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Biological Services Program

FWS/OBS-79/30
October 1981

An Introduction to the Environmental Literature of the Mississippi Deltaic Plain Region

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AN INTRODUCTION TO THE ENVIRONMENTAL LITERATURE OF THE MISSISSIPPI DELTAIC PLAIN REGION

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PREFACE

This report is a review of selected environmental literature of the Mississippi Deltaic Plain Region. This review introduces some of the major ecosystem components and processes, describes oil and gas production activities, and guides the reader to available literature.

The seven chapters in this review and the number of references used for each are as follows: Introduction - 5; Geology - 147; Hydrology - 98; Climate and Air Quality - 78; Plants, Fish, and Wildlife - 277; Ecology - 135; and Oil and Gas - 70. The format of each chapter is not always the same, but consideration is given to data deficiencies and research needs. This report may serve as a general reference work and aid in the synthesis of more specialized subject material.

This project was conducted under Contract FWS 14-16-0009-78-090. Funding was provided by the Bureau of Land Management and U.S. Fish and Wildlife Service. This study is designed to be used in planning for Outer Continental Shelf oil and gas development and for coastal zone management needs.

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ACKNOWLEDGEMENTS

We are indebted to a large number of people for making this report possible. We first thank the many persons at Federal, State, and local agencies, universities, and research institutes who responded kindly to requests for much of the information on which the present papers are based. While we cannot list each person or institution that has contributed in this manner, we would like to acknowledge their assistance and extend our appreciation.

We thank Curtis Latiolais and Judy Hanks for preparation of graphics, Susan Baugh for her perseverance in typing these papers, Diane Palliser for help in editing and typing the accompanying references, and Ronne Crain and Ava Haymon for proofreading and editing. Most of all we wish to thank Susan Pendergraft for a dedication to editing and report production without which completion of this report would not have been possible.

CHAPTER I: INTRODUCTION

Various Federal, State and local programs provide for the evaluation and management of resources within the coastal zone. However, we need to view the environment as an integrated system to facilitate coastal development and environmental management decisions. Interactions among physical, biological, and socioeconomic processes must be identified, described, and defined at various levels and related to environmental characteristics and changes.

The present report deals with parts of two regional ecosystems that have been combined for study purposes into the Mississippi Deltaic Plain Region (Figure 1-1). It is one of the nation's most productive fish and wildlife areas. The high biological productivity relates directly to the inflow of Mississippi River water and sediment and the resulting complex of wetlands and estuaries. Continued production of resources therefore depends on maintaining the functional relationship between the Mississippi River and the Deltaic Plain ecosystem to which diversity and quality of estuarine and deltaic habitats are tied. Deterioration of the delta complex is documented (Gagliano and van Beek 1970); the causes are essentially man-made. Man's activities (e.g. confinement of river flows, canal dredging, land reclamation, decline in water quality, and navigation and flood protection works) have allowed natural processes of subsidence, erosion, saltwater intrusion, and eutrophication to dominate over those processes formerly providing maintenance of the system, such as freshwater inflow and sediment deposition.

Extending along the Louisiana and Mississippi coast from Vermilion Bay to the Alabama border, the Mississippi Deltaic Plain Region includes the deltaic plain of the Mississippi River and the Mississippi Sound segment of the lagoon-barrier island system off Mississippi, Alabama, and the Florida panhandle. While both ecosystems have similar climates and exposure to the Gulf of Mexico, major differences exist as a result of physiographic evolution and process-environment relationships.

The Mississippi Sound area resulted from the submergence of a relatively steep coastal plain following the post-glacial rise in sea level and associated reworking of coastal plain sediments. A lagoon and four well-defined estuaries were formed, sheltered from the Gulf of Mexico by a narrow chain of barrier islands. The Pascagoula and Pearl Rivers carried sufficient sediment to maintain or re-establish a tidally influenced floodplain within their lower valley. Major wetland complexes occur here. Additional wetlands are limited mainly to the fringes of the estuaries that developed as Biloxi Bay and St. Louis Bay.

The lagoon, Mississippi Sound, is the principal feature and links four individual estuarine systems that provide much of the ecosystem support.

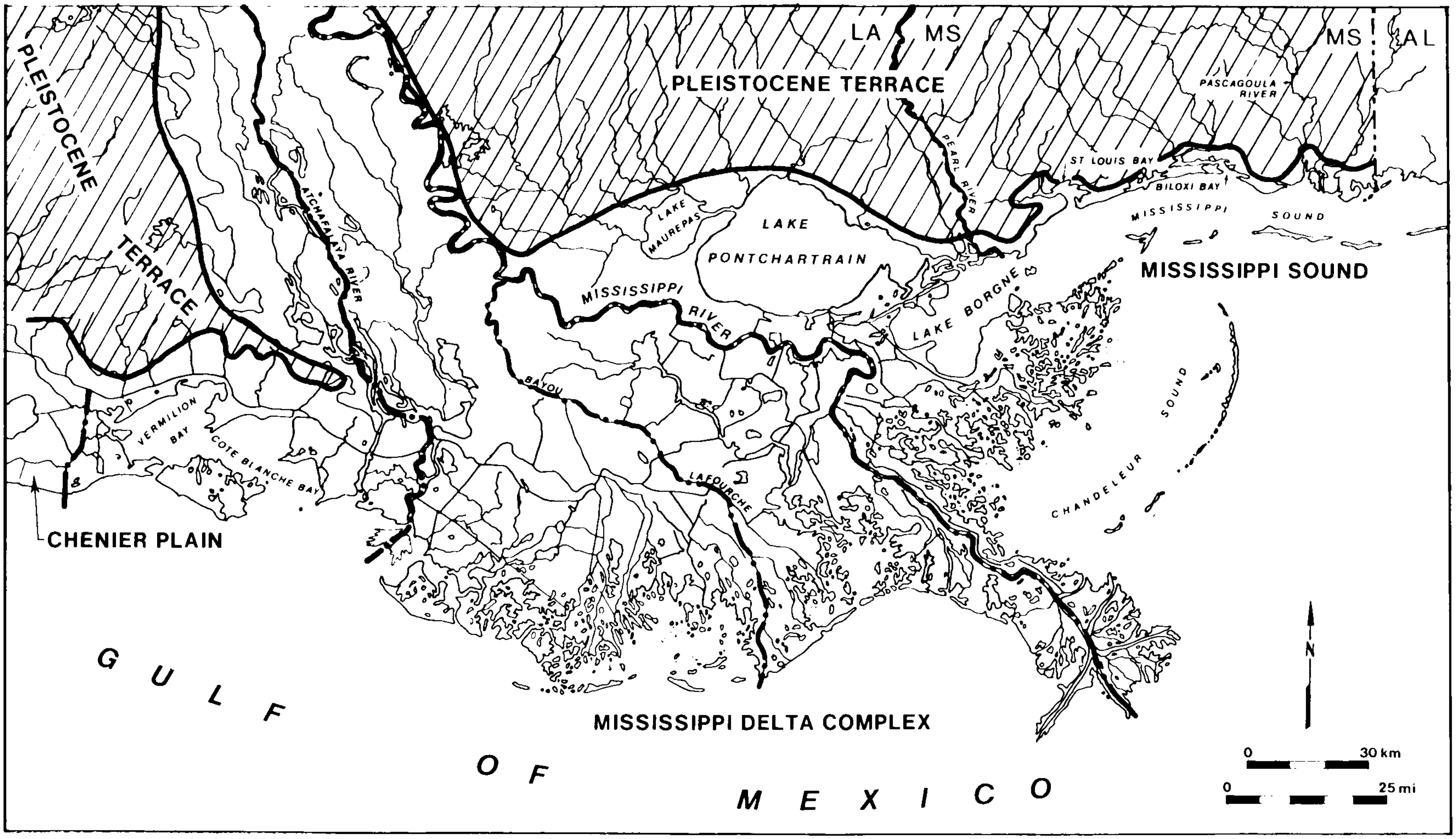

Figure 1-1. Natural setting of the Mississippi Sound and the Mississippi Delta complex which together form the Mississippi Deltaic Plain Region.

Additional contributions of fresh water and materials are derived from Mobile Bay to the east and the Pontchartrain estuary to the west. As a result of the slope of the coastal plain and the origin and limited size of inflowing rivers, the Mississippi Sound system has a comparatively narrow width, extending inland from the Gulf of Mexico approximately 32 km (20 mi). Consequently, salinity and habitat gradients are greater than those of the Mississippi Deltaic Plain. Combined with greater geologic stability, the result is much less rapid change in habitat types.

In contrast to the Mississippi Sound System, the Mississippi River delta system reflects coastal progradation following the post-glacial sea level rise. Unlike the Pascagoula and Pearl Rivers, sediment load of the much larger Mississippi River was sufficient to extend the floodplain beyond the valley into the Gulf of Mexico as a series of major coalescing delta lobes. Five delta complexes have developed during the last 6000 years, each initiated through a change in course or a major diversion of Mississippi River flows (Frazier 1967). As a result, a deltaic system developed, extending 240 km (150 mi) along the coast and nearly 160 km (100 mi) out into the Gulf of Mexico.

The development of each major delta complex initiated a cycle governed by three major sets of processes: 1) the introduction of fresh water and sediment by the Mississippi River, 2) subsidence of the area because of compaction of sediment and tectonic movement, and 3) the combined act of waves, tides, and currents. The cycle of a major delta complex may span several millennia, beginning with underwater growth and emergence of the delta, and ending with disintegration of the system due to subsidence and erosion. Major bays then develop as upstream river diversions and course changes reduce sediment input (Gagliano and van Beek 1975). Within delta complexes the same cycles are repeated on a smaller areal and time scale. Since development of individual delta complexes is time lagged, all phases are present within the Deltaic Plain. With the occurrence and distribution of habitats directly related to the phase of the delta cycle, the lagged cyclic development of delta complexes produces maximum diversity and continuous environmental change. The Deltaic Plain thus represents a comparatively dynamic and unstable system. This instability is further evidenced by the measureable effects of man's influence on freshwater inflow.

Each delta complex is associated with a major channel of Mississippi River origin from which additional distributaries radiate seaward. Associated with each channel are natural levee ridges. A particular delta complex can be regarded as a principal structural component of the delta system. From an ecological point of view, it is the basins between the major river courses or between a major course and Pleistocene uplands that form the principal functional components, or subsystems, on a scale similar to that of the Mississippi Sound area. Each of these basins forms a naturally defined hydrologic entity with limited or no exchange of water across lateral boundaries. Every basin is characterized by a specific assemblage of habitats whose type, distribution, and occurrence relate to phases of the incorporated delta complexes. In general, each shows an environmental sequence in seaward direction from natural levee or Pleistocene uplands into freshwater swamp, marshes, and lakes, through a brackish and saltwater wetland complex, to an open bay that is partially sheltered from the Gulf of Mexico by barrier islands.

From a natural systems point of view, four such basins can presently be defined within the Deltaic Plain. These are respectively the basins between the modern Mississippi River and Pleistocene uplands (Chandeleur-Breton Basin), between the modern Mississippi River and Bayou Lafourche (Barataria Basin), between Bayou Lafourche and the Atchafalaya River (Timbalier Basin), and between the Atchafalaya River and the Chenier Plain (Vermilion Basin). Environmental characteristics within each of these basins are governed by basin morphology and a common set of interacting processes. These functional relationships are schematically shown in Figure 1-2 and are equally applicable to the Mississippi Sound System. The diagram utilizes Odum's (1967) symbolic representation of energy and materials flow, storage, and conversion.

Recognizing the dominance of river inflow and structure of available ecological information for the Mississippi Deltaic Plain Region, two areas within the Region may be broken out from the basic units. These are the areas of the active Mississippi River delta and the area dominated by Atchafalaya River flows and sediments. Seven units are recognized within the Mississippi Deltaic Plain Region (Figure 1-3) and referred to as follows: I: Mississippi Sound, II: Chandeleur Breton Sound, III: Active Delta, IV: Barataria, V: Timbalier, VI: Atchafalaya, and VII: Vermilion.

The objective of the present study is to review the state of knowledge concerning the functional relationships governing environmental characteristics and changes of the Mississippi Deltaic Plain Region. The project was undertaken in two phases: 1) the development of an information base through an extensive search of published and unpublished environmental data and 2) the development of a computerized storage retrieval system. The second phase, represented by the present report, was aimed at a systematic review of the information base corresponding to the major physical and biological processes that govern the Mississippi Deltaic Plain Region's ecological structure and the effect of oil and gas extraction. Subject papers include geology, hydrology, meteorology and air quality, biology, ecology, and oil and gas activities.

The papers provide an overview of current information concerning the ecological structure and function of the Mississippi Deltaic Plain Region, not a comprehensive and technical description of process-environment interactions. Where possible, each paper deals with a defined set of processes and components as delineated in Figure 1-2 to prevent excessive repetition. Geology and physiography concerns geological processes as well as riverine, marine, and socioeconomic processes affecting basin morphology and substrate characteristics. Hydrology incorporates riverine, atmospheric, marine, and socioeconomic processes insofar as they govern the hydrologic regime and its aspects of water level, water movement, and water quality. Meteorology concerns climatological characteristics and weather phenomena affecting hydrologic conditions and ecosystem functions. Biology focuses primarily on mutual relationships between physical processes, habitat characteristics, and populations of plants, fish, and wildlife. Ecological aspects considered are those of trophic relationships, nutrient cycles, and productivity. The overview of existing knowledge also deals with the effect of oil and gas exploration upon the geology, hydrology and biology of the Mississippi Deltaic Plain Region.

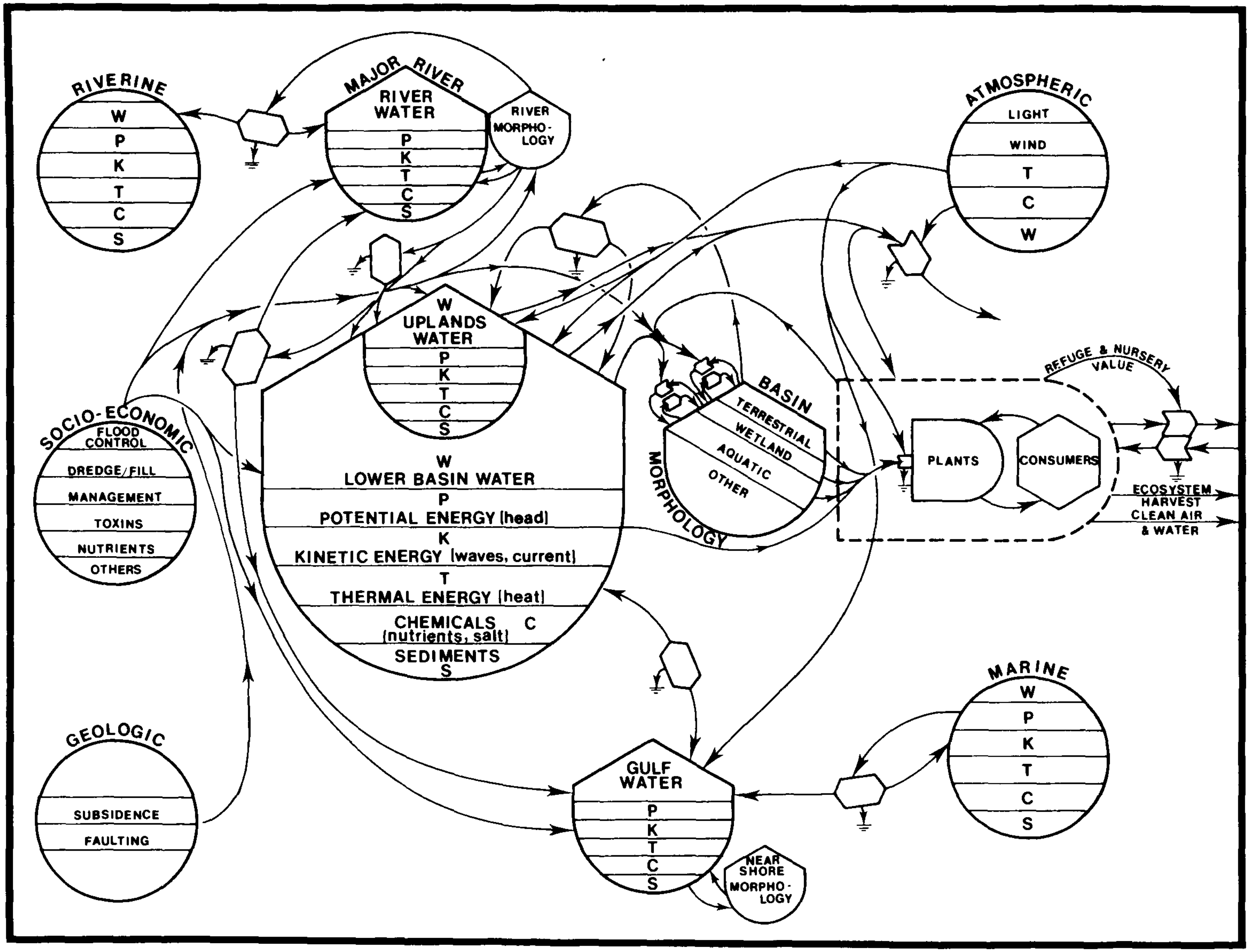

Figure 1-2. Ecological function and structure of a basin within the Mississippi Deltaic Plain Region (van Beek and Gael 1979).

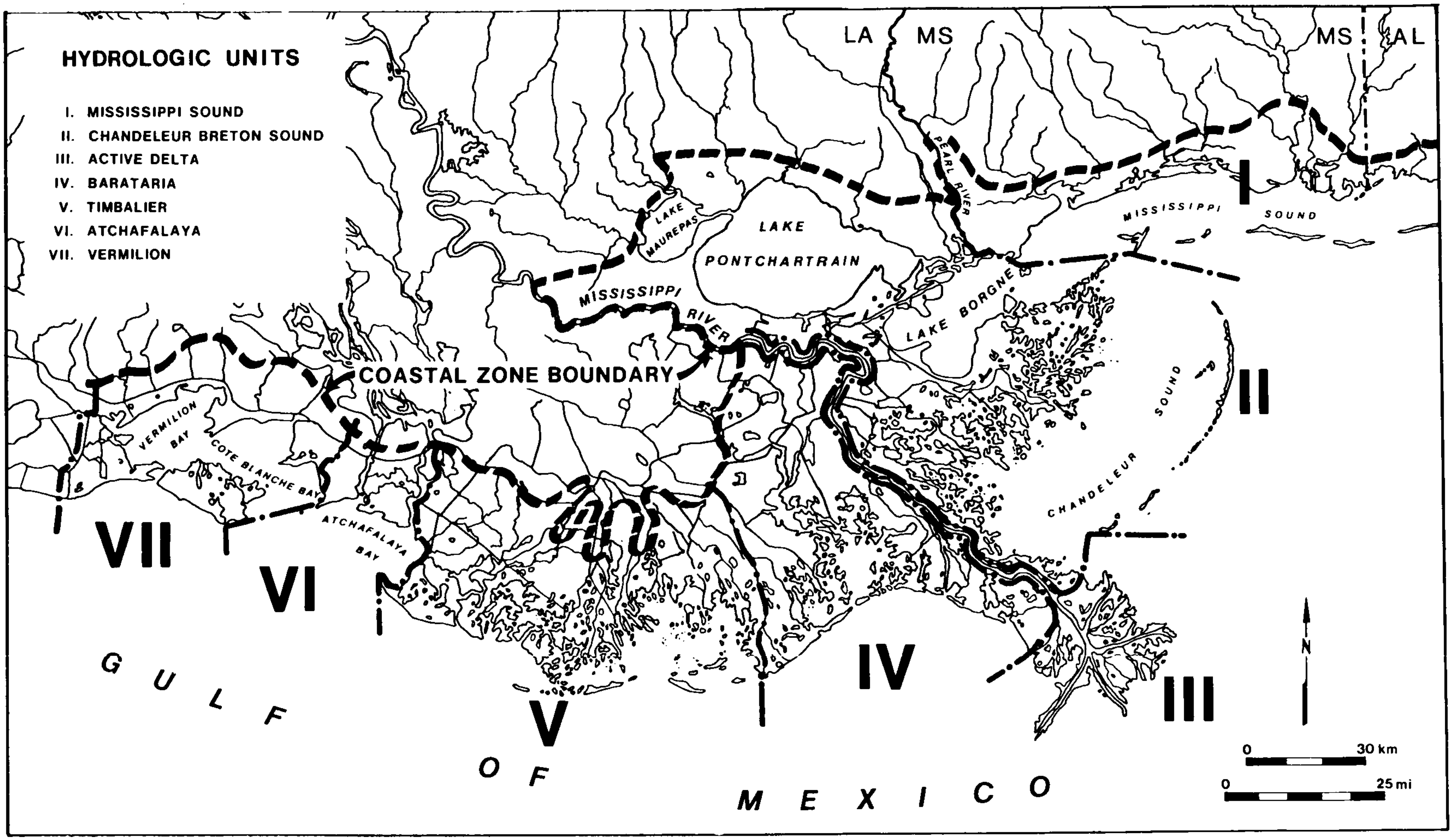

Figure 1-3. Hydrologic units of the Mississippi Deltaic Plain Region.

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CHAPTER II: GEOLOGY

Rod E. Emmer

INTRODUCTION

The Mississippi Deltaic Plain Region is located along the north central coast of the Gulf of Mexico and is divided into two physiographic sub-regions: the Mississippi River Deltaic Plain of southeastern Louisiana (Kolb and van Lopik 1958a) and the Estuary-Lagoon System of Mississippi (Emery and Stevenson 1957) (Figure 2-1). The sub-regions are defined on the basis of tangible, characteristic geomorphic landforms resulting from independent but interrelated physical, biological, and cultural processes.

The Deltaic Plain is a zone of prograding, shifting, and then retreating sediment wedges of massive volume resulting from a river system which drains over 40% of the contiguous United States. Holocene sediments have accumulated to form the present surface since the last stillstand of sea level, approximately 7000 years ago. Five deltaic complexes have formed during this period (Frazier 1967) (Figure 2-2), beginning with the Maringouin complex on the western edge of the Deltaic Plain. The Mississippi River partially shifted to the east forming Bayou Teche about 5700 years ago and prograded into south central Louisiana. A complete diversion to the east began 4800 years ago as the St. Bernard Delta built into the shallower nearshore waters south of the Pleistocene terraces. Thought once to have reached beyond the Chandeleur Islands, the channels extended until the gradient became too low for maintenance of the system. Approximately 3500 years ago, a new delta, the Lafourche, began to fill the basin between the long abandoned Teche and St. Bernard Deltas. The Lafourche Delta prograded to the south, overlapping parts of both the Teche and St. Bernard Deltas. These four deltas are fan-shaped because they were built in the shallower continental shelf waters. The active modern delta, fifth in the series composing the Deltaic Plain, is a birdsfoot type delta which began forming 1000 years ago on the continental slope in deep water. Finally, a new delta, the Atchafalaya, is forming in the Atchafalaya Bay, once again initiating the cycle of the deltaic system.

Each deltaic lobe is an accumulation of unconsolidated sand, silt, and clay having a finite vertical and lateral distribution. An orderly cycle of events occurs which results in the low relief and low elevations of the lobe, a cycle which extends over hundreds of years and may range in size from

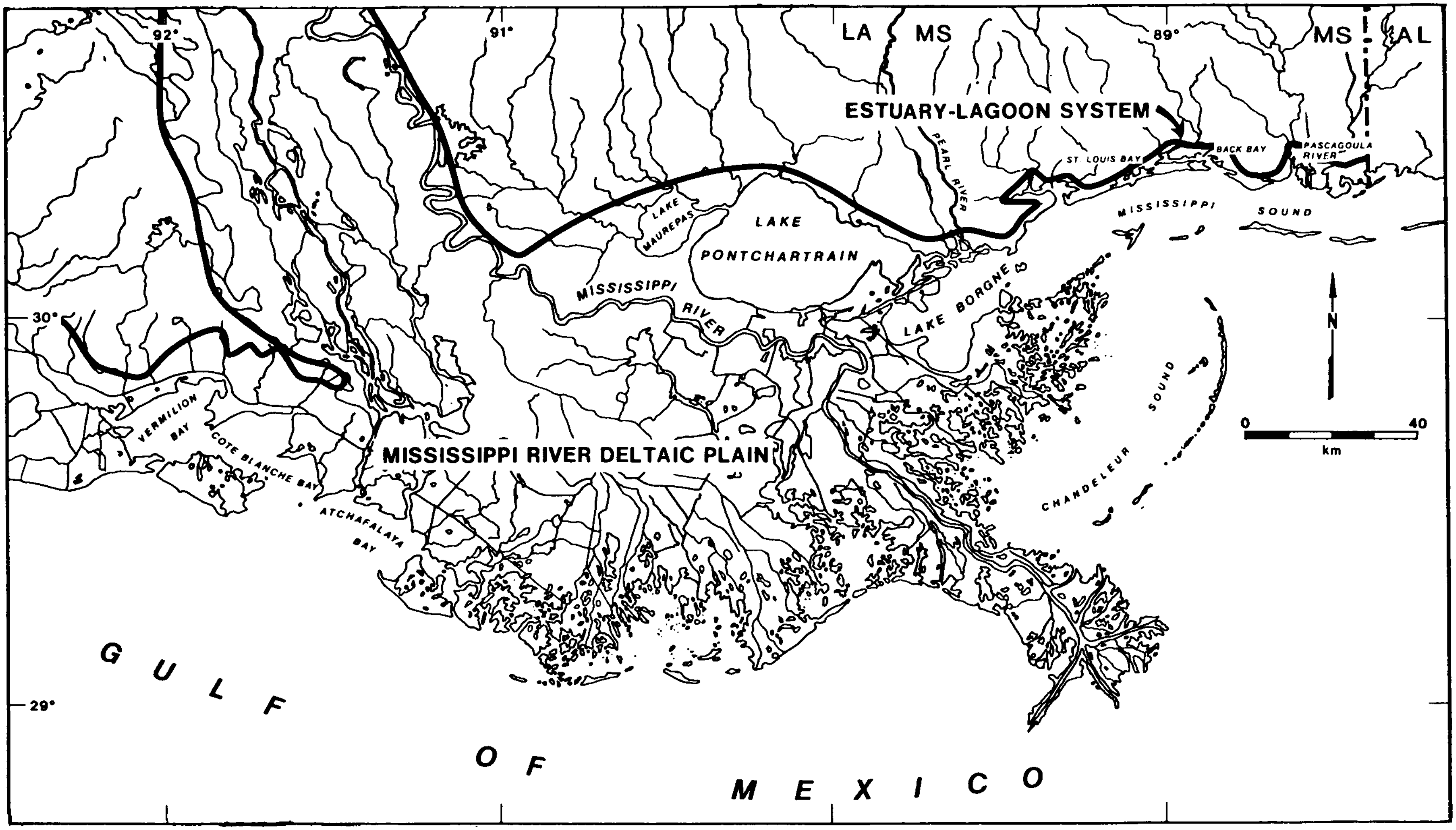

Figure 2-1. The Mississippi Deltaic Plain Region (Russell 1936).

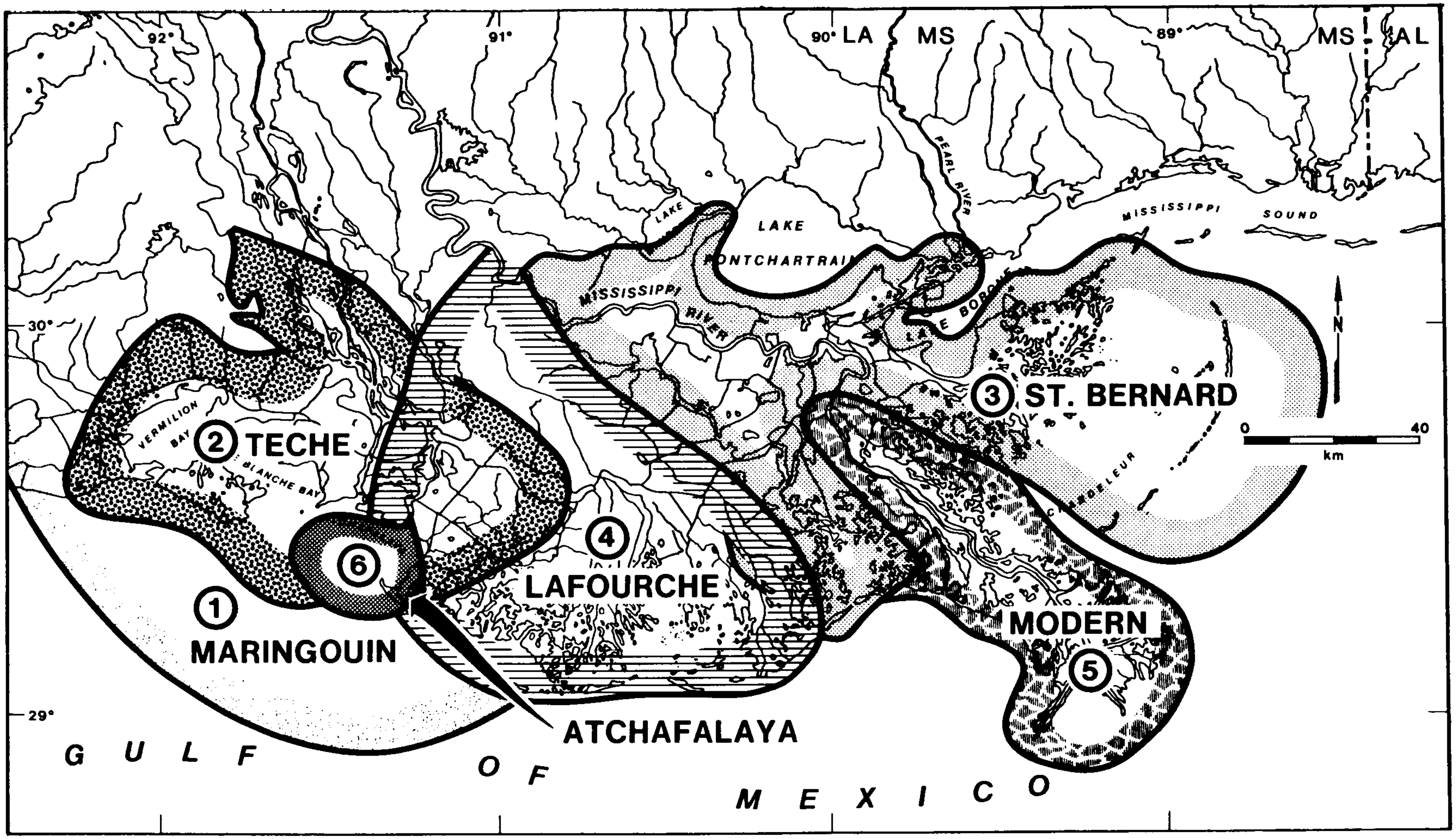

Figure 2-2. Subdelta chronology of the Mississippi River Deltaic Plain (Frazier 1967).

hundreds of meters thick and thousands of square kilometers in area to only meters thick and square meters in area. The series of events in a riverine system which forms a deltaic lobe are as follows (Coleman and Gagliano 1964):

- a levee breaks or is over-topped during flood, a diversion results
- flow increases through successive floods
- there is a peak of maximum discharge and sediment accumulation
- flow decreases and sediment supply decreases
- the system is abandoned
- subsidence dominates and there is a general coastal retreat under marine or lacustrine processes

In the Estuary-Lagoon System, the cycle is characterized by marine processes reworking and redistributing sediments. Wave and littoral currents erode one end of the barrier island and deposit sediments at the other end or in the bays. Tides and storms move sediment onto and off beaches while keeping it in the overall system. Rivers prograde into entrenched valleys but do not fill them. Marshes form in the quiet zones away from waves and currents.

As expected, nature is not as simple as the models devised to explain events. In both sub-regions, deposition occurs in one area, while erosion simultaneously occurs in another. There are many variations in form configuration, process intensity, and the interrelationships between the two; however, one factor remains constant: the geologic component of the Deltaic Plain and Estuary-Lagoon System is the base upon which the biological and cultural elements rest.

Geomorphic knowledge of the Mississippi Deltaic Plain Region consists of information about the surface and near-surface lithologic elements--important information because of the relationship between the physical base, the distribution and configuration of detritus, and the biological elements of the Deltaic Plain and Estuary-Lagoon System. This discussion centers on these phenomena and is not concerned with paleontological observations, petrologic reports, geologic articles on oil and gas formations, or basic engineering geology. For example, regional subsidence as related to geosynclinal sediment accumulation is mentioned but is not discussed in geophysical terms; sediment movement by water is covered but the physics of particle entrainment is not considered. Some reports which may be classified as being in one or more of the above fields are cited because they are examples of near-surface geologic or geomorphic information which ordinarily appear in this type of treatise.

In order to evaluate the geomorphic knowledge of this area and then establish the gaps in knowledge, familiarity with the published and unpublished research which has been conducted throughout the Mississippi Deltaic Plain Region is mandatory. In preparation for this paper, a bibliography of the published and unpublished data on the Mississippi Deltaic Plain and the Estuary-Lagoon System was assembled, thoroughly reviewed, and analyzed for significant contributions to an understanding of this coastal system.

Research in the Mississippi Deltaic Plain may be divided into four phases: general description, physiographic interpretation patterned after William M. Davis (1899), geomorphology at the regional scale, and intensive geomorphic investigation at a specific location (Figure 2-3, Phases I-IV). A study in

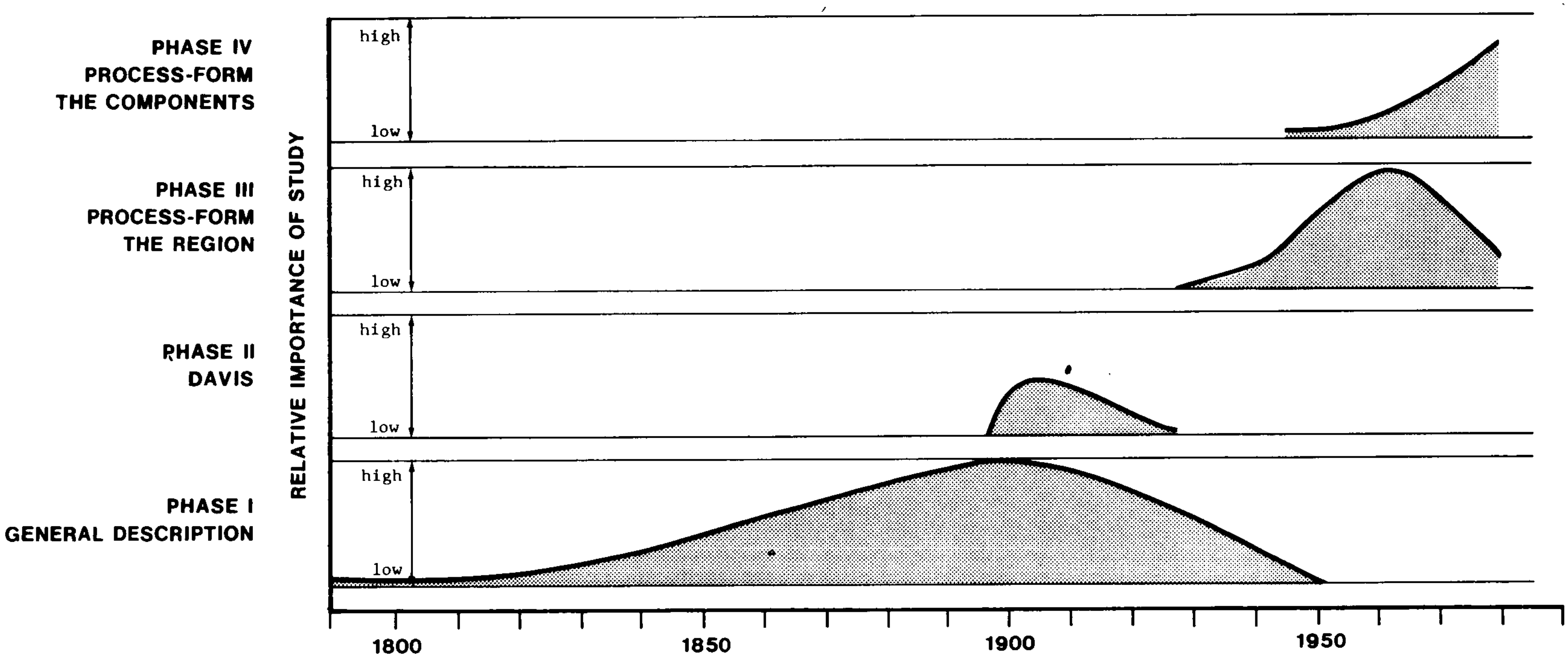

Figure 2-3. The relative importance and estimated time span of the four phases of research in the Mississippi Deltaic Plain Region.

the 1890s is probably an inventory of an area; a paper in the 1950s is more than likely to be either a regional discussion of forms and processes or a description of a specific locale; and an article in the 1970s would probably involve an analysis of a portion of a basin or a single entity and would quantify the processes responsible for the form. Thus, an understanding of the development of knowledge in this field allows an estimation of the content of an article and/or data by placement of the research in context of time of publication and authorship.

In the Estuary-Lagoon System, general descriptions of the State of Mississippi were the only documents on the geology of the area until the 1940s. Unlike research on the Deltaic Plain, students of the geology of the Estuary-Lagoon System are only recently compiling regional reports based on previous detailed works.

The objectives of this report are as follows: to summarize the knowledge on the forms and processes within the Mississippi Deltaic Plain Region, thus providing a background for an analysis of the geomorphic and related geologic knowledge; to present the gaps in knowledge concerning the geomorphic environment; and finally to point out recommendations for future research in the Mississippi Deltaic Plain Region.

GEOLOGY

In this section, the forms and processes in the Mississippi Deltaic Plain Region will be described, followed by an analysis of geomorphic knowledge in the Region.

FORMS AND PROCESSES IN THE MISSISSIPPI DELTAIC PLAIN REGION

The surface of the Deltaic Plain and Estuary-Lagoon System is shaped by four independent but interrelated constituents: sediment, moving water, surface motion, and man. Sediments are the sands, silts, clays, inorganic matter, and organic matter which are the basic physical building elements of the Deltaic Plain and Estuary-Lagoon System. These constitute the forms of the Region. The processes are water movement, surface motion, and man's actions. Moving water is the action force transporting sediment in river water, longshore currents, tides, waves, and storm surge. Water is the connector, the common denominator, among all forms in the Deltaic Plain and Estuary-Lagoon System. Surface motion influences the character of moving water and the patterns of deposition. Man's actions contribute to sediment load, manipulate water movement, and influence surface motion. Each of these four constituents is made up of separate units, which in total compose the whole; interaction among these constituents covers the complete range of intensity and composition, from absence to dominance. A summary of each of the four components of the geomorphic landscape will follow. Form (sediment) will be discussed first, followed by processes (water movement, surface motion, and man's actions).

Sediment (form) is the inorganic and organic matter carried from a river basin through the alluvial valley into the delta and along the coast from adjacent systems. Sediment is reworked and combined with residual inorganic and organic matter to create distinctive geomorphic forms having recognizable topographic expressions. Generically distinct patterns have similar generic origin and respond to outside stimulation in known and predictable manners; however, the degree and rapidity of response depend on the status of the surrounding environmental parameters. Thus, although it is possible to estimate what will or will not happen under a given set of circumstances, exact and precise impact projection is not possible at this time.

The geomorphic forms of the Mississippi Deltaic Plain Region may be grouped into two catagories: the Deltaic Plain and the Estuary-Lagoon System. These two systems are subdivided into the following environments:

Deltaic Plain (Kolb and van Lopik 1966)

- Fluvial
- Paludal
- Fluvial-Marine
- Marine

Estuary-Lagoon (Otvos 1973a)

- Offshore barrier islands and inter-island shoals
- Mississippi Sound
- Major semi-closed estuaries
- River estuaries

Numerous studies have characterized the Mississippi Delta depositional environments (Russell 1936; Fisk 1947, 1952, 1955, 1961; Kolb and van Lopik 1958a, 1966; Scruton 1960; Welder 1959; Priddy et al. 1955; Saucier 1963; Coleman et al. 1964; Coleman and Gagliano 1964; Coleman 1966; Upshaw et al. 1966; Otvos 1973a, 1976). Additional research citations appear in the references to this paper and in other literature surveys prepared on the Deltaic Plain and the Estuary-Lagoon System, therefore only a general characterization of each depositional environment is presented.

Forms in the Deltaic Plain

Fluvial. Meander belts are fluvial deposits of natural levees, point bars, and abandoned channel fill. Natural levees aggrade through sedimentation of suspended load and bed load during overbank flooding and crevassing. Overbank flooding is an area-wide inundation which is relatively shallow (<5 m [<16 ft]) and 3-5 km (2-3 mi) across. Overflows are not persistent through time as may be the crevasse. Most suspended material settles on the existing levee system. Crevasses, on the other hand, are narrower, 153 to 336 m (500 to 1100 ft) wide, and deeper, up to 31 m (100 ft), where they breach the crest of the levee. Channels may remain active for a number of years before eventually filling (Fisk 1947, Saucier 1963). Most sediment finds its way to the toe of the levee and into the backswamp.

In general, levee elevations and sediment grain size decrease in a downstream direction and away from the channel. Subaerial levees trend north-south across the Deltaic Plain and continue as subaqueous levees where watercourses prograde into lakes, bays, or other water bodies. Because of their greater mass, natural levees slowly subside into the underlying sediments (Morgan 1973). In addition, regional subsidence is occurring because of compaction of sediments, water expulsion from interstitial spaces, and geosynclinal movement (Morgan 1973).

Point bars are the product of lateral channel migration and are on the inside, or convex side, of meanders. The lateral and vertical extent of point bar deposits is a result of channel size; therefore rivers such as the Mississippi will have point bars that are 6.4 km (4 mi) long by 3.2 km (2 mi) wide and 50 m (164 ft) deep, and watercourses such as the Amite River will have point bars which are 0.8 km (0.5 mi) long by 0.4 km (0.25 mi) wide and 10 m (33 ft) deep. Topography is characterized by alternating ridges of coarser material and swales of finer material. In the vertical perspective, point bars approximate the maximum scour of the river and sediment size increases with depth (Kolb 1962a). The coarsest grain sizes exposed in the alluvial system are on the point bar because sediment is derived from bed load as well as suspended load. Point bars have subaqueous and subaerial components and transition zones which are periodically inundated during floods.

Abandoned courses are channels which were once active distributaries of the river system. As a result of increasing discharge through a new course and less river water flowing through the existing course, the older channel is gradually filled with sands, silts, clays, and organics. Sandy deposits fill the channel downstream from the diversion. Gradually, less water flows through the older course and eventually only floodwaters pass the point of diversion. The abandoned course is filled mostly with the finer materials (e.g., silts and clays) carried in suspension during flood and with organics which have accumulated from plant growth. Tidal action may introduce some sands and silts into the system from the Gulf of Mexico (Kolb and van Lopik 1966). Abandoned courses range in size from main channels of the Mississippi River 1000 m (3050 ft) across and 50 to 60 m (152 to 183 ft) deep, such as the Teche or Lafourche courses, to distributaries in the lower deltas only a few meters across and deep.

Paludal. Paludal deposits fill the broad, low-lying basins between the meander belts, and are the swamps, marshes, and lacustrine environments which compose 90% of the Deltaic Plain. The dominant characteristic of sediments in paludal environments is their high organic content (Kolb and van Lopik 1966). Swamps, found inland from the Gulf, are areas of low elevation, low relief, and poorly organized drainage systems in which there are few defined watercourses. Silts and clays arrive in the basins during flooding and are the inorganic fraction of the deposit. Because silts and clays settle from floodwaters, inorganic sediment content decreases with increasing distance from the source of supply. Peats and highly organic clays are found toward the center of larger basins where little, if any, inorganic sediment is transported.

Fresh, brackish, and saline marshes occur in more than half of the Deltaic Plain (Kolb and van Lopik 1966). Marshes are distinguished from swamps by vegetation (marshes contain grasses and sedges; swamps are vegetated by trees and woody plants) and a high organic content in the nature of peats, organic ooze, and humus. Having less inorganic material than swamps, marshes build on themselves or on the organic matter which gathers on the consolidating sediments and regionally subsiding facies. Inorganic sediments from floods, storm surge, and tides must be maintained, however, because organic accumulation cannot keep pace with subsidence. Eventually, marshes open into lakes if inorganic supplies are terminated.

