Bay system (Little Lake) and the spectral density plots for the northern part of the system are presented in Figures 6.12 and 6.13. Time series plots for the intermediate and fresher areas of the Barataria system are presented in Figure 6.14.

Examples of the water level and salinity patterns for the salt and brackish areas of the Terrebonne Bay System are presented in Figures 6.15 through 6.19. These figures also present examples of three-hour means (from April 1984 through April 1985) of water levels, salinities, and temperatures as well as spectral density plots based upon the data. Time series data from the coast (Cocodrie) and the spectral density plots for the coast are presented in Figures 6.15 and 6.16. Time series data from the approximate middle of the Terrebonne Bay system (Sister Lake) and the spectral density plots for the middle of the system are presented in Figures 6.17 and 6.18. Time series plots for the intermediate and fresher areas of the Terrebonne system are presented in Figure 6.19.

The time series data patterns of water level and salinity in both Barataria and Terrebonne are characterized by a diurnal tidal signal superimposed upon other, longer period signals. This type of signal is typical for Louisiana salt and brackish marshes (Byrne et al. 1976, Adams and Baumann 1980, Chuang and Swenson 1981, Swenson and Turner 1987). The longer period events (three days and greater) are the dominant time scales in the intermediate and fresh marshes. At the intermediate marsh sites when there was a noticeable diurnal tidal signal (~25% of the sites), it was responsible for less than 50% of the water level fluctuations. This decrease in astronomical tides as one

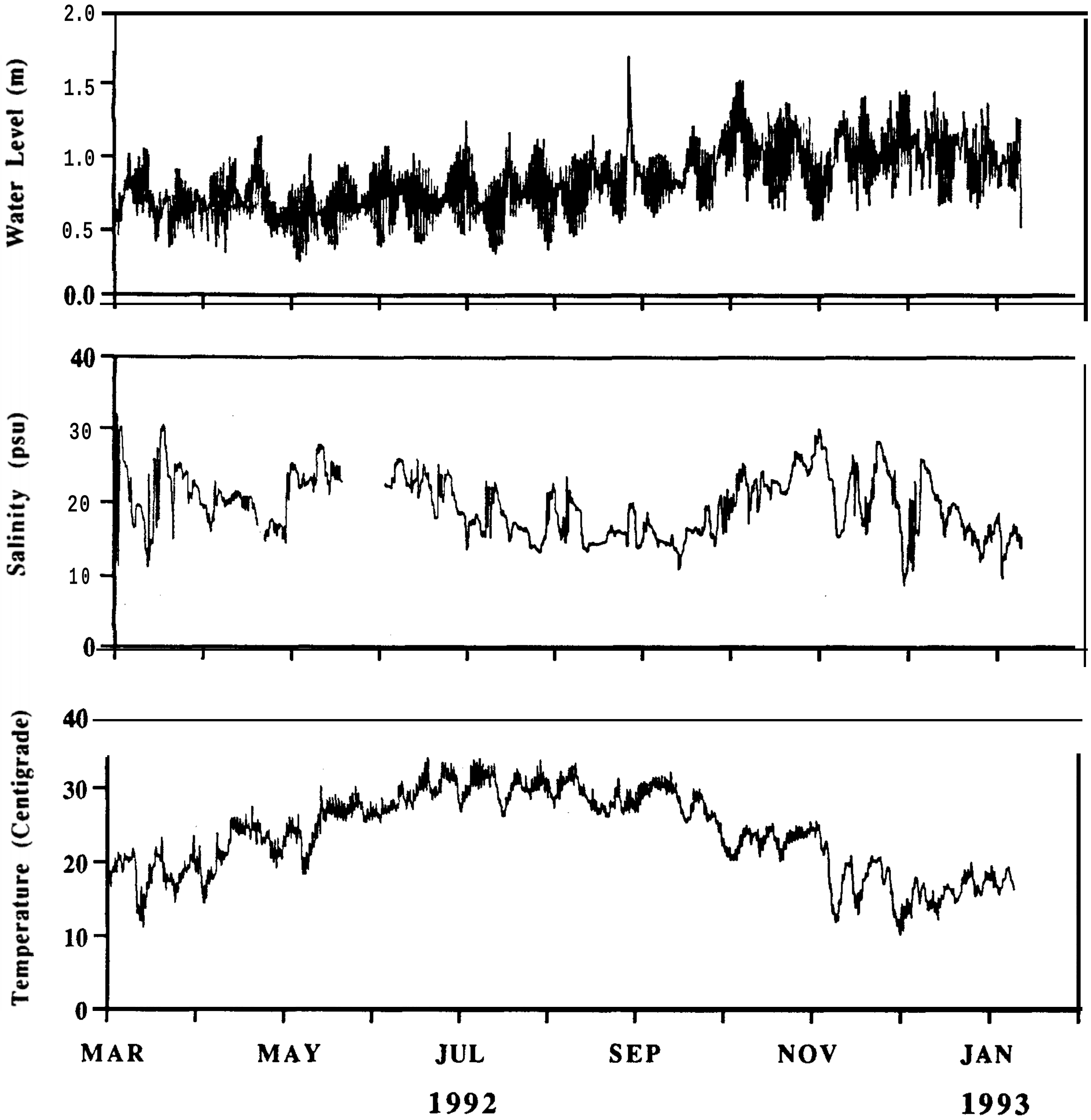


Figure 6.8 Time series of three hour mean water levels, salinity, and temperature for Grand Terre from March 1992 through January 1993.

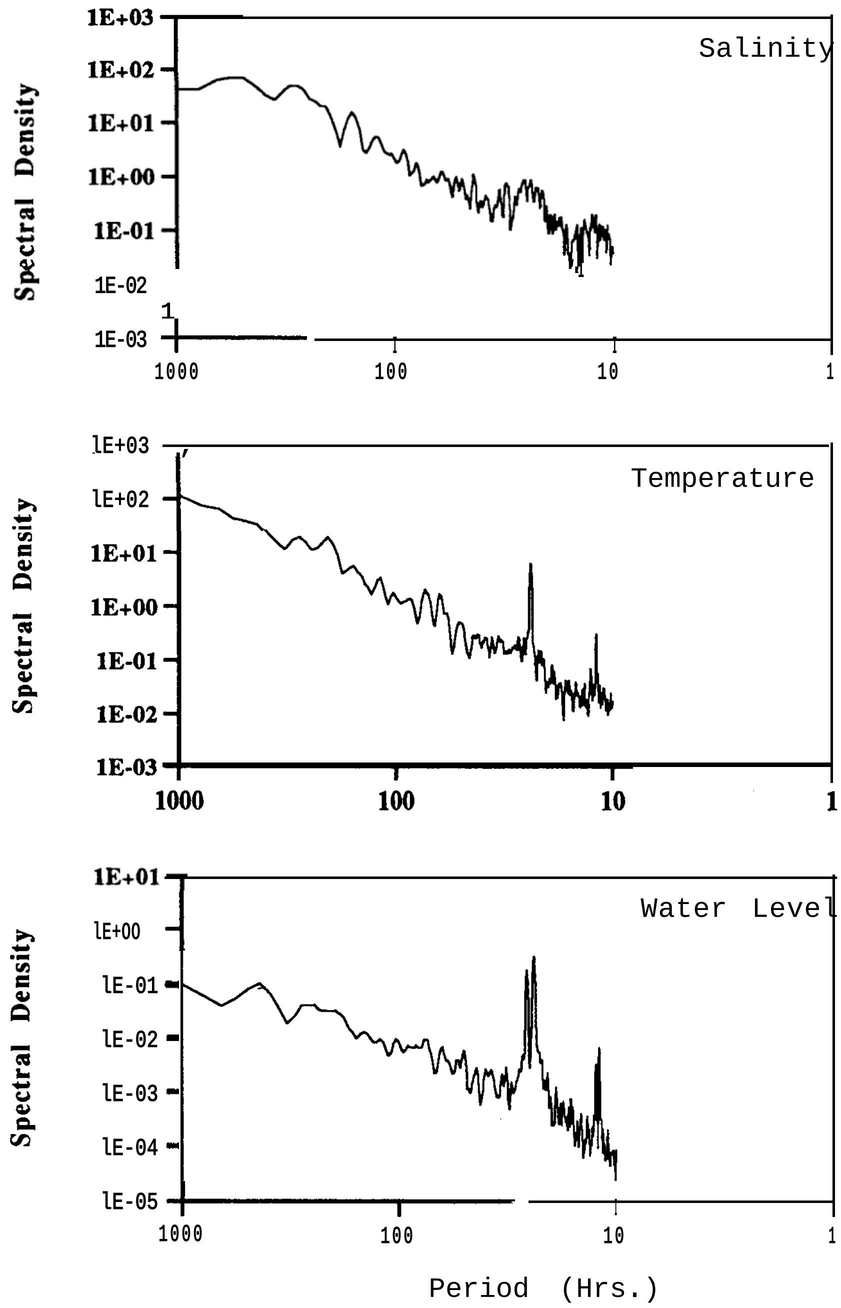


Figure 6.9 Spectral density plots of three hour mean water levels, salinity, and temperature for Grand Terre from March 1992 through January 1993.

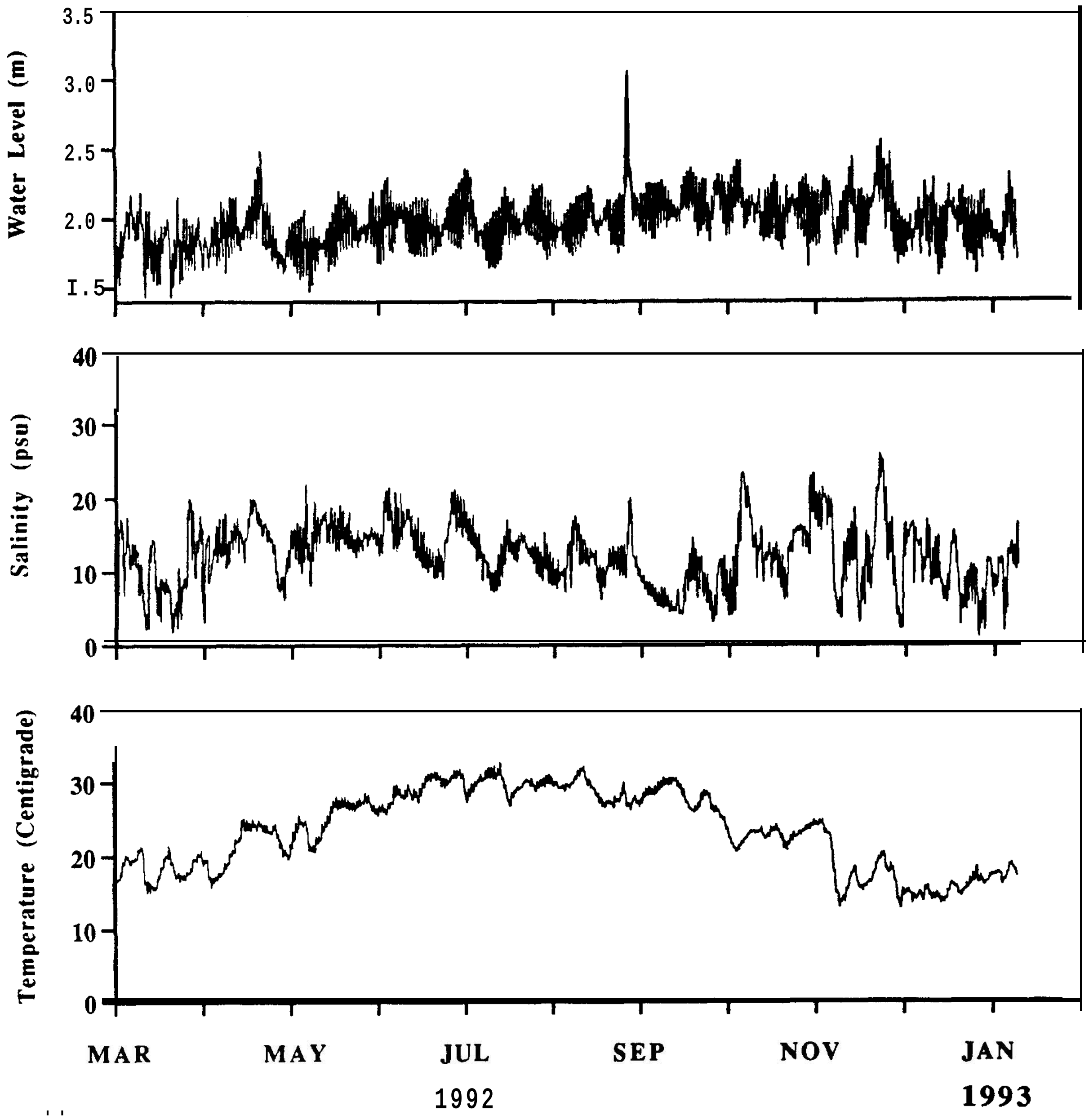


Figure 6.10. Time series of three hour mean water levels, salinity, and temperature for St. Mary's Pt. from March 1992 through January 1993.

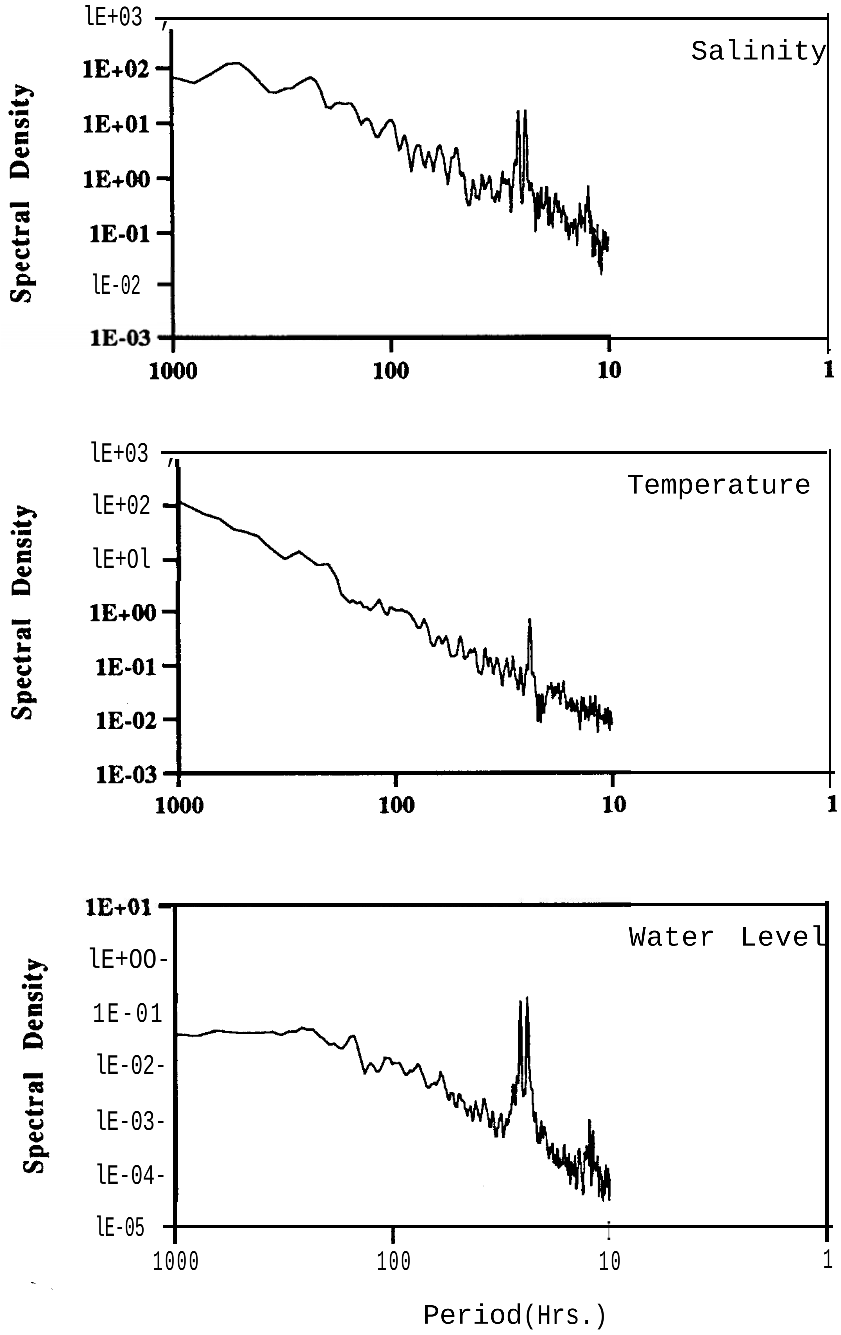


Figure 6.11 Spectral density plots of three hour mean water levels, salinity, and temperature for St. Mary's Pt. from March 1992 through January 1993.

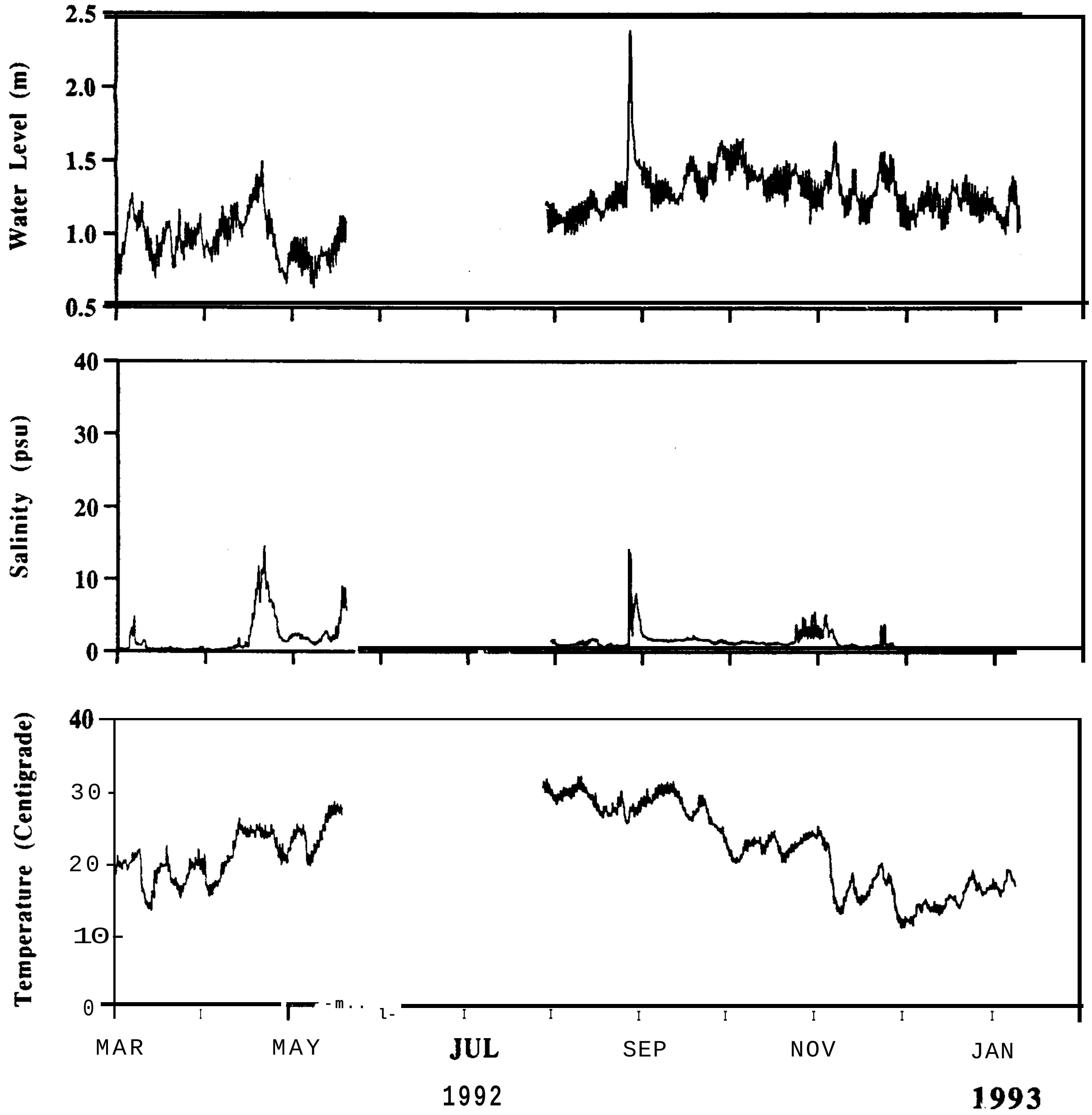


Figure 6.12 Time series of three hour mean water levels, salinity, and temperature for Little Lake from March 1992 through January 1993.

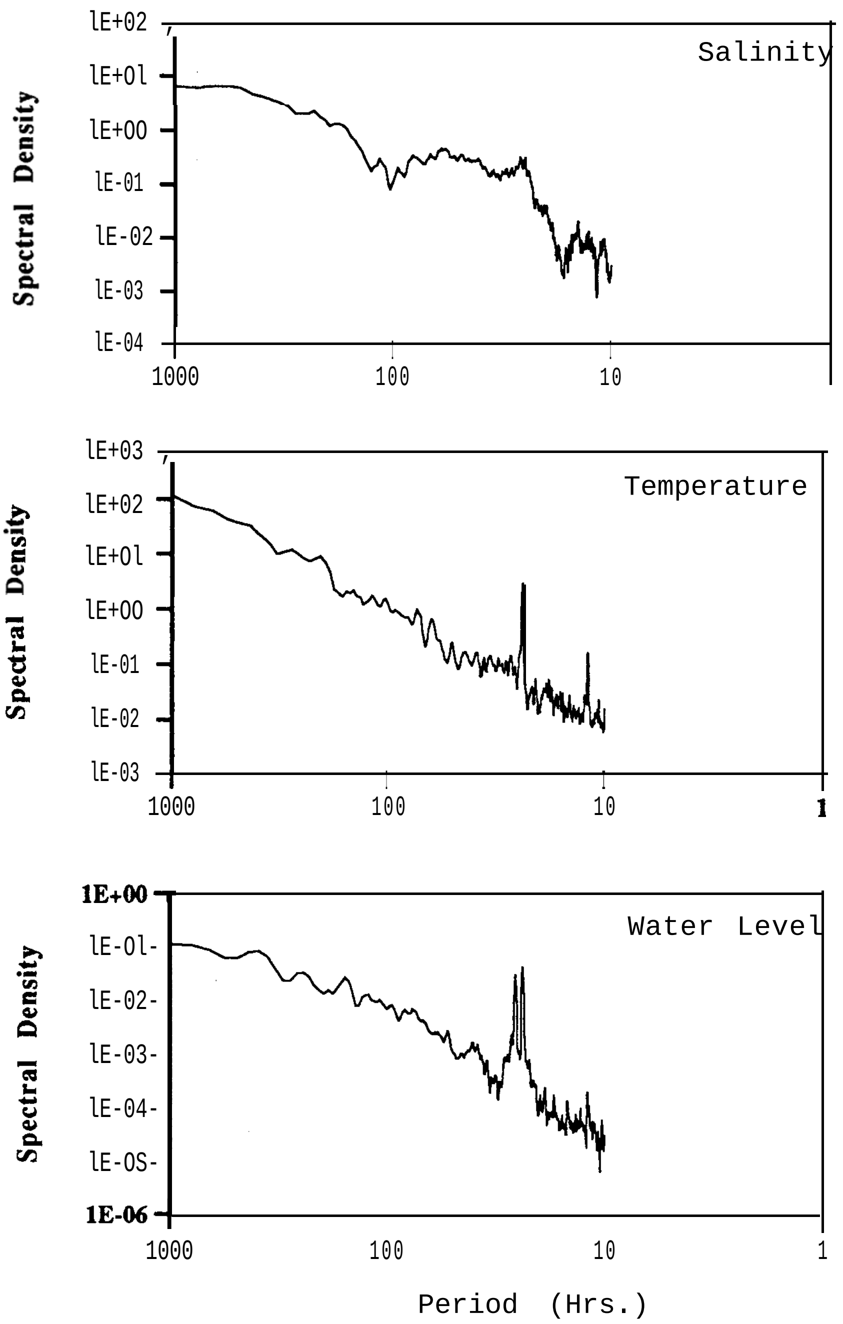


Figure 6.13 Spectral density plots of three hour mean water levels, salinity, and temperature for Little Lake from March 1992 through January 1993.

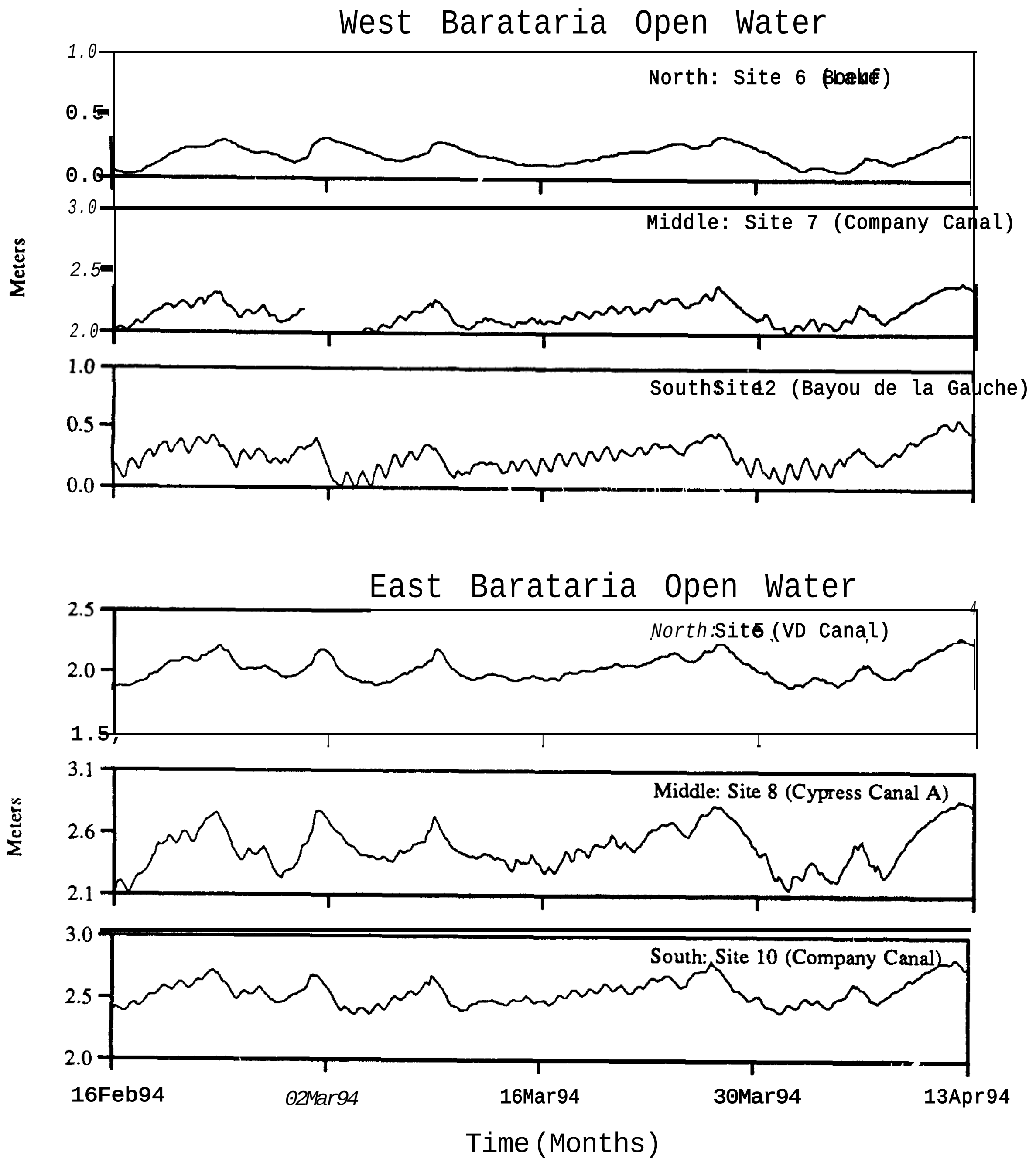


Figure 6.14. Time series plots for water levels in the fresh and intermediate marahses in Barataria basin, based on subset of data collected from March 1993 through May 1994.

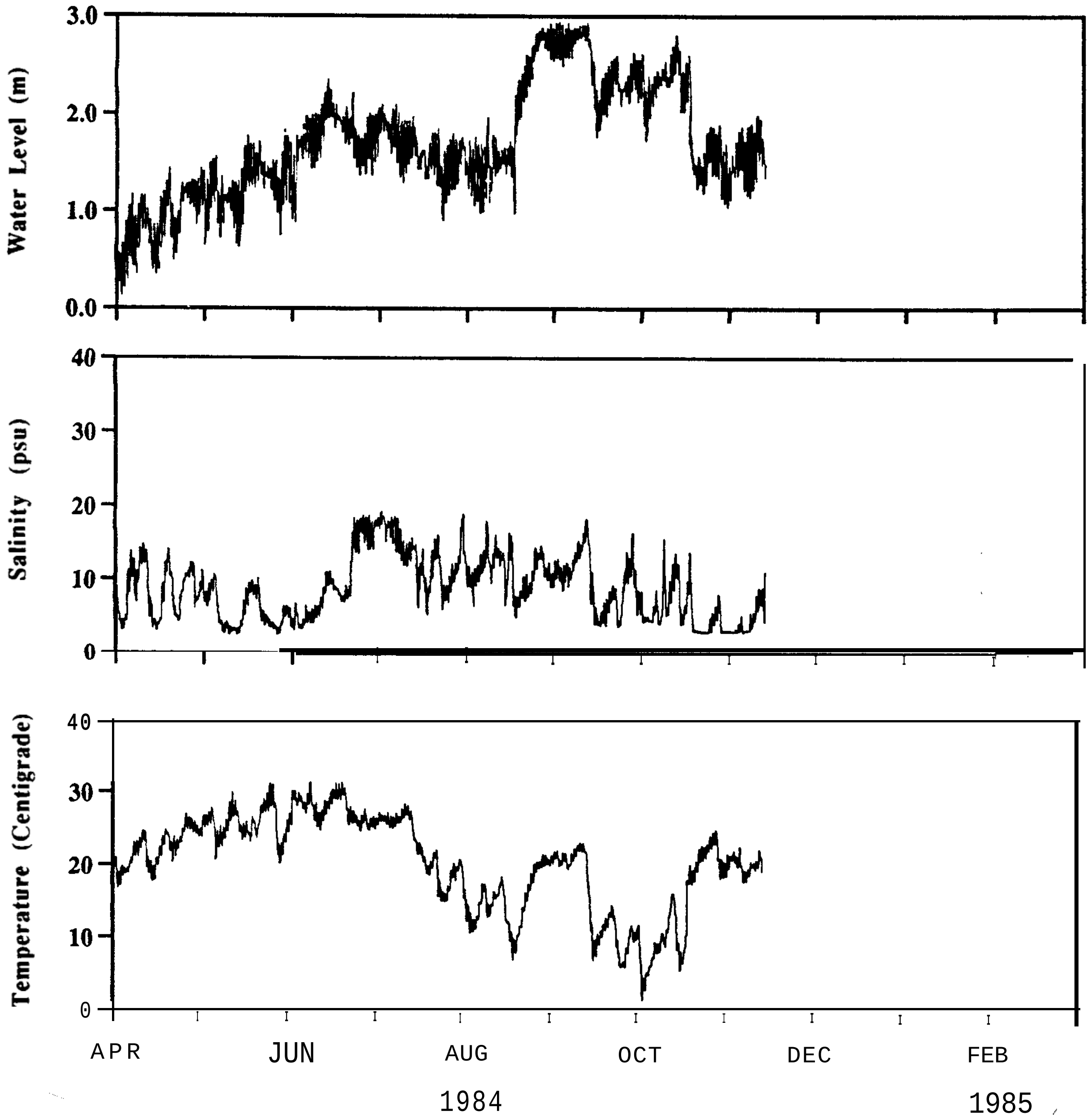


Figure 6.15. Time series of three hour mean water levels, salinity, and temperature for Cocodrie from March 1992 through January 1993.

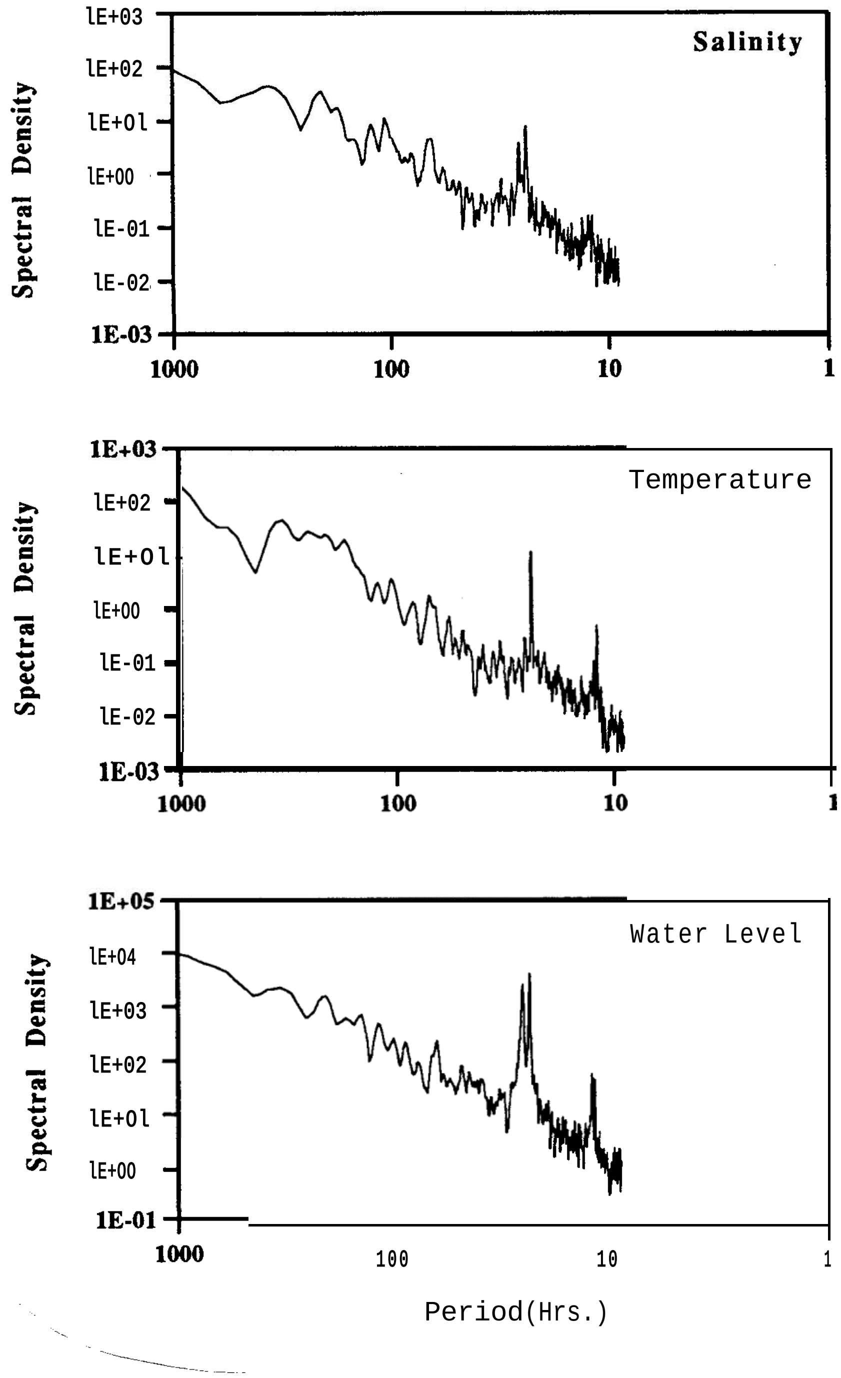


Figure 6.16. Spectral density plots of three hour mean water levels, salinity and temperature for Cocodrie from March 1992 through January 1993

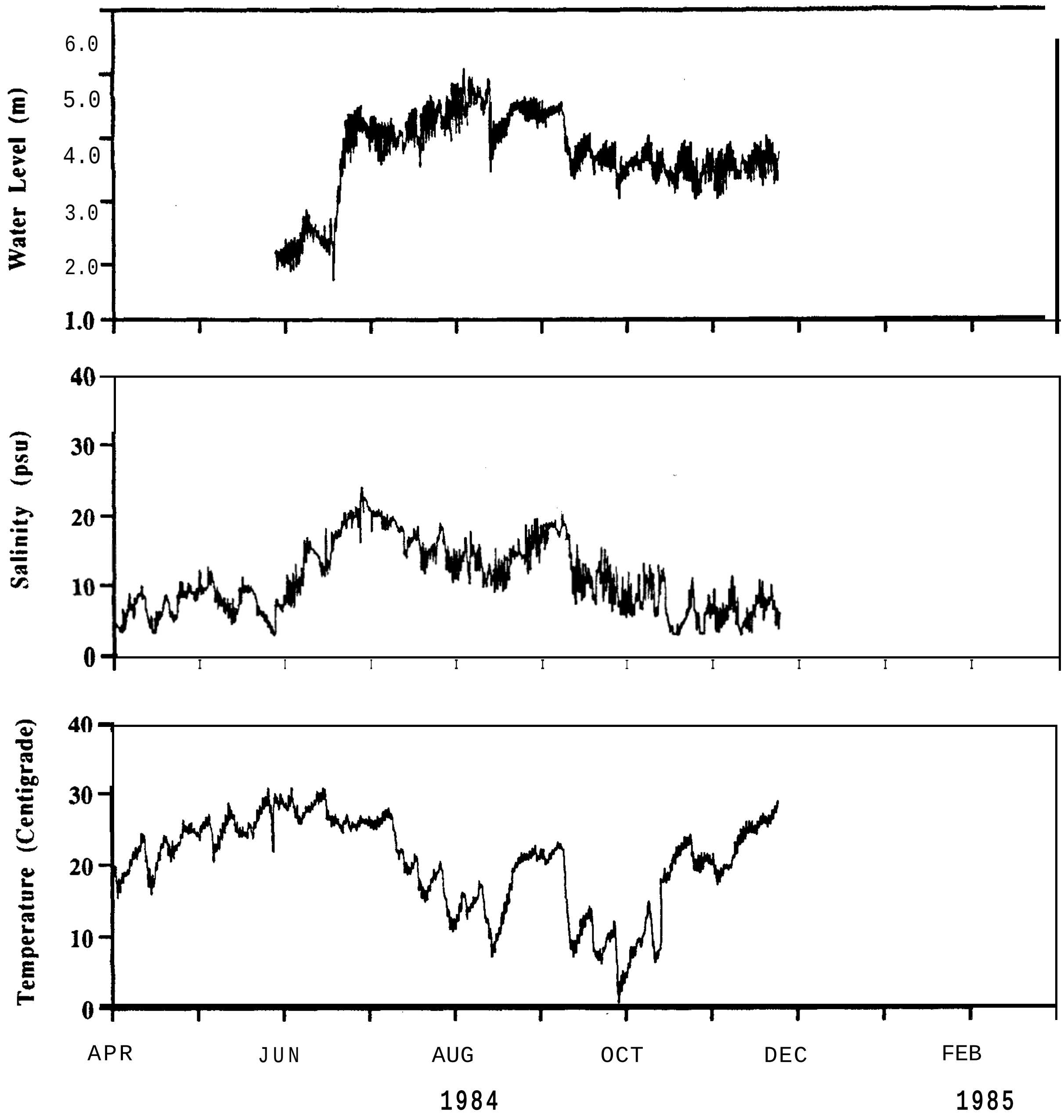


Figure **6.17**. Time series of three hour mean water levels, salinity, and temperature for Sister Lake from March 1992 through January 1993.

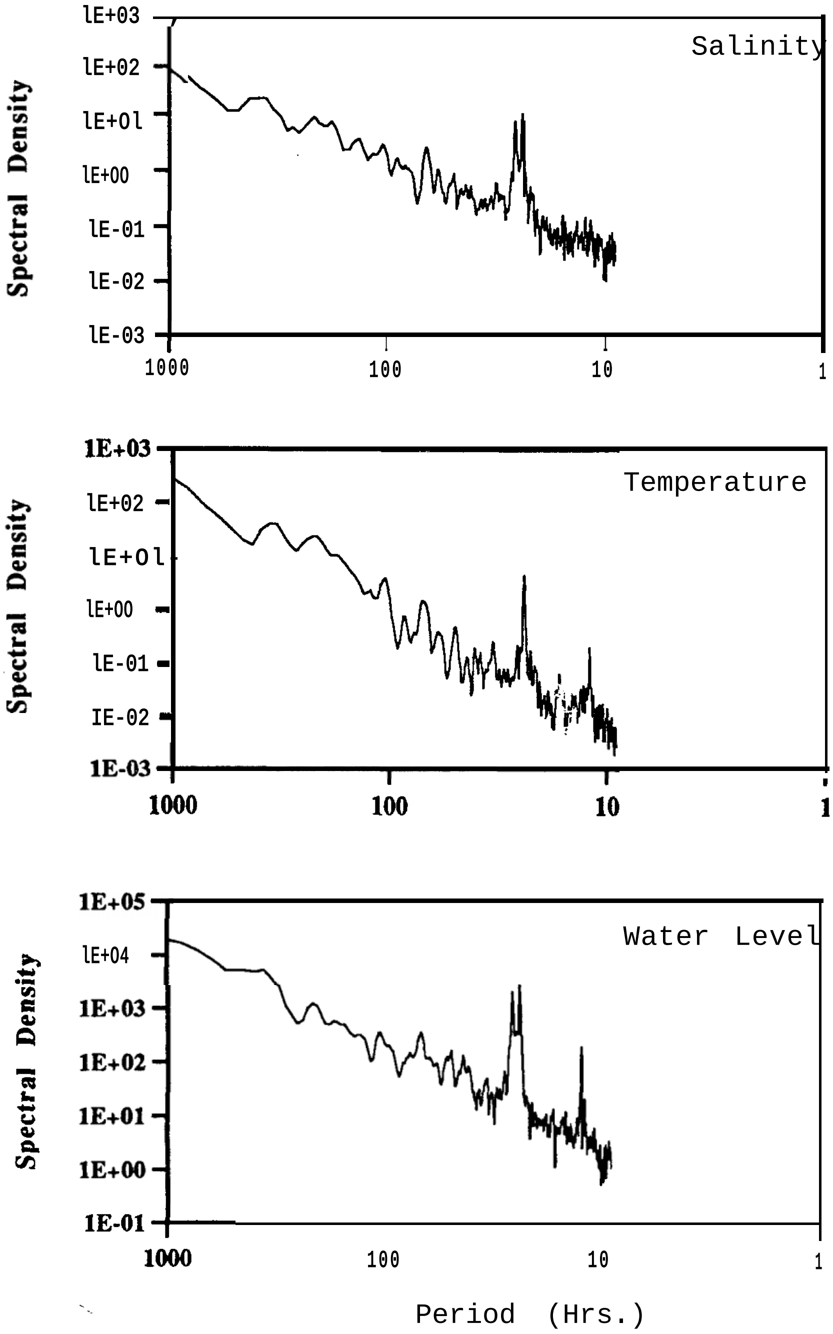


Figure 6.18. Spectral density plots of three hour mean water levels, salinity and temperature for Sister Lake from March 1992 through January 1993

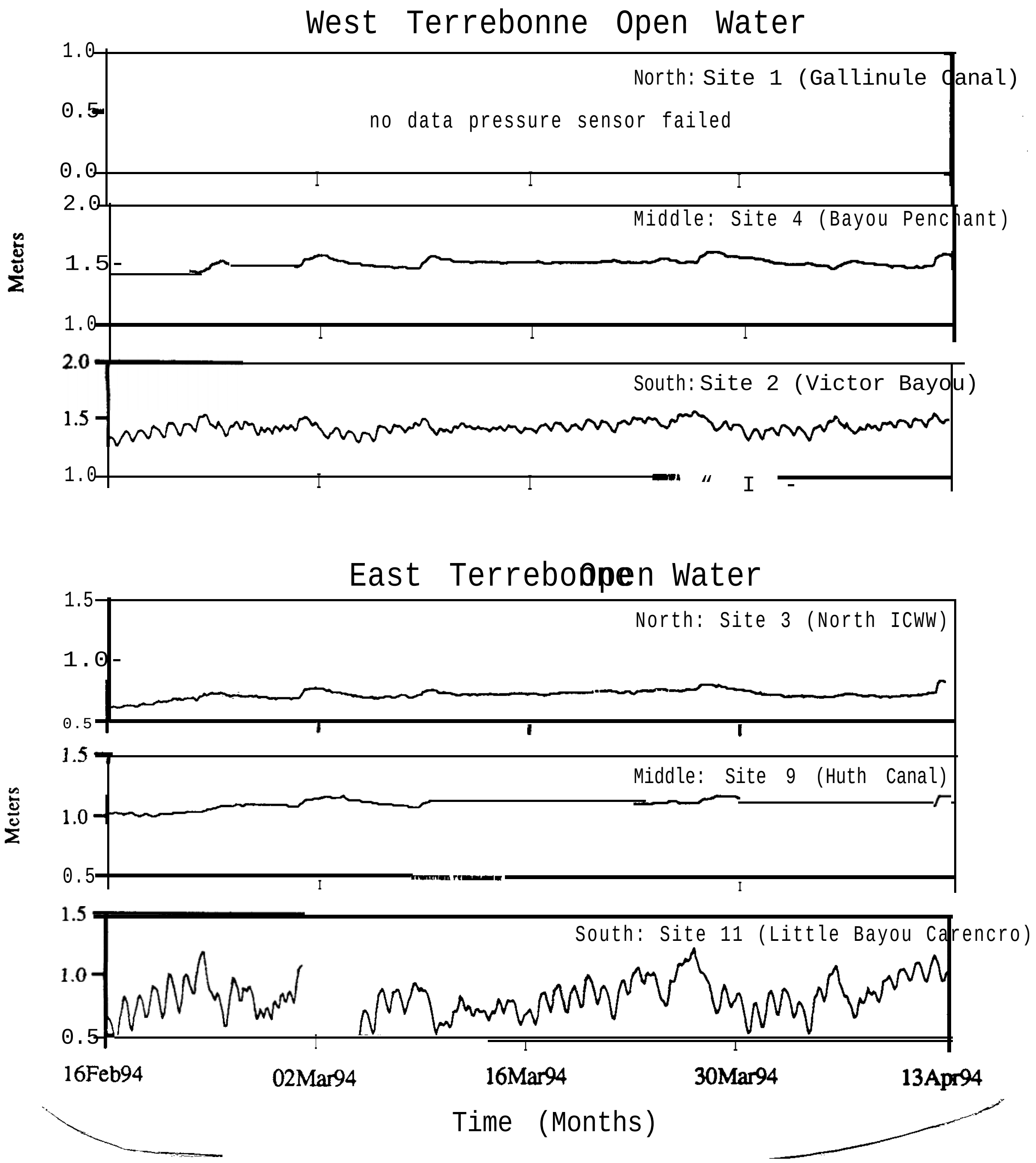


Figure 6.19. Time series plots for water levels in the fresh and intermediate marshes in Terrebonne basin, based upon data collected from March 1993 through May 1994.

moves inland was summarized for Barataria Bay by Byrne et al. (1976). They noted that the tide moves north as a progressive wave after entering Barataria Pass and is almost fully attenuated by the time it reaches des Allemandes. A similar attenuation can be observed in the Terrebonne system. The change in astronomical tidal amplitude as a function of distance inland for the BTES is shown in Figure 6.20. The tidal amplitude drops fairly rapidly in both systems, decreasing to 25% of the coastal value by a distance inland of 40 to 50 km (25 to 31 mi).

The time series data from this time period also show the effect of Hurricane Andrew (in August 1992) on the open water in the Barataria system. The Barataria system, which is quite open, shows a fairly uniform surge (of about 1.0 m or 3.2 ft) throughout the entire system. The data set from the Terrebonne area covering the time period for Hurricane Andrew was not available in time to include in this document. The specific impacts of storms and hurricanes are discussed in a separate section of this document.

The water level spectral density plots for all stations show the influence of both the K1 and the 01 diurnal tidal constituents, which have periods of 23.9 hours and 25.8 hours (Godin 1972), respectively. The influence of the M2 semi-diurnal tidal constituent, with a period of 12.4 hours (Godin 1972) can also be seen, particularly at the coastal or more open water stations (Grand Terre, Cocodrie, and Sister Lake). This semi-diurnal constituent has less of an impact on the stations in the upper portions of Barataria Bay (St. Mary's Point, Little Lake). The salinity spectra show a strong diurnal tidal influence (with both K1 and the 01 constituents) at all stations except Little Lake and Grand Terre, but very little, if any semi-diurnal tidal influence. The less pronounced diurnal tidal peaks at Grand Terre and Little Lake indicate that those particular stations due not reflect a strong advection of water by the station with the tides. At Grand Terre this may be due to the fact that the station is located behind the island in a dead end canal. The Little Lake station has restricted exchange with the lower bay (through Bayou St. Denis and Grand Bayou), again leading to less advection of higher salinity water past the gage by tidal currents. The temperature spectral density peak occurs at the 24-hour period, indicating that the temperature is responding to a day-night difference as opposed to water of different temperatures being advected by the measuring station by tidal currents.

The correlations between the daily mean water levels at various stations in the fresh and intermediate marshes are presented in Table 6.6. The station distribution is shown in Figure 6.4 (stations 1 through 12). In general, one can see a high level of correlation between stations within a basin, indicating that the water moves as a unit at time scales greater than a day. Spectral analyses conducted on the three-hourly data from these sites were used to determine the dominant time scale at which the fluctuations were occurring for the fresh and intermediate marshes. The results (Sasser et al. 1994) indicated that the majority of the water level fluctuations occurred at time scales on the order of three days (or longer) for most of the sites. The only sites that showed a strong spectral density peak at the diurnal tidal period were stations 2, 11, and 12 (Figure 6.4). However, the height of the tidal energy peak compared to the longer-period fluctuations indicated that the tidal signal was less than 50% of the total fluctuations.

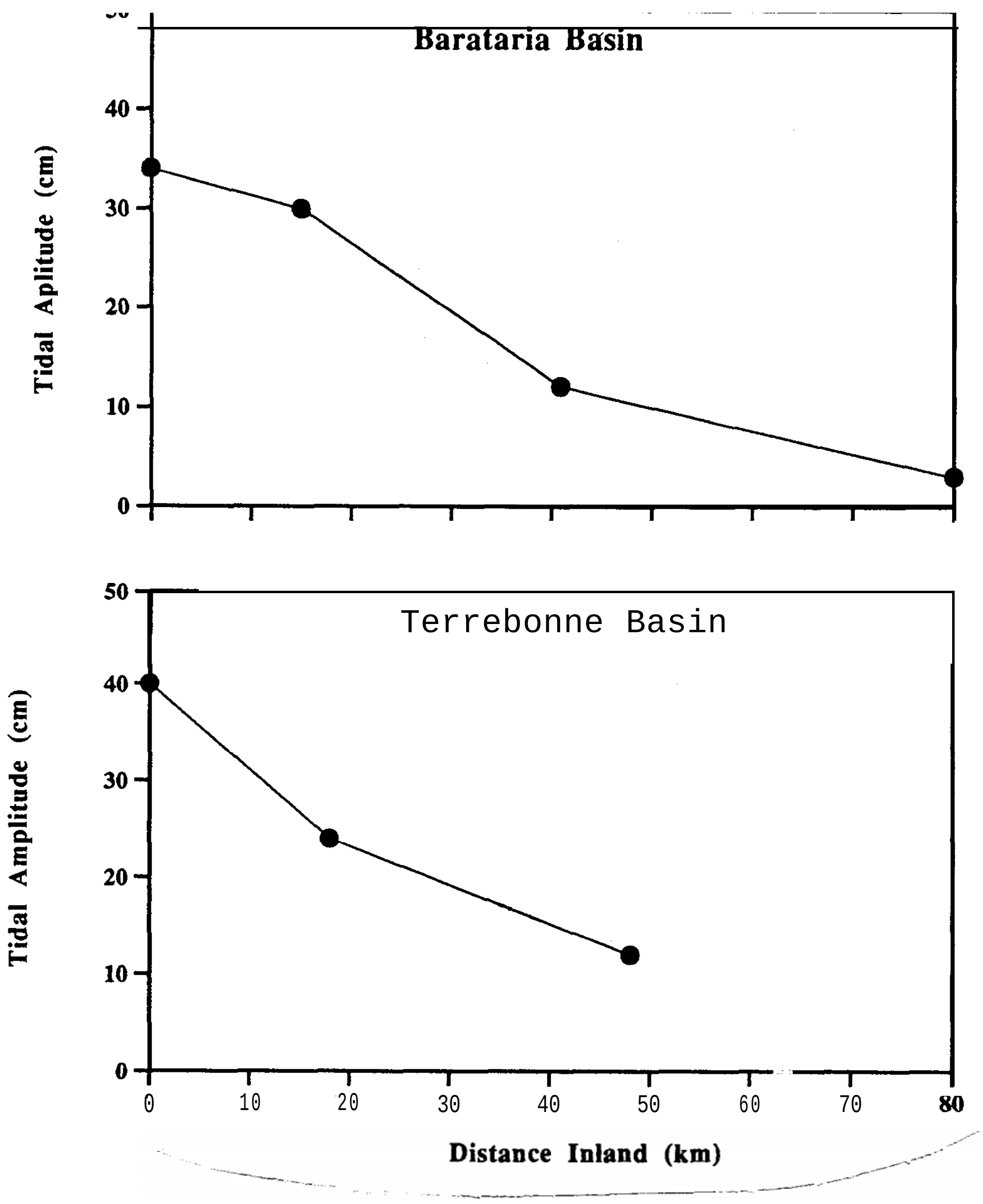


Figure 6.20. Tidal amplitude versus distance inland.

Table 6.6. Correlation matrix for daily mean water levels (based upon hourly data from March 1993 through May 1994) for water level gages located in the fresh and intermediate marshes of Terrebonne and Barataria basins (Figure 6.4). Indicated are the Pearson correlation coefficients. The symbol .nd indicates that no data were available for the indicated comparison.[1]

Terrebonne Basin

	Station 1 Gallinule Canal	Station 4 Bayou Penchant	Station 2 Victor Bayou	Station 3 North GIWW	Station 9 Huth Canal	Station 11 Little Bayou Carencro
Gallinule Canal		0.98	0.95	0.98	0.88	.nd
Bayou Penchant			0.87	0.95	0.99	0.45
Victor Bayou				0.88	0.76	0.71
North GIWW					0.78	0.68
Huth Canal						0.52
Little Bayou Carencro						

Barataria Basin

	Station 6 Lake Boeuf	Station 7 Company Canal	Station 10 Delta Farms	Station 5 VD Canal	Station 8 Cypress Canal	Station 12 Bayou de la Gauche
Lake Boeuf		0.47	0.75	0.72	0.87	0.72
Company Canal			0.99	0.96	0.97	0.60
Delta Farms				0.96	0.97	0.97
VD Canal					0.95	0.72
Cypress Canal						0.91
Bayou de la Gauche						

[1]Based upon data collected by the Coastal Ecology Institute of Louisiana State University study (funded by the EPA) of the floating marshes in these basins (Sasser et al. 1994).

Thus, the daily means are sufficient to describe the hydrologic characteristics of the intermediate and fresh marshes.

A correlation matrix for hourly and daily mean water levels for stations in the Barataria system, based upon hourly data from the USACOE Davis Pond study (Figure 6.3), is presented in Table 6.7. The daily mean water levels show fairly high correlations throughout the system. The hourly water level correlations show that the stations in the northern part of the system show fairly high correlations among themselves at the hourly level, and the stations south of Little Lake (open bay) show fairly high correlations among themselves. However the northern and southern stations do not correlate with each other. This is due to using a linear correlation which does not account for the lags present in the tidal forcing at the hourly level. Byrne et al. (1976) developed co-tide lines for the Barataria Bay system. Their analysis indicated a lag (relative to Bayou Rigaud at Grand Isle) of ~3 hours at St. Mary's Point, ~ 5 hours at the Little Lake-Bayou Perot Junction, ~7 hours at the Bayou Perot-GIWW junction, ~10 hours to the middle of Lake Salvador and ~15 hours at des Allemands.

A correlation matrix for hourly and daily mean salinities for stations in the Barataria system, based upon hourly data from the USACOE Davis Pond study (Figure 6.3), is presented in Table 6.8. The salinity shows a general pattern in which there is a fairly high degree of correlation (R ~ 0.7) for most of the stations in the lower estuary (south of the GIWW) at both the hourly and the daily time scales.

The COE Davis Pond study measured water speed and direction at several points throughout the Barataria system. Representative times series plots are presented in Appendix P, and the overall results are summarized in Table 6.9. In general, the current data indicated relatively low average speeds of ~5 cm s^{-1} (~0.1 knot), with maxima on the order of 50 cm s^{-1} (~1 knot), Quatre Bayoux Pass, however, had peak speeds of ~96 cm s^{-1} (almost 2 knots). Marmer (1948) reported peak currents in the passes of ~2 knots, with the weakest being less than 1 knot, with currents on the bay proper, with the maximum usually being less than 0.5 knot. The results in Table 6.9, show the decrease in tidal effect as you move inland. The tidal passes and lower estuary show an approximate 50–50 distribution of the percentage of time that the water is either flooding or ebbing. The upper stations show a greater percentage of time during which the water is flowing south, indicating the effect of freshwater input from the upper basin. Bayou des Allemands flows south ~64% of the time, on the average. During the spring, however Bayou des Allemands flowed toward the south ~81% of the time.

Tidal Prism Estimates

Wiseman and Swenson (1989) used the salinity data from the stations shown in Figure 6.4 to construct a simple tidal prism mixing model for both Barataria Bay and Terrebonne-Timbalier Bay. The model uses the measured tidal amplitudes (Table 6.10) to determine the local tidal excursion of a water particle assuming linear shallow-water wave theory. These data are then used to segment the estuary. The segment mixing parameters were adjusted so as to obtain a reasonable model fit to the longitudinal

Table 6.7. Correlation matrix for water levels in Barataria basin. Indicated are the Pearson correlation coefficients for the hourly data and the daily means (from water level meters deployed from February 1988 through September 1988).[1]

Hourly Data

	T01 Bayou des Allemands	T03 Lafitte	T11 Bayou St. Denis	T18 St. Mary's Point	T12 Caminada Pass	T20 Bay Batiste
Bayou des Allemands		0.90	0.58	0.43	0.48	0.38
Lafitte			0.76	0.58	0.45	0.54
Bayou St. Denis				0.95	0.82	0.91
St. Mary's Point					0.91	0.97
Caminada Pass						0.84
Bay Batiste						

Daily Data

	T01 Bayou des Allemands	T03 Lafitte	T11 Bayou St. Denis	T18 St. Mary's Point	T12 Caminada Pass	T20 Bay Batiste
Bayou des Allemands		0.94	0.81	0.73	0.83	0.72
Lafitte			0.93	0.87	0.80	0.87
Bayou St. Denis				0.98	0.89	0.94
St. Mary's Point					0.89	0.96
Caminada Pass						0.78
Bay Batiste						

[1]Based upon data collected by the U.S. Army Corps of Engineers in connection with a study for the Davis Pond Freshwater Diversion Project.

Table 6.8. Correlation matrix for salinities in Barataria basin. Indicated are the Pearson correlation coefficients for the hourly data and the daily means (from flow meters deployed from February 1988 through September 1988).[1]

Hourly Data

	V01 Bayou des Allemands	V04 Bayou Villars	V07 B. Perot GIWW	V08 B. Perot L. Lake	V11 Bayou St. Denis	V21 Grand Bayou
Bayou des Allemands		0.42	0.55	0.54	0.35	0.50
B. Villars			0.84	0.79	0.67	0.62
B. Perot GIWW				0.89	0.74	0.80
B. Perot L. Lake					0.82	0.91
Bayou St. Denis						0.87
Grand Bayou						

Daily Data

	V01 Bayou des Allemands	V04 Bayou Villars	V07 B. Perot GIWW	V08 B. Perot L. Lake	V11 Bayou St. Denis	V21 Grand Bayou
Bayou des Allemands		0.45	0.57	0.57	0.39	0.53
B. Villars			0.86	0.81	0.72	0.66
B. Perot GIWW				0.91	0.77	0.82
B. Perot L. Lake					0.84	0.92
Bayou St. Denis						0.88
Grand Bayou						

[1]Based upon data collected by the U.S. Army Corps of Engineers in connection with a study for the Davis Pond Freshwater Diversion Project.

Table 6.9. Summary, by tidal stage, of water current direction, mean and maximum water current speed (in cm / sec), and mean and maximum salinity (in ppt) for stations from the USACOE Davis Pond diversion study.

Current Meter Station	Range of Direction	Tide Stage	Percent of Time	Speed (cm / sec) Mean	Speed (cm / sec) Max	Salinity (ppt) Mean	Salinity (ppt) Max
Station 01	>=60 and <=240	Ebb	64	4.6	42.2	0.0	0.5
des Allemands	All other directions	Flood	36	3.9	41.2	0.0	0.4
Station 04	>=10 and <=190	Ebb	60	3.9	42.2	0.7	5.7
B. Villars	All other directions	Flood	40	3.6	51.0	0.8	5.9
Station 05	>=120 and <=300	Ebb	58	2.5	51.5	0.7	1.9
B. Couba	All other directions	Flood	42	2.4	30.9	0.6	1.9
Station 06	>=70 and <=250	Ebb	55	4.1	63.8	0.6	1.8
B. Bardeaux	All other directions	Flood	45	3.7	39.7	0.7	1.8
Station 07	>=0 and <=180	Ebb	62	5.7	74.1	0.8	6.3
B. Perot	All other directions	Flood	38	5.1	63.8	0.9	6.4
Station 8	>=180 and <=360	Ebb	60	4.5	53.0	1.6	12.0
Little Lake	All other directions	Flood	40	4.2	53.0	2.1	11.9
Station 10	>=180 and <=360	Ebb	55	4.9	52.0	1.3	7.2
B. Rigolettes	All other directions	Flood	45	4.4	30.9	1.4	7.5
Station 11	>=20 and <=200	Ebb	56	6.5	63.8	5.7	23.1
B. St. Denis	All other directions	Flood	44	5.9	42.2	6.6	24.6
Station 13	>=40 and <=220	Ebb	50	4.9	53.0	15.7	34.8
Caminada P.	All other directions	Flood	50	4.7	41.7	17.1	34.9
Station 14	>=20 and <=200	Ebb	44	6.0	30.9	17.9	37.3
Pass Abel	All other directions	Flood	56	6.0	41.2	19.0	44.0
Station 15	>=40 and <=220	Ebb	48	3.6	95.7	19.2	36.2
Quatre B. P.	All other directions	Flood	52	3.4	94.7	20.0	37.7
Station 21	>=30 and <=210	Ebb	61	4.0	41.7	5.5	31.3
Grand Bayou	All other directions	Flood	39	4.3	40.7	7.0	30.7

Table 6.10. Summary of tidal prism data for the BTES. Indicated for various sub-sections of the system, identified by a major water body, is the water surface area (square meters), the average low water depth (meters), the total low water volume in the section (cubic meters), the tidal range (meters), and the estimated tidal prism volume (cubic meters). Bold numbers indicate measured data; all other tidal ranges were estimated from a tidal range-distance inland relationship.[1]

Section of System	Major Water Body	Area (sq. m)	Depth (m)	Water Volume (cubic m)	Tidal Range (m)	Tidal Prism (cubic m)
			Barataria System			
North	Lac Des Allemands	6.43E+07	2.00	1.29E+08	0.01	1.29E+06
North	Bayou D. Allemands	2.45E+07	3.50	8.57E+07	0.02	1.71E+06
North	Lake Cataouatche	3.73E+07	2.00	7.45E+07	**0.03**	2.24E+06
North	Bayou Couba	2.22E+06	3.50	7.80E+06	0.03	2.34E+05
North	Bayou Bardeaux	3.00E+06	3.50	1.05E+07	0.02	2.10E+05
North	Lake Salvador	1.93E+08	2.50	4.82E+08	**0.02**	9.64E+06
Middle	Delta Farms	2.44E+07	3.00	7.32E+07	0.05	3.66E+06
Middle	Bayou Perot	2.41E+07	2.00	4.81E+07	**0.08**	3.85E+06
Middle	Bayou Rigolettes	1.63E+07	1.50	2.44E+07	**0.08**	1.95E+06
Middle	Little Lake	6.15E+07	2.00	1.23E+08	**0.12**	1.48E+07
Middle	Turtle Bay	2.26E+07	0.91	2.06E+07	0.12	2.47E+06
Middle	Round Lake	3.83E+06	0.91	3.48E+06	0.12	4.18E+05
Middle	Bay L'ours	1.15E+07	0.91	1.05E+07	0.12	1.26E+06
Middle	Gr. Bayou Channel	2.49E+06	4.42	1.10E+07	0.12	1.32E+06
Middle	Gr. Bayou Shoals	4.74E+06	1.60	7.60E+06	0.12	9.12E+05
Middle	Mud Lake Channel	4.08E+06	5.43	2.22E+07	0.12	2.66E+06
Middle	Mud Lake Shoals	1.52E+07	0.91	1.39E+07	0.12	1.67E+06
Middle	Wilkinson Bay	1.55E+07	1.31	2.02E+07	0.20	4.04E+06
South	Gr. Bayou Channel	1.54E+06	3.05	4.70E+06	0.20	9.40E+05
South	Gr. Bayou Shoals	7.24E+06	0.91	6.60E+06	0.20	1.32E+06
South	St. Mary’s Pt.	8.39E+07	1.67	1.40E+08	**0.30**	4.20E+07
South	Bay Batiste	2.88E+07	1.22	3.51E+07	0.25	8.78E+06
South	Hackberry Bay	1.88E+07	1.07	2.02E+07	0.25	5.05E+06
South	Crane Island	2.20E+07	0.91	2.00E+07	0.25	5.00E+06
South	Bay Rambo	3.82E+07	0.76	2.90E+07	0.25	7.25E+06
South	West Champagne Bay	5.10E+07	1.07	5.46E+07	0.31	1.69E+07
South	Pelican Pt.	2.27E+07	1.52	3.44E+07	0.32	1.10E+07
South	Mid Reef	2.45E+07	1.68	4.12E+07	0.32	1.32E+07
South	Cat Bay	2.51E+07	1.22	3.06E+07	0.33	1.01E+07
South	Bay Ronquille	4.90E+07	0.91	4.46E+07	0.33	1.47E+07

South	Caminada Bay	7.73E+07	0.91	7.03E+07	0.34	2.39E+07
South	Barataria Pass	2.23E+06	6.10	1.36E+07	**0.34**	4.62E+06
South	Bay Melville	1.75E+07	1.83	3.21E+07	0.34	1.09E+07
Total		**1.00E+09**		**1.74E+09**		**2.30E+08**

Table 6.10. (cont.)

				Terrebonne System		
North	Lake Boudreaux	2.25E+07	1.07	2.41E+07	0.10	2.41E+06
North	Lake Quitman	1.73E+07	1.07	1.85E+07	0.10	1.85E+06
North	Other	2.36E+06	0.61	1.40E+06	0.10	1.40E+05
North	Lake Tambour	1.08E+07	1.07	1.15E+07	0.10	1.15E+06
North	Madison Bay	1.51E+07	1.07	1.62E+07	0.10	1.62E+06
North	Other	5.17E+06	0.61	3.10E+06	0.10	3.10E+05
North	Lake Felicity	4.02E+07	1.83	7.36E+07	0.10	7.36E+06
Middle	Old Lady Lake	2.05E+07	1.22	2.50E+07	0.10	2.50E+06
Middle	Other	2.36E+06	0.53	1.20E+06	0.10	1.20E+05
North	Catfish Lake	7.31E+06	1.07	7.80E+06	**0.12**	9.36E+05
North	Grand Bayou Blue	1.20E+06	2.00	2.40E+06	0.15	3.60E+05
North	Other	1.20E+07	0.70	8.40E+06	0.20	1.68E+06
Middle	East Petit Caillou	7.11E+06	0.91	7.36E+07	0.24	1.77E+07
Middle	West Petit Caillou	1.21E+08	0.61	4.40E+06	**0.24**	1.06E+06
Middle	Houma Channel	3.96E+06	3.96	1.57E+07	0.24	3.77E+06
Middle	Lake Barre	7.53E+07	1.52	1.15E+08	0.24	2.75E+07
Middle	Pass Barre	4.09E+06	5.00	2.04E+07	0.24	4.90E+06
Middle	Bayou Terrebonne	1.31E+06	1.52	2.00E+06	0.25	5.00E+05
Middle	Other	3.33E+07	0.91	3.03E+07	0.26	7.88E+06
Middle	Lake Raccourci	6.06E+07	1.22	7.39E+07	0.27	2.00E+07
Middle	"Timbalier Bay, NE"	6.28E+07	1.52	9.54E+07	0.29	2.77E+07
Middle	"Timbalier Bay, NW"	7.87E+07	1.22	9.59E+07	0.30	2.88E+07
Middle	Other	1.13E+07	0.91	6.90E+06	0.30	2.07E+06
Middle	Little Lake	1.02E+07	0.91	9.20E+06	0.32	2.94E+06
Middle	Bayou Blue	7.80E+05	4.50	3.50E+06	0.34	1.19E+06
Middle	Grand Bayou Blue	1.67E+06	2.50	4.20E+06	0.36	1.51E+06
Middle	Other	4.29E+06	0.61	2.60E+06	0.38	9.88E+05
Middle	Terre. Bay Basin	8.35E+07	2.50	2.09E+08	0.40	8.35E+07
Middle	Terre. Bay Shoals	1.55E+08	1.50	2.33E+08	0.41	9.54E+07
Middle	Houma Channel	1.00E+06	3.96	3.90E+06	0.42	1.64E+06
South	Lake Pelto Shoals	1.06E+08	1.52	1.61E+08	0.43	6.90E+07
South	Lake Pelto Basin	1.24E+07	2.13	2.64E+07	0.43	1.14E+07
South	Pelican Lake	1.15E+07	0.61	1.87E+07	0.43	8.04E+06
South	Cat Island Pass	1.28E+06	4.50	5.70E+06	0.43	2.45E+06
South	Caillou Boca	2.35E+06	4.33	1.02E+07	**0.43**	4.35E+06
South	Timbalier Bay	1.01E+08	1.83	1.84E+08	**0.37**	6.73E+07
South	Caillou Pass	1.71E+07	1.83	3.12E+07	0.37	1.15E+07
Total		**1.12E+09**		**1.63E+09**		**5.23E+08**

[1]Data from Wiseman and Swenson (1989).

salinity gradient in the estuary. The model was then used to estimate the flushing times of the systems. The model was originally intended for systems with simple geometry where tidal forcing is dominant and the freshwater input is well known. This is not the case in the BTES, where we have multiple entrances to the systems, large-scale wind forcing, and a poor understanding of the freshwater inflow to the system. Nevertheless, some general points can be made. In Barataria, the time required to flush a concentration down to about 10% of its initial value was about 52 tidal cycles (1.75 months). The lower portions of the estuary flushed more rapidly (~1 month) due to the greater tidal range. In the Terrebonne system, the flushing time was on the order of 2 months. The model was used to assess the potential impacts of produced water inputs into the BTES. In general, the results indicated that the amount of produced waters added has a negligible effect on the circulation. It is also unlikely that the amount of salt added by the presently occurring produced waters discharge has affected the mean salinities by more than a few percent.

Wiseman and Swenson (1989) estimated tidal prisms for the BTES. Their estimate was made by multiplying the area (based upon 1978 land-water boundaries from 1:100,000 maps) of individual subsections of the basin by the tidal amplitude for the subsection. The tidal amplitudes were based upon measured data, and were then interpolated across the whole basin, using the amplitude distance relationship. The results are presented in Table 6.10. The bold face entries indicate the points at which the tidal amplitude was measured, all other tide amplitude values are interpolated. The results indicated a tidal prism volume of ~2.3 x 10^8 m^3 (3 x 10^8 yd^3) for Barataria and ~5.2 x 10^8 m^3 (6.7 x 10^8 yd^3) for Terrebonne.

Marmer (1948) estimated the tidal prism in the Barataria Bay system (from measurement of volume flux through the tidal passes over the time period of August 12 through 28, 1947) to be ~1.4 x 10^8 m^3 (1.9 x 10^8 yd^3). Marmer (1948) also states that this is only an order of magnitude estimate since it was based upon this one set of observations, and there may be substantial changes throughout the year. His data also indicated that ~66% of the total exchange was through Barataria Pass, 18% was through Quatre Bayoux Pass, 13% was through Caminada Pass, and 3% was through Pass Abel. Marmer (1948) also noted that the ebb prism is greater than the flood prism by ~1.3 x 10^7 m^3 (18.5 x 10^6 yd^3). He attributed this difference to freshwater inflow to the system. It is interesting to note that this difference would correspond to an input of ~280 m^3s^{-1} (10,176 cfs) to the Barataria system, which is close the estimates of ~200 m^3s^{-1} (7,076 cfs) discussed previously. List et al. (1991) estimated a tidal prism volume for Barataria Bay of ~1.43 x 10^8 m^3 (1.87 x 10^8 yd^3) for the 1890s, ~1.86 x 10^8 m^3 (2.43 x 10^8 yd^3) for the 1930s, and ~2.33 x 10^8 m^3 (3.05 x 10^8 yd^3) for 1978. The List et al. (1991) estimate for the 1978 tidal prism agrees quite well with the Wiseman and Swenson (1989) estimate for the 1978 tidal prism. However, the Marmer (1948) estimate for the 1947 tidal prism is quite low compared to the List estimate of the 1930s tidal prism. This may be due to methodology differences as opposed to actual changes in the tidal prism. We were therefore unable to determine any impacts (on water levels) that may have occurred due to any changes in the tidal prism, due to the limited data base. However, the data do agree on the estimate of the order of magnitude of the tidal prism (10^8 m^3 or 1.3 x 10^8 yd^3).

Marsh Flooding

Sasser (1977) described the distribution of vegetation in the Louisiana coastal marshes in relation to marsh flooding frequency and duration. His results indicated that the duration of flooding significantly influenced the frequency of occurrence of the nine species and two of the five associations used in the study. Frequency of flooding and elevation relative to mean water level were of lesser importance. All plants withstood a large range of flooding *S. alterniflora*, for example, occurred at values ranging from 952 to 8605 hours per year. All species, with the exception of *B. halimifolia* could survive a minimum duration range of 4500 hours per year.

Swenson (1983) measured flooding frequency and duration in brackish marsh sites north of Golden Meadow from August, 1982 through September 1983 (BF on Figure 6.4). His results indicated that the percentage of time that the marsh was flooding showed a strong seasonal pattern with peaks in June and November–December and the minimum in February (Figure 6.21). The amount of time the marsh was flooded per month ranged from 20 to 80%. The presence of canal spoil banks around one of the sites (referred to as the partially impounded site) had a significant impact on the flooding characteristics of that site, with the percentage of time the marsh was flooded increasing by ~20% per month. The data (Swenson and Turner 1987) indicated that the partially impounded site was characterized by having fewer flooding events per month (4.5 as opposed to 12.9 for the natural site) with these events being much longer in duration (150 hours as opposed to 30 hours for the natural site). The end result was that the partially impounded site was flooded ~200 hours more per month.

Marsh inundation frequency and duration measured in the marshes north of Cocodrie (FLM and LUM on Figure 6.4) from December 1989 through September 1990 (Swenson, unpublished data) also showed a strong seasonal pattern (Figure 6.22) with the minimum amount of flooding occurring during the winter months. The percentage of time flooded ranged from 5 to 80% of the time per month.

Patterson et al. (1993) measured marsh flooding in the salt marshes on Bay Champagne in the Barataria system. Their data showed flooding for the low *Spartina* marshes of 65 to 85% per month, 50 to 70% per month for the high *Spartina* marshes, and 35 to 60% per month for the *Avicennia*. They concluded that a 1 cm (0.39 in) increase in elevation translates to an ~3% (absolute) increase in the percentage of time the marsh is flooded (i.e. a marsh that is flooded 20% of the time would be flooded 23% of the time if the water level rises 1 cm (0.39 in)).

Childers and others (1990) measured marsh flooding in the brackish marshes near Little Lake and in the salt marshes near Airplane Lake (Caminada Bay) from March 1987 through April 1989. Their results showed flooding frequencies ranging from 20 to 40% for the brackish marshes and from 10 to 70% for the salt marshes over the measurement period.

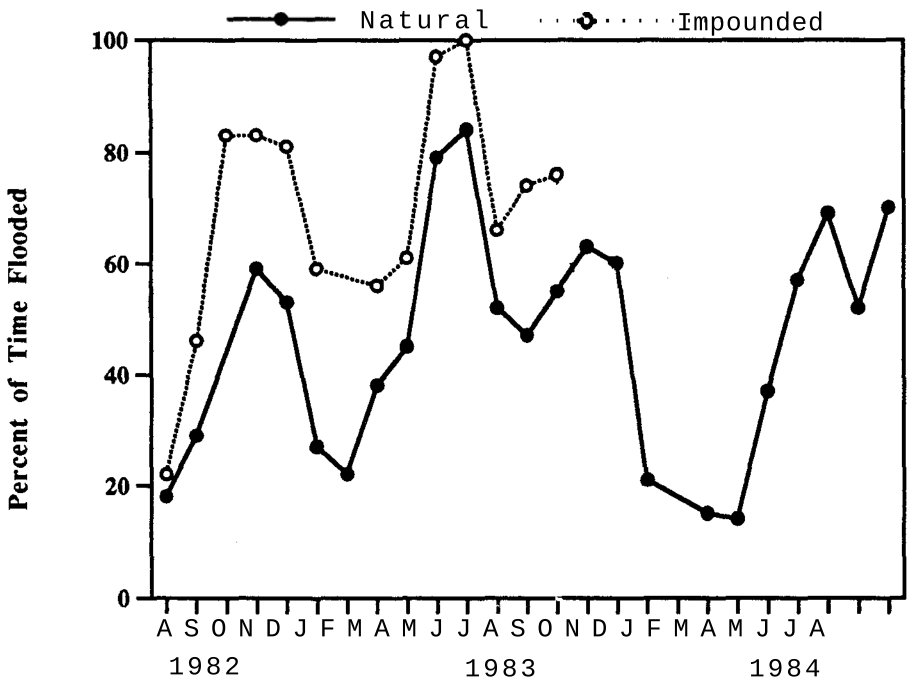


Figure 6.21. Percentage of time the marsh is flooded at the study sites in the brackish marshes north of Golden Meadow.

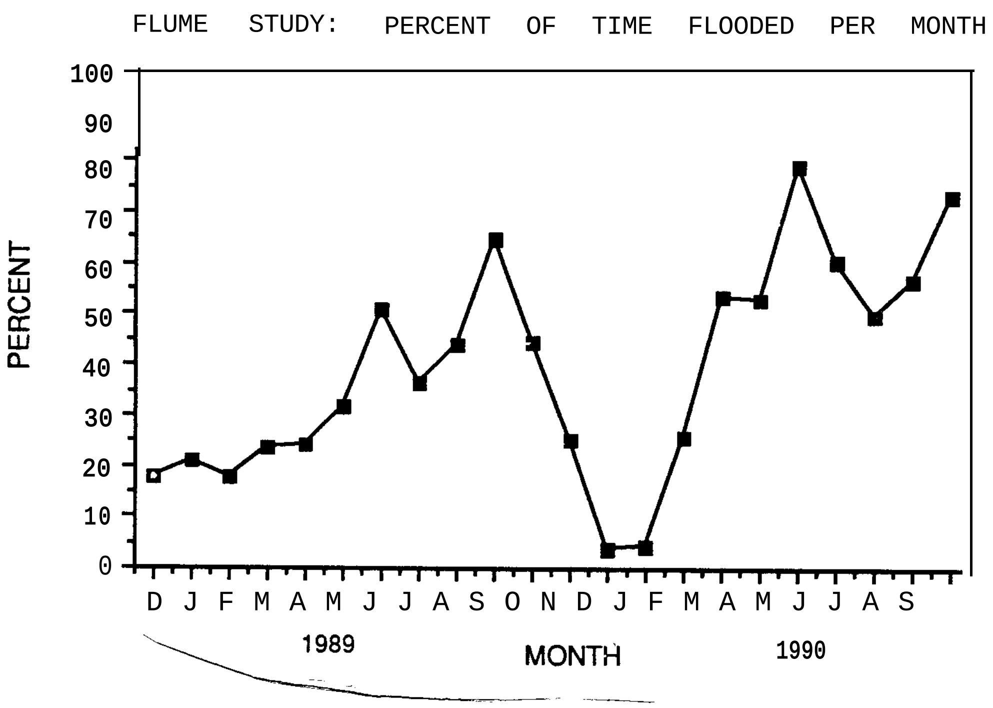


Figure 6.22 Percentage of time the marsh is flooded for the Brackish marshes north of Cocodrie.

The EMAP Salt Marsh Pilot Study in Louisiana measured marsh flooding frequency and inundation at several salt marsh sites in the BTES (TH4, TH6, TI4, TI5, BH2, BH3, BI2, and BI6 on Figure 6.4) over the time period from October 1991 through July 1992. The results of this study (Turner and Swenson 1993) indicated that the marshes are flooded from 15 to 75% of the time per month.

Swarzenski (1992) measured marsh flooding in the intermediate marshes around Lake Salvador from January through November 1989 (LS on Figure 6.4). He noted marsh flooding ranging from 33 to 52% per month. His data also showed a seasonal pattern with the greatest amount of flooding occurring in the early summer.

Figure 6.23 summarizes the marsh flooding data from the above studies. In general, there appears to be no obvious spatial patterns to the data. This may be due to the fact that each of the data sets are from different time periods, when there may be large differences in the coastal water level patterns.

Marsh Substrate Salinity

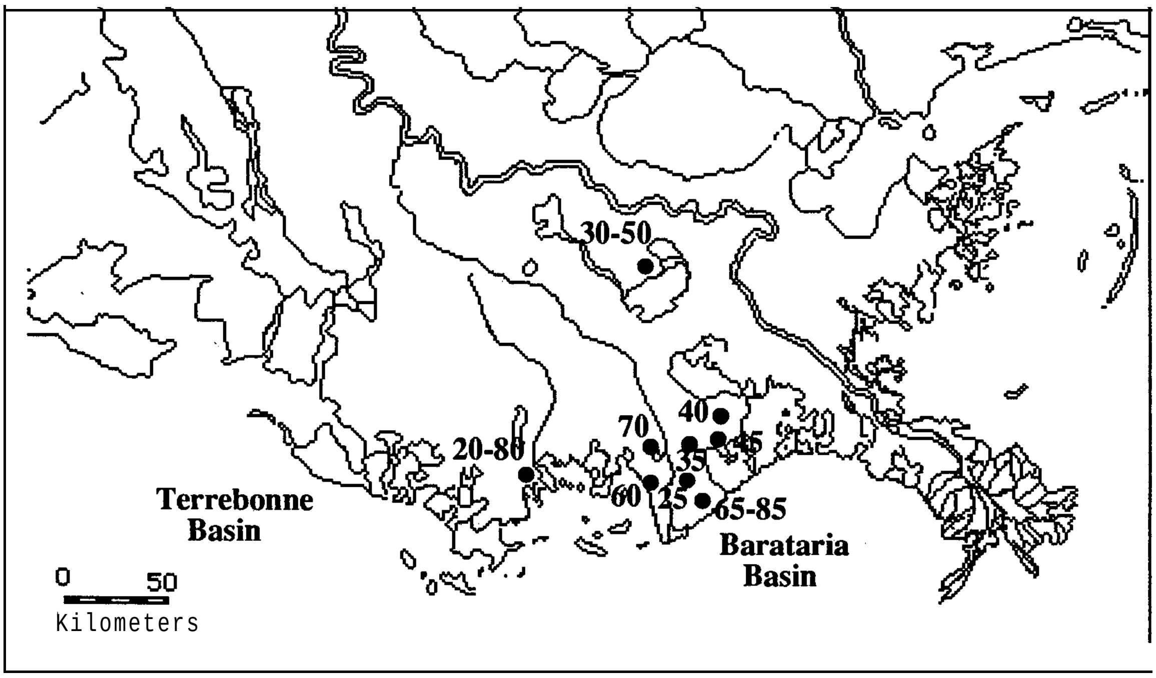
Available records for soil salinities in the marshes of Terrebonne and Barataria basins were tabulated as much as possible. There were no records taken from fresh marshes. There are few records, but some generalizations are possible.

One long-term record exists from a rooted intermediate marsh in Barataria basin (LS on Figure 6.4). The marsh appears to be stable and is dominated by *Sagittaria lancifolia*, and not much change in plant communities is noticeable from the past decade or so. In measurements spanning the period 1987 to 1991 taken at frequencies of a month to three months, soil salinities varied from 0.5 to 5 ppt in the upper 100 cm (39 in). Salinities were slightly higher with depth (Figure 6.24). More complete records for this and two adjacent floating marshes can be found in Swarzenski and Swenson (1994).

Salinities were higher for two marshes located slightly closer to the Gulf of Mexico, near the Clovelly area (CL on Figure 6.4). In contrast to the Lake Salvador marsh, this area appears to have undergone rapid changes in vegetation recently, possibly being a transition zone between intermediate and brackish marsh. The period of record are four sampling dates between the fall of 1987 and the summer of 1988 (Swenson, unpublished data). Mean salinities were around 3.5 to 6 ppt. Departures from the mean were greatest near the surface and decreased with depth. Mean values were closer to the maximum value for both marshes. Salinities decreased from the top to the middle depths before increasing again (Figure 6.24).

The site at Cocodrie (FLM on Figure 6.4) represents a brackish marsh dominated by *Spartina patens*. The vegetation has not appeared to change recently. Salinities were measured from mid 1988 to mid 1989 on a monthly basis (Swenson, unpublished data). Means represent average conditions for 12 months. Surface waters varied from around 3 to 18 ppt. In the marsh soil, salinities increased with depth from about 8 ppt to above 12 ppt. Variability of soil salinities decreased with depth.

Soil salinities were measured in salt marshes of both Barataria and Terrebonne basins once in a short time interval, in the fall of 1991, from the EMAP Pilot Study (Turner and Swenson 1993). The vegetation at all sites was predominately *Spartina*



Ranges in Observed Marsh Flooding (Percent of time Flooded)

Figure 6.23 Map of the BTES showing percentage of time flooded at various locations.

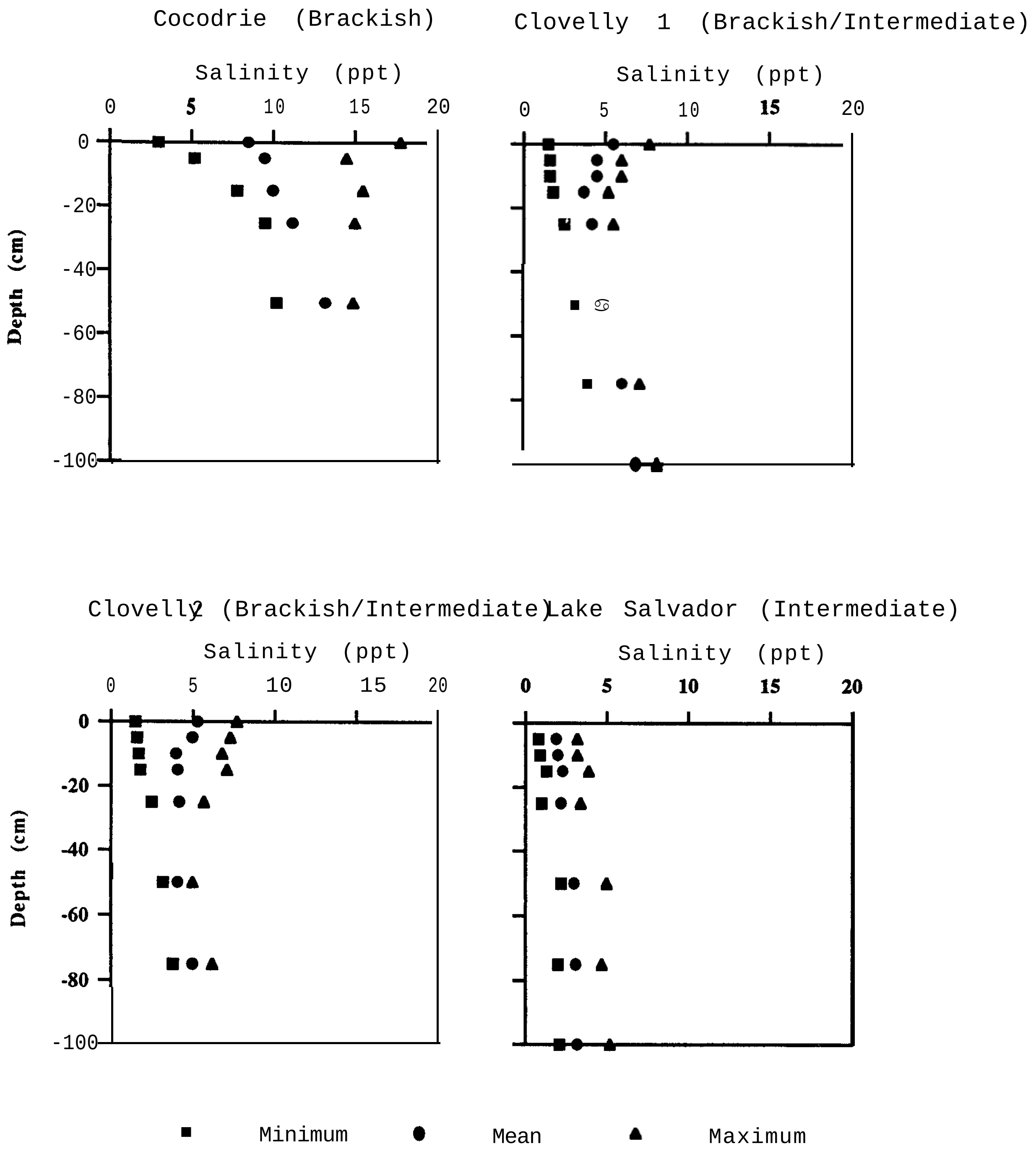


Figure 6.24 Summary of substrate soil salinities measured over time for various marshes in the BTES (see Figure 6.4).

alterniflora. Mean salinities averaged from all sites ranged from around 10 ppt near 20 ppt (Figure 6.25). Salinities in 1991 were substantially higher in Barataria basin than in Terrebonne basin. The range of soil salinities under which only vegetation indicative of salt marshes occurs was very surprising. In Terrebonne basin, some soil salinities were close to 0 ppt. In Barataria, the low end of soil salinities was higher, at around 4–5 ppt. Over the long term, salinities must reach levels high enough to eliminate species that would generally be found in fresher environments. Caution should be used when attempting to infer processes form the EMAP data set, the data present a "snapshot" of the spatial variability of salt marsh substrate salinity within the BTES, over a ~3 week period in August–September 1991.

To date, few studies have measured soil salinities in the marshes of Barataria and Terrebonne at several depths over time. The information provided by such studies appear to be quite valuable in setting boundaries for the transition of plant communities from fresh marsh through intermediate and brackish to salt marsh.

The closer one gets to the coast, the larger the variability in soil salinities. In the intermediate marsh soil salinities stayed within a range of 3.5 ppt over four years of sampling. Means varied over even a smaller range, from about 1.5 to under 3 ppt. Presumably, in fresh marshes, mean soil salinities need to be below this threshold to continue to contain the diversity of species typically associated with this marsh type.

The data are sparse, with few real replicates in the intermediate and brackish marsh sites to narrow down the range of salinities typical of the four plant community classes based on salinity that have been used in coastal Louisiana. Much additional work is needed.

LONG-TERM TRENDS

Plots of the long-term monthly mean water levels for Barataria are presented in Figure 6.26 and for Terrebonne in Figure 6.27. Plots of the long-term monthly mean salinities for Barataria are presented in Figure 6.28 and for Terrebonne in Figure 6.29. The most obvious feature on the water level curves, is the generalized upward trend at all stations. The two major contributors are, global eustatic sea level rise, subsidence of the gage. The relationship between apparent sea level rise at each station relative to the Grand Isle (Bayou Rigaud) gage is shown in Figure 6.30. All stations, except West Bay and Bayou Boeuf, show excellent agreement with the Grand Isle gage. The Lake Boeuf gage shows a poor relationship primarily due to outliers from high Atchafalaya River stages. The West Bay station is located in the Mississippi River delta area. The observed trend in water levels is influenced by the length of record used in the analysis. Turner (1991) showed sea level rise estimates for Grand Isle ranging from 0.32 cm yr^{-1} to 1.15 cm yr^{-1} depending upon the length of record used. Using the relationship between the

Grand Isle gage and the long-term gage a Galveston to estimate the expected 72-year trend at Grand Isle., Turner (1991) indicated the 72-year trend at Grand Isle to be 0.63 cm yr^{-1}. There is a general pattern (for Barataria) with the largest water level trends as well as the greatest amount of fluctuations to occur at the coast. This is summarized in Figure 6.31, which shows the relationship between sea level rise

Substrate Salinity: EMAP Phase 1, 1991

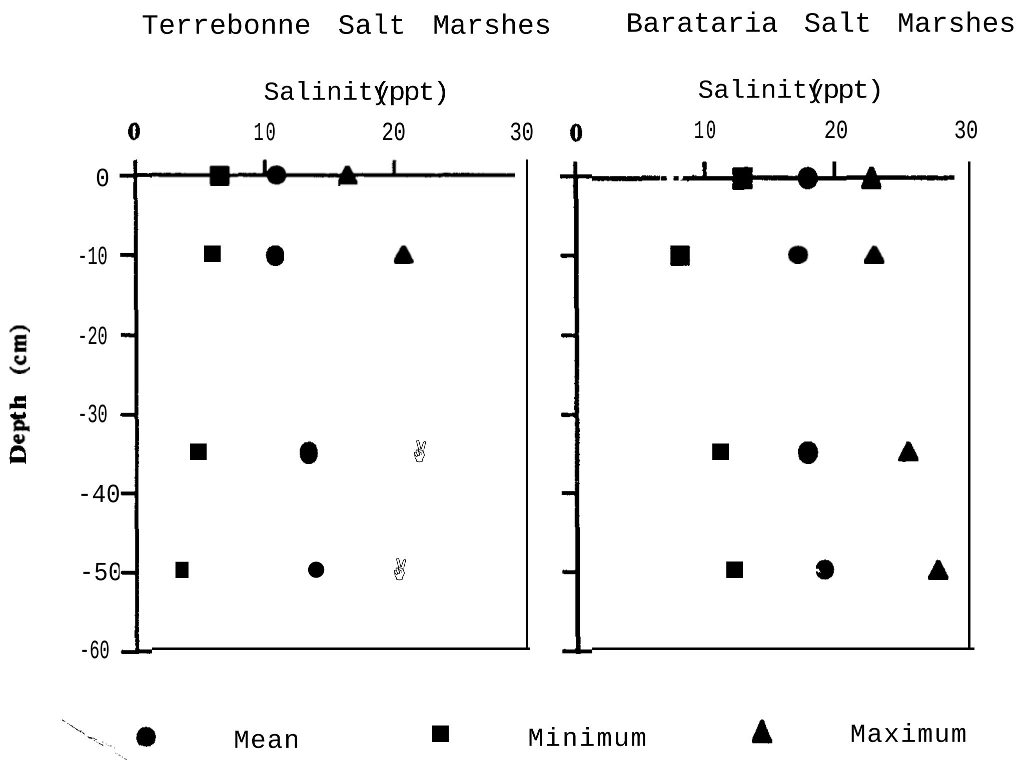


Figure 6.25. Summary of vertical distribution of substrate salinity for marshes in the BTES. Data were collected at seven stations throughout the Terrebonne system and six stations in the Barataria system (Figure 6.4) in August-September 1991. Data from Swenson et al. (1992).

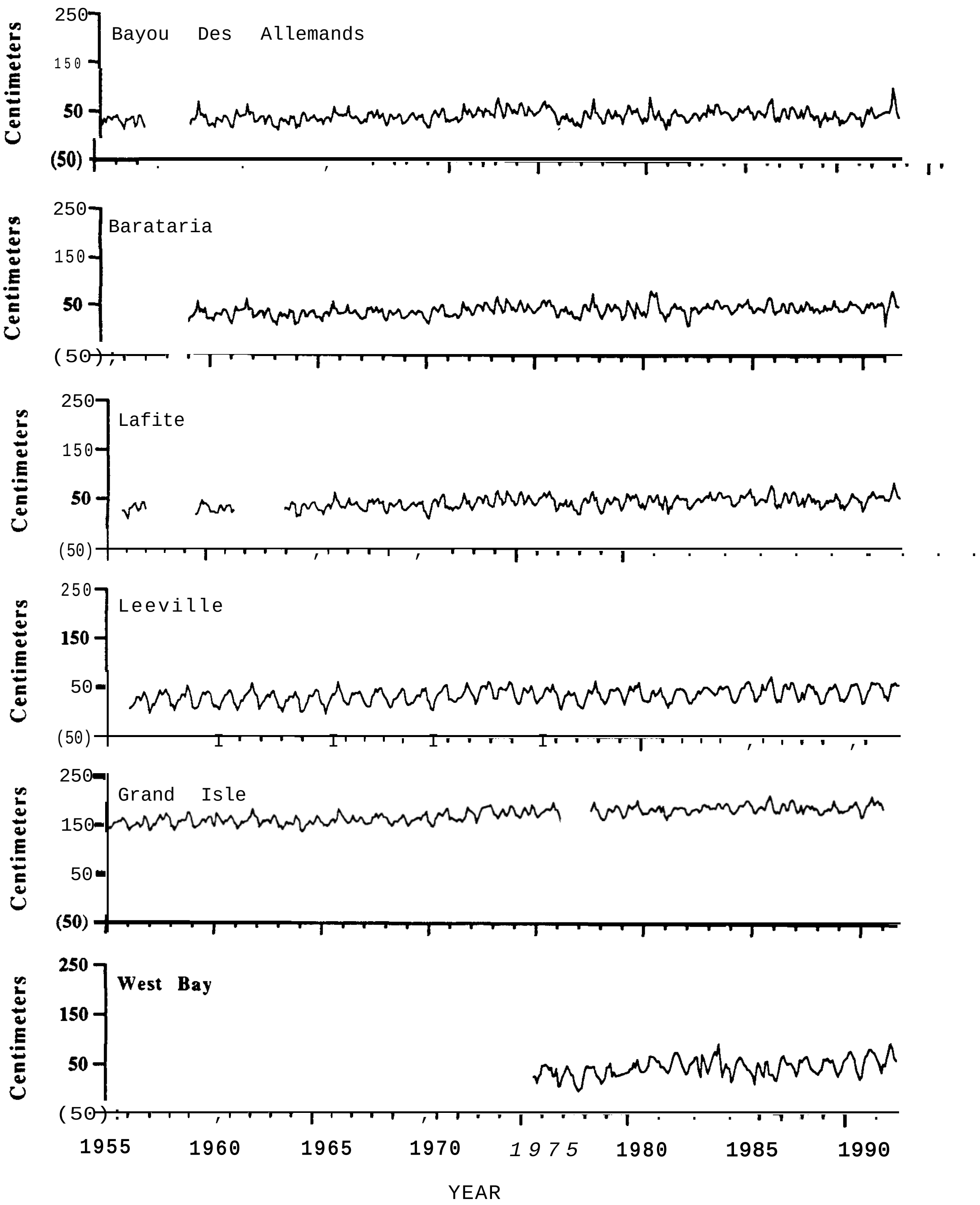


Figure 6.26 Time series plots of mean monthly water levels in Barataria.

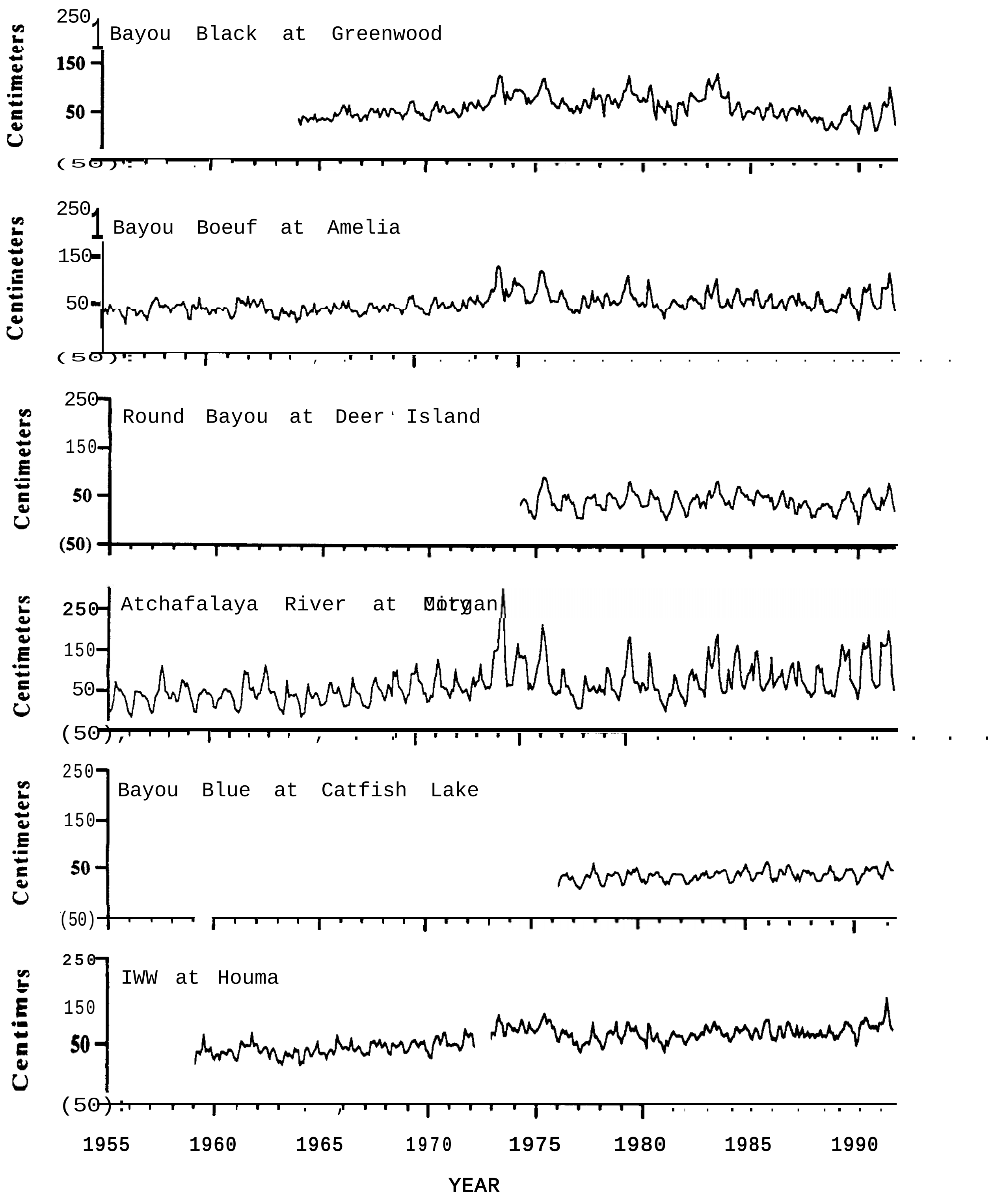


Figure 6.27 Time series plots of mean monthly water levels in Terrebonne.

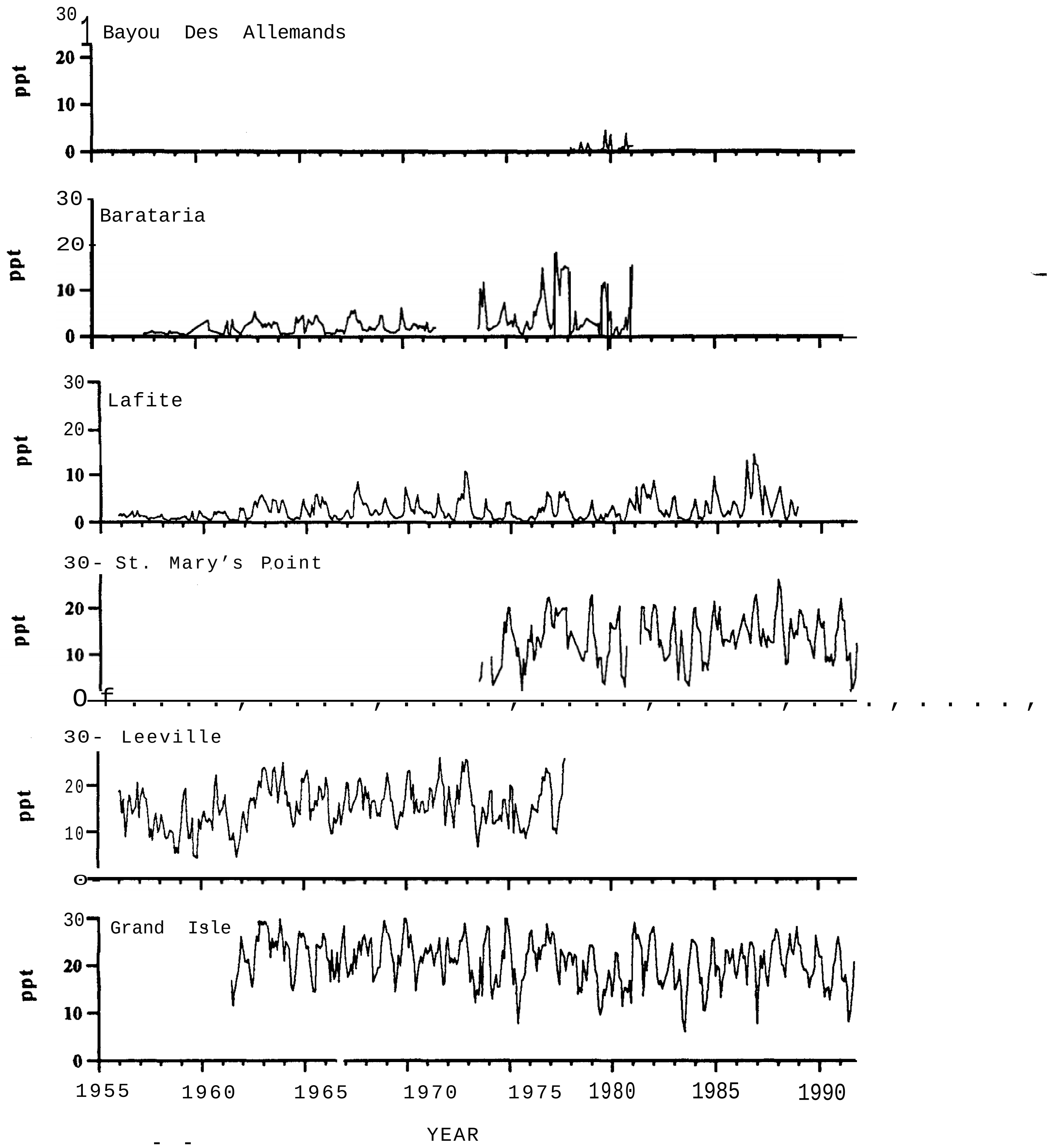


Figure 6.28. Time series plots of mean monthly salinity in Barataria.

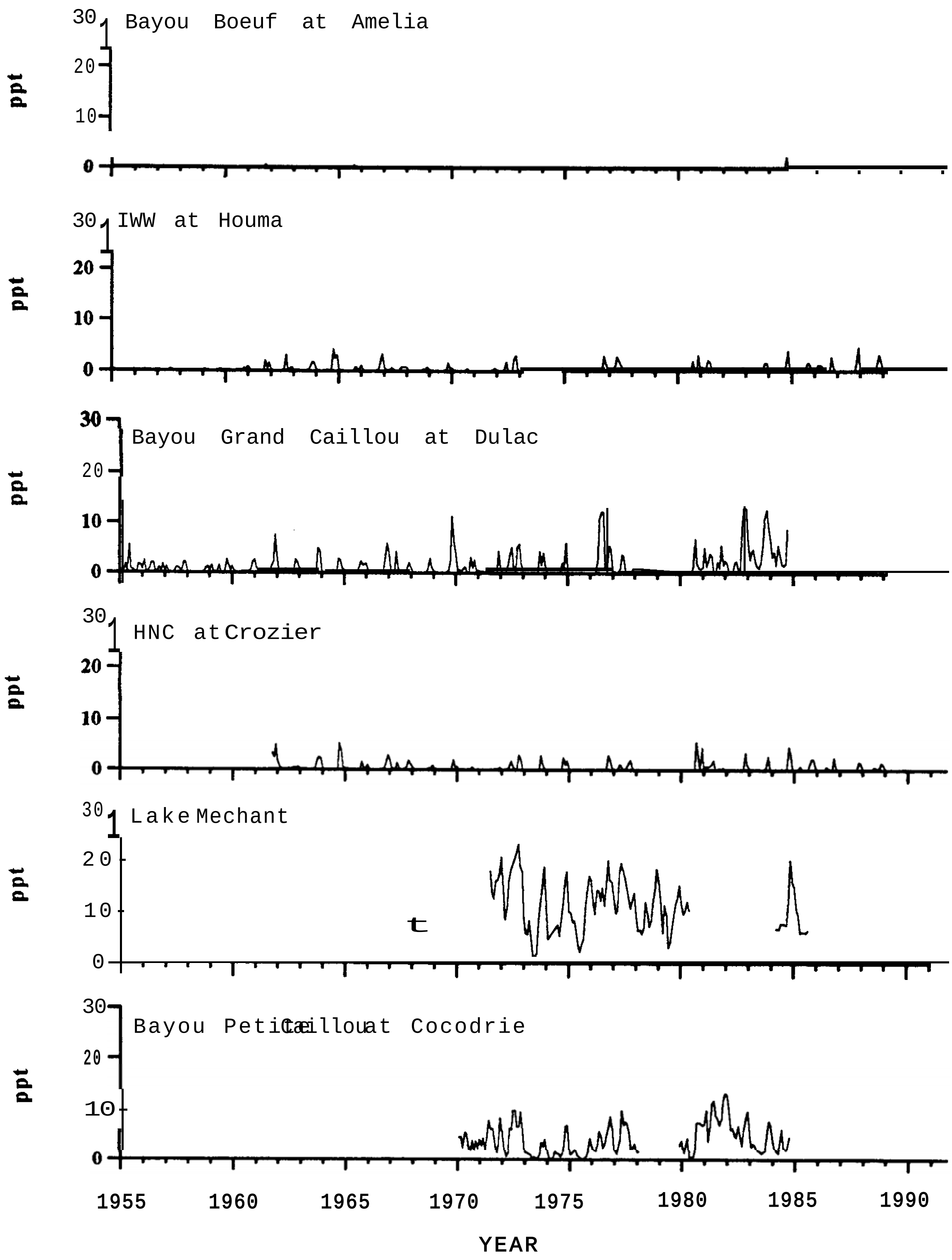


Figure 6.29. Time series plots of mean monthly salinity in Terrebonne.

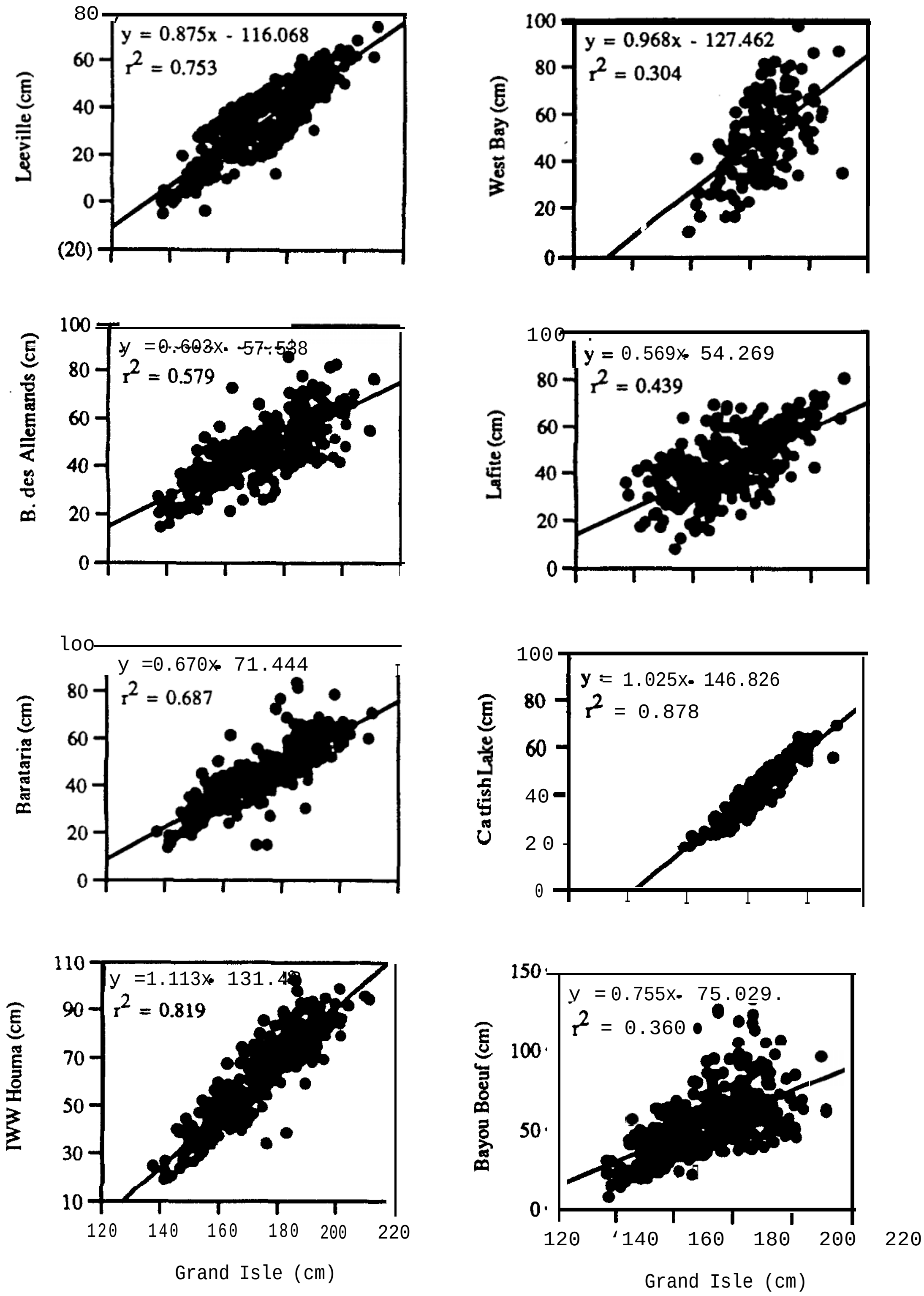


Figure 6.30. Plot of mean monthly water levels at Grand Isle (Bayou Rigaud) versus mean monthly water levels at other stations in the BTES.

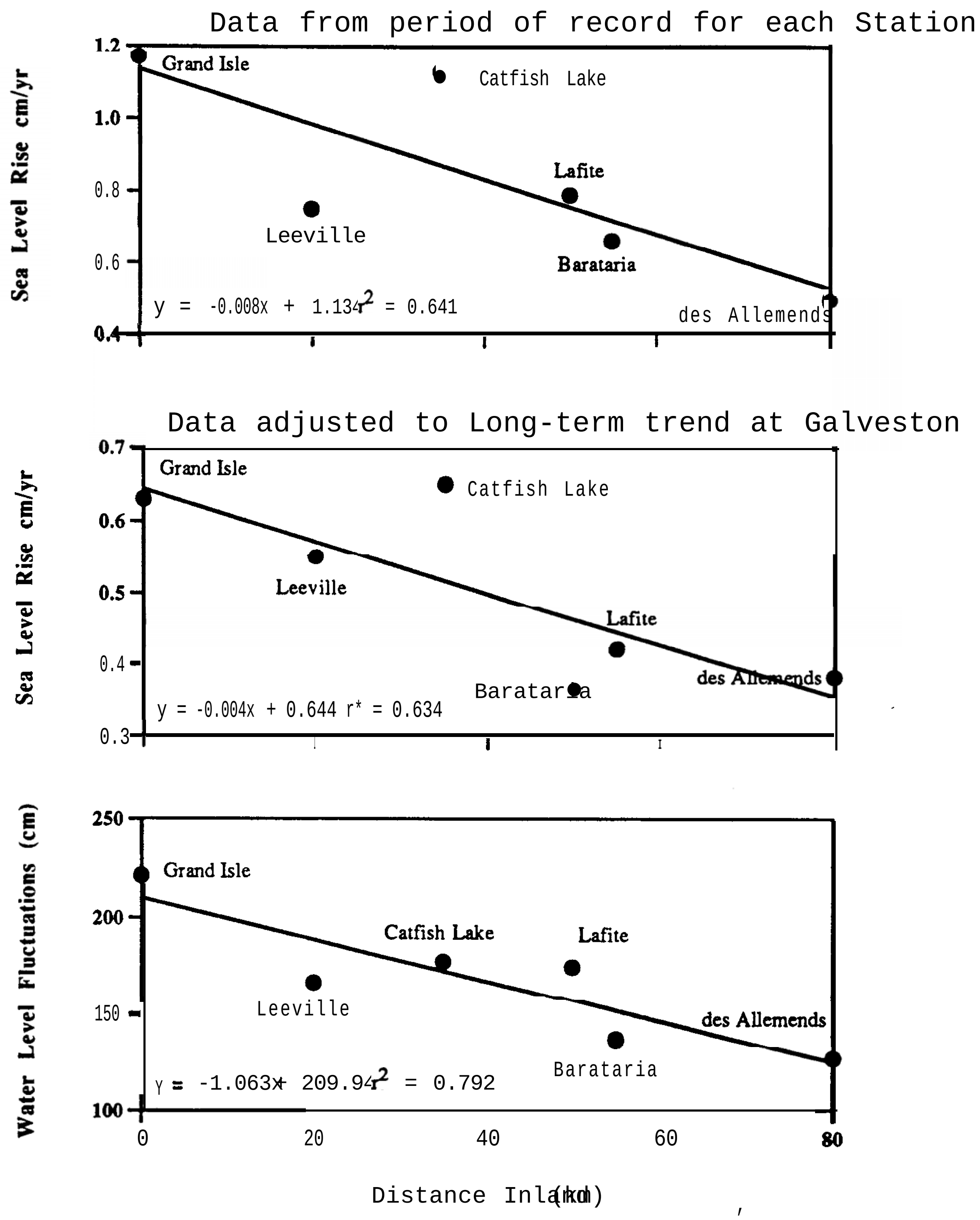


Figure 6.31 Sea level rise and total water level fluctuations as a function of distance inland for Barataria system.

at a given station and distance inland, and total water level fluctuations as a function of distance inland. The sea level rise is presented as the trend for the period of record for each as well as the estimated 72-year trend for each gage (based upon the relationship with the Grand Isle and the Galveston gage as discussed in Turner 1991).

There are relatively few stations that have measured salinities for a long time (from the 1950s to the present). Those that have are located in major navigation channels trending north-south (Barataria Waterway at Lafitte, Houma Navigation Channel at Crozier) or at the mouth of such a waterway (Grand Terre). The stations in the navigable waterways are much deeper than adjacent ponds and marshes. They serve as a conduit for salt water from the Gulf of Mexico towards the uplands, and also shunt precipitation and runoff from the uplands towards the Gulf of Mexico, bypassing the extensive marsh lands. Such effects interfere with the ability to detect long-term changes in mean salinities. They also make interpretations difficult. As is the case with water level, salinity trends are also influenced by length of record.

The salinity plots show no general coastwide trends of increase or decrease at all of the stations as there was for the water levels. Similar results were obtained by Wiseman et al. (1990) when they analyzed salinity records for the entire Louisiana coast. The only "trend" that is visible on the data is an increase in "spikiness" after about 1960–1962. The term "spikiness" refers to pulses in salinity which tend to be a factor of two or three greater than the baseline salinity. This behavior is noticeable at the GIWW at Houma, Lafitte, and Barataria. Possibly this is a result of the dredging of the Barataria Waterway and the Houma Navigation Channel.

The long-term trends in water level and salinity for all of the stations used in the analysis are presented in Tables 6.11 and 6.12. Table 6.11 presents the trend analysis results using the linear model without a seasonal interaction term, and Table 6.12 presents the results from the trend analysis results using linear model with a seasonal interaction term. In general the water level data show increasing trends at all stations with slopes ranging from ~0.6 to 1.5 cm / yr (2 to 5 ft per century). The salinity trends showed no coherent spatial trends. Correlation of the trends in the mean versus the trends in (1) the minimum and (2) the maximum, and (3) correlations of trends in the maximum with trends in the minimum for both water levels and salinities are presented in Table 6.13. In general, the results show that if there is a trend in the mean, the same trend usually exists in both the minimum and the maximum.

Salinities at one station, Barataria Waterway at Lafitte, were analyzed in several ways, including trends of long-term annual change with a block for month using the non-parametric Kendall's Tau statistic to detect direction (Hirsch et al. 1982), modified using SAS programming language to estimate the magnitude (R. Alden, Applied Marine Research Laboratory, Old Dominion University, personal communication); determining salinity classes for each year; and determining patterns of long- and short-term salinity elevations. The latter was done by (1) averaging monthly salinities for those years when salinities reached 4 ppt for at least 100 days in an year (high chloride years) and for those years when salinities fell beneath levels (low chloride years) and (2) examining the effect storm events (hurricanes and tropical storms) had on salinity levels.

Table 6.11. Summary of long-term trends in mean monthly salinity and water levels, based upon the results of a linear model without a month and date interaction, over the period of record. Listed is the slope of the salinity trend (ppt/yr), the slope of the water level trend (cm/yr), and the r-square for the fit. Trends were not significant (at the 95% level) for stations marked with the symbol .ns; all other trends were significant at the 95% level.

Station	Mean		Minimum		Maximum	
Name	ppt/yr	r-square	ppt/yr	r-square	ppt/yr	r-square
				Mean Monthly Salinity		
S03780	-0.003	0.24	-0.002	0.30	-0.004	0.06
S52800	-0.004	0.07	-0.003	0.05	-0.005	0.05
S52880	.ns	.ns	.ns	.ns	.ns	.ns
S76303	0.150	0.05	0.182	0.13	.ns	.ns
S76320	.ns	.ns	.ns	.ns	.ns	.ns
S76323	0.090	0.11	0.019	0.03	0.184	0.06
S76343	.ns	.ns	-0.005	0.17	.ns	.ns
S76403	.ns	.ns	-0.004	0.05	.ns	.ns
S82203	.ns	.ns	.ns	.ns	.ns	.ns
S82300	0.062	0.03	.ns	.ns	0.198	0.05
S82350	0.170	0.06	.ns	.ns	0.184	0.07
S82700	.ns	.ns	.ns	.ns	.ns	.ns
S82750	0.196	0.15	0.126	0.08	0.277	0.17
S82875	0.067	0.08	0.026	0.03	0.129	0.07
S315	-0.123	0.06	-0.088	0.02	-0.132	0.07
S317	.ns	.ns	.ns	.ns	.ns	.ns
S323	-1.570	0.13	-1.932	0.16	-1.469	0.12
S325	-0.336	0.06	-0.301	0.11	-0.362	0.05
S326	-0.435	0.13	-0.212	0.13	.ns	.ns
S416	-0.233	0.05	-0.154	0.03	-0.264	0.05
S518	.ns	.ns	.ns	.ns	.ns	.ns

Station	Mean		Minimum		Maximum	
Name	cm/yr	r-square	cm/yr	r-square	cm/yr	r-square
					Mean Monthly Water Level	
S03780	2.230	0.29				
S03850	.ns	.ns	.ns	.ns	.ns	.ns
S52800	0.870	0.24	0.782	0.17	0.908	0.26
S52880	.ns	.ns	.ns	.ns	.ns	.ns
S76320	1.480	0.64	1.455	0.54	1.527	0.58
S82301	1.126	0.24	0.969	0.11	1.272	0.16
S82350	0.780	0.30	0.749	0.21	0.831	0.22
S82700	0.493	0.17	0.492	0.16	0.560	0.17
S82750	0.662	0.29	0.678	0.28	0.727	0.22
S82875	0.789	0.36	0.748	0.25	0.902	0.31
S88350	1.470	0.18	1.277	0.14	1.683	0.16
S88600	0.644	0.13	0.302	0.03	0.600	0.05
3731	1.170	0.63	1.016	0.41	1.290	0.47

Table 6.12. Summary of long-term trends in mean monthly salinity and water levels, based upon the results of a linear model with a month and date interaction, over the period of record. Listed is the slope of the salinity trend (ppt/yr), the slope of the water level trend (cm/yr), and the r-square for the fit. Trends were not significant (at the 95% level) for stations marked with the symbol .ns; all other trends were significant at the 95% level.

Station	Mean		Minimum		Maximum	
Name	ppt/yr	r-square	ppt/yr	r-square	ppt/yr	r-square
			Monthly Mean Salinity			
S03780	-0.002	0.337	-0.002	0.384	.ns	.ns
S52800	.ns	.ns	.ns	.ns	.ns	.ns
S52880	-0.026	0.479	.ns	.ns	.ns	.ns
S76303	.ns	.ns	.ns	.ns	.ns	.ns
S76320	.ns	.ns	.ns	.ns	.ns	.ns
S76323	0.032	0.196	.ns	.ns	.ns	.ns
S76343	.ns	.ns	.ns	.ns	0.115	0.121
S76403	0.041	0.057	.ns	.ns	0.201	0.041
S82203	-0.034	0.158	-0.008	0.115	-0.120	0.153
S82300	.ns	.ns	.ns	.ns	.ns	.ns
S82350	.ns	.ns	.ns	.ns	.ns	.ns
S82700	.ns	.ns	.ns	.ns	.ns	.ns
S82750	.ns	.ns	-0.008	0.178	.ns	.ns
S82875	0.014	0.187	-0.003	0.150	.ns	.ns
S315	.ns	.ns	.ns	.ns	.ns	.ns
S317	.ns	.ns	.ns	.ns	.ns	.ns
S323	.ns	.ns	.ns	.ns	.ns	.ns
S325	.ns	.ns	.ns	.ns	.ns	.ns
S326	.ns	.ns	.ns	.ns	.ns	.ns
S416	.ns	.ns	.ns	.ns	.ns	.ns
S518	.ns	.ns	.ns	.ns	.ns	.ns

Station	Mean		Minimum		Maximum	
Name	cm/yr	r-square	cm/yr	r-square	cm/yr	r-square
			Mean Monthly Mean Water Level			
S03780	.ns	.ns	.ns	.ns	.ns	.ns
S03850	.ns	.ns	.ns	.ns	.ns	.ns
S52800	1.240	0.296	1.210	0.226	1.250	0.311
S52880	.ns	.ns	.ns	.ns	.ns	.ns
S76320	.ns	.ns	.ns	.ns	.ns	.ns
S82301	.ns	.ns	.ns	.ns	.ns	.ns
S82350	.ns	.ns	.ns	.ns	.ns	.ns
S82700	.ns	.ns	.ns	.ns	.ns	.ns
S82750	.ns	.ns	.ns	.ns	.ns	.ns
S82875	.ns	.ns	.ns	.ns	.ns	.ns
S88350	.ns	.ns	.ns	.ns	.ns	.ns
S88600	.ns	.ns	.ns	.ns	.ns	.ns
3731	.ns	.ns	.ns	.ns	.ns	.ns

Table 6.13. Correlations between (1) the trends in the monthly mean water level and salinity and the trend in the monthly maximum water levels and salinities, (2) the trends in the monthly mean water level and salinity and the trends in the monthly minimum water levels and salinities, (3) the trends in the monthly maximum water level and salinity and the trends in the monthly minimum water levels and salinities.

Station Name	Water Level Mean: Max	Water Level Mean: Min	Water Level Max: Min	Salinity Mean: Max	Salinity Mean: Min	Salinity Max: Min
S03780	0.97	0.96	0.90	0.73	0.93	0.58
S03850	0.75	0.93	0.61			
S52800	0.96	0.93	0.85	0.90	0.94	0.71
S52880	0.95	0.88	0.78	0.55	0.74	0.56
S76303				0.76	0.85	0.44
S76320	0.93	0.90	0.78	0.87	0.42	0.17
S76323				0.74	0.64	0.26
S76343				0.88	0.49	0.35
S76403				0.90	0.43	0.34
S82203				0.87	0.68	0.48
S82300				0.81	0.74	0.41
S82301	0.76	0.84	0.49			
S82350	0.78	0.93	0.63	0.86	0.83	0.58
S82700	0.89	0.89	0.69	0.81	0.61	0.18
S82750	0.83	0.86	0.58	0.94	0.92	0.73
S82875	0.80	0.87	0.57	0.87	0.90	0.66
S88350	0.90	0.88	0.68			
S88600	0.29	0.91	0.10			
S315				0.85	0.42	0.61
S317				0.82	0.84	0.55
S323				0.93	0.95	0.80
S325				0.97	0.95	0.88
S326				0.87	0.87	0.61
S416				0.69	0.79	0.39
S518				0.80	0.87	0.58
3731	0.83	0.92	0.70			

Mean annual salinities increased by about 0.5 to 1 ppt over the time period 1955 to 1987. The increase was statistically significant. The increase was attributable mainly to levels during a short time in late fall (October and November). During this time period, the rate was three to five times faster than that for the entire year (Figure 6.32). Mean salinities for the two months increased by about 2.5 to 3 ppt for the time interval 1955 to 1987.

Two years during the period of observation stand out as having exceptionally high salinities for an extended period. In 1972 and in 1986, salinities in the navigation channel remained above 6 ppt for 150 and more days. Salinities were above 10 ppt for almost a month in 1972, and close to 15% of the time in 1986. Salinities remained above 4 ppt for at least 100 days in 9 of 31 years (Figure 6.33). Monthly-averaged salinities during these years were mostly significantly higher than those in the remaining low-salinity years. The precipitation record averaged along the same lines shows that droughts in early spring and/or fall, coinciding with seasonal peaks in ambient water level, corresponded to high chloride years (Figure 6.34). It can be inferred that without an adequate head in the upper Barataria basin to balance seasonal changes in sea level, more saline waters can easily encroach in an inland direction. Presumably, the long-term increase in salinities observed for the fall reflects the same underlying mechanism.

Despite the limitations inherent in using a station in a major north-south trending navigation channel to monitor long-term salinity trends, there is a significant increase in salinities. To what extent this relatively small rate of increase will impact plant communities of the marshes occurring here is uncertain. It is clear that there are recurring extended time periods when open-water salinities are elevated far beyond the magnitude that would occur even after several decades at the present annual rate of increase. It seems likely that these extended high chloride years bracket the range of salinities under which the dominant plant community can continue to persist.

Presumably, the marsh communities growing in this part of Barataria basin are adapted to and in balance with the recurring events. The question for the plants then becomes whether the episodes of high chloride are actually increasing in magnitude over time. Combining the climatic factors underlying the periodic elevated salinities (co-occurrence of drought and seasonal high water) with the mechanisms underlying the gradual encroachment of more saline Gulf waters in an inland direction in Barataria basin (apparent sea level rise) suggests that the episodic high chloride years will increase in magnitude over time as well. This effect would likely dwarf those impacts to plant communities occurring from long-term annual trends.

The trend in both the salinity and the water level changes over the period of record, there are time periods when the water level rise is quite rapid, and time intervals when the water level rise is very small. The salinity also shows time periods when there is an increase in salinity, times when there are decreases in salinity and times when there is no trend. In order to ascertain whether or not these trends over subsections of the data are related to patterns in habitat change, the data were analyzed by year classes. The year classes were picked to correspond with the date of the aerial photos used for the

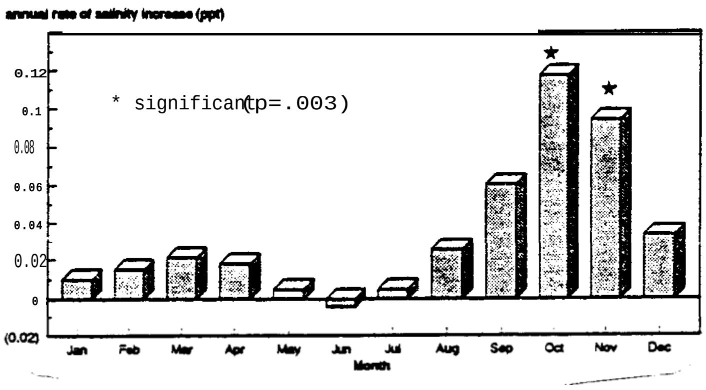


Figure 6.32. Plot of mean monthly salinity increase in Bayou Barataria at Lafitte, 1955 to 1987.

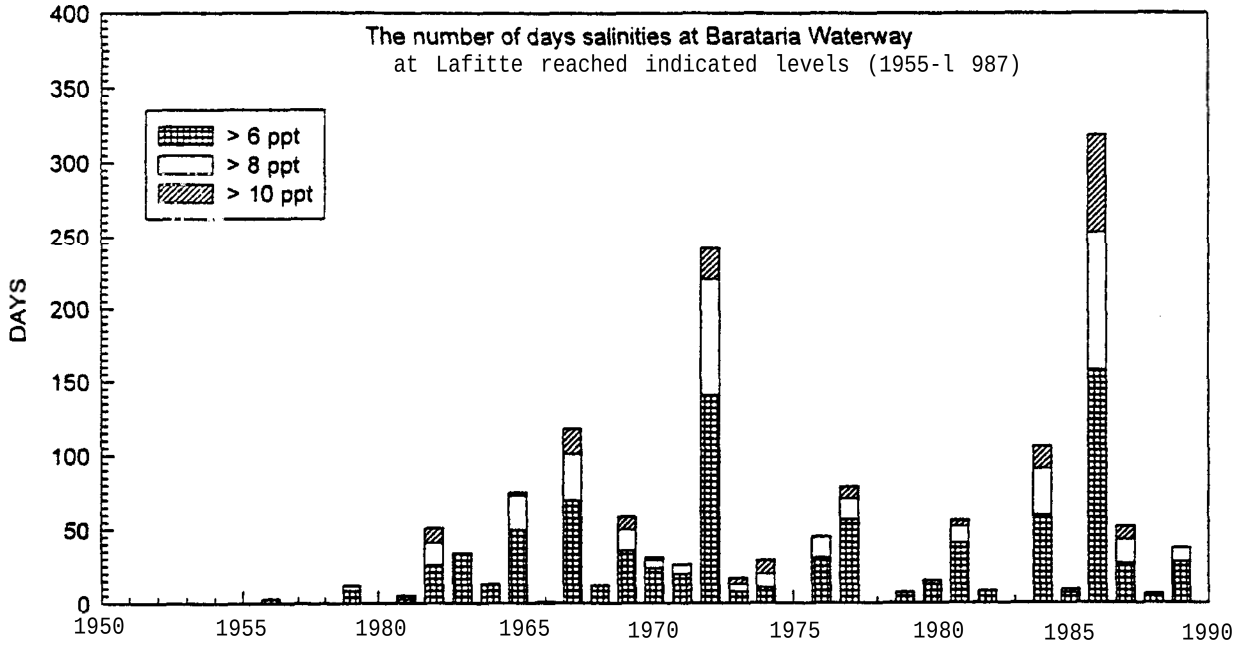


Figure 6.33 The number of days per year that salinities at Lafitte reached levels of 6 ppt, 8 ppt, and 10 ppt. Based upon data from 1966 to 1987.

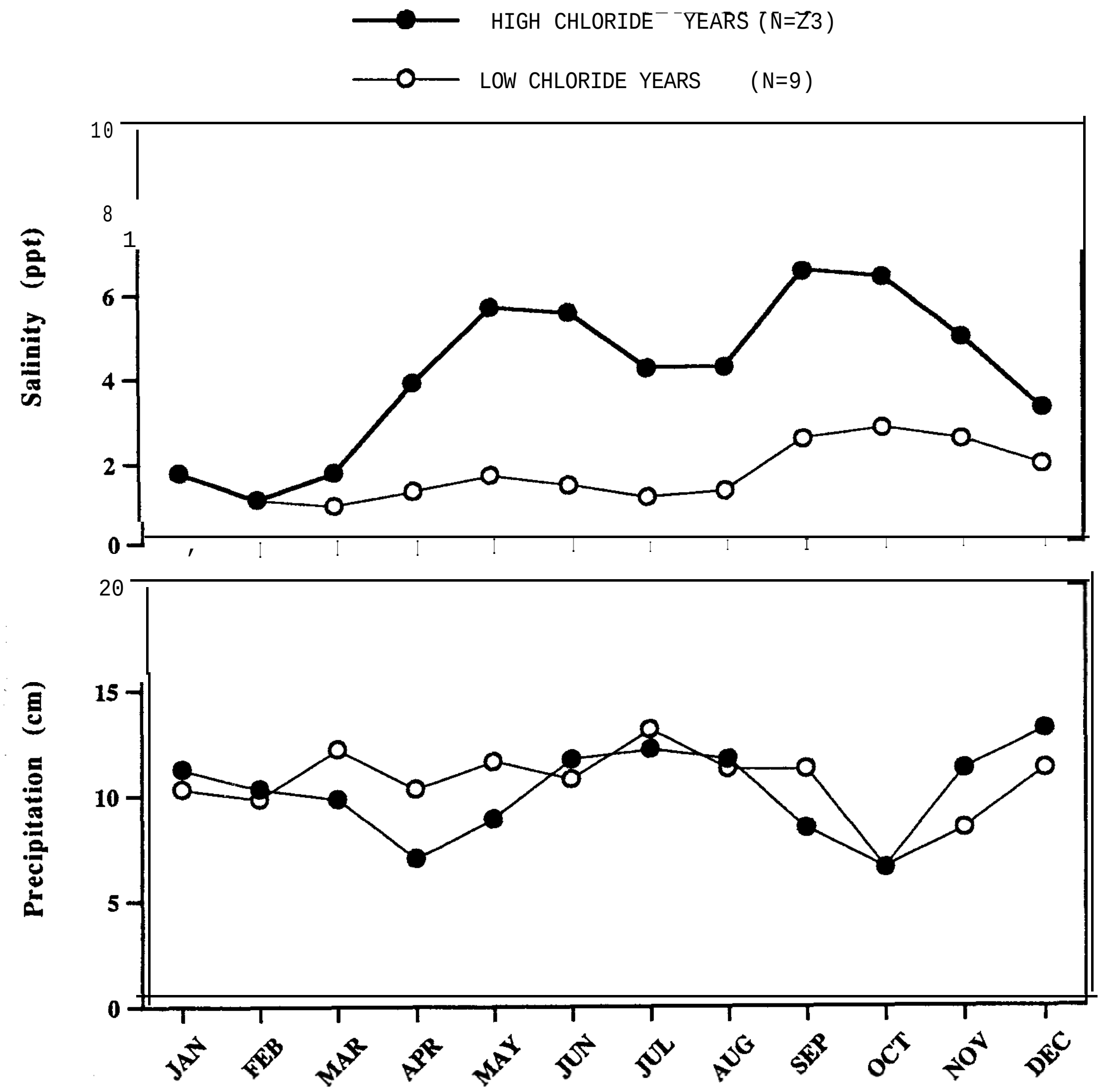


Figure 6.34. Plot of mean monthly salinity at Lafitte for high chloride (>4 ppt) years (black squares), low (< 4 ppt) chloride years (black circles), mean monthly precipitation for high chloride years (hashed bars), and low chloride years (open bars).

vignettes discussed in Part 8. The results are presented in Table 6.14. In general the data indicated the following trends, by year class:

Salinity
pre 1955: no data
1955–1965: small trends (<0.1 ppt/yr), 9 were positive, 2 were negative
1965–1969: small trends (<0.1 ppt/yr), 5 were positive, 8 were negative
1969–1972: large trends (>1 ppt/yr), 11 were positive, 4 were negative
1972–1985: moderate trends (~0.1 ppt/yr), 17 were positive, 1 was negative
1985–1990: small trends (<0.1 ppt/yr), 5 were positive, 6 were negative
1990–1994: large trends (>1 ppt/yr), 1 was positive, 5 were negative

Water Level
pre 1955: no data
1955–1965: small trends (0.5 cm/yr), 5 were positive, 4 were negative
1965–1969: moderate trends (~2.0 cm/yr), 7 were positive, 3 were negative
1969–1972: large trends (>6.0 cm/yr), 9 were positive, 1 was negative
1972–1985: moderate trends (~2.0 cm/yr), 9 were positive, 4 were negative
1985–1990: moderate trends (~2.0 cm/yr), 11 were positive, 2 were negative
1990–1994: moderate trends (~2.0 cm/yr), 5 were positive, 7 were negative

SUMMARY

Based upon the analysis of salinities and water levels in the BTES, the overall water level and salinity patterns are characterized as follows.

(1) The coastal water level patterns within the BTES is typically a diurnal tidal signal of 30–40 cm (12–16 in) which is superimposed on a lower frequency (~3 days), higher amplitude (up to 1 meter) signal. The tidal fluctuations explain 60–70% of the water level variations. The lower frequency signal is mainly due to atmospheric forcing events (frontal passage). In general, the coastal water levels exhibit ~1 m (3.2 ft) of movement throughout the year (tides and fronts combined). The tidal amplitude decreases as one moves inland. In Barataria, the tidal signal has decreased to <5 cm (1.9 in) at des Allemands. There is not enough data from Terrebonne to determine the "head of tides."

(2) The water level patterns in the fresh and intermediate marshes were similar to those in the brackish marshes:

- Water levels measured in these systems were characterized by a diurnal tidal signal superimposed upon other, longer period signals.

Table 6.14. Summary of trends in mean monthly salinity and water levels, based upon the results of a linear model without a month and date interaction, for various year classes. Listed is the slope of the salinity trend (ppt / yr) the slope of the water level trend (cm / yr), and the r-square for the fit. Trends were not significant (at the 95% level) for stations marked with the symbol .ns; all other trends were significant at the 95% level. Year classes for which there was no data are marked with the symbol .nd.

	Year Class					
Station	55–65	65–69	69–72	72–85	85–90	90–94
			Salinity Trends in ppt/yr			
S03780	0.00	-0.01	0.00	0.00	.nd	.nd
S52800	0.50	-0.02	-0.02	0.01	0.04	.nd
S52880	.nd	.nd	.nd	.nd	0.09	-0.37
S76303	.nd	.nd	1.31	0.34	.nd	.nd
S76320	0.07	-0.01	0.29	0.02	0.09	.nd
S76323	0.00	0.15	0.34	0.32	.nd	.nd
S76343	-0.14	-0.01	-0.01	0.02	0.08	.nd
S76403	0.09	0.05	0.22	0.06	.nd	.nd
S82203	.nd	.nd	0.45	0.01	0.41	.nd
S82300	-0.10	0.15	1.22	0.04	.nd	.nd
S82350	0.64	-0.01	1.31	1.06	.nd	.nd
S82700	.nd	.nd	.nd	0.29	.nd	.nd
S82750	0.15	-0.12	1.23	0.15	.nd	.nd
S82875	0.13	-0.16	0.70	0.11	-1.80	.nd
S315	1.45	0.60	-0.05	-0.14	-0.36	-0.22
S317	.nd	.nd	.nd	0.08	-0.65	-1.16
S323	.nd	.nd	.nd	.nd	-2.21	7.45
S325	.nd	.nd	.nd	0.91	-0.17	-0.45
S326	.nd	.nd	.nd	.nd	-13.46	-0.45
S416	.nd	0.33	-9.77	0.05	.nd	.nd
S518	.nd	-4.54	3.74	0.02	.nd	.nd
			Water Level Trends in cm/yr			
S03780	-0.03	0.15	0.03	0.02	0.06	0.00
S03850	.nd	.nd	.nd	1.17	0.55	2.76
S52800	0.00	2.21	6.02	-1.62	0.96	-2.29
S52880	.nd	3.19	6.87	-1.73	-2.68	-1.57
S76320	-0.47	2.09	7.32	-0.19	2.48	-1.65
S82301	.nd	.nd	.nd	1.46	1.56	2.34
			Water Level Trends in cm/yr			
S82350	-0.26	0.55	9.20	0.69	1.79	1.58
S82700	0.46	-0.27	6.73	-0.18	-0.92	-7.64

S82750	-0.45	-0.30	6.56	0.19	1.36	-1.78
S82875	0.54	0.34	6.42	0.59	0.80	-1.36
S88350	.nd	.nd	.nd	2.03	2.97	-15.08
S88600	2.57	-1.05	-6.33	0.63	2.21	0.69
3731	0.39	1.11	7.41	0.83	1.34	.nd

- The longer period events (three days and greater) were the dominant time scales for the measured fluctuations. At sites where there was a noticeable diurnal tidal signal, it was responsible for less than 50% of the fluctuations.

(3) At the longer time scales (lower frequencies) of several days (or greater) the water level and salinity patterns are quite similar throughout each of the Estuaries, as evidenced by the strong relationship between water levels at Grand Isle and various stations throughout the BTES.

(4) The systems exhibits a bi-model seasonal water level pattern with peaks in May–June and September–October.

(5) The system exhibits a seasonal pattern of salinity in which the peak occurs in October–November, often with a secondary (but less pronounced) peak in April–May.

(6) The coastal salinities are inversely related to the Mississippi River flow. Wiseman et al. (1990) found that Mississippi River discharge accounted for 30 to 50% of the variance of Louisiana coastal salinities (Grand Terre, St. Mary's Pt., Cocodrie, and Sister Lake). Although the models were statistical, they are consistent with a model of downstream (westward) dispersion of waters discharged from the Mississippi coupled with an upstream dispersion within the estuaries.

(7) There is excellent agreement between daily water levels and salinities estimated from hourly values and from daily 8 am readings, indicating that the daily 8 am readings are adequate to characterize the systems. However, hourly data are needed to investigate the dynamics of the system.

(8) Data collected on marsh flooding indicate that the coastal marshes are flooded on the order of 50–80% of the time.

