OCS Study
MMS 87-0119

Causes of Wetland Loss in the Coastal Central Gulf of Mexico

Volume I: Executive Summary

MMS
U.S. Department of the Interior
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Causes of Wetland Loss in the Coastal Central Gulf of Mexico

Volume I: Executive Summary

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EXECUTIVE SUMMARY

by

R. Eugene Turner
Program Manager

The purpose of this study was to determine the extent to which the most extensive offshore oil and gas activity in the U. S. is contributing to the well documented and dramatic alteration of Louisiana, Texas and Mississippi onshore wetland habitats (from East Bay, Texas to Waveland, Mississippi; Figure 1). These coastal wetlands converted to open water at an average annual rate of 12,700 ha (1 ha = 2.47 acres) or 0.86% from 1955/6* to 1978, thereby continuing a geometric increase this century (Figure 2). There is, naturally, concern about these habitat changes because of the enormous economic, social, geopolitical, and environmental values involved in such massive and rapid landscape alterations (Table 1). These wetlands directly support 28% of the national fisheries harvest, the largest fur harvest in the U.S., the largest concentration of overwintering waterfowl in the U.S., a majority of the marine recreational fishing landings, and a variety of wildlife.

More than 70% of the oil and 90% of the gas from U.S. coastal waters will continue to come from offshore of the study area, move through it, and enter the industrial processing plants supporting the entire country. The rationale for the study was that wetland

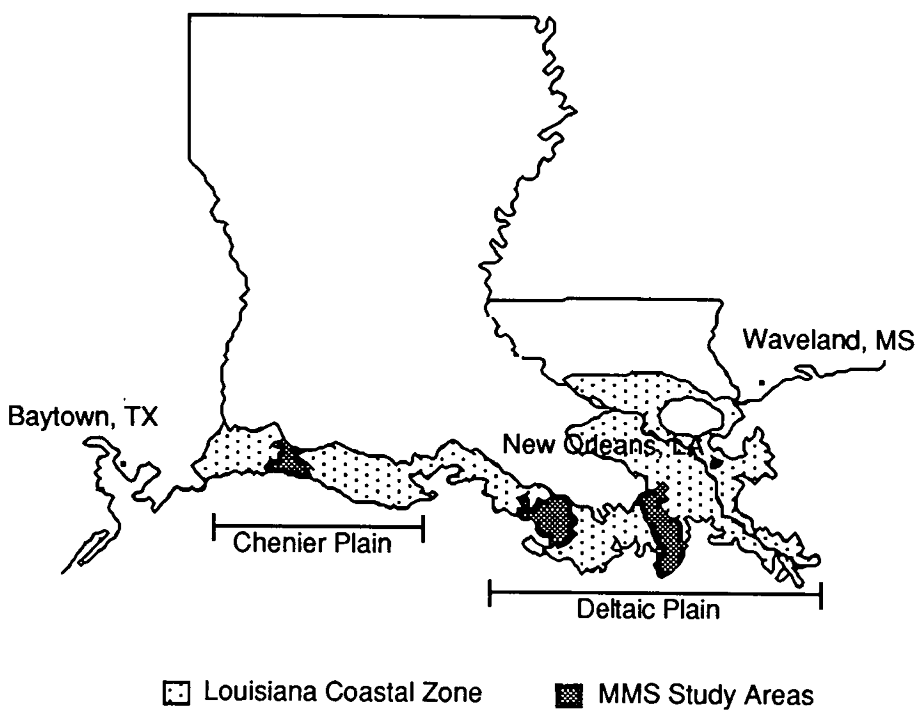


Figure 1. The geographical limits of the study area. The three shaded areas were the primary study areas for field work.

* 1955/6 refers to the maps used to measure wetland area. These maps were compiled from aerial photography collected throughout 1955 and 1956. We have combined the data from both 1955 and 1956 to simplify comparisons with data from later decades.

Table 1. Some values of Louisiana wetlands.

Fisheries:	• 28% of the total U.S. fisheries in volume in 1986. • $321,514,000 in dockside value, or 12% of the total dockside value for the U.S. • 4 of the 10 largest fishing ports are in Louisiana. • 12,092 fishermen on board and dockside in Louisiana in 1977, or 4.3% of the U.S. total. • 68,894 commercial fishing applications were filed in 1986. • 1,000,000 recreational fishermen in Louisiana.
Fur:	• Bobcats, fox, otter, mink, raccoons, muskrats, nutria, and other trapped species. provided over $18,000,000 to the state's economy in 1980-81. • Trapping provided employment for approximately 10,000 people in 1986.
Waterfowl:	• 5,000,000 waterfowl migrate down the central and Mississippi Flyway to winter on Louisiana's 1.5 million ha of coastal marshlands. • 3,000,000 waterfowl were found in a January,1986, mid-winter survey of the coastal marsh and inland areas of the Mississippi Delta. • 102,000 hunters bagged 1.2 million ducks in 1985-86.
People:	• Wetlands provide a buffer from storm damages. • Wetlands enhance water quality. • Wetlands provide homes for 1,000,000 people, including the oldest bilingual population in the U.S.

management is possible and that improved knowledge is useful to understand, predict, mitigate, and avoid undesirable impacts. Water, plants, sediments, soils, landscapes, history, and industry were studied by experts over a 27- month period to develop findings and a consensus report (Technical Narrative, Vol II and Appendices, Vol III). The reader is advised to consult these other volumes for a more complete description and explanation of the results that are summarized here.

Landscape Changes

Two basic questions about current wetland loss rates are: (1) why does it happen at all?, and, (2) why are the rates increasing geometrically? The potential causal agents of wetland habitat change are many, and the significant ones are listed in Table 2. In a natural marsh, mineral solids from rivers, reworked sediments, and plant debris are required to build wetlands. At the same time, wetlands on this sedimentary coast are sinking (because of compaction, for example), and global sea level is rising. Wetland scientists generally agree that because wetlands require water, plants, and a stable and appropriate soil matrix, subtle alterations can easily determine whether an area gains or loses wetland to the sea.

This coast has undergone changes for thousands of years. The Mississippi River delta has switched course at least six times in the last 5-6,000 thousand years (Figure 3), as it has moved back and forth across the coast building up the Deltaic Plain underneath and the Chenier Plain from sediments drifting westward to be deposited on the southwestern coast. Sediments overlaid over sediments to form thick deposits near the coast that eventually

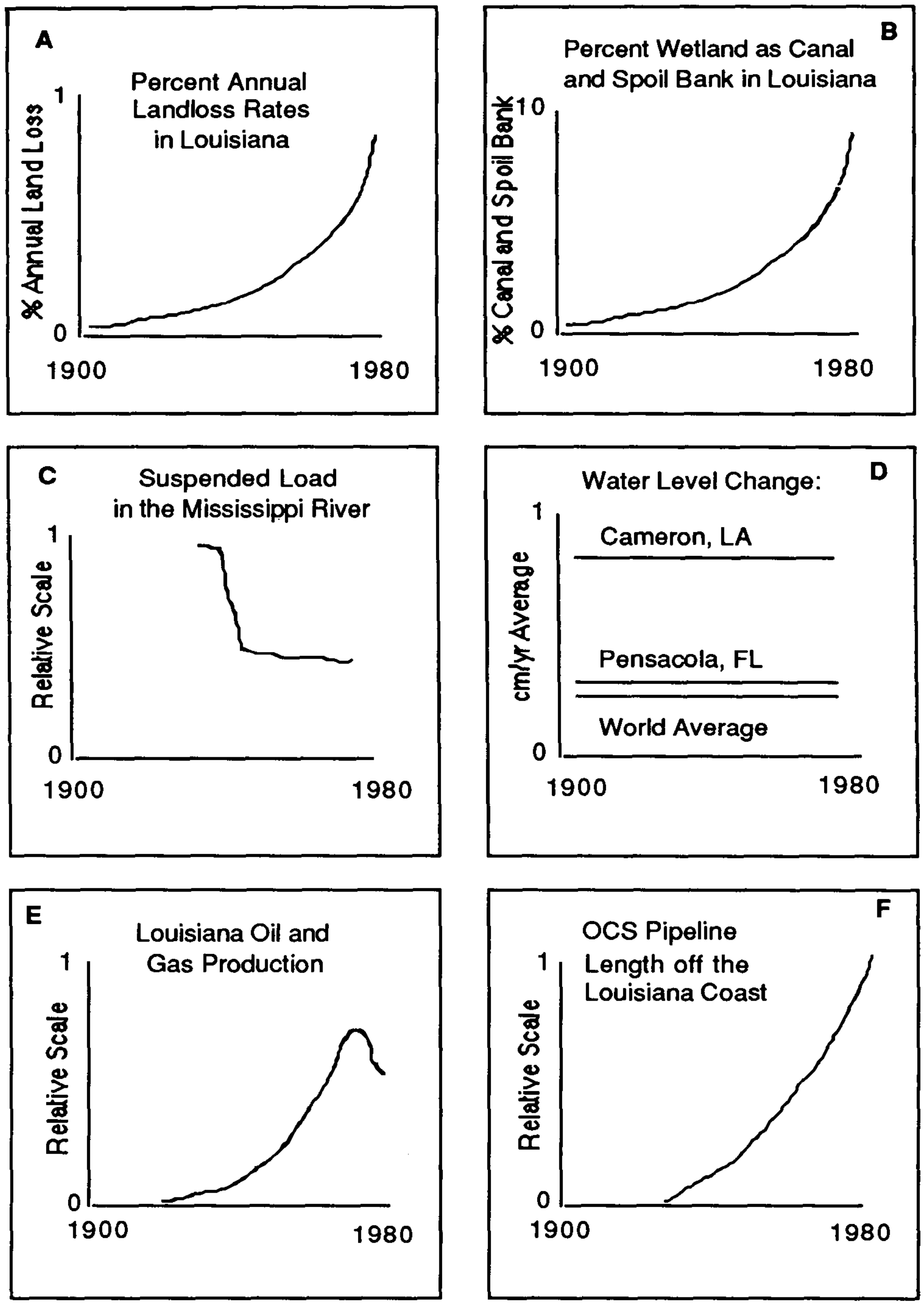


Figure 2. Changes in landscape patterns and use in the study area. A. Landloss rates versus time. B. Canal and spoil bank density since 1900. C. Suspended sediment concentrations in the Mississippi River since 1950. D. Water level changes for the world ocean, Pensacola, Florida, and, Cameron, Louisiana. E. Cumulative oil and gas production for Louisiana. F. Pipeline miles in the Central Gulf of Mexico OCS region since 1950.

Table 2. Causes and mechanisms of wetland loss in the study area.

Cause	Primary Mechanism
Direct habitat change	dredging, construction, filling in or over, erosion, prospecting machinery (marsh buggies)
Sea Level Rise	net loss in vertical accretion
Subsidence increases:	
natural	net loss in vertical accretion without compensation
oil and gas withdrawal	accelerated net loss in vertical
soil drying	soil shrinkage, net loss in vertical
Hydrologic Changes/Effects	
saltwater balance	physiological stress leading to plant community change or death
river levees	restricted sediment supply and distribution
sediment sources	change in sediment distribution
canals	change in sediment source and distribution, salinity and water levels; widening; channel theft
spoil banks	change in sediment source and distribution, salinity and water levels; water movement over and under marshes
hurricanes	marsh destruction
boat wakes/waves	bank erosion
Vegetation Changes	
quantity	change in physiological responses to salinity, sediment trapping, organic deposition, or flooding
quality	change in organic deposition, sediment trapping, intraspecific competition
Pollutants (e.g. brine, drilling fluids)	death of plants
Other	
introduced pests	death of plants by parasitic insect (primarily on Alligator weed)
muskrat "eat-outs"	reduced vegetation cover leading to pond formation

weighed down and warped the ancient sediments below. Sea level and climate fluctuated over these thousands of years as the plants adapted and assisted in the perhaps episodic local extension and retreat of a regional and longer-lived net growth of wetland into the sea.

Changes over the last 100 years have been diverse, intensive, and extensive. Navigation channels, oil and gas canals, trappers' trails, flood protection levees and urban and agricultural developments are found throughout the coast (Figure 4). About 7% of the wetlands are now man-made waterways and spoilbanks, which is an area equal to the area of drainage features in a natural marsh. Barrier islands are retreating inland at rates faster than earlier this century, and the anticipated deltaic abandonment has been temporarily arrested as one-third of the Mississippi River is diverted into the Atchafalaya River north of Baton Rouge, Louisiana. Although hydrologic manipulations of other wetlands have resulted in wetland changes similar to those in Louisiana, those other wetlands were not situated in the same geologic setting nor were those manipulations of the same scale and duration. We have incomplete knowledge of the causes and consequences of events occurring in our own backyard.