Lacustrine environments range in size from Lake Salvador (21 by 10 km [13 by 6 mi] and 1 to 3 m [3 to 10 ft] deep) to very small lakes only a few tens of meters in diameter and one meter deep. Such small lakes result from marsh subsidence and are enlarged by wave erosion, tidal action, and storm surge.

Bottom deposits in the smaller lakes consist of organics from the recently lowered marsh surface; as the lake enlarges, the fines are winnowed from the shoreline and lake bed and coarser sediments veneer the bottom. Sediment may accumulate in lakes from floodwaters, progradation of a river into the lake, or organic accumulation in the lake. With the exception of the occurrence of a major diversion resulting in rapid aggradation--such as in the Atchafalaya Basin--filling of lakes is very slow.

Fluvial-marine. Fluvial-marine environments are the deposits associated with an advancing distributary and may be divided into prodelta, intradelta, and interdistributary environments. Prodelta deposits are formed in deep waters in front of the prograding delta and are the clays and silts carried in suspension by the river. Silts settle closer to the distributary and clays are carried farther seaward, and both are distributed by riverine and littoral currents. The prodelta deposits are the foundation on which the subaerial part of the deltaic system is built.

Intradelta deposits are the terrigenous sediments carried as bed load or suspended load which are too coarse to be transported offshore. These sediments form the distributary mouth bars and the subaqueous and low subaerial natural levees of the prograding channel (Fisk et al. 1954). These are the coarsest materials in the delta and overlay the prodelta deposits.

Interdistributary environments of underconsolidated clays are deposits between the distributaries (Fisk et al. 1954). Clays are moved into the basins by overbank flow, littoral currents, or tidal action. If there is no channel diversion into the interdistributary basins, the areas slowly fill with sediment from overbank flooding and eventually become marshes or swamps.

Marine. Marine environments are composed of beach, reef, bay-sound, and nearshore Gulf sediments. Beaches and reefs are depositional in origin while bay-sound and nearshore Gulf environments are predominantly erosional features. Beaches are composed of either sand or shell and are found as barrier islands or retreating shorelines throughout the Deltaic Plain. Availability of source material determines whether the beach is sand or shell; most sand beaches are barrier islands associated with abandoned distributaries, while most shell beaches are found along retreating marsh shorelines landward of bays and sounds. The fines are winnowed, leaving the coarser sands and shells. Reefs are composed of the American oyster (*Crassostrea virginica*) and form in shallow water (0.3 to 4 m [1 to 12 ft]) on firm mud and sandy mud bottoms. Their areal extent varies from a few meters to 6 to 7 km (3.7 to 4.3 mi) wide and they range from 1 to 3 m (3 to 10 ft) in thickness (Kolb and van Lopik 1966).

Bay-sound environments are found landward of barrier islands and are the coarser sands and silts of the delta which have been winnowed and redistributed by wave action. Nearshore Gulf environments are also erosional features in that they result from wave action and winnowing of sediments. These deposits are located seaward of the barrier islands and are indicative of a transgressing sea. Coarse materials remain from the available sediment.

Forms in the Estuary-Lagoon System

The Estuary-Lagoon System is within the State boundaries of Mississippi, with Alabama on the east and Louisiana on the west. The inland boundary is the 4-m (15-ft) contour; the seaward boundary is the barrier islands off the mainland. The topography of this system is either Pleistocene Terrace (alluvium and deltaic deposits) or Recent unconsolidated sediments. The Recent surface is of principal concern because of the wetland habitat. Otvos (1973a) divides the Estuary-Lagoon System into four units:

- Offshore barrier islands and inter-island shoals
- Mississippi Sound
- Major semi-closed embayments
- River estuaries

Offshore barrier islands and inter-island shoals. The barrier islands south of the Mississippi mainland are Cat, West and East Ship, Horn, and Petit Bois. Elongated and narrow in an east-west orientation, the islands are composed of well-sorted fine to medium sands. Water depth between the islands is less than 4 m (15 ft) except where inter-island passes scour slightly deeper channels. Shoals between the islands are well-sorted medium sands. Littoral drift is to the west, eroding the islands on the eastern tip and prograding on the western tip. Storm surge may destroy islands and shoals as Hurricane Camille did in 1969 when storm surge eroded the center of Ship Island, creating West and East Ship Island.

Mississippi Sound. Mississippi Sound is a long, narrow, shallow (5 to 10 m [16 to 33 ft]) body of water between the Mississippi mainland and the barrier islands. Muds from the river systems are deposited in the center of the Sound while sands are deposited in the shallower waters (Upshaw et al. 1966). Some fines are carried into the Sound by tidal currents. Oyster reefs form a significant part of the west portion of the Sound (Otvos 1973a).

Major semi-closed embayments. There are two bays in the Estuary-Lagoon System: Bay St. Louis and Back Bay of Biloxi. Bay St. Louis is the western of the two and is slowly being filled by sediment from the Jourdan and Wolf Rivers; most of the bay is mud (Hoskin 1971).

Back Bay of Biloxi is probably a drowned river valley (Christmas 1973). Marshes are found along the margins of and in the Bay. Two rivers, the Tchoutacabouffa and the Biloxi, are discharging sediment into the Bay; in addition, some sediment is being introduced into the system by tides. In general, fine-grained deposits dominate bottom sediments; however the composition varies greatly between locations.

River estuaries. The principal river estuaries in the Estuary-Lagoon System are the Pearl, Jourdan, Wolf, Biloxi, Tchoutacabouffa, and Pascagoula Rivers. The Pearl and Pascagoula Rivers are building deltas and are filling drowned river valleys which open directly into the Mississippi Sound (Christmas 1973). The Biloxi and Tchoutacabouffa Rivers are filling the bay system of Biloxi, also a drowned river valley. These rivers and deltas are unlike the Mississippi Delta because the source material is different, the chemical composition of the sediments is different, tides have a greater influence on sediment distribution because of the smaller volumes and less channel training works (such as levees, revetments, and jetties), and the deltas are building onto shallow bay bottoms or drowned river valleys.

Soils in the Mississippi Deltaic Plain Region

Soils in the Deltaic Plain are divided into two general soil areas: Mississippi River Alluvial Soils and the Coastal Marshlands (Lytle 1968). Representative series of the Mississippi River Alluvial Soils are the Commerce, Sharkey, and Mhoon soils (Lytle 1968). Forming the highest natural elevations in the Deltaic Plain, Commerce soils make up the natural levee ridges bordering the main channel and upper lengths of the distributaries and are silt loams and silty-clay loams that are fairly well drained. Sharkey soils are the backswamps of the interdistributary basins and are low and flat. These clayey soils have a noticeable organic content and are usually poorly drained. The Mhoon soils occupy a zone between the Commerce natural levees and the Sharkey backswamps and are level silt loams and silty-clay loams which have a moderate content of organic matter. Drainage characteristics vary with location.

Coastal Marshlands consist of the marsh peats, clays, and mucks of the low-lying coastal system. Organic matter and water content are high. Elevations of the areas are less than 2 m (6 ft) mean sea level, and therefore Coastal Marshlands range from being occasionally flooded by storm surge to daily covered by tides.

Soils of the Estuary-Lagoon System are the tidal marsh associations, the Vicksburg-Bibbs-Ochlockonee association, and the Eustis-Klej-Lakeland association (U.S. Soil Conservation Service [SCS] 1964). The tidal marshes fringe the Pleistocene uplands and are level wetlands. The soils are highly organic, overlay mineral soils, and are affected by brackish water (SCS 1964). The Vicksburg-Bibb-Ochlockonee association are loamy soils along stream bottoms and are subject to flooding. The Eustis-Klej-Lakeland association is a sandy and loamy soil of rolling topography. The soils are of low elevation and low relief and have good drainage characteristics.

Processes in the Mississippi Deltaic Plain Region

All of the physical forms of the Mississippi Deltaic Plain Region are the result of and are affected by external processes: water movement, surface motion, and man's actions. The relation of these processes to the Deltaic Plain and Estuary-Lagoon System is discussed below.

Water movement--Deltaic Plain. Alluvial processes, such as the entrainment of sediment and the transportation and deposition of detritus, are related to the annual flood regime of the River system. The hydraulic cycle of the Mississippi River shows a low stage during September and October and a rising discharge from November to April when maximum flood occurs. The thalweg, a line which connects the deepest points of the channel, migrates across the channel as discharge increases and decreases. During low water, the thalweg is normally close to the cutbank and maximum turbulence and velocity are toward the cutbank (Russell 1967). With rising water, the thalweg migrates toward the convex, or point bar, side of a meander; channel cross-sections are asymmetrical and deeper toward the outside. In the relatively straight sections of channels (called reaches) between bends, channel cross-sections are symmetrical and more shallow. Turbulence in the reaches is greatest toward the bottom of the channel and along both banks, while maximum velocity is in the center of the channel. Suspended load and bed load increase during flooding, as does the particle size being carried. During low stage, stream capacity and total quantity of suspended sediment decrease.

River migration as a result of bank failure occurs due to 1) undercutting of the bank by scouring in meanders, 2) oversteepening of the bank, and 3) sudden change in hydrostatic pressure from a falling river, falling groundwater levels or river turbulence (Kolb 1962b, Krinitzsky 1965, Coleman 1969). Failures usually occur during floods and during a rapidly falling river. A composite silt and clay bank fails more often than a homogeneous clay bank because of the erosional resistance of the clay.

Once a river discharges into a relatively quiet body of water, such as a gulf or lake, current velocity decreases rapidly. The coarsest-grained material in transport is deposited as mouth bar and subaqueous levee (Welder 1959); the finer silts and clays are carried farther from the mouth before settling as a result of gravitation or flocculation. The delta progrades on its own sediments. Small channels breach low levees and crevasse-splays; miniature deltas prograde into interdistributary basins (Arndorfer 1973). Levees are built vertically by deposition of material during annual floods, while the whole system slowly compacts and sinks into the underlying clays. Spits and barrier islands may form downdrift of the distributary mouth as distributary mouth bar sands are reworked.

Away from the source of detritus, marine processes become dominant, giving the delta a double identity: prograding at the distributary and transgressing at points away from the mouth. Principal processes include wave action (energy), tidal oscillation (rise and fall), longshore currents (regional and local), and related climatic phenomena (winds, hurricanes, and frontal passage). Wave energy along the coast is low and sediment is not reworked and redistributed rapidly. If the Gulf coast were a high energy system, there would be a great deal of turbulence: currents eroding and reworking sediment and winnowing bay bottoms to a smoother shoreline than the one represented by the birdsfoot delta.

Tides in the Deltaic Plain are primarily diurnal (having one high water and one low water daily) with a weak semi-diurnal component (two high waters and two low waters) (Kjerfve 1975). Although the tidal range in the Deltaic Plain is only 40 cm (16 in), it plays an important role in influencing sediment movement and water dispersal (Arndorfer 1973). Tidal ranges for most of the Louisiana coast vary from 5 cm to 61 cm (2 in to 24 in) (Stone et al. 1972). Tidal dynamics are also important in the shallow water systems along the Gulf coast (Kjerfve 1975). Tidal currents contribute to erosion of shorelines in the estuarine system (Stone et al. 1972).

Longshore currents redistribute sediment in the barrier island systems east and west of the active distributaries. Inlet positions shift as sediment is eroded from one end of an island and is deposited on the other end, a highly variable process as a result of storm surges. The tidal passes are the exchange points for water and sediment between the Gulf and the shallow interdistributary basins.

Finally, climate-related actions affect sediment distribution. Storm surges from hurricanes sometimes exceeding 4 m (13 ft) above mean sea level carry sediment into the fluvial marine environment from offshore. Barrier islands are breached and sediment is redistributed inland. Erosion is accelerated along shorelines of lakes and canals. Winds affect circulation patterns, water elevations, and wave action (Kjerfve 1975). Frontal passage affects water elevation and sediment distribution in the wetlands.

Water movement--Estuary-Lagoon System. In the Estuary-Lagoon System, marine processes dominate. The barrier islands which separate the Gulf of Mexico from the Mississippi Sound are migrating from east to west, being driven by waves and longshore currents. Tides along the coast have an average range of 0.49 m (1.6 ft) and are diurnal (Paulson et al. 1978). Tidal currents transport material through the tidal passes. Seaward of the tidal passes are shoals or ebb tidal deltas of well-sorted coarse sands (Kwon 1969, Otvos 1973b, Waller and Malbrough 1976). Within the sounds and bays, bottom sediments are reworked, redistributing the fines and leaving the coarser sediments. Hurricane storm surge is a catastrophic event in geomorphic processes: storm surge breaches the barrier islands, forms new tidal channels, and deposits washover fans on the sound side of the islands. Large quantities of sediment are entrained and moved from the beach offshore and downdrift.

Surface motion. Subsidence is the gradual lowering of the land surface relative to sea level. The rate of subsidence varies across the Mississippi Deltaic Plain Region. In the active delta, and throughout most of the Deltaic Plain, the rate exceeds 5 mm/yr (0.2 in/yr) (Holdahl and Morrison 1974). In the Estuary-Lagoon System, regional subsidence is very slight, less than 1 mm/yr (0.04 in/yr) (Holdahl and Morrison 1974). However, readings on the Biloxi tide gauge indicate a rising sea level of 244 mm/century (9.6 in/century) (Waller and Malbrough 1976).

Subsidence is related to the regional geology and the unique composition of the depositional environments. The Mississippi Deltaic Plain Region, in the north central Gulf of Mexico, is in a geologic area that is dominated by the Gulf coast geosyncline (a long, narrow trough filled with sediment). The axis of the geosyncline is seaward of the present shoreline; therefore the geologic formations under the Mississippi Deltaic Plain Region dip as a monocline toward the axis. Accumulating sediment for millions of years, the geosyncline has become a huge prism of clastic sediment derived from the north and northwest. The stratigraphy is a sequence of thick transgressive and regressive sections of Tertiary and Quaternary sediments deposited in off-lapping wedges.

The Gulf coast geosyncline is a huge, tectonically subsiding basin. Rapid, thick, deltaic deposition resulted in normal growth faults (faults in which the hanging wall has been depressed relative to the footwall [Howell 1960]) along the boundary between the sand and clay units and intrusion of salt stocks into the overlying sedimentary beds. Regional subsidence has a number of natural causes, including downwarping in the geosyncline because of sedimentary loading. At the same time, sediments compact and water is driven from interstitial spaces. Finally, a degree of subsidence may be caused by sediments rotating into the fault plane as a displacement occurs (Jones 1975).

Local subsidence may be caused by consolidation of recently-deposited sediments through compaction and water expulsion. The more massive distributary levees subside more rapidly than the interdistributary basin sediments (Morgan 1973).

Man's actions. The final independent process which contributes to shaping the geomorphic forms and other processes of the Deltaic Plain and the Estuary-Lagoon System is man's actions. Man has the ability to manipulate to some degree sediment, moving water, and surface motion, but at the same time he is limited by the availability of natural resources. Man's activities have the effect of compressing the geologic cycle in time and space and causing events to occur in areas where they normally would not occur. Selected examples illustrate man's effect on the Deltaic Plain and Estuary-Lagoon System.

Sediment load in streams is increased by accelerated soil erosion on cultivated fields. Artificial levees and spillways which prevent annual floods deny natural levees and interdistributary basins the sands, silts, and clays necessary for maintenance of elevation and topographic expression. Regional and local subsidence are no longer offset by aggradation and the landscape changes physical character, e.g., from a marsh to an open water body. Entrained sediment in the river system is transported to the Gulf and released offshore into deeper water, lost as a natural resource. Marshes and spoil banks contribute to sediment supply because they erode more rapidly due to increased wave activity and tidal flow. Sediment is transported to new areas via ship channels or is deposited as spoil banks or artificial beaches (e.g., on the Mississippi Gulf coast). These sediments are not in naturally occurring zones and will ultimately be reworked and redistributed into adjacent environments.

Man affects water movement and erosional and depositional processes by dredging canals in the wetlands or across open bodies of water, enlarging open bodies of water, channelizing by straightening and deepening meandering tidal channels, and installing structures such as groins or jetties which interrupt longshore currents. Wave action is increased as water bodies enlarge and currents increase as meandering channels are straightened.

Although affected by man's actions, surface motion of the Mississippi Deltaic Plain Region cannot be controlled at present. Oil and gas withdrawals have caused subsidence along the Gulf coast (Atherton et al. 1976). Groundwater withdrawal for irrigation and industrial use has caused subsidence in Louisiana (Smith and Kazmann 1978). Finally, leveeing and drainage of wetlands for agricultural and urban development has resulted in oxidization of peaty soil and subsidence (Earle 1975). Subsidence in turn affects water movement and sediment deposition.

ANALYSIS OF GEOMORPHIC KNOWLEDGE IN THE MISSISSIPPI DELTAIC PLAIN REGION

Three approaches have been used to analyze the available geomorphic knowledge of the Mississippi Deltaic Plain Region. The first approach involved a brief review of the evolution of knowledge concerning the region. Consideration of the geographic distribution of research projects throughout the region is a second approach, whereby the zones within the Mississippi Deltaic Plain Region which have not yet been adequately investigated may be determined. A third approach is an evaluation of the type and quality of data on sediment, moving water, surface motion, and man's actions in order to identify areas where research is needed. Based on the information gained from these approaches, it is possible to report on the gaps in knowledge and to make recommendations for future research. An analysis of the Deltaic Plain and the Estuary-Lagoon System based on the second and third approaches will follow.

Deltaic Plain

Areal distribution of research. Four zones have been intensely studied in the Deltaic Plain. The first of these (Figure 2-4), the Mississippi River, has been the laboratory for the U.S. Army Engineer Waterways Experiment Station (WES) since its founding in 1928. WES conducts applied research on the sediment load of the river (WES 1930, 1937, 1939, 1940; Keown et al. 1977; Robbins 1977), the flow characteristics of the water (WES 1950, Pierce and Elliott 1967, Woods et al. 1975), and the geology of the banks and adjacent levees (Kolb 1962a, 1962b; Stanley 1964; Krinitzsky 1965; Kolb 1975). All of these studies are applied research designed to prevent flooding and to maintain a navigation channel for ship and barge commerce on the River. Much factual information on the River system and interpretation of the processes responsible for and active in the channel are contained in these and other reports by the WES (Dale and Peck 1978).

A second zone which is under intense investigation is the Atchafalaya Basin and Delta. The U.S. Army Corps of Engineers (USACE), New Orleans District, is preparing a lengthy report in relation to an Environmental Impact Statement of a proposed water resource plan for the Atchafalaya Basin (Skinner et al. 1973). The USACE, New Orleans District, is also sponsoring research in the Delta (H. Roberts, Louisiana State University, Coastal Studies Institute, Baton Rouge, Louisiana 70803, personal communication, 1978). The WES has been active for years in the Atchafalaya Basin, especially regarding use of the Basin as a floodway (WES 1934, Fisk 1952) and maintenance of levees (Krinitzsky and Smith 1969, Krinitzsky and Lewis 1972). The U.S. Environmental Protection Agency (EPA), through its contractors, has been studying the Basin since 1973. Other works which contribute data on sediment, water movement, and man's impact in this zone include Thompson (1951, 1956); van Lopik (1955); SCS (1959); Coleman (1966); Shlemon (1972); Barrett (1975); Cratsley (1975); and van Beek et al. (1977).

The third zone of intensive research is the Active Mississippi Delta at the mouth of the main channel. Detailed studies have been carried out since the 1930s (Trowbridge 1930, Russell 1936, Shepard 1956, WES 1959, Fisk 1961). Coordinated efforts have been directed by the Coastal Studies Institute at Louisiana State University since its founding in 1953. Numerous reports on the forms and processes active in the delta have resulted from this work (Treadwell 1955; Welder 1959; Coleman et al. 1964; Morgan et al. 1963; Coleman and Gagliano 1964; Wright and Coleman 1971, 1975; Hart 1978; Hart and Murray 1978). Emphasis in the earlier studies was on the subaerial features--such as subdeltas, crevasses, and mudlumps--and the processes responsible for their formation. In the last ten years, research interests have shifted to the offshore slopes and current movements.

The final zone of concentrated research is the Barataria Basin (Figure 2-4). Data have been collected on sediment (Krumbein and Aberdeen 1937; Krumbein 1939; Caldwell 1940; Siegert 1961; SCS 1973, 1976, 1977, 1978) and water movement (Kjerfve 1975, Adams et al. 1976). The barrier islands which separate the Basin from the Gulf of Mexico have been studied by Kwon (1969), Conatser (1971), USACE (1972), and Whitehurst and Self (1974). Louisiana State University (Stone et al. 1972) has produced a baseline study for the Louisiana Offshore Oil Port south of Grand Isle. Detailed soil research has been conducted by Brannon and Patrick (1973) on the chemistry of wetland soils.

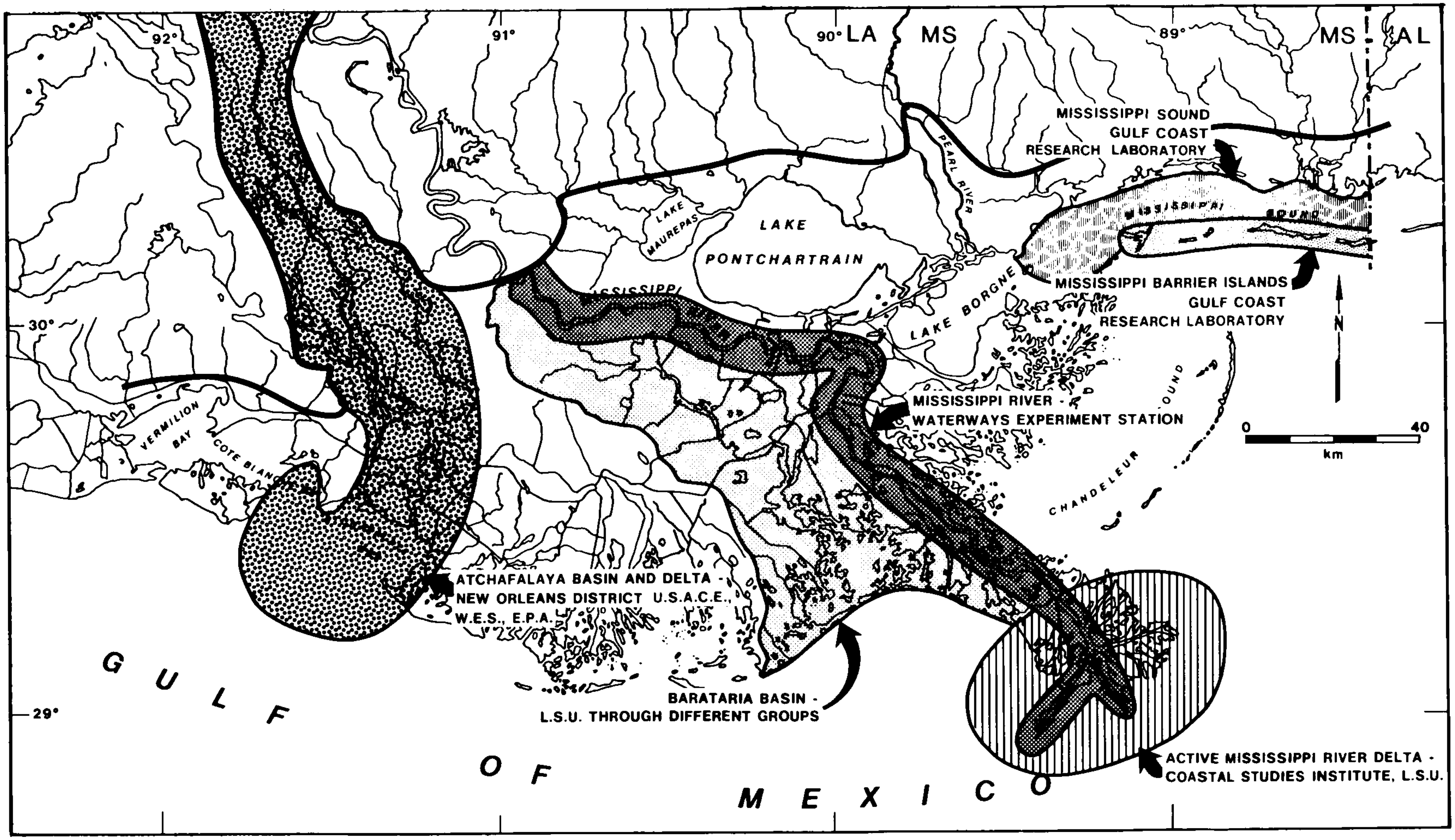

Figure 2-4. The six zones of concentrated research in the Mississippi Deltaic Plain Region.

Research in the Barataria Basin has been carried out primarily by a single organization, Louisiana State University. Whitehurst is presently associated with the Division of Engineering Research at Louisiana State University; Kjerfve was with Coastal Studies Institute at the time of his research, and Adams and Patrick are with the Louisiana Sea Grant Program.

Only the four zones (Mississippi River, Atchafalaya Basin and Delta, Active Mississippi Delta, and Barataria Basin) have been the subject of continuing research on the geomorphology of the Deltaic Plain. The other areas of the Deltaic Plain have been studied on a more regional scale. In the Maurepas-Pontchartrain Basin, Brooks and Ferrell (1970) and Ferrell and Brooks (1971) studied the distribution of clays; Saucier (1963) described the geomorphology of the Pontchartrain Basin; and the geology of the Deltaic Plain is described only at selected sites (Schultz and Kolb 1954; WES 1966; McAnear 1975; Kolb et al. 1975). To the southeast, the St. Bernard Delta-Chandeleur Island region was studied by Russell (1936), but only studies limited in scope have followed. Kolb and van Lopik (1958b) investigated the geology of the route of the Mississippi River-Gulf Outlet. Morgan and Treadwell (1954) examined the cemented sandstone slabs of the Chandeleur Islands, Hart (1978) described currents and energy dissipation in Chandeleur and Breton Sounds, and Briggs (1968) discussed sedimentation in Breton Sound.

To the west, between Bayou Lafourche and the East Guide Levee of the Atchafalaya Basin, descriptive studies are regional in nature and do not discuss the processes active in the area in detail (Kolb and van Lopik 1958a, Kolb 1962a, Fisk 1952, Saucier 1969). Finally, the zone between the West Guide Levee of the Atchafalaya Basin Floodway and the Bayou Teche has been studied in detail only in relation to USACE projects at Bayou Courtableau and the Vermilion River and in relation to SCS projects along Bayou Teche.

Geomorphic data. An analysis of the character of data collected on the four interrelated components of the geomorphic system (sediment, water movement, surface motion, and man's actions) reveals that most data thus far have related to sediment: its type (whether sand, silt, clay, organic, chemical, or a combination of all), composition (quartz, feldspar, kaolinite, carbonate), origin (detritus or in situ), and distribution and form across the Deltaic Plain. There is a marked scarcity of knowledge about the Deltaic Plain regarding the remaining three components of the geomorphic system--water movement relative to sedimentation, man's inpact on the environment, and surface motion of the region.

Most studies of sedimentation have concentrated on the Mississippi River and Atchafalaya Basin because of their socio-economic importance. The first studies were reports of observations accompanied by some measurement of grain size and topographic features (Russell 1936). The next series of studies were regional surveys of sediments compiled from data derived from old maps, air photos, borings, and field surveys (Fisk and McFarlan 1955, Kolb and van Lopik 1958a, Welder 1959, Kolb 1962a, and Shlemon 1972). Generalizations were made about water movement as interpreted from the geomorphic form. It is in the more recent studies that specific information on the hydrodynamic character of an area could be interpreted by examination of the primary sedimentary structures (Moore and Scruton 1957, Coleman and Gagliano 1965, Coleman 1966, Davis 1966). Studies on erosion of the physical system give estimates of rates of deterioration of coastal features (Morgan 1955, Gagliano et al. 1970, USACE

1972, Harper 1977, Morgan 1977). Rates of erosion in the study area are being established through a Habitat Mapping Project (K. Wicker, Coastal Environments, Inc., Baton Rouge, Louisiana 70802, personal communication, 1979).

There is less known about man and his impact on the deltaic system than there is about water movement and sedimentation. Davis (1973) and Gagliano (1972) have discussed the effects of canals on the environment; Wintz et al. (1970) and Kazman and Heath (1968) have described subsidence resulting from the withdrawal of groundwater in the Baton Rouge and New Orleans areas. Fisk (1943) investigated the relationship between petroleum extraction and fault displacement in the Vacherie community. Okey (1914, 1918), Harrison (1961), Earle (1975), and the SCS (1977, 1978) determined the subsidence resulting from impounding and draining a wetland environment. Environmental assessments and statements describe the expected primary and secondary adverse and beneficial impacts of proposed actions on the environment. Selected statements contain valuable basic data on the geology, soil, and geomorphology of the area (Gulf States Utilities 1974) and man's modification of surface features.

Of the four components of the Deltaic Plain, surface motion is the least known and the least studied. The Deltaic Plain is located over the northern edge of the Gulf coast geosyncline, a long narrow trough filled with Cenozoic deposits (Hardin 1962, Bernard and LeBlanc 1965, Antoine et al. 1974). The geosyncline is a huge, tectonically subsiding basin which has been active since Mesozoic times. Natural subsidence varies greatly from one area to the next because of faults and lithologic changes. Kolb and van Lopik (1958a) and Holdahl and Morrison (1974) show subsidence rates for specific sites in the Deltaic Plain, but detailed information is not available for most locations within this region.

In summary, the gross composition of the system and the basic processes that are affecting the system are known. The Deltaic Plain is composed of organic and inorganic sediments arranged in a systematic sequence. Water movement is the connecting medium among the geomorphic units and in turn is affected by the landscape. Man works to modify the landscape and to a degree can manipulate aggradation, degradation, water movement, and, as a result, subsidence. Regional tectonic stability is beyond man's control but is probably influenced by sediment diversion and river training.

Conclusions. A number of conclusions may be drawn from the evaluation of geomorphic knowledge in the Deltaic Plain:

1) Research is utilizing more sophisticated techniques for describing and analyzing the forms and processes in the Deltaic Plain. Where once a report described a region and observation was the principal source of data, now atomic absorption spectrophotometry, x-ray diffraction, radiographs, and color infrared photographs supplement observation and gross measurements.

2) Models are being programmed to project forms and processes in selected areas and to estimate the impacts of changes in the system.

3) Research is concentrating on more detailed elements of the system, measurements are becoming more precise, study areas are decreasing in size, and costs are increasing.

4) Four zones in the Deltaic Plain have been the subject of most of the research thus far undertaken. The other zones have received merely an overview and general treatment.

5) There are areas within the intensely studied zones in which forms and processes have not been investigated.

6) Studies along the Mississippi River and in the Atchafalaya Basin are, for the most part, applied research conducted by the WES in Vicksburg, Mississippi. These studies concern flood control and navigation on the River.

7) Studies in the active delta have been carried out largely by Louisiana State University, Coastal Studies Institute. Initial studies were on subaerial forms; however, currently the emphasis is offshore.

8) Barataria Basin, the barrier islands, and Atchafalaya Bay have been investigated by researchers from numerous organizations such as universities and private industry. Research has been both applied and basic.

9) State agencies, except for occasional reports published by the Wildlife and Fisheries Commission, no longer conduct applied or basic research in the Deltaic Plain.

10) Local and regional agencies are not active in geologic, geomorphic, or soils research.

11) The sedimentological framework of the deltaic system is known, but knowledge about specific sites or areas is generally lacking outside the vicinity of the present Mississippi meander belt.

12) Sedimentary maps exist for some of the bays and lakes near the shoreline, but many of the interior lakes have not been studied.

13) Water movement and sedimentary processes have been studied in the active delta and along the barrier islands, but processes of erosion and deposition have not been investigated in any detail in the interior of the estuarine basins.

14) Man's impact on the geomorphic element is documented, however detailed studies are, for the most part, non-existent.

15) Groundwater and petroleum extraction are known to cause subsidence, but extensive research has not been conducted in this area.

16) Regional subsidence is recorded, but data on specific sites are not available.

17) Except for the Mississippi River and the Atchafalaya Basin, research is concentrated along the shoreline, leaving a void of ongoing or recent research in the interior of the Deltaic Plain.

Estuary-Lagoon System

Areal distribution of research--geomorphic data. The evolution of geomorphic knowledge of the Estuary-Lagoon System is considerably different from that of the Mississippi Delta. Research in the Estuary-Lagoon System was negligible until the late 1940s. A few general geology reports on southern Mississippi (Lowe 1915, 1925; Stephenson et al. 1928; Brown et al. 1944) describe the Estuary-Lagoon System, but do not examine it in detail. With the formation of the Gulf Coast Research Laboratory in the late 1940s, geology received immediate attention. Basic research in sediments and sediment chemistry is the thrust of their geology program (Otvos 1973b).

An updated regional geology of southern Mississippi was not prepared until 1973 (Otvos 1973b). An environmental geologic atlas is currently in press (Gazzier et al. 1977). Detailed studies are concentrated on the Mississippi Sound and the barrier islands which separate the Sound from the Gulf (see Figure 2-4). Sediment composition and distribution in the Mississippi Sound are described by Priddy (1954), Priddy et al. (1954), Priddy and Crisler (1955), Foxworth and Ellis (1960), and Upshaw et al. (1966).

Sediments and geology of Bay St. Louis were studied by Hoskin (1972), while Biloxi Bay was studied by Barton (1952), Robbins (1961), Snowden (1961), and Hoskin (1972). Foxworth (1958) and Foxworth et al. (1962) investigated the heavy minerals in beaches and islands along the coast.

Otvos (1970, 1973a, 1976), Waller and Malbrough (1976), and Shabica et al. (1978) discussed the composition, development, and migration of the barrier islands. Priddy and Smith (1960) described recent sedimentation on Horn Island, while Holladay et al. (1957) described the shifting of the Marsh Point Sand Spit. Zones of shoreline erosion are shown by the USACE (1971). The Pearl River is described by the USACE, Mobile District (1970). Snowden and Forsthoff (1976) discussed clay sedimentation in the Pearl River Delta. The Pascagoula River Delta is described by the USACE, Mobile District (1968).

X-ray diffraction, atomic absorption spectrometers, aerial photographs, and other sophisticated techniques have been used by scientists in analyzing the Estuary-Lagoon System. Subsidence for the area was established by Holdahl and Morrison (1974). Keady et al. (1973) showed that there is no subsidence due to groundwater withdrawal. The USACE, Mobile District (1978) is studying the effects of dredging on the morphology of the Sound and the barrier islands.

In summary, the composition of the Mississippi Sound and the barrier islands is known. The principal processes dominating the system are longshore currents causing the barrier islands to migrate from east to west, tidal action scouring the tidal passes and redistributing sediment in the Sound and offshore, currents eroding the artificial beaches and spoil banks, and hurricane-generated currents. Man has an impact on the system by dredging and maintaining navigation channels and artificial beaches. Finally, subsidence is relatively insignificant throughout the Estuary-Lagoon System and is not the problem it is in the Mississippi River Deltaic Plain.

Conclusions. A number of conclusions can be arrived at concerning the knowledge of geomorphology of the Estuary-Lagoon System:

1) The area is not a center for concentrated research as is the Deltaic Plain, probably due to the greater economic inportance of the Mississippi River and Alluvial Valley.

2) Research did not begin with any intensity in this area until the late 1940s following the founding of the Gulf Coast Research Laboratory at Ocean Springs, Mississippi. Research is directed toward the Mississippi Sound, the connected bays, and the barrier islands.

3) Initial studies were limited in space and effort. The emphasis was on the physical and chemical characteristics of the sediment.

4) Sophisticated methods such as atomic absorption spectrophotometry, x-ray defraction, and aerial photography are being used to examine and collect data.

5) The deltas filling drowned valleys of the Pearl River and the Pascagoula River have not been studied as intensively as have the Sound and barrier islands.

6) There are areas within the intensely studied zones which have not been investigated and there may be little or no information at specific locations.

7) The USACE, Mobile District, is studying the impacts of their dredging projects on sedimentation and erosion in the coastal zone.

8) Detailed studies of specific areas and processes, such as quantitative measurements of sediment transport on and in the vicinity of the barrier islands, have not yet been carried out.

GAPS IN KNOWLEDGE

A number of gaps in the existing knowledge of forms and processes have become apparent from the review of the existing literature, both published and unpublished. In the Deltaic Plain, physical and chemical sediment and soils data must be collected on the Maurepas-Pontchartrain-St. Bernard, the Verret-Terrebonne, and the Bayou Teche regions. Quantitative data on water movement and sediment characteristics in canals, bayous, lakes, tidal deltas, barrier islands, and wetlands must be collected for the entire Deltaic Plain with the exception of the main channel of the Mississippi River. The chemical and physical processes active in the basins must be studied so that impacts may be projected. Man's impact on the system must be assessed, especially with regard to the potential and probable subsidence resulting from petroleum extraction.

In the Estuary-Lagoon System, data on the forms and processes active in the river deltas are almost non-existent. Quantitative information on processes in specific areas of the Estuary-Lagoon System is not available. Man's impact on the rivers and estuaries has not yet been quantified.

RECOMMENDATIONS

The following are recommendations for research in the Mississippi Deltaic Plain Region:

1) Priorities must be set for geomorphic research in the Mississippi Deltaic Plain Region. Restoration of the wetlands should have priority over other research at this time. Critical areas must be identified from physical, biological, and cultural perspectives and then ranked to establish priorities for wetland restoration. Such studies may be achieved by integrating existing data with interpretation of color infrared photographs and fieldwork.

2) A basic research program must continue on the Atchafalaya Delta to provide information about the natural processes of delta formation. The information from this natural laboratory system may be applied to other controlled diversions in the future.

3) The Pearl and Pascagoula River deltas should also be studied in order to determine the natural processes of delta building. Such information may also be applied to eventual river training.

4) Additional basic data is needed in order to estimate impacts from proposed projects, such as highways, levees, and sewerage systems. A system of recording stations should be established across the Deltaic Plain and Estuary-Lagoon System to monitor physical and chemical processess. Because of the nature of this type of data collection, a university or laboratory facility in each state might be designated as the lead agency responsible for coordinating basic geomorphic research; for example, Coastal Studies Institute at Louisiana State University and Gulf Coast Research Laboratory at Ocean Springs in Mississippi.

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CHAPTER III: HYDROLOGY

Johannes L. van Beek

INTRODUCTION

Not even the casual observer can escape the conclusion that hydrologic processes play a major role in determining ecological characteristics of the Mississippi Deltaic Plain Region. Plant and animal populations change in character as one moves from fresh to saltwater or from short to long hydroperiods. Sediment and substrate characteristics change along energy gradients of water movement, and aquatic habitat may be succeeded by wetland and terrestrial environments, or vise versa, in response to changes in flow patterns and sediment introduction.

When considered in this manner, hydrology emerges as a determinant and modifier of environmental characteristics by means of water movement and water levels and physical and chemical characteristics of the water. However, the hydrologic regime must be seen as a functional part of the ecosystem, linking geologic, riverine, marine, atmospheric, and socioeconomic forces as well as those forces with the biotic and abiotic forms of that system.

Consideration of hydrology as a linking mechanism among various components of the environment is not a new concept. It dates back to at least the fifteenth century version of the hydrologic cycle as suggested by Leonardo da Vinci. Hydrology as a science deals with all aspects of water on the earth, and many of its concepts were developed separately in various disciplines.

Little quantitative work was done in hydrology until the 1930s, when expanding needs for flood control, drainage, water supply, etc, required accurate predictions of channel flows and runoff. These needs emphasized the necessity for understanding interrelationships among atmospheric processes, ground water, and stream flow; between characteristics of stream flow and channel morphology; and between basin morphology and surface runoff. Increased understanding of hydrology was further made possible because systematic stream flow and precipitation measurements by Federal agencies had been underway since the 1880s, providing some of the long-term records required for accurate determination of the interrelationships.

Advances in measurement technology and concerns with shoreline erosion, harbor shoaling, and other adverse coastal phenomena instigated similar progress in estuarine and nearshore hydrodynamics in the 1950s. These studies were concerned with physical processes, linking marine, riverine, atmospheric, and geological driving forces and related physical forms.

For many years interest in hydrology concerned basic water quality parameters such as turbidity, oxygen, temperature, and salinity as habitat descriptors. With growing environmental concern in the 1960s, programs were initiated and legislation directed at resource management, and a holistic approach was taken in the field of ecology. The need to accurately predict the effects on the ecosystem resulting from man-induced changes, in driving forces, the realization of the importance of hydrodynamics in nutrient cycling, primary productivity, and species diversity, and the need to define desired hydrologic conditions for the management of natural resources all contributed to a rising interest in hydrology as it relates to biological systems.

The objective of this paper is to evaluate the extent of present knowledge of hydrology in the Mississippi Deltaic Plain Region. The discussion will be confined primarily to two areas: the first area is that of hydrologic processes, and deals with the relationship between the driving forces and the hydrologic regime; the second area concerns the major hydrologic components of the ecosystem and associated structural and functional characteristics. An attempt has been made to relate this review to hydrologic functions, as a basis for identification of areas in which data are lacking and for recommendations for further investigation.

DRIVING FORCES AND THE HYDROLOGIC REGIME

The hydrologic regime of the Mississippi Deltaic Plain Region is established through interaction among the driving forces and between those forces and the physical and biogenic forms of the system. On a day-to-day and seasonal basis, these driving forces are the riverine, atmospheric, and marine processes and, to some extent, socioeconomic processes such as waste discharges and seasonal management operations. Socioeconomic processes such as flood control become more important when the time scale is enlarged. The same is true for the geologic processes as a driving force.

RIVERINE PROCESSES

The term "riverine processes" refers collectively to the inflow of fresh water across the northern Mississippi Deltaic Plain Region boundary. Major characteristics that affect functioning of this inflow as a driving force are: location of inflow, inflow rate, water level, temperature, chemical load, and sediment load. Inflow of fresh surface water for the Region as a whole is dominated by the Mississippi River and its distributary, the Atchafalaya River. With a combined average discharge rate of 170,000 m^3/s (6,002,700 cfs), these streams account for more than 90% of freshwater inflow (U.S. Army Corps of Engineers [USACE] annual data). This figure is misleading because of present limitations on the distribution of this water and associated materials through the Region.

Mississippi River water remains confined within the channel until it reaches the active delta. Its direct contribution to the Region, except for minor diversions and operations of the Bonnet Carré Spillway, is limited to the delta and adjacent nearshore waters. Only after mixing with saline waters of the Gulf of Mexico does Mississippi River water enter adjacent estuarine systems as a result of nearshore circulation and tidal exchange. This indirect input of Mississippi River water has the largest influence on the Barataria estuary and to a lesser extent influences the Timbalier estuary because of a predominant westward drift in coastal waters. Further westward, indirect effects of Mississippi River discharge become more difficult to evaluate because of the increasing influence of Atchafalaya River discharge and an easterly nearshore drift during summer months (Kimsey and Temple 1962, Oetking 1974).

Inflow of Atchafalaya River water is subject to a similar, but lesser, limitation. Following initial confinement between levees, the river is allowed to overflow its banks and adjacent wetlands within the Atchafalaya Basin Floodway which occupies approximately one-third of the Atchafalaya Basin. Limitations on the effects of flow and storage are entirely removed below Morgan City, Louisiana, where river waters disperse into adjacent bays and water exchange occurs with the wetland systems of the Vermilion and Timbalier hydrologic units. Thus, contribution of river water to these units is both directly through inflow and indirectly after mixing of Atchafalaya River waters with nearshore Gulf waters.

Hydrologic characteristics of both the Mississippi and Atchafalaya Rivers are well understood. Daily stage, discharge, suspended sediment, and temperature values are available at the point of inflow into the Mississippi Deltaic Plain Region, as are monthly measurements of water quality for a large number of chemical parameters (in U.S. Geological Survey [USGS] annual water data reports for Louisiana [a] and Mississippi [b], and in USACE annual stages and discharges reports).

Because of the limitations of the distribution of Mississippi River and Atchafalaya River waters, additional inflow of fresh water into the Mississippi Deltaic Plain Region, even though accounting for less than 10% of the total input (Gagliano et al. 1972), is very important. Unfortunately, this inflow is not as well documented as that of the Atchafalaya and Mississippi Rivers, and ranges from significant streams such as the Pearl and Pascagoula Rivers, with average discharges on the order of 300 to 400 m^3/s (10,590 to 14,120 cfs), to unconfined runoff from adjacent uplands. Discharge, stage, and water quality measurements are available for all streams with average discharges greater than several m^3/s (in USGS annual water data reports a, b; in USACE annual stages and discharges reports). Suspended sediment load measurements are limited to a few of the larger streams, such as the Pearl and Pascagoula Rivers.