(9) Data collected on the relationship between salinities in the marsh substrate and in adjacent open water bodies indicate that, in general, the soil salinities (in brackish and salt) respond to variations on the order of several days, and reflect the mean of the open water salinity as opposed to the maximum or minimum. Thus, the soil salinity is moderated relative to the fluctuations in the adjacent water body.

Based upon the analysis of the long-term monthly water levels at 15 stations in the BTES and 21 monthly salinity stations in the BTES, the following general conclusions can be made:

(1) The long-term (20+ year) water level records in the BTES showed relative sea level rises ranging from essentially zero to ~2.0 cm / yr (6.5 ft / century). Stations nearer to the coast tended to have more rapid rises than the inland stations (at least for Barataria).

(2) Analysis of long-term (20+ year) salinity stations indicated that there is no generalized coastwide increase in salinity for the estuarine waters, indicating that widespread salinity increases have not occurred. However, specific stations may show an increase which may be of local importance. For example, the salinities at Barataria, Lafitte, show an increase in the number of higher salinity "spikes" (>5 ppt) after about 1960. Possibly this is an effect of the Barataria Waterway.

(3) Analysis of the water level records by year class indicated that the increase in water levels were not the same over each time period, the most dramatic change was the 1969–1972 period. The general trends are summarized below (many of the small trends were not statistically significant):

pre 1955:	no data
1955–1965:	small trends (0.5 cm / yr), 5 were positive, 4 were negative
1965–1969:	moderate trends (~2.0 cm / yr), 7 were positive, 3 were negative
1969–1972:	large trends (>6.0 cm / yr), 9 were positive, 1 was negative
1972–1985:	moderate trends (~2.0 cm / yr), 9 were positive, 4 were negative
1985–1990:	moderate trends (~2.0 cm / yr), 11 were positive, 2 were negative
1990–1994:	moderate trends (~2.0 cm / yr), 5 were positive, 7 were negative.

(4) Analysis of the salinity records by year class indicated that the increase in salinities was not the same over each time period. The most dramatic change was the 1969–1972 period. The general trends are summarized below (many of the small trends were not statistically significant):

pre 1955:	no data
1955–1965:	small trends (<0.1 ppt / yr), 9 were positive, 2 were negative
1965–1969:	small trends (<0.1 ppt / yr), 5 were positive, 8 were negative

1969-1972: large trends (>1 ppt/yr), 11 were positive, 4 were negative
1972–1985: moderate trends (~0.1 ppt/yr), 17 were positive, 1 was negative
1985–1990: small trends (<0.1 ppt/yr), 5 were positive, 6 were negative
1990-1994: large trends (>1 ppt/yr), 1 was positive, 5 were negative.

CONCLUSIONS

The BTES is characterized by a salinity structure determined by the balance between a source of higher salinity water from the Gulf endpoint and the fresh water entering the system primarily from precipitation-produced runoff. The salinity of the Gulf endpoint is influenced by the freshwater plume of the Mississippi River. The precipitation-produced runoff enters the system through a complex series of coastal swamps and wetlands, providing a mechanism for the slow release of fresh water over large wetland areas (Gosselink 1985). Model results from Light et al. (1973) showed the upper basins to be important to generating and conserving freshwater flow. It is in these upper basins that management can most effectively influence estuarine conditions. The natural system, however, has had extensive hydrologic modification that has changed the way in which water (and salt) move through the system, causing problems such as impoundment and saltwater intrusion, which can lead to vegetation loss.

The existing water level and salinity data bases show no coherent coast-wide trends that can explain all of the land loss or change. The trends showed a mixture of both positive and negative trends, depending upon location. The trends observed in the water level and salinity data are also very much dependent upon the length of record used in the analysis—the longer the record the better. There are very few records that cover the ~40-year period over which the vegetation changes have been observed. In addition, the long-term trend signals are very difficult to find in the data due to the large amount of "noise" (natural variation).

Sasser (1977) described the broad empirical limits of vegetation species distribution in the Louisiana coastal zone as related to flooding and salinity. His results suggest that a species shift from *S. patens* to *S. alterniflora*, for example, can be caused either by an increase in flooding, an increase in salinity, or a combination of the two. This points out the need to examine the water levels and salinity patterns on a case-by-case basis to ascertain the most probable cause of vegetative loss (or change) for a given area.

PART 7

CAUSES OF WETLAND LOSS

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SPATIAL AND TEMPORAL SCALES

The causes of wetland loss operate at many scales. Global warming and resulting sea level rise lead to marsh submergence in decades or more, and affect marshes worldwide (Figures 7.1 and 7.2). The same can be said for province-scale cycles of wet and dry years caused by El Niño southern oscillation climate events. Closer to home, construction of flood-control levees on the Mississippi River has prevented the spring overbank flooding that formerly nourished the coastal marshes with fresh water and river sediments. Upstream dams on the tributaries have reduced the sediment load of the river. Confinement in its channel forces river water and sediments onto the continental shelf where most of the sediments are lost to the coastal system.

Within the Barataria-Terrebonne estuarine system (BTES), subsidence and compaction of marsh sediments occurs, varying spatially according to the depth of Recent deposits, age, the composition of underlying geological strata, and the location of faults. Circulation no longer delivers fresh water and sediments where it used to as patterns of flow have changed, not only because of natural processes but also by the complex pattern of drainage ditches, navigation channels, and oil and gas access canals that have been dredged across the landscape. The balance of fresh and marine water is changed and saltier water reaches farther inland, or is excluded by spoil banks and constructed levees. Dredged material deposited along canals and large structural marsh management projects limit, control, or deny surface flows across the marsh, and/or impound water on it. Increases in fertilizer use have elevated nitrogen and phosphorus concentrations in the Mississippi River. This and local runoff from fertilized fields eutrophy estuarine waters and change loading rates to coastal marshes.

At an even more local scale, the fate of a marsh is determined by a complex interaction of plant species, local flooding regimes, circulation patterns that determine mineral sediment inputs, and the extent of damage caused by waterfowl and mammalian herbivory. At this scale, remote events such as sea level rise and canal construction are recorded simply as changes in depth, duration, and frequency of flooding, and as changes in mineral sediment and nutrient input, without regard to the cause. It is these local changes that determine whether a small parcel of marsh remains viable or degrades to an open water body. Thus, understanding the local processes is the key to understanding and managing the basin system to minimize wetland loss and to restore lost marshes. This section describes what is understood about the local processes that result in interior marsh degradation and loss. Interior marsh loss accounts for 67% of coastal losses (Wayne et al. 1994), and is probably less well understood than shoreline erosion. Although interior marsh loss has been studied intensely at all scales (see the list of references), many of the insights about local processes have been achieved within the last few years. Even so, important questions remain unanswered, as will become apparent in the following discussion.

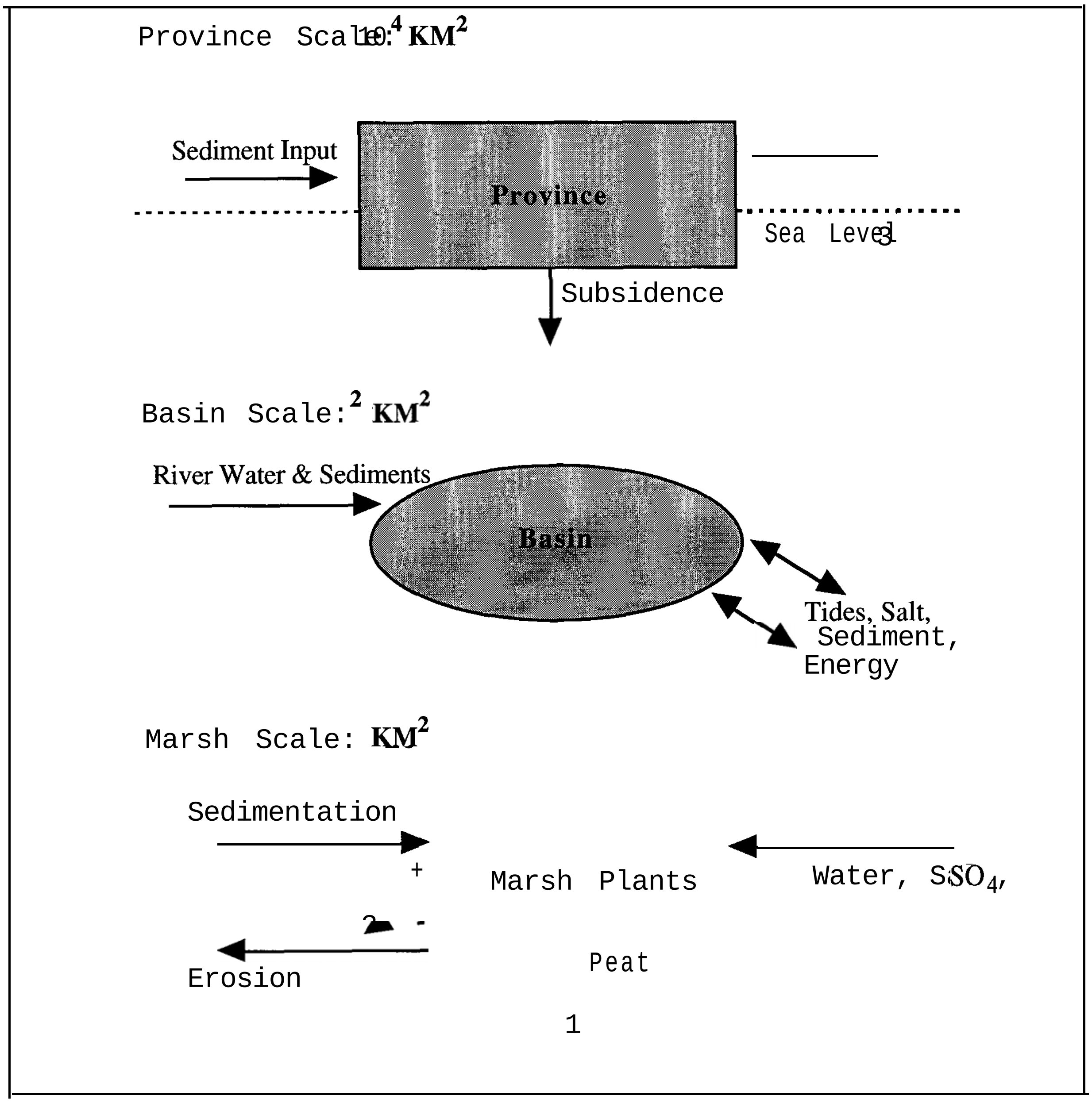
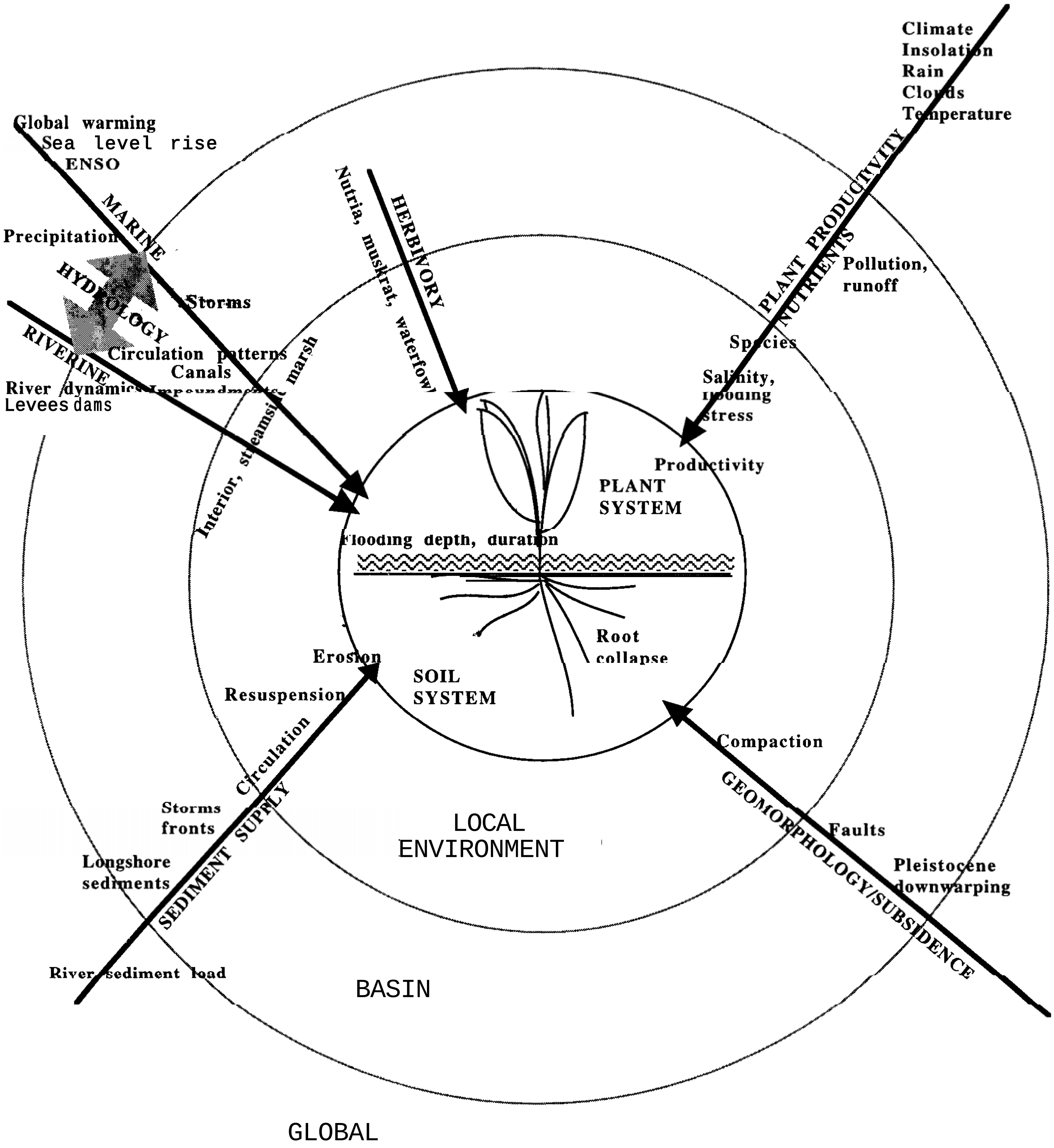


Figure 7.1. Conceptual framework of dominant processes operable over three spatial scales in Louisiana's coastal wetlands (Boesch et al. 1994).



SCALES OF PROCESSES CONTROLLING WETLAND LOSS

Figure 7.2 The continuum of scales controlling wetland loss in the Louis
coastal zone.

INTERIOR WETLAND LOSS

Accretion Deficit

Interior marshes flourish or degrade depending on whether or not they remain in the intertidal zone. Plants growing in a local marsh patch "see" only the duration, frequency, and depth of flooding, which ultimately is determined by two sets of opposing processes: a rise in relative sea level (RSL, the water level relative to the wetland surface), which is the net effect of (1) eustatic sea level rise; (2) isostatic factors, including crustal downwarping, compaction of Tertiary, Pleistocene and Holocene deposits, consolidation of marsh soils and sediments, and tectonic activity, all of which increase the depth and duration of flooding (Figure 7.3); accretionary processes composed of (3) mineral sediment and organic detritus introduction; and (4) organic production of live roots by emergent plants. When RSL rise exceeds accretion plants sink slowly below the water level, are unable to survive the increasingly anoxic root environment, and die. Without root aggradation, and a healthy root system to hold the soils together, the substrate erodes and the marsh disappears below the surface of the water.

Eustatic sea level rise is driven by such processes as global warming, expansion of warming ocean water, and episodic glacial melting. The mean global eustatic rise has been estimated at between 0.09 to 0.30 cm yr^{-1} (0.04 to 0.12 in yr^{-1}) (Gornitz and Lebedeff 1987, Kraft 1971). In the Gulf of Mexico, eustatic sea level ranges from 0.23–0.24 cm yr^{-1} (0.091 to 0.094 in yr^{-1}) (Gornitz et al. 1982, Penland et al. 1989a, Ramsey and Penland 1989).

RSL rise has been estimated at about 1 cm yr^{-1} (0.39 in yr^{-1}) in the Barataria and Terrebonne basins (Ramsey 1991), but varies across the area, depending largely on the thickness of Holocene sediments. For example, Coleman and Roberts (1989) showed a four-fold increase in subsidence rates between an area of thin Recent (Holocene) sediment fill over the Pleistocene surface and an area of thick Recent fill (Figure 7.4). Turner (1991) analyzed records from 42 Louisiana tide gauge stations and found variations in RSL rise from 0.2 to 2.7 cm yr^{-1} (0.08 to 1.06 in yr^{-1}). He stated, "In effect, relative water level rise recorded on the gauges is lowest where deltaic sediment accumulations are thin and old, and away from barrier islands and human-made water control structures" (Turner 1991, p. 144). Most of the compaction occurs in the upper 2 m (6.5 ft) of the sediment profile, and is due primarily to biological processes (peat decomposition) in the first few years, after which sediment compaction and soil dewatering appear to predominate (Figure 7.5). Mineral lenses in the depth profile compact very little compared to organic deposits (Penland et al. 1994). Comparing eustatic rates to RSL rise, it is clear that under most conditions found along the Louisiana coast eustatic sea level rise is a minor portion of total RSL, varying from 50% to <10%. Most of RSL is related to subsidence of the marsh surface.

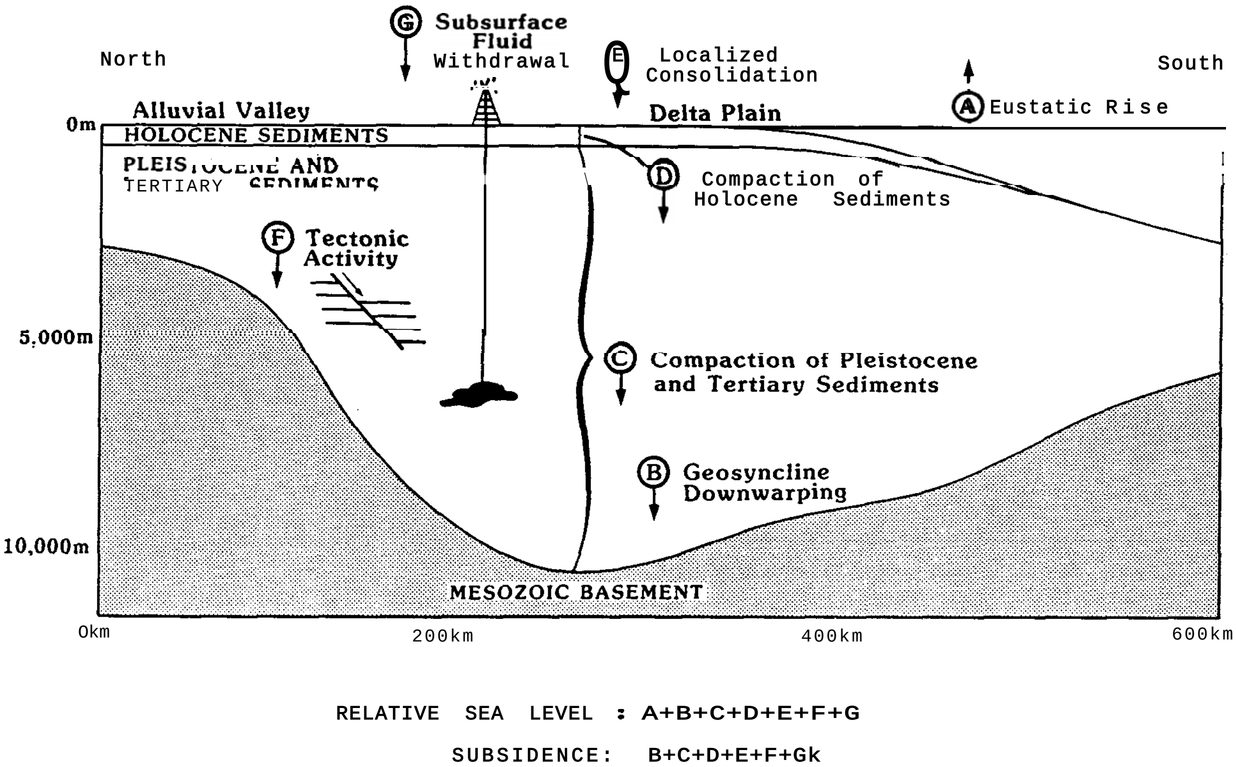


Figure 7.3 Factors controlling relative sea level in the Mississippi R
(Penland et al. 1988b).

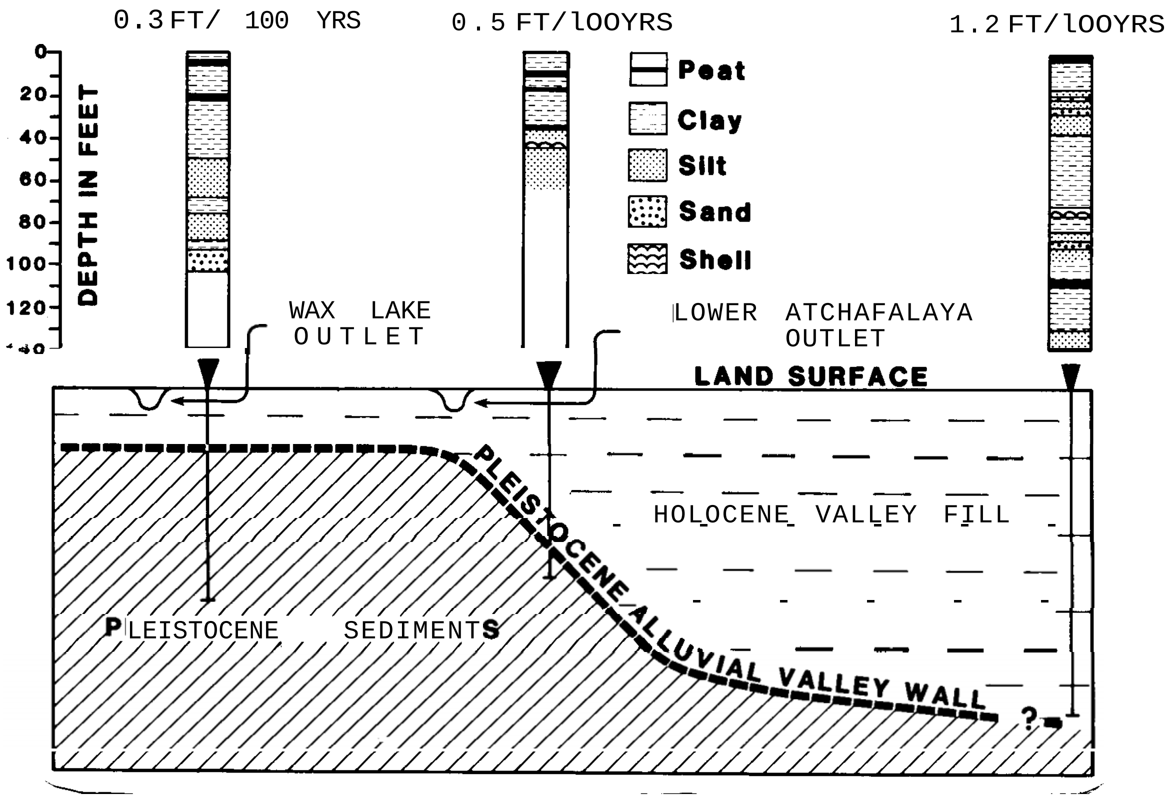


Figure 7.4. Subsidence rates across the central Louisiana coastal plain (Rober 1985).

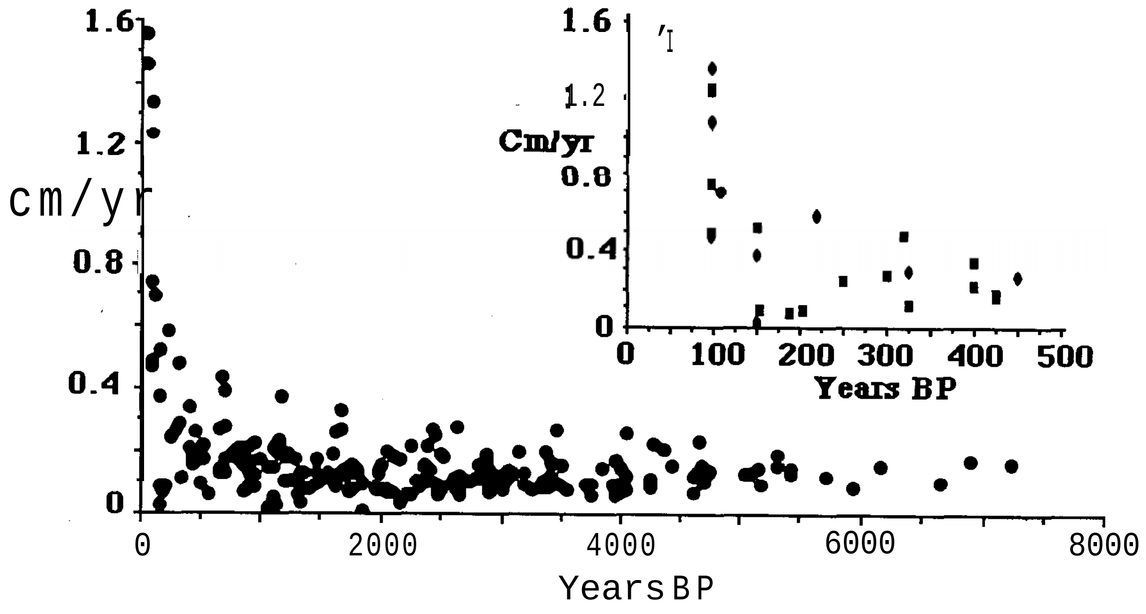


Figure 7.5. The burial rate of ^{14}C-dated sediments (Turner 1991); data from Frazier (1967) and Penland et al. (1987).

Vertical accretion to balance RSL rise occurs as mineral sediments are carried into a marsh, and as roots grow, raising the marsh substrate. Recent analyses (Boesch et al. 1994, Day et al. 1994, Gosselink et al. 1984, Nyman et al. 1990) demonstrate that the balance between root production and decomposition is the major mechanism of accretion in all organic-rich marshes of the inactive delta (including all of the BTES). For example, Gosselink et al. (1984) analyzed a wide range of soils from Louisiana wetlands, with bulk densities from 0.05–0.60 g cm^{-3}. Bulk density was linearly related to mineral density, but was independent of organic carbon density, which was constant at ~26 mg cm^{-3} (~50 mg cm^{-3} organic matter) of soil. This implies that the organic material forms a structural framework with a constant ratio of mass to volume in highly organic marsh soils, while mineral sediment infiltrates this matrix and determines bulk density but not volume. Most freshwater marshes in inactive Mississippi River delta lobes such as the Barataria and Terrebonne basins contain little mineral material, and bulk density increases as marine influence (and sediment introduction) increases. On a volume basis, organic matter occupies more volume than mineral matter in all but salt marsh soils (Table 7.1, Nyman et al. 1990). However, the sum of mineral and organic volume is seldom more than 10% of the total soil volume. The rest is occupied by water and gasses. Live roots in anaerobic conditions develop extensive aerenchyma (Burdick 1989, Jackson et al. 1985) and it seems likely that the structural integrity of live roots is important in maintaining both the soil volume and the gas volume of the soil (DeLaune et al. 1994).

In the inactive delta of the Mississippi River, most marshes appear to have an annual accretion deficit, that is, accretionary processes are not keeping up with RSL rise. This is demonstrated by data from many studies (Bricker-Urso et al. 1989, Cahoon and Turner 1987, Delaune et al. 1983a, Dolan et al. 1985, Hatton et al. 1983, Penland et al. 1986, Penland et al. 1989a, Ramsey and Penland 1989, Reed and Cahoon 1993, Roberts 1985, U.S. Geological Survey 1988), and illustrated in Figure 7.6. Whereas RSL rise rates are typically >1 cm yr^{-1} (0.39 in yr^{-1}) accretion rates are on the order of 0.6–0.9 cm yr^{-1} (0.24 to 0. 35 in yr^{-1}), except in the active Atchafalaya River delta and along some active streams. Thus there is an accretion deficit in most of the basin marshes, and this is directly translated into loss of marsh to open water (DeLaune et al. 1983b).

The Role of Organic Production and Decomposition

Organic material for accretion occurs mostly through the growth of plant root system. Vertical organic accretion is determined by the balance between production and senescence/decomposition (Day et al. 1994, Nyman et al. 1990, Nyman and DeLaune 1991b). If there is net submergence, then plants are stressed by increased flooding (Pezeshki et al. 1988a, Pezeshki et al. 1988, Mendelssohn and Burdick 1988, Burdick 1989), leading to a lower photosynthetic rate (Pezeshki et al. 1989, Pezeshki et al. 1987a), sulfide toxicity in marine-influenced areas (Pezeshki et al. 1988b, DeLaune et al. 1983, Mendelssohn and McKee 1988), elevated respiration rates, and reduced mineral absorption (Bandyopadhyay et al. 1993, Pezeshki et al. 1988b). The result is

Table 7.1. Bulk density, percentage organic carbon by weight, vertical accretion rates, mineral matter, and water and gas in the upper 10 cm of soil from inland marshes of the Mississippi deltaic plain (Nyman et al. 1990).

Marsh Type	No.of sites	No. of cores	Bulk density (g cm $^{-1}$) Mean	(SD)	Organic carbon (% dry wt) Mean	(SD)	Vertical accretion[1] (cm year $^{-1}$) Mean	(SD)	Percent by volume: Organic matter	Mineral matter	Water & gas
Active											
Fresh	3	7	0.14	(0.05)	19.19	(4.32)	0.86	(0.108)	4.91	3.18	91.91
Inactive											
Fresh	2	8	0.07	(0.03)	17.29	(4.91)	0.67	(0.015)	2.36	1.63	96.02
Intermediate	1	7	0.08	(0.05)	25.50	(5.52)	0.64	(0.38–1.06)[r]	3.96	1.33	94.70
Brackish	4	17	0.16	(0.07)	16.45	(4.41)	0.72	(0.077)	5.11	4.03	90.86
Saline	7	18	0.24	(0.11)	12.24	(5.95)	0.72	(0.137)	5.27	6.89	87.84

[1]Vertical accretion rates were determined at the same sites, but from a total of 69 cores.
[r] Range.

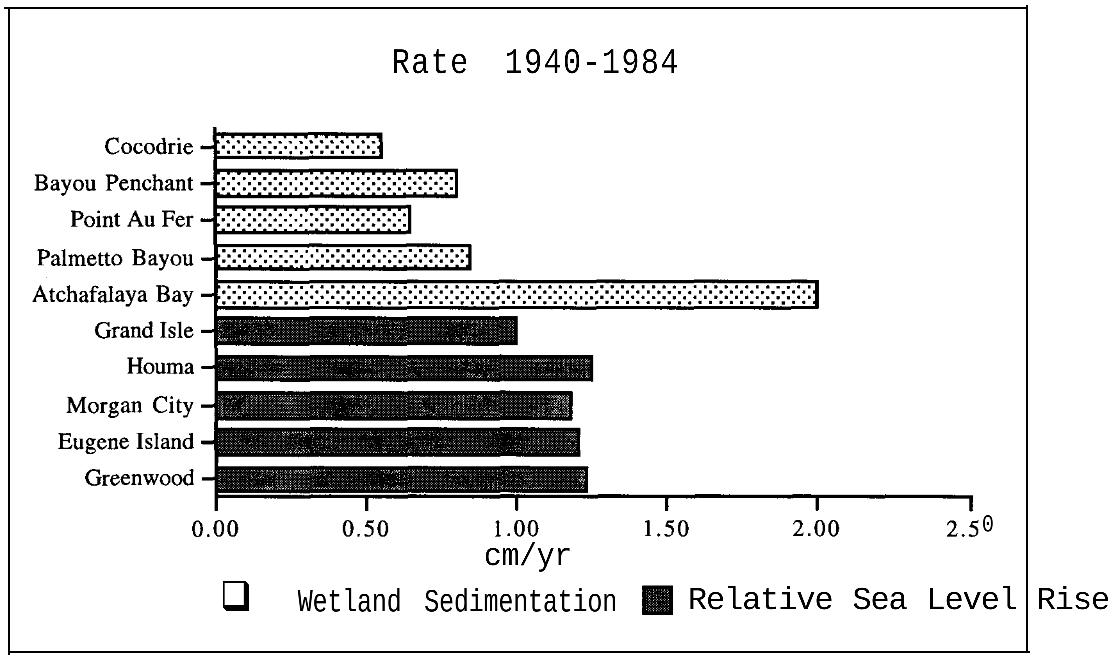


Figure 7.6. Sedimentation rates compared to relative sea level rise for sites i Mississippi River delta plain (Penland et al. 1988). Only in the active delta of the Atchafalaya River is sedimentation keeping up with sea level rise.

lower net production. Under these circumstances, many plants shift more production to roots (Good et al. 1982), but this reduces leaf area and may further reduce net primary production. If root production decreases as a result of flooding stress, vertical accretion also decreases and primary production is further reduced. Thus a positive feedback loop is established that leads to plant death and cessation of organic deposition in the root zone (Nyman et al. 1993a).

The roots of many flood-tolerant plant species respond to anaerobic stress by an increased production of aerenchyma (Burdick 1989, Jackson et al. 1985, Naidoo 1985, Pezeshki et al. 1991, Smits et al. 1990, Webb and Jackson 1986), which presumably increases the diffusion of oxygen from aerial parts of the plant to the roots. Increased aerenchyma is associated with lower specific gravity, a measure of the increased gas content of the roots (Naidoo et al. 1992), and perhaps also of the decreased strength of the root system. The response is species specific. In *Spartina patens* aerenchyma development does not improve oxygen availability to the roots sufficiently to compensate for increased flooding, since there is a simultaneous significant increase in metabolically inefficient anaerobic fermentation, as determined by an increase in alcohol dehydrogenase activity (Naidoo et al. 1992, Pezeshki et al. 1991). *Spartina alterniflora*, under similar flooding conditions that stimulate the formation of aerenchyma, shows no shift to anaerobic metabolism (Naidoo et al. 1992). Under these conditions *Spartina alterniflora* will produce numerous positively gravitropic roots, but *Spartina patens* produces few and these tend to be negatively gravitropic and protrude up 8 to 10 cm (3.15 to 3.9 in) above the soil surface (Naidoo et al. 1992).

Despite its apparent importance, the role of plant root production and decomposition in wetland loss has been virtually ignored until recently, and there are no comprehensive studies of the dynamics of root production, decomposition, and peat formation in degrading marshes. The following discussion is pieced together from a number of different studies.

Table 7.2 summarizes most of the available data on production and roots dynamics of three dominant plant species in the Louisiana coast. They represent the major marsh types: salt marsh (*Spartina alterniflora*), brackish marsh (*Spartina patens*), and fresh marsh (*Panicum hemitomon*). There are large differences in the soil and root characteristics of these three species. Organic density in all the soils is fairly constant at about 50 mg ml^{-1}, and shows no consistent change with depth, but bulk density (g cm$^{-3)}$ usually increases from fresh marshes (0.05) to brackish marshes (>0.07) to salt marshes (>0.2). This increase reflects the higher mineral content of soils near the coast, which are exposed to higher energy flooding water with larger suspended sediment loads.

Belowground root dynamics are difficult to determine, because of the difficulty of separating live roots from the rest of the organic matrix. As a result, most studies of "root" biomass and production actually refer to "macro-organic matter" (MOM), which is the material left after the soil sample is washed thoroughly through a fine screen. (The size of the screen varies in different studies, but in the Sasser et al. (1994) and Valiela et al. (1976) studies cited in Table 7.2, the screen mesh openings

Table 7.2 Soil and plant properties of dominant species.

Species		BULK Density	ORGANIC content	MOM	ROOTS Live	ROOTS Prod	ROOTS Time	ABOVEGROUND Biomass	ABOVEGROUND Rod	TOTAL Rod.	ROOT:S Biomass
		g ml⁻¹	g m⁻²	g m⁻²	g m⁻²	g m⁻² yr⁻¹	years	g m⁻²	g m⁻² yr⁻¹	g m⁻² yr⁻¹	
S. alterniflora	MA			10,100	700	3,500	3.06	320	510		2.80
S. alterniflora	NC					460-500			330–1,300		
S. alt. stream	GA			3,163		2,109	1.5	1,500	3,700		
S. alt. inland	GA			9,595		2,020	4.75	325	1,300		
S. alt. stream	LA							3,600	3,683	6,024	
S. alt. inland	LA							2,000	2,008	3,047	
S. alt. mid	LA							754	2,178		
S. alterniflora	LA							1,473	2,895		
S. alt. inland	LA	>0.2	19,766								
D. spicata	GA	0.6		3,563		1,070	3.33′	395	1,260		
D. spicata	DE	0.3		11,200		3,400	3.33′	856	1,274		
D. spicata	LA							2,194	1,428		
J. roemerian	MS			10,300	~4,000[3]	1,360	3′		1,700		2.35
J. roemarian	GA			812,300		3,358	3.67′	1,250	2,200		
S. patens	MA			8,900	900	2,500	0.36	440	632		2.05
S. patens	GA	1.2		1,750	(585)[2]	309	5.67′	946	3,925		
S. patens	DE			3,620	(990)[2]	472	7.67′	807	2,753		
S. patens	ME	0.2		4,157	(1,400)[2]	542	7.67′	910	5,833		
S. patens -11	LA	0.070	19,535	3,374	1,456	(600)[2]	(3)[2]	828			1.76
S. patens -12	LA	0.068	1,600	5,096	1,231	(500)[2]	(3)[2]	1,091			1.13

Table 7.2 Cont.

S. patens	LA							3,600	3,677	5,702	
S. patens	LA							2.194	1.428		
S.pateos	LA							1,376	4,159		
S.lancifolia	LA	0.047		5,327	1.678			635			2.64
S.falcata								648	2,310		
P.hem/Sag-2	LA	0.106	19,392	3,586	2,614	(1,500)[2]	(1.7)[2]	980			2.67
P.hem/Sag-7	LA	0.110	18,880	2,265	893	(300)[2]	(3.2)[2]	587			1.52
P.hemi-4	LA	0.051	17,868	7,373	3,295	(1,200)[2]	(2.8)[2]	755			4.36
P.hemi-5	LA	0.049	14,875	3,538	2,417	(1,300)[2]	(1.8)[2]	964			2.51
P.hemi-6	LA	0.050	16,262	4,522	2,992	(1,600)[2]	(1.9)[2]	898			333
P.hemi-9	LA	0.056	17,256	7,589	4,770	(2,400)[2]	(2)[2]	1,067			4.47
P.hemi	LA							1,160	1.960		
P.hemi	LA	0.09	18,330					1,500	1,640	2,912	
MEANS											
S alterniflora	LA	xl.2	580	8,000	700	500–3,500	3-5	750–2,000	2,000–3,000	2,500–6,500	0.7
S. patens	LA	>0.07	400	4.000	1350	-500	-3	~2.000	1.500–5.000	2.000–6.000	0.7
P. hemitomoa	LA	0.05	475	5,780	3,370	(1,500)[2]	(2.1)[2]	970	1,800	3,150	3.5

[1] MOM/Production (Gallagher and Plumley 1979)
[2] Estima Turnover time=1.25(MOM)/Live Roots Production-Li Roots/Turnover time
[3] from Eleuterius (197 [Eleuterius, 197 #1900]

References:
(1) De Cruz and Hackney 1977, (2) Gallag Plumley 1979, (3) Gallagh 1980, (4) Gosselink et al. 197 Hatton (5) et al. 198 Linthurst et al. 197 Ny
(8) Pezeshki DeLaune 1991, (9) Sa and Gosselink 1984, (10) Sasser et (11) Stroud 1976, (12) Valiela 1975, (1 Valiela et al. 1976, White et al.

were 0.5 mm (0.02 in).) Washing removes most of the mineral content and the finely decomposed peat. What remains is probably the fraction largely responsible for the structure of the soil, and is a mixture of live roots and dead roots in early stages of decomposition (Figure 7.7). MOM is a variable fraction of total organic content. It decreases with depth as decomposition occurs, and varies with species.

Live root biomass is a variable fraction of MOM. Usually, greatest live biomass is in the surface increment of the soil, and decreases with depth, but in some species live biomass is fairly constant to the depth of rooting, or has a peak somewhat below the surface, especially in species with a large biomass of rhizomes (Gallagher and Plumley 1979, Valiela et al. 1976). Examples from Louisiana are illustrated in Figure 7.8. Note that total organic matter, on a volumetric basis, is fairly constant with depth, that *P. hemitomon* has larger MOM and surface live root masses than has *S. patens*, but that they decrease more rapidly with depth. This is probably a reflection of a faster MOM decomposition rate in *P. hemitomon*, a suggestion borne out by the estimates of root turnover times in Table 7.2, and by the soil respiration rates quoted by Nyman and Delaune (1991a). There appear to be no comparable data on MOM and live root biomass for *S. alterniflora* from Louisiana, but data from Valiela et al. (1976) show the same sort of depth curve.

Root and rhizome biomass vary seasonally. In Massachusetts *S. alterniflora* marshes, both rhizomes and roots peak in mid-summer (Valiela et al. 1976). At the same time dead material reaches its annual minimum. The same pattern is also seen for *S. patens* but not as clearly. The pattern suggests early rapid growth of live material while dead material is decomposing. Later in the year the death of live roots and rhizomes builds up the dead biomass again.

Average live belowground biomass appears greater in *P. hemitomon* (3370 g m^{-2}) than in *S. patens* (1350 g m^{-2}), and even lower in *S. alterniflora* (900 g m^{-2}). In Massachusetts low live biomass is combined with very high belowground production and MOM, suggesting that live tissues have a high turnover rate (3–5 times per year), but decomposition of dead material is slow (10 yr for *S. patens*, 11 yr for *S. alterniflora*). Gallagher and Plumley (1979) compared belowground production rates and turnover times in Georgia, Delaware, and Maine, and found that production, MOM turnover time (5+ yr in Georgia, 7+ yr in New England), and MOM all increased with latitude. In colder climates decomposition is slowed, leading to both longer turnover times and larger standing stocks. Louisiana data pieced together from several studies, support the results of Valeila and Gallagher and their co-workers except that decay rates are generally faster in Louisiana. Root turnover is 0.9 and 0.63 yr, and root decay is 6.6 and 3 yr for *S. alterniflora* and *S. patens*, respectively. *P. hemitomon* live roots live much longer (T=2.8 yr) but MOM decomposition is more rapid (only 1.7 yr).

The Louisiana root production values (Table 7.2) are calculated from Pezeshki and Delaune (1991), who measured total net production of the three species of interest by CO_2 flux analysis, and aerial production by harvest. The difference sets an upper limit

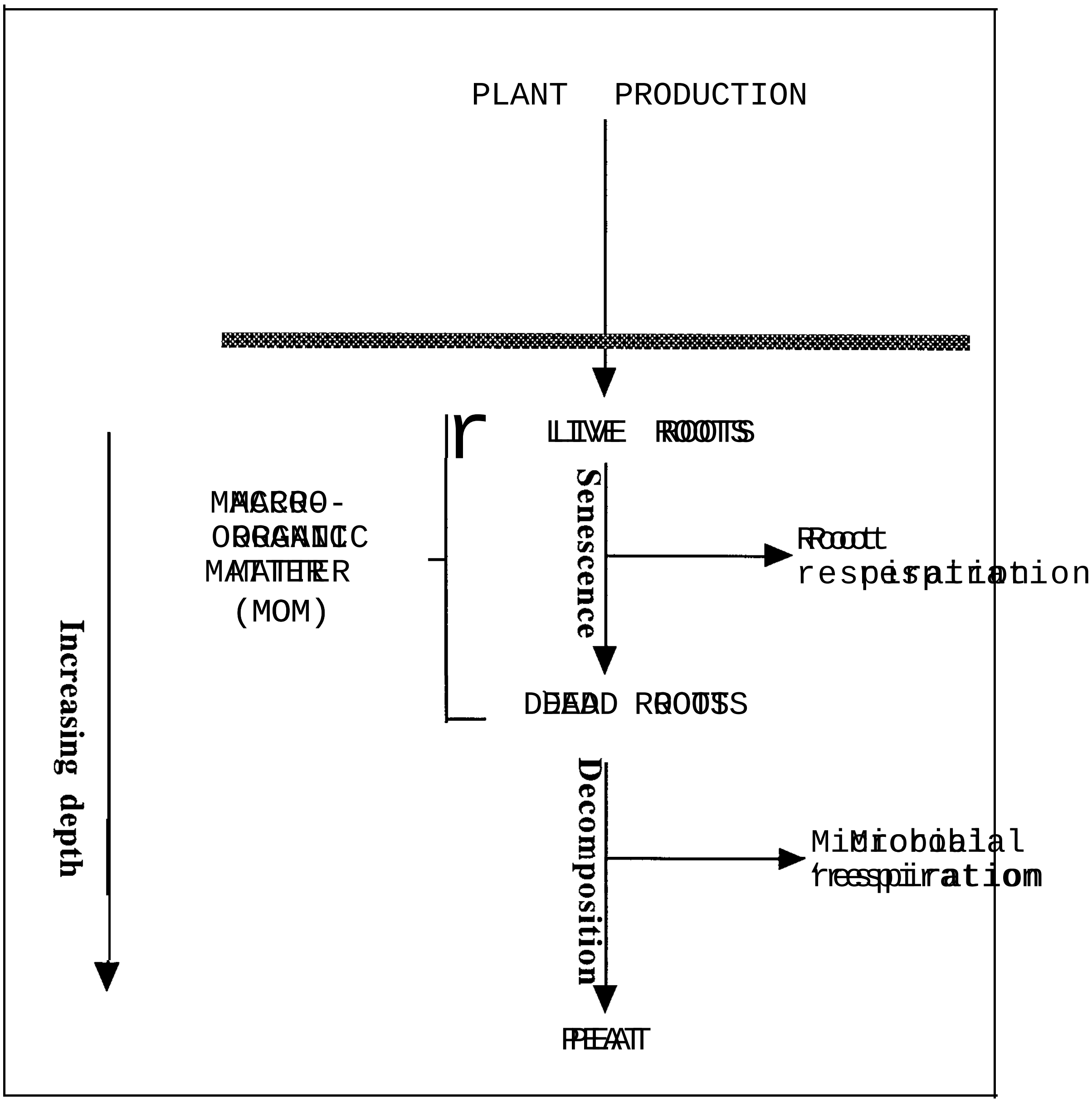


Figure 7.7. Conceptual model of organic matter relationships in marsh soi

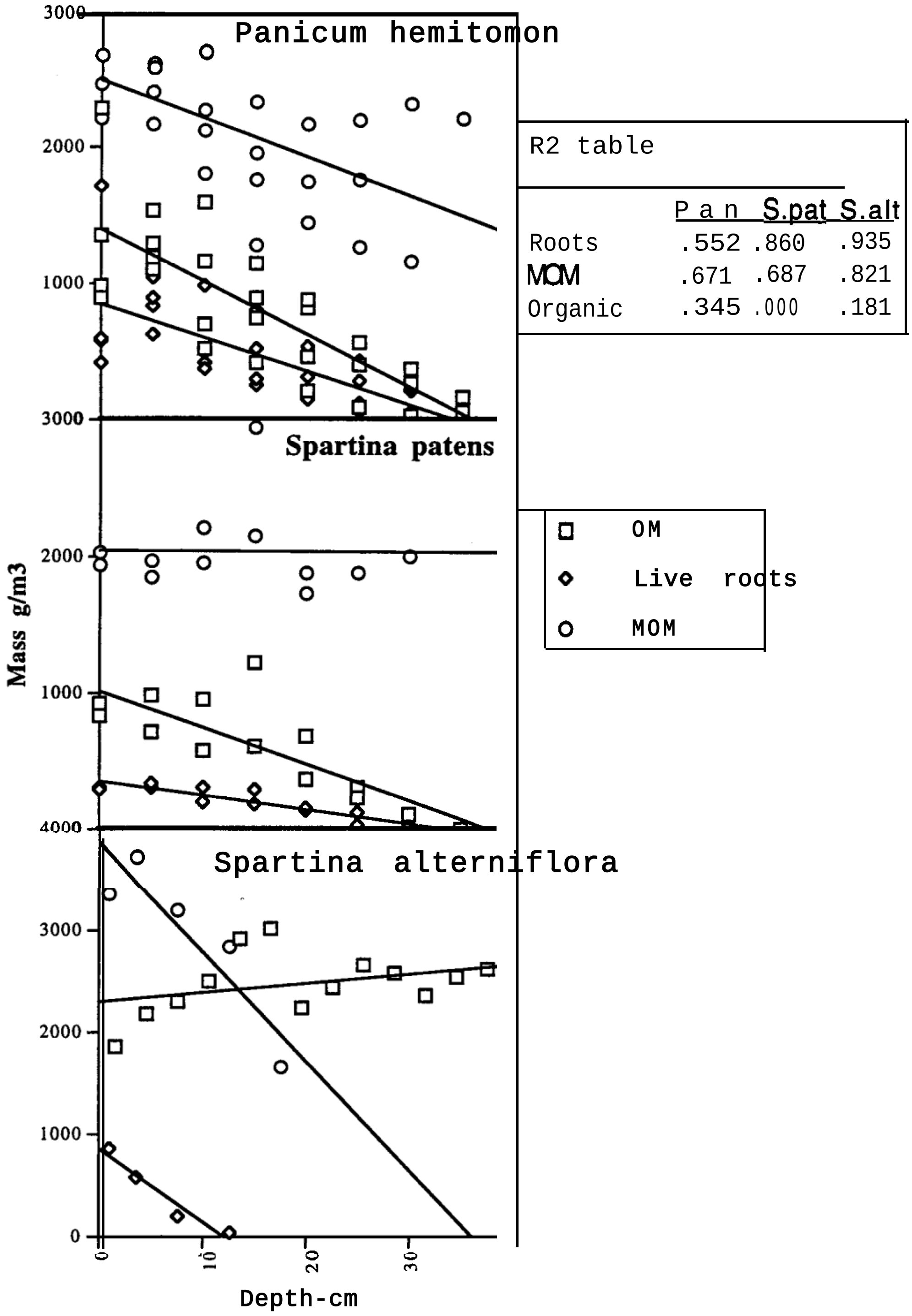


Figure 7.80. Organic components of the P. hemitomon, S. patens, and S. alterniflora marshes, as they change with depth (data from DeLaune et al. 1981, Sasser et al. 1994, Valiela et al. 1976).

to belowground production (although the harvest technique used probably underestimates aerial production, and no correction was made for belowground respiration). From the difference between net photosynthesis and aerial biomass production, *S. alterniflora* and *S. patens* belowground production are estimated at about 2000 g/m^{-2}, and *P. hemitomon* production at about 1200 g m^{-2}. If these estimates are in the ballpark, it suggests that *S. patens* and *S. alterniflora* both allocate about one-third of their production to root growth, and the roots are relatively short-lived (turnover times <1 yr), while *P. hemitomon* allocates almost one-half to root growth and the roots live longer.

Summarizing the last several paragraphs, it appears that inland *S. alterniflora* is only moderately productive, about one half of that productivity is allocated to the roots, the roots live less than a year, but the dead roots decay very slowly. *S. patens*, in contrast, is highly productive (at least in the environments assayed). It allocates about one-third of its production to roots, but these roots die even faster than those of *S. alterniflora* and the decay rate is also faster. As a result, live root biomass is somewhat greater than for *S. alterniflora*, but total MOM biomass is lower. (This conclusion does not agree with Nyman and DeLaune (1991a), who reported that *S. patens* had lower soil respiration rates than either *S. alterniflora* or *P. hemitomon*.) *P. hemitomon*'s production and root allocation are similar to that of *S. alterniflora*, but the roots live almost three years instead of one. MOM decay rates are the fastest of the three species. The net result is a MOM biomass comparable to *S. alterniflora* but with a much higher proportion of live roots.

When plants die the marsh surface rapidly falls by ~10 cm (4 in) (Day et al. 1994, Nyman et al. 1993). Death of the roots is associated with loss of shear strength of the soil, and these events result in shallow open ponds, too deep to revegetate (Day et al. 1994). Nyman et al. (1993c) call this a collapse of the soil. Day et al. (1994) refer to rapid decomposition, perhaps enabled by the presence of sulfate as an electron acceptor, when plant roots die. Since most of the sediment volume is pore space (Delaune et al. 1983b), probably maintained by functional membranes of live roots, one possibility is that the collapse is mostly a loss of void space as dying roots lose integrity and the ability to compartmentalize air in tissues (DeLaune et al. 1994). If this is true, one would expect a decrease in pore space and an increase in organic density with depth in the soil, associated with a shift from predominantly live roots to dead roots and peat. This apparently does not happen: organic density appears to decrease with depth in *P. hemitomon* marshes, while it remains relatively constant in *S. patens* and *S. alterniflora* marshes (Figure 7.8). One would also expect gas-filled space to be associated primarily with live roots, less with MOM, and least with peat. Pore space in these organic soils is almost always >90% of root volume. It (pore space) does not vary appreciably with depth, indicating that total pore space is little affected by the live root biomass. However, the proportion of total pore space filled with water increases as organic content increases, while gas volume decreases (Figure 7.9). *P. hemitomon* has the largest mass of roots and its gas volume averages 35%. *S. patens* has about one-third the live root biomass of *P. hemitomon* and its gas volume is 24%. These figures suggest that gas-filled pore space is associated with live roots.

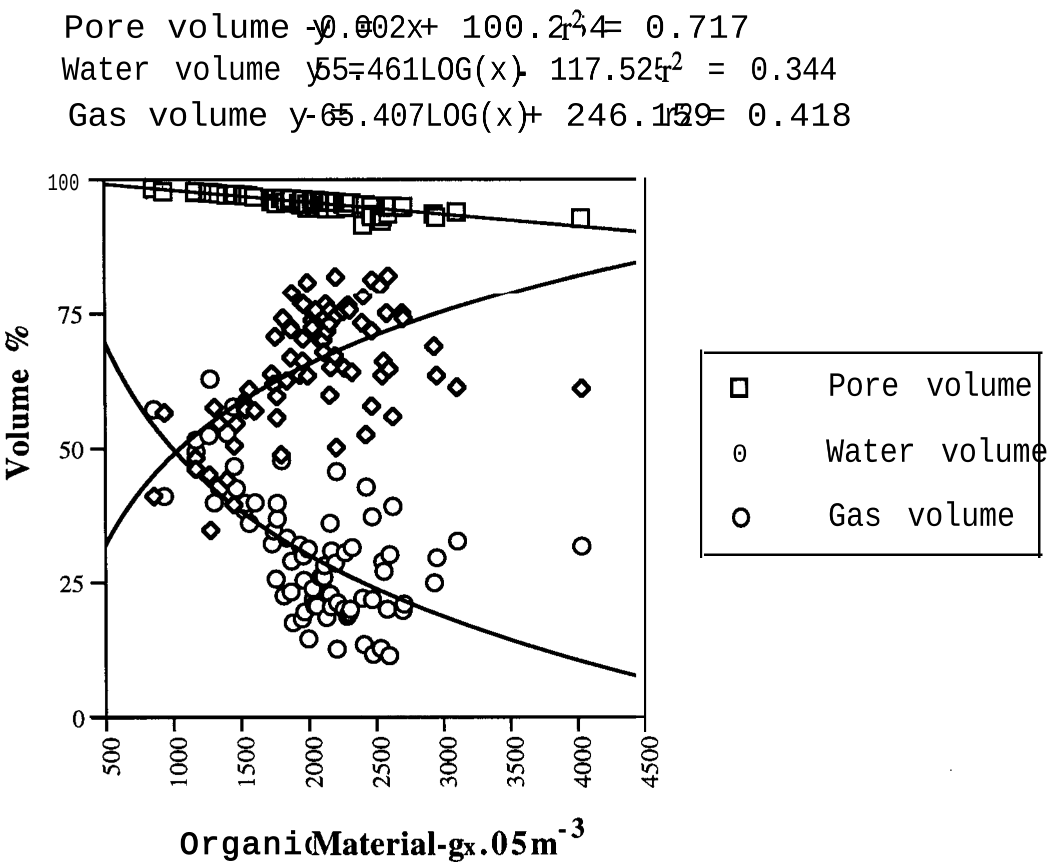


Figure 7.9. The relationship of soil organic content to pore space, gas vo
water volume in Louisiana marsh soils (data from Sasser et al.

However, plots of live roots, MOM, peat (OM-MOM), and total organic material vs. gas volume for these two species show no significant relationship between live root biomass and gas volume, a poor (negative) relationship with MOM and peat, and an R^2 of over 0.5 for gas volume on total organic content (Figure 7.10). Thus, gas volume is replaced by water as organic content increases in the soil, and this replacement is loosely associated with the death of roots (that is, it is associated with the total soil organic content, not with live roots). But most importantly, the loss of gas volume is simply replaced by water volume, and there does not appear to be a significant collapse of the pore space with death of the roots, or with their decomposition.

If the sudden decrease in marsh elevation associated with plant death is not related to collapse of the structure of the root system, then the alternative of a rapid decomposition of root material must be considered. There is no experimental evidence available to evaluate this alternative.

The Role of Mineral Sediment Deposition

Most of the literature about marsh loss in coastal Louisiana has assumed that a deficiency of mineral sediment deposition is a major cause of wetland deterioration and loss, that is, that mineral inputs must be sufficient to make up for the high rate of RSL rise. As discussed above, several recent studies have emphasized the importance of organic root production. If root production is the major source of vertical accretion, then what is the role of mineral sediments? DeLaune et al. (1990) documented a positive relationship between mineral sediments and *S. alterniflora* biomass and noted that *S. alterniflora* is not generally found where soil bulk density <0.2 g cm-3 (equivalent to mineral density of <0.15 g cm^{-3}). Nyman et al. (1994) documented a positive relationship between mineral sediments and *S. patens* biomass. Minimum bulk densities associated with *S. patens* are unknown, however, because even the lowest *S. patens* biomass observed by Nyman et al. (1994) exceeded 500 g/m^2. It is well documented that in tidal portions of the marsh, streamside marshes receive more minerals than inland marshes, sustain more vigorous plants, and accrete more rapidly (Hatton et al. 1983). In contrast, healthy *P. hemitomon* marshes often contain essentially no mineral sediments. In the absence of a direct role in marsh accretion, there have been a number of suggestions about the function of marsh minerals. Marshes have been shown to respond to the nutrient elements contained in mineral sediments (Broome et al. 1975, DeLaune et al. 1979, DeLaune and Pezeshki 1988, Nyman et al. 1994). Another function of mineral sediments may be related to the buffering effect of mineral sediments on the redox potential of the soil, helping to reduce the deleterious effects of highly reduced soils on plant metabolism (Burdick 1988, Ernst 1990, McKee et al. 1989, Mendelssohn and McKee 1987, Morris and Dacey 1984, Pezeshki et al. 1991). In particular, sulfates introduced in sea water and reduced under anaerobic conditions to toxic sulfides by soil bacteria, are precipitated by soil iron, removing them from the soil solution, enabling plant growth in sulfide-rich environments (King et al. 1982, Mendelssohn and McKee 1988). Regardless of

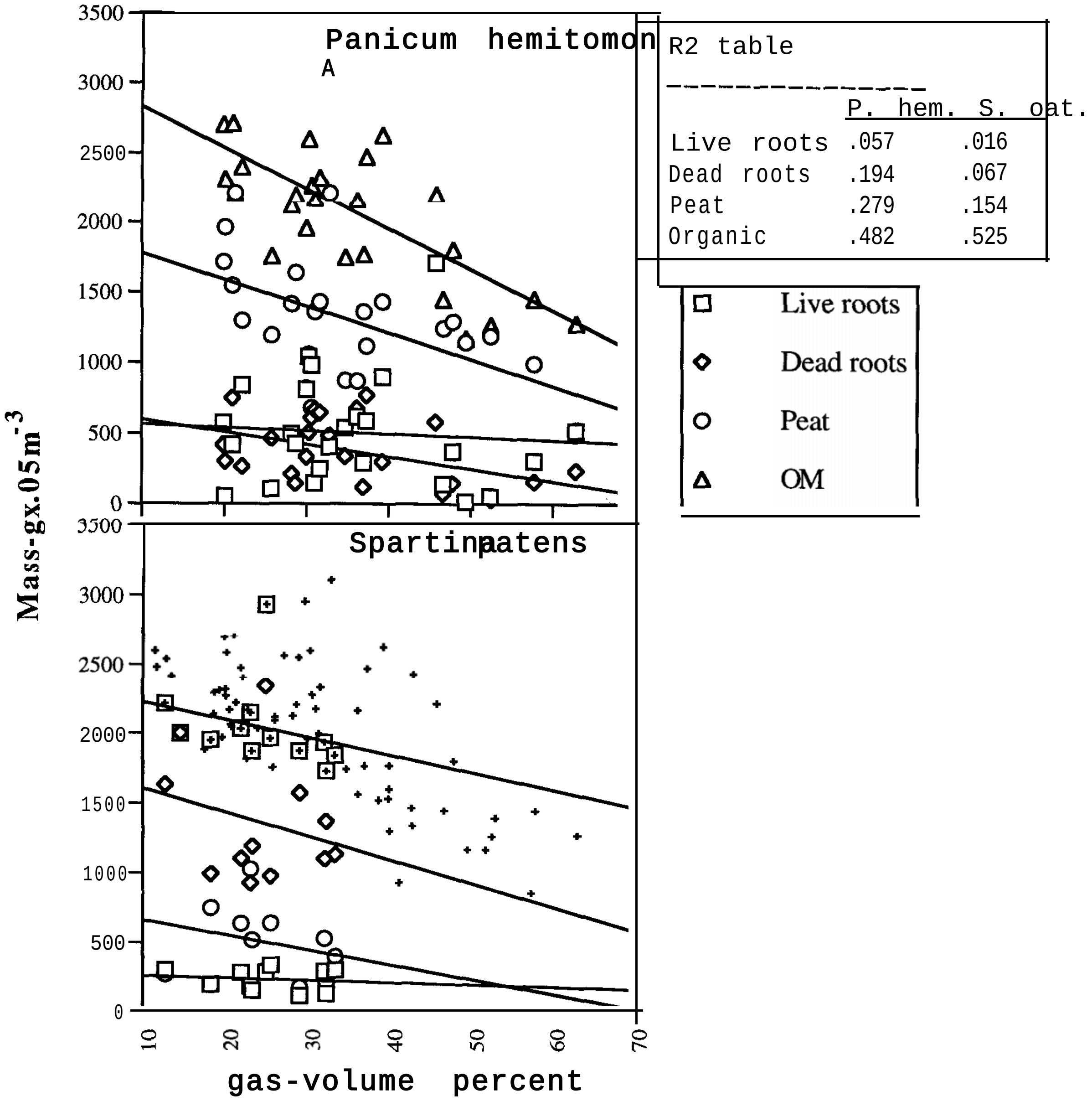


Figure 7.10. The relationship of mass vol.$^{-1}$ of soil components to gas volume in marshes dominated by (a) S. patens, and (b) P. Hemitomon. (Data from Sasser et al. 1994.)

its specific role(s), the experimental evidence indicates that mineral input is a requirement for a stable marsh, and that the amount of sediment required is related to the type of marsh, specifically to the degree of marine influence. Nyman, DeLaune, and others have calculated the mineral sediments requirements and the sediment deficit for several types of marsh, based on observed subsidence and accretion rates (DeLaune et al. 1990, Nyman and DeLaune 1991b) (Table 7.3).

Herbivory

Two groups of animals graze on marsh vegetation in Louisiana marshes, and may accelerate the rate of wetland loss. These two groups are waterfowl, including mallard (*Anas platyrhynchos*), pintail (*A. acuta*), mottled duck (*A. fulvigula*), gadwall (*A. strepera*), shoveler (*A. clypeata*), teals (*A. crecca* and *A. discors*), and canvasback (*Aythya valisineria*); and mammals, including muskrat (*Ondatra zibethicus*), nutria (*Myocastor coypus*), and to a lesser extent deer (*Oidocoileus virginianus*). In one study carried out in early successional marshes of the Atchafalaya River delta the two groups seemed to have about equal impacts (Evers et al. in review), but large waterfowl populations are found in Louisiana marshes only during the winter and they seem to have a minor impact on established marshes. Muskrats and nutria, on the other hand, are ubiquitous, are active year-around, and are generally considered to cause much more marsh damage. Therefore we focus in this report on the influence of furbearers on marsh degradation.

The muskrat is probably native to Louisiana, since it was described as far back as 1700 in Father Jacques Gravier's journal. The nutria is a native of South America. A captive population was introduced to Avery Island, but escaped in 1938 and spread rapidly throughout the Louisiana coast. Whereas the muskrat is found most abundantly in brackish marshes, the nutria prefers fresh marsh and swamp forests, and often ventures into nearby rice fields to feed. Although both species often exist side by side and appear to have the same food habits, Lowery (1974) indicated that the present muskrat distribution results from the invasion of fresh marshes by the more robust nutria which displace muskrats into less desirable brackish areas. It has been noted that when nutria are heavily trapped, the muskrat population can soar (Evans 1970).

In early successional marshes such as those in the active deltas of the Mississippi and Atchafalaya rivers, controlled studies have shown a strong influence of herbivores, both waterfowl and furbearers, on species composition and biomass of marsh vegetation (Chabreck et al. 1983, Evers et al. in review, Fuller et al. 1985) (Figure 3.1). This includes both a decrease in the number of species and a shift in dominance. In extreme cases, as in the Atchafalaya delta, vigorous stands of vegetation have been entirely removed, leaving an unvegetated mud flat (Evers et al. in review).

Table 7.3. Mineral and organic matter accumulation rates required to form marsh soil for a submergence rate of 1 cm yr^{-1} (from Nyman et al. 1991).

Marsh Type	**Organic Matter ($g\ m^{-2}\ yr^{-1}$)**	**Mineral Matter ($g\ m^{-2}\ yr^{-1}$)**
Fresh	269	424
Intermediate	452	348
Brackish	583	1,052
Saline	601	1,798

The influence of furbearers on established marshes of the inactive delta is more anecdotal. The best descriptions are from O'Neil (1949), who had extensive experience with muskrat management in Louisiana. Muskrats often seem to undergo a 10- to 14-year population cycle of boom and bust which is tied to survival of the marsh vegetation. The animals kill much vegetation digging for the preferred roots. In addition, their house-building activity, underground runs, and surface trails destroy much more marsh than is directly eaten. For example, in a 10-ha (25-acre) brackish marsh area that contained 24 active and 30 inactive muskrat houses in April 1982, 31 new houses were built and 10 refurbished during the next year. Sixty percent of the active houses and 57% of the inactive ones simply disappeared (Sasser et al. 1982). When muskrat populations are dense, all this activity can decimate a marsh, creating large "eat-outs," especially in the favored brackish three-corner grass (*Scirpus olneyi*) marshes. Subsequently the local population, with no food, crashes. If water levels are low for a year or two to allow regrowth of the vegetation, the marsh may recover, but often the damage extends so deeply into the marsh surface that recovery is poor at best.

It is interesting that "eat-outs" occasionally occur in salt marshes (Nyman 1993) but are almost always found in brackish marshes and are always attributed to muskrats, not nutria (O'Neil 1949). The nutria has a much longer gestation period (130 days compared to 28 days for the muskrat) so that its potential for response to environmental change is slower than the muskrat's. Consequently, its population is more stable. Nevertheless, because of the large observed populations and grazing damage to vegetation, nutria are considered to be a major cause of marsh degradation. For example, preliminary results from an exclosure study in a thin *Eleocharis*-dominated floating marsh show vigorous growth where plants are protected, compared to the adjacent open marsh where the vegetation had a lawn-like appearance as if mowed.

Kinler et al. (1987) summarized earlier studies of vegetation damage caused by nutria. Hilbrecht and Ryszkowski (1961) studying nutria in Poland observed that habitat destruction was of two types, focal and linear; focal destruction resulted from patches of destroyed vegetation, whereas linear destruction occurred mainly along the water-land boundary. These two kinds of damage are common to Louisiana also. Ehrlich and Jedynak (1962) described the destruction by nutria of a floating reed marsh. Reports by Wentz (1971) in Oregon and Willner (1982) in Maryland described less destructive nutria damage. In Louisiana, Harris and Webert (1962), Linscombe and Kinler (1984), and Taylor and Grace (1993) concluded that nutria did not cause major permanent damage to marsh vegetation. It is clear from their studies that the damage is selective for certain species, for example, *Scirpus californicus* and *Spartina cynosuroides* (Harris and Webert 1962). It has also been speculated that hurricane damage is increased in marshes that have been heavily grazed by nutria (Linscombe and Kinler 1994).

The best evidence of the importance of herbivory by furbearers is from a helicopter survey of the BTES recently completed by Linscombe and Kinler (1994). In their survey they detected 91 damaged areas totaling approximately 6,275 ha (15,500 acres) (Table 7.4). Since they surveyed roughly 28% of the total fresh, intermediate and brackish marsh in the BTES, this translates to about 22,250 ha (55,000 acres) of damage in the basin. Floating marshes are the preferred habitat with nutria densities as high as 7/ha (18/acre). Over one half of the damage occurred in fresh marshes and 66–86% of the damage was classified as moderate or severe. Short-term recovery (<1 yr) was not as good as the authors' prediction.

Linscombe and Kinler (1994) are currently studying the longer term recovery rate, and recommend development of an efficient trapping system to facilitate larger nutria harvests and to control nutria population density.

HURRICANES

Storm surges associated with severe tropical storms and winter fronts may be several meters above normal water levels at the coast. For example, a 1909 hurricane with 200 km h^{-1} (124 mi hr^{-1}) winds killed about 350 people, and was reported to have a storm surge of about 5 m (16.5 ft) over Timbalier island (Williams et al. 1992). Damage to coastal wetlands caused by the winds and storm surges of these hurricanes has been reported in a number of studies (Chabreck and Palmisano 1973, Gardner et al. 1992, Meeder 1987, Pimm et al. 1994). Most of these studies have been localized and focused on single factors. They have generally concluded that major, long-lasting changes are usually geomorphic and that coastal wetland plant communities recover rapidly (Conner et al. 1989, Penland et al. 1989b), except where physical disruption of the substrate occurs (e.g. Guntenspergen et al. 1995). A major exception was Hurricane Audrey, in 1957. The salt water associated with the 4 m (13 ft) storm surge is widely reputed to have killed thousands of acres of fresh marsh dominated by sawgrass (*Cladium jamaicense*) in the southwest chenier plain portion of the Louisiana coast. The sawgrass never recovered and has been replaced with other species, especially bulltongue (*Sagittaria lancifolia*) (Valentine 1976).

Table 7.4. Nutria damage to marshes of the Barataria-Terrebonne estuarine system (Linscombe and Kinler 1994).

	Area damaged		Sites damaged	
Marsh Type	**May 1993 (acres)**	**December 1993 (acres)**	**May 1993 number (%)**	**December 1993 number (%)**
Fresh	8,663	10,428		
Intermediate	656	1,346		
Brackish	3,295	3,702		
Total	12,614	15,476	51 (27%)	90 (60%)

Hurricane Andrew was probably studied in more detail than any previous Gulf Coast hurricane. Swenson (1994) described the storm surge from Hurricane Andrew, which crossed the Louisiana coast on August 26, 1992, with sustained winds of 190 km h^{-1} (118 mi hr^{-1}) and unofficial gusts of over 240 km h^{-1} (149 mi hr^{-1}) (Figure 7.11). The surge was about 2.0 m (6.5 ft) along the coast near landfall, with lower surges 1.25 to 1.5 m (4.1 to 4.9 ft) at locations farther from landfall. Coastal marshes dampened the surge: the open Barataria bay system showed a uniform surge of about 1.0 m (3.2 ft) throughout the system, while in the Terrebonne system, which is characterized by less open water and more channels within the marsh, the surge decreased from 2.0 m (6.5 ft) at the coast to about 0.15 m (0.5 ft) in marshes east of the Atchafalaya River. This surge was usually less than twice the height of average winter storms, and in areas influenced by the Atchafalaya River it was lower than average spring floods. Swenson (1994) also documented a salinity surge that decreased inland. The peak was well defined in the central portion of the Barataria bay but was much less pronounced at the coast and in the marshes, even though the water has large peaks at both locations.

Guntenspergen et al. (1995) described the ecological consequences of this storm surge.

> Wind and water movements associated with the hurricane resulted in the formation of compressed marsh, thick sediment deposits, wrack deposition, areas of salt burning, and scour. No sites were entirely without some impact. Sediments were deposited over large areas of coastal marsh. Marsh sites near Atchafalaya Bay had the thickest post-storm accumulations documented, up to 16 cm on average, while inland marsh sites accumulated lesser amounts of sediments . . . . Lateral compression resulted in surface relief 5–10 times greater than normal surface relief. Plant cover quickly recovered in all hurricane impact types except for scour areas and areas of thick wrack accumulation. Shifts in species dominance occurred in laterally compressed areas and are related to increased elevations.

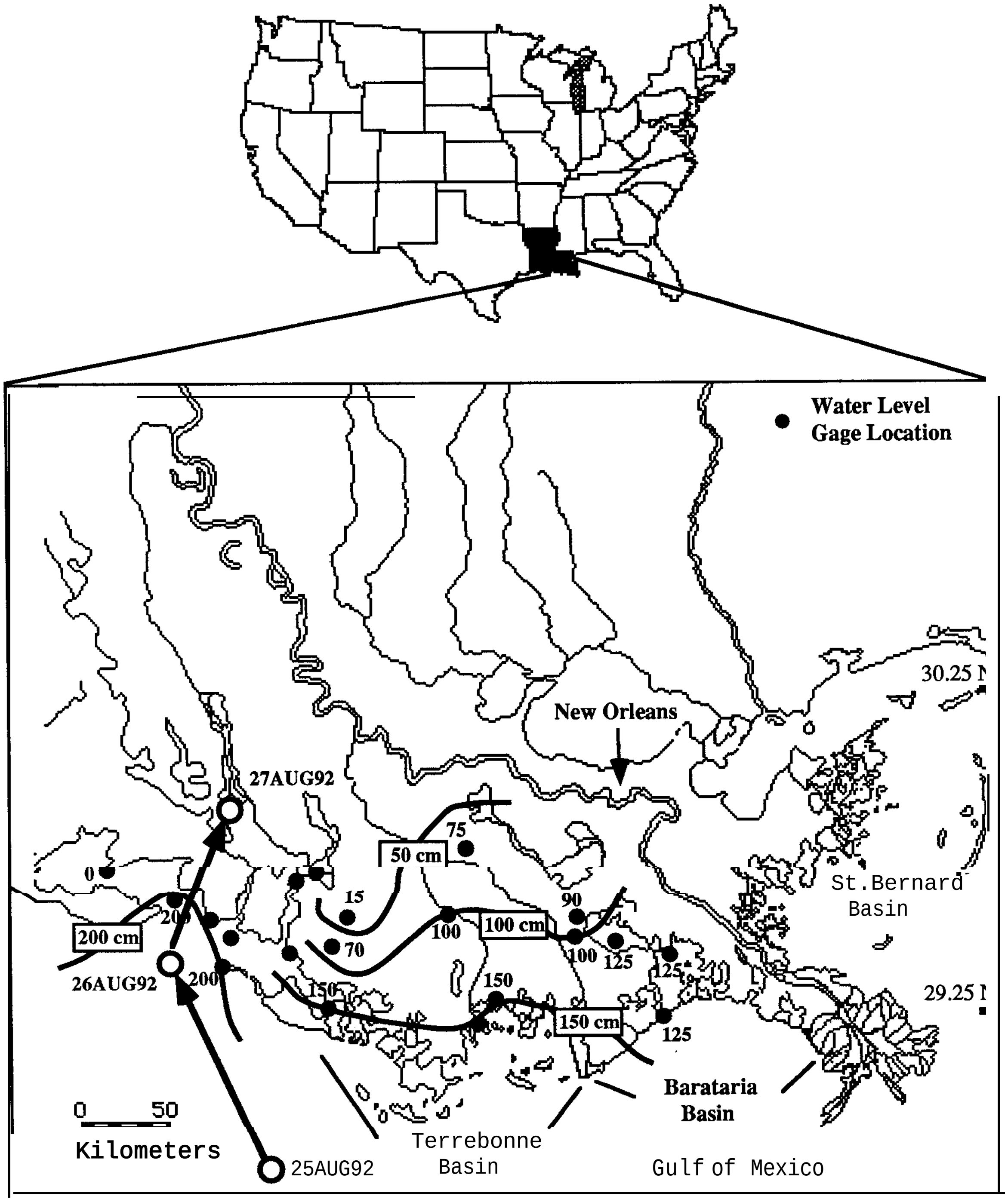


Figure 7.1 Estimates of storm surge depth associated with Hurricane Andr
Swenson 1994).

The authors suggested that hurricanes result in a variety of impacts in coastal Louisiana marshes and that the heterogeneity of the coastal landscape contributes to the magnitude and distribution of these impacts.

HABITAT VULNERABILITY TO RELATIVE SEA LEVEL RISE

Stress Factors in the Wetland Environment

Flooding

Wetland plant species have developed structural and biochemical adaptations to flooding (Mitsch and Gosselink 1993). Nevertheless, their adaptations are not sufficient to overcome the deleterious effects of sustained and deep flooding. Growth suffers as a result; the degree of growth reduction is related to the frequency and duration of flooding and is species specific. Typical structural adaptations of emergent herbaceous plants are the development of aerenchyma in the root cortex which helps alleviate the oxygen deficiency, and the production of adventitious roots. Metabolic adaptations are the production of the hormone ethylene, which leads to structural changes; and the ability to metabolize anaerobically, leading to the accumulation of alcohol, organic acids and/or in some cases lipids in the tissues. Since anaerobic metabolism is inefficient compared to normal oxidative metabolism, a plant under anoxic stress shows a number of metabolic responses that are deleterious to plant growth (Mendelssohn and Burdick 1987, Mendelssohn and Burdick 1988, Mendelssohn and McKee 1987, Mendelssohn et al. 1982, Pezeshki and DeLaune 1988, Pezeshki and DeLaune 1993, Pezeshki et al. 1988a, Pezeshki et al. 1991, Pezeshki et al. 1987a, Pezeshki et al. 1989, Pezeshki et al. 1993). These metabolic responses are typical of plants growing on a subsiding marsh surface, and lead to death if the severity of flooding stress is sufficient.

Salt

A second influence on plant growth and survival related to marsh subsidence is saltwater intrusion. As the coast subsides and water levels rise, marine water may move further up estuary, raising salinity levels in the marshes. This effect is aggravated by deep and straight canals that enhance saltwater movement from the coast into an estuary, replacing the shallow, sinuous natural channels that historically carried the water (Gosselink 1984, Wang 1988). Saline water has both an osmotic and a direct toxic effect on most plants. Wetland species have developed adaptations that exclude salt from their tissues, that balance the osmotic potential of the salt with endogenous osmotica, and/or that secrete salt from their tissues through specially produced salt glands (Mitsch and Gosselink 1993). But the tolerance for salt varies widely among wetland plants. In the Louisiana marshes the occurrence of plant species in broad bands parallel to the coast is primarily a response to salinity. *S. alterniflora*, the dominant salt marsh species, for example, grows in Louisiana marshes at an average salinity of about 15 ppt (Chabreck 1972) but tolerates ambient salt concentrations up to or above full strength seawater. In comparison, *S. patens*, usually considered a salt-tolerant species and found in Louisiana at an average salinity of 8.5 ppt (Chabreck 1972), is inhibited by salt concentrations above about 5 ppt (Pezeshki and DeLaune 1993). *P. hemitomon*, which is typically a fresh marsh species, was able to tolerate up to 9 ppm salt, although with reduced growth, for a month in one study (McKee and Mendelssohn 1989), and showed 76% carbon assimilation at 5 ppt in another (short-term) study (Pezeshki et al. 1987b).

Sulfide

One stress that combines anoxia with marine influence is sulfide. Sulfate carried by marine water is reduced in anoxic marsh sediments to toxic sulfide. As indicated above, sulfides can be precipitated out of solution by ferrous ions in the soil (iron is a common constituent of mineral sediments). Sulfide toxicity has been implicated in *S. alterniflora* "dieback" (Mendelssohn and McKee 1988). Pezeshki et al. (1988b) reported that both this species and *S. patens* are inhibited by H_2S concentrations >0.34 mg ml^{-1}, a concentration often exceeded in salt and brackish marshes. In comparison, *P. hemitomon* photosynthesis is inhibited by H_2S concentrations as low as 0.22mg l^{-1} and is much more sensitive to increasing H_2S concentrations than *S. patens*. Under normal circumstances H_2S concentrations in fresh marsh soils are an order of magnitude below toxic levels (Pezeshki et al. 1991), but the plants are highly sensitive to marine intrusions.

Although it is possible to do little more than speculate concerning the impact of additional fresh water on soil salinity and sulphide concentration, especially an additional 2,304 m^3 (3,015 yd^3) each year in the spring and summer as may have been contributed by Bayou Lafourche, some evidence is available on the influence of contemporary freshwater inputs. Hargis (1994) found that the soil salinity and pore water sulfide levels were coupled to the salinity of water in the surrounding basin. Barataria sites (east of Little Lake) had higher pore water salinities than Terrebonne sites (close to Jug Lake), and salinity and sulfide in Barataria were more sensitive to river discharge into the coastal zone than in Terrebonne. Hargis (1994) attributes these differences to the presence of significant freshwater inputs from the Atchafalaya into the Terrebonne basin, and a concomitant lack of significant river discharge into Barataria. Hargis states that the most significant changes in pore water sulfide occurred about two months following salinity increases. Consequently, if historical spring floods kept salinities suppresses until July, pore water salinity and sulfide may not have been significant until August or September when plant growth is mostly over for the year.

Nutrients

Most marsh plants appear to be nutrient-limited for maximum growth (Cramer 1978, DeLaune and Lindau 1990, DeLaune and Pezeshki 1988, Delaune et al. 1986a, Gosselink et al. 1977, Hester and Mendelssohn 1990, Payonk 1975). The most common limiting element is nitrogen, although phosphorus may also be limiting growth in fresh marshes, and other elements (such as iron) have also been implicated. If root production is an important factor in accretion, and flooding adversely affects growth, then perhaps nutrient addition through sewage treatment or fertilization could alleviate the problem. This approach has been tried in forested wetlands (Breaux 1992), but the effect of fertilization on vertical marsh accretion has not been documented.

Marsh Burning

Fire is a traditional management tool in coastal marshes. It is used to prevent the invasion of woody species, and to promote the growth of plant species desirable for food for waterfowl and furbearers (O'Neil 1949). Burning may increase plant production (Nyman and Chabreck in press), but its relationship to net organic matter production (subtracting the burned organic material, which is unavailable for ecosystem function) is unknown. Burning under the wrong conditions (for example, when water levels are too low) can lead to deep peat burns that destroy marshes.

It is not known how burning affects vertical accretion, and this is a key question in the context of the rapid loss of marshes in Louisiana. Burning might reduce vertical accretion if peat production is reduced. However, it might enhance accretion if burning increases root production. The frequency of burning is probably important in the net effect, but this has not been studied (Nyman and Chabreck in press).

Summary

Specific vulnerabilities of fresh, brackish, and salt marshes, and management options are listed in Tables 7.5–7.7, along with a list of major limiting factors for their growth, and managment strategies to maximize marsh success. Seldom is one factor (except the general problem of rapid subsidence) an overriding problem. Rather, there are usually a number of factors contributing to marsh degradation, and all should be addressed.

For salt marshes a mineral sediment deficiency is the major factor leading to salt marsh degradation. Management strategies should optimize opportunities for sediment input by maintaining an open system without artificial barriers.

Brackish marshes are problematic. The dominant species, *Spartina patens*, is more sensitive than *S. alterniflora* to flooding and salt, but the plant requires mineral sediements to flourish. The trick is to maximize sediment introduction without adverse salt and sulfide effects.

Although burning is reported to increase production, elimination of burning may be advantageous, since unburned *S. patens* makes a thick

Table 7.5. Habitat vulnerability of salt marsh (*Spartina alterniflora*).

Property	**Response**
Root production/ decomposition	Moderate root production (2000 g m^{-2} yr^{-1}), annual root turnover, slow decomposition
Nutrient status	Responds to N[1,2,3]; P in excess[1,4]
Flooding tolerance	Found at lowest elevation and greatest flood duration of common marsh plant species[5]
Structural adaptations	Extensive and effective aerenchyma (rhizosphere typically oxidized)[6]
Salinity tolerance	Tolerant of salinity at concentrations found in Louisiana estuaries
Sulfide sensitivity	Toxic at levels exceeding 0.34 mg H_2S ml^{-1}
Mineral requirement	Requires bulk density >0.2 mg ml^{-1}, highest requirement of common marsh species
Wave/tide energy	Grows in high energy environment, e.g. 3 m semi-diurnal tides on Atlantic coast, without apparent marsh degradation
Herbivore activity	Minimal; nutria and muskrats prefer fresher habitats
Marsh burning	Minimal; salt marshes seldom burned
Major limiting factor(s)	Mineral sediment deficit is the major factor leading to salt marsh degradation. This is especially true in making the transition from brackish to salt marsh, where bulk densities are below 0.2 mg ml^{-1}
Management strategies	Maximize opportunity for sediment input by maintaining an open system without artificial barriers. Sediment introduction via river diversion, slurries, etc.

[1](Buresh et al. 1980)
[2](DeLaune et al. 1984)
[3](Morris 1982)
[4](Patrick and DeLaune 1976)
[5](Sasser 1977)
[6](Mendelssohn 1993)

Table 7.6. Habitat vulnerability of brackish marsh (*Spartina patens*).

Factor	**Response**
Root production/ decomposition	High root productivity, but rapid turnover time (0.63 yr), and rapid decomposition (T=3 yr). Peat often very decomposed below root zone.
Nutrient status	Responds to N?[1]
Flooding tolerance	Not as flood tolerant as *S. alterniflora* (found @±2 cm above LMWL, with flood duration of ~3800 hr/yr)[2]
Structural adaptations	Aerenchyma formation but inadequate to prevent anaerobic respiration; few adventitious roots produced in anoxic soil[3]
Salinity tolerance	Average salinity 8.5 ppt, found over wide salinity range but growth reduced by salinities above ~15ppt[4,5]
Sulfide sensitivity	Toxic at levels exceeding 0.34 mg H_2O ml^{-1} [6]
Mineral requirement	Requires bulk density >0.7 mg ml^{-1};[7] growth much enhanced at greater bulk densities[7].
Wave/tide energy	Grows commonly in mid-tidal range (~15 cm), higher in intertidal zone than *S. alterniflora*. Elsewhere found in upper part of tidal zone[8].
Herbivore activity	Low nutria activity; zone of highest muskrat activity[9]
Marsh burning	Regularly burned to encourage growth of *Scirpus olneyi*[10]
Major limiting factor(s)	More sensitive to subsidence than *S. alterniflora*; poorer root system; salt intrusion probably reduces growth rate; H_2S toxicity probably common; may be sensitive to tidal and wave energy because of high decomposed organic content. All these factors may be limiting.
Management strategies	Maximize sediment introduction. Carefully control burning and assess on a site-specific basis: unburned *S. patens* makes a thick aboveground vegetation mat which can trap mineral sediments and within which rooting occurs. Control muskrat activity.

[1](Hester et al. 1994)
[2](Sasser 1977)
[3](Naidoo et al. 1992)
[4](Pezeshki et al. 1987c)
[5](Pezeshki and DeLaune 1993)
[6](Pezeshki et al. 1991a)
[7](Nyman et al. 1994)
[8](Valiela et al. 1976)
[9](Palmisano 1973)
[10](O'Neil 1949)

Table 7.7. Habitat vulnerability of fresh marsh (*Panicum hemitomon*).

Factor	Response
Root production/ decomposition	Moderately high root production (1200 g m^{-2}) combined with long-lived root system (T=3 yr) give large root biomass. Rapid decomposition (T=1.7 yr). Deep root system giving way to peat with depth.
Nutrient status	Responds to N and P[1]
Flooding tolerance	? (see note 2, below). Usually floats ~5 cm above water surface, so controlled anoxia.
Structural adaptations	Floating habit avoids effects of accretion deficit.
Salinity tolerance	Fresh marsh species; PS strongly reduced by 5 ppt salt[3], but can tolerate 9 ppt for at least 1 month[4]
Sulfide sensitivity	Sensitive to H_2S >0.22 mg ml^{-1}, but fresh marsh concentration usually much lower.
Mineral requirement	Bulk density ~0.05 mg ml^{-1} indicating no mineral requirement except for nutrients.
Wave/tide energy	Usually found in low energy energy environment; wind tides, not lunar tide.
Herbivore activity	High nutria activity, especially in *Eleocharis* marshes. Damage evident.
Marsh burning	Regularly burned. Burning limits growth of *Myrica cerifera*.
Major limiting factor(s)	Sensitive to salt and sulfate intrusion. Healthy mats of *P. hemitomon* stable to most storms, but *Eleocharis* thin mats probably easily disrupted. Mats may be degraded by herbivore activity and burning (?). Transformation to more salt tolerant association made problematic by lack of bouyant roots systems in plants such as *S. patens*.
Management strategies	Avoid oceanic influence (freshwater introduction). Heavy sediment introduction may sink mat if seasonally floating; otherwise moves under mat and acts as nutrient source (?) Nutria control. Fertilization? Burning.

[1](Delaune et al. 1986b)
[2](Feijtel et al. 1988)
[3](Pezeshki et al. 1987b)
[4](McKee and Mendelssohn 1989)

aboveground vegetation mat which appears to trap mineral sediments efficiently (Hatton et al. 1983) and within which rooting occurs (A. Nyman, pers. comm.). Burning increases the carrying capacity for muskrats by increasing the abundance of preferred muskrat food, brackish three-corner grass, and this increases the carrying capacity for muskrats, which could, in turn, result in more "eat-outs." This is a zone of high muskrat activity, and control of muskrat density is recommended. Nutrient additions may enhance plant productivity.

Fresh marshes, as characterized by *Panicum hemitomon*, are sensitive to salt and sulfate intrusion. Healthy mats are stable during most storms, but thin mat floating marshes are easily disrupted. They are sensitive to herbivore activity and probably to burning. Transformation to more salt-tolerant associations is problematic because salt-tolerant species do not appear to be able to maintain a buoyant, sediment-free mat. Management actions should aim at maintaining a freshwater environment, control of nutria,careful use of burning, and perhaps the use of nutrient additions to enhance mat growth.

PART 8

VIGNETTES

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INTRODUCTION

The Barataria-Terrebonne estuarine system (BTES) makes up the central region of the Mississippi River delta plain in coastal Louisiana. It is well documented that in general this entire region is a subsiding environment, with an associated basin-wide trend of marsh degradation. Significant loss of marsh to degraded marsh and open water has occurred (see earlier land loss discussion). We include in this status and trends review of habitat loss a look at four small study areas (vignettes). The purpose is to focus down from the broad scale, basin-wide look at habitat change and marsh loss trends (earlier section) to several discrete study areas in different parts of the basins for evidence of processes and/or events that accelerate or slow down the general trend of degradation.

How are the processes that lead to broad scale wetland loss worked out at fine scales? What kinds of identifiable land-cover changes occur at these fine scales and what is the time sequence of these occurrences? Are there similarities in the processes and sequences at different sites? Are different patterns of wetland loss correlated with concurrent or earlier events such as hurricanes, canal dredging, oil and gas field exploration, and marine intrusion? We studied these questions by looking carefully at a similar times series of aerial photography of several small study areas, emphasizing different and shorter time intervals than previous studies.

MATERIALS AND METHODS

The vignette areas were chosen to represent different sections of the basins where loss had occurred. The four vignette study sites are located in the BTES (Figure 8.1) in southeastern Louisiana. Three sites are in the Barataria basin (representing intermediate, brackish, and saline marshes) and one in Terrebonne basin (salt/brackish). The Bayou Perot and Bayou L'Ours sites are in the middle region of the Barataria basin, and their bounds are shown in Figures 8.2 and 8.4, respectively. Leeville, in the lower Barataria basin, follows Bayou Lafourche on the west within the bounds shown in Figure 8.6. Madison Bay site, in the salt/brackish marsh in Terrebonne basin, is within the bounds shown in Figure 8.8, with the western boundary following Bayou Terrebonne. The areas comprise marshes, open water, canal/spoil, natural levees and swamp-forests along bayous and their distributaries, and agricultural, urban, and industrial sites located on and adjacent to the bayou natural levees and on canal spoil.

Imagery (listed in Table 8.1) were visually photo-interpreted, using either a Bausch and Lomb stereo zoom transfer scope or a Kargl reflecting projector to correct for image distortions in the transparencies. The minimum mapping unit of 1 ha (2.47 acres) was small enough to capture most linear features of interest, such as

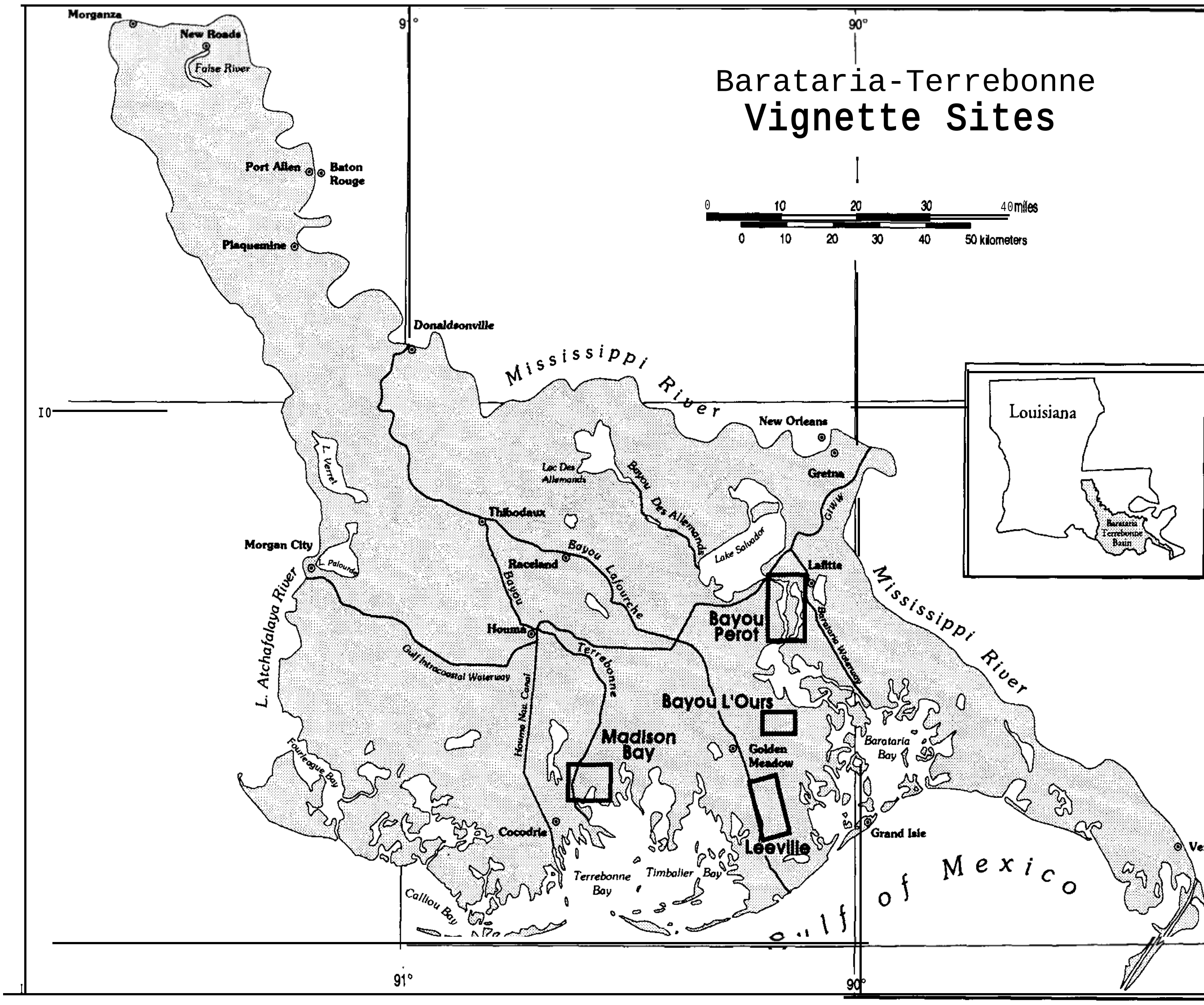

Figure 8.1. General location map of vignettes in BTES.

canals. The pixel (grid-cell) size was 0.25 ha (0.62 acres). Following Dozier (1983), imagery was differentiated visually into categories of wetland, open water, canal/spoil, natural levees, and developed areas. The wetland category was subdivided into six classes according to the percentage of open water bodies within themarsh. Although there was no control for water levels in the photographs, the marsh-open water interface is sharp, and even when the surface is flooded, marsh vegetation is visible and can be differentiated from the open water. For some analyses and for reporting purposes, the six marsh and open water classes were merged into solid marsh (class I), degraded marsh (classes II, III, and IV), and open water (classes V and VI). ("Degraded marsh" refers to marsh fragmented by 10–60% open water bodies, as observed from aerial photographs; "open water" refers to aquatic areas where broken marsh occupied less than 40% of the surface area.) The raster data containing classified land-cover information from 1945, 1956, 1969, and 1980, and 1985 for Bayou L'Ours and Leeville were digitized manually at Louisiana State University's Remote Sensing and Image Processing Laboratory (RSIP) in ELAS (Earth Resources Laboratory Applications Software—a software package developed by the National Aeronautics and Space Administration (NASA) and modified by RSIP). These data, originally reported by Sasser et al. (1986) and Evers et al. (1992), were converted to Intergraph format for this report. The 1989 data for Bayou L'Ours and Leeville were also input at RSIP in Intergraph system (developed by Intergraph Corporation) in vector format. All data for Madison Bay and Bayou Perot and 1965 data for Bayou L'Ours were scanned and semi-automatically digitized into vector format onto an Intergraph mapping system at the Louisiana State University Computer Aided Design and Geographical Information System Research Laboratory (CADGIS).

Correlative Data

Events and trends—hydrologic, geologic, meteorologic, human, etc.—that might have influenced the pattern and rate of wetland change in each vignette were assembled for roughly 10-year intervals corresponding to the aerial imagery dates from historic records. This information is summarized in a matrix for each site.

BAYOU PEROT AND BAYOU RIGOLETTES AREA

Introduction

Location and Current Description

The Bayou Perot and Rigolettes study area lies in central Barataria basin (Figure 8.1). The marshes were formed as part of the Lafourche delta complex (Kolb and van Lopik 1958) when the Bayou des Familles and Bayou Barataria distributaries were active. The Bayou Barataria ridge occurs in the east of the area and remains as an area of levee and channel sandy deposits, in contrast to the Kenner mucks and

Table 8.1. Aerial photography used both for visual and mapped photointerpretation.

Year	Month	Type	Format	Scale	Source	Used for sites:
1941		Black-&-white				Madison Bay[p]
1945		Black-&-white			U.S. Army Corps of Engineers	Bayou L'Ours[p,i], Leeville[p,i]
1956[p,i]		Black-&-white	Photographically controlled photomosaic	1:24000	Ammann International (IntraSearch, Inc.)	Bayou L'Ours[p,i], Madison Bay[p,i], Bayou Perot[p,i], Leeville[p,i]
1965	Jan 19, Feb 19	Black-&-white	Film positive	1:62,000	Tobin, Inc.	Bayou L'Ours[p,i], Madison Bay[p,i], Bayou Perot,[p,i] Leeville[p]
1968–69	Nov, Dec '68 Feb, Mar, Oct '69	Black-&-white	Photographically uncontrolled photomosaic	1:20000	U.S. Army Corps of Engineers	Bayou L'Ours[p,i], Madison Bay[p], Bayou Perot[p], Leeville[p,i]
1972	Mar 17	CIR	Film positive	1:62,000	NASA/MSC	Bayou L'Ours[p,i], Leeville[p,i]
1978	Oct	CIR	Film positive	1:63,500	NASA	Bayou L'Ours[p], Madison Bay[p], Bayou Perot[p], Leeville[p]
1980	Oct	CIR	Film positive	1:24,000	Gulf Coast Aerial Mapping	Bayou L'Ours[i], Leeville[i]
1985	Dec	CIR	Film positive	1:63,500	NASA	Bayou L'Ours[p], Madison Bay[p], Bayou Perot[p], Leeville[p]
1985	Oct 7	CIR	Film positive	1:24,000	Gulf Coast Aerial Mapping	Bayou L'Ours[p,i],Leeville[p,i]
1989	Oct 3	CIR	Film positive	1:24,000	Gulf Coast Aerial Mapping	Bayou L'Ours[i],Leeville[i]
1990	Dec	CIR	Film positive	1:63,500	NASA	Bayou L'Ours[i], Madison Bay[p,i], Bayou Perot[p,i], Leeville[i]

[p]Photograph used visual interpretation
[i]Used for photointerpretation

Lafitte-Clovelly associations that dominate the remainder of the area (USDA 1984). Relative sea level rise rates can be estimated at 0.7 cm/yr (0.28 in/yr) from the Barataria and Lafitte water level gauges.

Two large water bodies in this area are Bayou Perot and Bayou Rigolettes, which are wide, elongated lakes with an orientation generally north to south (Figure 8.2). These two water bodies are the major waterways connecting Lake Salvador to the north and the Little Lake system in the southwestern Barataria basin. At the north Bayou Perot narrows in a northwest direction, crosses the Gulf Intracoastal Waterway (GIWW) and connects directly to Lake Salvador through the south shore. Likewise, Bayou Rigolettes narrows in the north and connects with Bayou Barataria at Lafitte. In the south Bayou Perot and Bayou Rigolettes become narrower and merge together, flowing through a pass into northeastern Little Lake. Bayou Rigolettes is also connected through a human-made canal (Harvey Cut) with Turtle Bay.

Between the two water bodies is a long peninsula of marsh that has decreased in width over the years as Bayous Perot and Rigolettes increased in width.

USCOE land loss data indicate that over the period 1939–1990 about 70% of the wetlands in the Bayou Perot area were lost to open water. This loss occurred at a rate of about 2%/yr except for a period of slower loss during the late 1970s and early 1980s.

Results

General Description of Landscape Changes

Historically, both Bayou Rigolettes and Bayou Perot were narrow meandering bayous typical of riverine flows. Maps from the 1800s indicate narrow bayous with expansive marsh on either side. By the 1940s both bayous exhibited estuarine stream configuration of oblong pools connected by narrow channels at the bends, exhibiting sinuous curves with narrow and long point bars. The morphologic changes in the these channels suggest erosion at the channel edge associated with the transition from river-dominated to tide-dominated processes after the closure of Bayou Lafourche, and formation of what Ahnert (1960) has termed "estuarine meanders." Major changes noted from reviewing aerial photography from the 1940s to the present are described below, and summarized in Table 8.2 along with available correlative data or events. During the period between the 1940s and 1955–56, points on both shores of both bayous eroded, with widening of open water. The sigmoid series of lakes in the northern portion of the peninsula separating Bayous Perot and Rigolettes developed during this period. In the southeast of the study area some interior marsh breakup also occurred.

Between 1955 and 1965, shoreline retreat continued, particularly along the western shore of Bayou Rigolettes. In the northwest, shoreline loss was increased due to shoreline retreat into the complex of oil field canals. Interior degradation of the north peninsula continued, as did interior marsh breakup in the southern peninsula and in marshes in the southeast quadrant of the area. The Dupre Cut Canal widened.

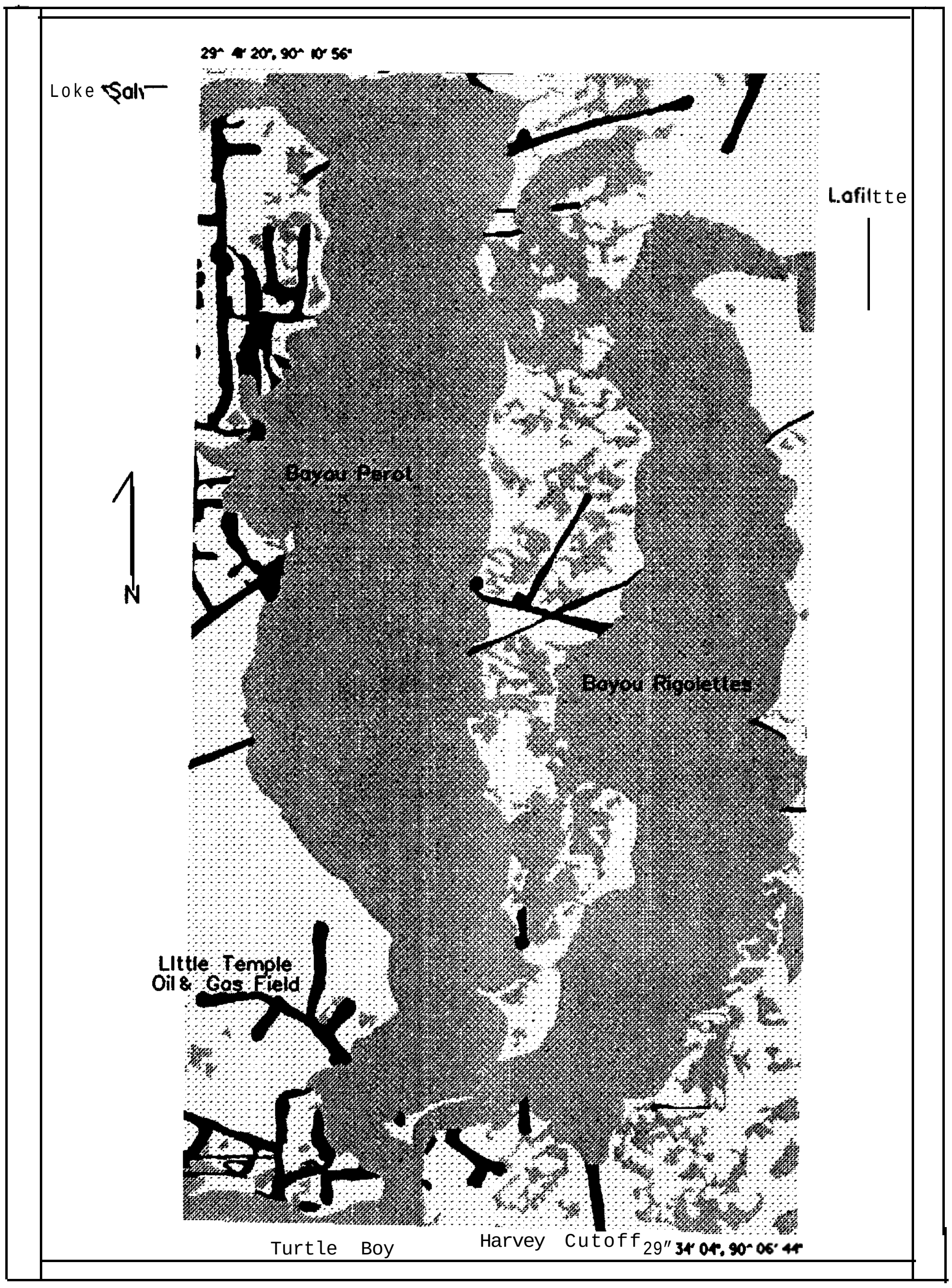

Figure 8.2. Bayou Perot study area.

Table 8.2. Bayou Perot matrix of historical wetland loss and correlative data or events.

Year	Marsh Loss	Human Impacts	Meteorological Event
1940s	Area fairly intact. Both B. Perot and Rigolettes narrow, with typical riverine stream configuration (sinuous curves with narrow and long point bars).	Dupre cut present. Extreme NW-pipelines laid (Texaco 1935, 1937).	Hurricane Sep 29 1915
40s-56	Shoreline erosion on points on both shores of both bayous and widening; N peninsula beginning inland degradation; SE quadrant-some inland breakup; -50% marsh solid.	N-S oilfield canal complex in NW quad (United Gas 1953); SW-2 short canals, each with branches (Exxon 1952, 1955) Dupre cutoff present; E-W canal across mid-peninsula; SW-pipeline canal (Exxon 1955).	Hurricane Sep 19/20 1947 Hur Baker Aug 30 1950 TS Brenda Jul 26/27 1955 (TS TS Unnamed Aug 26 1955
56-65	N peninsula degradation continuing, -30% ow; shoreline erosion continues in NW and SW B. Rigolettes; both bayous wide; SE-breakup continues.	SW-canal network expands, Tennessee Gas (1956); Dupre cut widens; new canal in mid-peninsula diagonal to mid-peninsula canal in place by 1956; NE-pipeline canal (Shell 1958); Mid-peninsula-pipeline canal (SNG 1959).	Hur Flossy Sep 23/24 1956 (T Hur Audrey Jun 27 1957 Hur Betsy Sep 9/10 1965 (H)
65-69	N peninsula degraded to -60% and continuing S; shoreline erosion continues slowly; NW and SW quads breakup beginning; SE breakup continues, large ponds & marsh/water mix	No new canals with surface expression; however, Extreme SW-pipeline canal (Exxon 1966), NW-pipeline canal (Texaco 1966), and Extreme NW-pipeline canal (Texaco 1968).	Hur Camille Aug 17/18 1969

Table 8.2. cont.

Year	Marsh Loss	Human Impacts	Meteorological Events	V
69-72	Minor changes	No new canals.	Hurricane Fern Sep 16 197	
78-85	Major passes develop across peninsula (continuation of trend, see 68-78); S peninsula breached to island and shrunk; SW and S quadrants unchanged; narrowing of central peninsula.	No new canals.	Hur Bob Jul 11 1979 (TD) Hur Elena Sep 2 1985 (TS) Hur Juan Oct 27/31 1985 (TS)	
85-90	N breaches of peninsula make it an island; SW, S quadrants slow degradation; SE quadrant-large areas of OW and broken marsh.	No new canals.		

From 1965 to 1968 some major additional deterioration occurred in the peninsula, with widening of open water areas in the north and intensified breakup of interior marsh in the central and southern peninsula. Deterioration continued in the southeast marshes.

The period 1968 through 1972 was relatively stable, with minor observable change noted from aerial photos.

Between 1972 and 1978 marsh deterioration is noted in the southern peninsula. Otherwise this period is also relatively stable.

From 1978 to 1990 major passes developed across the northern peninsula. The southern tip eroded and separated from the peninsula. Much of the peninsula decreased in width. General shoreline erosion and loss of point bars along southwest Bayou Perot occurred.

By 1990 the two bayous dominated the site, having enlarged into broad north-south trending lakes, the many shallow cusps along the eastern shorelines the only remnants of the earlier riverine expression. The central peninsula was dramatically reduced in area, cut off to form an island, and severely degraded.

Total wetland area decreased from 5,450 ha (13,463 acres) in 1956 to 2970 ha (7336 acres) in 1990. Of this, the solid marsh category (class I) decreased from 3,299 ha (8149 acres) in 1965 to 21 ha (51 acres) in 1990. The degraded marsh category (classes II, III and IV) increased from 2150 ha (5316 acres) in 1965 to 2948 ha (7284 acres) in 1990. The total area of open water increased from 3,401 ha (8,402 acres) in 1956 to 5,749 ha (14,200 acres) in 1990. The areas of habitats in the study area in 1956, 1965, 1972 and 1990 are illustrated in Figure 8.3.

Concurrent Events

Vegetation

According to O'Neil (1949) the general area including this site was a floating *Scirpus olneyi/Spartina patens* marsh in the 1940s. These species are salt tolerant so the site probably experienced salinities in the 5–10% range. It is unlikely that the marshes in the narrow fringe bordering the bayous were floating since erosive storms threw considerable mineral sediment back across the streamside marshes. The signatures in the 1955–56 aerial imagery suggest that interior marshes on the northern end of the peninsula were freshwater species and probably flotant marsh. Chabreck et al. (1968) classified the vegetation as brackish in 1968. The site remained brackish at the time of Chabreck and Linscombe's 1978 survey, with the exception of the area north and east of Bayou Rigolettes, which was intermediate. Today the area is dominated by *Spartina patens*, a brackish marsh species.

Hydrology, Canals, and Other Human-made Features

The Harvey Cut Canal was dredged before 1955–56. It connected Bayou Rigolettes to Turtle Bay on the south. It has widened over the years and is a major pathway of flow into and out of Bayou Rigolettes.

The Bayou Perot and Delta Farms oil fields were established in 1940s and canals in the northwest edge of the site date from these days. The canal across the central peninsula (Berstein Canal) connecting Bayous Perot and Rigolettes was also in place in 1955–56. Most canals in the southwest quadrant, probably associated with the Little Temple and Little Lake oil field, were excavated from 1955–56 to 1965.

Direct wetland loss due to human activity (nearly all canals) is about 10% of the total loss.

Discussion

Wetland Loss and Spatial Trends

Two types of major wetland loss occurred in the Bayou Perot study area, shoreline erosion and interior marsh degradation. Shoreline erosion accounts for a significant amount of the total loss. The erosion of point bars of Bayous Perot and Rigolettes that were characteristic of the earlier, riverine-dominated period, greatly increased water surface area, forming the present elongated lake form of these two bayous. The erosion of the point bars and shoreline has probably occurred due to erosional tidal estuarine processes which have increased in this part of the Barataria basin since major limitations on freshwater input were imposed on the system by closure of Bayou Lafourche at the Mississippi River in 1904 and elimination of overbank flooding from the Mississippi River by leveeing in the early 20th century. In the northwest quadrant of the study area some additional marsh loss was caused by shoreline erosion into an existing oilfield canal network. Boat wakes and increased wave action as fetch increased with widening of the bayous likely contributed to the shoreline erosion.

The second type of wetland loss in this study area is interior marsh degradation, which itself appears to take several forms. In the northern peninsula interior marsh breakup was apparent at the time of our earliest available aerial photos (1955–56). Based on signatures evident in our examination of aerial photography, and classification by O'Neil (1949) this area was probably freshwater/intermediate flotant marsh at that period. The processes causing the initial breakup of this marsh are not known, but may be due to physical storm damage of the flotant marsh. Southern parts of the peninsula and the southeastern marsh in this study area were probably brackish attached marsh, based on different photographic signatures of these areas. The process of breakup of these marshes appears to be different than that in the northern peninsula, with a more gradual change from relatively complete marsh cover to small

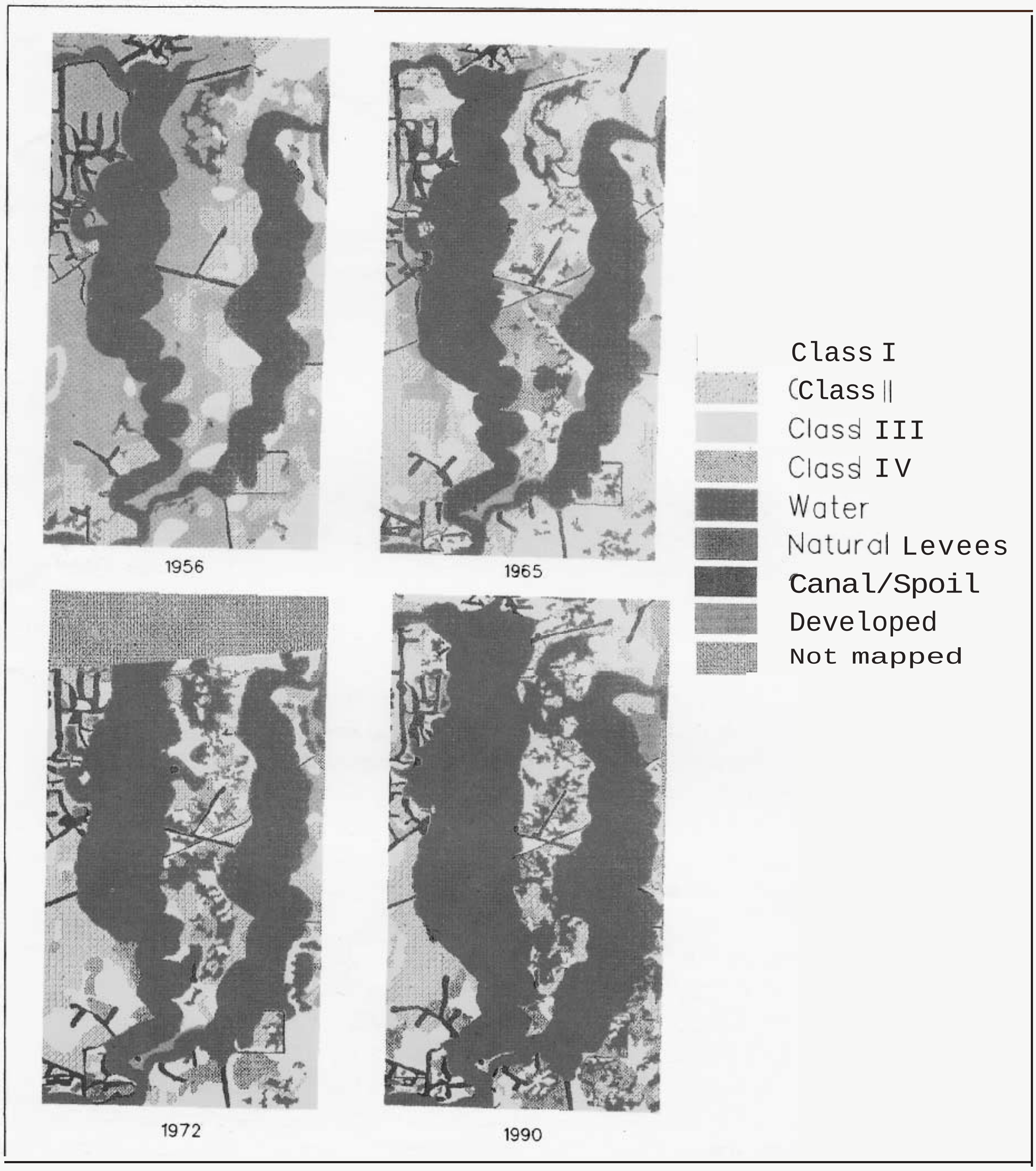

Figure 8.3. Classification maps for the Bayou Perot and Bayou Rigolettes site

ponds, enlargement and coalescence to form larger water bodies. The pattern of degradation is more likely related to slowly increasing vegetation stress, due to salinity increases and/or prolonged flooding rather than rapid wholesale loss of large areas that could be related to a single major event.

BAYOU L'OURS AREA

Introduction

The Bayou L'Ours study area lies in southwestern Barataria basin (Figures 8.1 and 8.4), and covers an area of about 5,500 ha (13,600 acres). The study area includes marshes north, south, and between the Bayou L'Ours and Bayou Raphael natural levees, abandoned distributaries of Bayou Lafourche. They extend southeastward from Bayou Lafourche in the area of Larose (Figure 8.1). The subsiding natural levee remains evident, with relict live oak trees present along the highest elevations, in stark contrast to the adjacent marsh. One small lake is located in the marsh of the study area, at the source of John-the-Fool Bayou. The marshes were formed as part of the Lafourche delta complex during the period when Bayou Lafourche was a primary distributary of the Mississippi River. The soils in the area are classified primarily as Lafitte-Clovelly associations and Timbalier-Bellpass associations (USDA 1984).

Data from the U.S. Army Corps of Engineers indicate the area in the vicinity of the site has lost over 60% of its marshes since 1932, with major degradation occurring between 1958 and 1974, at a rate of over 2%/yr, decreasing to a present rate of about 0.9%/yr, perhaps because most of the marsh is gone.

Results

General Description of Landscape Changes

In the 1940s this area was probably freshwater flotant marsh. Some freshwater input, although probably not much, was available from Bayou L'Ours and drainage from the Clovelly fresh marsh system to the north.

In 1956 the marsh was generally intact throughout the study area with over 90% of the marsh area classified as solid marsh (class I) (Figure 8.5). Based on our interpretation of this aerial photograph, much of the northern half and southwestern portions of the study area were probably freshwater flotant marsh. Narrow rift features are evident, probably caused by tearing from strong storm impacts. The signature of some marshes in the eastern part of the study area indicates a nonfresh marsh community. These marshes contain areas of relatively minor deterioration, with small scale ponding and tidal channels. King's Canal is in place, breaching the Bayou L'Ours ridge and connecting canal networks north and south of the ridge (Figure 8.4).

During the period 1956 to 1965 interior marsh degradation occurs as a change from solid marsh to degraded marsh categories (classes II, III and IV) (Figure 8.5). The TGT Canal was constructed during this period, in 1956, breaching the Bayou

Figure 8.4. Bayou L'Ours study area.

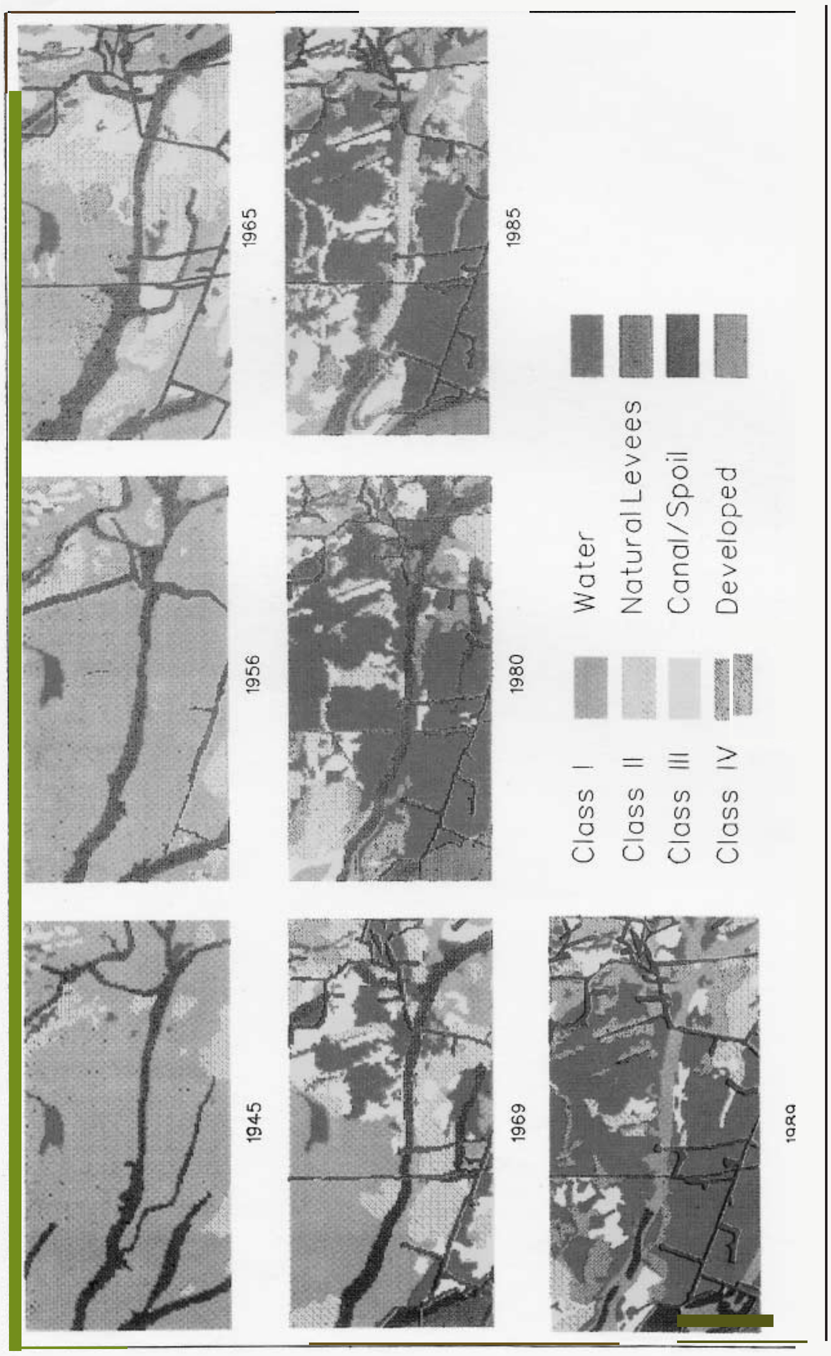

Figure 8.5. Classification maps of Bayou L'Ours site.

L'Ours and Mink Bayou ridges. This pipeline canal is oriented north to south connecting to Bayou Lafourche through the Tidewater Canal (constructed in 1954) in the south and Little Lake to the north. The canal is plugged in several places, notable where it crosses Mink Bayou.

From 1965 to 1969 major interior marsh degradation and loss to open water began throughout much of the study area. The loss of marsh was most acute in the northeast of Bayou L'Ours ridge, and between the two ridges in the central and southwestern portions as indicated by Figures 8.5c and d.

From 1969 to 1972 relatively little change took place north of Bayou L'Ours ridge, with additional degradation continuing between the ridges, especially in the southwest.

The period 1972 to 1978 was one of massive interior marsh loss. The remaining marshes in the northeast sector of the study area and south of the Bayou L'Ours ridge were lost to open water in most areas. The northwestern marshes (north of the ridge) were significantly degraded along the flanks of Bayou L'Ours and along trenasses in the interior marsh. Degradation spread south of Bayou Raphael along the 80 Arpent Canal in the southwest corner of the study area.

Between 1978 and 1985 small scale marsh loss occurred, but most of the study area was already open water other than the northwestern quadrant, and several smaller areas.

From 1985 to 1990 little new marsh loss occurred. This was a relatively stable period for the remaining marsh.

Overall, total wetland area within the Bayou L'Ours study area changed from 4,635 ha (11,448 acres) in 1945 to 2,171 ha (5,363 acres) in 1989. Solid marsh (class I) covered 4,312 ha (10,650 acres) in 1945, compared to 628 ha (1,552 acres) in 1989. Degraded marsh categories (class II, III and IV) increased from 331 ha (818 acres) in 1945 to 1,543 ha (3,810 acres) in 1989. As indicated earlier, much of the marsh in this area was lost to open water, indicated by the increase in open water area from 112 ha (277 acres) in 1945 to 2,621 ha (6,474 acres) in 1989. Table 8.3 summarizes the changes in the study area.

Concurrent Events

Vegetation

As described earlier, the signature of the 1945 aerial imagery indicates this area was freshwater floating marsh at that time. This is supported by references of trappers and surveyors (Gagliano 1990) that these marshes were flotant, and aerial imagery observations by Dozier (1983) of freshwater water hyacinth rafts on water bodies south of the site. O'Neil (1949) mapped it as floating *Scirpus olneyi/Spartina patens*, indicating some saltwater influence, but this marsh was not easily accessible in the early 1940s and O'Neil may have been influenced by dominant vegetation along streams where it is more easily influenced by periodic salt intrusions.

Table 8.3. Bayou L'Ours matrix of historical wetland loss and correlative data or events.

Year	Marsh Loss	Human Impacts	Meteorological Events	Vegetati
1945	Marsh is intact throughout the study area. Numerous rifts. Very little interior marsh deterioration.		Hurricane Sep 29 1915	Freshwater O'Neil mappe putens float
1945-1956	Marsh is still intact throughout the study area. Numerous rifts are still visible Still very little interior marsh deterioration.	King's Canal in place. Several canals south of B. L'Ours Ridge.	Hurricane Sep 19/20 1947 Hur. Baker Aug 30 1950 (TS) TS Brenda Jul 26/27 1955 (TS) TS Unnamed Aug 26 1955 (TS)	Freshwater and southw
1956-1965	Some minor marsh deterioration but overall, interior marsh loss is small during this period.	TGT Canal in place (1956). Additional canals in E. Central area Tie-in to TGS (1961).	Hur. Flossy Sep 23/24 1956 (TS) Hur Audrey Jun 27 1957 (TD) Hur Betsy Sep 9/10 1965 (H)	
1965-1969	Major interior marsh degradation and loss in NE quadrant. Significant widespread marsh breakup S of B. L'Ours Ridge, especially in central and SW quadrant. Trenasses in marsh widen.	3 short canals.	Hur Camille Aug 17/18 1969 (H)	
1969-1972	N-Little change in marsh. S of ridge-Continuous degradation	No new major canals.	Hurricane Fern Sep 16 1971 (TS)	
1972-1978	Massive interior marsh loss. Remaining marsh in NE quadrant and south of B. L'Ours ridge is lost. Significant breakup in NW.	Short elbow canal in SW quadrant.	Hur Carmen Sep 7/8 1974 (TS) Hur Babe Sep 5 1977 (TS)	By 1978 th brackish, a intermediat
1978-85	Continued marsh degradation, but major loss has occurred. Only two areas of relatively intact marsh: in NW and SE quadrants.	No new canals.	Hur Bob Jul 11 1979 (TD) Hur Elena Sep 2 1985 (TS) Hur Juan Oct 27/31 1985 (TS)	
1985-1990	Little new marsh loss (not much left). Relatively stable period.	Hurricane Protection Levee built (in place by 1986).		
Summary	The marsh was intact in 1945. The two major periods of marsh loss were: 1) 1965-1969, and 2) 1972-1978			

By 1978 the eastern half of the site was certainly brackish, while the western half was fresh to intermediate. During the next decade vegetation changes north of the Bayou L'Ours ridge indicate progressive salinization except at the extreme western edge of the site where perhaps freshwater drainage from the north along the Bayou Lafourche natural levee has maintained low salinities.

Hydrology, Canals, and Other Human-made Features

The site is situated in the old distributary system of Bayou Lafourche. Historically flows were southeast trending, through old distributaries and across or under the floating marsh. In 1904 Bayou Lafourche was plugged at the Mississippi River, and became tidal and saline. By 1955–56 the marsh circulation pattern had been disrupted by east-west and north-south canals that crossed through the natural ridges. South of the study area a major canal (Tidewater Canal) connected the interior marsh and canal system to the tidal Bayou Lafourche. A second canal north of the study area (Exxon Canal ?) similarly connected Bayou Lafourche to Little Lake.

The canal system evolved through time with major extensions through 1974. By this time the marshes south of the Bayou L'Ours ridge were compartmentalized by spoil banks into semi-impounded areas. By 1972 a levee ran along the west edge of the site, separating "fast" land along Bayou Lafourche from the marsh. This levee was enlarged as a hurricane protection levee during the late 1980s.

Salinity

Louisiana Department of Wildlife and Fisheries salinity records from 1983 show salinities averaging 7–8 ppt with maxima to 20 ppt in King's Canal south of the Bayou L'Ours ridge. Above the ridge stream salinities peaked at 8–9 ppt in late fall. In marsh interstitial water it was about 5 ppt just north of the ridge, decreasing in a northward direction.

Discussion

Marsh loss in the Bayou L'Ours area is all interior marsh degradation. Only one large lake is in this study area. Its shoreline remained notably intact for the duration of the massive marsh loss. In 1956 it was isolated in a large unbroken tract of marsh. Today, the lake's boundaries remain evident on aerial photographs, a silhouette of vegetated edge in a sea of open water.

The major periods of marsh loss in this area are 1965 to 1968–69 and 1972 to 1978. Most of this area was freshwater marsh, probably flotant in the 1940s and 1950s. North to south canals constructed through the area put in place avenues for transfer of saline water into the interior marshes from Barataria Bay and from the tidal Bayou Lafourche. These salinities have consistently been high enough to stress freshwater marshes. Salinities have not increased in the bays and Bayou Lafourche (Swenson and Swarzenski 1995), but new avenues (canals) were provided for the intrusion of salt water into interior marshes when physical parameters provide the head for flow into these formerly isolated regions. In the Bayou L'Ours area canals providing access into the freshwater marshes were in place prior to 1965. This suggests freshwater floating marshes beginning to be stressed by salt intrusion, with drainage impeded by spoil banks. In September 1965 Hurricane Betsy pummeled the coastal region, striking Grand Isle with a 3-storm surge. It is likely Betsy brought the driving physical force that introduced highly saline water into the fresh water marshes in the Bayou L'Ours area. The semi-impounded compartments probably retained this water. The resulting prolonged inundation with saline water could have stressed freshwater vegetation beyond its ability to recover.

The freshwater marshes that persist in the region are north of the Bayou L'Ours ridge in the Clovelly area. We have evidence from long-term vegetation species composition data that a successful transition of marsh habitat dominated by the freshwater species *Sagittaria lancifolia* to one dominated by *Spartina patens* and even to *Spartina alterniflora* is occurring in some areas (Sasser, unpublished data). This is probably due to the location of these marshes in the northwest corner of the area, north of the ridge and farthest removed from the access routes of saline water across the Bayou L'Ours ridge.

LEEVILLE AREA

Introduction

The Leeville study area is located in southwestern Barataria basin (Figure 8.1). This study area covers about 11,000 ha (27,170 acres). It is situated east of Bayou Lafourche, with the town of Leeville in approximately the center of the defined area on the western border (Figure 8.6). Leeville has long been a crossroads for the region. Southwestern Louisiana Canal was built in the late 1800s to cross Bayou Lafourche at Leeville, connecting Caminada Bay with Timbalier Bay. Leeville has been a focus of oil extraction activity since the 1940s and is still active. The region is criss-crossed with oilfield access canals. Prior to 1955 most activity was west of Bayou Lafourche. By the mid 1950s a smaller network of canals had developed north and south of Southwestern Louisiana Canal near the Bayou Lafourche natural levee.

Geologically, the marshes are of similar age to those discussed in the Bayou L’Ours area, being part of the Lafourche delta complex and formed when Bayou Lafourche was an active distributary. Being close to the coastline, they have been subjected to progressively increasing marine influences for the past 700–800 years as Bayou Lafourche became a less important distributary after building of the Modern delta commenced. Because Bayou Lafourche is a major distributary the marshes close to the Bayou are underlain by thick channel and levee deposits with a high sand content. Subsidence of these areas would therefore be less than the marshes remote from Bayou Lafourche which are underlain by interdistributary sediments and peats. Levee flank depression is possible in the marshes close to the natural levee of Bayou Lafourche where the weight of the levee sediments compacts underlying strata. The

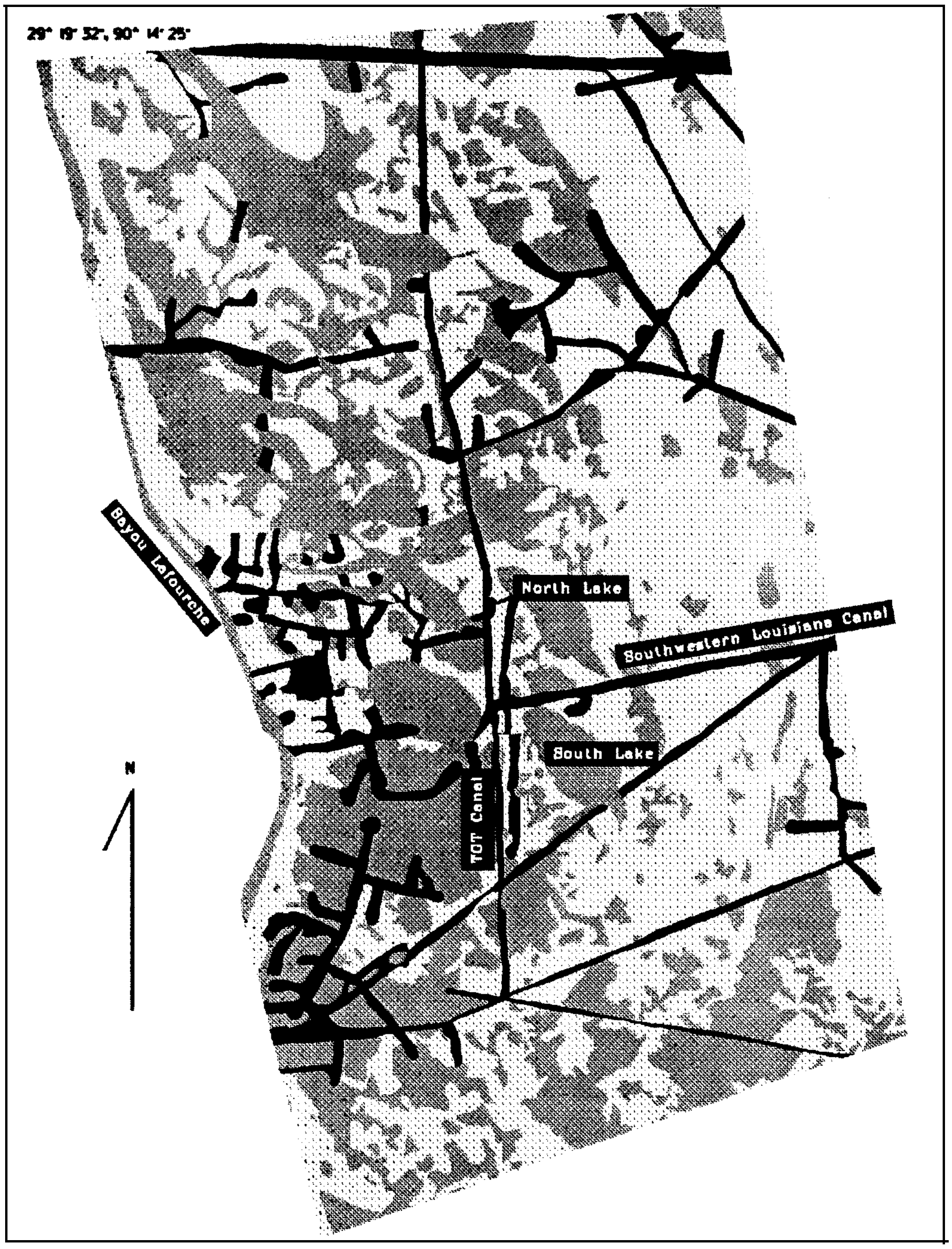

Figure 8.6. Leeville study area.

rate of relative sea level rise calculated for Leeville in Part 6 was almost 8 mm/yr. The soils in the area are classified as Timbalier-Bellpass associations (USDA 1984).

The USACOE data base provides estimates that about 70% of the wetlands in the area were lost from 1932 to the present. The rate has accelerated from about 0.07%/yr prior to 1958 (of which most was canal construction), to over 2%/yr during the last decade (with almost no additional canal construction).

Results

General Description of Landscape Changes

Based on our review of the aerial photography, at least two different types of marsh habitat were present in the study area in the 1940s. The northwestern portion of the study area was probably freshwater flotant marsh. Two irregularly shaped lakes are located in this area, referred to in this report as "star" lakes, and the general region as the star lake area. These lakes are reported to have originated by tearing of the floating mat during hurricanes around the early part of this century, possibly during the large hurricanes of 1893 and 1915 (Gagliano, personal communication). The second habitat type identified from aerial photography is nonfresh marsh covering most of the remaining study area. Table 8.4 shows major changes in the study area.

Three additional large lakes are within the study area. Lake Jesse is east of Leeville, and North Lake and South Lake are east of Lake Jesse located to the north and south of Southwestern Louisiana Canal. All three of these lakes are more or less rounded to oblong, with regularly shaped boundaries.

In 1945 the star lake marshes were expansive and intact as evident in Figure 8.7. Numerous rifts were present in this marsh. The signature on aerial photography of the nonfresh marshes was "pockmarked" in appearance, indicating some mild degradation of this habitat.

Between 1945 and 1956 some significant expansion of the rifts occurred, with marsh breakup in the star lakes area. The nonfresh areas remain about the same. The Tidewater Canal was constructed east from Bayou Lafourche a short distance north of the study area in 1954.

During the period 1956 to 1965 some additional degradation occurred in the star lakes area in the northwest and north-central portions. Other areas exhibit slow small scale breakup. The "Highline" canal (TGT Canal) was constructed north/south across the central region during this period, from 1956 to 1960. The oilfield canal complex expanded, connecting Lake Jesse to the southern star lake. Additional canals were added in other places in and near the study area.

Between 1965 and 1969 moderate to heavy marsh loss is evident in the star lakes region. Additional loss also occurred in the marshes south of Lake Jesse and in the boat "graveyard" area in the extreme southwestern region of the study area. However, the shorelines of Lake Jesse, North Lake, and South Lake remained intact. Figure 8.7 indicates the network of canals crossing the region by 1969.

Table 8.4. Leeville matrix of historical wetland loss and correlative data or events.

Year	Marsh Loss	Human Impacts	Meteorological Events
1945	NW quadrant-marsh is expansive and intact, probably *Panicum* flotant. Two large star lakes present. Numerous rifts in marsh. Forests present along B. Lafourche east natural levee.	Southwest Louisiana Canal (SWL) is present. One short canal N of SWL Canal, W of Lake Jesse. Oil-field canals present west of B. Lafourche and S of SWL Canal.	Hurricane Sep 15 19
1945-1955/56	NW-Some significant rift expansion/marsh breakup between star lakes in flotant area. NE, SE, SW-Little change. Mottled marsh signature remains.	NW-Canal from B. Lafourche to E, then S across small natural levee ridge. Extreme W-Texaco Canal Leeville oil-field complex is developing N of L. Jesse. SW-Major canal from SWL canal west of L. Jesse to south with 6 stems. Williams Canal in place.	Hurricane Sep 19/20 1947 Hur Baker Aug 30 1950 (TS TS Brenda Jul 26-27 1955 (TS) TS Unnamed Aug 26 1955 (TS
1955/56-1965	NW-Marsh breakup evident in this area. Some erosion of southern star lake shoreline. Rifts expand. NW and N central quadrant marsh appears more broken up than other areas. New small water bodies along B. Lafourche. Small trenasse widens across Snake Ridge natural levee. NE, SE, SW-Continuing slow breakup of marsh in other areas. Big lake boundaries remain intact.	NW-Double pipeline canal N of study area. TGT (Highline Canal) (1956-1960). Several plugs installed in southern star lake system. Levee flank Lake Jesse connected by canal to star lake system. NE-Canal connecting B. Jacque and B. Ferblanc (1964). Leeville oil field expands with new canals. SE-Long E/W canal from B. Lafourche to Caminada Bay. SW-Several short extensions of existing canals. Dogleg Canal almost connects SWL Canal to South Lake.	Hur Flossy Sep 23/24 1956 (TS) Hur Audrey Jun 27 1957 (TD) Hur Betsy Sep 9/10 1965 (T-I)
1965-1969	Continued general marsh breakup throughout study area, with increases in open water. Moderate to heavy loss in star lakes region and south of Lake Jesse. Configuration of lakes remain intact.	NW-none NE-Canal from B. Ferblanc at Bay Diego toward NW with 3 stems. Leeville area-about the same. SE-Long NE/SW Canal intersecting SWL canal at B. Ferblanc (1969). SW-Several short stems added to existing canals.	Hur Camille Aug 17/18 1969 (H)

Table 8.4. Cont.

Year	Marsh Loss	Human Impacts	Meterological Events	Veget
1972-1978	NW, NE, SE-Marsh appears relatively stable over the period. Snake Ridge natural levee in NW is increasingly breached. SW-Large marsh areas are degrading and appear submerged south of L. Jesse and between B. Lafourche and south canal system. This is major marsh loss event. In general, big lake shorelines throughout study area are still intact.	NW-none NE-none SE-one short canal off of B. Ferblanc. SW-one canal southward from SWL Canal parallel to High Line Canal (1977) Extreme W-pipeline canal constructed in 1978.	Hur Carmen Sep 7/8 1974 (TS) Hur Babe Sep 5 1977 (TS)	By 197 mapped
978-1985	NW, NE, SE quadrants-little change in marsh has occurred over this period. SW-Most of the marsh in this section is seriously degrading. Those areas that appeared submerged on the 1978 photo are open water in 1985 or look increasingly submerged. These are large-scale marsh losses in the area SW of SC canal between B. Lafourche and High Line Canal.	NW-new canals N of existing canal N of Snake's Camp. NE-Canal connected (but plugged) between B. Ferblanc and area to west. SE-none SW-none LOOP pipeline constructed (1978).	Hur Bob Jul 11 1979 (TD) Hur Elena Sep 2 1985 (TS) Hur Juan Oct 27-31 1985 (TS)	salt ma
985-1989	Little change in study area over this period. The marshes have been relatively stable between 1985-1989.	NW-none NE-stem canal off of existing canal north of North Lake. SE-none SW-none		salt ma
Summary	Most of area marsh intact in study area in 1945, but some breakup already in SW quadrant. Major deterioration occurred in N area (star lakes area and SW areas. Most severe degradation between 1972 and 1985.			

For the period 1969–1972 widespread additional degradation did not occur, however localized degradation occurred in several areas, generally in the southwest.

From 1972–1978 major loss of marsh occurred in the southwestern quadrant, particularly in the areas south of Lake Jesse and between Bayou Lafourche and the southern oilfield canal complex. This loss is evident in Figure 8.8d. Large areas of marsh appear "submerged" on the 1978 aerial photograph. Other marshes in the study area appear relatively stable over this period.

Between 1978 and 1985 additional major marsh loss occurred in the southwestern quadrant (Figure 8.7d and e). Most of the marsh in this section suffered serious degradation to open water. The areas that appeared "submerged" on the 1978 photograph were mostly open water in 1985.

During the period 1985 to 1990 little change is detectable. The marshes appeared relatively similar.

Overall, wetland area changed from 9,192 ha (22,704 acres) in 1945 to 5,545 ha (13,697 acres) in 1989. Of this, the 7,042 ha (17,393 acres) of solid marsh (class I) in 1945 decreased to 369 ha (912 acres) in 1989. Degraded marsh (class II, III and IV) increased from 2,150 ha (5,312 acres) in 1945 to 5,176 ha (12,784 acres) in 1989. Much of the marsh over this period was lost to open water, as is apparent in Figure 8.7 and documented by an increase from 1,464 ha (3,617 acres) in 1945 to 4,167 ha (10,292 acres) in 1989.

Concurrent Events

Vegetation

As discussed earlier, the study area in 1945 was probably freshwater floating marsh in the northwest, changing to nonfresh in the south and northeast. O'Neil described the vegetation in the 1940s as brackish (*Scirpus olneyi/Spartina patens*) in the north and west, and salt marsh (*Spartina alterniflora*) in the southeast. The reasons for the discrepancy are unclear but may relate to O'Neil's mapping scale. We have detected, in aerial imagery, rafts of floating aquatics (probably water hyacinth) in the earliest imagery of the study area. Since the only floating aquatics in south Louisiana are freshwater species, this suggests a freshwater environment. By 1978 Chabreck and Linscombe mapped the whole area as salt marsh, and it has remained so to the present.