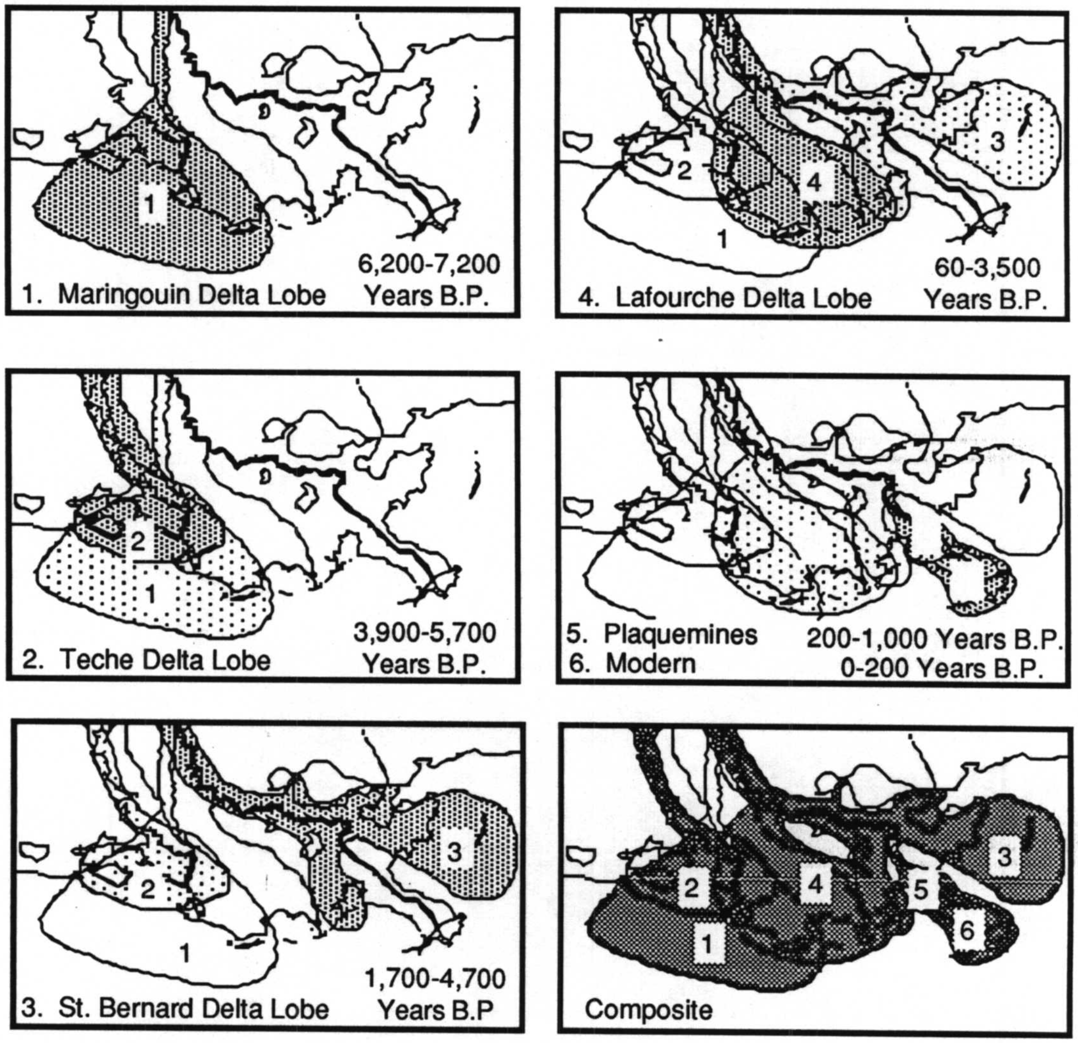


Figure 3. The major delta lobes of the study area for the last 5-6,000 years.

Project Goals and Approach

Our goal was to isolate and quantify the impacts of OCS-related activities upon habitat change in the northern Gulf of Mexico coastal wetlands. The enormous environmental changes in this region may be due to many combinations of human activities (including OCS), natural processes, and/or interactions of natural and human events acting over a bewildering range of temporal and spatial scales. In order to allocate a multitude of effects to the most probable cause or set of causes, it was necessary to impose a classification scheme upon effects and possible causative agents. As with any classification of complex objects or events, it was necessary to deal with the system in simple terms. We made three major classifications.

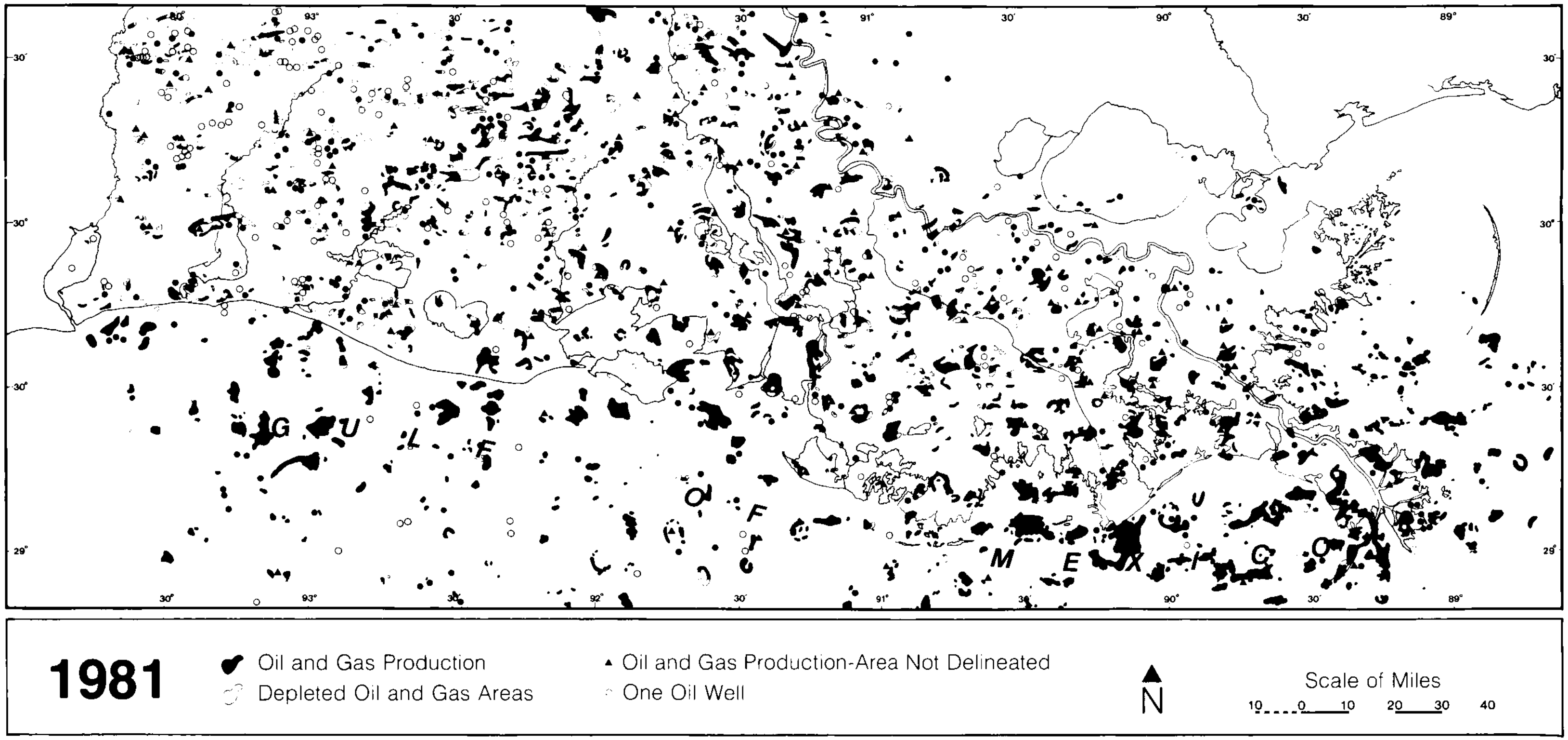


Figure 4. Distribution of oil and gas fields in southern Louisiana.

(1) Wetland habitats are complex, reflecting a mix of gradual adaptation and catestrophic alteration in a physical environment dominated by topographic, chemical and hydrologic changes. Rather than attempt to deal with this complex range, we elected to use a simple, but powerful, dichotomy to classify change.

Wetland is any area covered by emergent vegetation.

Open water, as the name implies, is land covered by water without appreciable emergent vegetation.

(2) Impacts to natural systems can be complex, ranging from gross alterations restricted to the immediate area of change (holes, canals, levees, etc.) to more distant effects resulting from some unanticipated change in a natural process (e.g. decline in vegetation downstream from the initial impact). Rather than attempt to deal with all possible types of impact, we elected to use a simple and, again, powerful dichotomy to distinguish direct impacts from indirect impacts.

Direct impacts are those cultural activities directly linked to the physical conversion of one habitat type to another. Two examples of direct impacts are dredge and fill activities that change wetlands to open water (the canal) and upland (the spoil bank). The direct impacts of OCS-related activities were assessed and compared with all other direct impacts in the study area.

Indirect impacts result from direct impacts but at a different time and place and often with subtle consequences. One example of an indirect impact is the change of water movement in and out of a wetland when a spoil bank (a direct impact) acts as a hydrologic barrier. Long-term sedimentation, soil chemistry, and salinity may be affected. Indirect impacts were estimated by investigating how OCS activities affect the natural processes controlling wetland loss and by quantifying wetland loss that is indirectly the result of OCS activities. To use a medical analogy, if a puncture wound is a direct impact, then the indirect impact is the resulting infection, illness, and lack of healthfulness.

3. The concept of an indirect impact quickly becomes inoperably vague if not defined in operable terms. Since we envision impacts as those which involve a significant alteration of a critical ecological process or environmental condition, it is necessary to focus on a defined set of processes or environmental change. Drawing from past research on these wetlands, three sets of processes or change were selected.

Salinity and its effects. Salinity may affect wetland loss through the biological impacts on plant health, sediment flocculation dynamics and chemical reactions.

Subsidence (absolute or relative) and its effects. Subsidence may result from geologic or biological processes, and changes in sea level or local hydrology.

Sedimentation and its effects. Sediment source, distribution and burial may change in rivers, oceans, estuaries, and wetlands and thereby influence wetland plant health through hydrologic, chemical and biological couplings.

With this classification scheme we were able to isolate the impacts of OCS development activities on habitat change in the study area. The project results that follow are divided into direct and indirect impacts and include a summary of all impacts caused by OCS development activities. The last section is a consensus response to several key questions.

Project Results

Direct Impacts

Approach: Direct Impacts

The major human activities involved in creating direct impacts are land drainage and dredge and fill. The major habitat changes resulting from these activities are the conversion of wetlands to open water, spoil, and agricultural and urban development. The major onshore dredge and fill activities associated with OCS development are the construction of pipelines and related support facilities and the construction or enlargement of navigation channels that began in the early 1950s and decreased by the 1980s (Figure 5a; Table 3). We measured direct impacts through an analysis of aerial imagery, data summaries of maps, field investigation and literature review.

Results: Direct Impacts

Total direct impacts accounted for an estimated 26% of total net wetland loss *within the Louisiana* portion of the study area from 1955 to 1978. Agricultural and urban expansion accounted for 10%, canals 6%, and spoilbanks 10%. Together, these direct impacts amount to about 29% of all wetland losses in the study region (including a 3% change to forest and upland habitat).