Summaries of certain hydrologic characteristics are available for some streams. These include: drainage areas (Sloss 1971), stream temperatures (Calandro 1967), and magnitude and frequency of floods for Louisiana streams (Neely 1976); frequency of floods (Wilson and Trotter 1961), average discharges (Christmas and Eleuterius 1973), and low flow characteristics (Speer et al. 1964) for streams in Mississippi; discharge rates, velocities, and stage hydrographs for the Mississippi River (USACE 1968); and hydrologic characteristics and water quality conditions of the Mississippi (Everett 1971) and Atchafalaya Rivers (Wells and Demas 1977).

While these records provide for an accurate measurement of many individual surface water inflows, they do not allow accurate total assessment of inflowing water and materials into the Mississippi Deltaic Plain Region as a whole or on a hydrologic unit basis. This is because all discharges, with the exception of the Atchafalaya and Mississippi Rivers, are gauged a considerable distance above the Mississippi Deltaic Plain Region boundary, and therefore the records do not account for inflow of water and materials below the gauging point. Also not accounted for are surface drainage through unconfined runoff, drainage canals, and streams of less than several m^3/s average discharge.

Riverine processes have been considered only on a limited basis as a driving force for hydrologic conditions in the Mississippi Deltaic Plain Region. Gagliano et al. (1970a) determined statistical relationships between freshwater input and salinity fluctuation on a hydrologic unit basis within the Louisiana segment of the Region. This analysis indicated that between 50% and 70% of monthly salinity variation resulted from differences in yield of fresh surface water available from inflowing streams and ungauged runoff and from precipitation surplus generated within each unit. The relative importance of riverine and atmospheric processes as driving forces for the salinity regime was determined through multiple regression analysis and successive deletion of variables of least significance.

Despite its importance to the Mississippi Deltaic Plain Region, the effect of Mississippi River discharge on hydrologic conditions remains poorly known other than at the mouth of the River. Except for hydrodynamic studies concerning interaction between effluent river waters and ambient Gulf waters (Wright and Coleman 1971) at the Mississippi River mouth, information about relationships between Mississippi River hydrologic regime and nearshore conditions in the Region is sparse. Collections of hydrologic and hydrographic data in nearshore waters, other than for parameters such as salinity and temperature, have been of too short duration or too low frequency to fully evaluate the effects of temporal variation in Mississippi River discharge.

Atchafalaya River discharges and stages have been analyzed as forcing factors with regard to depth, duration, and extent of flooding within the Atchafalaya River Basin (van Beek et al. 1977a, 1978). In this same area, several studies have dealt with the effect of river flow on water quality (Lantz 1974; Bryan et al. 1974, 1975, 1976; Wells and Demas 1977; Hern and Butch 1979) and productivity and related energy export as measured by organic carbon (Hern and Lambou 1978).

In summary, it can be stated that information available with regard to riverine processes as a driving force of the Mississippi Deltaic Plain Region's hydrologic regime is confined largely to measurement of the inflow of fresh water and associated materials through the larger streams. Attempts to summarize this inflow information have been limited. Understanding the relationship between these driving forces and the hydrologic regime of the Mississippi Deltaic Plain Region as a whole is almost entirely qualitative except for salinity data from the Louisiana coastal zone. Information from individual hydrologic units receiving riverine inflow is largely qualitative also. However, many unit-specific studies contain inferences about the effects of riverine input at the time of study (i.e., Ho and Barrett 1975, Eleuterius 1979) which, when analyzed and integrated, may yield a more complete picture.

ATMOSPHERIC PROCESSES

Atmospheric processes are a major driving force of the hydrologic regime. The most important elements are wind, precipitation, and insolation. For information concerning present knowledge of these parameters in the Mississippi Deltaic Plain Region, the reader is referred to the accompanying paper dealing with meteorology and climatology. The following paragraphs will deal primarily with the relationships between atmospheric processes and the hydrologic regime.

Responses of the hydrologic regime to atmospheric processes are in the form of changes in water level, water movement, and water temperature, with resultant secondary changes in water quality. On a regional scale, evaluation of relationships between atmospheric processes and the hydrologic regime is limited to water level and salinity. Wax (1977) showed that in the Louisiana coastal zone, synoptic weather types characterized by frontal passage and veering winds from northerly to southerly or easterly are the meteorologic events that cause the sharpest and most consistent rise or fall in estuarine water levels. Occurrence of precipitation surplus was found to be much less effective in causing water level change than was wind. The magnitude of the response was found to decrease with distance from the coast and open waters. Salinity responses to precipitation surplus and runoff were measured by Gagliano et al. (1970a) for the Louisiana portion of the Mississippi Deltaic Plain Region (see "Riverine Processes").

A number of studies have been carried out in individual hydrologic units in which atmospheric effects were considered but not evaluated. These studies were directed toward an understanding of estuarine circulation dynamics. The importance of wind stress as a driving force for estuarine circulation of Barataria Bay is discussed by Hacker (1973), Kjerfve (1975), and Banas (1978). Kjerfve showed that wind stress accounted for less than 50% of the time-averaged slope of the water surface and only modified the direction of the tide-induced surface slope.

Circulation in Lake Pontchartrain was analyzed for varying wind conditions by Stone et al. (1972) through use of aerial photography. While limited to direction of surface water movement, these data suggest a predominant response to wind direction and speed rather than to tidal and riverine forces. Hart (1976) and Hart and Murray (1978) analyzed the effect of wind stress on tidally forced circulation for Chandeleur-Breton Sound, through numerical modeling, and found that northerly winds produced a significant increase in net flow through the Sound but only minor effects on circulation patterns.

Information concerning the effect of precipitation in forcing flow through wetlands is sparse. A single, preliminary, modeling study has been carried out in the upper Barataria Basin above Lac des Allemands (Light et al. 1973). This study evaluated short-term stage (3 months), discharge, and storage characteristics of flow arising from local rainfall. Byrne et al. (1976) studied the effect of synoptic weather types and associated precipitation and wind conditions on salinities and water levels in Barataria Basin, while Wax et al. (1978) analyzed those relationships for the Vermilion area.

The majority of work involving the effects of atmospheric processes on nearshore circulation has focused on deeper offshore waters adjacent to and west of the Mississippi River Delta. This lack of information for the nearshore area results partly from the difficulty of eliminating variability due to discharges of fresher water from the Mississippi River and major estuaries. Present knowledge in the study area appears limited to isolated observations confirming the importance of wind in driving nearshore circulation (Harper 1974, Murray 1975, Wiseman et al. 1975). A number of qualitative studies comparing patterns of turbid riverine outflow of the Mississippi River to weather conditions (Rouse and Coleman 1975) also emphasize wind-driven circulation.

MARINE PROCESSES

In the context of this paper, marine processes as a driving force include the areawide input of energy and materials into the nearshore waters of the Mississippi Deltaic Plain Region from the Gulf of Mexico. The marine elements that affect hydrologic conditions of the Region are tidal variation, circulation, wave regime, and physical and chemical characteristics of water exchanged between the open Gulf and the nearshore waters.

Oceanographic characteristics of the Gulf of Mexico have been the subject of many studies since the 1900s. On a macro-scale, these studies have resulted in a general definition of surface circulation and seasonal variations of salinity and temperature and, in some cases, of vertical structure. For the Mississippi Deltaic Plain Region east of the Mississippi Delta, these conditions are summarized by Drennen (1963), Ichiye et al. (1973), and Eleuterius (1974). Circulation, salinity, and temperature characteristics over the nearshore continental shelf west of the Mississippi River were defined in studies by Wiseman et al. (1975) in the area south of Barataria Bay, and by Oetking et al. (1974) in the shelf waters off the eastern part of the Region. Of particular interest in evaluating the mechanisms involved in exchange of nearshore Region waters and offshore Gulf waters are the detailed studies in the Barataria bight (Wiseman et al. 1975, Murray and Wiseman 1976) and immediately east of the Mississippi Delta (Murray 1975).

A number of studies (including those mentioned above) deal with salinity and temperature characteristics of inner shelf waters, for the area west of the Mississippi Delta. A few longer-term records provide a general picture of seasonal and spatial variation (Allen et al. 1977, Huh et al. 1977, Barrett et al. 1978, Thompson and Leming 1978) and show the importance of frontal movement with regard to the seasonal cycle of water temperature for the coastal and deeper waters.

The tidal regime of the Mississippi Deltaic Plain Region also remains poorly known despite its importance and the fact that tides are probably the best-characterized element of marine forces, beginning with Marmer's (1954) summary of tides and water levels in the Gulf of Mexico. Basic to the evaluation of tidal influences are the daily predictions of the National Oceanic and Atmospheric Administration (NOAA) which provide expected time and level of high and low water at many locations along the Region's coastline. These data have been utilized for the construction of co-phase lines (Wiseman et al. 1975); for numerical modeling of tide-induced circulation in Barataria Bay (Kjerfve 1973), Chandeleur-Breton Sound (Hart 1976), and Atchafalaya-Cote

Blanche Bay (van Beek et al. 1977a); and for the delineation of the tidal current regime of Mississippi Sound (Eleuterius 1976a).

While numerical modeling of tidal currents is a basic step toward delineating actual circulation, shortcomings of this technique have been pointed out by Wiseman et al. (1975). Major deviations from predicted currents occur as a result of the perturbation induced by density gradients related to freshwater discharge and by wind stress.

Tidal influences in the form of water level changes and effects on water movement extend well into each of the hydrologic units. While daily water level records are available from USACE gauging stations (in USACE annual reports on stages and discharges) throughout the coastal zone, the extent to which tidal variation contributes to short- and long-term water level variation has been investigated in detail only for the Barataria estuary (Byrne et al. 1976).

One of the least-studied marine forces with regard to its effect on Mississippi Deltaic Plain Region hydrologic processes is wave action. Presently available information pertains to offshore wave characteristics, except for daily visual observations of surf conditions made by the U.S. Coast Guard at Grand Isle, Louisiana. Despite the fact that wave-induced longshore currents play an important role in the littoral transport of sediments and the sand balance of the barrier island system, no systematic studies of these currents have been undertaken. Observations are limited to incidental observations such as those at Petit Bois Island (U.S. National Park Service, National Space Technology Laboratory [NSTL] Mississippi, personal communication 1979) and in the Barataria area (Wiseman et al. 1975). Minimal information is available about the distribution of wave energy along the Mississippi Deltaic Plain Region coast (Becker 1973).

SOCIOECONOMIC PROCESSES

The occupation of the Mississippi Deltaic Plain Region by man has resulted in substantial modification of the use and morphology of the Region and of the balance of materials--including sediments, nutrients, and toxins--within the Region's waters. Because of the direct effect of morphologic changes on water levels and water movement, and of the materials balance on water quality, socioeconomic processes such as flood control, dredging and filling, water level management, and waste discharge must be viewed as major driving forces of the hydrologic regime. Present information concerning these socioeconomic processes is limited, consisting mainly of input information; i.e., many of the activities are documented but their effects on the hydrologic regime are not. In many cases, functional relationships remain unknown other than in qualitative terms, or the opposite is true, in that environmental changes are documented but causes of change can only be ascertained in general terms.

Morphologic changes as a result of socioeconomic processes have been documented by maps, aerial photographs, and actual measurements (Gagliano and van Beek 1970, Gagliano et al. 1973). Estimates as to direct effects on the hydrologic regime have, for the most part, remained speculative. Notable exceptions are a comparison of man-made and natural channel flushing characteristics along the Bay of St. Louis, Mississippi (Paulson and Pessoney 1975);

an attempt to evaluate, through numerical modeling, flow changes in a brackish marsh under a variety of dredge and fill conditions (Stone and McHugh 1977); and a comparison between freshwater swamps that are subject to and severed from riverine overflow, respectively (van Beek et al. 1978, Hern and Lambou 1978).

In a limited number of cases effects on water quality directly related to flood control and dredge and fill operations in the Region have been monitored and resultant conditions reported (Mackin 1971, USACE 1977) or baseline conditions established for future monitoring (Paulson et al. 1978). Stone et al. (1978) estimated release of nutrients into adjacent waters as a result of canal dredging through a marsh environment.

Effects of canal and waterway dredging on salinity remain poorly documented in terms of absolute contribution of dredging activity to salinity changes. Various cases can be identified where salinities showed a major increase (Gagliano et al. 1970c) following project implementation, such as the Mississippi River-Gulf Outlet, but in most cases effects have been cumulative and definitive evaluations have not been made.

As a socioeconomic process, input of materials into Mississippi Deltaic Plain Region waters is known, in part, because of required permits from State and Federal agencies for industrial and sewage discharge. For confined streams such as the Mississippi and Atchafalaya Rivers, input can be further determined by means of comparison of upstream and downstream sampling stations (Everett 1971, Wells and Demas 1977). Studies of this type have been carried out on major streams that serve as a domestic or industrial water supply or have shown dramatic increase in waste loads, as in the case of the Pearl River (Everett et al. 1973).

The quantity of sediments, nutrients, and toxins from economic processes having nonpoint-source discharges, such as agricultural and urban development, remains unknown in the study area. While general estimates can be made on the basis of studies of national scope (Omernik 1977), this topic has been little studied within the Mississippi Deltaic Plain Region (Cook 1971, Craig and Day 1976, Dunigan et al. 1976, U.S. Soil Conservation Service [SCS] 1977).

Management, as a socioeconomic process which affects the hydrologic regime, encompasses a variety of structural and nonstructural measures. While nonstructural measures, such as coastal zone management legislation and permit requirements, function primarily as regulators of modification, the structural measures, such as weirs, have a direct effect on the hydrologic regime. The construction of weirs to manage waterfowl habitat and provide access for hunters and trappers has been widespread. The effect of weirs upon water levels, salinity, and turbidity conditions has been the subject of detailed investigation (Herke 1971, Chabreck et al. 1978), yet little is known about the cumulative effects of the weirs. These effects include a decrease in tidal prism which in turn influences the magnitude of water exchange and current velocities.

A second, more recent, structural measure has been the implementation of a number of small-scale diversions of Mississippi River waters into wetlands below New Orleans. While some data are available (Louisiana Department of Wildlife and Fisheries, Louisiana Department of Health and Human Resources) concerning water quality prior to and after diversion, no in-depth evaluations have been made of the hydrologic effects.

GEOLOGIC PROCESSES

The geologic processes considered as long-term forces in changing the hydrologic regime are subsidence and compaction of substrate sediments. In the absence of counteractive sedimentation, the lowering of the substrate results in enlargement of water bodies. The gradual increases in water depth and water surface have secondary effects upon tide-induced water exchange between estuaries and nearshore waters and the development of wind waves. The associated intensification of erosional processes involving currents and waves may then act to further increase areal size of the water bodies. Simultaneously, these changes modify water quality characteristics, especially salinity.

Geologic processes have been qualitatively identified as major causes for modification of the deltaic environment, with emphasis on morphologic change, i.e., delta growth and land loss (Gagliano and van Beek 1970).

HYDROLOGIC ENVIRONMENTS AND INTERACTIONS

Mississippi Deltaic Plain Region waters may be divided into four components, or subsystems, that interact in various ways depending on subsystem morphology and internal hydrologic characteristics. These four subsystems are: 1) the rivers providing temporary storage of water introduced into the Region by riverine processes; 2) the upland, or nonwetland, areas providing temporary storage for local runoff, overflow from rivers, and overflow from adjacent wetlands due to tidal or wind forces; 3) the lower basin, or wetland areas, subject to inflow from adjacent uplands, from rivers directly or via adjacent uplands, and from nearshore Gulf waters; and 4) the nearshore Gulf area which provides storage for water introduced by marine processes and receives water from rivers and local runoff directly or via the lower basin subsystem.

RIVERS

Knowledge of Mississippi Deltaic Plain Region rivers primarily concerns descriptive parameters of stage, flow rate, and water quality. The stage data are the most comprehensive. Stages are recorded on a daily basis by the USACE and/or the USGS along all streams, with additional gauges functioning during flood periods. Stage information usually concerns discrete locations along the entire stream reach from the upper boundary of the Region to the stream mouth.

Flow rate information is much more limited, as indicated earlier in this paper under "Riverine Processes." Except for the Mississippi and Atchafalaya Rivers, long-term records of discharge are available only for gauging stations outside the Mississippi Deltaic Plain Region. Flow duration and peak flow exceedence probability are available for USGS discharge gauging points from the USGS, but this information does not necessarily extend into the Mississippi Deltaic Plain Region because of the tidal influences and flow losses from the river through overflow and diversion.

Water quality records have been collected by a large number of Federal and State agencies. The annually published records of the USGS are the most easily accessible. Records vary considerably with regard to frequency of collection, length of record, and number of parameters measured. Parameters range from temperature of chloride on a daily basis to a total of nearly one hundred parameters including heavy metals, pesticides, and nutrients. Variations in type of data, period of record, and frequency of measurement are too great to allow an adequate summary statement here. Data-collecting organizations and types of data available are indexed and obtainable through the USGS National Water Data Exchange (NAWDEX). Major sources from which data may be retrieved are the USGS Water Data Storage and Retrieval (WATSTORE) and the U.S. Environmental Protection Agency's Storage and Retrieval System (STORET), to which data are contributed by many Federal and State governmental agencies and institutions. A review of STORET information revealed a total of 28 organizations that have collected water quality data within the Mississippi Deltaic Plain Region at approximately 3000 locations including streams, lakes, and estuarine waters.

While large amounts of basic data are available for the Region's major rivers, summaries of this data are limited in scope to statistical parameters such as mean, maximum, minimum, and standard deviation. These data characterize a river as a driving force, but leave many questions unanswered with regard to interaction between the rivers and other hydrologic components of the system. These questions are vital to management of the Region's surface waters for renewable resource conservation.

As a result of development and natural processes, hydrologic characteristics of the rivers have changed and continue to change. Cases in point are the elimination of annual overflow of the Mississippi River and the ongoing changes of stage-discharge relationships for the Atchafalaya River. What do these changes mean in terms of perturbations of the adjacent systems that are functionally linked to the river? The processes of annual overflow have been described in qualitative terms (Gagliano and van Beek 1970, van Beek et al. 1977b), but little quantitative information is available about volumes of sediment diverted from the river through overbank flow (Gagliano et al. 1972) or the effect on water quality and sedimentation of various means of water diversion into the overbank area. Likewise, river characteristics have remained undefined with regard to maintenance of present ecological systems. Such characteristics include the annual river stage and discharge hydrographs to which river-related ecosystems are adjusted, or trends in those hydrographs as a cause for biological habitat change.

Interactive processes between river hydrology and upland and wetland systems are also important, although poorly defined. The effect on river water of annual overflow and the subsequent return of water to the river is presently an unknown quantity for most rivers. Yet it is exactly this process that forms a link between many of the rivers, riverine wetlands, and the coastal environment. Some extrapolation concerning this process may be made on the basis of water quality studies in the Atchafalaya Basin (Hern and Butch 1979) and nutrient transport studies in the Barataria area (Day et al. 1977).

Interactions between rivers of the Mississippi Deltaic Plain Region and the marine environment involve, in particular, delta building and salinity. In terms of delta hydrology, little is known about how to manage water and sediment for wetland restoration. Preliminary studies estimated rates of delta building for a given diversion of river discharge (Gagliano and van Beek 1976), but at the same time illustrated the possible variability of the hydrology of the distributary network. Much needed information concerning the diversion requirements for optimum distributary development remains unavailable.

Interest has focused on saltwater intrusion at major river mouths, including the Mississippi River (Wright 1972, Rattray and Mitsuda 1974), the Pearl River (USGS 1977), and the Pascagoula River (Zitta et al. 1977). Influences of tide and saltwater intrusion on discharge and flow distribution have received little attention other than for the Mississippi River, where seaward discharge and vertical mixing were defined in the South Pass channel for various tidal conditions (Wright 1972). No such information is available for the Atchafalaya River.

UPLANDS

Within the Mississippi Deltaic Plain Region, upland environments are confined to the Pleistocene Terrace along the inland boundary of the study area and to major natural levee ridges of the Mississippi River and its distributaries. Formerly occupied by forests, uplands are now largely under development for urban, industrial, and agricultural use. Drainage has been accelerated through changes in surface characteristics and through construction of drainage channels in the course of development practices. Since most drainage from the uplands is directed into adjacent wetlands, the drainage process forms a major hydrologic link between socioeconomic processes and the wetlands and waters of the lower Mississippi Deltaic Plain Region. This linkage is further augmented where uplands are, in reality, developed wetlands and are subject to frequent overflow by rivers or to backwater flooding from adjacent wetlands.

In view of the above relationships between uplands and the estuarine environment, major concerns are the quantity and quality of surface drainage generated in upland areas, the rate of runoff, and hydrologic effects on receiving wetlands through changes in flooding characteristics and water quality. None of these topics have been adequately addressed for the Mississippi Deltaic Plain Region. While water yield from upland areas is included in water yield calculations for each of Louisiana's hydrologic units (Gagliano et al. 1970a), these data have not been separately presented to allow estimates of input of associated material. Equally limited in scope are the determination of rainfall-runoff relationships for southeast Louisiana and southwest Mississippi (Calandro 1967), and estimated freshwater yield from natural levees in the upper Barataria unit (Light et al. 1973). Information concerning the effects of development on the rate and water quality of runoff in the Region appears to be limited to inferences on the basis of hydrologic changes that are occurring in the adjacent, receiving water bodies (Craig and Day 1976). No quantitative information has been presented concerning nutrient and sediment contribution from upland areas. The most extensive information available about the additional linkage through periodic flooding of uplands are the flood frequency contour maps for the period of June through November published by the U.S. Department of Agriculture (SCS 1973, 1975). In general, the function and contribution of uplands to the hydrology of the Mississippi Deltaic Plain Region are poorly documented.

LOWER BASINS

A major part of each hydrologic unit within the Mississippi Deltaic Plain Region is occupied by a complex of wetlands, natural channels, canals, and major water bodies. For the purpose of discussion, this complex within each hydrologic unit is referred to as the lower basin and extends from the uplands to the open water of the Gulf of Mexico. Aquatic and wetland environments in each of the lower basins range from fresh to brackish or saline, depending on the magnitude and location of freshwater inflow and basin morphology. Freshwater inflow and tidal exchange also determine circulation and current patterns for a given basin morphology. With the exception of the Mississippi coastline, basin morphology in the study area is experiencing rapid change as a result of natural processes and man's activities. Consequently, freshwater inflow, drainage, tidal exchange, and circulation patterns are continuously being modified with resultant changes in salinity.

Freshwater Flows and Dispersion

Freshwater flows to the lower basins of the Mississippi Deltaic Plain Region involves two major processes. The first is the introduction of fresh water and related sediment and nutrients necessary for physical and biological maintenance. The second is annual overflow of the forested wetlands and the resultant support provided to the aquatic ecosystem (see "Riverine Processes").

Available information concerning freshwater flow distribution within the lower basin wetlands appears limited to the Atchafalaya Basin and upper Barataria Basin. Within the Atchafalaya Basin Floodway, the USACE, New Orleans District (1976), determined flow distribution through major distributary channels for various discharges of the Atchafalaya River. Individual contributions of local runoff and river water and of water exchange for two smaller swamp basins within this same area were estimated (van Beek et al. 1978). Flow measurements were made in association with a nutrient export study in the Barataria Basin (Day et al. 1977). In addition, a numerical modeling approach was designed by Light et al. (1973) to determine overall discharge patterns as a result of local runoff in the freshwater environment of the Barataria Basin. In all other units, information of freshwater movement is limited to general inferences on the basis of aerial photo interpretation of vegetation and salinity patterns. The lack of information, even for major flows, such as those diverted into wetlands from the Lower Atchafalaya River, severely limits accurate prediction of impacts of channelization and other major projects affecting hydrology of the lower basins, and to implement effective management of available fresh water.

Tidal Influences, Water Levels, and Circulation

The extent of tidal influence on water level variation has been presented only for the Barataria hydrologic unit (Byrne et al. 1976) and the Mississippi coastal area (Mississippi Marine Resources Council 1977). In the Barataria area, water level responses were analyzed at 17 stations maintained by State and Federal agencies. This analysis yielded a picture of temporal and spatial variation in tidal range and of the progression of the tide. For a number of years, water levels were also analyzed for seasonal variation, revealing a significant semi-annual periodicity with maxima during spring and fall, respectively. The study of Byrne et al. (1976) provides both a good indication of limitations in presently available data and shows the extent to which presently available water level data for each hydrologic unit can be utilized in characterization of the hydrologic regime of the lower basins. Unfortunately, no other similar efforts appear to have been undertaken, except for the freshwater environment of the Atchafalaya Basin Floodway (van Beek et al. 1977b).

From an ecological point of view, water level information is most useful when it can be expressed relative to substrate elevation in order to provide information on depth, duration, and extent of seasonal or annual flooding. Acquisition of information about these relationships is probably more hindered by lack of detailed topographic information than by lack of water level data. Topographic information is limited mainly to contours at 1.5 m (5 ft) intervals and spot elevations, while in the wetland environment most elevations are less than 1.5 m (5 ft) above mean sea level (MSL) and elevation differences of 0.15 m (0.50 ft) are significant in terms of habitat type.

Circulation in each of the lower basins of the Mississippi Deltaic Plain Region is highly complex because of the many forces involved and because of the complex network of interconnecting waterbodies. Circulation is important because of the transport of materials (detritus, silts and clays, salts, nutrients) and organisms and because of its effect upon water quality (dissolved oxygen, salinity, nutrients). Of major concern, therefore, are patterns of water movement, flow velocities, and rates of water exchange. None of these appear to be known for any of the hydrologic units as a whole.

An indication of the lack of knowledge about circulation is its absence as a topic of discussion in the hydrologic characterization of the Barataria Basin (Byrne et al. 1976), the most studied of the hydrologic units. The availability of information about water movement in relation to tidal forces and wind stress has been discussed earlier in this paper (Stone et al. 1972, Hacker 1973, Kjerfve 1975, Eleuterius 1976a, Hart 1976, van Beek et al. 1977b, Banas 1978, Hart and Murray 1978). However, this information in most cases is not directed toward characterization of lower basin circulation in an ecological sense. Rather, the emphasis is on understanding particular physical aspects of that circulation in relation to driving forces. Yet these studies are a significant beginning, since ultimately the numerical modeling of circulation for various seasonal conditions may be a more economical and reliable means than field measurements of developing seasonal images of circulation characteristics or assessing impacts of proposed actions. A recent study of the effect of canals on circulation in the Barataria area (Stone and McHugh 1979) is an example of the modeling approach. Despite the many shortcomings of this study, including insufficient verification and elimination of the consideration of wind and freshwater inflow, the study provides relative and order of magnitude measures of flow in the various vegetative zones for the overall basin.

Present knowledge concerning circulation of the lower basins thus remains extremely limited. The state of knowledge does not yet allow accurate numerical simulation, and unit-wide field measurements have been absent or are too limited in scope. Knowledge of general circulation characteristics is limited to large, open water bodies including Mississippi Sound (Eleuterius 1976a, b; Paulson et al. 1978), Lake Pontchartrain (Stone et al. 1972), Breton-Chandeleur

Sound (Hart 1976), Barataria Bay (Kjerfve 1973), and Atchafalaya-Cote Blanche Bay (van Beek et al. 1977b).

Water Quality Parameters

Measurements concerning hydrologic conditions of the lower basins of the Mississippi Deltaic Plain Region have been primarily of water quality parameters, in particular salinity. Networks of salinity and temperature recording stations have been maintained in Louisiana by the USACE, New Orleans District, since 1947, and by the Louisiana Department of Wildlife and Fisheries since 1968. Long-term and historic records for the Mississippi area are more limited, since water quality data collection has been associated with specific study efforts of one year or less (Mississippi Marine Conservation Commission 1973).

The availability of records and the importance of salinity as an environmental characteristic have resulted in a broad knowledge of salinity conditions in the Mississippi Deltaic Plain Region estuaries. Area-wide conditions have been documented through various studies, including the cooperative Gulf of Mexico estuarine inventories for Louisiana (Louisiana Wildlife and Fisheries Commission 1971) and Mississippi (Mississippi Marine Conservation Commission 1973), and geologic and hydrologic studies of coastal Louisiana (Gagliano et al. 1970b, 1970c; Chabreck 1972, Eleuterius 1976b; Barrett et al. 1978). In most cases, information is treated by hydrologic unit and summarized in terms of statistical parameters or average location of isohalines. In some cases, salinity is related to flow patterns, such as in Mississippi Sound (Eleuterius 1976b). Summaries include treatments on a seasonal basis or according to specific annual climatic conditions, such as relatively dry or wet years. These summaries have greatly facilitated the use of salinity data for management purposes, such as assessment of the need for additional fresh water to obtain a more desirable salinity regime for oyster production and fur trapping in each of the hydrologic units of coastal Louisiana (Gagliano et al. 1972a).

Long-term salinity changes have been the subject of limited investigation, although data for this purpose are available for all hydrologic units except Mississippi Sound and ancillary bays. Long-term weekly averages for stations in Barataria Bay were analyzed by Byrne et al. (1976). A comparison of averaged weekly means for two periods, 1956-1974 and 1961-1974, revealed a probable increase in salinity due to increased tidal storage. These same data give a good indication of seasonal differences and variability within the estuary. On a shorter-term basis, similar information is provided for all Louisiana estuaries by Barrett et al. (1978).

Annual salinity statistics for the period 1940-1965 (Gagliano et al. 1970d, 1973) allow visual inspection of annual variation and long-term trends at all monitoring stations maintained by the USACE. Graphic display of the data permits grouping of stations as well as years according to salinity regime, and illustrates the difficulty of determining trends because of cyclic or longer-term variation.

An indirect but important source of information about long-term trends and distribution of salinity values throughout the Region is found in the successive vegetation distributions compiled by Chabreck (1972, 1979). The location of isohalines is difficult to establish on the basis of salinity data alone because recording stations are widely spaced and many are located on channels that serve both freshwater drainage and saltwater intrusion. Thus, vegetation boundaries can significantly aid in interpolation between stations.

Water quality parameters other than salinity that have been monitored for a number of years on at least a monthly basis are temperature, dissolved oxygen, turbidity, and nutrients including nitrates, phosphates, and total phosphorus. Major data sources for these parameters are the annual USGS water resources data reports and the cooperative Gulf of Mexico estuarine inventory and study reports for Louisiana and Mississippi (Louisiana Wildlife and Fisheries Commission 1971, Mississippi Marine Conservation Commission 1973). Following the initial estuarine inventory, surveys were continued by the Louisiana Wildlife and Fisheries Commission providing additional data along transects through the major estuarine systems (Barrett 1978) and for selected estuarine complexes including Pontchartrain and Vermilion-Atchafalaya Bay. While caution should be used in assigning average values on the basis of these data because of the short period of record, the data provide valuable information about seasonal trends, gradients normal to the shoreline, differences between hydrologic units, general nutrient levels, and differences between years of high and low freshwater inflow. Furthermore, the simultaneous observations of a large number of parameters allow preliminary and qualitative conclusions of the effects of river discharge and runoff on estuarine water quality.

NEARSHORE WATERS

Nearshore waters of the Mississippi Deltaic Plain Region constitute a transitional zone between the marine waters of the Gulf of Mexico and the estuarine environments of the sounds and bays because of the large quantities of fresh waters that are discharged by the Mississippi and Atchafalaya Rivers. The effects of these discharges on temperature, salinity, and turbidity conditions is most profound in the area westward of the Mississippi Delta because of predominantly westward currents. Off the Barataria estuary, this effect is reinforced by the presence of a circulation gyre tending to trap Mississippi River water within the nearshore area. Freshwater discharge from the Barataria and Timbalier estuaries exerts additional influence on the nearshore water mass.

To the east of the Mississippi Delta, similar processes contribute to modification of marine conditions in nearshore waters, but, because of westerly currents, these conditions are less dominated by Mississippi River discharge. Important seasonal contributions of fresh and low salinity water come from the Pontchartrain Basin, the Pearl and Pascagoula Rivers, and, to some extent, Mobile Bay.

A number of studies have dealt with the seasonal variation of salinities as a result of freshwater discharges and the movement of fresh or less saline waters in the nearshore zone. Area-wide salinity and temperature measurements of surface water were made on a monthly basis during the 1960s by the Gulf Coast Research Laboratory, Ocean Springs, Mississippi (Drennan 1963) and the Bureau of Commercial Fisheries, U.S. Department of Interior (USDI). These data were summarized in atlas format by Gagliano et al. (1970b, c) with maps showing the seasonal variation in salinity gradients and isohaline positions as related to river and estuarine discharges for 1964-1965 conditions.

Subsequent studies, in particular those dealing with the Louisiana Offshore Oil Port (LOOP), have further detailed water mass and circulation characteristics immediately to the west of the Mississippi Delta (Wiseman et al. 1975); ecological investigations by the Gulf Universities Research Consortium have recently focused on nearshore waters adjacent to the Timbalier estuary and westward of the LOOP area (Gulf Universities Research Consortium 1975). The studies by Wiseman et al. (1975) substantiated the transitional nature of the nearshore waters, showing a mixing of warm saline water, cold saline water, and fresh water with a seasonally varying temperature. A vertical structure of the water column was also shown by these studies, i.e., a distinct halocline marks the boundary between saline Gulf waters and brackish coastal waters. In the area off Timbalier Bay, Oetking (1974) showed this density stratification to exist from winter through summer, with greatest vertical salinity variation during high Mississippi River discharges. Density stratification as a result of high river discharge has been shown to contribute to oxygen depletion in both the area influenced by Mississippi River discharge (Brent and Oetking 1974) and the area influenced by discharge from the Mobile Bay system (Schroeder 1977).

While salinity and temperature information is most comprehensive, other hydrologic parameters have received attention related to the importance of nearshore water for fisheries. Monthly sampling by the Louisiana Department of Wildlife and Fisheries (Barrett et al. 1978) included a nearshore station which provided information on basic nutrient levels and turbidities from 1974-1976 in each of Louisiana's hydrologic units. Happ et al. (1978) studied organic carbon enrichment of nearshore water off Barataria Bay in comparison with the contribution from estuarine water. Similar observations were made during a study of Timbalier Bay by Brent et al. (1975).

INFORMATION DEFICIENCIES

Review of current information concerning hydrology of the Mississippi Deltaic Plain Region indicates that, despite collection of vast quantities of data, understanding of the hydrologic regime has remained very limited. This is particularly true with regard to 1) the functional relationships between driving forces and hydrologic characteristics, and 2) the characterization of internal hydrologic processes in terms of the ecology of the Region. As a result, it is difficult to determine to what extent available descriptive and quantitative data collected through a multitude of short-duration studies can be considered representative for a given area, or to what extent findings in a given area are likely to be applicable to similar environments in other parts of the Region for use as management principles.

Although stage, flow, and water quality data exist for most streams entering the Mississippi Deltaic Plain Region, only in a few cases have these data been summarized in a form from which their influence on the Region's ecosystem can be determined. Lack of summarized information about water and materials delivered to the Region's wetlands estuaries through local runoff and waste discharge allows only preliminary and qualitative conclusions regarding observed or expected water quality changes. This insufficiency is more disturbing when one considers that maintenance of the Deltaic Plain as a renewable resource is increasingly dependent on managed introduction of fresh water and materials. Present knowledge of freshwater inflows is sufficient for this task, as is knowledge concerning management needs and results to be expected from the management of freshwater flows.

Summarized information about freshwater introduction from precipitation and resultant overland runoff is also needed. While relationships between runoff and water salinities have been studied on a statistical basis, the importance of retention of fresh water to abate saltwater intrusion requires additional information about rates of runoff, mixing, and the effects of canals and navigation channels.

The delta-building cycle has been identified as a basis for hydrologic change of the estuarine and wetland environments of southeastern Louisiana. Its importance with regard to environmental change has only been assessed in qualitative terms however. No detailed information is available concerning the effect of the cycle on tidal storage volume, related water exchange between the estuaries and the Gulf of Mexico, and associated changes in circulation and water quality regimes.

Present knowledge about marine processes remains inadequate. While considerable progress has been made in the identification of these processes and their importance in the immediate vicinity of the Mississippi Delta, a large void remains in the data available for tide-induced circulation in the major estuaries and the exchange of water between the Gulf of Mexico and the estuarine environment. Little is known in particular about the role of the remaining barrier islands and associated tidal passes relative to marine influences on the estuarine environment, or about littoral currents and associated material transport controlling rapid change of those islands.

Information about socioeconomic processes as a driving force reveals major needs for additional information concerning the individual and cumulative impacts of the major activities in the coastal zone. These information deficiencies include the effects of oil and gas canals on water levels, circulation, and water quality of the wetland environment; the effect of weirs on circulation and sediment transport relative to wetland maintenance; and the effects of agricultural development and associated drainage on hydrologic conditions in adjacent wetlands. Virtually no information is available about introduction of waste into the Mississippi Deltaic Plain Region estuaries through drainage from developed natural levee ridges and adjacent uplands. Introduction from point sources can be assessed but would require extensive compilation of information.

The second major area in which current understanding of hydrology of the Mississippi Deltaic Plain Region is incomplete is that of the temporal, spatial, and dynamic aspects of hydrologic processes and their relation to habitat distribution, function, and change.

Seasonal flooding of swamps and bottomland hardwoods is recognized as a key factor in the biological productivity of these systems and of adjacent aquatic environments. The structure and function of these ecosystems are tied to flooding characteristics, including hydroperiod and the timing, intensity, and frequency of flooding. These factors, in turn, vary with the source of water and relative importance and timing of local rainfall and external streamflow. Directly related to the annual flooding is the input and export of nutrients and the deposition of sediments affecting habitat changes and influencing the nutrient budget.

While investigation of the ecological relationships associated with flooding has begun (Day et al. 1977, Wells and Demas 1977, Hern and Lambou 1978, van Beek et al. 1978), these studies have mainly identified the importance of the annual overflow and dewatering function and the role of overflow variables. At present, a number of hydrologic factors remain insufficiently studied to allow qualified statements of hydrologic management principles. These factors include the importance of circulation characteristics in terms of dissolved oxygen levels, the role of annual dewatering of the swamp floor with regard to decomposition of organic materials, the contribution of the swamps to the annual water budget, and plant succession as related to changes in the hydrologic regime.

Within the marsh and aquatic habitats of the estuarine complexes of the Mississippi Deltaic Plain Region, functional linkages involving the hydrologic regime are understood only in a general way. The most apparent lack of information within the estuarine complex concerns the movement of water through the wetlands, the exchange between wetlands and bays, the circulation within the bays and sounds, and the exchange between the Gulf and estuaries. Such knowledge of net and short-term rates and directions of water movement is a requirement for dealing effectively with management of the Mississippi Deltaic Plain Region through freshwater introduction, with determination of contributions by the wetlands to the aquatic environment, with function of the wetlands as a buffer zone between uplands and the estuarine waters, with migration of aquatic biota, and with many other functional considerations.

A second major deficiency in hydrologic information is the relationship between changes in hydrologic regime and changes in habitat, in particular the loss of wetlands. While causes for wetland losses have been identified in general, hydrologic processes involved in these changes have been little studied. No information is available, for example, on the areal extent and specific nature of spoil bank and canalization effects, on limiting factors that determine when fresh or brackish marsh will be lost or will succeed into more saline communities, or on the exact nature of hydrologic changes that occur during evolution of the delta cycle.

In the Region's coastal waters, including Mississippi and Breton-Chandeleur Sounds, there is a shortage of information on both hydrologic characteristics and functional relationships. Major missing elements, except for the area adjacent to Barataria Bay, are temporal and spatial characteristics of tidal-, wave-, and wind-driven circulation and the seasonal changes in water quality as related to discharges from rivers and estuaries. Particularly disconcerting are the data gaps regarding the extent and nature of Atchafalaya River discharge effects on the western portion of the Region and the lack of background data, such as seasonal salinity and temperature distributions, in Chandeleur-Breton Sound. These two areas represent a major part of the Region's coastal waters and involve an equally large part of associated fisheries resources.

Related to the lack of basic information concerning the nearshore waters is the limited knowledge of interaction between the nearshore and estuarine components of the ecosystem through exchange of water and associated materials. Such interaction not only involves the enrichment of nearshore waters through nutrient export from the estuaries, but also the discharge of pollutants from the Mississippi River into the estuarine environment through mixing with nearshore waters and subsequent tidal exchange. Evaluation of these and similar water quality factors requires a much more thorough knowledge of nearshore circulation and mixing processes.

In summary, lack of data about the hydrology of the Mississippi Deltaic Plain Region can be assessed as follows. Through long-term measurement programs of State and Federal agencies, researchers have obtained a rudimentary knowledge of seasonal variation and spatial patterns of basic water quality parameters such as salinity, temperature, and some nutrients. Short-term, site-specific studies by public and private institutions have refined this knowledge in some areas such as Mississippi Sound, Barataria Bay, and in the coastal waters adjacent to the Mississippi Delta. Dynamic aspects of Mississippi Deltaic Plain Region hydrology have been studied to a much lesser extent, and are mostly limited to river discharges, circulation in Barataria Bay and adjacent coastal waters, and water levels in Barataria Bay and the Atchafalaya Basin. Almost a total void exists in the understanding of functional relationships between hydrologic components of the Mississippi Deltaic Plain Region and between hydrologic processes and the ecosystem. Exceptions are a limited number of studies concerning nutrient export, water salinities and freshwater inflow, annual flooding of swamp forests, and relationships between overflow and water quality of river and swamp waters.

RECOMMENDATIONS

The acceleration of adverse change in the Mississippi Deltaic Plain Region's ecosystem in recent years makes it increasingly urgent that future research concerning hydrology of the area be coordinated and focused on the protection, restoration, and management of the area's natural resources. For this reason, future research should emphasize the function of hydrology in the Region's ecosystem and the relationships between ecosystem differentiation and hydrologic structure.

Various habitats should be defined precisely with regard to rate of water movement; flooding characteristics including frequency, duration, time, and depth of flooding; and limiting conditions such as water quality, ponding, and dewatering. Only when relationships between biological communities and the hydrologic regime are better known can hydrologic management objectives be defined.

Circulation through wetlands should be studied relative to rate of water movement, retention time, and water quality change. These aspects are important for determining minimally needed width of buffer zones between uplands and aquatic systems, in evaluating the effect of canals in routing freshwater runoff, in determining materials transport and exchange between adjacent systems, and in defining management principles for location and rate of freshwater introduction.

Studies should be undertaken to define circulation patterns in each of the major estuaries and the nearshore Gulf waters relative to current patterns, water exchange, and mixing. This information is crucial to the planning of freshwater introduction projects to abate increasing water salinity levels, and in view of the susceptibility of the Region's estuaries to severe damage from a major oil spill or point source waste discharge.

Future studies should attempt to delineate functional relationships between hydrologic processes and Mississippi Deltaic Plain Region morphology relative to loss of wetlands, management of deltaic sedimentation processes for wetland development, and management of barrier islands.

The above recommendations involve two types of data acquisition: site specific studies and long-term regional monitoring. Site specific studies are primarily needed to delineate function and relative importance of hydrologic parameters in controlling habitat characteristics and change and to define goals and measures for management of hydrologic conditions. Secondly, site-specific studies should serve, in combination with existing information, as a basis for determining long-term monitoring needs relative to station locations and type of data to be collected. The present network of gauging and recording stations has developed historically in response to needs for flood protection, navigation, and domestic and industrial water supply. The need for management of the Region's wetland-related resources has added a new dimension that must be fully acknowledged through expansion or modification of present data acquisition programs.

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CHAPTER IV: METEOROLOGY AND AIR QUALITY

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INTRODUCTION

Discussion of a coastal location usually includes some consideration of the numerous and ubiquitous renewable resources, such as food and water, located there as well as some description of the moderated "coastal" or "marine" climate. In fact, the moderated climate of the coastal region is one of the most important physical variables allowing biomass productivity and geomorphic processes to occur as they do, thus characterizing the coastal environment as one of rich natural resources and high biological productivity. Because of the unique and complex nature of the coastal setting, understanding the nature of atmospheric parameters in their role of shaping and driving the ecologic systems of the coastal environment is also complex.

The objective of this paper is to summarize how much is known about the ways in which climatological/meteorological/air quality parameters govern the development and functioning of natural systems in the Mississippi Deltaic Plain Region. The scope of the paper is limited to a broad overview of the subject, resulting in a general, substantial understanding of what is currently known about the influences of atmospheric inputs upon the natural systems of the Region. To accomplish this objective, existing literature has been reviewed to present an overall picture of the present state of knowledge. Gaps in existing knowledge are identified, and areas where research or data collection need to be concentrated or reinforced are specified.