Hydrology, Canals and Other Human-made Features

Canal density in the Leeville oil field was already high in 1955–56, especially west of Bayou Lafourche. Through 1974 the network expanded, but few canals have been constructed since then. Circulation was influenced in two ways: first, the major canals—e.g. Southwestern Louisiana Canal, and the Highline Canal—changed circulation patterns. Southwestern Louisiana Canal, for example, was the first major channel to enable east-west flows across the western

Barataria basin marshes from Bayou Lafourche east to Barataria Bay and west to Terrebonne Bay. This provided direct avenues for tidal water in Bayou Lafourche to enter the low salinity marshes adjacent to Bayou Lafourche. Interlocking canals also opened up marshes, changing overland flows to confined channel flows. For example, in 1955–56 there was already a canal extending north from Southwestern Louisiana Canal into the marshes, and by 1965 another canal opened the area further from Southwestern Louisiana Canal through Lake Jesse. Second, the interlocking canal spoil banks compartmentalized the marsh into impoundments with restricted circulation, between which water levels were probably frequently deeper and more prolonged (Swenson and Turner 1987).

Discussion

The Leeville study area includes the northern star lake region that was freshwater marsh as recently as the 1950s, and eastern and southern areas that were nonfresh marshes in 1945, the time of the earliest aerial photography used in this review. These two areas exhibited different spatial and temporal marsh degradation trends.

Although marsh degradation occurred throughout the period of this study (1945–present), the major periods of acute marsh loss in the Leeville study area were 1965–1969 and 1972–1985.

The northern star lakes area degraded most in the earlier interval, from 1965–1969, although some loss had already occurred prior to this period. The nonfresh southern region of the study area south of Lake Jesse also degraded in the earlier period, but suffered the heaviest degradation from 1972–1985 when large areas became open water.

The star lakes area was mostly intact in the 1940s, with small rifts and open water probably caused by the tearing of the buoyant marsh mat during hurricanes. The construction of canals connecting this region to adjacent areas by 1965 probably allowed higher salinity water into this system. The strong surge of Hurricane Betsy in September 1965 may have been a physical force that drove saline bay water into these fresher interior marsh areas (similar scenario to Bayou L'Ours). The storm surge from Betsy at Grand Isle was reported to be about 3 m (10 ft) (Williams et al. 1992). Water levels at the Leeville gauge were recorded at least 1 m (3.2 ft) above the long-term average highs during this event (Swenson, this report). As noted before severe degradation in this area occurred over the period immediately after Betsy's impact, 1965–1968–1969.

The nonfresh portion of the study area would not have been similarly affected by saltwater intrusion. The severe degradation in the nonfresh southwestern portion of the study area is in the area of intense oil extraction activities of the Leeville oil field. A network of canals is in place in this area, although marsh loss does not occur simultaneously at all other areas within the region with similar canal density. This area appears to have suffered from prolonged flooding, based on the "shadow" type of signature apparent on aerial photography. Prolonged flooding and reduced water exchange has been documented in semi-impoundments of this type (Swenson and

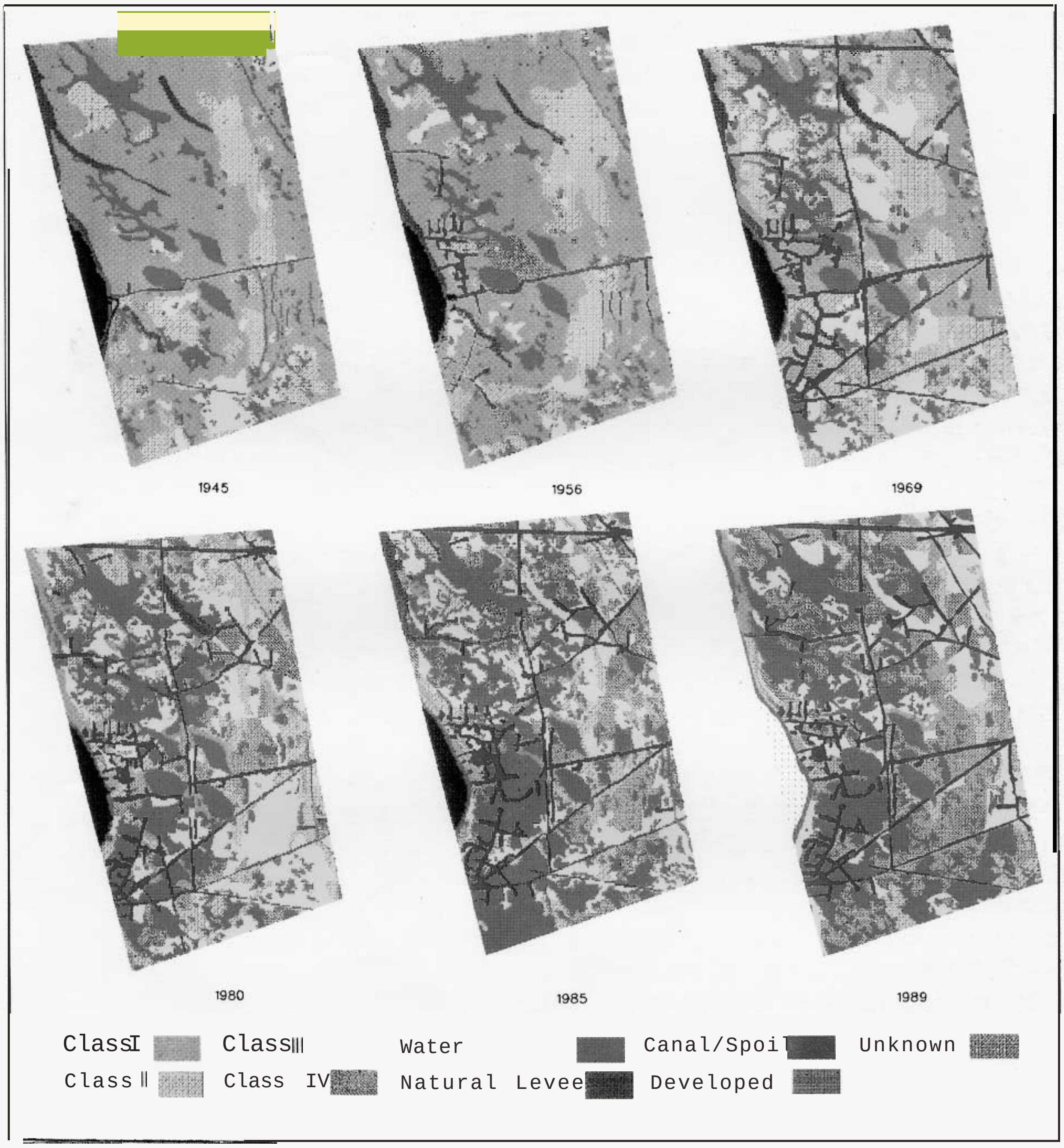

Figure 8.7. Classification maps of Leeville site.

Turner 1987), and their more subtle chronic stress (compared to a sudden salt influx into fresh marshes) could be responsible for a delayed and prolonged degradation.

The easternmost region of the study area remained relatively stable throughout the period of record, with no wholesale shifts from marsh to open water, although ponding and small scale breakup of marsh is evident. The eastern area contains five (or more) closely spaced, parallel distributaries that run from north to south. The natural levees of these relict distributaries apparently provide a stable substrate that supports marsh that has so far resisted the widespread loss of adjacent areas.

MADISON BAY AREA

Introduction

The Madison Bay study area is located in the south central Terrebonne basin (Figure 8.1). This study area is situated in salt/brackish marshes east of Bayou Terrebonne (Figure 8.8). The area is bounded on the east by Bayou Terrebonne and on the south by Lake Barre. Several tidal bayous connect the interior marshes to Lake Barre, including Grand Bayou, Bayou du Courant, Bayou Chitigue, and Bayou de Mangue.

Geologically the area is older than the previous vignettes. The marshes in the area were originally formed when Bayou Terrebonne was an active distributary, several thousand years ago. The area has been subject to dominantly marine influences for probably at least 1700 years, the period after Bayou Lafourche to the east became the major distributary. Levee flank depression is possible in the marshes close to the natural levee of Bayou Terrebonne where the weight of the levee sediments compacts underlying strata. Local rates of relative sea level rise are difficult to estimate for the area as there are no long-term water level records. Soils vary from saltwater marsh clays and lucky clays, to saltwater marsh peats to brackish marsh deep peats (USDA 1960).

Compared to the other vignette sites land loss has been moderate at Madison Bay. Approximately 27% of the marshes in the area of this site were lost between 1932 and 1990 (USCOE). The rate before 1958 was low, increasing to 1983, and apparently slowing somewhat since then. Most of the lost was "natural," with few canals constructed in the area.

Results

General Description of Landscape Changes

In 1941 the northern portion of the study area was moderately degraded, especially along the flank of the Bayou Terrebonne natural levee. The southern area was more intact, with numerous tidal channels connecting the interior marsh to Lake Barre to the South. No canals were in place.

During the period 1941 to 1956 only minor changes in the marsh were noted.

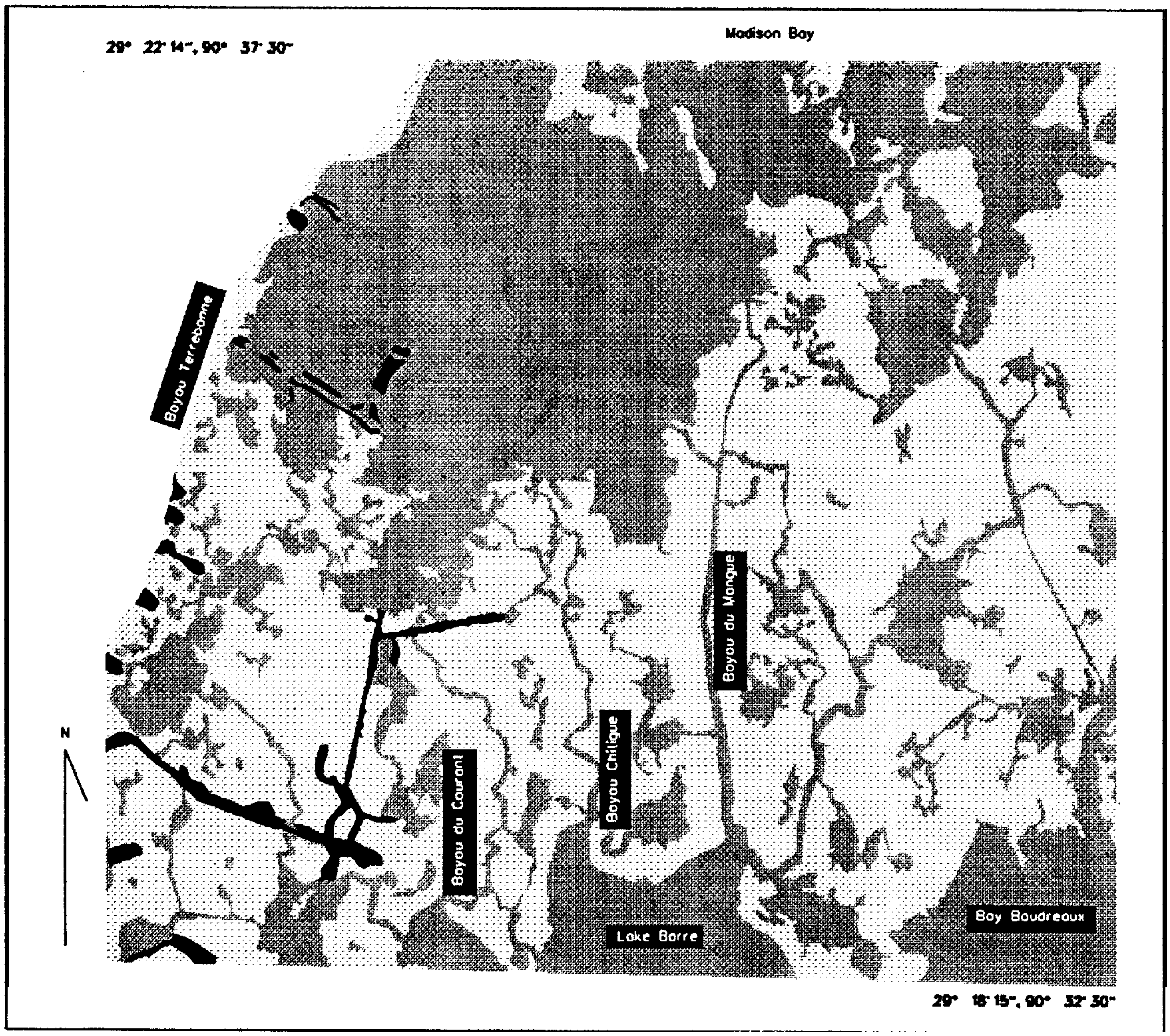

Figure 8.8. Madison Bay study area.

From 1956 to 1965 continued minor degradation occurred as indicated in Figure 8.9a and b.

During the period 1965–1969 little change occurred in the northern area. In the southern area coalescing of small ponds and continued minor breakup occurred.

From 1969 to 1972 much of the northern part of the study area was submerged, as indicated by a "shadow" on the aerial photograph. Other marshes in the study area were relatively stable.

During the time period from 1972 to 1978 a major change to submerged marsh and/or open water occurred in the northern area. The southern region remained relatively stable.

From 1978 to 1985 major marsh loss occurred in the northern part as the submerged marsh became open water. Marshes in the southern area remained relatively stable. Figure 8.9c shows the area of this major loss from a 1990 photo.

During the period from 1985 to 1990 additional small incremental marsh loss occurred in the northern area, with the southern area remaining stable.

Overall, wetland area within the Madison Bay study area changed from 4,279 ha (10,570 acres) in 1956 to 2,629 ha (6,496 acres) in 1990. Solid marsh changed from 911 ha (2,251 acres) in 1956 to 111 ha (275 acres) in 1990. Degraded marsh (class II, III and IV) covered 3,368 ha (8,319 acres) in 1956 and changed to 2,518 ha (6,220 acres) in 1990. As is evident in Figure 8.9, considerable conversion of marsh to open water occurred, changing from 1,077 ha (2,661 acres) in 1956 to 1,433 ha (3,540 acres) in 1965, and 2,674 ha (6,605 acres) in 1990. Table 8.5 shows the changes in the study area.

Concurrent Events

Vegetation

In the 1930s and 1940s the southern portion of the study area was salt marsh, changing to *Spartina patens*-dominated brackish marsh in the north. By 1978 the whole area was classified as salt marsh by Chabreck and Linscombe (1978), and has remained salt marsh.

Hydrology, Canals, and Other Human-made Features

The southern half of the study area has the typical salt marsh signature of sinuous tidal creeks, some of which penetrate into the previously brackish system.

There are few canals in the study area but between 1972 and 1978 two oil field access canals were dredged from Bayou Terrebonne into the area, one into the saline marsh, connecting to Lake Barre, and one farther north into the degrading brackish marsh. These breached the natural levee of Bayou Terrebonne, which had previously been a barrier to east-west flows.

Table 8.5. Madison Bay matrix of historical wetland loss and correlative data or events.

Year	Marsh Loss	Human Impacts	Meteorological Events	Veg
1945	NE (Madison bay area) -50% lost, especially along levee depression. Good natural levee with trees along B. Terrebonne, S-tidal channels with moderate degradation in interior marshes.		Hurricane Sep 29 1915	
45-56		E/W canal from B. Terrebonne to Madison Bay (1952); dredge B. Terrebone N of area brings sediments S into Madison Bay.	Hurricane Sep 19/20 1947 Hur Baker Aug 30 1950 (TS) TS Brenda Jul 26/27 1955 (TS) TS Unnamed Aug 26 1955 (TS)	
56-65	Continued slow degradation.	E/W oil-field access canal from L. Barre to B. Terrebonne (1962-1964)	Hur Flossy Sep 23/24 1956 (TS) Hur Audrey Jun 27 1957 (TD) Hur Betsy Sep 9/10 1965 (H)	
65-69	NE-not much change; N of L. Barre, continued breakup, coalescing of small ponds.	Dogleg branch N off oil-field access canal (see above).	Hur Camille Aug 17/18 1969 (H)	Brac
69-72	NW-submerged area ("shadow"), rest of area is stable.		Hurricane Fern Sep 11 1971 (TS)	
72-78	NW-submerged area becoming open water; major loss of marsh. Little change in S.	E/W dogleg canal off B. Terrebonne, N of L. Barre into interior marsh.	Hur Carmen Sep 7/8 1974 (TS) Hur Babe Sep 5 1977 (TS)	
78-85	NW-huge lake replaced marsh; S-little change.	No new surface expression of canals; however, middle of area-pipeline canal (1979) is laid.	Hur Bob Jul 11 1979 (TD) Hur Elena Sep 2 1985 (TS) Hur Juan Oct 27/3 1985 (TS)	
85-90	NE—dogleg canal, N and E-continue to degrade around edges of lake (see 78-85).	No new canals.		
Summary	NE-major deterioration, especially during 69-85. L. Barre area fairly stable through time-typical salt marsh pattern.			

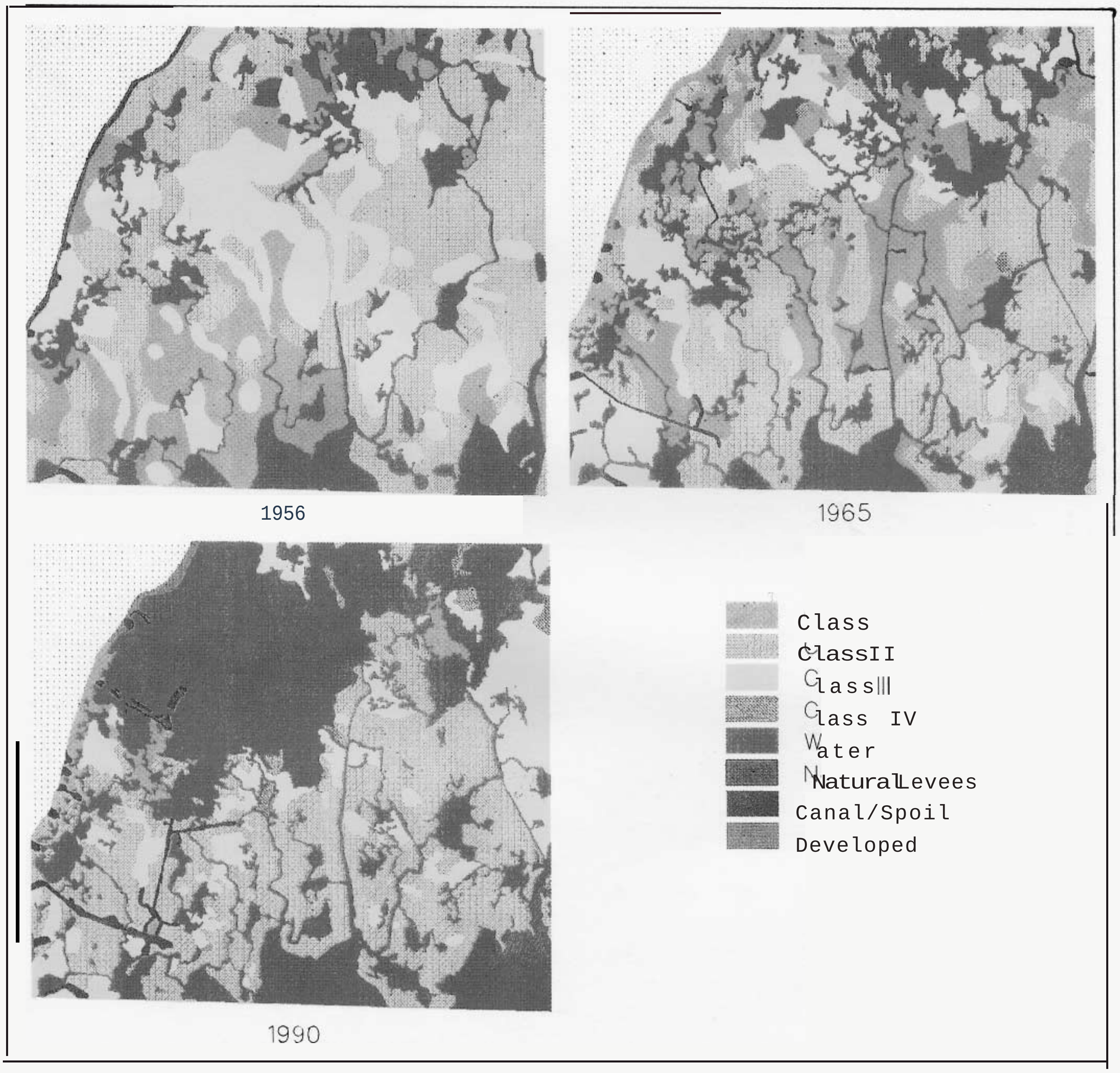

Figure 8.9. Classification map for Madison Bay site.

Discussion

Madison Bay area marshes were moderately degraded by 1941. Severe marsh loss in the area began after 1969, in the northern portion adjacent to Bayou Terrebonne but extending well into the interior marsh to Bayou de Mangue. The loss area is first indicated on the 1972 aerial photograph as a large "shadow" over the marsh area that ultimately changed to open water. The shadow indicates submergence of the marsh in this area, while remaining marsh areas are not submerged. Emergent marsh vegetation is apparent within the "shadow." The shadow was also evident on the 1978 photo, and by 1985 the submerged marsh had converted to open water. Little or no change is apparent in other marshes of the study area.

The process(es) causing marsh loss at Madison Bay is not clear. Several canals are present in this area, but no intense network of canals exist here. If the 1978 imagery "shadow" indicates flooding, it follows that substrate elevation in the area of marsh loss was lower relative to adjacent marshes after about 1969, and the marsh more frequently submerged than adjacent marshes. Why this section of marsh became lower than adjacent marshes is not clear, but DeLaune et al. (1994) reported high subsidence rates (1.38 cm/yr or 0.54 in/yr) that are not balanced by vertical accretion (~1 cm/yr or 0.39 in/yr). This would lead to a slow submergence with eventual plant death and pond formation by a process described by Day et al. (1994). The breakdown of formerly brackish marsh rather than the southern saline marsh may be related to the lower bulk density of the brackish marsh soils, the lower tolerance of *Spartina patens* to flooding, and the lower shear strength of brackish marsh soils (Day et al. 1994).

VIGNETTES SUMMARY

The goals of the case studies of small marsh areas were to assess the utility of historical aerial imagery to determine wetland status and wetland loss processes, and to gain insights into fine scale processes leading to wetland loss.

Aerial Imagery as a Tool to Determine Local Wetland Loss Processes

This study has shown that detailed examination of sequential aerial photos can provide significant insights into the mechanisms of wetland loss. Major examples seen in the vignettes are summarized in Table 8.6, and discussed below.

Some of the more obvious processes are shoreline retreat along bayous and beach barriers, and canals and canal impoundments. Much can also be implied about changes in circulation patterns by the alignment of canals, their size and widening rates, and the disappearance of natural channels in their vicinity.

Historic evidence of floating marshes is given by minute tears in a marsh that persist and sometimes enlarge through time; and by the sudden appearance of small irregularly shaped lakes (star lakes) in interior marsh (probably caused by hurricane-force winds and elevated water). Other hurricane damage can be seen as a pattern of

Table 8.6. Interpretations of features visible in aerial photography of the Louisiana delta plain.

Patterns in Aerial Imagery	Marsh Type/Status	Process
Rips & tears in marsh; small jagged-edged lakes (e.g., Star lakes and Bayou L'Ours)	Floating marsh, probably fresh	Hurricane damage
Inverted marsh, fine scale lines, linear ridges of slightly higher elevation	Herbaceous/shrubs	Hurricane damage
Small ponds, often linear & connected, parallel to adjacent natural levees	Levee flank depressions	Subsidence
"Shadow" over large marsh areas	Observed in salt/ brackish types	Incipient degradation, probably due to submergence
Dark areas with parallel striations	Burned marsh, found in many marsh types	Lightning, management
Dense dark vegetation with coarse texture	Forested marsh	—
Tiny, highly reflective white dots surrounded by darker area	Muskrat houses	Indicates an area with muskrat population increasing proportionate to the number of dots
S-shaped meanders	Riverine channels	Flow follows course in one direction
Meanders with sharp points forming a succession of oblong pools connected by narrow channels at the bends	Estuarine channels	Flow both in and out of the channel, depending on tide
Linear features with or without adjacent parallel tree/scrub vegetation	Canal with or without accompanying spoil	—
Interconnected linear features surrounding marsh or water	Impoundment	Poor water exchange & prolonged flooding causes are both natural & human-made
Marsh opening along or at end of narrow channels over time		Marsh scour
Differences in edge of marsh over time		Shoreline erosion or deposition

closely spaced linear ridges in a marsh, scoured areas, and overturned marsh.

Occasionally aerial images show "shadows" over large areas, presumably indicating flooded marsh. These shadowed areas almost always show widespread marsh degradation in subsequent images.

Processes Controlling Marsh Loss in the Case Studies

The four case studies represent marshes of different salinities (intermediate to saline), different geomorphic settings, and different major impacts. A close study of a time series of aerial photographs of each site taken between 1945 and 1990 brought home the complexity of the marsh, the number of different processes that can lead to marsh loss, and the complexity of the interaction of processes in space and time. Since the case studies were all different, and since the concept of "control" sites is inappropriate where the whole coast is changing, our conclusions about processes, although reasonable and confirmed by examples in the scientific literature, must be considered tentative. The primary insight that comes through this exercise is the complexity of the coastal system and the paucity of our knowledge when applied to specific small sites. With that caution, we discuss below the major processes that appear to be operating in these vignettes.

Shoreline Erosion

Changes in Bayous Perot and Rigolettes are primary examples of shoreline erosion. The change in configuration of these streams from the 19th century when they were narrow and sinuous, with dominant point bars, and the present configuration of wide lake-like water bodies with smooth shorelines or small cusps, suggests a major change in circulation from a flow-through riverine system to a tidal estuarine system. This circulation change could be a reflection of the blocking of Bayou Lafourche in the early 1900s and the construction of levees along the Mississippi River, whichdecreased freshwater input to Barataria basin. Locally, the construction of the Barataria waterway could have shifted downstream flows, bypassing bayous Perot and Rigolettes; while the increase in the tidal prism in the basin and the construction of Dupre Cut undoubtedly increased tidal exchange through the two bayous.

Canal Effects

The Leeville and Bayou L'Ours sites are primary examples of the results of canal construction associated with oil field development. The canal network tends to increase circulation and accelerate salt intrusion by connecting salt sources such as Bayou Lafourche to interior marshes, and by providing deep, straight pathways of water flow where formerly there was over-marsh sheet flow and shallow, sinuous natural bayous. Conversely, the spoil banks effectively isolate patches of marsh from the channels. These impoundments tend to prolong flood duration at deeper depths than normal, and reduce exchange. In combination, the channels and impoundments effectively route saline water into marsh areas where it overtops the spoil banks during storms, and is prevented from draining back out when storm waters decline. The result can be an acute, lethal stress on salt-intolerant plant species (the northern Leeville and the Bayou L'Ours sites), and chronic, long-term flooding stress on salt tolerant species (the southern part of the Leeville site). Both effects lead to death of the marsh plants and eventual marsh loss.

Major Storms

The damaging effects of Hurricane Andrew have been documented recently (e.g., Guntenspergen et al. 1995). Damage from past hurricanes is more difficult to document and therefore more speculative, but the timing of marsh losses at Bayou Perot, Bayou L'Ours, and Leeville suggests Hurricane Betsy in 1965 as a contributing factor, possibly exacerbating existing low level chronic stresses caused by impoundment, as discussed above.

Sudden Interior Marsh Loss

The large-scale, rapid interior marsh collapse at Madison Bay is impossible to pin down with certainty from available evidence. However, the chronic effect of slow submergence on plant root productivity, which finally triggered a positive feedback loop leading to plant mortality (Nyman 1993), is a likely partial explanation (see Madison Bay discussion).

Importance of Marsh History

In all case studies the history of the marsh appears to be of major importance. Bayou Perot, Bayou L'Ours, and Leeville were all fresh marsh sites as recently as the 1940s. Some, perhaps all, supported floating marshes, and were therefore highly organic. The northern portion of Madison Bay may also have been fresher as recently as mid-century (DeLaune et al. 1994). In most of the case histories there is evidence from vegetation changes and/or salinity records of gradual salt intrusion over time. Increased marine influence, and the rate of change to a more marine environment may be critical for the fate of fresh marshes, and the possibility of transition of a fresh and/or floating marsh to a brackish marsh, and finally to a salt marsh. Madison Bay provides an excellent example. The southern portion is a typical salt marsh configuration, with sinuous bi-directional tidal streams supplying broad, stable marshes. Farther north the vegetation was brackish in the 1960s and the soils more organic, with less mineral content. These brackish marshes have not had the same ability to cope with subsidence as the salt marshes, and over a period of about 15 years degraded rapidly. Because the dominant species, *Spartina patens*, is salt-tolerant, it is unlikely that salt intrusion is a dominant causative factor in this collapse, but the prior history of the marsh as a freshwater peat-forming system (DeLaune et al. 1994) may indicate a substrate more prone to compaction than the salt marsh soils. In addition, the paucity of mineral sediments, and the relative sensitivity of *Spartina patens* to submergence, may be contributing factors.

Broad Scale Implications: The Importance of Cumulative Effects

The vignette studies have demonstrated that habitat change and wetland loss at the local scale are rarely the result of a single factor. Rather, the cumulative effects of natural and human changes to the system have been shown to combine and result in the landscape patterns we see today. Human and natural structures and processes such as canals, impoundments, upland drainage and flood control ditches, river structures for flood control, water diversions, saltwater intrusion, and water pollution do not act in isolation. Cumulative effects are defined as the total effect of many individual actions occurring over time, either because different kinds of actions or structures interact at a wetland site or because many individual actions, any one of them relatively minor, result in an additive serious impact at the level of a hydrologic unit such as a coastal basin. Both kinds of effects can be dramatic.

Hydrologic Modifications

Water is the major organizing force driving and defining coastal estuarine ecosystems (Mitsch and Gosselink 1993). As a result, cumulative hydrologic modifications often result in major changes in coastal marshes. These effects are both direct, as when dredged channels change circulation patterns, and indirect, as when canals that link a marsh directly to the Gulf allow the intrusion of salt water which damages marsh plants. Examples illustrate the cumulative interaction of different kinds of actions.

Western Barataria Basin

The western portion of the Barataria basin was an actively prograding delta lobe 2000 years ago, and Bayou Lafourche, through its distributaries Bayou Raphael and the east and west forks of Bayou L'Ours, continued to deliver fresh water and sediments in significant amounts until as recently as 250 years ago (Adams et al. 1978, Frazier 1967, Penland et al. 1988b). Even after the Lafourche distributary was abandoned, fresh water continued to flow down the Lafourche channel. During this phase of the Lafourche delta the general pattern of flow was from northwest to southeast paralleling the paths of the distributaries of Bayou Lafourche. Most of this flow was sheet flow across the marshes as there were few defined channels. Overbank flooding from Bayou Lafourche was a common event in the late 1800s and levees were constructed to prevent flooding, but there was no active channel between Bayou Lafourche and the marshes to the east. Thus, the marshes in this area were fresh before the turn of the century and their hydrology was dominated by fresh riverine flows and upland runoff. The U.S. Army Corps of Engineers dammed Bayou Lafourche at Donaldsonville in 1904, limiting freshwater flows to that amount needed to keep the bayou fresh as far south as Thibodaux.

The Southwestern Louisiana canal breached the natural barrier of the Bayou Lafourche levee late in the 1800s, allowing marine water to flow from the Gulf through Bayou Lafourche into the southern marshes east of the bayou. Aerial imagery flown in 1945 shows several additional canals (Yankee canal and several others north of the present Tidewater canal) cutting through the Bayou Lafourche levee. In 1947 construction on the Tidewater canal system, which became part of a network of oil and gas access canals, was initiated. Thereafter salinities increased rapidly in the marshes north of Leeville. Figure 8.10 shows the growth of the canal system after 1945. The net results were a major change in circulation pattern from a unidirectional flow from northwest to southeast parallel to Bayou Lafourche, to east-west tidal flow across the natural levee barrier of Bayou Lafourche. Salinization and breakup of the interior marshes has been rapid during the past 40 years (Table 8.7), certainly in part related to the cumulative impact of the many canals (Gosselink 1990).

Impoundments in BTES

Both private owners and public agencies have impounded marshes in Louisiana since the turn of the 20th century. Many of the early impoundments were intended for drainage and agricultural use. Most of these have subsequently failed as subsidence occurred within the impoundment and levees were breached by hurricanes. Impoundments have also been created for urban development, wildlife enhancement, aquaculture, and as part of plans for marsh restoration (marsh management areas). Figure 8.11 shows that 370,000 ha (913,900 acres) were impounded in 1985. Of this total 58% fell into the developed category (urban, agriculture, aquaculture), 12% had failed and are now shallow open lakes, and the remaining 30% are still marshes, but with restricted hydrology. The original purpose of the impoundments which failed was not reported by Day et al. (1990). Between 1980 and 1989 permit applications were received by the Louisiana Department of Natural Resources for marsh management of 137,444 ac (24% of total marsh) in the Barataria basin, and 74,844 ac (13%) in the Terrebonne basin. Implementation has begun on only about 41% of this area, but based on previous permit issuance nearly all the permit applications will be approved (Cahoon and Groat 1990). Since there is a time overlap between the survey conducted by Day et al. (1986) (Figure 8.11) and the survey of Cahoon and Groat (1990) the total area of marsh either impounded or permitted for management is not known, but in the Barataria basin it is approaching 50%, and somewhat less in the Terrebonne basin. This impoundment is occurring without regard to the cumulative effects of hydrologic modification on the estuary as a whole.

Major objectives of marsh management are "hydrological isolation" (Chabreck and Junkin 1989) and water level regulation (Cowan et al. 1988). It is not surprising, therefore that Swenson and Turner (1987) found about one half the flux of water through a semi-impounded area as through an adjacent natural area. At the basin level this means that fluxes of water must increase outside the impoundment, and/or that the tidal prism must decrease. This kind of effect can be estimated only through modeling studies. There are no field data to document it, not because the hydrologic modification is not significant, but because it occurs slowly over time over the whole basin. There are, however, clear examples of dramatic changes in the directions and character of flow, from, for example, laminar flow across marshes to channelized flow, in part because of changes in the depth and serpentine quality of existing channels, blocking of natural channels, and/or construction of linear "borrow" pits in connection with levee construction. One part of the continuing controversy about marsh management (see Part 5) that needs to be addressed is the magnitude of hydrologic effects to the BTES, the impact of these effects, and the level of modification the system can sustain without serious degradation.

Lessons for System Management

All these examples of cumulative impacts point to the importance of integrated management of whole estuarine systems. Management should be guided by insights derived from considerations of cumulative impacts:

- A management action is a local action, but its impacts are basin-wide.

- There are seldom single cause–single solution instances of marsh loss. Rather, there is commonly a complex interaction of processes and actions, resulting in chronic stress, leading to gradual and continuing marsh degradation and loss (although "triggers" may be responsible for sudden rapid changes to these stressed systems).

- The accumulation of minor actions over time can cause major environmental changes. This suggests that any plan must specify limits on the total area of direct impact. Therefore it is imperative, first, that cumulative effects be carefully considered in the development of the Barataria-Terrebonne National Estuary Program's Comprehensive Coastal Management Plan, so that appropriate limits to human activities can be established and enforced; and second, that permitted actions be designed to support and enhance the plan, not to interfere with its implementation and operation.

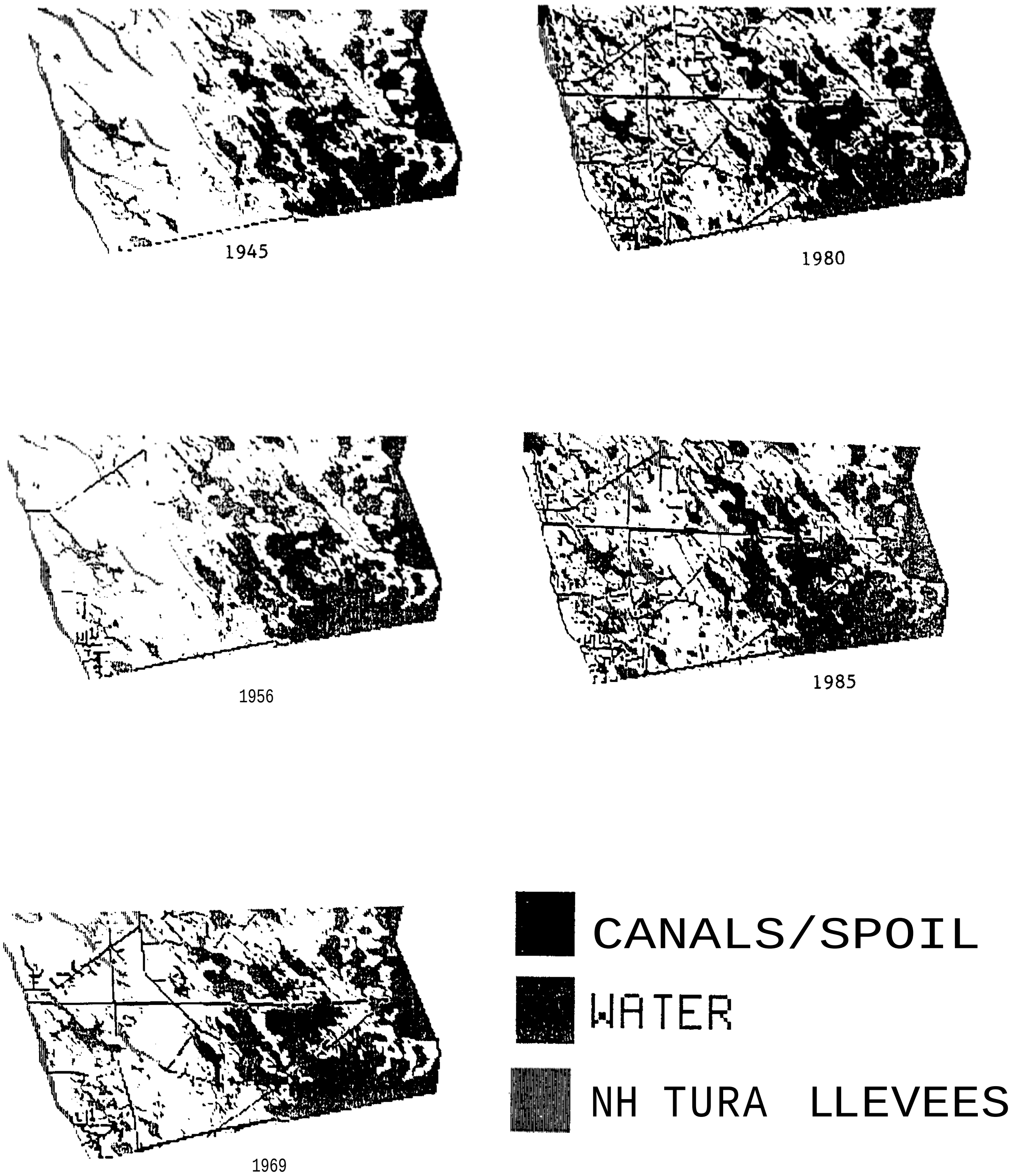

Figure 8.10 Growth of the canal network in the vicinity of the Tidewat
system. The area covers 101 mi², and is bounded by Bayou Lafourche
on the west, Barataria bay on the east, Southwestern Louis
the south, and an east-west line just north of Tidewater c
north. The Tidewater canal is clearly visible as the diago
1956 map (Gosselink 1990).

Table 8.7 Changes in the area (km^2) of marsh, canals, and natural levees in the environs of the Tidewater canal system from 1945 to 1985. The total area encompassed (101 mi^2) is the same as in Figure 8.6.

	1945	1956	1969	1980	1985
Total Marsh area	156	153	113	111	104
Solid marsh[a]	144	126	83	26	11
Degraded marsh[b]	12	27	51	85	93
Open water[c]	94	97	105	127	134
Natural levees	8	4	5	5	2
Canal and spoil areas	1	3	13	14	18
Developed	0	0	0	0	1
Other	0	2	2	2	2
TOTAL	259	259	259	259	261

[a]Solid marsh is less than 10% open water.
[b]Degraded marsh is 10–60% open water.
[c]Open water is all areas more than 60% open water.

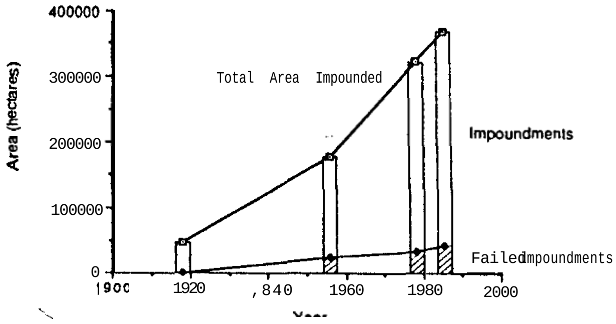

Figure 8.11 Cumulative area of current and failed intentional wetland imp
in the Louisiana coastal zone (Day et al. 1990).

PART 9

CONCLUSIONS AND RECOMMENDATIONS

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MAJOR ISSUES

Wetland Loss

The most striking trend identified in the Barataria-Terrebonne estuarine system is the massive conversion of land to open water that has been documented in this report. This is the primary issue to be addressed by management actions recommended by the National Estuary Program. The causes of vegetative deterioration and death have been described in the previous section and it is clear that the problem results from the combined influence of a number of factors (e.g., subsidence, reduced sediment availability, channelization of marshes, interruptions to tidal exchange, altered salinity regimes, increased water levels, etc.).

Of these, subsidence is the most important and the most pervasive—a coast-wide process impacting all coastal wetlands in the estuaries. In saline marshes, subsidence results in rising relative water levels requiring adequate accretion of organic matter and mineral sediments to prevent submergence. In many areas, supply of new mineral sediments is limited and conversion from *Spartina alterniflora* marsh to open water has occurred. Similar problems occur in brackish marshes where, although a greater component of the marsh soil is organic, mineral sediment is still important in maintaining surface elevation in the face of subsidence. In fresh systems, the impact of subsidence on marsh sustainability is less direct. Subsidence is an important process controlling the detachment of organic mats and the formation of floating marshes, estimated to cover more than 70% of the BTES freshwater marshes. These marsh types are more fragile than attached fresh marshes and more susceptible to both physical damage from excessive water movements and storms, and herbivory effects.

Understanding the natural evolution of the BTES based on shallow stratigraphy indicates that natural transitions have occurred during the Holocene from fresh to saline marsh types. All Louisiana marshes were originally deltaic and dominated by fresh marsh vegetation. As deltaic processes were replaced with marine processes after delta lobe abandonment and subsidence proceeded, a gradual change to more saline marsh types occurred. The patterns of coastal land loss documented in this report show that this transition from one marsh type to another is not always successful in today's estuaries. Areas of open water have developed at the boundaries between marsh types in many areas, suggesting that a conversion to open water is occurring rather than a conversion to a more saline marsh. This is exemplified in the loss of fresh floating marshes which do not, because of their particular hydrology and salt sensitivity, very often successfully convert to intermediate or brackish marsh.

The factors influencing marsh deterioration and loss in each wetland type are illustrated in this section. In fresh marshes (Figure 9.1), the limited supply of fresh water and nutrients from the Mississippi River and hydrologic modifications that decrease retention times in the marsh combine to constrain the areas where optimum growth conditions for fresh vegetation occurs. Plant growth is locally impacted by saltwater penetration into interior marshes along canals and stresses resulting from herbivory. These processes limit the accumulation of organic matter in fresh marsh soils and in areas of high subsidence the result may be the detachment of the root mat and the formation of floating marshes. While floating marshes do not require such high rates of organic matter accumulation to cope with subsidence, they are extremely susceptible to physical stresses such as storms or excessive water movements.

In saline marshes (Figure 9.2) the limited supply of sediment to the estuaries is a major cause of land loss. Even in areas and at times where sediment supply increases (e.g., during high river flow in the Atchafalaya) hydrologic alterations such as levees frequently impede the delivery of these sediments to the marsh surface. The net result in many areas is inadequate marsh accretion to combat subsidence and submergence of the marsh. At bay margins this is compounded by shoreline erosion which has increased as the barrier shoreline has become more fragmented.

Brackish and intermediate marsh systems (Figure 9.3) suffer from the combined impact of limited inputs of both fresh water and sediments. In the face of subsidence, brackish marshes require both mineral sediment and organic matter accumulation. The mineral sediment is essential to provide iron and prevent accumulation of toxic sulfides. In addition, increased saltwater penetration threatens the optimum growth conditions for intermediate and brackish marsh plants. Local problems such as herbivory can also be a problem in these areas.

In the forested wetlands (Figure 9.4) of the estuary, the declining supply of fresh water and sediments due to limited overbank flooding has presented problems to the habitat. As in intermediate/brackish marshes, both organic matter accumulation and sediment input are necessary to compensate for subsidence. The deficient delivery of fresh water and sediments to existing wetlands allows salt intrusion and nutrient deficiencies in some areas. With insufficient sedimentation and organic accumulation, flooding has increased, leading to the death of mature trees and at the same time poor conditions for new seed germination. Herbivory of cypress seedlings that are able to develop is known to be severe.

System Integrity

Natural estuarine ecosystems are ecotones between uplands and fresh rivers and the ocean. A major feature of this ecotone is the gradient of salinity from fresh water at the upland edge to oceanic salinities at the coast. This is reflected in a gradual transition from fresh to saline marshes on the same gradient. Louisiana estuaries are

open or semi-open systems connected by hydrologic circulation patterns. Historically, they were contained but not closed by high levees at the landward edge, which were overtopped during spring floods, and by a coastal barrier island system that limited

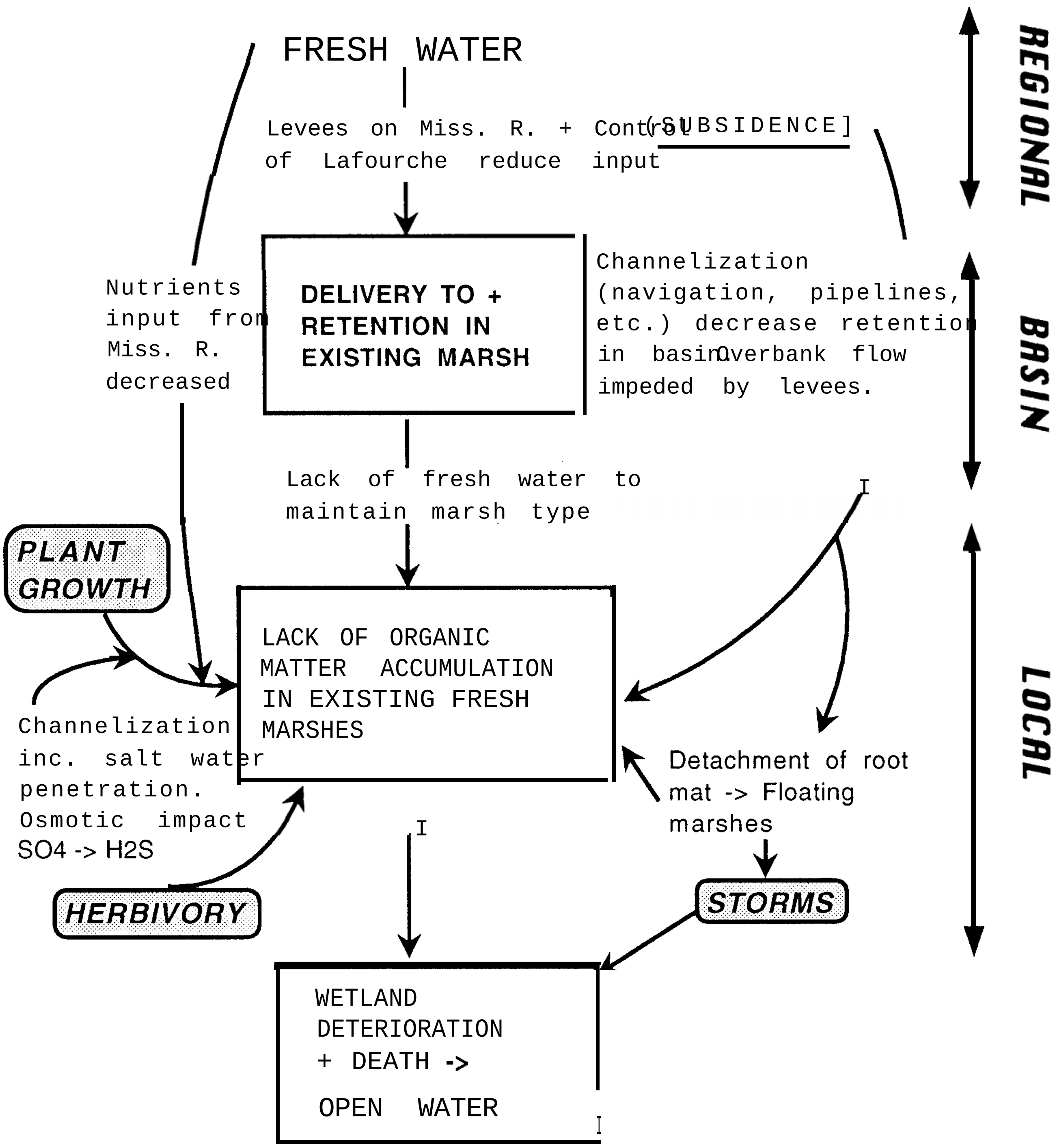

Figure 9.1 Processes contributing to deterioration of fresh marshes in BTES.

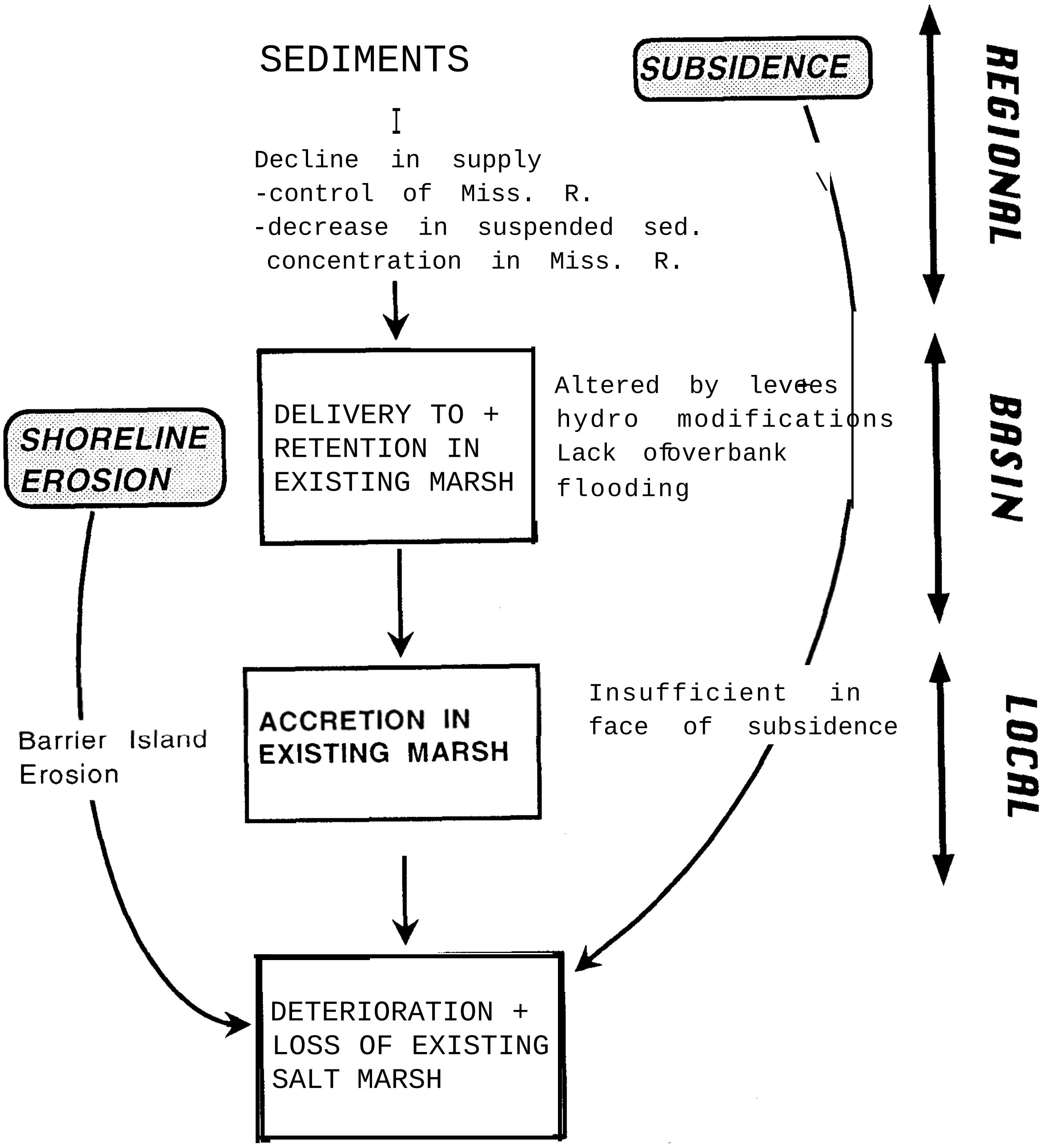

Figure 9.2 Processes contributing to deterioration of BTES salt marshes in

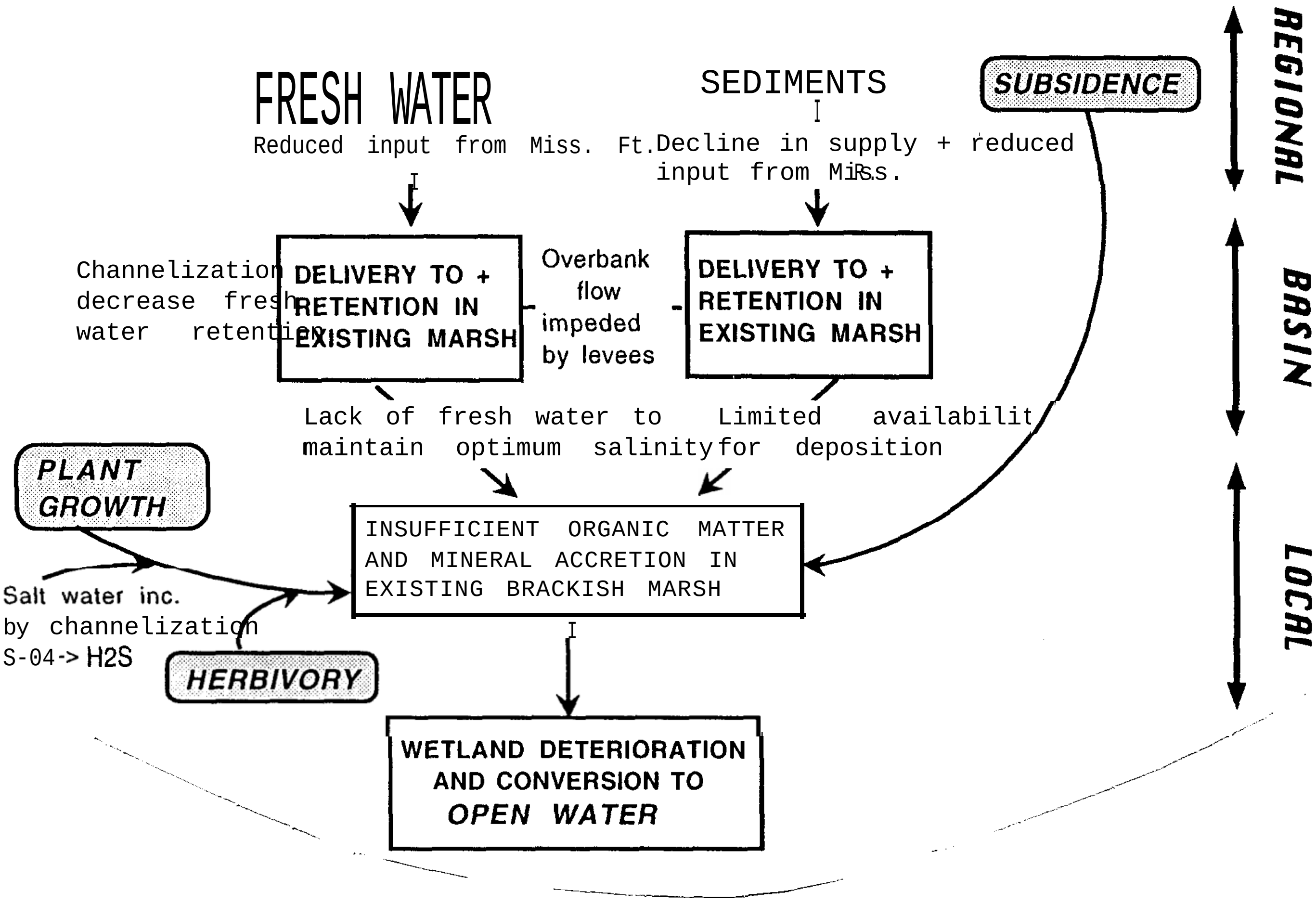

Figure 9.3 Processes contributing to deterioration of brackish marshes ir

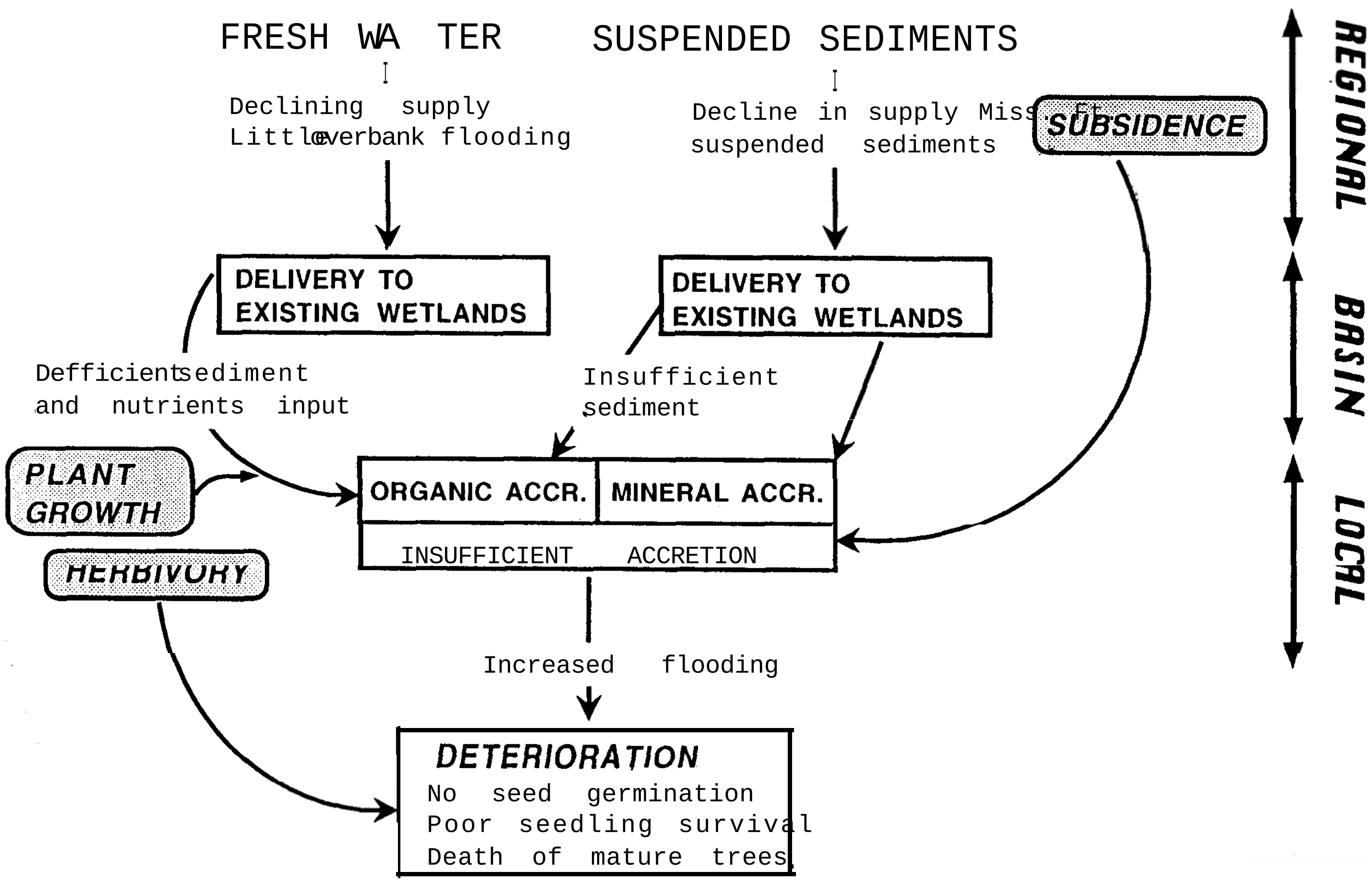

Figure 9.4 Processes contributing to deterioration of forested wetlands in BTES.

tidal exchange. This combination, in a region of high rainfall, probably kept the estuary fresher than at present, and maintained the fresh-salt gradient. Intra-estuary flows were dominated by shallow sinuous channels and sheet flow across wetlands, rather than today's channelized flows, ensuring sediment delivery to the marshes.

Louisiana estuaries are ebb-dominated because of freshwater inputs. Flows are downstream in the freshwater portions, and increasingly bi-directional at the seaward edge. This also ensures a fresh-salt gradient, and results in greater energy to carry sediments into saline marshes that need the most.

These characteristics of estuaries are important, not only to the marshes that depend on the salt gradient, but also for estuarine water quality and living resources. For example, fresh river water is typically nutrient-enriched by upland runoff. Many marshes act as nutrient traps, and hence water quality is improved if sheetflow dominates the estuary. Also, most fisheries species are marsh dependent, and their migratory patterns are strongly influenced by the estuarine gradient.

The present BTES still maintains most of the features of typical natural estuaries. Even though the changes in hydrology, salinity, and marshes documented in earlier sections have been severe, there is still a fresh-to-salt gradient, flow across many marshes, and an active fish and shellfish nursery. However, the ramifications of the massive human modification of the estuarine system are of considerable concern. The cumulative effects of multiple interacting actions on local sites, and of accumulating actions over time over the whole BTES, are major management issues and must be addressed in any comprehensive management plan.

MANAGEMENT RECOMMENDATIONS

System Integrity

In the following section specific management strategies to protect, restore, and create wetlands in BTES are described. Generally, management actions are developed for specific purposes at specific locations. Therefore, it is imperative to ensure that local plans enhance rather than detract from system integrity. The broad system-level goals of management might be described as: (1) to maintain and enhance system integrity as defined above; (2) to initiate delta building (the creation of new marshes); and (3) to slow or reverse degradation (wetland loss) of the estuary.

General strategies to carry out these goals are:

- Inputs. Increase freshwater and sediment introduction and use existing inputs more effectively. This is most effective in maintaining the salinity gradient if introduced to the head of the estuary, but freshening has generally a positive result on marshes, regardless of where it occurs. This also reduces the rate of salinity change at a site facilitating the transition from one marsh type to another.

- Intrabasin Plumbing. Maximize water flow *over* wetlands and through shallow, sinuous natural streams, rather than through deep straight channels that connect the ocean to interior marshes, or that shunt water directly from one bay or lake to another.

- Cumulative Effects. Human and natural actions, both beneficial and harmful to marsh loss and system integrity, are cumulative. Many of the events, such as subsidence and massive Mississippi River manipulation, cannot be controlled at the local level. It is imperative to recognize that these are contributory factors to present problems, and, therefore, an effective strategy should be "cumulative restoration"—maximizing the cumulative impact of beneficial actions and results, and minimizing those of harmful actions. In some cases, for example, canal construction or wetland impoundment, it may be necessary to set absolute limits to the area impacted and limit further developments of this kind.

Wetland Loss

The problems facing the estuaries have been outlined in terms of processes causing wetland loss, where the processes vary in nature and magnitude between marsh types. Based upon the identification of these problems the goal of estuarine management should be to maintain the integrity of the estuarine system. This goal can be achieved by implementation of process management to:

- prevent conversion of emergent marsh to open water,
- maintain the types of marsh (fresh, intermediate, brackish and saline marsh, and forested wetlands) present in the basin today, but not necessarily the relative acreages existing today, and
- increase, where possible, the extent of emergent marsh vegetation.

Management strategies should address the processes that result in land loss and work with natural processes to create new marsh. Subsidence of the substrate has been identified as the primary problem causing land loss with the basins and by its very nature cannot be addressed by the manipulation of surficial processes. However, surficial processes can be managed to more effectively counteract subsidence and this should be the cornerstone of estuarine management strategies.

The processes causing marsh loss were identified for each marsh type in Figures 9.1–9.4. Figures 9.5–9.8 identify management strategies which should be implemented to address land loss in each marsh type. In fresh marshes (Figure 9.5) the primary strategy is to maintain the accumulation of organic material to promote the retention of attached marshes. This prevents detachment of the root mat and the formation of floating marshes which are less resilient to storm impacts. Diversion of additional fresh water into fresh marshes provides a head to prevent saltwater penetration and provides nutrients to stimulate plant growth. Allowing natural exchange to marshes by removing high profile dredged material levees and maintaining overflow banks allows for inputs of fresh water and the prevention of excessive waterlogging. Management of these processes will facilitate the maintenance and restoration of existing fresh marsh areas. New fresh marshes may be created in areas where sediment diversion from the Mississippi River allows infilling of ponds and substrate for new fresh marsh growth.

In saline marshes (Figure 9.6) the primary strategy is to increase the supply of suspended sediment and allow natural processes to deposit sediment on the marsh surface. Increased sediment delivery from the Mississippi River could be combined with utilization of sediments from both maintenance and dedicated dredging projects to build new substrate in saline areas and help maintain existing marshes combat subsidence. The removal of levees to prevent waterlogging and allow deposition of sediments in interior marshes is an important component of this strategy, and one that is very important at a local scale.

The recommended strategy for managing brackish and intermediate marshes (Figure 9.7) provides for enhancing the combined influence of sediment and freshwater inputs. Diversions and siphons providing fresh water need to be combined with levee removal and canal plugging to allow natural processes to distribute available sediments.

In forested wetlands (Figure 9.8), the management strategy includes maximizing fresh water and suspended sediment input through river diversion, and enhancing their delivery to the habitat at the local scale by replacing levees with overflow banks. Additionally, forced drainage inputs routed over wetlands would provide more freshwater input as well as nutrients for plant growth. Herbivory problems should be controlled on a local scale as necessary.

The successful transition, where appropriate, from one marsh type to another (e.g., saline to brackish, or fresh to intermediate) is an important goal of these management straegies. The introduction of fresh water to some parts of the estuary may provide local conditions more conducive to the growth of *Spartina patens* than the existing *Spartina alterniflora*. The provision of an appropriate balance of fresh water and sediments will allow such changes to occur without the loss of emergent marsh cover. Ensuring this balance requires detailed understanding of marsh function and response and it is essential that management decisions be based upon the best available scientific knowledge.

In view of this, several existing management options require more study before further planning or implementation. More information is needed on the relative benefits and potential adverse impacts of marsh burning before it can be incorporated

into these management strategies. Some workers suggest burning stimulates marsh growth while others are concerned about the potential loss of marsh substrate. Experimental studies should be conducted to consider both positive and negative effects before burning is implemented as a strategy to combat marsh loss. In addition, the impact of the barrier islands on mainland marsh hydrology has yet to be well documented. Modelling studies may provide some indication of the relationship between the two, but these should be based on the best available information about both barrier island and marsh hydrologic and ecological processes.

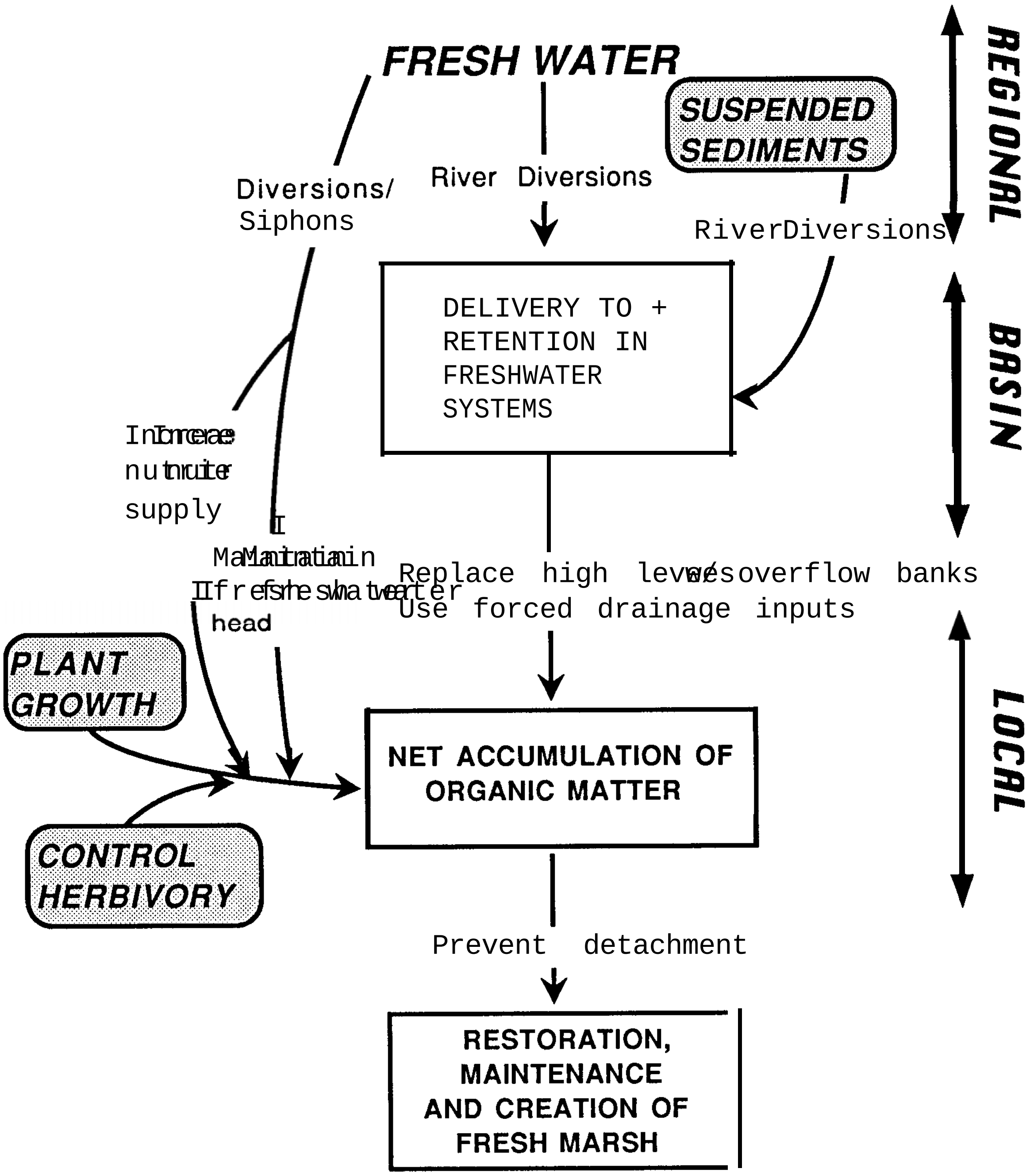

Figure 9.5 Process management strategies for fresh marshes in BTES.

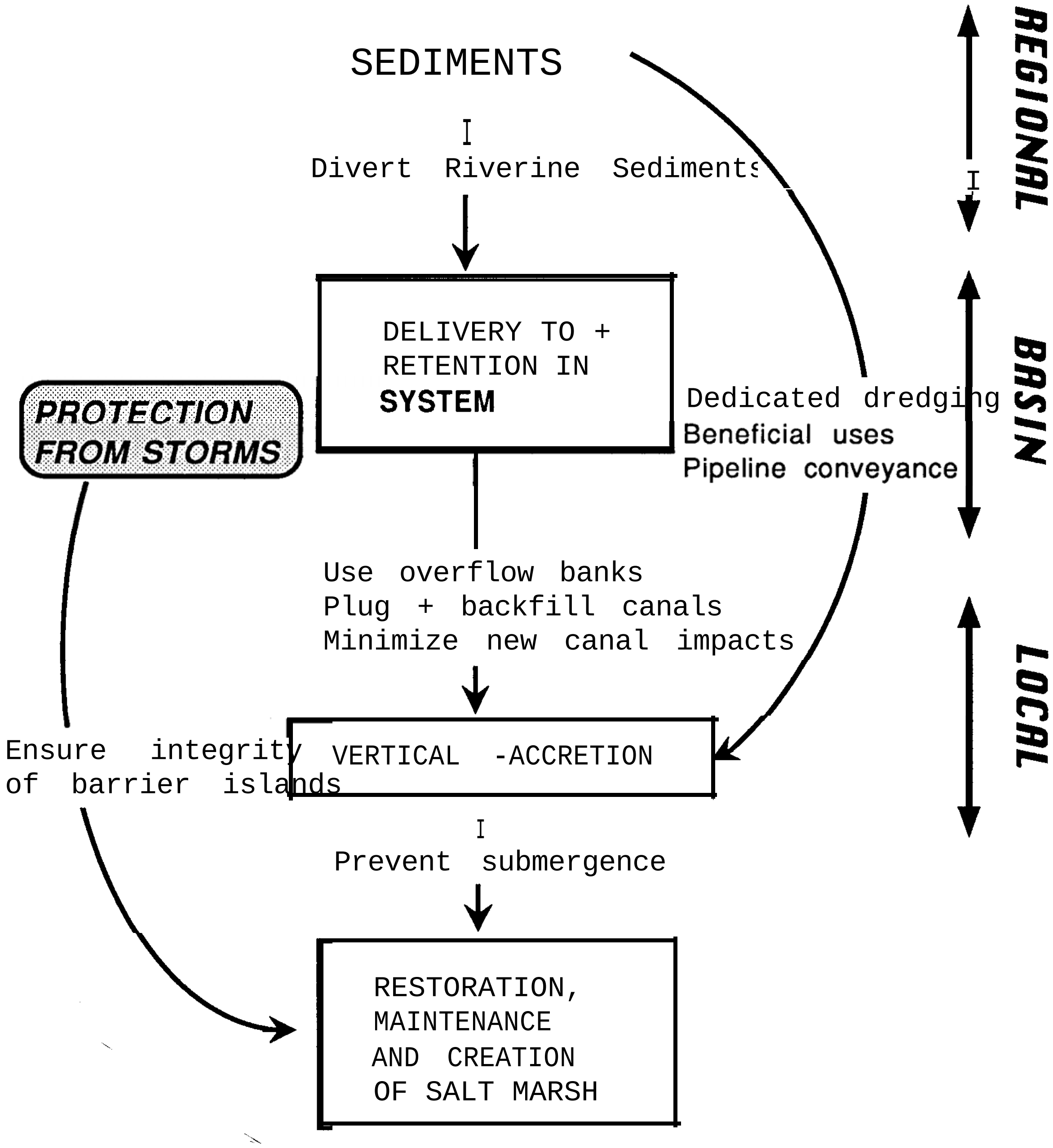

Figure 9.6 Process management strategies for salt marshes in BTES.

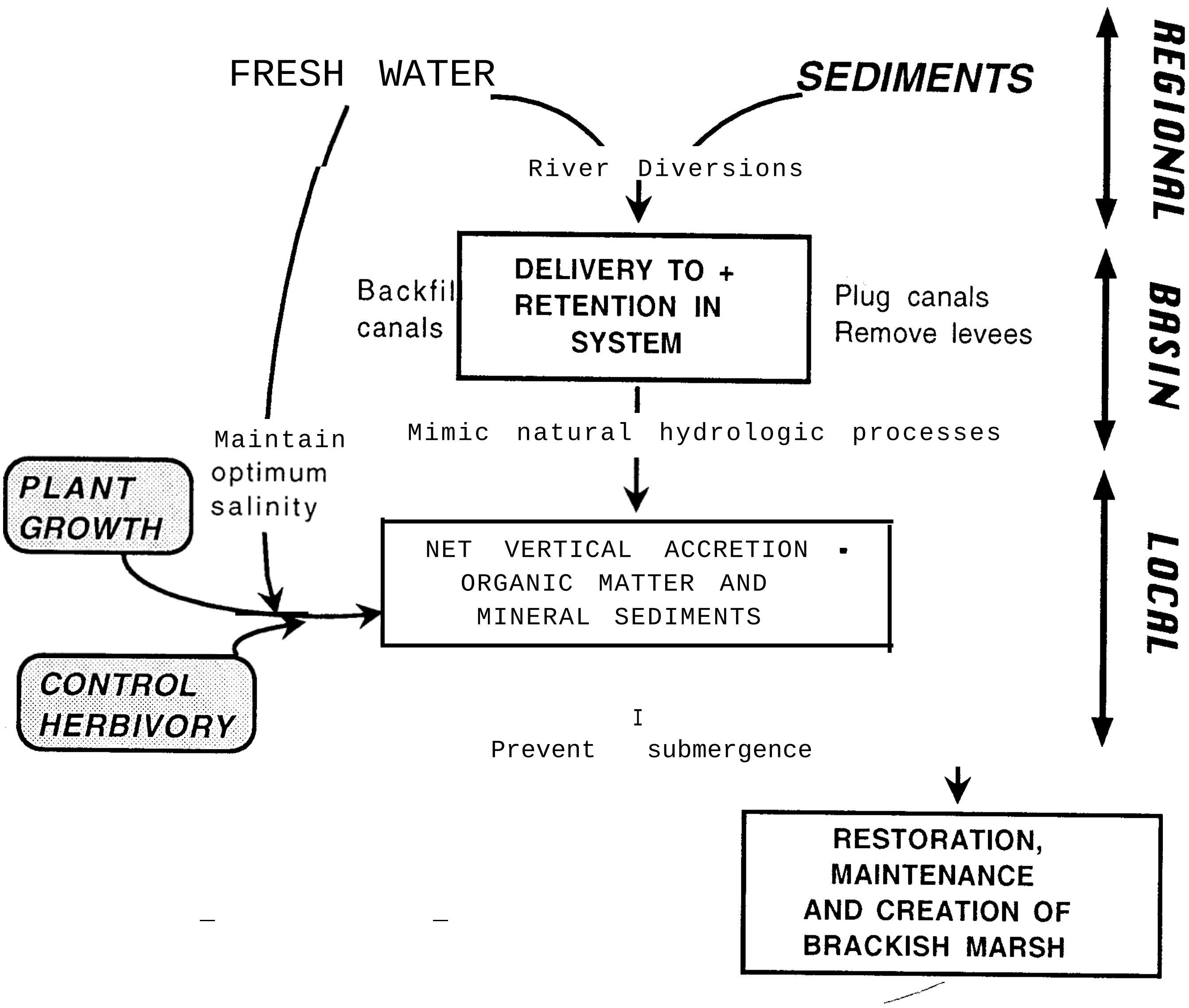

Figure 9.7 Process management strategies for brackish marshes in BTES.

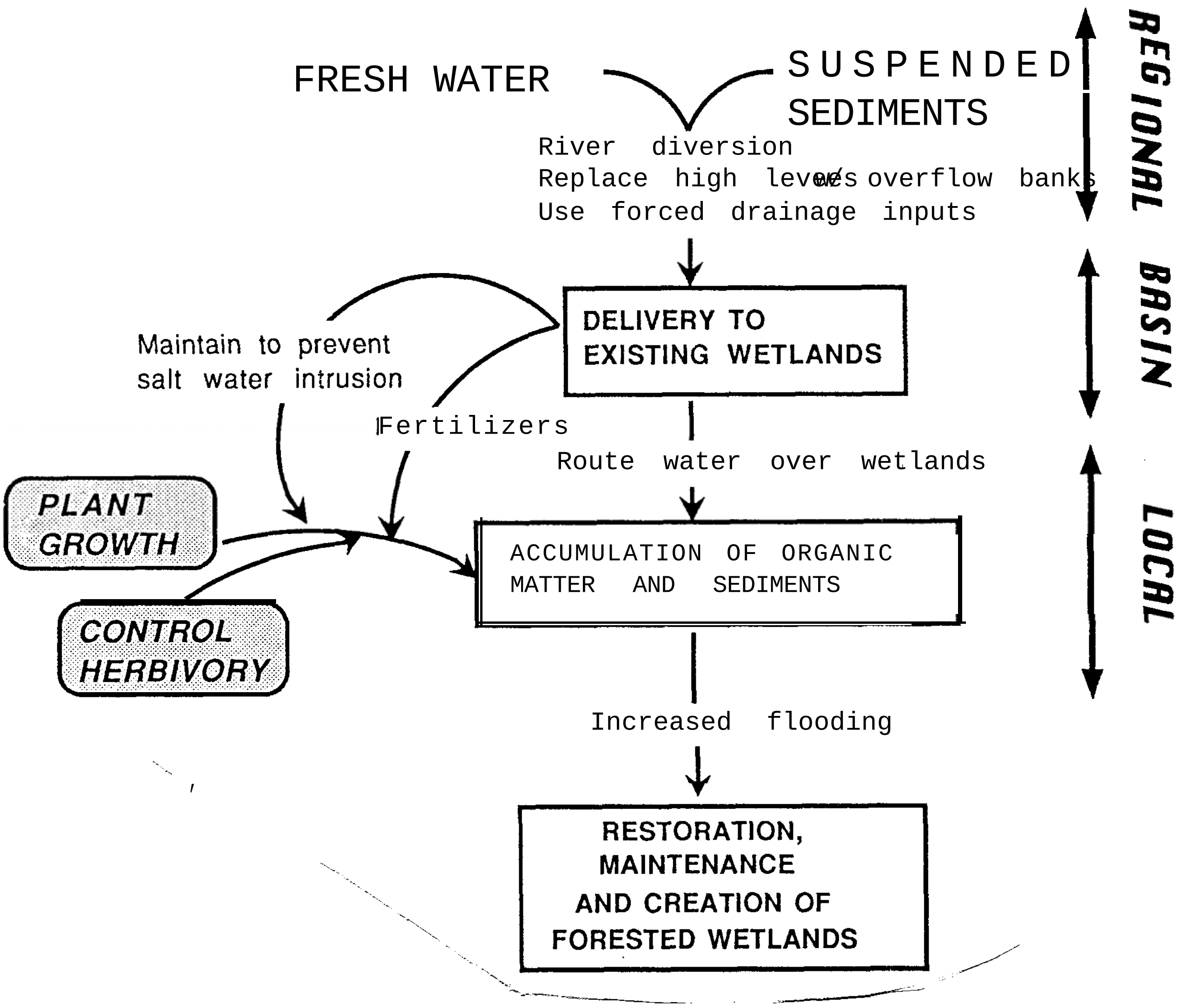

Figure 9.8 Process management strategies for forested wetlands in BTES.

The importance of tidal scour as a mechanism of marsh loss has been discussed in this report. A detailed process study is required to elucidate the magnitude of the problem and its impact on marshes of different types before management strategies are implemented to specifically address it as a problem.

SUMMARY OF PROCESS MANAGEMENT RECOMMENDATIONS

The management strategies recommended in this report have been classified into the following categories which do not take into consideration the availability of funds:

- **Offensive—primary objective is the creation of new vegetated wetlands.**
- **Defensive—primary objective is the maintenance and enhancement of existing wetlands.**
- **Short-term—can be implemented with existing technologies/information within five years.**
- **Long-term—requires development of new technologies, overcoming socio-economic challenges, or reaching more detailed understanding of system; but implementation is realistic within 10–15 years.**
- **Small-scale—benefits at local to sub-basin scale.**
- **Large scale—benefits at sub-basin to basin scale.**

The recommended process management strategies can be summarized as follows:

Offensive

Short-term: **Beneficial use of maintenance dredged sediments (small scale);**
Dedicated dredging to create new emergent marsh (small scale).

Long-term: **Diversion of river sediments into open water areas (large scale);**
Use pipelines to convey sediments from river source to areas of need (small or large scale).

Defensive

Short-term: **More effective use of existing inputs of fresh water and sediments, including siphons (small or large scale);**
Backfill pipeline canals and unused location canals where appropriate and feasible (small scale);
Plug pipeline canals and unused location canals where appropriate and feasible (small scale);
Remove dredged material levees and replace with low profile overflow-banks (small scale);
Control herbivory (small or large scale);
Prevent shoreline erosion of marshes (small scale).

Long-term: **Freshwater diversions from Mississippi River (large scale).**

In order to effectively management the BTES, scientific understanding of system processes and the interaction between system components must be increased. This report has documented the need for detailed study of two critical elements: the importance of tidal scour as a mechanism of marsh loss, and the role of barrier islands in maintaining the integrity of the estuarine system.

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APPENDIX A

PART 1: PLANT SPECIES OF LOUISIANA COASTAL MARSHES AND BEACHES

PART 2: PLANT SPECIES IN BOTTOMLAND HARDWOOD FORESTS, SWAMPS, AND LEVEES AND DISTURBED AREAS OF LOUISIANA'S COASTAL ZONE

Appendix A.
Part 1

Plant species of Louisiana coastal marshes and beaches (Gosselink 1984; Gosselink et al. 1979; Peterson et al. 1987; Chabreck 1972; Lester 1988; Montz 1977)

		Distribution		Vegetative type				
Species	Common name	CP[1]	DP[2]	SA[3]	BR[4]	IN[5]	FR[6]	BC[7]
Acnida alaamensis	Gulf coast waterhemp	x		--	x	--	--	--
Acnida cuspidata	southern waterhemp		x	--	x	--	--	--
Acnida tamariscina	Nuttall's waterhemp			--	--	--	--	x
Aeschynomene sp.	--		x	--	--	--	--	--
Aeschynomene indica	jointvetch		x	--	--	x	--	--
Aeschynomene virginica	sensitive jointweed		x	--	--	--	x	--
Agalinis maritima	seaside gerardia		x	--	--	x	--	x
Alternanthera sp.	--		x	--	--	x	x	x
Alternanthera philoxeroides	alligator weed	x	x	--	--	x	x	x
Amaranthus australis	southern waterhemp		x	--	x	x	x	--
Ambrosia trifida	giant ragweed	x		--	--	--	--	--
Ammannia sp.	--		x	--	--	--	--	--
Ammannia coccinea	purple ammannia		x	--	--	x	--	x
Anmonphilia breviligulata	American beach grass		x	--	--	--	--	x
Ampelopsis arborea	pepper-vine			--	--	--		x
Andropogon glomeratus	bushy beardgrass		x	--	--	x	--	x
Andropogon scoparius	broom sedge		x	--	--	--	--	x
Andropogon virginicus	--		x	--	--	--	--	x
Anthaenantia	--		x	--	--	--	--	x
Apios americana	American potatobean		x	--	--	--	x	--
Apios sp.	potatobean		x	--	--	--	x	--
Aster sp.	aster		x	--	x	x	x	--
Aster subulatus	annual saltmarsh aster	x	x	x	x	x	x	--
Aster tenuifolius	saltmarsh aster	x	x	x	x	x	--	--
Atriplex sp.	salt cedar	x		--	--	--	--	--
Avicennia germinans	black mangrove		x	x	--	--	--	x
Azolla caroliniana	Water fern		x	--	--	--	--	--
Baccharis sp.	baccharis	x	x	x	x	x	x	--
Baccharis halimifolia	eastern baccharis	x	x	x	x	x	x	--
Bacopa sp.	waterhyssop		x	--	--	--	--	--
Bacopa caroliniana	Carolina bacopa		x	--	--	x	x	--
Bacopa monnieri	coastal water hyssop		x	--	x	x	x	x
Bacopa rotundifolia	round leaf bacopa		x	--	x	x	--	--
Batis sp.	batis		x	--	--	--	--	--
Batis maritima	saltwort		x	x	--	--	--	x

Berchemia sp.	supple-jack		x	--	--	--	--	--
Berchemia scandens	rattan vine		x	--	--	--	--	--
Bidens sp.	beggarticks		x	--	--	--	--	--
Bidens laevis	smooth beggarticks		x	--	--	x	x	--
Boehmeria sp.	falsenettle		x	--	--	--	--	--
Boehmeria cylindrica	bog-hemp		x	--	--	--	x	--
Borrichia sp.	--		x	--	--	--	--	--
Borrichia frutescens	sea oxeye	x	x	x	x	--	--	x
Brasenia schreberi	water shield		x	--	--	--	x	--
Cabomba sp.	--		x	--	--	--	--	--
Cabomba caroliniana	fanwort		x	--	--	--	x	--
Cakile edentula	sea rocket		x	--	--	--	--	x
Calopogan pulchellus	grass pink orchid		x	--	--	--	x	--
Calystegia sepium	--		x	--	--	--	--	x
Cardius sp.	spinythistle	x		--	x	--	--	--
Carex sp.	sedge		x	--	--	--	x	--
Carex leavenworthii	--		x	--	--	--	x	--
Celtis laevigata	hackberry	x	x	--	--	--	x	--
Centella erecta			x	--	--	x	x	--
Cephalanthus	buttonbush		x	--	--	--	--	--
Cephalanthus occidentalis	common buttonbush		x	--	--	--	x	x
Ceratophyllum sp.	coontail hornwort		x	--	--	--	x	--
Ceratophyllum demersum	common coontail		x	--	--	--	x	--
Cladium sp.	sawgrass		x	--	--	--	x	--
Cladium jamaicense	Jamaica sawgrass	x	x	x	x	x	x	--
Colocasia antiquorum	elephants ear		x	--	--	--	x	--
Commelina sp.	dayflower		x	--	--	--	--	--
Commelina erecta var. angustifolia	widow's-tears		x	--	--	--	--	--
Crinum sp.	--		x	--	--	--	--	--
Crinum americanum	swamp-lily		x	--	--	--	x	--
Croton punctatus	beach-tea		x	x	--	--	--	x
Cuscuta sp.	dodder	x		x	--	--	--	--
Cuscuta indecora	pretty dodder		x	--	x	x	x	--
Cynanchum sp.	--		x	--	--	--	--	--
Cynanchum angustifolium	marsh swallow-wort		x	--	--	x	--	x
Cynodon compressus	sedge		x	--	--	--	x	x
Cynodon dactylon	Bermuda grass		x	--	--	--	x	x
Cyperus sp.	flatsedge		x	--	--	x	x	--
Cyperus filicinus	umbrella sedge	x		x	x	--	x	--
Cyperus ochraceus	flatsedge		x	--	--	--	x	--
Cyperus odoratus	fragrant flatsedge		x	--	x	x	x	x

Cyperus polystachyos	flatsedge		x	--	--	x	x	--
Decodon sp.	--		x	--	--	--	--	--
Decodon verticillatus	swamp loosestrife		x	--	--	x	x	--
Dichromena sp.	whitetop		x	--	--	--	--	--
Dichromena colorata	whitetop umbrella grass		x	--	--	x	x	x
Distichlis spicata	seashore saltgrass	x	x	x	x	x	x	x
Echinochloa sp.	cockspur		x	--	--	--	--	--
Echinochloa walteri	Walter's millet	x	x	--	x	x	x	--
Echinodorus sp.	burhead		x	--	--	--	--	--
Echinodorus cordifolius	creeping burhead		x	--	--	--	--	--
Eclipta alba	yerta-de-tage	x		--	x	--	x	x
Eichhornia sp.	--		x	--	--	--	--	--
Eichnornia crassipes	water hyacinth	x	x	--	--	x	x	--
Eleocharis sp.	spikerush		x	--	x	x	x	x
Eleocharis cellulosa	gulf spikerush		x	--	--	x	--	--
Eleocharis geniculata	capitate spikerush		x	--	--	x	--	--
Eleocharis macrostachya	creeping spikerush		x	--	--	x	--	--
Eleocharis palustris	common spike rush	x		x	x	--	--	--
Eleocharis parvula	dwarf spikerush	x	x	x	x	x	x	--
Eleocharis rostellata	spikerush		x	--	--	x	x	--
Epidendrum conopseum	green-fly orchid		x	--	--	--	--	x
Eragrostis sp.	--		x	--	--	--	--	x
Erianthus giganteus	sugarcane plumegrass		x	--	--	--	x	--
Erigeron canadensis	daisy fleabane		x	--	--	--	--	x
Eupatorium sp.	thoroughwort		x	--	--	x	x	--
Eupatorium capillifolium	Yankee weed		x	--	--	--	x	--
Eupatorium coelestinum	mistflower		x	--	--	x	--	--
Eupatorium perfoliatum	thoroughwort		x	--	--	--	x	--
Eupatorium pulchellus	--		x	--	--	--	x	--
Eupatorium serotinum	late eupatorium		x	--	--	--	x	--
Eustoma exaltatum	--		x	--	--	--	--	x
Fimbristylis castanea	sand rush		x	x	x	x	--	x
Galium tinctorium	dye bedstraw		x	--	--	x	x	--
Gerardia maritima	--		*x*	*x*	*x*	--	--	--
Gratiola sp.	hedgehyssop		x	--	--	--	x	--
Heliotropium sp.	heliotrope		x	x	--	--	--	--
Heliotropium curassavicum	seaside heliotrope	x		x	x	--	x	x
Heterotheca subaxillaris	--		x	--	--	--	--	x
Hibiscus sp.	hibiscus		x	--	--	--	x	--
Hibiscus lasiocarpus	rose mallow	x		--	x	--	x	--
Hibiscus militaris	halberd-leaved rosemallow	x	--	--	--	x	--	
Hibiscus moscheutos	marsh mallow		x	--	--	x	x	--

Hydrocotyle sp.	pennywort	x	x	--	--	--	--	x
Hydrocotyle bonariensis	pennywort		x	--	--	--	x	x
Hydrocotyle ranunculoides	floating pennywort		x	--	--	x	x	--
Hydrocotyle umbellata	umbrella pennywort		x	--	--	--	x	--
Hymenocallis crassifolia	spider lily	x		--	--	--	x	--
Hymenocallis occidentalis	spider lily		x	--	--	x	x	--
Hypericum sp.	St. John's wort		x	--	--	--	--	--
Hypericum drummondii	nits-and-lice		x	--	--	--	x	--
Hypericum fasciculatum	St. John's wort		x	--	--	x	--	--
Hypericum mutilum	dwarf St. John's wort		x	--	--	--	x	--
Hypericum virginicum	marsh St. John's wort		x	--	--	--	x	--
Hypericum walteri	--		x	--	--	--	x	--
Ipomoea sp.	morning-glory		x	--	--	--	--	x
Ipomoea sagittata	saltmarsh morning-glory	x	x	--	x	x	x	
Ipomoea stolonifera	beach morning-glory	x	x	x	x	--	x	x
Iris sp. iris		x	--	--	--	x	--	
Iris giganticaerulea	giant blue Iris	x		--	x	--	x	--
Itea sp.	sweet-spire		x	--	--	--	x	--
Itea virginica	Virginia-willow		x	--	--	--	--	--
Iva ciliata	swampweed		x	--	--	--	--	--
Iva sp.	sumpweed		x	--	--	x	--	--
Iva frutescens	marsh elder sumpweed	x	x	x	x	x	--	x
Juncus sp.	rush		x	--	--	x	x	--
Juncus effusus	soft rush		x	--	--	--	x	x
Juncus marginatus	grass-leaf rush		x	--	--	--	x	--
Juncus roemerianus	black needle rush	x	x	x	x	x	x	--
Juncus tenuis	slender rush		x	--	--	x	x	--
Kosteletzkya virginica	saltmarsh mallow	x	x	x	x	x	x	--
Lantana horrida	calico bush		x	x	x	--	--	--
Leersia sp.	cutgrass		x	--	--	--	x	--
Leersia oryzoides	rice cutgrass		x	--	--	--	x	--
Lemna minor	common duckweed	x	x	--	x	x	x	--
Lemna sp.	duckweed	x	x	--	--	--	x	--
Leptochloa sp.	sprangletop		x	--	--	--	--	--
Leptochloa fascicularis	bearded sprangletop		x	--	x	x	*x*	--
Leptochloa filiformis	red sprangle top		x	--	--	x	--	x
Limnobium spongia	American frogbit		x	--	--	--	x	--
Lippia nodiflora	--		x	--	--	--	--	x
Lobelia cardinalis	cardinal-flower lobelia		x	--	--	--	x	--
Ludwigia sp.	primrose		x	--	--	--	x	--
Ludwigia leptocarpa	anglestem waterprimrose		x	--	--	--	x	x
Ludwigia peploides	floating waterprimrose		x	--	--	x	--	--

Ludwigia suffruticosa	water primrose		x	--	--	--	x	--
Lycium carolinianum	salt matrimony vine		x	x	--	--	--	--
Lycium halimfolium	matrimony vine	x	--	--	--	--	--	--
Lythrum lineare	saltmarsh lythrum	x	x	x	x	x	x	--
Myrica cerifera	waxmyrtle		x	--	--	x	x	x
Myriophyllum sp.	water-milfoil		x	--	--	--	x	--
Myriophyllum heterophyllum	Euasian watermilfoil		x	--	--	--	x	--
Myriophyllum spicatum	watermilfoil		x	--	x	x	x	--
Najas sp.	waternymph		x	--	--	x	x	--
Najas guadalupensis	southern waternymph		x	--	--	x	x	--
Nelumbo sp.	lotus		x	--	--	--	x	--
Nelumbo lutea	American lotus		x	--	--	--	x	--
Nymphaea sp.	waterlily		x	--	--	--	x	--
Nymphaea odorata	white water-lily		x	--	--	--	x	--
Nymphoides aquatica	floating heart		x	--	--	--	x	--
Oenothear sp.	prim rose		x	--	--	--	--	x
Osmunda sp.	royal fern		x	--	--	x	x	--
Osmunda regalis	royal fern		x	--	--	x	x	--
Ottelia alismoides	--		x	--	--	--	x	--
Panicum sp.	panic grass		x	--	--	--	x	--
Panicum amarum	beachgrass		x	x	--	--	--	x
Panicum dichotomiflorum	fall panicgrass		x	--	--	x	x	x
Panicum hemitomon	maidencane		x	--	--	x	x	--
Panicum repens	dog tooth grass		x	--	--	x	x	x
Panicum scoparium			x	--	--	--	x	--
Panicum virgatum	feather grass		x	--	x	x	x	--
Paspalum sp.	paspalum		x	x	x	x	x	--
Paspalum vaginatum	seashore paspalum		x	x	x	x	x	--
Philoxerus vermicularis	Salt alligator weed		x	--	--	x	x	--
Phragmites sp.	--		x	--	--	x	x	--
Phragmites australis	roseau cane		x	--	x	x	x	--
Phyla sp.	frog-fruit		x	--	--	--	--	--
Phyla lanceolata	northern frog-fruit		x	--	--	x	x	--
Phyla nodiflora	common frog-fruit		x	--	--	--	x	--
Pluchea sp.	pluchea		x	--	--	--	x	--
Pluchea camphorata	camphor weed		x	--	x	x	x	--
Pluchea foetida	stinking fleabane		x	--	--	--	x	--
Pluchea odorata	saltmarsh pluchea		x	x	--	--	--	--
Pluchea purpurascens	saltmarsh pluchea		x	--	--	x	--	x
Polygonum sp.	smart weed		x	--	--	--	x	--
Polygonum punctatum	dotted smartweed		x	--	--	x	x	x
Polygonum sagittatum	tearthumb		x	--	--	--	x	--

Pontederia cordata	pickerel weed		x	--	--	--	x	--
Potamogeton nodosus	eongleaf pond weed		x	--	--	x	x	--
Potamogeton pusillus	slender pond weed		x	--	--	x	x	--
Ptilimnium sp.	mock-bishopweed		x	--	--	--	x	--
Ptilimnium capillaceum	threadleaf mock-bishopweed		x	--	--	--	x	--
Rhynchospora sp.	beakrush		x	--	--	--	x	--
Rhynchospora caduca	angelstem beakrush		x	--	--	--	x	--
Rhynchospora inexpanansa	nodding beakrush		x	--	--	--	x	--
Rotala sp.	toothcup		x	--	--	--	--	--
Rotala ramosior	toothcup		x	--	--	x	--	x
Rubus sp.	dewberry		x	--	--	--	--	x
Rubus sp.	blackberry		x	--	--	--	--	x
Ruppia maritima	widgeon grass		x	--	x	x	--	--
Sacciolepis sp.	--		x	--	--	--	--	--
Sacciolepis striata	American cupscale		x	--	--	x	x	--
Sagittaria sp.	arrowhead		x	--	--	x	--	--
Sagittaria falcata	bull tongue		x	--	--	x	x	--
Sagittaria lancifolia	bulltongue arrowhead		x	--	--	x	x	--
Sagittaria latifolia	broadleaf arrowhead		x	--	--	x	x	x
Sagittaria platyphylla	delta duckpotato		x	--	--	--	x	--
Salicornia sp.	glasswort		x	x	--	--	--	--
Salicornia bigelovii	glasswort	x	x	x	--	--	--	--
Salicornia virginica	woody glasswort		x	x	--	--	--	--
Salix sp.	willow		x	--	--	--	x	--
Salix nigra	black willow		x	--	--	--	x	--
Saururus sp.	--		x	--	--	--	x	--
Saururus cernuus	lizard tail		x	--	--	--	x	--
Schizachyrium maritimum	seacoast bluestem		x	--	--	--	--	x
Scirpus sp.	bulrush		x	--	--	x	--	--
Scirpus americanus	freshwater three square	x	x	--	--	x	x	x
Scirpus californicus	hardstem bulrush	x	x	--	x	x	x	--
Scirpus lineatus	rusty bulrush		x	--	--	--	x	--
Scirpus olneyi	Olney three square	x	x	x	x	x	x	--
Scirpus robustus	leafy three square	x	x	x	x	x	--	--
Scirpus validus	soft-stem bulrush		x	--	x	x	--	x
Sesbania sp.	rattlebox		x	--	--	x	x	--
Senecio glabellus	butterweed		x	--	--	--	x	--
Sesbania exaltata	tall sesbane	x	x	--	x	x	--	--
Sesuvium sp.	purslane		x	--	x	--	--	--
Sesuvium maritimum	marsh purslane		x	x	--	--	--	--
Sesuvium portulacastrum	sea purslane		x	x	x	--	--	x
Setaria sp.	bristlegrass		x	--	--	x	--	--

Setaria geniculata	knotroot bristlegrass		x	--	--	x	--	x
Setaria glauca	yellow foxtail		x	--	x	--	--	x
Setaria magna	giant bristle grass	x	x	--	x	x	x	--
Setaria verticillata	--		x	--	--	--	x	--
Smilax rotundifolia	common greenbrier		x	--	--	--	--	--
Smilax sp.	greenbrier	x		--	--	--	--	--
Solidago sp.	goldenrod		x	--	--	x	x	--
Solidago sempervirens	seaside goldenrod	x	x	x	x	x	x	x
Sparganium sp.	burreed	x		--	--	--	x	--
Sparganium americanum	eastern burreed		x	--	--	--	x	--
Spartina sp.	cordgrass		x	--	--	--	--	--
Spartina alterniflora	smooth cordgrass	x	x	x	x	x	x	x
Spartina cynosuroides	big cord grass	x	x	--	x	x	x	--
Spartina patens	wire grass	x	x	x	x	x	x	x
Spartina spartinae			*x*	*x*	*x*	*x*	--	--
Spiranthes sp.	ladies tresses		x	--	--	--	--	--
Spiranthes cernua	nodding ladies tresses		x	--	--	--	x	--
Spirodela polyrhza	duckweed		x	--	--	--	x	--
Sporobolus virginicus	coast dropseed		x	--	--	--	--	x
Strophostyles helvola	wild bean		x	--	--	--	x	x
Styrax americana	American snowbell		x	--	--	--	--	--
Suaeda linearis	sea-blite		x	x	--	--	--	--
Taraxacum officianale	dandelion		x	--	--	x	--	--
Thelypteris sp.	marsh fern		x	--	--	--	x	--
Thelypteris palustris	hale's marsh fern		x	--	--	x	x	--
Thelypteris thelypteroides	Southern marsh fern		x	--	--	--	--	--
Triadenum virginicum	marsh St. John's wort		x	--	--	--	x	--
Typha sp.	cattail		x	--	--	x	x	--
Typha latifolia	broadleaf cattail	x	x	--	x	--	x	--
Uniola paniculata	sea oats		x	--	--	--	--	x
Utricularia subulata	zigzag bladderwort		x	--	--	--	x	--
Utricularia sp.	bladderwort		x	--	--	--	--	--
Utricularia cornuta	horned bladderwort		x	--	--	--	x	--
Utricularia juncea	rush bladderpod		x	--	--	--	--	--
Vallisneria americana	wildcelery		x	--	x	--	--	--
Vicia ludoviciana	Louisiana vetch	x		--	--	--	--	--
Vicia augustifolia	--		x	--	--	--	--	x
Vigna sp.	--		x	--	--	--	--	--
Vigna luteola	yellow cowpea		x	--	x	x	x	--
Vigna repens	cowpea	x		--	x	--	x	--
Vitis sp.	grape		x	--	--	--	--	--
Wolffia sp.	watermeal		x	--	--	--	x	--

Wolffiella sp.	mud-midget		x	--	--	--	--	--
Woodwardia virginica	Virginia chain fern		x	--	--	--	x	--
Woodwardia sp.	chain fern		x	--	--	--	x	--
Xyris iridifolia	iris leaf yelloweye grass	x	--	--	--	x	--	
Zanthoxylum americanum	toothache tree		x	x	x	--	--	--
Zizania sp.	--		x	x	x	--	--	--
Zizania aquatica	wildrice		x	--	--	--	x	--
Zizaniopsis sp.	cutgrass		x	--	--	--	--	--
Zizaniopsis miliacea	giant cutgrass	x	x	--	x	--	x	--

[1]CP =Chenier plain (absence from the column may indicate lack of detailed studies)
[2]DP =Mississippi deltaic plain
[3]SA =Saline marsh
[4]BR =Brackish marsh
[5]IN =Intermediate marsh
[6]FR =Fresh marsh
[7]BC =Beach

Appendix A. Plant species found in bottomland hardwood forest, swamps, and levees and
Part 2. disturbed areas of Louisiana's coastal zone (Conner et al. 1986).

Species	Common name	Vegetative type BLH[1]	SW[2]	D[3]
Acalypha rhomboidea	three-seeded mercury	--	--	x
Acer negundo	boxelder	x	x	x
Acer rubrum var. *drummmondi*	swamp red maple	x	x	x
Aeschynomene indica	joint vetch	--	--	x
Agalinis purpurea	--	--	--	x
Allium bivalve	false garlic	--	--	x
Allium canadense	wild onion	x	--	x
Alternanthera philoxeroides	alligatorweed	--	x	--
Ambrosia artemisiifolia	ragweed	--	--	x
Ambrosia psilostachya	ragweed	--	--	x
Ambrosia trifida	giant ragweed	x	--	x
Ammannia coccinea	tooth-cup	--	--	x
Ampelopsis arborea	peppervine	x	--	x
Ampelopsis cordata	heartleaf peppervine	x	--	x
Amphora fruticosa	lead plant	--	--	x
Anagallis arvensis	scarlet pimpernel	--	--	x
Andropogon virginicus	broom sedge	--	--	x
Anisostichus capreolata	crossvine	x	x	--
Apium leptophyllum	marsh parsley	x	--	--
Arisaema dracontium	green dragon	x	--	--
Aristida	three awn grass	--	--	x
Arthraxon hispidus	makino	--	--	x
Arundinaria gigantea	cane	--	x	--
Asclepias perennis	milkweed	x	--	--
Asplenium platyneuron	ebony spleenwort	x	--	--
Aster lateriflorus	starved aster	--	--	x
Aster praealtus	blue aster	--	--	x
Avicennia germinans	black mangrove	--	--	x
Azolla caroliniana	mosquito fern	--	x	--
Baccharis halimifolia	groundsel-tree	--	x	--
Bacopa caroliniana	--	--	--	x
Bacopa monnieri	water hyssop	--	--	x
Bacopa rotundifolia	--	--	--	x
Batis maritima	saltwort	--	--	x

Berchemia scandens	rattan vine	x	x	x
Bidens bipinnata	Spanish needles	--	--	x
Bidens laevis	beggar ticks	--	x	--
Boehmeria cylindrica	false nettle	x	x	--
Borrichia frutescens	sea oxeye	--	--	x
Bromus catharticus	--	--	--	x
Brunnichia cirrhosa	ladies'-eardrops	x	--	--
Cabomba caroliniana	fanwort	--	x	--
Callicarpa americana	french mulberry	x	--	--
Calystegia sepium	hedge bindweed	x	--	--
Campsis radicans	trumpet creeper	x	--	--
Cardamine pensylvanica	bitter-cress	x	--	--
Cardiospermum halicacabum	ballon vine	--	--	x
Carduus spinosissimus	yellow thistle	x	--	x
Carex cephalophora	caric sedge	--	--	x
Carex cherokeensis	caric sedge	--	--	x
Carex comosa	bristly sedge	--	x	--
Carex crus-corvi	crowfoot sedge	--	x	--
Carex hyalinolepis	caric sedge	--	--	x
Carex lupulina	hop sedge		x	
Carya sp.	hickory	--	--	x
Carya aquatica	water hickory	x	x	--
Carya cordiformis	bitternut hickory	x	--	--
Carya illioensis	pecan	x	--	--
Carya ovata	shagbark hickory	x	--	--
Cassia fasciculata	partridge pea	--	--	x
Celtis laevigata	hackberry	x	--	x
Centrosema virginianum	butterfly pea	--	--	x
Cephalanthus occidentalis	buttonbush	x	x	x
Cerastium glomeratum	mouse-ear	x	--	--
Ceratophyllum demersum	hornwort	--	x	--
Chaerophyllum tainturieri	chervil	x	--	--
Chenopodium album	pigweed	--	x	--
Cicuta mexicana	water-hemlock	--	--	x
Cinnamomum camphora	camphor tree	x	--	--
Cissus incisa	marine-ivy	--	--	x
Citrus sp. --	x	--	--	
Cleistes divaricata	spreading pogonia	x	--	--
Clematis crispa	leather-flower	x	--	x
Clematis ternifolia	Japanese virgins-bower	x	--	--
Cocculus carolinus	coralbeads	x	x	x
Colocasia antiquorum	elephant's ear	--	x	x

Commelina communis	dayflower	--	--	x
Commelina diffusa	dayflower	x	--	--
Commelina erecta	dayflower	--	x	--
Commelina virginica	widow's-tears	--	--	x
Cornus drummondii	swamp dogwood	x	x	x
Crataegus opaca	western mayhaw	--	--	x
Crataegus viridis	--	x	--	--
Crepis japonica	hawk's-beard	--	--	x
Crinum americanum	swamp lily	x	x	--
Croton punctatus	--	--	--	x
Cuphea carthagensis	--	--	--	x
Cuscuta gronovii	love-vine	--	x	--
Cynoctonum mitreola	miterwort	--	--	x
Cynodon dactylon	Bermuda grass	--	--	x
Cyperus aristatus	--	--	--	x
Cyperus compressus	--	--	--	x
Cyperus elegans	flatsedge	--	--	x
Cyperus erythrorhizos	flatsedge	--	--	x
Cyperus esculentus	yellow nutgrass	--	--	x
Cyperus filicinus	--	--	--	x
Cyperus globulosus	--	--	--	x
Cyperus retrorsus	--	--	--	x
Cyperus virens	swamp sedge	--	x	--
Desmanthus illinoensis	prairie Mimosa	--	--	x
Desmodium canescens	beggar lice	x	--	x
Desmodium glabellum	beggar's-ticks	--	--	x
Desmodium laevigatum	beggar's-ticks	--	--	x
Desmodium paniculatum	beggar's-ticks	--	--	x
Dichondra caroliensis	--	x	--	--
Dicliptera brachiata	--	--	--	x
Digitaria ischaemum	crab grass	--	--	x
Digitaria sanguinalis	crab grass	--	--	x
Diodia virginiana	buttonweed	--	--	x
Diospyros virginiana	persimmon	x	x	--
Distichlis spicata	salt grass	--	--	x
Dryopteris ludoviciana	southern shield fern	--	x	--
Duchesnea indica	Indian strawberry	x	--	--
Echinochloa colonum	--	--	--	x
Echinochloa crusgalli	barnyard grass	--	--	x
Echinochloa walteri	Walter's millet	--	--	x
Echinodorus cordifolius	creeping burhead	--	x	--
Eclipta alba	--	--	--	x

Egeria densa	Brazilian elodea	--	x	--
Eichhornia crassipes	water hyacinth	--	x	--
Eleocharis albida	spike-rush	--	x	--
Eleocharis montevidensis	spike-rush	--	--	x
Eleocharis obtusa	--	--	--	x
Elephantopus carolinianus	elephant's-foot	--	--	x
Eleusine indica	goose grass	--	--	x
Elymus virginicus	wild rye	--	--	x
Epidendrum conopseum	green fly orchid	x	x	--
Equisetum sp.	horsetail	--	x	--
Eragrostis hypnoides	--	--	--	x
Eragrostis pilosa	--	--	--	x
Erianthus giganteus	sugarcane plumegrass	--	x	x
Erigeron canadensis	horseweed	x	--	--
Erigeron philadelphicus	daisy fleabane	--	--	x
Eupatorium capillifolium	dog-fennel	--	--	x
Eupatorium coelestinum	mistflower	x	x	x
Eupatorium rugosum	white snakeroot	--	--	x
Euphorbia cordifolia	spurge	--	--	x
Euphorbia heterophylla	painted leaf	x	--	--
Euphorbia hirta	spurge	--	--	x
Euphorbia nutans	spurge	--	--	x
Euphorbia prostrata	spurge	--	--	x
Euphorbia supina	spurge	--	--	x
Eustoma exaltatum	catchfly-gentian	--	--	x
Fagus gradifolia	beech	x	--	--
Forestiera acuminata	swamp privet	x	--	--
Fragaria virginiana	wild strawberry	x	--	--
Fraxinus caroliniana	water ash	x	--	--
Fraxinus pennsylvanica	green ash	x	x	x
Fraxinus tomentosa	pumpkin ash	x	x	--
Galium aparine	redstraw	--	--	x
Galium tinctorium	bedstraw	x	--	--
Gaura parviflora	--	--	--	x
Gelsemium sempervirens	yellow jessamine	--	x	--
Geranium carolinianum	wild geranium	--	--	x
Geum canadense	white avens	x	--	--
Gleditsia aquatica	water locust	x	x	--
Gleditsia triacanthos	honey locust	x	--	x
Habenaria repens	water-spider orchid	--	x	--
Helianthus strumosus	daisy	--	--	x
Heliotropium curassavicum	seaside heliotrope	--	--	x

Hemophila aphylla	baby blue-eyes	x	--	--
Hibiscus lasiocarpus	rose-mallow	--	x	--
Hibiscus militaris	Halberd-leaved marsh-mallow	--	x	--
Hordeum pusillum	little barley	--	--	x
Hydrocotyle ranunculoides	floating pennywort	--	x	--
Hydrocotyle umbellata	umbrella pennywort	--	x	x
Hydrocotyle verticillata	pennywort	--	x	--
Hydrolea ovata	--	--	x	--
Hygrophila lacustris	--	x	x	--
Hymenocallis eulae	spider lily	--	x	--
Hymenocallis occidentalis	spider lily	--	x	--
Hypericum sp.	St. John's wort	x	--	--
Hypericum hypericoides	St. Andrew's cross	--	--	x
Hypericum walteri	--	--	x	x
Ilex cassine	dahoon holly	--	--	x
Ilex decidua	possum haw	x	--	--
Ilex vomitoria	yaupon	x	--	x
Impatiens capensis	spotted touch-me-not	x	--	--
Ipomoea quamocit	cypress vine	--	x	--
Ipomoea sagittata	saltmarsh morning glory	--	x	x
Ipomoea trichocarpa	morning glory	--	--	x
Ipomoea wrightii	morning glory	--	x	--
Iris fulva	red-flag Iris	--	x	--
Iris giganticaerulea	giant blue Iris	--	x	--
Itea virginica	Virginia willow	--	x	--
Iva annua	marsh elder	--	--	x
Iva frutescens	marsh elder	--	x	x
Juncus effusus	soft rush	--	x	x
Juncus roemerianus	needle rush	--	--	x
Justicia lanceolata	lance-leaved water-willow	x	--	--
Koelreuteria paniculata	golden raintree	--	--	x
Kosteletskya virginica	seashore mallow	--	x	x
Lactuca canadensis	wild lettuce	x	--	x
Lactuca floridana	wild lettuce	--	--	x
Lantana camara	Lantana	--	--	x
Leersia virginica	white grass	--	--	x
Lemna minor	duckweed	--	x	--
Lepidium virginicum	pepperwort	--	--	x
Leptochloa filiformis	--	--	--	x
Leptochloa panicoides	--	--	--	x
Leptochloa uninervia	--	--	--	x
Ligustrum japonicum	privet	x	--	--

Ligustrum sinense	common privet	x	--	--
Lilaeopsis carolinensis	--	--	x	--
Limnobium spongia	frog's-bite	--	x	--
Limonium nashii	sea lavender	--	--	x
Lippia lanceolata	northern frog-fruit	--	--	x
Lippia nodiflora	frog-fruit	--	--	x
Liquidambar styraciflua	sweetgum	x	x	--
Lithospermum tuberosum	gromwell	x	--	--
Lobelia cardinalis	cardinal flower	--	x	--
Lonicera japonica	Japanese honeysuckle	x	--	--
Ludwigia glandulosa	ludwigia	--	x	--
Ludwigia octovalvis	primrose	--	x	--
Ludwigia palustris	marsh purslane	--	x	--
Ludwigia peploides	floating water primrose	--	x	x
Lycopersicon esculentum	tomato	--	--	x
Lycopus rubellus	water horehound	--	x	--
Lycopus virginicus	bugle-weed	x	--	--
Lygodium japonicum	Japanese climbing fern	x	x	x
Lythrum lanceolatum	loosestrife	--	--	x
Lythrum lineare	loosestrife	--	--	x
Magnolia virginiana	sweet bay	x	x	--
Matelea gonocarpa	shinners	x	--	--
Mayaca aubletti	bog moss	--	x	--
Mazus japonicus	--	--	--	x
Mecardonia acuminata	chelone	--	x	x
Mecardonia procumbens	--	--	--	x
Medicago arabica	spotted medic	--	--	x
Medicago lupulina	black medic	--	--	x
Medicago polymorpha	bur clover	--	--	x
Melia azedarach	Chinaberry	--	--	x
Melilotus indica	sour clover	--	--	x
Melothria pendula	creeping cucumber	--	--	x
Micranthemum umbrosum	shade mud-flower	--	x	--
Mikania scandens	climbing hempweed	x	x	x
Mimosa strigillosa	powder-puff	--	--	x
Mimulus alatus	monkey-flower	x	--	--
Modiola caroliniana	mauve	--	--	x
Mollugo verticillata	carpet-weed	--	--	x
Morus alba	white mulberry	--	--	x
Morus rubra	red mulberry	x	--	--
Myosotis macrosperma	forget-me-not	x	--	--
Myrica cerifera	wax myrtle	x	x	x

Myriophyllum brasiliense	parrot-feather	--	x	--
Nelumbo lutea	yellow nelumbo	--	x	--
Nymphaea odorata	white waterlily	--	x	--
Nyssa aquatica	water tupelo	--	x	--
Nyssa sylvatica	swamp blackgum	x	x	--
Oenothera biennis	evening primrose	x	--	x
Oenothera laciniata	cut-leaf evening primose	x	--	x
Oenothera speciosa	Mexican primrose	x	--	x
Onoclea sensibilis	sensitive fern	--	x	--
Oplismenus hirtellus	--	x	--	x
Oplismenus setaris	--	x	--	--
Osmunda cinnamonmea	cinnamon fern	--	x	--
Osmunda regalis	royal fern	--	x	--
Oxalis corymbosa	--	x	--	--
Oxalis dillenii	wood sorrel	--	--	x
Oxalis stricta	wood sorrel	--	--	x
Panicum anceps	panic-grass	--	--	x
Panicum capillare	--	--	--	x
Panicum commutatum	panic-grass	--	--	x
Panicum gymnocarpon	swamp panic-grass	--	x	--
Panicum hemitomon	maidencane	--	x	x
Panicum repens	torpedo grass	--	--	x
Panicum rigidulum	panic-grass	--	x	x
Panicum scoparium	--	--	x	--
Panicum virgatum	switchgrass	--	--	x
Parthenocissus quinquefolia	Virginia creeper	x	--	x
Paspalum dilatatlum	dallis grass	--	--	x
Paspalum distichum	knotgrass	--	--	x
Paspalum fluitans	water paspalum	--	x	--
Paspalum urvillei	vasey grass	--	--	x
Passiflora incarnata	maypopos	--	--	x
Passiflora lutea	yellow passion-flower	--	--	x
Persea borbonia	red bay	x	--	--
Persea palustris	sweetbay	x	--	--
Petunia parviflora	wild petunia	--	--	x
Phalaris caroliniana	canary grass	--	--	x
Phoradendron serotinum	mistletoe	x	x	--
Phyllanthus urinaria	leaf-flower	--	--	x
Physalis angulata	ground cherry	--	--	x
Phytolacca americana	pokeweed	x	--	x
Pilea pumila	clearweed	x	--	--
Pistia stratiotes	water lettuce	--	x	--

Planera aquatica	water elm	--	x	--
Plantago major	plantain	--	--	x
Platanus occidentalis	sycamore	x	--	--
Pluchea camphorata	fleabane	x	--	x
Pluchea odorata	camphor-weed	--	--	x
Poa annua	blue grass	--	--	x
Polygonum densiflorum	giant knotweed	--	x	--
Polygonum hydropiperoides	smartweed	--	x	--
Polygonum lapathifolium	--	--	--	x
Polygonum punctatum	dotted smartweed	--	x	x
Polygonum setacea	--	--	--	x
Polygonum virginianum	jump-seed	x	--	--
Polymnia uvedalia	bearsfoot	x	--	--
Polypodium polypodiodes	resurrection fern	x	x	--
Polypogon monspeliensis	rabbit-foot grass	--	--	x
Pontederia cordata	pickerelweed	--	x	--
Populus deltoides	cottonwood	x	--	x
Populus heterophylla	swamp cottonwood	x	x	--
Proserpinaca pectinata	--	--	--	x
Prunus serotina	black cherry	x	--	--
Ptilimnium capillaceum	bishop's-weed	--	x	--
Pueraria lobata	kudzu	--	--	x
Pyrrhopappus carolinianus	false dandelion	--	--	x
Quercus laurifolia	laurel oak	x	x	--
Quercus lyrata	overcup oak	x	--	--
Quercus nigra	water oak	x	x	x
Quercus nuttallii	nuttall oak	x	x	--
Quercus phellos	willow oak	x	--	--
Quercus shumardii	swamp red oak	x	--	x
Quercus virginiana	live oak	x	--	x
Ranunculus platensis	--	--	--	x
Ranunculus pusillus	buttercup	--	--	x
Ranunculus sceleratus	buttercup	--	--	x
Ranunculus trilobus	buttercup	x	--	--
Rhus radicans	poison ivy	x	--	x
Rhynchosia minima	snout-bean	--	--	x
Rhynchospora caduca	--	--	x	--
Rhynchospora corniculata	horned rush	--	x	x
Rhynchospora macrostachya	--	--	x	x
Rhynchospora miliacae	--	--	x	--
Robinia pseudoacacia	black locust	x	x	--
Rorippa islandica	borbas	--	--	x

Rorippa sessiliflora	--	--	--	x
Rubus argutus	blackberry	x	--	--
Rubus trivialis	dewberry	x	--	x
Ruellia nudiflora	--	--	--	x
Rumex crispus	yellow dock	--	--	x
Rumex pulcher	fiddle dock	--	--	x
Rumex verticillatus	swamp dock	--	--	x
Sabal minor	palmetto	x	x	x
Sabatia calycina	rose-gentian	x	--	--
Sacciolepis striata	American cupscale	--	x	--
Sagittaria lancifolia	bulltongue	--	x	x
Sagittaria platyphylla	swamp potato	--	x	--
Salicornia bigelovii	Bigelow glasswort	--	--	x
Salix interior	sandbar willow	--	--	x
Salix nigra	black willow	x	x	x
Salvia coccinea	red sage	--	--	x
Sambucus canadensis	elderberry	x	--	--
Samolus parviflorus	water pimpernel	x	x	--
Sanicula canadensis	black snakeroot	--	--	x
Sapium sebiferum	tallow-tree	x	--	--
Saururus cernuus	lizard's tail	x	x	x
Scirpus lineatus	rusty bulrush	x	--	--
Scutellaria lateriflora	mad-dog skullcap	--	x	--
Senecio glabellus	butterweed	x	x	--
Sesbania drummondii	rattlebox	x	--	x
Sesbania macrocarpa	hemp sesbania	x	--	x
Sesbania punicea	red rattlebox	--	--	x
Sesbania vesicaria	bladder-pod	x	--	x
Setaria glauca	yellow foxtail	--	--	x
Setaria magna	giant foxtail	--	--	x
Sida rhombifolia	--	--	--	x
Sisyrinchium rosulatum	blue-eyed grass	x	--	--
Smilax smallii	greenbriar	x	x	--
Smilax bona-nox	catbriar	x	--	--
Smilax glauca	sawbriar	x	--	--
Smilax hispida	dwarf greenbriar	x	--	--
Smilax laurifolia	bamboo-vine	x	--	--
Smilax rotundifolia	common greenbriar	x	x	x
Smilax walteri	coral greenbriar	--	x	--
Solanum americanum	nightshade	x	--	--
Solanum carolinense	horse-nettle	--	--	x
Solidago altissima	goldenrod	--	--	x

Solidago sempervirens	seaside goldenrod	--	x	x
Sonchus asper	spiny-leaved sowthistle	x	--	x
Sorghum halepense	Johnson grass	--	x	--
Sparganium americanum	eastern burreed	--	x	--
Spartina alterniflora	oystergrass	--	--	x
Spartina cynosuroides	big cordgrass	--	--	x
Spartina patens	marsh hay cordgrass	--	--	x
Spartina spartinae	gulf cordgrass	--	--	x
Spergularia marina	sand spurrey	--	--	x
Sphenoclea zeylanica	--	--	--	x
Sphenopholis obtusata	wedge grass	x	--	--
Spilanthes americana		x	--	--
Spiranthes cernua	fragrant ladies'-tresses	x	x	--
Spiranthes vernalis	spring ladies'-tresses	x	x	--
Spirodela polyrhiza	giant duckweed	--	x	--
Sporobolus indicus	smut grass	--	--	x
Sporobolus virginicus	seashore dropseed	--	--	x
Stachys crenata	shade betony	--	--	x
Stachys tenuifolia	helge nettle	x	--	--
Stellaria media	chick-weed	x	--	x
Stenotaphrum secundatum	St. Augustine grass	--	--	x
Strophostyles helvola	wild bean	--	--	x
Styrax americana	American snowbell	--	x	--
Styrax grandifolia	bigleaf snowbell	--	x	--
Suaeda linearis	--	--	--	x
Tamarix gallica	--	--	--	x
Taraxacum officinale	common dandelion	--	--	x
Taxodium distichum var. ascendens	pond cypress	--	x	--
Taxodium distichum	bald cypress	--	x	x
Thalictrum dasycarpum	purple meadow-rue	x	--	--
Thelypteris kunthii	southern shield fern	x	--	--
Thelypteris palustris	marsh fern	--	x	--
Tillandsia usneoides	spanish moss	x	x	--
Tradescantia ohioensis	spiderwort	x	--	--
Trifolium repens	white clover	x	--	x
Trifolium resupinatum	Persian clover	--	--	x
Trisetum pensylvanicum	--	--	--	x
Typha angustifolia	narrow-leaved cattail	--	x	--
Typha latifolia	common cattail	--	x	x
Ulmus alata	winged elm	x	x	--
Ulmus americana	American elm	x	--	x
Ulmus rubra	slippery elm	x	--	--

Urtica chaemaedryoides	nettle	x	--	--
Utricularia inflata	floating bladderwort	--	x	--
Utricularia vulgaris	common bladderwort	--	x	--
Verbena brasiliensis	Brazilian vervain	--	--	x
Verbena rigida	vervain	--	--	x
Verbena urticifolia	white vervain	--	--	x
Verbesina encelioides	cowpen daisy	--	--	x
Verbesina virginica	frost-weed	--	--	x
Vernonia gigantea	ironweed	--	--	x
Veronica peregrina	speedwell	--	--	x
Veronica persica	Persian speedwell	--	--	x
Viburnum dentatum	arrow-wood	--	--	x
Vicia ludoviciana	vetch	--	--	x
Vigna luteola	yellow cowpea	x	--	x
Viola septemloba	violet	--	--	x
Vitis rotundifolia	muscadine	x	x	--
Vitis cinerea	pigeon grape	x	--	--
Wolffia columbiana	water-meal	--	x	--
Wolffiella sp.	mud-midget	--	x	--
Wolffiella lingulata	--	--	x	--
Woodwardia virginica	Virginia chain-fern	--	x	--
Xanthium strumarium	cocklebur	--	--	x
Zanthoxylum americana	toothache tree	--	--	x
Zanthoxylum clava-herculis	Hercules'-club	--	--	x
Zizaniopsis miliacea	giant cutgrass	--	x	x

[1]BLH - Bottomland hardwood
[2]SW - Swamp
[3]D - Disturbed areas (levees)

Appendix B

Selected Plants of the Louisiana Barrier Shoreline

Appendix B. List of selected plants of the Louisiana barrier shoreline.

Taxon	**Common Name**
Agalinis maritima	marsh pink, seaside gerardia
Ambrosia artemisiifolia	common ragweed
Andropogon virginicus	beardgrass
Atriplex arenaria	seabeach orach
Avicennia germinans	black mangrove
Baccharis halimifolia	sea-myrtle, groundsel-tree
Bacopa monnieri	coastal water hyssop
Batis maritima	saltwort
Borrichia frutescens	sea ox-eye
Cakile geniculata	sea rocket
Chenopodium album	pigweed
Avicennia germinans	black mangrove
Baccharis halimifolia	sea-myrtle, groundsel-tree
Bacopa monnieri	coastal water hyssop
Batis maritima	saltwort
Borrichia frutescens	sea ox-eye
Cakile geniculata	sea rocket
Chenopodium album	pigweed
Fimbristylis sp.	
Heliotropium curassavicum	seaside heliotrope
Hydrocotyle bonariensis	sand pennywort
Ipomoea stolonifera	beach morning glory
Ipomoea sagittata	marsh morning glory
Iva frutescens	marsh elder
Juncus roemerianus	black rush
Limonium carolinianum	sea lavender
Myrica cerifera	wax myrtle
Panicum amarum	bitter panicum, torpedo grass
Panicum repens	dog tooth grass
Paspalum sp.	
Phragmites communis	roseau cane
Sabatia stellaris	small marsh pink, sea pink
Salicornia bigelovii	glasswort
Salicornia virginica	glasswort
Scirpus robustus	leafy three-square
Sesuvium portulacastrum	sea purslane
Solanum americanum	nightshade
Solidago sempervirens	seaside goldenrod
Spartina patens	marsh hay cordgrass
Sporobolus virginicus	coastal dropseed
Suaeda linearis	sea blite

Uniola paniculata	sea oats
Vigna luteola	deer pea, beach pea

APPENDIX C

CLASSIFICATION HIERARCHY OF WETLANDS AND DEEPWATER HABITATS

APPENDIX D

DERIVATION OF MARSH TYPES FOR THE 1950S AND 1978 MISSISSIPPI DELTAIC PLAIN REGION HABITAT MAP SERIES

Appendix D. Derivation of marsh types for the 1950's and 1978 Mississippi Deltaic Plain Region Habitat Map Series.

1949 Designation	1950's Designation	1978 Designation
Habitats mapped in Mississippi Louisiana by O'Neil (1949) (after O'Neil 1949)	Habitats on the 1950s Mississippi Deltaic Plain Region Map Series (after Chabreck & Linscombe 1978, Eleuterius 1973)	Habitats on the 1978 Deltaic Plain Region Series
Fresh water marsh	Fresh marsh	Fresh marsh
Floating fresh water marsh	Fresh marsh	Fresh marsh
Floating three-cornered grass marsh	Fresh marsh	Fresh marsh
Intermediate marsh[a]	Non-fresh marsh	Intermediate marsh
Saw grass marsh[b]	Non-fresh marsh	Intermediate marsh
Brackish three-cornered grass marsh[c]	Non-fresh marsh	Brackish marsh
Leafy three-cornered or coco marsh	Non-fresh marsh	Brackish marsh
Excessively drained salt marsh	Non-fresh marsh	Saline marsh
Sea rim	Non-fresh beach/dune	Saline beach/dune

[a.]These were broadly drawn, marrow marshes fringing the levees in St. Bernard, Plaquemines, St. Charles, and Orleans parishes. On the 1950's habitat map series, these areas were labeled as fresh or non-fresh according to their appearances on the aerial photographs and collateral information.

[b.]This was a broadly drawn, narrow marsh category fringing the levees in St. Bernard Parish. On the 1950s habitat map series it was mapped as fresh because it contained low salinity to fresh water marsh species according to O'Neil (1949).

[c.]A large area near Lafitte, Louisiana, was mapped as a fresh marsh on the 1950's habitat map series because of its appearance as a fresh marsh area on the aerial photographs and its location within the larger fresh marsh zone. O'Neil (1949), however, had mapped it as a brackish three-cornered grass marsh.

APPENDIX E

CLASSIFICATION TABLE FOR HABITAT CODES
TO LEVEL ONE CLASSES

Appendix E. Classification Table for Habitat Codes to Level One Classes

The following is a series of lists with accompanying descriptions for the Level One Land Cover classes used by Coastal Zone Management. The Level One Classes are based on aggregation of the USFWS cowardian coding system used to develop the 1956, 1978, and 1983 habitat maps of coastal Louisiana. The cowardian codes were aggregated to 15 level one land cover classes because most projects did not require the level of detail inherent in the cowardian system. The level one class value and class name with a list of the cowardian codes associated with the class are given first followed by a general description of the class.

01 WATER (Natural)

E10W.	E1OW.	E1OWL.	E1OWt.	E1OWT.
L1OW.	L1OWV.	L2OW.	M1OW.	M1OWL.
POW.	POWH.	POWV.	R1OW.	R1OWV.
R2OW.	R4OW.			

Water (Natural) - consists of all naturally occurring water bodies such as streams,rivers, ponds,lakes, bays, and marine waters occurring within the coverage of the habitat maps. Salinity modifiers were not kept for this class.

02 WATER (Artificial)

E1OWH.	E1OWO.	E1OWX.	L2OWH.	L2OWO.
L2OWX.	POW1O.	POWO.	POWX.	R1OWO.
R1OWVX.	R1OWX.	R2OWO.	R2OWX.	

Water (Artificial) - consists of all dredged/excavated water bodies such as impoundments, ponds, canals, pipelines, and brine discharge pits. This class includes failed agricultural impoundments, oilfield impoundments, navigation/oilfield access canals, and oil/natural gas pipelines canals.

03 FRESH MARSH

PEM.	PEM1N.	PEM1NS.	PEM1T.	PEM1TPH.
PEM5.	PEMD.	PEMM.	PEMW.	

Fresh Marsh - consists of all marsh types identified as fresh marsh. This includes partially drained/ditched fresh marsh as well fresh marsh that is leveed for the purpose of water level management.

04 INTERMEDIATE MARSH

E2EM5P6. E2EM5P6D. E2EM5P6M. E2EM5P6S. E2EM5P6W.

Intermediate Marsh - consists of all marsh types identified as intermediate (oligohaline) marsh. This includes partially drained/ditched intermediate marsh, leveed intermediate marsh, and intermediate marsh that is leveed for the purpose of water level management.

05 BRACKISH MARSH

E2EM5P. E2EM5P5. E2EM5P5D. E2EM5P5M. E2EM5P5W.

Brackish Marsh - consists of all marsh types identified as brackish (mesohaline) marsh. This includes partially drained/ditched brackish marsh, leveed brackish marsh, and brackish marsh that is leveed for the purpose of water level management.

06 SALINE MARSH

E2EM5D4. E2EM5N4. E2EM5N4D. E2EM5N4S. E2EM5P4. E2EM5P4D.

Saline Marsh - consists of all marsh types identified as saline (mesohaline) marsh. This includes partially drained/ditched saline marsh, leveed saline marsh, and saline marsh that is leveed for the purpose of water level management.

04 NON-FRESH MARSH (1956)

E2EM. E2EMD. E2EMM.

Non-fresh marsh - is a marsh type unique to the 1956 habitat maps and consist of all marsh types identified as non-fresh. intermediate, brackish, and saline marsh types were not identified when the 1956 habitat coverage was produced, causing all non-fresh marsh types to lumped under one category. This marsh type includes partially drained/ditched non-fresh marsh, leveed non-fresh marsh, and non-fresh marsh that is leveed for the purpose of water level management.

07 FOREST (Upland/Bottomland Hardwoods)

Upland Codes

UFO1.	UFO12.	UFO13.	UFO1/3.	UFO134.
UFO13S.	UFO1S.	UFO3.	UFO34.	UFO34S.
UFO4.				

Bottomland Hardwoods Codes

PFO123.	PFO13.	PFO132.	PFO134.	PFO13C.
PFO34.	PFO5.			

Forest (Upland/Bottomland Hardwoods) - consists of broad-leaved deciduous, broad-leaved evergreen, and needle-leaved evergreen vegetation greater than twenty feet in height which occur on elevated/drained areas within the coverage of the habitat maps. In most cases this land cover type occurs along natural levee systems, and older spoil bank systems. In general, most of the forested areas occurring within the coastal zone would be typified as bottomland hardwoods although a large percentage of the forest class occurring in the southern Florida parishes is representative of needle-leaved evergreen forest (pine). An example of the forest class that would be representative of bottomland hardwoods is a fringing forest parallel to a natural distributary.

08 SWAMP

PFO. PFO1. PFO1R. PFO12. PFO1/2.
PFO24.

Swamp - consists of plaustrine forested broad-leaved and needle -leaved deciduous vegetation (primarily cypress and tupelo gum).

09 SHRUB/SCRUB

E2SS2.	E2SS3.	PSS1.	PSS12.	PSS123.
PSS13.	PSS2.	PSS3.	USS.	USS1.
USS13.	USS1/3.	USS134.		

Shrub/Scrub - consists of broad-leaved deciduous, needle-leaved deciduous, broad-leaved evergreen, and needle-leaved evergreen vegetation that are less than twenty feet in height occurring within the coverage of the habitat maps.

10 SHRUB/SCRUB (Spoil)

PSS1R. PSS1S. USS13S. USS1S. USS1S3S.

Shrub/Scrub (spoil) - consists of all broad-leaved deciduous, needle-leaved deciduous, broad-leaved evergreen, and needle-leaved evergreen vegetation that are less than twenty feet in height and occur on spoil deposits. The forested spoil types were not broken out as spoil vegetation because they were not recognized as such at the inception of this coding scheme.

11 AGRICULTURE/PASTURE

UDV2. UDV21. UDV2E. UDV2O. UGRP.

Agriculture/Pasture - consists of nonwetland areas being cultivated for crops, maintained as pasture, or left as grasslands and also includes any wetlands that have been drained and are now being used as agricultural and/or pasture. This category also includes vegetated dunes.

12 DEVELOPED

PDV. UDV. UDV1. UDV1O. UDV1R.
UN1.

Developed - consists of regularly maintained right-of-ways and urban/residential/commercial/industrial/oil/gas/mineral developments on upland sites or in areas protected from flooding by levees and or drainage canals for the area covered by the habitat data.

13 AQUATIC VEGETATION (floating/submerged/undefined)

Aquatic Vegetation - floating

E1AB5.	E1AB5H.	E1AB5L.	E1AB5O.	E1AB5X.
L2AB45.	L2AB45H.	L2AB4V.	L2AB5.	L2AB5H.
L2AB5X.	PAB4.	PAB4V.	PAB5.	PAB5H.
PAB5X.	R1AB4V.	R1AB5.	R1AB5O.	R1AB5V.
R1AB5X.	R2AB5.	R2AB5O.	R2AB5X.	

Aquatic Vegetation -submerged

E1AB.	E1AB12.	E1AB2.	E1AB2O.	L2AB1.
L2AB12.	L2AB2.	L2AB2H.	L2AB25.	L2AB25H.
R1AB2.	PAB2.	PAB2X.	PAB25.	R1AB2.
R1AB2O.	R2AB2X.	R1AB25.		

Aquatic Vegetation - undefined

E2AB.	L2AB.	PAB.	R1AB.	R1ABO.

Aquatic Vegetation - consists of floating and submerged aquatic vegetation found in all types of natural and artificial water bodies and in all salinity regimes within the coverage of the habitat maps. This includes water hyacinth, duckweed, and undefined submerged vascular vegetation.

14 <u>INERT</u>

E1RS2R.	E1UB2.	E2FR2.	E2RF.	E2RF2.
E2RS2R.	E2UB34.	L2UBV.	M1UB2.	PUB4V.
PUBV.	R1BB2.	R1RS2R.	UD3V.	UDV3.

Inert-flats

E2FL.	E2FL2.	E2FL23.	E2FL24.	E2FL3.
E2FL34.	E2FL34H.	E2FL3H.	E2FL5.	L2FL3.
L2FL34.	L2FL34H.	L2FL5.	PFL2.	PFL3.
PFL34.	PFL5.	R1FL.	R1FL3.	R1FL5.

Inert - consists of any unvegetated land areas existing within the habitat coverage but not designated as a *developed* or *beach* class. This includes unvegetated spoil banks, tidal fats, exposed reefs, rock jetties, drained ponds, and mud banks exposed along bayous/tidal streams.

15 <u>BEACH</u>

E2BB2.	E2BB34.	M2BB2.	M2BB2S.	R2BB2.

Beach - consists of wave reworked sand and/or shell material along a land-water interface.

00 <u>OUT OF COASTAL ZONE</u>

OUT.

Areas out of the coastal zone.

00 UNASSIGNED

??.	~.	1.	2.	3.
4.	5.			

Areas that were not assigned a cowardian code.

00 UNASSIGNED (1983)

E1USN.	E2EM1NPH.	E2EM1NSP.	E2EM1NSPH.	E2EM1NSSP.
E2USN.	R1USN.	UBS.	UU.	UUO.

Unknown cowardian codes found in the 1983 habitat data.