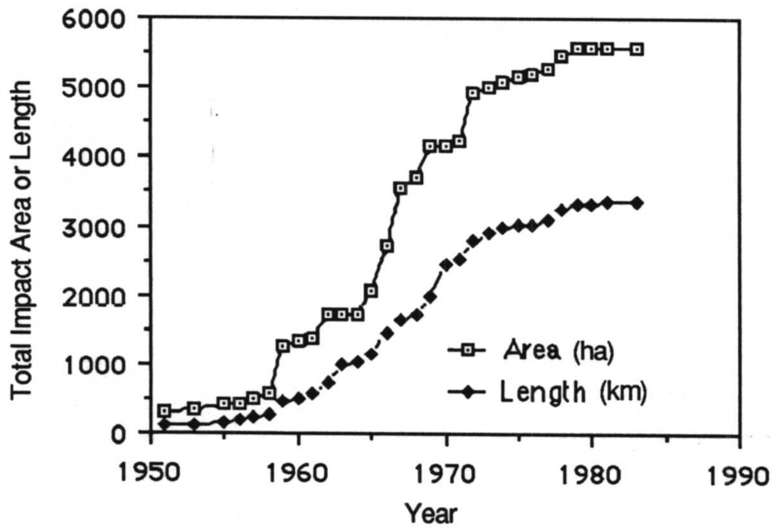
Of the total direct impacts of 74,000 ha in Louisiana, OCS activities accounted for 11,600 to 13,600 ha of the wetland loss during the same time interval . Although this is a substantial areal loss, these direct impacts represent only 4.0 to 4.7% of the total Louisiana wetland loss from 1955/6 to 1978 and 14-16% of all direct impacts. Of all direct habitat changes, canal and spoil changes were 56%, agricultural and urban development 33%, and forest and upland 11%.

The direct impacts from OCS pipelines averaged 2.5 ha/km (9.95 acres/mi) and accounted for >80 % of all OCS direct impacts. These direct impacts varied depending on construction technique, geologic region, habitat type (Figure 5b), age and diameter of pipeline, and other factors. This estimate is substantially lower than the published Minerals Management Service guideline of about 6.28 ha/km (25 acres/mi).

Pipeline impacts tend to increase with increasing pipeline diameter. The relationship is non-linear, however, and the effect of pipeline diameter appears to be substantially less than that of other factors examined. Usually direct impacts will be minimized where it is possible to install fewer, larger diameter pipelines in anticipation of future expansion instead of many smaller diameter pipelines. In other words, the number of pipelines is more significant than the size of individual lines.

The direct impacts will be different if an OCS pipeline canal is or is not filled in after construction. The direct impacts of non-backfilled canals in both the Chenier Plain and Mississippi Deltaic Plain and of backfilled pipeline canals in the Mississippi Deltaic Plain are positively related to the age of the pipeline. Backfilled pipeline canals have a lower impact than non-backfilled pipeline canals, regardless of age, but the direct impacts from backfilled OCS pipeline canals in the Chenier Plain are not significantly related to pipeline age. Building pipelines within a corridor, rather than separately, appears to be a valid consideration to minimize the direct impacts of non-backfilled pipeline canals. However, no significant difference in direct impacts for corridor versus random

A.



B.

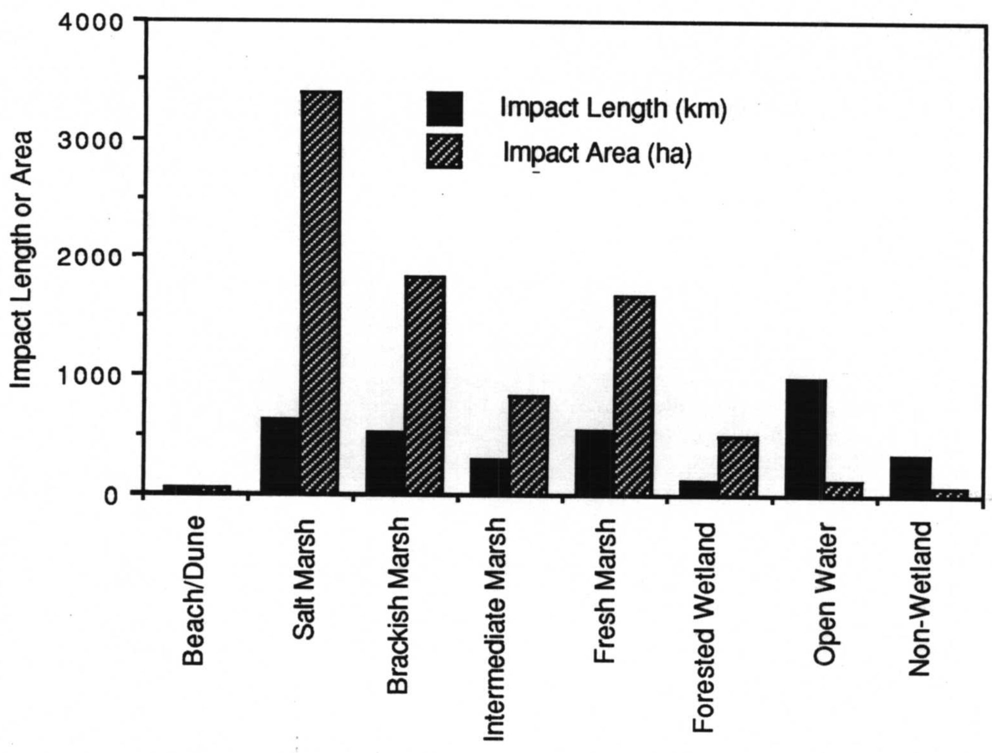


Figure 5. OCS development (A) and impacts (B) in the study region (70% sample).

Table 3. Direct impacts attributable to OCS activities in the Central Gulf of Mexico wetlands from Baytown, Texas to Waveland, Mississippi.

		Pipelines	Navigation Channels	Totals
Canal:	Length (km)	4,440	331	4,771
	Area (ha)	8,507	34-2,005	8,541-10,512
Spoil:	Length	849	242	1,091
	Area	3,466	23-880	3,489-4,346
Facilities:	Length	11.3	–	11.3
	Area	38.5	–	38.5
Totals[a]:	Length	4,827	331	5,158[a]
	Area	12,012	58-2,885	12,070-14,897

[a] Totals are not cumulative, e.g., pipeline can have both spoil length and canal length along the same section of line. Facility area can occupy spoil area.

distribution was found for backfilled pipeline canals. Backfilling reduces direct impacts by 75% and, therefore, should be the construction technique chosen over corridor construction. Because backfilling is now a standard procedure, we expect new pipeline construction to result in an average direct impact of 0.7 ha/km in the Chenier Plain and 1 ha/km in the Deltaic Plain. Most OCS pipelines are now backfilled during construction, and backfilling appears to be a positive management tool for minimizing direct impacts.

Widening of OCS pipeline canals does not appear to be an important factor contributing to direct total net wetland loss in the coastal zone. This is because few pipelines are open to navigation, and the impact width does not appear to be significantly different than that for open pipelines closed to navigation. Individual lines, however, may widen at locally significant rates.

Navigation channels account for a minimum of an additional 17,000 ha of habitat change. Of that total, some 13,600 ha resulted in the loss of wetland and beach habitats. The maximum amount of habitat change directly attributable to OCS activities was 2,900 ha (17%), of which 2,300 ha (17%) were the loss of wetland and beach habitats. OCS traffic appears to comprise a relatively small percentage of the total commercial traffic using navigation channels, thus the allocation of navigation channel impacts to OCS activities is small. Some 13,700 ha (81%) of the total direct wetland loss resulting from navigation channels are caused by the Mississippi River Gulf Outlet, Calcasieu Ship Channel, and Beaumont Channel/Sabine Pass, all of which have very low OCS destination usage.

Direct impacts per unit length of navigation channel are about 20 times greater than OCS pipeline canals; however, the area of all the navigational channels is much smaller than that of all the OCS pipelines. The dominant factor controlling the impacts per unit length is the project design. The surface width of navigation channels is invariably substantially greater than the design widths.

Summary: Direct Impacts

Direct impacts (from 1955/6 to 1978) are 26% of all wetland losses, and may be separated into OCS-related direct impacts (14-16%), land-use changes, dredge and fill, and others (Figure 6). These percentages, though small, represent significant acreage. The direct impacts of OCS pipelines were quantified, and found to be lower than previously assumed. These impacts vary depending on pipeline construction method, location, age, and diameter (Table 4). The direct impacts of navigation channels used by OCS are locally significant and represent a minority of all direct impacts.

Table 4. Factors contributing to low or high direct impacts from OCS pipelines.

Factor	Higher Impacts	Lower Impacts
Primary		
Habitat type	wetland habitat	beach habitat
Construction method	not backfilled	backfilled
Geologic region	Deltaic Plain	Chenier Plain
Number of pipelines	randomly distributed	built in a corridor
Secondary		
Pipeline Age	old	young
Pipeline diameter	large	small

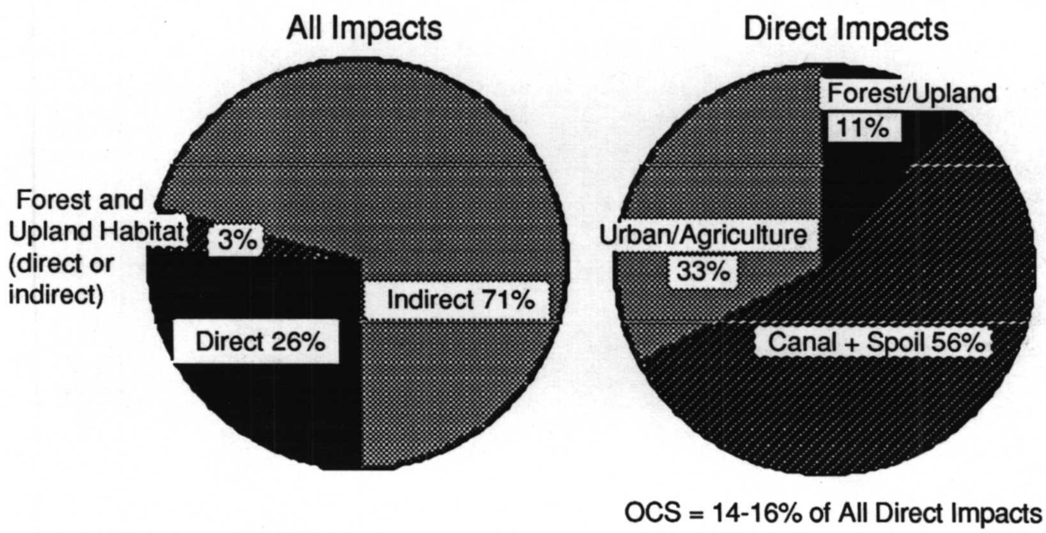


Figure 6. The distribution of direct and indirect impacts by type of change.

Indirect Impacts

Indirect impacts are not immediately evident when or where the direct impact occurs. The wetland ecosystem is robust enough so that not all changes or impacts occur coincidentally in time and place. These changes or impacts must interact with the natural cycles which are diverse. Plants, for example, have annual cycles of growth and senescence; wetland water levels change almost weekly with cold front passages and quite irregularly when hurricanes batter the coast; soils build and decline over decades, if not centuries.

All wetlands are not equal, either. Plant composition and biomass vary within a few steps from the shoreline; individual species have specific tolerances that result in distinctive heterogeneous adaptations and assemblages through ways we do not always understand. Soil compaction may take 500 years to reach an equilibrium. A direct impact affecting these "natural" cycles may have long-term consequences for the balance of geological, chemical and biological relationships and the results of such changes are termed indirect impacts. All relationships could not be examined. This study divided indirect impacts into five general areas of study: salinity, hydrology, sedimentation, plants, and landscape patterns.

The marsh salinity regime may affect the plant's robustness, ability to trap mineral matter and withstand physical stress, as well as the plant's contributions to belowground organic matter, etc. Key questions examined in this study were: (1) whether marsh salinity had increased in recent decades; (2) to what degree OCS-development activities have contributed to these changes; and, (3) if any observed salinity changes were significant to the plants. If salinity changes have occurred, these changes may have influenced wetland loss rates. We therefore: (1) conducted analyses of salinity records across the coastal zone to detect trends; (2) developed a computer model of the influence of OCS canals on saltwater intrusion; (3) made field measurements of saltwater movement between waterway and marsh; and, (4) completed complementary field and laboratory studies of saltwater stress on plant survival and growth.

<u>Temporal Trends in Estuarine Salinity</u>

<u>Approach: Temporal Trends in Estuarine Salinity</u>. We assessed the existing evidence for changing salinity levels in the coastal zone by analyzing data sets collected by the Louisiana Department of Wildlife and Fisheries (LDWF) and by the United States Army Corps of Engineers (COE). The LDWF data set was obtained principally from the open water in the lower reaches of estuaries that consistently exhibit salinities above 5 ppt. The COE data set was collected from the navigable waterways of south Louisiana. Salinity at many of these sites is fresh for most of the year.