In this paper, discussion of the various atmospheric parameters is structured by grouping existing literature into topical categories. Categories resulting from this process include: 1) winds, storms, and barometric pressure; 2) data collection, general climatology; 3) air quality; 4) precipitation; 5) temperature; and 6) insolation and evapotranspiration. The first category comprises the largest number of articles encountered in the literature. The others are ranked in terms of the attention they have received in the literature. Those parameters for which no existing literature was found are considered last.

Chronological development of the atmospheric sciences is much too long and complex to be appropriately included within the scope of this paper.

However, it is appropriate to note that the study of atmospheric components in a coastal zone, as a discrete geographical region, is relatively recent and has been approached from at least two different perspectives: regional scale and microenvironmental scale.

Examples of early coastal climatic research are Bailey's "Analysis of Coastal Climates with Particular Reference to Humid Mid-Latitudes" (1959) and "Climates of Coastal Regions" (1960). Understanding of the coastal climate and weather elements through such descriptive, geographic analyses has been enhanced in recent years by another perspective on the coastal climate, a perspective more oriented toward dynamics of atmospheric energy inputs characteristic of microscale interactions in the coastal region. Examples of this type of research are illustrated by Hsu's "Coastal Air-circulation System" (1970a) for land- and sea-breeze systems, "The Shear Stress of Sea Breeze on a Swash Zone" (1970b) for sediment transport, and "Atmospheric Dispersion Characteristics in the Louisiana Coastal Zone" (1976) for air pollution transport estimation. Investigations of this type have contributed toward the understanding of how localized many processes are in the coastal zone.

Effects of the atmospheric parameters in the Mississippi Deltaic Plain Region are reviewed in three ecological divisions: 1) nearshore waters, 2) lower basin, and 3) upper basin. Although atmospheric paramters are not considered causative factors in the development of these ecological divisions, the role of atmospheric inputs in influencing various natural systems does vary, as do responses to atmospheric inputs, in the different parts of the Deltaic Plain. Therefore, atmospheric parameters will be discussed as they relate to the development and characterization of each of these ecological divisions.

METEOROLOGY AND AIR QUALITY

The literature reflects a general understanding that the dynamic nature of coastal climatological and meteorological parameters creates natural processes (temperature gradients, lapse rates, flood, drought, etc.), responses (shoreline change, salinity variation, species distribution, etc.), and interactions which define and influence the natural systems operating within the Deltaic Plain Region. The ultimate source of energy for all natural systems is sunlight, and the amount and intensity of insolation entering the environment at any time is directly related to atmospheric conditions such as cloud cover, relative humidity, and air pollutants. The triple interface of air-water-land creates a unique setting that influences boundary layers, atmospheric lapse rates and stability, wind patterns, precipitation characteristics, temperature regimes, and evaporation rates. Temperature and relative humidity are both modified in such a way by the effect of the Gulf of Mexico that strong gradients exist inland, ranges are small annually, and an average of about 236-240 frost-free days (McWhorter 1962) results in a long growing season. Under some weather situations, a steepened lapse rate inland produces lines of clouds and precipitation along the coastline.

Particularly notable for their impact on the Deltaic Plain environments are storms. Synoptic scale meteorological events associated with mid-latitude traveling cyclones alter inputs of barometric pressure, insolation, precipitation, air and dew point temperature, evaporation rates, and wind characteristics on a daily or even hourly basis. Tropical cyclones bring devastating alterations to the coastal region as they are accompanied by high wind speeds, storm surges, torrential rainfalls, and flooding which amplify geomorphic processes in the Region and cause rapid changes in the landscape.

Other mesoscale events such as severe thunderstorms with associated hail, lightning, heavy rainfall, high wind speeds, and possible tornadic activity are potentially destructive atmospheric forces of the coastal environment. The land-sea breeze phenomenon is found in certain coastal areas, and although the associated winds are not generally stormy, the regularity of their diurnal and seasonal regimes certainly constitutes a local influence on the development and character of the natural systems within those areas. The following discussion examines what is specifically known about effects of atmospheric parameters in the Deltaic Plain.

WIND, STORMS, AND BAROMETRIC PRESSURE

Information about wind, storms, and barometric pressure is encountered most often in the existing literature on the Deltaic Plain Region. It is evident that this area of atmospheric input has received the most widespread and most concentrated attention in Deltaic Plain environmental investigations. Within this category, investigations and reportings on hurricanes are most numerous, followed by investigations on wind regimes and environmental responses.

The information presently available about hurricanes in the Deltaic Plain can be divided into three fields: 1) effects of given, individual storms on the Region or observations of the atmospheric variables during individual storms; 2) hurricane frequencies and probabilities for the Region; and 3) predicted tidal surge heights for the area calculated using storm surge models developed for design and planning purposes.

Relative to the three ecological environments, hurricane studies have been mostly concerned with water level changes, water movement, and water quality in the nearshore and lower basin areas. Coastal flooding is predictable, based on design hurricanes and standard project wind velocities and directions (U.S. Weather Bureau 1957a, b, c, 1959a; Reid et al. 1977; Wanstrath 1978; Crawford 1979). The nature of hurricane-generated coastal currents has been studied (Murray 1970), as has the possibility of hurricane-spawned tornadoes (Novlan and Grow 1974, Cry 1969a) and the impact of hurricanes on water resource allocation and land use change (Cross 1976).

Impacts of hurricanes to basin ecosystems encompass all three ecological divisions. For example, Hull (1977) examined meteorological conditions associated with Hurricane Camille in the nearshore environment, Adams (1970) examined changes in Barataria estuary as a result of Camille and Laurie, and Black (1970) examined effects of Camille on man's activities in the upper basin. These and other studies (Webert 1956; Wright et al. 1970; U.S. Army Corps of Engineers [USACE] 1966, 1970) have documented morphological and ecological changes in all three zones of the Deltaic Plain as a result of hurricanes.

General information about the nature of tropical cyclones as they affect the Deltaic Plain is available from a number of sources (Cline 1926, Neumann et al. 1978, USACE 1974). In addition, periodical publications such as Monthly

Weather Review and Climatological Data--National Summary (U.S. Department of Commerce) contain summary articles that discuss tropical cyclone activity and effects in the Deltaic Plain Region for each month and year.

The second field of major concern within the wind and storm category concentrates on wind regimes other than storms. Information in this field can be divided into three areas: 1) characteristics of regional wind regimes and flow patterns; 2) air-sea-land interface influences on wind; and 3) responses of water levels to changes in winds.

Analyses of wind data have provided characteristics of wind speeds and directions in the Deltaic Plain (U.S. Weather Bureau 1957a, b, c; Essenwanger and Reisig 1967; Cramer et al. 1975). Other analyses, more concerned with hydrodynamic responses and boundary layer meteorological characteristics, have resulted in information about wind drag-coefficients, dynamic roughness, wind stress, atmospheric stability, and atmospheric dispersion characteristics in the coastal region (Hsu 1972, 1973a, b, 1974, 1975, 1976). These studies have clearly detailed how winds change from nearshore to upper basin areas. The occurrence of the land-sea breeze phenomenon in the Deltaic Plain has not been studied in Louisiana. Data from Keesler Air Force Base in Biloxi, Mississippi, show indications of the phenomenon during certain weather types (Higgs, in press).

Changes in water levels and water movements in the nearshore area of the region have been shown to be strongly influenced by wind shifts and barometric pressure changes related to frontal passages and changes in synoptic scale weather patterns (Daddio 1977, Wax 1977). Similar relationships have been discerned in lower basin areas (Kjerfve 1975, Wax 1977) and in upper basin areas where surplus precipitation has been shown to be another major variable (Milliet 1975, Wax 1977).

Relationships to basin ecosystem functions have not been extensively explored in the wind regime analysis category. Prolonged durations of wind from the south in conjunction with fresh water flooding from the uplands are known to produce flooding in both lower and upper basins. If inundation persists, some changes in habitat--short-term or longer--must result from changes in water levels and salinities. Although these conditions were present during the 1973 flood on the Mississippi River, no temporal or regional analyses documenting resultant changes have been contributed to the literature. Another generalization, often referred to, but essentially ignored in the literature, is the effects of warm and cold front passages on migratory bird populations. The vagaries of these meteorological events could have major effects from year to year.

DATA COLLECTION, GENERAL CLIMATOLOGY

Data collection and general climatology is a topical category which groups the existing literature concerning the collection and synthesis of observed meteorological data within the Deltaic Plain. This category can be divided into two fields of information: 1) statistical summaries of observed conditions or bibliographies of available collected data; and 2) analyses of observed data in some format other than recorded statistics.

The first field of information in this category, recorded statistics, consists of all routinely observed and published data of the National Weather Service network within the Deltaic Plain Region, some data observed at a number of offshore rigs of various types, plus unpublished data collected at Coast Guard stations and Keesler Air Force Base. There are 32 of these sites in the Deltaic Plain, 27 in Louisiana and 5 in Mississippi. Of these, 9 record precipitation only, 19 record precipitation and temperature only, and only 3 (New Orleans Moisant, Boothville, and Keesler Air Force Base) routinely record and publish additional parameters, including: cloud cover; air, dew point, and wetbulb temperatures; relative humidity; wind speed and direction; and hourly precipitation. Furthermore, 13 of the 27 Louisiana stations are located within the New Orleans urban area. Solar radiation data are not collected anywhere within the Deltaic Plain. There is a clear need for more routine observations of all meteorological parameters throughout the Region.

The second field of information within this category encompasses use of the collected data to describe atmospheric conditions within the Region in some format other than statistical averages and means. For example, Muller (1970, 1975) assessed precipitation surplus and deficit potential of Louisiana marshes and estuaries using water balance techniques. Kalkstein (1972) characterized spatial and temporal attributes of air masses in the Region. Muller (1977) classified regional weather events and conditions into discrete synoptic weather types and constructed continuous calendars of durations of each of the weather types. In addition, his analysis characterized environmentally meaningful weather parameters associated with each weather type, identified a typical sequence of weather types in the Region, and demonstrated how temporal variances in the sequence and duration of the weather types characterizes climatological/meteorological input to the environments of the Deltaic Plain Region. Muller and Wax (1978) have used the synoptic weather type analysis method to construct a comparative climatic baseline for coastal Louisiana. Wax et al. (1977, 1978) have used the method to relate responses of water levels, surplus water production, salinity changes, and evaporation rates to changes in weather types. They have also analyzed input of solar radiation by weather type at locations west of the Deltaic Plain. Muller and Willis (1978) have evaluated climatic variability in the Region using departures from normals of precipitation and temperatures.

Concerning the ecological divisions, most data collecting sites are concentrated in the upper basin areas. Very few are located in lower basin sites, and, with the exception of some inconsistent buoy observations, there are no reporting sites located in the nearshore waters. Consequently, the data collection network does not report information that can be assumed to be representative of all three ecological divisions without some further level of refinement or rearrangement.

AIR QUALITY

The U.S. Environmental Protection Agency (EPA) (1973, 1975a, b) has published reports concerning environmental contamination from hexachlorobenzene and an Implementation Plan review for the Mississippi River and Louisiana by the Energy Supply and Environmental Coordination Act. Regional air quality studies have been reported by the National Air Pollution Control Administration (1970), South Alabama Regional Planning Commission (1970), Norwine (1971), and Mississippi Air and Water Pollution Control Commission (1977). Extensive and excellent air-quality data collections have been published annually by the EPA for several years; an example is given in EPA (1978). This report presents comprehensive summaries of data produced by the Nation's ambient air quality monitoring activities for 1976. The data are summarized in two formats: frequency distribution (Part I) and status of data with reference to standards (Part II). These summaries are based on data acquired through extensive monitoring activities conducted by Federal, State, and local pollution control agencies and submitted to the EPA's National Aerometric Data Bank. Information is provided on the six pollutants for which the National Ambient Air Quality Standards have been set: total suspended particulates, carbon monoxide, sulfur dioxide, nitrogen dioxide, total hydrocarbons, and total oxidants. For specific regulations concerning the air quality in Louisiana, see Louisiana Air Control Commission (1974).

Air pollution emissions inventory for the State of Louisiana has been reported by LaGrone and Burklin (1971) and for the New Orleans metropolitan area by Hoffman (1969). Modeling of the impact of power plants on ambient SO_2 concentrations in the Mississippi Delta as well as in southern Louisiana--southeast Texas Air Quality Control Region 106--have been published by Geomet in 1974 and 1975, respectively. Assessment of ambient air quality of the Mississippi Gulf coastal zone has been studied by Cross (1975). Arthur et al. (1976) have investigated atmospheric levels of pesticides in the Mississippi delta.

Atmospheric dispersion characteristics in the coastal zone are unique in that physical processes of air, sea, and land combine at the shoreline to create motions on many scales which differ in important respects from processes over land or over water. Some of these differences in coastal Louisiana are reviewed by Hsu (1976). Synoptic-scale characteristics indicate that the coastal zone is superior to areas farther inland for dispersing pollutants. However, mesoscale and microscale studies reveal that diurnal circulation of land-breeze and sea-breeze systems, and the development of an internal boundary layer because of aerodynamic roughness changes across the shoreline, may actually increase pollution concentration in the nearshore region. Specific studies on these scales of atmospheric motion in relation to the optimum siting for industrial plants are outlined and recommended.

PRECIPITATION

Investigations of precipitation in the Deltaic Plain can be divided into three fields of information: 1) precipitation probabilities--climatic normals and predictions from tropical storms and hurricanes; 2) modification of normal precipitation regimes by urban areas; and 3) flooding and surplus precipitation potential.

McWhorter et al. (1966) and Penn et al. (1969) have calculated precipitation probabilities within the Deltaic Plain Region based upon the climatic records available at the time of their investigations. Goodyear (1968) calculated frequency and areal distribution of tropical storm rainfall in the Region. Cry (1967) and Schoner and Molansky (1956) assessed effects of tropical disturbances on precipitation distribution in the Region. The U.S. Weather Bureau (1959b) has calculated rainfall estimates for standard project hurricane tracks across the Deltaic Plain.

Huff and Changnon (1972) investigated the effect of the New Orleans urban area on inadvertent modification of precipitation. Changnon (1972) studied the effects of aerosols, heat, moisture, and mechanical turbulence on convective processes over and downwind from New Orleans relative to urban-induced increases in thunderstorms and hailstorms.

Chin (1975) analyzed the floods of April 1974, in the Deltaic Plain Region by evaluating the storm track, its areal and temporal extent, and other characteristics which resulted in precipitation amounts locally exceeding the 100-year rainfall within the Deltaic Plain. Muller (1976) conducted a comparative analysis of the Mississippi River floods of 1927, 1973, and 1975, in which he evaluated the surplus precipitation generated within the Deltaic Plain Region during each of the flood events and its relative importance to the total flood discharge.

Muller (1977), Muller and Wax (1978), and Wax et al. (1977, 1978) have evaluated the meteorological conditions in terms of synoptic weather types, which cause precipitation in the Region. They report that about 70% of recorded precipitation in the Region is related to frontal passages, about 15% is related to tropical disturbances, and the remainder is produced by all other synoptic weather situations combined.

TEMPERATURE

Temperature has been less extensively investigated than the other parameters discussed. Cry (1969b) and McWhorter (1962) have calculated freeze probabilities for the Deltaic Plain. Climatic normals (monthly and annual) are computed at 11 locations throughout the Region, 9 in Louisiana and 2 in Mississippi. Ludwig (1967) studied urban effects of New Orleans on temperature and humidity in the city. Hilding (1979) has investigated horizontal temperature gradients inland across the Region. Muller and Wax (1978) have discussed the effects of Lake Pontchartrain on temperatures in New Orleans during different wind flow patterns.

INSOLATION AND EVAPOTRANSPIRATION

Investigations on solar radiation in the Deltaic Plain are completely absent from the literature. Regional rates of evapotranspiration have been estimated using water balance calculations (Gagliano et al. 1973). However, there have been no actual measurements of this parameter in any of the Deltaic Plain environments.

Variation in other meteorological parameters, such as cloud cover, wind speed, relative humidity, and temperature, influences receipt of insolation and rates of evapotranspiration. Ecological functions in nearshore waters, lower, and upper basin environments are dependent upon the energy received through insolation. At present, nothing beyond this general statement can be made about dependency on or influence of either solar radiation received or consequent evapotranspiration in any of the ecological divisions or natural systems operating in the Deltaic Plain.

GAPS IN AVAILABLE KNOWLEDGE

The foregoing discussion of the understanding of climatological/meteorological influences in the Deltaic Plain reveals several aspects of natural systems that are not currently well studied or well understood in this area. The following paragraphs outline specifically which parameters need investigation to provide better understanding of individual elements of atmospheric activity as well as a more complete understanding of the ecologic functioning of the Deltaic Plain in its entirety. The discussion is arranged following the same order or parameters as the state of knowledge discussion, with consideration for scale (regional or microenvironmental) and ecological division (nearshore waters, lower, or upper basin).

WIND, STORMS, AND BAROMETRIC PRESSURE

Effects of these parameters on water levels and water movement is well studied in all three ecological divisions and on regional and microscales. Effects on water quality characteristics (salinities, water temperature, and turbidity) are not well known. Long-term changes of habitat owing to seasonal differences in wind and pressure patterns on a regional scale are not known. The land-sea breeze phenomenon is not well documented in the literature. Effects of barometric pressure changes are only understood as they relate to frontal passages and wind shifts.

DATA COLLECTION, GENERAL CLIMATOLOGY

The present data collection network is completely inadequate to allow substantive assessments on a regional scale of any parameter except temperature. Microscale assessments of temperature are not possible with the present observation network because the network was not designed and is not operated to provide microscale detail. Precipitation, cloud cover, dew point temperature, relative humidity, wind speed, and wind direction are observed routinely at only three locations within the region, and of those three, only New Orleans Moisant Airport data are published regularly in the Local Climatological Data series. No insolation or evapotranspiration data area collected.

Efforts to synthesize the available data into meaningful climatic evaluations have been hindered by the paucity of data collected in the Region. Results and reliability of the on-going efforts are encouraging, but microenvironmental differences within and among the three ecological divisions are not adequately accounted for or represented under the current data collection network. Atmospheric inputs and ecological responses are not well enough observed to characterize the Deltaic Plain and its ecological divisions and microenvironments as an integrated, naturally-functioning unit.

AIR QUALITY

Section 5(a)(8) of Outer Continental Shelf Lands Act Amendments of 1978, PL 95-372, required compliance by oil, gas, and sulphur operations in the outer continental shelf with national ambient air quality standards pursuant to the Clean Air Act (42 U.S.C. 7401) because those activities significantly affect the air quality of any state. The U.S. Geological Survey (USGS) (1979) has proposed regulations that describe procedures to determine whether emissions from such activities must be abated, and explain criteria used to identify sources of emissions which would have significant onshore impacts. These regulations deviate from EPA national standards and criteria in some instances in order to prevent significant deterioration of onshore air which is cleaner than that mandated under primary or secondary ambient air quality standards.

Owing to exploration and production of oil and natural gas near the coast and offshore, accidents cannot be avoided. The results will be oil spills and air pollutants both in the water and atmosphere which may have a detrimental effect upon wildlife and fishery resources. Knowledge about these accident-related pollution levels is limited because few such measurements and studies have been conducted in this area. Furthermore, there are no air pollution measurement stations offshore, for instance, on the rigs or buoys. At least some mobile stations on research vessels should be added for such measurements. One area deserving attention--the long-range transport of pollutants during the winter season when the atmospheric inversion layers are low--should be studied and correlated with ecological studies. Land- and sea-breeze related local air-circulation systems which trap pollutants in a confined area of about 50 km (31 mi) on- and offshore should also be investigated. Other gaps in knowledge deserving attention are suggested by Hsu (1976) (e.g., the investigation of the inversion layer across the coastal zone).

PRECIPITATION

The major gap in knowledge of precipitation stems from inadequate measurement of the parameter. In both regional and microscale considerations, only estimates and generalizations can be made. It is not understood how the atmospheric input into the Deltaic Plain environments produces more or less precipitation, or whether precipitation regimes differ in localized places within the Deltaic Plain. Ecological responses to precipitation are better understood than the variations in the mechanisms which produce precipitation in the Region.

TEMPERATURE

Effects of air temperature on water quality (water temperature, density, oxygen content) are not known on a regional scale. Although EPA standards set 35°C (95°F) as the maximum temperature criterion for the nearshore waters, how often or to what degree this standard is exceeded across the Region is not known in a temporal or spatial context.

Effects of air temperature on other biometeorological parameters, such as evapotranspiration rates and their temporal and spatial variance and distribution, are not known for the Region as a whole. The effects of drastic changes in temperature on either side of fast-moving cold fronts has not been studied.

INSOLATION AND EVAPOTRANSPIRATION

Effects of solar radiation on the euphotic zone, phytoplankton, and benthic organisms in the nearshore waters and the lower basin environments, on the marshes of the lower basins, and on the swamps and forests of the upper basin are not known because solar radiation is not measured anywhere in the Deltaic Plain on a routine basis. Biomass productivity cannot be related to variation in insolation until measurements are made and evaluated. Evapotranspiration measurements are not made in the Region, so there is no way to evaluate the reliability of the empirically derived or calculated estimates of this parameter's temporal and spatial distribution. Energy transfers and moisture cycling in the Region are not adequately understood as a result.

RECOMMENDATIONS

Based upon the review of existing literature and the understanding of the role that atmospheric parameters play in development and functioning of the Mississippi Deltaic Plain coastal environment, several gaps in existing knowledge are indicated. The following subjects are recommended as areas in which research would be most beneficial in improving overall knowledge of atmospheric inputs into the Deltaic Plain Region:

1) Insolation and evapotranspiration

2) Observations of meteorological data

3) Weather event - environmental responses

4) Land-sea breeze phenomenona

5) Climatic variation and regional ecological adjustments

6) Inversion layers across the coastal zone

Insolation and evapotranspiration inputs are essential to complete understanding of natural systems in all three ecological divisions of the Region. Primary productivity, biomass production, water quality, and general vigor and resilience of all systems are strongly related to temporal and spatial variances in these atmospheric parameters. From a physical process perspective, these parameters index energy-moisture exchanges and responses to that flow of energy within the environment.

A denser network of data observations would be beneficial to all research endeavors. Particularly needed are observations of parameters not routinely observed anywhere except at first-order weather stations--cloud cover, relative humidity, wind speed and direction, evaporation, and hourly precipitation. Availability of standardized, homogeneous climatic records in all environments of the Deltaic Plain would allow characterization of the various meteorological components as they relate to ecological functions in the Region.

Use of synoptic weathertypes to relate weather conditions and changes of weather to environmental responses would prove useful for a number of objectives. The method of condensing the totality of climate into repetitive types of weather with known characteristics and a known sequence of occurrence, and then relating the occurrence and duration of those types to environmental responses, would substantially improve our understanding of the impact of weather on natural systems.

Documentation and characterization of the land-sea breeze phenomenona in the Deltaic Plain would enhance understanding of daily and seasonal wind regimes. Not all parts of the Region are likely to exhibit the diurnal wind feature, but an understanding of where it does occur would help explain other processes such as aeolian erosion and deposition patterns, diurnal patterns of evapotranspiration, cloud patterns, water movements, and other processes which might be dependent upon the wind for energy or for developmental influences.

Climatic variation on a seasonal or annual basis is probably strongly related to the development and functioning of the natural systems in the Region. Exceptionally warm, cold, wet, or dry periods are known to produce some limited amount of climatic stress. Investigation of the other components of climatic variability such as presence of continental polar (cold, dry) or maritime tropical (warm, moist) air masses, location in the Region of the mean polar front position over a number of years, and precipitation habitually falling through cold or warm air behind or in advance of fronts will allow assessment of short- and long-term alterations in natural systems owing to changing climatic inputs.

Inversion layers across the coastal zone are very important for the dispersion of air pollutants, particularly during on- and offshore accidents due to oil and natural gas operations. The concentration of pollutants at ground level and into the water also depends upon other meteorological-oceanographic parameters; but inversion layers play an important role, particularly during winter and nighttime when these layers are low.

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CHAPTER V: BIOLOGY

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INTRODUCTION

There are few truly general biology papers. Because of the range of material covered by that science, studies tend to deal with more restricted fields such as botany, fisheries, or wildlife. For this reason, this biology synthesis paper is organized in three separate parts. The first is botany, in which the state of knowledge in the Mississippi Deltaic Plain Region is assessed, deficiencies in available knowledge are identified, and recommendations are made for future study. The second is fisheries, within which the same topics are covered. The third is wildlife.

BOTANY

INTRODUCTION

The Mississippi Deltaic Plain Region is a geologic unit consisting of Recent alluvium deposited by the Mississippi River during the last 12,000 years. The area's humid subtropical climate (Newton 1972) permits an almost year-long growing season, and abundant rainfall and sunshine enhance vegetation production. The forest type of the Region is sometimes classed as a mid-latitude deciduous forest with oak-hickory as the climax forest association (Fowells 1965). Baldcypress-tupelo gum swamps, a major forest component in the Region, are considered to be a subclimax association because they are maintained almost indefinitely in a "subfinal stage of succession by edaphic and physiographic conditions" (Fowells 1965:675). The naturally nonforested portions of the Deltaic Plain Region consist of wet grasslands composed of fresh, intermediate, brackish, and saline marshes. Within this area there is a close correlation between specific vegetation associations and physiographic features (Figure 5-1). Association traits such as species composition, density, diversity, distribution, and viability are closely correlated with the type, age, soil composition, and elevation of the landform relative to water levels and water salinities (Figure 5-2).

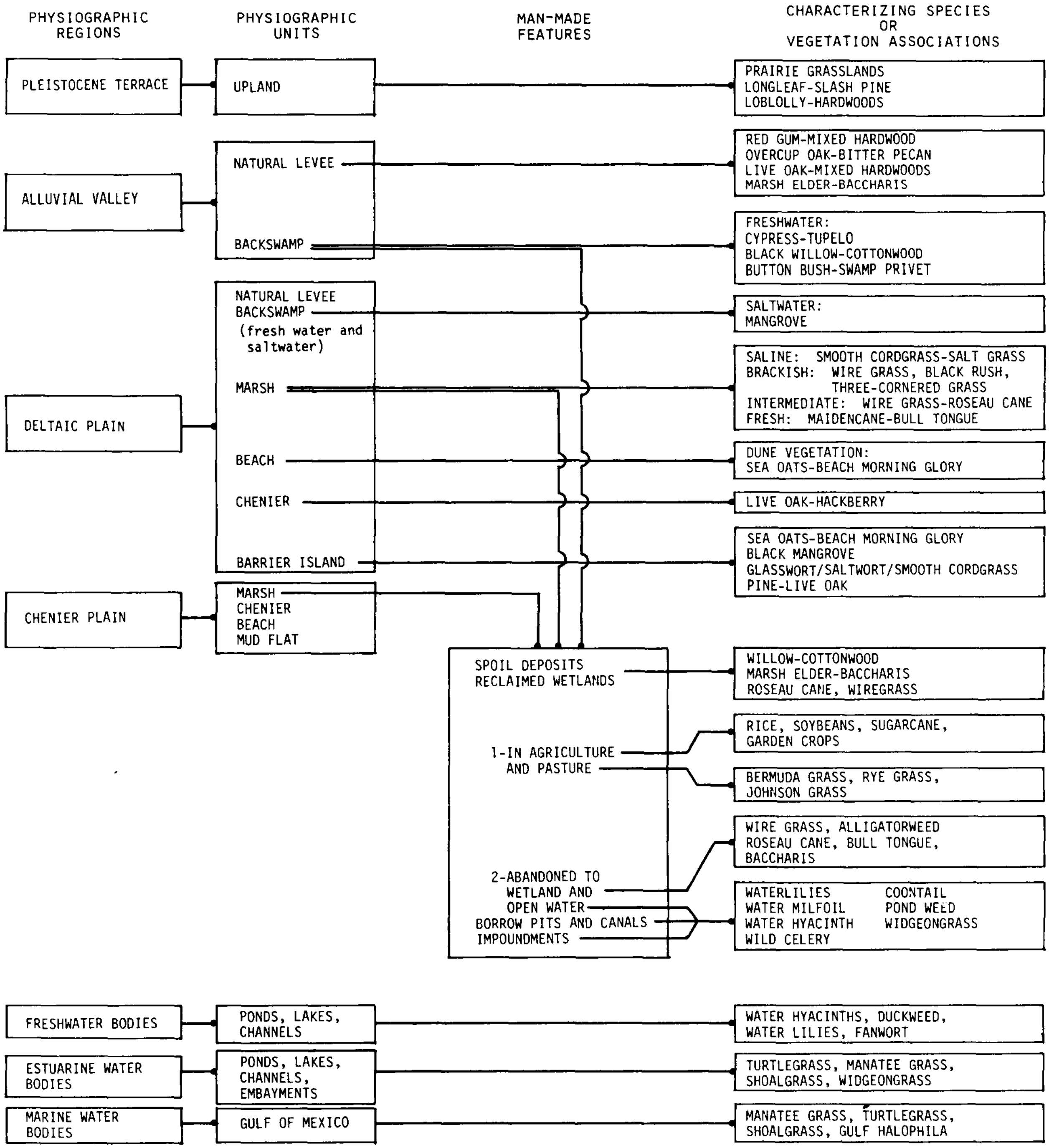


Figure 5-1. Relationships among physiographic regions, physiographic units, man-made features, and major vegetation associations in the Mississippi Deltaic Plain Region and adjacent areas.

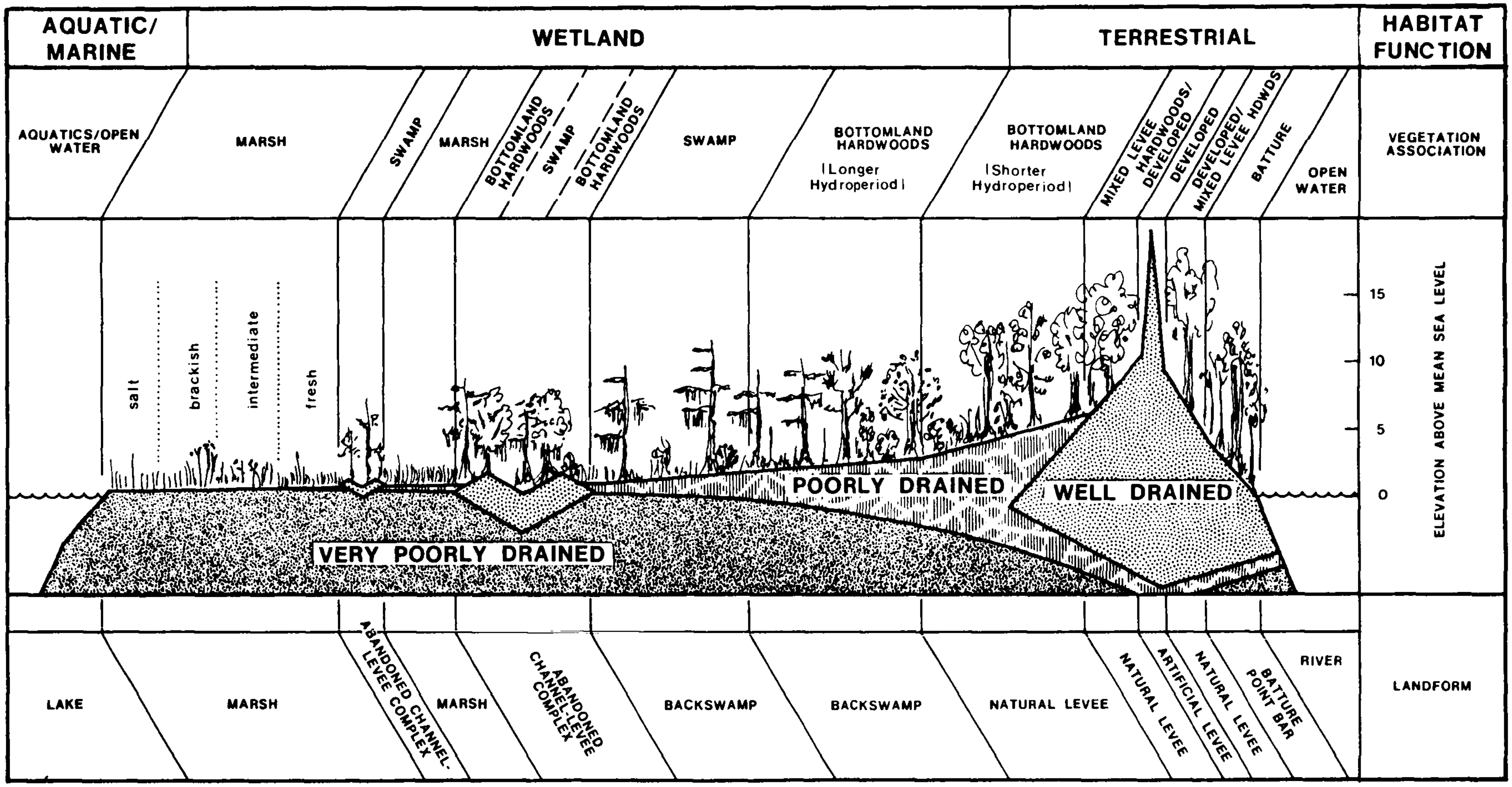


Figure 5-2. Relationship of habitat and vegetation associations to landforms in the Mississippi Deltaic Plain Region. (Note: as the levees subside, their normally better drained silts and silty clays are exposed to longer hydroperiods and their previously associated mixed levee forest associations are replaced by bottomland hardwood and swamp associations.)

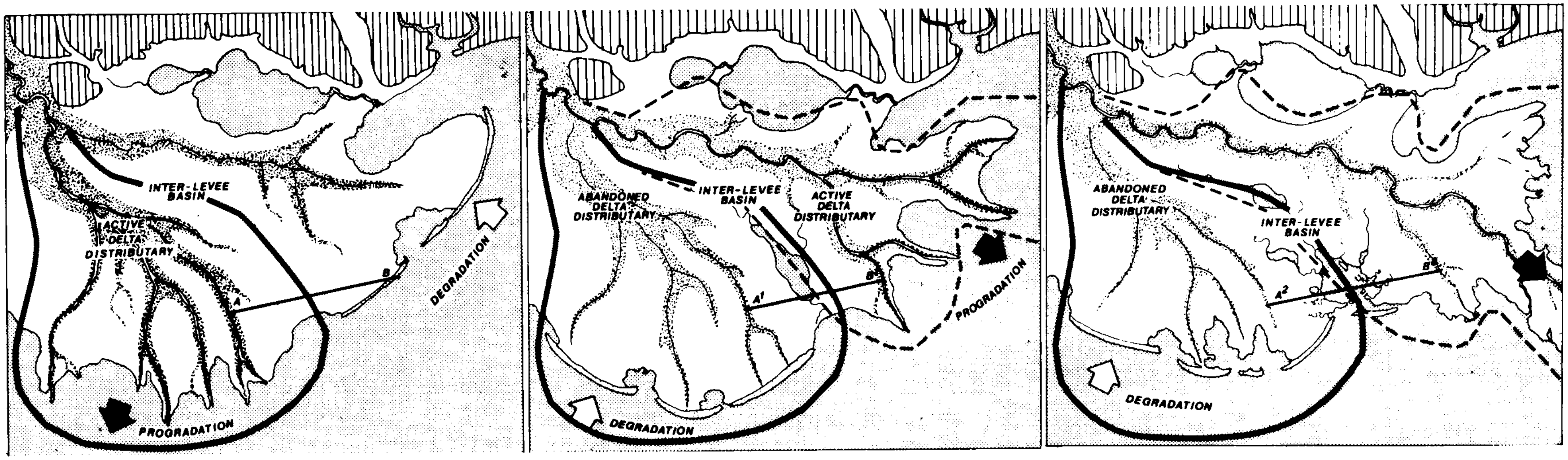
The extent and distribution of vegetation associations in the Region change through time in response to the cyclic stages of the Mississippi River Delta. For example, the shifting of the Mississippi River and abandonment of a delta lobe in one area of the Deltaic Plain will result in the gradual subsidence and marine erosion of the deltaic landforms. With decreasing elevation, associations that require short hydroperiods (such as mixed levee forests) will gradually be replaced by associations that can tolerate longer hydroperiods (such as bottomland hardwood forests and cypress-tupelo gum swamps). If salinities and hydroperiods increase, the forest vegetation will be replaced by salt-tolerant grasslands such as intermediate, brackish, and saline marshes or open water bodies containing submerged and/or floating aquatics (Figure 5-3).

The function of a vegetation habitat, even when imprecisely understood, can be viewed in terms of its role in the ecosystem and its utilization by man. Primary production is the major function of plants in any association and constitutes the base of the food chain for all higher organisms. Additional functions which benefit man specifically include production of medicine, raw materials, timber, clothing, an energy source, recreation, fisheries and fur products, and aesthetic enjoyment. In addition to contributing to soil composition, terrestrial vegetation coverage retards wind and water erosion of soil. In coastal areas, broad expanses of marsh and swamp vegetation serve to buffer inland human habitation sites from the direct impact of storm surges and marine erosion and to provide nutrients to the aquatic and marine systems. Wetland habitats also function as water storage and filtering reservoirs, lessening the impact on the ecosystem of sudden, large inputs of precipitation, floodwaters, and harmful elements such as heavy metals and pesticides.

In addition to the above beneficial functions of vegetation, there are detrimental aspects that have received much attention. For example, there are undesirable native and introduced plants such as water hyacinths (Eichhornia crassipes) and milfoil (Myriophyllum spicatum) which man seeks to control or eradicate in farmed and managed areas and in navigable water bodies and freshwater reservoirs. Man's alteration of certain forms and processes of the natural ecosystem has also resulted in imbalances detrimental to the normal functioning of the system and to man. For example, oversaturation of aquatic systems with organic and inorganic wastes lessens the system's ability to function properly and results in degradation (e.g., accelerated rates of eutrophication) of all or part of the aquatic system.

Chronological History

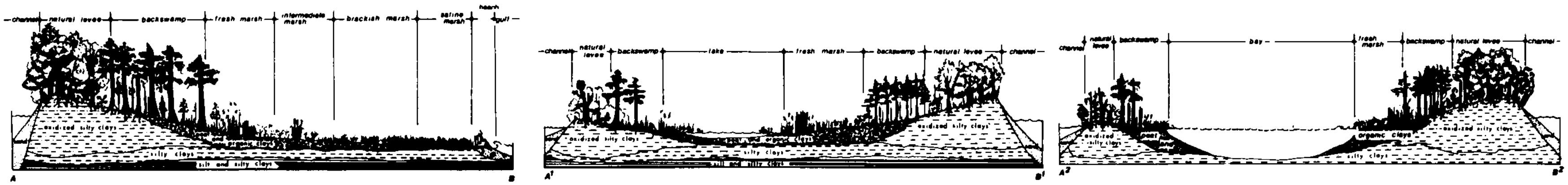
The existing flora of the Mississippi Deltaic Plain Region is presently categorized by its characteristic vegetation associations because the plants usually appear in discreet units that are relatively easy to identify, map, and describe qualitatively, quantitatively, and functionally. A chronological review of the previous 200 years of vegetation literature reveals that the earliest botanical studies in this area involved primarily the taxonomic identification and naming of individual species. Later, in addition to plant identification, scientists began to study and qualitatively describe the whole habitat or vegetation association. In recent years, research has concentrated on the functions and interrelationships of species within the community and the encompassing environment.



Areal extent of a prograding delta

Areal extent of a prograding and an eroding delta.

Areal extent of an abandoned delta and a well-advanced delta.



Environments of a mature, active delta.

Environments located between a prograding delta and one in the early stage of abandonment.

Environments within an eroding inter-levee basin.

Figure 5-3. Alteration of the coastal environment in response to alternating progradational and degradational processes of an active, shifting Mississippi River Delta (Wicker 1979).

The emphasis of much of this latter habitat research has been on the ecosystem rather than the species level and is often pursued through the science of ecology rather than classical botany. Ecology may be viewed as an outgrowth of botany in that plants were one of the first areas to be investigated by ecologists, and many ecological terms developed in reference to botanical concepts (Clarke 1954). Today it is sometimes difficult to distinguish between botanical and ecological habitat studies because they share similar research interests and techniques.

INFORMATION REVIEW

The majority of the literature pertaining to vegetation in the Deltaic Plain Region is aimed at identifying and describing species, habitats, and functions; determining the factors that affect species and habitat distribution and quality; promoting the growth of selected species and habitats beneficial to man, either directly or indirectly; and suppressing the distribution of species detrimental to man's interest. While most research can be classified as either pure or applied science, many studies employ aspects of both approaches in order to understand the functions and interrelationships necessary for manipulating the species or habitat for man's benefit. Botanical research is frequently concentrated in one of the three major habitat categories: terrestrial, wetland, or aquatic, and can be focused on a statewide, regional, or local area.

Terrestrial Vegetation

Darby (1817) and Lockett (1969) were among the first to describe Louisiana's geography and generalize about plant distribution. In the mid-twentieth century, Penfound (1944) and Brown (1944) emphasized the relationships between plant distribution and geology and topography. Other similar studies have succeeded in qualitatively identifying vegetation associations and mapping them statewide on a small-scale base map or on a larger scale for a particular region or habitat type. A review of existing maps (Küchler and McCormick 1965, Chabreck et al. 1968, Eleuterius 1973a, Chabreck and Linscombe 1978) indicates that vegetation associations and distributions have been more thoroughly researched in Louisiana than in Mississippi.

The major terrestrial environments within the Deltaic Plain Region include natural levees, spoil deposits, and artificial levees; reclaimed wetlands; and beach/barrier islands. Bottomland hardwoods are sometimes considered a terrestrial habitat because they often experience prolonged dry conditions, but they are usually classified as wetlands because they require periodic flooding to maintain their characteristic vegetation association.

Virgin natural levee hardwood forests are rare in the Deltaic Plain Region because virtually all natural vegetation has been cleared to prepare the land for agriculture and development. One of the few studies of natural levee vegetation was undertaken by Penfound and Howard (1940). Their phytosociological study of a 50 year-old live oak forest near New Orleans revealed that live oak (*Quercus virginiana*) and water oak (*Quercus nigra*) were dominant but had as associates hackberry (*Celtis mississippiensis*), American elm (*Ulmus americana*), white ash (*Fraxinus americana*), honey locust (*Gleditisa triacanthos*) and hawthorn (*Crataegus* sp.). However, in view of Viosca's previous (1933) study of the area, Penfound and Howard (1940) concluded that there is considerable diversity in the composition of evergreen oak forests and that numerous studies are necessary to adequately describe this forest type.

Studies on vegetation succession have been directed toward abandoned farmlands on natural levees (Bonck 1942, Bonck and Penfound 1945), drained wetlands near New Orleans (Schneidau 1940), spoil deposits in coastal wetlands (Spindler and Noble 1974, Monte 1978), and artificial levees along the Mississippi River and Bonnet Carré Spillway (Montz 1972, 1973a). With regard to natural levees, it was decided that their vegetation would proceed toward a live oak climax forest after going through an annual weed stage, a perennial weed stage, and a shrub stage (Bonck 1942, Bonck and Penfound 1945). The draining of a wetland containing a cypress swamp and nearly fresh and brackish marsh communities resulted in the emergence of five major plant communities: *Baccharis halimifolia* (eastern baccharis), *Phragmites communis* (roseau cane [*P. australis*]), *Spartina patens* (wire grass), *Scirpus olneyi* (three-cornered grass), and *Solidago mexicana* (golden rod) (Schneidau 1940). The author's conclusion was that "the area has been transformed into a huge weed field which, in its present state, is practically worthless for wildlife" (Schneidau 1940:32).

Spindler and Noble (1974) found that low-lying spoil banks along canals in brackish marshes support eastern baccharis and roseau cane in addition to many of the same plants found in the surrounding wetland, e.g., wire grass, thoroughwort (*Eupatorium serotinum*), savi (*Vigna luteola*), salt marsh-mallow (*Kosteletzkya virginica*), salt marsh bulrush (*Scirpus robustus*). They concluded that as the spoil subsided to marsh level, the dominant marsh plants would reclaim the former spoil deposits as marsh land.

In contrast, Monte (1978) observed that the higher, more stable spoil deposits resulting from the dredging of rig cuts and pipelines "contain terrestrial, upland plant species which are succeeding toward a bottomland hardwood forest" (Monte 1978:xvi).