APPENDIX F

1988 COWARDIN CLASSIFICATION BREAK-DOWN

Appendix F. 1988 Cowardin Classification Break-Down

BRACKISH AB FLOATING
E1AB4L5 E2AB4L5

BRACKISH AB SUBMERGED
E1AB3L5 E1AB5L5 E2AB5L5

BRACKISH AB SUBMERGED EX
E1AB5Lx5

BRACKISH DEAD FOREST
E2FO5M5 E2FO5N5

BRACKISH MARSH
E2EM1N5 E2EM1N5ph E2EM1N5sp E2EM1P5
E2EM1P5sp

BRACKISH MARSH DR
E2EM1Pd5

BRACKISH MARSH EX
E2EM1Nx5 E2EM1Px5

BRACKISH MARSH IMP
E2EM1Ph5

BRACKISH MARSH SPOIL
E2EM1Ns5 E2EM1Ns5ph E2EM1Ns5sp E2EM1Phs5
E2EM1Ps5 E2EM1Ps5ph E2EM1Ps5sp

BRACKISH SHORE IRREG
E2USM5 E2USP5 M2USP5

BRACKISH SHORE IRREG DR
E2USPd5

BRACKISH SHORE IRREG EX
E2USMx5

BRACKISH SHORE REG
E2USN5

BRACKISH SHORE REG EX
E2USNx5

BRACKISH SHORE REG SPOIL
E2USNs5 E2USPs5

BRACKISH SS DECIDUOUS
E2SS1P5

BRACKISH SS DECIDUOUS SPOIL
E2SS1/3Ps5 E2SS1Ps5

BRACKISH SS EVERGREEN
E2SS3N5 E2SS3P5

BRACKISH SS EVERGREEN SPOIL
E2SS3Ps5

BRACKISH WATER
E1UBL5 E2UBL5 M1UBL5

BRACKISH WATER HUMAN
E1UBLh5 E1UBLhx5 E1UBLx5

CYPRESS FOREST
PFO2/1A PFO2/1C PFO2/1F PFO2/1F
PFO2/1R PFO2/1T PFO2/PAB4H PFO2A
PFO2C PFO2F PFO2H PFO2R
PFO2T PFO2V

CYPRESS FOREST DR
PFO2/1Ad PFO2/1Cd PFO2/1Fd PFO2/1Rd
PFO2Ad PFO2Cd PFO2Fd

CYPRESS FOREST EX
PFO2/1Fx PFO2Fx

CYPRESS FOREST IMP
PFO2/1Adh PFO2/1Cdh PFO2/1Fdh PFO2/1Fh
PFO2/1Th PFO2Ch PFO2Fdh PFO2Fh
PFO2Hh PFO2KFh

CYPRESS FOREST SPOIL

PFO2/1Cs PFO2/1Rs PFO2Rs PFO2Ss

DEAD FOREST

PFO5A PFO5F PFO5H PFO5T
PFO5V

DEAD FOREST DR

PFO5/1Ad

DEAD FOREST EX

PFO5Vx

DEAD FOREST IMP

PFO5Fh PFO5Hh PFO5Vh

DEAD FOREST SPOIL

PFO5Cs

DECIDUOUS FOREST

PFO1/2F PFO1/2A PFO1/2C PFO1/2R
PFO1/2S PFO1/2T PFO1A PFO1C
PFO1F PFO1H PFO1N PFO1R
PFO1S PFO1T

DECIDUOUS FOREST DR

PFO1/2Ad PFO1/2Cd PFO1/2Fd PFO1Ad
PFO1Cd PFO1Fd PFO1Rd PFO1Sd
PFO1Td

DECIDUOUS FOREST EX

PFO1/2Rx PFO1Ahx PFO1Ax PFO1Cx
PFO1Fx

DECIDUOUS FOREST IMP

PFO1/2Adh PFO1/2Cdh PFO1/2Ch PFO1/2Fdh
PFO1/2Fh PFO1Adh PFO1Ah PFO1Cdh
PFO1Ch PFO1Fh PFO1KCh

DECIDUOUS FOREST SPOIL

PFO1/2Cs PFO1/2Rs PFO1/2Ss PFO1/2Ts
PFO1Adhs PFO1Ads PFO1Ahs PFO1As

PFO1Chs	PFO1Cs	PFO1Fs	PFO1Rhs
PFO1Rs	PFO1Rs	PFO1Ss	PFO1Ts

ESTUARINE AB FLOATING

E1AB4L

ESTUARINE AB SUBMERGED

E1AB5L

ESTUARINE SHORE IRREG

E2USP M2USP

ESTUARINE SHORE REG

E2USN M2USN

ESTUARINE WATER HUMAN

E1UBLx E1UBLxS

EVERGREEN FOREST

PFO3A	PFO3R	PFO3T	PFO4A
PFO4C	PFO4S		

EVERGREEN FOREST DR

PFO3Ad PFO3Sd

EVERGREEN FOREST IMP

PFO4Ah

FRESH AB FLOATING

L1AB4H	L1AB4V	L2AB4F	L2AB4H
L2AB4T	L2AB4V	PAB4/FO1F	PAB4/FO2T
PAB4F	PAB4H	PAB4T	PAB4V
R1AB4T	R1AB4V	R2AB4H	

FRESH AB FLOATING EX

L1AB4Hx	L2AB4Hx	L2AB4Vx	PAB4Fx
PAB4Hhx	PAB4Hx	PAB4KHx	PAB4Vx
R1AB4Hx	R1AB4Vx	R2AB4Hhx	R2AB4Hx

FRESH AB FLOATING IMP

L1AB4Hh

FRESH AB FLOATING IMP

L1AB4KHh	L2AB4Fh	L2AB4Hh	L2AB6Fh
PAB4Fh	PAB4Hh	PAB4KHh	PAB4Vh
R2AB4Hh			

FRESH AB FLOATING SPOIL

R1AB4Vs

FRESH AB SUBMERGED

L1AB3H	L1AB3V	L1AB5H	L1AB5V
L2AB1V	L2AB3F	L2AB3H	L2AB3V
L2AB5H	L2AB5L	L2AB5V	PAB3F
PAB3H	PAB3V	PAB5H	PAB5V
R1AB3V	R1AB5L	R1AB5N	R1AB5T
R1AB5V	R2AB3H	R2AB5V	

FRESH AB SUBMERGED EX

L1AB3Hx	L2AB5Hx	PAB3Fx	PAB3Hx
PAB3Vx	PAB5Hx	R1AB3Hx	R1AB3Vx
R2AB3Hx			

FRESH AB SUBMERGED IMP

L1AB3Hh	L1AB3KHh	L2AB3Hh	L2AB3KHh
L2AB3Vh	PAB3Hh	PAB3KHh	PAB3Vh

FRESH MARSH

PEM/PSS1A	PEM/PSS1F	PEM1/FO2T	PEM1/PAB4F
PEM1/PFO2F	PEM1/PFO2Fh	PEM1/PFO2T	PEM1A
PEM1C	PEM1Csp	PEM1F/PSS1F	PEM1F
PEM1H	PEM1N	PEM1Nph	PEM1Nsp
PEM1R	PEM1S	PEM1T	PEM1Tph
PEM1Tsp	PEM1V	PEM2N	PEM2T

FRESH MARSH DR

PEM1Ad	PEM1Cd	PEM1Fd	PEM1Rd	PEM1Sd

FRESH MARSH EX

PEM1Ax	PEM1Cx	PEM1Fhx	PEM1Fx
PEM1Hhx	PEM1Hx	PEM1Nx	PEM1Tx
PEM1Vx			

FRESH MARSH IMP

PEM1Adh	PEM1Ah	PEM1Cdh	PEM1Ch
PEM1Fdh	PEM1Fh	PEM1Hh	PEM1KAh
PEM1KCh	PEM1KFh	PEM1Th	

FRESH MARSH SPOIL

PEM1Ahs	PEM1As	PEM1Chs	PEM1Cs
PEM1Fhs	PEM1Fs	PEM1KHhs	PEM1Ns

PEM1Nsph	PEM1Nssp	PEM1Rs	PEM1Rsph
PEM1Ss	PEM1Ts	PEM1Tsph	PEM1Tssp
PEM1Vs			

FRESH SHORE IRREG

L2USA	L2USC	PUSA	PUSC
R1USA	R1USM	R1USR	R1UST
R2USA	R2USC		

FRESH SHORE IRREG EX

L2USAx	L2USCx	PUSAx	PUSCx
PUSKCx			

FRESH SHORE IRREG IMP

L2USCh	PUSAdh	PUSCh

FRESH SHORE IRREG SPOIL

PUSAhs	PUSAs	PUSChs	PUSCs
R1USRs	R1USSs		

FRESH SHORE REG

L2USN	L2USR	PUSN	PUSR
R1USN	R2USN		

FRESH SHORE REG EX

PUSNx

FRESH SHORE REG SPOIL

L2USAhs	L2USAs	L2USChs	R1USNs

FRESH WATER

L1UBH	L1UBV	L2UBF	L2UBH
L2UBV	PUBF	PUBH	PUBT
PUBV	R1UBH	R1UBT	R1UBV
R2UBH			

FRESH WATER HUMAN

L1UBHh	L1UBHhx	L1UBHx	L1UBKHh
L1UBKh	L1UBVx	L2UBFh	L2UBHh
L2UBHhx	L2UBHx	L2UBKFh	L2UBKHh
L2UBVh	L2UBVx	PUBAh	PUBCKx
PUBCx	PUBFKx	PUBFh	PUBFx

PUBHKh	PUBHKs	PUBHKx	PUBHh
PUBHhs	PUBHhx	PUBHx	PUBKFx
PUBKHh	PUBKHhx	PUBKHx	PUBTs
PUBVh	PUBVx	R1UBHx	R1UBLx
R1UBVx	R2UBHh	R2UBHhx	R2UBHx
R2UBVx			

INTERMED AB FLOATING

E1AB4L6 E2AB4L6

INTERMED AB FLOATING EX

E1AB4Lx6 E2AB4Lx6

INTERMED AB FLOATING IMP

E1AB4Lh6

INTERMED AB SUBMERGED

E1AB3L6 E1AB5L6 E2AB3L6 E2AB3Lh6
E2AB5L6

INTERMED AB SUBMERGED EX

E1AB3Lx6 E1AB5Lx6

INTERMED AB SUBMERGED IMP

E1AB3Lh6 E1AB5Lh6

INTERMED DEAD FOREST

E2FO5L6 E2FO5M6 E2FO5N6 E2FO5P6

INTERMED EVERGREEN FOREST

E2FO3P6

INTERMED MARSH

E2EM1N6 E2EM1N6ph E2EM1N6sp E2EM1P6
E2EM1P6ph E2EM1P6sp

INTERMED MARSH EX

E2EM1Nx6

INTERMED MARSH IMP

E2EM1Kh6 E2EM1Ph6

INTERMED MARSH SPOIL
E2EM1Ns6 E2EM1Ns6ph E2EM1Ns6sp E2EM1Phs6
E2EM1Ps6 E2EM1Ps6sp

INTERMED SHORE IRREG
E2USM6 E2USP6

INTERMED SHORE IRREG SPOIL
E2USMs6

INTERMED SHORE REG
E2USN6

INTERMED SHORE REG EX
E2USNx6

INTERMED SHORE REG SPOIL
E2USNs6 E2USPhs6 E2USPs6

INTERMED SS DECIDUOUS
E2SS1/3P6 E2SS1P6

INTERMED SS DECIDUOUS DR
E2SS1Pd6

INTERMED SS DECIDUOUS IMP
E2SS1Ph6

INTERMED SS DECIDUOUS SPOIL
E2SS1Phs6 E2SS1Ps6

INTERMED SS EVERGREEN
E2SS3N6 E2SS3P6

INTERMED SS EVERGREEN IMP
E2SS3Ph6

INTERMED SS EVERGREEN SPOIL
E2SS3Ns6 E2SS3Ps6

INTERMED WATER
E1UBL6 E1UBL6ph

INTERMED WATER HUMAN

E1UBLh6	E1UBLhx6	E1UBLx6	

MIXED FOREST

PFO1/3A	PFO1/3C	PFO1/3R	PFO1/3S
PFO1/3T	PFO1/4A	PFO1/4C	PFO1/4R
PFO1/4S	PFO2/4A	PFO2/4C	PFO3/1A
PFO3/1C	PFO3/1T	PFO4/1A	PFO4/1C
PFO4/1R	PFO4/1S	PFO4/2A	PFO4/2C

MIXED FOREST DR

PFO1/3Ad	PFO1/4Ad	PFO4/1Ad	

MIXED FOREST IMP

PFO1/4Ah	PFO1/4Ch	PFO4/1Ah	

MIXED FOREST SPOIL

PFO1/4As	PFO1/4Cs	PFO4/1As	

SALINE AB FLOATING

E1AB4L4

SALINE AB SUBMERGED

E1AB3L4	E1AB5L4	E2AB5M4	

SALINE MARSH

E2EM1M4	E2EM1N4	E2EM1N4ph	E2EM1N4sp
E2EM1P4	E2EM1P4sp		

SALINE MARSH DR

E2EM1Pd4

SALINE MARSH EX

E2EM1Nx4

SALINE MARSH IMP

E2EM1Nh4	E2EM1Ph4		

SALINE MARSH SPOIL

E2EM1Ns4	E2EM1Ns4sp	E2EM1Phs4	E2EM1Ps4

SALINE SHORE IRREG

E2USM4	E2USP4	M2USM4	M2USP4

SALINE SHORE REG

E2USN4	M1USN4	M2USN4

SALINE SHORE REG EX

E2USNx4

SALINE SHORE REG SPOIL

E2USNs4	E2USPhs4	E2USPs4

SALINE SS DECIDUOUS

E2SS1P4

SALINE SS DECIDUOUS DR

E2SS1Pd4

SALINE SS DECIDUOUS SPOIL

E2SS1Ps4

SALINE SS EVERGREEN

E2SS3P4 E2SS7P4

SALINE SS EVERGREEN SPOIL

E2SS3Ps4

SALINE WATER

E1UBL4	E2UBL4	M1UBL4

SALINE WATER HUMAN

E1UBLh4	E1UBLhx4	E1UBLx4

SS CYPRESS

PSS2/1C	PSS2/1F	PSS2/1T	PSS2A
PSS2C	PSS2F	PSS2H	PSS2T

SS CYPRESS IMP

PSS2Fh

SS DEAD

PSS5C

SS DECIDUOUS

PSS/PFO1A	PSS1/2A	PSS1/2C	PSS1/2F
PSS1/2R	PSS1/2T	PSS1/3A	PSS1/3C
PSS1/3F	PSS1/3R	PSS1/3S	PSS1/3T
PSS1/4A	PSS1/4C	PSS1/4R	PSS1A
PSS1C	PSS1F	PSS1H	PSS1N
PSS1R	PSS1S	PSS1T	

SS DECIDUOUS DR

PSS1/3Ad	PSS1/3Rd	PSS1Ad	PSS1Cd
PSS1Fd	PSS1Rd	PSS1Sd	PSS1Td

SS DECIDUOUS EX

PSS1Cx	PSS1Fx	PSS1Hx	PSS1Rx
PSS1Tx			

SS DECIDUOUS IMP

PSS1/2Ch	PSS1/3Fh	PSS1Adh	PSS1Ah
PSS1Cdh	PSS1Ch	PSS1Fdh	PSS1Fh
PSS1Rdh	PSS1Rh	PSS1Th	

SS DECIDUOUS SPOIL

PSS1Adhs	PSS1Ahs	PSS1As	PSS1Chs
PSS1Cs	PSS1Fs	PSS1Rhs	PSS1Rs
PSS1Ss	PSS1Ts		

SS EVERGREEN

PSS3/PFO5Fh	PSS3A	PSS3C	PSS3F
PSS3N	PSS3R	PSS3T	PSS4A

SS EVERGREEN DR

PSS3Cd

SS EVERGREEN IMP

PSS3Rh

SS EVERGREEN SPOIL

PSS3As	PSS3Rs

SS MIXED

PSS2/4A	PSS2/4C	PSS3/1A	PSS3/1C
PSS3/1F	PSS3/1R	PSS3/1T	PSS4/1A

PSS4/1C

<u>SS MIXED DR</u>
PSS3/1Ad PSS4/1Ad

<u>UPLAND AGRICULTURE</u>
UA

<u>UPLAND AGRICULTURE RICE</u>
UAr

<u>UPLAND AGRICULTURE SPOIL</u>
UAs

<u>UPLAND BARREN</u>
UB

<u>UPLAND BARREN DUNE</u>
UBd

<u>UPLAND BARREN EX</u>
UBx

<u>UPLAND BARREN SPOIL</u>
UBs

<u>UPLAND DECIDUOUS FOREST</u>
UF6

<u>UPLAND DECIDUOUS FOREST SPOIL</u>
UF6s

<u>UPLAND EVERGREEN FOREST</u>
UF7

<u>UPLAND EVERGREEN FOREST SPOIL</u>
UF7s

<u>UPLAND MIXED FOREST</u>
UF8

UPLAND MIXED FOREST SPOIL
UF8s

UPLAND OIL/GAS
UUo

UPLAND RANGE
UR

UPLAND RANGE DUNE
URd

UPLAND RANGE SPOIL
URs

UPLAND SS
USS

UPLAND SS DR
USSh

UPLAND SS DUNE
USSd

UPLAND SS EX
USSx

UPLAND SS SPOIL
USSs

UPLAND URBAN
UU

UPLAND URBAN SPOIL
UUs

APPENDIX G

AGGREGATED HABITAT CLASSIFICATIONS USED FOR TREND ANALYSES FOR 1956, 1978, AND 1988/90 U.S. FISH AND WILDLIFE HABITAT DATA FOR BARATARIA-TERREBONNE ESTUARINE SYSTEM

Appendix G. Aggregated habitat classifications used for trend analyses for 1956, 1978, and 1988/90 U.S. Fish and Wildlife habitat data for BTES.

	1956	1978	1988
Water	Water Natural	Water Natural	Water
	Water Artificial	Water Artificial	Ab
Floating			
		Aquatic Vegetation	Ab
Submerged			
			Fresh
Water			
			Estuarine
Water			
Marsh	Fresh Marsh		
	Non-Fresh Marsh		
Fresh Marsh			Fresh
Marsh			
Non-Fresh Marsh		Intermediate	
Intermediate			
		Brackish	Brackish
Marsh			
		Saline	Saline
Marsh			
			Estuarine
Marsh			
Forested	Forest	Forest	Cypress
Forest			
	Swamp	Swamp	
Bottomland Forest			
	Shrub/Scrub	Shrub/Scrub	Upland
Forest			
	Shrub/Scrub Spoil	Shrub/Scrub Spoil	Dead
Forest			
Bottomland Shrub/Scrub			
			Upland
Shrub/Scrub			

Ag/Pasture Ag/Pasture	Ag/Pasture	Ag/Pasture	
Developed Developed	Developed	Developed	
Other Barren Land	Inert Beach	Inert Beach	Shore/Flat Upland Other

APPENDIX H

DETAILED U.S. FISH AND WILDLIFE SERVICE
1956, 1978, AND 1988/90
HABITAT DATA FOR THE
BARATARIA-TERREBONNE
ESTUARINE SYSTEM AREA

Appendix H. Detailed U.S. Fish and Wildlife Service 1956, 1978, and 1988/90 habitat data for the BTES Area.

1956		1978		1988/90
Water (Natural)	1004818	Water (Natural)	1193533	Water
	1428533			
Water (Artificial)	30998	Water (Artificial)	58412	Ab Floating
	9399			
Fresh Marsh	602760	Fresh Marsh	217420	Ab Submerged
	6745			
Non-Fresh Marsh	609031	Intermediate Marsh	143398	Fresh Marsh
	232664			
Not Interpreted	0	Brackish Marsh	247589	Intermediate Marsh
	109042			
Not Interpreted	0	Saline Marsh	308958	Brackish Marsh
	192778			
Forest	53193	Forest	51842	Saline Marsh
	228990			
Swamp	83323	Swamp	60537	Estuarine Marsh
	0			
Shrub/Scrub	3534	Shrub/Scrub	18149	Cypress Forest
	28042			
Shrub/Scrub Spoil	7997	Shrub/Scrub Spoil	36837	Bottomland Forest
	58940			
Agriculture/Pasture	46774	Agriculture/Pasture	51001	Upland Forest
	18444			
Developed	25503	Developed	56733	Dead Forest
	337			

Aquatic Vegetation	312	Aquatic Vegetation	27303	Bottomland Shrub/Scrub
	37680			
Inert	6905	Inert	4922	Upland Shrub/Scrub
	12904			
Beach	4592	Beach	2485	Shore/Flat
	4224			
				Ag/Pasture
	57226			
				Upland Barren
	949			
				Developed
	52840			
				Other Land
	158			

APPENDIX I

DETAILED U.S. FISH AND WILDLIFE SERVICE 1956, 1978, AND 1988/90 HABITAT DATA FOR THE BARATARIA BASIN

Appendix I. Detailed U.S. Fish and Wildlife Service 1956, 1978, and 1988/90 habitat data for the Barataria Basin.

1956		1978		1988/90
Water (Natural)	407174	Water (Natural)	493382	Water
	619694			
Water (Artificial)	21770	Water (Artificial)	36386	Ab Floating
	2419			
Fresh Marsh	259376	Fresh Marsh	50783	Ab Submerged
	1262			
Non-Fresh Marsh	268623	Intermediate Marsh	76426	Fresh Marsh
	67200			
Not Interpreted	0	Brackish Marsh	107409	Intermediate Marsh
	56604			
Not Interpreted	0	Saline Marsh	153464	Brackish Marsh
	86173			
Forest	35424	Forest	32081	Saline Marsh
	97105			
Swamp	33889	Swamp	25161	Estuarine Marsh
	0			
Shrub/Scrub	3093	Shrub/Scrub	5948	Cypress Forest
	11479			
Shrub/Scrub Spoil	3076	Shrub/Scrub Spoil	17054	Bottomland Forest
	31820			
Agriculture/Pasture	34031	Agriculture/Pasture	34984	Upland Forest
	14212			
Developed	22775	Developed	49615	Dead Forest
	54			
Aquatic Vegetation	0	Aquatic Vegetation	8235	Bottomland Shrub/Scrub
	11351			
Inert	4003	Inert	3637	Upland Shrub/Scrub

	9564			
Beach	2425	Beach	1091	Shore/Flat
	1723			
				Ag/Pasture
	37934			

APPENDIX J

DETAILED U.S. FISH AND WILDLIFE SERVICE 1956, 1978, AND 1988/90 HABITAT DATA FOR THE TERREBONNE BASIN

Appendix J. Detailed U.S. Fish and Wildlife Service 1956, 1978, and 1988/90 habitat data for the Terrebonne Basin.

1956		1978		1988/90	
Water (Natural)	597693	Water (Natural)	700257	Water	808934
Water (Artificial)	9232	Water (Artificial)	22034	Ab Floating	6980
Fresh Marsh	343392	Fresh Marsh	166638	Ab Submerged	5483
Non-Fresh Marsh	340479	Intermediate Marsh	66972	Fresh Marsh	165464
Not Interpreted	0	Brackish Marsh	140181	Intermediate Marsh	52438
Not Interpreted	0	Saline Marsh	155567	Brackish Marsh	106605
Forest	17788	Forest	19766	Saline Marsh	131960
Swamp	49434	Swamp	35379	Estuarine Marsh	0
Shrub/Scrub	441	Shrub/Scrub	12206	Cypress Forest	16564
Shrub/Scrub Spoil	4925	Shrub/Scrub Spoil	19787	Bottomland Forest	27123
Agriculture/Pasture	12767	Agriculture/Pasture	16027	Upland Forest	4238
Developed	2858	Developed	7276	Dead Forest	283
Aquatic Vegetation	312	Aquatic Vegetation	19068	Bottomland Shrub/Scrub	26331
Inert	2968	Inert	1286	Upland Shrub/Scrub	3345
Beach	2168	Beach	1395	Shore/Flat	2501
				Ag/Pasture	19304
				Upland Barren	130
				Developed	6818
				Other Land	109

APPENDIX K

SUMMARY OF VERTICAL ACCRETION STUDIES USED IN THIS REPORT AND PRESENTED IN FIGURE 4.8

Appendix K. Summary of vertical accretion studies used in this report and presented in Figure 4.8a and b.

Map Reference No./ Site Location	Reference	Accretion (cm/yr)[1]	Notes
1: South Pass	DeLaune et al., 1992	>2.00	
2: Empire	DeLaune et al., 1992	1.40	
3: Grand Terre	DeLaune et al., 1986	0.55	
	DeLaune et al., 1992	0.55	
4: Grand Isle	DeLaune et al., 1986	0.78	
	DeLaune et al., 1992	0.79	
5: Caminada Bay Marsh	Smith et al., 1983	0.76	marsh surface
		1.1	sed. from adj. water body
	Hatton et al., 1983	0.75	backmarsh site
6: Barataria Bay Marsh	Baumann et al., 1984[2]	1.50	streamside, w/ hurricane effects
		1.10	streamside, w/out hurr. effects
		0.90	backmarsh, w/ hurricane effects
		0.60	backmarsh, w/out hurr. effects
7: Three Bayou marshes	Reed unpub. data	3.26	Jul 1991 to Jan 1993, annualized
		2.87	Jan 1993 to Jul 1994, annualized
	Cahoon et al., in press	1.40	pre- Andrew
		5.80	encompassing Andrew

8: Marshes NE of Little Lake	Reed unpub. data	2.62	Jul 1991 to Jan 1993, annualized
		1.64	Jan 1993 to Jul 1994, annualized
	Cahoon et al., in press	0.60	pre- Andrew
		5.20	encompassing Andrew
9: Marshes NE of Lake Salvador	Taylor et al., 1989	0.72	sites close to sediment source
		0.28	backmarsh sites
10: L. Cataoutche area	DeLaune et al., 1992	1.00	
11: Marshes W of B. Perot	Hatton et al., 1983	0.64	backmarsh site
		1.4	streamside on natural levee
	Smith et al., 1983	0.95	marsh surface
12: Clovelly Farm - Little Lake	DeLaune et al., 1992	0.78	
13: Marshes SW of Little Lake	Hatton et al., 1983	0.59	backmarsh site
		1.40	streamside on natural levee
14: North Bayou Ferblanc, North Lake	DeLaune et al., 1992	0.78	
15: Bayou Ferblanc	DeLaune et al., 1978	1.35	streamside salt marsh site
		0.75	backmarsh salt marsh site
	Cahoon and Turner 1989	0.99	50 m inland from natural bayou
		0.72	50 m transect perpendic. to above
	DeLaune et al., 1989	0.47	Cs dating
		0.42	Pb^{210} dating
	Knaus and Van Gent 1989	1.29	
	DeLaune et al., 1990	0.44	backmarsh
		1.25	streamside
	DeLaune et al., 1992	0.74	

16: Airplane Lake	DeLaune et al., 1978	1.1	lake bottom
	Childers and Day 1990	4.39	creekside
		1.41	backmarsh
17: Leeville	Nyman et al., in press	0.00	thickness Andrew deposits in cm
18: Golden Meadow Oil Field	DeLaune et al., 1992	0.70	
19: Grand Bayou Blue	Pardue et al., 1988	0.86	
	DeLaune et al., 1992	0.86	
20: Bayou Blue	Cahoon et al., in press	0.41	pre- Andrew
		7.08	encompassing Andrew
21: Lower Pointe au Chien	Reed 1992	4.20	streamside, control site only
		3.30	backmarsh, control site only
22: Bayou Jean La Croix	Reed 1992	1.8	control site only
23: Montegut Marsh	Reed 1992	4.20	backmarsh, control site only
24: Billy Goat Bay	Nyman et al., in press	0.00	thickness Andrew deposits in cm
25: Madison Bay	Nyman et al., in press	4.0	thickness Andrew deposits in cm
26: Bayou Barre	Nyman et al.,1993	0.96	(brackish marshes)
27: Bayou Barre	Nyman et al.,1993	0.99	(saline marshes)
28: Bayou Chitigue	DeLaune et al., 1992	1.02	
	Cahoon et al., in press	5.50	encompassing Andrew
		2.30	post- Andrew
	Nyman et al., in press	3.0	thickness Andrew deposits in cm

29: Cocodrie	DeLaune et al., 1992	0.7	
	Cahoon et al., in press	2.5	2 wks. accum., after Andrew
	Cahoon and Reed, in press	0.99	Apr 1988 - Mar 1990, annualized
		3.40	Dec 1989 - Jul 1991, annualized
30: Bayou Chauvin	Reed 1992	5.10	control site only
31: Falgout Canal	Cahoon et al., in press	4.80	encompassing Andrew
		4.60	immediately after Andrew
32:Fina LaTerre	Cahoon 1994	0.3	control sites only
33: Bayou DuLarge	Nyman et al., in press	3.3	thickness Andrew deposits in cm
34: Bayou de Cade	Reed 1992	1.8	control site only
35: Otter Bayou	Reed unpub. data	4.73	Jul 1991 to Jan 1993, annualized
		3.81	Jan 1993 to Jul 1994, annualized
	Guntenspergen et al., in press	3.60	least impacted marsh by Andrew
		1.70	compressed marsh by Andrew
		7.20	thick sediment marsh by Andrew
36: Jug Lake Area	Reed unpub. data	3.46	Jul 1991 to Jan 1993, annualized
		0.99	Jan 1993 to Jul 1994, annualized
	Cahoon et al., in press	8.25	encompassing Andrew
37: Grand Pass	Nyman et al., in press	6.5	thickness Andrew deposits in cm

38: King Lake	Nyman et al., in press	3.6	thickness Andrew deposits in cm
39: Old Oyster Bayou	Cahoon, in press	3.76 -0.24	encompassing Andrew post- Andrew
	Nyman et al., in press	3.5	thickness Andrew deposits in cm
	Childers and Day 1990	1.40 0.20	creekside backmarsh

40: Blue Hammock Bayou	Nyman et al., in press	9.0	thickness Andrew deposits in cm
41: Carencro Bayou	Cahoon et al., in press	1.34	pre Andrew
		14.74	encompassing Andrew
42: FourLeague Bay Bottom sediment	DeLaune et al., 1987b	>1.5	
	Pardue et al., 1988	>1.5	
	DeLaune et al., 1992	>1.5	
43: FourLeague Bay Marshes	Baumann et al., 1984[3]	1.30	streamside, no hurricane effects
		0.56	backmarsh, no hurricane effects
	DeLaune et al., 1987b	0.65	mean of four sites
44: Point au Fer	DeLaune et al., 1992	0.65	
45: Willow Bayou	Rejmanek et al., 1988	1.28	mean 5 plant community samples (includes Danny and Juan)
46: Palmetto Bayou	DeLaune et al., 1989	0.90	Cesium dating
		0.73	^{210}Pb dating
	Knaus and Van Gent 1989	2.97	
	DeLaune et al., 1987b	0.92	sites in Palmetto, Creole and Plumb Bayous
	DeLaune et al., 1992	0.93	sites in Palmetto, Creole and Plumb Bayous
47: Bayou Penchant (Terrebonne Marsh Complex)	DeLaune et al., 1987b	0.81	Cesium dating
		0.76	^{210}Pb dating
	DeLaune et al., 1992	0.81	
48: Lake Palourde	Pardue et al., 1988	1.1	bottom sediment

49: Lake Verret, South	Connor and Day 1991	4.44	on the edge
		1.32	100 m inland
50: Lake Verret area	DeLaune et al., 1987a	0.63	avg. of 5 sites around the Lake
51: Lake Verret, NW	Connor and Day 1991	0.24	NW of the Lake, dry area
		0.60	NW of the Lake, semi-wet area
		0.84	NW of the Lake, wet area
	DeLaune et al., 1992	0.63	swamp forest
52: Marshes S of L. des Allemands	Hatton et al., 1983	0.65	backmarsh site
		1.10	streamside on natural levee
	Smith et al., 1983	0.85	marsh surface
		0.52	water bottom

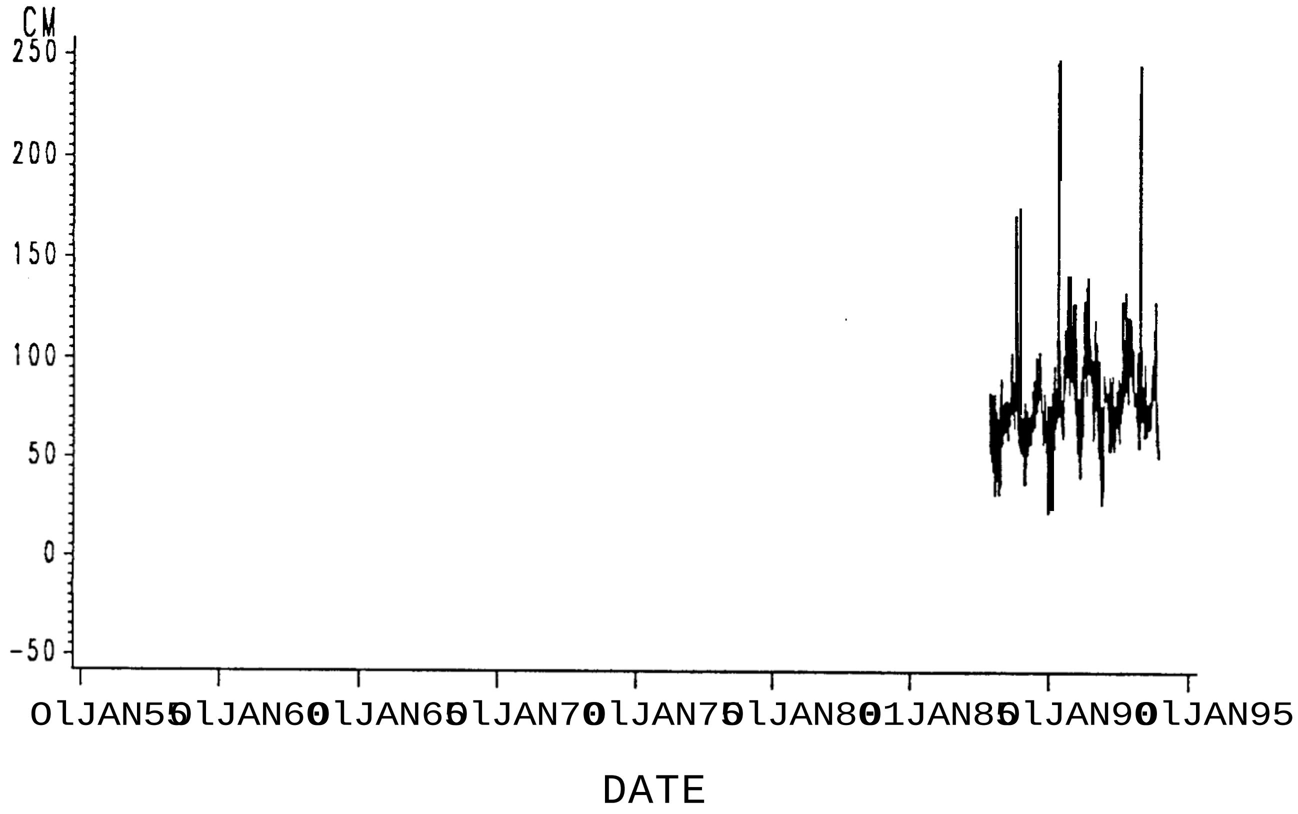
[1] Rates converted from published data to cm/yr, unless otherwise indicated
[2] Mean of 8 sites throughout Barataria Bay
[3] Mean of 14 sites around Fourleague Bay

APPENDIX L

TIME SERIES PLOTS OF DAILY WATER LEVELS AND SALINITIES

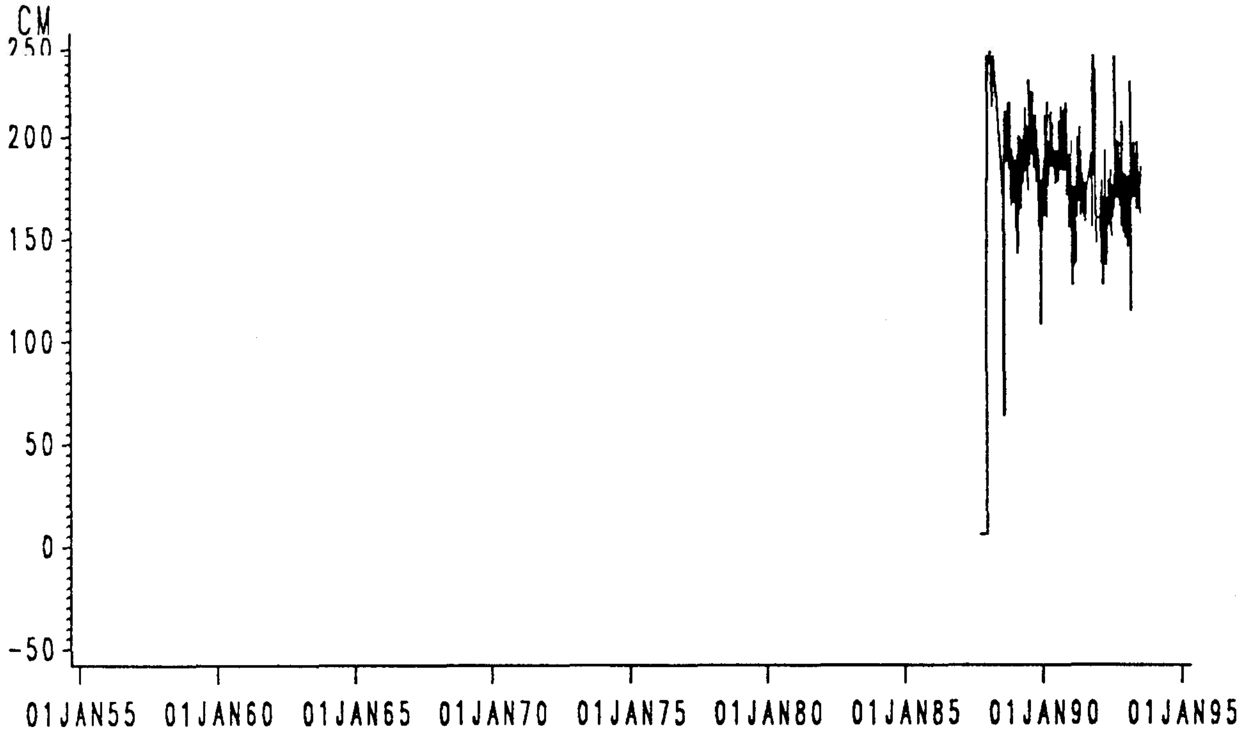
GAILY WATER LEVEL

STATION=31 5 GRAND TERRE



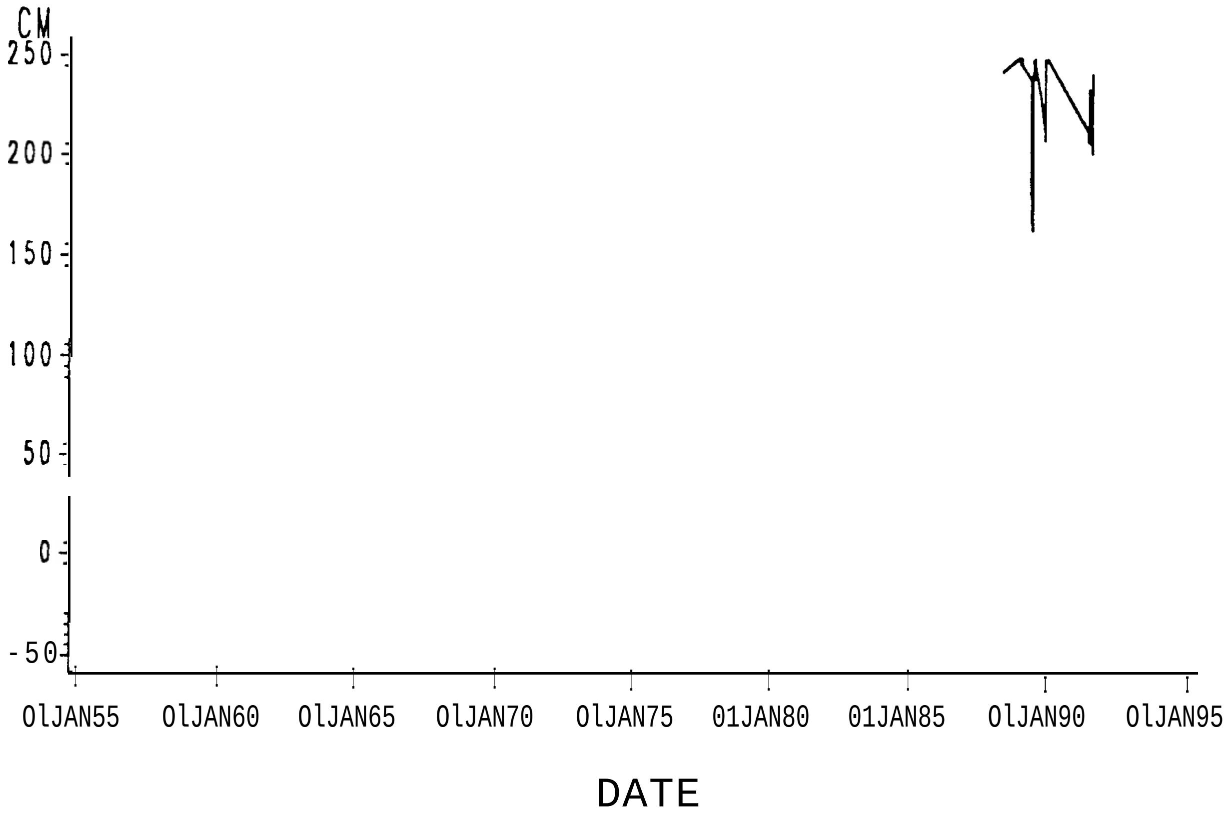
DAILY WATER LEVEL

STATION=3 17 ST.MARYS PT.



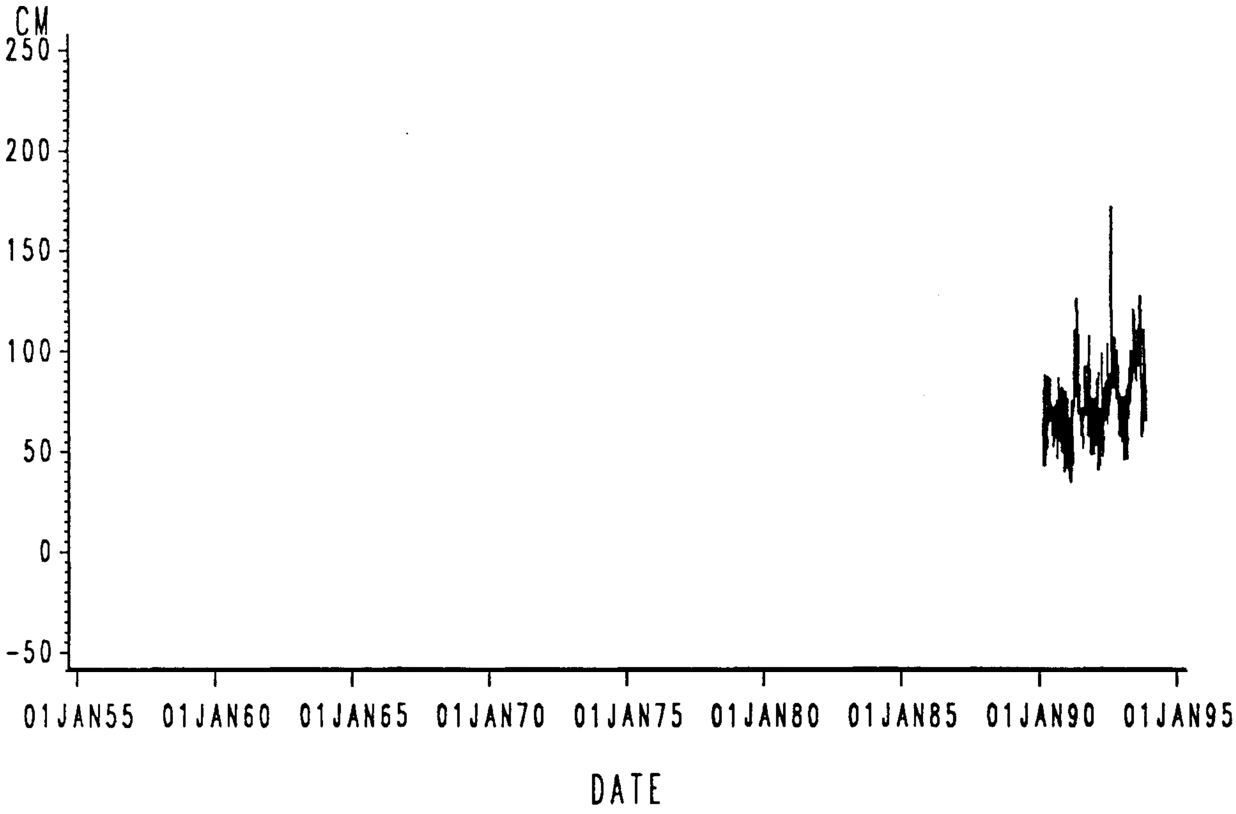
DAILY WATER LEVEL

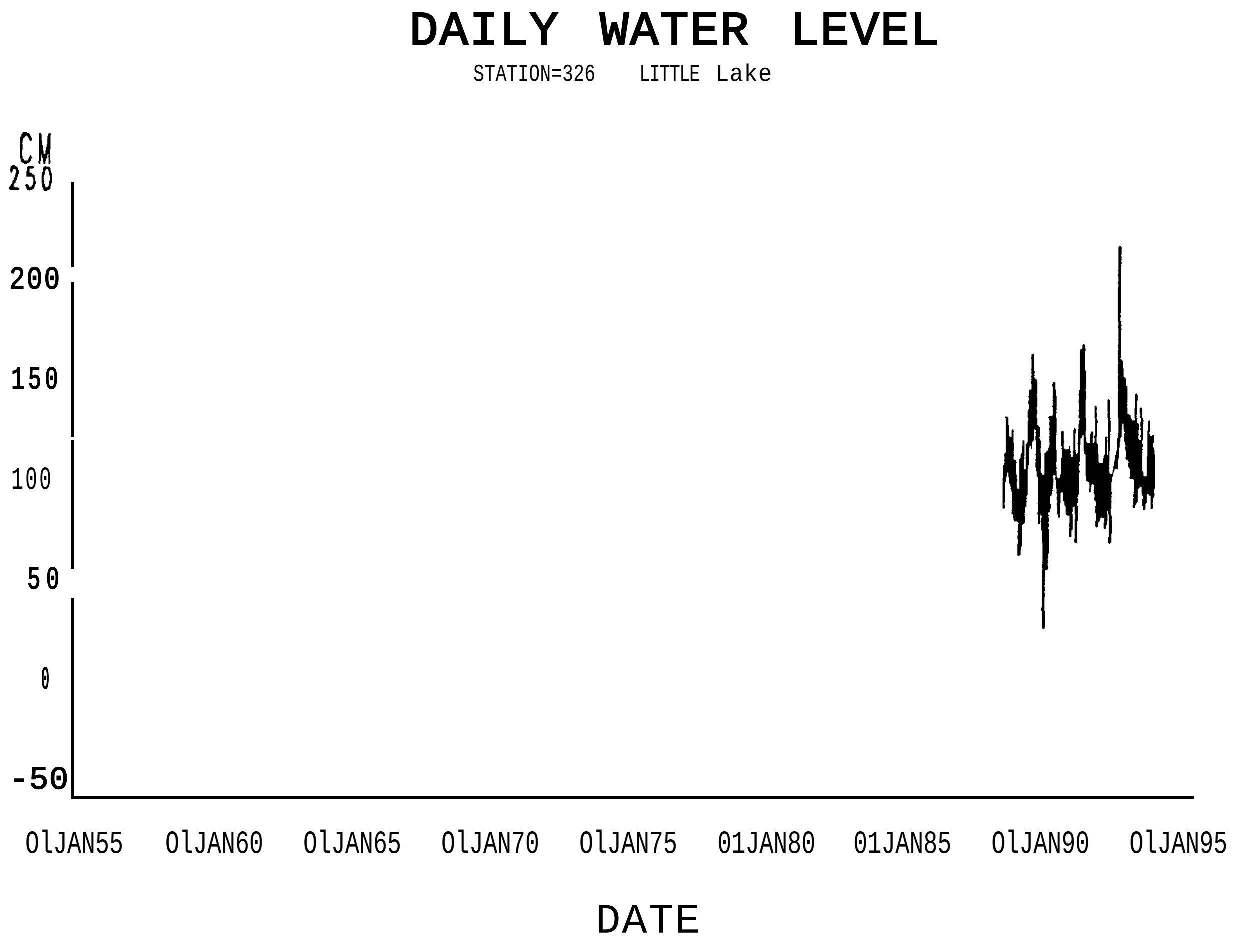
STATION=323 LAKE PALOURDE



DAILY WATER LEVEL

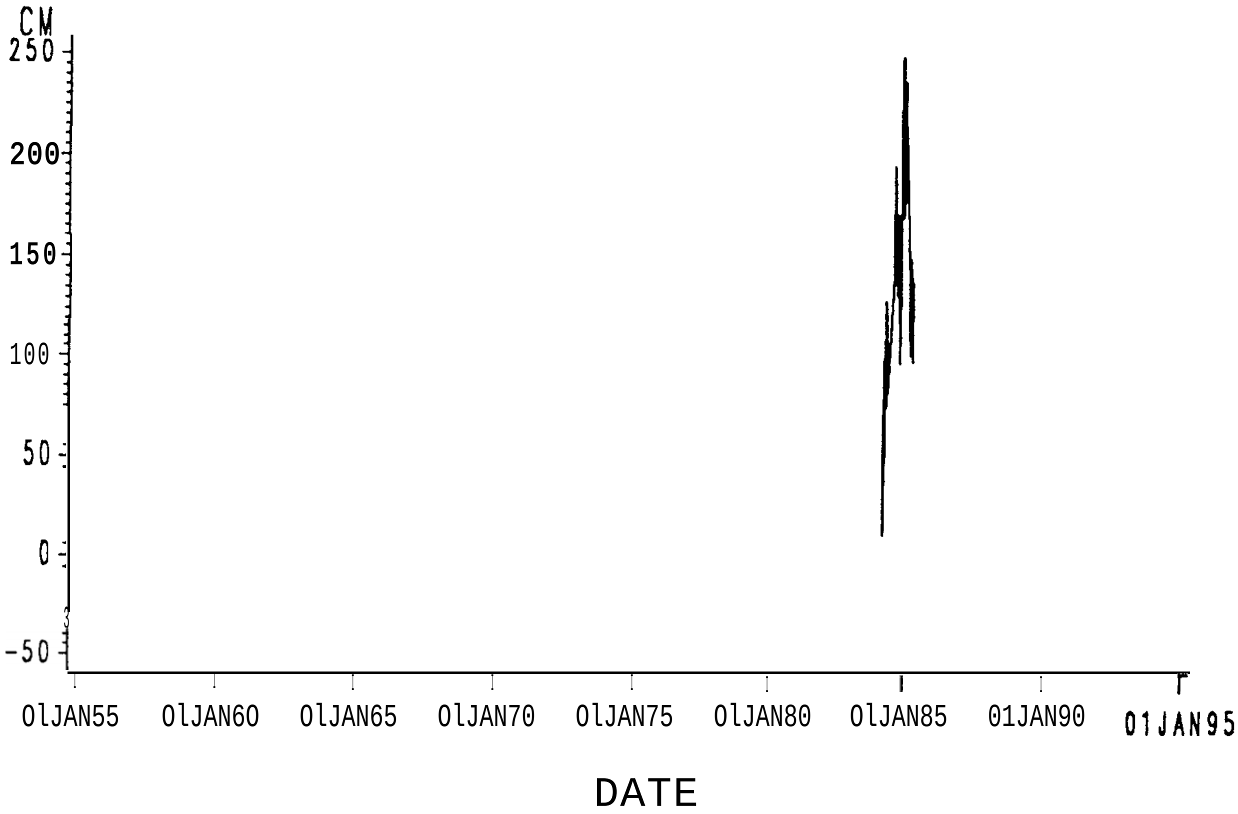
STATION=325 TENN. GAS CANAL




DAILY WATER LEVEL
STATION=326 LITTLE Lake
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

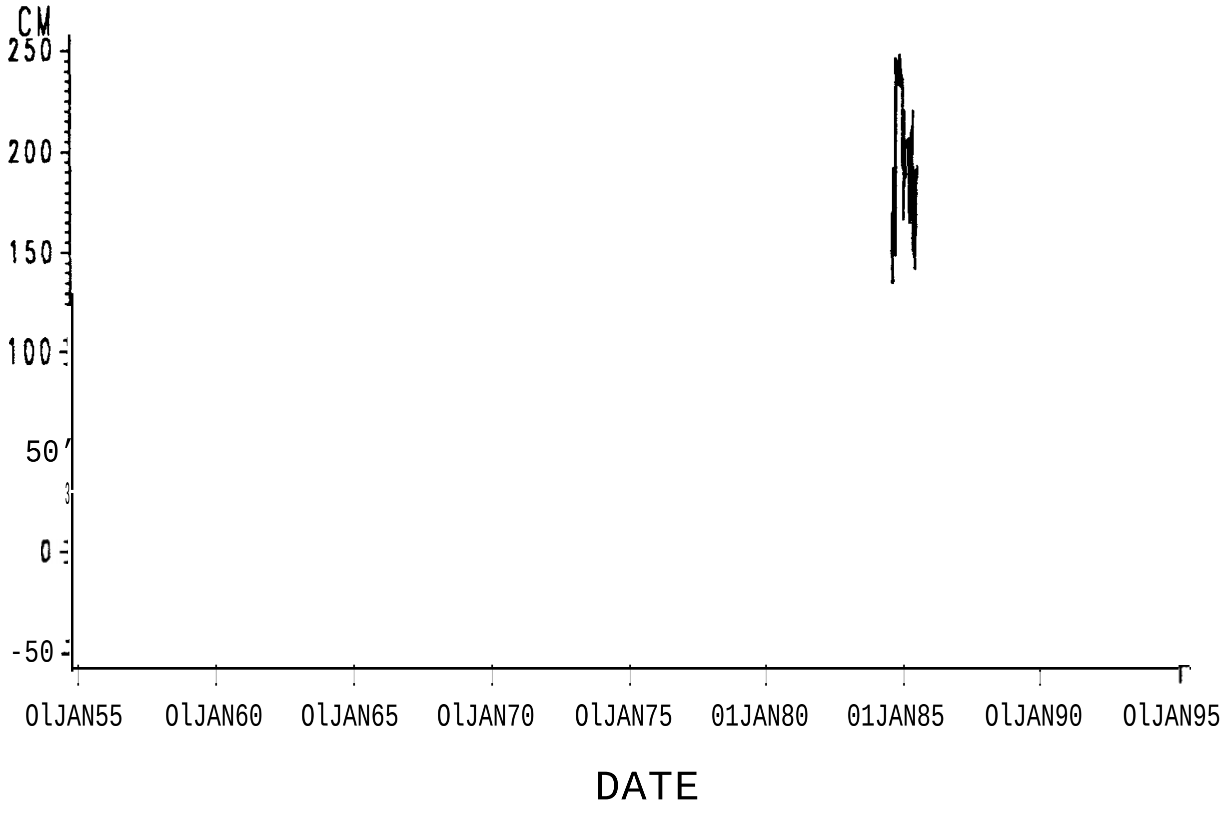
DAILY WATER LEVEL

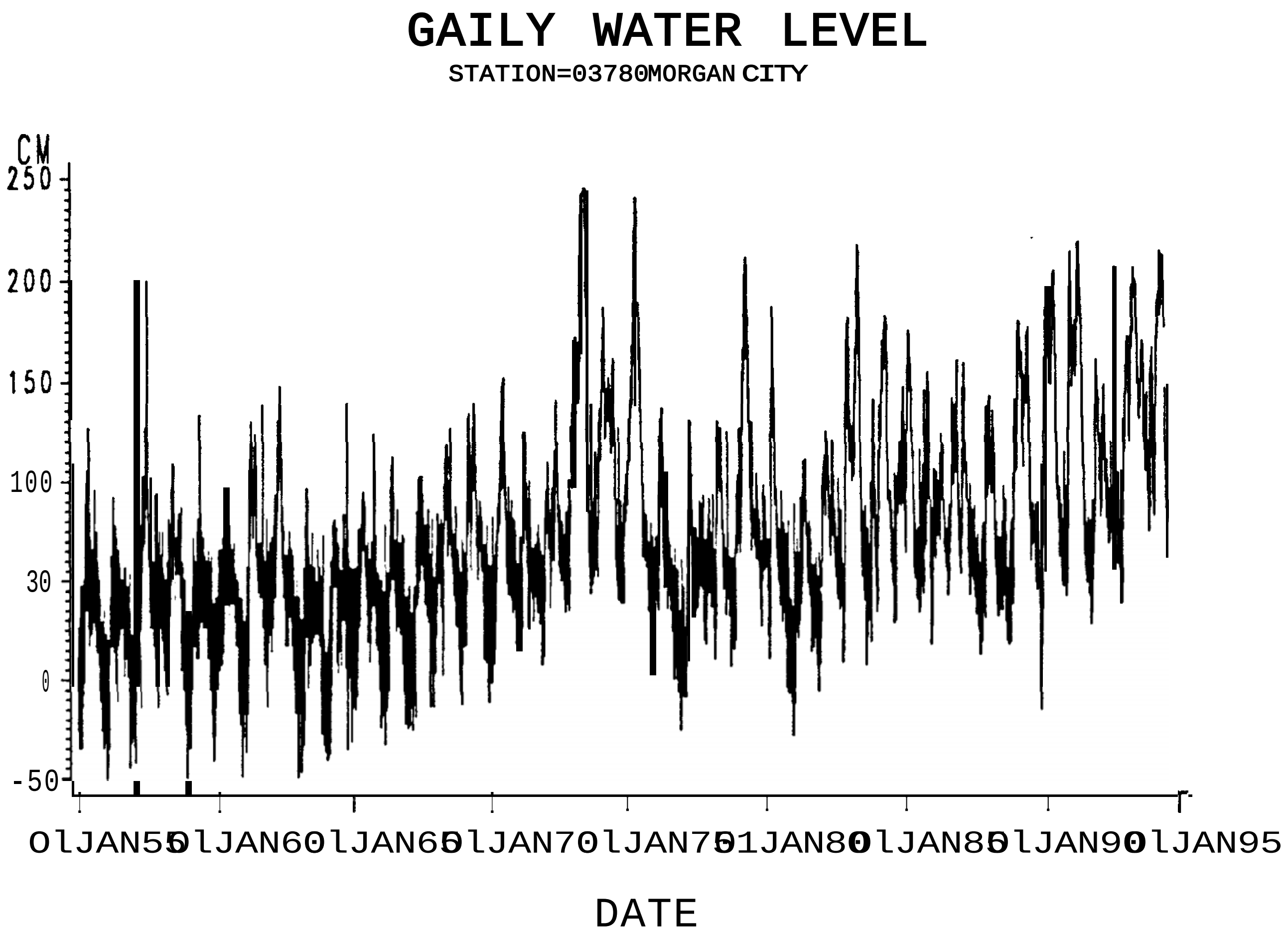
STATION=41 6 COCODRIE



DAILYWATER LEVEL

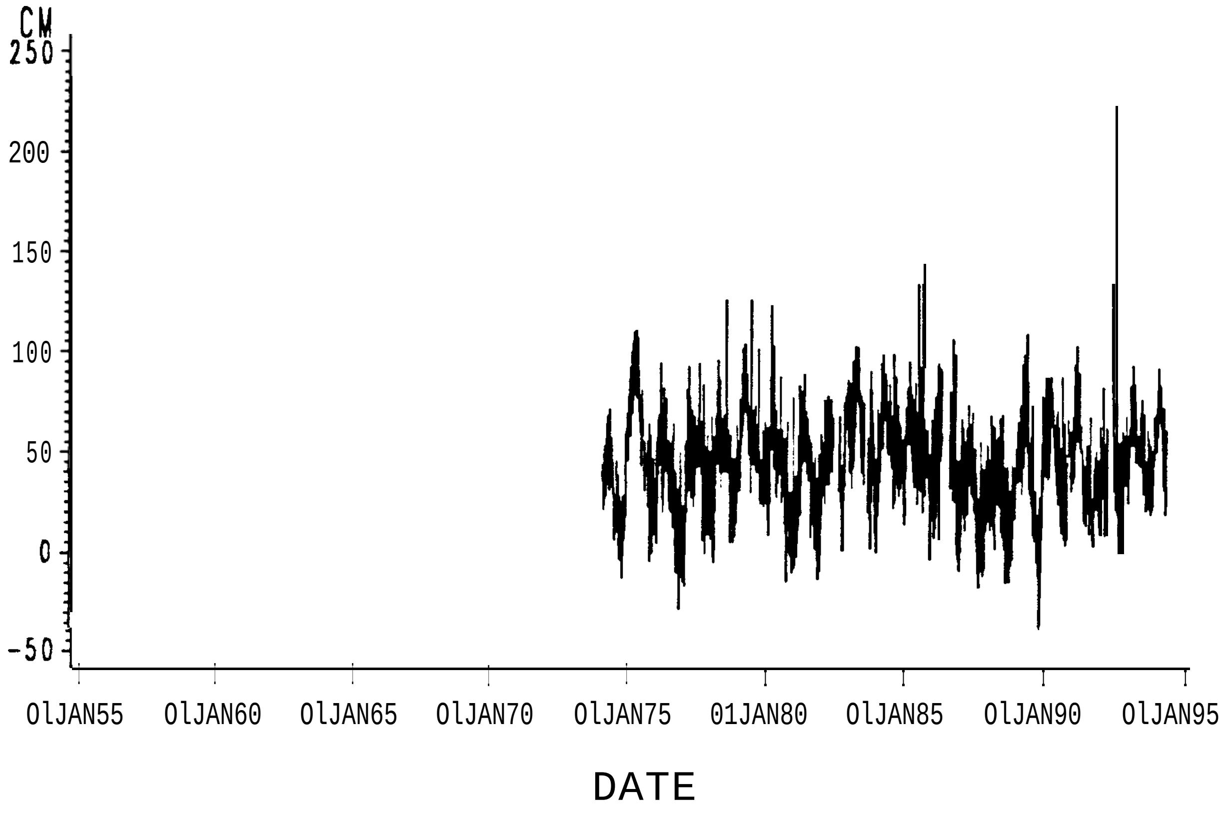
STATlON=518.lAKE MECHANT




GAILY WATER LEVEL
STATION=03780MORGAN CITY
CM
250
200
150
100
30
0
-50
OlJAN55 OlJAN60 OlJAN65 OlJAN70 OlJAN75 01JAN80 OlJAN85 OlJAN90 OlJAN95
DATE

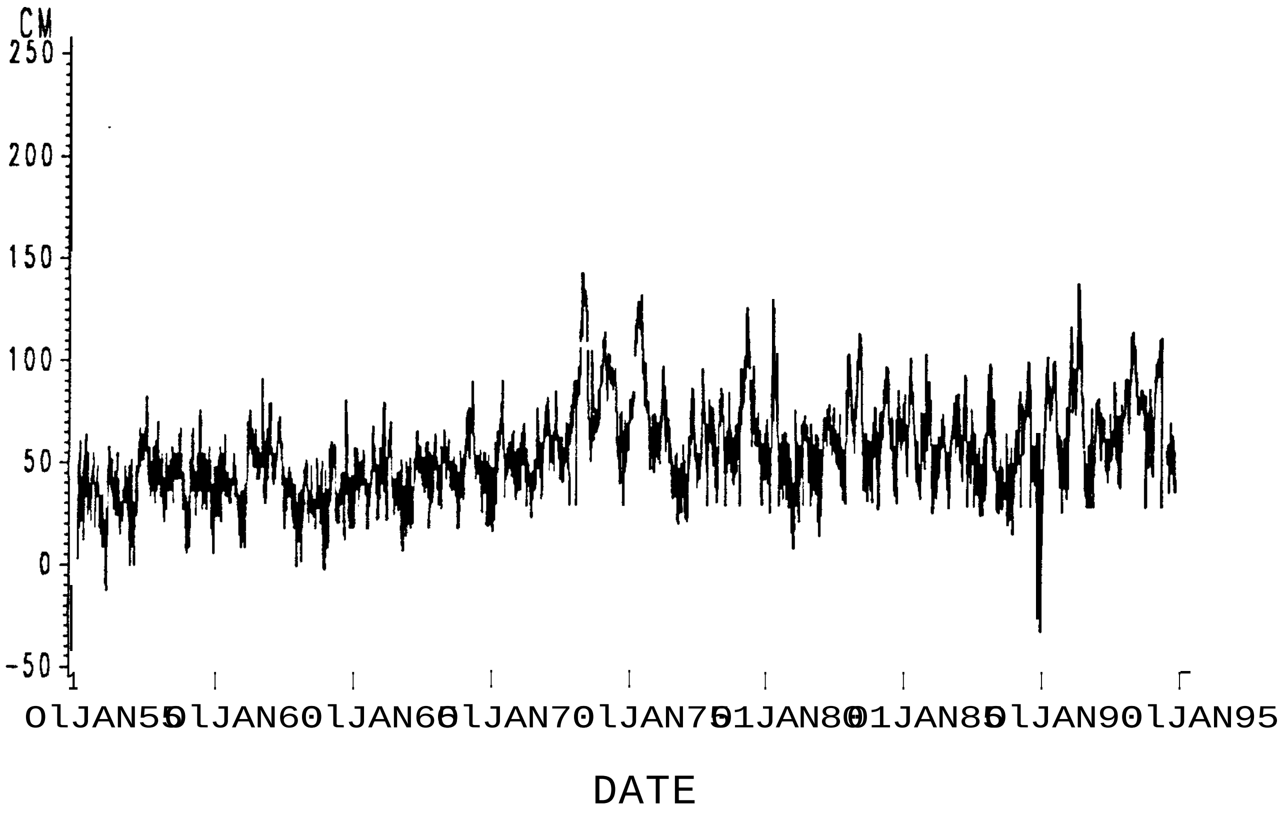
DAILY WATER LEVEL

!2TATlON=O3850DEERISLAND



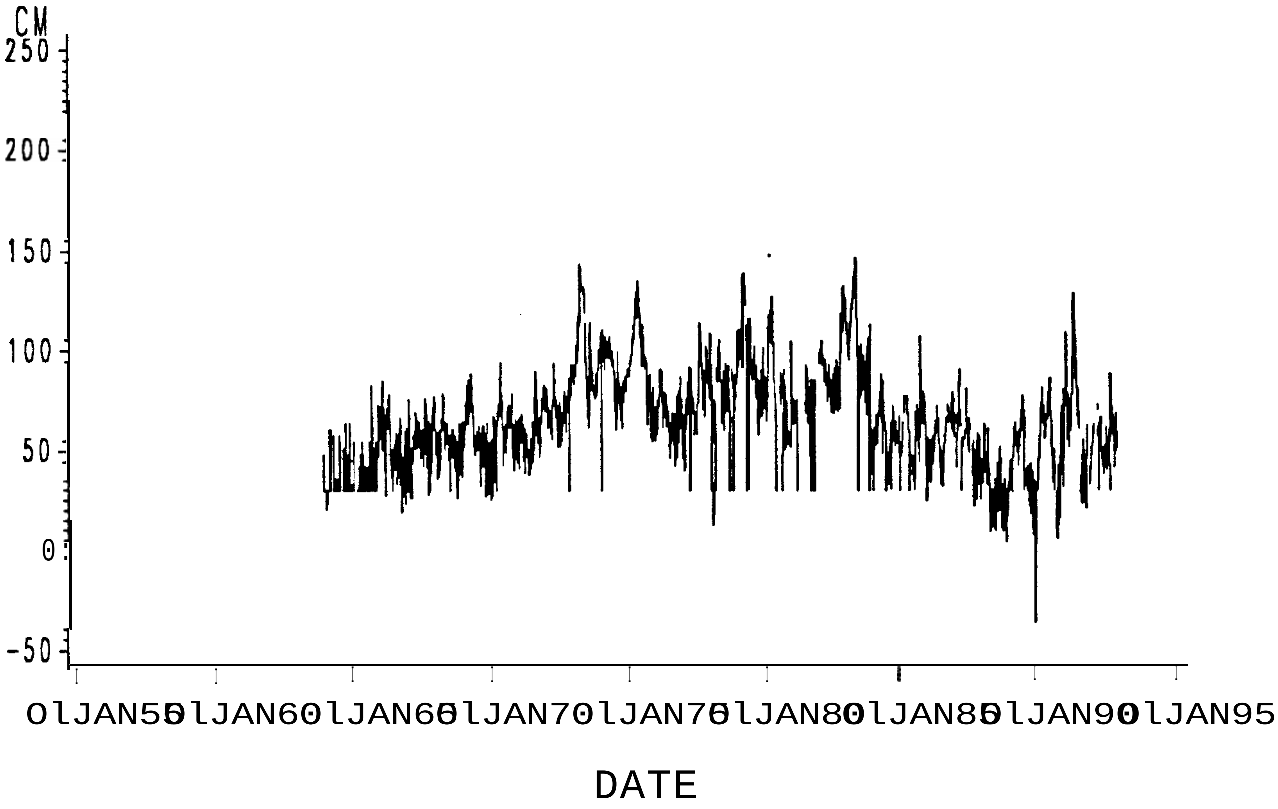
GAILY WATER LEVEL

STATION=52800 BAYOU BOEUF



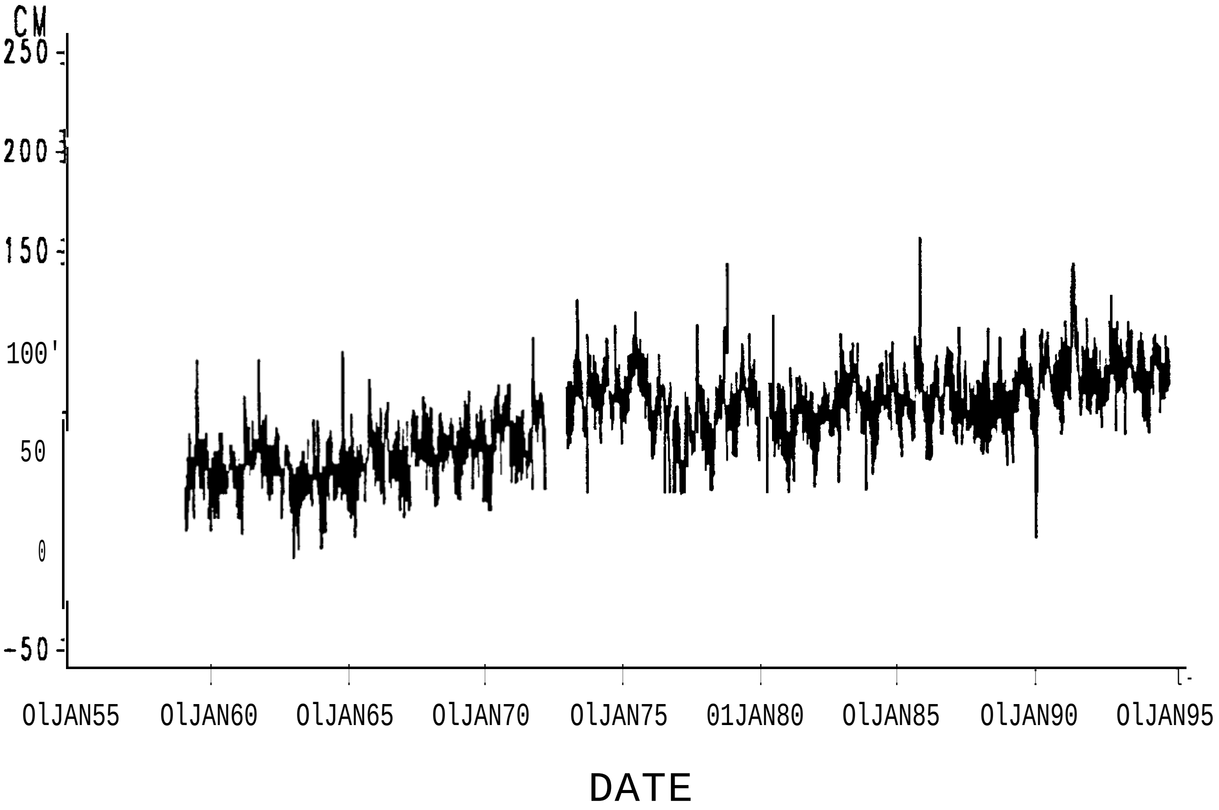
DAILY WATER LEVEL

STATION=52880 BAYOU BLACK



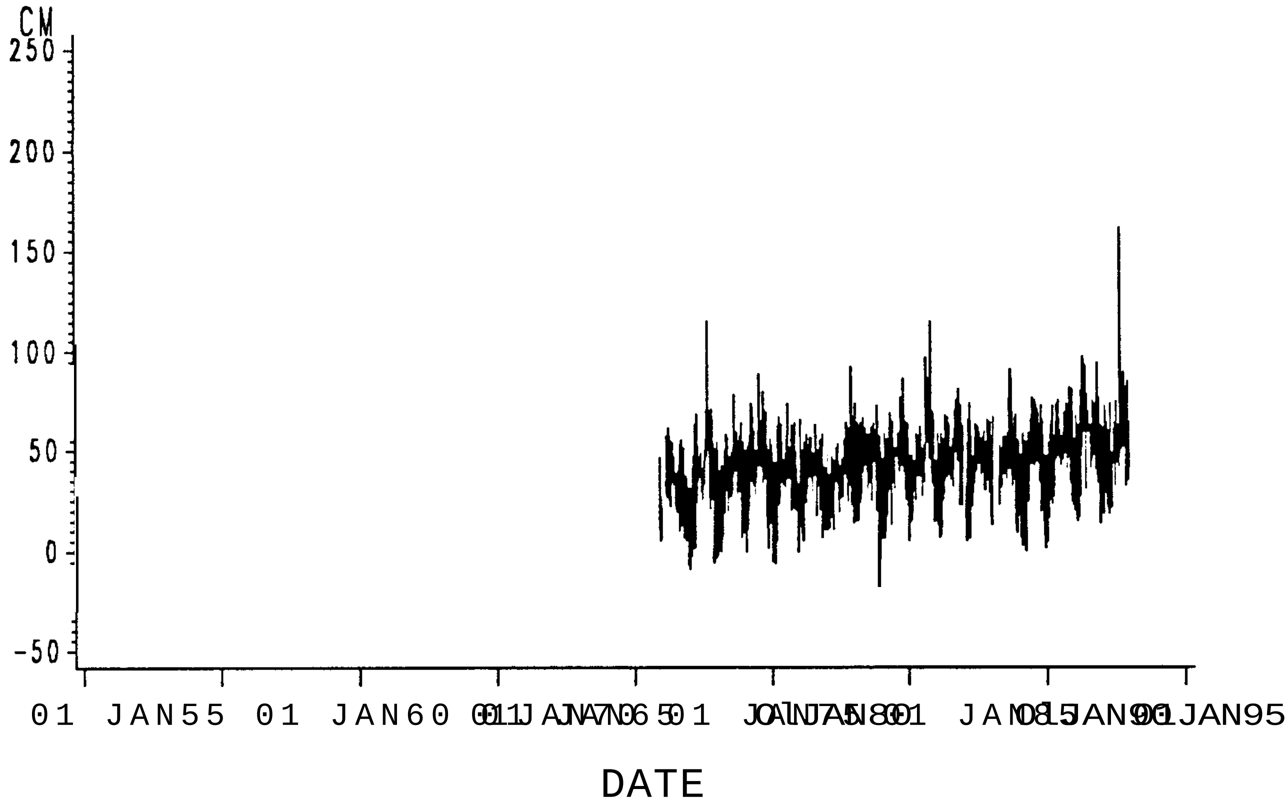
DAILY WATER LEVEL

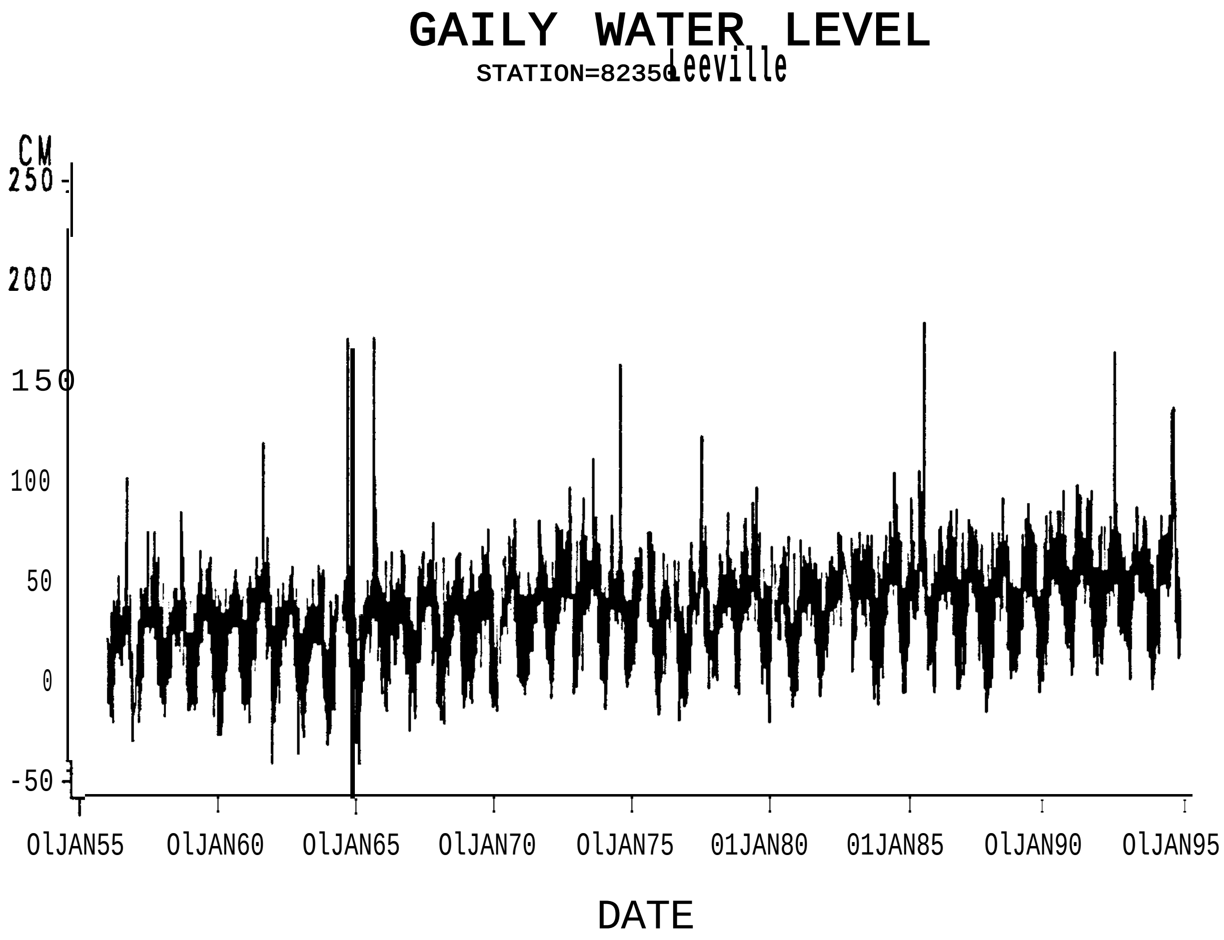
STATION=76320 IWW AT HOUMA



DAILY WATER LEVEL

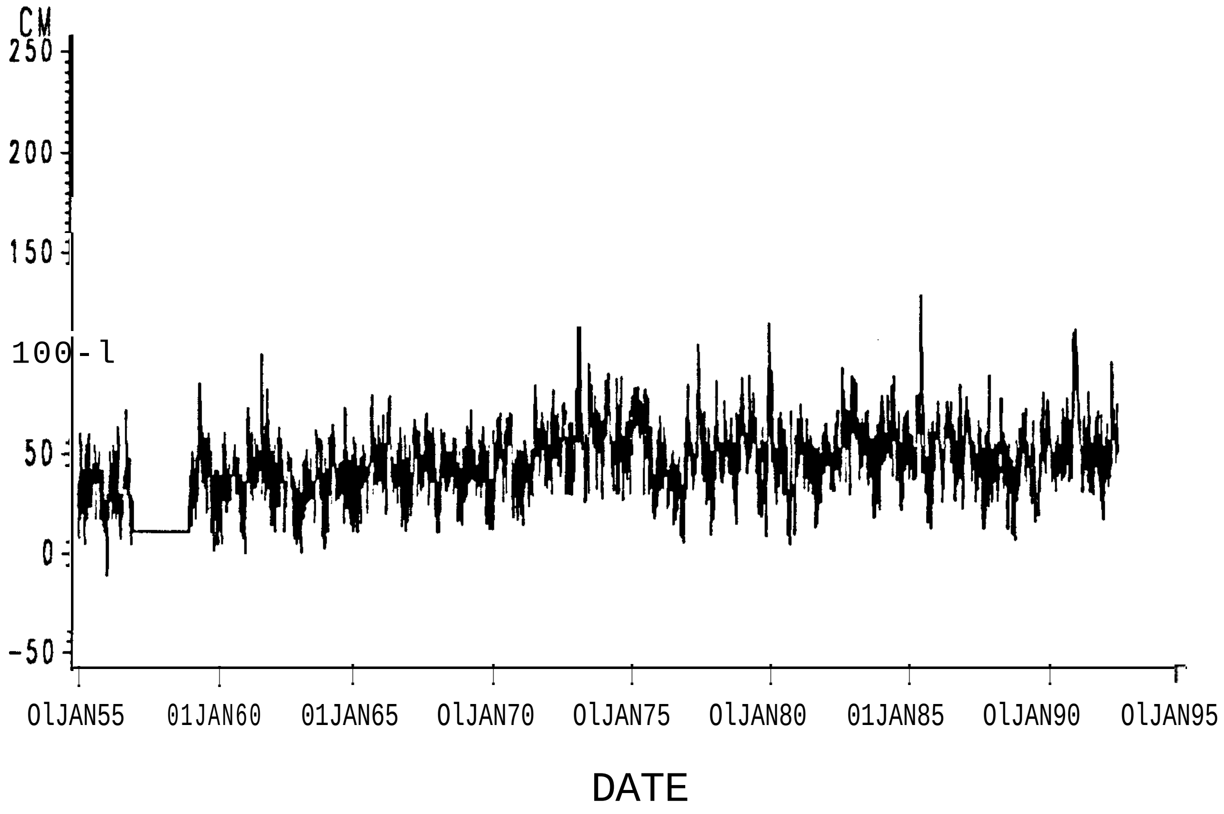
STATION=82301CATFISHLAKE

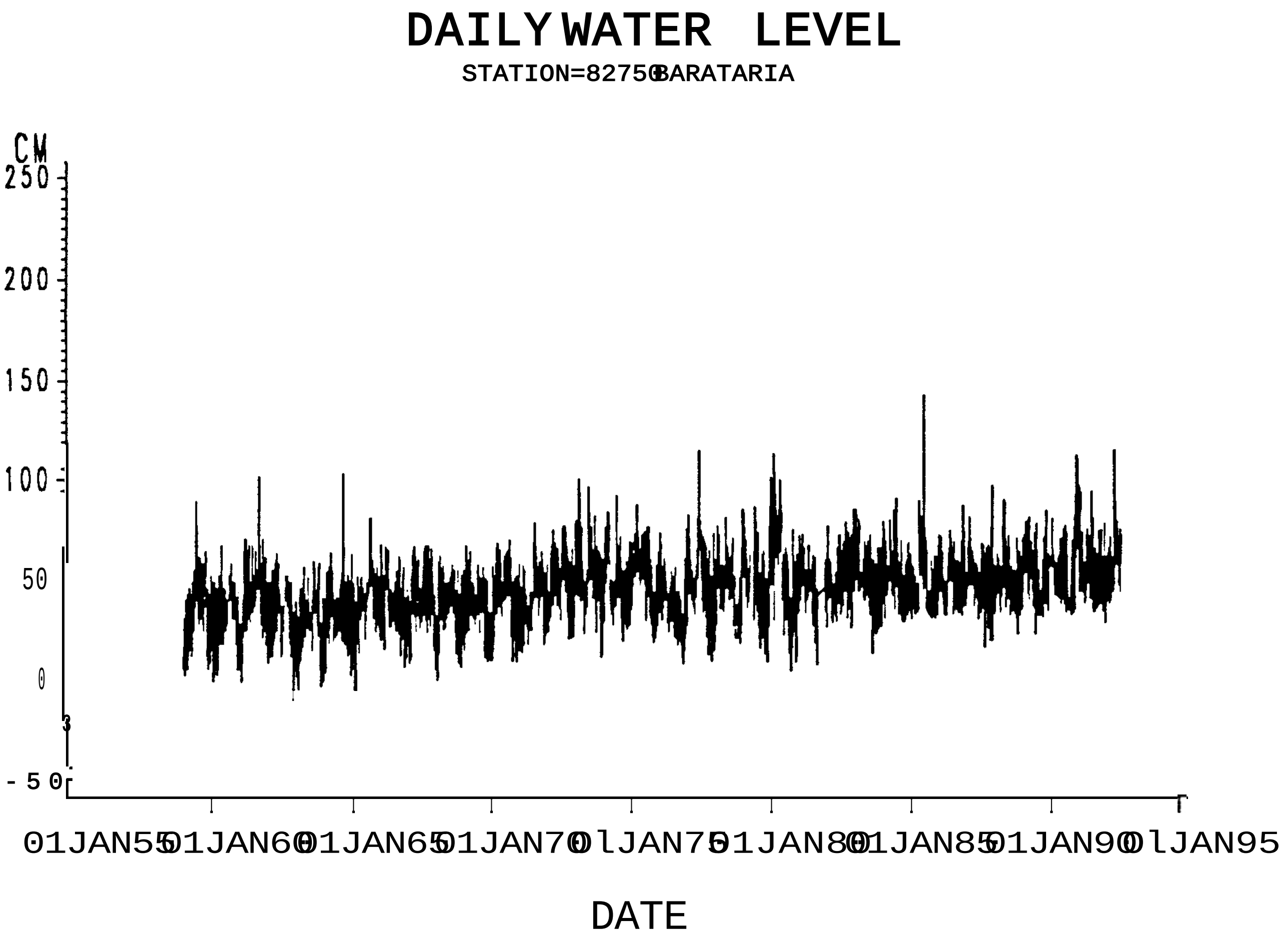



GAILY WATER LEVEL
STATION=82350 Leeville
CM
250
200
150
100
50
0
-50
OlJAN55
OlJAN60
OlJAN65
OlJAN70
OlJAN75
01JAN80
01JAN85
OlJAN90
OlJAN95
DATE

DAILY WATER LEVEL

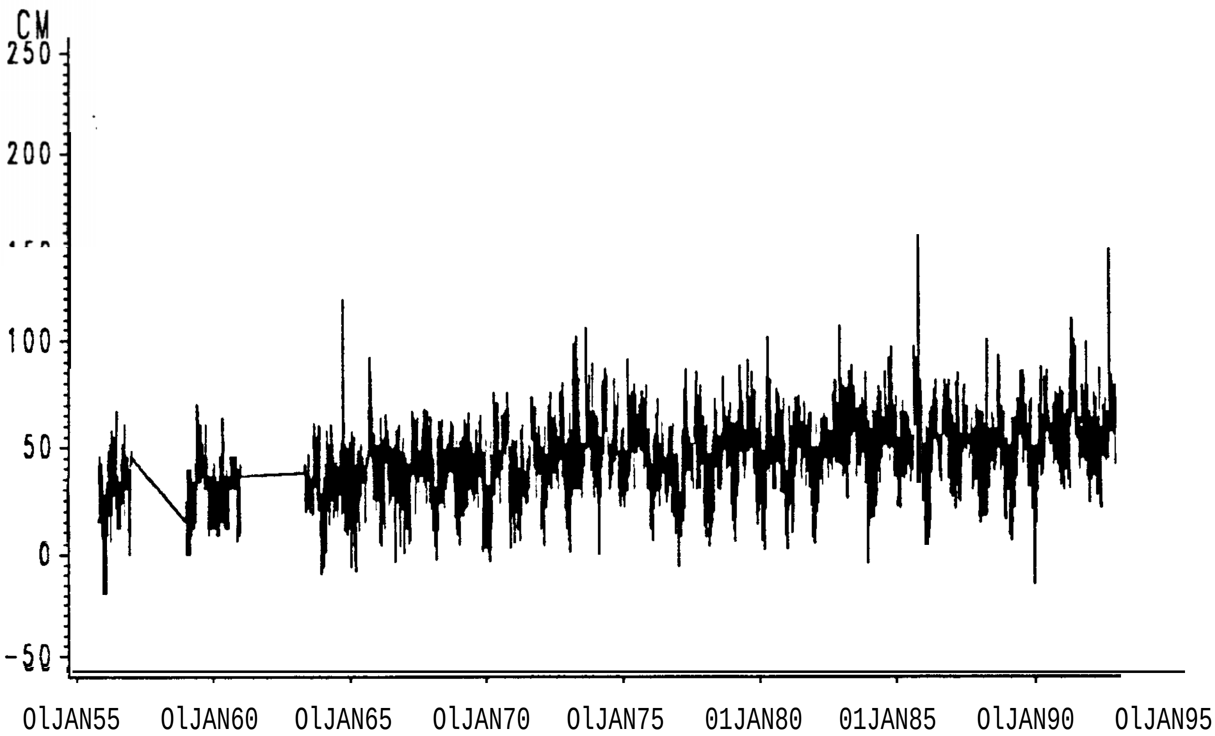
STATION=82700 DES ALLEMENDS




DAILY WATER LEVEL
STATION=82750 BARATARIA
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

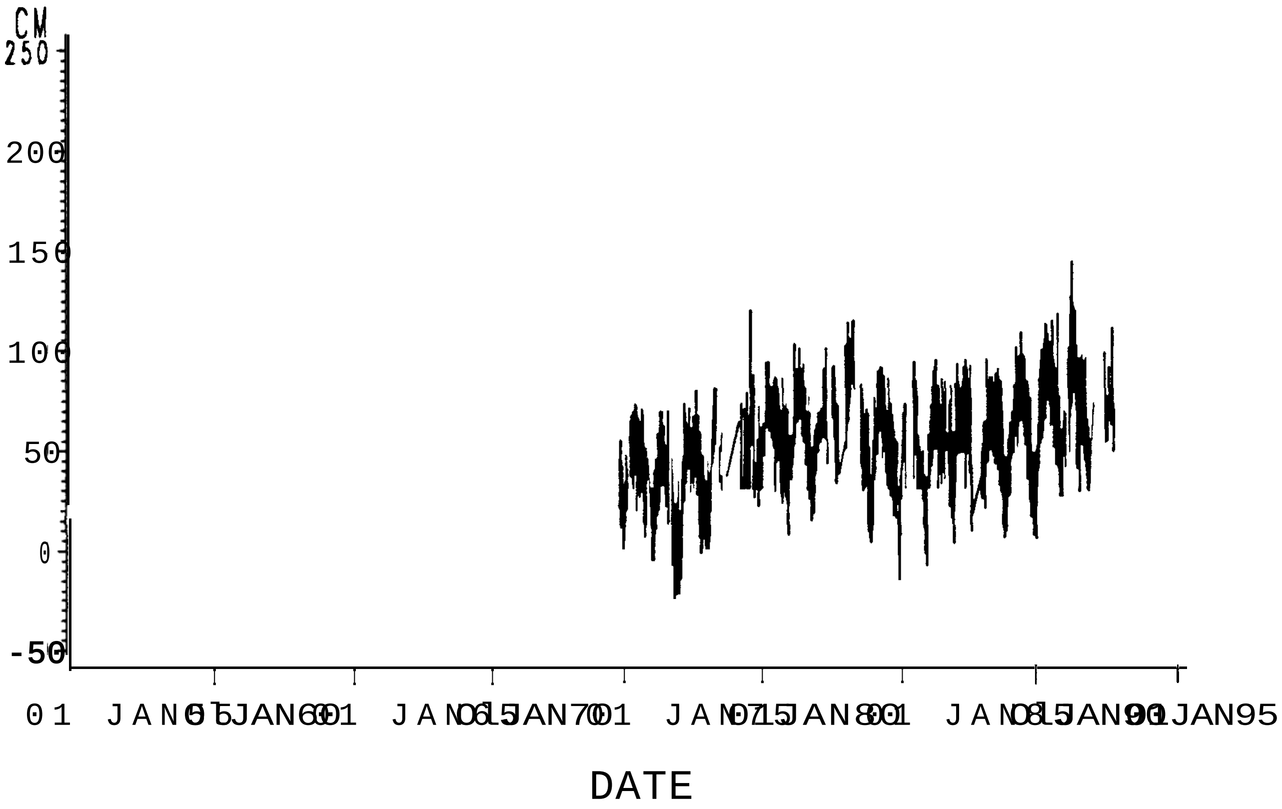
DAILY WATER LEVEL

STATION=82875 LAFITE



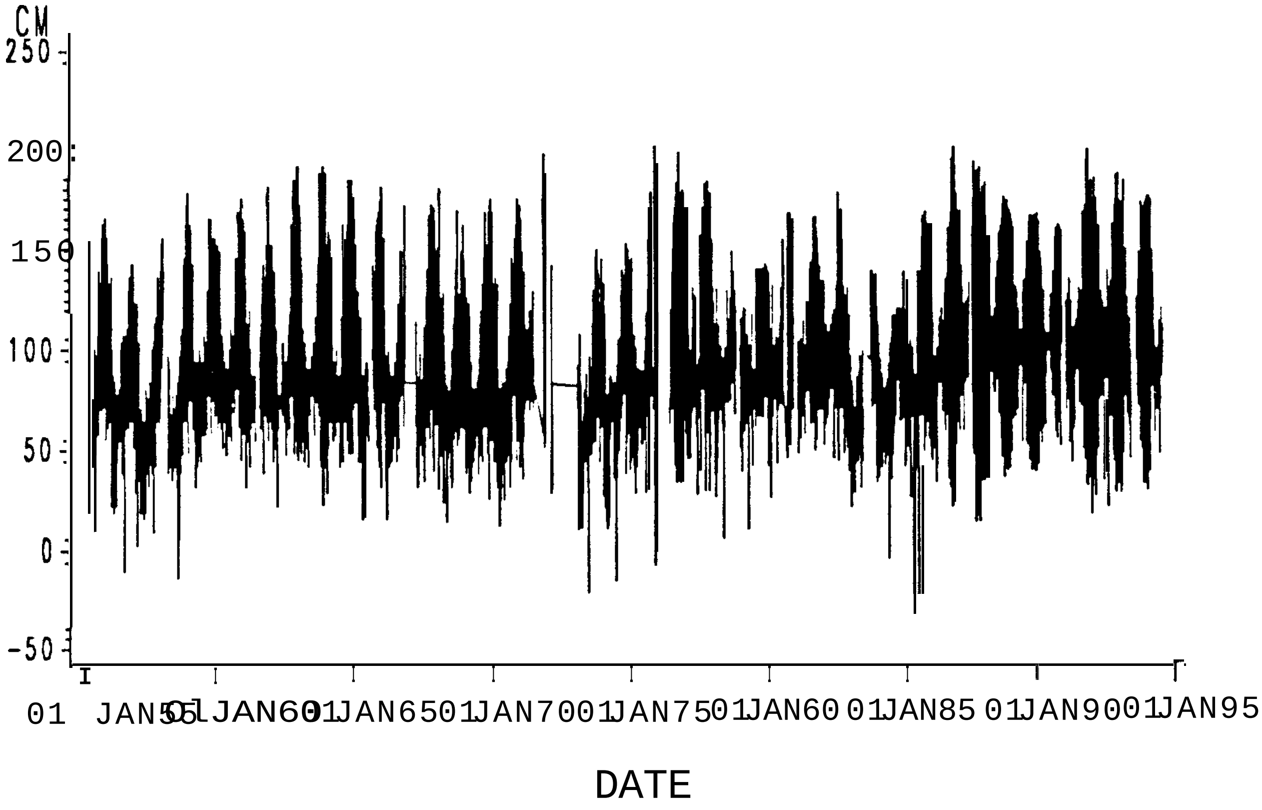
GAILY WATER LEVEL

!ZTAllON=88350 BAY



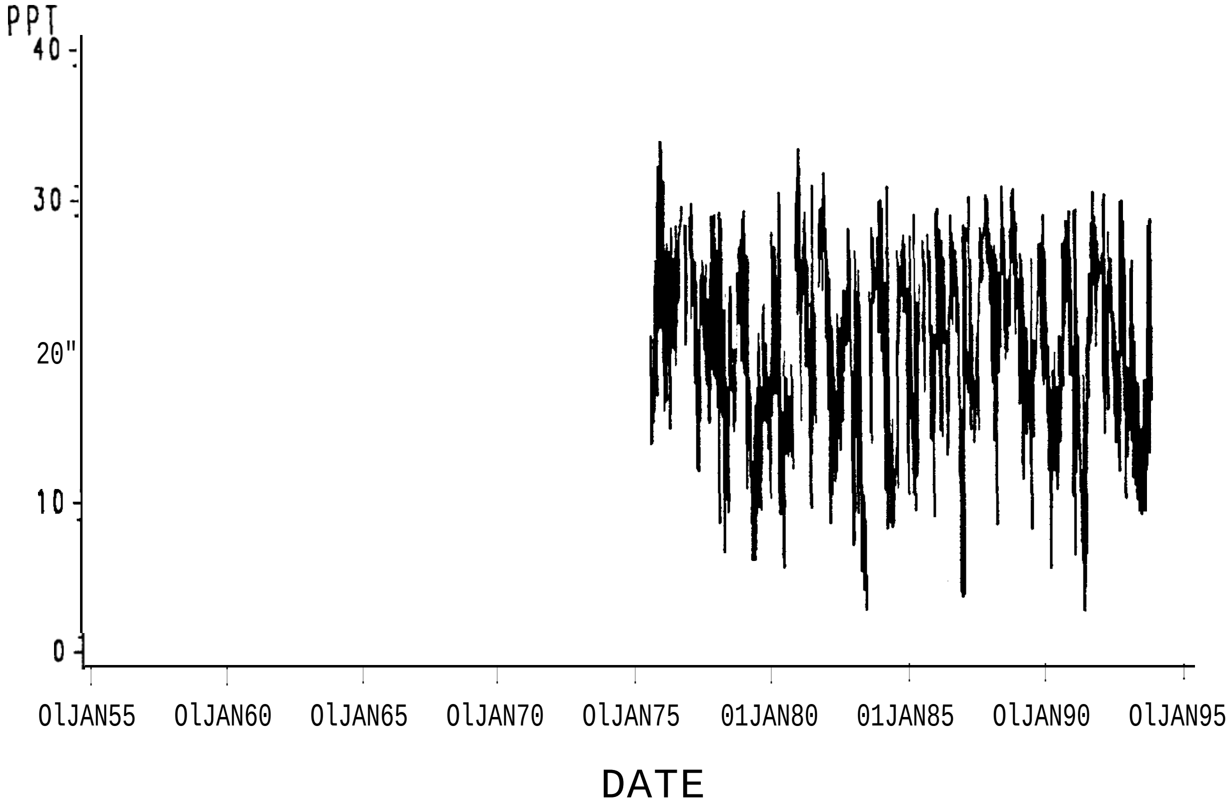
DAILY WATER LEVEL

STATION=66600 EUGENE ISLAND



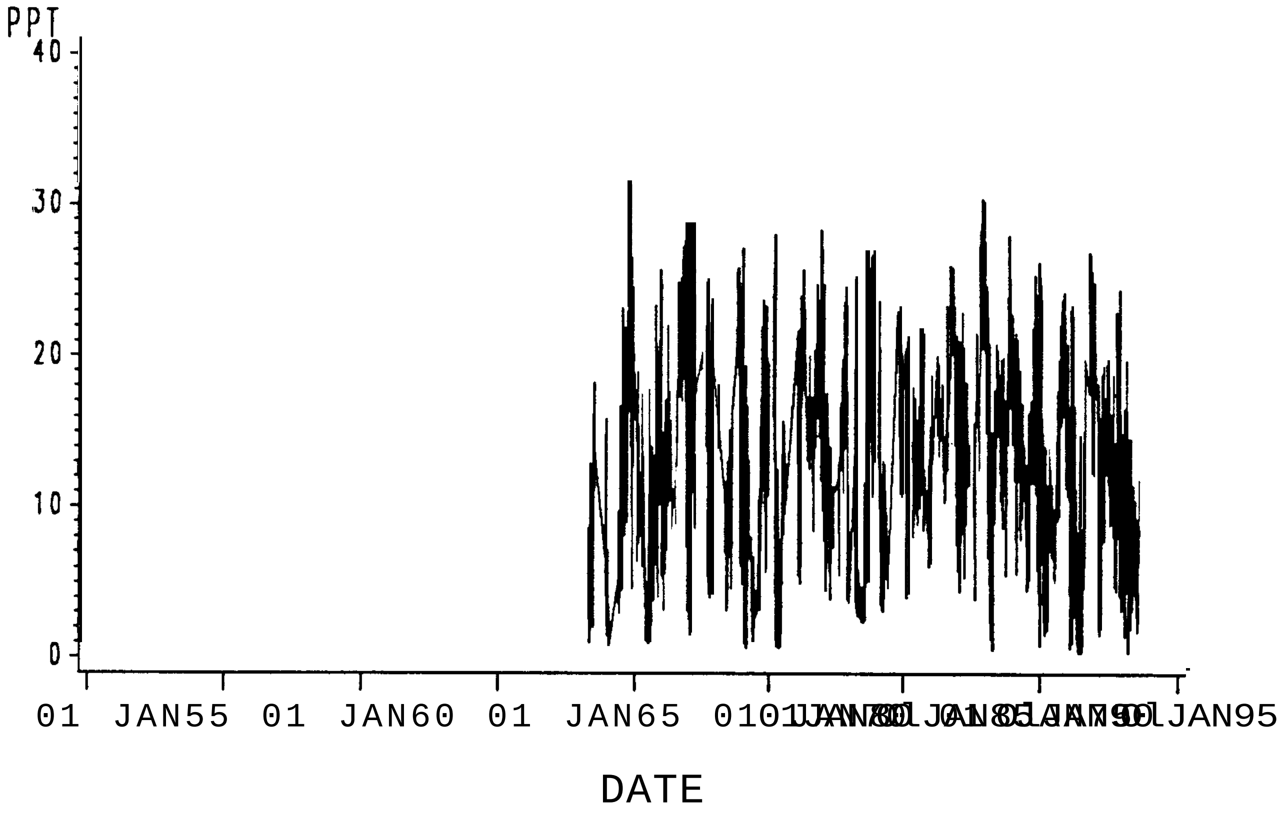
DAILY SALINITY

STATION=31 5 GRAND TERRE



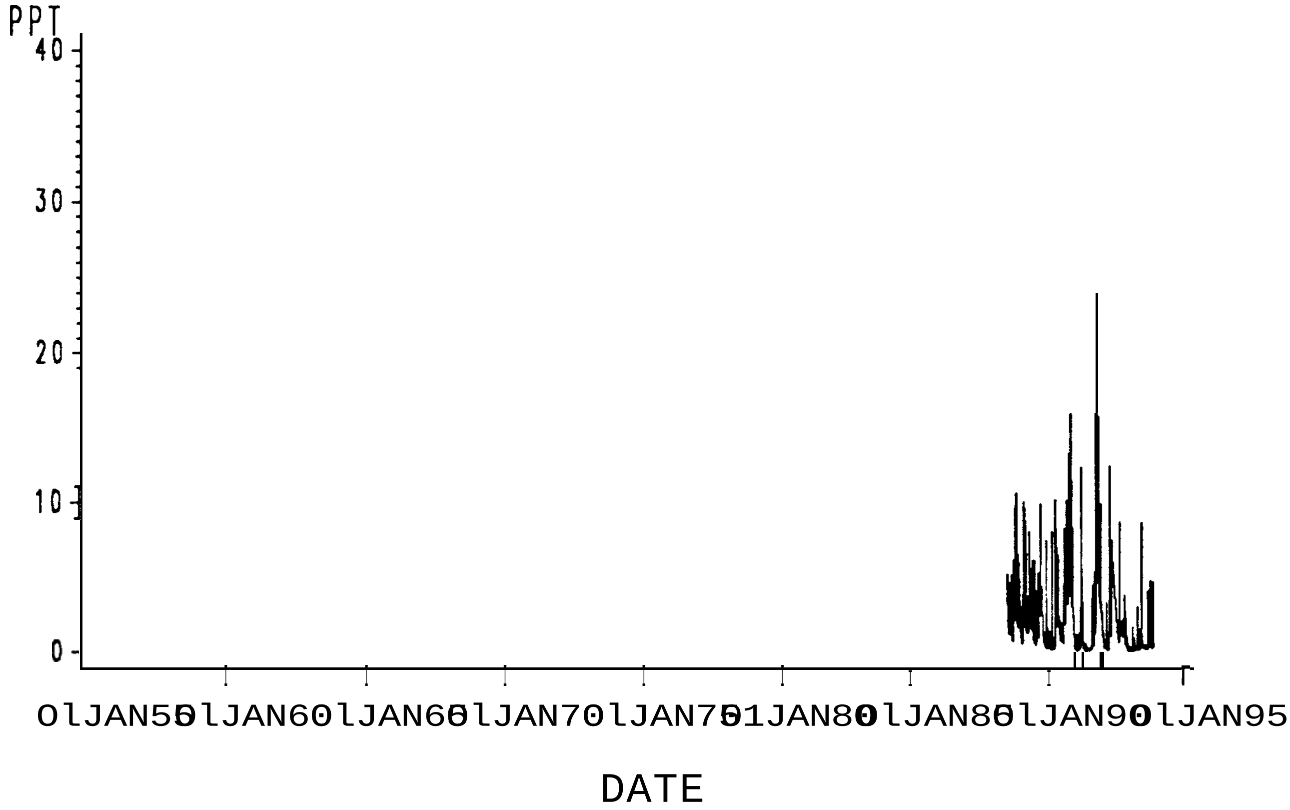
DAILY SALINITY

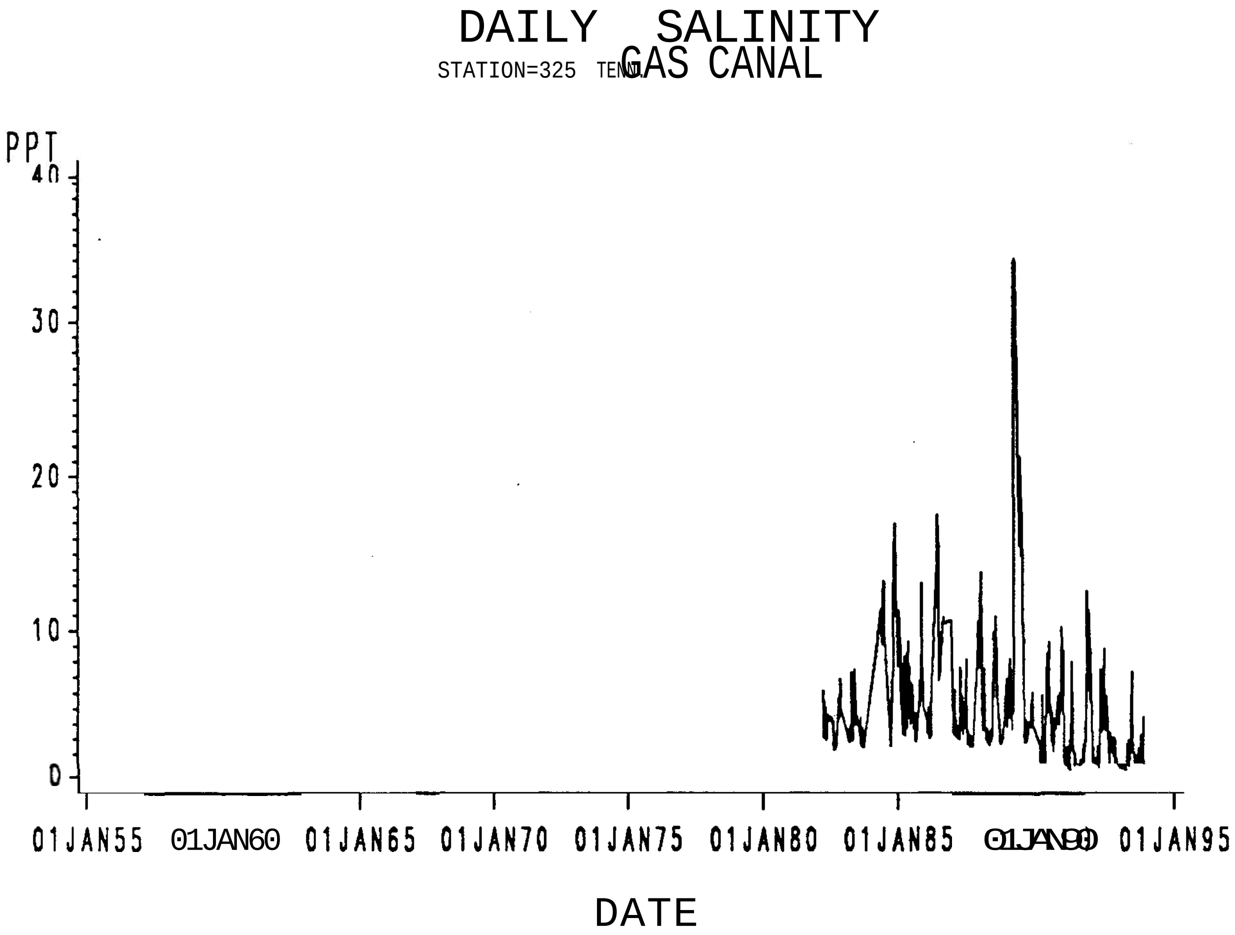
Station=31 STMARYS PT.



DAILY SALINITY

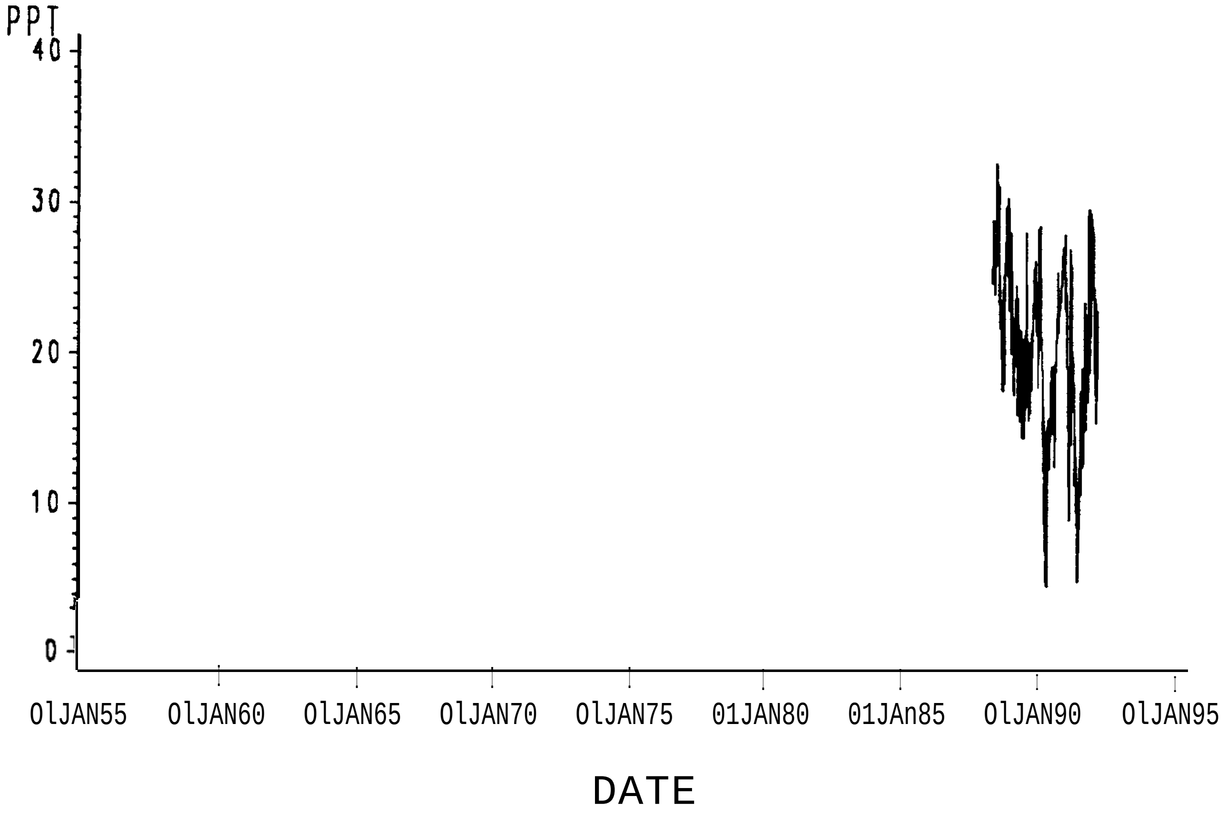
STATION=326 LITTLE LAKE




DAILY SALINITY
STATION=325 TEN
GAS CANAL
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

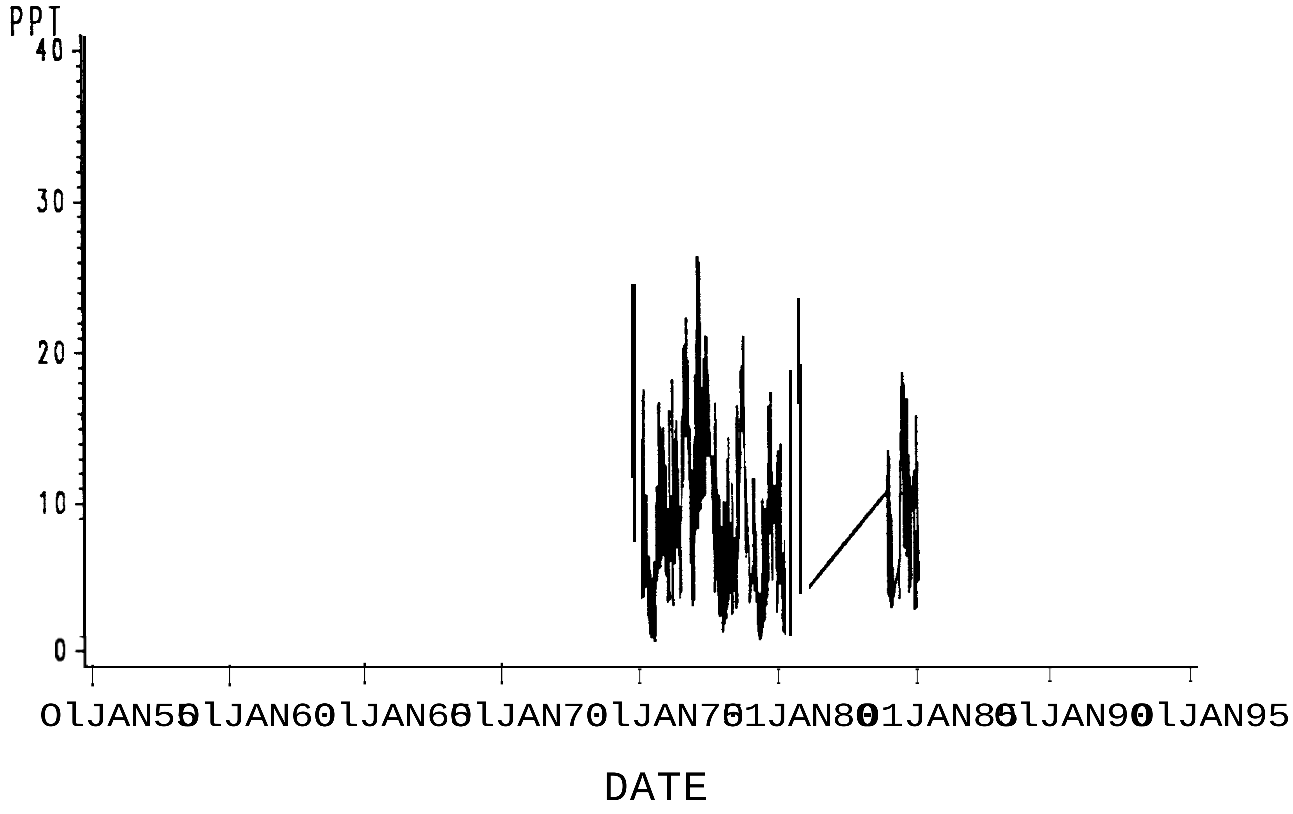
DAILY SALINITY

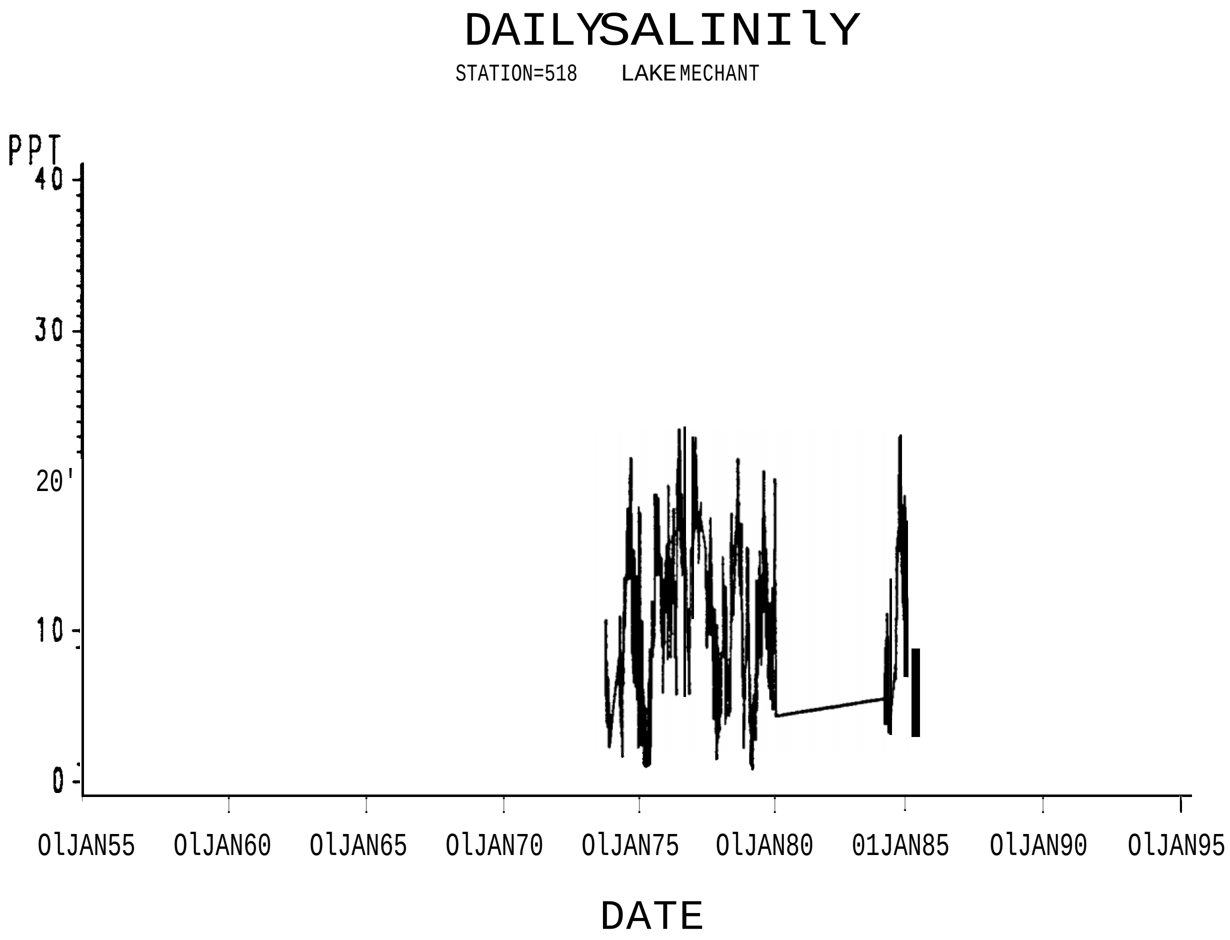
STATION=323 LAKE PALOLJRDE



DAILY SALINITY

STATION=41 6 COCODRIE




DAILY SALINITY
STATION=518 LAKE MECHANT
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
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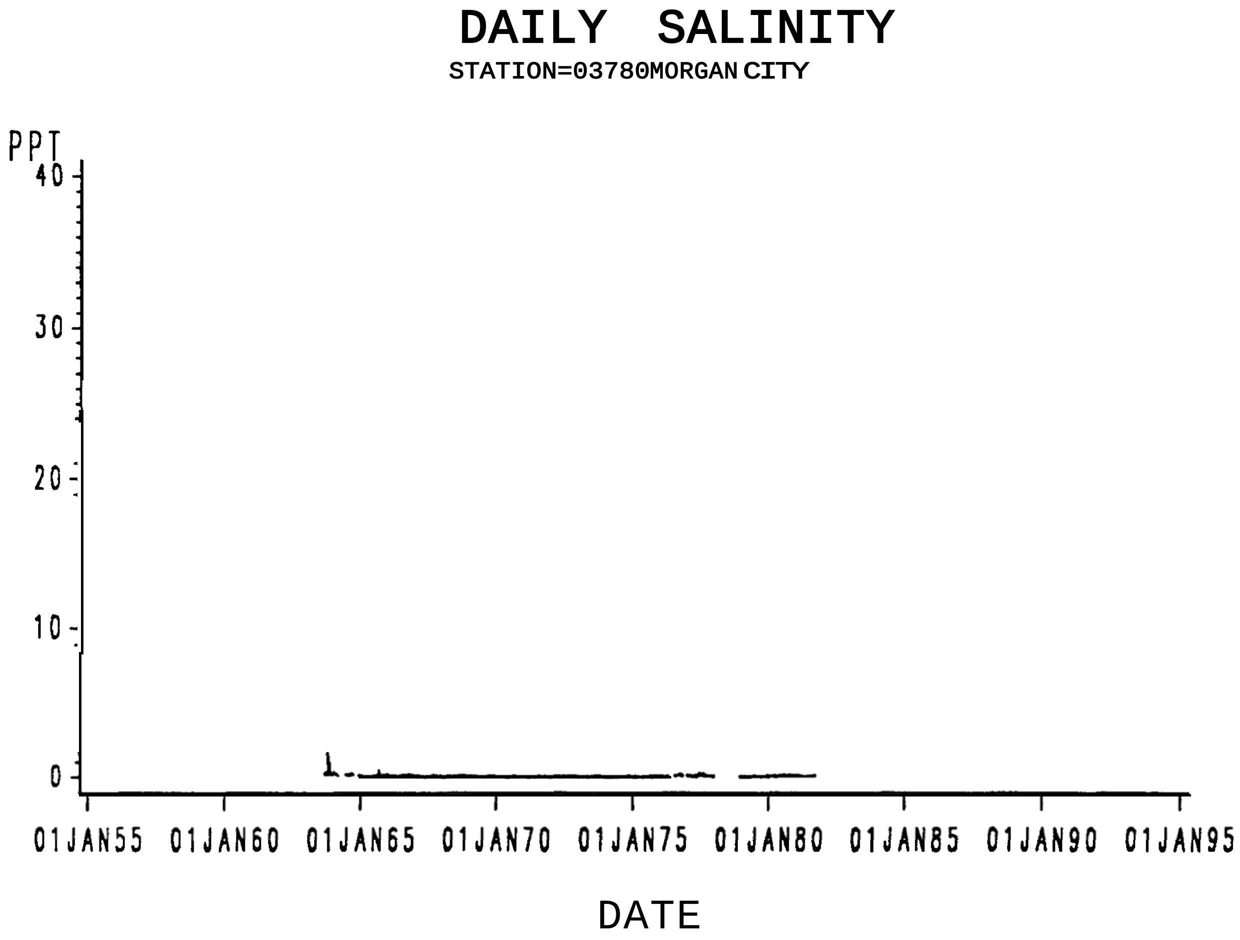
01JAN85
01JAN90
01JAN95
DATE


DAILY SALINITY
STATION=03780MORGAN CITY
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
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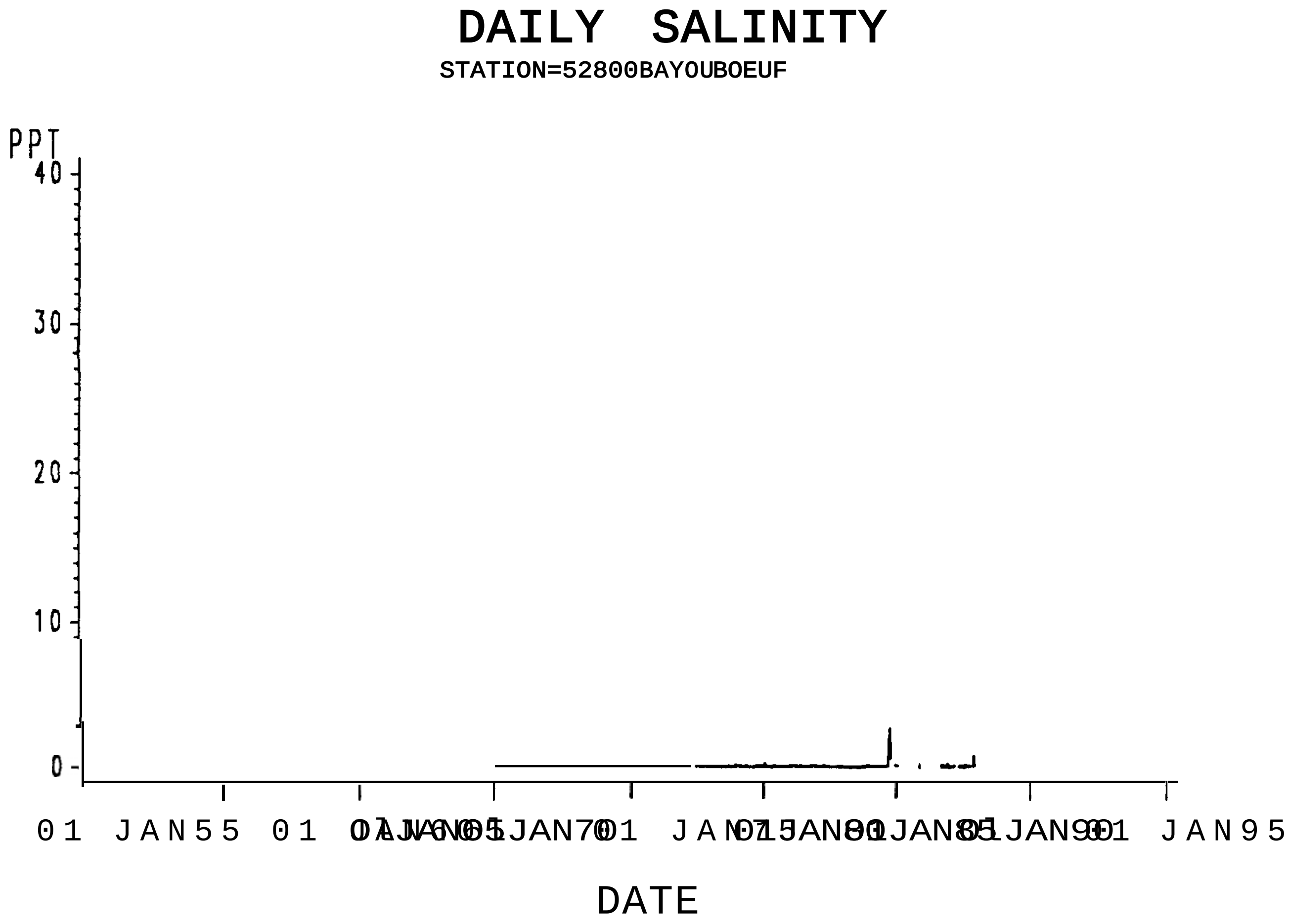
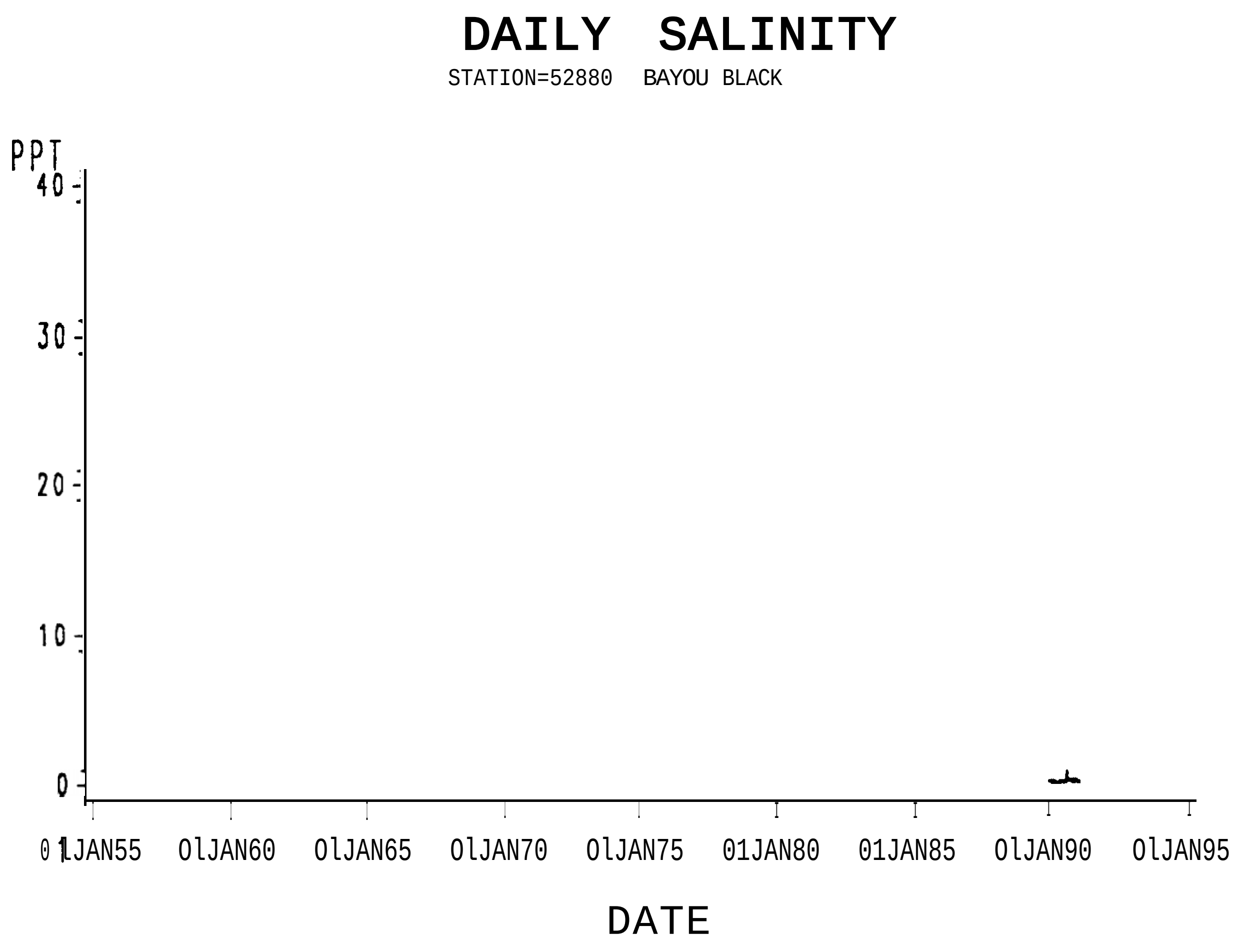
01JAN85
01JAN90
01JAN95
DATE

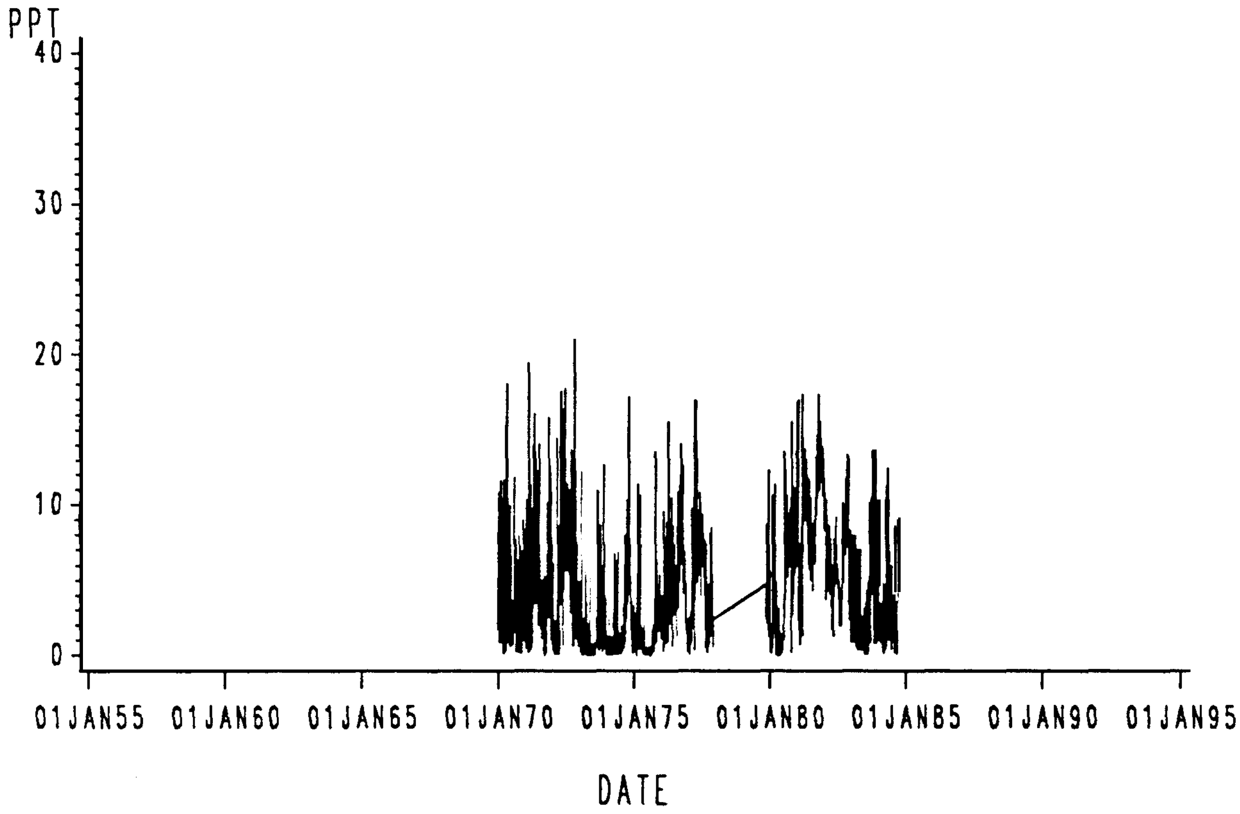

DAILY SALINITY
STATION=52800BAYOUBOEUF
PPT
40
30
20
10
0
01 JAN55
01 JAN60
01 JAN65
01 JAN70
01 JAN75
01 JAN80
01 JAN85
01 JAN90
01 JAN95
DATE



DAILY SALINITY
STATION=52880 BAYOU BLACK
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