Climate, river runoff, and relative sea level rise affect estuarine salinities, and their influences vary over decades. The longest salinity records are only beginning to be long enough to detect any weak trends hidden within this natural variability. For example, many records extend from the early sixties to the late seventies when Mississippi River discharge was increasing. This increase in river discharge would, presumably, result in lower coastal salinities. An inverse relation of coastal salinity to river discharge is clearly evident in the data from 1975 to 1979 (Figure 7).

<u>Results: Temporal Trends in Estuarine Salinity</u>. Mean salinity *decreased* at many stations, and increased at other stations, for the period of record. This result is in constrast to the widely held belief that a long-term and coastwide increase in salinity does exist and that this increase is responsible for the death of marsh plants and subsequently increased

wetland loss. Many of these salinity data are near-surface measurements. If either upland runoff or the local water depth increases, then bottom water salinities in the deeper channels could also increase while the surface salinities decrease. Nevertheless, it is precisely these surface salinities that are most likely to affect marsh plant health, either through overbank flooding or groundwater flow within the root zone. Furthermore, except in the deep waterways very near the coast, the vertical salinity gradient appears to be weak.

Five examples can be used to illustrate how estuarine salinity has or has not changed and whether these results are consistent with previously-held opinions. Marsh vegetation type has changed in two regions of the coast which suggests a concurrent estuarine salinity change. From 1948 to 1978 some of the vegetation in the vicinity of lower Bayou Lafourche changed from brackish to salt marsh. During the same time period, the mean and maximum salinity and the salinity variance increased in the lower part of Bayou Lafourche. Although the lower bayou was dredged to a depth of 6 m in 1968, and is maintained at a minimum depth of 2.7 m, there is no evidence of salinity intrusion being higher or more frequent after construction activity in 1968.

Second, vegetation between the Mississippi River Delta and Lake Pontchartrain changed from salt to brackish vegetation from 1968 to 1978. The salinity data from this region are from records of only ten years. They do show, however, the anticipated decreasing salinity trend.

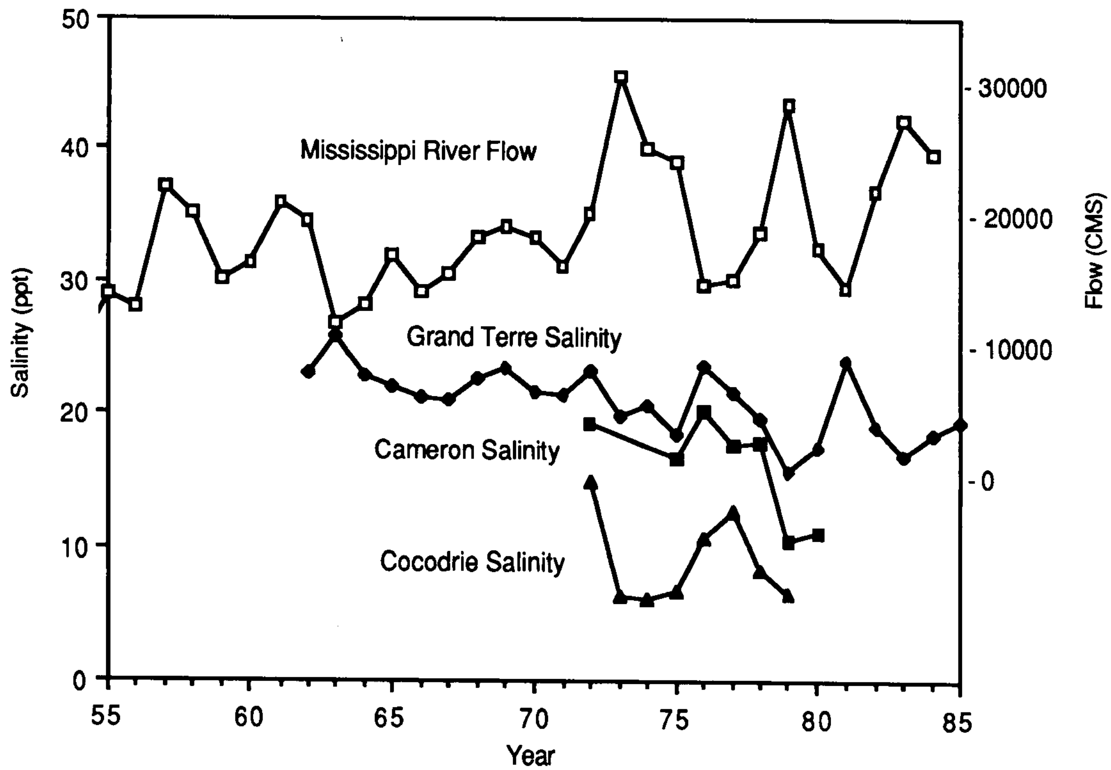


Figure 7. Time series plots of the combined annual mean flow of the Mississippi and Atchafalaya Rivers and plots of mean annual salinity from selected Louisiana Department of Wildlife and Fisheries sampling stations.

Third, the Mississippi River Gulf Outlet (MRGO), which connects Lake Pontchartrain with Breton Sound, was opened in 1964, and other researchers have found a lake salinity increase that they attribute to the completion of MRGO. While we also found an increase in lake salinity (and also in salinity variance) from the 1950s to the present decade, the record does not show any conclusive effect from man-made hydrologic changes during the mid-sixties.

The opposite occurred at stations east and west of the Vermilion Locks on the Intracoastal Waterway. The most striking change is in the salinity maxima, which increased east of the locks and decreased west of the locks.

Lastly, a previous analysis of a single station within the Barataria Bay watershed suggested that salinities throughout the system prior to 1962, when the Barataria waterway dredging began, were lower than after 1962. By using somewhat longer records and different data quality-control criteria, we concluded that a negative trend in mean salinity has occurred recently at the mouth of Barataria Bay, and no mean change in mean salinity has occurred in the upper reaches of the Bay.

Summary: Temporal Trends in Estuarine Salinity. In many cases, any regional salinity changes resulting from OCS activities cannot be separated from the natural variability until the record length improves. Statistically significant trends (higher and lower) are present in the long-term salinity records. However, (1) the observed trends are not consistently observed throughout the coastal zone, and (2) the predicted changes are generally not of a magnitude that would appear to be detrimental to the marsh plants. Local changes, of course, may be significant, and the local changes in salinity often, but not always, are reflected in the changes in vegetation quality.

Saltwater Intrusion in Waterways

Approach: Saltwater Intrusion in Waterways. Saltwater intrusion within natural and dredged channels was simulated using a computer model and the results were verified with field measurements.

Results: Saltwater Intrusion in Waterways. Riverflow, tidal exchange, and surface wind stress influence saltwater movement inland, and the relative importance of each varies with channel morphology, location, and dimension. Under similar environmental conditions (e.g., wind, tides, and freshwater inflow), salt water will move farther inland in large and deep channels compared to small shallow channels. The influence of wind stress is much stronger in shallow channels. Deepening a channel changes the patterns of salinity and the degree of saltwater intrusion. For example, increasing the Houma Navigation Channel depth from its present 6.5 m to 13 m would result in the 5 ppt isohaline migrating 35 km (56 mi) inland. For Bayou Petit Caillou, deepening the depth to 6 meters would result in the 5 ppt isohaline moving 23 km (37 mi) inland.

Summary: Saltwater Intrusion in Waterways. Compared with undredged marshes, saltwater intrusions inland are more frequent and severe because of channel dredging, and this type of salinity model may quantify such effects.

Saltwater Movement in Marshes

Approach: Saltwater Movement in Marshes. Many processes (e.g. overbank flooding, vertical percolation, rainfall, evapotranspiration, and groundwater flow) influence the salinity of the marsh soil and water surrounding plant roots. How salt water moves from the bayou (or canal) into the adjacent marsh soil is not well known, so we investigated this issue in a winter-spring field study within a brackish to intermediate marsh. Salinity and water level gages were established in the marsh and adjacent bayou to determine the importance and movements of groundwater flow.

Results/Summary: Saltwater Movement in Marshes. We anticipated, but did not observe, nearly simultaneous salinity variations within the marsh, the adjacent channel system, and the nearby bayou. Salinities in the bayou and marsh often were not similar in time and space. This suggested to us that: (1) there are other significant sources of salinity than from only the nearby bayou; (2) salt moves over the marsh and through the soils at different and poorly defined rates; and, (3) other salt transfers significantly influence marsh salinity. Some of these relationships are probably not linear and are not predictable. However, we could distinguish between the magnitude of importance of overland and belowground flow in this marsh.

The velocity of water flow within the undisturbed inland marsh soil was estimated to be an order of magnitude greater than through the spoilbank or natural levee soils. Clearly, on the time scales of our measurements, salt will not be advected great distances into the marsh through groundwater flow. The only other possible mechanism for extensive salt transfer to the marsh is via overbank flooding. The large-scale topographic gradient of southern Louisiana is extremely small, and, the marsh surface, natural levee, and any spoilbanks in a given region are not of uniform elevation. Thus, given a small area of marsh surrounded by bays, bayous, and canals, the small-scale changes in the water level slopes may preferentially allow water to enter the marsh from different regions and to flow through the marsh along channels created by the relative lows in the interior topography. Large continuous levees clearly disrupt the movements of water into and out of a marsh and therefore affect the marsh salinity regime.

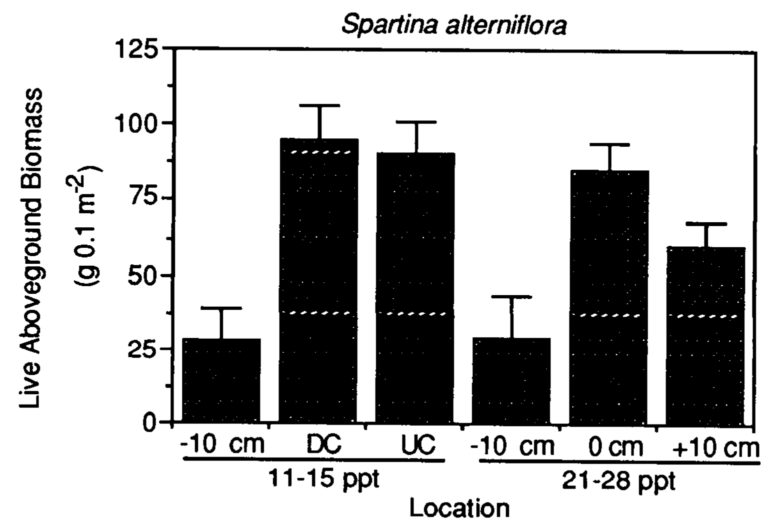
Plant Responses to Salinity Changes and Submergence

Approach: Plant Responses to Salinity Changes and Submergence. We conducted complementary field and laboratory experiments with several dominant wetland species to determine the influences of changing salinity and submergence on plant vigor.

Results: Plant Responses to Salinity Changes and Submergence. Growth of the salt marsh dominant plant, *Spartina alterniflora*, is not inhibited by salinity levels usually found in Louisiana's coastal waters and grows successfully at higher salinities (Figure 8). However, increased soil flooding brought about by a 10 cm decline in surface elevation significantly inhibited the growth of this species. These results, and others, indicate that the reduced vigor of *S. alterniflora*-dominated salt marshes in Louisiana may be caused primarily by factors associated with the chronic waterlogging characteristics associated with root oxygen deficiencies and/or natural geochemical cycles occurring in highly reduced soil substrate.

Spartina patens, the dominant species of brackish marshes, was not only sensitive to increased soil waterlogging but was less tolerant to increases in salinity than *S. alterniflora*. When the salinity in a *S. patens*-dominated brackish marsh was increased to 21 ppt, the above-ground biomass was significantly reduced in a single growing season, and the combined effect of increased waterlogging and salinity had a greater potential for causing deterioration of a brackish marsh than that of either factor acting alone. However, *S. patens* did acclimate to a slow increase in salinity to 28 ppt in the greenhouse experiments, and regrowth at similar salinity levels was also observed in the field.

Fresh marsh plants are adversely affected by increases in salinity or waterlogging, but this response varies depending upon the species, as well as salinity level. Broad-leaved species such as *Sagittaria lancifolia,* may be relatively more sensitive to increases in salinity than grasses. *Panicum hemitomon* and *Leersia oryzoides* were able to survive and grow for one month (although at a reduced rate) at salinities up to 8 to 11 ppt in the greenhouse. Even *Sagittaria lancifolia* survived salinity levels of 4 to 5 ppt. Thus, marshes comprised of these species might be able to survive small increases in salinity for short periods of time but would probably quickly succumb to sudden influxes of salt water above 10 ppt. Although *P. hemitomon* was more sensitive to submergence in the field than the other two species, the relative flood tolerance of the three species is not yet fully known and requires further investigation. Because the flood tolerance can vary among fresh marsh plant species, the effect of subsidence in fresh marshes would likely be dependent on species composition.