The major flood protection levees are maintained in an early successional state by mowing and grazing, and many of the species are nonnative (Montz 1972). Common species include: Johnson grass (*Sorghum halepense*), Bermuda grass (*Cynodon dactylon*), giant ragweed (*Ambrosia trifida*), pigweed (*Amaranthus* spp.), smut grass (*Sporobolus poiretii*), and Dallis grass (*Paspalum dilatatum*).

The barrier islands of Louisiana and Mississippi are subject to constant reworking by wind and wave action and all vegetation is exposed to salt spray on a frequent basis. The barrier islands of Louisiana are generally lower in elevation than those of Mississippi. The gulfward side of the islands consists of wide sand or sand and shell beaches with little vegetation; the foredunes are generally less than 3 m (10 ft) in elevation and contain salt-tolerant species such as sea oats (*Uniola paniculata*) and beach morning glory (*Ipomoea pescaprae*) (Environmental Laboratory 1978). Some of the larger Louisiana islands, such as Grand Isle, have live oak forests growing on the relic sand ridges on the bayward side of the island. The remaining barrier islands of Louisiana either have no forests or, as in the case of I'lle Derniere, the forests have been cleared (Waldo 1963). Salt marshes dominated by smooth cordgrass (*Spartina alterniflora*) and salt grass (*Distichlis spicata*) grow on the bayward side of these islands which are often fringed by mangroves (Avicennia germinans).

Portions of the larger barrier islands of Mississippi such as Cat Island and Horn Island have remained fairly stable over a long period of time and some have relic beach ridges over 9 m (30 ft) in elevation (Eleuterius 1979). A recent study (Eleuterius 1979) of Horn and Petit Bois Islands identified six vegetational units with characteristic species (Table 5-1).

For a more complete listing of species present on barrier islands in the Region, especially with regard to temporal changes and brief notes on environmental conditions, see Lloyd and Tracey (1901), Brown (1930), Behre (1950), Lemaire (1961), Thompson (1965), Huguley and Eleuterius (1976), Gould and Ewan (1975), Miller (1975), Waller and Malbrough (1976), Montz (1977a), and Stoneburner (1978).

Table 5-1. Major vegetational units and associated species present on Horn and Petit Bois Islands, Mississippi (Eleuterius 1979).

Vegetational Unit	Vegetation Species
Beach dune	Beach morning glory (Ipomoea stolonifera) Sea oats (Uniola paniculata) Bluestem (Andropogon maritimus) Dog tooth grass (Panicum repens)
Relic dunes	Live oak (Quercus geminata) Yaupon (Ilex vomitoria) Golden rod (Solidago pauciflosculosa)
Woodland	Slash pine (Pinus elliottii) Live oak (Quercus geminata) Umbrella-grass (Fuirena scirpoidea) Wax myrtle (Myrica cerifera)
Meadow or high marsh	Umbrella-grass (Fuirena scirpoidea) Dog tooth grass (Panicum repens) Broomsedge bluestem (Andropogon virginicus)
Tidal or freshwater marsh	Wire grass (Spartina patens) Black rush (Juncus roemerianus) Roseau cane (Phragmites communis)* Cattail (Typha angustifolia)
Pond or lagoon	Widgeongrass (Ruppia maritima) Wild celery (Vallisneria americana) Stonewort (Chara sp.) Cattail (Typha spp.)

*Now listed as Phragmites australis

Wetland Vegetation

Bottomland hardwoods. One of the earliest reports on Gulf coast forest distribution in relation to flooding was done by Mohr (1833). Subsequent forest studies have continued to concentrate primarily on the distribution of vegetation with reference to the hydrologic regime and post-flood succession. Putnam and Bull (1932) wrote one of the first in-depth descriptions of various swamp-bottomland hardwood habitats in the Lower Mississippi Valley and detailed the relationship between the distribution of forest types and the existing hydrologic regime (Table 5-2). Similar studies on distribution in relation to flooding tolerances of individual species in the Mississippi River Valley have also been reported by Shelford (1954), Applequist (1960), McKnight (1966), and Thieret (1971), and within the Atchafalaya Basin by Jennings and O'Neil (1976). Bottomland hardwood forests often constitute the ecotone between the poorly drained backswamps and the better-drained upland forests. The composition of this forest type varies according to its location within the floodplain as illustrated in the following diagrams (Figures 5-4 through 5-7).

The extensive Mississippi River flood of 1927-1928 provided an excellent opportunity to study vegetation survival and succession after the floodwaters receded. Brown (1929) found that typical batture vegetation such as black willow (*Salix nigra*), sandbar willow (*Salix interior*), cottonwood (*Populus deltoides*), sycamore (*Platanus occidentalis*), swamp-privet (*Forestiera acuminata*), water locust (*Gleditsia aquatica*), peppervine (*Ampelopsis arborea*), heartleaf peppervine (*Ampelopsis cordata*), saw greenbriar (*Smilax bona-nox*), nutgrass (*Cyperus esculentus*), poison ivy (*Rhus radicans*), southern dewberry (*Rubus trivialis*), blackberry (*Rubus* spp.), and perennial aster (*Aster tenuifolius*) withstood the effect of full or partial submergence. The opening of the Bonnet Carré Floodway also revealed the impact of flooding and sedimentation on vegetation. Howard (1939) and Howard and Penfound (1942) observed that alluvial deposits greater than 0.3 m (1 ft) killed virtually all herbaceous plants; a significant amount of shrubs, seedling trees, and vines; and a few sapling trees. Shrubs were killed by floodwaters, but trees greater than 15 cm (6 in) in diameter survived. A later study by Montz (1970) concurred with previous findings and concluded that a greater number of herbs, vines, semi-woody herbs, shrubs, and saplings were damaged by alluvial deposits than by floodwaters. The mature trees (sandbar willow, black willow, cottonwood, sycamore, and roughleaf dogwood [*Cornus drummondii*]) near the river were not affected by alluvial deposition less than 0.6 m (2 ft).

Swamps

One of the more comprehensive descriptions of southern swamps of the Mississippi Deltaic Plain Region was prepared by Penfound (1952) (Table 5-3). Examples of the deep and shallow water swamps are found in both Mississippi and Louisiana, while peaty swamps are most common in Mississippi, and saltwater swamps (black mangroves [*Avicennia nitida*]) are exclusively situated in Louisiana. The major component of the deep water swamps, baldcypress (*Taxodium distichum*), was one of the earliest species to be described (de Cubieres 1809, Bush 1897), and research on its characteristics and ecological requirements has continued to the present (Mattoon 1915, Demaree 1932, Kurz and Demaree 1934, Kennedy 1972).

Table 5-2. Distribution of forest cover types in the Mississippi Deltaic Plain Region (Putnam and Bull 1932).

Forest Cover Type	First Bottoms								Second Bottoms			
	River margins	Loamy ridges	Clay ridges	Washboardy sites	Flats[a]	Very low, very poorly drained, tight clay flats	Swags and drains	Swamps and sloughs	Loamy ridges	Washboardy sites	Loamy flats[a]	Borders of tidal marshes
Oak hickory		2		1					4	2	2[d]	
Loblolly pine-hardwood									2	2		
Cottonwood	4	2[b]										
Red gum-loamy ridge oaks		4		2					3	1		
Red gum		3	4	2	2		2				2	
Willow oak-cherrybark oak-cow oak				4						4		
Willow oak							2			3	4	
Oak-elm-ash				2	4	2	2		3	2	2	
Red gum-clay land oaks			4	2	4	1	2			1	2	
Hackberry-elm			2	2	4	2					2	
Southern cypress-hardwood			1	2	3[c]	1	3	2				
Willow	4						1	3				
Overcup oak-water hickory					2	4	3	2			2	
Southern cypress	1				1			4				
Tupelo gum					1			4				
Live oak												4

1 = rare; 2 = occasional; 3 = common; 4 = very common

[a] flats in both first and second bottoms vary considerably both in texture of soil and in drainage, and accordingly support nearly as great a variety of types as the washboardy or hummocky sites which are a mixture of ridge and flat conditions. Types featured by red gum, cypress, and elm occupy the flats with the more pervious soils, and the quality and growth of the oaks is better on such flats than on the very impervious flats.

[b] mainly old fields on front ridges

[c] mainly in northern Arkansas and southern Louisiana

[d] only in Arkansas and Missouri

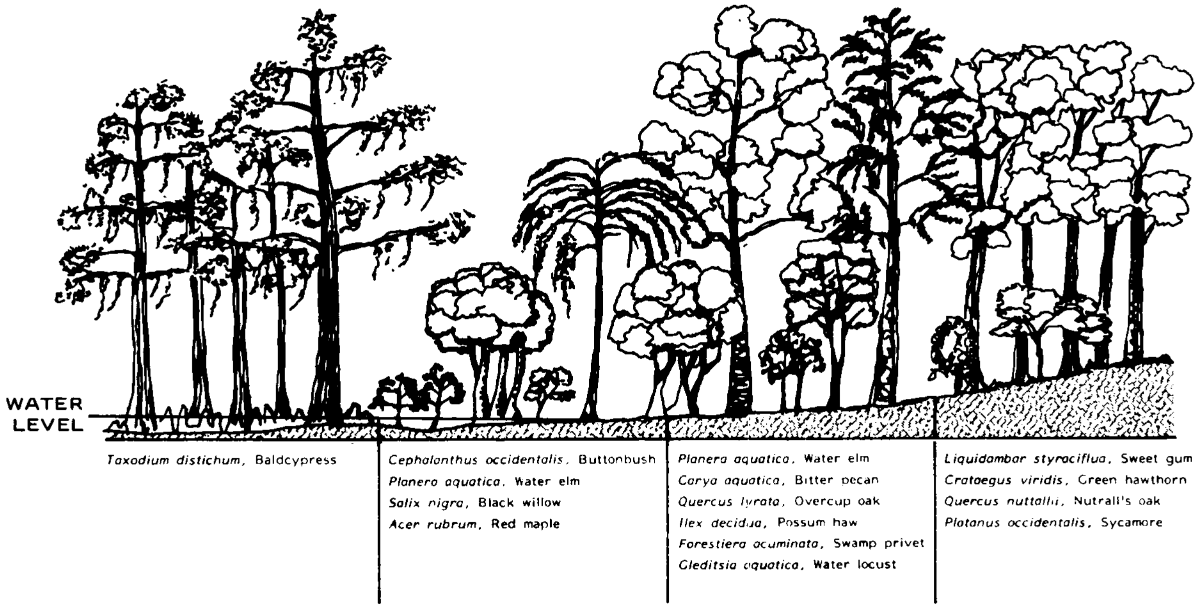


Figure 5-4. Transition from swamp through bottomland hardwoods complex in the northern portion of the Mississippi Deltaic Plain Region (Environmental Laboratory 1978).

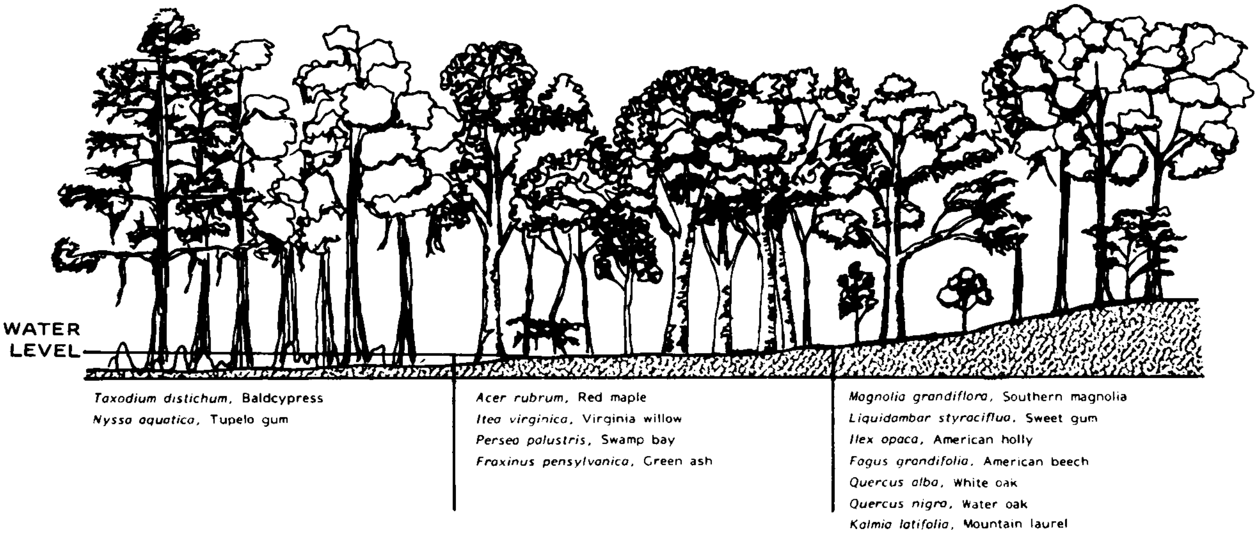


Figure 5-5. Transition from swamp through bottomland hardwoods complex into upland in the southern portion of the Mississippi Deltaic Plain Region (Environmental Laboratory 1978).

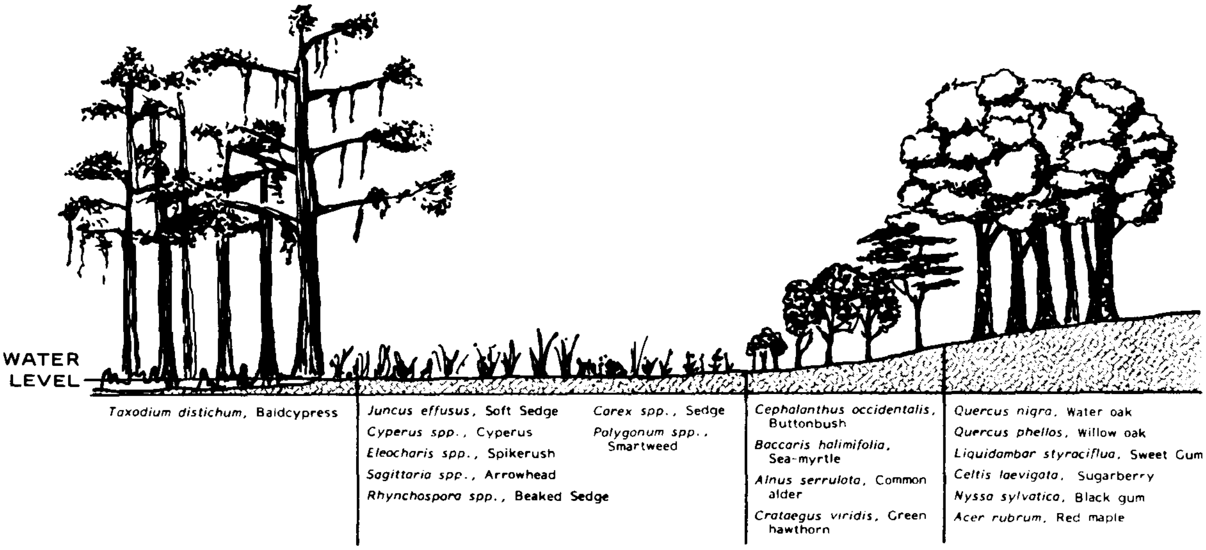


Figure 5-6. Transition from swamp to wet meadow into bottomland hardwoods (Environmental Laboratory 1978).

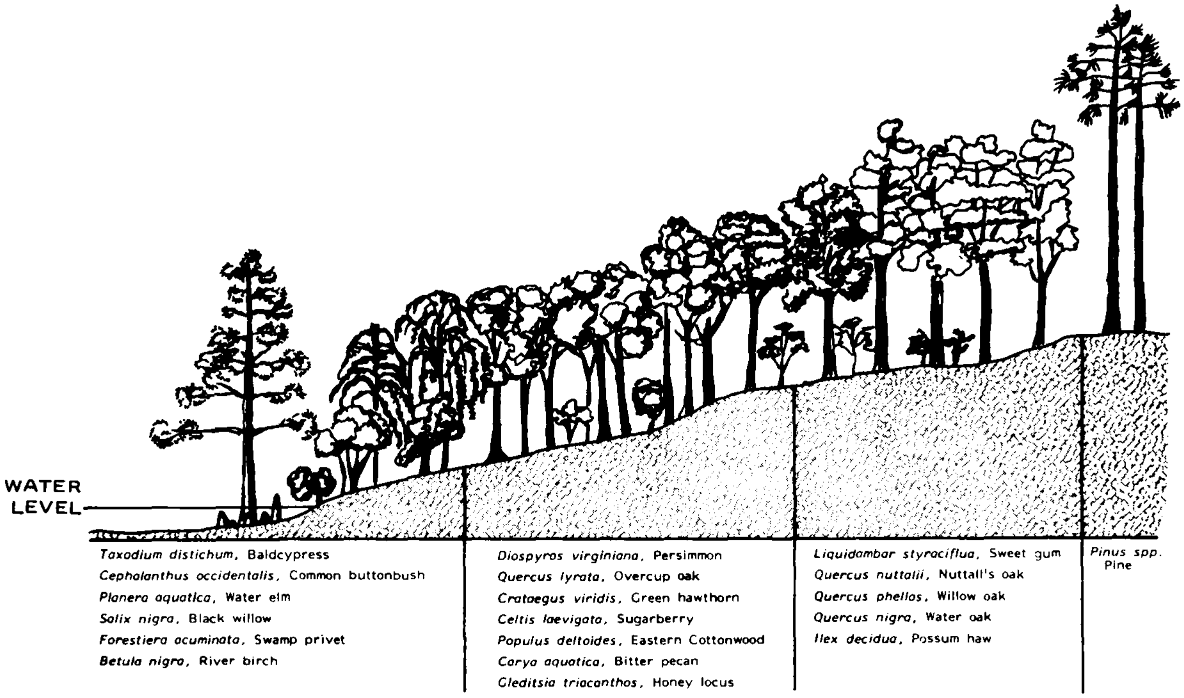


Figure 5-7. Transition from riparian swamp through first- and second-bottoms and into upland (Environmental Laboratory 1978).

Table 5-3. List of major types of southern swamps (Penfound 1952).
(Note: Common and scientific names are cited as given by Penfound 1952.)

FRESH WATER SWAMPS

Deep Swamps: fresh water, woody communities, with surface water throughout most or all of the growing season.

a. Southern cypress-tupelo gum
   (*Taxodium distichum*-*Nyssa aquatica*)
b. Swamp gum-pond cypress
   (*Nyssa biflora*-*Taxodium ascendens*)

Shallow Swamps: fresh water, transitional woody communities, the soil of which is inundated for only short periods during the growing season.

a. Black willow-sandbar willow
   (*Salix nigra*-*Salix interior*)
b. Buttonball-dogwood-willow
   (*Cephalanthus*-*Svida*-*Salix*)
c. Overcup oak-water hickory
   (*Quercus lyrata*-*Hicoria aquatica*)
d. Hackberry-elm-ash
   (*Celtis*-*Ulmus*-*Fraxinus*)
e. Maple-red gum- oak
   (*Rufacer*-*Liquidambar*-*Quercus*)
f. Alder-birch
   (*Alnus*-*Betula*)

Peaty Swamps: oxylic, peat-forming, sclerophyllus woody communities, with surface water only during a part of the growing season.

a. Red bay-sweet bay
   (*Tamala pubescens*-*Magnolia virginiana*)
b. Pond pine-slash pine
   (*Pinus serotina*-*Pinus caribaea*)
c. Southern white cedar
   (*Chamaecyparis thyoides*)
d. Evergreen shrub swamp
   (*Ilex*-*Cyrilla*-*Zenobia*)

SALT WATER SWAMPS

Salt Water Swamps: woody plant communities in brackish or saline habitats.

a. Mangrove swamps (usually with surface water)
   Red mangrove (*Rhizophora mangle*)
   Black mangrove (*Avicennia nitida*)

b. Transitional communities (usually without surface water)
   Button wood (*Conocarpus erecta*)
   Buckbrush-marsh elder (*Baccharis*-*Iva*)

Transferral of swamplands from the Federal government through State governments to private interests and development of swamp lumbering technology in the late nineteenth and early twentieth centuries resulted in massive clearing of virtually all southern cypress swamps (Rugan 1911, Mims 1945, Mancil 1972). A few studies have dealt with natural and man-made efforts to restore these swamp forests (Rathborne 1951) and to manage them as a renewable resource (Langdon 1958, Johnson 1973, Krinard and Johnson 1976). Gum, including black tupelo (*N. sylvatica*), swamp tupelo (*N. sylvatica* var. *biflora*), and water tupelo (*N. aquatica*), have also been studied extensively by foresters interested in their second growth yield (Hadley 1926), seed germination (Shunk 1939), and soil and water requirements (Kennedy 1969, 1970).

Ecological studies of the cypress-tupelo gum communities in southeastern Louisiana were done by O'Neill (1931), Hall (1938), Hall and Penfound (1939), and Montz and Cherubini (1973). The study by Montz and Cherubini (1973) concluded that cypress with a salinity tolerance of 0.0% to 0.89% had extended its range shoreward into the St. Charles marsh, possibly in response to changing hydrologic conditions associated with construction of the Illinois railroad in the 1830s. However, increasing salinities resulting from inundation by the 1915 hurricane and construction of the Mississippi River-Gulf Outlet in 1962 (which raised Lake Pontchartrain chloride concentrates three times higher than in the 1959-1961 period) resulted in a 56% cypress mortality.

In recent years, many swamp ecology studies have focused on the Upper Barataria Basin, Louisiana, and have involved productivity (Conner 1975, Conner and Day 1976), nutrient assimilation (primarily agricultural inputs), and nutrient export to adjacent water bodies (Butler 1975, Day et al. 1977, Kemp 1978). Conner and Day (1976) investigated the composition and productivity of the 50 to 95 year-old second growth Lac des Allemands cypress-tupelo gum swamp in the Upper Barataria Basin. By comparing the productivity of the bottomland hardwood forest (Table 5-4) with the cypress-tupelo gum swamp (Table 5-5), they found that the hardwood forest was slightly more productive than the former Mississippi River overflow swamp (Table 5-6). The authors concluded that the higher growth rate may be due to the hardwood forest's younger age and the fact that water does not flow through the swamp as efficiently as it did prior to leveeing of the Mississippi River.

Marshes

The most recent compilation of marsh acreage figures (Chabreck 1972) shows that these wetlands in southeastern Louisiana (Hydrologic Units 1 through 7 [Chabreck 1972]) consist of 189,040 ha (466,766 ac) of saline marsh, 260,630 ha (643,531 ac) of brackish marsh, 85,365 ha (210,779 ac) of intermediate marsh, 214,550 ha (529,753 ac) of fresh marsh, and 28,819 ha (71,158 ac) of dewatered marshlands. In contrast, there are only 25,913 ha (63,982 ac) of nonfresh marshes, 333 ha (832 ac) of fresh marshes on the Mississippi mainland, and 861 ha (2126 ac) of salt marshes on the barrier islands (Eleuterius 1972). The individual marsh zones in both Louisiana and Mississippi contain basically the same vegetation associations (Tables 5-7 and 5-8). One major difference is that blackrush is a major component in the saline marshes of Mississippi (Eleuterius 1973a), whereas smooth cordgrass is the dominant species in the Louisiana salt marshes (Chabreck 1972). Marsh studies within the Deltaic Plain Region include plant lists, descriptions, distributions, maps, and an explanation of ecological relationships. A

Table 5-4. Overstory of the Lac des Allemands bottomland hardwood forest (Conner and Day 1976).

Scientific Name	Common Name
Acer rubrum var. drummondii	Drummond red maple
Nyssa aquatica	Water tupelo
Acer negundo	Box elder
Populus heterophylla	Box elder
Taxodium distichum	Baldcypress
Cornus drummondii	Swamp dogwood
Salix nigra	Black willow
Ulmus americana	American elm
Carya ovata	Shagbark hickory
Fraxinus tomentosa	Pumpkin ash
Quercus nigra	Water oak
Celtis laevigata	Hackberry
Diospyros virginiana	Persimmon
Ilex decidua	Deciduous holly
Carya cordiformis	Bitternut hickory
Quercus shummardii	Shumard red oak
Liquidambar styraciflua	Sweetgum
Forestiera acuminata	Swamp-privet
Quercus nuttallii	Nuttall oak
Persea palustris	Swamp bay persea
Styrax americana	Snowbell
Quercus laurifolia	Laurel Oak
Sambucus canadensis	Elderberry

Table 5-5. Overstory of the Lac des Allemands baldcypress-water tupelo swamp (Conner and Day 1976).

Scientific Name	Common Name
Taxodium distichum	Baldcypress
Nyssa aquatica	Water tupelo
Acer rubrum var. drummondii	Drummond red maple
Fraxinus tomentosa	Pumpkin ash
Cephalanthus occidentalis	Button bush
Celtis laevigata	Hackberry
Salix nigra	Black willow
Fraxinus caroliniana	Carolina ash
Styrax americana	Snowbell

Table 5-6. Measured and estimated values of net productivity for the bottomland hardwood (BLHD) and baldcypress-water tupelo (CT) areas (Conner and Day 1976).

	BLHD g dry wt/m^2/yr	CT g dry wt/m^2/yr
Measured		
Stem biomass increase	800	500
Leaf litter	574	620
Understory production	200	20
Total net production	1574	1140
Estimated		
Understory production	312	312
Insect consumption	47	84
Total estimated net primary productivity	1933	1536

Table 5-7. Vegetation species characterizing the marsh zones in southeastern Louisiana (Chabreck 1972).

Scientific Name	Common Name
Saline	
Spartina alterniflora	Smooth cordgrass
Distichlis spicata	Salt grass
Juncus roemerianus	Black rush
Spartina patens	Wire grass
Brackish	
Spartina patens	Wire grass
Distichlis spicata	Salt grass
Intermediate	
Spartina patens	Wire grass
Phragmites australis	Roseau cane
Sagittaria falcata	Bull tongue
Fresh	
Panicum hemitomon	Maiden cane
Sagittaria falcata	Bull tongue
Eleocharis sp.	Spikerush
Alternanthera philoxeroides	Alligatorweed

Table 5-8. Selected vegetation species characterizing the marsh zones in Mississippi (Eleuterius 1973a).

Scientific Name	Common Name
Saline	
Juncus roemerianus	Black rush
Spartina alterniflora	Smooth cordgrass
Spartina cynosuroides	Hogcane
Spartina patens	Wire grass
Scirpus olneyi	Three-cornered grass
Salt Flats	
Distichlis spicata	Salt grass
Salicornia bigelovii	Bigelow glasswort
Suaeda linearis	Sea-blite
Batis maritimus	Saltwort
Brackish	
Spartina cynosuroides	Hogcane
Spartina alterniflora	Smooth cordgrass
Juncus roemerianus	Black rush
Spartina patens	Wire grass
Intermediate	
Phragmites australis	Roseau cane
Scirpus validus	Softstem bulrush
Cladium jamaicensis	Sawgrass
Sagittaria latifolia	Duck potato
Fresh	
Eleocharis cellulosa	Gulf spikerush
Eleocharis obtusa	Blunt spikerush
Crinum americanum	Swamp lily
Saururus cernuus	Lizards tail
Sagittaria latifolia	Duck potato
Iris virginica	Southern-blue flag

distribution and description of Louisiana's marsh flora has been published by Sperry (1949). An illustrated guide to common wetland plants of Louisiana was recently published by the U.S. Army Corps of Engineers (USACE), New Orleans District (1977), and descriptive guides showing the relationship between marsh plants and the Gulf coast environment were prepared by Gosselink et al. (1977) and the Environmental Laboratory (1978). Eggler (1955, 1961) described the vascular flora of the Grand Bayou Blue area, Lafourche, Louisiana; Texas A&M (1960) and Giles (1968) did a similar study including vegetation maps of the St. Bernard Parish wetlands. Major marsh zones were mapped in Louisiana by Chabreck et al. (1968), Chabreck and Linscombe (1978), O'Neil (1949), and in Mississippi by Eleuterius (1973a). The wetland flora of Mississippi has also been described by Jones (1974, 1975). Comparative discussions of marsh species and productivity along the Gulf and Atlantic coasts have been written by Linton (1968), Eleuterius (1971a, 1972), and Smith and Monte (1975), de la Cruz (1973, 1974), Gabriel and de la Cruz (1974), and Kirby (1971). De la Cruz (1974:353) concluded that "compared to salt marshes in the South Atlantic coast, ... the Mississippi marshes are more dense and diverse, and are, in general, slightly more productive."

In the 1960s, research began to concentrate on the ecological relationships, controlling factors, and functions of marsh environments. Shiflet (1963) reviewed the ecological factors controlling plant communities in Louisiana marshes. Other researchers (Palmisano 1970, Palmisano and Chabreck 1972) investigated the relationship between variations in marsh soil types and plant distribution. Palmisano and Chabreck (1972) concluded that salinity and soil organic matter are the principal factors affecting plant growth and distribution. They also discovered that soil organic matter was lowest and water salinity and total soil salts were highest near the coast in the vicinity of salt marshes. Moving inland toward the fresh water marshes, soil organic matter increased while water salinity and total soil salts decreased. Vegetation succession in Atlantic and Gulf coast marshes has been studied (Uhler and Hotchkiss 1968), as have recent changes in the marshlands adjacent to Vermilion Bay (Eleuterius 1971a). In the 1970s, energy flow (Hacker et al. 1971), productivity and decomposition (Nelson, F. R., ongoing research), and coastal wetland functions (de la Cruz 1976) have come under investigation. Ecological relationships between wetland flora and fauna are also a current topic of interest in Louisiana (Newson et al., ongoing research).

There have been numerous descriptive vegetation studies of salt marshes in Louisiana and Mississippi. Thorne (1954) described the flowering plants, both emergent and submergent, along the Gulf of Mexico and included an extensive bibliography of specific plants. The distribution, abundance, and diversity of Louisiana salt marsh vegetation have been studied in Plaquemines Parish (Ekvall 1930), around Bayou Bienvenue (Center for Wetland Resources 1972), in the Mississippi River-Gulf Outlet (Montz 1973b), and in Lower Bayou Lafourche (Whitehurst 1975). Virtually all of the research on the composition and distribution of Mississippi salt marshes has been conducted by Eleuterius. His work includes general marsh descriptions (Eleuterius, L. N., ongoing research (a), Eleuterius and McDaniel 1978), population variations in Juncus roemerianus marshes (Eleuterius 1977, 1978), and salt marsh and submerged aquatic population studies (Eleuterius, L. N., ongoing research (b). Vegetation succession in Louisiana salt marshes was discussed briefly by Walker (1940), and Turner (1976) investigated the relationship between variations in Louisiana geography and production of salt marsh macrophytes.

Ecological salt marsh studies in Louisiana and Mississippi include an analysis of their distribution with regard to salinity (Hathaway 1936, Penfound and Hathaway 1938, Giles 1968, Gosselink 1970, Palmisano 1970, Chabreck 1972, Smalley and Thien 1976, Parrondo et al. 1977) and tidal inundation (Hinde 1954, Sasser 1977). For information on the salt tolerance of various plants, see Penfound and Hathaway (1938) and Chabreck (1972). Major research on productivity, decomposition, detrital formation, and energy flow in coastal Louisiana marshes, primarily Scirpus and Spartina marshes, was undertaken in the 1970s by persons associated with the Louisiana State

University wetlands program (Day et al. 1973, Gosselink and Kirby 1974, Kirby and Gosselink 1976, Hopkinson et al. in press, Meyers, ongoing research). Comparable studies, many of which emphasize Juncus marshes, have been undertaken by researchers associated with the Gulf Coast Research Laboratory in Mississippi (de la Cruz 1974, Gabriel and de la Cruz 1974, Eleuterius 1974, de la Cruz and Hackney 1977, Hackney 1977).

Distribution of species within a fresh marsh with regard to landform age and elevation has been researched in the emerging Atchafalaya River Delta (Montz 1976), at Southwest Pass (Montz 1977b), at Sawdust Bend, in the present Mississippi Delta (Leatherman 1970), and in the East St. Charles Parish marsh (Montz 1970). Montz (1976) observed that elevation, drainage patterns, edaphic, and biotic factors were important in determining species distribution in the emerging freshwater Atchafalaya River Delta. Ridge associations characterized by eastern baccharis, sandbar willow, golden rod, and Bermuda grass developed at elevations above 0.5 m (1.66 ft) mean sea level (MSL), while marshes characterized by duck potato (Sagittaria latifolia and Sagittoria platyphylla), Walter's millet (Echinochloa walteri), spikerush (Eleocharis spp.) and cyperus (Cyperus spp.) occurred between 0.3 m (0.98 ft) and 0.4 m (1.37 ft) MSL. In Southwest Pass, marshes with dwarf spikerush (Eleocharis parvula) as an indicator species occupied lands up to 0.6 m (1.96 ft) MSL, and shrub zones with eastern baccharis as an indicator species developed on higher elevations.

Another recent study evaluated the distribution of roseau cane (sometimes considered an intermediate to brackish marsh species) in coastal Louisiana with regard to landform elevation and salinity (Luelling 1979). Valentine (1965) investigated plant succession in an intermediate marsh of southwest Louisiana following extensive sawgrass mortality.

Fresh marshes in Mississippi compose less than 400 ha (988 ac) of coastal wetlands and have been described only briefly (Eleuterius 1973a). The floristics and ecology of the inland coastal bogs were discussed by Eleuterius (1968), who, along with Jones (Eleuterius and Jones 1969), also described Mississippi pitcher plant bogs. The pitcher plant bogs, closely associated with coastal fresh marshes, appear on open grasslands sparsely populated by pine with scattered cypress, sweet bays, wax myrtles (Myrica cerifera), virginia chain fern (Woodwardia virginica), pitcher plants (Sarracenia spp.), spikerushes (Eleocharis spp.), and a variety of grasses (U.S. Department of Interior [USDI] 1955). Many have been drained for pasture, and while they have an insignificant value for waterfowl, they are important to passerine and wading birds, quail, and small mammals (USDI 1955).

Aquatic-Marine Vegetation

Phytoplankton. Studies on Mississippi Deltaic Plain Region aquatic microflora began to appear in the literature around the mid-1950s. The major areas of research center on the Pontchartrain, Atchafalaya, and Barataria Basins, St. Louis Bay, Mississippi Sound, and the Lower Mississippi Delta. The primary research topics include productivity (Thomas et al. 1957, Bogdanov et al. 1968), carbon cycles (Malkana 1968), phytoplankton distribution (Felder 1975, Housely 1976, Sager 1976, Holland 1977, Sullivan 1977, Williams et al. 1977, Hern et al. 1978), and microflora identification (Simmons and Thomas 1962; Cook, L. L., Department of Botany, Louisiana State University, Baton

Rouge, personal communication 1978; Bahr and Stone, ongoing research). Darnell (1962) studied the trophic spectrum of Lake Pontchartrain, while Brown (1973) and Magee (1973a, b, c) considered the microflora and food webs in St. Louis Bay.

Theriot (1978) investigated limnology and phytoplankton ecology in Atchafalaya River impoundments. Other limnological studies have been conducted in Grand Lake, Atchafalaya Basin (Dotson 1966), and Bryan and Herke maintain ongoing research on the Basin. Studies on the aquatic ecology of brackish marshlands (Cali 1972), fresh water impoundments in saline marshes (Conner and Truesdale 1972), temporary ponds (Moore 1970), and salt marsh ponds (Hewatt 1953) have also been published. Sullivan (1978) investigated the taxonomy and community structure of diatoms on seagrasses in Mississippi Sound and is currently studying the environmental parameters affecting salt marsh diatoms.

Within recent years, yeasts and bacteria have come under closer scrutiny. Research has been carried out on the yeasts found in the Barataria Basin and Mississippi salt marshes and their role in the aquatic food chain (Ahearn et al. 1970, Meyers and Ahearn 1972, Goter 1973, Meyers and Eleuterius 1974). Identification and distribution of various types of bacteria in Barataria Bay (McCleaskey and Valentine 1955, 1956), St. Louis Bay (Graves 1972), Mississippi Sound (Priddy and Johnson 1966), the Mississippi River (Rai and Hill 1977), and estuaries in the Delta (Hood and Meyers 1973, 1974) have also contributed to an understanding of the estuarine environment in recent years.

Floating aquatics. Most of the research on floating aquatics (especially water hyacinths and alligatorweed) in the Mississippi Deltaic Plain Region has centered on their control or eradication (Geagan 1954, Thompson 1972, Gangstad 1974). However, Russell (1942) discussed the distribution and composition of floating fresh water marshes or flotant in Louisiana in terms of coastal geomorphology, and Clark (1970) published a study on Lemnaceae of Louisiana.

Submerged aquatics. Seagrasses have been studied in terms of their distribution, the ecological factors affecting this distribution, and their value in the food chain. Humm (1956) and Pecora (1977) identified the seagrasses in the Gulf of Mexico and Eleuterius (1971b, 1973b) discussed the distribution of submerged vegetation in Mississippi Sound. Eleuterius (1973b) noted that the major seagrasses (turtlegrass [*Thalassia testudinum*], shoalgrass [*Halodule beaudettei*], manatee grass [*Cymodocea filiformis*], Gulf halophila [*Halophila engelmannii*]) growing on sandy bottoms in shallow waters shoreward of the Louisiana and Mississippi barrier islands are a valuable marine resource because they: 1) provide a stable habitat for invertebrates and juvenile fish; 2) provide a stable substrate for epiphytic algae, fungi, bacteria, and protozoa; 3) filter out organic materials by slowing water movement; 4) create a stable bottom by binding bottom sediment; 5) create detritus, an important component of the food chain; and 6) aerate the surrounding seawater through photosynthesis.

Eleuterius and Miller (1976), also observed that Hurricane Camille destroyed 58% (4727 ha [11,676 ac]) of the seagrasses behind the Mississippi barrier islands in 1969. Between 1972 and 1975, an additional 16% of the beds were lost because of the low salinity associated with high rainfall and high river discharge.

Montz described and mapped or located submerged aquatics in Vermilion Bay (1977c) and Lake Pontchartrain (1975, 1978). In 1979 he prepared a brief report on the distribution of selected aquatic species in Louisiana, and is currently working on a more comprehensive study (Montz, G. N., ongoing research). Factors such as water salinity and water levels which affect the distribution of widgeon grass have also been closely studied because of its value as a waterfowl food (Bourn 1935, Joanen 1964, Mayer and Low 1970). The role of eel grass (Zostera marina) in the estuarine ecosystem has also been explored in terms of its nutritive value to aquatic organisms (Cottam and Munro 1954).

INFORMATION DEFICIENCIES

The distribution of major vegetation associations or habitat types within the Mississippi Deltaic Plain Region has been fairly well delineated and mapped within the coastal zone in Louisiana and is in the process of being mapped in coastal Mississippi. The relationship between the dominant species and critical environmental parameters in each habitat, such as soil and water salinity, elevation, hydrologic regime, soil composition, etc., have also been identified in many instances. However, additional knowledge of the relationships between species distribution and environmental parameters, especially those associated with human activity (such as leveeing, draining, channelization, spoil deposition, dredging, etc.) is needed. Fresh to intermediate marshes have not been as thoroughly studied in these terms as have salt marshes.

The distribution and function of mangroves in the estuarine environment also needs further study because Louisiana is their northernmost distribution in the United States and because in other areas mangroves constitute a vital detritus source within the food chain. Because coastal Louisiana and, to a lesser extent, Mississippi, are in a state of constant change due to shoreline erosion, subsidence, channelization, leveeing, and saltwater intrusion, the individual and aggregate effects of these processes on local flora demand increased study. Until the natural effects of these actions are better understood, it will be difficult, if not impossible, to assess the impact of man's actions on coastal flora or to manage for a specific, man-desired habitat. An example of such a dilemma involves the baldcypress, which has failed to reestablish itself in some areas where it has been clearcut. Attempts to reestablish natural cypress stands in areas where they are desirable will be difficult without understanding the reasons behind failure to regenerate.

The impact of leveeing, spoil deposition, and road embankments on coastal wetlands has never been fully documented. Reclaimed and abandoned wetland reclamation sites are common in coastal Louisiana and Mississippi, yet the impact of these landuse actions is not well-documented with regard to the overall loss of wetland productivity.

There is much evidence of wetland loss in coastal Louisiana that is attributed to saltwater intrusion related to canal dredging. However, documentation of increases in salinity is scarce, and the impact of these increases on less salt-tolerant species, especially the fresh-floating marshes of Louisiana, is not clear. Some wetland loss may be due to natural or man-induced (mineral extraction) subsidence or to deprivation of transport of riverborne sediment to these areas, but the relative impacts of these actions have not been investigated.

While the role of brackish and saline marshes in the estuarine system is fairly well-known, that of fresh and intermediate marshes is not well-understood. In view of the attempt to mitigate wetland losses due to man-made changes in the landscape, it is imperative that each of the wetland habitats be thoroughly investigated with regard to its function, requirements, and relative value as a habitat type for humans and wildlife.

RECOMMENDATIONS

There are more data available for the Louisiana wetlands than for wetlands in Mississippi. This is especially true with regard to baseline data on the distribution and interrelationships of salinity, tidal influence, marsh vegetation, swamps, and bottomland hardwoods.

The following are recommendations for further study in both Louisiana and Mississippi:

1) Inventory reclaimed wetlands with regard to their extent and present condition or use, and evaluate their effect on the total wetland ecosystem.

2) Determine factors influencing distribution of mangroves in the Mississippi Deltaic Plain Region and define their function in the environment.

3) Determine factors that influence distribution of marsh species. Determine parameters that influence succession of marsh types. For example, with regard to increasing salinity in fresh marshes and swamps, what factors determine whether the area will become open water or succeed into intermediate or brackish marsh types.

4) Determine the impact on wetlands of structural forms that disrupt surface drainage patterns such as spoil deposits, roads, and levees.

5) Determine the individual and cumulative impacts on wetland species and associations of flood control leveeing, spoil deposition, canal dredging, saltwater intrusion, and short-circuiting of sediment nutrients.

6) Determine factors which promote natural regeneration of cypress.

7) Determine the effect of water hyacinths and other floral exotics on the total wetland ecosystem.

8) Determine conditions necessary for marsh establishment by means of management practices such as controlled Mississippi River diversions.

9) Determine the value of wetlands to the total biological environment in terms of function and monetary return in order to evaluate the effects of wetland destruction.

In Mississippi, more fieldwork should be undertaken to determine:

1) The extent and composition of wetland habitats.

2) The distinctions between wetland and nonwetland habitat areas.

3) The distribution of submerged estuarine and marine aquatics (present maps are very general).

4) The distribution and ecology of wetlands that are related to overbank flooding of major river systems in upland areas.

FISHERIES

INTRODUCTION

The fisheries of the Mississippi Deltaic Plain Region represent a valuable renewable resource. Collectively, commercial fisheries landings of the Deltaic Plain Region and Louisiana's portion of the adjacent Chenier Plain Region are exceptional when compared with other regions, accounting for 20% or more of the United States total during most years since 1960 (Gunter 1967). The magnitude of the fisheries resources is exemplified by the Louisiana landings which in 1975 were greatest of all states in volume (1.1 billion pounds) and ranked fourth in value ($89 million) (U.S. Department of Commerce 1976). During 1975, the Deltaic Plain Region in particular accounted for at least 67% of the value of Louisiana's landings (U.S. Department of Commerce 1976). Accordingly, the Deltaic Plain-Louisiana Chenier Plain Complex, of which the Deltaic Plain comprises the greater part, has been called the "fertile fisheries crescent" (Gunter 1963) and recognized as one of the largest estuarine zones in North America and among the world's most productive fishery areas (Gunter 1967).

The major fishery species consist of one crustacean and at least 10 fishes which spawn in fresh waters; one mollusk, 3 crustaceans, at least 10 fishes considered estuarine; and at least 8 fishes which are basically marine (Table 5-9). Four of these species are harvested mainly for sport, 11 are of strictly commercial importance, and the majority (19 species) are utilized jointly by sport and commercial industries.

Penaeid shrimps (Penaeus spp.) are the most valuable Louisiana fishery species in this region, the value of the catch exceeding $30 million annually since 1969 (approximately 46% of the total value in 1975) (U.S. Department of Commerce 1969-1975). On the average, shrimp are followed in value by Gulf menhaden (an industrial species used for animal food; 33% of the value), American oyster (8%), fresh water crawfish (4%), blue crab (3%), and fresh water catfish (3%). The value of the sport fishery has not been adequately reported to date, but considering all economic aspects (including the invertebrate sport fishery for shrimp, crab, and crawfish), it probably approaches the commercial value (Harvath 1974, Soileau et al. 1975). Popular sport fishes include such fresh water forms as largemouth bass and black crappie (sac-a-lait); the estuarine species, spotted seatrout (speckled trout) and red drum (redfish); and marine fishes of the nearshore Gulf of Mexico, Spanish

Table 5-9. Major fishery species of the Mississippi Deltaic Plain Region.