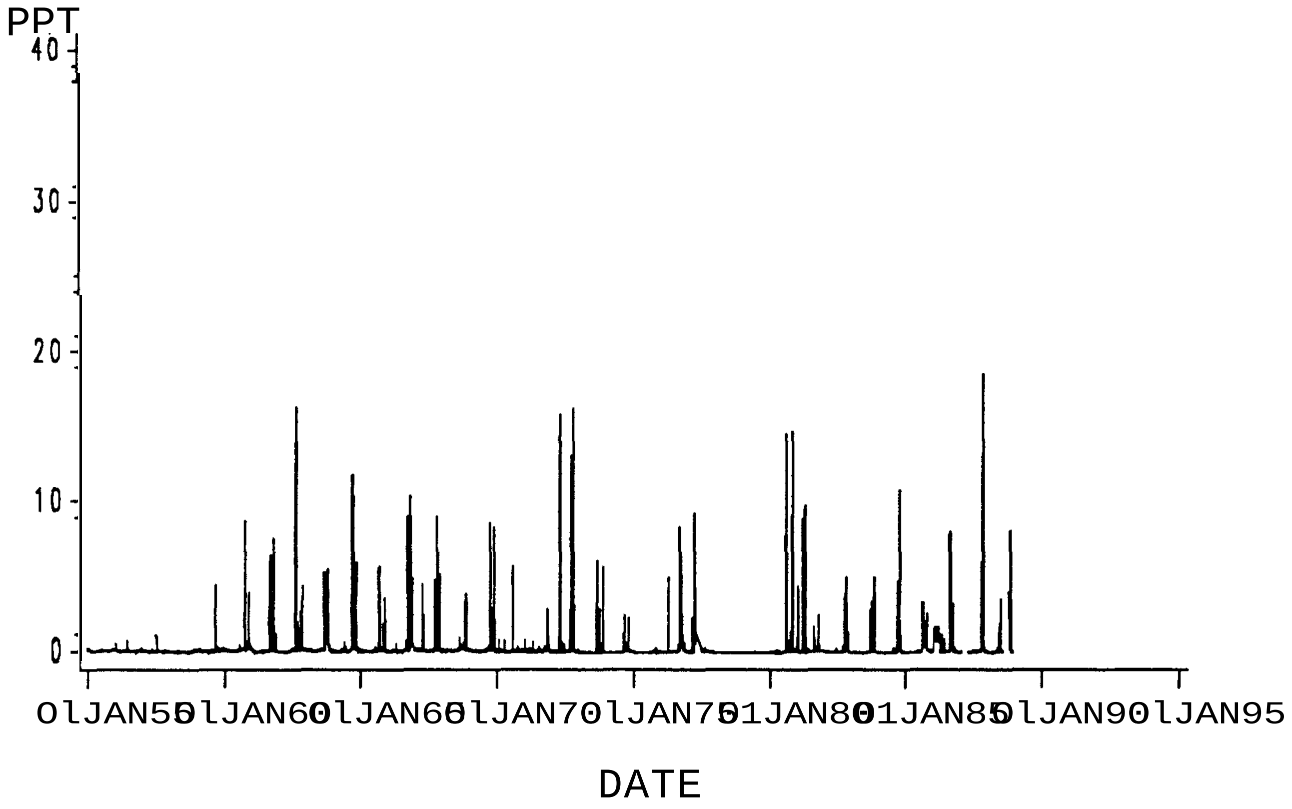
DAILY SALINITY

STATION=76303 BAYOU PETITE CAILLOU



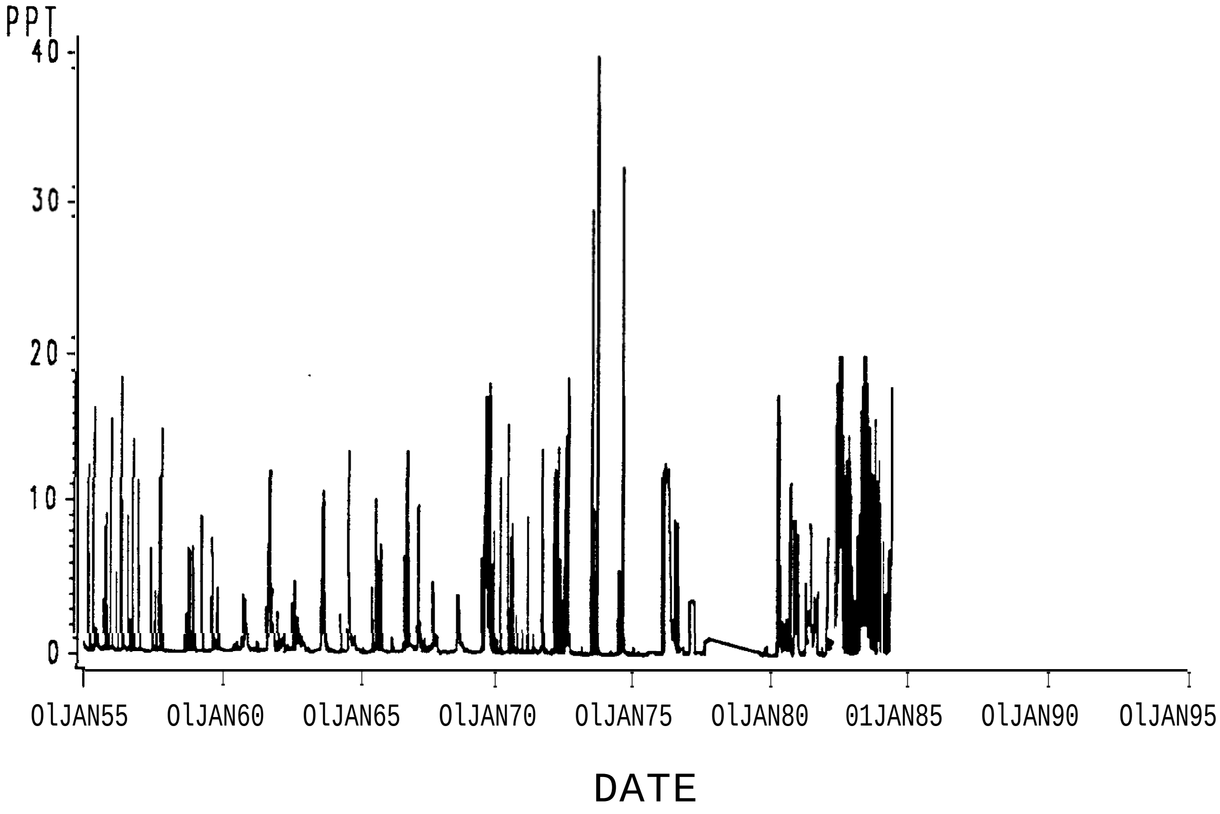
DAILY SALINITY

STATION=76320IWW AT HOUMA



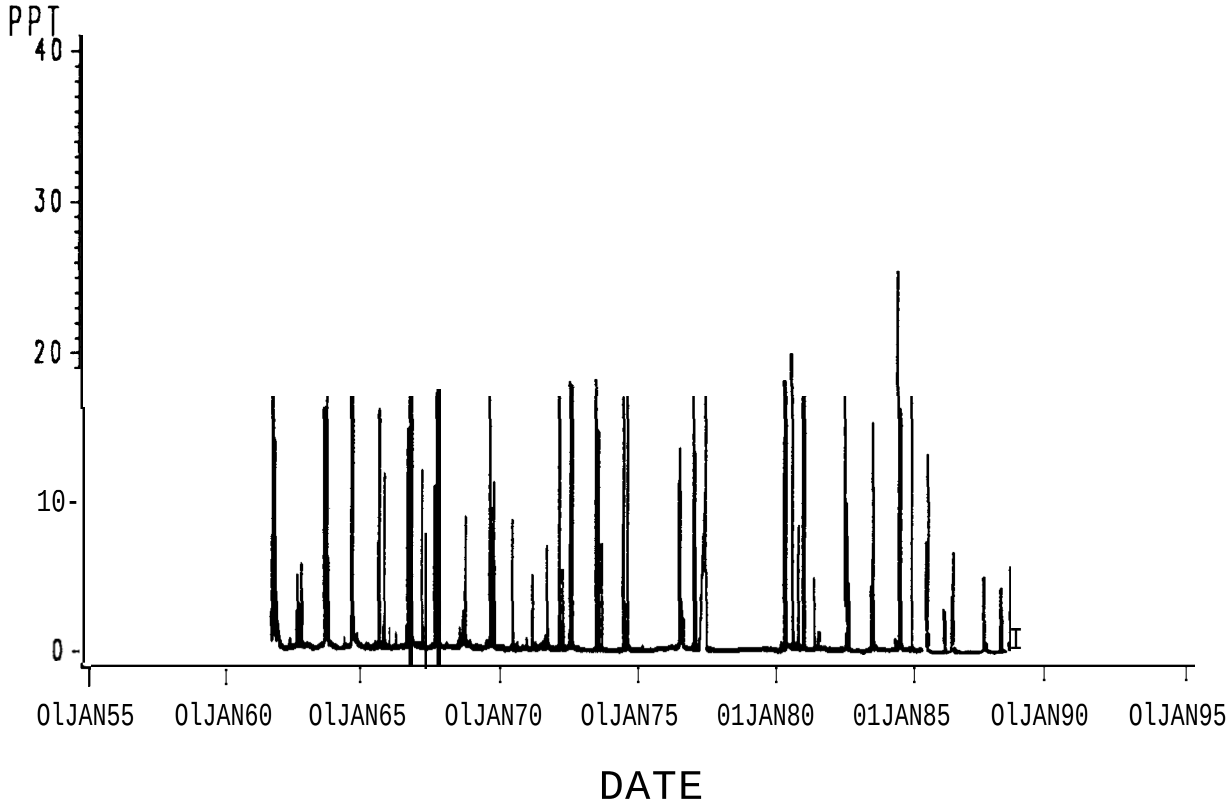
DAILY' SALINITY

STATION=76323 BAYOU GRAND CAILLOU



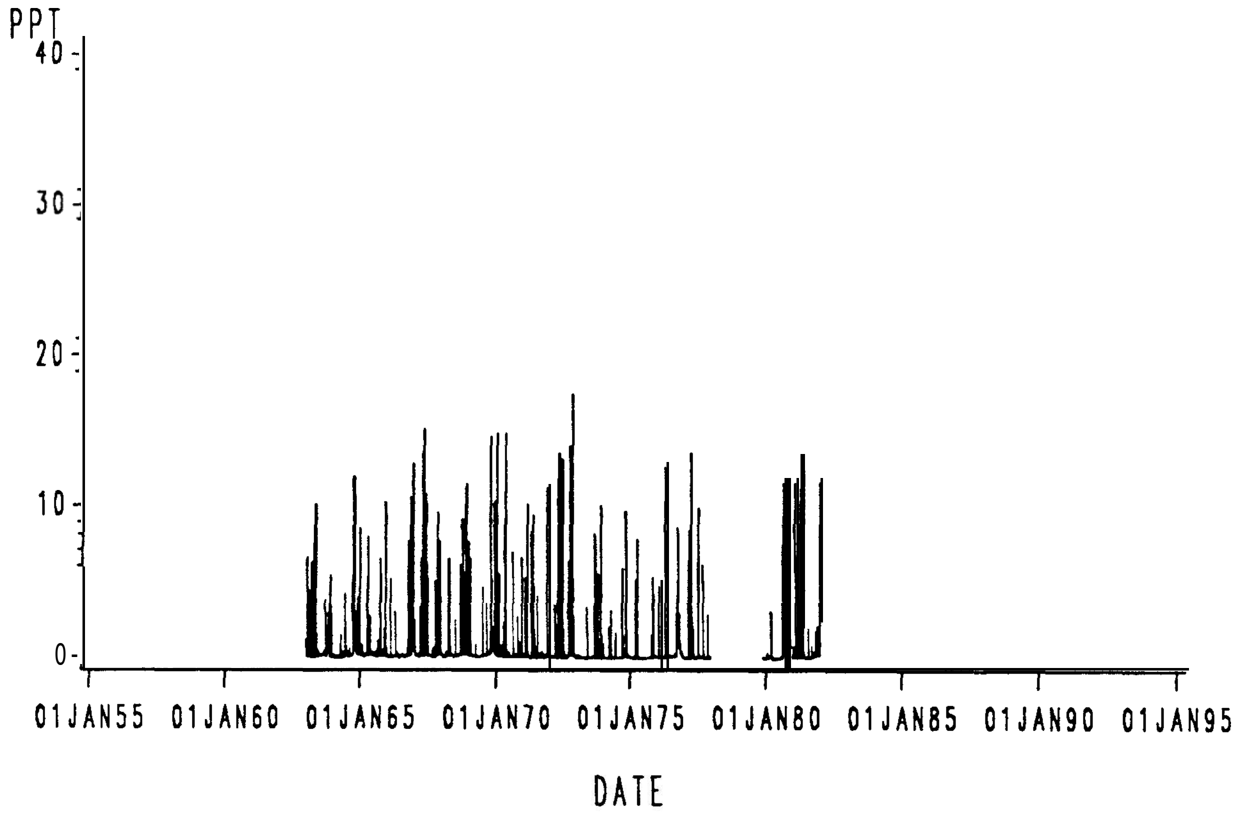
DAILY SALINITY

STATION=76343HNC AT CROZIER



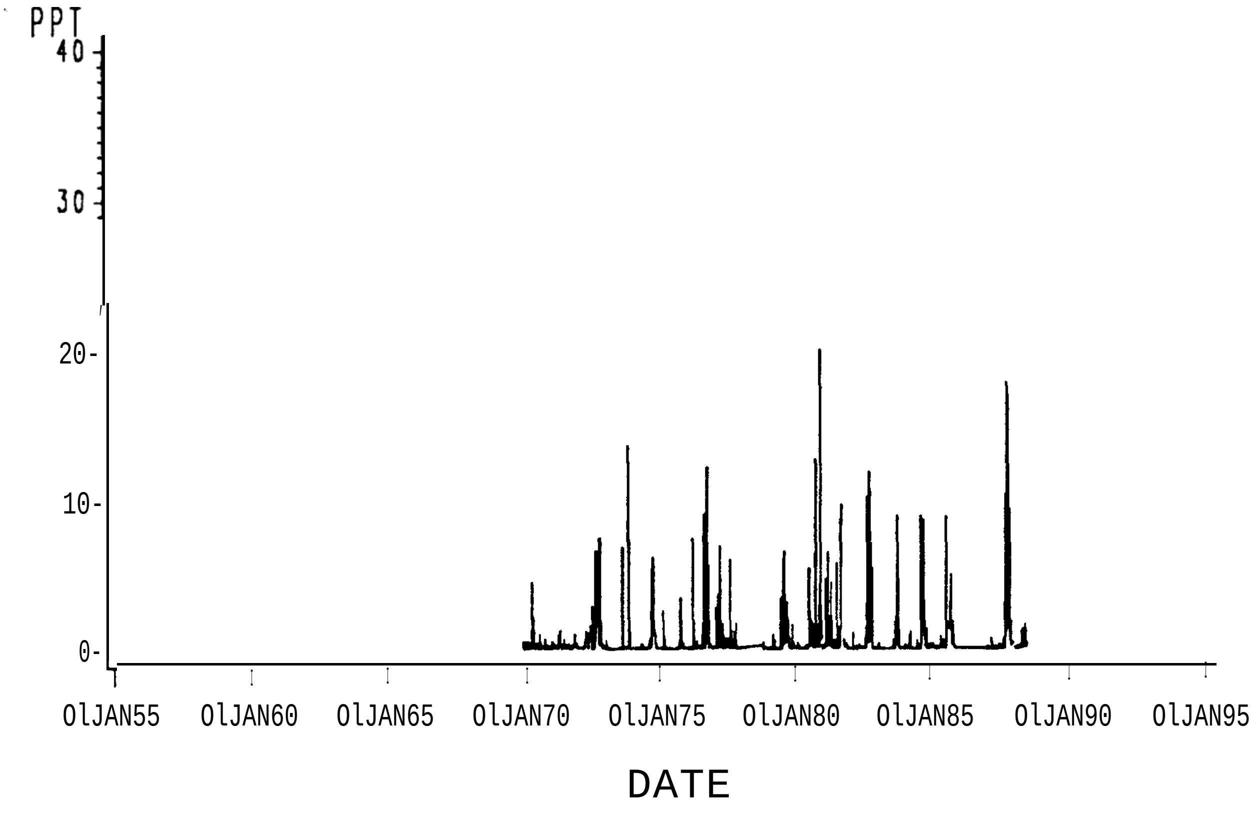
DAILY SALINITY

STATION=76403 BAYOU TERREBONNE



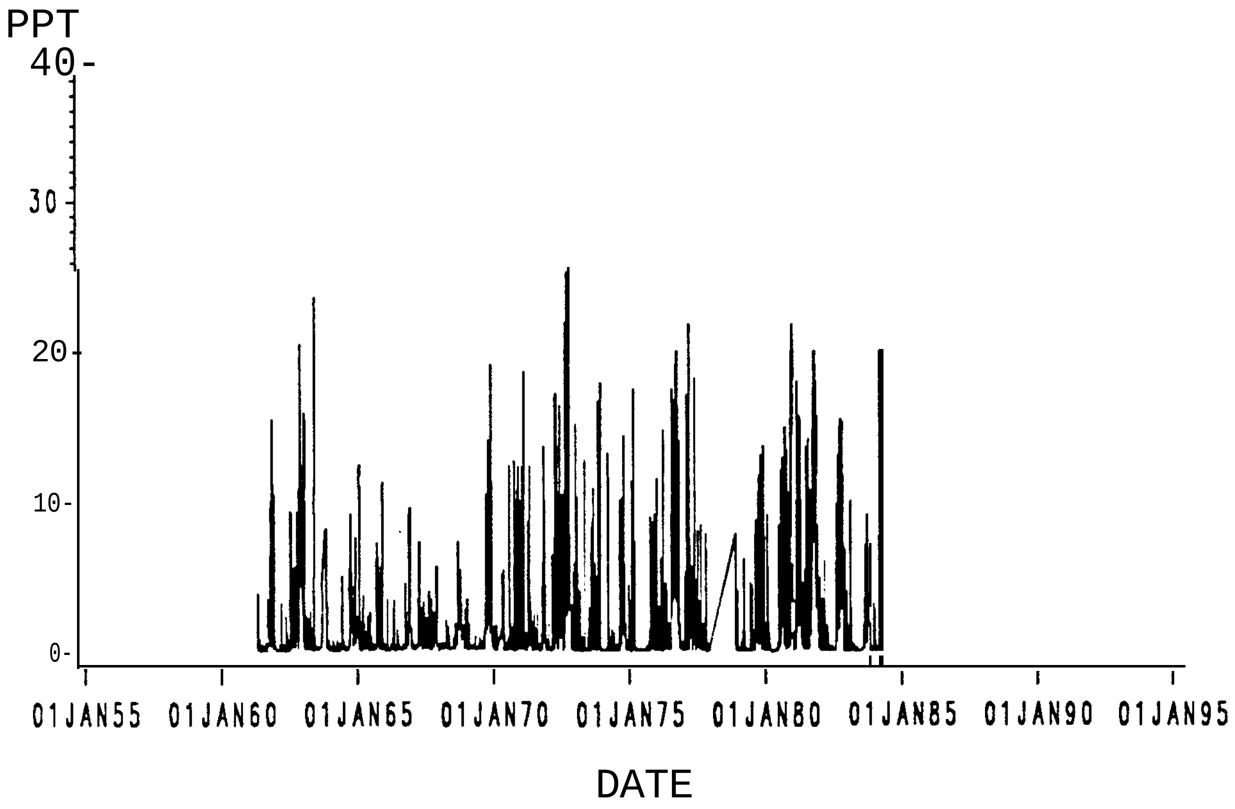
DAILY SALINITY

STATION=82203 LAROSE



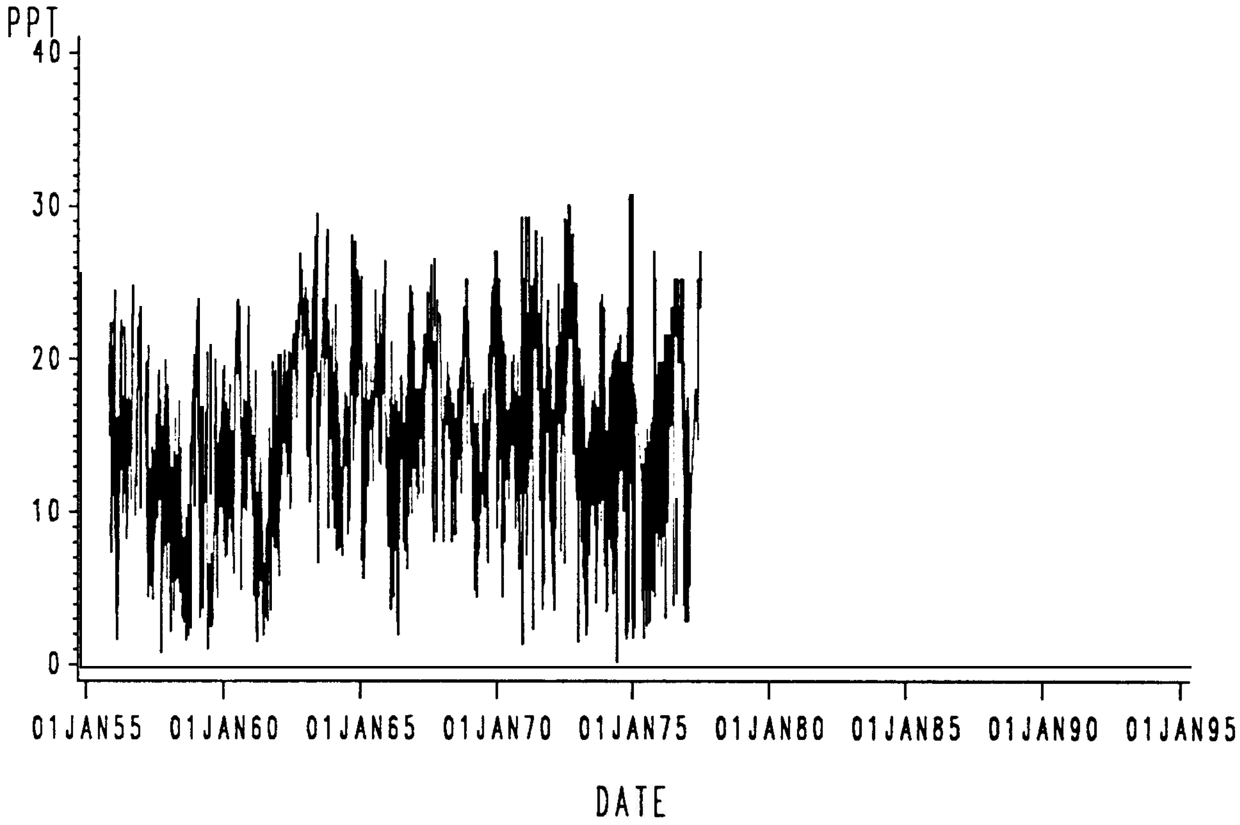
DAILY SALINITY

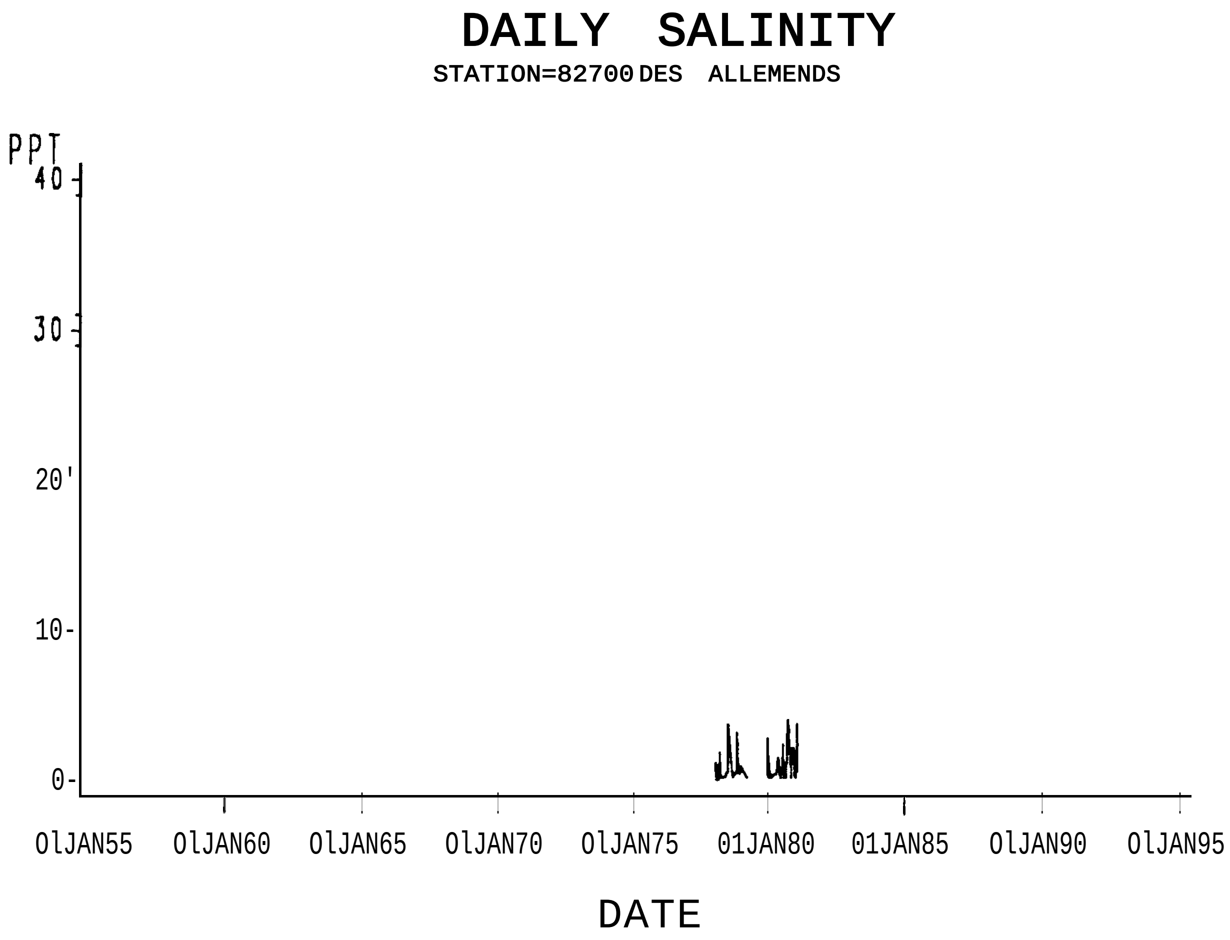
STATION=8230 GALLANO



DAILY SALINITY

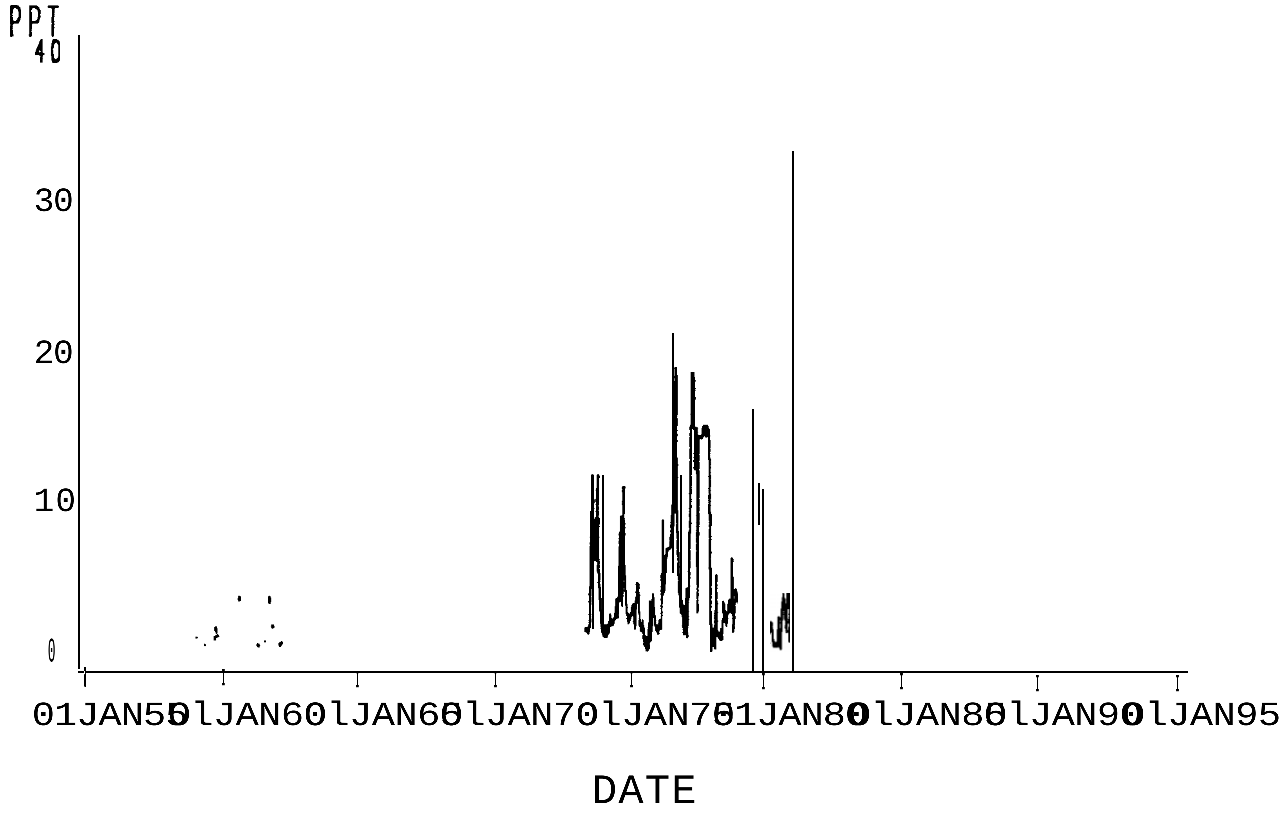
STATION=82350 LEEVILLE




DAILY SALINITY
STATION=82700 DES ALLEMENDS
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

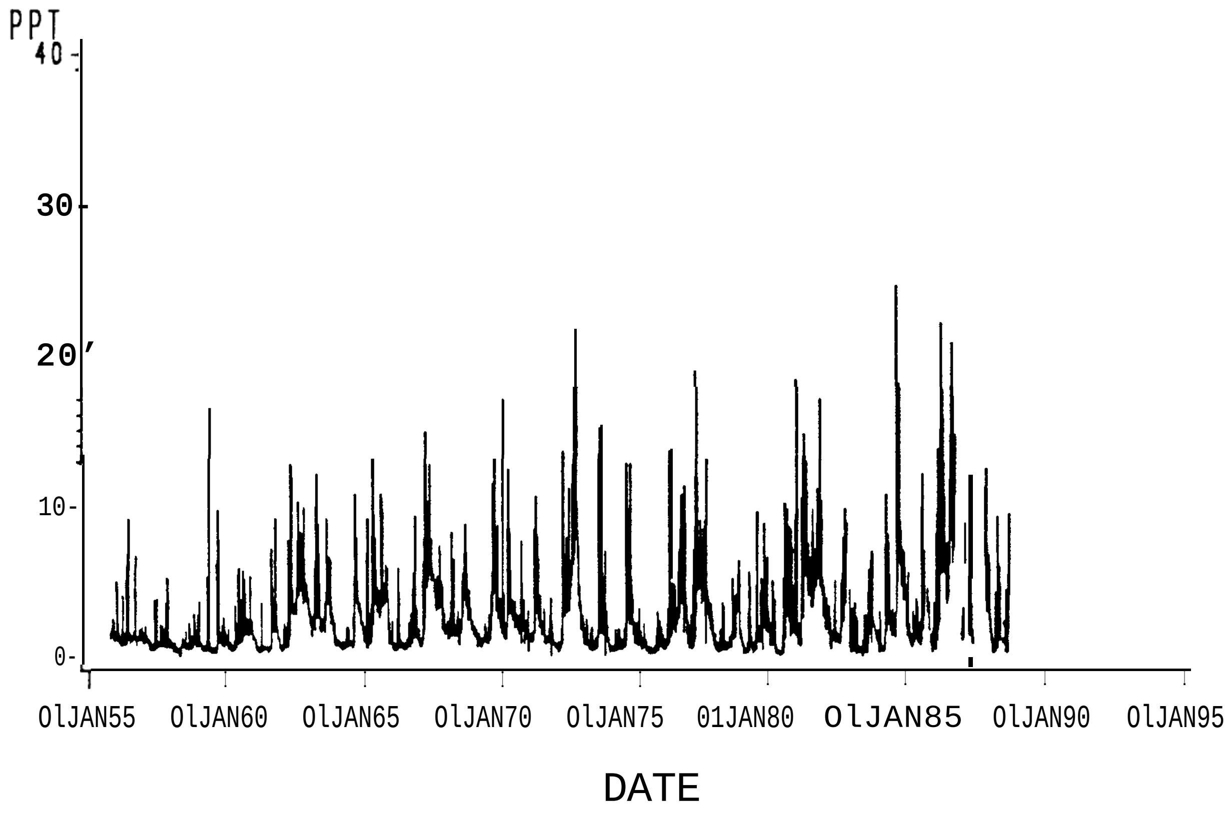
DAILY SALINITY

STATlON=82750 BARATARIA



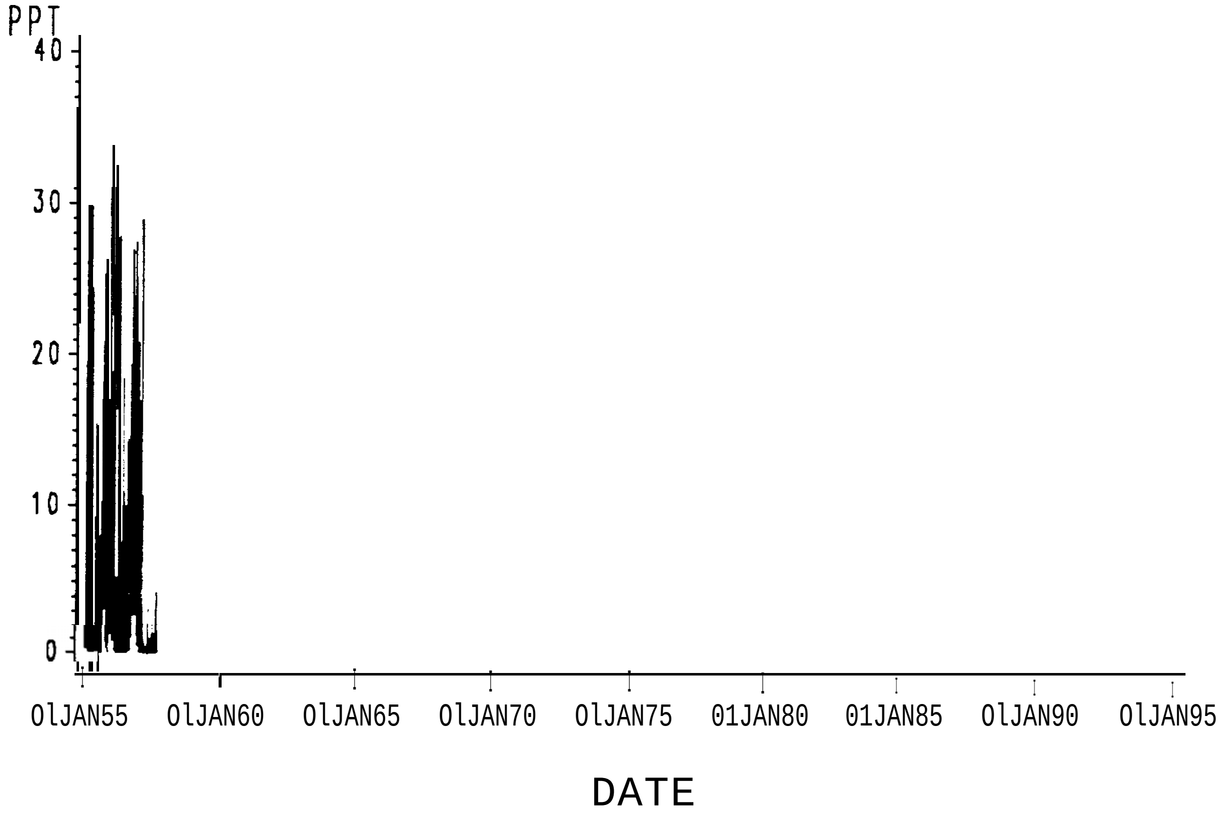
DAILY SALINITY

STATION=82875 LAFITTE



DAILY SALINITY

STATION=88600 EUGENE ISLAND

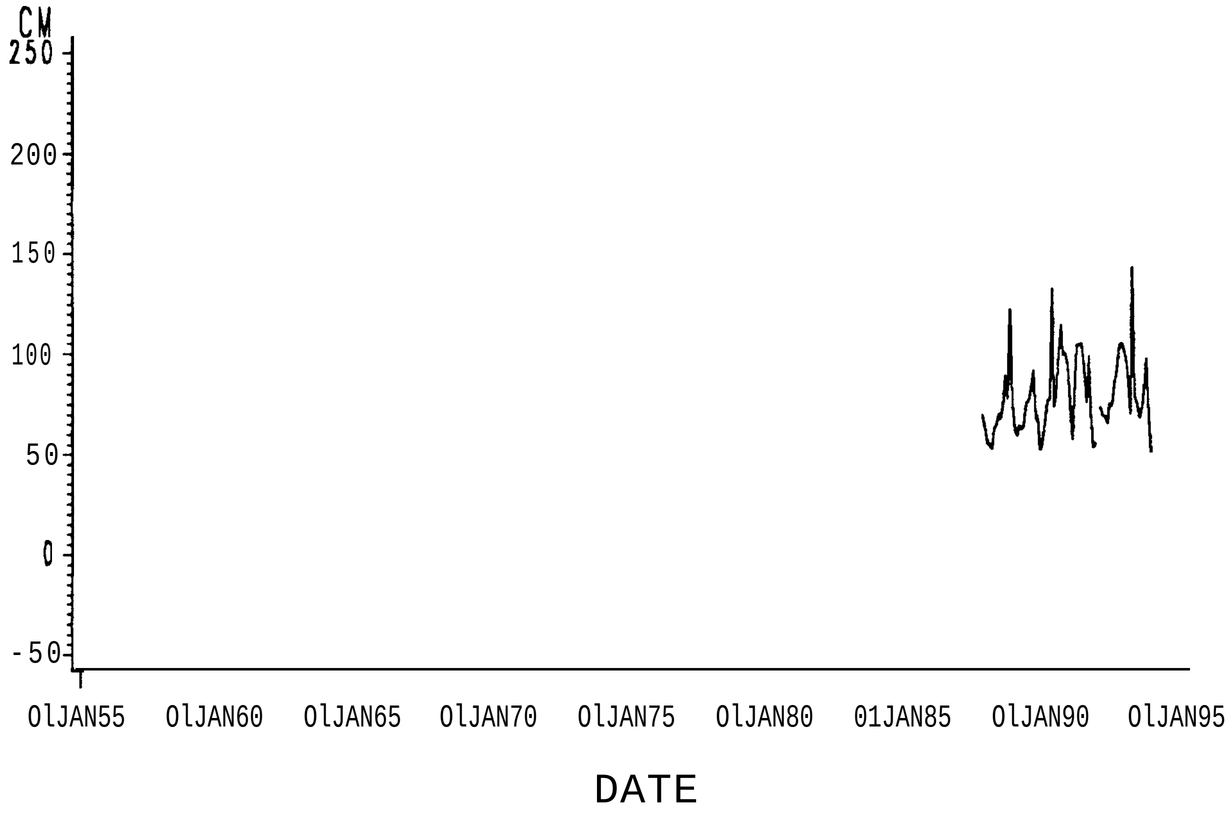


Appendix M

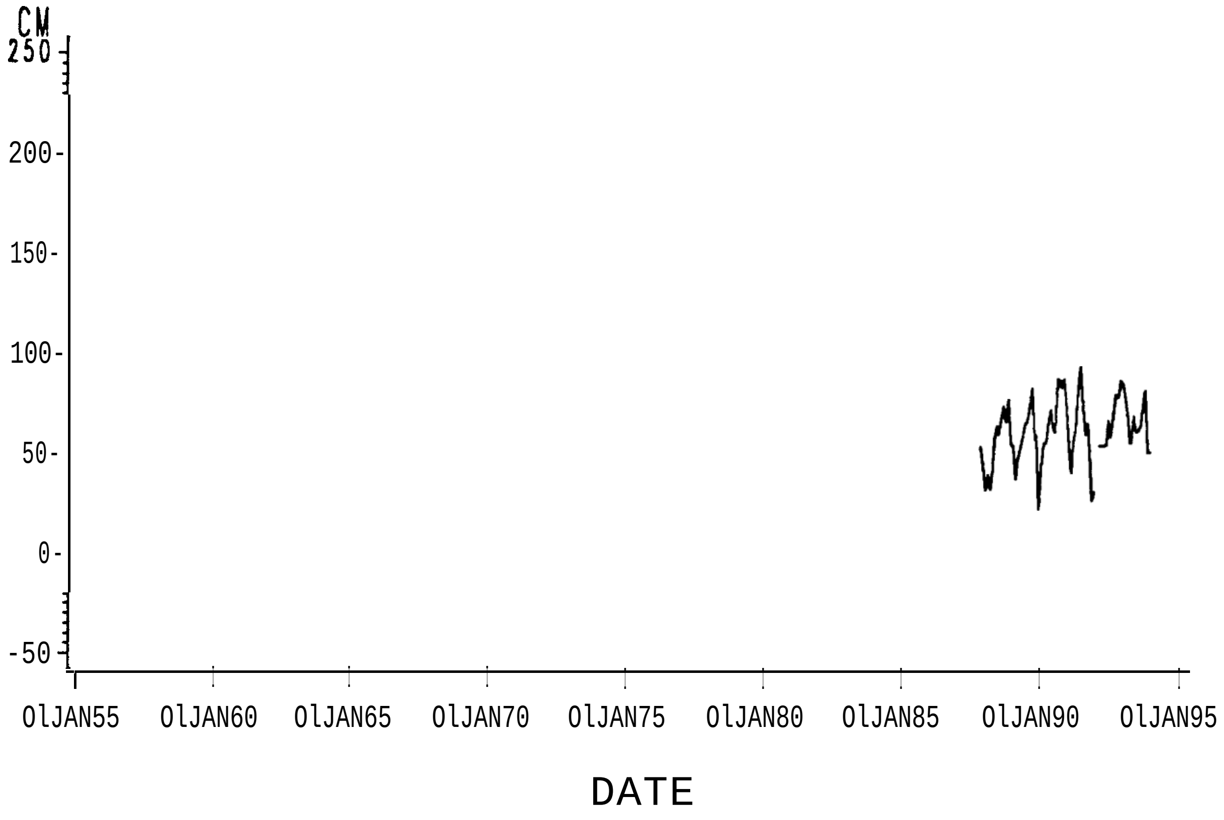
Time Series Plots of Monthly Mean, Minimum, and Maximum Water Levels and Salinities

MONTHLY MEAN WATER LEVEL

STATION=315GRANDTERRE

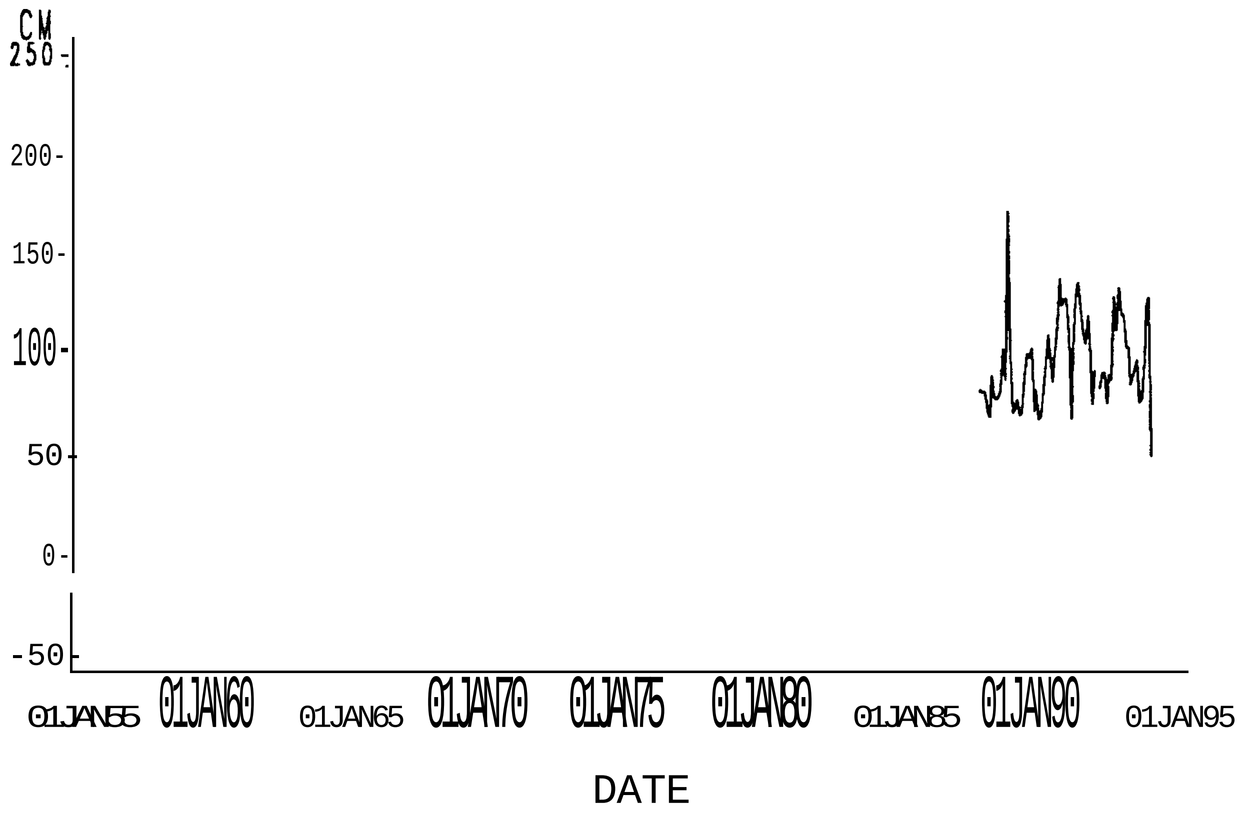


MONTHLY MINIMUM WATER LEVEL
STATION=315GRANDTERRE



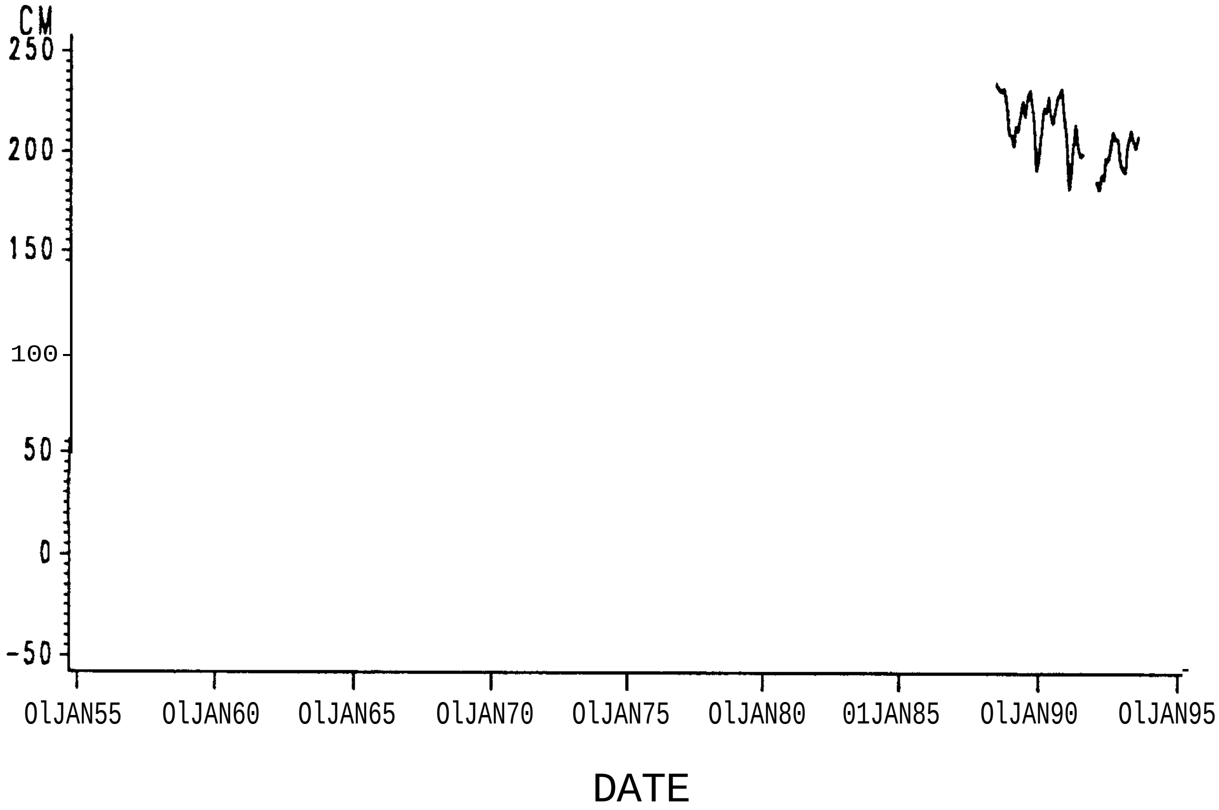
MONTHLY MAXIMUM WATER LEVEL

STATION=315 GRAND TERRE



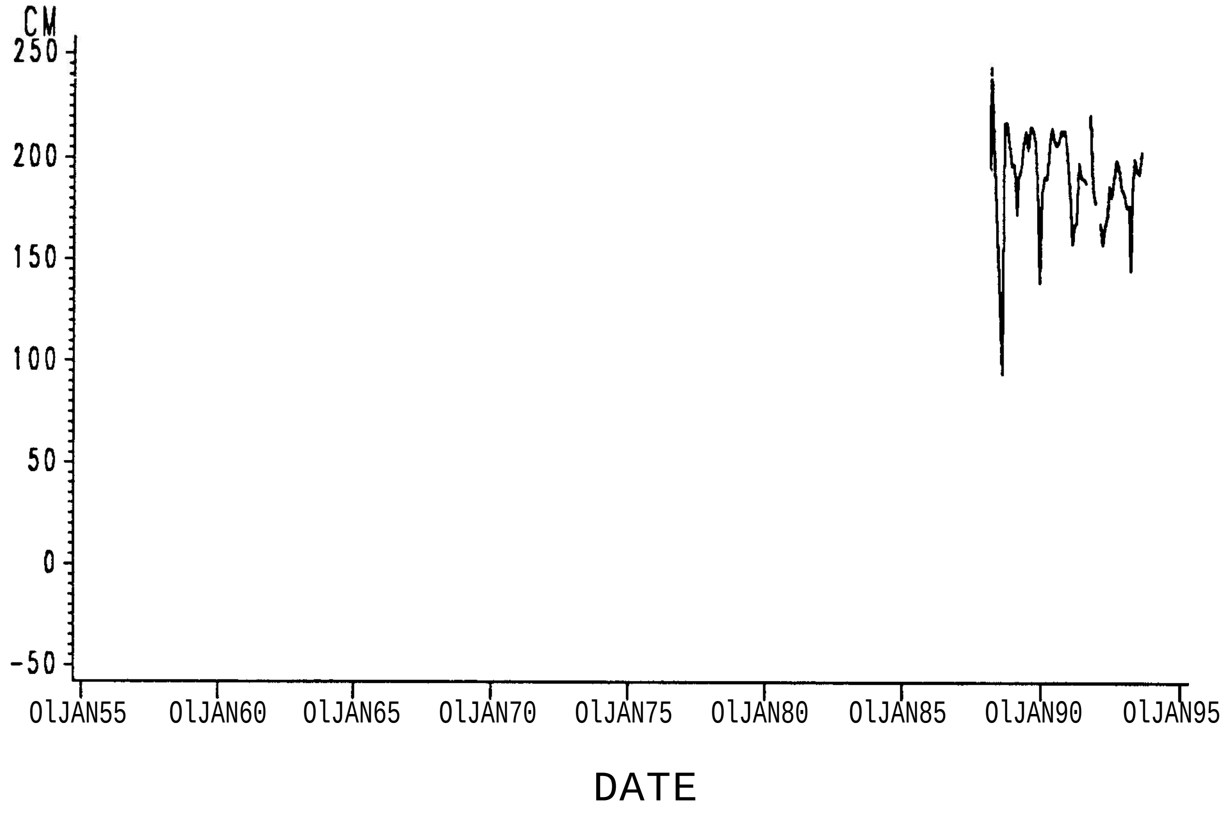
MONTHLY MEAN WATER LEVEL

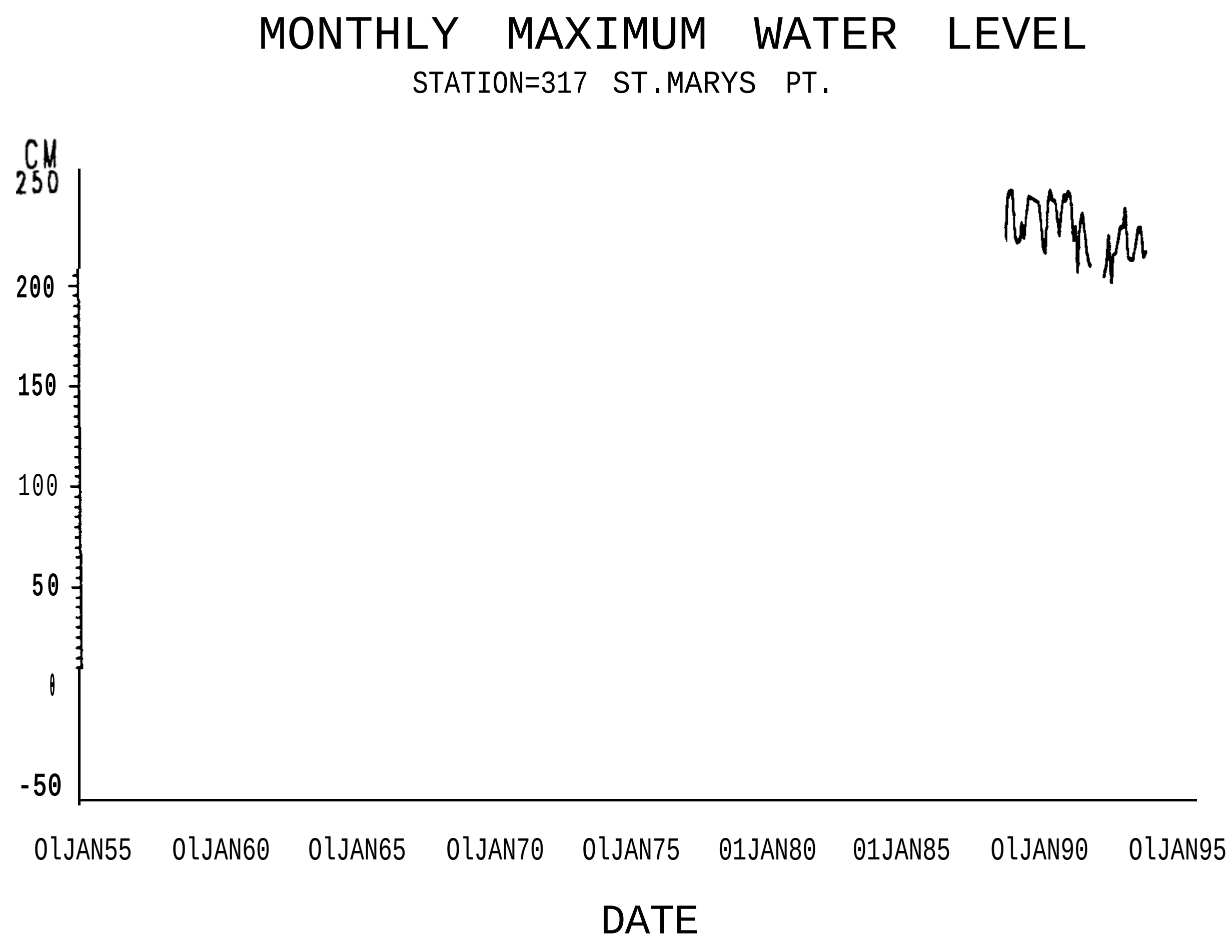
STATION=317 ST.MARYS PT.

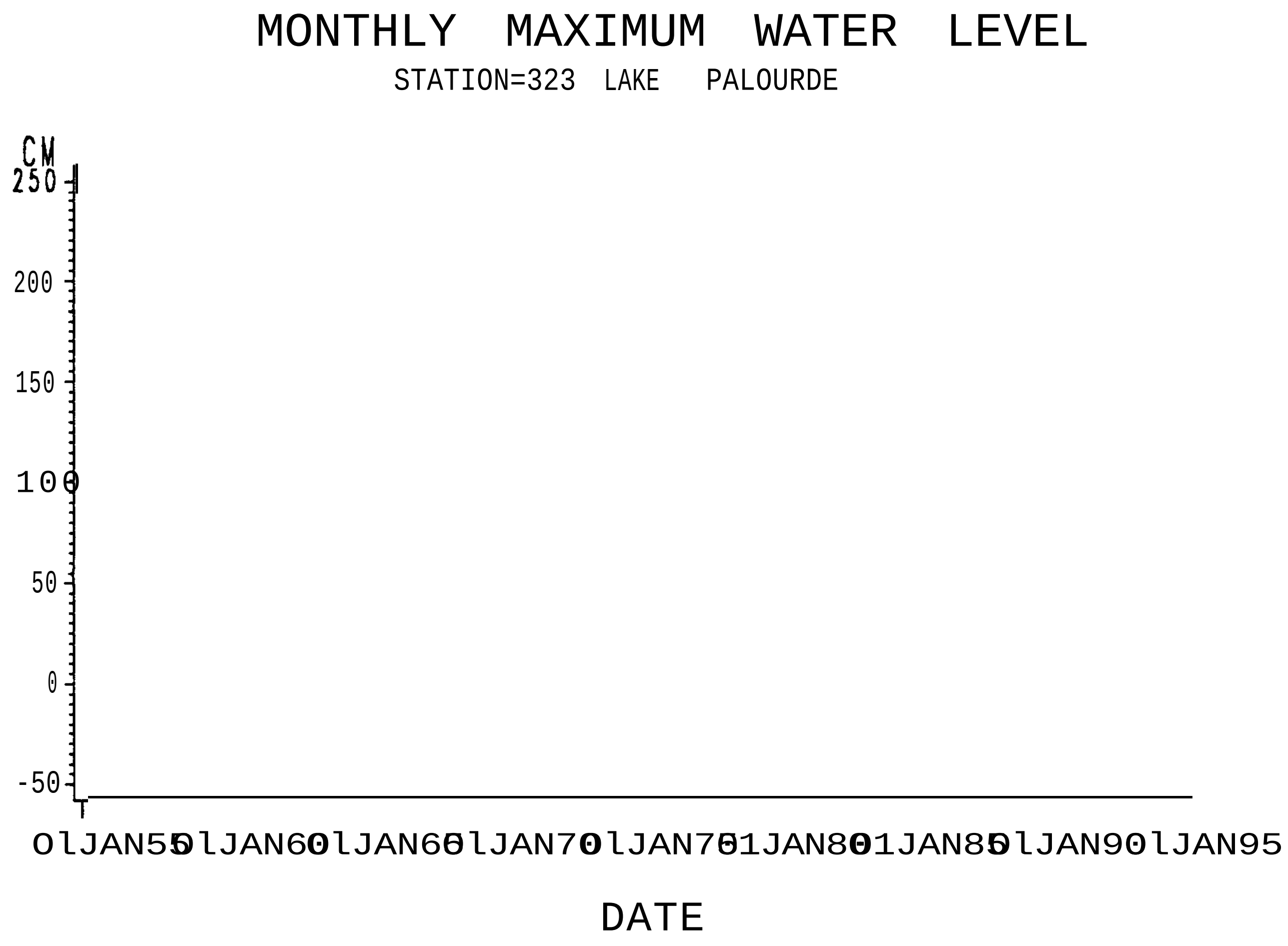


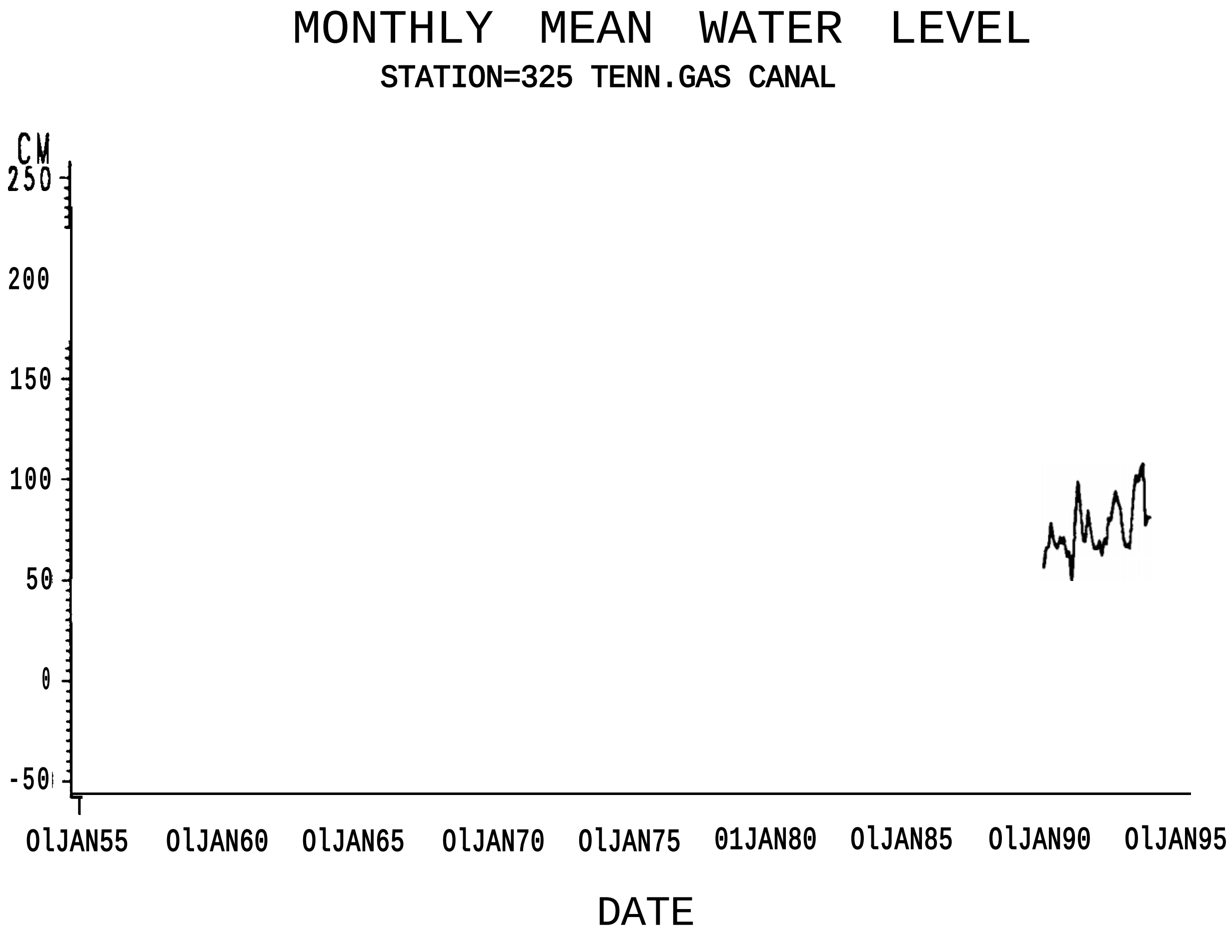
MONTHLY MINIMUM WATER LEVEL

STATION=317 ST. MARYS PT.



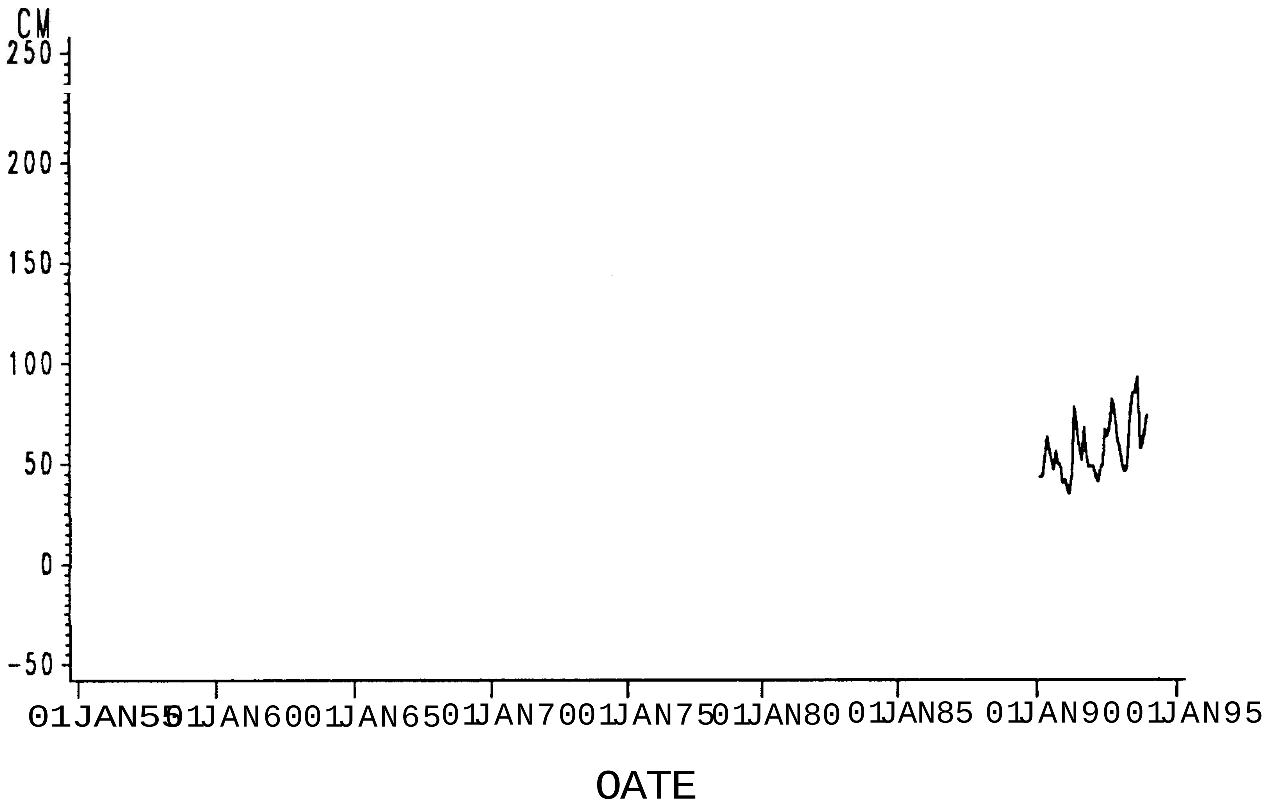

MONTHLY MAXIMUM WATER LEVEL
STATION=317 ST.MARYS PT.
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

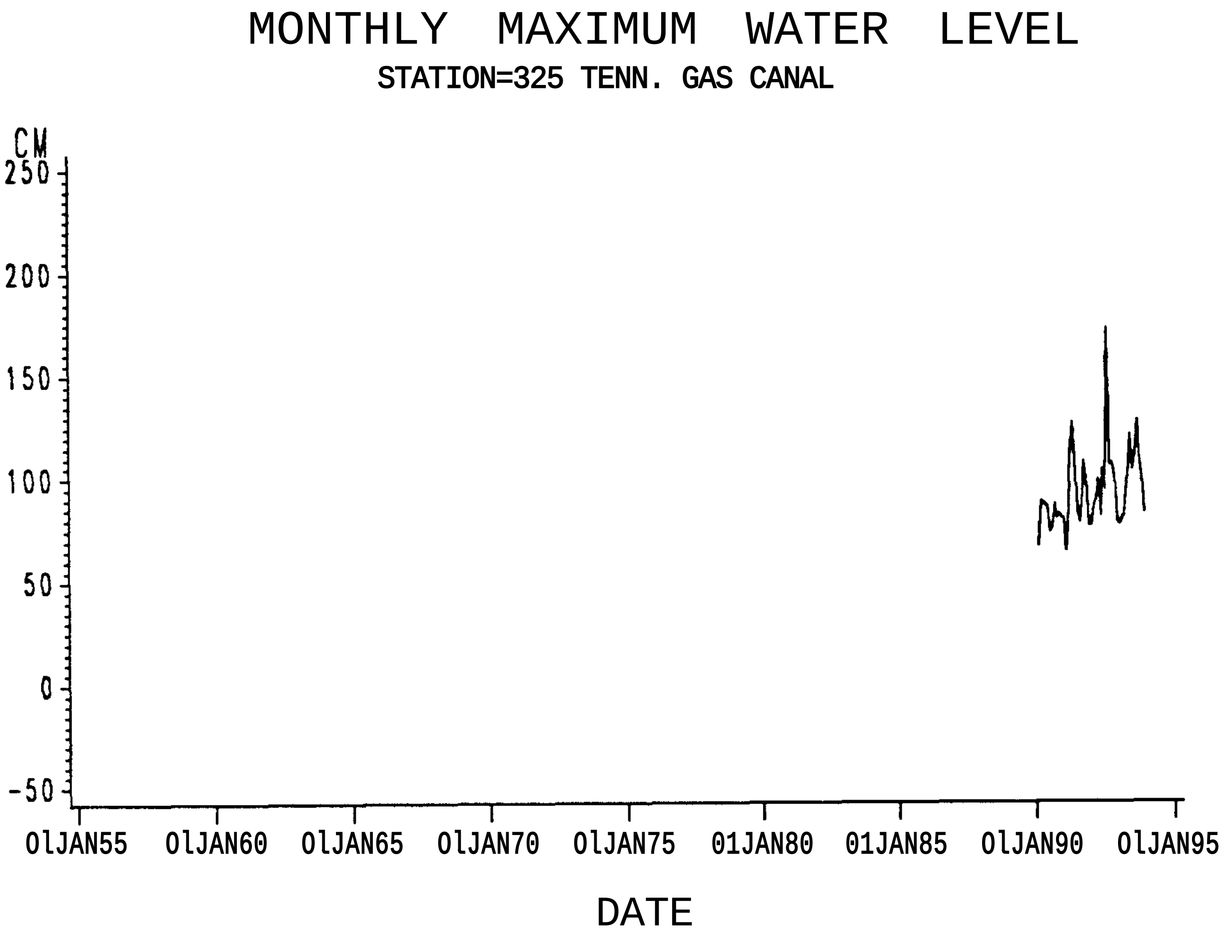

MONTHLY MAXIMUM WATER LEVEL
STATION=323 LAKE PALOURDE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

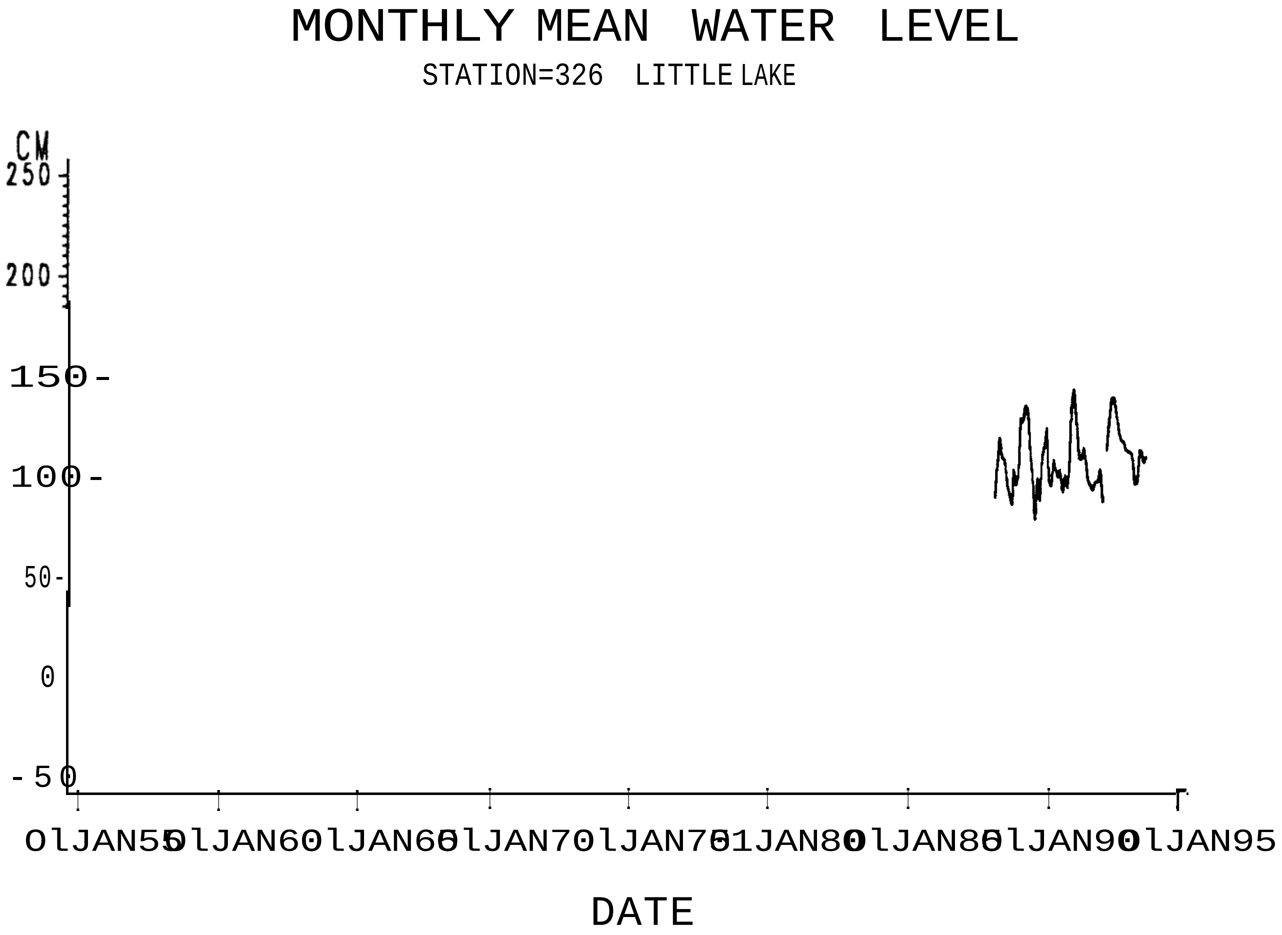

MONTHLY MEAN WATER LEVEL
STATION=325 TENN.GAS CANAL
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

MONTHLY MINIMUM WATER LEVEL

STATION=325 TENN. GAS CANAL

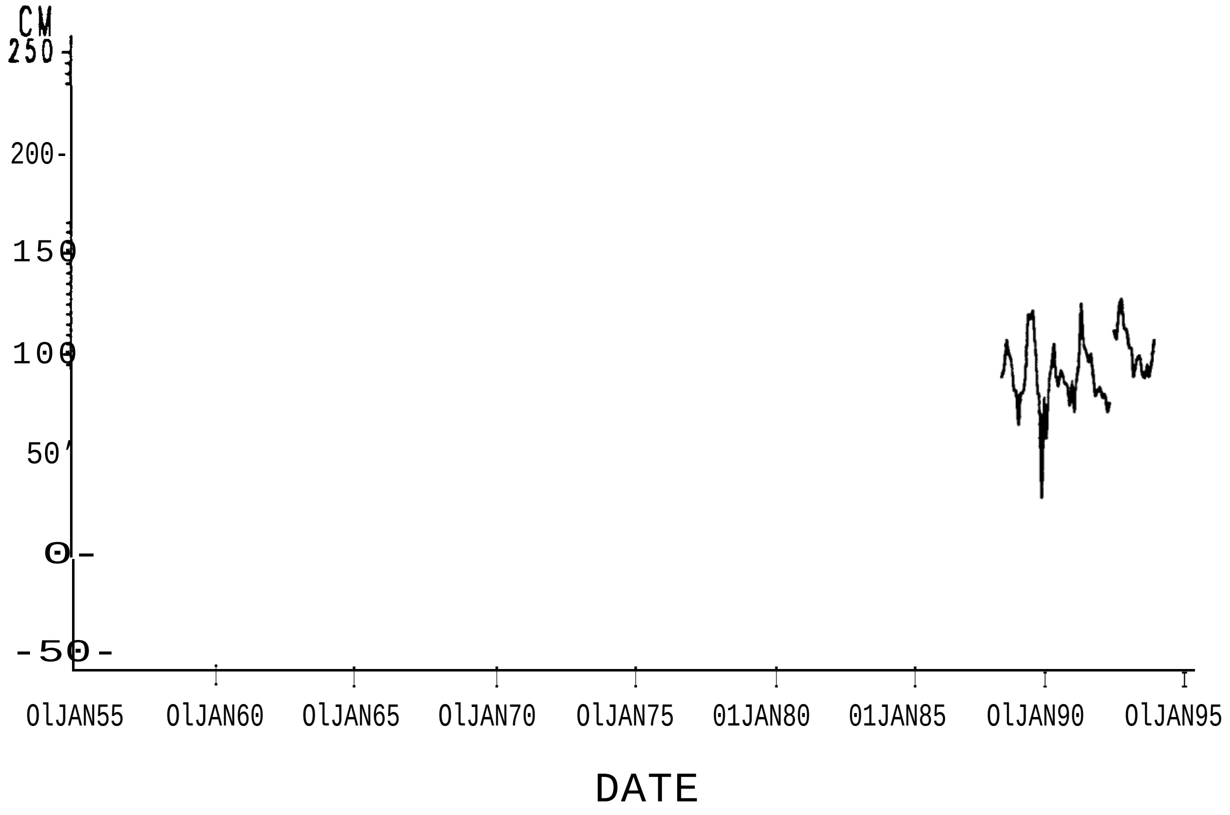


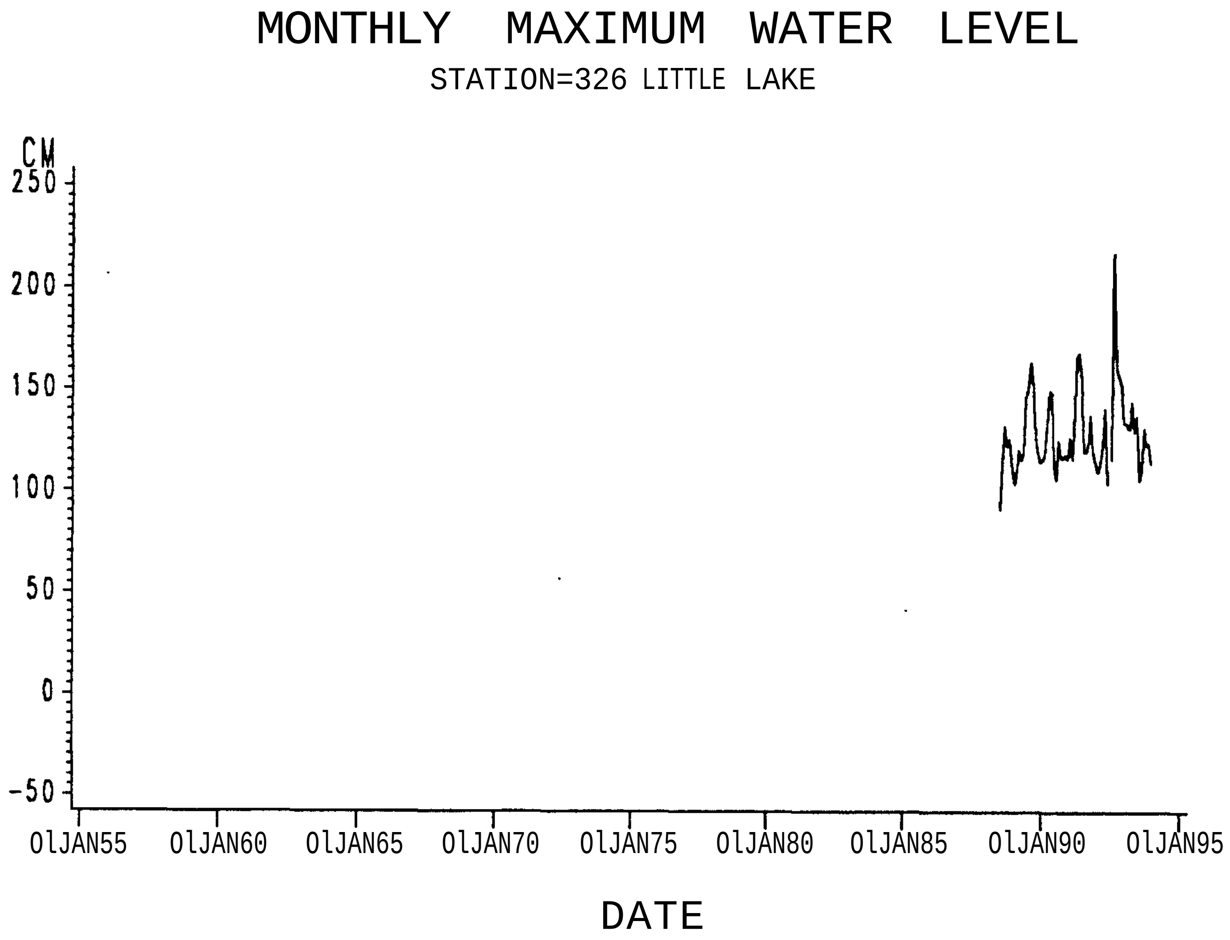

MONTHLY MAXIMUM WATER LEVEL
STATION=325 TENN. GAS CANAL
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE


MONTHLY MEAN WATER LEVEL
STATION=326 LITTLE LAKE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

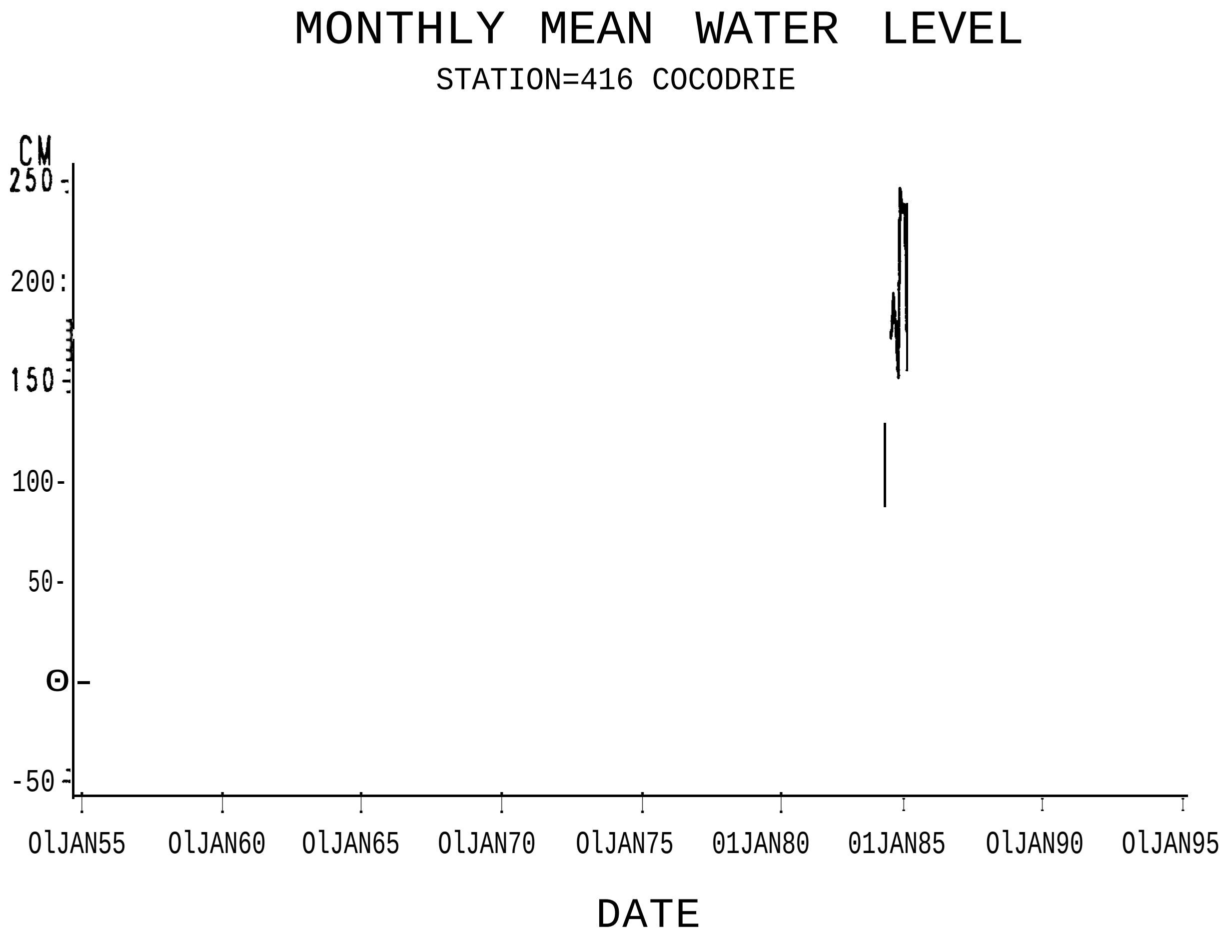
MONTHLY MINIMUM WATER LEVEL

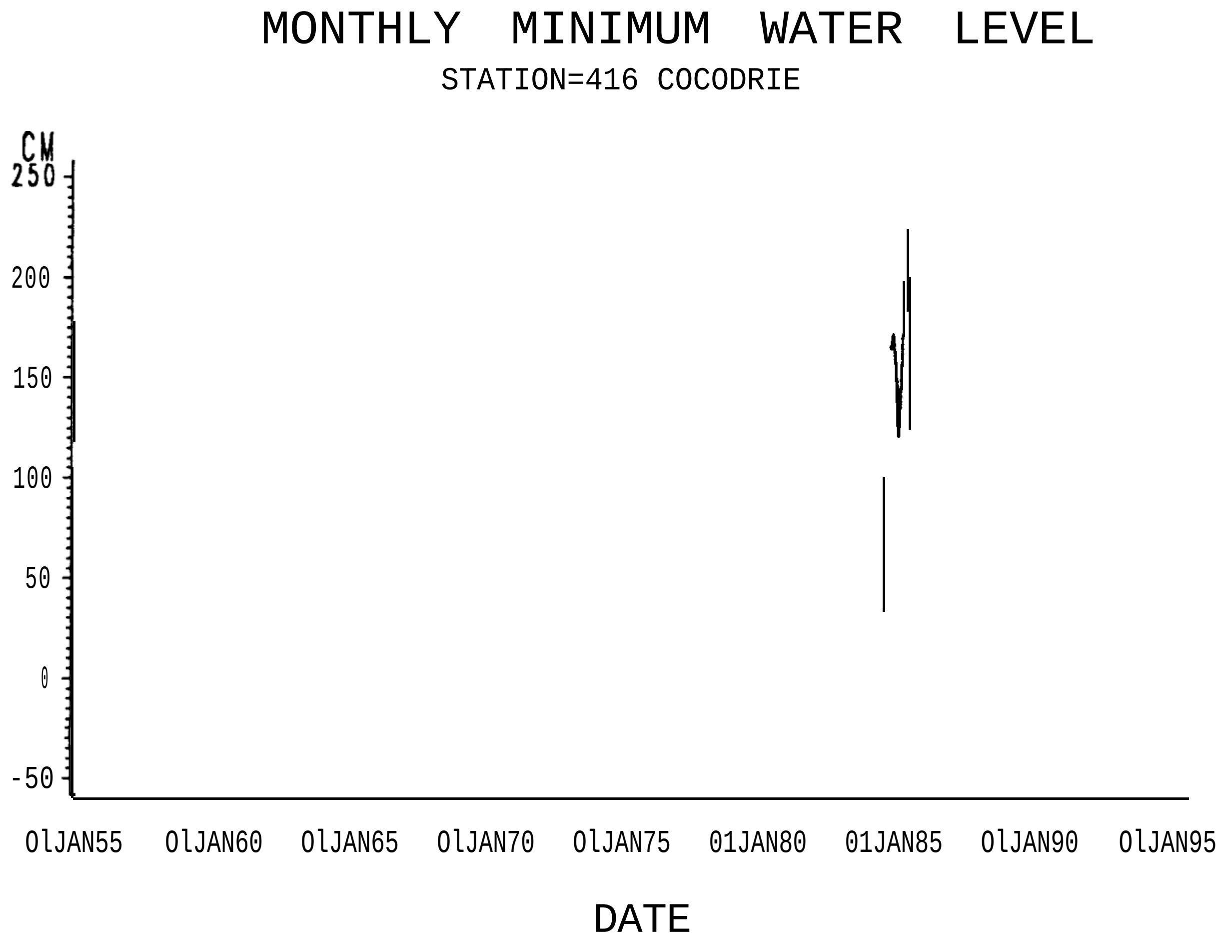
STATION=326 LITTLE LAKE





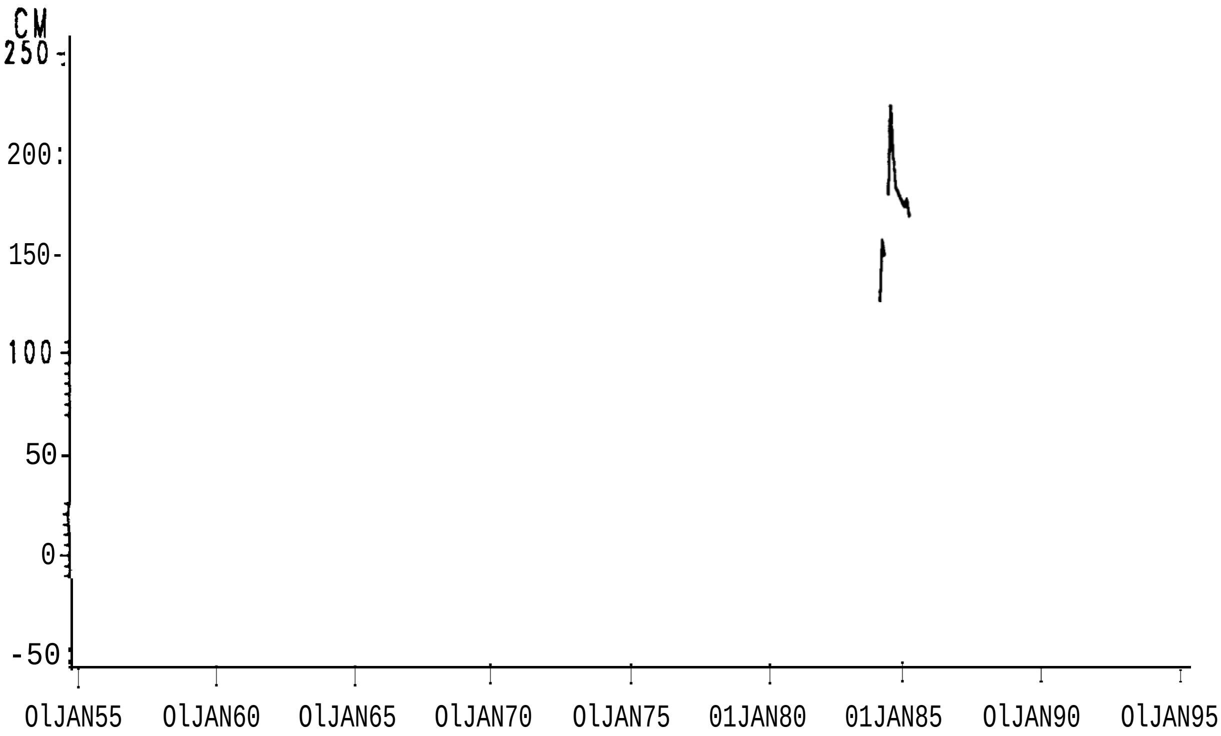
MONTHLY MAXIMUM WATER LEVEL
STATION=326 LITTLE LAKE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE


MONTHLY MEAN WATER LEVEL
STATION=416 COCODRIE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE


MONTHLY MINIMUM WATER LEVEL
STATION=416 COCODRIE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

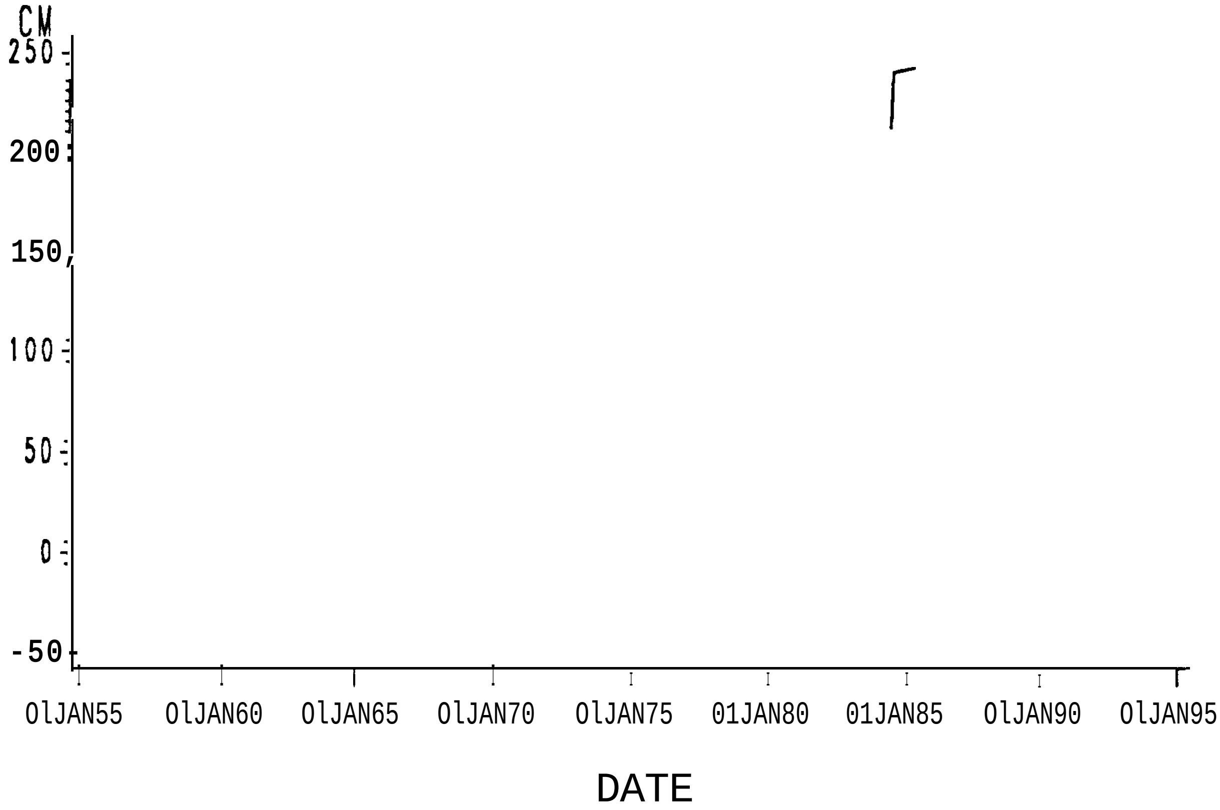
MONTHLY MAXIMUM WATER LEVEL

STATION=416 COCODRIE



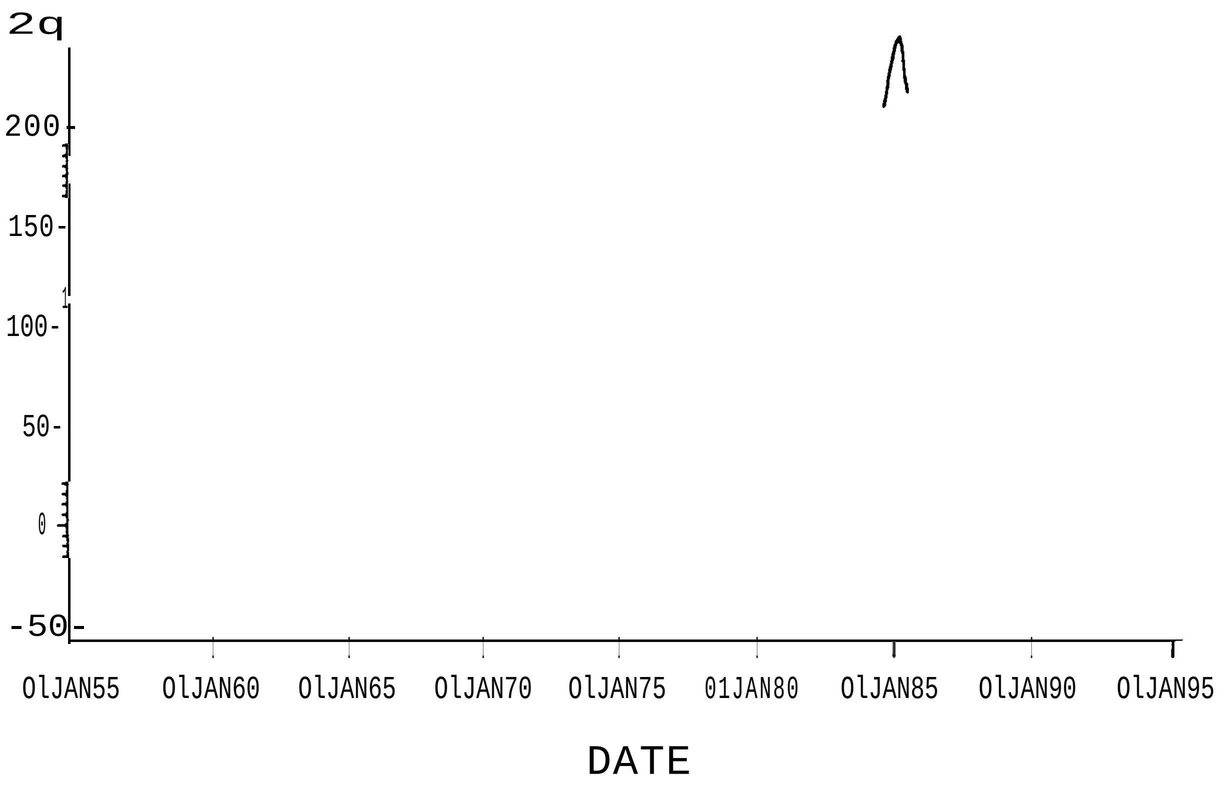
MONTHLY MEAN WATER LEVEL

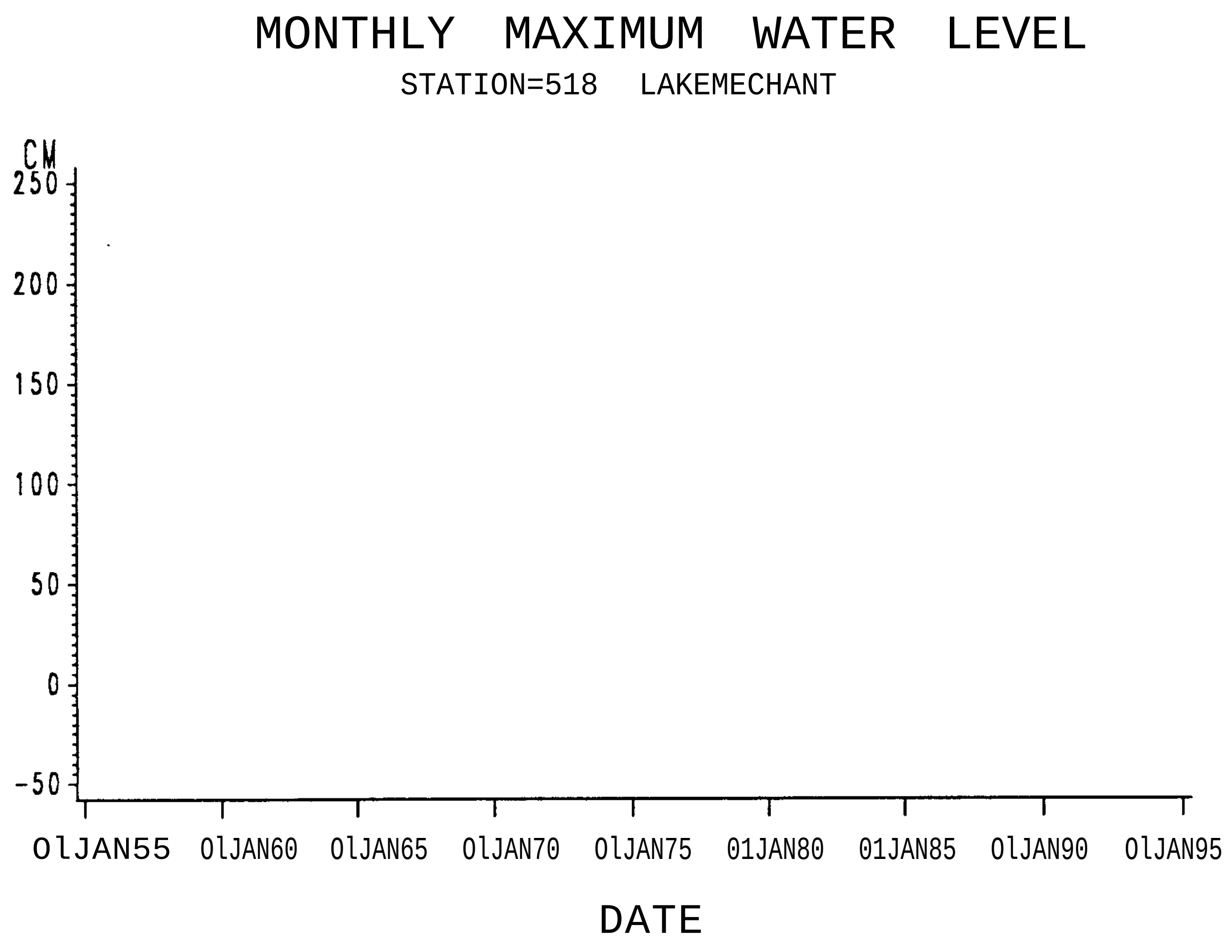
STATION=518 LAKE MECHANT



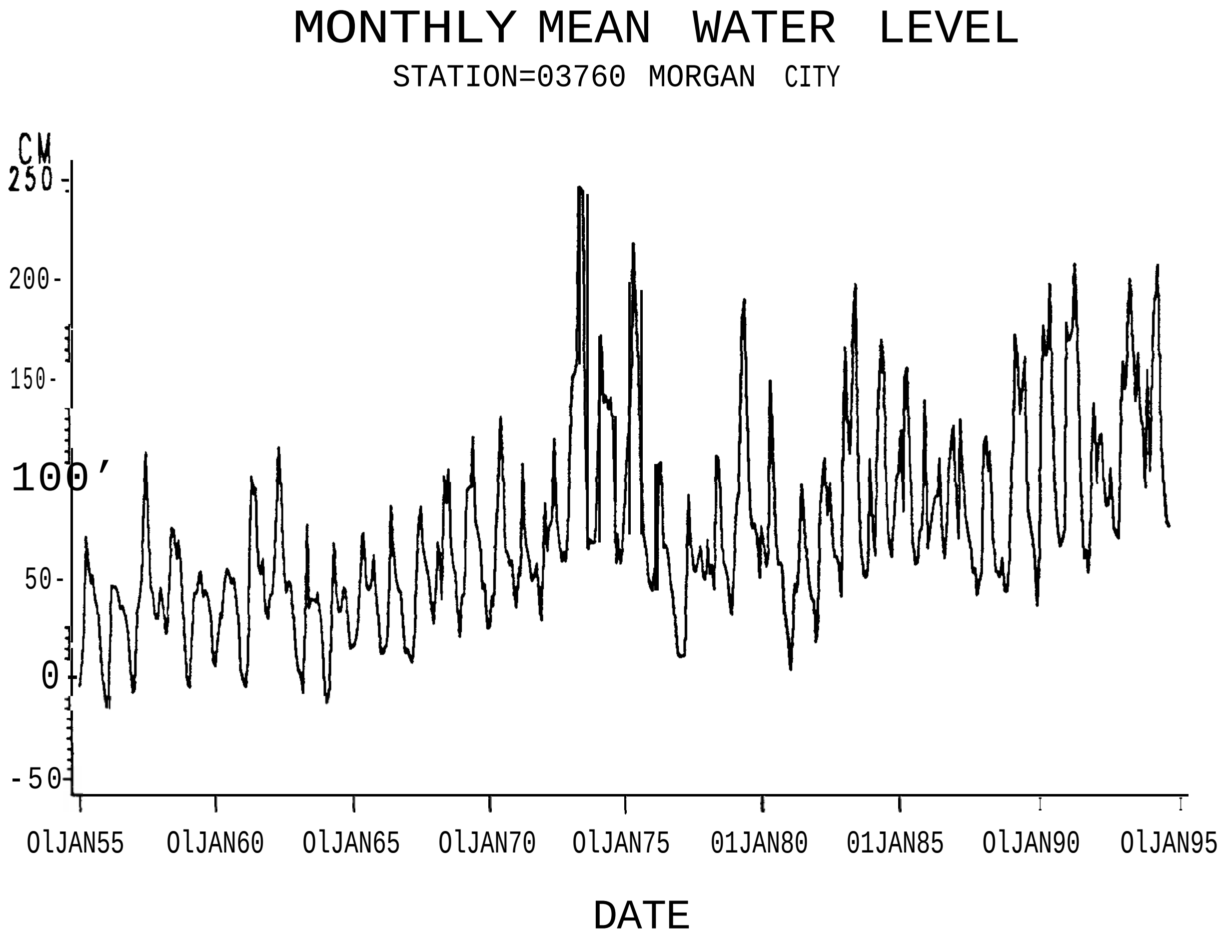
MONTHLY MINIMUM WATER LEVEL

STATION=518 LAKE MECHANT





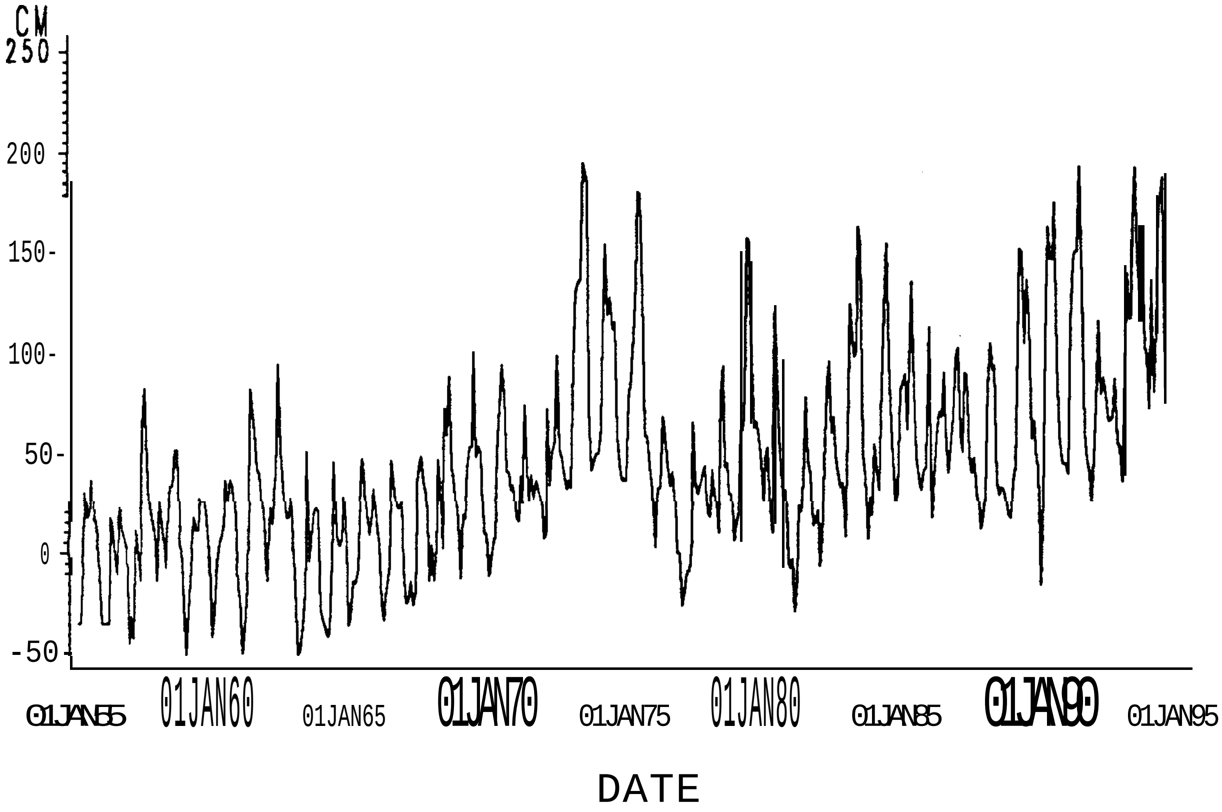
MONTHLY MAXIMUM WATER LEVEL
STATION=518 LAKEMECHANT
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE



MONTHLY MEAN WATER LEVEL
STATION=03760 MORGAN CITY
CM
250-
200-
150-
100’
50-
0
-50
OlJAN55
OlJAN60
OlJAN65
OlJAN70
OlJAN75
01JAN80
01JAN85
OlJAN90
OlJAN95
DATE