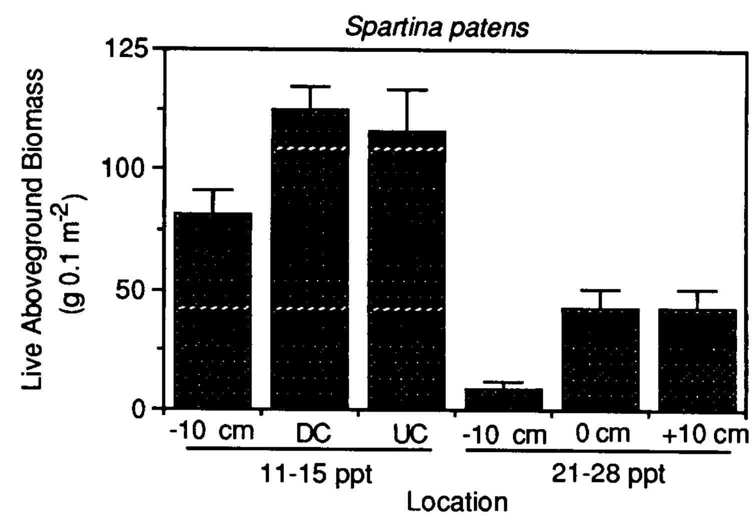


Figure 8. Live aboveground biomass of *Spartina alterniflora* and *S. patens* swards after six months growth at different elevations within two marshes of different salinity. DC = disturbed control; UC = undisturbed control. A 95% confidence interval is plotted for the five samples in each experimental treatment.

Summary: Plant Responses to Salinity Changes and Submergence. Vegetative change is not necessarily followed by marsh deterioration which implies less biomass and elimination of marsh plants. Vegetative change may involve a change in species composition, biomass or both. Several possible results may occur depending upon the interaction of biotic and abiotic factors. Salinity changes, for example, may eliminate one species but may not necessarily result in marsh deterioration if the eliminated species is replaced by another more salt-tolerant species. The key factors determining whether a marsh deteriorates or simply undergos a change in species may be: (1) the abruptness of exposure to the stress; (2) the relative vulnerability of the dominant species to that stress; or, (3) the presence of propagules of a more tolerant species.

In addition, the effects of saltwater intrusion or subsidence may occur simultaneously. These individual and combined impacts depend on a number of factors. In some cases, saltwater intrusion may only result in a change in species composition. On the other hand, an increase in water level (with or without a change in salinity) has a greater potential for causing marsh deterioration because rapid colonization by an invading species (through seed) may depend on exposed substrates for germination. In any case, recolonization would have to occur quickly to prevent erosion and further submergence of the marsh surface. Succession to more salt-tolerant vegetation types is possible (in areas where mean water depth does not increase) because there are various species tolerant of 36 ppt. Plant succession is less likely where salinity changes are accompanied by increased flooding levels because (1) seed germination has specific requirements, and (2) salt-tolerant species are not necessarily more flood-tolerant than fresh marsh species. Thus, fresh or intermediate marsh may deteriorate not only because of an increase in salinity that initiated the process, but also because a more salt-tolerant species could not establish itself or tolerate the new flooding conditions.

Subsidence, Water Level Rise, and Sediments

Approach: Subsidence, Water Level Rise, and Sediments. We analyzed tide gage records to estimate absolute water level changes and how much these changes were a consequence of variations in climate, subsidence, and global sea level. Records of river sediment concentration were re-analyzed to determine long-term trends. Marsh sedimentation rates were estimated using three different sedimentation marking techniques for seasonal, yearly, decade- and century-long estimates.

Results: Subsidence, Water Level Rise, and Sediments. Recent subsidence is the dominant geological process causing wetland inundation, not sea level rise. Geological subsidence rates seem constant over the last 40 to 50 years. Subsidence rates for the last 50 years are about 0.3 to 2.0 cm/yr and are predictably influenced by sediment characteristics. Based on modeling studies, fluid withdrawal from oil/gas reservoirs appears to have a localized influence on subsidence, amounting to a lifetime subsidence of as much as 80 cm directly above the reservoirs. The total area of oil and gas fields having a subsidence potential greater than 10 cm is estimated to be 50,992 ha (126,000 acres).

Sea level rise appears to have been relatively constant over the last 80 years, at a rate of about 2.3 mm/yr, and varies over decades from -3 to +10 mm/yr. Basin water level changes significantly influence marsh water levels and, together with climatic effects, have produced decade-long rises and lowerings of water levels at tide gage stations of as much as 60 cm (Figure 9). Water level rise from climatic changes, subsidence, and sea level rise can often exceed additions of sediments at the marsh surface, at least over short time periods ($\leq$ 25 years), resulting in a surface disparity (water rise > accretion at the marsh surface).

It appears that the suspended sediments in the Mississippi River have decreased dramatically in the last 100 years, perhaps as much as 60%. Fluctuations in the bedload transport do not appear sufficient to compensate for the decline in suspended load. This decrease, coupled with the elimination of direct input to the marsh via overbank flooding in the 1930s (when the flood protection levees on the Mississippi River were completed), undoubtedly has influenced marsh sedimentation rates. Approximately 3% of the suspended mineral matter presently confined within the levees would be delivered directly to the marshes via overbank flooding and crevassing if the levees did not prevent it.

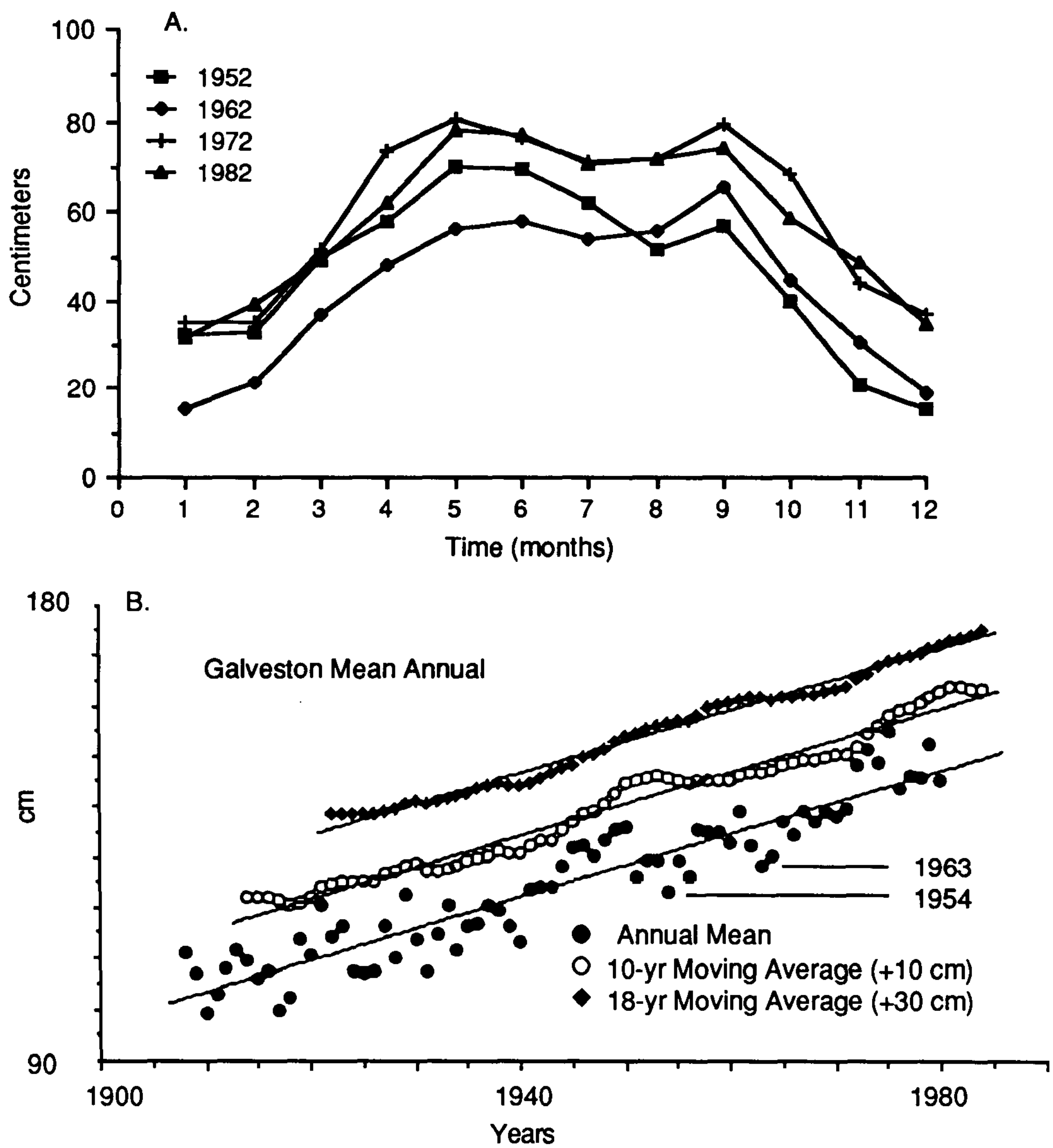


Figure 9. Water levels in estuaries within the study areas. A. Monthly water level for the Cameron tide gage averaged for four year intervals. B. Mean annual water level at Galveston, Texas, from 1909 to 1983: the annual mean, a 10-year moving average of the annual mean, and, an 18-year moving average of the annual mean.

Sediment deprivation appears to limit marsh growth in several regions of the coast. This conclusion is based on estimates of sedimentation rates in the salt marshes of lower Barataria Bay near both natural and man-made waterways. Sedimentation appears to be at the minimum level required to sustain marsh growth. In the brackish marshes east of Lake Calcasieu, current sedimentation rates appear to be much lower than rates of 25 years ago, and the level of sediment supply there could become a critical factor in marsh growth and stability.

Canals and spoilbanks influence sediment distribution in many marshes, and this influence may be different from the influence of natural waterways (Figure 10). On a local scale, canals and spoilbanks may cause an annual 0-6 mm *increase or decrease* in vertical accretion compared to natural waterways, depending on canal alignment, local hydrologic patterns, and sediment supply. Of course, only the decrease in vertical accretion usually contributes to plant stress and wetland loss. These differences are usually attributed to the influence of the spoilbank on marsh surface hydrology.

Short-term (<1 year) accretion rates were essentially the same behind adjacent natural and man-made waterways. This result does not preclude the possibility that a surface disparity could develop behind spoil levees but not behind natural levees. Spoil levees can influence surface hydrology and, therefore, affect marsh water levels. Thus, a disparity between marsh accretion and water level rise could develop near spoil levees but not near natural waterway sites, even though accretion rates were the same at both sites. However, we cannot confirm that such disparities existed at any of our study sites because estimates of water level and marsh surface elevation were not available for comparison to measured accretion rates.

Summary: Subsidence, Water Level Rise and Sediments. Natural processes dominate the marsh surface-to-water surface relationships, but human activities are also influential. Sea level rise and geological subsidence rates appear constant over decades and subsidence due to belowground fluid withdrawal appears to be an important local but not regional influence on land sinking. Sediment supply from rivers to the coastal marshes is reduced compared to earlier this century. Sedimentation appears to be at the minimum to sustain marshes. The potential for insufficient sedimentation to occur increases near canals because the localized effects of spoilbank compaction and subsidence, canal construction, spoilbank levee effects on water circulation and height, subsurface fluid withdrawal and sediment redistribution are additive with all regional influences.