Fresh-Brackish (spawn in fresh water, < 0.5 ppt)		
Procambarus clarkii	Red swamp crawfish	CS*
Lepisosteus oculatus	Spotted gar	C
L. spatula	Alligator gar	C
Dorosoma cepedianum	Gizzard shad	C
Ictiobus bubalus	Smallmouth buffalo	C
I. cyprinellus	Bigmouth buffalo	C
Ictalurus furcatus	Blue catfish	CS
I. punctatus	Channel catfish	CS
Micropterus salmoides	Largemouth bass	S
Pomoxis nigromaculatus	Black crappie (Sac-a-lait)	S
Aplodinotus grunniens	Freshwater drum	C
Fresh-Brackish-Saline (Estuarine)		
Crassostrea virginica	American oyster	C
Penaeus aztecus	Brown shrimp	CS
P. setiferus	White shrimp	CS
Callinectes sapidus	Blue crab	CS
Brevoortia patronus	Gulf menhaden	C
Cynoscion arenarius	Sand seatrout	C
C. nebulosus	Spotted seatrout (Speckled trout)	CS
Leiostomus xanthurus	Spot	CS
Micropogonias undulatus	Atlantic croaker	CS
Pogonias cromis	Black drum	CS
Sciaenops ocellata	Red drum (Redfish)	CS
Paralichthys lethostigma	Southern flounder	CS
Archosargus probatocephalus	Sheepshead	CS
Mugil cephalus	Striped mullet	C
Brackish-Saline (Marine)		
Harengula pensacolae (*H. jaguana*)	Scaled sardine	C
Trachinotus carolinus	Florida pompano	CS
Lutjanus campechanus	Red snapper	CS
Scomberomorus cavalla	King mackerel (Kingfish)	S
S. maculatus	Spanish mackerel	CS
Chaetodipterus faber	Atlantic spadefish	S
Pomatomus saltatrix	Bluefish	CS
Rachycentron canadum	Cobia (Ling)	CS

* C = Commercial species
S = Sport species
CS = Commercial and sport species

mackerel and king mackerel (kingfish). Gulf menhaden are typically the leading commercial species in pounds landed, followed by penaeid shrimps (brown and white), unclassified industrial fishes (mostly Atlantic croaker), blue crab, American oyster, fresh water crawfish, and fresh water catfish (primarily blue and channel). Virtually the entire fresh water harvest comes from Louisiana, but Mississippi waters contribute about one-third of estuarine and marine landings. In recent years, Louisiana fishery landings alone have exceeded one billion pounds (U.S. Department of Commerce 1969-1975). Presently, no Deltaic Plain aquatic species is reported to be endangered or threatened.

Fishery species compose a significant portion of aquatic animal consumers in the Deltaic Plain ecosystem and are represented at primary, secondary, and tertiary (top) consumer trophic levels. Most occupy more than one aquatic zone (fresh, brackish, saline) during the course of their life cycle, and some (e.g., Atlantic croaker, Gulf menhaden, penaeid shrimp) species utilize all zones (Table 5-9). Fresh water habitats (<0.5 ppt salinity) occupied include wetland floodplains, swamps, and marshes--as well as rivers, distributaries, bayous, lakes, ponds, and bays. Brackish (approximately 0.5-12 ppt) and saline (>12 ppt) habitats utilized include tidal marshes, ponds, lakes, bayous, and bays. The saline zone extends into the nearshore Gulf of Mexico.

Fresh Water Region

The majority of fresh water habitats occur in the Louisiana portion of the Deltaic Plain and are concentrated in the Atchafalaya Basin and associated marshes. The red swamp crawfish (*Procambarus clarkii*) is the most valuable species in the fresh water fishery. Although restricted primarily to sluggish interior waters of cypress-tupelo swamps, bayous, and fresh marshlands (Bryan et al. 1976), the species is also a valuable food for fishes. River shrimp (*Macrobrachium ohione*), an important species in riverine habitats, is a significant food for fishes and supports a minor fishery. Major fresh water fishes include the ubiquitous gizzard shad, buffalo fishes, catfishes, gars, freshwater drum, largemouth bass, and black crappie (Table 5-9). Other abundant fishes of lesser importance to the fishery include threadfin shad (*Dorosoma petenense*), bowfin (*Amia calva*), carp (*Cyprinis carpio*), and several members of the sunfish family, especially bluegill (*Lepomis macrochirus*). Numerous non-fishery invertebrates and fishes are ecologically valuable as forage in the freshwater environment. Among the more important are mosquitofish (*Gambusia affinis*), minnows (Cyprinidae), aquatic insects, small crustaceans (especially cladocerans), bivalve molluscs, oligochaetes (tubificid worms) and rotifers.

Water level fluctuation initiated by the Mississippi River and other Deltaic Plain river systems is the principal factor that regulates aquatic animals in fresh water habitats. The inundation of wetlands (floodplains, swamps, marshes) by river waters creates rich aquatic environments for spawning and rearing and is believed to be a primary factor in maintaining high standing stocks. Modification or elimination of river overflow into wetlands has been shown to substantially alter and often reduce the fresh water fishery (Bryan and Sabins 1979).

Estuarine Region

The estuarine region encompasses the lower end of the fresh water zone, the brackish zone, and the inshore saline zone, and contains the greatest amount and diversity of aquatic habitats in the Deltaic Plain. The predominant estuarine organisms represent a diverse array of euryhaline invertebrates and fishes. American oyster, brown and white shrimp, and blue crab are the most valuable large invertebrates, each important in the commercial fishery and as food for secondary and tertiary consumers. Large estuarine fishes include Gulf menhaden, spot, Atlantic croaker, black drum, red drum, spotted seatrout, sand seatrout, southern flounder, sheepshead, and striped mullet (Table 5-9).

Dynamic life history cycles including extensive migrations and ontogenetic changes in food habits and habitat preferences characterize many local estuarine species (Darnell 1961; Gunter 1967). Typically, spawning occurs in or near the Gulf of Mexico, but the young eventually make their way into inshore nursery areas which, for some, are in the freshest part of the estua- [illegible] the more common inshore fishes and invertebrates and their economic potential (e.g., Evermann 1898). A biological laboratory founded in the early 1900s at Cameron, Louisiana (Gulf Biological Station), began the first organized research on the Deltaic Plain's fishery resources, concentrating on the culture of oysters in Louisiana bays (Cary 1906a, 1906b, 1907). The white shrimp (Penaeus setiferus) was among the first fishery species to be investigated, and detailed studies of its life history led to similar research on other forms (Viosca 1920, Weymouth et al. 1933). Early research on fishes centered around the ecology of Louisiana estuarine forms (Gunter 1938a, 1938b, 1938c), but at least two publications dealt with fresh water species (Gowanloch 1933, Fowler 1945). By the late 1930s, a general life history pattern had been agreed upon for the commercially valuable estuarine organisms of the Deltaic Plain (Gunter 1938b, 1968). Also, by this time the beneficial effect of the Mississippi River water and nutrients on the aquatic productivity of the Deltaic Plain was generally understood (Viosca 1927, Riley 1937).

More intensive ecological studies were initiated during the late 1940s and early 1950s, and one classic publication summarized existing aquatic research on the Gulf of Mexico (Galtsoff 1954). A detailed study of the impact of the oil industry on oysters in Barataria and Terrebonne bays of Louisiana revealed practical information on the relationship of an organism to its total environment, and represented the first serious attempt to evaluate man's effect on a fishery resource (Mackin and Hopkins 1961). In addition, an ecological study of the Lake Pontchartrain estuary provided a first insight into complex nutritional relationships among consumer fish species in this Deltaic Plain ecosystem (Darnell 1958, 1961).

Recent fishery research (since 1960) has tended to be species- or habitat-specific or quantitative in approach, although general surveys of fishes and invertebrates have continued. Overall, there has been an increase in studies probing human impact on all aquatic biota, due particularly to mineral extraction, agriculture, and flood control. Passage of the National Environmental Policy Act (1970) has resulted in increased interest in human impact and has stimulated baseline research in the Deltaic Plain Region.

The condition of fishery science in the Deltaic Plain may best be described as in transition between qualitative and quantitative approaches. Since biologists have inventoried and surveyed aquatic habitats of the Deltaic Plain for more than half a century, the more common species are now relatively well known. There is some understanding of population structure of the aquatic community in the Deltaic Plain, while specific information (e.g., biomass and productivity data) is available for a few particular habitats (Day et al. 1973, Bryan and Sabins 1979). The trophic spectrum has been clarified for some communities (Darnell 1961, Day et al. 1973). Life histories of more common forms are fairly well understood, but some critical early aspects are not clear (e.g., exact spawning locales and larval transport mechanisms).

INFORMATION DEFICIENCIES

Among the more significant gaps in present knowledge of Deltaic Plain Region aquatic systems are those involving reproduction and early life history of key consumer species. Spawning habitats of many fishery forms and methods of transport of their larvae to nursery grounds are not well known. The need to identify Gulf of Mexico spawning grounds of estuarine species is particularly needed in view of increased human activity in offshore waters. Likewise, transfer of young to appropriate nursery areas, which occurs during the most vulnerable developmental stage, is known only to be related to current patterns. A better understanding of the role of specific habitats in the life history of important species is also needed. In upper estuarine regions where fresh and brackish waters meet, a variety of both young and adult aquatic species are supported. These regions appear to be particularly valuable to several species (i.e., Gulf menhaden and penaeid shrimp) which spawn in the Gulf of Mexico. In addition, although known to be very productive of commercial and sport fishes for several years (Lambou 1964), the Atchafalaya Basin has only recently been studied in relative detail (Bryan et al. 1976).

Quantitative knowledge of consumer communities is also lacking. Standing crop and productivity measurements are needed for fresh, brackish, and saline habitats. There is also a need for more quantitative information on nutritional relationships among consumer species and on community structure.

RECOMMENDATIONS

More detailed studies on spawning and early life history of predominant fishery species would be a logical starting point for future fishery research. A delineation of specific spawning grounds of penaeid shrimp, blue crab, Gulf menhaden, Atlantic croaker, spotted seatrout, red drum, and other motile species should be attempted. Coupled with reproductive studies, research on larval transport from spawning to nursery grounds would provide useful information for managers concerned with maintaining high fishery production. Research would probably be especially fruitful in upper estuarine areas and adjacent coastal fresh water systems. Historically, these areas in the Deltaic Plain Region have received little attention despite their recognition as important nursery areas for commercial species. A unique research opportunity now exists in the emerging Atchafalaya River Delta. As the Delta progrades into Atchafalaya Bay, new marshlands and potential nursery grounds are being formed. Research on nursery use by estuarine and fresh water forms would provide insight into reasons for the apparent value of fresh and low salinity marshes to aquatic animals. In the immediate future, the emerging Atchafalaya Delta is predicted to create large areas of low salinity marshes in close proximity to suspected Gulf spawning grounds and may eventually contain the largest concentrations of such marshes in the Deltaic Plain (Shlemon 1972).

Quantitative aspects within consumer communities are also deserving of further research. Standing crop and productivity data are reliable indicators of which species play the more important trophic roles, as well as which habitats are most valuable in maintaining community structure. Quantitative food habit studies of important consumer species would also prove useful in contributing to an understanding of each species' relationship in the community.

Input from research would significantly add to understanding the role which fishery and other aquatic animals play as consumers in Deltaic Plain environments and would help perpetuate the Region's exceptional fishery resource. Additional information on life history of abundant species, followed by identification of trophic interrelationships, would be valuable. With regard to applied science, an increase in life history and quantitative data would facilitate the managerial task of predicting and buffering human impact on the Deltaic Plain. In particular, it is hoped that such research will aid in developing the ability to make reliable estimates of the value of specific habitat types in terms of their total contribution to fishery harvests. Until such estimates can be made, valuable fishery habitat that otherwise might have been saved or satisfactorily mitigated will probably be lost.

WILDLIFE

INTRODUCTION

In this paper the term wildlife includes mammals, birds, reptiles, and amphibians as well as terrestrial and wetland invertebrates. The Mississippi Deltaic Plain Region has a rich variety of faunal types: over 400 species of birds (Lowery 1974a), 70 species of mammals (Lowery 1974b), and approximately 130 species of reptiles and amphibians (Keiser and Wilson 1969) have been reported as permanent or seasonal inhabitants. A large percentage of these animals occur throughout the Mississippi Deltaic Plain Region.

Wildlife species are intimately related to botanical elements, morphological characteristics, and physical processes which define their various habitats. Their role in the ecosystem is principally that of consumers in a trophic sense, and as secondary producers in the energy flow scheme comprising the food chain. A few species constitute the majority of man's harvest for both sport and commercial purposes.

During the mid to late nineteenth century, scientists and naturalists began publishing accounts of their experiences and studies in the Region. These first works usually did not stem from formal scientific inquiry but were accounts of personal observations consisting of species lists, habits, habitat preferences, and general life history notes. The work of such people as Audubon (1867), Beyer (1897), and later Bent (1910, 1921) and Bailey (1919) paved the way for further study, and in the first decades of the twentieth century, life histories were further clarified for mammals (Svihla 1929) and birds (Arthur 1931, Oberholser 1938) of the Deltaic Plain. Furbearers, such as muskrat (*Ondatra zibethicus*), and numerous waterfowl species became the object of increased attention, probably due to their growing economic importance. As a result of monitoring harvests of hunters and trappers, more reliable estimates of the relative abundance of fur and sport species were made available and more specific habitat requirements of the important species became apparent. For example, work by Cottam (1939) and Martin and Uhler (1939) on food habits of ducks and O'Neil's study of the Louisiana muskrat (1949) remains classic today. The first insights into winter requirements of migratory waterfowl in the Region were documented by Arthur (1930).

Wildlife biology developed into a true science in the 1940s and 1950s, as State, Federal, and university affiliated scientists increased the scope of knowledge concerning the distribution, reproduction, and management of many species. As ecological concepts gained wider attention, wildlife studies began to integrate factors of physical processes and man's activities in order to reach a more holistic understanding of the science. This led, in the 1960s and 1970s, to studies of population dynamics, community structure, and systems modeling--and the beginning of the science of wildlife ecology, an offshoot of wildlife biology. Although rather complete lists of species and general life histories now exist, quantification of habitat requirements is incomplete, and precise functional roles of many species in coastal Louisiana remain unclear.

In order to discuss the status of available knowledge of wildlife biology in the Deltaic Plain, classification by animal group (birds, mammals, and amphibians and reptiles) and then by broad habitat usage categories (terrestrial, wetland, and aquatic) will be used. It becomes obvious that many species cannot be strictly defined as either terrestrial, wetland, or aquatic, but the outline does facilitate discussion.

INFORMATION REVIEW

Birds

Since the early compilations of Arthur (1931) and Oberholser (1938), the most thorough research done on identification, occurrence, and life history of Louisiana birds is that of Lowery (1974a). The information is not specific for the Deltaic Plain but does include all species inhabiting the Region. Burleigh (1944) gives similar but less complete information for the Mississippi Gulf coast.

Terrestrial. Several orders of birds may be considered predominately terrestrial in nature, including most of the Passeriformes, Galliformes, Falconiformes, Columbiformes, Strigiformes, and Piciformes. Although general life history information is available for most species (Lowery 1974a), very few precise studies have involved terrestrial birds in the Deltaic Plain Region with the exception of the American Woodcock (*Philohela minor*). Work by Glasgow (1958), Williams (1969), Britt (1971), and Dyer (1976) has provided fairly complete information about this species regarding distribution, abundance, population dynamics, and habitat utilization in southern Louisiana. Other than Swainson's Warbler (Meanley 1971), most of the wood warblers have not been intensively studied in the Region. The same is true for most predatory woodland species such as hawks (Accipitridae) and owls (Strigiformes). Able (1970, 1972) and Gauthreaux (1971, 1972) have helped to clarify the concepts of passerine migratory behavior in the region. Detailed studies relevant to the Deltaic Plain are lacking for many species.

Wetland. The waterfowl of the Region have probably received more study in this area than any other bird group. Estimates of distribution, abundance, and harvest by species are made annually along the coast by Louisiana Department of Wildlife and Fisheres personnel, and food habits have been well established in most areas of the Deltaic Plain. A majority of the research has been aimed toward marsh management for wintering waterfowl, especially in southwest Louisiana. The reproductive biology and nesting ecology of the Wood Duck (*Aix sponsa*) and the Fulvous Tree Duck (*Dendrocygna bicolor*) are fairly well documented in coastal Louisiana, but less so for the Hooded Merganser (*Lyphodytes cucullatus*) in the Atchafalaya Basin and the Mottled Duck (*Anas fulvigula*) in the marshes. A reasonably precise understanding of the population dynamics of a few species such as the Mallard (*Anas platyrhynchus*) (Anderson and Henry 1972, Anderson et al. 1974, Pospahala et al. 1974, Anderson 1975, Anderson and Burnham 1976, and Martin and Carney 1977) and the Green-winged Teal (*Anas carolinensis*) (Moisan et al. 1967) has been established in the Region; however, concepts such as interspecific behavior and competition have received little attention. The biology of the Clapper Rail (Rallus longirostris) in Louisiana--including habitat, distribution, abundance, and nesting ecology--is well documented (Roth 1972, Sharpe 1976). Much less is known of the biology of the gallinules in coastal marshes.

Population levels of wintering geese in Louisiana are monitored annually by personnel of the U.S. Fish and Wildlife Service and the Louisiana Department of Wildlife and Fisheries. The decline in numbers of Canada Geese (Branta canadensis) wintering in coastal Louisiana and an attempt to introduce a resident flock of this species at Rockefeller Wildlife Refuge, Louisiana, is discussed by Lowery (1974a) and Belsom (1974). Food habits and flock behavior of Snow Geese (Chen caerulescens) have received some attention in the Region (Glazener 1946, Schroer 1974). Escuriex (1973) provided a history of the blue morph Snow Goose and some productivity information.

Aquatic. Sea birds, wading birds, and shore birds are included in this category. Portnoy (1977) has furnished the most complete and recent information concerning the distribution, abundance, habitat utilization, and nesting of these birds in coastal Louisiana, Mississippi, and Alabama. Breeding biology and food habits have been intensively investigated for only a few species such as the Louisiana Heron (Hydranassa tricolor) (Rodgers 1978) and the Brown Pelican (Pelecanus occidentalis). The demise of the Brown Pelican has been well documented although the causes are only partially understood (King et al. 1977). This problem has led to an increased awareness of how environmental pollutants can affect wildlife populations in the Deltaic Plain, but the intricate mechanisms involved need further study.

Mammals

Terrestrial. Although the white-tailed deer (Odocoileus virginianus) is probably the most important big game mammal in the United States, it has been little studied in the Deltaic Plain Region. Population indices were obtained for various deer habitats in the Atchafalaya Basin (Evans 1976) and marshland food habits were studied by Self et al. (1974). Breeding biology of this species is known for various areas in the State. Glasgow and Ensminger (1957) provided insight into deer-habitat relations in the marsh. Life histories are known in general for many other mammals and relative abundances have been obtained for many in areas such as the Atchafalaya Basin. Only general information is available for most of the small mammals inhabiting the Mississippi Deltaic Plain Region, and very limited data are available on rare species such as the black bear (Ursus americanus).

Wetland. The important fur producers, such as nutria (Myocastor coypus) and muskrat, have received more attention than most other mammals in the Region, and biological parameters such as distribution, relative abundance, habitat preferences, food habits, and breeding periods are well known for these species (Svihla and Svihla 1931, O'Neil 1949, Adams 1956, Kays 1956, Palmisano 1972). Carrying capacities for particular habitat types have been examined (O'Neil 1949, Palmisano 1972). Man's impact from oil and gas activities on fur production in the Deltaic Plain has only recently come under observation (St. Amant 1971). Although habitat manipulation using burning techniques and controlling water levels to increase fur production is a standard practice, little data are available concerning optimum habitat conditions. Unlike the nutria and the muskrat, the neartic river otter (Lutra canadensis), a carnivore which occurs in much lower number in the Region, has not been adequately studied. This is true for other members of the Mustelidae family (including the mink [*Mustela vison*]).

Aquatic. A few aquatic mammals of the orders Cetacea and Pinnepedia sometimes occur in the nearshore coastal waters of Louisiana and Mississippi. Lowery (1974b) presents a good discussion of the biology of these species; since these are infrequent visitors to the Deltaic Plain, only peripheral information, such as records of occurrence, is available. Gunter (1968) provides some information as to the occurrence of seals (Otariidae) in the Gulf of Mexico, but in-depth knowledge regarding the relationship of these species to the Deltaic Plain is lacking.

Amphibians and Reptiles

Because of the scarcity of literature pertaining to these animals in the Deltaic Plain Region, they will be discussed without categorization into terrestrial, wetland, or aquatic habitat. The American alligator (*Alligator mississipiensis*) has been the most thoroughly studied of the species in this group. This is the case in Louisiana, where the alligator is managed for legal harvest in 15 parishes. Distribution, estimates of abundance, food habits, nesting ecology, and habitat preference of the species are known for most of coastal Louisiana (Joanen 1969, Chabreck 1971, Joanen and McNeese 1972). Management techniques have been established (Nichols et al. 1976) in order to produce a sustained yield of hides for the market.

Knowledge of other reptiles in the Deltaic Plain is scarce. Records of occurrence and some life history notes form the bulk of the information on snakes, lizards, and turtles. Keiser (1976) has provided a very thorough survey of amphibians and reptiles of the Atchafalaya Basin. Hebrard and Mushinsky (1976) reported on aquatic snake habitat utilization, whereas Majure (1975) provided a thorough account of the Mississippi snake species. Sea turtle nesting ecology along the coast is now being more intensively studied by the National Park Service and Center for Wetland Resources, Louisiana State University, Baton Rouge.

Distribution and life history of salamanders (Caudata) in the Deltaic Plain are known for a few species, but quantitative data regarding population indices or habitat requirements are scarce. The numerous species of frogs and toads (Anura) that inhabit the Deltaic Plain, including the bullfrog (*Rana catesbeiana*), have received little attention.

Summary

The economically important species such as furbearers and the game species, especially waterfowl, have been studied most intensively of the Deltaic Plain wildlife. Information concerning abundance, distribution, food habits, harvest, and general life history is available for these species and management guidelines have been devised for many. Many questions still remain concerning the interactions of these species with the environment. Habitat requirements have generally not been quantified. The effect of man's activities on wildlife, including pesticides and oil and gas production, has only recently come under close scrutiny.

The myriad of nongame wildlife species that lie outside the realms of sport and commercial harvest have received less attention. Relatively complete life history accounts, reproductive biology, and qualitative habitat requirements are known for some species (for example, the Louisiana Heron [Hydranassa tricolor]) while little is known for other species (for example, the Bald Eagle [Haliaeetus leucocephalus]). Generally, more is known for those species that breed in the Region than those that are migratory transients. Management for many nongame species (other than protective measures) in the Mississippi Deltaic Plain Region would be difficult at best.

INFORMATION DEFICIENCIES

In order to understand the biotic system in a holistic sense, knowledge of the elements comprising the system is necessary. Although general information is available for many game and commercial wildlife species, at present little quantitative data are available. Such data are needed so that when man's impact on the physical environment produces a measureable habitat change, accompanying carrying capacity changes for particular species can be projected more accurately. Optimum and suboptimum edaphic conditions also need quantification. Interspecific behavior and its relationship to population densities is poorly understood. Food chains and trophic relationships need to be more precisely defined.

For many of the nongame birds, small mammals, and herpetofauna (amphibians and reptiles) of the Deltaic Plain Region, even general life history information is incomplete, and the functional role of many of these species is poorly understood. Habitat requirements are, in most cases, not well known and population indices are scarce. The effects of environmental pesticide contamination have been studied only for a few species (Brown Pelican, Woodcock, and Snow Goose). Food habits, precise data on habitat utilization, and behavioral components need investigating. Present understanding of trophic relations is vague and incomplete.

RECOMMENDATIONS

The wildlife elements of the biotic ecosystem function as consumers. They can be considered a manifestation of the botanical and physical habitat which, in turn, has been largely influenced by basin morphology. Relationships between an animal species and its habitat are well understood for only a few species of the Deltaic Plain, primarily game animals, waterfowl, and furbearers. Future research should be directed toward quantification of basic carrying capacities for particular species in specific habitats. Estimates of carrying capacities for various habitats will be facilitated if evaluation is founded on a quantitative rather than qualitative basis. To develop such techniques, modes of habitat utilization must be refined for each species. The food habits, breeding behavior, cover requirements, and nesting or loafing habitats must be more clearly defined. (Long-term kill records are useful for estimating carrying capacity).

Very little research has been done on the large number of wildlife species which are not considered economically valuable in the Mississippi Deltaic Plain Region. Many of the nongame birds, small mammals, and much of the herpetofauna need investigation with regard to their life histories. Research should be directed to food habits, habitat requirements, breeding behavior, and population dynamics for these species. A knowledge of present population levels and carrying capacities for particular species in specific habitats in the Deltaic Plain Region for key sport and commercial species is needed. Without such data, the impact of man's activities on the species will be difficult to quantify.

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CHAPTER VI: ECOLOGY

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INTRODUCTION

In the broadest sense, the term "ecology" refers to the totality of interactions between physical and biological parameters. For the purpose of this paper, however, the term will be used in a more restricted sense. This report will discuss the influence of natural and man-influenced environmental factors on the flora and fauna in the Mississippi Deltaic Plain Region, with special emphasis on productivity and/or species abundance. Also, interactions between primary producers (plants) and secondary producers (animals), and those interactions within each taxon will be discussed where applicable. With reference to the overall functioning of the Mississippi Deltaic Plain, this synthesis paper will document the influence of geologic, atmospheric, socioeconomic, and riverine (as affecting hydrology and water nutrient regimes) forces on the geological systems within this region.

Ecology is a relatively young science. The term "ecology," from the Greek oikos, meaning "place to live," was first proposed in 1869 by the German biologist Ernst Haeckel. As a distinct field of biology, the science of ecology dates from about 1900. The majority of ecological studies before the 1950s were descriptive with little quantitative data. The presence of species in particular habitats was documented with some inferences concerning species adaptations and the range of environmental conditions in which species survive and reproduce. With the advent of more sophisticated equipment and the use of computer technology for statistical analysis, the science of ecology became more exacting and quantitative. Within the last 10 to 15 years, the discipline of systems ecology has gained momentum. Systems ecology is the utilization of systems analysis to mathematically model large ecosystems with the ultimate goal of predicting changes in the system due to various perturbations (anthropogenic and natural). Advances in technology in the past 20 years have made it possible to handle semi-quantitatively large complex systems such as natural ecosystems.

Since ecology is a relatively new science and quantitative studies concerning population, community, and/or ecosystem structure and function are recent developments, researchers are far from a complete understanding of the ecology of the Mississippi Deltaic Plain. In fact, the greatest percentage of information concerning this region has been derived from research of the last 10-15 years. In this report, the state of knowledge of the ecology of the Mississippi Deltaic Plain will be described and recommendations for future research in the region will be suggested.

ECOLOGY

PRIMARY PRODUCTIVITY

The ultimate source of all animal food is green plants. In the Mississippi Deltaic Plain Region a variety of plant types--including submerged and floating aquatic vegetation, phytoplankton, benthic and epiphytic algae, emergent marsh grasses, arboreal swamp vegetation, and coastal plain pine forests--contribute energy in the form of carbon to support animals at various trophic levels.

The importance of green plants as the only source of primary organic productivity is readily appreciated in aquatic environments. Secondary productivity (biomass produced by consumer organisms per unit area per unit time) of any body of water depends on the productivity of the green plants within that body, which in turn depends on the interaction of certain factors: 1) the input of solar radiation, 2) the physical and chemical characteristics of the water, and 3) the physical and chemical nature of the substratum. The occurrence of extremely productive fishing and shell fishing grounds at or near extensive tidal wetlands indicates the important roles of marshes and swamps in the fertility of coastal waters.

Plant material may be utilized by consumers in two ways: 1) as detritus, i.e., dead and/or decomposing plant material, or 2) by direct grazing of living plant material. Marine systems are generally phytoplankton-based and support a grazing food chain, while estuarine systems have a more diverse group of primary producers, giving rise to a detritus-based estuarine structure.

Both types of carbon, i.e., living plant material and detritus, provide protein for consumer organisms. Detritus generally increases in protein content as decomposition proceeds, due to increased microbial colonization; in fact, this decomposing detritus often has a greater protein content than the living plant material itself. Detritivores are responsible for supplying the link between detritus production and the production of higher consumers.

Phytoplankton

Coastal waters. As is the case with coastal systems in general, the primary productivity of the Mississippi Deltaic Plain continental shelf waters is strongly affected by the velocity of discharge of the Mississippi River (Sklar 1976). Phytoplankton productivity in this area is limited primarily by nutrient levels, which are significantly associated with river discharge. Nitrogen to phosphorous ratios of continental shelf waters imply a nitrogen-limited system (Sklar 1976).

Maximum surface productivity (1.07 g C $m^{-3}d^{-1}$) occurs in April during maximum river discharge, whereas minimum productivity (0.1 g C $m^{-3}d^{-1}$) occurs in October, when river discharge is lowest (Sklar 1976). Primary productivity is least in the summer and increases in the fall. Surface productivity averages 178 g C $m^{-3}yr^{-1}$ for brown water (water strongly affected by the Mississippi River discharge) and 125 g C $m^{-3}yr^{-1}$ for green water (water which is more representative of the Gulf of Mexico). Phytoplankton productivity in deeper waters of the Gulf of Mexico ranges from 0.09-0.35 g C $m^{-2}d^{-1}$ (Hobson et al. 1973). Day et al. (1973) estimated primary productivity rates of approximately 0.32 g C $m^{-2}d^{-1}$ in continental shelf waters west of the Mississippi delta plume.

Coastal waters off the Mississippi Deltaic Plain are among the most productive in the United States. This area has twice the phytoplankton productivity of Long Island Sound and three times that of the Oregon coast (Sklar 1976). In addition, the average aquatic productivity of the waters of the Gulf of Mexico (0.73 g C $m^{-2}d^{-1}$) is 78% greater than that of the Atlantic continental shelf (0.41 g C $m^{-2}d^{-1}$) (Sklar 1976).

Marsh, lake, and bay waters. Estimates of phytoplankton productivity in coastal lakes and marsh habitats, although limited, are available. In a small saline lake near Barataria Bay, Louisiana, gross and net annual phytoplankton productivity was estimated at 220 g C m^{-2} and 198 g C m^{-2}, respectively (Stowe et al. 1971). This figure represents approximately 13% of the total carbon available to the area and 25% of the primary productivity due to macrophytic and epiphytic algae and phytoplankton. Phytoplankton productivity estimates in Barataria Bay itself average 300 g C $m^{-2}yr^{-1}$ and 210 g C $m^{-2}yr^{-1}$ for gross and net production, respectively (Day et al. 1972). The phytoplankton blooms which commonly occur in the spring in north temperate water bodies do not occur in the shallow waters of Barataria Bay; rather, phytoplankton production is higher in mid-summer than in spring. Barataria Bay waters are autotrophic from approximately March to August but metabolize heterotrophically the remainder of the year, resulting in slight net community production (19 g C $m^{-2}yr^{-1}$).

Phytoplankton productivity estimates have also been made for freshwater coastal plain lakes. Water column primary productivity in Lac des Allemands, located in the Barataria hydrological basin, Louisiana, is approximately 443 g C $m^{-2}yr^{-1}$ (net daytime photosynthesis); while that for a bayou entering the lake ranges from 93-163 g C $m^{-2}yr^{-1}$ (Day et al. 1977). Gross production at the bayou stations is 27% of that in the lake itself, probably because of shading from surrounding trees and high water turbidity due to suspended silt and clay particles. Day et al. (1977) have hypothesized that in the bayous, light, rather than nutrients, is limiting, since concentrations of nitrogen, phosphorus, and carbon were somewhat higher than in the lakes. However, in the lakes (e.g., Lac des Allemands), phosphorous is suspected as the primary limiting nutrient, although carbon dioxide may be limiting at specific points in time. In general, phytoplankton productivity (569 g C $m^{-3}yr^{-1}$) does not vary significantly from saline to fresh marsh sites in Louisiana (Allen 1975). However, levels of chlorophyll ^{a} and organic carbon are highest in fresh marshes and decrease toward the Gulf.

Epiphytic and benthic algae. Information concerning the importance and role of benthic and epiphytic algae in the Mississippi Deltaic Plain is extremely scarce. Epiphytes on streamside, smooth cordgrass (Spartina alterniflora) marsh may contribute as much as 16 g C $m^{-2}yr^{-1}$, while inland epiphytes on S. alterniflora are net consumers of carbon (Stowe 1972). Net annual production of streamside epiphytes is 60 g C m^{-2}, while that of the inland community is -18 g C m^{-2}. Epiphytic net production reaches a maximum in the late fall and winter and a minimum in the summer. On a per unit basis, streamside epiphytes account for as much as 10% of the total primary productivity of the system. Thus, the carbon contribution of epiphytes for consumption at higher trophic levels may be of relatively little importance compared to that contributed by other primary producers. Estimates of benthic algal net production average 210 g C $m^{-2}yr^{-1}$ in Barataria Bay, Louisiana (Day et al. 1972). This could account for almost 20% of the total primary productivity of a marsh-estuarine system (extrapolated from the data of Stowe et al. 1971).

Relatively little is known concerning the major factors controlling the productivity of epiphytic and benthic algae; however, light, temperature, and nutrient limitations are generally considered important.

Submerged aquatic vegetation. The ecology of submerged aquatic vegetation in the Mississippi Deltaic Plain has received little attention. Humm (1956), in his study of the sea grasses of the northern Gulf coast, reviewed the distributions of the dominant sea grasses. Salinity and light requirements primarily determine the location of these plant species. The dominant species are shoal grass (Halodule beaudettei), turtle grass Thalassia testudinum), and manatee grass (Cymodocea filiformis).

Although submerged aquatic vegetation has been investigated in terms of substrate stabilization in the shallow waters of the Gulf of Mexico (Eleuterius 1975a), little manipulative research delineating the important limiting ecological factors has been conducted. Thalassia and Cymodocea grass beds are generally found in deeper and far less turbulent waters than Halodule (Eleuterius 1975b); however, the effect of these factors on growth has not been determined. Although submerged aquatic vegetation of the Mississippi Deltaic Plain is probably nitrogen limited, as is the case with most rooted aquatics, investigations from this area are lacking concerning the mineral nutrition of these plants. The ecology of these plants has been studied extensively in Florida (Phillips 1960a, 1960b, 1962), but research in the Mississippi Deltaic Plain Region still needs to be conducted.

Marsh vegetation. Of all the aquatic ecological systems in the Mississippi Deltaic Plain, marshes (particularly salt marshes) have received the greatest attention. Considerable data concerning the productivity of the major marsh plants are available (de la Cruz and Gabriel 1974a, Kirby and Gosselink 1976, de la Cruz and Hackney 1977, Hopkinson et al. 1978, White et al. 1978).

The productivity of Spartina alterniflora, the dominant salt marsh angiosperm (vascular plants having the seeds in a closed ovary), ranges from 1410-2658 g dry wt $m^{-2}yr^{-1}$, depending upon sampling method, height form, and geographical location. Salt meadow hay (Spartina patens), salt grass (Distichlis spicata), and black needlerush (Juncus roemerianus) have production rates ranging from 1806-6043, 1162-3237, and 2895-3416 g dry wt $m^{-2}yr^{-1}$, respectively. Marsh primary production rates in the Mississippi Deltaic Plain are, on the average, from 100-200% greater than those determined for marshes along the Atlantic coast. The reasons for these higher production rates are: 1) many of the studies on the Mississippi Deltaic Plain have accounted for decompositional and mortality losses between sampling intervals, while earlier studies on the Atlantic coast have not; and 2) the longer growing season in the Mississippi Deltaic Plain.

Investigations concerning the major factors controlling marsh primary productivity in the Mississippi Deltaic Plain have been relatively superficial, and deal primarily with salt marshes. Nitrogen is apparently limiting to primary productivity of inland *Spartina alterniflora* marshes (Patrick and Delaune 1976). However, the factors causing *Spartina* "dieback" and other low productivity sites have not been investigated intensively. W. G. Smith (1970) has suggested a number of potential causes of *Spartina* dieback: 1) increased salinity, 2) trash wrack coverage, 3) waterlogging, 4) lack of available iron, 5) hydrogen sulfide toxicity, 6) oxygen deficiency in roots, 7) change in tidal regimes, and 8) pollution.

Probably the most important natural factor affecting coastal marshes in this region is subsidence, i.e., the gradual lowering of the land with respect to sea level. Ponding, in part a result of subsidence, is the most important overall contributor to land loss in Louisiana (Blackmon 1979). Deltaic marshes which are formed via deltaic sedimentary processes are extremely susceptible to subsidence caused by sediment compaction and dewatering. Subsidence results in waterlogging of the marsh substrate, extreme soil anaerobiosis, and the death or decreased vigor of the indigenous marsh plants. Land loss also occurs as a result of artificial means (e.g., flood control practices, impoundments, dredging, and subsequent erosion of artificial channels). Land loss in Barataria Basin, Louisiana, varies from 0.5% yr^{-1} in brackish marshes to 0.22% yr^{-1} in saline marshes (Blackmon 1979); total land loss in Louisiana's coastal zone is at least 4300 ha yr^{-1} (Craig et al. 1979).

Salinity can be an important factor in controlling marsh productivity. Saltwater intrusion in low salinity or freshwater marshes can result in a change in species composition and/or a decreased primary productivity, and may contribute to marsh dieback. While salinity may decrease the productivity of a number of salt marsh grasses in greenhouse experiments (Gosselink 1970, Parrondo et al. 1978), the importance of salinity in causing differences in primary productivity observed in the natural environment has not been determined, with the exception of salt panne conditions where productivity is greatly reduced.

Edaphic factors are important in determining marsh primary productivity. Minerals in the marsh substrate may be important in regulating productivity by maintaining marsh elevation, supplying nutrients, and neutralizing plant toxins such as sulfide. Marsh grass primary productivity is directly related to soil mineral content in Louisiana marshes (Delaune et al. 1981).

The degree of soil waterlogging is another important edaphic parameter affecting marsh primary productivity. Highly anoxic soils resulting from constant waterlogging generate potentially toxic substances (e.g., organic acids, hydrogen sulfide, ethylene, and reduced metals) which may inhibit growth. Also, the large oxygen demand of anaerobic soils may cause a root oxygen deficit, resulting in anaerobic root respiration and reduced growth. This area has received little attention in marshes.

The nutrient content of marsh soils directly affects marsh plant productivity, with nitrogen generally considered limiting. Other nutrients (e.g., phosphorus, calcium, magnesium, potassium, manganese, iron, etc.) may, under specific circumstances, also limit marsh plant growth.

Fire is both a natural and a man-induced factor which affects marshes. During the first growing season after a fire, marsh primary productivity increases. The marsh changes from a field of burned stubble to a field of luxurious vegetation in a three-month interval (Hackney and de la Cruz 1977). Marsh grass productivity is higher during the first growing season after the fire than in non-burned sites. However, post-recovery productivity varies with marsh plant species. In a marsh in Mississippi, the productivity of giant cordgrass (*Spartina cynosuroides*) returned to pre-burn rates by the end of the second growing season, while the productivity of a *Juncus roemerianus* community was subsequently lower than pre-burn rates (Hackney and de la Cruz 1977).

Hurricanes, another natural factor prevalent in the Mississippi Deltaic Plain, can have a drastic effect on marsh communities. Hurricane Camille, which occurred in 1969 and had record storm surges of greater than 7 m, resulted in a radical reduction of marsh vegetation as a result of uprooting by wind and waves, with rapid regrowth after one year. Recovery of vegetation was slower in ponds and lakes. Floating aquatics, e.g., water milfoil (*Myriophyllum*), were most disturbed, while rooted vegetation, such as *Spartina alterniflora* and reed grass (*Phragmites australis*), were less affected (Chabreck and Palmisano 1973).

Arboreal Swamp Vegetation

Although a number of swamp community studies have described plant habitat and associations in the Mississippi Deltaic Plain, until recently little research on the ecology of these systems has been conducted. Conner and Day (1976) determined the primary productivity of a bald cypress-water tupelo community near Lac des Allemands, Louisiana. This swamp community was dominated by swamp red maple (*Acer rubrum* var. *drummondii*) and water tupelo (*Nyssa aquatica*) and had a net primary productivity of 1574 g dry wt $m^{-2}yr^{-1}$, while the bald cypress-tupelo community had a net production of 1140 g dry wt $m^{-2}yr^{-1}$. In sites of low elevation and poor drainage bald cypress and water tupelo are most abundant, while areas of higher elevation and better drainage are dominated by bottomland hardwoods.

Periodic flushing of the swamp controls primary productivity by acting as an energy subsidy affecting hydric conditions, temperatures, nutrient levels, and available oxygen. The effect of flooding on swamp primary productivity is dependent upon age and species of plants present, depth and duration of flooding, and soil chemical properties.

Growth of the dominant bottomland hardwood trees is 50-100% greater in flood versus non-flood years (Broadfoot and Williston 1973). Spring floods in the Mississippi Deltaic Plain improve growth by preventing water stress late in the growing season. In addition, spring floods provide a source of nutrient-laden sediments for plant uptake. Flood resistant hardwoods may be damaged in areas where soil conditions are adverse, and in depressions where water does not drain promptly (Broadfood and Williston 1973). Prolonged flooding detrimentally affects the roots via an oxygen deficiency and causes death after one, two, three, or even four years, depending on the species.

Soil chemical properties determine flooding effects on trees to a large extent. Soil with high sodium content in the topsoil may become toxic. Flooding strongly acidic soils may dissolve manganese and aluminum in quantities sufficient to cause toxic reactions. When oxygen is excluded from the soil, toxic concentrations of ferrous iron, nitrite, sulfides, and manganese may accumulate through evaporation, causing severe moisture stress in the soil, making it difficult for trees to absorb sufficient water.

Barrier Island Vegetation

Although barrier islands are valuable buffers against coastal erosion by waves, tides, and storms, little ecological research concerning vegetational dynamics on the Mississippi Deltaic Plain barrier islands has been conducted. Sauer (1967) conducted a reconnaissance of seashore vegetation along the Mexican Gulf coast, but did not investigate factors affecting primary productivity and sand stabilization. Eleuterius (1976) studied artificial establishment of dune species on barrier islands of Mississippi Sound. Panic grass (*Panicium repens*) survived better than any other species tested. There tended to be a greater survival rate at the lowest soil water salinities. Survival of transplants rooted in peat pellets was greater than when sprigs were planted. Survival of species such as *Panicium repens*, running beach grass (*P. amarum*), and *Spartina patens* is enhanced by rooting in peat pellets; while for other species (sea oats [*Uniola paniculata*] and *Phragmites communis*), the peat pellet method has no value (Eleuterius 1976).

Terrestrial Vegetation

Longleaf pine (*Pinus palustris*) and slash pine (*Pinus elliottii*) are dominant species of terrestrial vegetation found in the Mississippi Deltaic Plain. Because of their importance as a timber source, considerable information concerning these communities is available. Generally longleaf pine is found on drier sites than slash pine. Longleaf pine requires less water to produce a unit of dry weight than slash pine, and thus is a better competitor on drier sites (Pessin 1938). However, highest productivity for longleaf pine occurs on moist sites (25% soil moisture by weight), while slash pine can withstand a broader range of soil moisture conditions (15-25% soil moisture by weight) and still maintain maximum productivity (Pessin 1938). Although longleaf and slash pine can both survive in extremely wet or dry conditions, growth is reduced. Moisture deficiencies are generally not a significant problem for either of these two pine species in the Mississippi Deltaic Plain because of high annual rainfall. The primary nutrient limiting the growth of pines on coastal plain sediments is nitrogen; phosphorous may be secondarily limiting under specific conditions (Walker and Youngberg 1962).

SECONDARY PRODUCTIVITY

Fisheries

Fishery species (marketable aquatic animals) of the Deltaic Plain account for a significant portion of secondary production in the aquatic ecosystem. As heterotrophs and animal consumers, they are represented at all trophic (feeding) levels: primary, secondary, and tertiary (Table 6-1). For some species, assignment to a specific trophic level is difficult and may be misleading unless life history stage and environmental setting are taken into consideration. The use of basic trophic levels, however, provides a convenient base for discussion of ecological relationships among species.