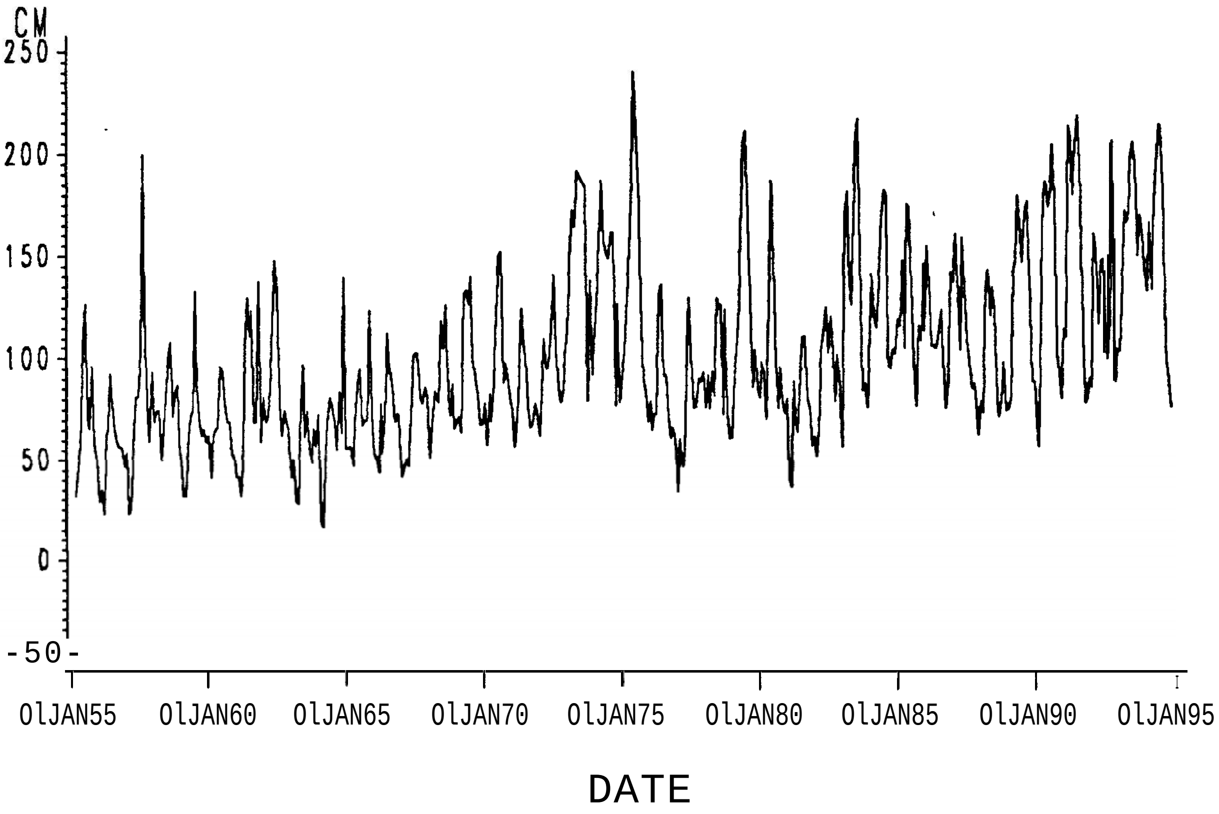
MONTHLY MINIMUM WATER LEVEL

STATION=03780 MORGAN CITY



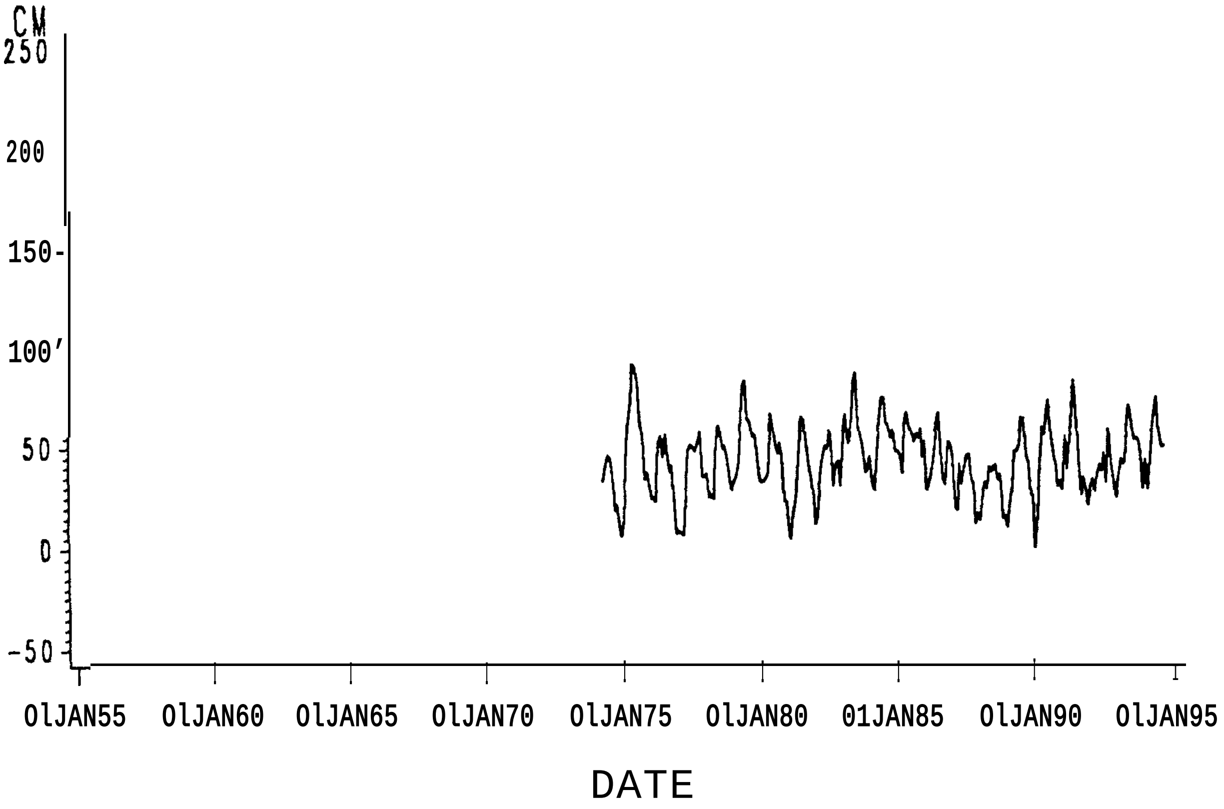
MONTHLY MAXIMUM WATER LEVEL

STATION=03780 MORGAN CITY



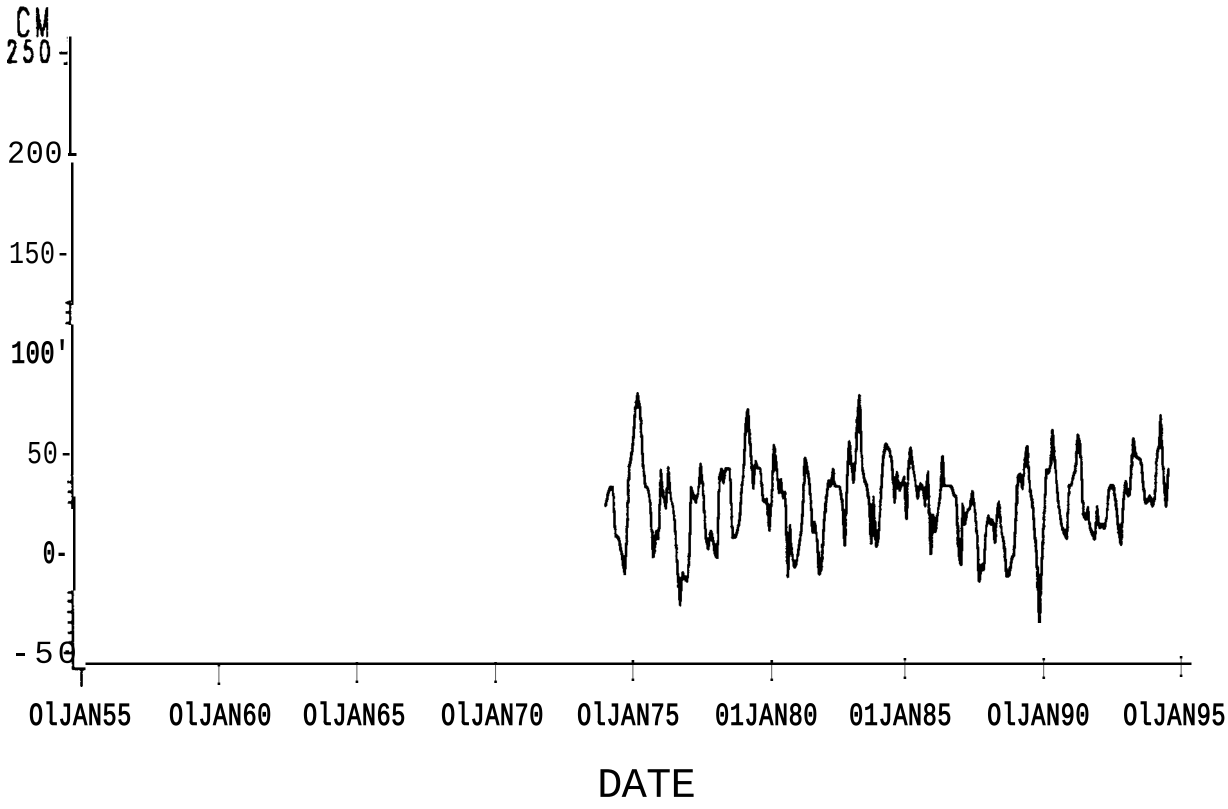
MONTHLY MEAN WATER LEVEL

STATION=03850 DEER ISLAND



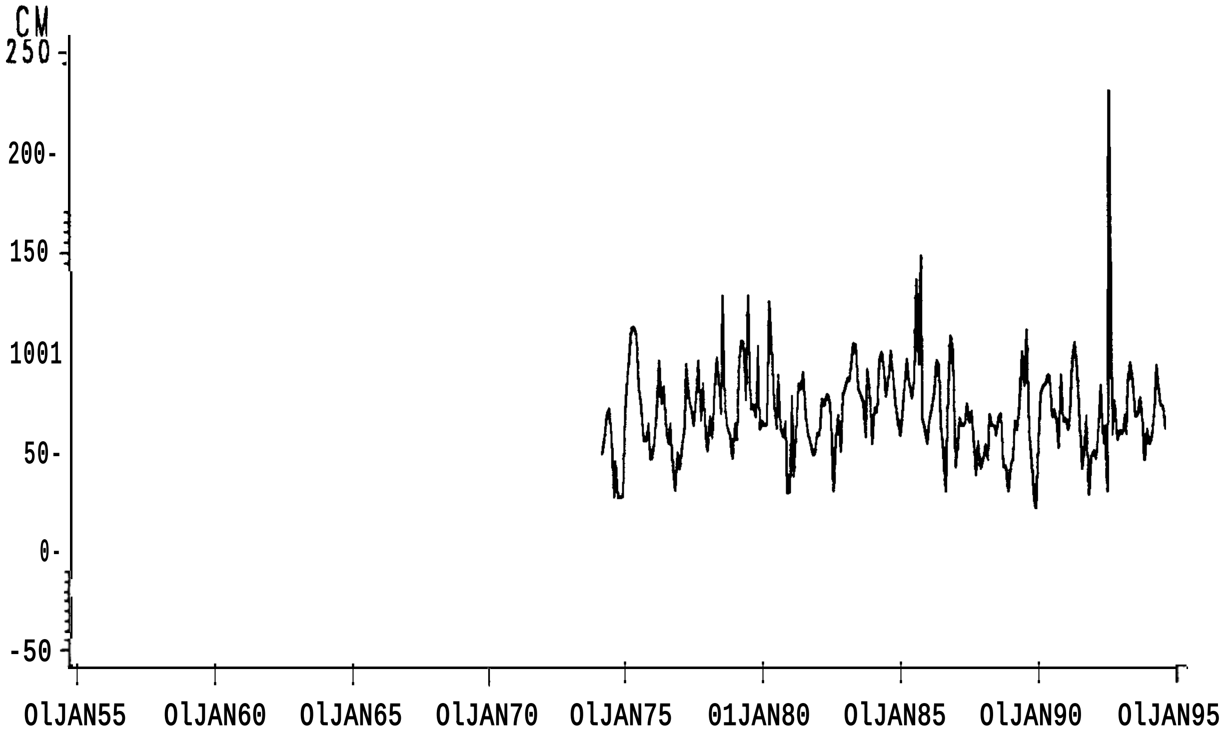
MONTHLY MINIMUM WATER LEVEL

STATION=03850 DEER ISLAND



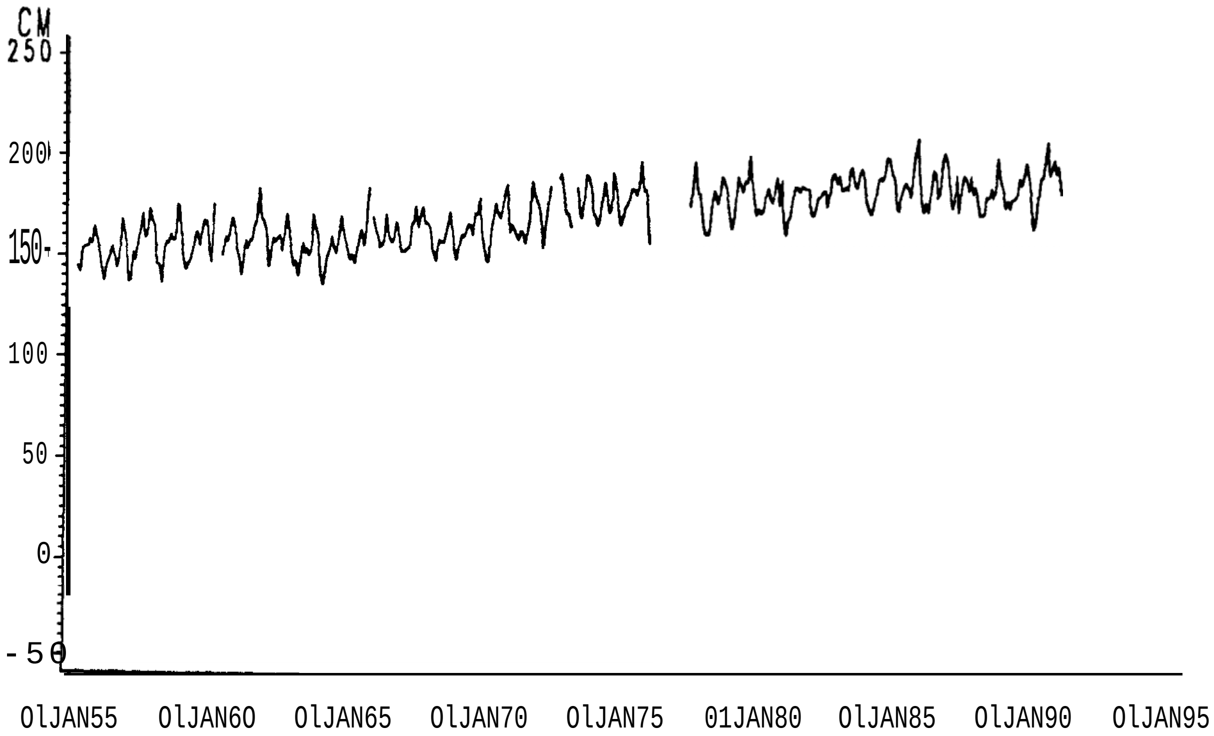
MONTHLY MAXIMUM WATER LEVEL

STATION=03850 DEER ISLAND



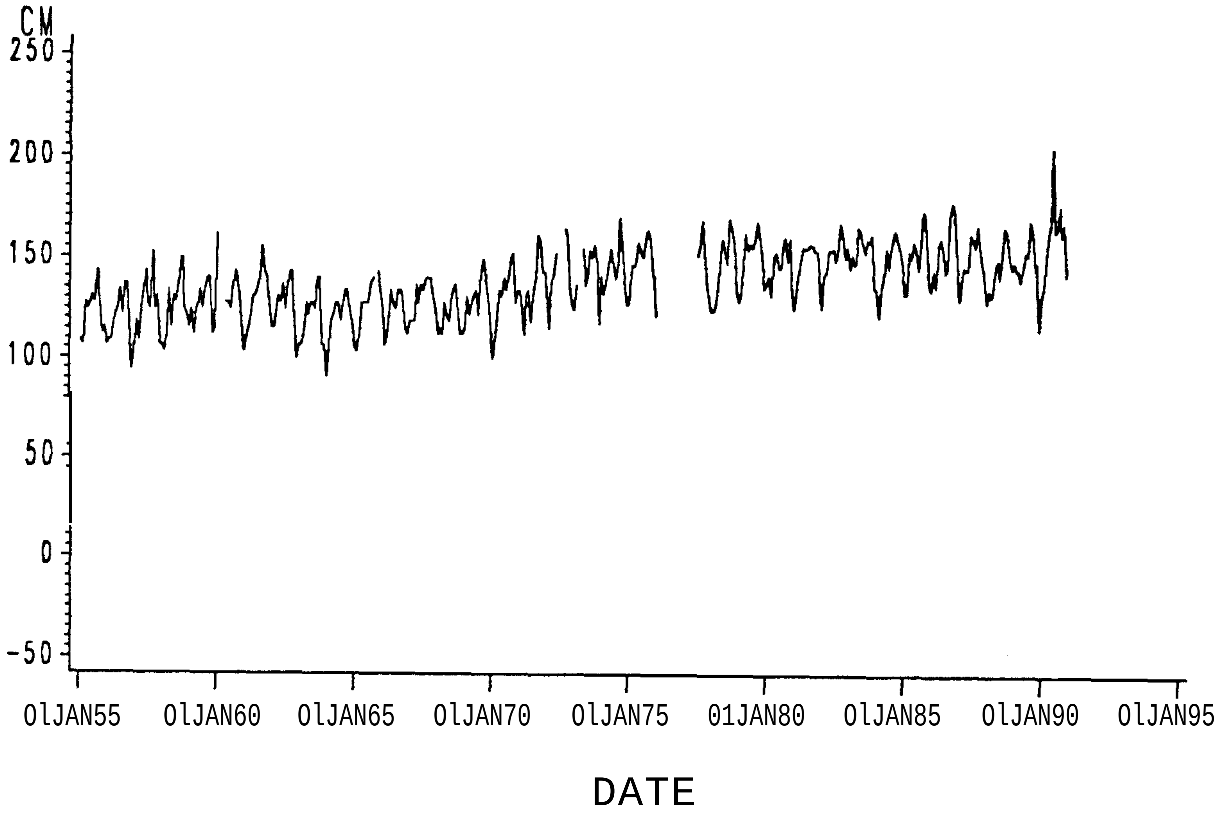
MONTHLY MEAN WATER LEVEL

STATION=3731 BAYOU RIGAUD



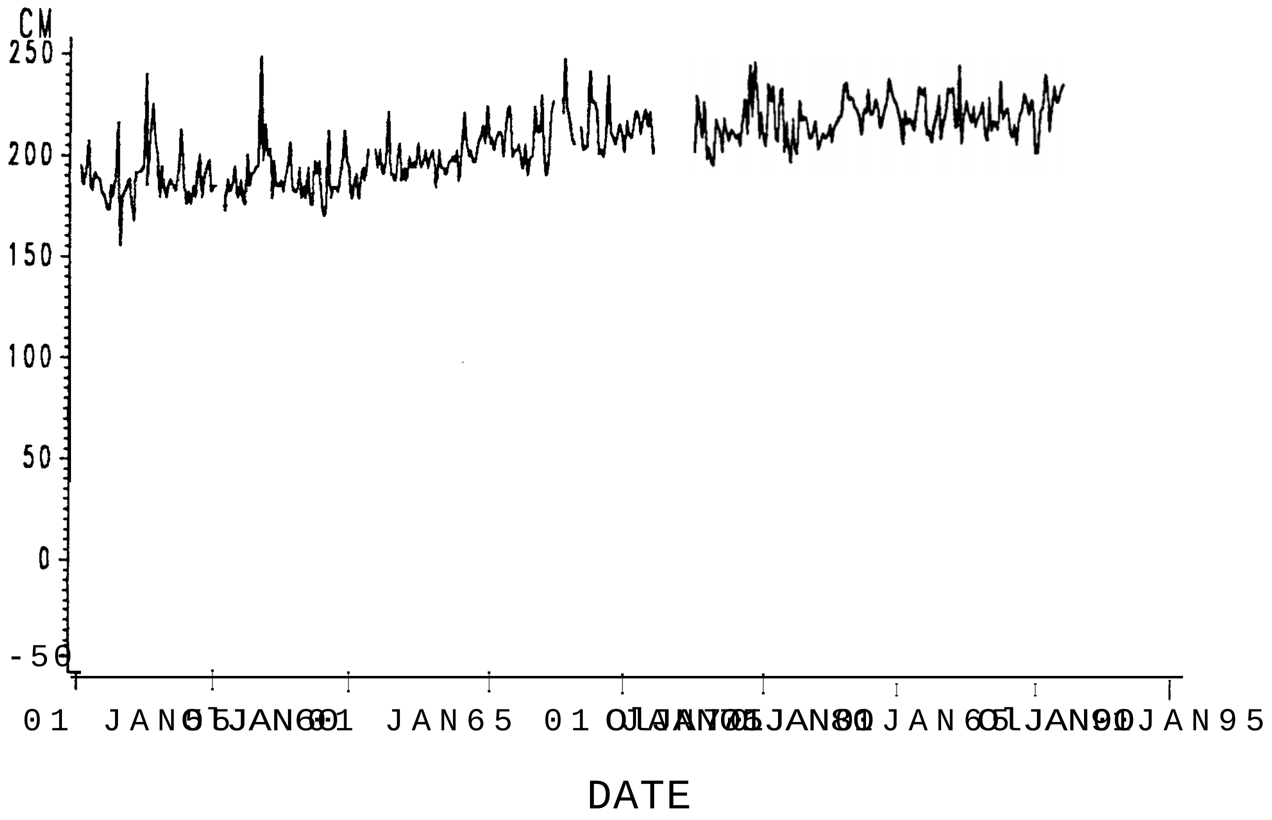
MONTHLY MINIMUM WATER LEVEL

STATION=3731 BAYOU RIGAUD



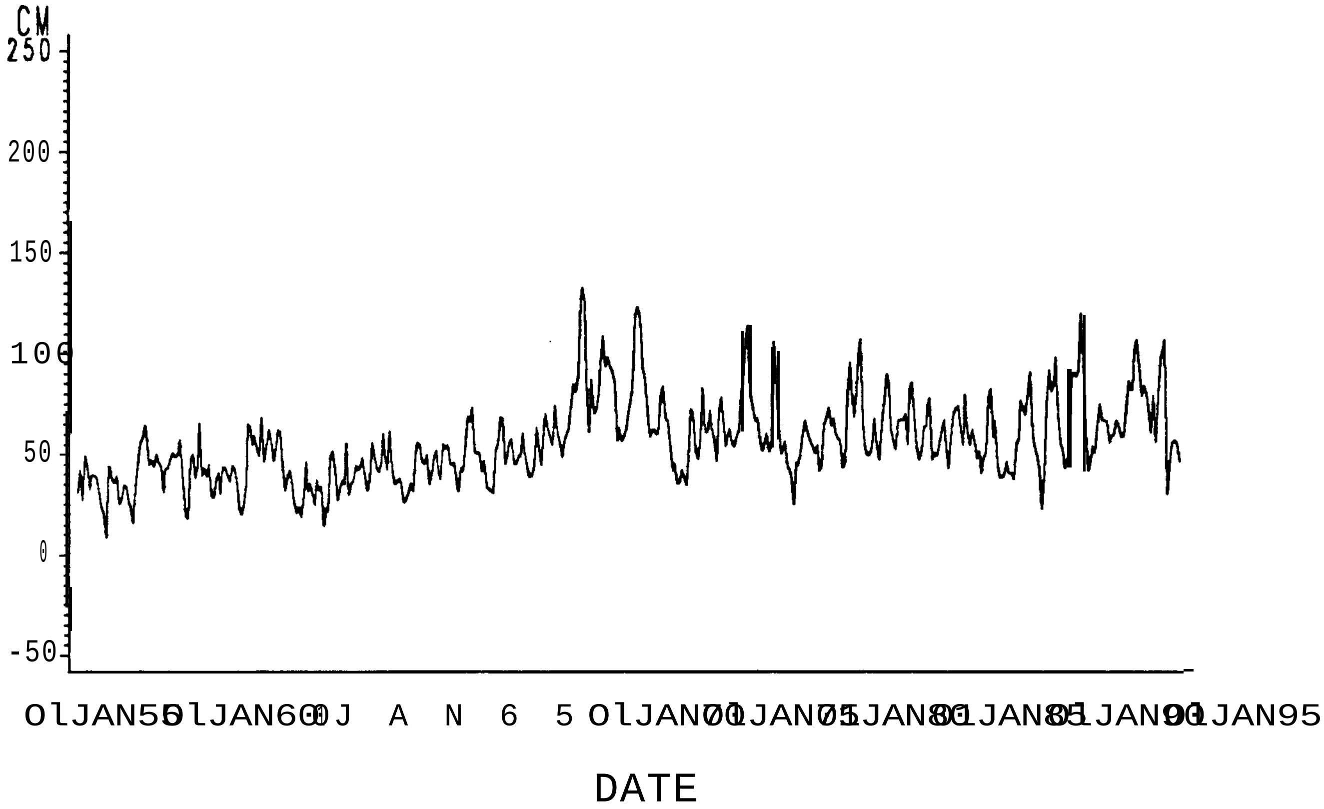
MONTHLY MAXIMUM WATER LEVEL

STATION=3731 BAYOU RIGAUD



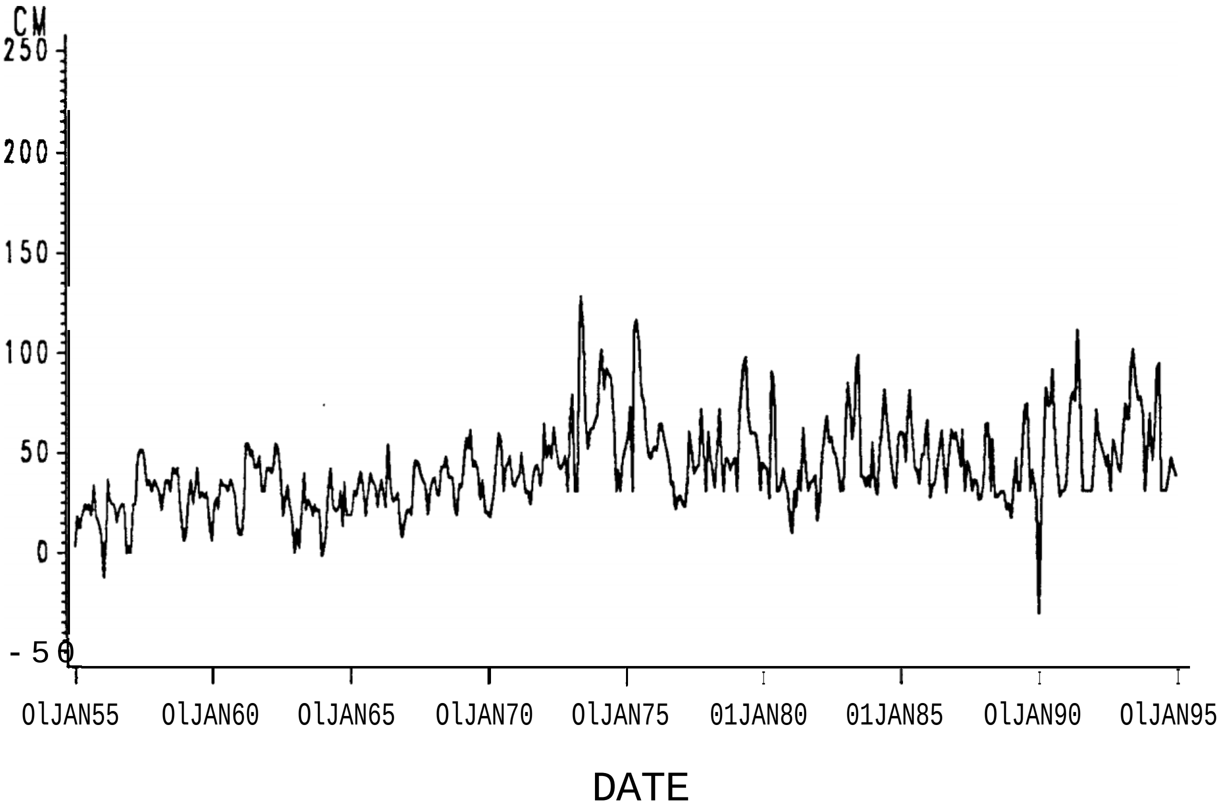
MONTHLY MEAN WATER LEVEL

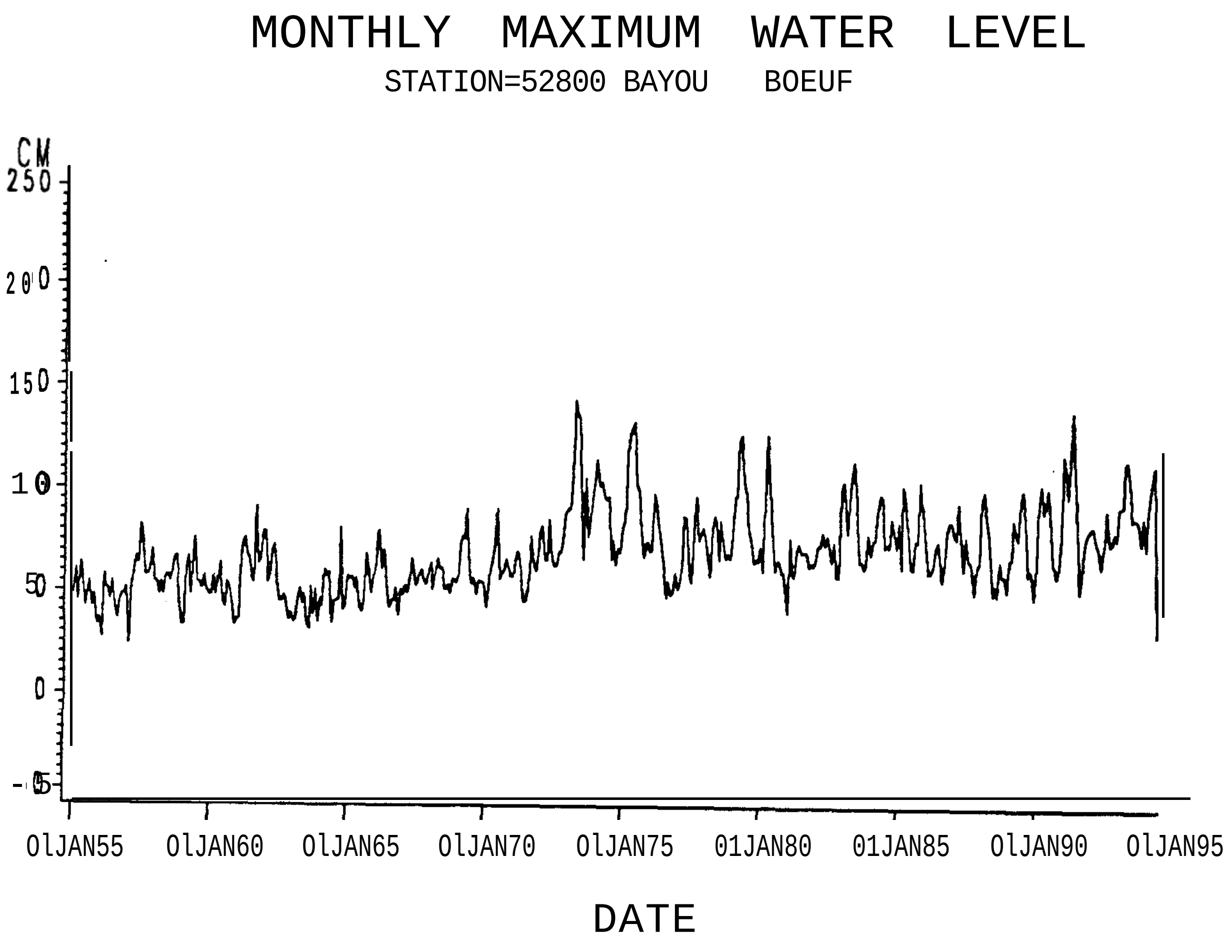
STATION=52800 BAYOU BOEUF



MONTHLY MINIMUM WATER LEVEL

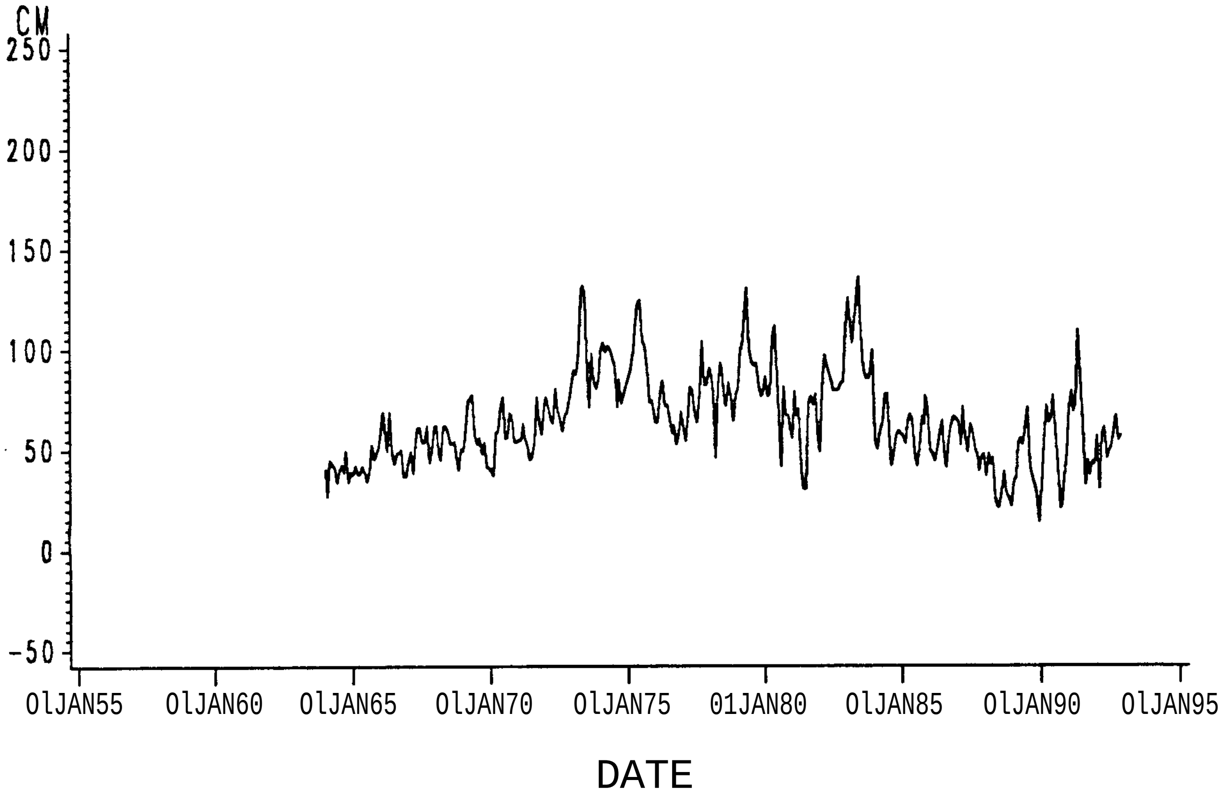
STATION=52800 BAYOU BOEUF




MONTHLY MAXIMUM WATER LEVEL
STATION=52800 BAYOU BOEUF
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

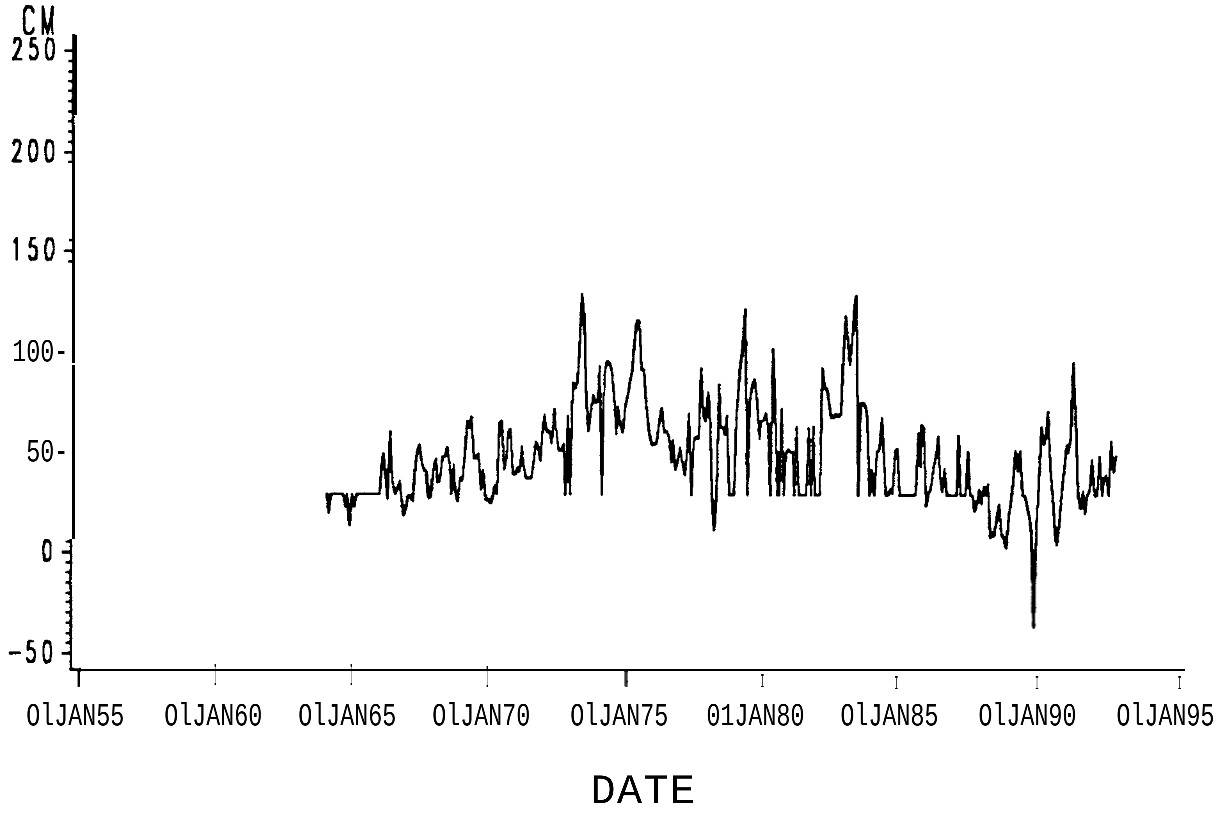
MONTHLY MEAN WATER LEVEL

STATION=52880 BAYOU BLACK



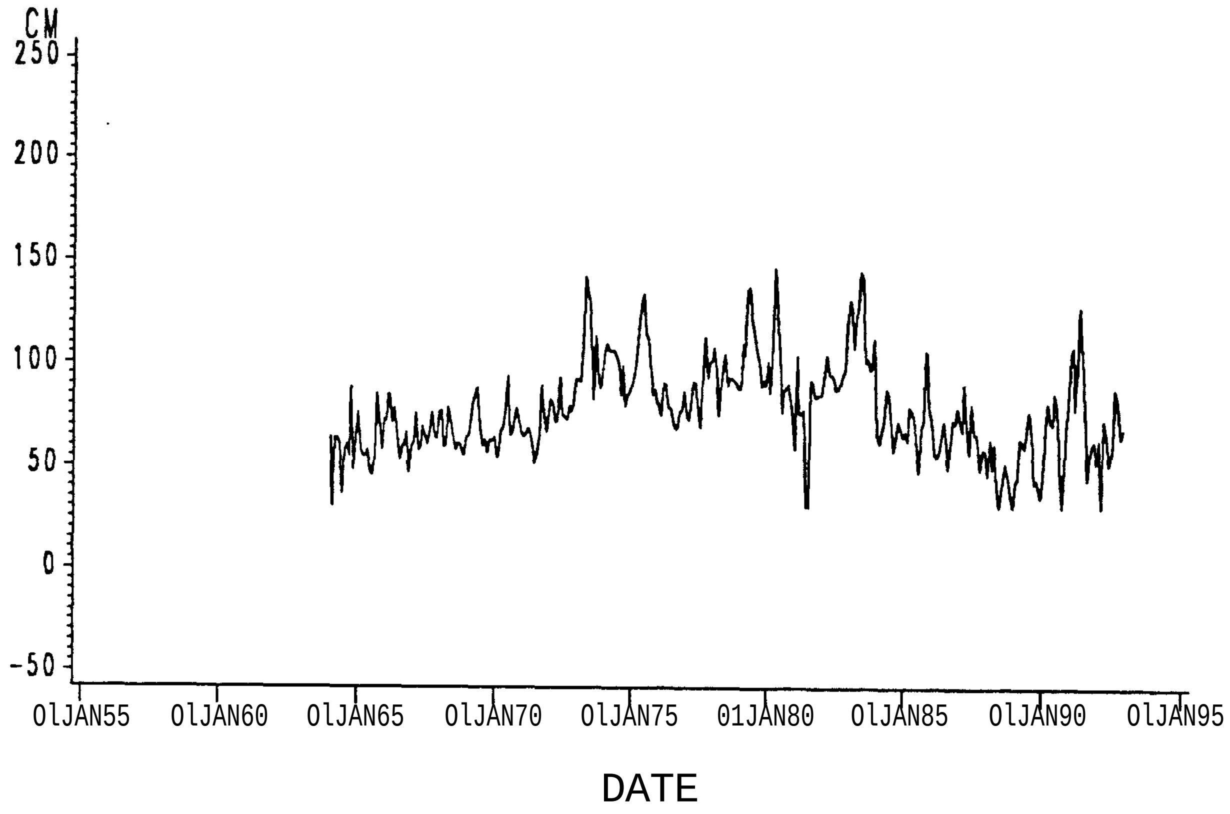
MONTHLY MINIMUM WATER LEVEL

STATION=52880 BAYOU BLACK



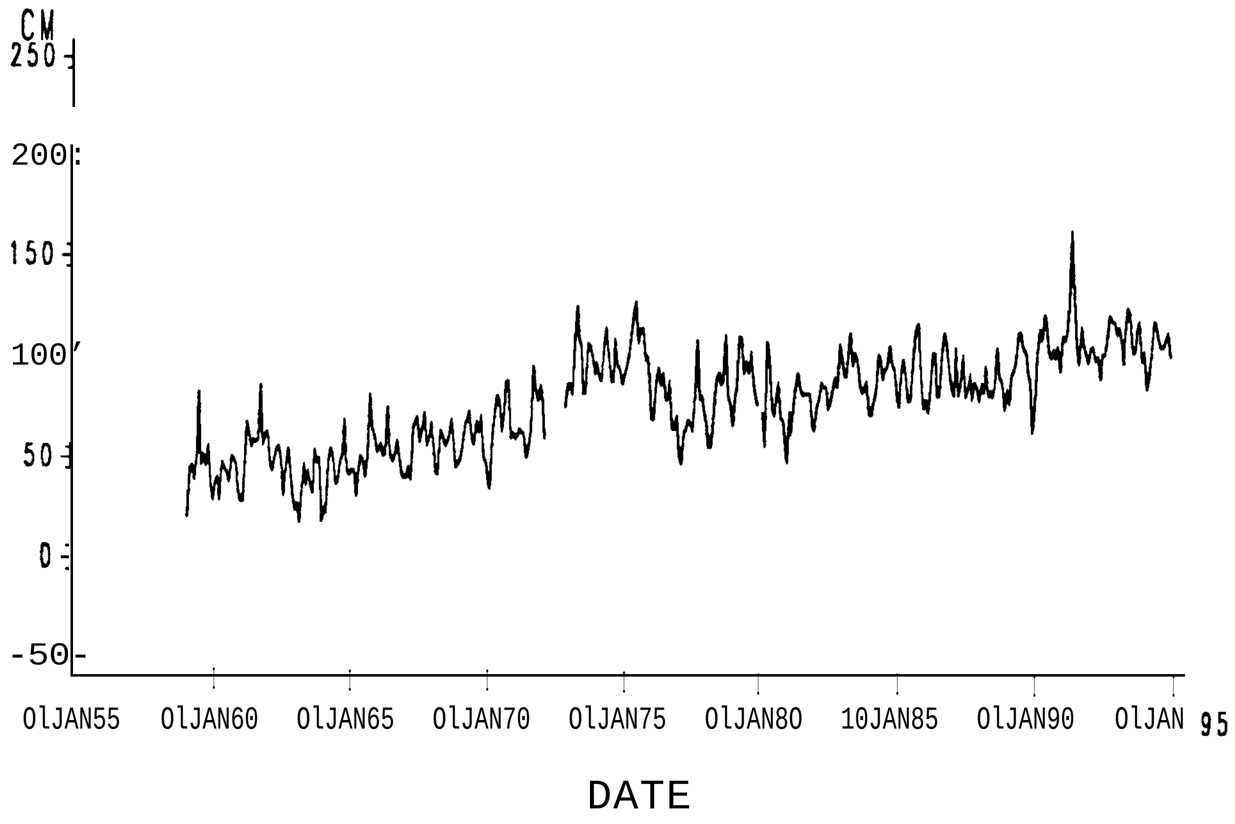
MONTHLY MAXIMUM WATER LEVEL

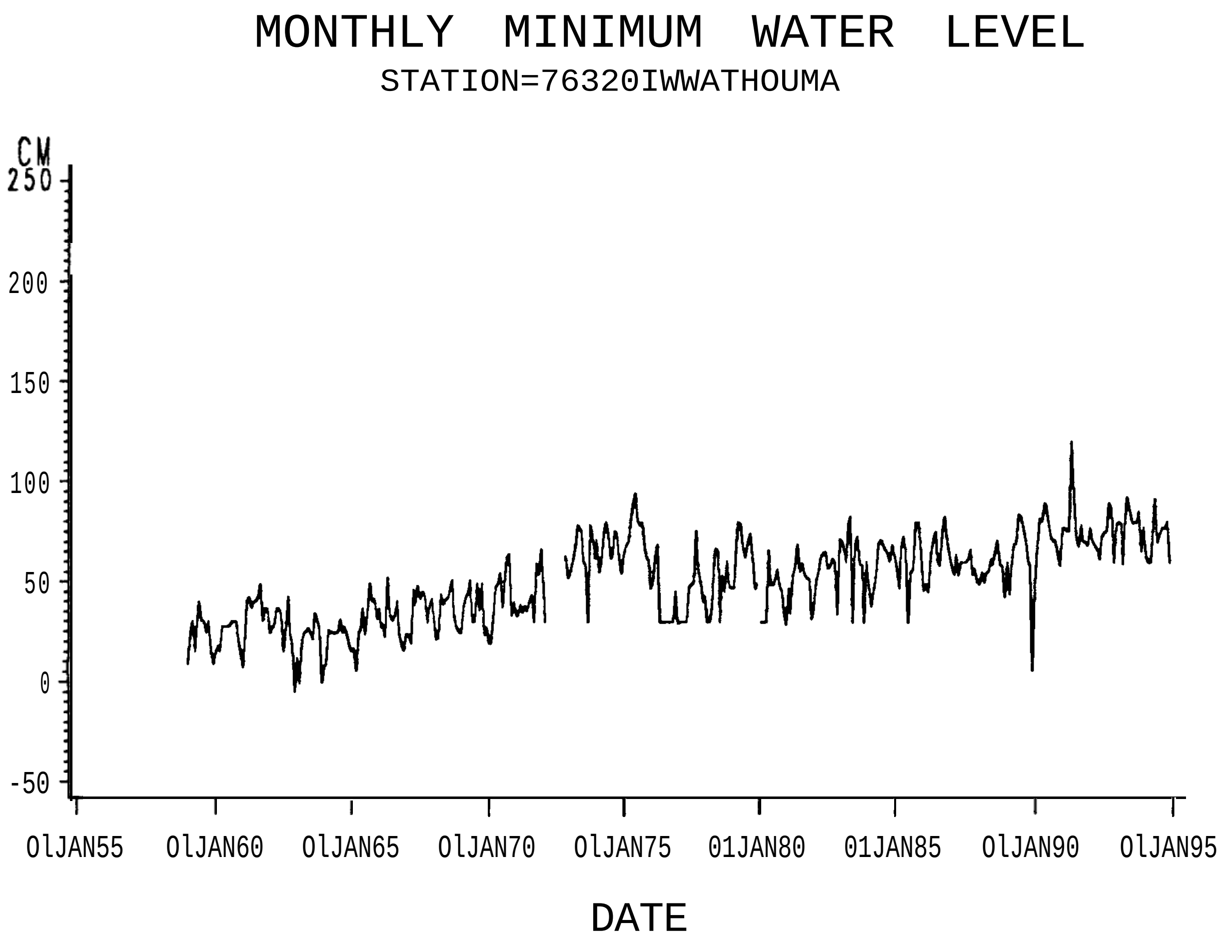
STATION=52880 BAYOU BLACK



MONTHLY MEAN WATER LEVEL

STATION=76320 **IWWAT HOUMA**

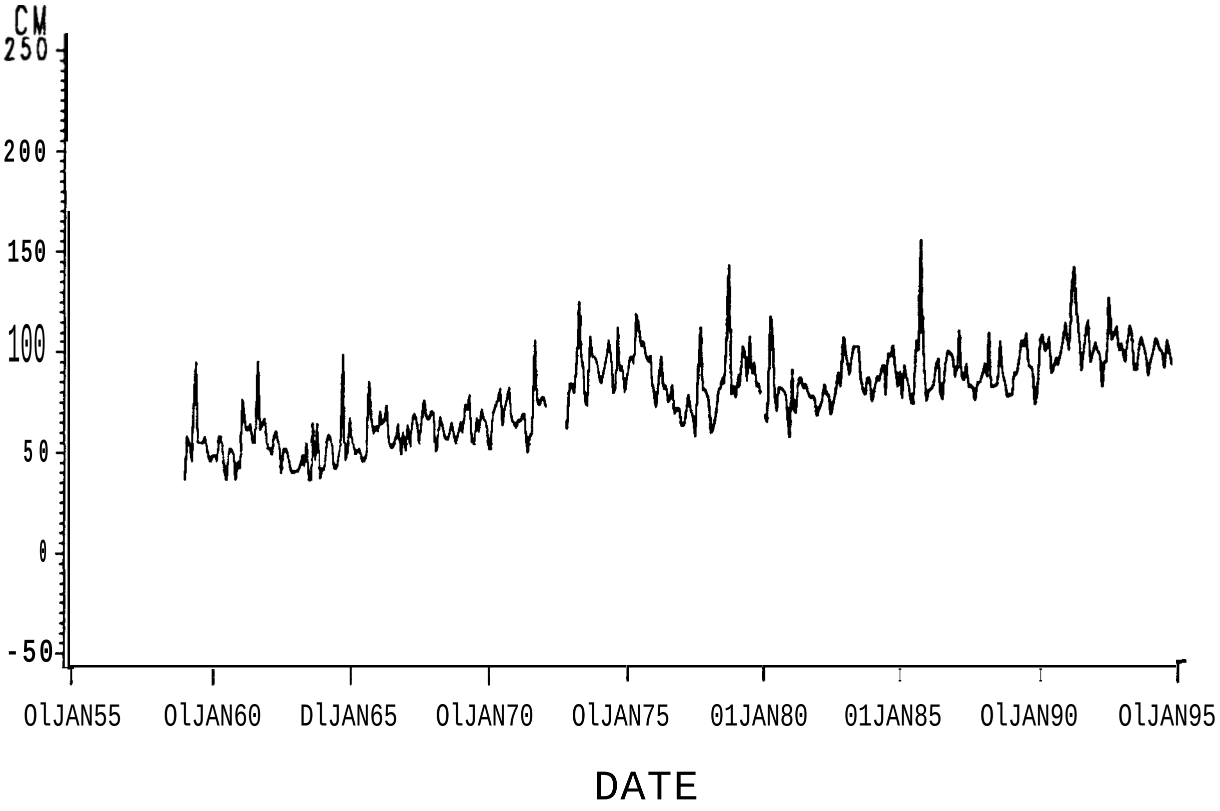




MONTHLY MINIMUM WATER LEVEL
STATION=76320IWWATHOUMA
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

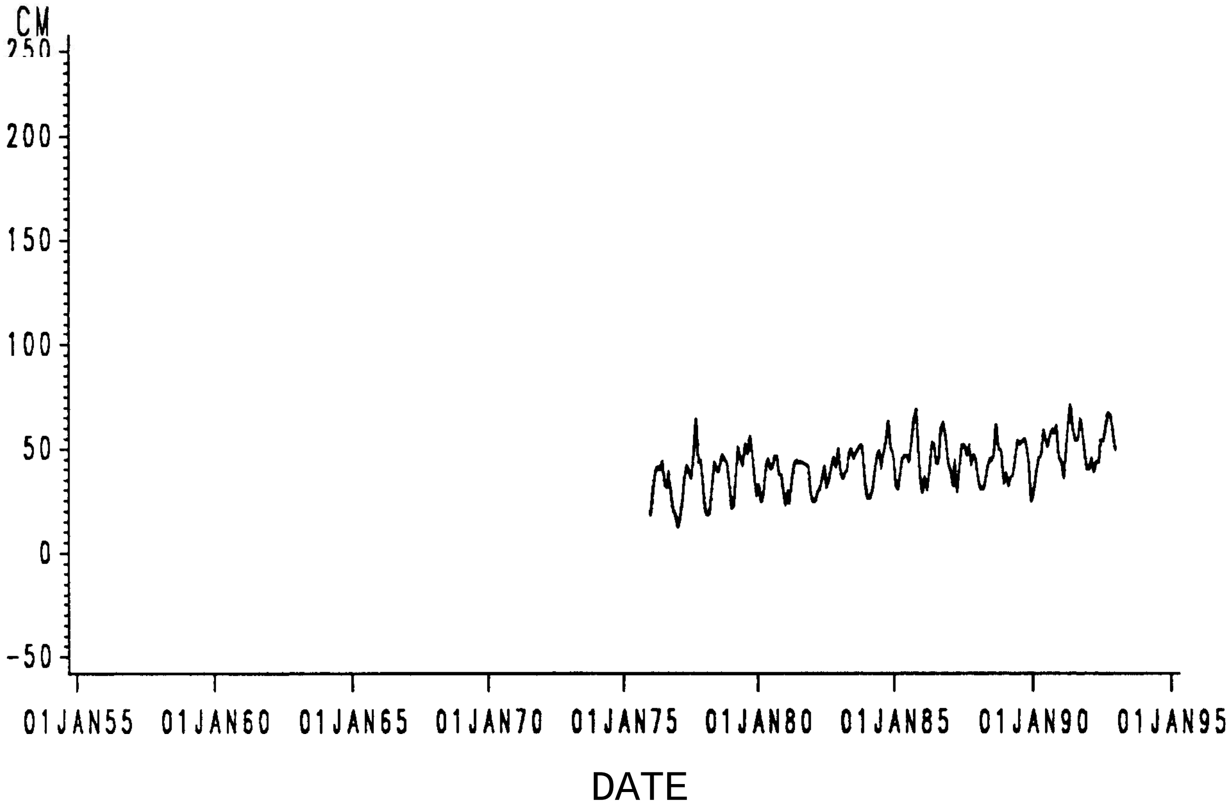
MONTHLY MAXIMUM WATER LEVEL

STATION=76320 IWW AT HOUMA



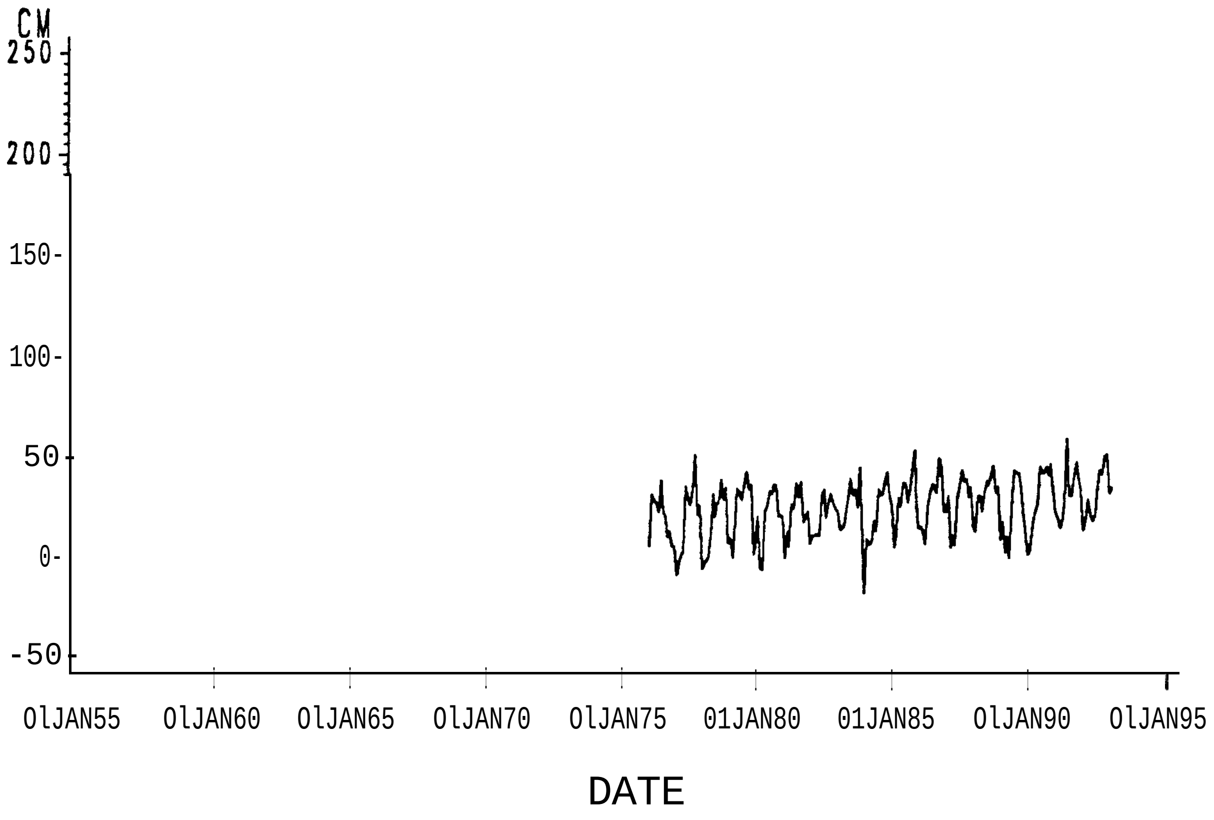
MONTHLY MEAN WATER LEVEL

STATION=82301 CATFISH LAKE



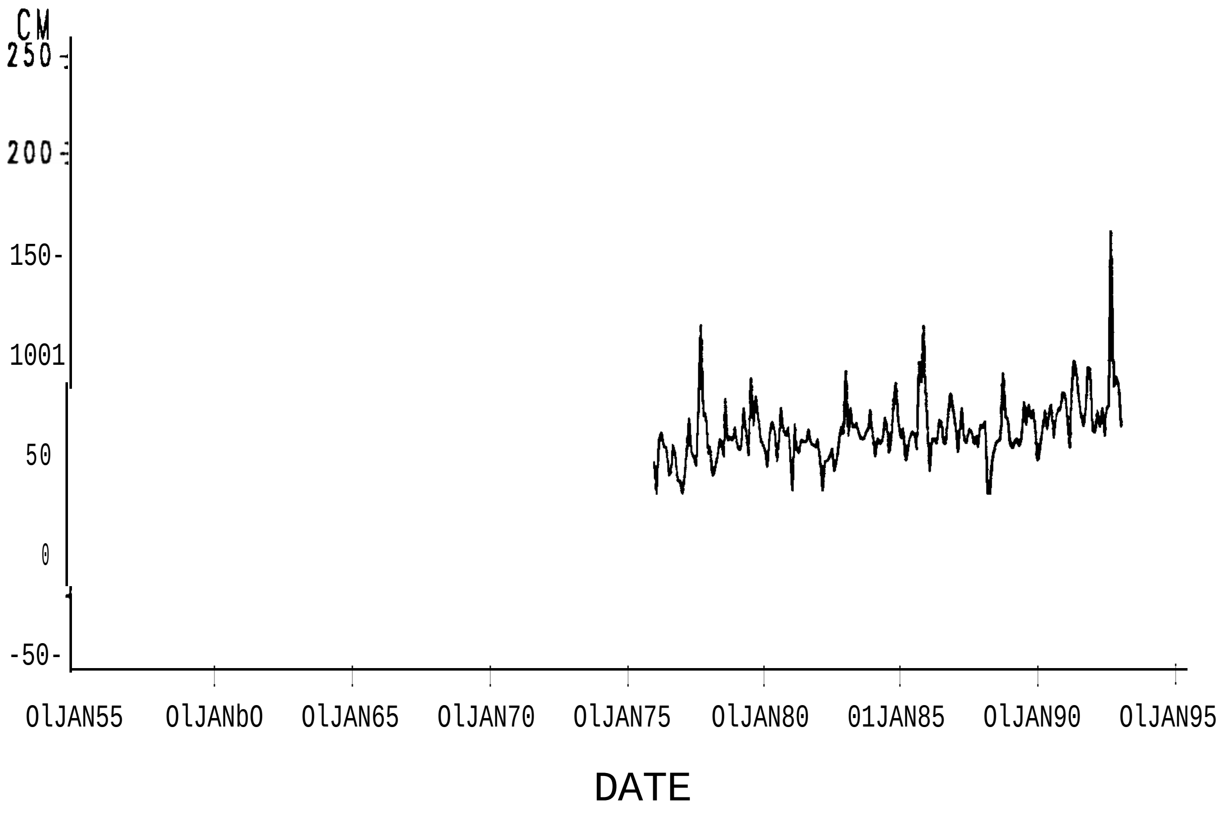
MONTHLY MINIMUM WATER LEVEL

STATION=62301 CATFISH LAKE



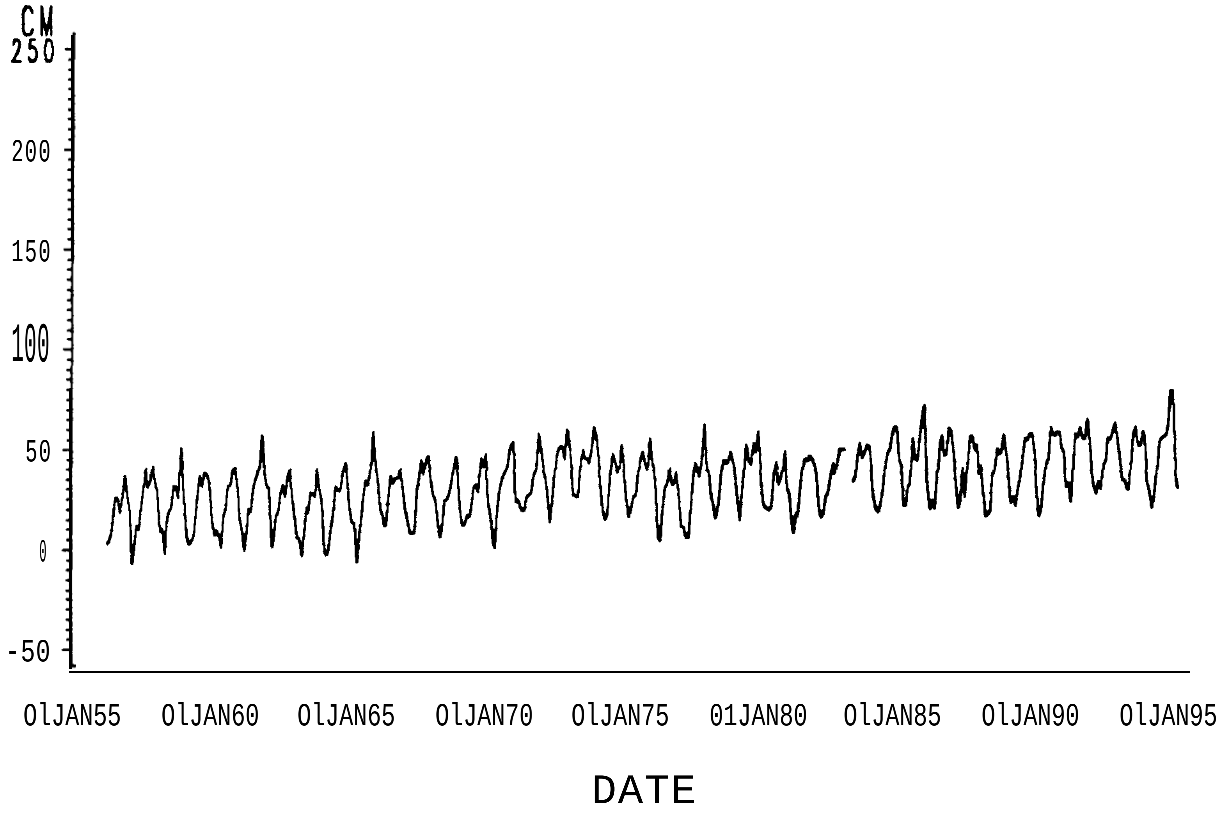
MONTHLY MAXIMUM WATER LEVEL

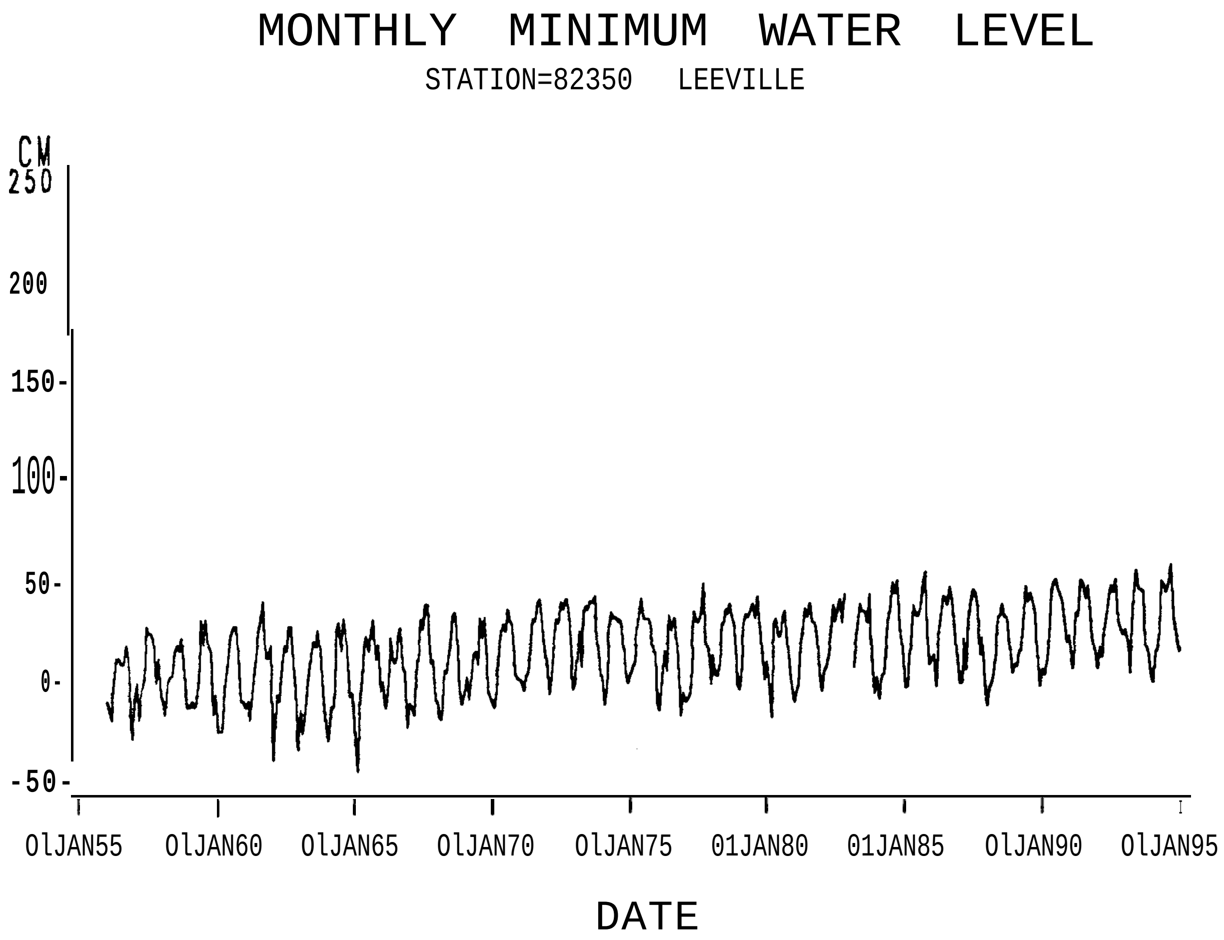
STATION=82301 CATFISH LAKE

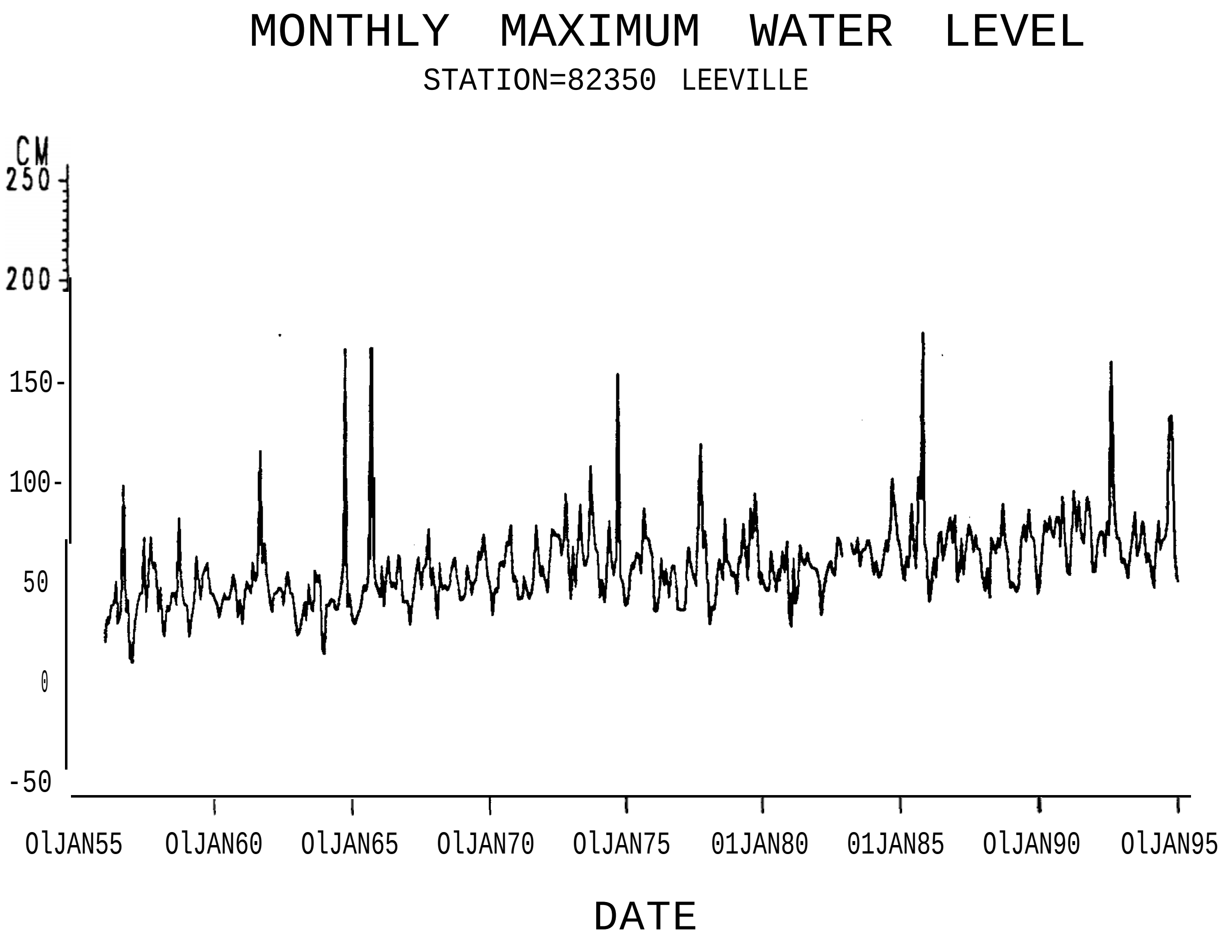


MONTHLY MEAN WATER LEVEL

STATION=82350 LEEVILLE

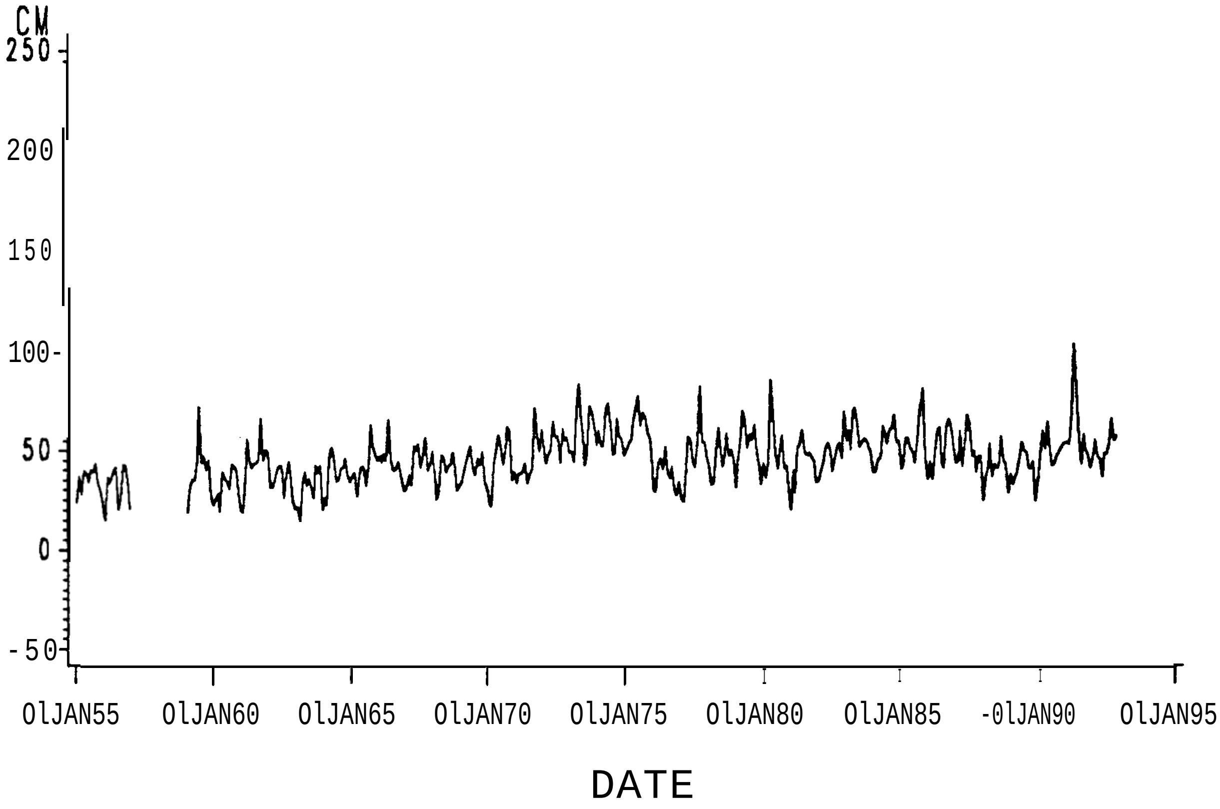



MONTHLY MINIMUM WATER LEVEL
STATION=82350 LEEVILLE
CM
250
200
150-
100-
50-
0-
-50-
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE


MONTHLY MAXIMUM WATER LEVEL
STATION=82350 LEEVILLE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

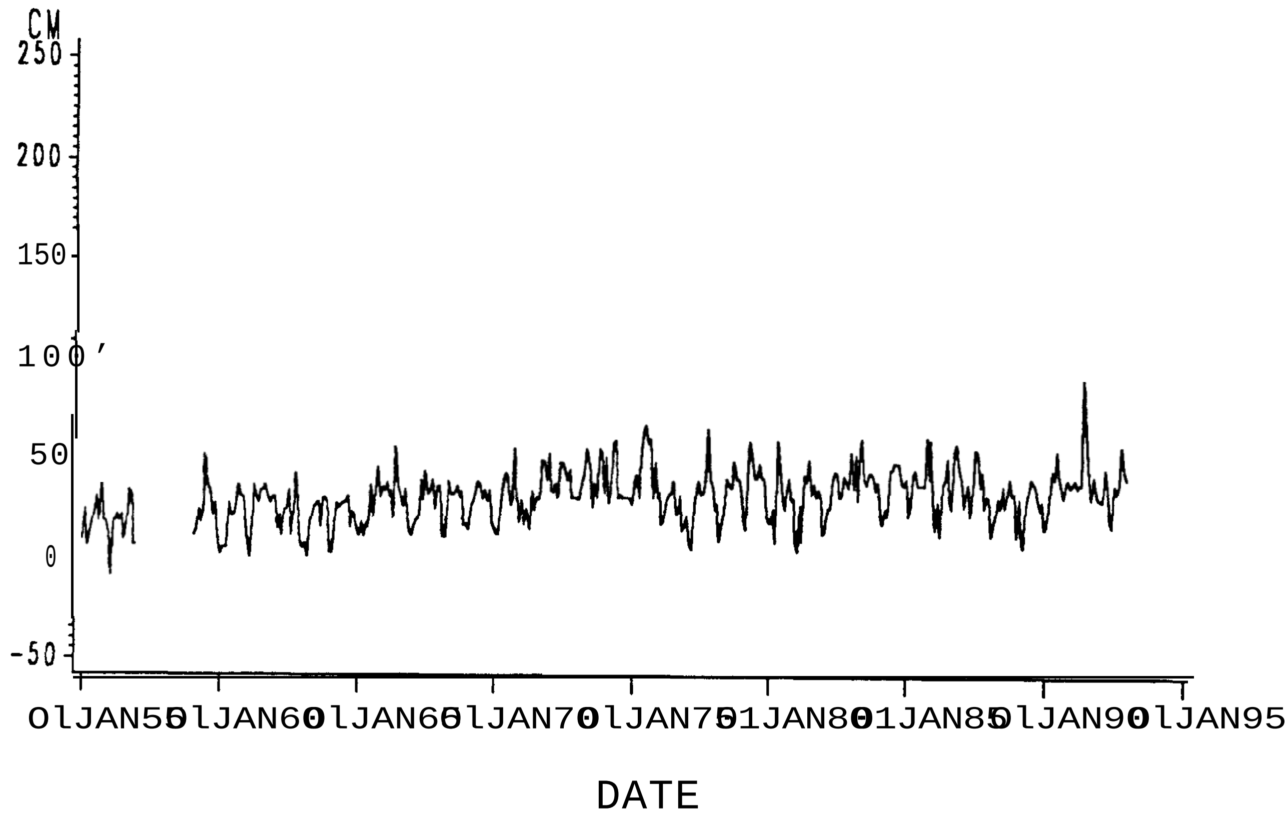
MONTHLY MEAN WATER LEVEL

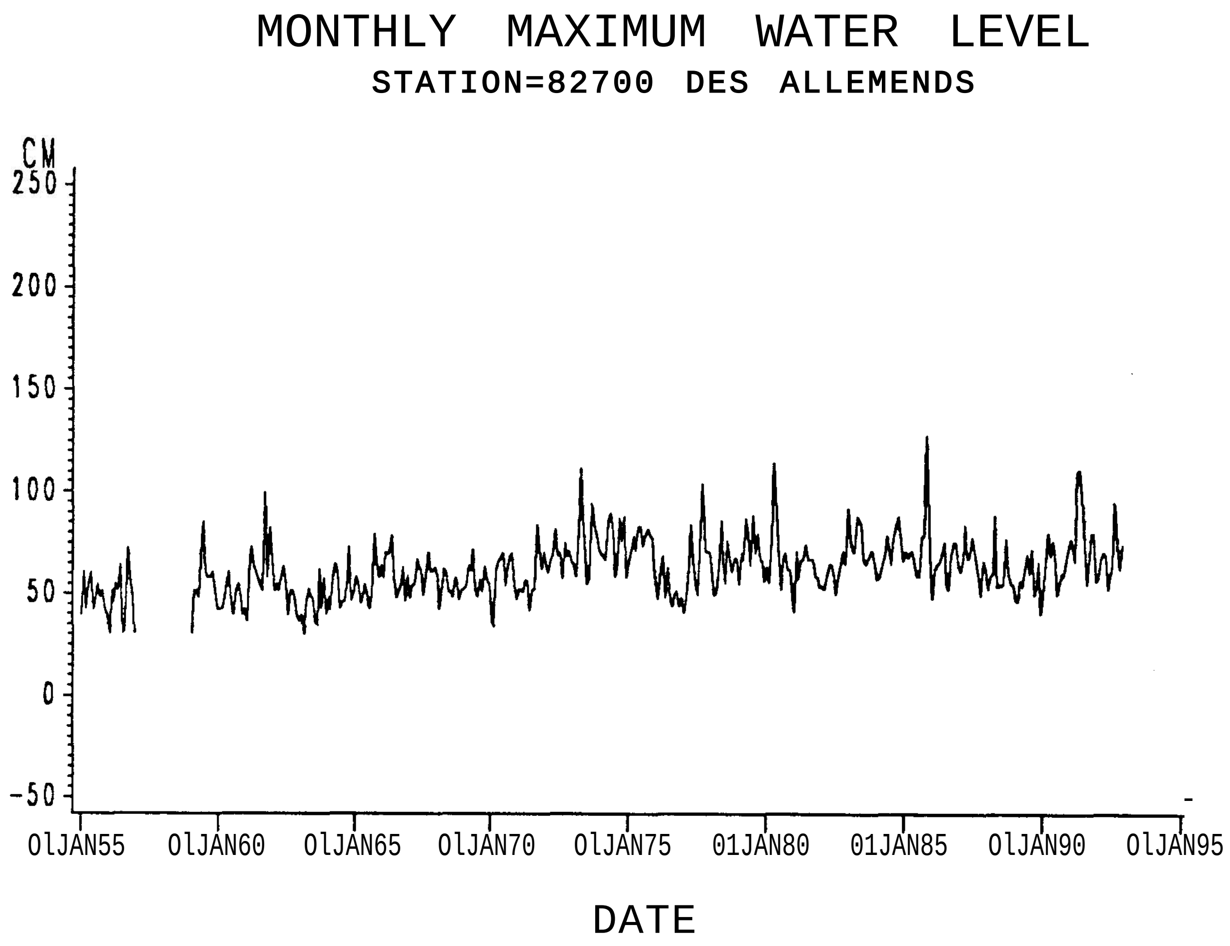
STATION=82700 DES ALLEMENDS



MONTHLY MINIMUM WATER LEVEL

STATION=82700 DES ALLEMENDS




MONTHLY MAXIMUM WATER LEVEL
STATION=82700 DES ALLEMENDS
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
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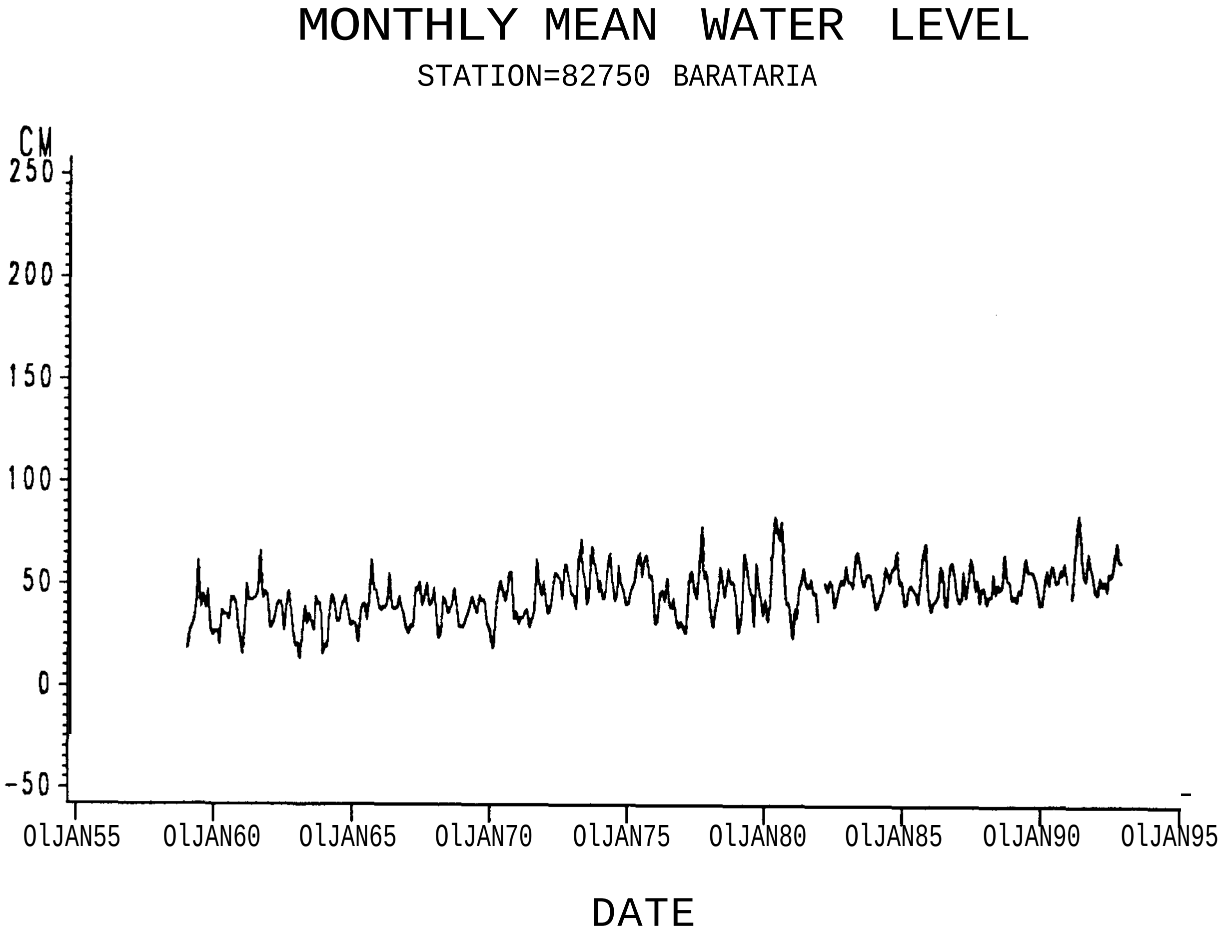
01JAN90
01JAN95
DATE


MONTHLY MEAN WATER LEVEL
STATION=82750 BARATARIA
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
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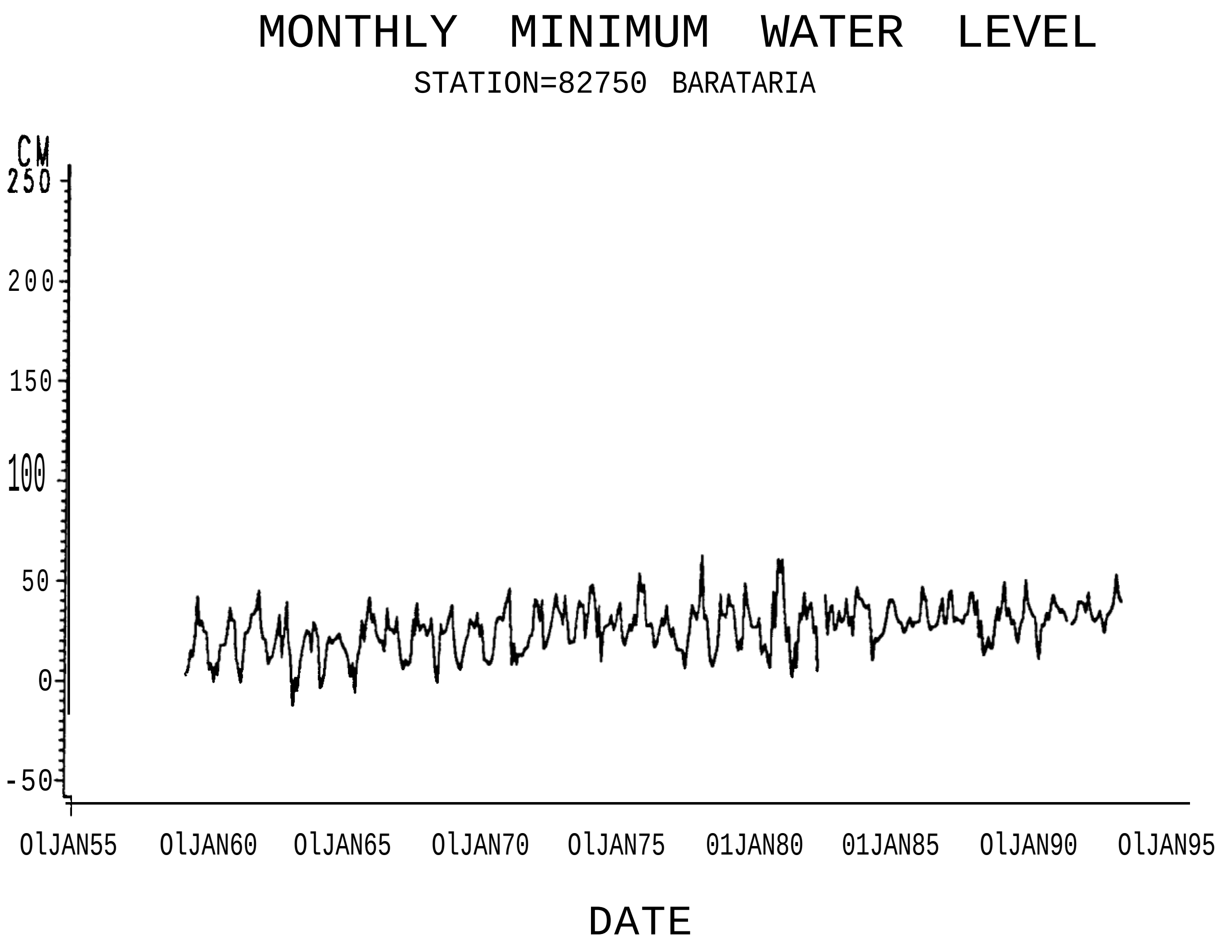
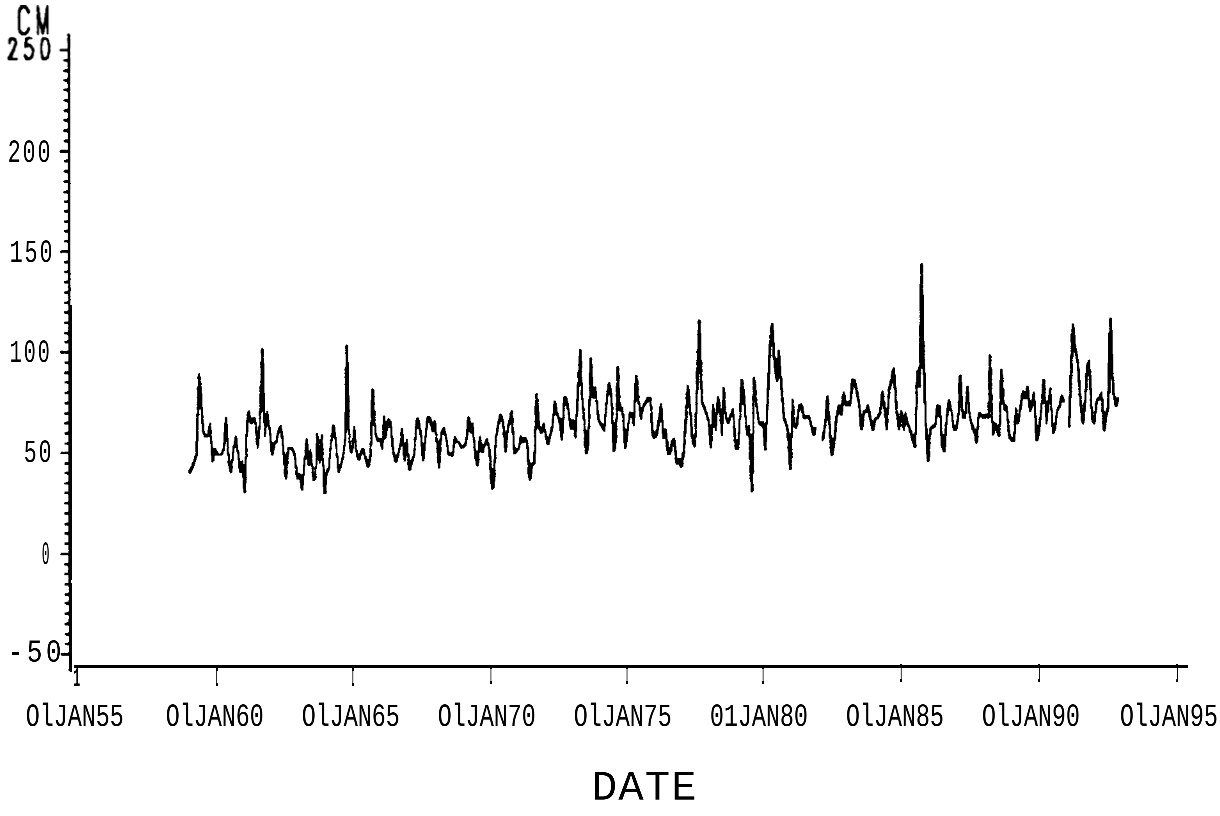
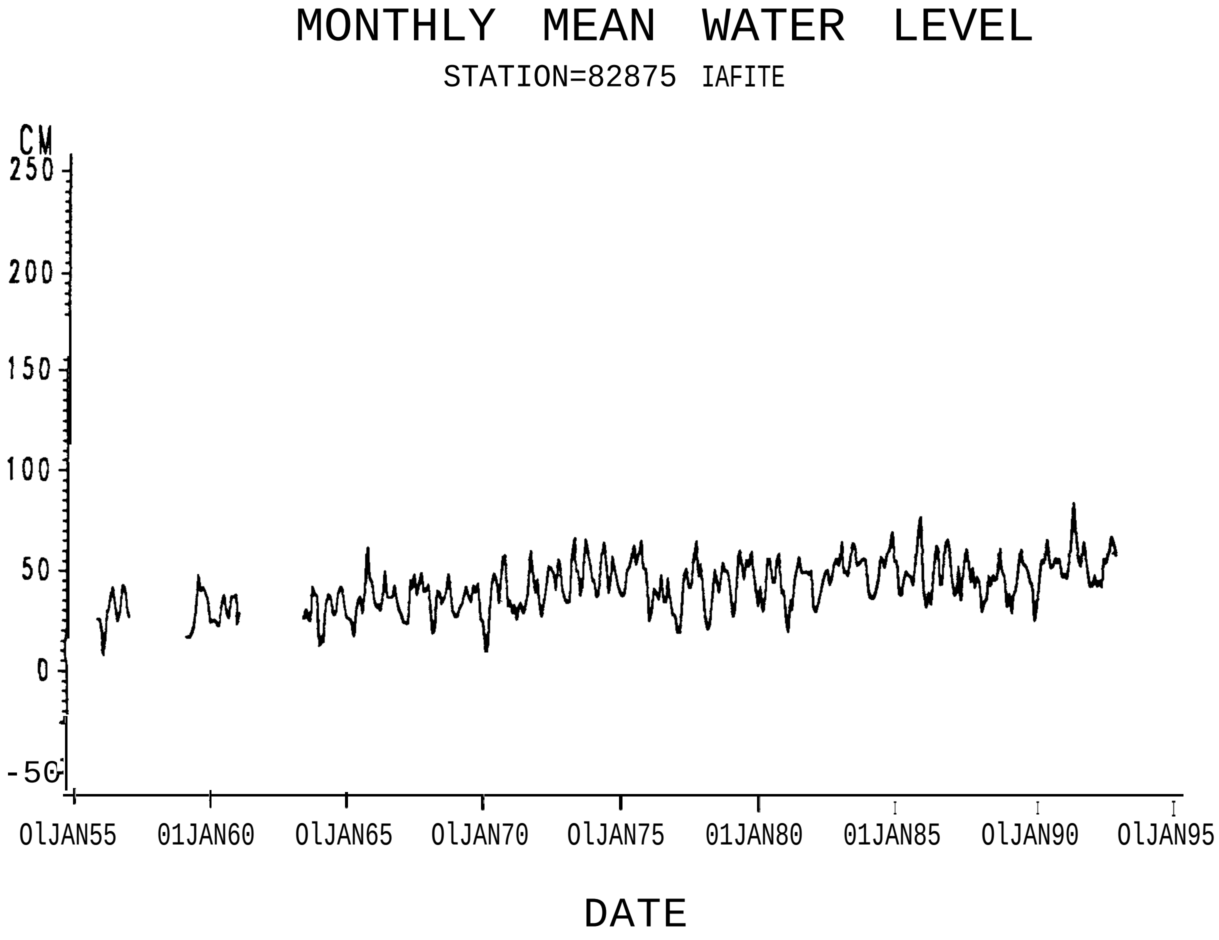
01JAN90
01JAN95
DATE


MONTHLY MINIMUM WATER LEVEL
STATION=82750 BARATARIA
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

MONTHLY MAXIMUM WATER LEVEL

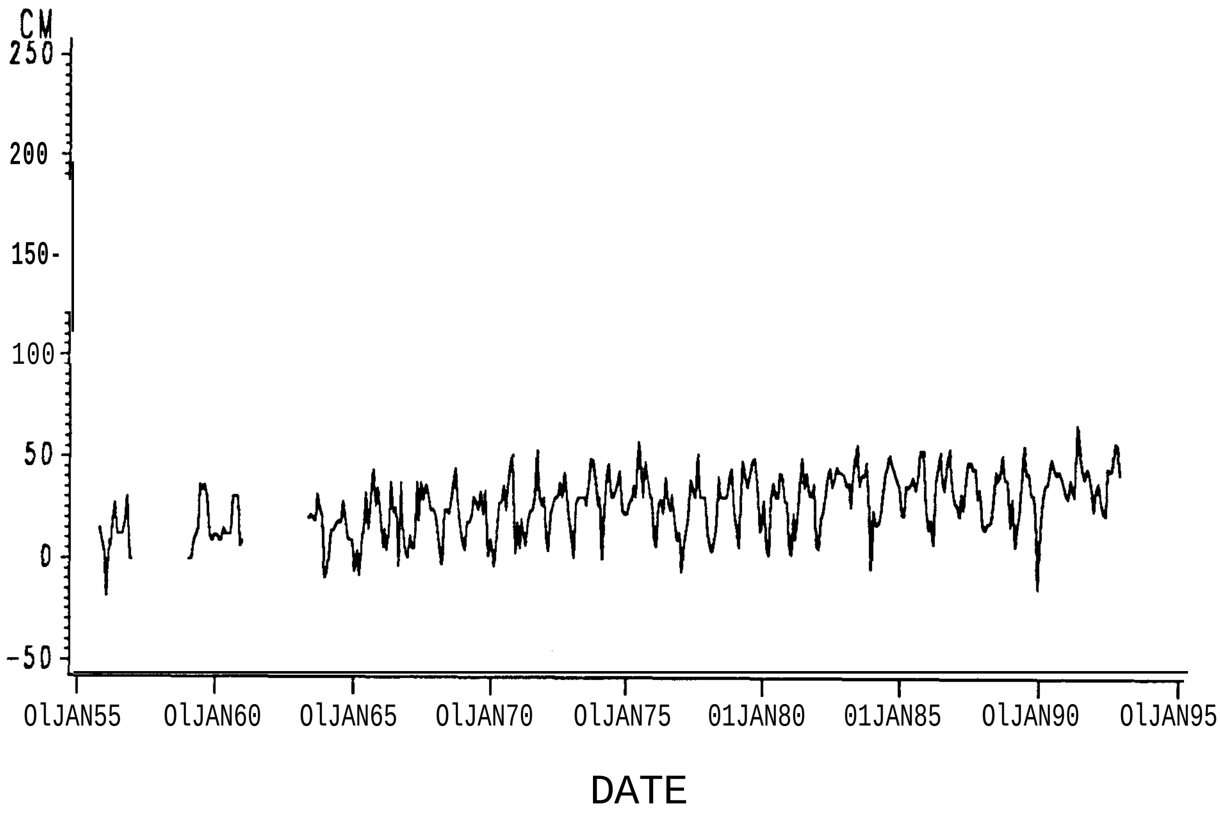
STATION=8275000 BARATARIA




MONTHLY MEAN WATER LEVEL
STATION=82875 IAFITE
CM
250
200
150
100
50
0
-50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

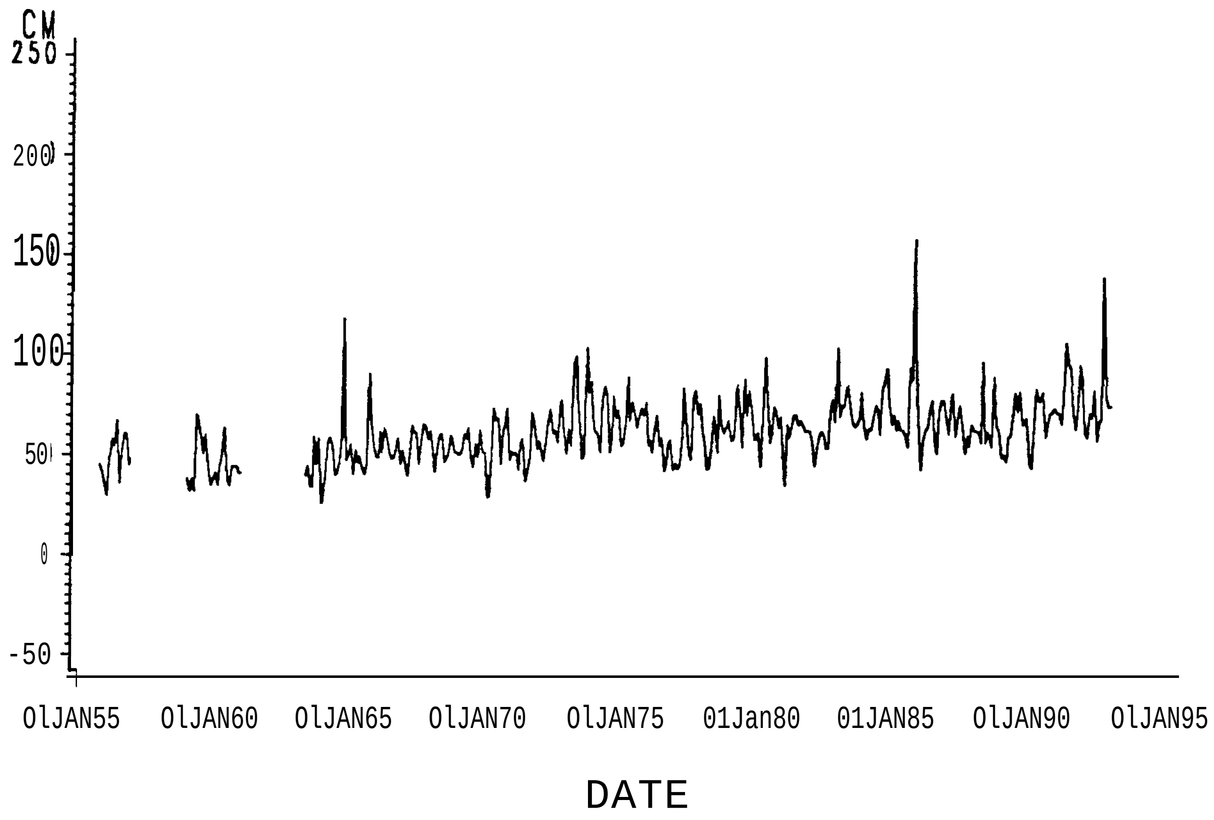
MONTHLY MINIMUM WATER LEVEL

STATION=82875 IAFITE



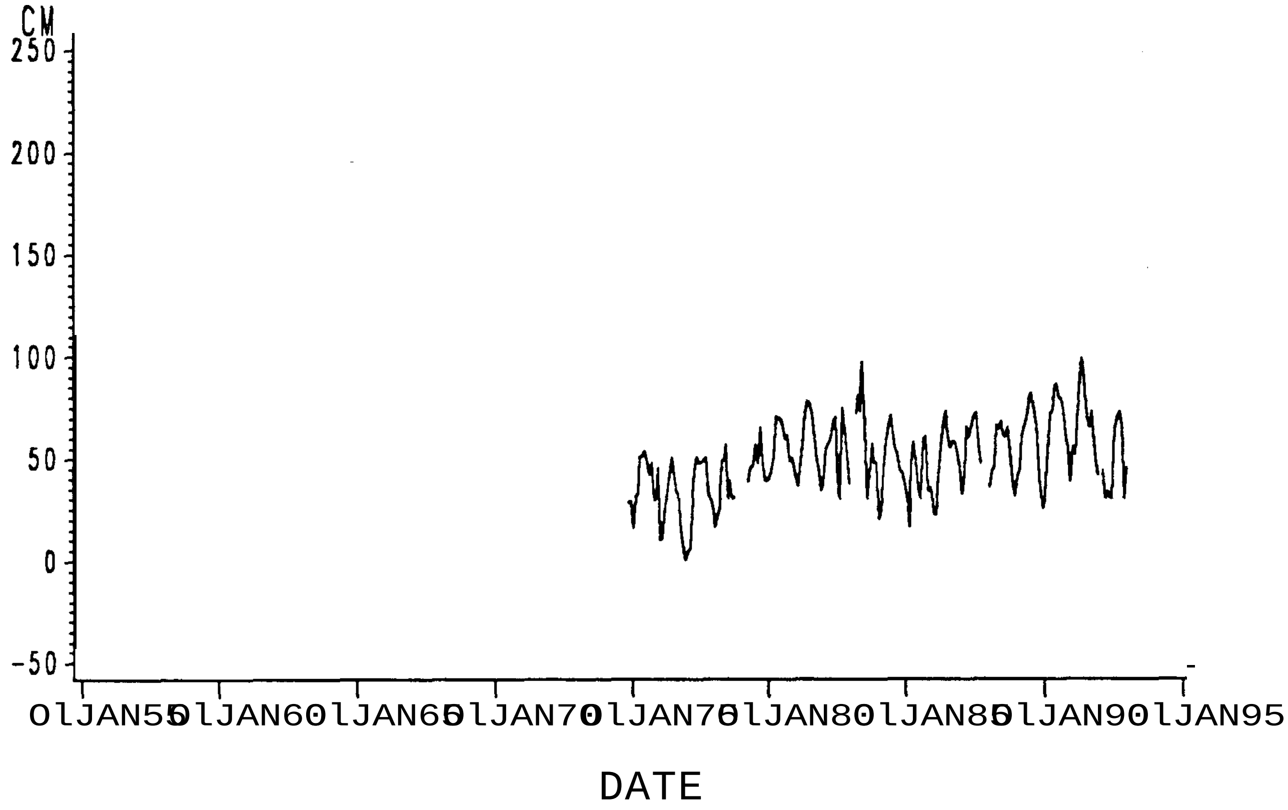
MONTHLY MAXIMUM WATER LEVEL

STATION=82875 Lafite



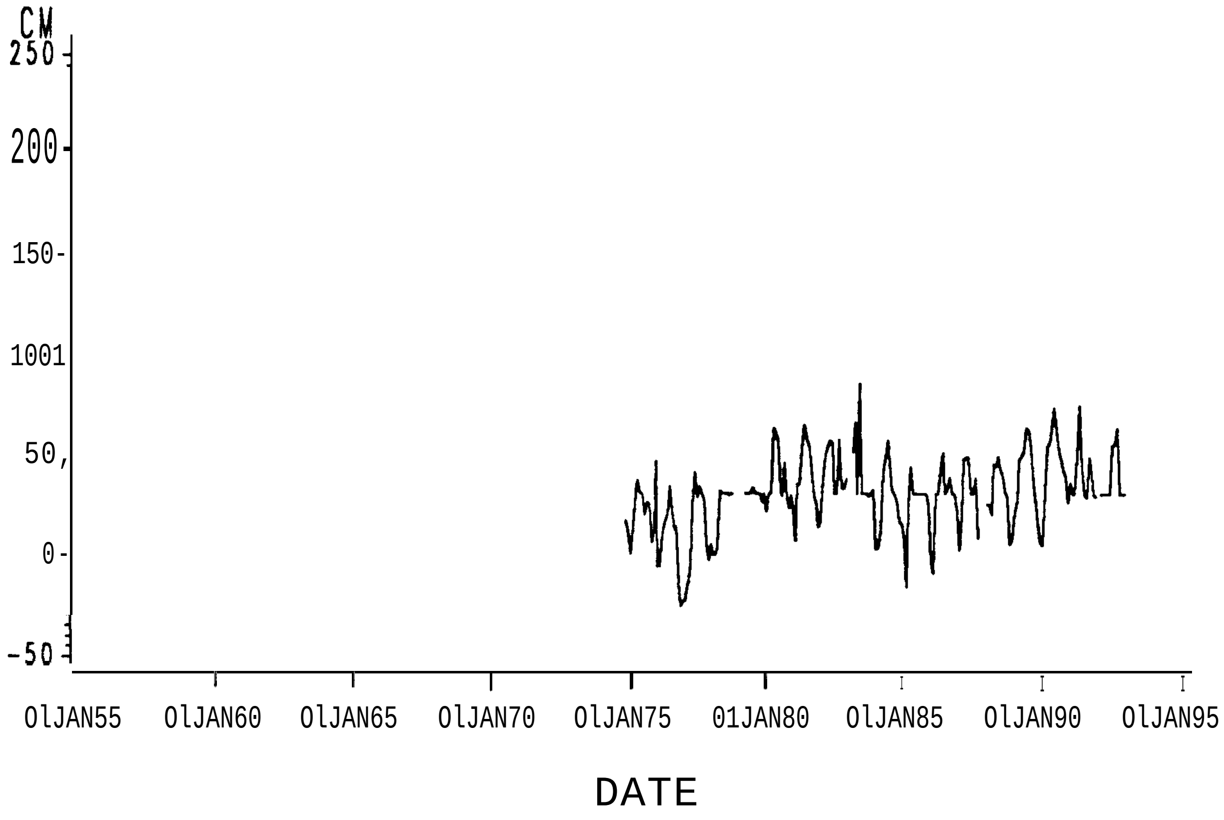
MONTHLY MEAN WATER LEVEL

STATION=88350 WEST BAY



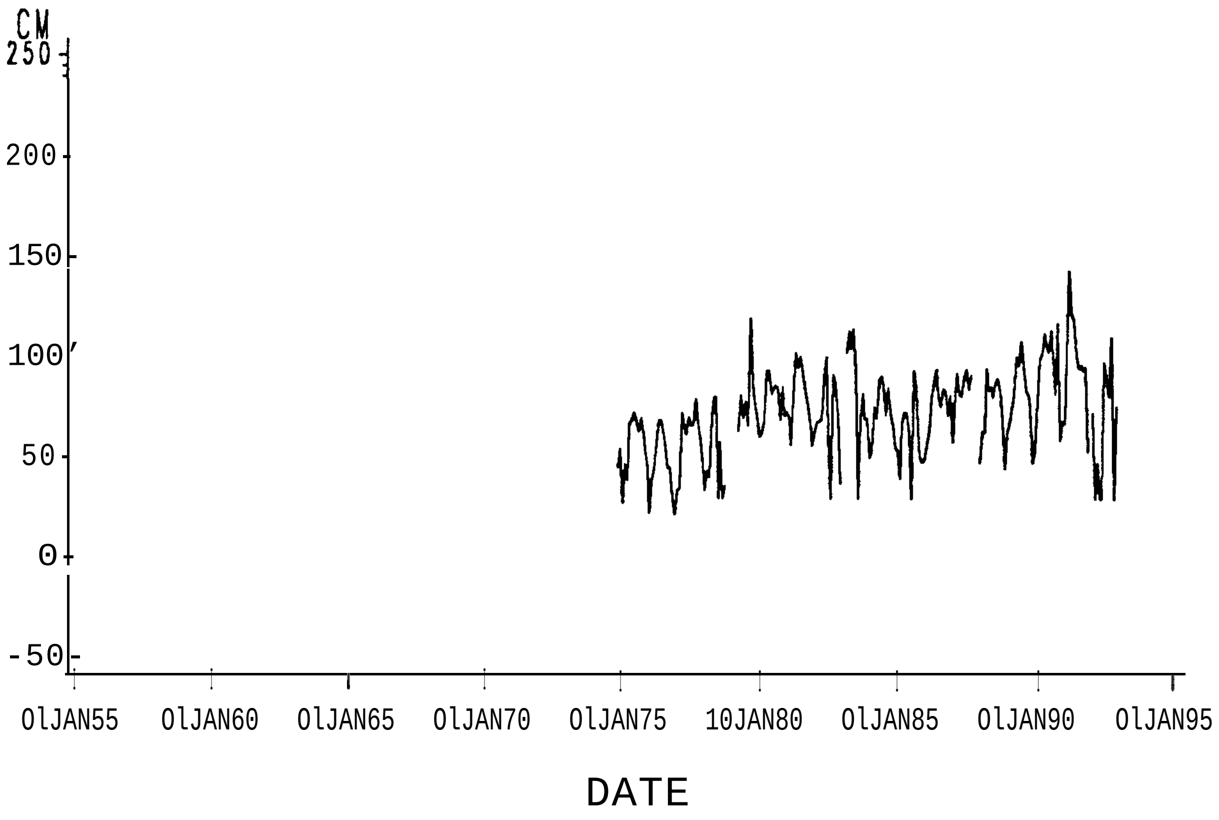
MONTHLY MINIMUM WATER LEVEL

STATION=88350 WEST BAY



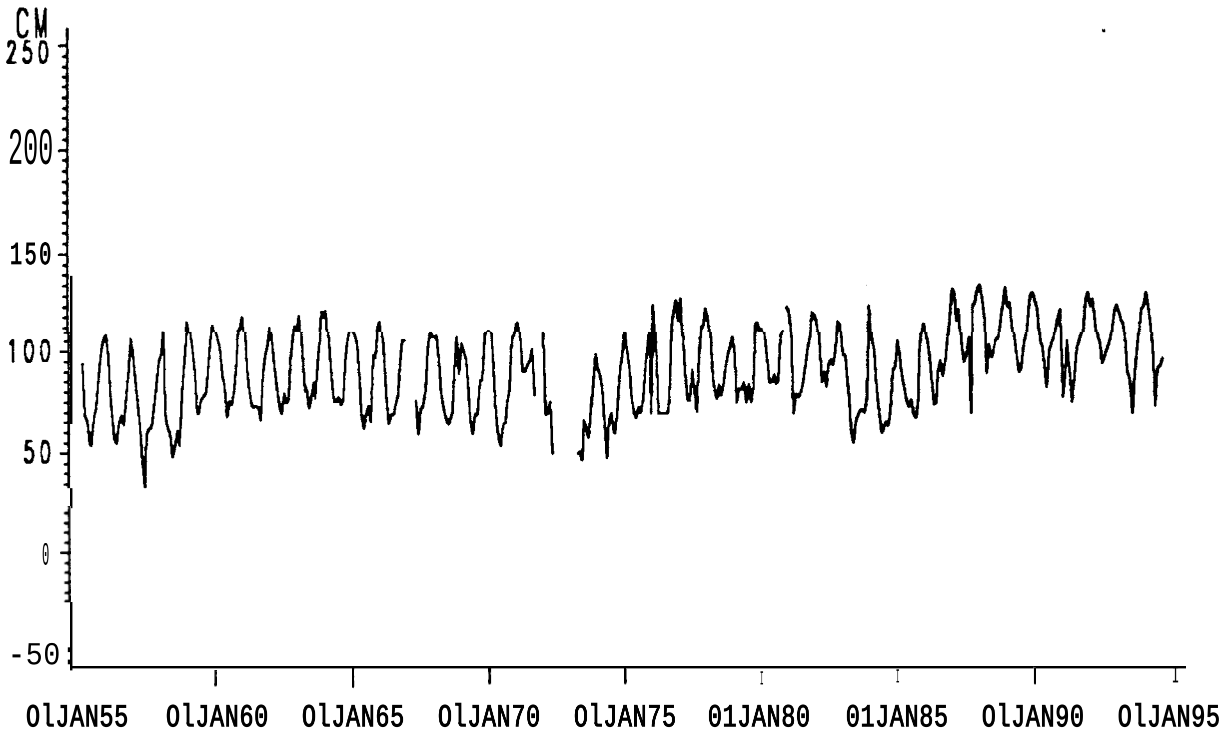
MONTHLY MAXIMUM WATER LEVEL

STATION=88350 WEST BAY



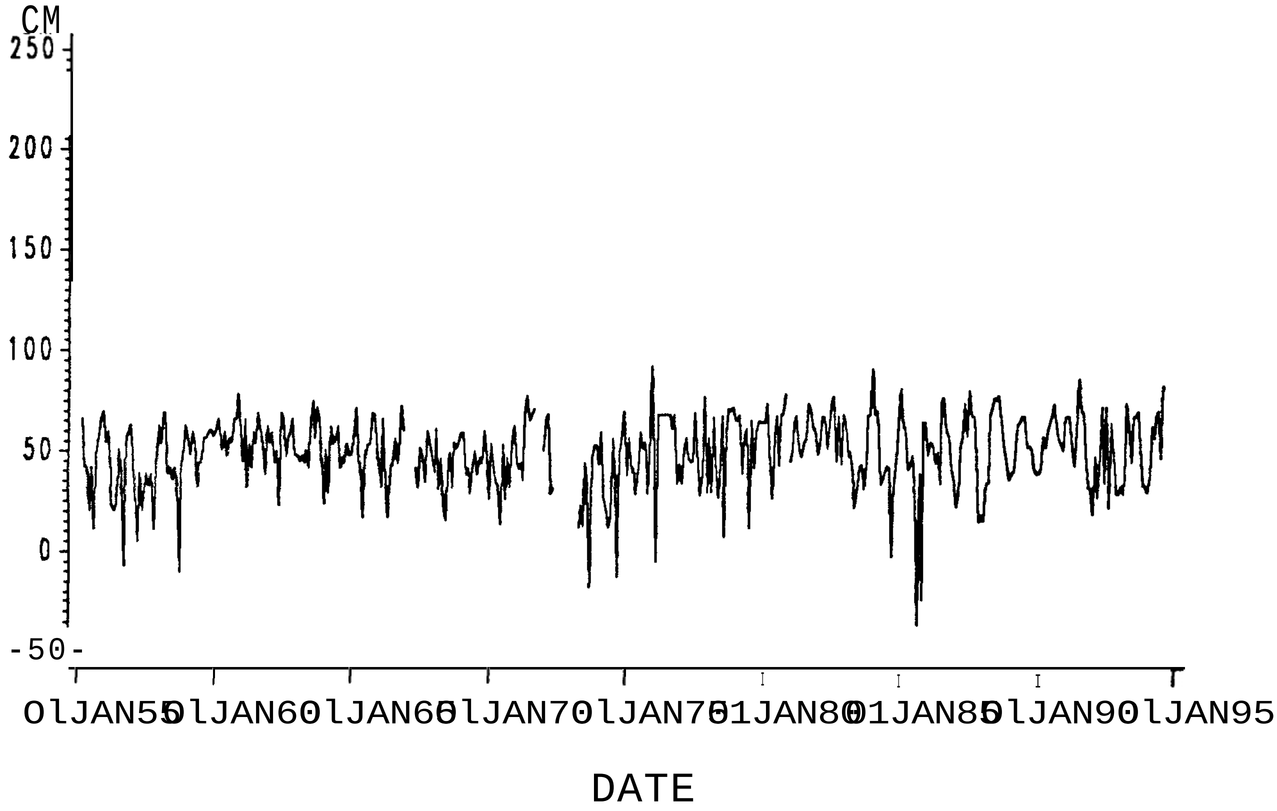
MONTHLY MEAN WATER LEVEL

STATION=88600 EUGENE ISlAND



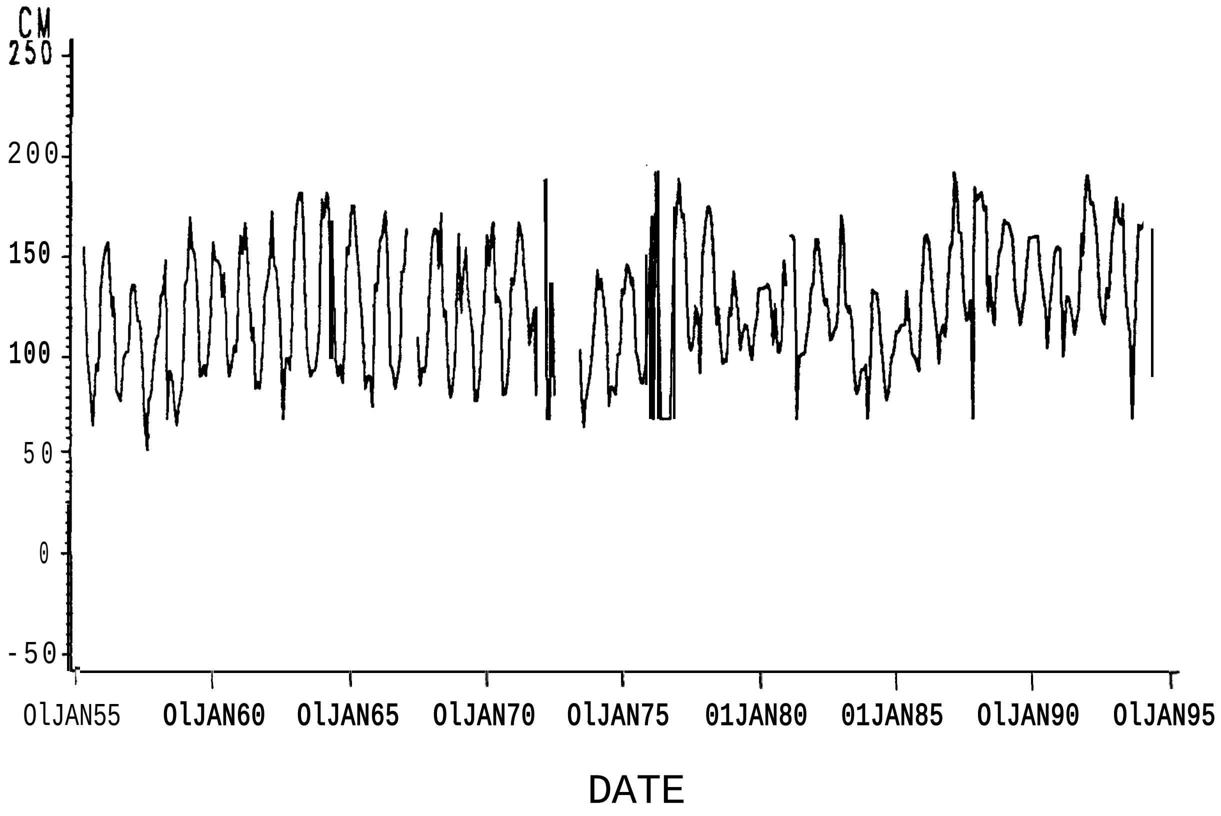
MONTHLY MINIMUM WATER LEVEL

STATION=88600 EUGENE ISLAND



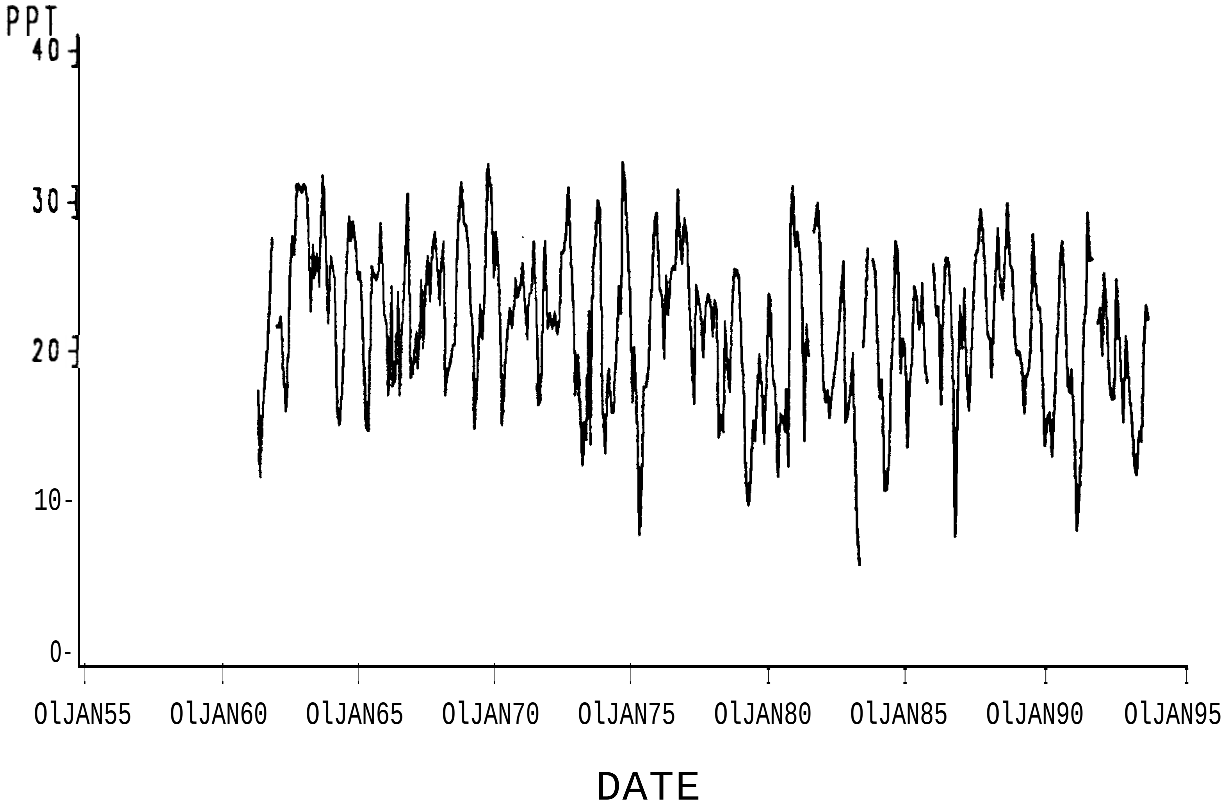
MONTHLY MAXIMUM WATER LEVEL

STATION=88600 EUGENE ISLAND



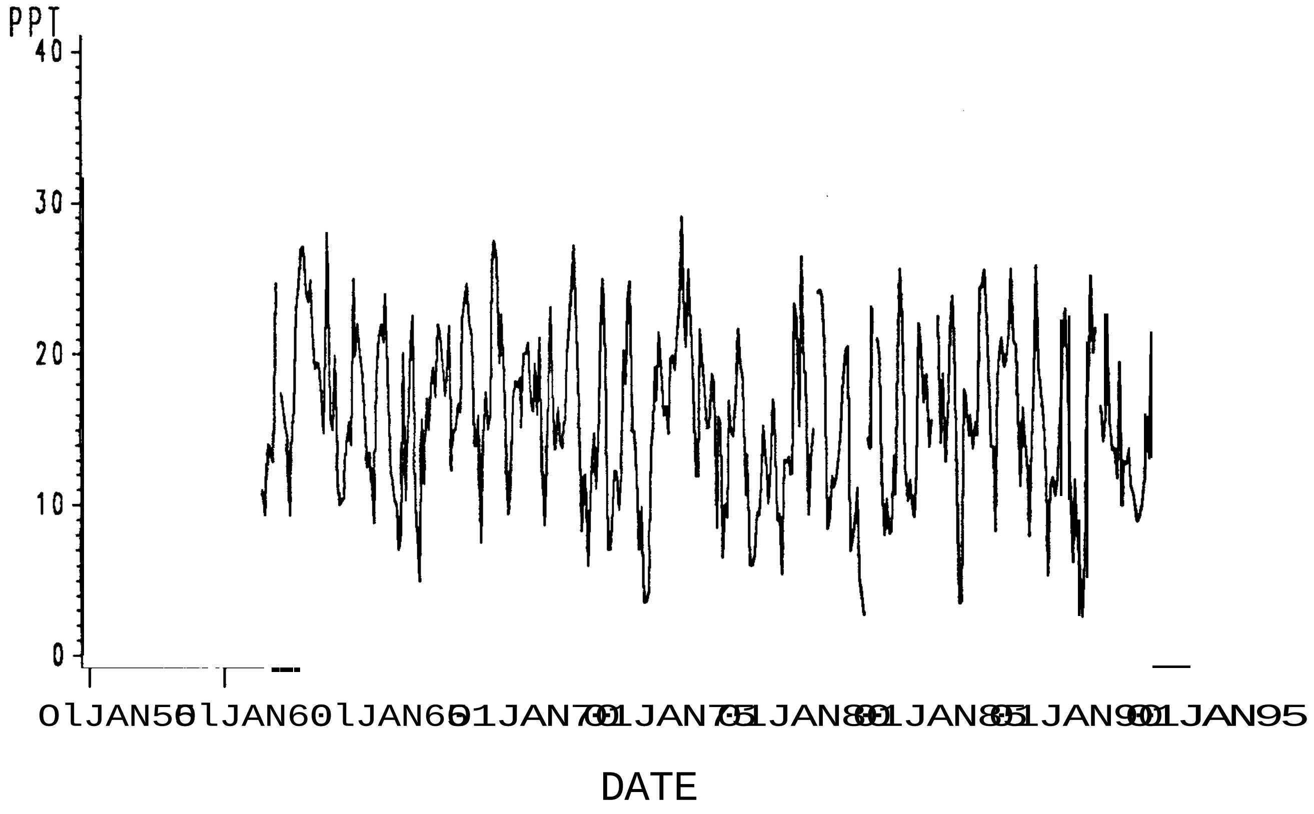
MONTHLY MEAN SALINITY

STATION=31 5 GRAND TERRE



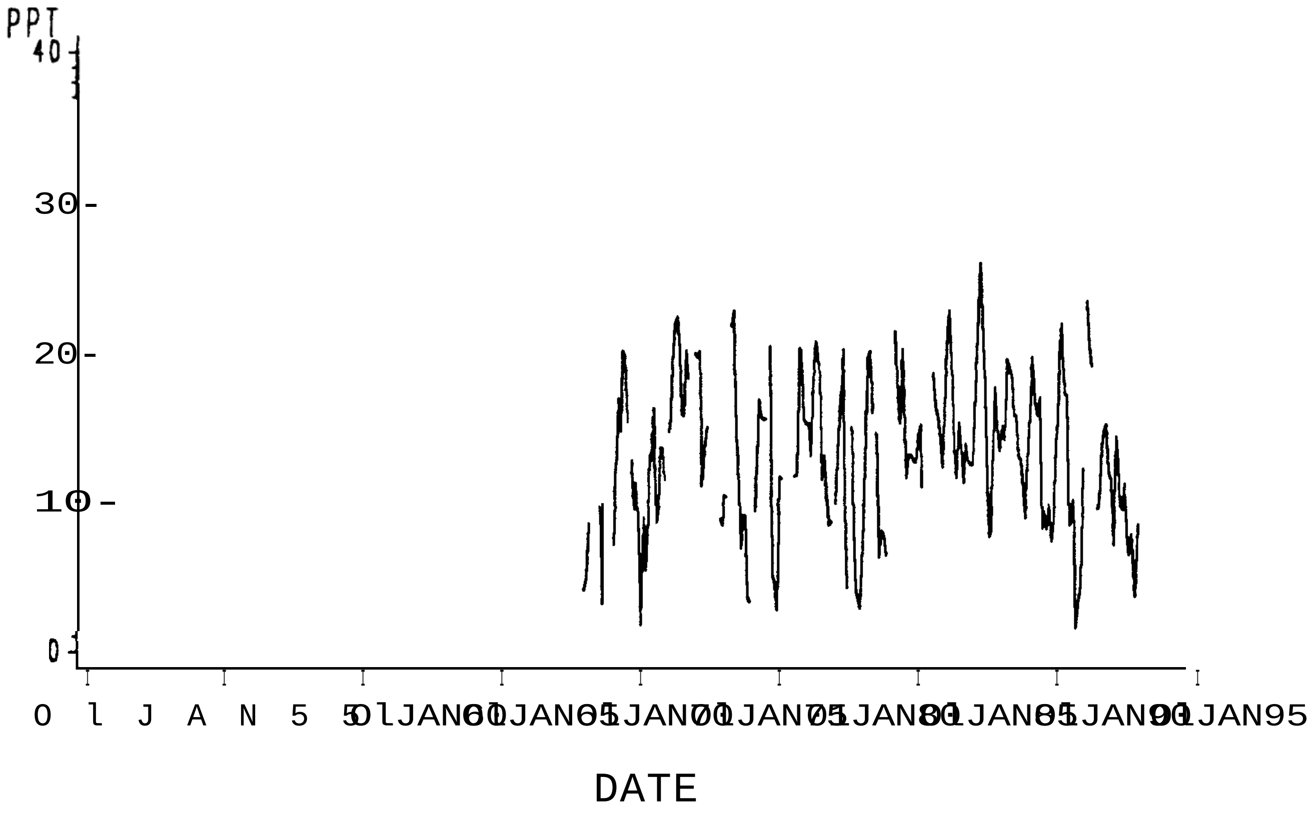
MONTHLY MINIMUM SALINITY

STATION=315 GRAND TERRE



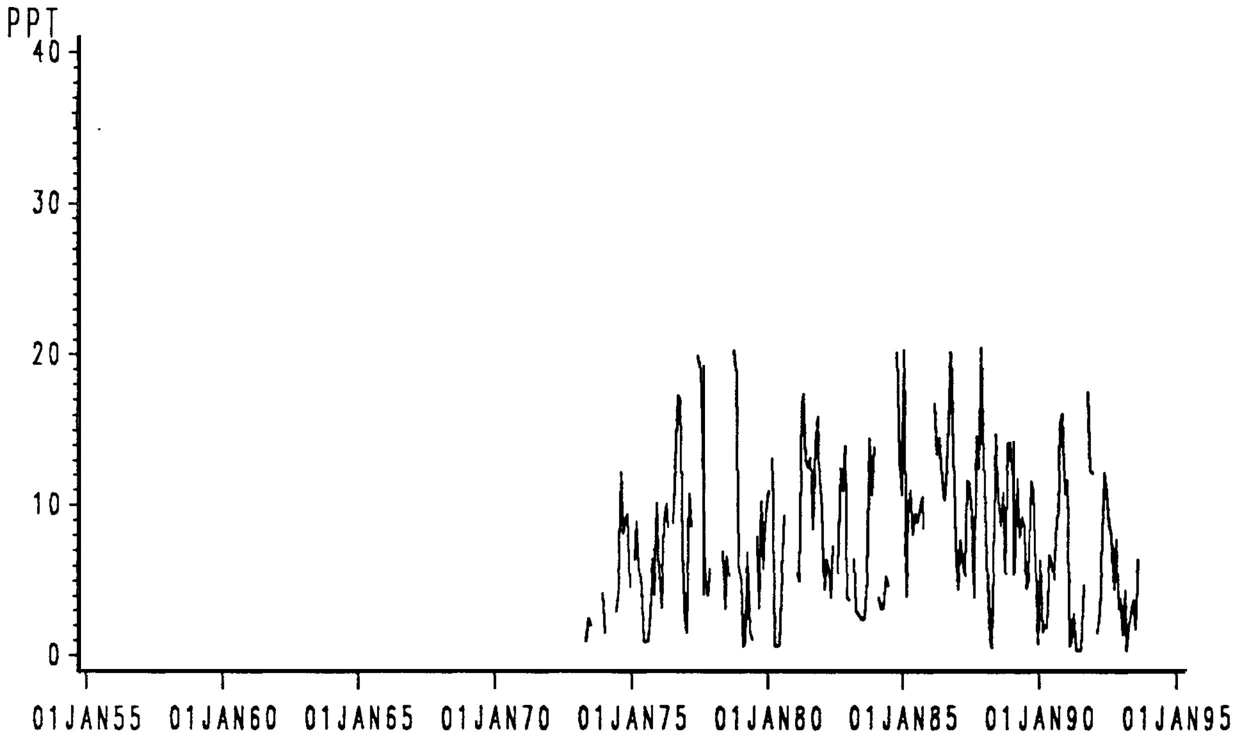
MONTHLY MEAN SALINITY

STATION=31 7ST. MARYS PT.



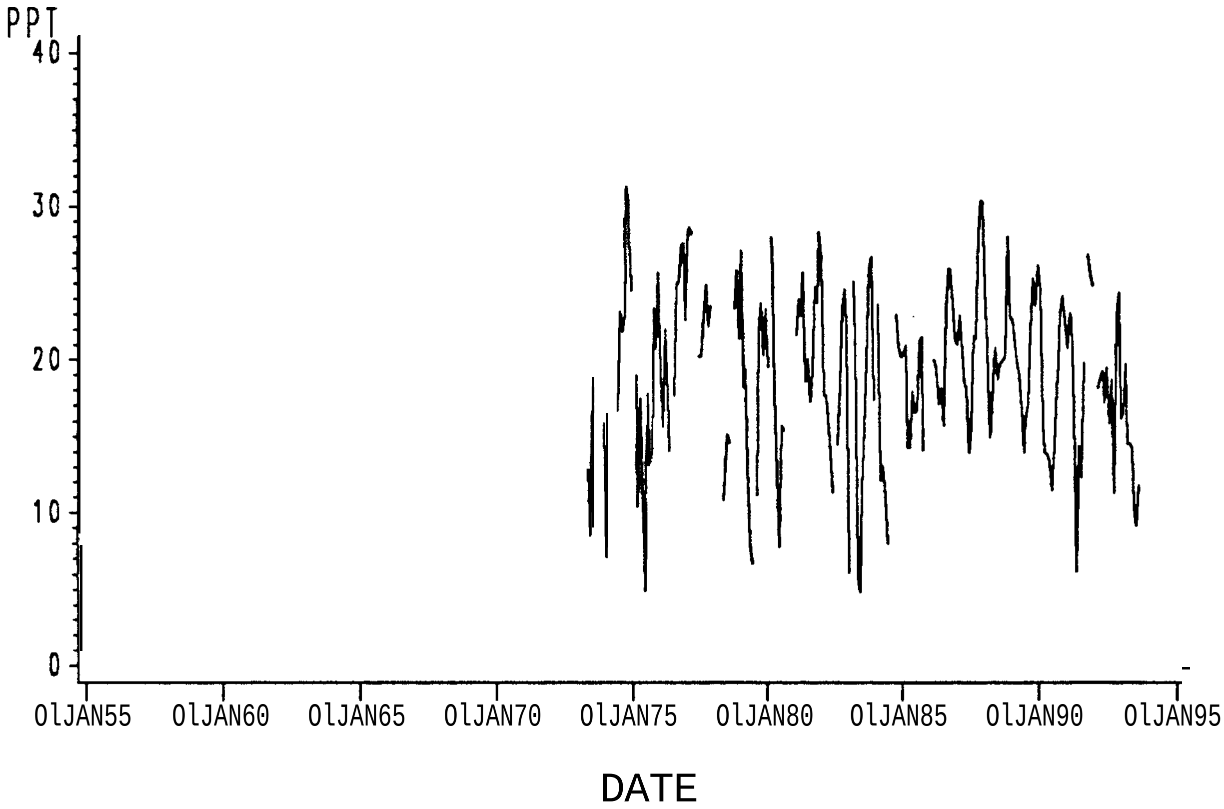
MONTHLY MINIMUM SALINITY

STATION=31 7 ST. MAWS PT.



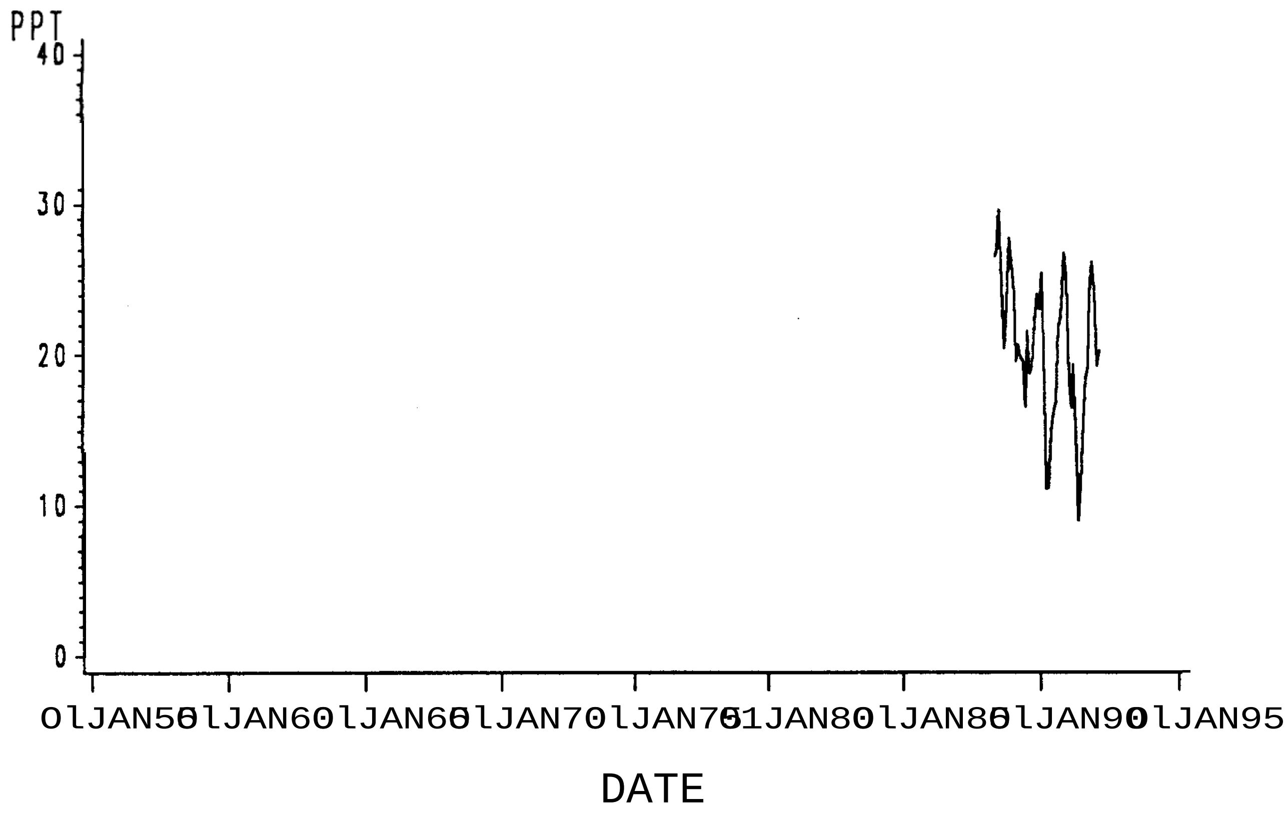
MONTHLY MAXIMUM SALINITY

STATION=31 7 STMARYS PT.



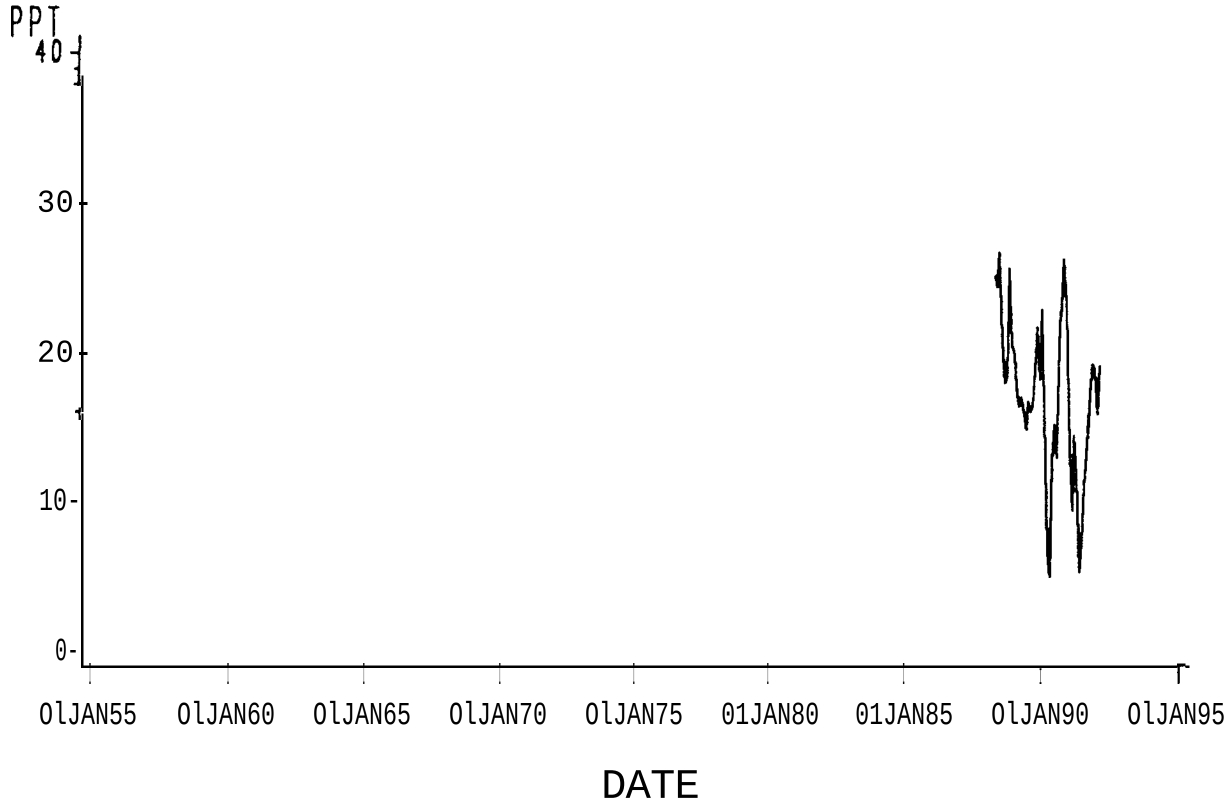
MONTHLY MEAN SALINITY

STATION=323 LAKE PALOURDE



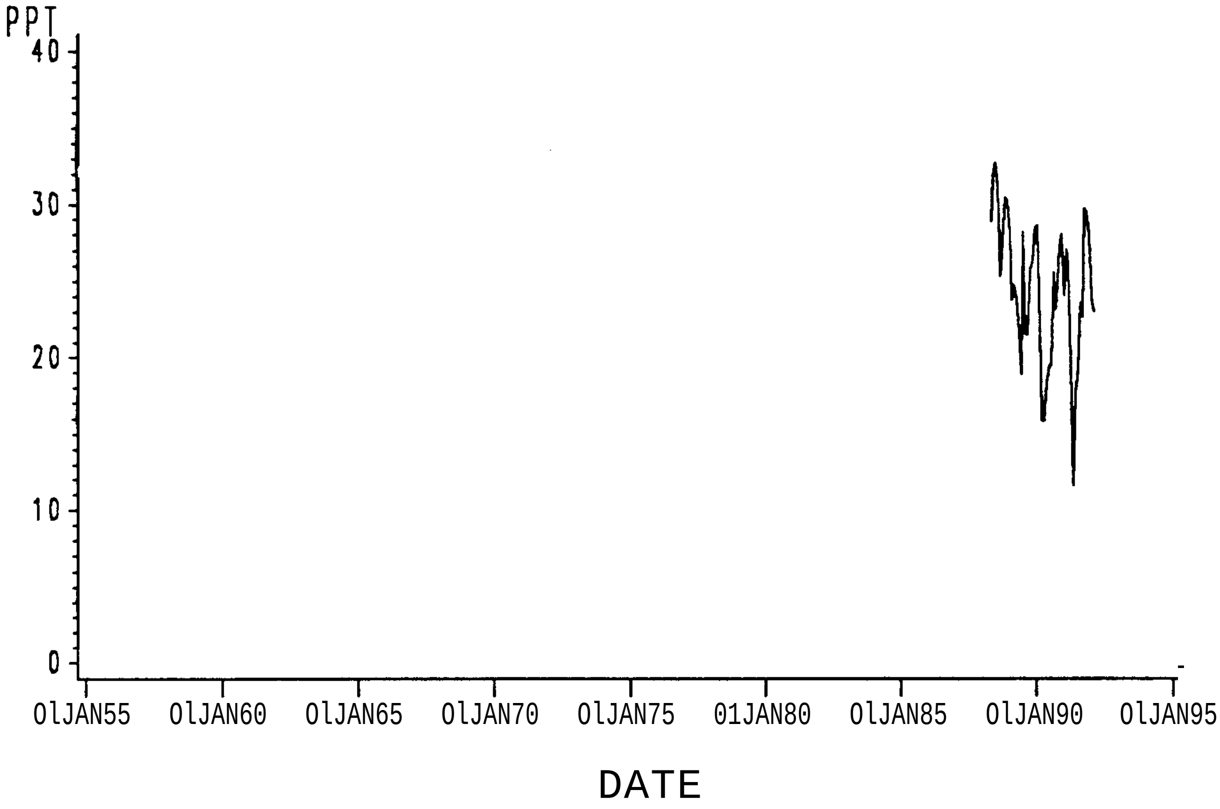
MONTHLY MINIMUM SALINITY

STATION=323 LAKE PALOURDE



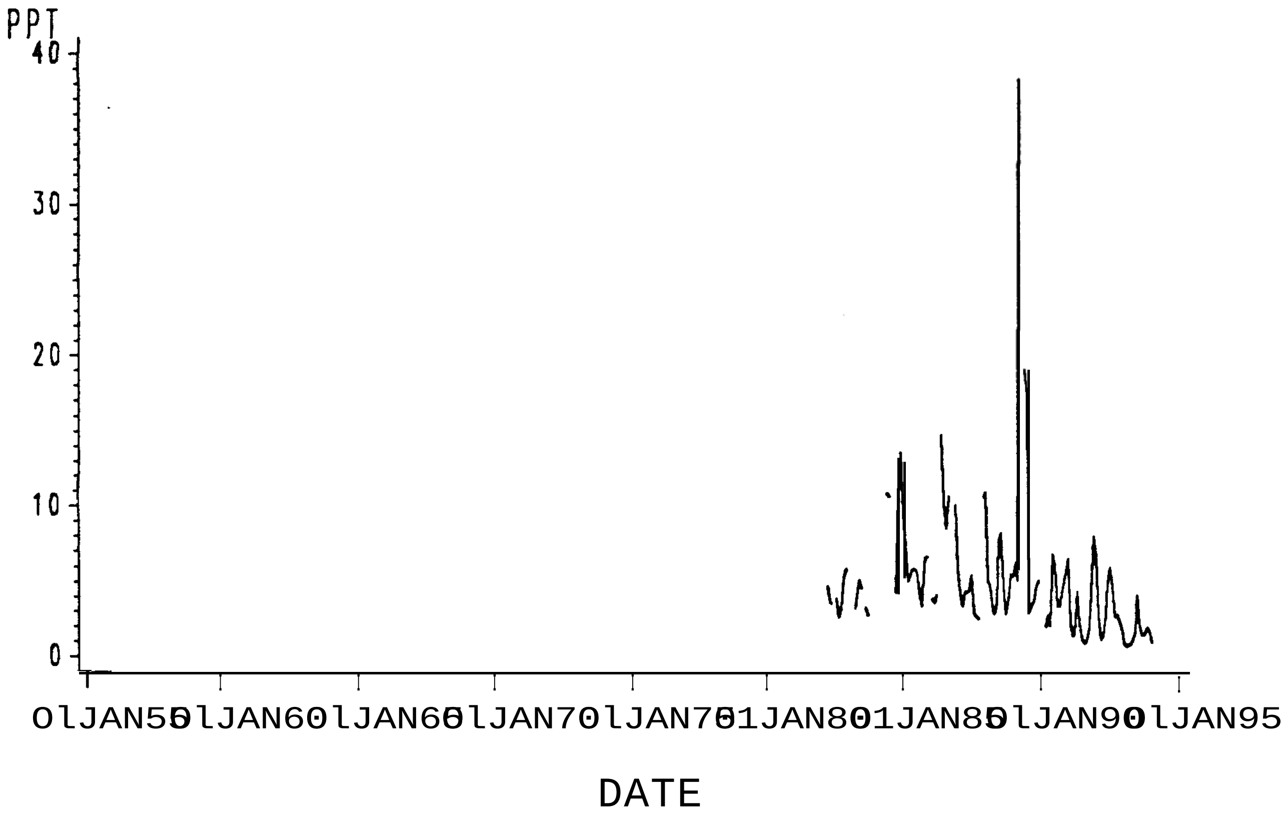
MONTHLY MAXIMUM SALINIIY

STATION=323 LAKE PALOURDE



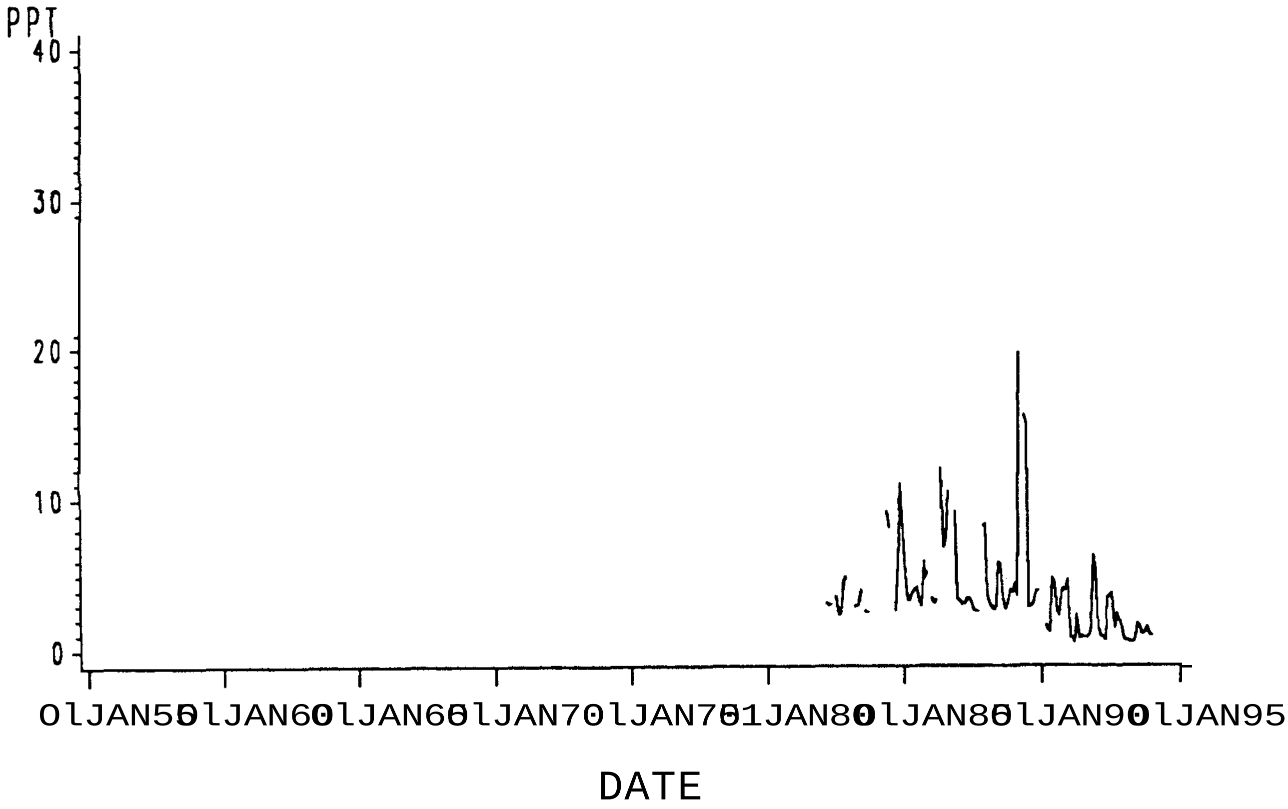
MONTHLY MEAN SALINITY

STATION=325 TENN. GAS CANAL



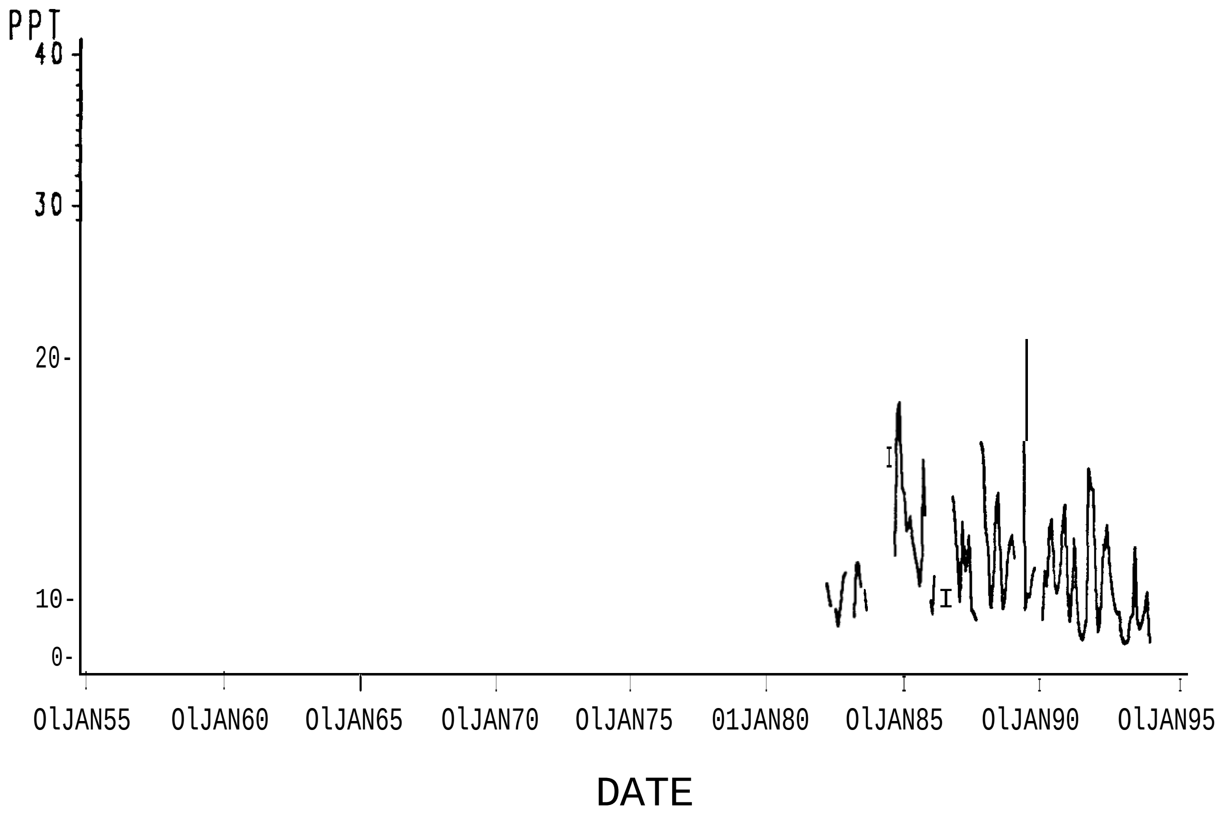
MONTHLY MINIMUM SALINITY

STATION=325 TENN. GAS CANAL



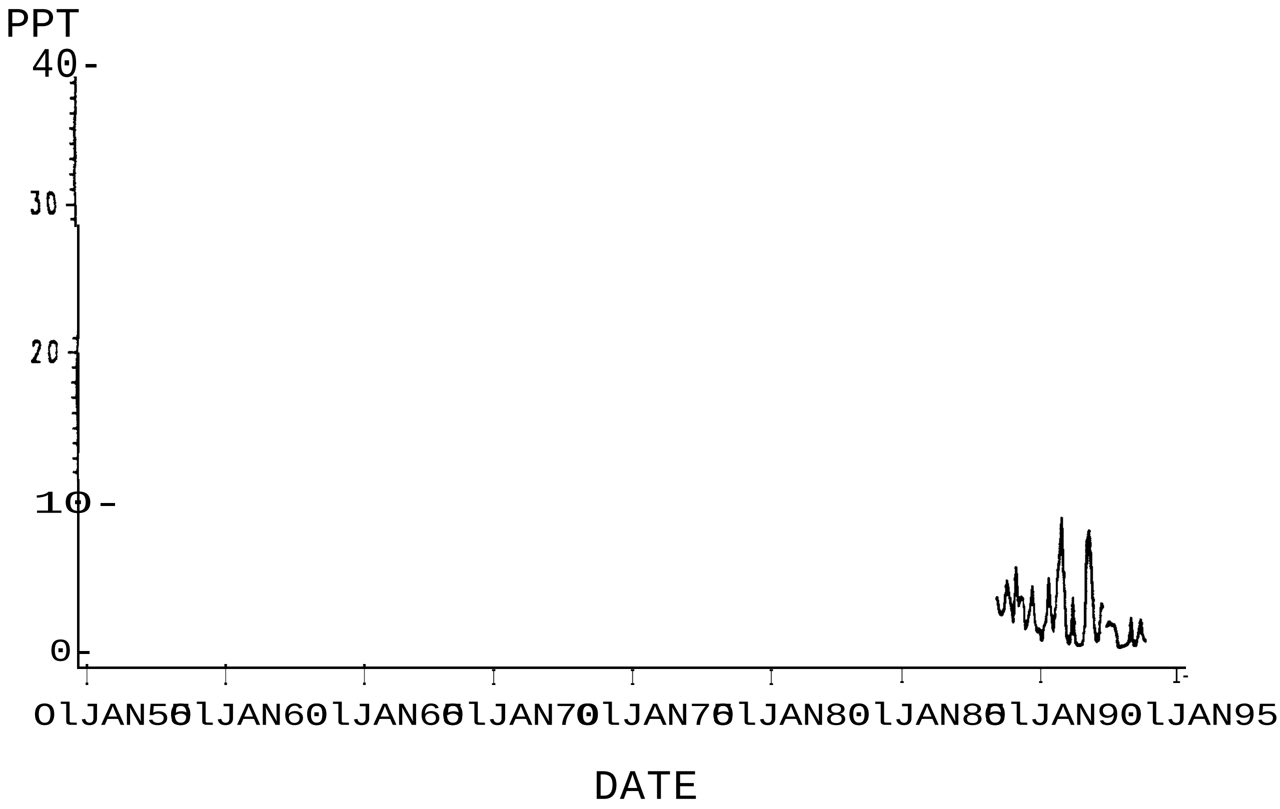
MONTHLY MAXIMUM SALINITY

STATION=325 TENN GAS CANAL



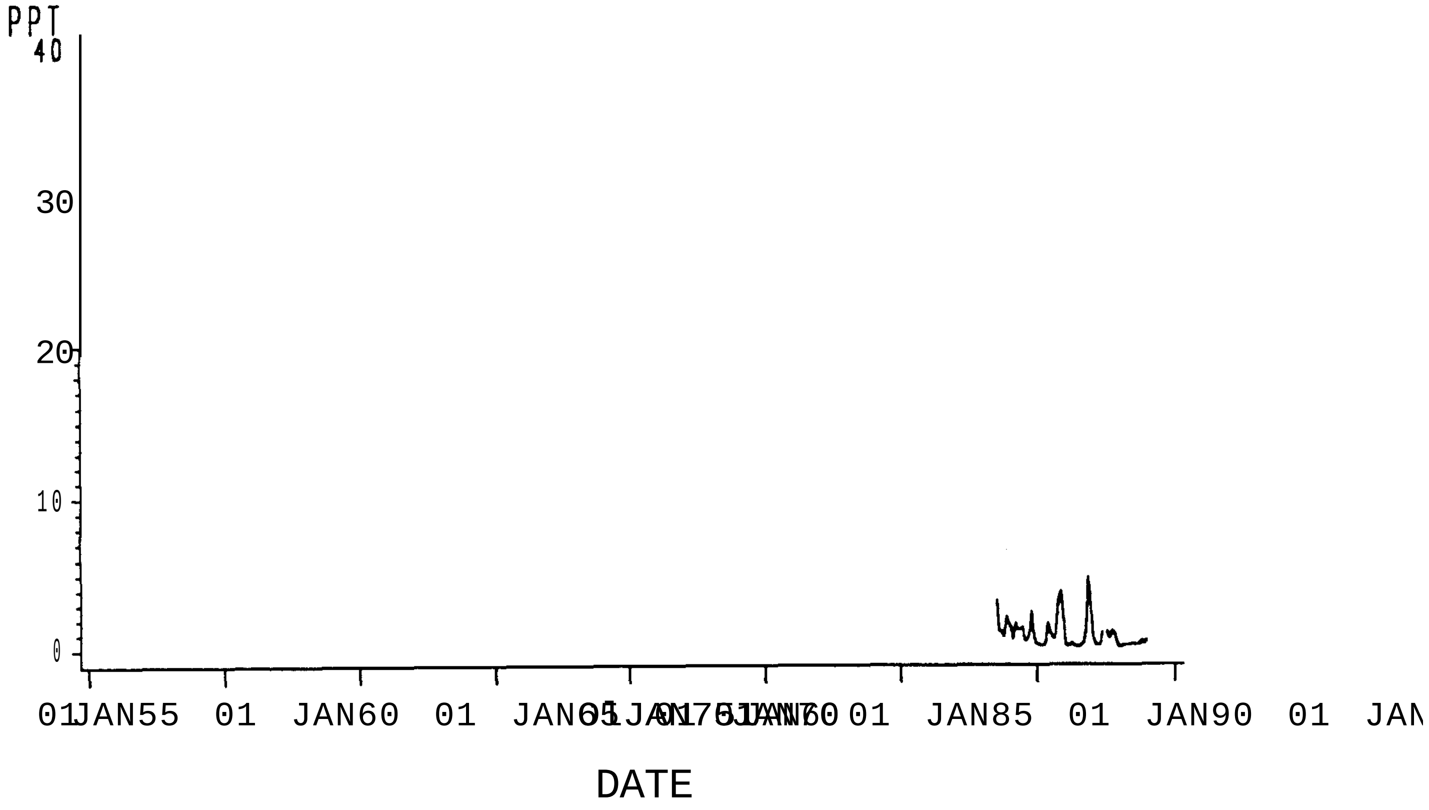
MONTHLY MEAN SALINITY

STATION=326 LITTLE LAKE



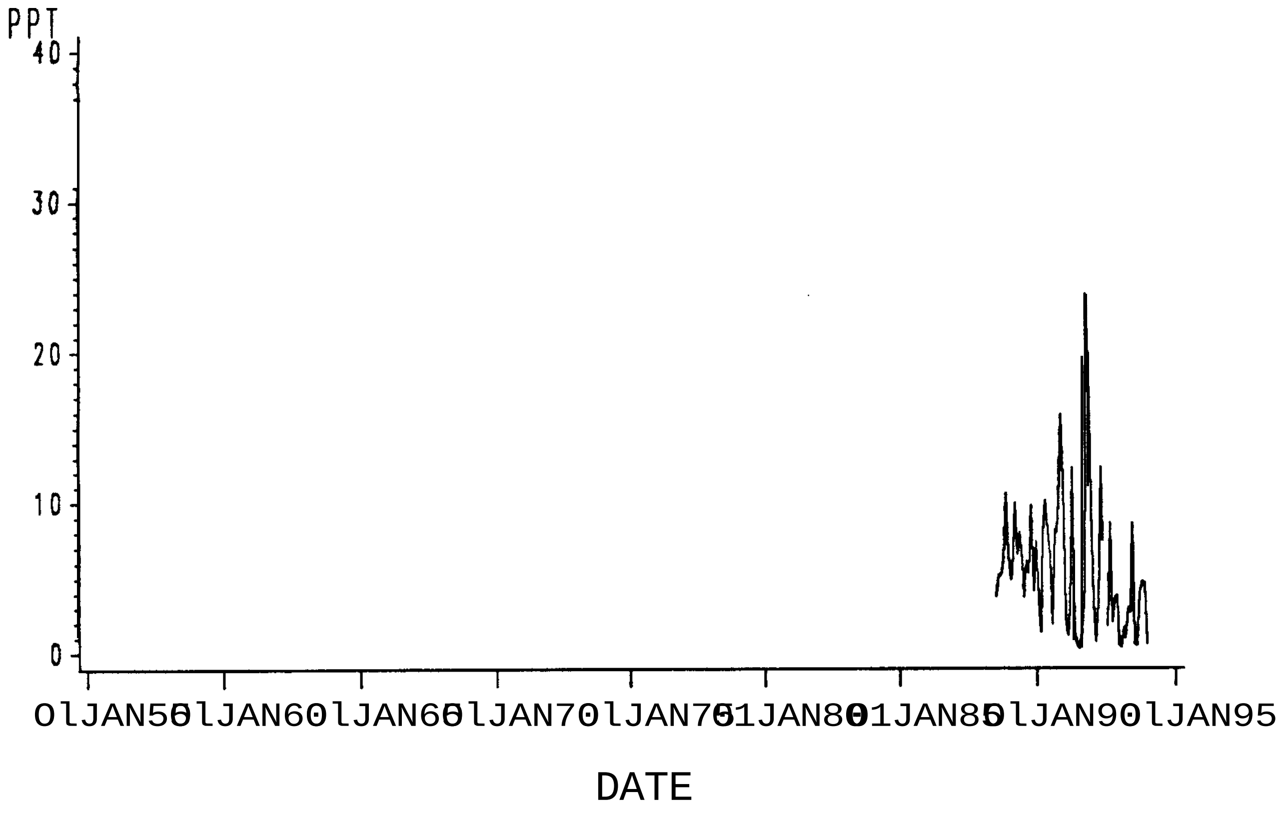
MONTHLY MINIMUM SALINITY

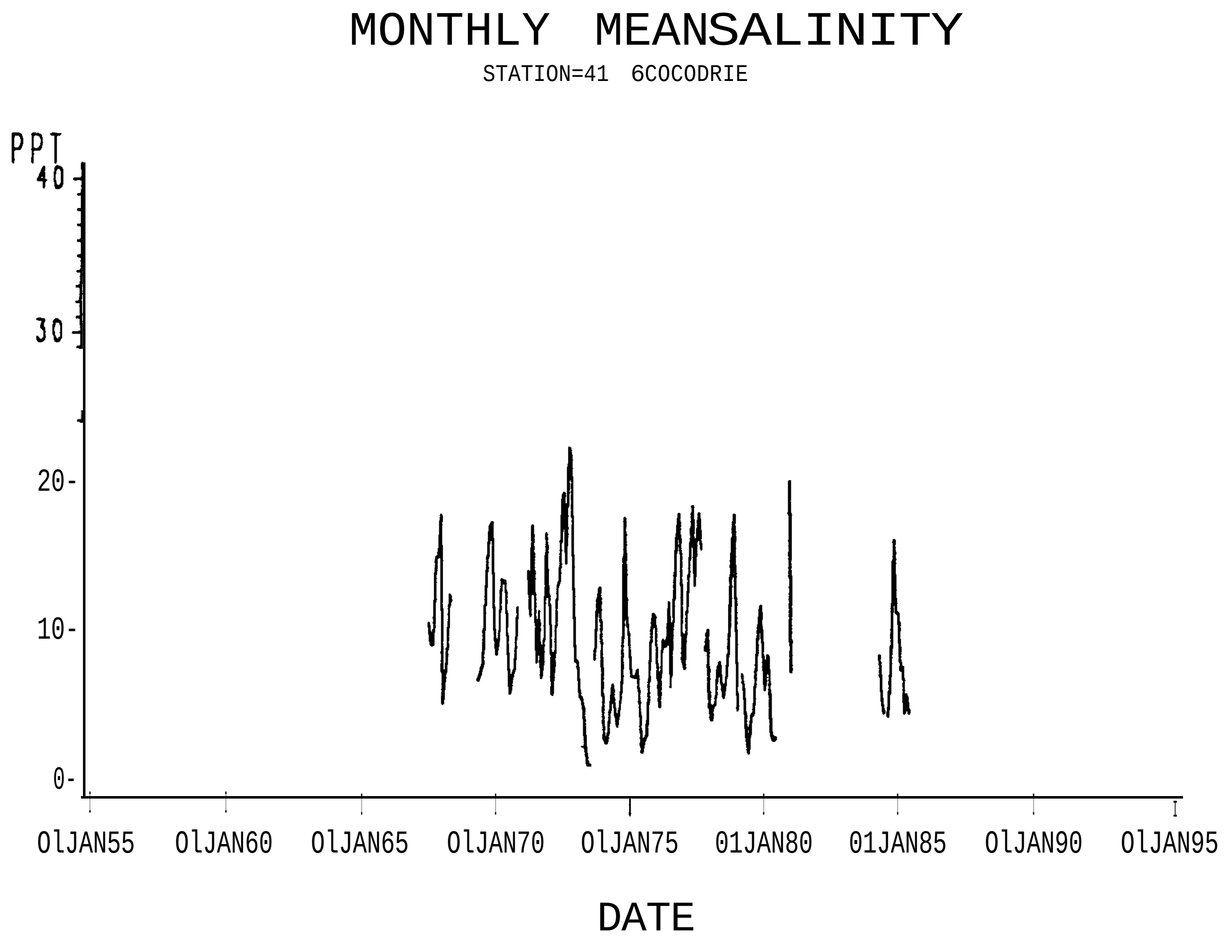
STATION=326 LITTLE LAKE



MONTHLY MAXIMUM SALINITY

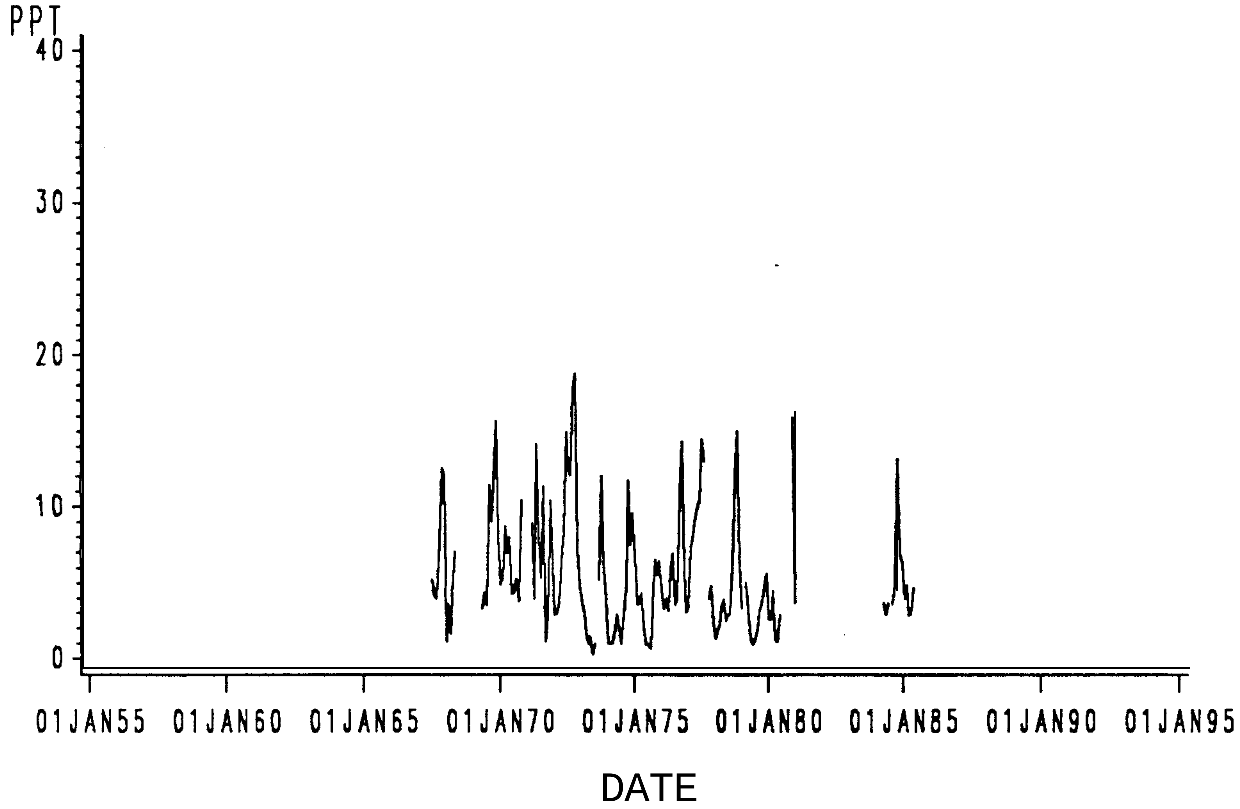
STATION=326 LITTLE LAKE




MONTHLY MEANSALINITY
STATION=41 6COCODRIE
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