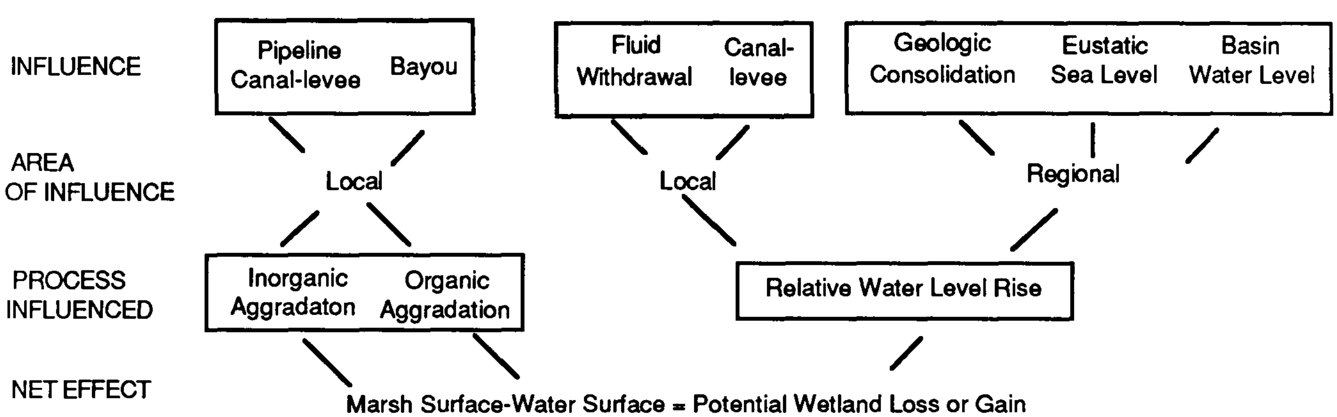


Figure 10. Relationship between man-made and natural influences on vertical aggradation and relative water level rise processes in Louisiana coastal marshes.

Landscape Pattern Analysis

Approach: Landscape Pattern Analysis. Three projects used aerial imagery of 1955/6 to 1978 habitats to analyze changes. Each project examined the distribution and/or number of habitat changes with respect to geology, distance, and density measures. Gross landloss rates in the three study areas (Figure 1; comprising together 14% of the wetlands present in 1978) were examined using sample sizes of 100 m2 to 1 km2 within subsets of the data. In the second approach, the formation of ponds in four categories based on size was determined within selected 7.5 minute quadrangle maps (around 16,000 ha, each), which together accounted for 35% of the open water formation in the coastal zone from 1955/6 to 1978. The third approach used net habitat changes in the 7.5 minute quadrangle maps (comprising 76% of the coastal zone) to select appropriate variables for the subsequently developed statistical models of wetland loss and definition of regions.

Results: Landscape Pattern Analysis. Five types of wetland change were evident: (1) spoilbank-parallel pond formation; (2) pond formation with apparent random distribution; (3) semi- or complete impoundment and resulting open water formation; (4) cutting off stream channels upstream from where a spoilbank crosses a natural channel; and, (5) erosion at the land-water interface. Only ponds <20 ha appear to form and disappear. This observation might be considered a result of mapping errors; however, the large number (10% of the total number of ponds), a different distribution of the transient ones compared to the new ponds, and mapping of smaller features suggest otherwise. Whereas ponds formed between 1955/6 to 1978 and ponds present in 1955/6 and 1978 tend to cluster next to canals, the ponds which disappear have the highest density 1.5 km away from canals (Figure 11). Areas of high gross landloss or wetland loss were obvious; for example, some study areas comprised 10% of the total area, but had 40% of the gross land loss (Figure 12). The major form of gross (not net) land loss at all three smaller study sites was conversion to inland open water.

Identified factors associated with either wetland loss or land loss rates include: (1) the age and thickness of previously deposited sediments, (2) the distance to sediment sources and freshwater, (3) indicators of hydrologic change, such as canals and spoilbanks, and, (4) various associated factors related to distance and density. In general, loss rates are lower where sediment thickness is thin and the sediments old, where spoilbanks, canals and the seashore are far away, and where rivers are close. The reverse was also true: loss rates were highest where sediments are likely to consolidate the most, where new sediment sources are in shortest supply, and where canals and spoilbanks are dense. However, the loss rates in specific areas may not always follow the general tendency. Because of the interactions between these factors, regions differ geologically, biologically, and physically. In terms of loss rates and the relationship between these factors, the Chenier Plain was distinct from the Deltaic Plain. Similarly, the Deltaic Plain could also be subdivided into smaller regions. Boundary definition is important in analyzing landscape changes, and all three studies fortunately analyzed areas at appropriate scales, which were identified for the first time. The regional salinity changes did not influence the rate of habitat conversion to open water in some areas but may have affected the rate in two other areas.

The statistical analysis of quadrangle maps by hydrologic units resulted in a projected decrease in wetland loss by 4 to 51%, if no canals were present. The analysis of pond formation (from wetland) within selected regional groupings of quadrangle maps had zero wetland loss rates where there were no canals. These two results are not precise estimates, however, and are based on hindcasting with considerable variation about the estimate. Other results indicate that 40 to 80% of gross land loss within selected regions can occur in areas without canals or spoilbanks. There were indications that at a certain canal density, a

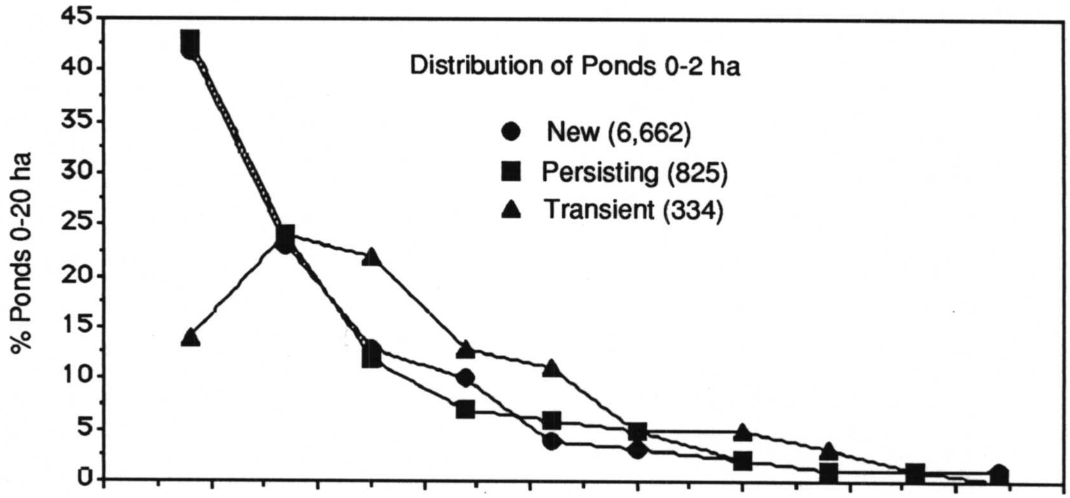


Figure 11. The distribution of new, persistent and transient ponds <20 ha within 4.2 km from 1978 canals for 35% of the study area. Zero distance is at the canal edge. The number of ponds in each category is in parentheses.

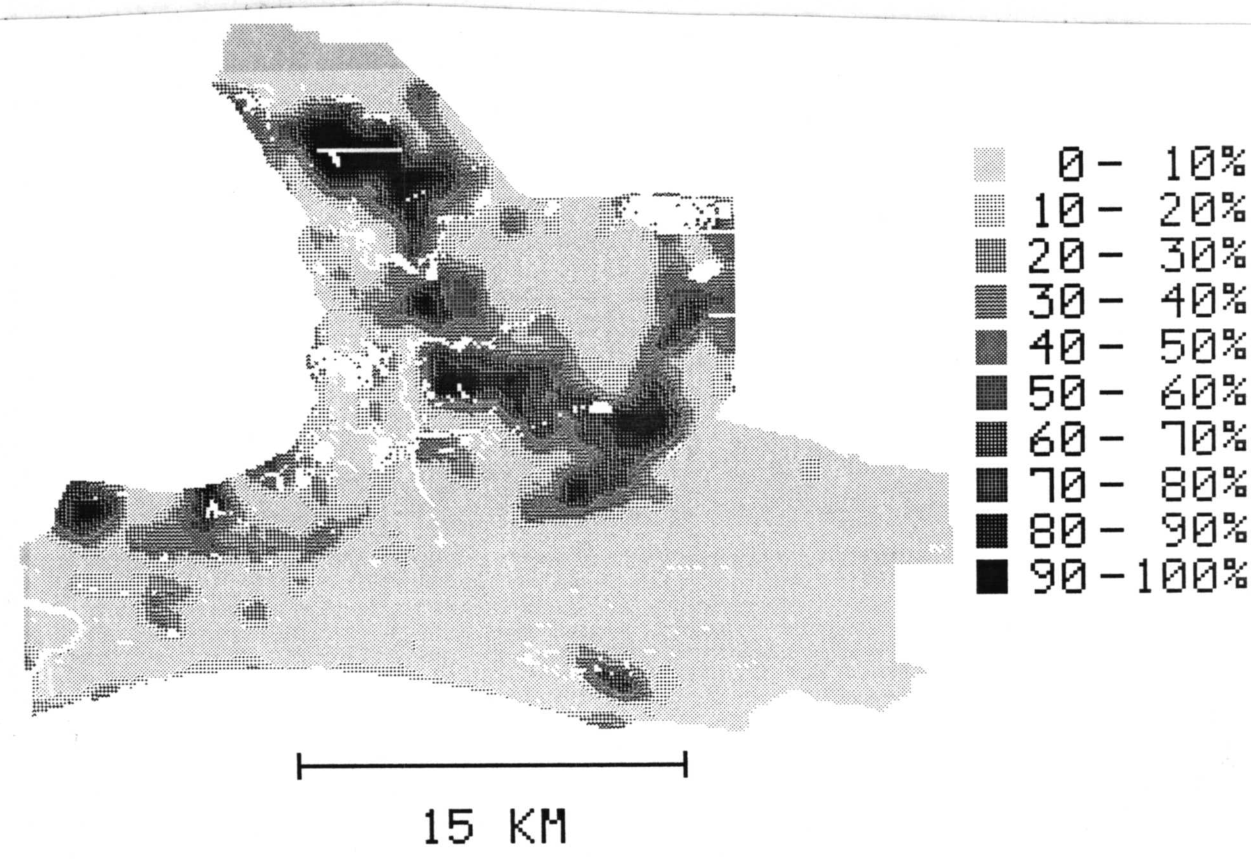


Figure 12. Areas of high gross landloss (percent loss per km^{-2}).

saturation point was reached, beyond which gross landloss rates did not increase with the addition of another canal.

Many of the above findings are the results of correlation analyses, not controlled experiments. We could not prove these relationships were the result of cause-and-effect relationships. However, based on the common appearance of all factors in the three studies, results in the scientific literature, and the lack of a more efficacious explanation, we accept that all factors identified above are intimately involved in wetland loss on this coast.

Summary: Landscape Pattern Analysis. Four patterns in habitat change were apparent in the three studies: (1) large and widespread habitat changes are more appropriately described as inland fragmentation or loss, not erosion at the shoreline; (2) differences in the regional geology appear to be significant influences affecting habitat changes; (3) man-made factors, including agricultural and urban development, and canals and spoilbanks, were spatially related to these changes; and, (4) the regional salinity changes did not influence the rate of habitat conversion to open water in some areas but may have affected the rate in two other areas.

Consensus Estimate of Direct and Indirect Impacts

Approach: Consensus Estimate of Direct and Indirect Impacts. At the end of the project data collection effort, the scientists arrived at a consensus estimate of the impacts of OCS activities and the factors driving wetland losses in the study region. Based on the results of this study and others, the project scientists estimated the causes of wetland loss from 1955/6 to 1978, and the role of OCS development activities in those losses. This estimate is not precise. It is simply a state-of-the-art estimate and we could not pinpoint the causes of *all* the changes in wetland area. We also were not able to treat these estimates as anything but a coastwide estimate, and they are not meant to describe the wide variety of conditions within local areas.

Given these caveats, we estimated how much OCS development probably contributed to wetland loss from 1955/6 to 1978. Because of the interrelationships between driving forces, and also because of incomplete knowledge, only the broadest categories were used, e.g., direct versus indirect impacts, OCS versus non-OCS development activities, and major land-use categories.

Summary: Consensus Estimate of Direct and Indirect Impacts. Of all direct impacts from 1955/6 to 1978, OCS development accounted for an estimated 14-16% of all direct impacts, or 4-5% of the total wetland loss (Table 5). Of all indirect impacts, OCS development accounted for an estimated 10,000-36,000 ha (5-18%) of all indirect impacts, or 4-13% of the total wetland loss. Combining the direct and indirect impacts, OCS development accounted for 8-17% of all wetland loss, or 22,000-50,000 ha. Land use changes, and, oil and gas canals and spoilbanks (OCS and non-OCS) accounted for 13, and 30-59%, respectively, of the total wetland losses. Altogether, we identified 43-72% (124,000-206,000 ha) of the causes of all wetland losses. Some of the remaining 28-57% (82,000-164,000 ha), may also be caused by OCS or non-OCS economic development, agricultural and urban expansion, and oil and gas canals and spoil banks, but are likely to involve the more non-manageable influences, particularly water level rise, geological factors, and the decreased sediment content of the Mississippi River.