Primary consumers. Primary fishery consumers have been described as "packagers" of plant food sources (Day et al. 1973), i.e., the species that feed directly on plant materials, organizing their organic material into forms available for transfer to higher trophic levels. Some are herbivores and feed on live plant material (phytoplankton, macroalgae, aquatic vascular plants), while others are detritivores which feed mainly on plant detritus with its attendant bacteria and fungi. Some animal material (zooplankton, insect larvae, animal detritus) may be incidentally ingested. Varying degrees of primary consumerism are displayed, from virtual dependence on plant materials by some forms to utilization of relative amounts of animal foods (up to 10-20% by volume) by others. Organic detritus of plant origin is probably the most valuable primary food source in all aquatic zones (fresh, brackish, saline) (Darnell 1961, Day et al. 1973, Bryan and Sabins 1979). Primary fishery consumers include adults of two freshwater species, five estuarine forms, and at least one marine species (Table 6-1). Polychaetes, the marsh clam (*Rangia cuneata*), larval molluscs and crustaceans, chironomids, planktonic and nektonic crustaceans (especially copepods, cladocerans, grass shrimp, and river shrimp), and some cyprinodont fishes also fall into the primary consumer category. Together, primary consumers provide the first animal link in the passage of plant nutrients through the food web to other consumers.

Secondary consumers. Secondary consumers represent an intermediate trophic level in the aquatic ecosystem. According to Day et al. (1973), they are the "regulators" of the packaged energy source of primary consumers and provide a medium to pass some of the energy on to top consumers. Secondary consumers prey upon the primary consumers, thus regulating their populations to a great degree. Two categories of secondary consumers, primary and mid-carnivores, are generally recognized, although these distinctions are not easily defined (Day et al. 1973). "Primary carnivores" can exist on either predominantly plant or animal material, but they show preference for an animal diet, particularly insects and crustaceans. Both live plant material and detritus is consumed. Included in this group are freshwater fishes such as mosquito fish (*Gambusia affinis*), buffalofishes (*Ictiobus* spp.), and carp (*Cyprinis carpio*), and at least one estuarine fish, the sheepshead. Mid-carnivores show a more carnivorous preference in diet, deriving nourishment from primary consumers and only intermittently or incidentally from detritus. The group contains a diverse array of freshwater, estuarine, and marine fishes, and a few primarily estuarine invertebrates. Included here are ctenophores, blue crab (*Callinectes sapidus*) and other large crabs, larval and postlarval fishes (including those of some herbivorous adult forms), and juveniles of tertiary consumers. Many fishes typically referred to as "forage fishes" because of heavy predation by tertiary consumers are mid-carnivores and are among the most abundant fishes in the Deltaic Plain, especially in estuarine environments. Some of the more common mid-carnivore fishes are the freshwater sunfishes (*Lepomis* spp.) and catfishes (*Ictalurus* spp.), the estuarine anchovies (*Anchoa* spp.), silverside (Atherinidae) and croakers (Sciaenidae), and the marine spadefish (*Chaetodipterus faber*) and pompano (*Trachinotus carolinus*) (Table 6-1).

Table 6-1. Trophic spectrum of major Deltaic Plain fishery species (adults).

Primary Consumers (Packagers) - Herbivores, Detritivores

Fresh-Brackish (spawn in fresh water, <.5 ppt)
Procambarus clarkii - Red swamp crawfish
Dorosoma cepedianum - Gizzard shad

Fresh-Brackish-Saline (estuarine)
Crassostrea virginica - American oyster
Penaeus aztecus - Brown shrimp
Penaeus setiferus - White shrimp
Mugil cephalus - Striped mullet
Brevoortia patronus - Gulf menhaden

Brackish-Saline (marine)
Harengula pensacolae - Scaled sardine

Secondary Consumers (Regulators) - Primary (P) Mid (M) Carnivores

Fresh-Brackish (spawn in fresh water)	
Ictiobus bubalus - Smallmouth buffalo	P
Ictiobus cyprinellus - Bigmouth buffalo	P
Ictalurus furcatus - Blue catfish	M
Ictalurus punctatus - Channel catfish	M
Aplodinotus grunniens - Freshwater drum	M
Pomoxis nigromaculatus - Black crappie	M
Fresh-Brackish-Marine (estuarine)	
Callinectes sapidus - Blue crab	M
Archosargus probatocephalus - Sheepshead	P
Leiostomus xanthurus - Spot	M
Micropogonias undulatus - Atlantic croaker	M
Pogonias cromis - Black drum	M
Brackish-Saline (marine)	
Chaetodipterus faber - Atlantic spadefish	M
Trachinotus carolinus - Florida pompano	M

Tertiary Consumers (Regulators) - Top-Higher Carnivores

Fresh-Brackish (spawn in fresh water)
Lepisosteus oculatus - Spotted gar
Lepisosteus spatula - Alligator gar
Micropterus salmoides - Largemouth bass

Fresh-Brackish-Saline (estuarine)
Cynoscion arenarius - Sand seatrout
Cynoscion nebulosus - Spotted seatrout
Sciaenops ocellata - Red drum
Paralichthys lethostigma - Southern flounder

Brackish-Saline (marine)
Lutjanus campechanus - Red snapper
Scomberomorus cavalla - King mackerel
Scomberomorus maculatus - Spanish mackerel
Pomatomus saltatrix - Bluefish
Rachycentron canadum - Cobia

Tertiary consumers. At the top of the aquatic trophic spectrum are the tertiary consumers, more commonly referred to as "top" or "higher" carnivores. They represent the terminal end of the food chain and the ultimate in secondary aquatic production. Foods of top carnivores come from all consumer levels but especially from the ranks of mid-carnivores and certain primary consumers. As with primary and mid-carnivores, top carnivores are consumer regulators, and most are voracious predators. Spotted and alligator gars, bowfin (*Amia calva*), and largemouth bass are the most important tertiary consumers in fresh water, while spotted and sand seatrouts, red drum, and southern flounder are abundant in estuarine environments. King and Spanish mackerel, red snapper, bluefish, and cobia are major top carnivores of the marine region (Table 6-1).

Trophic dynamics. All consumer species do not conveniently conform to rigid trophic levels. Individuals of a given size group (life history stage) often consume significant amounts of foods from several different sources. Indeed, many of the most successful species of Deltaic Plain fishes and invertebrates are opportunists, with their food habits governed to a large extent by what is readily available. Some species consume their own young, and others feed to some extent on species of the same basic trophic level while most feed on organic detritus at some stage of their life cycle.

A significant occurrence in the trophic spectrum of Deltaic Plain aquatic communities is the ontogenetic progression of food habits within a given species with successive specialization upon different types of foods (Darnell 1961). Some aquatic consumers show broad disregard for narrow or restricted trophic lines. This ability to utilize alternative food sources acts as a buffering action that tends to stabilize population levels. Some species, especially detritivores and secondary consumers, are omnivores in the broadest sense. This probably relates to the unique abundance and diversity of food items for all consumers in Deltaic Plain aquatic environments.

At present, estimates of either standing crop or productivity of aquatic species in the Deltaic Plain are largely unavailable. Only one productivity estimate was found (Day et al. 1973). Standing crop estimates are available for scattered freshwater areas, but only a few brackish or saline areas have been sampled. One of these studies emphasizes that standing crop of at least some Deltaic Plain species is above the maximum reported for comparable systems in other locales (Bryan and Sabines 1979). The exceptional fishery yield is further evidence of the high productivity of the Deltaic Plain relative to other coastal regions.

Wildlife

A large number of species of birds (Lowery 1974a), mammals (Lowery 1974b), amphibians, and reptiles (Keiser and Wilson 1969) occur as either permanent or seasonal inhabitants of Louisiana and the Mississippi Deltaic Plain. These vertebrate groups act as heterotrophs, or consumers, within the biotic ecosystem. They represent secondary production in the ecosystem and include primary and secondary consumers as well as top carnivores. Wildlife ecology deals with how these species relate to each other, the botanical elements of the system, and the physical processes which drive the system. The physical processes include the riverine, socioeconomic, geologic, atmospheric, and marine processes.

Wildlife ecology has evolved most directly from wildlife biology and zoology. It is a young science, having gained attention in Louisiana and the Deltaic Plain only during the last 25 years. As the biology and life history of many of the game and furbearer species became known in greater detail, wildlife biologists and zoologists began to take a wider study approach to manage the resource more effectively. Rather than viewing a species as a self-contained entity, biologists began to investigate how the species interrelated with other zoological elements, botanical elements, and the physical processes. This ecosystem approach led to attempts at defining functional roles for various species. Wildlife ecology now deals with questions concerning such subjects as trophic relations, food chains, nutrient cycling, energy flow and conversion, resource partitioning, energy budgets, behavioral components, and precise habitat requirements, as well as other biotic and abiotic interactions. Recently, attention has been directed to adverse impacts on wildlife populations resulting from man's activities.

In order to discuss the scope of wildlife ecology in the Mississippi Deltaic Plain, the animal species will be categorized by habitat usage (terrestrial, wetland, or aquatic) and, where applicable, by trophic roles. The nature of many wildlife species is such that they may not fit well in just one category. Some species, for example the raccoon (Procyon lotor), may use terrestrial and wetland habitats and are omnivorous in feeding habits. However, as a whole, this categorization facilitates discussion.

Terrestrial. Ecological processes involving the terrestrial fauna of the Mississippi Deltaic Plain have been largely unexplored. This is especially true for mammalian and herpetofaunal species. However, work involving terrestrial avifauna includes the Dickson and Noble (1978) study of vertical distribution of birds in a bottomland hardwood forest located in St. Landry Parish, Louisiana. Information is presented concerning resource partitioning by various bird species, including seasonal variation and interspecific competition. Dyer (1976) has provided a precise definition of diurnal habitat requirements of the American Woodcock (Philohela minor) in Louisiana. Biomagnification of pesticides in the Woodcock has been discussed by McLane et al. (1971) and Clark and McLane (1974).

Wetland. Day et al. (1973) studied community structure and carbon budget of the salt marsh in the Barataria Bay, Louisiana region. This is perhaps the only work in Louisiana which attempts to incorporate wetland birds and mammals into the study of energy flow, community structure, and secondary production. Data are given for carbon flow in the system and include estimates for the major marsh mammals and bird groups. Trophic relations, production, seasonal abundance, biomass, and respiration are estimated for ducks, wading birds, sparrows, wrens, rails, shore birds, and fishing birds, as well as the raccoon and muskrat (Ondatra zibethicus). Although this study is not complete, it is the first step toward clarification and quantification of functional roles of wildlife species in the Deltaic Plain.

Habitat utilization and resource partitioning by sympatric water snakes in a swamp and bayou area adjacent to the Mississippi Deltaic Plain has been discussed by Hebrard and Mushinsky (1978). Evidently, both food (Mushinsky and Hebrard 1977a) and time (Mushinsky and Hebrard 1977b) are resources that are partitioned to avoid direct competition. A study of diurnal activities of Greenwinged Teal (Anas carolinensis) and Pintail (Anas acuta) has shown behavioral differences in modes of habitat utilization between species that may be of significance in management (Tamisier 1976).

Aquatic. Day et al. (1973) have included the aquatic birds of the Louisiana salt marsh in the study of community structure and carbon budget. Energy flow, biomass, production, respiration, and seasonal abundance were estimated. Blus et al. (1975) discussed the status of the Brown Pelican (*Pelecanus occidentalis*) in relation to levels of organochloride pesticides. The taxa of aquatic mammals (Cetacea, Pinnipedia) that frequent Louisiana coastal waters have not been studied in regard to their ecological roles.

NUTRIENT CYCLING AND DECOMPOSITION

Elements tend to move in characteristic paths throughout the environment. Chemical transformations from abiotic to biotic components and then back to abiotic are common. The movement of those elements required by living organisms is referred to as nutrient cycling. Decompositional processes are important to nutrient cycling in releasing organically-bound elements into the biosphere. In addition, decomposition often results in protein-enriched substrates which are utilized as an energy source by primary consumers.

Plant communities are important in affecting and contributing to the cycle of nutrients in an ecosystem. Plants absorb and store large amounts of nutrients and then slowly release these nutrients back into the environment via decomposition.

Despite some studies investigating nutrient cycling and decomposition in specific habitats within the Mississippi Deltaic Plain, a thorough understanding of these processes is still far out of reach. Wetlands act as buffers in bays, lakes, and estuaries against large inputs of nutrients from agricultural runoff and/or industrial processes. For example, bald cypress swamps can act as a sink for inorganic nitrogen via denitrification in anoxic waters and sediments; they also serve as a source for phosphorous which is subsequently absorbed onto the sediments (Kemp 1978). Nutrient concentration data from the wetlands surrounding Lake Pontchartrain suggest that swamps are receiving the highest inputs from urban-industrial runoff. These inputs are taken up and/or diluted as they are transported from swamp to lake environments, resulting in a decreasing gradient of nitrogen, phosphorus, and carbon (Cramer 1978).

Bayou waters surrounding Lac des Allemands, Louisiana, are rich in nitrogen and phosphorus, presumably derived from agricultural sources. As the waters flood over the swamp floor, nutrients become available to the biota. Later, in the form of detritus, these nutrients are transported downstream to lake and marsh systems. The lake itself reduces carbon, nitrogen, and phosphorus inputs to the lower estuary by 43%, 47%, and 46%, respectively (Day et al. 1977). The lake sediments apparently serve as a eutrophication buffer by removal or storage of large amounts of phosphorus and nitrogen.

Marshes also act as regulators of nutrient cycling. This can best be illustrated from the standpoint of nitrogen which generally limits primary productivity in *Spartina* marshes. Salt marshes adjacent to Barataria Bay, Louisiana, contain 7850 kg ha^{-1} of nitrogen in the soil alone (Delaune et al. 1976). This nitrogen is mainly organic (derived from *Spartina* roots and rhizomes), some of which is capable of being mineralized. Approximately

250 kg ha^{-1}yr^{-1} of the soil organic nitrogen is mineralized to inorganic nitrogen which is available to plants. *Spartina alterniflora* incorporates 130 kg ha^{-1}yr^{-1} in shoot tissue, and 100 kg ha^{-1}yr^{-1} is estimated to be incorporated in the roots, or a total of 230 kg ha^{-1}yr^{-1} in the whole plant. The remaining 20 kg ha^{-1}yr^{-1} is thought to be lost through denitrification (Delaune et al. 1976). Detrital export is estimated to remove 40 kg ha^{-1}yr^{-1} from the system. The two pathways in which nitrogen is lost from the system are detrital export and denitrification which removes a total of 60 kg ha^{-1}yr^{-1}.

The main nitrogen inputs into the marsh system are from sediment deposited at streamside areas and from biological nitrogen fixation. Nitrogen is fixed at a rate of approximately 10 kg ha^{-1}yr^{-1} (Delaune et al. 1976); greater fixation rates are observed in the warmer months of spring and summer. Nitrogen input via sediment deposited at a streamside area was estimated to be 40 kg ha^{-1}yr^{-1}. An additional 8-10 kg ha^{-1}yr^{-1} is added through rainfall. Thus, total nitrogen input is estimated to be 60 kg ha^{-1}yr^{-1} (Delaune et al. 1976).

The process of decomposition is essential to the recycling of nutrients bound in plant tissue. Rates of decomposition vary with plant species, method of measuring decomposition, and environmental site differences. Although rates of decomposition for the majority of plants in the Mississippi Deltaic Plain are relatively scarce, a number of estimates are available for salt marsh angiosperms.

Spartina alterniflora tissue is 80-90% decomposed (i.e., 80-90% of its biomass is lost) after one year in the Mississippi Deltaic Plain (Gosselink and Kirby 1974, White et al. 1978). This decomposition rate is one of the highest for salt marsh macrophytes. *Juncus roemerianus* decomposes at a slower rate than *Spartina alterniflora*, with a 50-80% weight reduction/one year (de la Cruz and Gabriel 1974b, White et al. 1978). Seventy-six percent of *Distichlis spicata* tissue will decompose after one year, while *Spartina patens* exhibited a slightly lower loss rate of 62% (White et al. 1978).

With time, decomposing plant tissue generally increases in nutritive value. The value of detritus as a food source lies in the energy value it can supply to consumers. More research concerning this area is needed. De la Cruz and Gabriel (1974b) demonstrated increased caloric values (energy content) and lower carbon to nitrogen ratios as *Juncus roemerianus* tissue decomposed. *Spartina alterniflora* also tends to increase in caloric value and percent protein as decomposition proceeds to fine particles of detritus (de la Cruz 1973).

Research concerning the role of microbial and fungal populations in the biodegradation of estuarine plant material is scarce from this region. Myers (1974) has shown that *Spartina* is systematically attacked by selective fungal populations throughout its development and decomposition. Fungal attack is correlated with seasonal development and subsequent decomposition of the plant. A large yeast biomass, notably sporagenous taxa *Picia spartinae* and *Kluyveromyces drosophilarum*, is prevalent in the oxidized portions of the *Spartina* rhizosphere and within peripheral tissue. Cellulolytic studies have demonstrated comparatively low levels of cellulose decomposition, suggesting that the fungus is not a vigorous decomposer of the cellulose portion of the plant carbohydrates. In all likelihood, the fungus is utilizing carbohydrate substrates other than cellulose in its growth.

Numbers of yeast cells in the water and submerged sediments tend to be highest in the summer and lowest in the winter, while yeast cell numbers in the marsh soil are generally higher in the winter (Myers et al. 1971). Yeasts were most abundant in the marsh soil. A number of species of molds have been found in association with *Spartina* stems. The exact role of fungi in decomposition relative to bacteria has not yet been determined. Hood (1970), studying bacterial types and population densities in the Barataria hydrological basin of the Mississippi Deltaic Plain, found that bacteria in the top few centimeters of the soil are typically inactive and slow growing. The predominant bacteria in both aerobic and anaerobic sediments are in the genus *Bacillus*, which makes up 50-60% of the total number of bacteria. Less important in the aerobic zone are the *Pseudomonas* species. In the lower anaerobic zone, *Clostridium* species are abundant. Cellulolytic bacteria are found in high concentrations within the marsh soil, but the highest biomass of cellulose utilizers is found at the base of *Spartina* stalks (Hood 1970). These data suggest that greatest cellulose utilization occurs on the plant itself.

Although fungi, bacteria, animals, and abiotic factors (e.g., temperature, salinity, and anaerobiosis) are all presumably important in controlling plant decomposition, direct measurements concerning the functional significance of these parameters as they relate to plant decomposition within the Mississippi Deltaic Plain have not been reported. Estuarine and coastal microbial systems in this area have not been adequately studied.

Although this section deals mainly with the role of plants in nutrient cycling and decomposition, it should be emphasized that animals also play a significant role. Unfortunately, there are no reports of research dealing with this aspect of plant decomposition from the area.

INTERRELATIONSHIPS OF ENVIRONMENTAL PARAMETERS AND MANAGEMENT OF WETLAND ECOSYSTEMS

Much of the research into the ecological interrelationships between organisms and the environment of the Mississippi Deltaic Plain has concentrated on understanding and managing the environment for the benefit of man. The major areas of interest involve creation and management of forest and marsh habitats for the enhancement of extractable resources and the control or eradication of undesirable species, such as introduced or unprofitable flora.

The once ubiquitous bottomland hardwood forests have been virtually eliminated from all but the lowest lying regions of the lower Mississippi River alluvial valley. Today they remain only where they are protected by floodplain, forest, and wildlife management programs, and in areas where it is not economically feasible to manage the land for agriculture or development. These remnant forests are frequently inventoried by State, Federal, and private foresters to determine the extent and distribution of the regions' timber resources (McKnight 1966, Kennedy 1969, Sternitzke 1976, Thielges and Land 1976). Because bottomland timber is a national resource whose production area has been diminishing in recent years, foresters must enhance production to meet the growing timber demands by determining environmental conditions most suitable for individual tree species, as well as by proper harvesting and marketing techniques (Maisenhelder 1945, 1958; Putnam 1951; Putnam et al. 1960; Miller 1969; Walker and Watterston 1972; Johnson 1975). Of prime concern has been the determination of the effect of various flooding regimes on established timber species (Bonck 1945, Parker 1950, Briscoe 1957, Hosner 1960, Dickson et al. 1965, Broadfoot and Williston 1973, Kennedy and Krinard 1974, Noble and Murphy 1975, Baker 1977) and on the germination and survival of seeds and seedlings (McDermott 1954, Hosner 1958, Broadfoot 1959, Briscoe 1961). The beneficial and detrimental impacts of artificially impounding and permanently raising ground water tables on established timber sites has also been documented for the more valuable timber species (Broadfoot 1958, Eggler and Moore 1961).

Many bottomland hardwood forests are managed for both timber and wildlife. It has been well documented that wetland forests are valuable wildlife habitat (Viosca 1928; U.S. Fish and Wildlife Service [FWS] 1954a, 1954b; Oefinger and Halls 1974). These areas provide shelter, nesting habitat, and abundant wildlife forage species (Pearson and Sternitzke 1976, Chabreck 1964, Glasgow and Linnartz, ongoing research). In recent years, conflicting land use demands, such as cattle grazing in bottomland hardwoods (Johnson 1960) and the displacement of bottomland hardwoods by agriculture and urban development (Yancey 1970), have enhanced the awareness of the functioning of these habitats and resulted in the desire to preserve a balance among various ecological systems.

Whereas forest management studies have emphasized timber production, marsh management research has concentrated on enhancing wet grasslands for wildlife, especially waterfowl and furbearers. Some researchers have looked at controlling water levels in marshes to manage plant and animal production (Gunter and Shell 1958, E. R. Smith 1970, Larrick 1975), while others have investigated the impact of canals on marsh viability (Stone et al. 1978). Brown and de la Cruz are presently undertaking research on proper marsh management techniques in Mississippi (de la Cruz, ongoing research, 1979). In Louisiana, research on tidal marsh management tools (Gosselink and Pope 1973), effects of management on primary production, and salt marsh ecosystem modeling in Barataria Bay are among recent studies undertaken through the Louisiana State University Marine Science Program.

For over 50 years, wildlife biologists and managers have investigated the availability of waterfowl food in coastal marshes (Sperry 1925, Martin and Uhler 1939, Chamberlain 1959a, Glasgow and Bardwell 1962, Olinde 1977) and experimented with techniques to improve food production (Lynch et al. 1947, Jemison and Chabreck 1962). Fresh to brackish marsh management for improved nutria and muskrat habitat has also been a prime concern in Louisiana (O'Neil 1949, U.S. Dept. of Interior 1956, Harris and Webert 1962).

Fire has been used frequently to remove undesirable marsh species, such as wiregrass, in order to allow more desirable species, such as three-cornered grass (Scirpus olneyi), to dominate the marsh providing abundant marshland food for furbearers and waterfowl (O'Neil 1949). Despite its acceptance as a habitat management technique, the effects of fire on wetlands have received only limited study. Viosca (1931) looked at the possibility of marsh fires beginning from spontaneous combustion, and Hoffpauir (1969) measured and determined the effects of marsh fires on Louisiana marshes.

Man's impact on wetlands and wildlife has often resulted in environmental degradation and habitat loss. The major reclamation programs in the first half of the twentieth century were initially viewed in terms of their benefit to man's agricultural endeavors (Okey 1914, Harrison and Koilmongan 1947) and only secondarily in terms of wildlife habitat destruction (Penfound and Schneidau 1945). More recent studies have attempted to evaluate the effects of man's activities on wetlands with regard to ditching and draining (Bourn and Cottam 1950, Parrondo et al. 1978) and maintenance canal dredging (Vaughan and Kimber 1977). This awareness of wetland destruction has resulted in recent attempts to establish new marsh habitat on spoil (Eleuterius 1974a, Wentz 1974) and new submerged aquatic beds in the Mississippi sound (Eleuterius 1974b, 1975a).

Among the many environmental parameters affecting bottomland hardwoods, swamps and marsh distribution, growth, value and viability, the impacts of hurricanes and freezes have been the least frequently studied. While these two factors can have a significant impact on vegetation because of their ability to disturb the normal growth cycles, their infrequent appearance in the lower Mississippi Deltaic Plain may explain the paucity of data. The primary research on the impact of freezing involves the determination of stunting and mortality of nonfreeze tolerant plants, both native and exotic (Penfound and MacKaness 1940, U.S. Dept. of Agriculture 1955). Other studies have been conducted on the impact on vegetation of two of the most severe hurricanes ever to come ashore in recent years. Camille hit the central Mississippi Gulf coast in 1969 and temporarily devastated narrow banks of forests along the coast with high winds and salt spray (Van Hooser and Hedland 1969, Gunter and Eleuterius 1971), but the impact was not permanent. Hurricane Audrey came ashore along the south central Louisiana coast in 1957 affecting salt marshes in the vicinity of Marsh Island. The immediate impact and the eventual ability of the marshes to recover were studied by Harris and Chabreck (1958) and Chamberlain (1959b). Chabreck and Palmisano (1973) investigated the impact of this hurricane on the predominantly fresh marshes in the lower Mississippi delta.

In recent years, as much research has been directed toward the eradication of undesirable species, especially the alligatorweed (_Alternanthera philoxeroides_) and water hyacinth (_Eichhornia crassipes_), as toward the enhancement of desirable flora production. Major attempts have been aimed at controlling or eradicating these species because of their tendency to spread unchecked throughout freshwater environments, displacing the more desirable plant species and degrading the quality of certain environments for aquatic fauna (Viosca 1949, Bennett 1968, Vogel and Oliver 1969, Zurberg et al. 1970, Rintz 1973, Long and Smith 1975, Spencer and Coulson 1976, Addor 1977). In the process of trying to control the water hyacinth, a great deal of information has been collected concerning its biology (Gowanloch 1945, Penfound and Earle 1948, Hitchcock et al. 1949, Mulcahy 1975), but little progress has been made so far in the elimination of this currently undesirable species.

INFORMATION DEFICIENCIES

PRIMARY PRODUCTIVITY

The majority of research concerning the primary productivity of the Mississippi Deltaic Plain vegetational communities has been descriptive rather than experimental. Although estimates of primary productivity have been quantitative, little manipulative or experimental research has been conducted to determine the important factors controlling productivity. Thus, the major gaps in current knowledge of primary productivity concern its limiting factors.

This is especially true for phytoplankton productivity. Although primary productivity data exist for phytoplankton in a number of areas of the Mississippi Deltaic Plain, what is known about limiting factors is generally inferred from the literature or speculated from peripheral data. Data gaps also exist in the area of phytoplankton community dynamics. The significance of phytoplankton carbon relative to carbon produced by other primary producers in supporting consumer organisms should be further investigated.

Little data are available for benthic and epiphytic algal productivity. No productivity estimates exist for benthic and epiphytic algae indigenous to coastal communities other than salt marshes such as swamp, submerged aquatic, and freshwater marsh. In addition, the importance of light and nutrients in determining productivity has not been investigated in this area.

The primary productivity and ecology of submerged aquatic vegetation in the Mississippi Deltaic Plain have received little attention. Both structural and functional studies are needed for saline and freshwater submerged aquatics. Productivity and limiting factor information about these vegetational communities is lacking.

Primary productivity estimates are available for macrophytes in brackish and saline marshes but are scarce for freshwater marsh habitats. Also, investigations of factors controlling the distribution of freshwater macrophytes and specific marsh "dieback" sites are few.

Relatively few ecological studies of arboreal swamp vegetation in the Mississippi Deltaic Plain have been conducted. There is a lack of information concerning total productivity, factors controlling productivity and vegetational success, and the importance of these communities to the system as a whole.

The ecology of barrier island vegetation in the Mississippi Deltaic Plain has not been studied to any extent. Data gaps exist in almost every area of the ecology of these plants, including productivity, limiting factors, distribution, etc.

Terrestrial communities in the Mississippi Deltaic Plain have received considerable attention because of their importance to the lumber industry. Factors affecting the productivity of longleaf and slash pine stands have been investigated. Information concerning the ecology of terrestrial levee and dredge spoil communities is deficient.

SECONDARY PRODUCTIVITY

The most noticeable gap in the ecological knowledge of Deltaic Plain aquatic environments is concerned with secondary productivity. The work of Day et al. (1973) probably represents the first encompassing study of secondary production in a particular Deltaic Plain environment. Standing crops of aquatic consumers are more thoroughly studied, but not adequately addressed. The dearth of information on productivity and standing crop is due primarily to the fact that only recently has sufficient background information (on species and habitats) been available. Some information on what was termed "species mass" has been available for several years but has not been usable for quantitative analysis (Gunter 1967).

Despite the availability of several studies on food habits of certain aquatic consumer species, sufficient information to adequately designate trophic levels is lacking. Detailed quantitative food habit studies of some of the more abundant aquatic consumers are expecially lacking in this area.

The study of ecological processes involving wildlife species in Louisiana has barely begun. The work by Day et al. (1973) is the only study available that incorporates wildlife species into a systems modeling approach. Similar studies need to be carried out in other marsh habitats and terrestrial systems. Little or nothing is known concerning energy flow, secondary production, or biomass levels in these habitats, either generally or on a species level. Trophic interactions have not been quantified. Nutrient cycling and the role of the decomposers in the systems have not been studied. Information concerning resource partitioning is available for only a few species. Modes of behavior and their roles in influencing functional relations are poorly understood. Generally, these subjects represent a large void in the available knowledge concerning the functional roles of wildlife species in the Mississippi Deltaic Plain.

NUTRIENT CYCLING AND DECOMPOSITION

Knowledge of nutrient cycling and decompositional processes in the diverse habitats of the Mississippi Deltaic Plain is limited. There is little information available concerning nitrogen, phosphorus, and carbon cycling, or the cycling of micronutrients (e.g., zinc, copper, iron, manganese) in these habitats. Deficiencies also exist in an understanding of the importance of cycling processes within the ecosystem as a whole.

Although plant decomposition data are much more available than nutrient cycling data, there are still large data gaps for rates of decomposition other than for salt marsh plants. Very little information is available concerning nutritive value changes of decomposing tissue with time, and the functional role of microbial populations during decomposition is an area which is relatively unstudied.

Animal contributions to the cycling of nutrients and decomposition has been unreported in the Mississippi Deltaic Plain and represents a deficiency in regional knowledge of these processes.

INTERRELATIONSHIPS OF ENVIRONMENTAL PARAMETERS AND MANAGEMENT OF WETLAND RESOURCES

Most of the available literature on bottomlands, swamps, and marshes of the Deltaic Plain Region details the function of these habitats as a timber or wildlife resource base that can be harvested by man. What is crucially needed at this time is a greater understanding of the functioning and interrelationships of these natural environments and the adjacent man-made habitats. An awareness of the proper balance between natural, productive environments and man-made consumer systems is essential for the preservation and protection of viable floral and faunal habitats as well as a high quality environment for humans. It is probable that this in-depth knwoledge of the components and functioning of individual systems can be achieved only with research directed at all facets of the environment from both holistic and atomistic viewpoints and not just at that which is of immediate value to man. In view of the present rapid trend toward deterioration and destruction of natural wetland habitats, it is reasonable to ponder this question: What would it matter if there were no more natural stands of bottomland hardwood forests, bald cypress and tupelo gum swamps, and coastal marshlands?

RECOMMENDATIONS

PRIMARY PRODUCTIVITY

Future research concerning the ecology of the Mississippi Deltaic Plain should emphasize functional relationships and interactions among various components of the syetem (i.e., energy conversion, nutrient cycling, primary and secondary productivity) as well as its structural characteristics (i.e., species composition, abundance, diversity, distribution). In addition, research should be directed not only toward describing these processes, but more importantly toward delineating their controlling factors. For example, primary productivity of marsh macrophytes has received much attention, but relatively little research has been conducted to investigate the factors controlling this productivity. For a number of biotic communities, such as epiphytic and benthic algae, and to some extent submerged vegetation, there is so little information available that the first research step must be to define structural characteristics. After structural parameters have been identified and described, further research must concentrate on how the ecosystem functions, with emphasis on controlling factors. This approach is necessary before a thorough understanding of any ecological system can be attained.

Specific recommendations for future research in the area of primary productivity in the Mississippi Deltaic Plain are:

1) Phytoplankton measurements should be continued in a variety of habitats, and controlling factors should be determined. Phytoplankton carbon as a source of energy for consumer organisms should be further studied.

2) The contributions of benthic and epiphytic algae to the overall system should be determined, and research concerning the structural and functional characteristics of these communities should be conducted.

3) The general ecology and value of submerged aquatic vegetation as a source of food and habitat should be identified.

4) Marsh macrophytic primary productivity studies should concentrate on limiting factors and causes of marsh deterioration. An exception is freshwater marshes, where relatively few primary productivity studies have been conducted.

5) Research concerning the biology and physiological ecology of arboreal swamp vegetation should be continued. Productivity studies, of which there are presently few, should be carried out.

6) An intensive effort to study the ecology and dynamics of barrier island vegetation is recommended.

7) Research into the ecology of dredge spoil and natural levee plant communities is needed.

SECONDARY PRODUCTIVITY

Studies on productivity of the various Deltaic Plain aquatic environments should be priority research investment. Basic standing crop data also need to be provided for each habitat region. By providing accurate estimates of both standing crop and productivity of important fishery species, researchers can better address the need for identifying and preserving vital habitat at all life history levels: larva, juvenile, and harvestable adult.

Ecologically, trophic positions of valuable species need to be better understood for all developmental stages. Food habits of commercially valuable species need to be further addressed to better understand the role of prey species in energy transfer. These requirements can be met only by continuing quantitative food habit studies.

There is also a need for more research on the relationships of aquatic animals with various physical and chemical parameters. Salinity has long been known to be an important factor in faunal distribution, but finer details of its relationship to fishery harvests have only begun to be studied. In addition, factors such as dissolved oxygen, conductivity, and pH are known to affect fishes, especially in fresh water where periodic natural fish kills occur.

Because wildlife ecology is a relatively unexplored science in the Deltaic Plain, it is difficult to be specific as to research needs. Certainly an expansion and continuation of systems modeling in all habitats would be warranted. Regarding the role of consumers in the biotic ecosystem, wildlife species take part in the conversion of energy into forms harvestable by man; precise data concerning this conversion and the patterns of an energy flow are needed. As man's activities will no doubt continue to impact all biotic systems in the Deltaic Plain, a better understanding is needed of how wildlife function within the system. Numerous species have been studied little or not at all, and in these cases even basic ecological relations would be of value. In addition, investigations concerning the effects of environmental contamination on wildlife species need to be continued.

NUTRIENT CYCLING AND DECOMPOSITION

Because of the many areas in which current knowledge of nutrient cycling and decomposition in the Mississippi Deltaic Plain is limited, specific research directions are difficult to recommend. Although many types of research in this area would add important information which could be used to understand the whole system, priorities should be defined, and the following recommendations for future research are suggested:

1) In-depth research concerning the cycling of nutrients which are generally limiting to primary productivity (e.g., phosphorus, nitrogen, carbon, silicon, etc.) should be conducted.
2) The cycling of elements which are potential pollutants (e.g., lead, mercury, cadmium, etc.) should be studied further.
3) The importance of coastal plain plant communities in absorbing nutrient inputs needs further study.
4) The factors controlling the supply of nutrients via decompositional processes for primary productivity require further study.
5) The role of microbial communities in the cycling of nutrients and plant decomposition in wetland communities should be pursued.
6) Decompositional studies of plants from other than salt marsh environments should be conducted.
7) Investigations concerning changes in nutritive value during plant decomposition and the significance of these changes to primary consumers should be further studied.
8) Research concerning the importance of animals in nutrient cycling and decomposition is needed.

INTERRELATIONSHIPS OF ENVIRONMENTAL PARAMETERS AND MANAGEMENT OF WETLAND RESOURCES

In reviewing the literature on bottomland hardwood, swamp, and marsh ecology, it is readily apparent that the majority of research has focused on those species with greatest economic value. An evaluation of the total ecosystem, not just of individual species, is also needed with emphasis on methods to re-establish forest and marsh species that are presently being destroyed by changing land use demands and natural processes.

In this age of maximum utilization of resources and conflicting land use demands, it is crucial to determine the maximum multiuse functions of forests and marshes, and to establish legal and social means to facilitate effective forest management. Better cost/benefit assessments are needed to evaluate the real cost of habitat destruction. In addition, research into secondary impacts of development--such as canals, highways, and spoil deposits--would be beneficial, especially in the wetlands.

Marshes need to be re-established in areas where they have been altered beyond the point of natural rejuvenation by abandoned reclamation projects, saltwater intrusion, subsidence, erosion, levees, and canals. For this to be possible, a greater understanding will be required of the relationship between marsh species and environmental parameters such as soils, salinity, water levels, nutrients, sediment inputs, and time. This information will also aid man in managing the marshes for harvestable resources such as furbearers, waterfowl, fish, and reptiles, and will help to prevent inadvertent mismanagement. A better understanding of the forms and functions of individual ecosystems is essential to distinguish and evaluate the impacts of man and nature on the natural system and to establish a reasonable balance between the needs of man to harvest resources and the ability of the system to maintain itself.

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CHAPTER VII: OIL AND GAS ACTIVITIES

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INTRODUCTION

No single human activity has so totally and visibly affected the Mississippi Deltaic Plain Region as the search for, development of, and transportation of oil and gas, even without taking into account the associated support structure and related needs for housing, transportation, navigation, and flood control. The range of the effects not only relates to the areal extent and level of oil and gas operations but also to the associated changes in morphologic and hydrologic characteristics and the resultant perturbation of ecosystem functions.

There has been much debate about the exact nature of these effects because similar modifications of the ecosystem are induced by natural and man-induced processes such as natural subsidence and limitation of river water introduction. Effects of oil- and gas-related activities range from acceleration of existing natural trends in ecosystem changes, such as saltwater intrusion, to clearly identifiable changes, such as removal of wetlands through canal dredging. This paper reviews existing information concerning the effects of oil and gas operations on the Mississippi Deltaic Plain Region environment relative mainly to exploration and extraction.

From a historical perspective, oil and gas development is a recent event in the Mississippi Deltaic Plain Region. Early studies (Harris and Veatch 1902, Harris 1910) by the Louisiana Geological Survey personnel described the occurrence of oil and gas in that state and related their distribution to salt domes. However, for many years there was no systematic evaluation of the petroleum potential and consequently only limited extraction. Extraction within the Mississippi Deltaic Plain Region was further limited initially by poor foundation conditions of swamp and marshes for the early wooden and steel oil rigs. Even though extraction began in 1901 in a rice field in southwest Louisiana, no major inroads into the Mississippi Deltaic Plain Region were made until the 1930s.

Two events were instrumental in stimulating a boom in oil and gas activities at that time. Following establishment of a professional school of geology at Louisiana State University in 1922, understanding of Mississippi Deltaic Plain Region geologic structure and process advanced rapidly, allowing more complete evaluation of oil and gas resources. Equally important were the invention of the submersible drilling barge in the mid-1930s and the introduction of the barge-mounted draglines in 1938, thereby providing the technical means for extraction and for obtaining access to well sites through dredging of canals. Canal dredging was further employed for laying of oil and gas pipelines. By 1969, these events had made possible the development of some 307 fields through a total of over 20,000 wells in the Mississippi Deltaic Plain Region (Gagliano 1973).

Offshore petroleum extraction began in 1947 when the Kerr-McGee Oil Company completed a well in the Ship Shoal area. This effort had increased to 10,000 wells by 1969 (Gagliano 1973) in more than one hundred fields.

All of this development is concentrated in the Louisiana segment of the Mississippi Deltaic Plain Region. There are no known active oil or gas fields in the Mississippi part of the study area (International Oil Scouts Association 1977), including Mississippi offshore regions (Mumphrey and Carlucci 1978). The Ansley Gas Field in southwest Hancock County is the only petroleum field near the Mississippi area and it was abandoned as unproductive in 1967. Regional pipelines cross the area from west to east, and two routes come onshore from activities off the Louisiana coast. A few petroleum-related industries occur in the Pascagoula, Mississippi area.

Oil and gas activities in the Mississippi Deltaic Plain Region may be divided into two major classes: the exploration and primary extraction activities and the secondary support and processing facilities. It is the first group that has been investigated with regard to environmental effects upon the Mississippi Deltaic Plain Region ecosystems and which are dealt with in this paper.

For the purpose of drilling, access to well sites in wetlands may be gained in two ways. In more easily accessible wetlands adjacent to existing agricultural fields or close to avenues of communication, plank or shell roads are built. Shell roads are formed by hauling in loads of shell to form the road base and surface. For the plank roads an embankment is formed by placing material removed from borrow pits along either side of the desired route. Layers of planks are then placed on the bed to fashion the road surface (Figure 7-1). If the rig is brought to the site by truck, construction of the drill pad requires that an area of about 1.4 ha (3.5 ac) be leveled and cleared of vegetation. The pad accommodates the drilling rig and accessories, temporary structures, and parking and maneuvering room for service and delivery vehicles. The pad may be surfaced with rock or gravel. A reserve pond, several square meters to several hundred square meters in area and 1 to 3 m (5 to 10 ft) deep (depending on the planned depth of the hole to be drilled) receives waste fluids and drill cuttings. The pond may be lined with impervious material to reduce leaching and groundwater contamination.

If a well is drilled in more inaccessible wetlands or shallow water bodies, barge-mounted draglines or dredges excavate access canals and well slips (Figure 7-2). Typical access canals are 23 m (70 ft) wide and have a

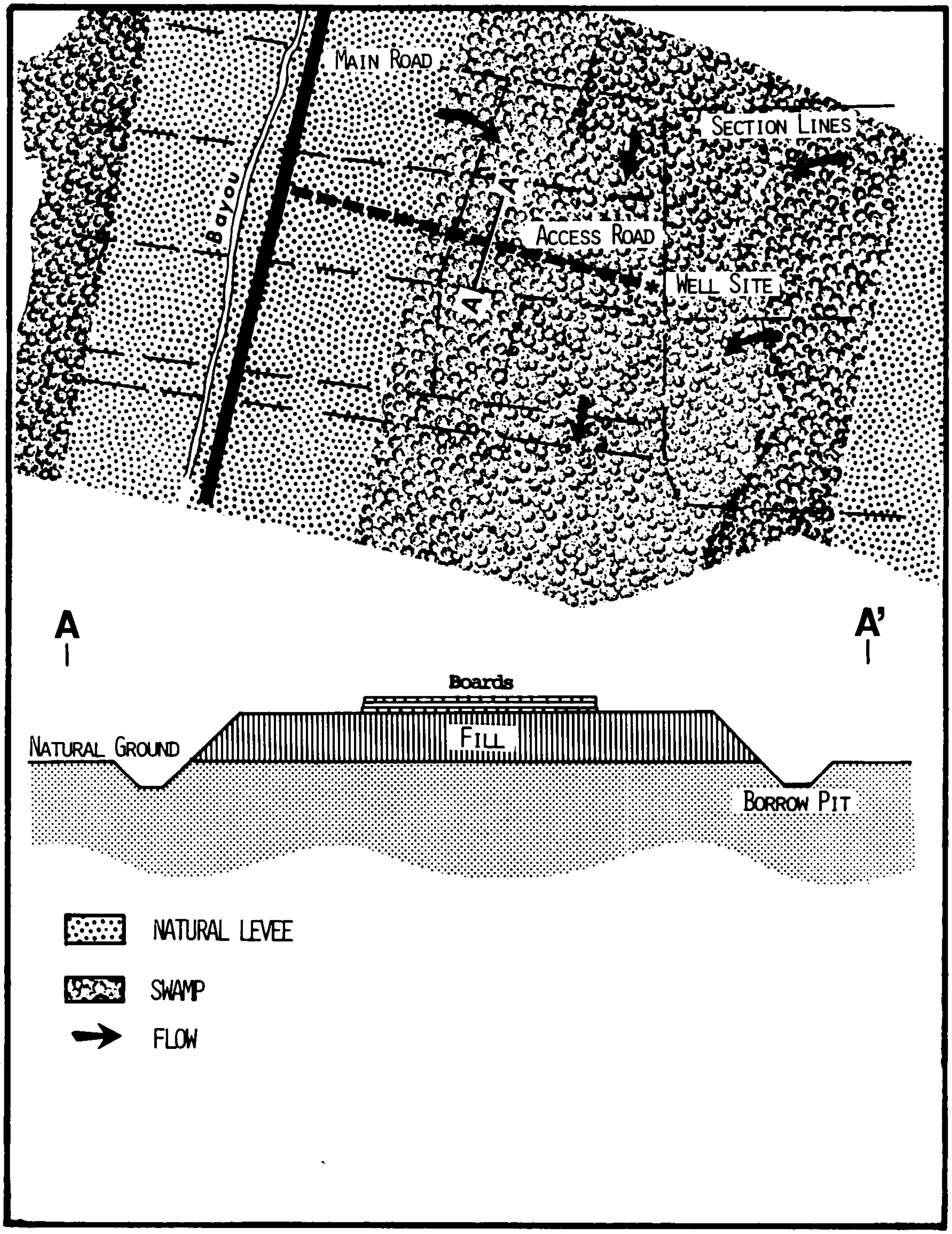

Figure 7-1. Oil field access road schematic (Coastal Environments, Inc. 1974).