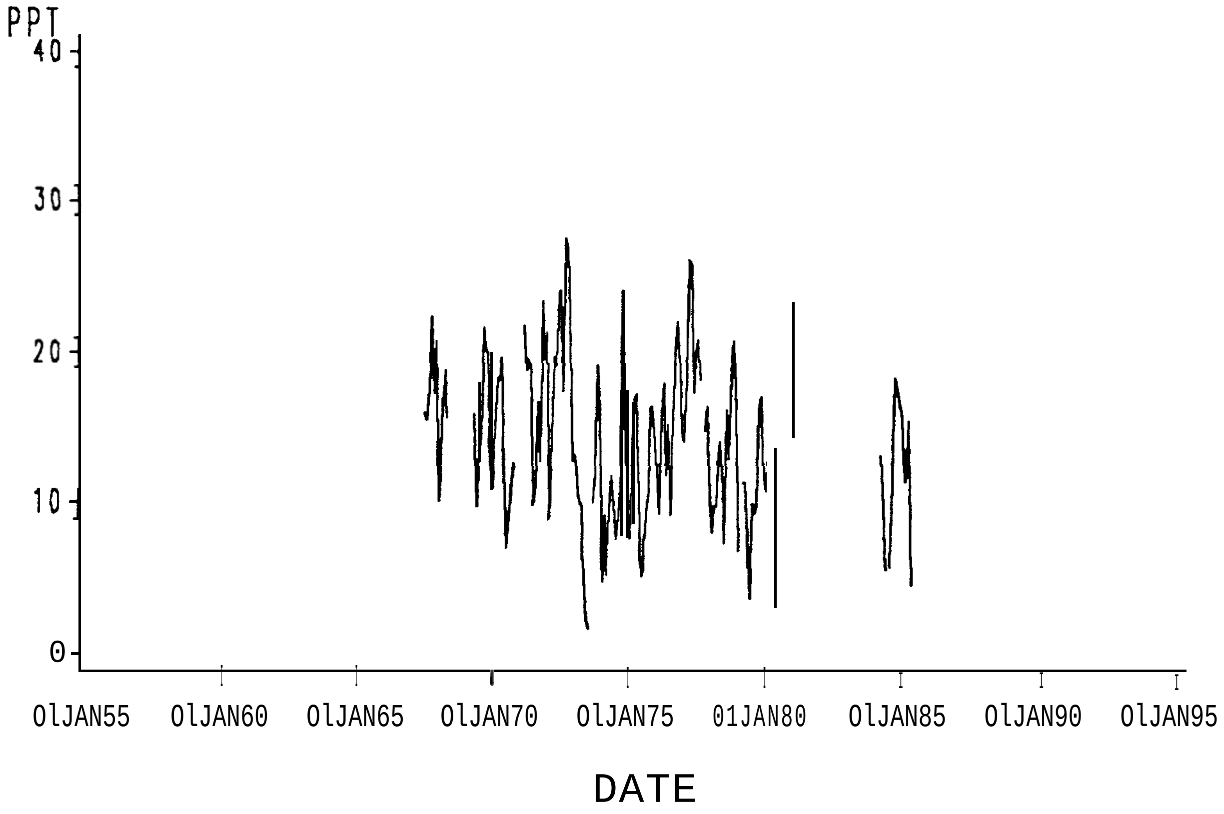
MONTHLY MINIMUM SALINITY

STATION=41 6 COCODRIE



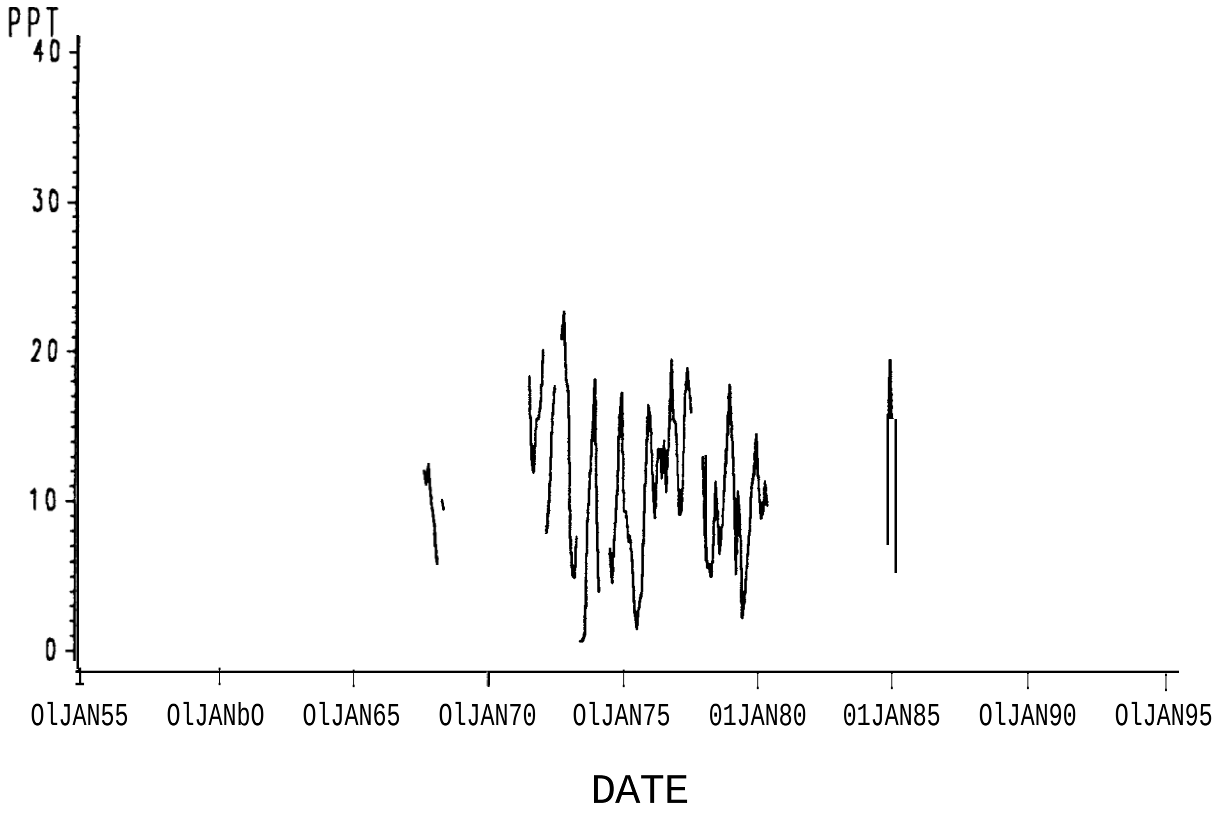
MONTHLY MAXIMUM SALINITY

SIATION=416 COCODRIE



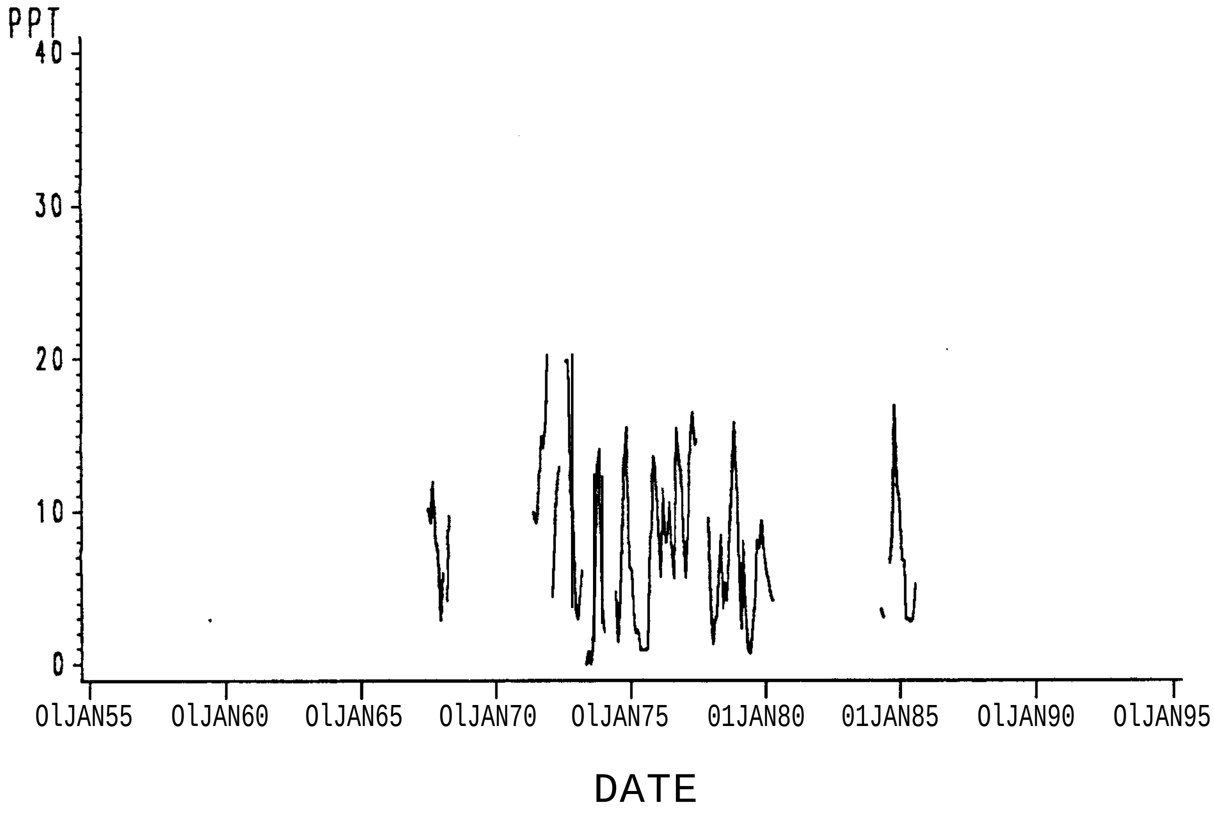
MONTHLY MEAN SALINITY

STATION=518 LAKE MECHANT



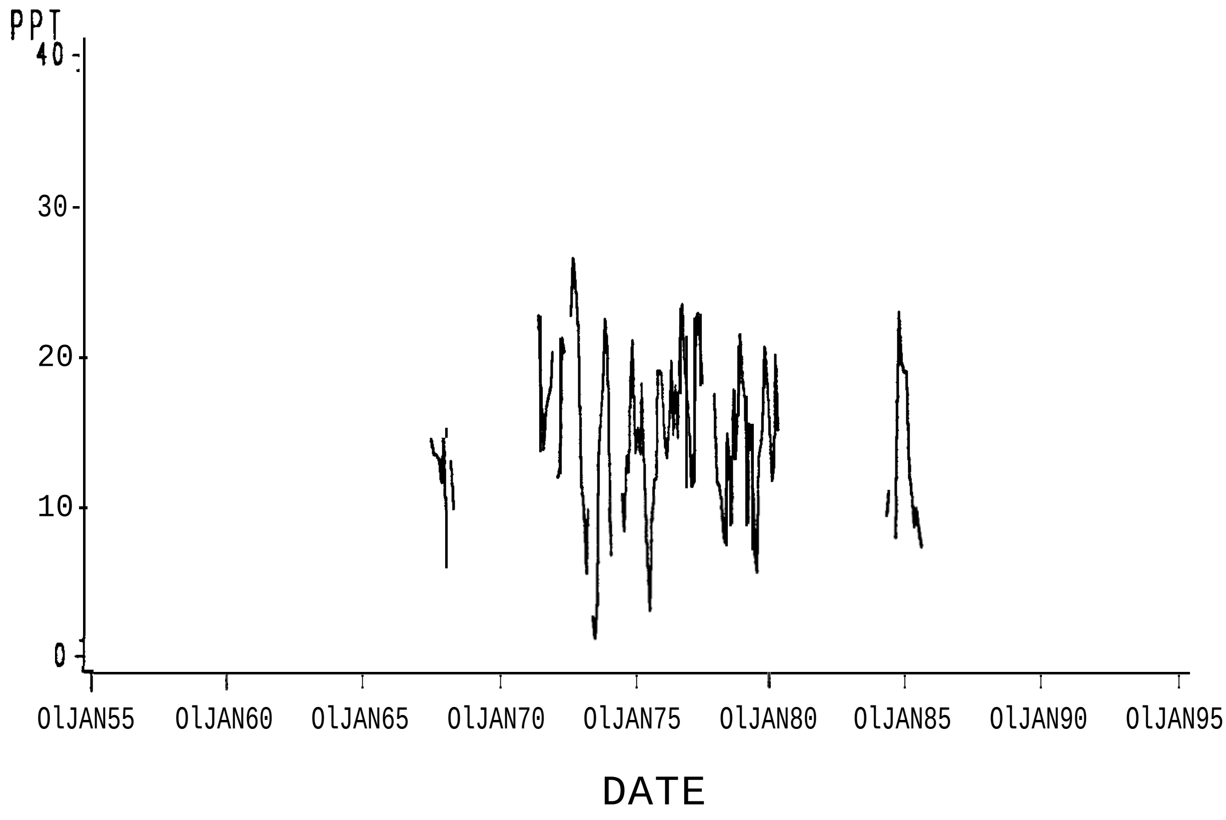
MONTHLY MINIMUM SALINITY

STATION=518 LAKE MECHANT



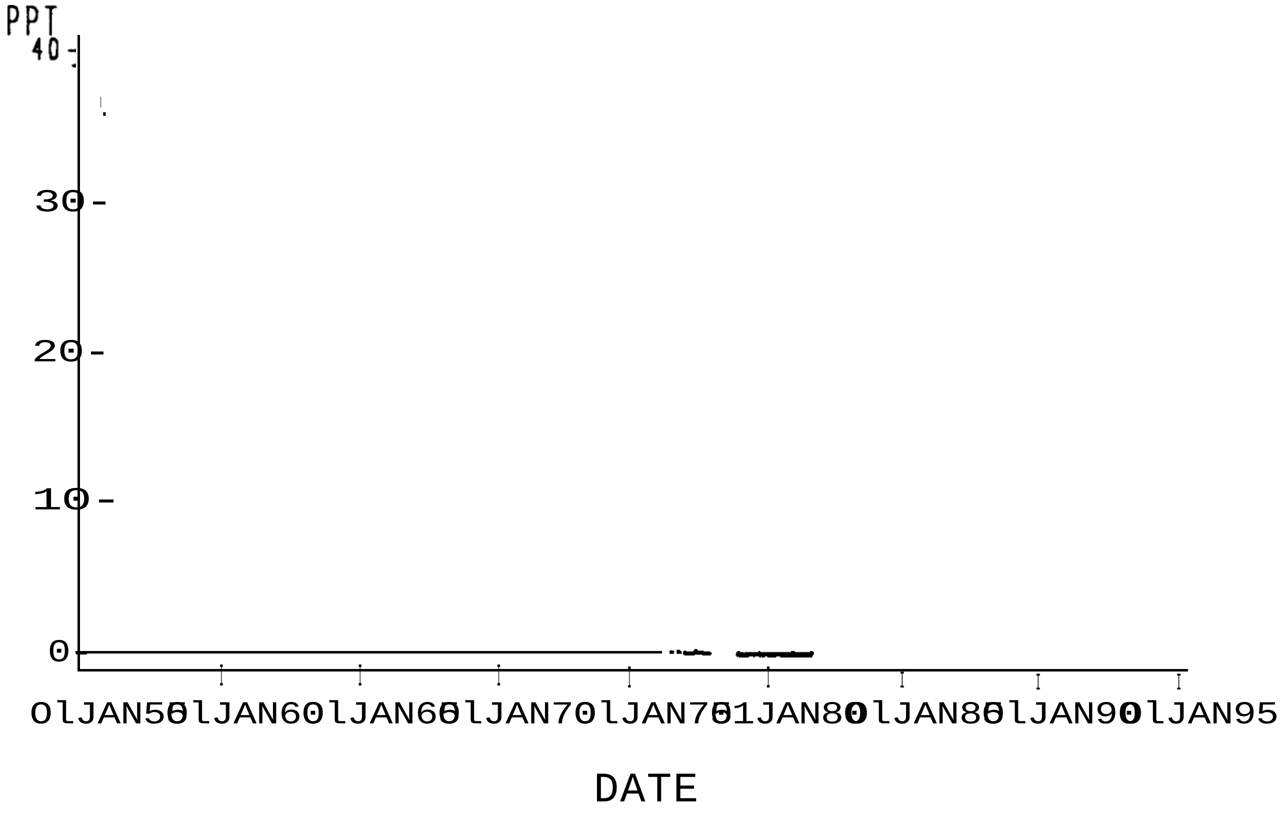
MONTHLY MAXIMUMSALINIIY

STATION=51 a LAKE MECHANT



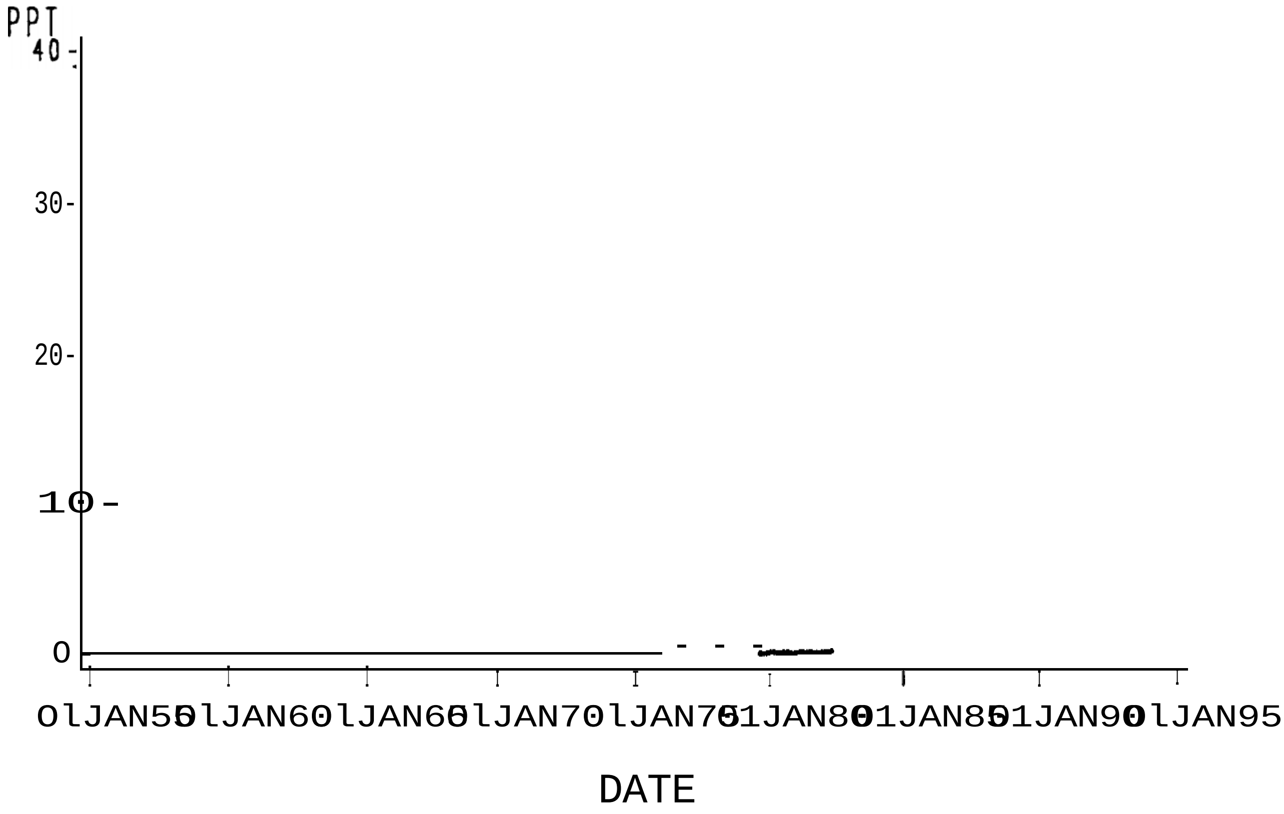
MONTHLY MEAN SALINITY

STATION=03780 MORGAN CITY



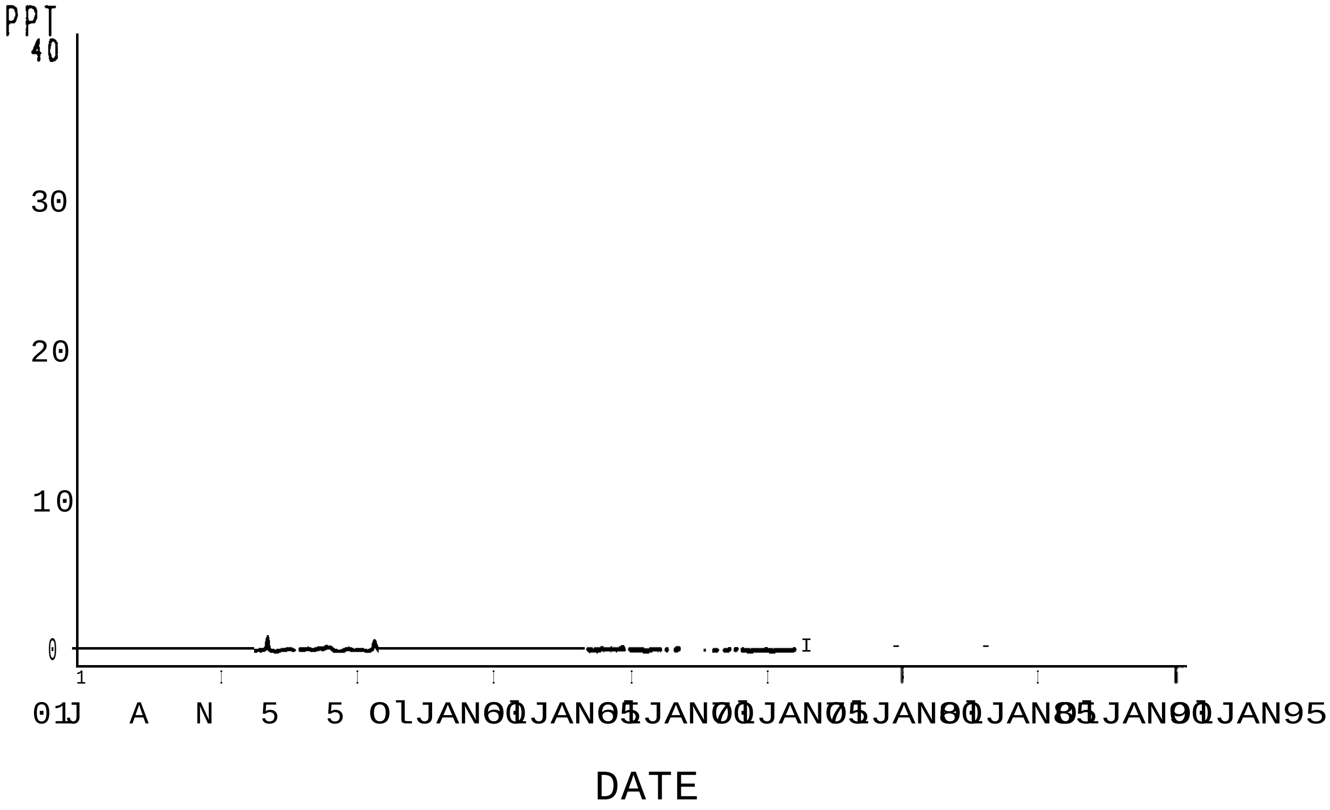
MONTHLY MINIMUM SALINITY

STATION=03780MORGAN CITY



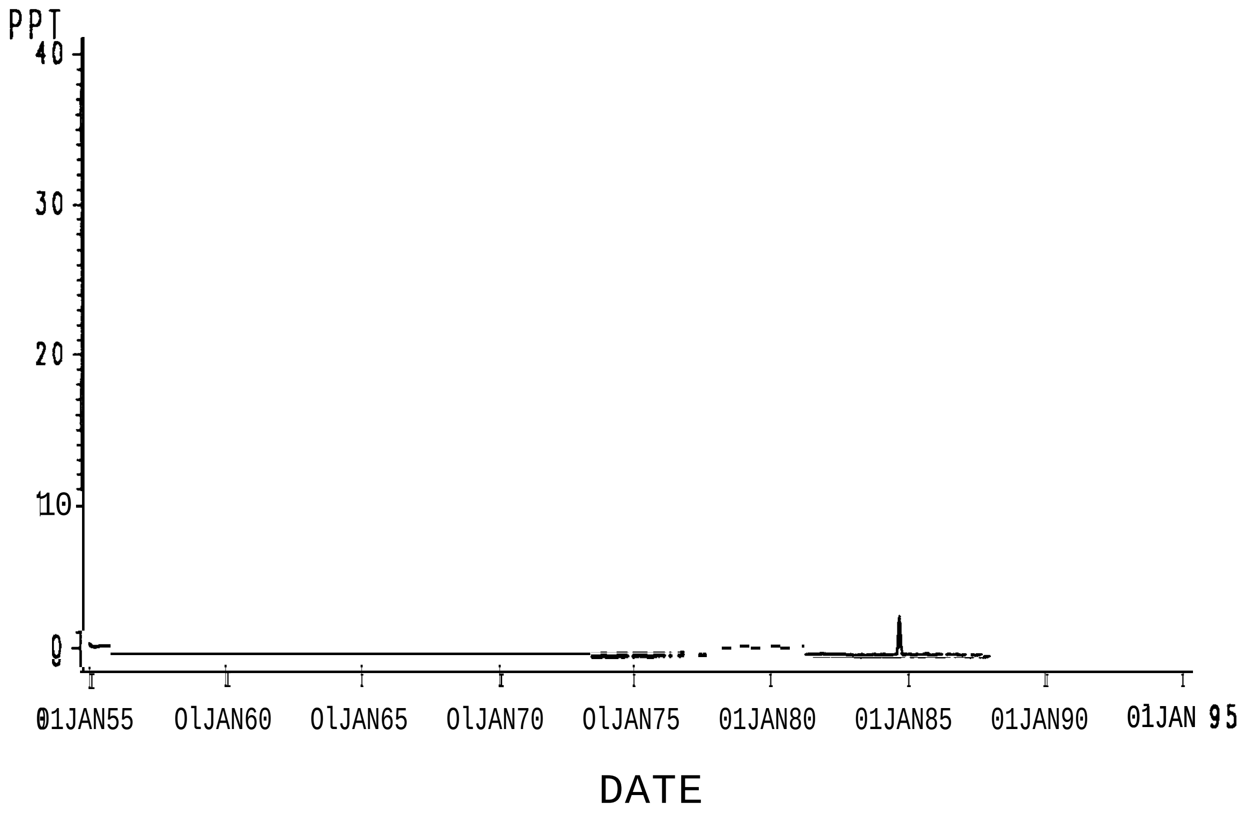
MONTHLY MEAN SALINITY

STATlON=52BOO BAYOU BOEUF



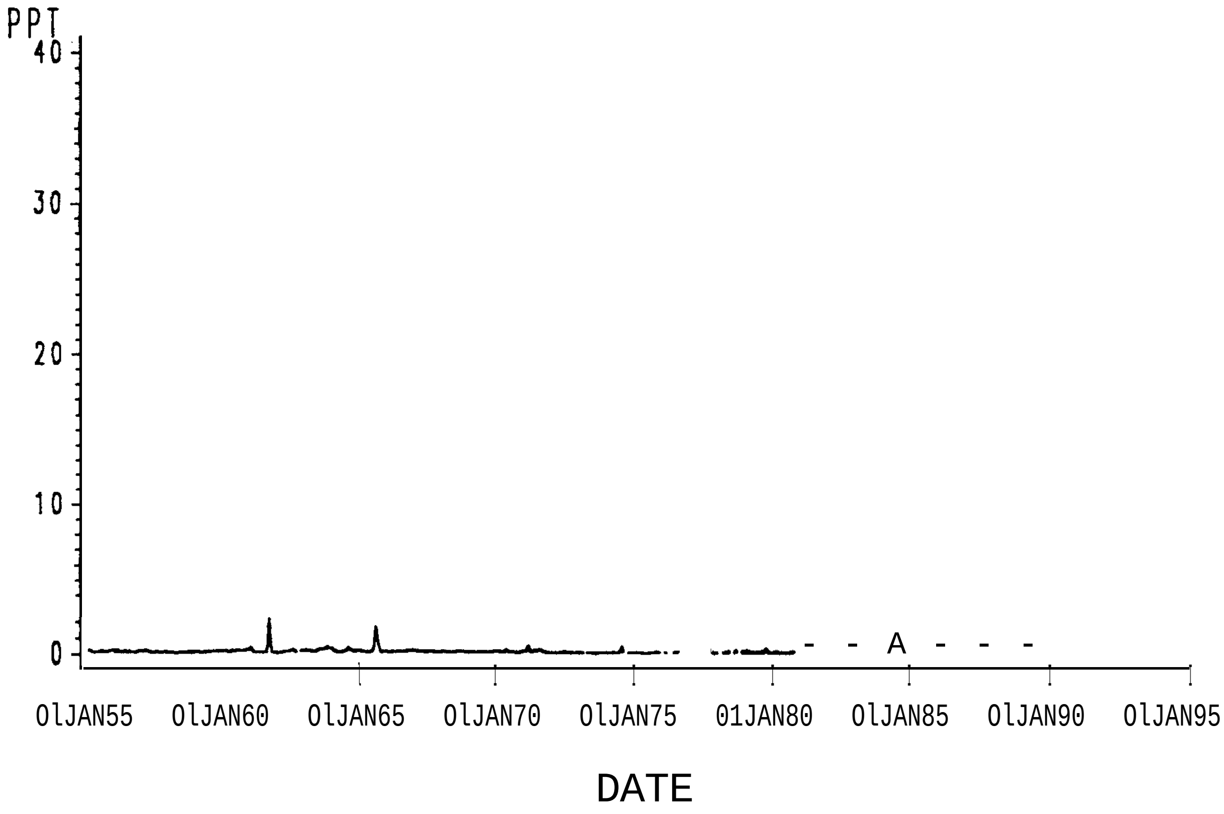
MONTHLY MINIMUM SALINITY

!ZTATlON=52800 BAYOU BOEUF



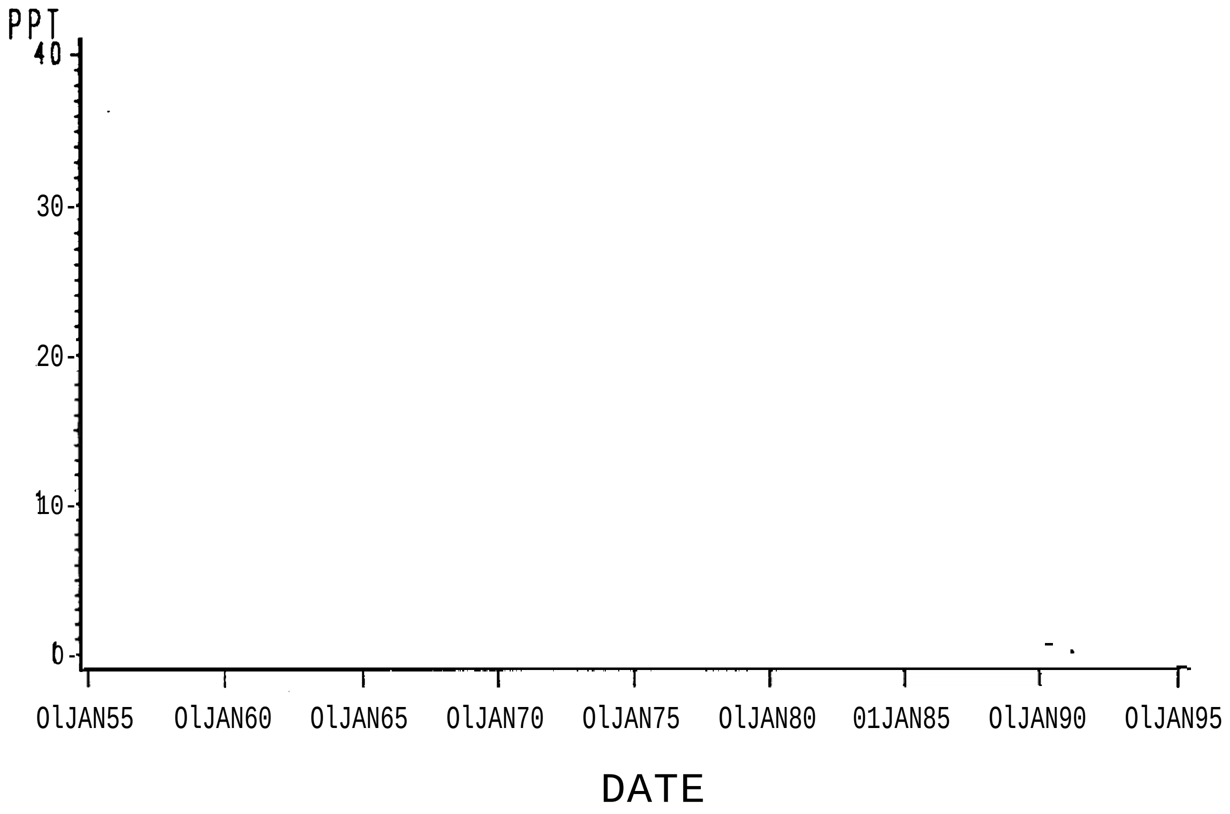
MONTHLY MAXIMUM SALINITY

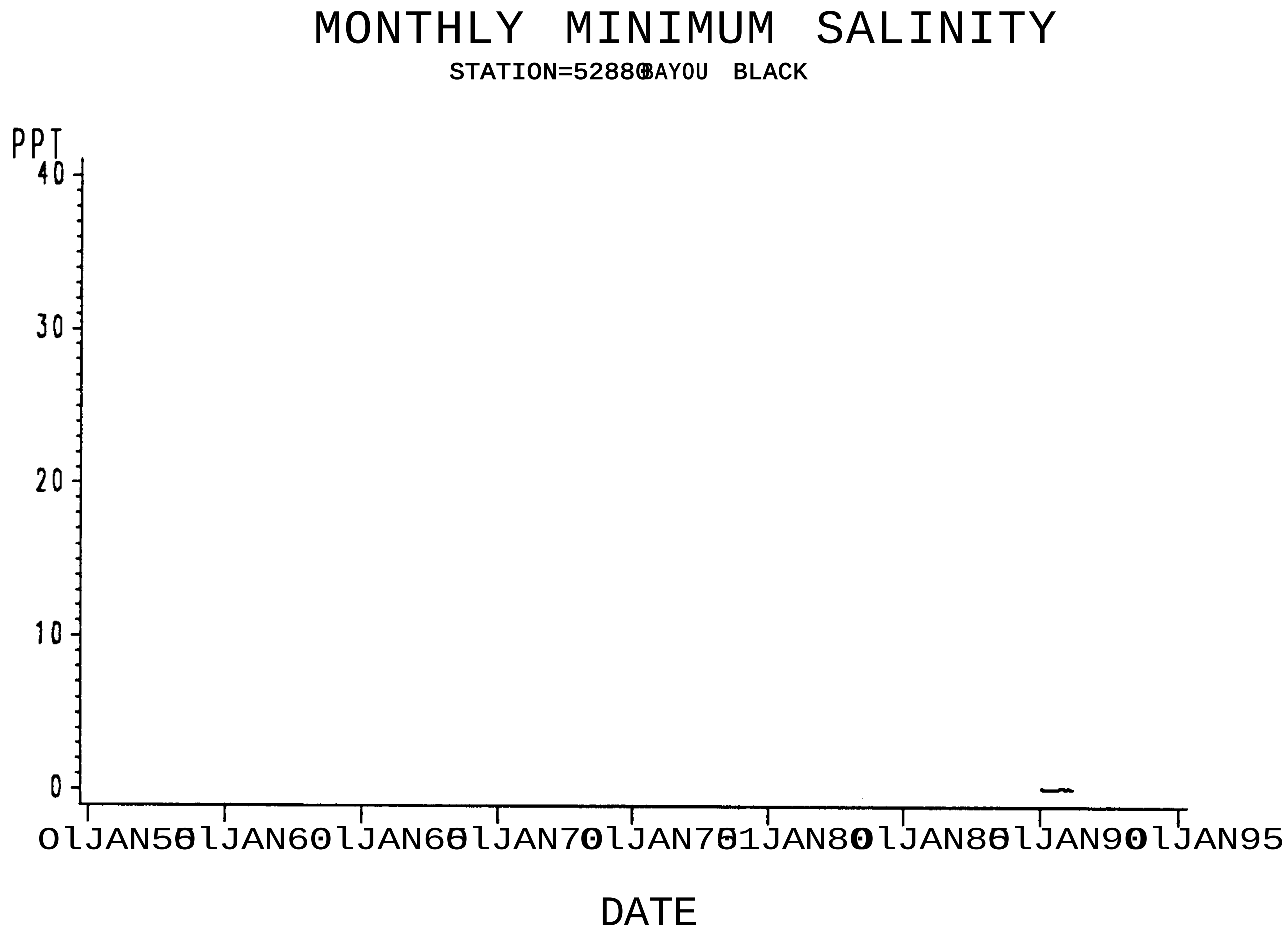
STATION=52800 BAYOU BOEUF



MONTHLY MEAN SALINITY

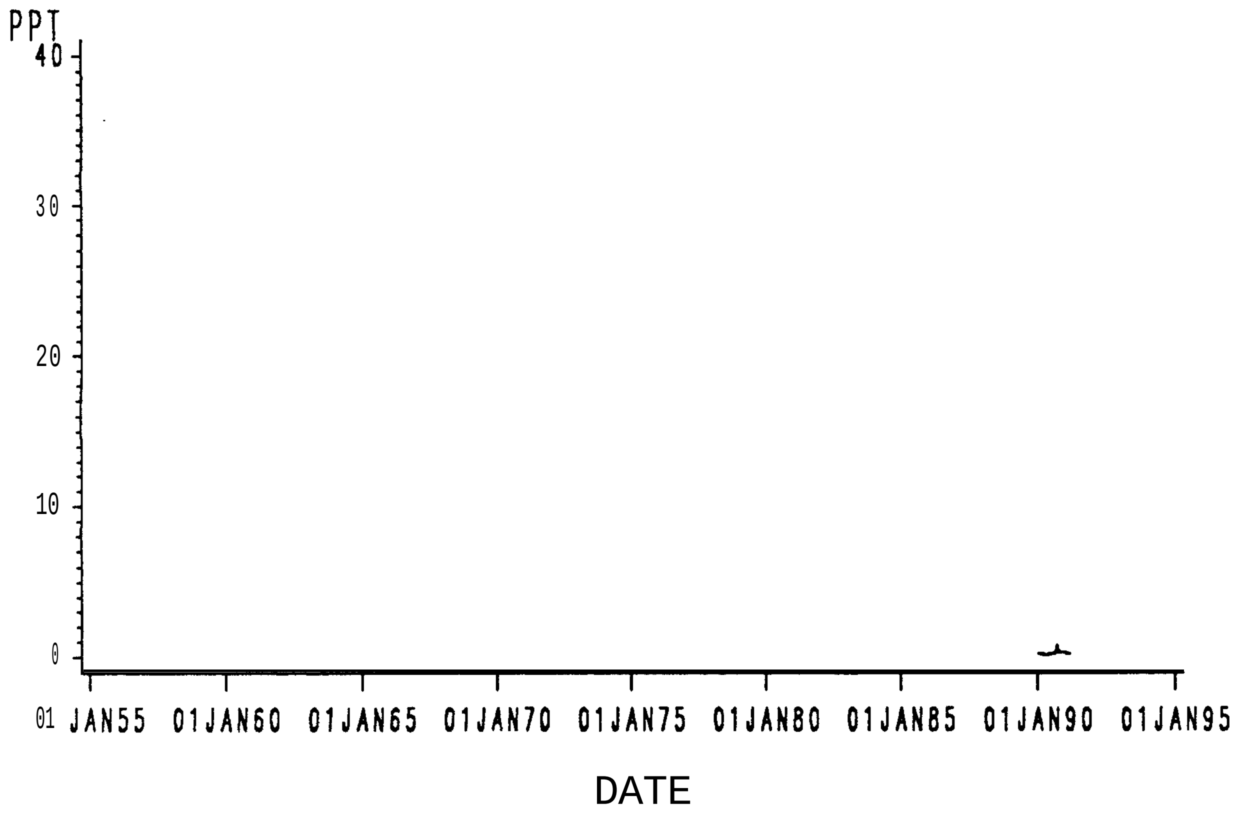
STATION=52880 BAYOU BLACK




MONTHLY MINIMUM SALINITY
STATION=52880 BAYOU BLACK
PPT
40
30
20
10
0
01JAN50
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

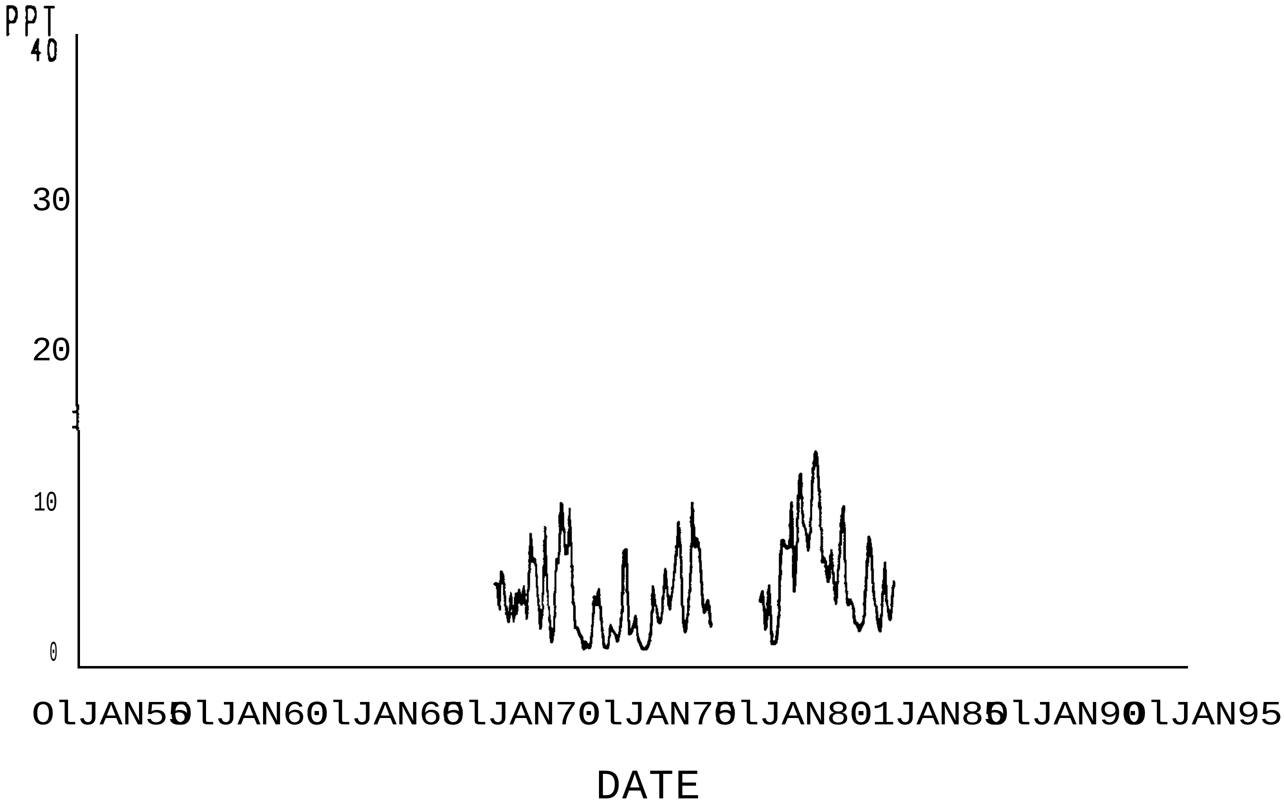
MONTHLY MAXIMUM SALINITY

STATION=52880BAYOUBLACK



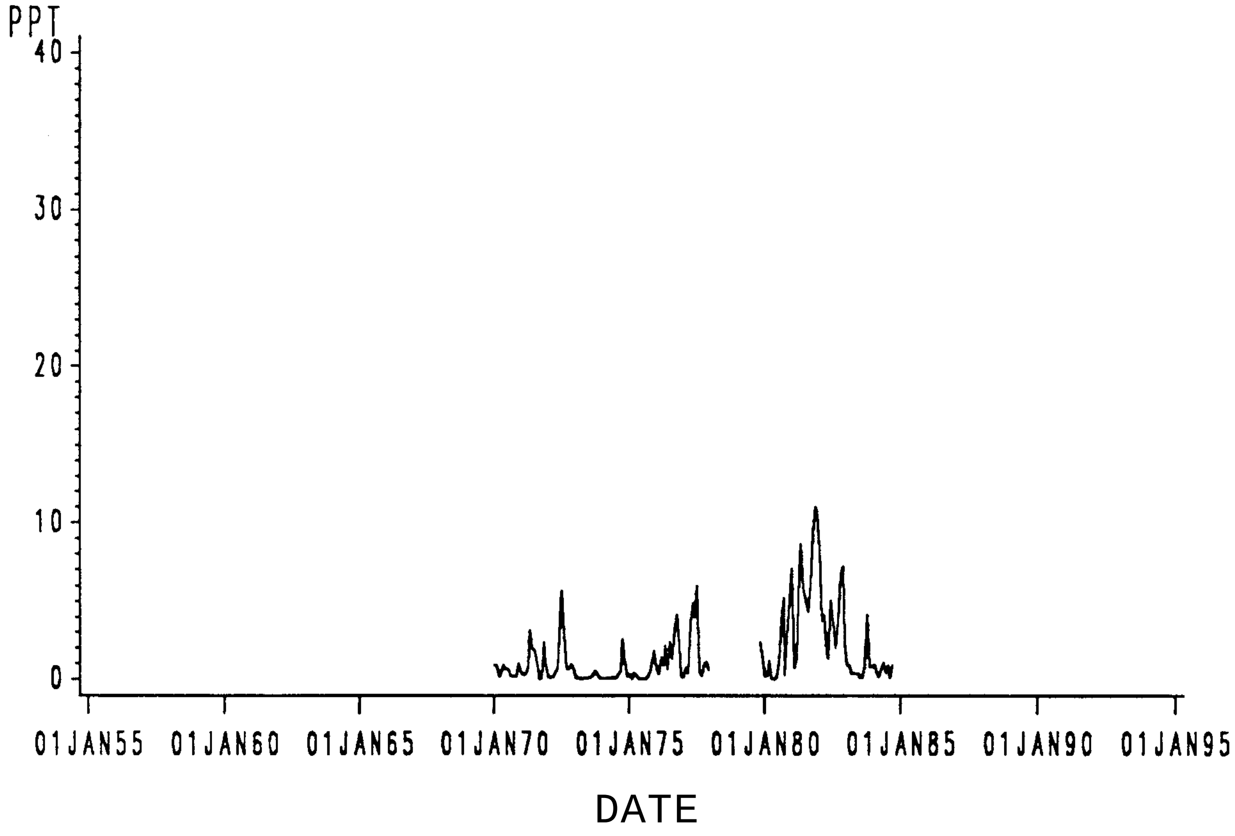
MONTHLY MEAN SALINITY

STATION=76303 BAYOU PETITE CALLOU



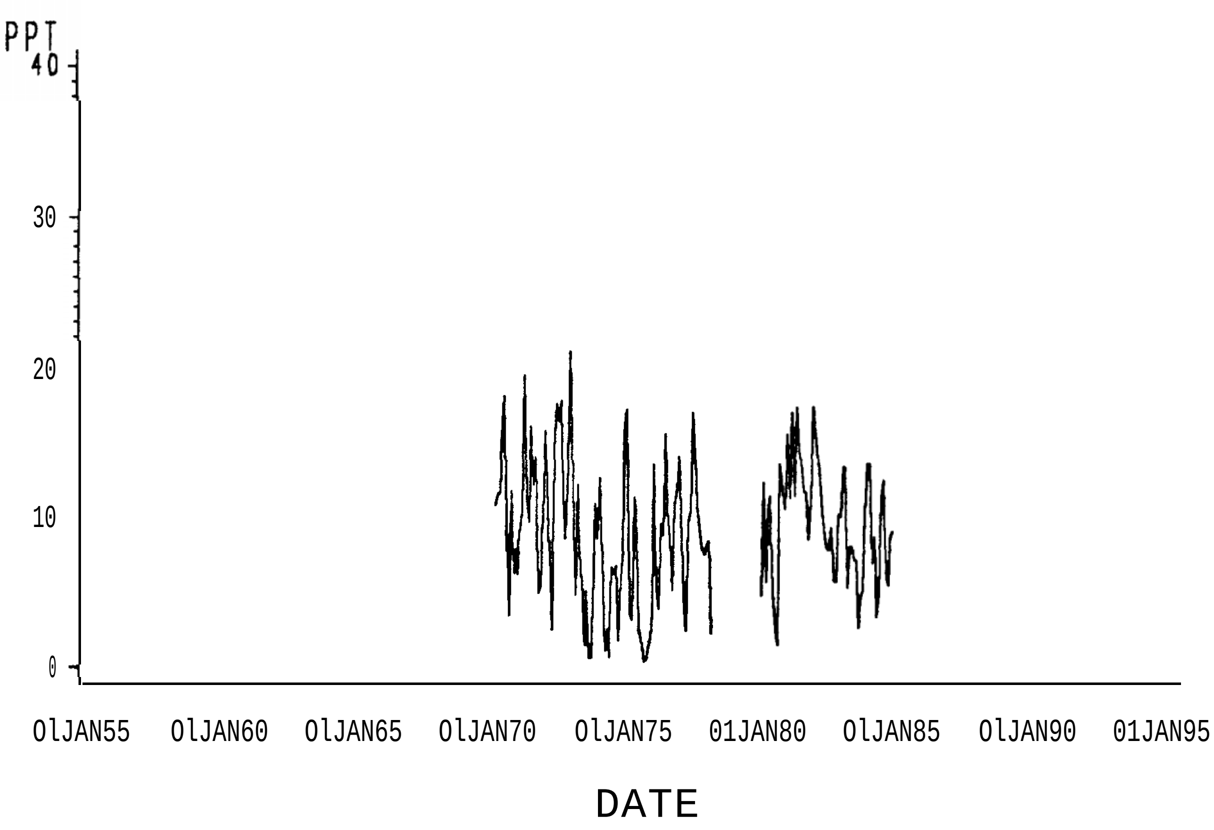
MONTHLY MINIMUM SALINITY

STATION=76303 BAYOU PETITE CAILLOU



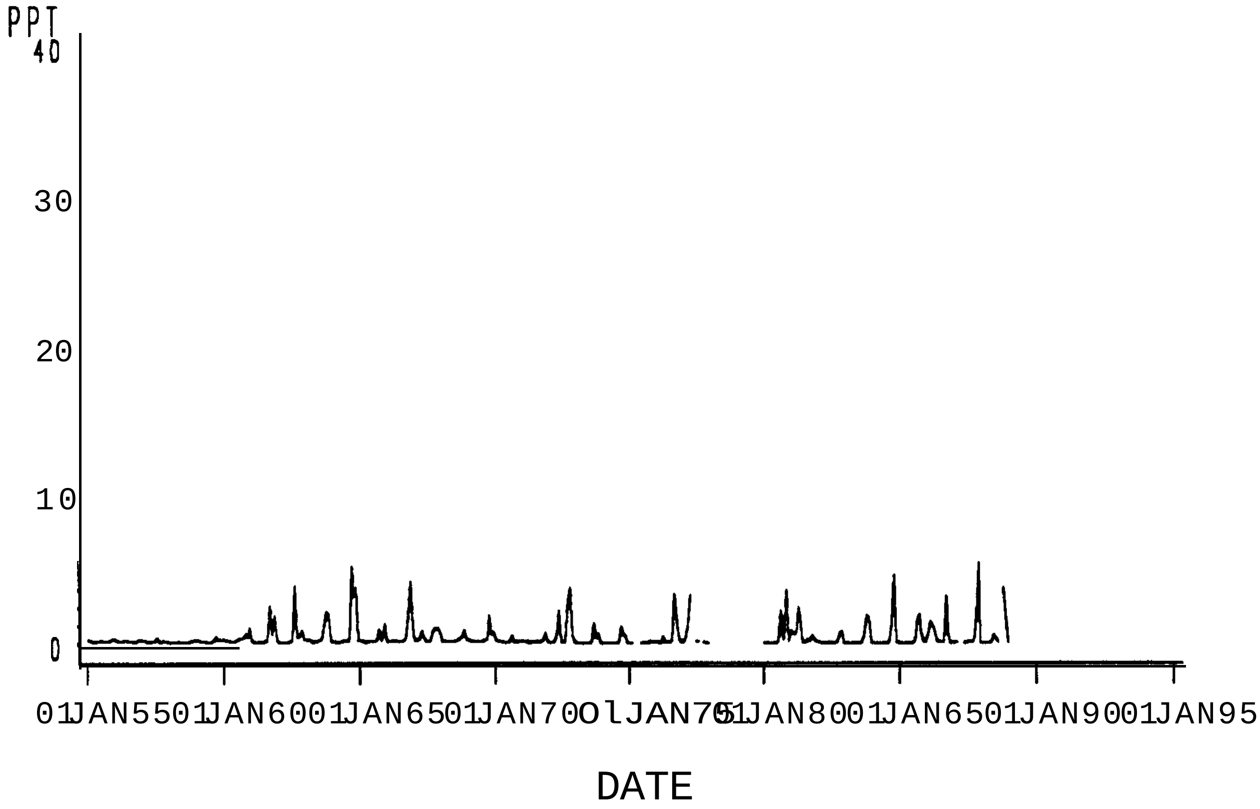
MONTHLY MAXIMUM SALINITY

STATION=76303 BAYOU PETlTE CAILLOU



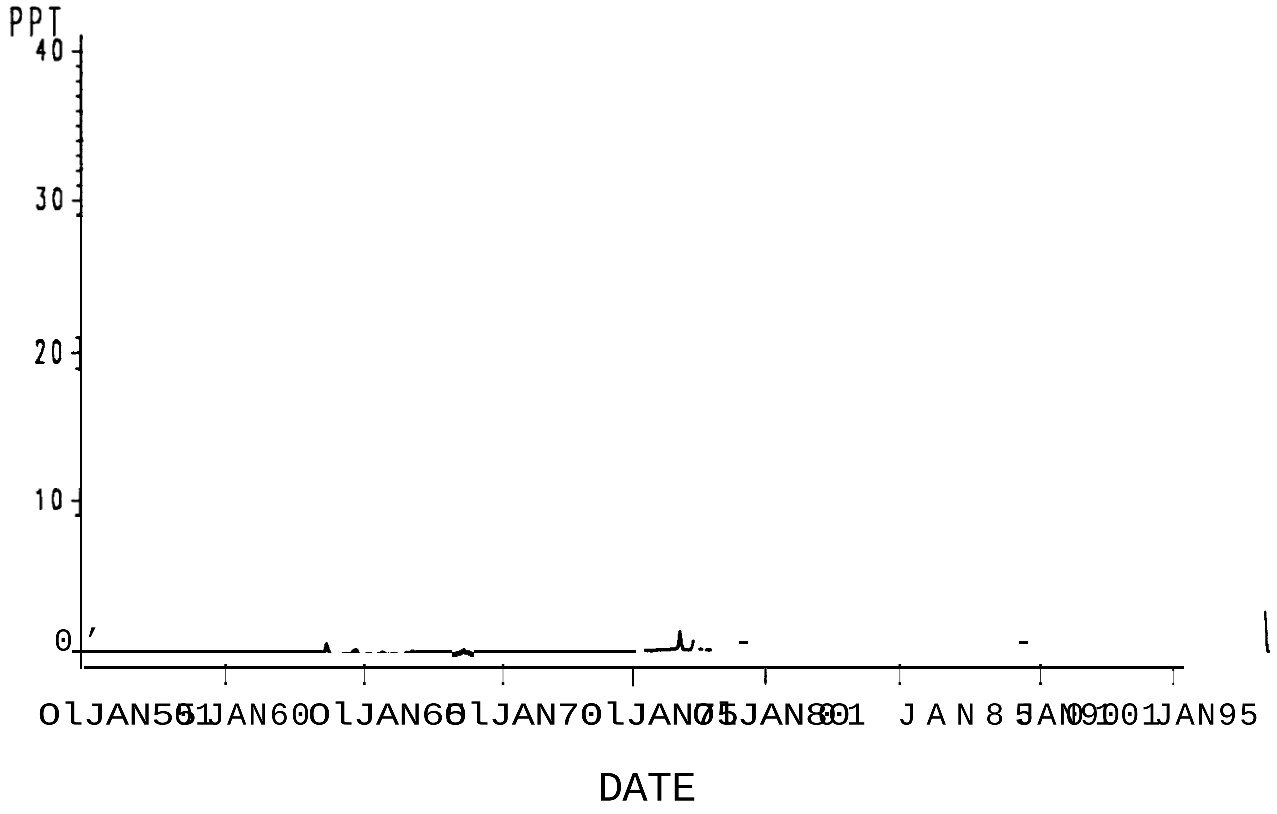
MONTHLY MEAN SALINITY

STATION=76320 IWW AT HOUMA



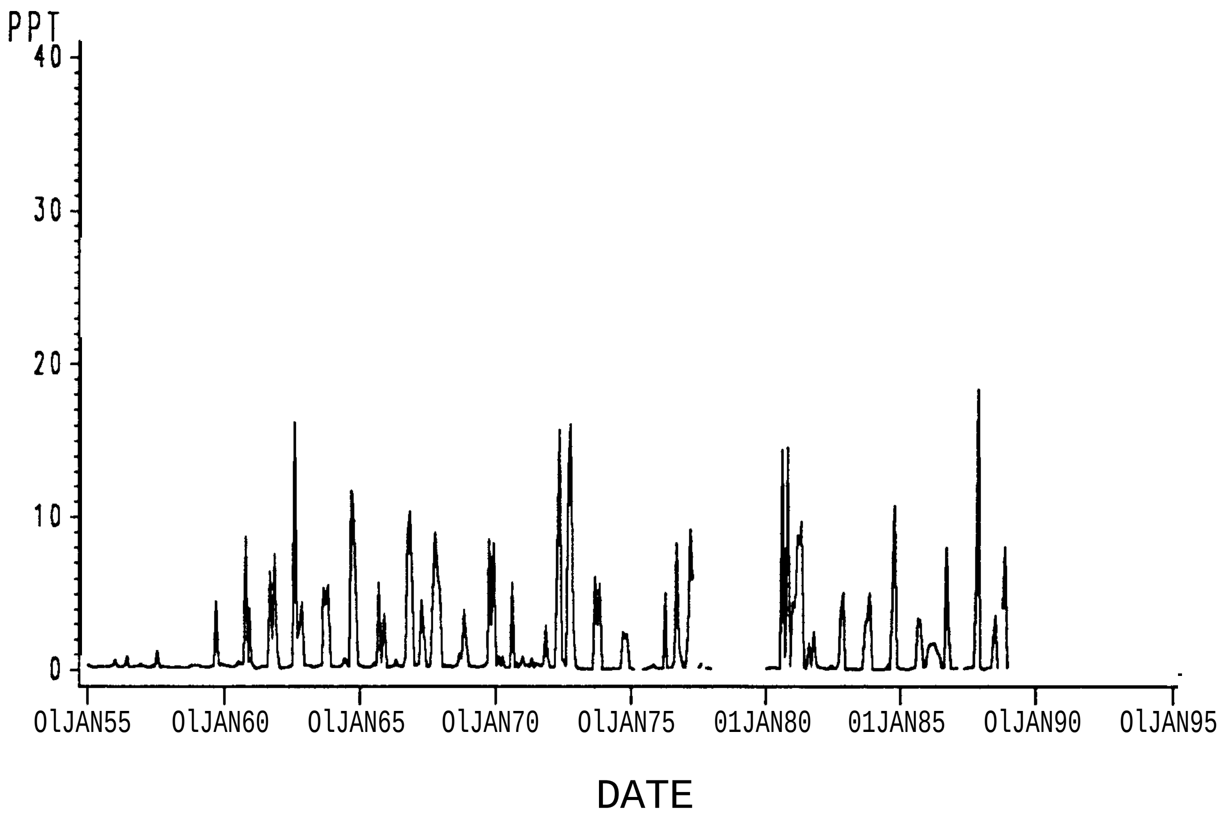
MONTHLY MINIMUM SALINITY

STATION=76320 IWW AT HOUMA



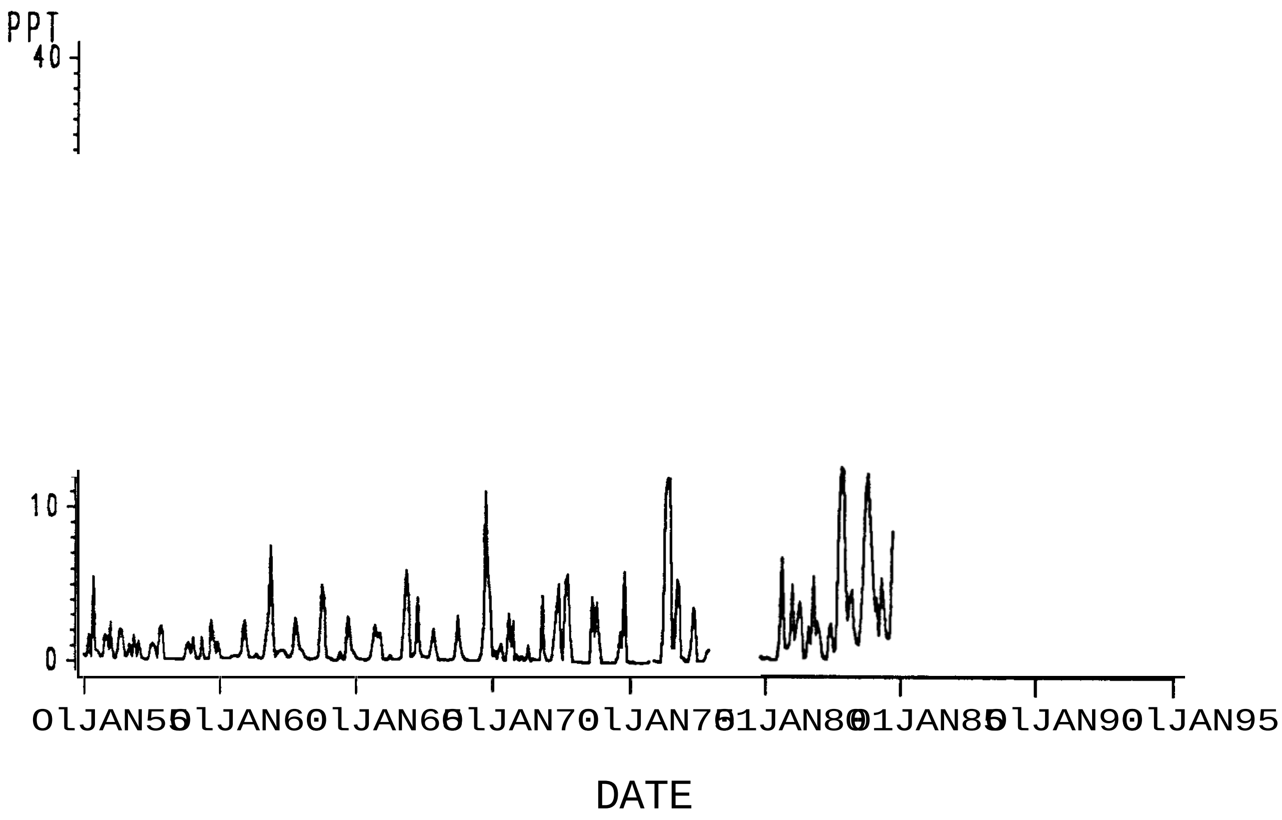
MONTHLY MAXIMUM SALINITY

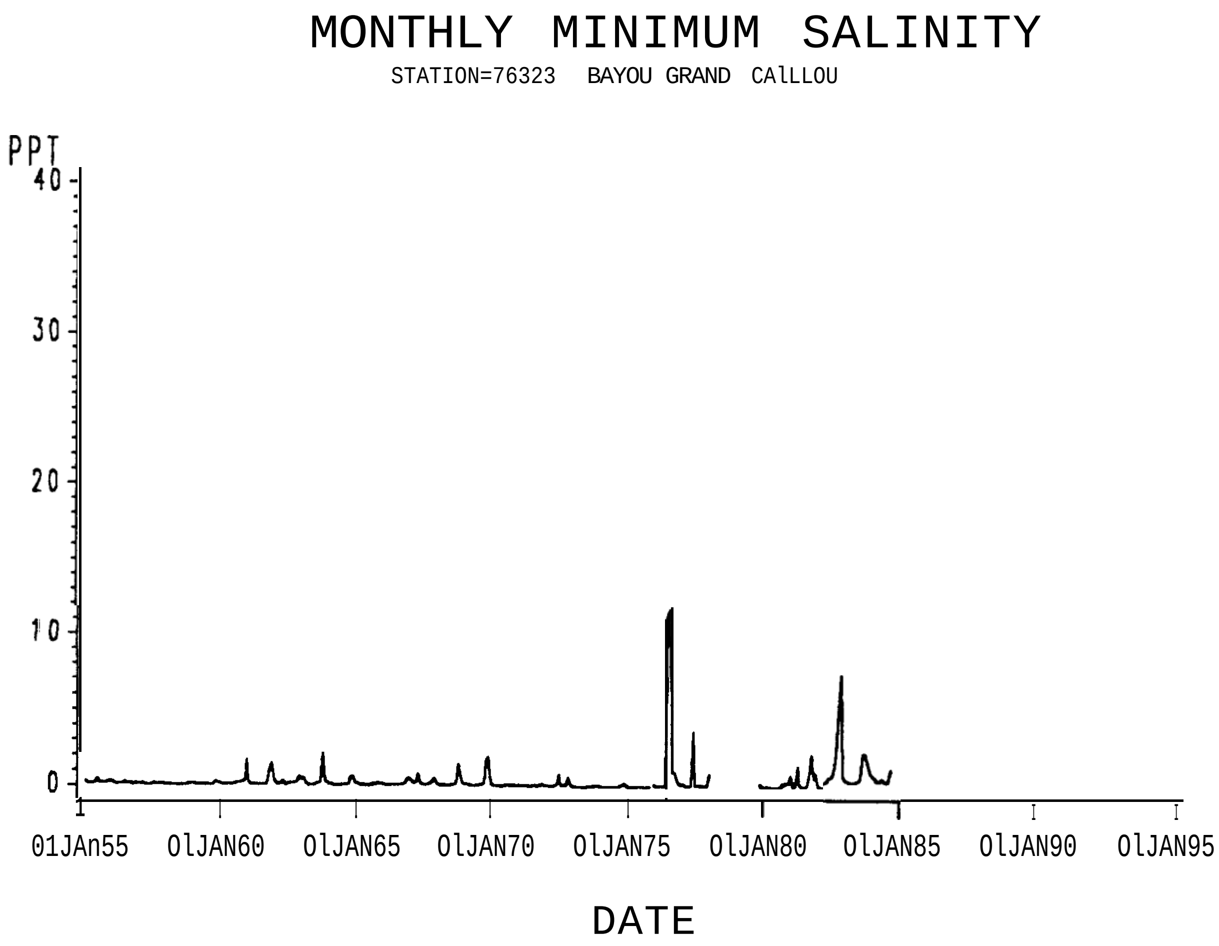
STATION=76320IWW AHOLJMA



MONTHLY MEAN SALINITY

STATION=76323 BAYOU GRAND CAILLOU

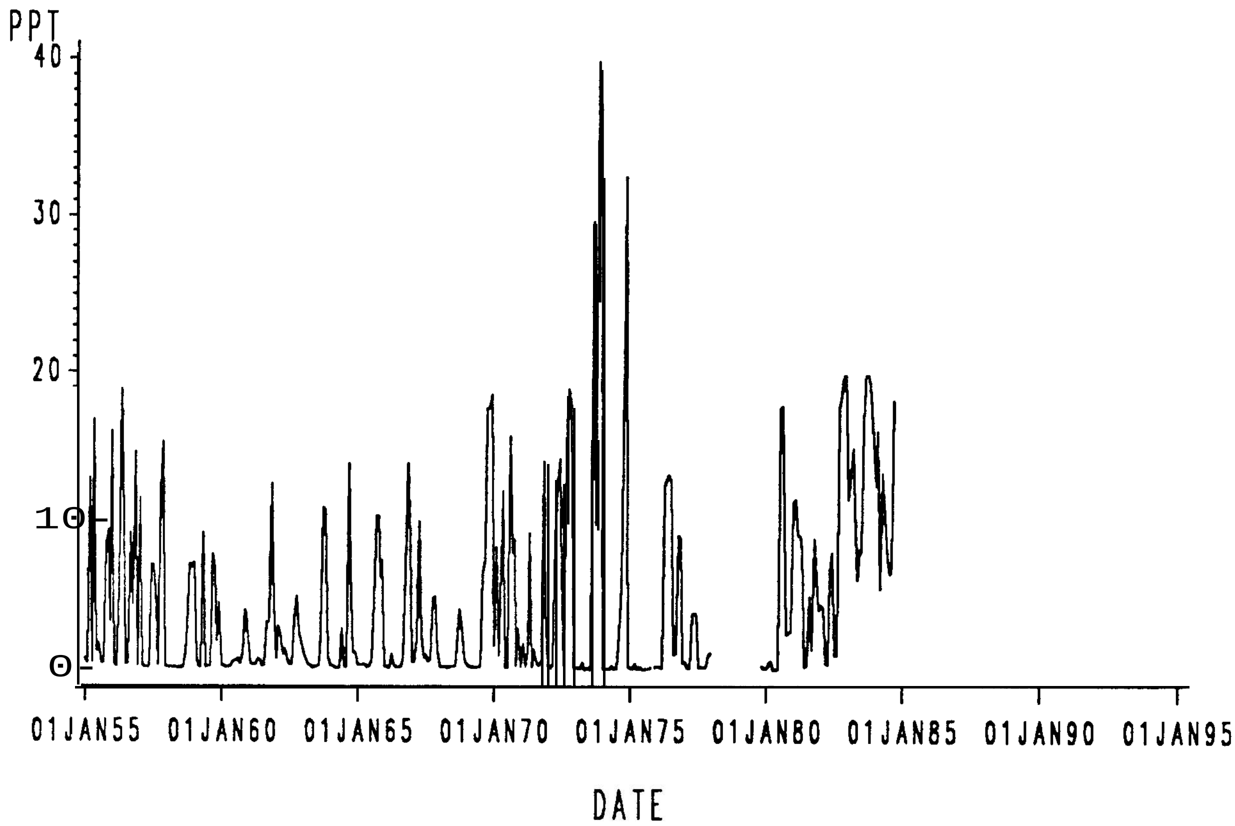


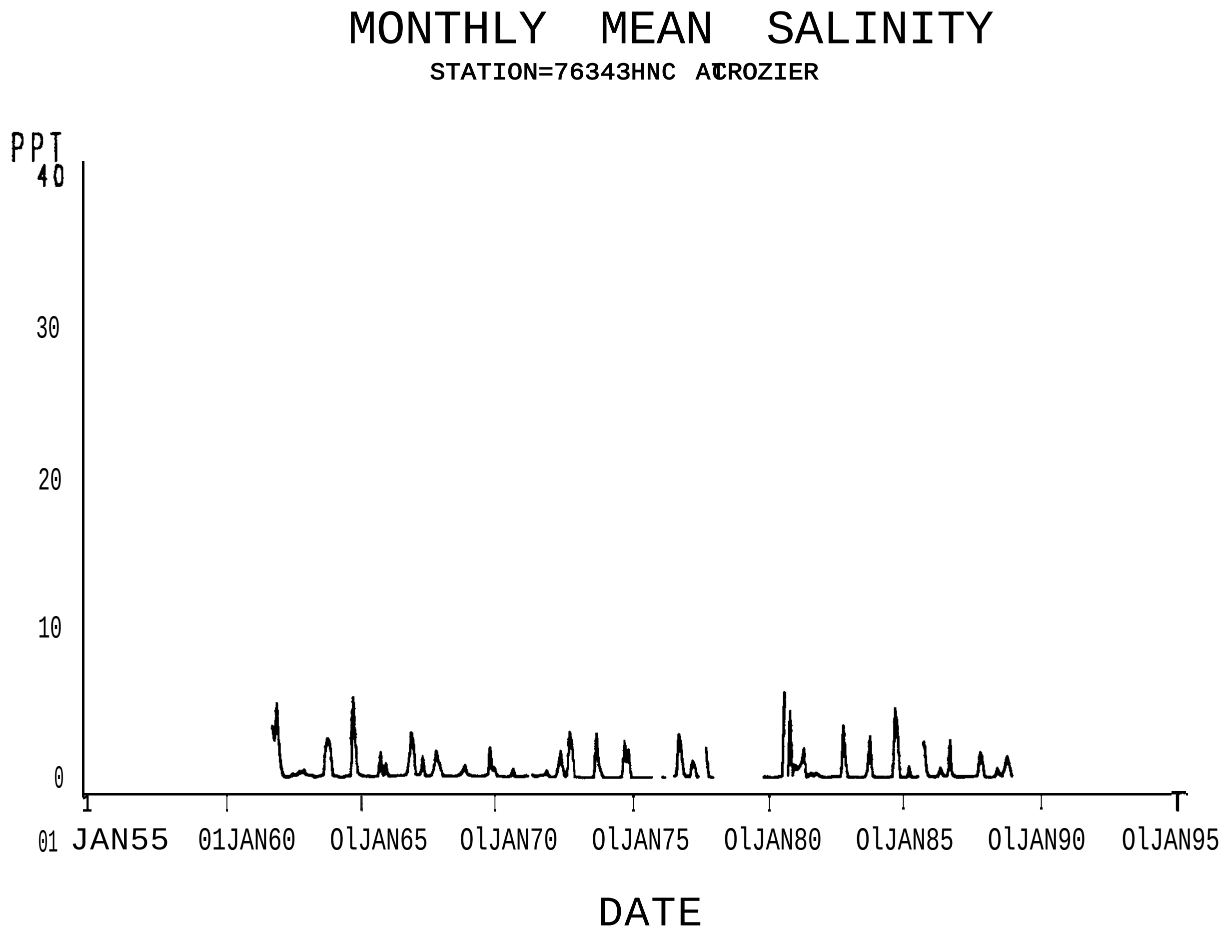


MONTHLY MINIMUM SALINITY
STATION=76323 BAYOU GRAND CAlLLOU
PPT
40
30
20
10
0
01JAn55
OlJAN60
OlJAN65
OlJAN70
OlJAN75
OlJAN80
OlJAN85
OlJAN90
OlJAN95
DATE

MONTHLY MAXIMUM SALINITY

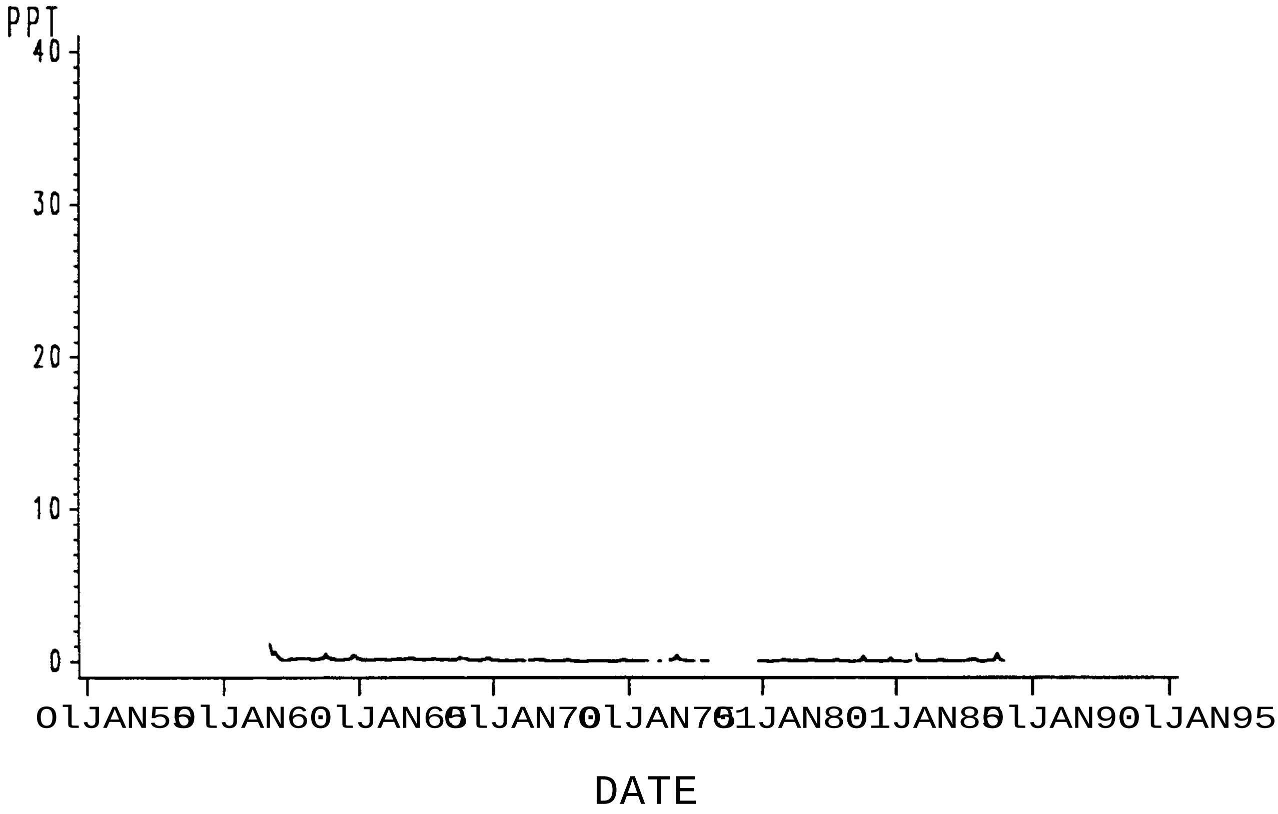
STATION=76323 BAYOU GRAND CAlLLOU

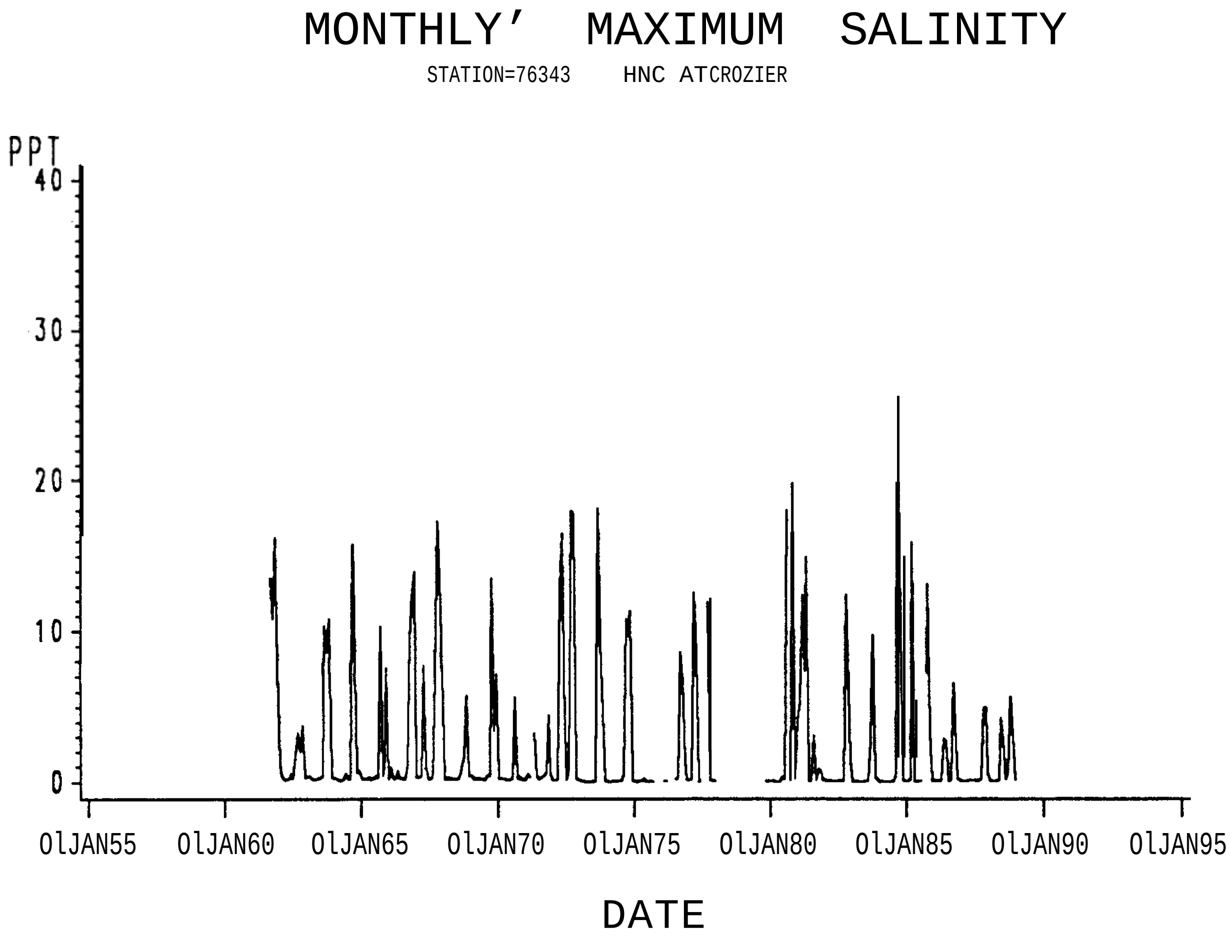



MONTHLY MEAN SALINITY
STATION=76343HNC AT CROZIER
PPT
40
30
20
10
0
01 JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

MONTHLY MINIMUM SALINITY

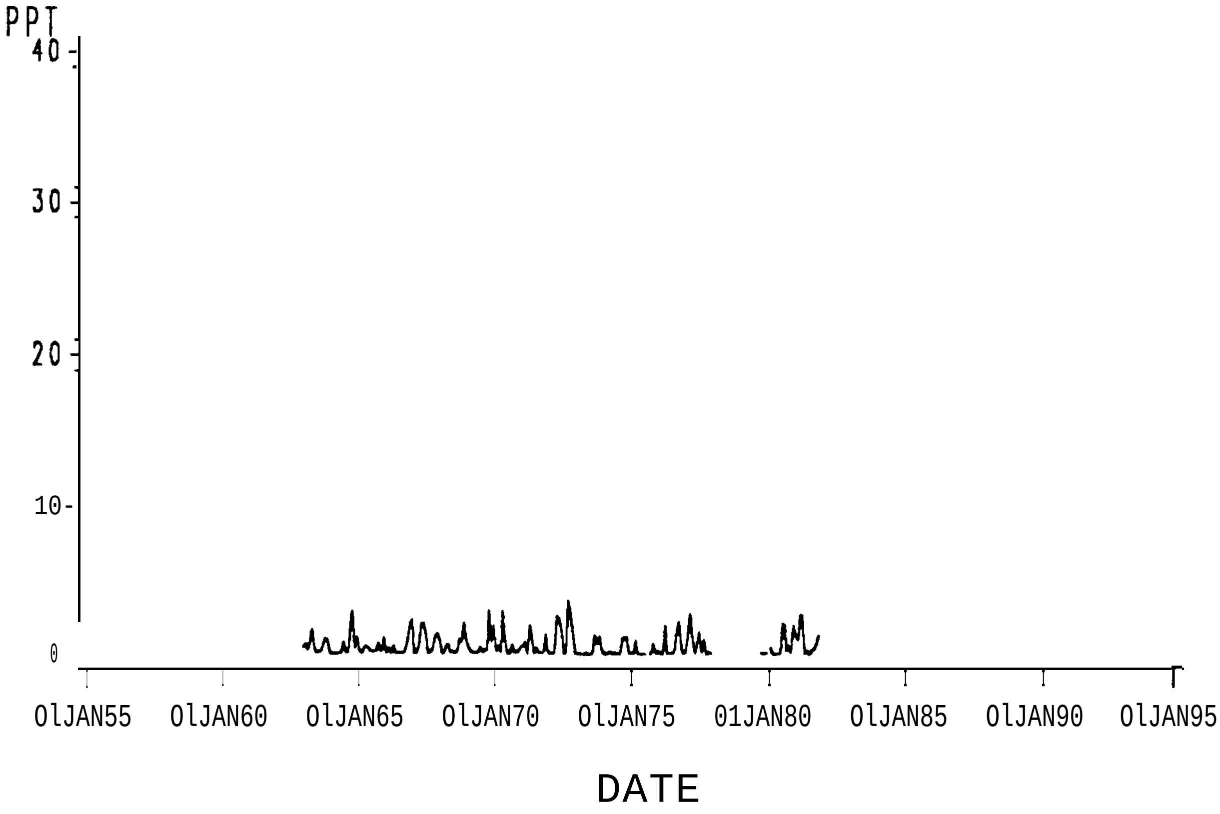
STATION=76343 HNC AT CROZIER

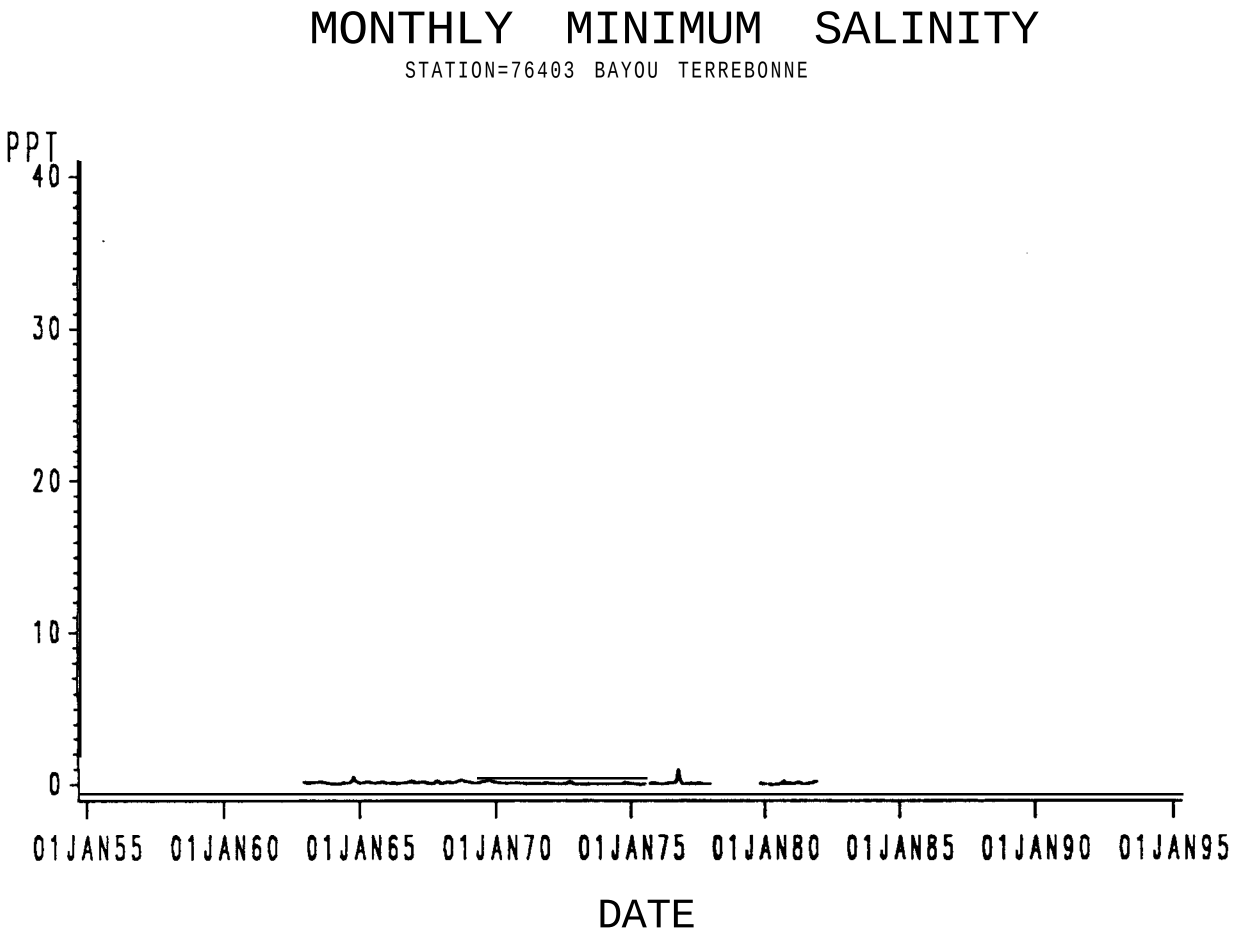


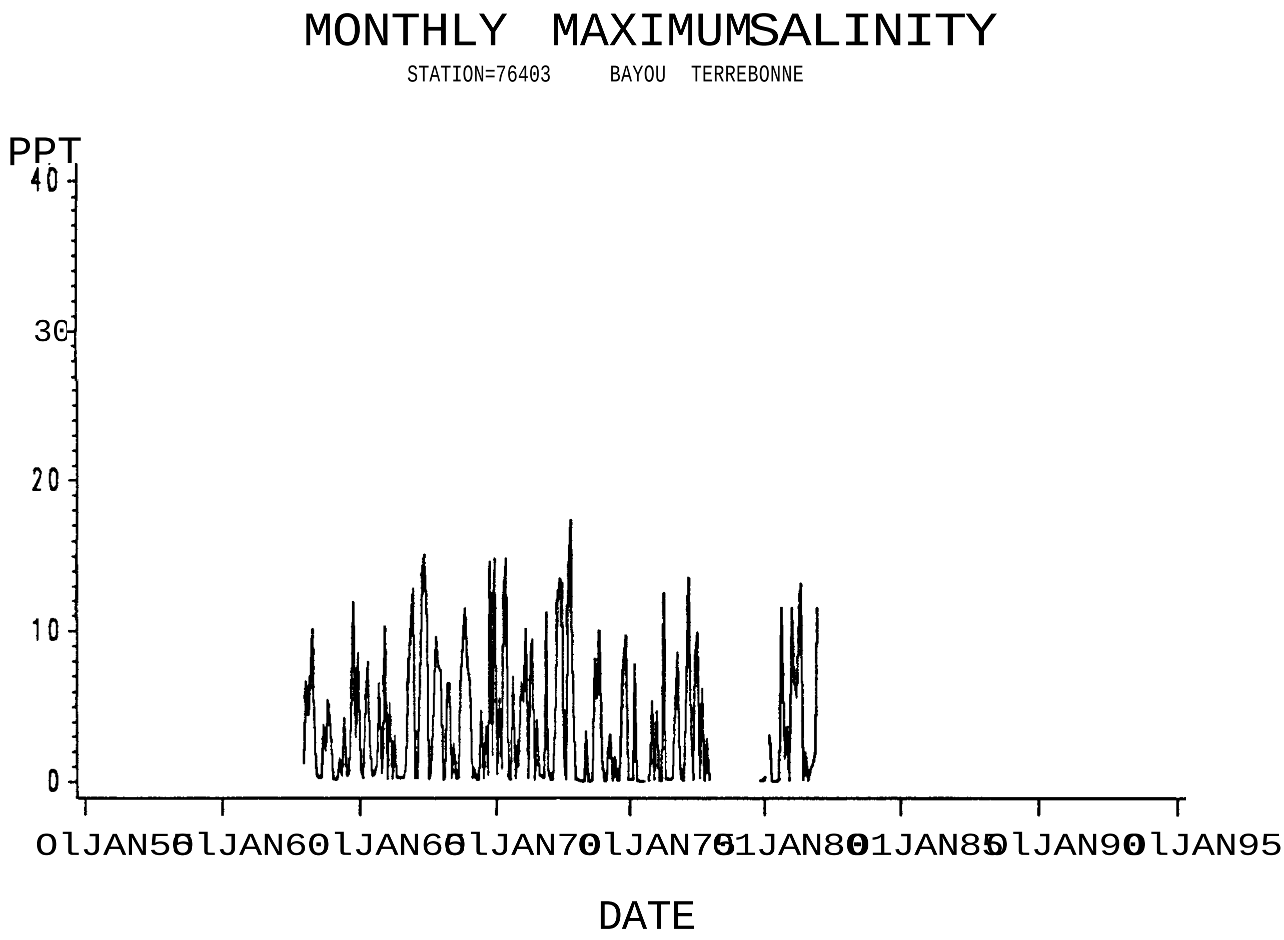

MONTHLY' MAXIMUM SALINITY
STATION=76343 HNC ATCROZIER
PPT
40
30
20
10
0
OlJAN55
OlJAN60
OlJAN65
OlJAN70
OlJAN75
OlJAN80
OlJAN85
OlJAN90
OlJAN95
DATE

MONTHLY MEAN SALINITY

STATION=76403 BAYOU TERREBONNE

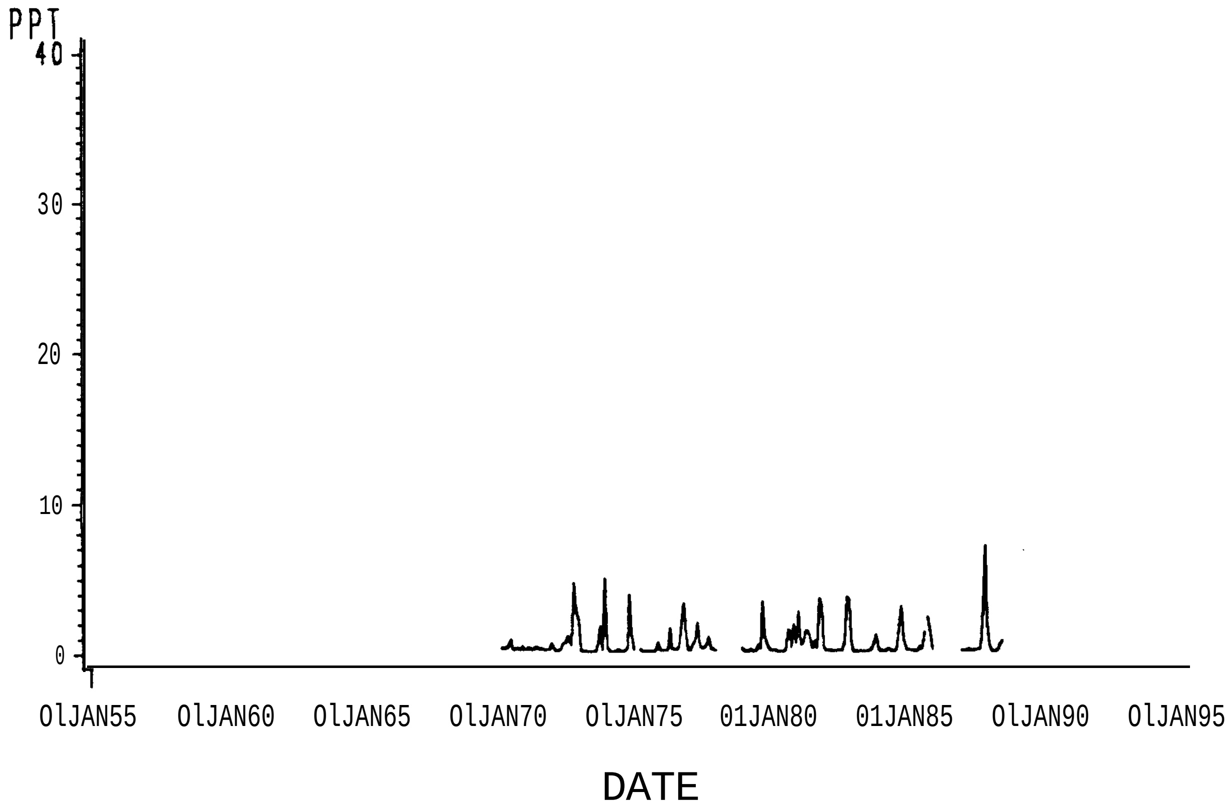



MONTHLY MINIMUM SALINITY
STATION=76403 BAYOU TERREBONNE
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE


MONTHLY MAXIMUM SALINITY
STATION=76403 BAYOU TERREBONNE
PPT
40
30
20
10
0
01JAN50
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

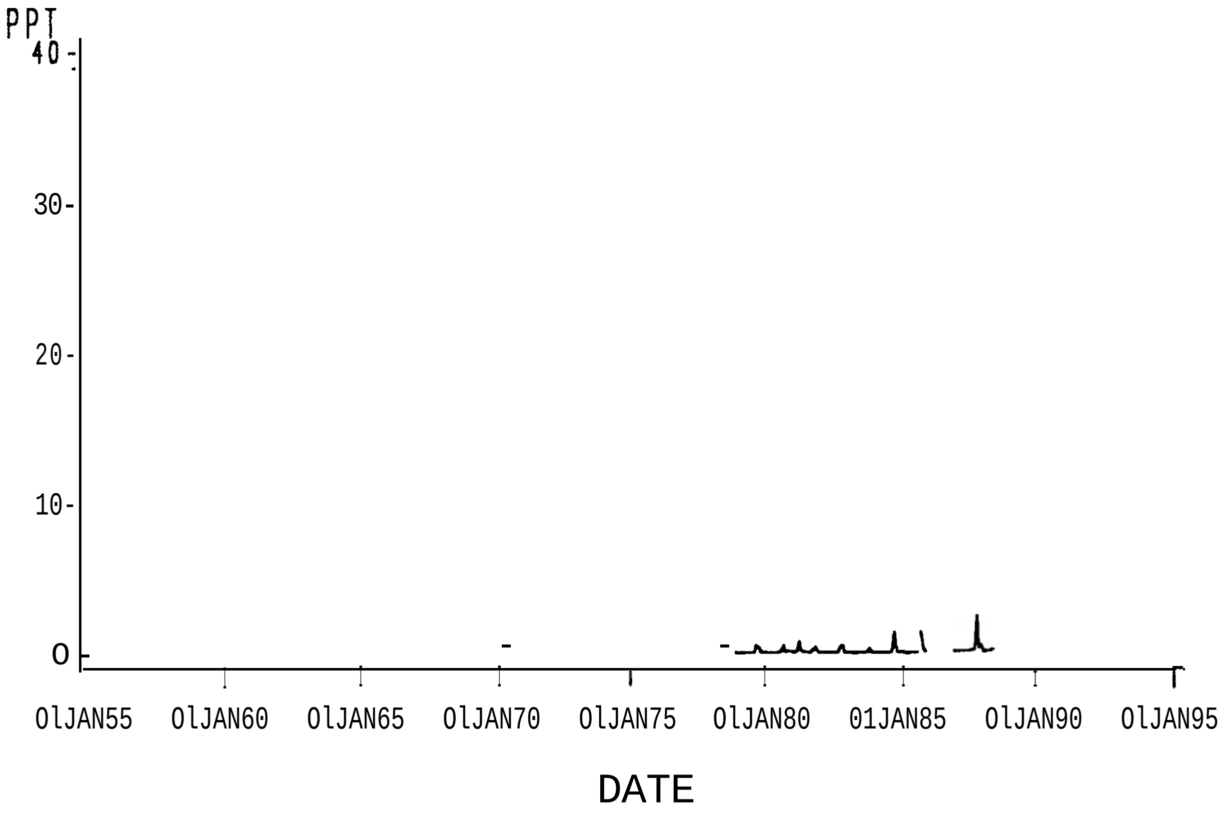
MONTHLY MEAN SALINITY

STATION=82203 LAROSE



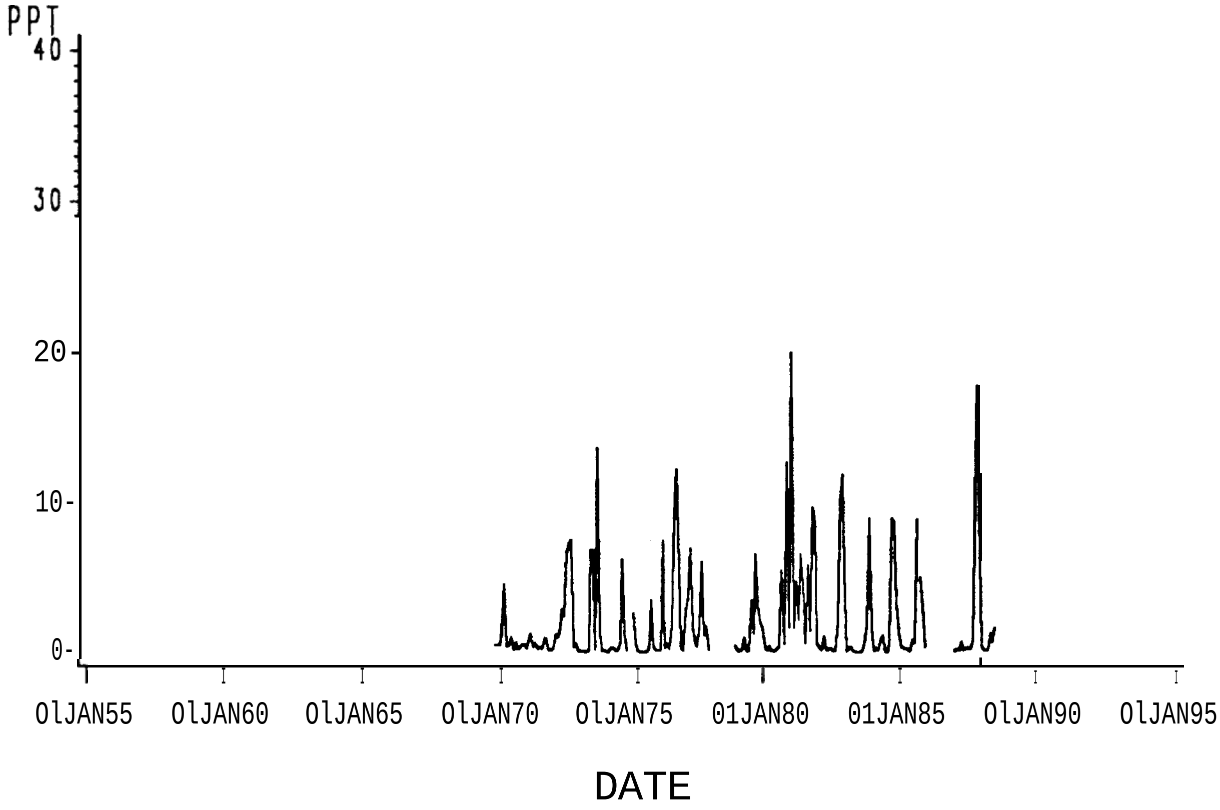
MONTHLY MINIMUM SALINITY

STATION=82203 LAROSE



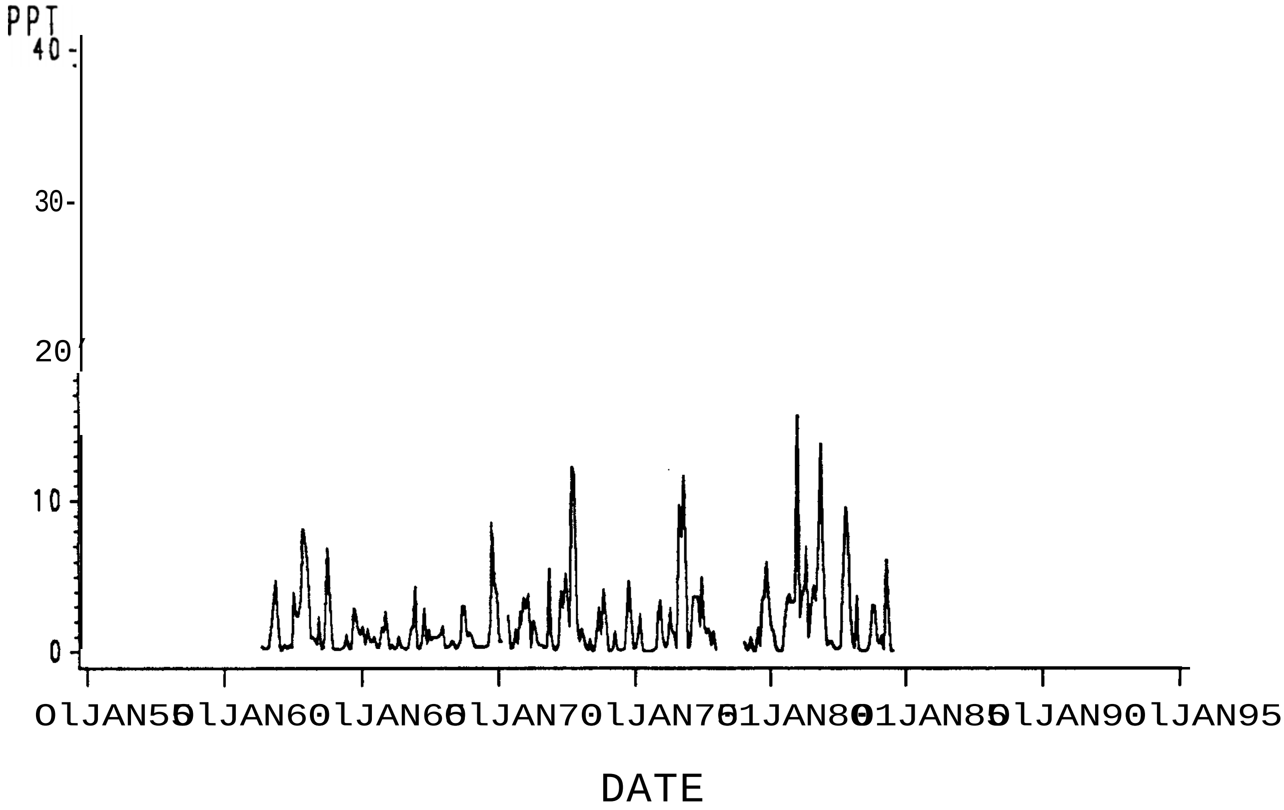
MONTHLY MAXIMUM SALINITY

STATION=82203 LaRose



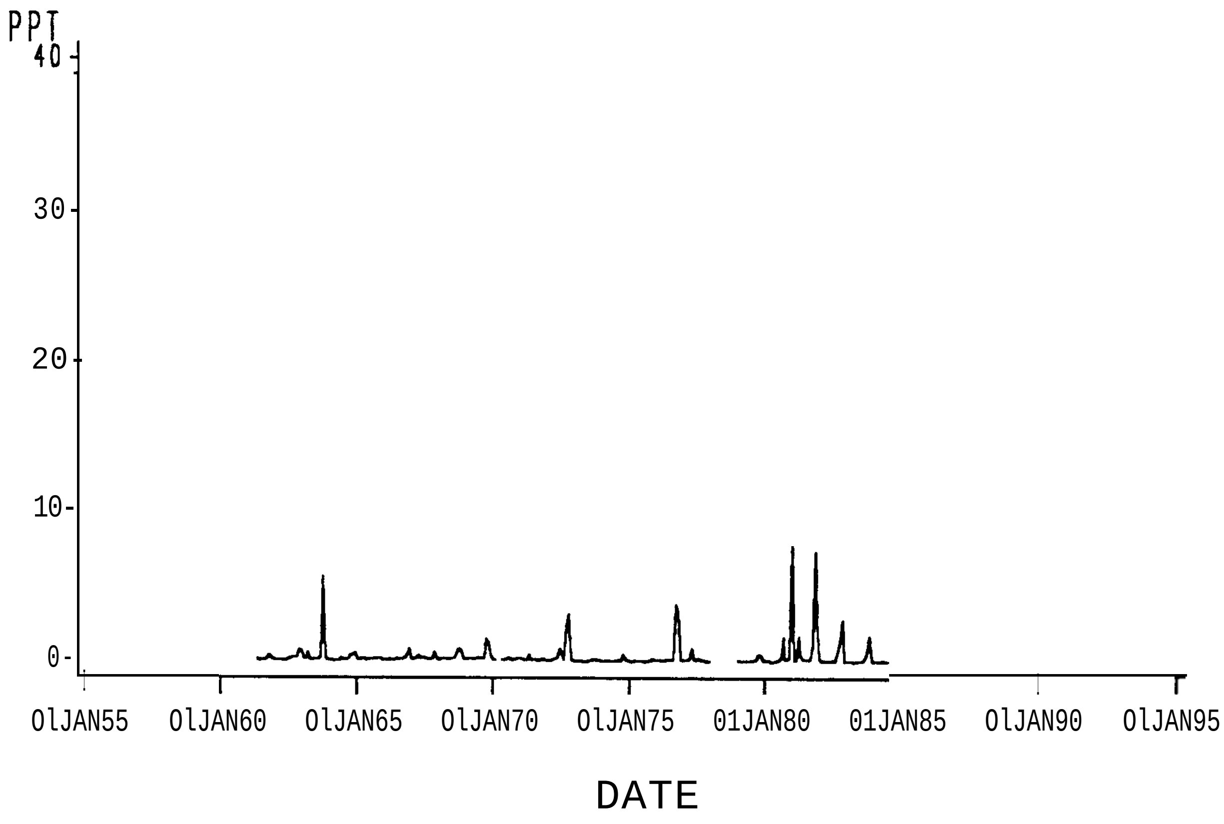
MONTHLY MEAN SALINITY

STATION=82300 CALLLANO



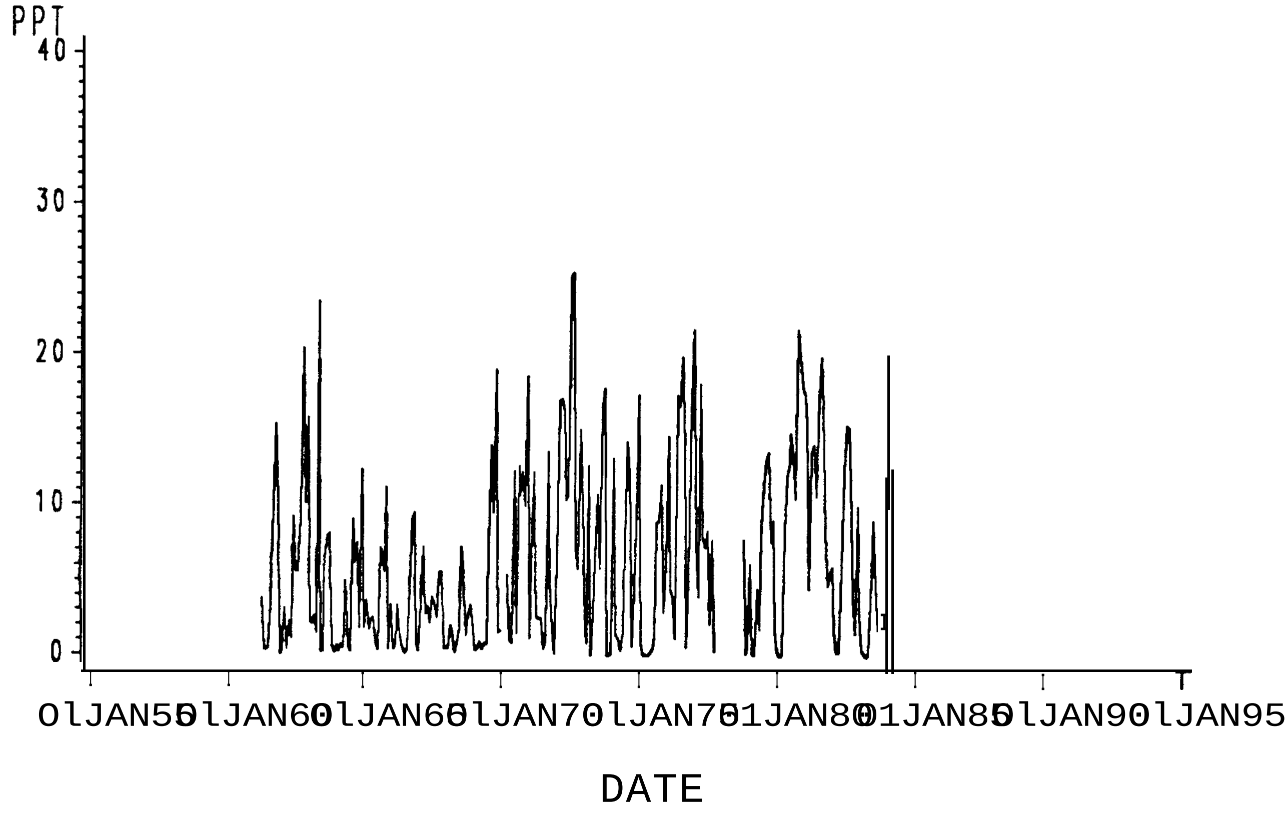
MONTHLY MINIMUM SALINITY

STATION=82300 GALLIANO



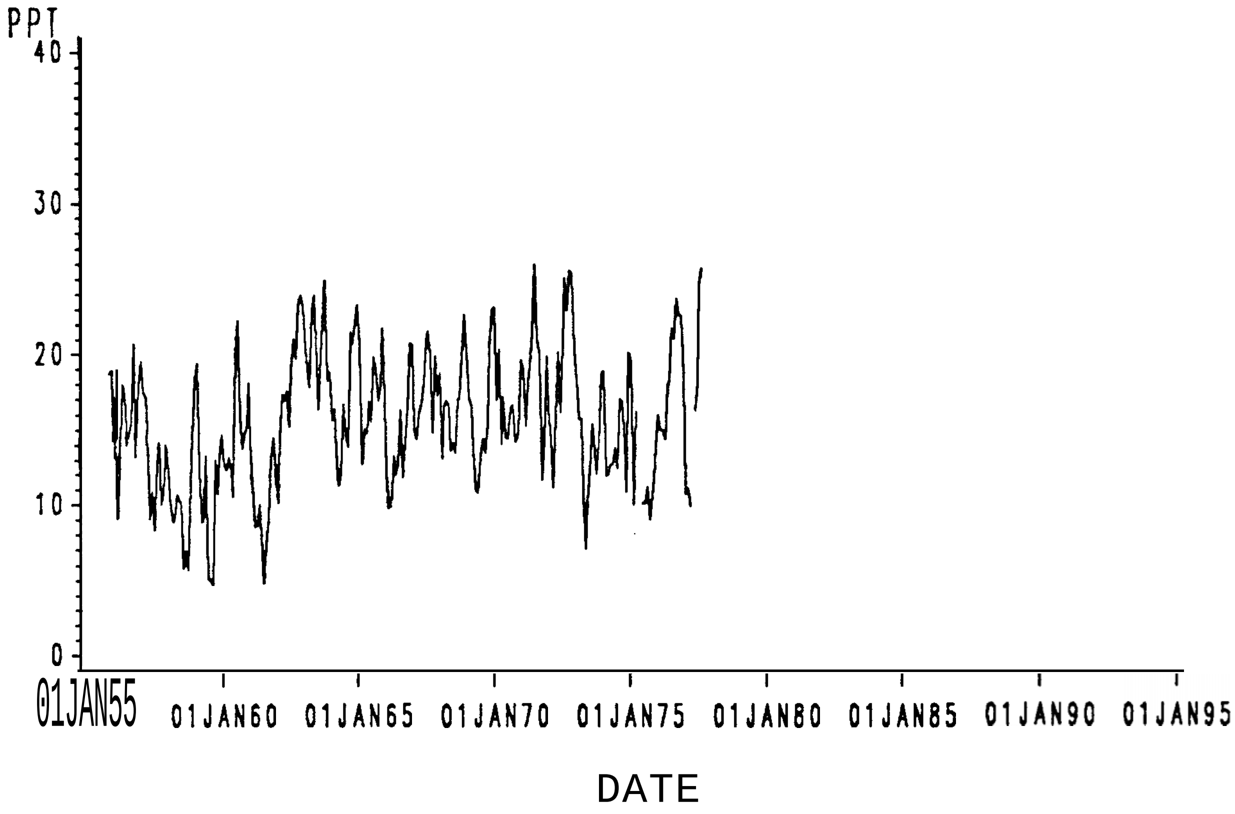
MONTHLY MAXIMUM SALINITY

STATION=82300 GALLIANO



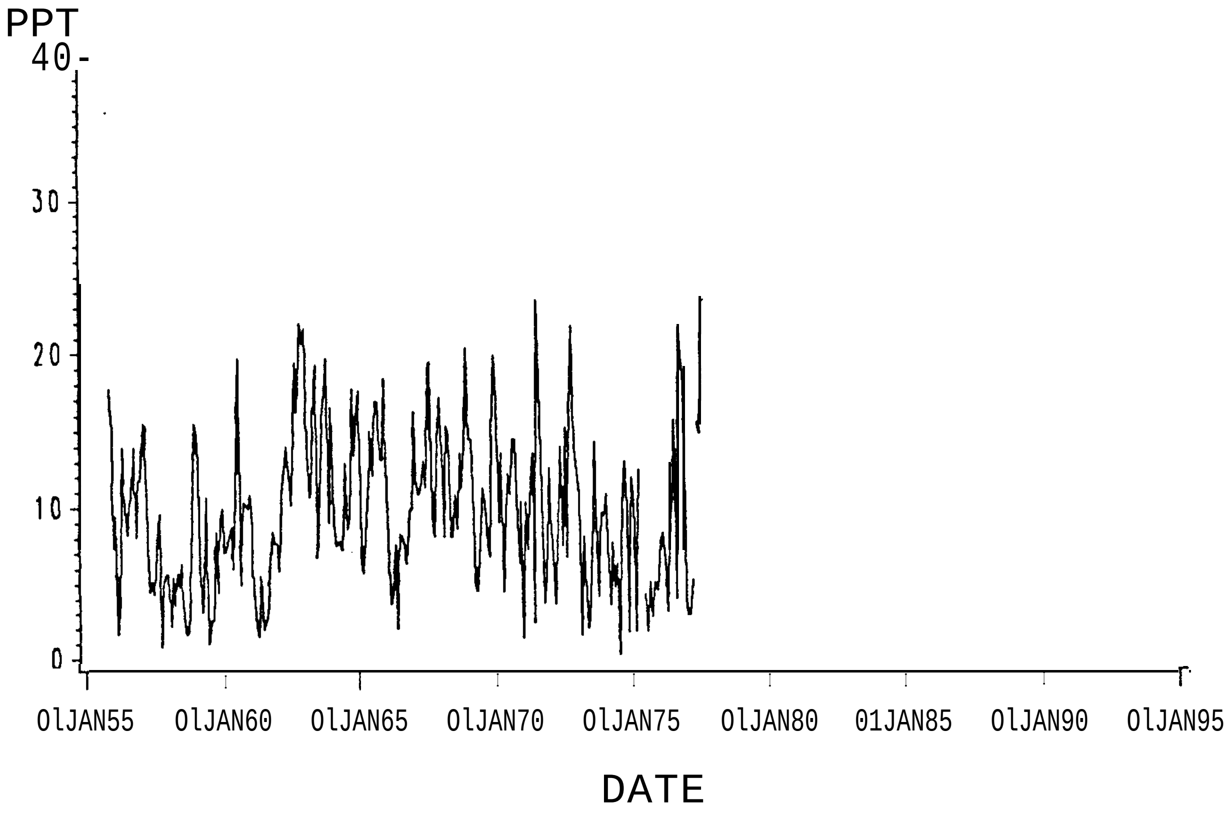
MONTHLY MEAN SALINITY

STATION=82350LEEVLLE



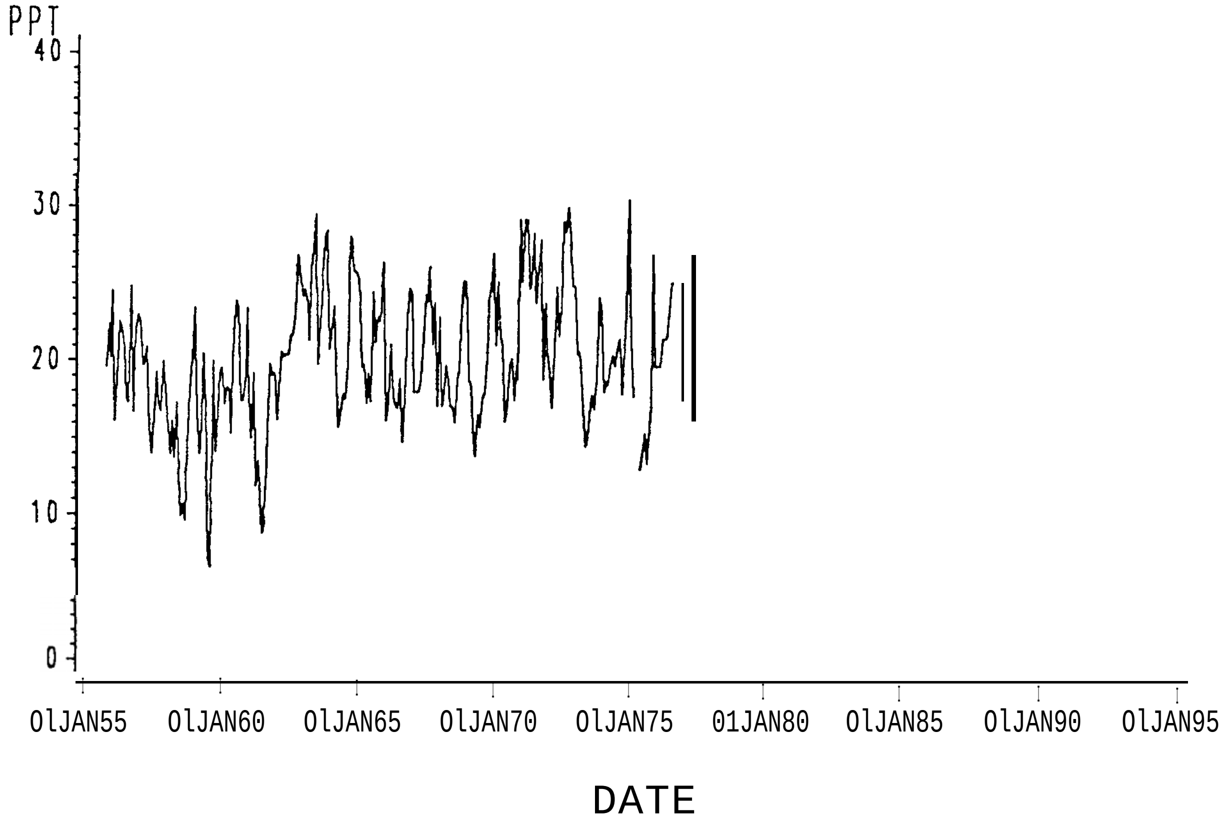
MONTHLY MINIMUM SALINITY

STATION=82350 LEEVILLE



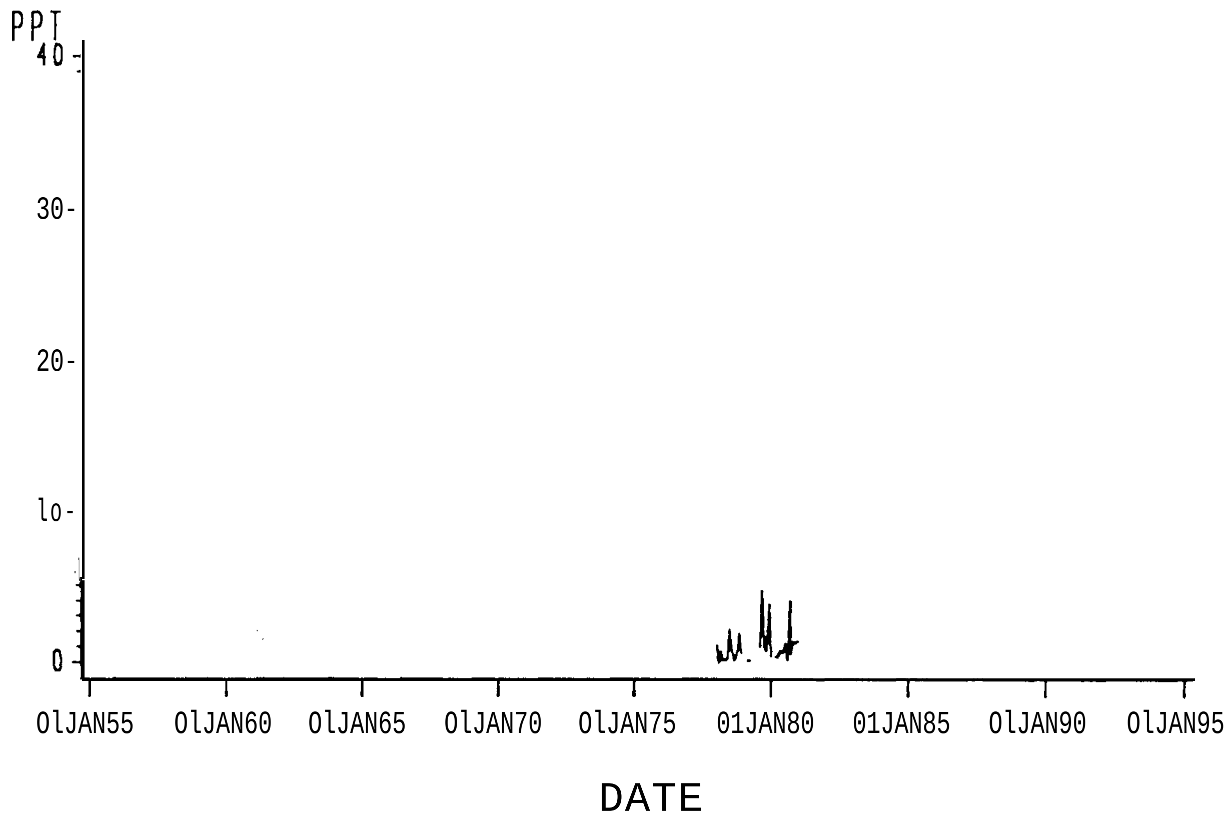
MONTHLY MAXIMUM SALINITY

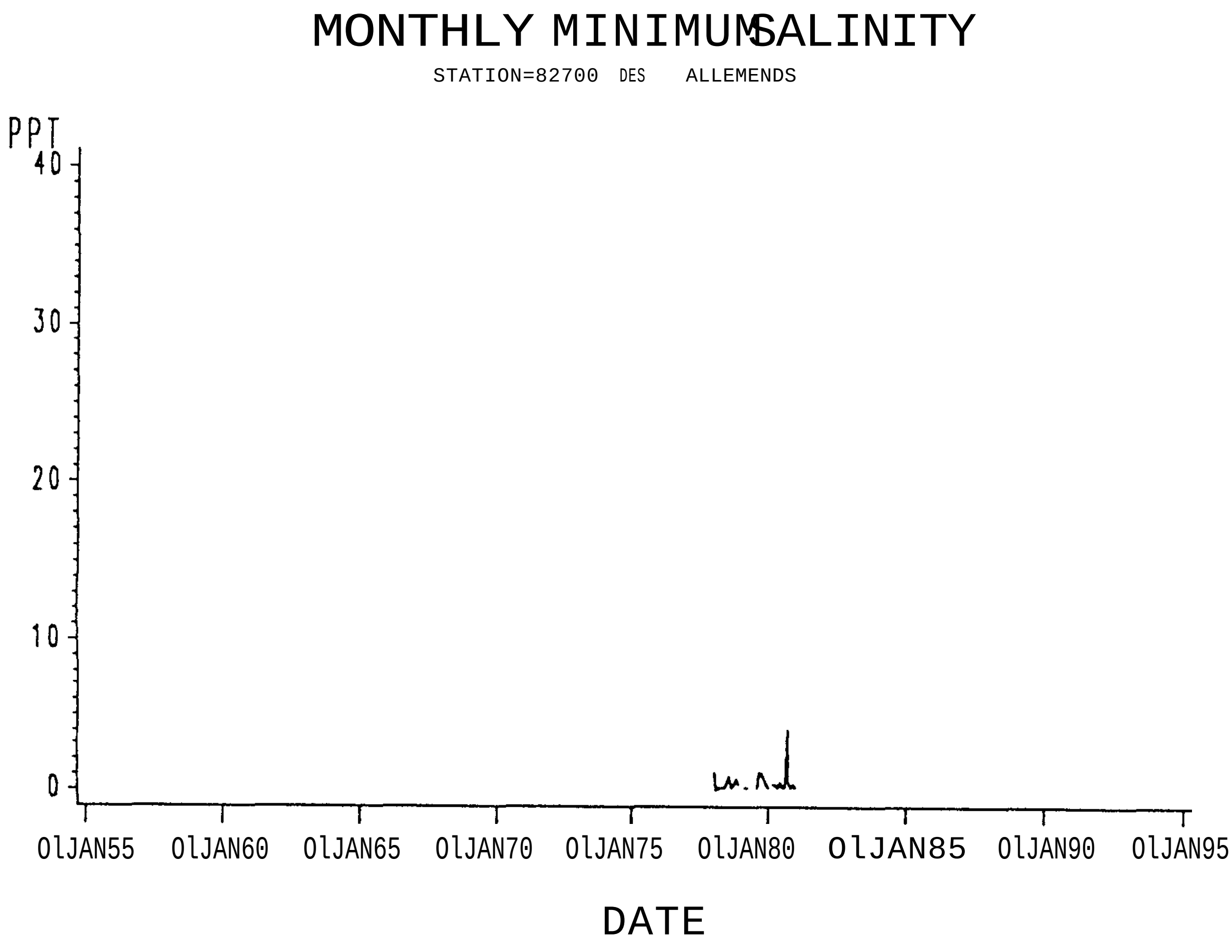
STATION=82350 LEMLLE



MONTHLY MEAN SALINITY

STATION=82700 DES ALLEMENDS

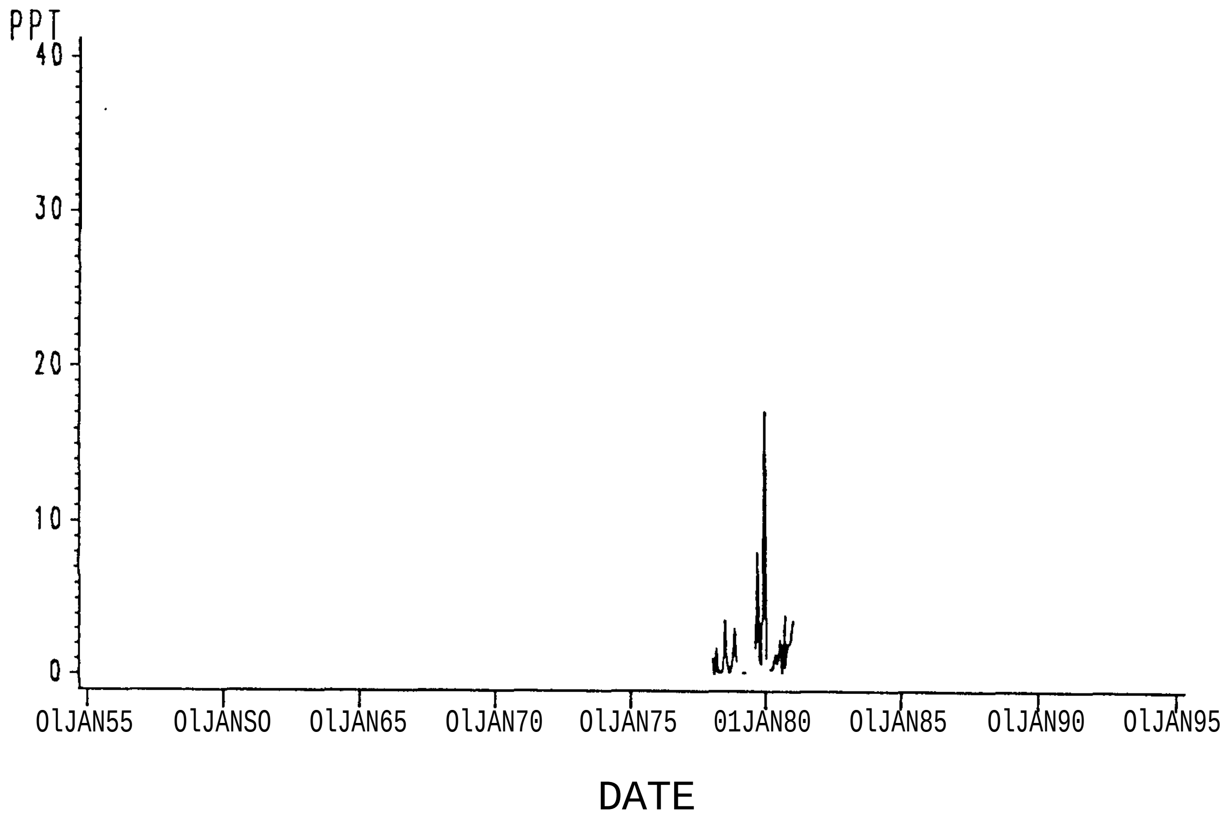




MONTHLY MINIMUM SALINITY
STATION=82700 DES ALLEMENDS
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
DATE

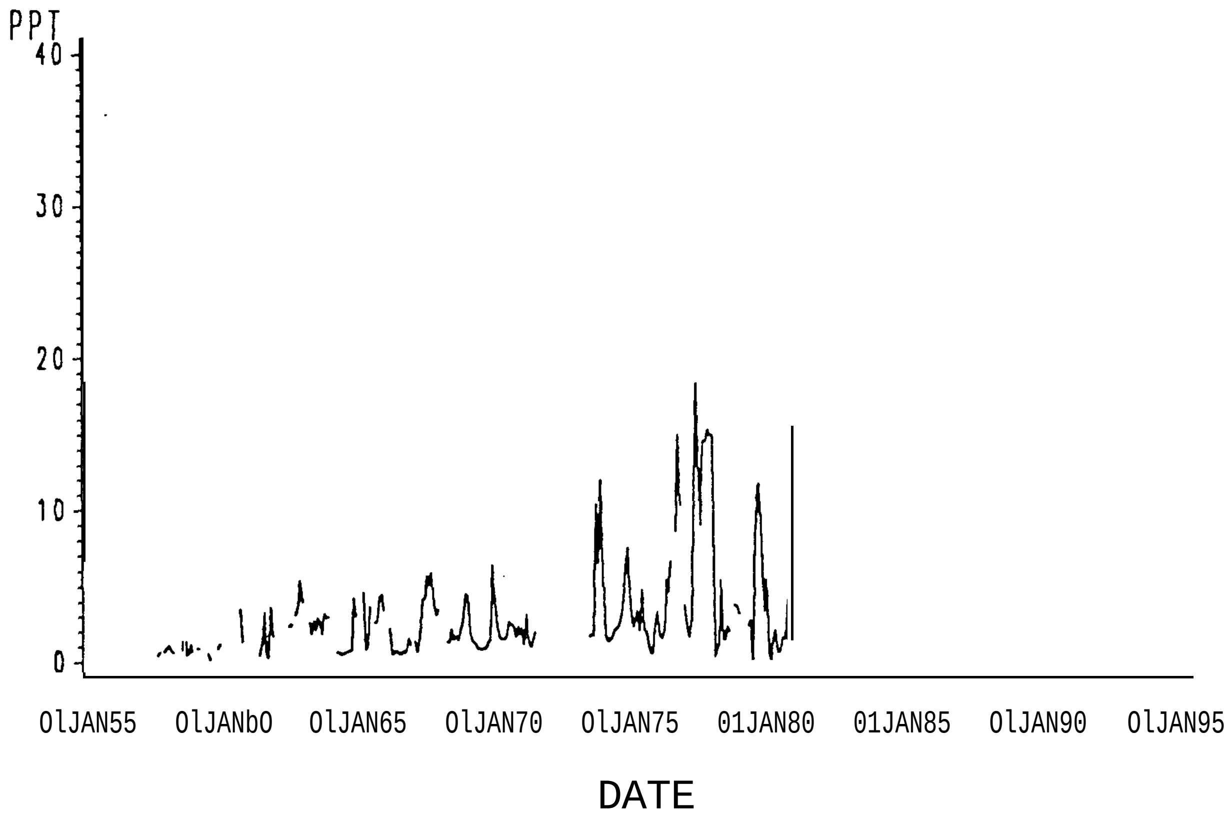
MONTHLY MAXIMUMSALINIlY

STATION=82700 DES ALLEMENDS



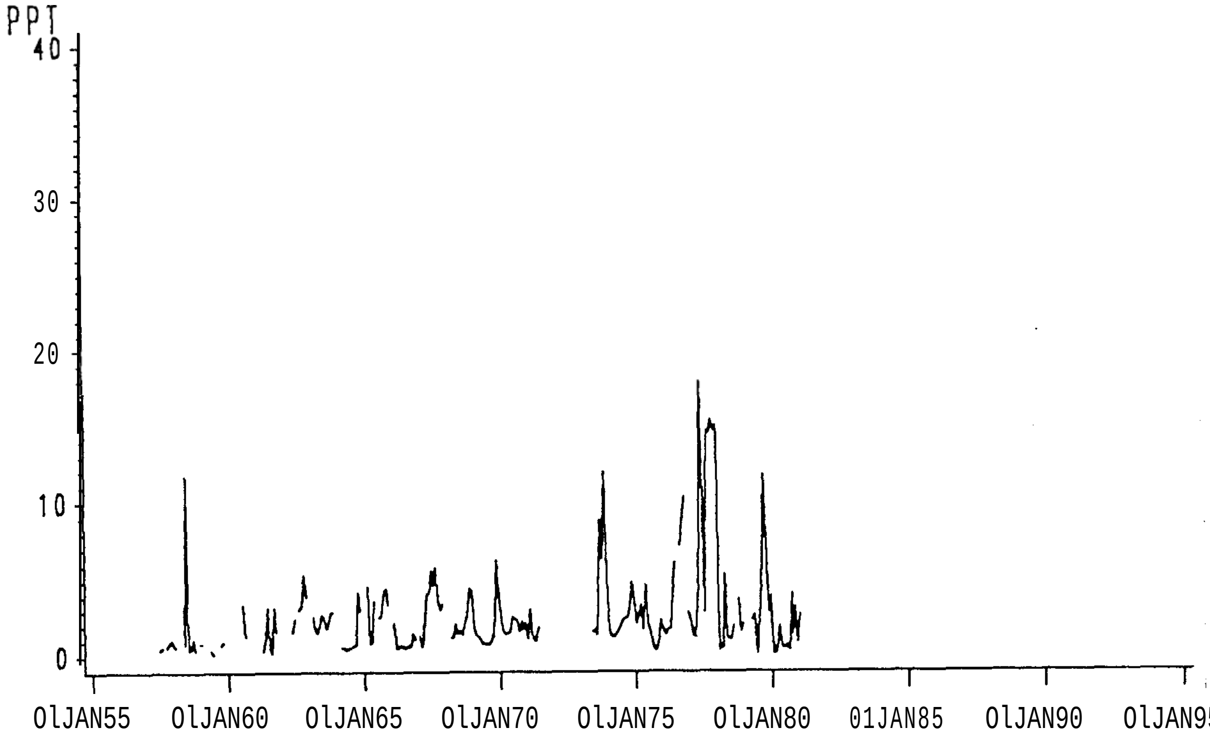
MONTHLY MEAN SALINITY

STATION=82750 BARATARIA



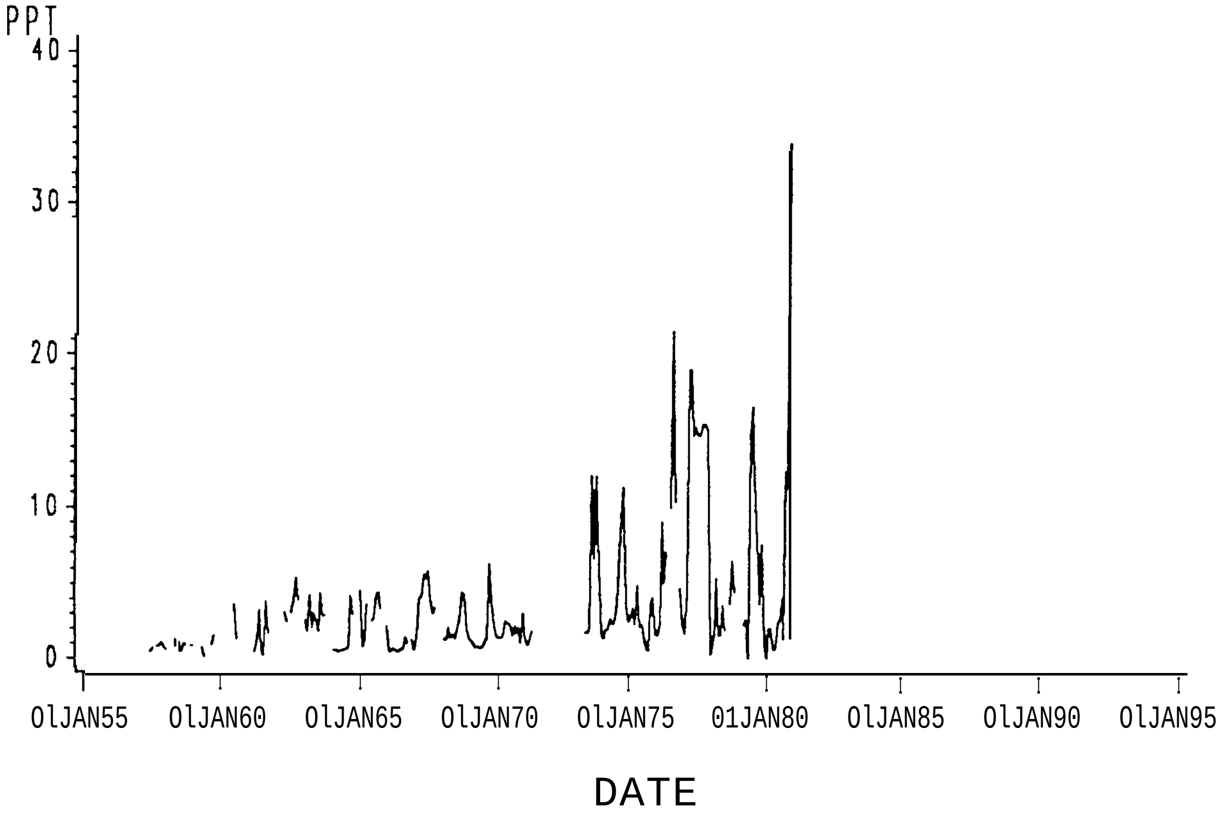
MONTHLY MINIMUM SALINITY

STATION=8275BARATARIA



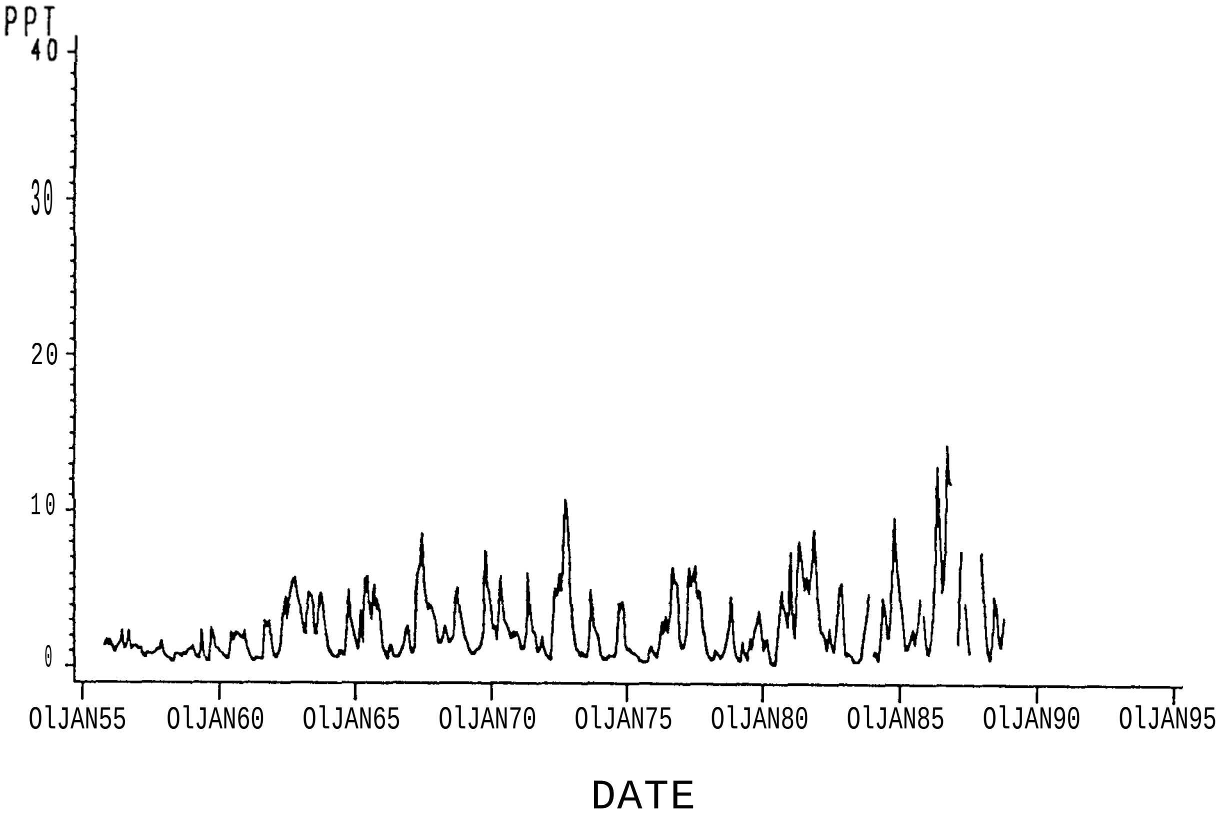
MONTHLY MAXIMUM SALINITY

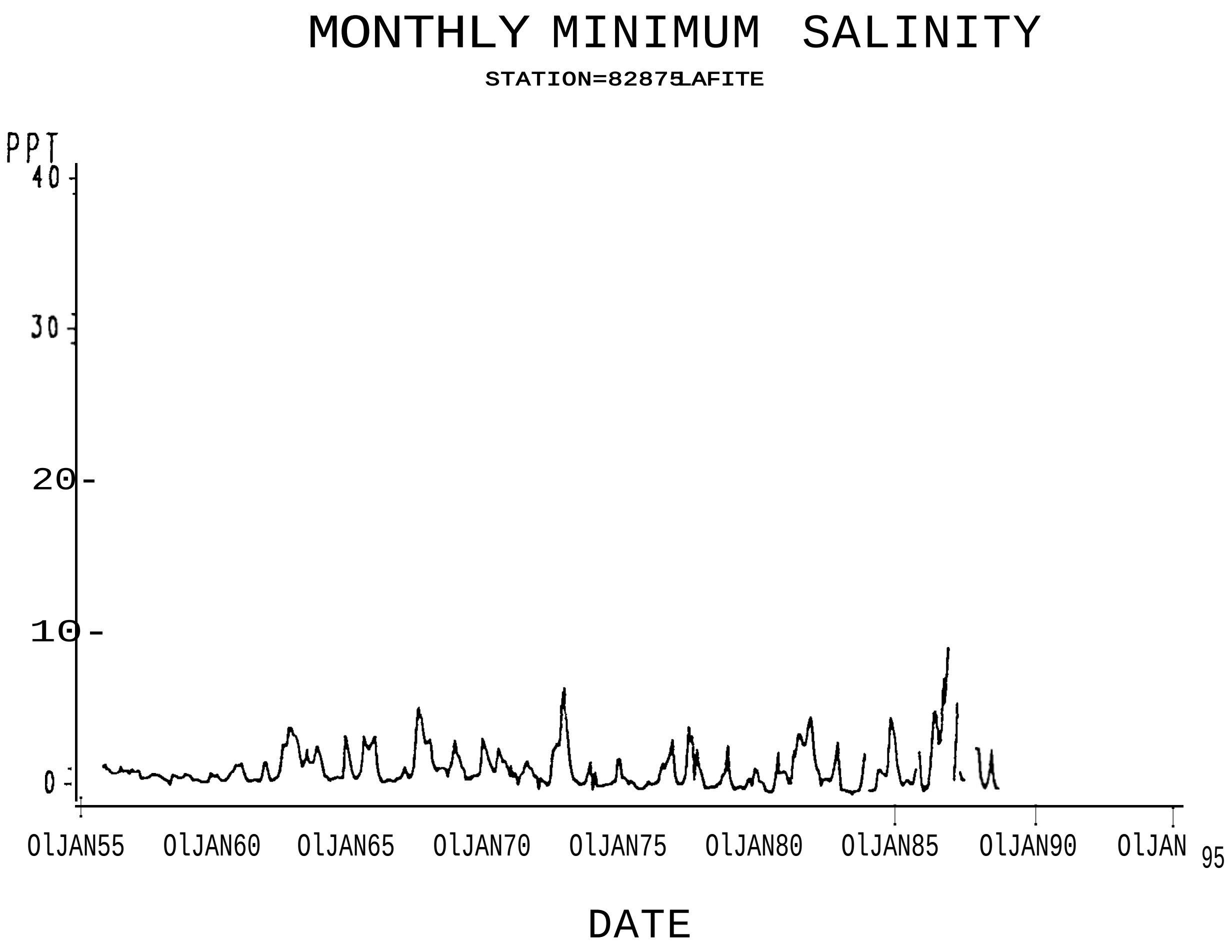
STATION=82750 BARATARIA



MONTHLY MEAN SALINITY

sTATlON=a2a75 lAFiTE

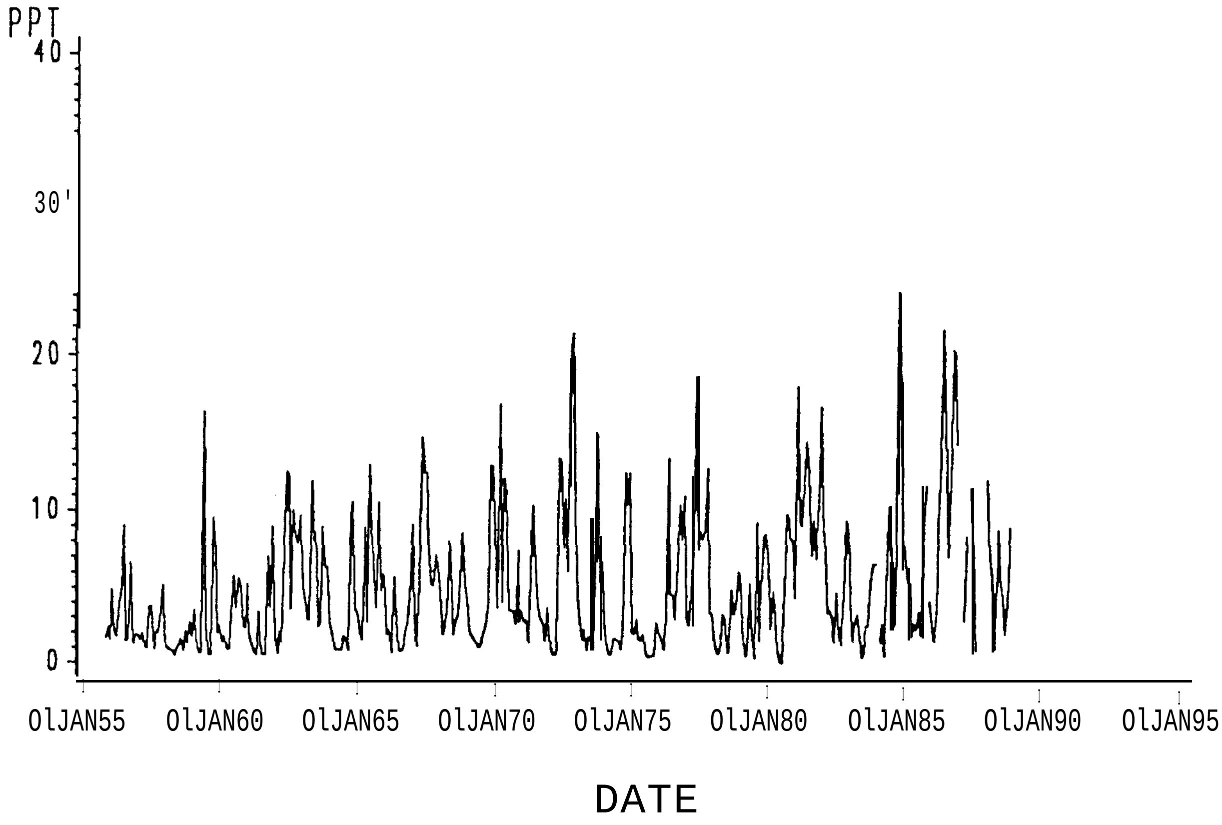




MONTHLY MINIMUM SALINITY
STATION=82875LAFITE
PPT
40
30
20
10
0
01JAN55
01JAN60
01JAN65
01JAN70
01JAN75
01JAN80
01JAN85
01JAN90
01JAN 95
DATE

MONTHLY MAXIMUM SALINITY

STATION=82875 lA!=lTE

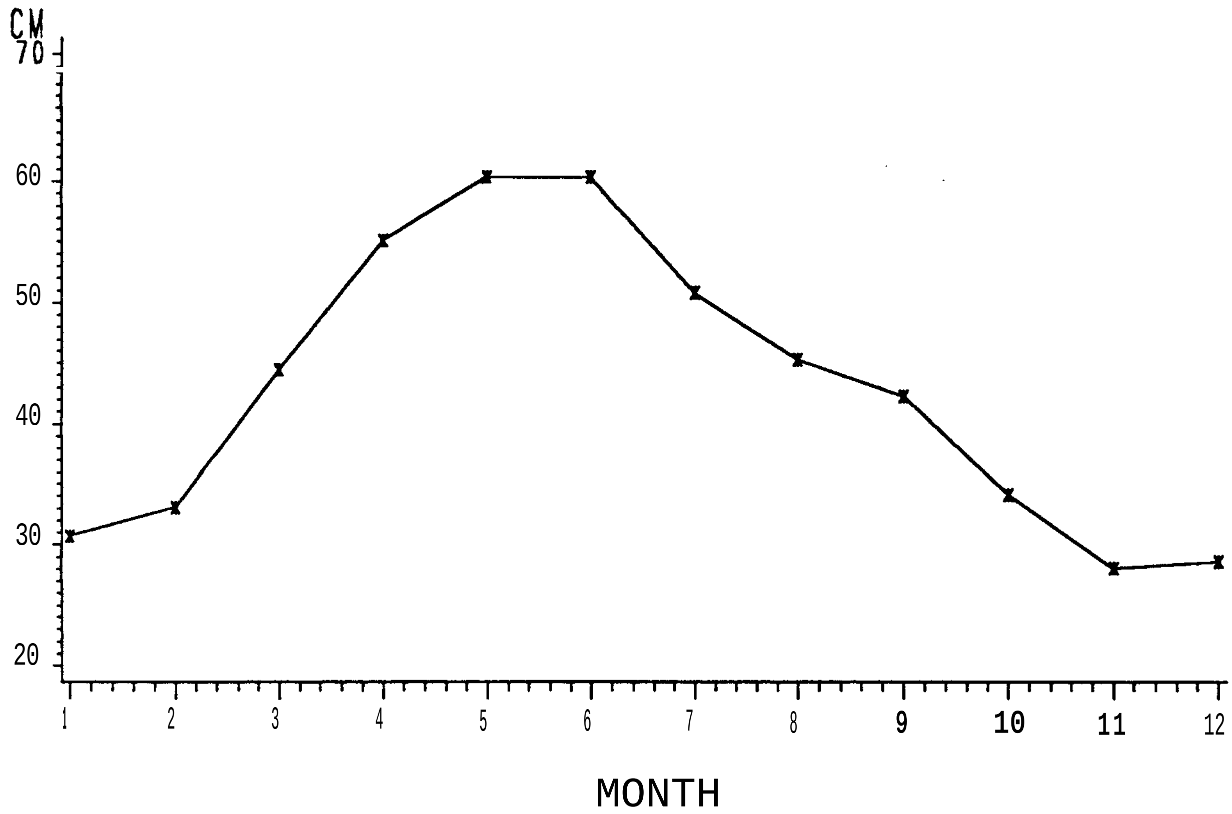


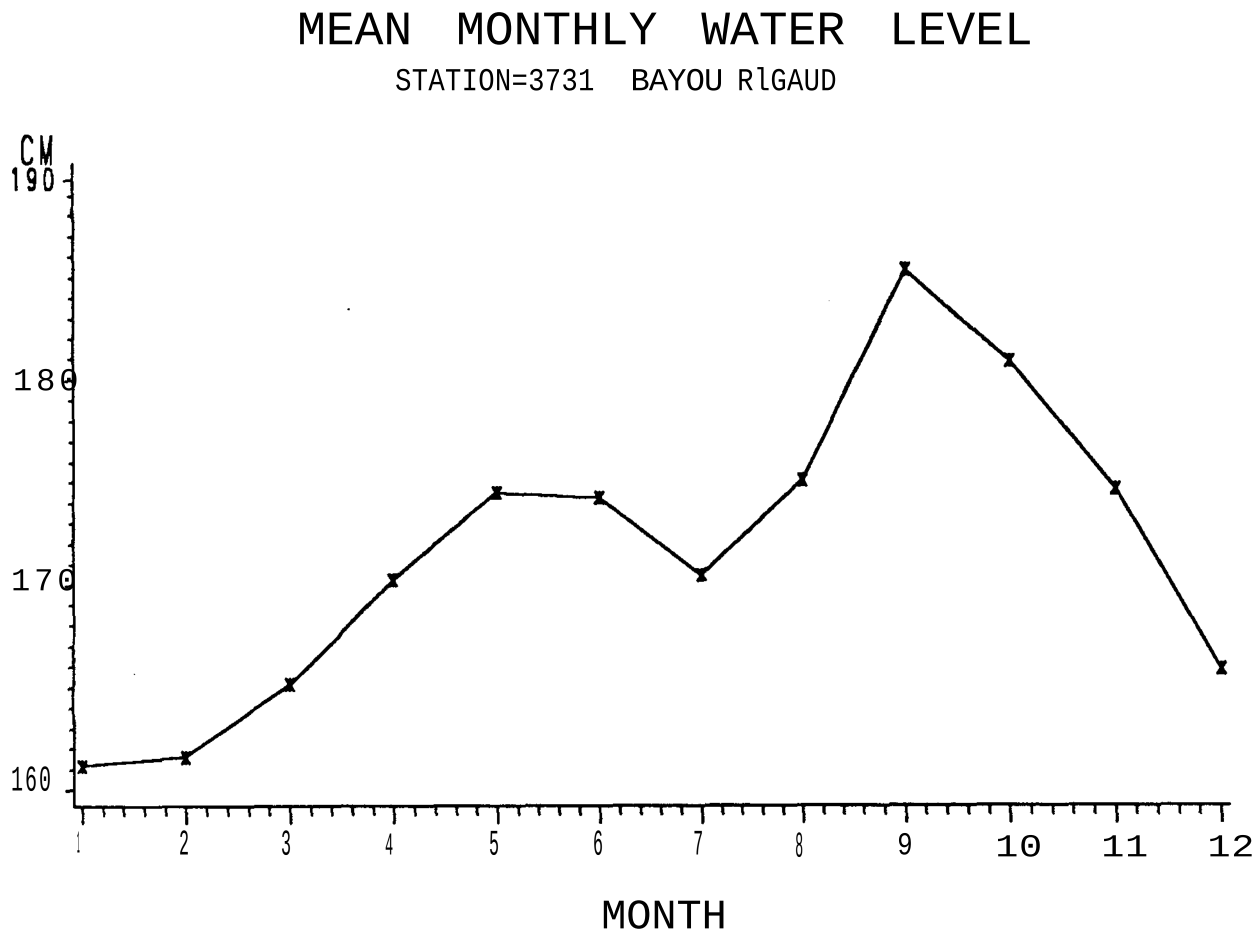
APPENDIX N

TIME SERIES PLOTS OF MEAN MONTHLY WATER LEVELS AND SALINITIES

MEAN MONTHLY WATER LEVEL

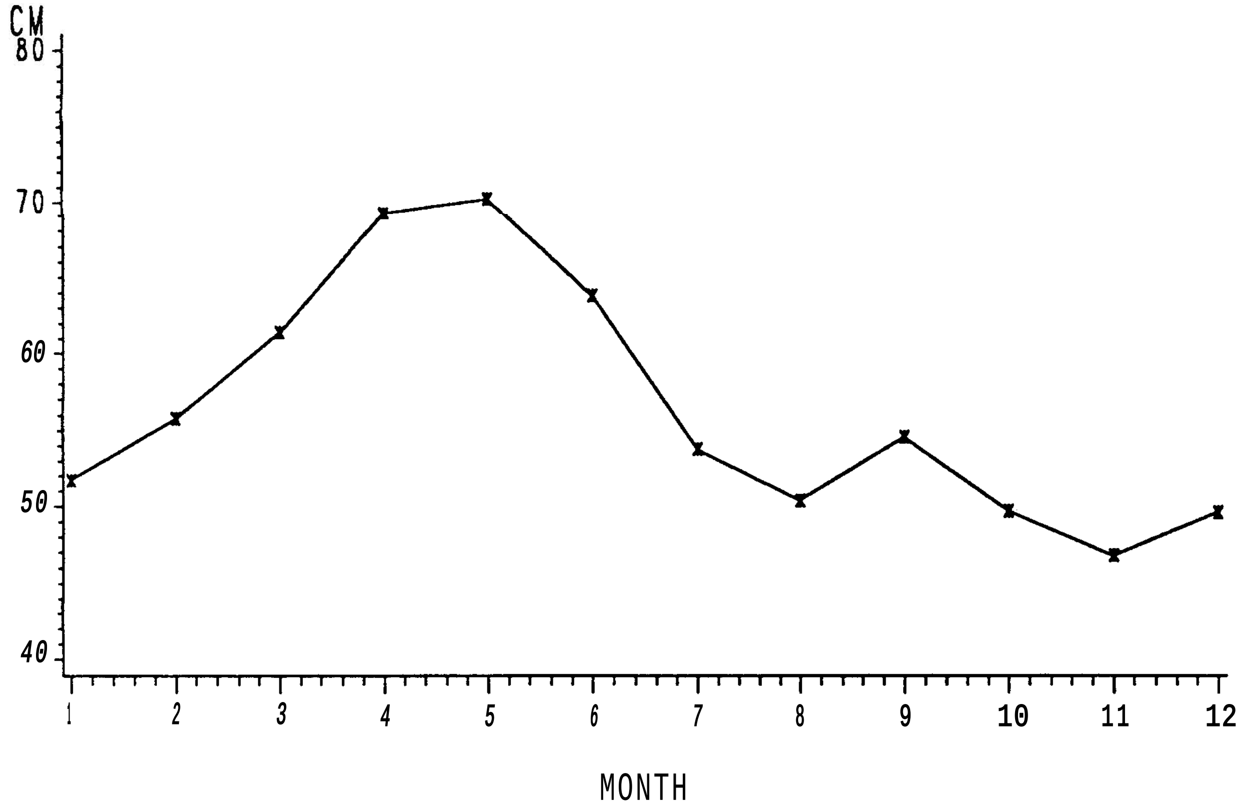
STATION=03850 DEER ISLAND




MEAN MONTHLY WATER LEVEL
STATION=3731 BAYOU RlGAUD
CM
190
180
170
160
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