Table 5. Summary of direct and indirect impacts on wetland losses from 1955/6 to 1978 for the Louisiana portion of the study area. One hectare (ha) = 2.47 acres.

	Area (ha)	% Total Direct+ Indirect Impacts	% Direct Impacts	% Indirect Impacts
A. Total Direct + Indirect Impacts	288,414	100	29	71
B. All Direct Wetland Losses	82,937	29	100	-
Canal + Spoil	46,355	16	56	-
Urban/Agr.	27,550	10	33	-
Forest/Upland	9,032	3	11	-
TOTAL direct changes	82,937	29	100	-
TOTAL direct habitat changes	73,905	26	-	-
OCS Direct Impacts only				
low estimate	11,589	4	14	-
high estimate	13,631	5	16	-
C. Indirect Wetland Losses	205,477	71	-	100
Canal and Spoil (consensus estimates)				
low estimate @ 20%	41,095	14	-	20
high estimate @ 60%	123,286	43	-	60
OCS				
low estimate	10,274	4	-	5
high estimate	36,253	13	-	18
D. All Indirect+Direct Impacts Combined	288,414	100	-	-
Canal+spoil (consensus estimate)				
low estimate	87,450	30	-	-
high estimate	169,641	59	-	-
Urban/Agr/Upland	36,582	13	-	-
OCS				
low estimate	21,863	8		
high estimate	49,884	17		
Identified Impacts				
low estimate	124,032	43	-	-
high estimate	206,223	72	-	-
Unidentified Impacts				
low estimate	82,191	28	-	-
high estimate	164,382	57	-	-

Consensus

A series of questions were addressed by the project scientists to further clarify different points and approaches to the study. The questions and answers are given below.

Question 1

If land is sinking more quickly than land is building and the rates of each process are changing, to what extent is this disparity caused by changes in (1) sediment supply reaching the marshes; (2) organic matter accumulation; (3) subsidence rates; and, (4) water level rise?

Answer 1

In the face of regionally high but historically (80 years BP) non-accelerating rates of relative water level rise, low rates of inorganic sediment accumulation coupled with annual fluctuations in basin water levels have led to biologically significant periodic (20 to 25 years), and perhaps longer-term, disparities between land building and water level rise processes.

Relative water level rise (RWLR) results from geologic subsidence (compaction) and water level rise (sea level and basin water level changes). Land building occurs through the aggradation and accretion of matter, both organic and inorganic. Disparity can be defined as the difference between accretion and RWLR and has recently increased within the Louisiana coastal zone. This study is concerned with cases in which accretion is less than RWLR. An example of a surface disparity between RWLR and accretion is described in Eqn. 1 below.

R = relative water level rise = 1.2 cm/yr
A = vertical marsh accretion = 0.7 cm/yr

and

$$\text{Disparity} = \quad \begin{aligned} Dis &= R - A \\ Dis &= 1.2 - 0.7 \\ Dis &= 0.5 \text{ cm/yr} \end{aligned} \qquad \text{Eqn. 1}$$

The four factors mentioned above have different relationships with each other. Geologic subsidence is independent of marsh processes as is water level rise. Subsidence and water level rise affect the marsh through their sum, i.e., RWLR. The organic component of marsh accretion is strongly related to and controlled by the inorganic component. In other words, the marsh standing crop is dependent upon the bulk density of soil, given as g/cm^3. For example, salt marsh plant growth has been shown to become very stressed at a minimum bulk density, i.e., $\approx$ 0.2 g/cm^3. The standing crop increases proportionately as bulk density increases so that a maximum bulk density of approximately 0.4 g/cm^3 is reached. The salt marsh is viable when the bulk density is between 0.2 to 0.4 g/cm^3 and when its surface elevation is in the optimum flooding range of *Spartina alterniflora*. The salt marshes we investigated are at a minimum bulk density needed to support marsh vegetation because of the increase in the rate of water level rise and because the aggradation rate appears too low to maintain an adequate bulk density, at least during the 1986-87 time period.

The relationship between the organic and inorganic components of brackish and fresh marshes is less clearly understood, although these marsh types require certainly no more and most likely less inorganic sediment to maintain plant production than salt marsh systems. Therefore, the low rates of mineral accumulation and bulk densities measured in these marsh types are probably more adequate at maintaining plant standing crop. How adequate is not known, however.

Vertical marsh accretion is related to marsh aggradation (mineral and organic matter accumulation) because the inorganic and organic components of the marsh are correlated. The relationship can be expressed as:

$$S = \rho \cdot A \qquad \text{Eqn. 2}$$

where S is the marsh aggradation rate (mineral and organic accumulation) in g/cm^2/yr, A is vertical marsh accretion in cm/yr, and ρ is bulk density, with values 0.2 to 0.4 g/cm^3. Therefore, disparity also can be described in terms of S (marsh aggradation) if the bulk density of the soil is known.

R = relative water level rise = 1.2 cm/yr
ρ = soil bulk density = 0.3 g/cm^3
S = marsh aggradation = 0.1 g/cm^2/yr

and

$$DIS = R - \frac{S}{\rho} \qquad \text{Eqn. 3}$$

$$DIS = 1.2 \text{ cm/yr} - \frac{0.1 \text{ g/cm}^2\text{/yr}}{0.3 \text{ g/cm}^3}$$

$$DIS = 0.87 \text{ cm/yr}$$

For example, given a bulk density of 0.3 g/cm^3 with a submergence of 1.2 cm/yr and an aggradation rate of 0.1 g/cm^2/yr, then the vertical accretion rate is 0.33 cm/yr and the disparity is 1.2 - 0.33 = 0.87 cm/yr. The minimum aggradation rate (mineral and organic accumulation) needed to produce a vertical marsh accretion rate of 1.2 cm/yr at a density of 0.3 g/cm^3 would be 0.36 g/cm^2/yr.

$$S = 0.3 \text{ g/cm}^3 \cdot 1.2 \text{ cm/yr}$$
$$S = 0.36 \text{ g/cm}^2\text{/yr}$$

Therefore, the disparity expressed in terms of marsh aggradation is 0.36 - 0.1 = 0.26 g/cm^2/yr.

A schematic representation of these concepts is presented in Figures 13 and 14. Relative water level rise is defined in Figure 13 as the difference between the water level and subsidence. In Figure 14 accretion and disparity are shown compared with RWLR. The accretion rate increases after the water level rise rate increases but at a rate less than that needed to equal RWLR.

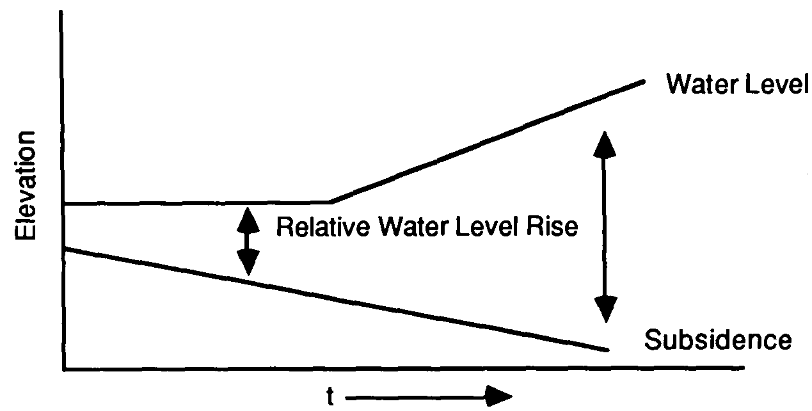


Figure 13. Relative water level rise defined as the difference between water level rise and subsidence.

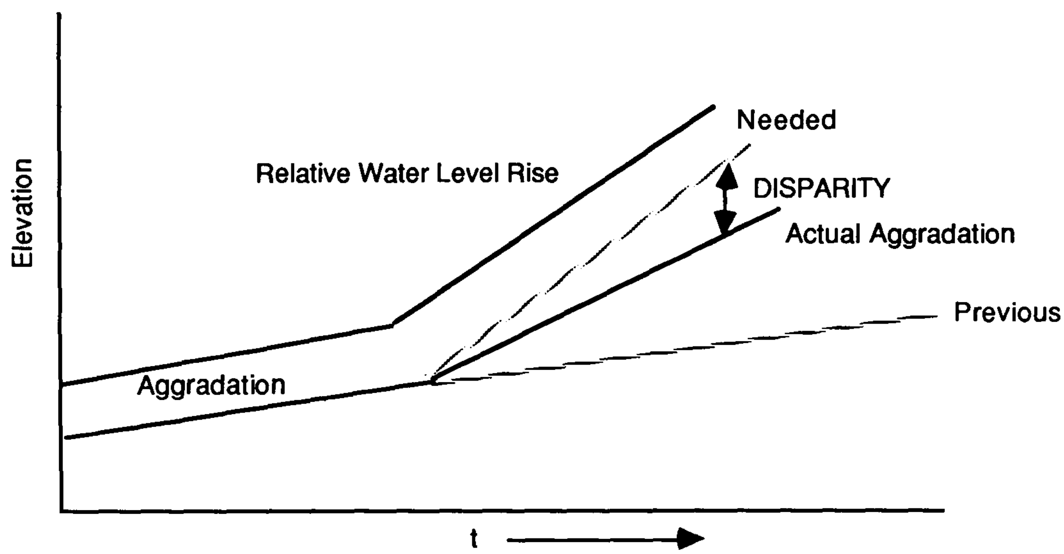


Figure 14. Relative water level rise, aggradation, and disparity for constant inorganic sedimentation.

Question 2

Do levee construction, canal dredging, and oil and gas production influence the rates of sedimentation, organic matter accumulation, and subsidence in coastal Louisiana? If so, do these impacts contribute to the high rate of coastal submergence?

Answer 2

The flood control levees of the Mississippi River have reduced the supply of sediment directly available to the marshes by over-bank flooding (a quantity equal to, on average, 3% of the total annual suspended sediment load). Spoil banks associated with man-made canals have a clearly defined direct effect on compaction of the marsh surface but a far less clearly defined influence on marsh aggradation (mineral and organic matter accumulation) caused indirectly by changes to local hydrology. Oil and gas production (i.e., fluid withdrawal) have a direct, potentially significant but local effect on subsidence in coastal wetland habitats. All of these factors contribute, in varying degrees, to submergence of the wetlands.

Flood control levees on the lower Mississippi River restrict the supply of sediment to the marsh through overbank flooding. Not only have the sites at which overbank flooding occurs been eliminated, but damming and flood control structures in the upper river basin have trapped sediment. The levels of suspended sediment and the size of the suspended particles carried by the river have decreased during this century. Thus, both the quantity and quality of sediments carried by overbank flooding to the marsh, where such events are allowed to occur, have been altered. The result is decreased mineral sediment supply to the marsh, less aggradation directly caused by this sediment reduction, an altered nutritional value of the resultant marsh substrate, and the potential for reduced plant growth and organic sedimentation.

Spoil banks for canals and navigation channels cause the underlying marsh to compact. This lowers the marsh level on the marsh side of the spoil bank, and often results in pond formation. Those ponds may enlarge with time in a region that does not have an alternate hydrologic connection into the marsh.

Spoil banks may alter the hydrology of the marsh. Partially or fully impounded portions of the marsh are often flooded less frequently than nearby natural marsh, but the flooding events are of longer duration. The marsh vegetation in salt, brackish, intermediate, and fresh marsh are all known to be sensitive to waterlogging stress. Higher mineral sediment content and bulk density immediately behind the levee (edge effects) and lower values farther into the marsh were found at the natural bayou study sites but not at the spoil bank sites. Aggradation rates in the marsh behind natural levees were higher, on average, than behind spoil banks. However, this difference is not statistically significant. In some cases lack of replicates precluded a statistical test (stable isotope technique), while in other cases low sample size and high variance resulted in a test with low power. If the difference in sedimentation rates is real, it would be botanically significant. However, the present analysis could not demonstrate that canals significantly affect sediment aggradation and accumulation.