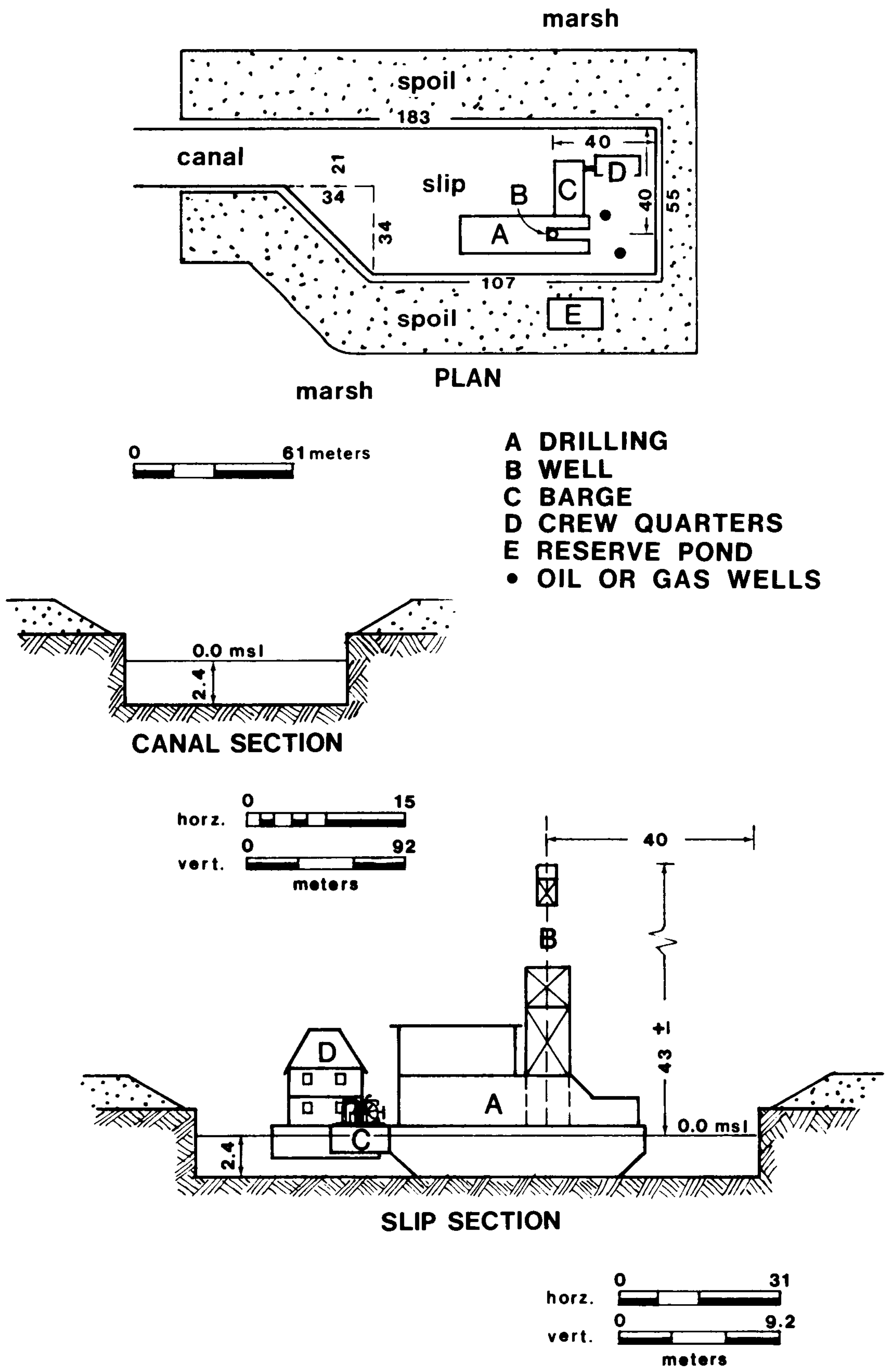

Figure 7-2. Typical rig and barge configuration for a well site in wetlands (Modified from Emmer 1978).

depth of 2.6 m (8 ft) below mean sea level (MSL). Well slips are rectangular and measure approximately 110 m (362 ft) long by 47 m (155 ft) wide with a depth of 2.6 m (8 ft) below MSL. Spoil is deposited on one or both sides of the canal and around the well site. Drilling barges are floated into place and anchored. Wells for disposal of brine water are located in the slip, while pits for disposal of drilling mud are constructed on the spoil area surrounding the well slip.

Offshore drilling takes place from drilling barges, semi-submersibles, drill-ships, jack-ups ("...platforms with legs that can be extended up or down, depending on the desired depth of water at which the drilling will take place." [Mumphrey et al. 1976:73]), and fixed platforms. After completion of the well, production equipment on the platforms separates oil, gas, water, and solid impurities. By 1975, over 2700 platforms had been built on the Louisiana shelf (Pequegnat 1975). The petroleum is then shipped onshore to refining facilities. An extensive infrastructure of support facilities is related to offshore activities (Mumphrey and Carlucci 1978) which includes platform fabrication yards, ports, waterways, service industries, storage facilities, highways, airports, heliports, pipelines, and electrical power.

The laying of pipelines is an inseparable part of the oil and gas extraction. In wetlands, pipelines are commonly laid by utilizing barge-mounted equipment, thus requiring canal dredging or deepening of shallow water bodies for navigation. Alternatively, pipelines in wetlands may be laid by utilizing a marsh buggy-mounted dragline to cut a ditch, after which the pipeline is floated in. In areas with a firm foundation, such as natural levees, land-based excavation may be employed utilizing back-filling techniques. The width of pipeline excavations and canals varies greatly, depending on the method of pipe laying and size and number installed simultaneously. Once lines are installed, additional capacity along the same route usually requires an additional canal.

GEOLOGIC ASPECTS

The effects of oil and gas activities on the Mississippi Deltaic Plain Region's geologic characteristics are twofold: subsurface effects having surface expression and direct changes of surface morphology. Little is known concerning subsequent effects beyond speculative information. With regard to changes in surface morphology, attention has focused mainly on canal dredging (Chapman 1968, Gagliano 1973, St. Amant 1972, Adams et al. 1978, Stone et al. 1978).

Fisk (1943) demonstrated a probable relation between a well-blowout and subsidence near Vacharie, Louisiana. The Vacherie Fissure grew to a length of 1616 m (5300 ft), a width of 15.24 cm (6 in), and a maximum vertical displacement of nearly 20.32 cm (8 in) in an oil field just west of Louisiana State highway 20. The well penetrated a high pressure (2000 psi) saltwater zone at 2640 m (8800 ft) below MSL, and flowed unchecked before it could be cemented and abandoned. Approximately a half day after the well was closed, the fissure appeared. The most likely cause of the fissure was the sudden release of high-pressured saltwater.

A debated but unanswered question is whether the massive oil and gas withdrawal accelerates the rate of subsidence of the Mississippi Deltaic Plain Region surface. Such subsidence is known to occur elsewhere along the Gulf coast (Pratt and Johnson 1926, Snider 1927, Atherton et al. 1976) and in other areas of the world (Gilluly and Grant 1949, Mayuga and Allen n.d., Yerkes and Castle n.d., Geertsma 1973). At present nothing more is known than the existence of a correlation between the area of most rapid conversion of wetland to water due to marsh deterioration (the area of greatest subsidence as indicated by dated peat surfaces) and the area of maximum oil field concentration (Gagliano and van Beek 1970, Gagliano et al. 1972).

A more precise effort has been made to document morphologic changes resulting directly from canal dredging for access, pipe laying navigation, and other water-dependent support activities. Gagliano et al. (1972), utilizing 1969 aerial photography, measured the total canal surface area between the Mississippi River and the eastern Atchafalaya Basin Floodway levee. Oil- and gas-related canals accounted for 65%, or 179 sq km (69 sq mi), of the total canal surface. This fact becomes even more significant when one considers the instability of the canal banks and bottom and resultant erosion by waves, currents, and boat traffic (Davis 1973). Craig et al. (1979), summarized measured increases in canal width, showing that doubling in width over a 20-year period is a reasonable expectation. Presently, canal area in the Barataria Hydrologic Unit (Unit IV) already accounts for 2.6% of the total marsh environment.

Morphologic change resulting from canal dredging also concerns the deposition of spoil. Estimates have been made of observed spoil width along access and pipeline canals (Gagliano 1973, Craig et al. 1979). The extent of morphologic change is difficult to evaluate on the basis of canal area because of subaqueous spoil deposition in bays and varying methods of spoil disposal (e.g., continuous, one side of the canal only, both sides of the canal, discontinuous).

Canal dredging has an apparently random pattern of occurrence (Figure 7-3) and disregard for natural topography (Gagliano 1972). The only obvious determinants of canal routes are the well locations as related to subsurface stratigraphy and location of navigation channels. As a result, movement of water and sediments is modified, which may contribute to secondary topographic changes. Examples are the removal of sediment from a barrier island system when canals interrupt sand in transport or the introduction of river sediments into riparian wetlands. In bays, disposed spoil is subject to wave action and may be redistributed, thus producing additional hydrographic and substrate change (Chapman 1968).

Available information is less specific concerning the secondary support structure related to oil and gas exploitation. Clearing of land for oil-related development results in increased runoff and associated soil erosion. Size of individual facilities, from fabrication yards to ports, varies from a few to several hundred hectares. Frequently, facility development requires additional dredging, spoil disposal, or leveeing for flood protection, drainage, or navigation improvement.

In summary, present knowledge about the effects of oil and gas activities on the geology of the Mississippi Deltaic Plain Region is for the most part

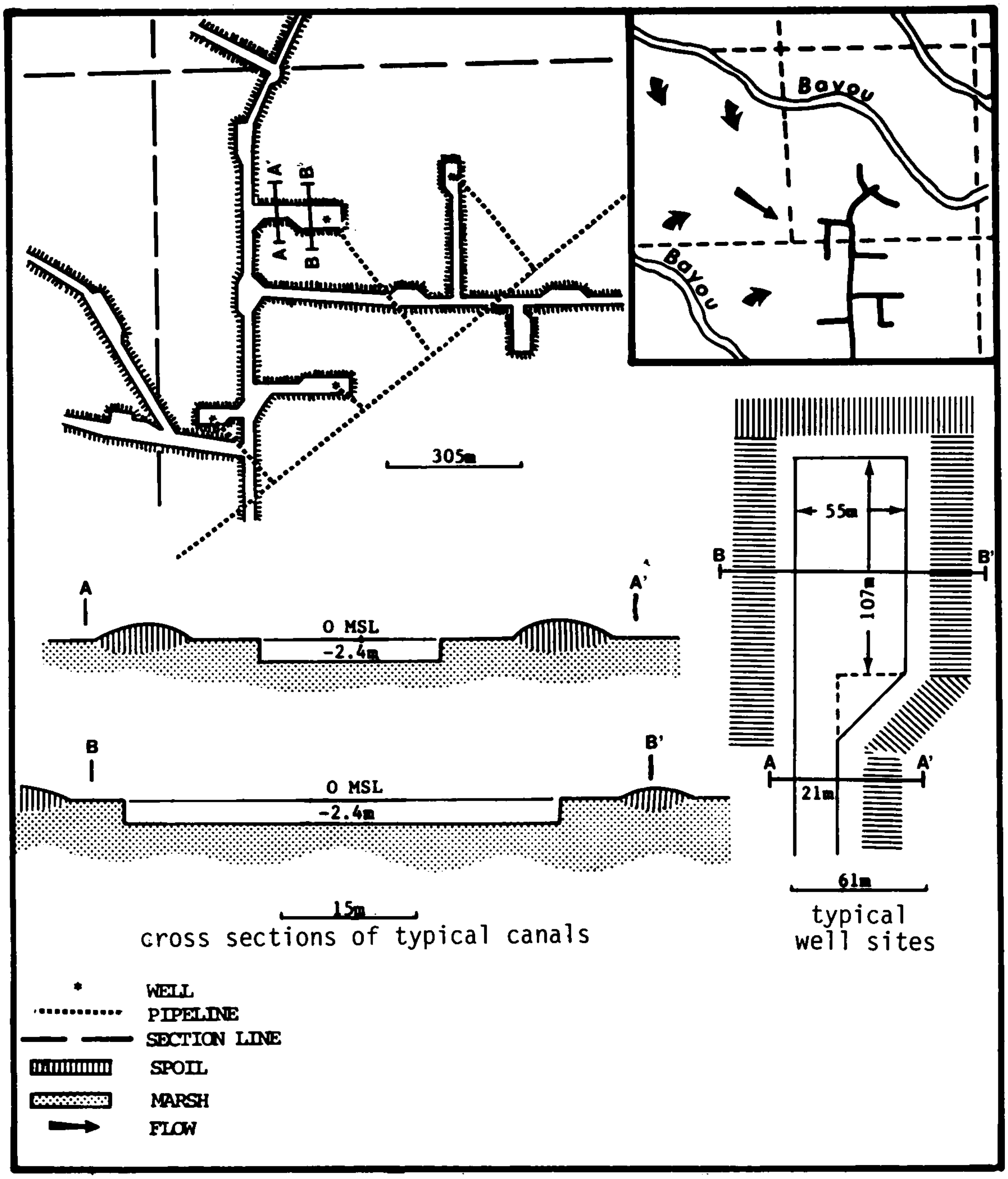

Figure 7-3. Random distribution of access canal and well sites in the wetland system. Canals and spoil banks cross regional flow patterns and disrupt the hydrologic character of the area. Spoil banks and canals change the morphology of the wetlands to uplands and open waterbodies (Coastal Environments, Inc. 1974).

limited to estimates of the topographic change resulting directly from dredging of pipeline and access canals and rig cuts. Only inferential documentation exists relative to the possibility of additional topographic change resulting from interference with morphologic function in relation to hydrologic and biologic processes and characteristics. There are no studies which have accurately evaluated subsidence due to oil and gas extraction. Further studies in both areas are needed to minimize presently occurring and future adverse changes.

HYDROLOGIC ASPECTS

Oil- and gas-related activities are major causes of ongoing changes in the hydrology of the Mississippi Deltaic Plain Region. Exploration, extraction, and transport, as well as supporting development, all require or induce varying degrees of hydrologic modification of water surface area and volume, water movement and levels, and water quality. Since ecosystem functions and characteristics are closely linked to the hydrologic regime, these man-induced changes result in a cumulative perturbation of the ecosystem that extends beyond the location of a given activity.

The dredging of access canals, rig cuts, and pipeline canals through wetlands and the associated increase in water surface area is a readily identified change which corresponds to topographic changes. These changes are most apparent in the brackish water marshes of the Barataria and Timbalier Hydrologic Units (Units IV and V) (Gagliano et al. 1973). These access canals and rig cuts are clustered around major oil fields, such as those of Leeville and Lafitte. In these areas, canal density (canal area:total surface area) attains a value of as much as 25%.

The effect of canal dredging on the hydrologic regime goes far beyond the surface conversion of wetland to open water. Canals are linear features that differ from the shallow and sinuous natural drainage channels of the wetland environment. This artificial characteristic is further reinforced by associated spoil banks.

Water movement through the wetlands is modified in several ways. First, canals provide for additional and more rapid exchange of water among various components of the system. When aligned in the direction of surface drainage, they allow more rapid removal of water from the freshwater swamps and marshes to lakes and streams, through intermediate and brackish marshes into estuarine waters. This situation minimizes natural treatment of upland runoff and the function of the wetlands as a hydrologic buffer. Because of reduced retention time and bypassing of wetlands, nutrient exchange between the water and wetland systems is presumably reduced with resultant water quality changes. Second, the increased rate of freshwater movement toward the lower estuary necessarily means reduced freshwater availability for lowering salinities during months of high evapotranspiration. Consequently, together these conditions produce increased instability of salinity conditions compared with natural conditions.

While not sufficiently documented, the above hydrologic aspects of canal dredging have been increasingly subject to investigation and appear to have basis in fact. Numerical simulation of wetland circulation modified by canals and spoil banks indicated reductions from 9% to 36% in water movement through the marsh proper, depending on alignment and configuration of these man-made structures (McHugh 1976, Stone et al. 1978). Similar procedures for the Barataria Basin as a whole indicated significant changes in water levels of the freshwater environment and a measurable increase in flow per tidal cycle (Stone and McHugh 1979).

The effects of dredging operations on water quality have been studied. Mackin (1961) showed changes in turbidity occurring during dredging in shallow open bays. Turbidities were found not to exceed natural levels (20 to 200 ppm) beyond a hundred meters from the dredge. Oxygen depletion due to dredging was found to be a relatively minor factor relating mainly to oxidation of hydrogen sulfide gas. Stone et al. (1976) considered potential releases of nutrients as a result of dredging and spoil disposal in a freshwater wetland and estimated that 1 x $10^6 m^3$ of spoil could add to the surrounding aquatic environment a total inorganic nitrogen component of 2400 kg, a phosphate component of 610 kg, a Biological Oxygen Demand load of 4.1 x 10^6 kg, and a hydrogen sulfate component of 2.0 x 10^5 kg.

Additional water quality aspects concern low level release (as opposed to accidents) of oil, brine water, drilling mud, or other pollutants from normal oil and gas operations. Milan and Whelan (1979) compared petroleum hydrocarbon accumulation for an oil field and an unmodified environment in the Barataria Basin, focusing mainly on uptake by organisms rather than water quality. An ecological study of Timbalier Bay compared conditions at the location of a production platform with those of a control station (Gulf Universities Research Consortium 1974). This study suggested that hydrocarbon concentrations in water are not significantly different when oil-producing and nonoil-producing areas are compared. N-paraffin levels are approximately equal and in the range of 0.60 to 0.03 micrograms per liter (mgl). Nutrient levels were found to be consistently higher at the platform site, although within the limits of seasonal fluctuation. Surface sampling showed organic carbon levels to be slightly higher in the vicinity of the platform and related structures.

In summary, knowledge of the effects of oil and gas activities upon the hydrology of the Mississippi Deltaic Plain Region is limited. Effort has concentrated on inventory of increases in water area through loss of wetland habitat. A beginning has been made in the evaluation of dynamic effects such as modification of circulation and water quality. Conclusions about effects upon hydrologic functions remain largely inferential and qualitative.

Since effects of oil and gas activities are propagated through the ecosystem largely by means of hydrologic processes, an urgent need exists for detailed monitoring of hydrologic conditions prior to, during, and long after development of a given oil or gas well. Even more critical is the need to better understand functional relationships between hydrology and the ecosystem so that observed modification of the hydrologic regime can be accurately translated into potential effects and monitoring can be focused on the most critical problem areas.

VEGETATION ASPECTS

Impacts on vegetation of oil and gas activities in the Mississippi Deltaic Plain Region fall into two categories. One is the loss of land and alteration of vegetative composition resulting from channelization and dredging of navigation and pipeline canals. The other is the impact upon vegetation of oil contamination due to oil spillage or leakage.

As a result of petroleum industry dredging, various ecological changes may occur that subsequently alter vegetative composition in the Mississippi Deltaic Plain Region. These are summarized below by Gagliano (1971), Mumphrey et al. (1975), and Stone et al. (1978):

1) Alteration of natural drainage patterns.

    a) Disruption or interference with sheet flow through marshes.
    b) Changes in water cycling rates and water volume.
    c) Increased water salinities which result in death of salt-tolerant vegetation and erosion of the marsh.
    d) Decreased marsh productivity by the presence of straight versus sinuous channels that accelerate removal of fresh water and in some instances confine water movement.
    e) Production of freshwater deficient areas.
    f) Eutrophication when runoff water is shunted through marsh into open water bodies.

2) Erosional changes.

    a) Accelerated erosion of barrier islands with resultant increased destruction of marsh.
    b) Accelerated erosion resulting from increased extent of land water interface.
    c) Accelerated erosion from boat-generated wash along unstable canal banks.

Vegetation is permanently lost from the system when rig cuts and access and pipeline canals are dredged in marsh and swamp environments. Additional loss occurs with widening of the canals due to bank erosion. Spoil disposal associated with the dredging produces additional loss. Depending on spoil elevation and location, the loss may be irreversible, as in the case of high spoil banks in marsh, or temporary as in the case of freshwater swamps. Invariably, a change in plant community occurs which frequently undergoes successional development toward bottomland hardwoods (Monte 1978).

A study of wetland alteration due to spoil disposal along canals indicated that spoil bank habitats alter wetlands over an area four times the width of the originally dredged canal (Monte 1978). In the historic Lafourche Mississippi Delta, spoil bank habitats were estimated to cover 91,498 ha (226,000 ac), while the estimate for the entire Louisiana coastal zone was 202,429 ha (500,000 ac) in 1978 (Monte 1978).

In many areas of the Mississippi Deltaic Plain Region petroleum industry activities have produced an intricate maze of canals with coalescing spoil banks. In such instances, impoundments or semi-impoundments (areas of wetlands partially enclosed by coalescing spoil banks) may be formed. In the Bayou Lafourche Delta region, Monte (1978) found that with time impounded vegetation became more aquatic, while semi-impounded vegetation became more terrestrial. Increased plant zonation occurred in semi-impoundments due to slight rises in elevation near spoil banks as a result of silting. In impoundments, vegetative composition became more aquatic in nature due to subsidence, decreased drainage, subsidence, and decreased water salinities in saline and brackish marshes due to precipitation (Monte 1978).

Processes causing vegetative changes are interdependent and usually occur concurrently. Alteration of marsh to open water by construction of pipeline and navigation channels results in lower marsh productivity per unit area because benthic plants and phytoplankton are considered to be less productive than marsh grasses (Stone 1972). Estuarine food chains in the Mississippi Deltaic Plain Region are detritus-based. Because a major source of detritus is marsh grasses, reduction of marsh grass production could have deleterious impacts on the consumer species of the system (Stone 1972). When water flow volume is confined principally to man-made canals, water exchange with the marsh is reduced and marsh primary productivity may be lowered (Stone 1972).

In addition to dredging of navigation and pipeline canals and associated spoil disposal, the other primary source of impacts on vegetation from the petroleum industry is contamination from oil spillage and leakage. Two major oil spills occurred off the Louisiana coast in 1970 and 1971. Most of the spill was apparently carried away from the marshes by currents, and little damage to the biota was reported (Stone 1972). The probable effects of oil spillage, therefore, must be inferred from other areas.

While impacts resulting from massive oil spills occurring in the Santa Barbara Channel, California, and the Torrey Canyon along the British coast have been studied exhaustively, most of the available literature concerns oil spill impacts along the British coast. According to Straughan (1972), several factors determine the extent of biological damage caused by oil spills. The most important of these include 1) the type of oil spilled, 2) the dose of oil, 3) the physiography and hydrology of the spill site, 4) the weather conditions at the time of the spill, 5) the biota of the area, 6) the season of the spill, 7) previous exposure of the area to oil, 8) exposure to other pollutants, and 9) the treatment of the spill. The complexity of these interrelating factors make it difficult to predict the outcome of any spill.

In the Torrey Canyon accident, most of the damage occurred to inter-tidal algae and lichens. Thick oil deposits smothered the plants by cutting off light and air (Ranwell 1968). Although salt marsh contamination was not as great as contamination to intertidal areas, a chief component grass of European salt marshes, alkali grass (Puccinellia maritima), suffered mortality from oil which had been at sea for seven days or more (Ranwell 1968).

Other observations of oil spills along the British coast have shown that annuals such as sea blite (Suaeda sp.) and glasswort (Salicornia sp.) suffered the highest mortality, although recovery for annual plants in general was fair (Cowell and Baker 1969). In some instances species distribution was changed because the oil did not affect all species equally and sometimes inhibited germination. Algal populations are often severely damaged but also recover quickly. Cowell (1969) reported severe damage to Spartina townsendii and oystergrass (Spartina alterniflora) in British salt marsh associations near Milford Haven. Evidently the quicker the oil reaches the plants after being spilled, the more toxic it is. While the oil is floating on the sea, the volatile and most toxic fractions evaporate, and components such as phenols and cresols may be dissolved and dispersed. Thus when oil has been at sea for several days it undergoes weathering (Cowell 1969) and loss of some degree of its toxicity.

Baker (1971) reported little long-term damage to perennials but severe damage to annuals as a result of experimental spraying of salt marsh transects with oil. If oiling occurs as flower buds are developing, flowering is reduced. Oiled flowers rarely produce seeds. Spring germination may be reduced when seeds are oiled the previous winter (Baker 1971); thus the season of the spill may be important in determining the extent of vegetative damage.

When marsh plants were exposed to a single oil spill, most species appeared to die but, in fact, recovered by putting out new growth shoots within about three weeks (Baker 1973a). However, annuals and seedlings do not have sufficient food reserves to recover in this way and usually are killed. Lytle (1975), in an experimental application of oil in a Gulf coast marsh pond, found that oystergrass, saltgrass (Distichlis spicata) and black rush (Juncus roemerianus) turned yellow three days after application and in 10 days all appeared dead. Within three weeks these plants began producing new shoots and good recovery was observed after two months.

When areas are exposed to successive oil spillage the results may be more drastic. In an experiment by Baker (1973b), marsh habitats on the British coast were exposed to 2, 4, 8, or 12 successive monthly oil sprayings. Most species other than annuals recovered from a maximum of four oilings; eight or more oilings caused rapid decline in vegetation from which recovery was likely to be very slow. Annual plants were the most susceptible, while grasses and rosette perennials were more tolerant. Most tolerant were the members of the parsley family (Umbelliferae) which thrived even after 12 oilings (Baker 1973b).

Persistent refinery effluent has caused damage to cordgrass (Spartina sp.) communities in England (Baker 1973c). The most critical problems occur when effluent is discharged into salt marsh and mudflat areas where sheltered conditions exist. Oil sticks to plants and accumulates in the mud. In this situation, influx of oil may exceed oil degradation rates, and eventual destruction of marsh vegetation results. This process might be significant in the marshes of the Mississippi Deltaic Plain Region where tidal amplitudes are small and oil would not be quickly dispersed after leakage or spillage. Gebhart and Chabreck (1975) performed a tank experiment in which three-cornered grass (Scirpus olneyi) and marshhay cordgrass (Spartina patens) were subjected to various levels and concentrations of a light and a heavy crude oil. Growth and survival of three-cornered grass was greatly reduced at a fluctuation water level (+5 to -5 cm) with a treatment of 80 parts per thousand (ppt) of heavy crude oil for a five-month period at fluctuating water levels (+5 to -5 cm). However, at a constant water level of +5 cm above the soil surface, crude oil actually enhanced the growth of three-cornered grass as much as 15 cm (38 in) in culm height more than the control (Gebhart and Chabreck 1975). Except for the 80 ppt heavy oil treatment, growth increased with increasing oil concentration. Only at the highest concentrations of crude oil was this plant damaged. On the other hand, marshhay cordgrass was detrimentally affected at both fluctuating and constant water levels. Growth and survival of marshhay cordgrass decreased with increasing oil concentration and damage was more severe in the heavy oil treatment. The differences in response to crude oil shown by these two species were thought to be related to species differences in oxygen transport systems (Gebhart and Chabreck 1975), and Gebhart (1973) found oil applications reduced dissolved oxygen levels in the water. Although Baker (1973d) also observed enhanced growth of plants in the presence of crude oil, no satisfactory explanation is presently available. One possible explanation is related to the apparent increase in activity of nitrogen-fixing bacteria in oil-treated soil (Baker 1973d).

Baker (1973e) reported that oils may enter plant tissue and travel through intercellular spaces. Cell membranes are damaged by penetration of hydrocarbon molecules, which leads to leakage of cell contents (Baker 1973e). Oils reduce transpiration rate and photosynthesis, possibly due to destruction of chloroplast membranes and inhibition caused by accumulation of end products of photosynthesis. There is often an increase in respiration rate due to mitochondrial damage. The extent of these effects depends upon type and amount of oil, environmental conditions, and plant species (Baker 1973e).

Phytoplankton populations may also be affected by petroleum-related activities. Dredging and boat traffic evidently increased turbidities and phosphate-P concentrations in the waters of the Leeville oil field in southeast Louisiana (Hart 1979). This, in turn, produced a change in the community structure of phytoplankton in the area, lowering chlorophyll a values and mean cell length. However, Fucik (1974) found negligible effects on phytoplankton populations from oil production around offshore platforms in the Gulf off Louisiana. Light intensity and nutrient concentrations are the principal factors regulating phytoplankton growth (Fucik 1974).

In summary, impacts on vegetation related to oil and gas activities in the Mississippi Deltaic Plain Region have two main causes. One is the alteration or loss of vegetation as a result of canalization and channelization for navigation and pipeline installation. The other is alteration or loss due to contamination from oil spillage and leakage. Petroleum industry dredging causes various ecological changes which ultimately alter vegetative composition. Most of these impacts are related to actual loss of land or alteration of the hydrologic regime. Oil spills result in contamination of vegetation and have varying degrees of impact. Such factors as the type and amount of oil, site physiography, the season of the year, and the type of vegetation affected determine the damage caused by any spill. Usually perennial grasses have greater ability to recover than annuals. Alteration of vegetative composition or loss of vegetation is most likely when oil consistently covers the biota for long time periods under sheltered conditions.

WILDLIFE ASPECTS

Oil and gas recovery operations produce both direct and indirect impacts on wildlife populations within the Louisiana segment of the Mississippi Deltaic Plain Region. Although the impacts of these industries have received close scrutiny in recent years, quantitative information regarding impacts on wildife is scarce. Most studies have dealt with changes in aspects of the environment such as vegetation, water quality, and hydrology or with impacts of oil-related activities on aquatic organisms such as fish and shellfish. In most cases wildlife impacts may be inferred only indirectly from these studies.

The most direct impacts on wildlife populations are related to pollution from oil spills and land loss resulting from channelization and dredging for oil navigation and pipeline canals. Direct impacts from oil spills have been studied mainly in relation to birds. According to Szaro (1977), seabirds such as diving ducks and alcids are the species most susceptible to oil pollution. These species are among the most frequent casualties because they are common in areas of heavy sea traffic, occur in large numbers, spend a high percentage of time on the water, and dive to feed (Szaro 1977).

The main effects of oiling on birds are loss of buoyancy due to matting of feathers which destroys the waterproofing and insulating properties of the plumage (Hartung 1967). Oil ingestion is evidently not a major cause of seabird mortality. However, ingestion may affect the physiological and reproductive condition of the birds (Szaro 1977). In addition, a large number of seabird eggs may be destroyed within the nesting range each year due to oil contamination. Moore and Dwyer (1974) reported that marine organisms, including birds, may experience interference with cellular and sub-cellular processes, especially membrane activity, as a result of hydrocarbons released by crude oil. Juvenile age classes are usually more sensitive than adults, and the lower boiling point aromatics are the most toxic. Oil pollution can also cause sub-lethal effects from incorporation of hydrocarbons into food chains and alteration of biological habitats such as substrate characteristics (Moore and Dwyer 1974). Sublethal effects may, in fact, be more deleterious to bird populations in the long-term than massive oil spills (Stickel and Dieter 1979).

Land loss as a result of canal dredging represents a direct loss of wildlife habitat for many commercially important fur-bearers as well as many species of wetland birds including waterfowl and wading birds. In some cases, revegetation of spoil banks can be viewed as added habitat to support additional terrestrial wildlife species such as white-tailed deer (Odocoileus virginianus) and swamp rabbit (Sylvilagus aquaticus). Spoil banks also provide nesting habitat for many seabirds and wading birds. Portnoy (1977) lists four species of terns, plus the Black Skimmer (Rynchops niger), as users of bare ground on spoil as nest sites along coastal Louisiana, Mississippi, and Alabama. He also reported seven species of herons and egrets as well as the Olivaceous Cormorant (Phalacrocorax olivaceus), the Roseate Spoonbill (Ajaia ajaja), and the White-faced Ibis (Plegadis chihi) as using shrub vegetation on spoil as nesting sites. In North Carolina, 35 species of birds representing 17 families were found nesting on dredge islands (Soots and Parnell 1975).

Several indirect impacts on wildlife habitats are associated with the oil and gas industries. Indirect effects, such as those resulting from modified water movement and the acceleration of erosion, are more difficult to evaluate but actually may be more far reaching in their significance (St. Amant 1971).

Changes in salinity characteristics of marsh areas alter vegetative composition. This, in turn, has reduced fur production as muskrat populations declined and has lowered the value of waterfowl feeding and wintering areas (St. Amant 1971). Dredging has, in some cases, accelerated the erosion of barrier islands that are important nesting habitats for shorebirds, seabirds, and wading birds (Mumphrey et al. 1975). Ditching may act as a migrational and home range barrier for some terrestrial species. The necessity of crossing spoil banks may increase vulnerability to predators for some species (McGinnis et al. 1973).

The response of birds to habitat perturbation varies with the species, from no effects to complete abandonment or exclusion of the habitat (McGinnis et al. 1973). When drainage pattern and salinity are altered, the distribution of the food supply may be affected in such a way that the habitat is no longer adequate for a particular species. If changing the habitat removes the food source to a great distance from nesting sites, it may become too costly in a caloric sense to exploit the food source. In such cases nesting sites are abandoned. Pelicans, herons, and cormorants show such responses (McGinnis et al. 1973). Long-term oil operations have been shown to reduce macrobenthic communities (Lindstedt 1978) and lead to hydrocarbon accumulation in the marsh ecosystem (Milan 1978). Food webs are usually complicated and dependent on a number of parameters. Evaluation of the influence of oil and gas operations upon food webs is difficult, but alteration of the availability of invertebrate prey of many birds seems inevitable.

The effects of oil and gas operations on wildlife habitat in the Mississippi Deltaic Plain Region are varied and interrelated. Although general statements are sometimes made concerning impacts on wildlife populations, little or no concrete data are available about any particular species. The response of various species to alteration of habitat by oil and gas activities and the significance of toxic materials in the food chain have not been intensively studied in this area. Obtaining this information should be one objective of further research.

FISHERIES ASPECTS

Effects of oil and gas activities upon fisheries presently extend from the most inland sections of the freshwater region throughout estuarine environments onto the outer continental shelf. Much debate, however, exists as to the exact nature of these effects and their overall relationship to fishery production and harvest.

The most obvious impact of oil and gas activities on fishery resources is the destruction or alteration of habitat (living space). To determine whether this impact is direct or indirect, short-term or long-term, as has been attempted by some authors, may be helpful in some specific cases, but overall is probably too simplistic an approach. Most perturbations of oil and gas activity have proved long-lasting and cumulative, whether judged detrimental or beneficial.

The single most detrimental activity of the petroleum industry is generally considered to be dredging (canalization) and associated spoil disposal. The most negative impacts of the industry are presently considered to have occurred inshore in estuarine and freshwater environments as opposed to the offshore marine region. Besides the physical loss of habitat, dredging of canals causes a series of disruptive events which eventually affect the fisheries. By changing the natural drainage patterns of coastal wetlands, newly created canals accelerate freshwater drainage during rainfall and low tides and increase flooding during high tides and storms, allowing saltwater intrusion. A regular fluctuation in the salinity conductivity regime is thereby imposed on an area that was relatively stable except during irregular weather phenomena. Moreover, as canal development increases, wave-wash from winds, tides, and boat traffic leads to increased wetland erosion and turbidity. Eventually, canals and the natural waterways they traverse begin to coalesce, producing new or enlarged lakes and bays. The end effect is an accelerating increase in open water habitats at the expense of marsh, swamp, or other productive wetlands (Morgan 1973).

Loss of wetland habitat is viewed with particular alarm since these areas are known to be nursery and/or spawning grounds for several of the Region's most valuable fishery species. Studies have shown that semi-enclosed waters of intertidal marsh (i.e., shallow lakes, potholes, blind bayous, tidal creeks, and interconnecting channels) are of direct importance as physical habitat for young brown and white shrimp (the most valuable commercial species), Gulf menhaden, Atlantic croaker, reddrum, spotted seatrout, southern flounder, and young of other desirable estuarine species (Gunter 1967; Day et al. 1973). In freshwater systems, swamps and bottomland floodplains serve similar roles for crawfish, shad, buffalofish, catfish, and sunfish (Bryan and Sabins 1979). Concern is that habitat critical to the success of a species' year class (early life history phase) is being systematically removed from use, and thus the amount of harvestable adults available to the fishery at a later period will be reduced. Although these relationships have not been conclusively demonstrated, the strong concern over wetland loss remains.

Of the other detrimental activities related to oil and gas extraction, drilling operations are especially harmful to fishery animals. Impact, however, apparently diminishes with time, although some effects may last longer than others (Perry 1974). Drilling activities overall are more damaging in marshes, swamps, and floodplains than in open water areas. In both types of areas, the most serious consequence of drilling is the overboard discharge of drilling mud solutions which compact on the bottom and virtually eliminate benthic animals, many of which serve as food for sport and commercial fishes (Perry 1974). Exclusion of benthic populations is apparently still the case around some production platforms for several years after drilling has ceased. Some damage to fishery resources also occurs annually from spillage of crude or refined oil, but this is viewed as reversible (St. Amant 1972). Oysters have been found virtually free from obvious effects of a severe oil spill in as short a time as two months (Mackin and Sparks 1961). Other deleterious effects of oil and gas operations are those related to reductions in water quality. Fish kills due to dissolved oxygen depletions occur with some frequency in closed and semi-closed estuarine canals (Adkins and Bowman 1976).

Petroleum platforms, especially in marine areas, are recognized as the least damaging aspect of oil and gas activities in the Mississippi Deltaic Plain Region. Their effect on the ecology of the Gulf of Mexico has been described as neutral at the least, and mildly beneficial at best (Gulf Universities Research Consortium 1974, Pequegnat 1975). Platforms serve as a hard substratum and a geometric figure in the otherwise amorphous water column. Legs and cross structures offer habitat for a variety of animals dependent upon hard substrates over a wide range of depth. These organisms, in turn, provide food for pelagic and reef fishes, while demersal fishes are attracted and sustained by the "rain" of organic materials from above and by animals attracted around the legs. In effect, the roughly 2700 platforms present in the Mississippi Deltaic Plain Region act as a large reef with a surface area of almost 2000 ha (5000 ac) (Pequegnat 1975).

There seems little doubt that the secondary production of epifaunal invertebrates has been increased by the addition of platforms, but whether an increase in fish or other secondary production or primary production has occurred is debatable. The initial attraction of fishes to rig structures is, to a large extent, the result of a visual stimulus, but some may be attracted by the abundance of prey while others may school around platforms for protection from predators. Overall, the ichthyofauna of petroleum platforms bears a strong resemblance to that of rock or coral reefs in the northern Gulf, although diversity at the platforms is less than at natural reefs (Sonnier et al. 1976). For whatever reasons, oil platforms have proven to be popular sport fishing areas in recent years and have probably added to the economic value of the fishery (Dugas et al. 1979).

The least-known aspect of petroleum industry impact on the aquatic environment concerns the fate of introduced metals and other toxic substances. Since these effects are not immediately felt or easily detected, they will probably be the most difficult to evaluate. One study has shown that higher values of zinc, lead, and cadmium occur in substrates closer to platforms than in areas remote from oil development (Montalvo and Brody 1974). This study further stressed that levels were even higher in bay samples than in offshore samples and that the occurrence of dangerous levels is a possibility.

In another study of low-level crude oil contamination in an estuarine salt marsh, cycloalkane and aromatic hydrocarbons, which are unique to petroleum, were found in the tissues of marsh grass, periwinkles, snails, oysters, mussels, grass shrimp, and Gulf killifish (Milan and Whelan 1979). Hydrocarbon concentrations were found to be greater in benthic organisms than in pelagic ones, and the main mechanism for transport within the ecosystem was believed to be by way of contaminated marsh grass and its detritus. Since accumulations of toxic, longlasting substances can be transferred to fishery species through the food chain, studies of this matter are warranted in the future.

In summary, there has been considerable impact of oil and gas activities in the Mississippi Deltaic Plain Region. Canalization has resulted in the destruction of wetlands from dredging, leveeing, silting, and erosion and, consequently, the loss of fishery habitat. Accidental or incidental spillage of oil and other substances has affected fishery animals, although such effects have been generally reversible. Typically, activities of the industry have been planned exclusively around economy and efficiency. Recent initiatives by oil interests, however, have indicated that the industry plans an era of "new awareness" for environmental concerns and a multiple use approach to further exploration and development (Bybee 1973). New technology may impact fishery resources substantially less through directional drilling of single wells, drilling more wells from one platform to reduce habitat loss, and better methods of pipeline location and development. All three of these technologies may substantially reduce the need for destructive dredging of canals.

Most of the large petroleum reserves in the Mississippi Deltaic Plain Region have already been tapped, and in the future, exploration and development activity is expected to decline. The present energy situation assures that oil and gas activities in the Mississippi Deltaic Plain Region will continue into the forseeable future and increased cooperation between the industry and coastal resource managers will be increasingly important.

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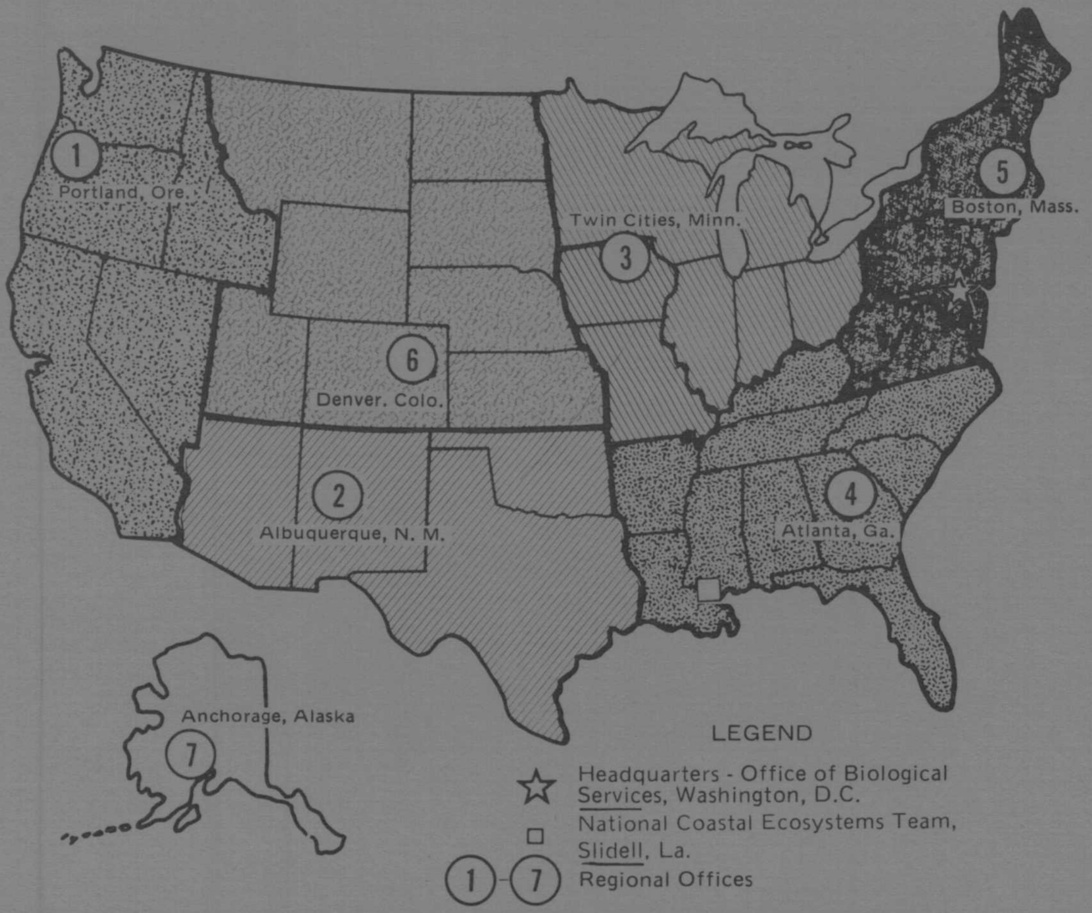

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DEPARTMENT OF THE INTERIOR
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