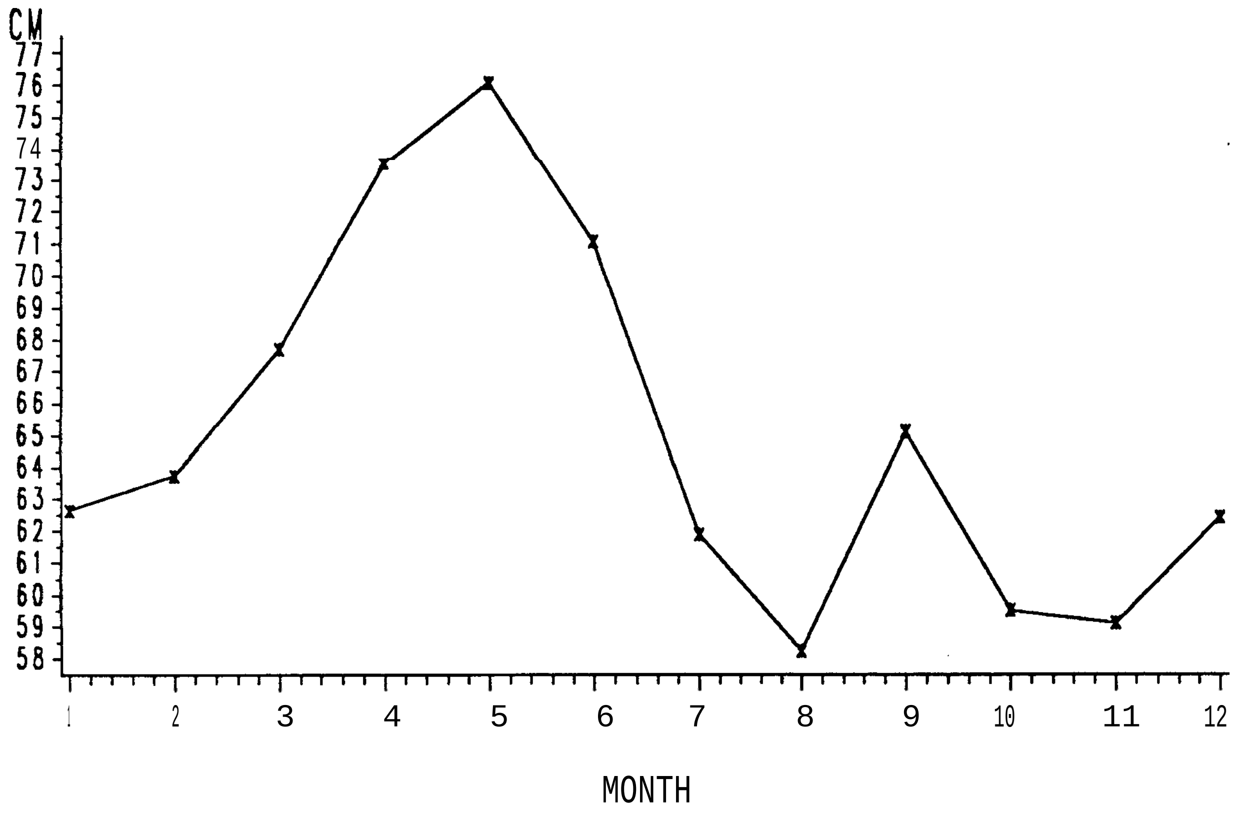
MEAN MONTHLY WATER LEVEL

STATION=52800 BAYOU BOEUF



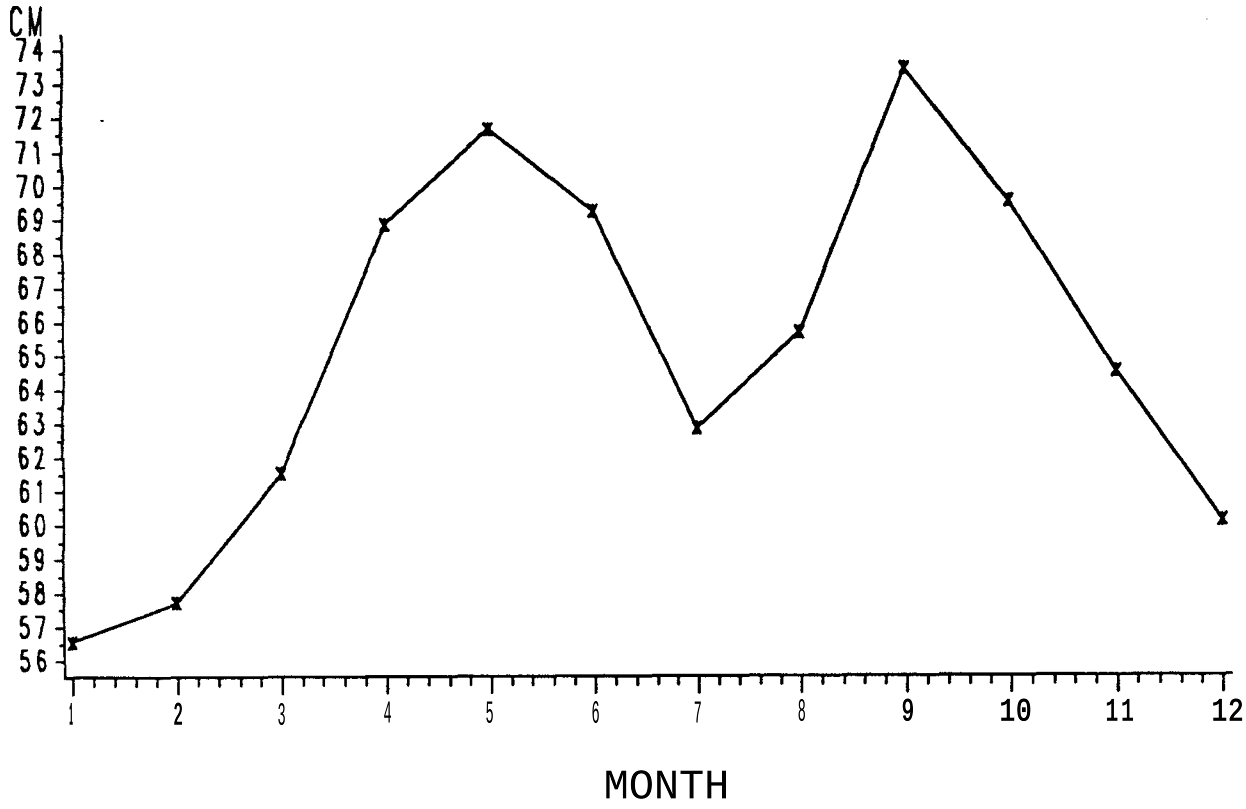
MEAN MONTHLY WATER LEVEL

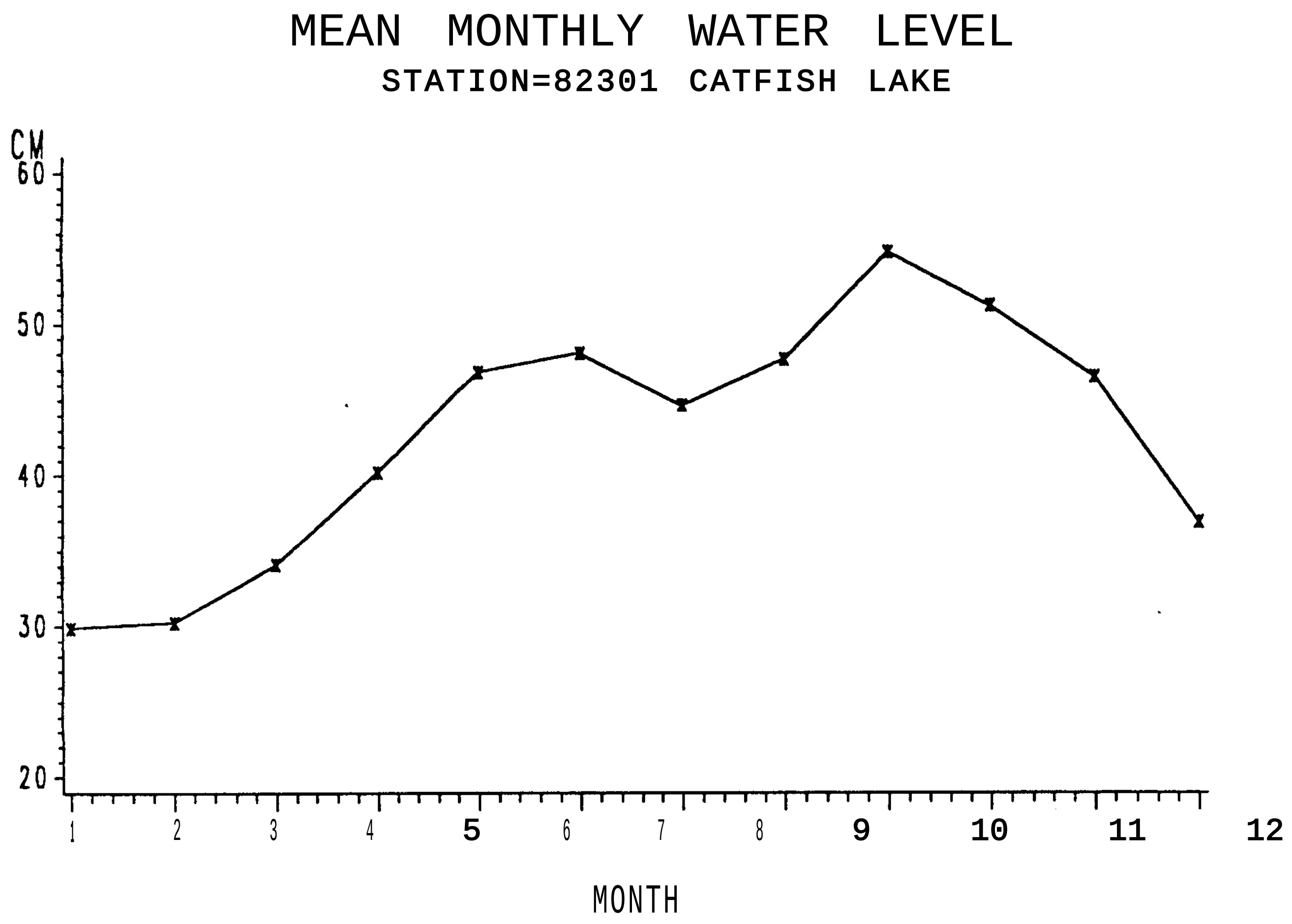
STATION=52880 BAYOU BLACK



MEAN MONTHLY WATER LEVEL

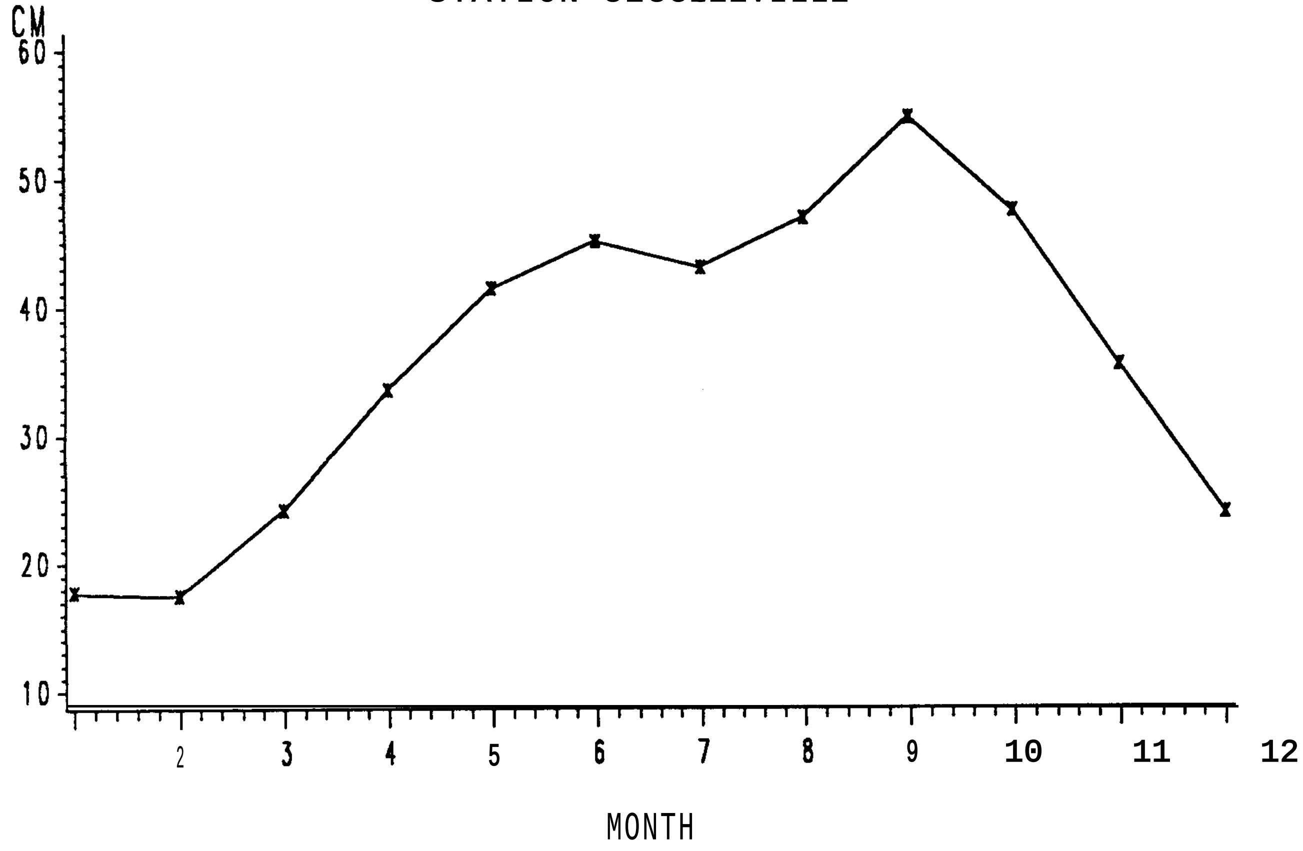
STATION=76320 IWW HOUMA




MEAN MONTHLY WATER LEVEL
STATION=82301 CATFISH LAKE
CM
60
50
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

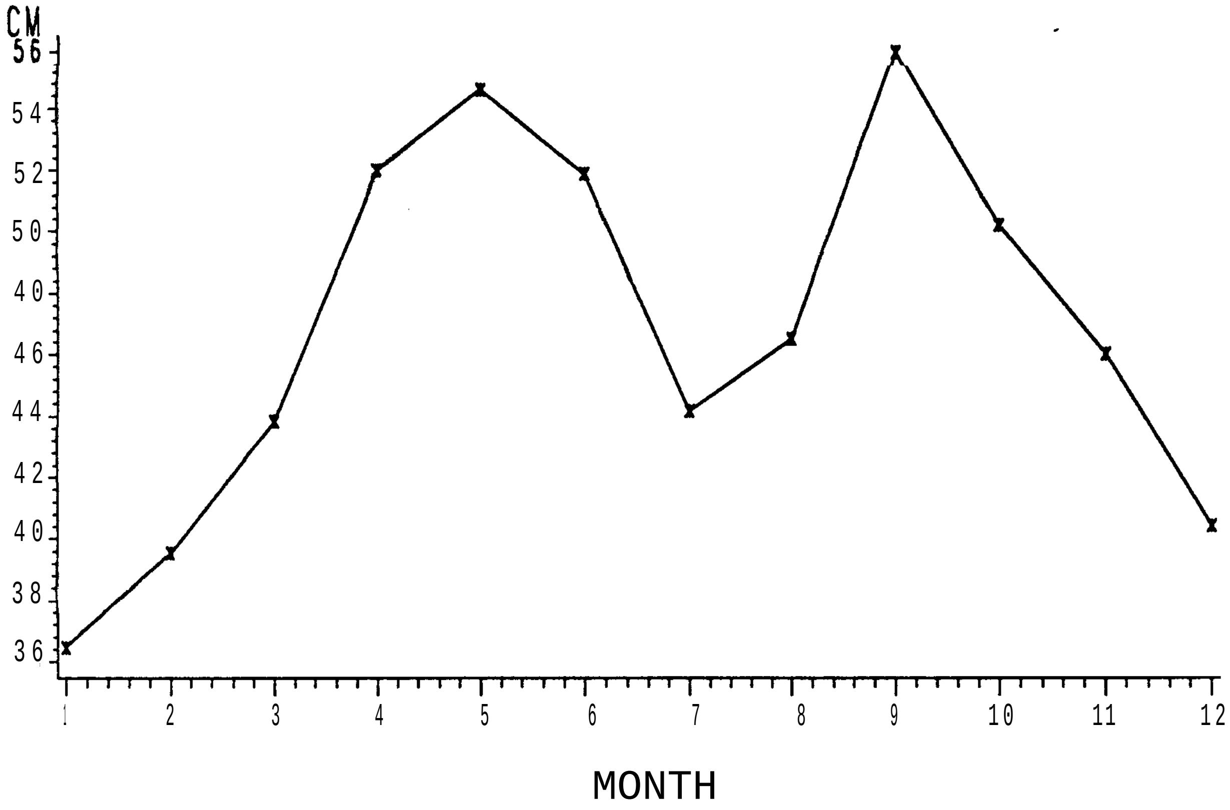
MEAN MONTHLY WATER LEVEL

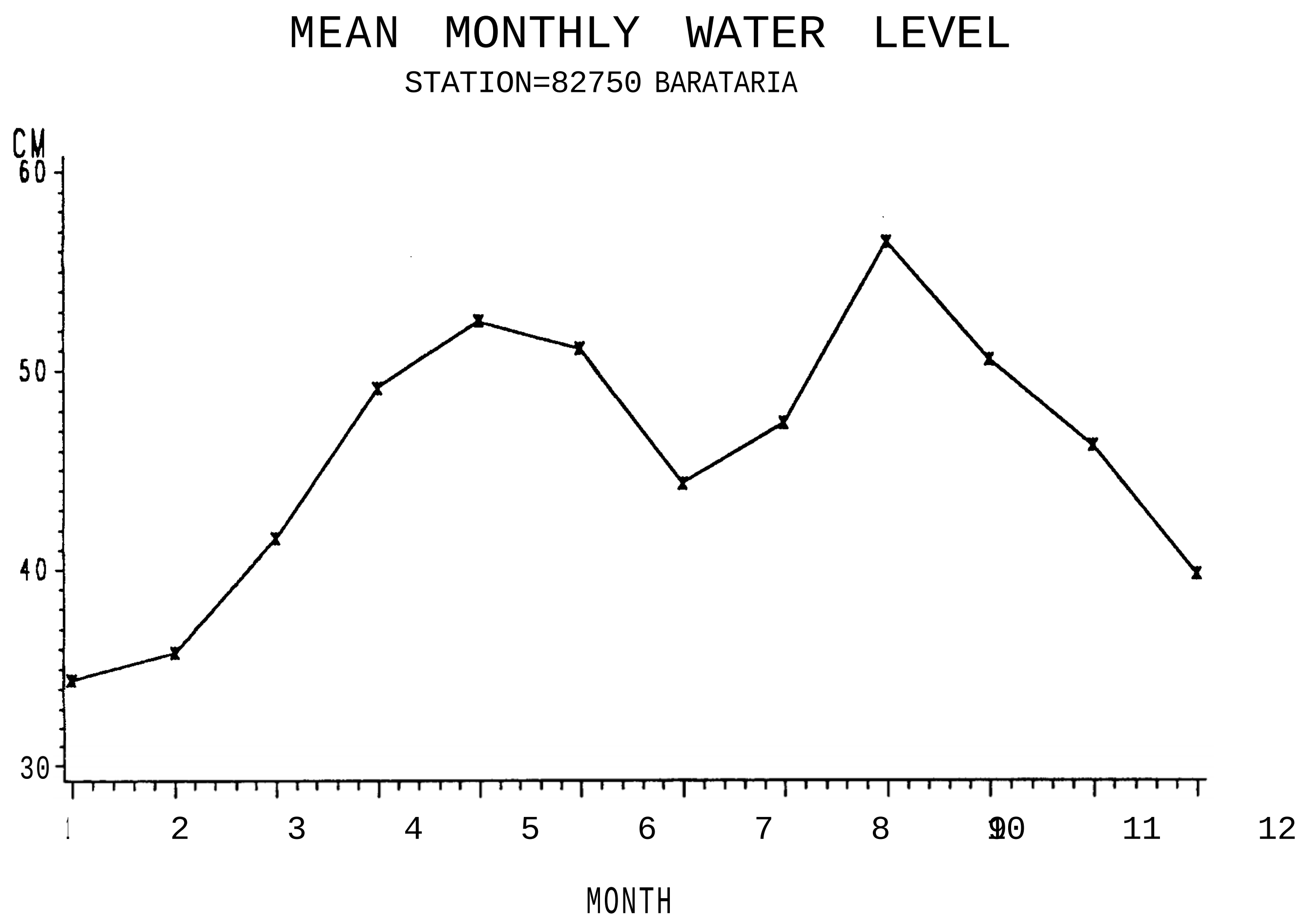
STATION=8235DEEVILLE



MEAN MONTHLY WATER LEVEL

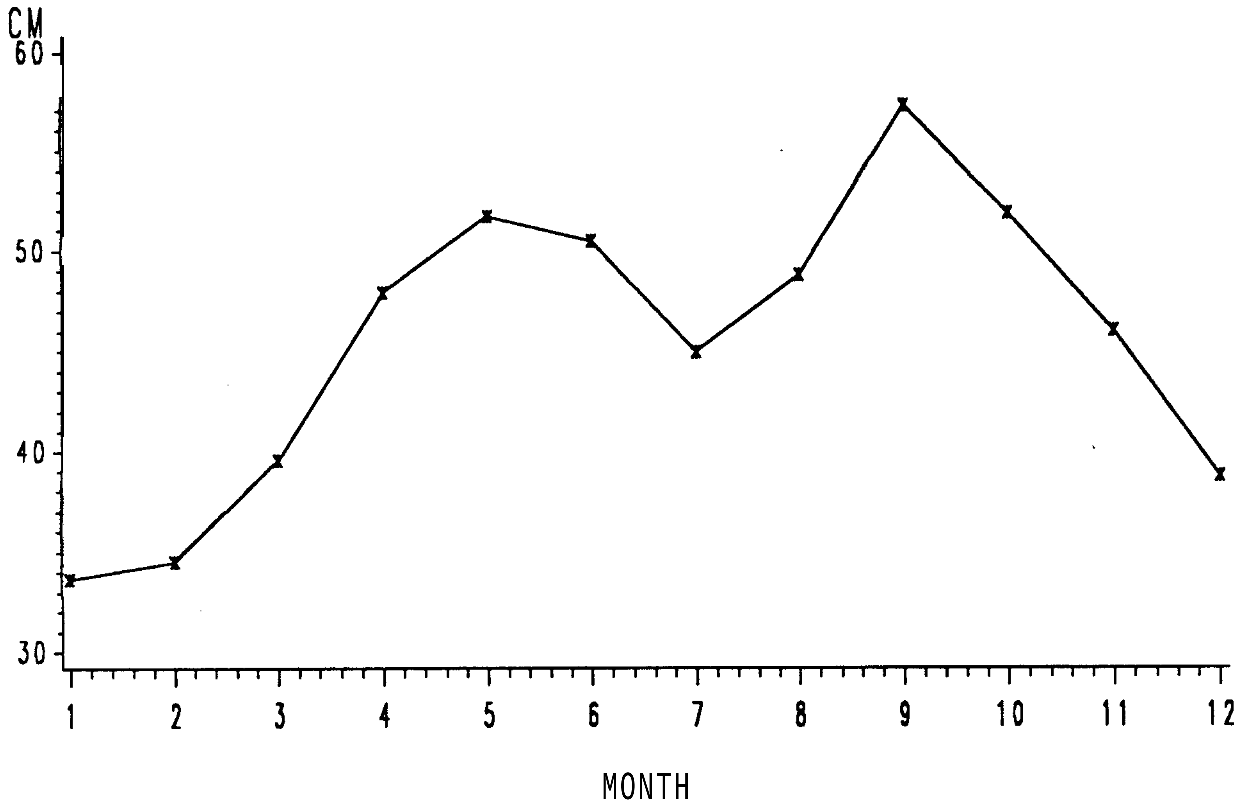
STATION=B2700 DES ALLEMENDS




MEAN MONTHLY WATER LEVEL
STATION=82750 BARATARIA
CM
60
50
40
30
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

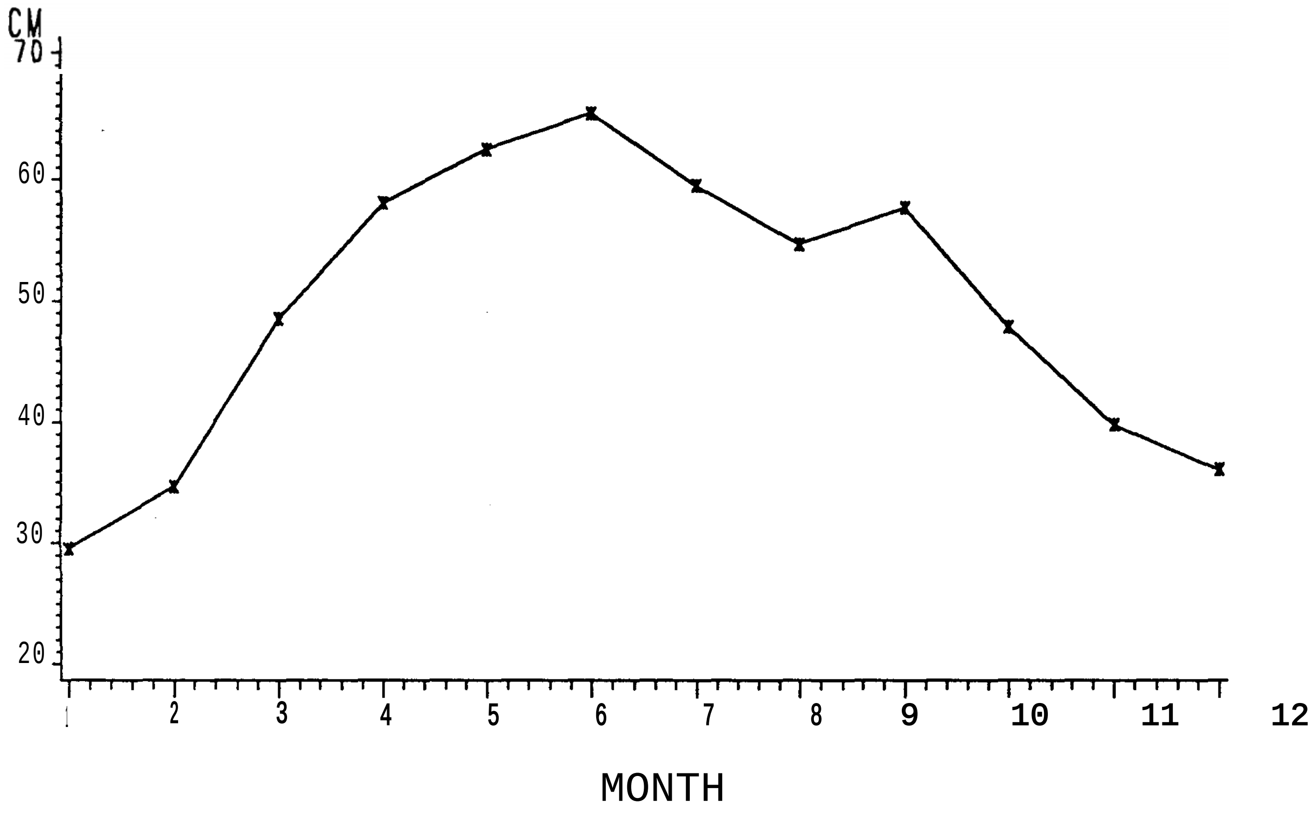
MEAN MONTHLY WATER LEVEL

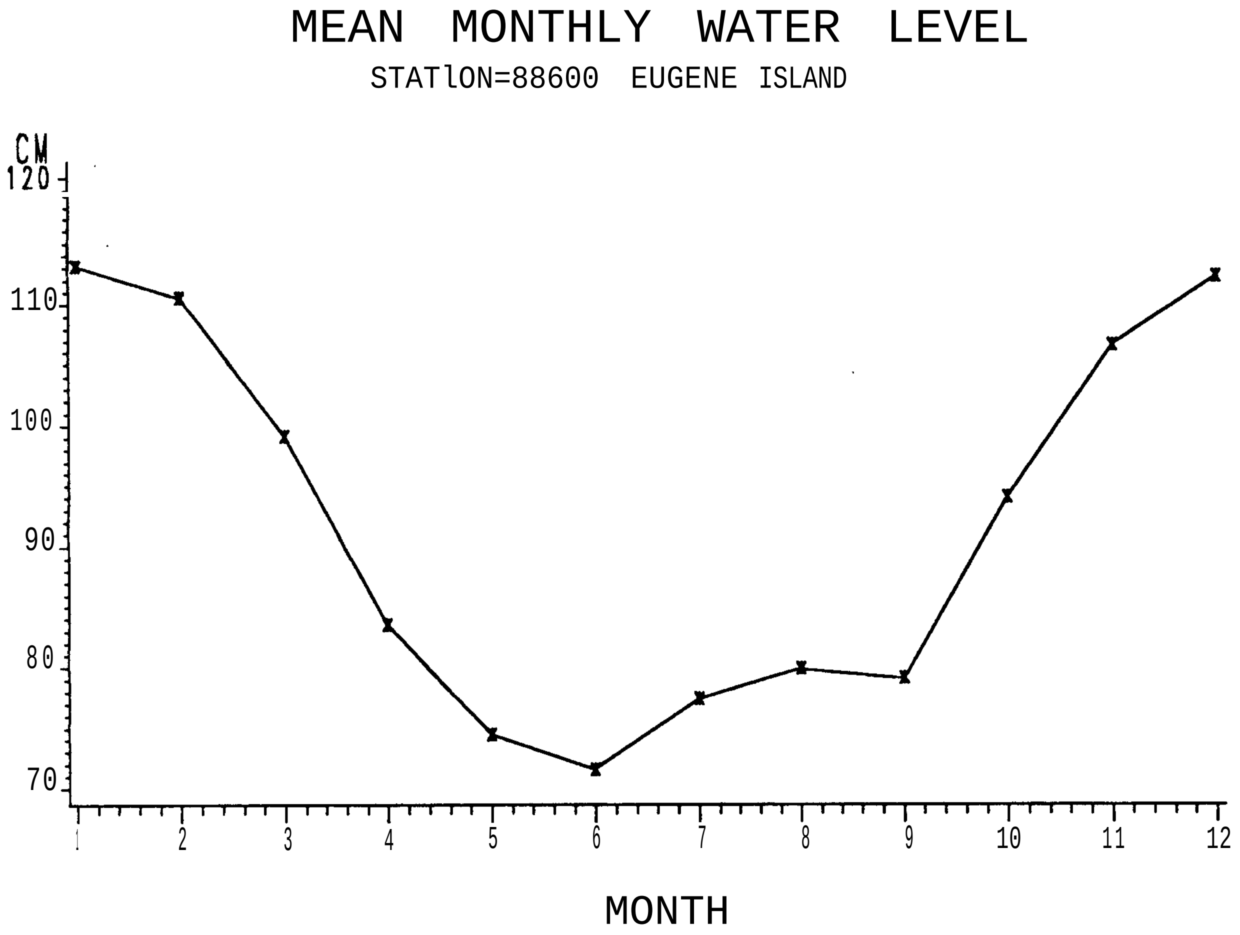
STATION=82875 LAFITTE



MEAN MONTHLY WATER LEVEL

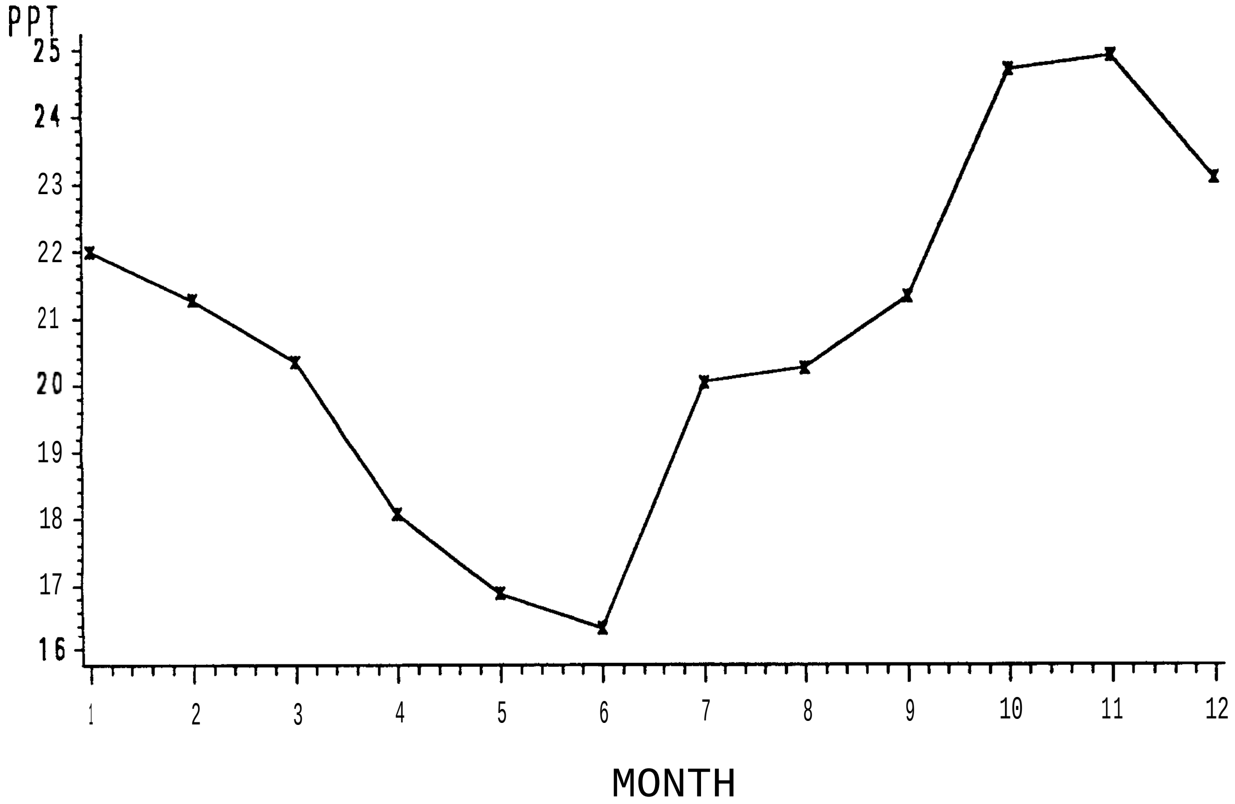
STATION=88350 WEST BAY




MEAN MONTHLY WATER LEVEL
STATlON=88600 EUGENE ISLAND
CM
120
110
100
90
80
70
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

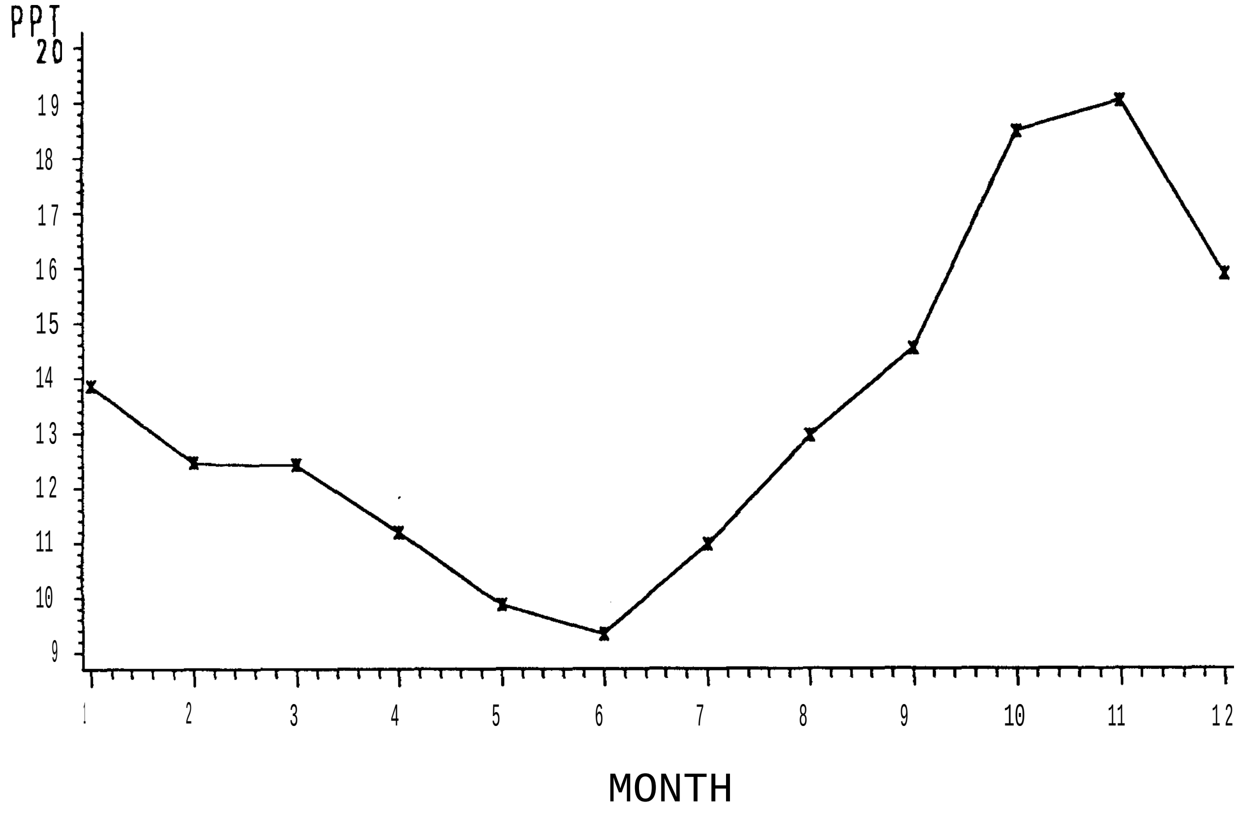
MEAN MONTHLY SALINITY

STATION=315 GRAND TERRE



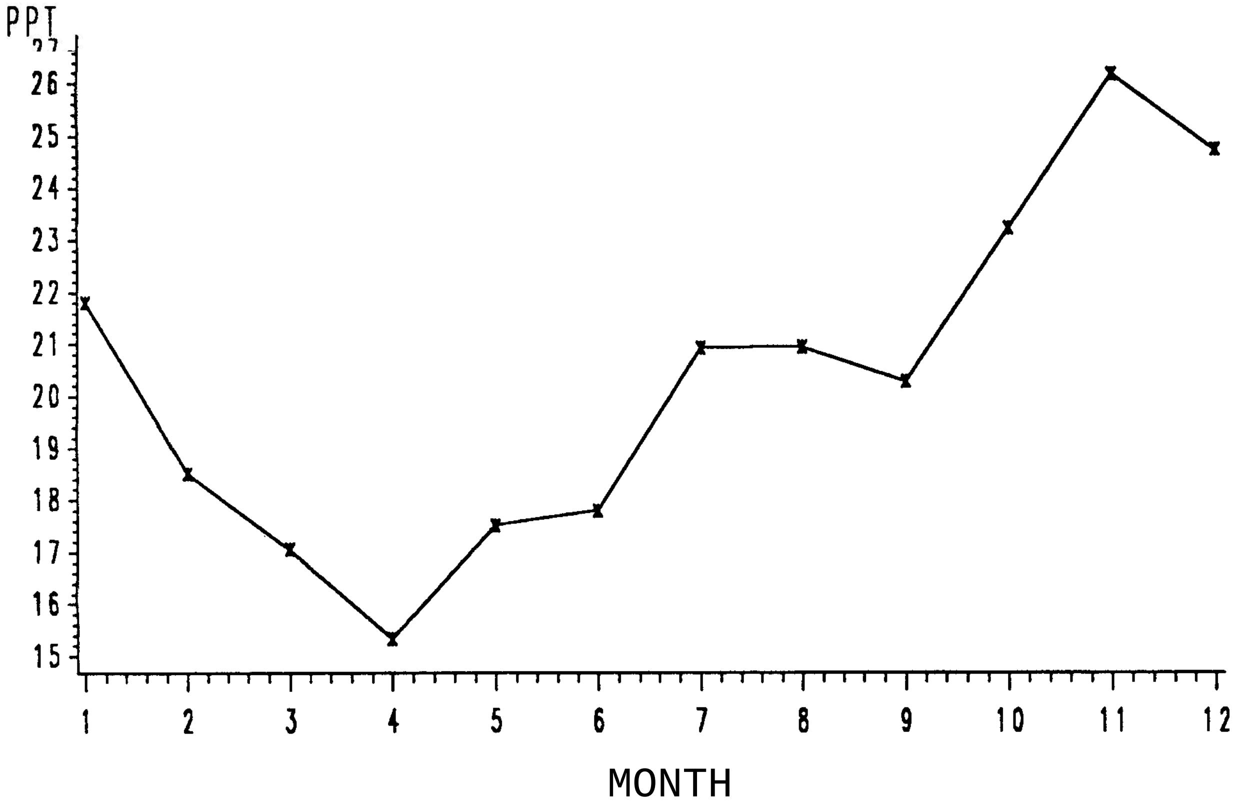
MEAN MONTHLY SALINITY

STATION=31 7ST. MARYS PT.



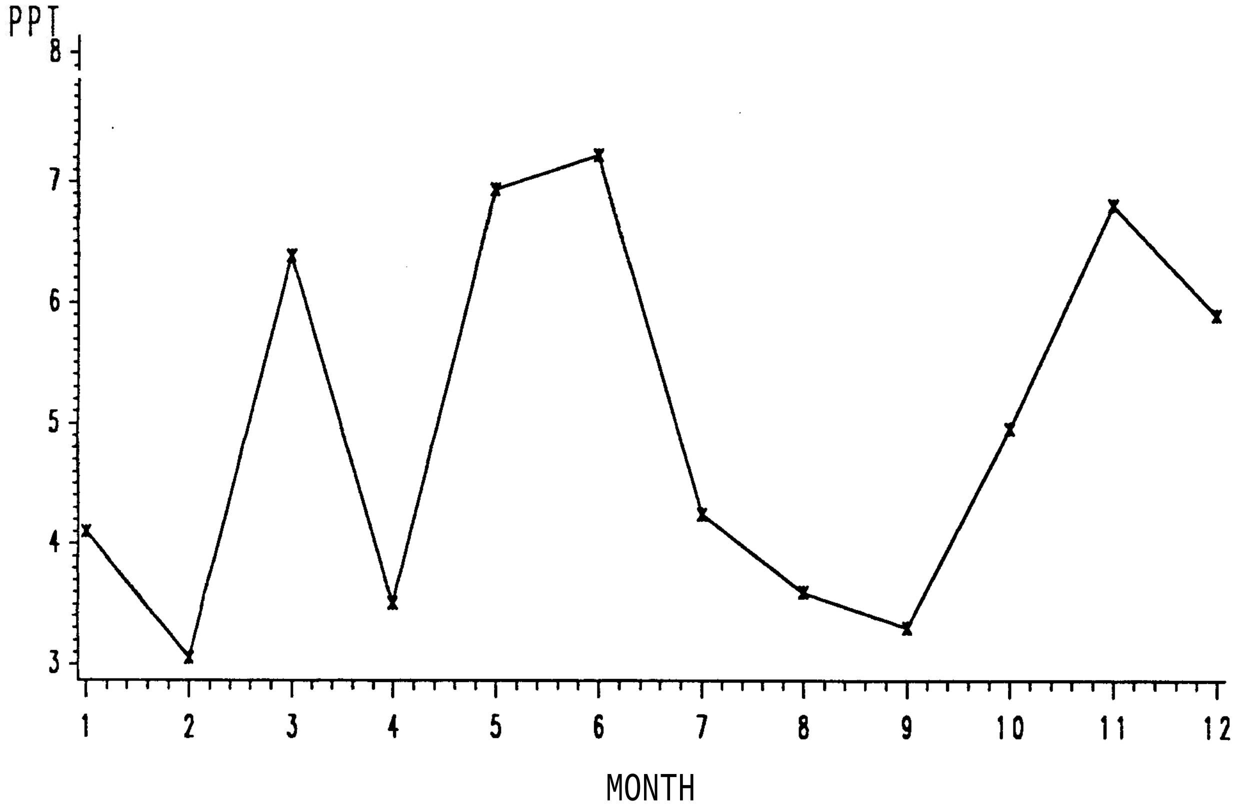
MEAN MONTHLY SALINITY

STATION=323 LAKE PALOURDE



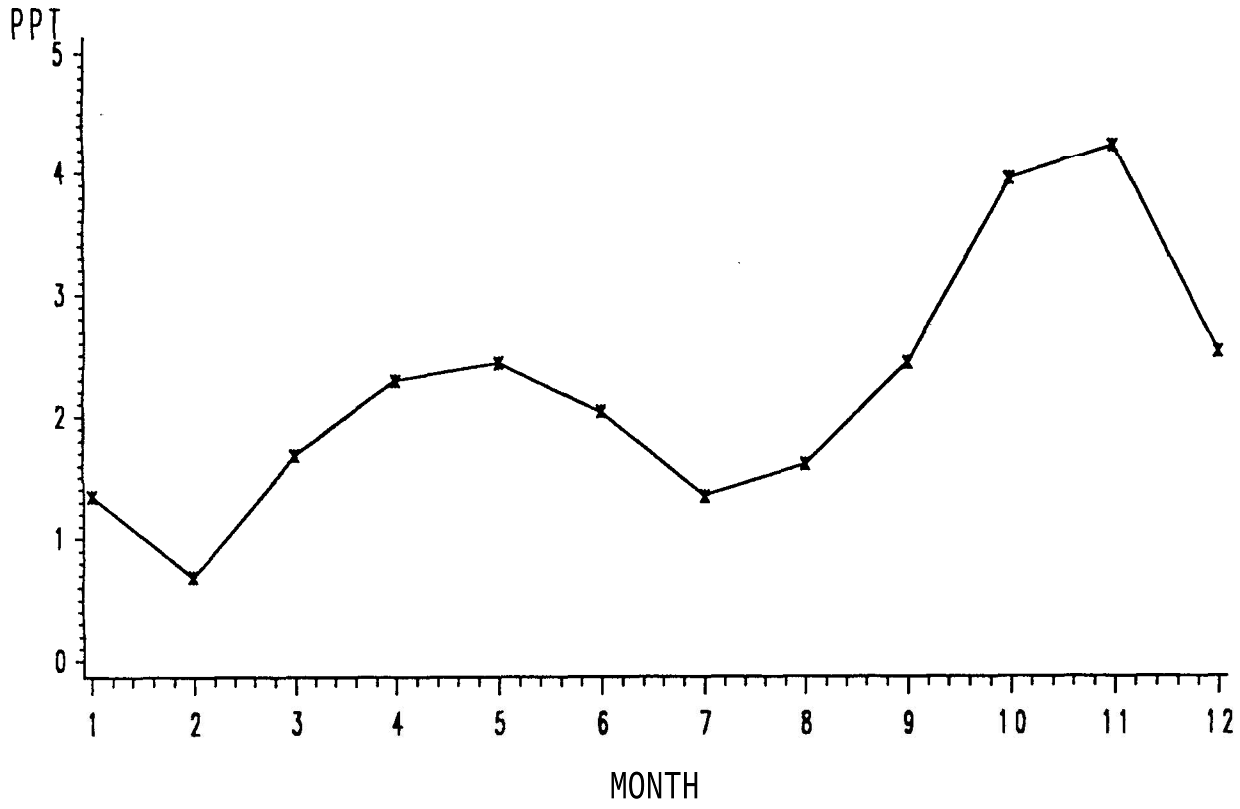
MEAN MONTHLY SALINITY

STATION=325 TENN. GAS CANAl



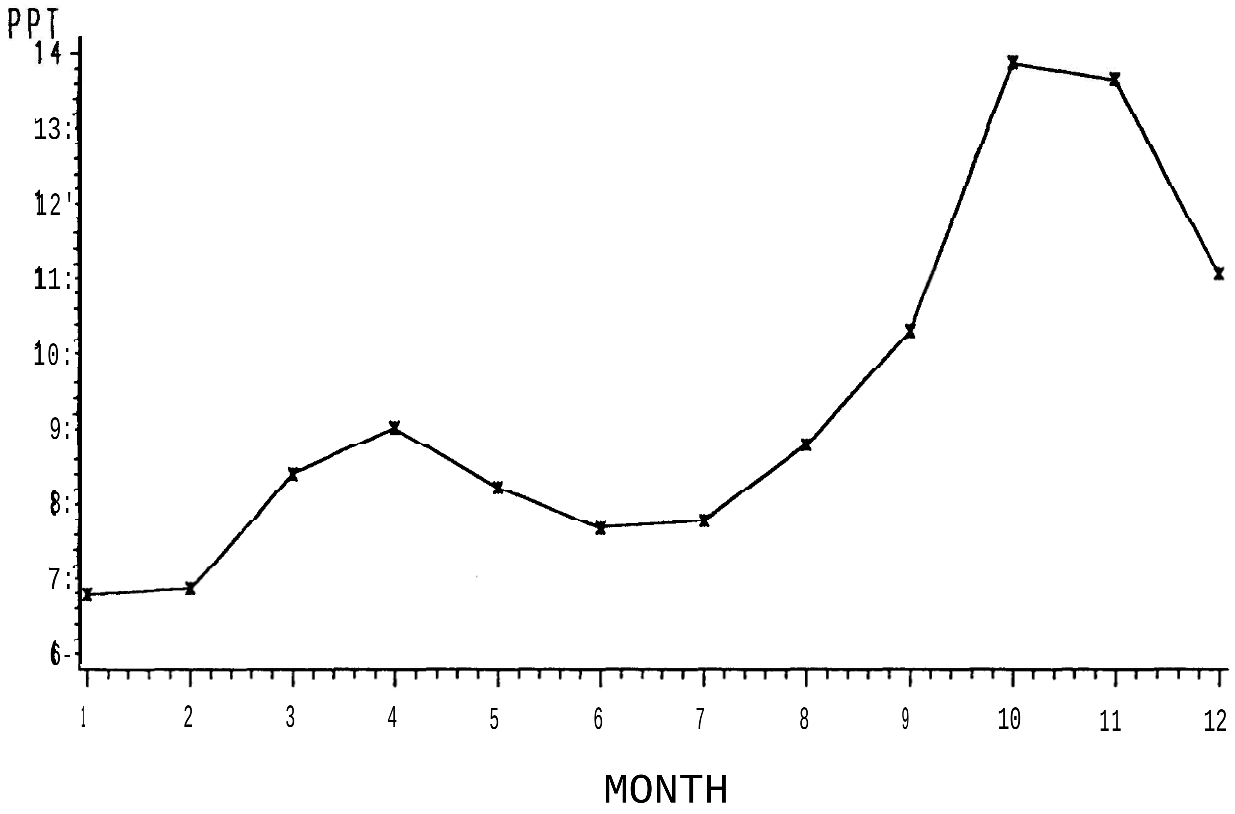
MEAN MONTHLY SALINITY

STATION=326 LITTLE LAKE



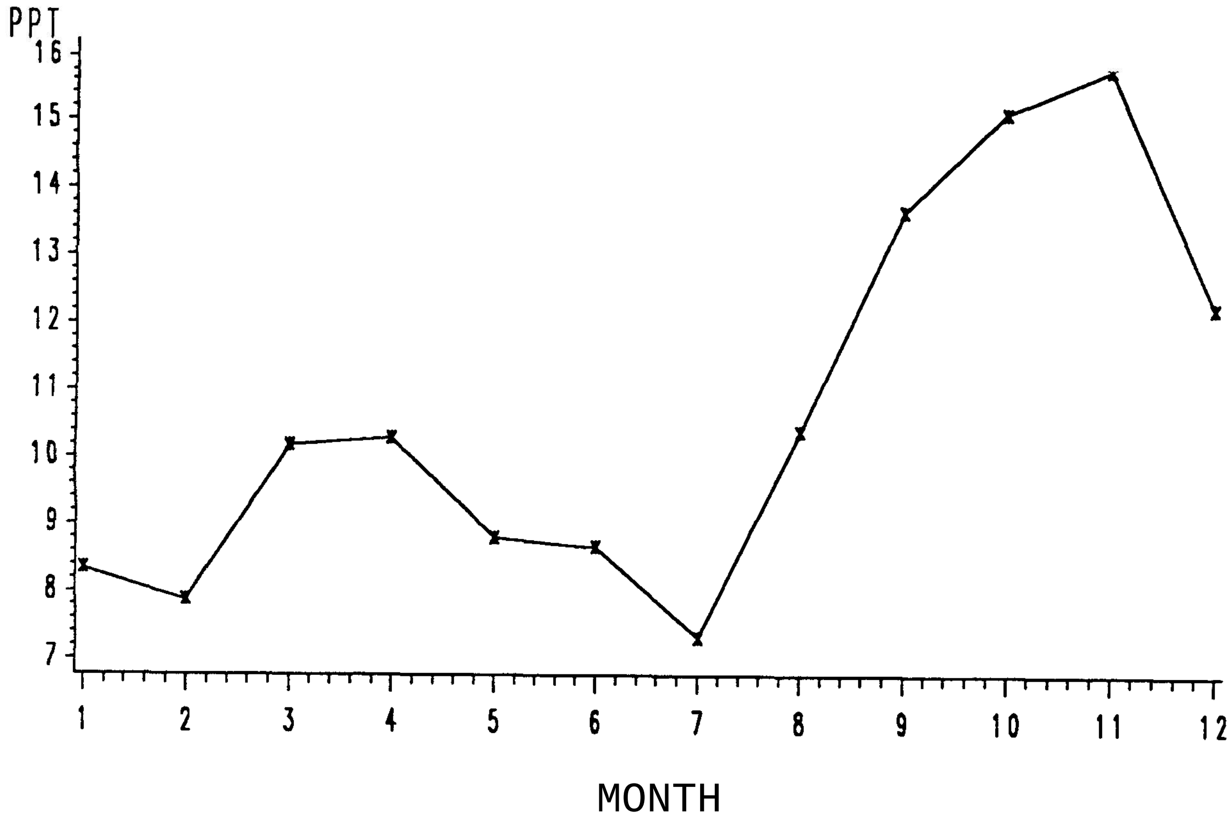
MEAN MONTHLY SALINITY

STATION=41 6 COCODWE



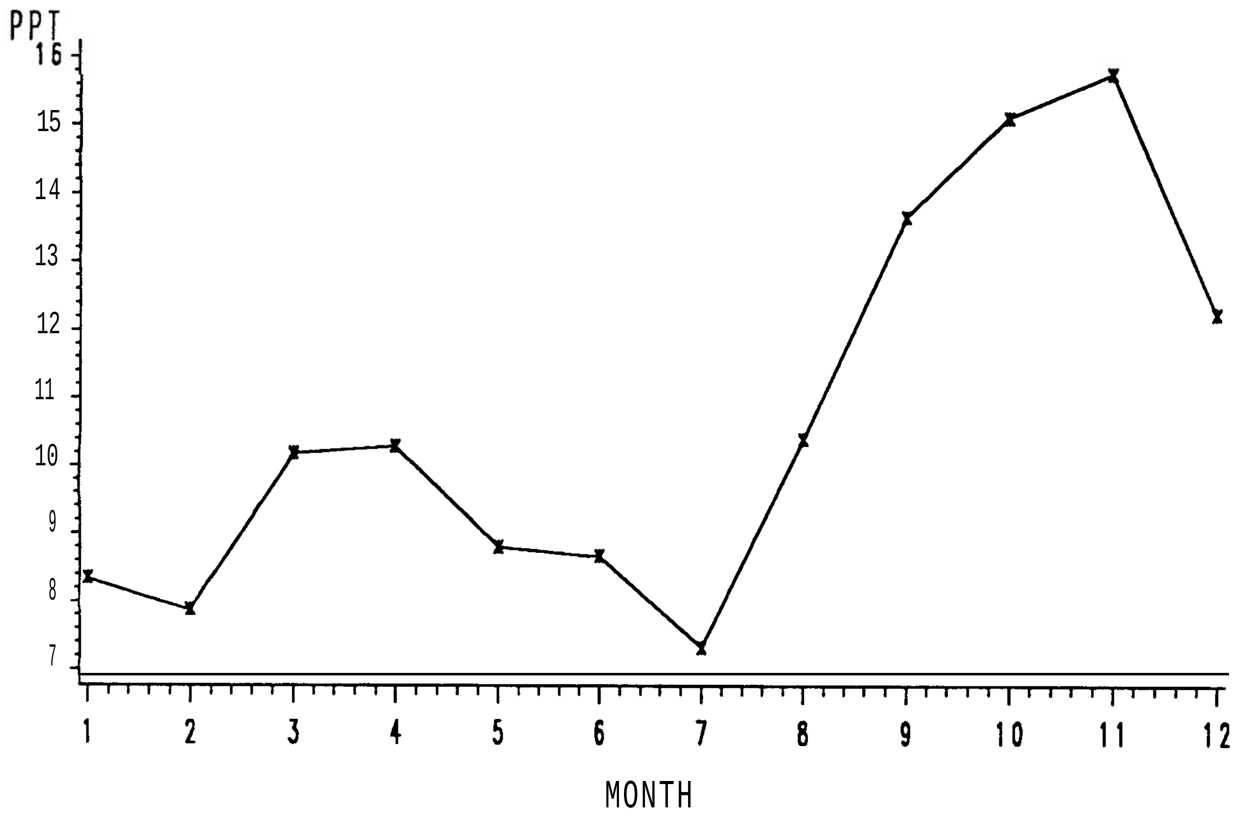
MEAN MONTHLY SALINITY

STATION=518 LAKE MECHANT



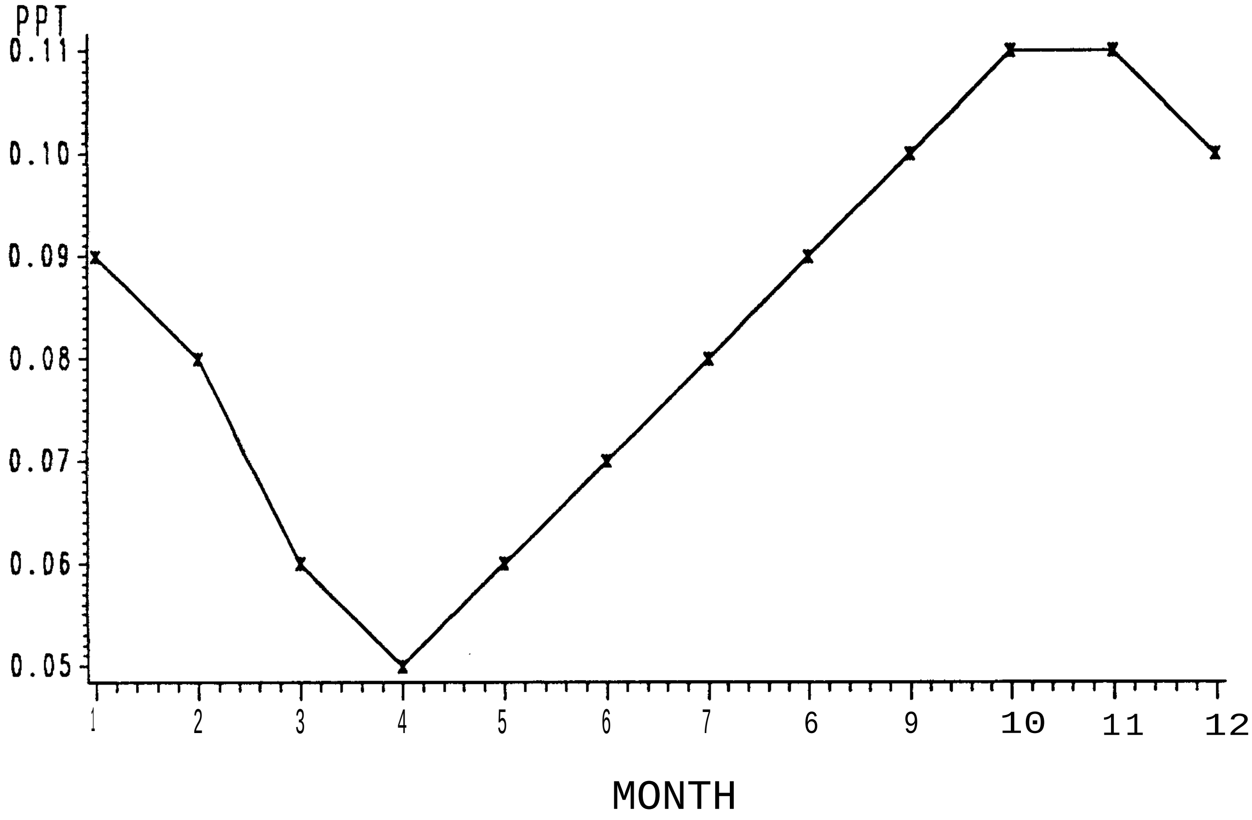
MEAN MONTHLY SALINITY

STATION=518 LAKE MECHANT



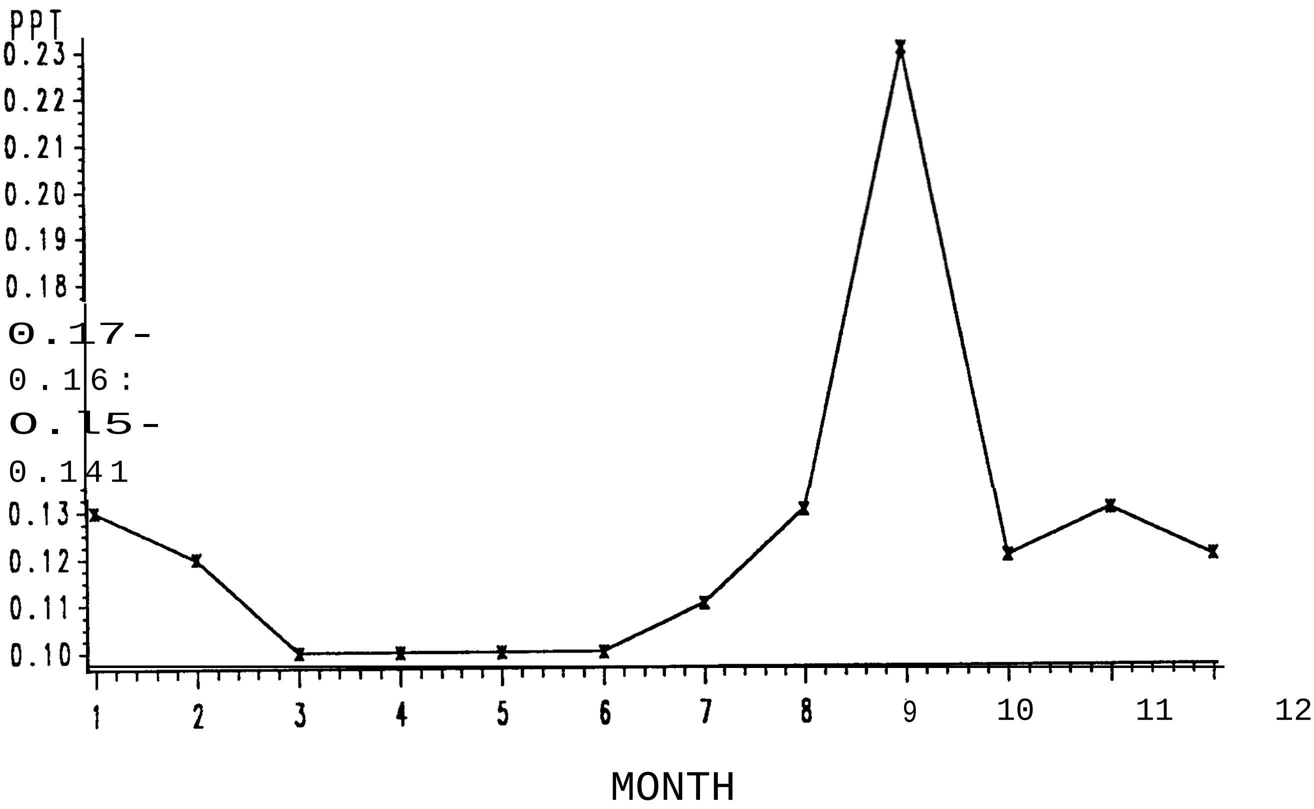
MEAN MONTHLY SALINITY

STATION=03780 OREGON CITY



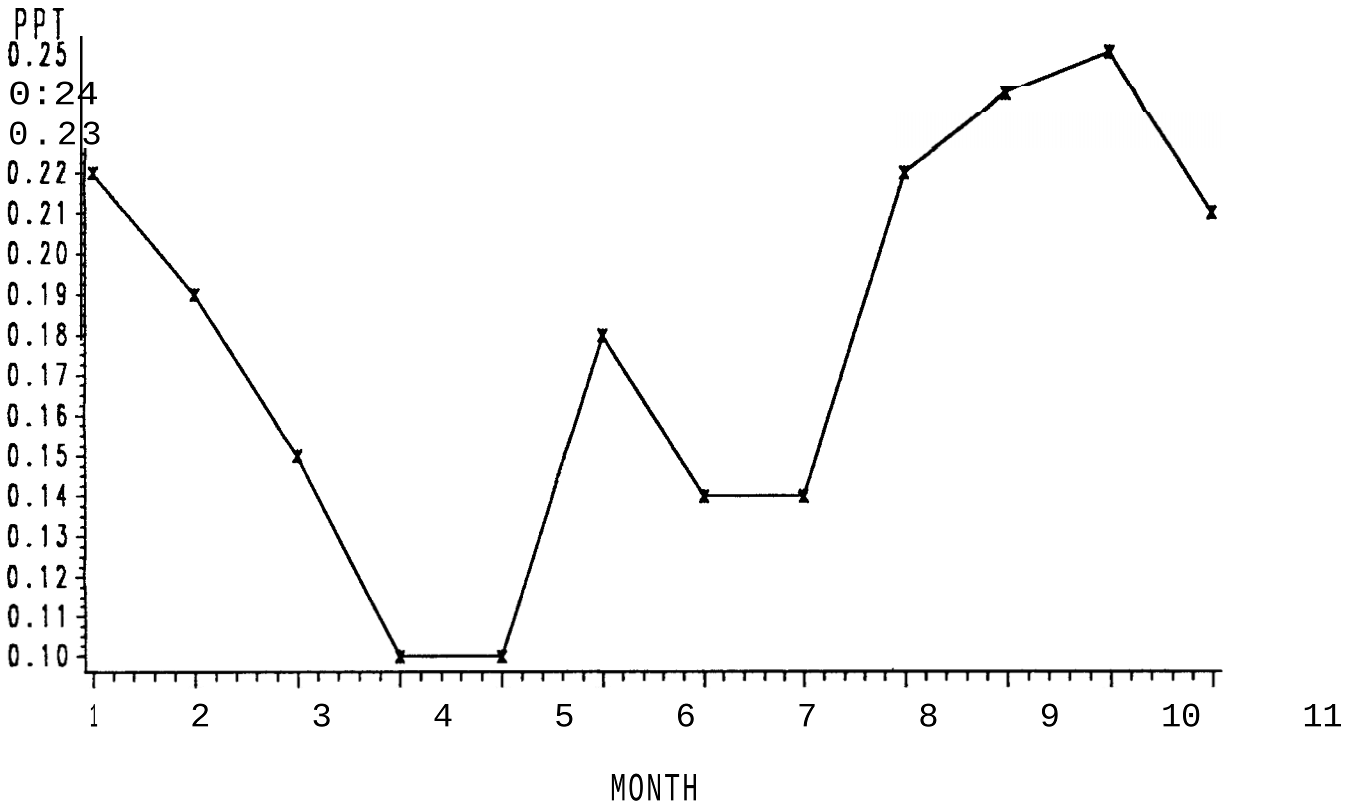
MEAN MONTHLYSALINITY

STATlON=52800 BAYOU BOEUF



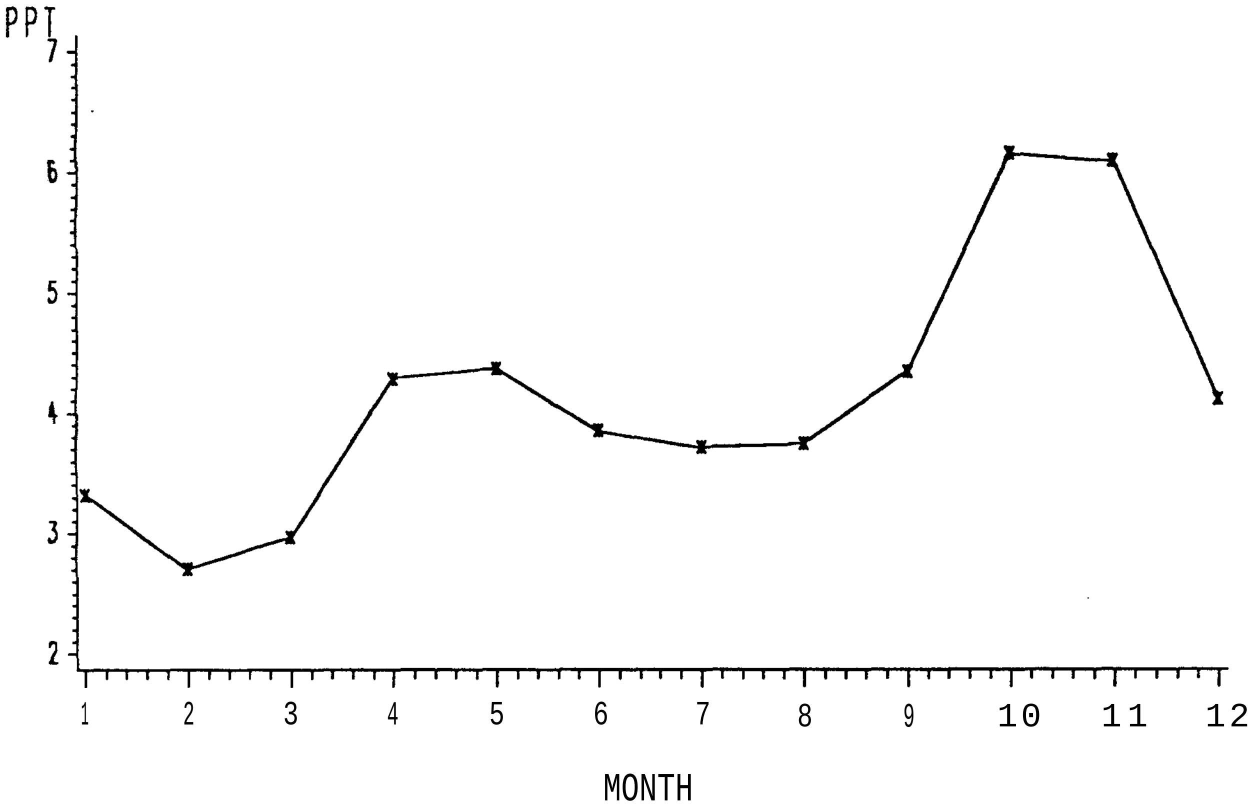
MEAN MONTHLY SALINITY

STATION=52880 BAYOU BLACK



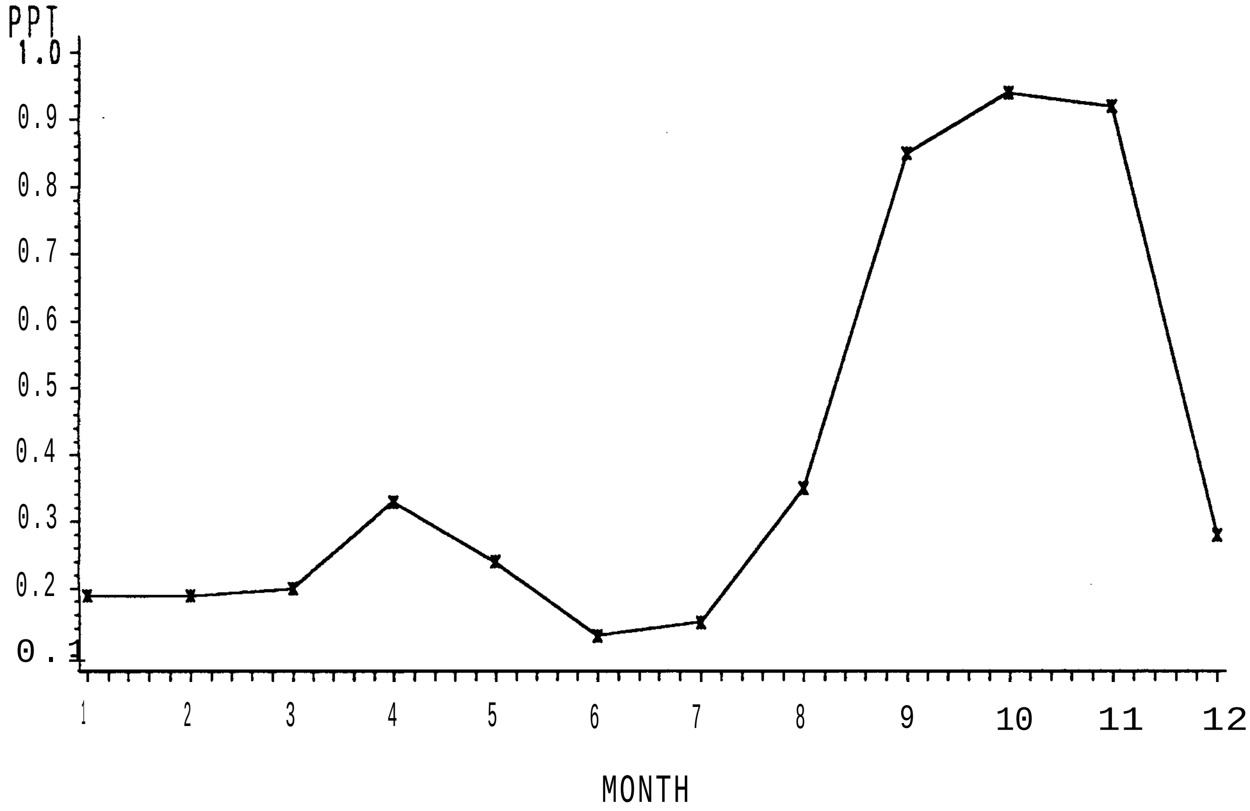
MEAN MONTHLY SALINITY

STATION=76303 BAYOU PETITE CAILLOU



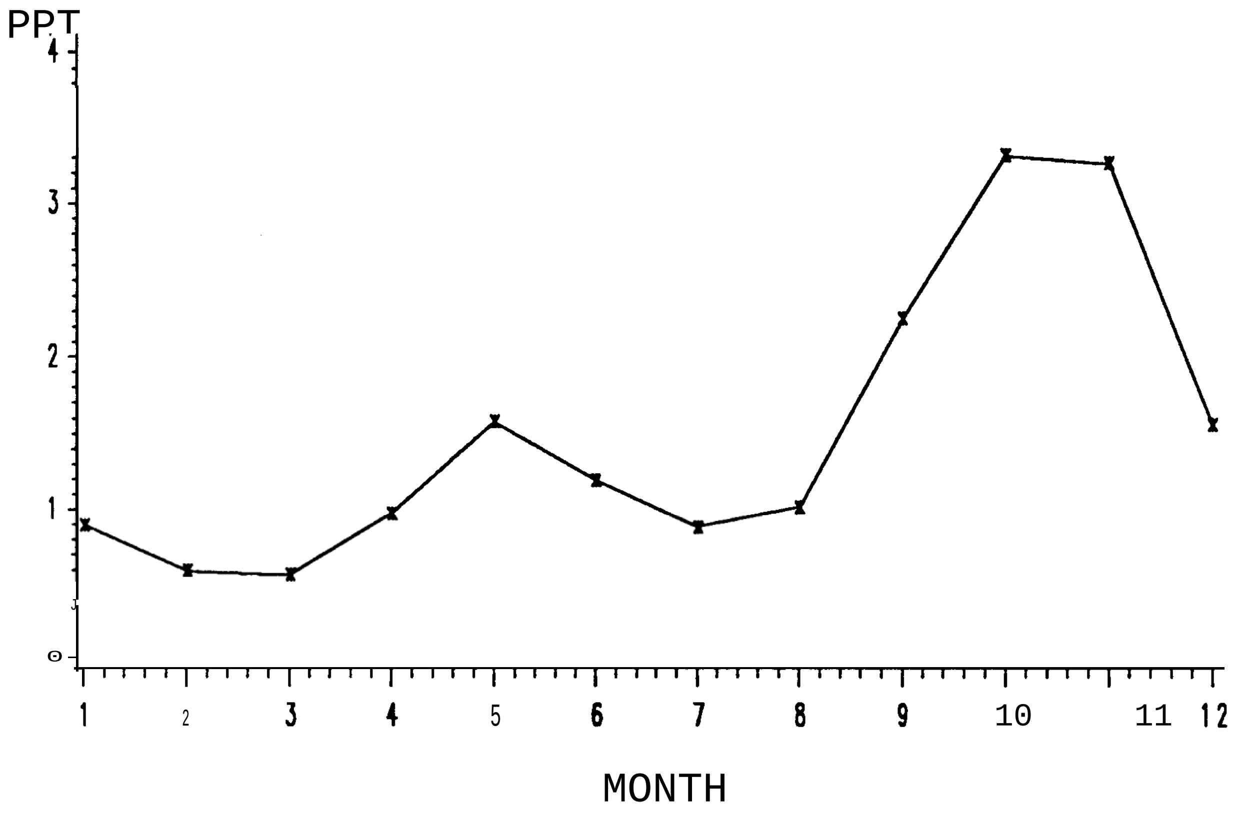
MEAN MONTHLY SALINITY

STATION=76320 IWW AT HOUMA



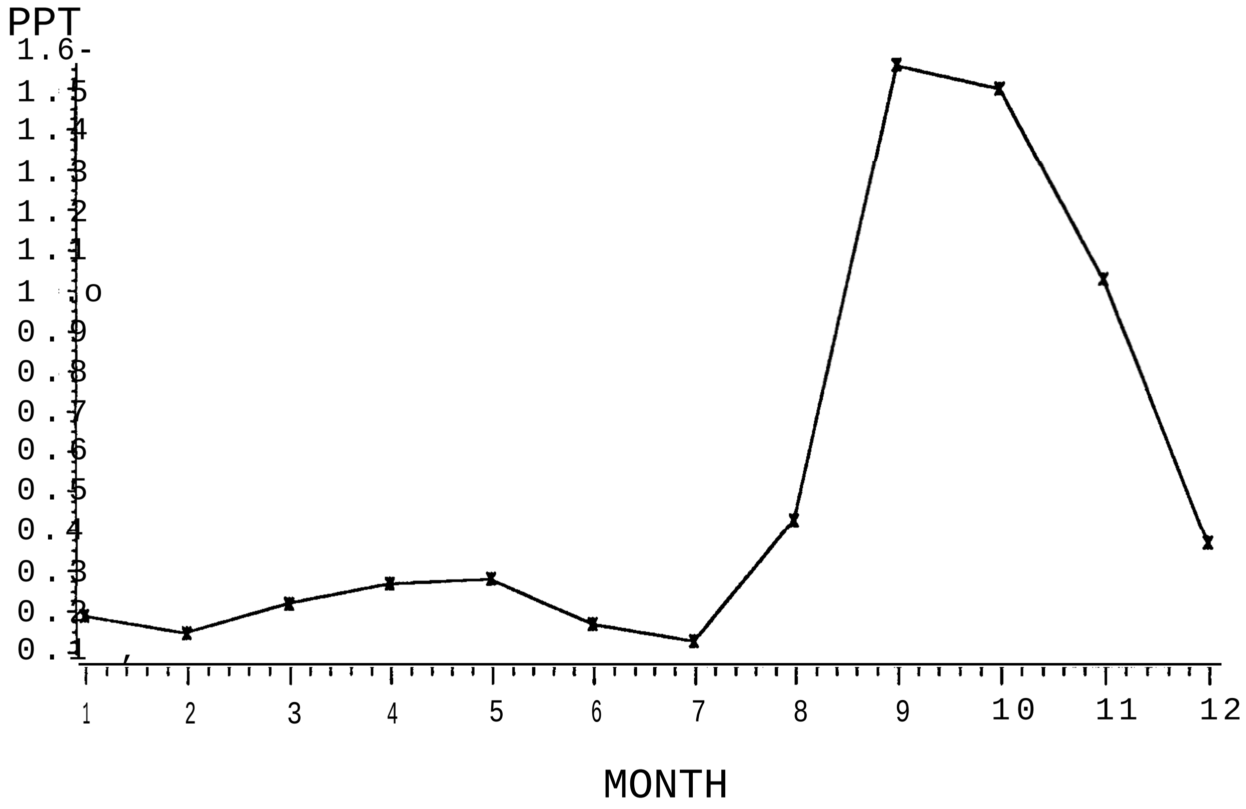
MEAN MONTHLY SALINITY

STATION=76323 BAYOU GRAND CAILLOU



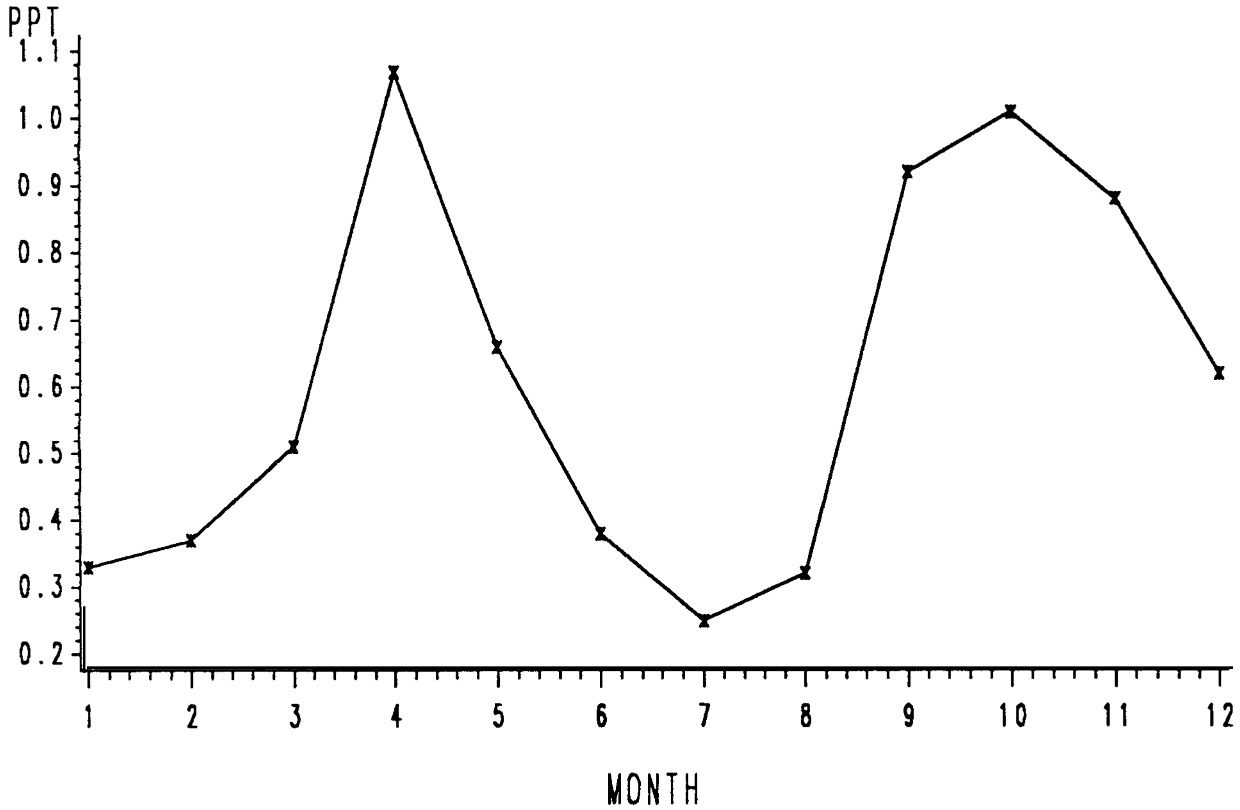
MEAN MONTHLY SALINITY

STATION=76343 HNC AT CROZIER



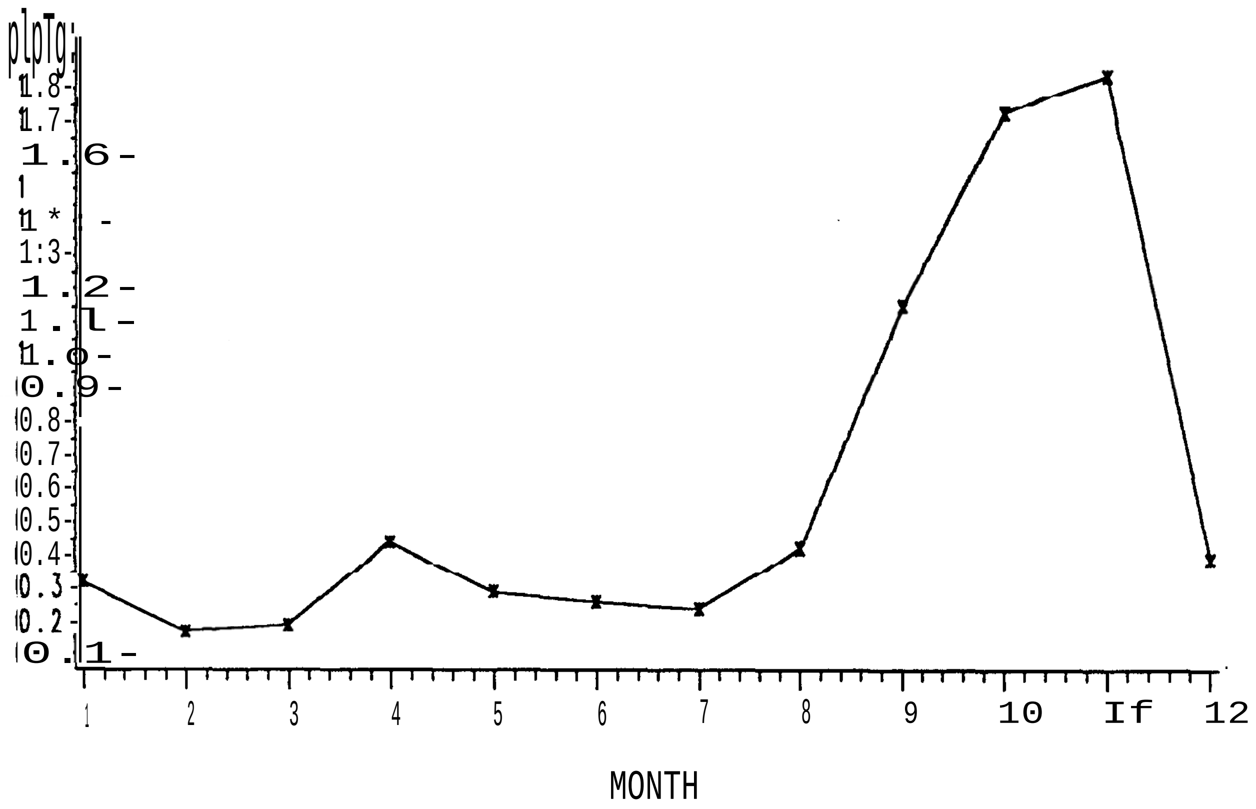
MEAN MONTHLY SALINITY

STATION=76403 BAYOU TERREBONNE



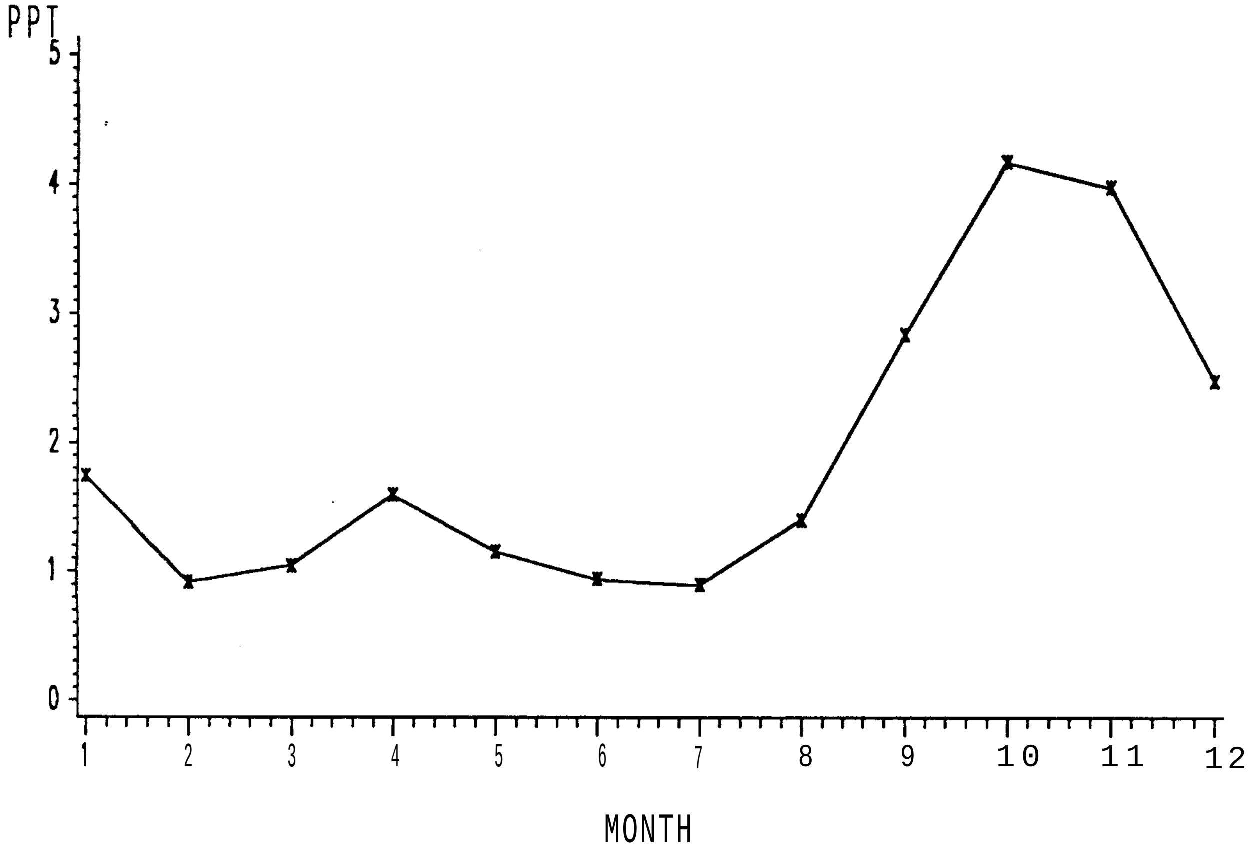
MEAN MONTHLY SALINITY

STATION=82203 LAROSE



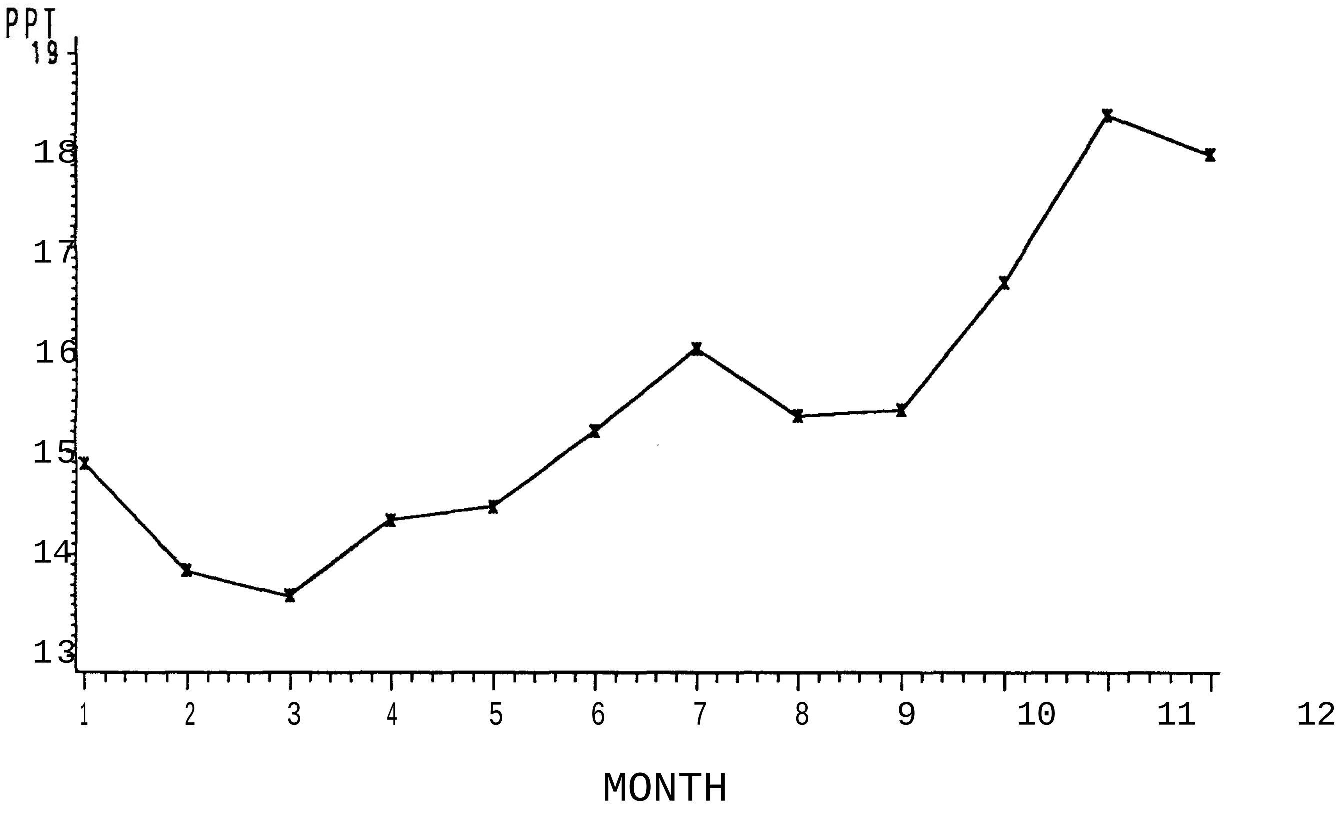
MEAN MONTHLY SALINITY

STATION=82300 GALLLANO



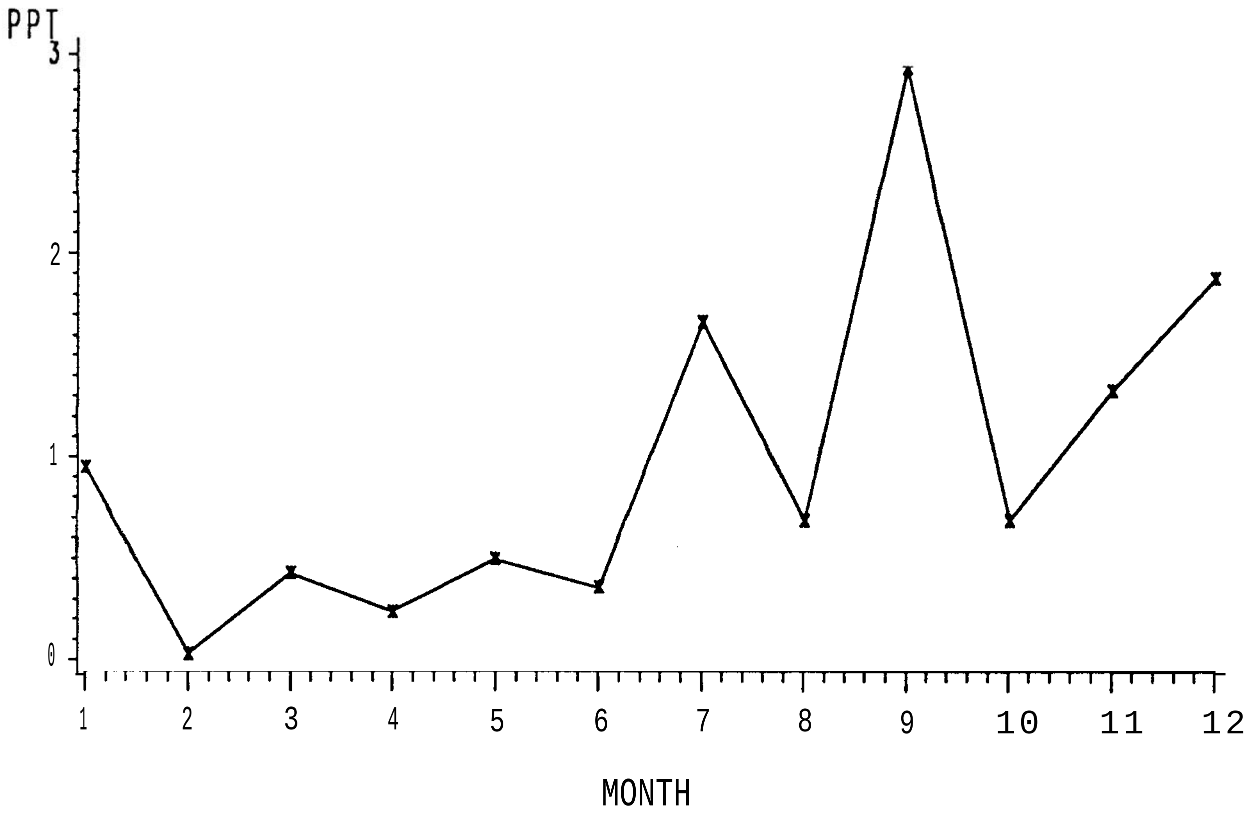
MEAN MONTHLY SALINITY

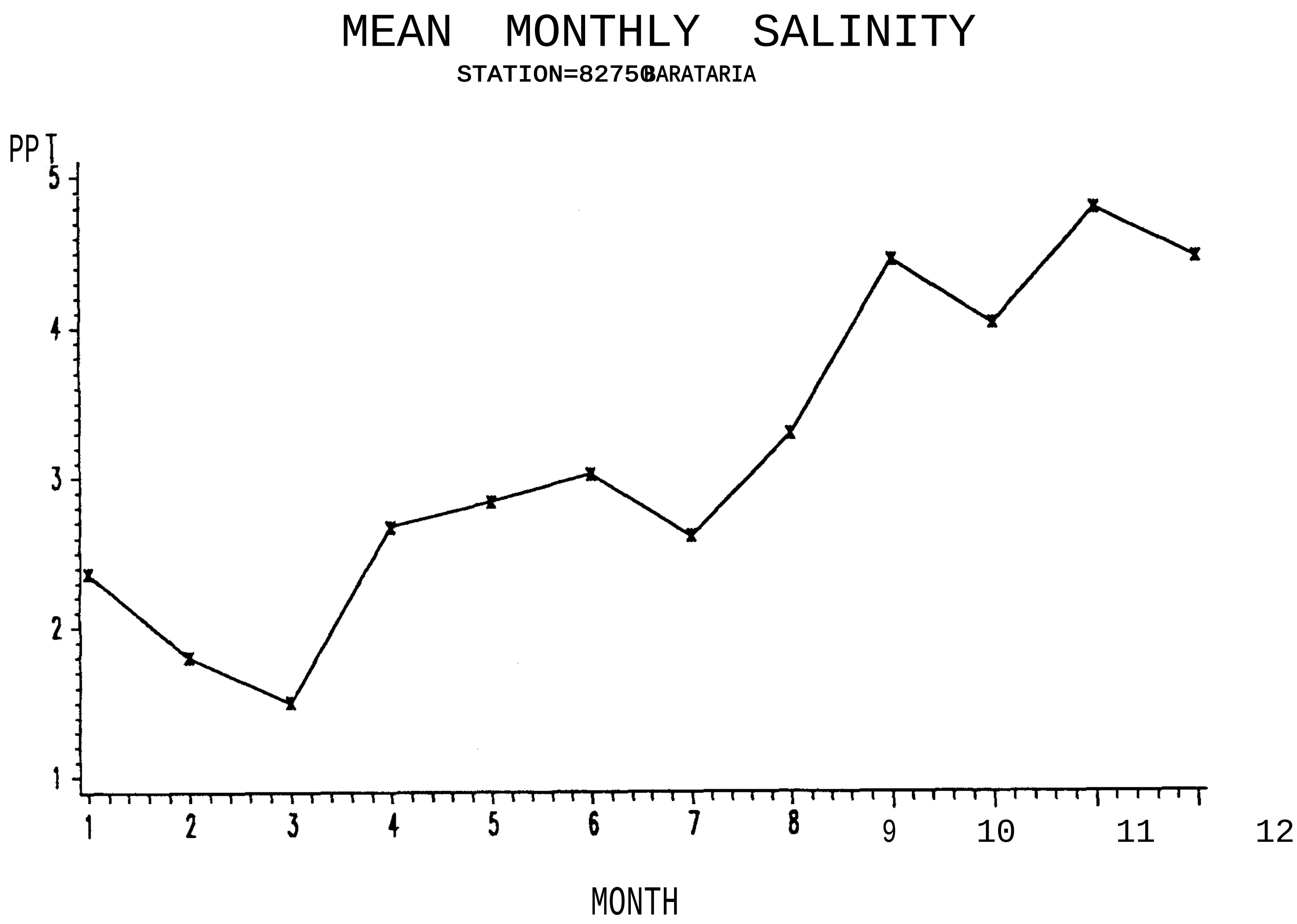
SIATION=82350 LEEVILE

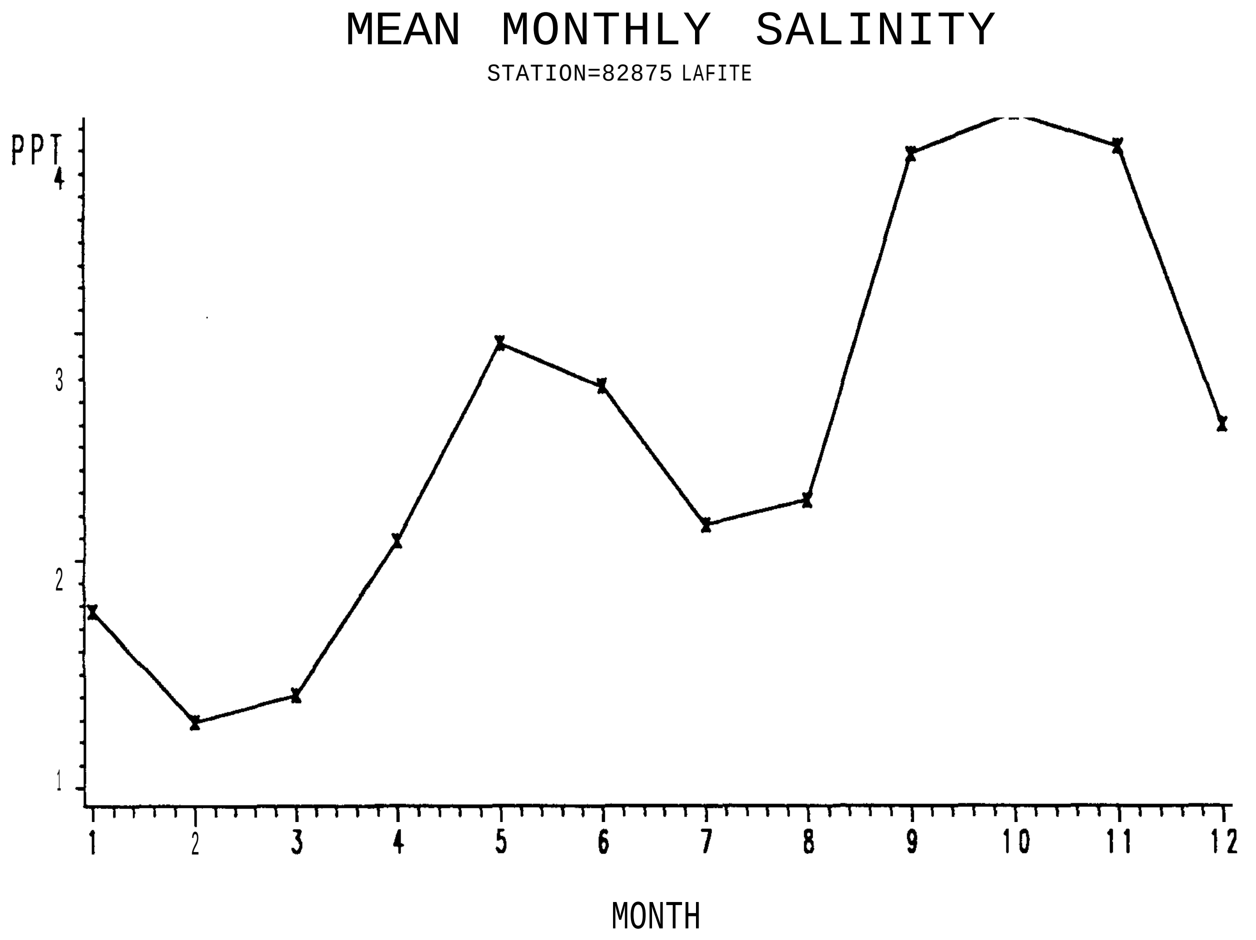


MEAN MONTHLY SALINITY

STATION=82700 DES ALLEMENDS



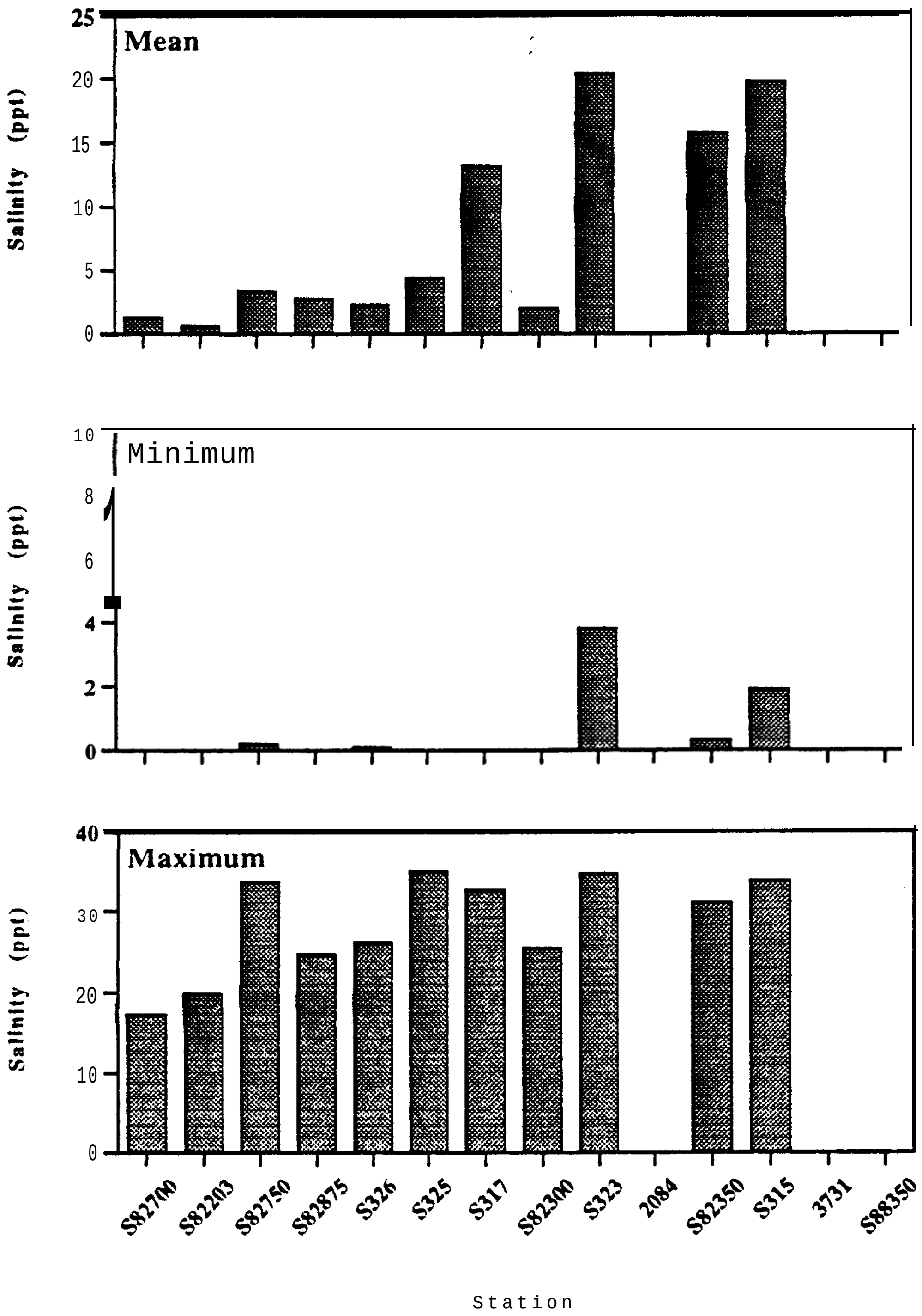

MEAN MONTHLY SALINITY
STATION=82750 BARATARIA
PPT
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
11
12
MONTH


MEAN MONTHLY SALINITY
STATION=82875 LAFITE
PPT
4
3
2
1
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

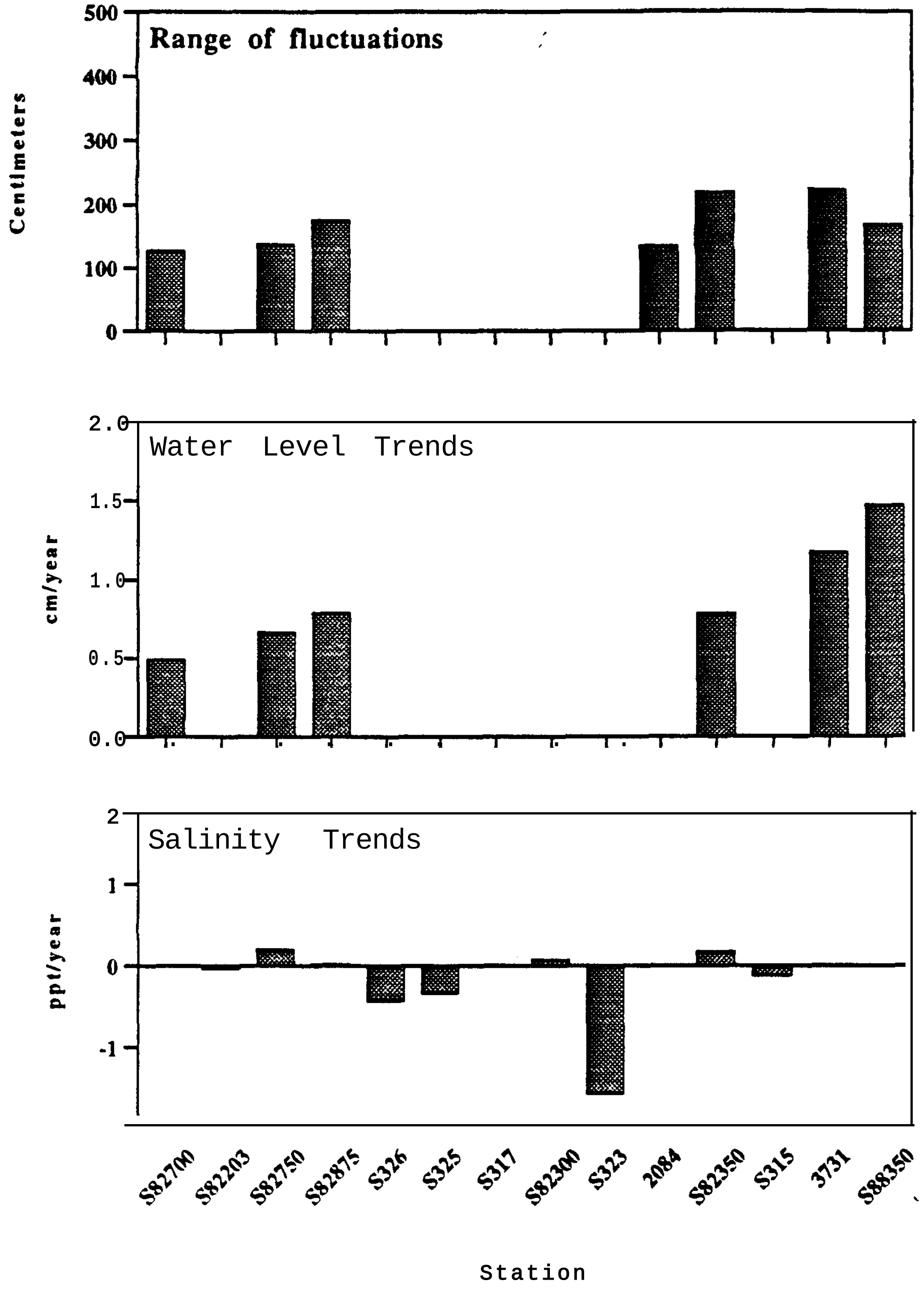
APPENDIX 0

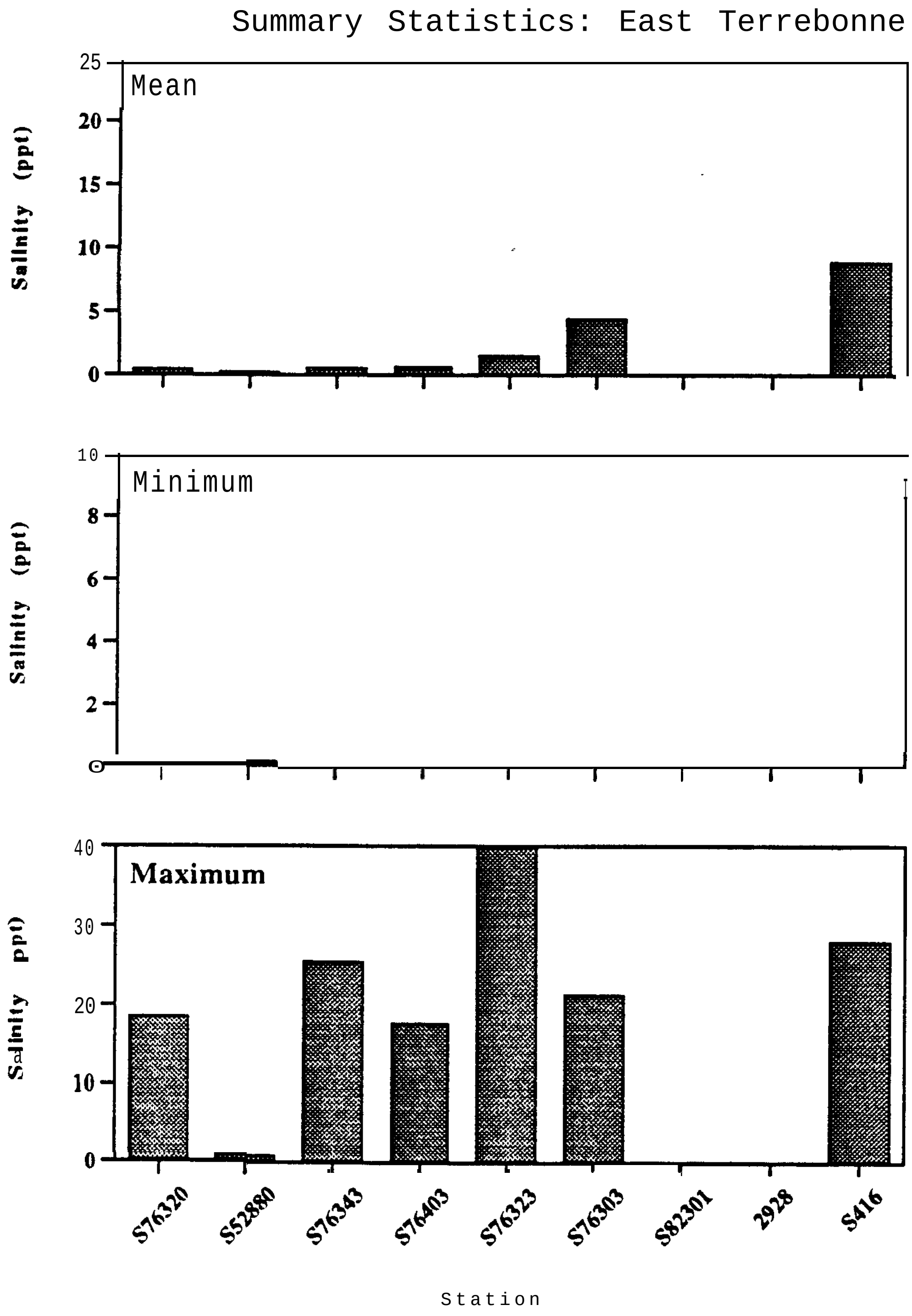
SUMMARY OF LONG-TERM SALINITY AND WATER LEVEL DATA

Summary Statistics: Barataria

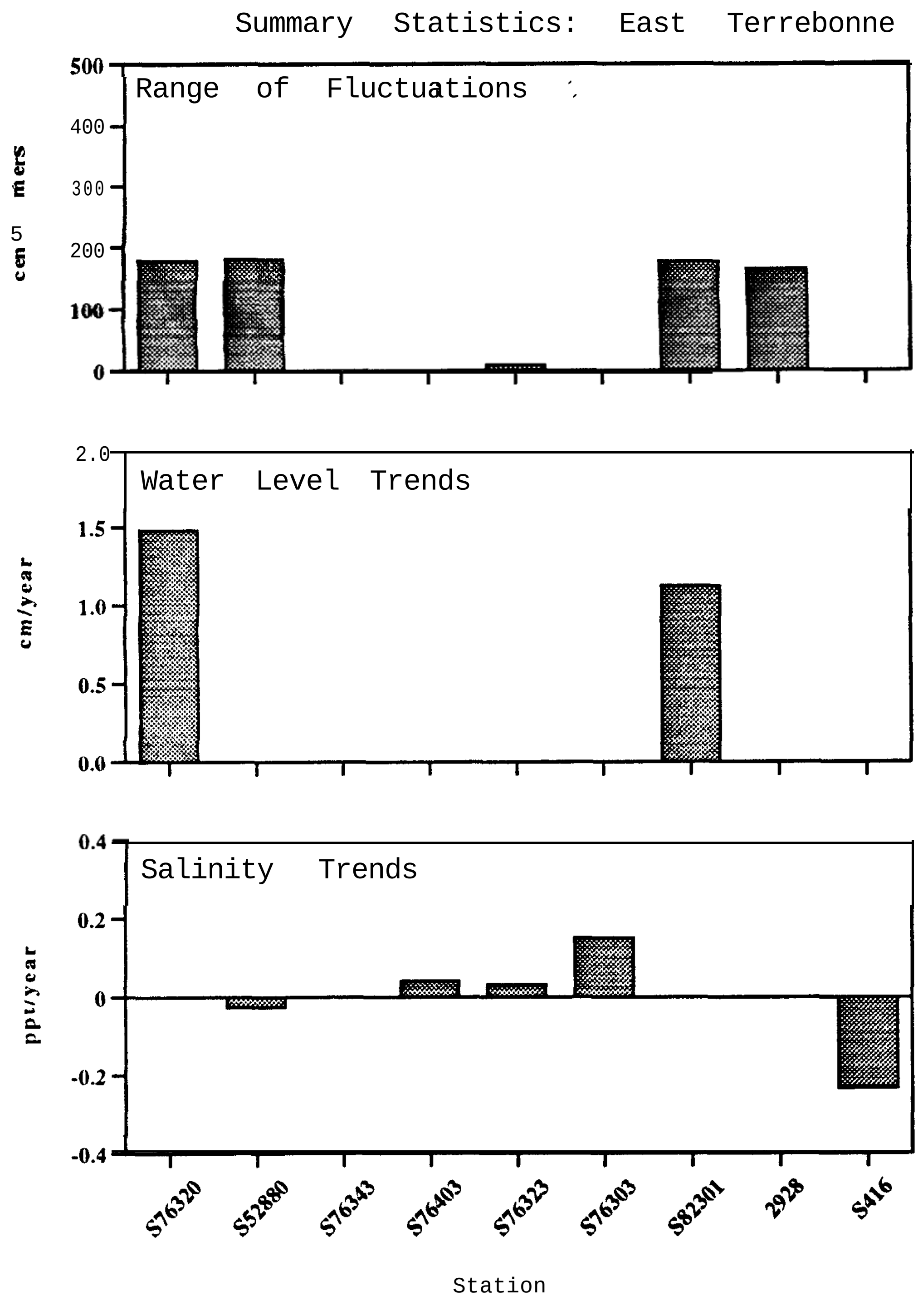


Summary Statistics: Barataria

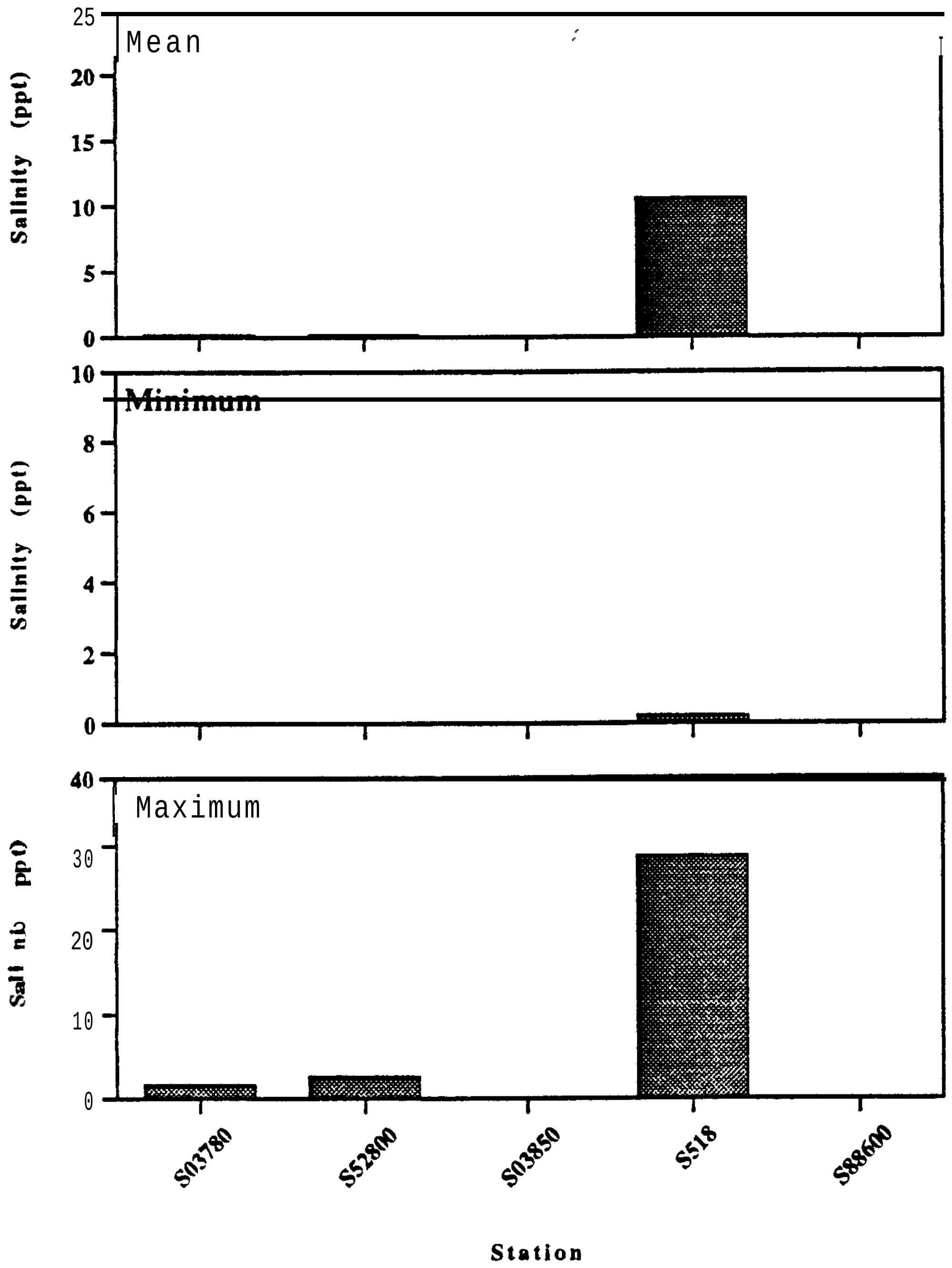




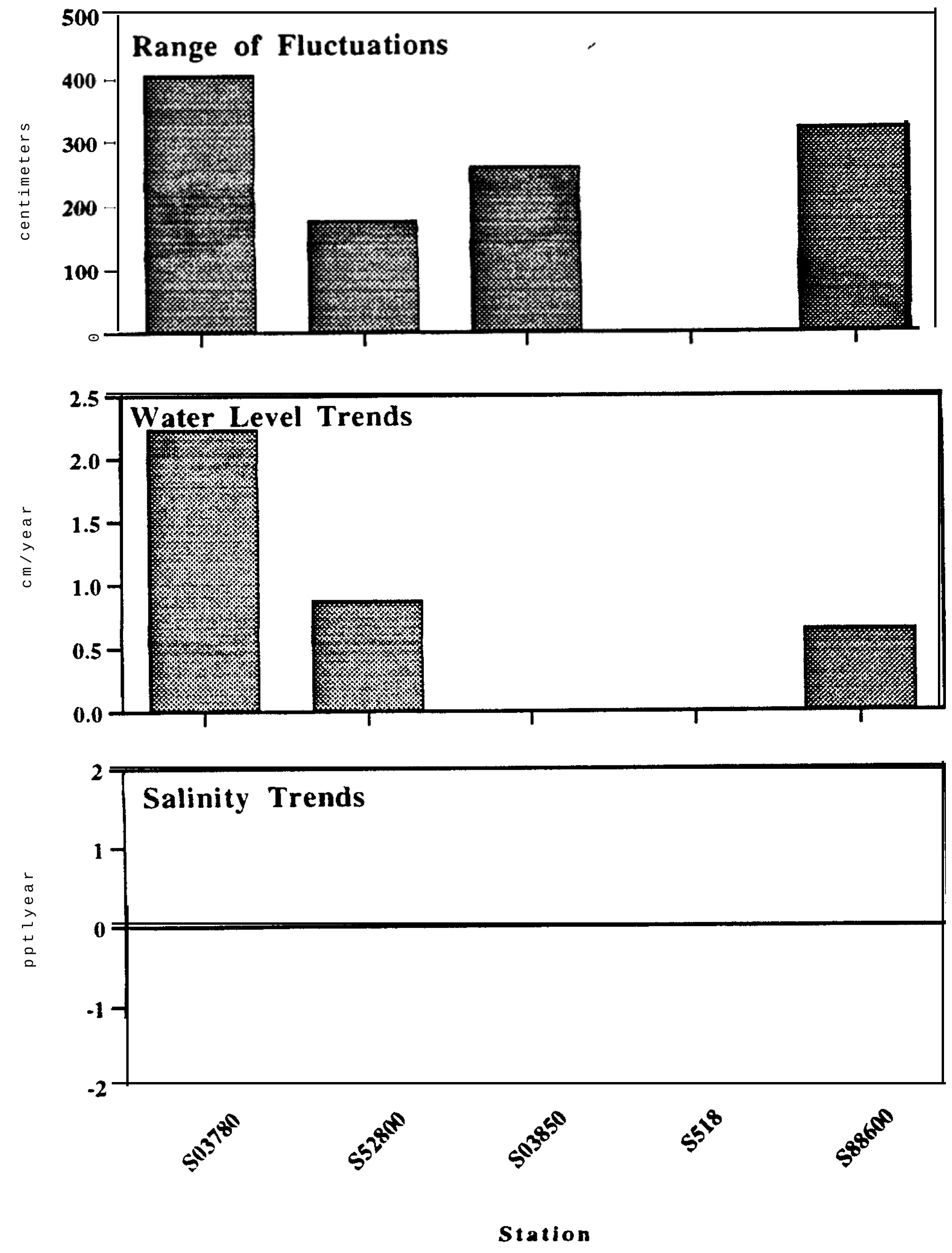
Summary Statistics: East Terrebonne
Mean
Minimum
Maximum
Salinity (ppt)
25
20
15
10
5
0
10
8
6
4
2
40
30
S76320
S52880
S76343
S76403
S76323
S76303
S82301
2928
S416
Station


Summary Statistics: East Terrebonne
Range of Fluctuations
centimeters
500
400
300
200
100
0
Water Level Trends
cm/year
2.0
1.5
1.0
0.5
0.0
Salinity Trends
ppt/year
0.4
0.2
0
-0.2
-0.4
S76320
S52880
S76343
S76403
S76323
S76303
S82301
2928
S416
Station

Summary Statistics: West Terrebonne



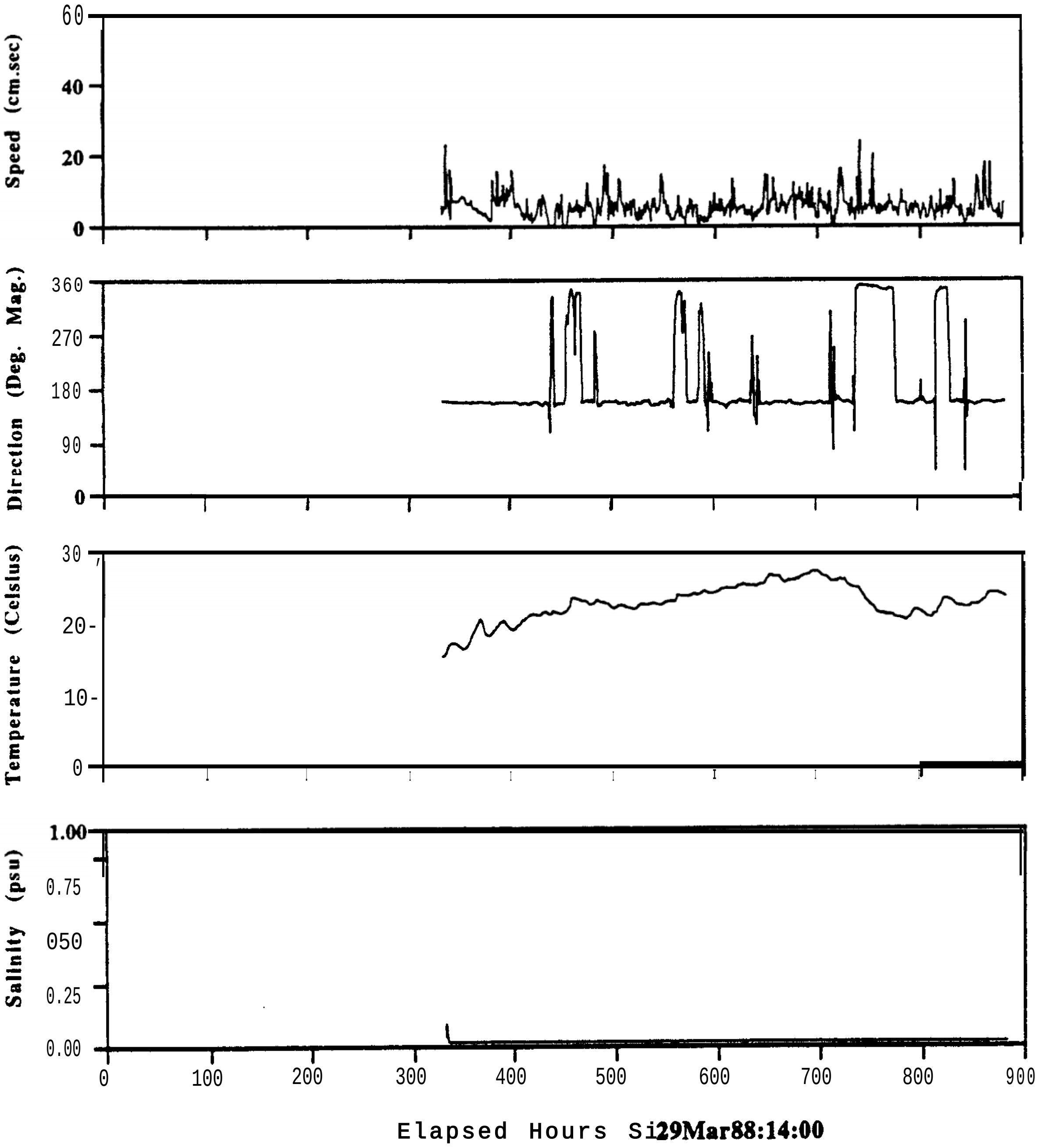
Summary Statistics: West Terrebonne

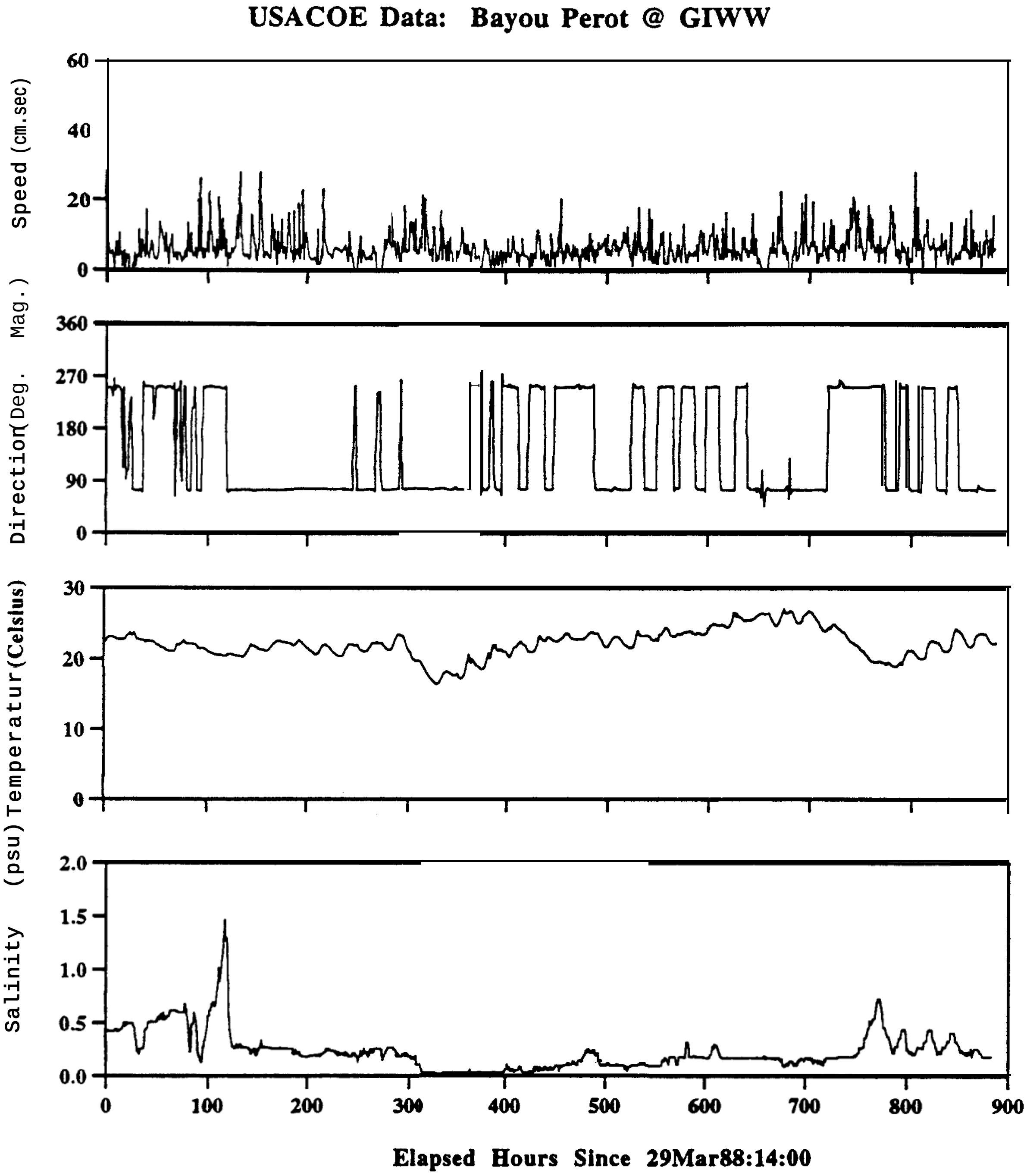


APPENDIX P

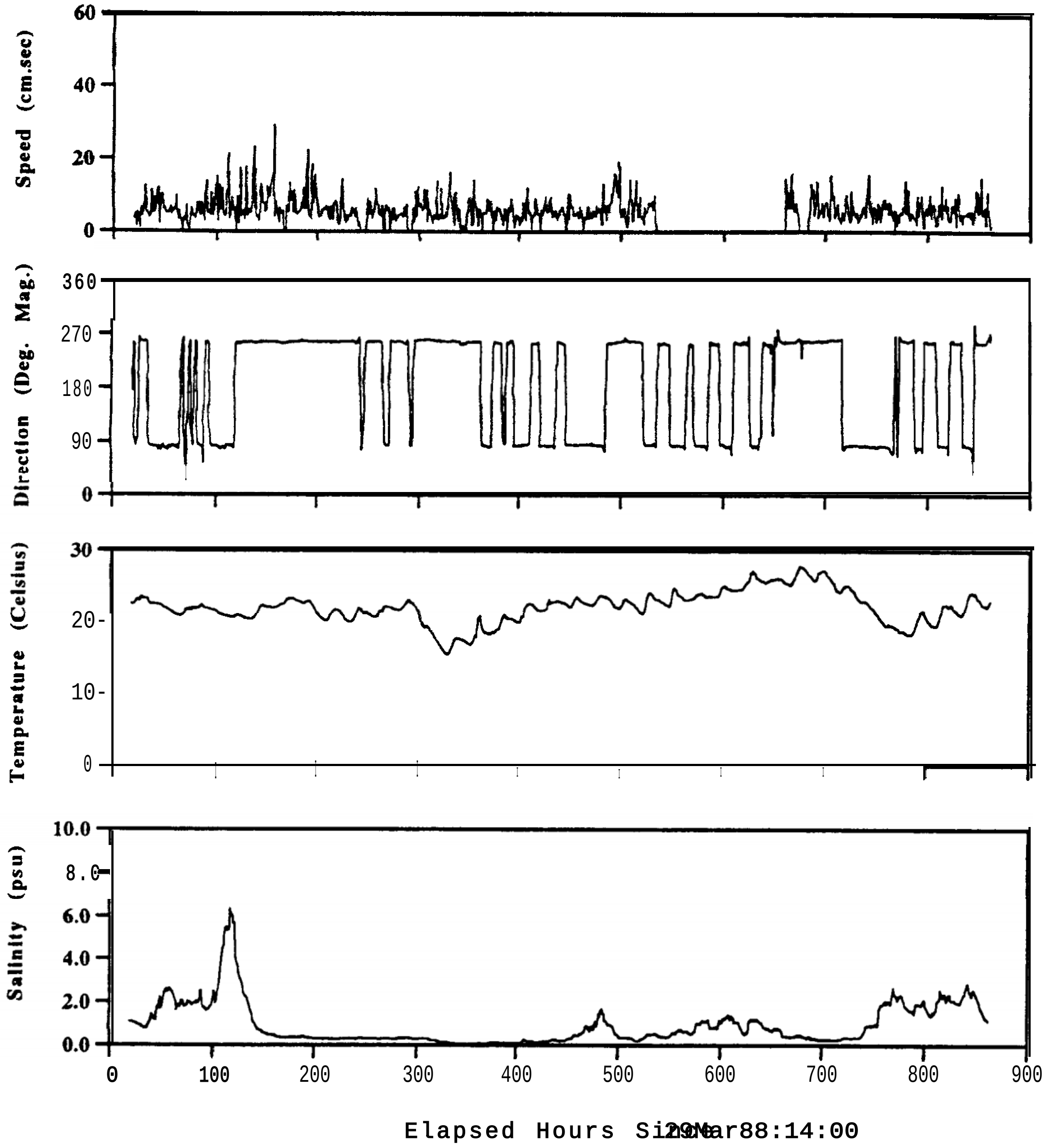
EXAMPLE OF HOURLY WATER SPEED AND DIRECTION, TEMPERATURE, AND SALINITY FROM FIVE STATIONS FROM THE USACOE DAVIS POND DIVERSION STUDY

USACOE Data: Bayou des Allemands @ Des Allemands

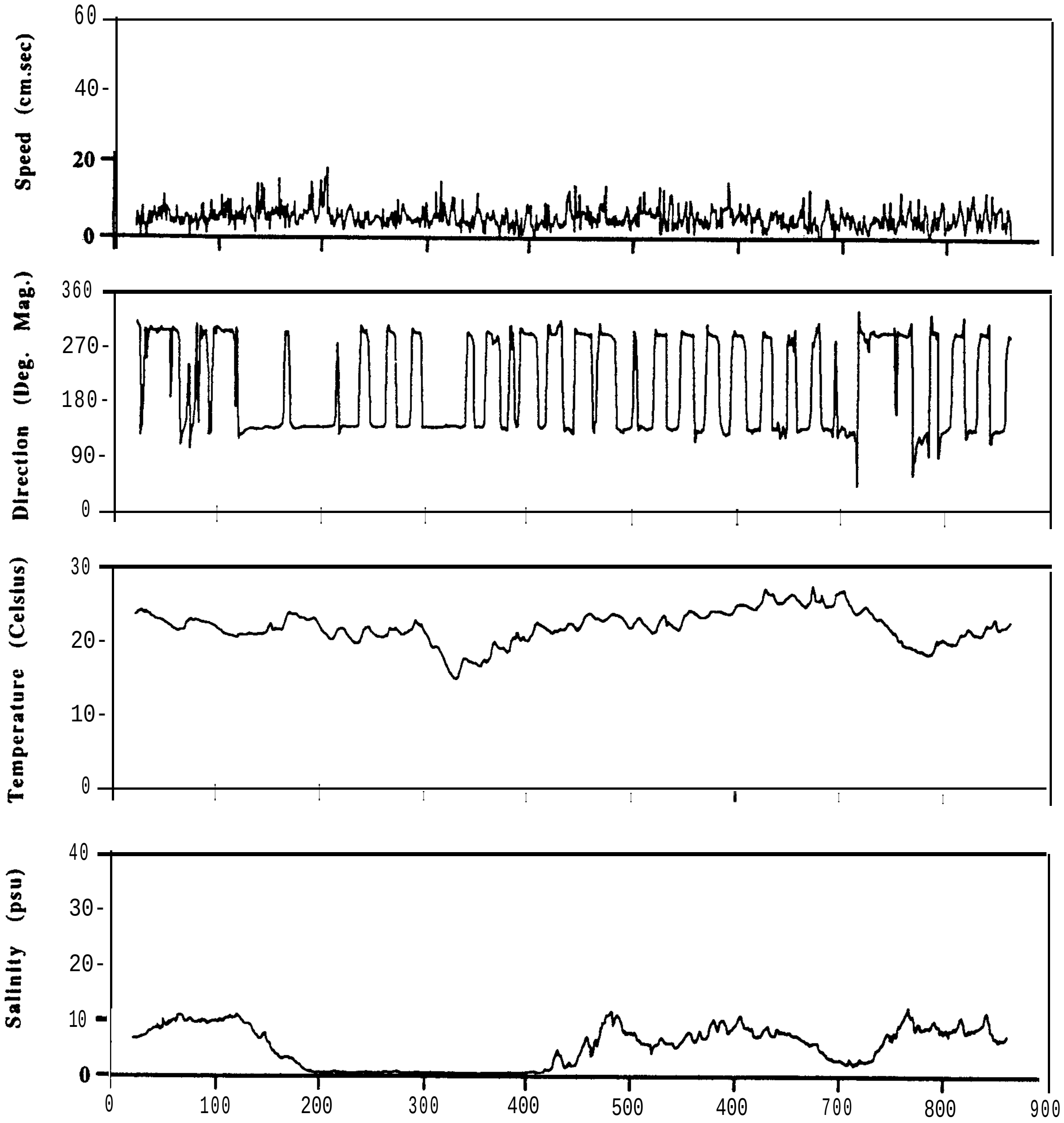



USACOE Data: Bayou Perot @ GIWW
Speed (cm.sec)
Direction(Deg. Mag.)
Temperatur(Celsius)
Salinity (psu)
Elapsed Hours Since 29Mar88:14:00

USACOE Data: Bayou Perot @ Little Lake

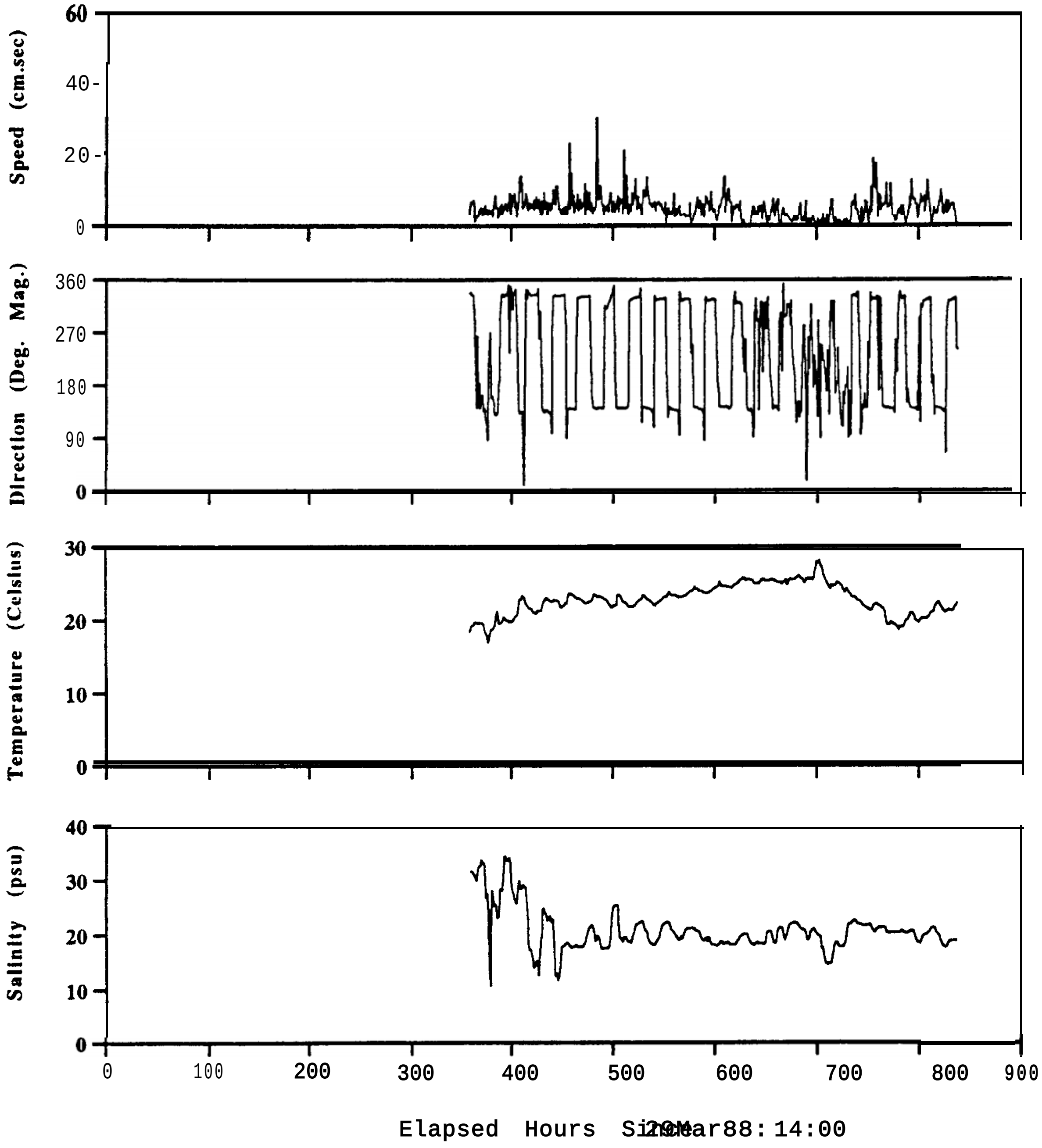


USACOE Data: Grand Bayou Little Lake



Elapsed Hours Since 29Mar88:14:00

USACOE Data: Barataria Pass



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