At one OCS pipeline spoil bank site, notably high sedimentation rates (comparable to earlier published estimates from the immediate vicinity) were observed on the southern side of the bank. The spoil bank at this one site was extensive in the east/west direction. The observed sedimentation rates were much higher than those measured at a nearby north/south trending bayou site and several shorter east/west-trending canal sites. We interpret these results to indicate a blockage of the wind-driven storm surge flow associated with winter frontal passages.

The extra water introduced into bayous and canals during winter storm surges is derived from the lower estuaries and near-shore waters of the Gulf of Mexico. Those waters are, therefore, often saltier than those to which they are added. Thus, while spoil banks may reduce the occurrence of flooding, when winter, wind-driven storm surges do cause flooding, the associated water is of relatively high salinity, thus potentially increasing the resultant stress on the marsh vegetation. After the flood waters drain off, the remaining interstitial waters are expected to increase in salinity because of evapotranspiration unless they are diluted by rainfall or a freshwater flooding event. Unfortunately, we have no direct data to confirm this conjecture.

Local subsidence greater than 10 cm potentially can occur over shallow reservoirs because of fluid withdrawal and occurs over the lifetime of the reservoir. The coastal area of known shallow reservoirs with such potential is approximately 51,000 hectares.

Question 3

Are there spatial patterns of land loss and, if so, can these patterns be interpreted?

Answer 3

Yes, there are clearly discernible patterns of land loss in the coastal landscape. Even though there is no one primary factor highly correlated with the spatial patterns identified, analysis of several factors in combination does allow for interpretation of these patterns.

The deltaic and chenier plains of southern Louisiana are the result of the shifting position of the Mississippi River and the construction and subsequent abandonment of a series of deltaic lobes. The southwestern coast was constructed from fluvial sediments and organic materials of the Mississippi River and other local rivers reworked by marine processes. Rates of erosion and subsidence within the deltaic plain are correlative with the time of abandonment of the delta lobe. During the last decade, the major area of new land formation has shifted from the main Mississippi River channel and delta front to the Atchafalaya River distributary. The decline in new land build-up along the Mississippi River and around the delta front may be related to the 60% decline in suspended sediment load carried by the river. A similar decline in bedload has not been documented but is highly likely.

There are numerous other examples documenting differences in the spatial pattern of land loss in coastal Louisiana. From a coastwide perspective, there is no one primary factor which is highly correlated with all the spatial patterns identified. There is a combination of primary factors, which include man-induced alterations (MIA) and geology (age and depth of soils). There are three distinct regions (clusters) where these factors interact differently. South central Louisiana has young, thick sediments with relatively low canal densities and high land loss (36%). This area is perhaps most sensitive to new MIAs. The Chenier Plain has older, relatively thin sediments with many MIAs and moderately low land loss (20%). It does not appear to be very sensitive to the indirect effect of MIAs. The region east of the bird-foot delta has moderately old, thick sediments with moderate land loss (22%) and moderately high canal densities.

One cannot accurately predict spatial patterns of coastwide land loss because they are dependent on the interactions of geology and MIAs. These factors are multiplicative, nonlinear, and the coefficients vary geographically in magnitude. The interaction of these factors within hydrologic units, however, does seem to be moderately predictable.

It appears that the spatial data we examined exhibit significant spatial patterns at any scale. Some of these patterns are summarized in Table 6. Direct impacts are well documented, and many other causes of land loss are inferred. Other spatial patterns are, however, unexplained, perhaps because of a lack of measurements or a lack of understanding of the cumulative relationships. These particular areas are "hot spots" of contiguous land loss that are small in aerial extent but account for up to 40% of regional loss.

Table 6. Patterns of land loss in the Louisiana coastal zone by spatial unit, scale, and potential mechanisms.

Spatial Unit	Scale	Potential Mechanism
Coastal Zone	10,000s km^2	Delta decay, major MIAs[a], cumulative impacts of minor MIAs
Regional/Hydrologic Unit	10,000s km^2	Subsidence, sea level rise, distance to sediment sources, sediment depth and age,damming of distributary channgels, major MIAs
Sub-delta Lobes	100s km^2	Proximity to coast, sediment age, sediment depth, distance to sediment sources, major MIAs
Quadrangle Maps	10s km^2	Local geology, distance to channels and canals
"Hot Spots"	10-100s km^2	Local geology, new pond formation, impounding, canal density, shoreline erosion, fluid withdrawal, point source erosion
Pixel	<1 km^2	Variation in marsh accretion, minor topographic effects

[a] Man-induced alterations (i.e., canals, agriculture, spoil banks).

There are many generalized, preconceived patterns of land loss that this project has helped clarify or refute. Three major generalizations, contrasted with our findings, are presented here:

	Hypothesis	Finding
1.	The majority of land loss is from the coast inward and uniform.	Land loss is actually internal to the marsh and its rate is highly dependent on site-specific factors.
2.	Saltwater intrusion is a major contributing contiguous factor coastwide.	Saltwater intrusion is (at most) localized.
3.	Man-induced alterations are a major contributor to coastwide land loss.	The impact of man-induced alterations is not uniform.

In summary, it appears as if man-induced factors are operating on the scale of geologic processes coastwide, and their influences can occur on a time scale of decades, a time considerably shorter than the normal geologic period. Consequently, land loss in geologically eroding areas is accelerated by man's activities. For example, the rapidly constructed levees along the Mississippi River have contributed to land loss on a geologic scale in a matter of 30 to 40 years.

Question 4

How long does it take for a change in subsidence, sedimentation or accumulation, i.e., surface disparity, to be expressed as land loss?

Answer 4

An annual surface disparity rate of 0.5 cm/yr could result in a surface disparity great enough to significantly reduce plant growth in salt marsh systems to the point where the viability of the marsh is in jeopardy in 20 years.

The time interval needed for the occurence of a significant effect on the marsh vegetative community caused by a surface disparity depends on the rate of relative water level rise, marsh vertical accretion rate, marsh type and species composition, and interacting local abiotic and biotic variables. An analysis of this surface disparity for a specific time interval was conducted. We selected the period from 1962 to 1980 for this analysis because (1) it is a period of high observed land loss; and, (2) data for marsh aggradation by ^{137}Cs dating and estimates of water level rise from tide gauge records were available for this interval.

Although relative water level rise exhibited variable rates during the past 80 years, the period from 1962 to 1980 showed a rate of 1.2 cm/yr (see Table 7). This value is a representative average for salt marshes across the coastal plain of Louisiana. The average aggradation rate in this area is 0.7 cm/yr, resulting in a surface disparity of 0.5 cm/yr. Over a 21-year period, this will produce a 10-cm water level/marsh surface disparity, which can significantly reduce plant growth. This statement is supported by the salinity/submergence experiments reported in this study that showed decreases in biomass of 75% following a rapid 10-cm decrease in marsh surface elevation in salt marshes over one growing season. Based on this vegetative response to increased flooding level, it is probable that some marsh deterioration would occur during this period and most certainly if the surface disparity continued. If one assumes a similar situation in fresh and brackish marshes, these habitats would be similarly affected. However, because of the greater species diversity in fresh marshes and the variable flood tolerance of fresh marsh plant species, the effect of increased flooding level on this habitat will be modified by species composition. If the surface disparity is also accompanied by a biologically significant rise in salinity, then the rate of marsh loss will likely be accelerated in fresh and brackish, but not salt, marshes.

We do not know just how well a marsh can adapt to decade-long disparities between water level rise and sedimentation. Also, a ten-year disparity may be temporary when viewed over 20 years or more. Water level rise during 1963 to 1982 was higher (two times) than that recorded during this century, but within the observed amount of variation; sedimentation rates for 100 years BP are nearly equal to that for 1963 to present. If (1) the marsh can adjust to temporary disparities or (2) longer-term water level rise records are more appropriate to use in these comparisons, then the surface disparity may be less severe than implied in Table 7. Future measurements of water level rise and marsh aggradation should clarify this issue.

Table 7. Comparison of apparent water level rise and marsh aggradation rate for various locations in Louisiana.

Area	Apparent Water Level Rise 1962-1983[a]	Aggradation 1963-present[b,c]	21-year Disparity[d]
Coastal Louisiana	1.2 cm/yr	0.7 cm/yr	10.5 cm
Eastern Pontchartrain	0.15 to 2.16	0.54 to 1.07	none to 22.9
Mississippi Delta	1.8	1.8>2.0	none
Lower Barataria	1.8 to 1.91	0.68 to 1.2	12.6 to 25.6
Terrebonne Delta Plain	1.64 to 2.11	0.65 to 0.99	13.6 to 30.6
Vermilion	0.78 to 0.93	0.69 to 0.86	none to 5.0
Cameron	1.17	0.57 to 0.70	9.9 to 12.6

[a] From Penland et al., 1987.
[b] From DeLaune et al. (1987) and this study; based on ^{137}Cs horizon technique.
[c] We assume that the aggradation rate/year is relatively uniform with time during the period from 1963 to 1987.
[d] Calculated using "best guess" average of ranges in other columns

Question 5

What are the direct and indirect impacts of OCS activities on wetland losses in coastal Louisiana?

Answer 5

The direct impacts of OCS activities account for 4 to 5% of the total Louisiana wetland loss from 1955 to 1978 (≈ 11,000 to 14,000 ha). Indirect impacts from OCS activities are estimated to account for 4 to 13% of all indirect impacts.

The total direct impact of OCS activities is documented in Chapter 4. The study team estimates that these direct impacts are approximately 4 to 5% of the total Louisiana wetland loss from 1955 to 1978, or approximately 11,000 to 14,000 ha. The vast majority of these direct impacts is caused by the conversion of wetlands into spoil bank levees and canals. A minor amount (38.5 ha) is caused by construction of facilities and less than 20% (up to 2,900 ha) is caused by navigation channels. In general, the impact per length of pipeline is highest in wetlands and lowest in non-wetlands. The total net change in canal and spoil area from 1955/6 to 1978 was 46,000 ha, equivalent to 16% of the total net wetland loss for the same interval. OCS pipeline and navigation channel direct impacts are in the range of 12,000 to 15,000 ha, or as much as 32% of the total net increase in spoil and canal area for the same period. The direct impacts of OCS construction are therefore a small percentage of the total direct impacts, but may represent a change of local importance or encompass a significant total area.

The indirect impacts of OCS pipelines, facilities, and navigation channels are more difficult to assess, but it is possible to establish ranges of impacts in relation to the total net change in wetlands. The amount of indirect changes caused by facilities is relatively unimportant because of the relatively small direct impact (38.5 ha). The indirect impacts by pipeline canals and navigation channels on wetland losses are considered the more important issues.

Navigation channels, especially OCS channels, are normally deeper, straighter, and wider than natural channels and encourage more frequent and severe saltwater intrusion events. We could not quantify the impact of increased salinity intrusion on wetland loss, even though it is thought to be locally significant in some cases. Consequently, we could not demonstrate whether navigation channels have a major indirect impact on wetlands on a coastwide basis.

Significant indirect impact can be attributed to the impacts of spoil bank levee and canal area. The rationale and mechanism for these indirect impacts are generally related to the hydrologic changes resulting from the spoil bank. We can pro-rate the indirect impacts of OCS spoil banks based on the minimum total indirect impacts of spoil bank levees of all kinds and the relevant percentage of OCS-related spoil bank levees. The OCS and non-OCS channels, canals, and spoil banks are not necessarily equal, however. For example, we know that their depth-to-width relationships, alignment, density, and uses are not exactly the same. Further, because of mapping scale issues, OCS pipeline canals and spoil bank levees may be more accurately mapped than the non-OCS equivalents and therefore be relatively over-represented. The numbers are estimated based on the best available data.

Correlative models of wetland loss and spatial analyses of land loss resulted in a consensus loss range of 20 to 60% for indirect impacts associated with all spoil banks and canals. We recognize that other geological and biological factors may contribute to these losses. We used spoil bank and canal area as a surrogate for indirect impacts and pro-rated their influence among OCS and non-OCS pipeline and navigation channels. Indirect impacts were assumed to be equal to the net change in wetlands from 1955/6 to 1978 minus net changes in that interval caused by (1) agricultural and urban development and (2) spoil and canal construction. Indirect impacts from OCS activities were thus estimated to be 4 to 13% of all indirect impacts. These numbers are necessarily based on interpretation of limited data and correlation, as opposed to cause-and-effect experimentation, and should therefore be used with caution to indicate only the relative magnitude of possible indirect impacts, and only on a regional, not local, basis.

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