# Natural Factors and Human Modifications Contributing to Marsh Loss in Louisiana's Mississippi River Deltaic Plain

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ABSTRACT / Natural factors and human modifications contribute to the estimated annual loss of 10,200 ha of coastal land in the Mississippi River Deltaic Plain Region of south Louisiana. This paper combines information on regional geology and human-induced habitat alterations to evaluate the relative importance of human and natural factors to marsh loss. Data on marsh area and habitat type for 139 7.5-min quadrangles were calculated from maps based on aerial photographs from 1955/56 and 1978, and data on regional geology obtained from published maps were used to construct multivariate model relating initial marsh area, change in urban and agricultural area, change in canal and spoil area, canal area in 1978, depth of sediment overlying the Prairie terrace, and subdelta age to marsh loss. The model indicated that between 25.0% and 39.0% of the marsh loss that occurred during the 23-year period was related to canal and spoil construction, and between 9.5% and 12.7% was related to urban and agricultural development. These are minimal estimates of loss because they do not include many secondary effects (for example, canal orientation, saltwater intrusion, and eutrophication) that can also result in indirect loss. Depth of sediment, initial marsh area, delta lobe age by 1978 canal and spoil area interaction, and indirect effects not included in the model accounted for remaining marsh loss.

The disappearance of coastal marshes in the Mississippi River Delta region of Louisiana is a chronic state problem. Causes for the marsh loss are complex but can be divided into two general categories: (a) the natural geologic process of delta decay, and (b) human modifications in the coastal zone. Wise management and impact mitigation depend on an understanding of the relationship between marsh loss and human activity. Unfortunately, conclusive data detailing the role of wetland modification in marsh deterioration are scarce. Answers to questions about how much of the wetland loss is caused by human activity, what alterations have the most severe effects, and how much wetland loss is the inevitable result of natural geologic processes are essential to coastal managers in devising management guidelines and setting regulatory priorities.

Previous studies (Gagliano 1973, Craig and others 1979, Scaife and others 1983) have examined the effects of human alterations to marshes but have not incorporated the effects of geologic processes. This paper presents a statistical model relating marsh loss to geologic factors and human alterations in marshes. The results of the model form the basis of recommendations for management of the state's coastal marshes.

## The Setting

Approximately 80% of the land in Louisiana's coastal region has been formed during the last several thousand years by sediments deposited in deltaic formations of the Mississippi River (Frazier 1967). The landscape consists of narrow ridges of high ground several feet above sea level located along abandoned river distributaries, between which lie vast expanses of low-lying fresh and saline marsh (Chabreck 1972). These wetlands comprise more than 40% of the coastal wetlands in the conterminous United States and more than 65% of the marshes surrounding the US Gulf of Mexico (Turner and Gosselink 1975). The wetland region is rich in renewable natural resources. Louisiana supports the nation's largest commercial fishery with landings of more than 1.2 billion pounds in 1981 (US Department of Commerce 1982) and leads the USA in fur harvest (Chabreck 1979). Louisiana's coastal marshes are widely used for recreation. Hunting and recreational fishing contribute $235 million annually to the economy of the state known as the "Sportsman's Paradise" (US Department of the Interior, US Department of Commerce 1982). In addition, marshes serve as important habitat for wildlife and buffer populated inland areas from floods and coastal storms.

Coastal Louisiana is also rich in oil and gas resources. In 1980, Louisiana ranked third in crude oil and first in natural gas production in the United States (American Petroleum Institute 1981). About 75% of the oil and gas is produced in the coastal parishes (Maruggi and Hartl 1981). Oil and gas activities in marshes consist primarily of canal dredging for pipeline construction and access to drilling sites. Construction of major navigation channels has also taken place. Dredging of oil and gas canals currently represents significant development pressure on Louisiana's wetlands. Of the approximately 2000 permit applications for alterations to wetlands received in

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1981 by the state's Coastal Management Section, 75% were oil and gas related (Louisiana Department of Natural Resources 1982). Development of oil and gas resources in Louisiana has also spurred urban development in the coastal zone.

### The Problem

Louisiana is estimated to be currently losing 10,200 hectares (ha) of coastal land annually (Gagliano and others 1981). The loss rate is high compared to other US regions (Gosselink and Baumann 1980) and may be rising exponentially (Gagliano and others 1981). Most of this land loss is wetlands. Of the 201 7.5-min US Geological Survey (USGS) quadrangles in the Mississippi River Deltaic Plain Region that have wetlands, 94% have lost wetlands since 1955. The high rate and broad extent of wetland loss pose a threat to the natural resources, lifestyle, and economy of the state. Louisiana's commercial fishery, worth more than $194 million in 1981 (US Department of Commerce 1982), depends to a large extent on marsh- and estuarine-dependent species. In addition to renewable resource losses, state revenues from oil and gas leases decrease as wetlands are lost, the coastline changes, and state lands convert to federal ownership. Nunez and Sour (1981) estimated that the state could lose approximately $20 million annually—at 1981 oil and gas production and price levels—if the state boundary were moved inland uniformly by 0.8 km.

## Factors Contributing to Wetland Loss

The areal extent of Mississippi River deltaic systems is controlled by the relative balance of land building and land loss. Land building is the result of riverine sediment input. Natural land loss is caused by subsidence resulting from regional downwarping and sediment compaction, submergence caused by actual sea-level rise, and erosion (Morgan 1963, Morgan 1977). Although geosynclinal downwarping and actual sea-level rise may be important when contemplating geologic time spans, they are overshadowed by subsidence caused by compaction and erosion during shorter time periods (Morgan 1967). Sediment compaction and erosion rates of deltaic deposits depend on the age of the underlying delta lobe (Morgan 1963), location within the delta lobe, the amount and type of sediment input (Morgan 1963), and the depth of recent and late Quaternary sediments overlying the downwarped Prairie (Pleistocene) terrace (Kolb and Van Lopik 1958). In general, sediment compaction in Louisiana's coastal area declines as the distance from the coast increases (Kolb and Van Lopik 1958). Sediment input counteracts sediment compaction and erosion, and contributes to subaerial delta growth that forms the base for marsh vegetation. Sediment input to marshes is achieved through overbank flooding of bays, rivers, and bayous. Rates of marsh loss may also be related to the area of marsh in a given location because larger expanses of marsh may be more stable and less susceptible to erosion than smaller areas.

Human modifications in Louisiana's coastal wetlands include draining and filling for urban or agricultural expansion, impoundments and levee building for flood control, canal dredging, and spoil-bank construction. Filling or draining marshes, construction of levees along rivers and bayous, and the dredging of canals and deposition of spoil in marshes are the most common practices that result in premature or accelerated marsh loss (Craig and others 1979, Scaife and others in press). Canals directly convert marsh to open water. Canals also alter marsh hydrology, increase saltwater intrusion leading to damage of marsh vegetation, and increase local erosion (Stone and others 1978, Stone and McHugh 1979, Gagliano and others 1981). Spoil banks and levees contribute to marsh loss by covering vegetation and raising land elevation, making it unsuitable habitat for wetland vegetation. They also alter hydrology by blocking overland flow of water and reduce sediment input to marshes (Craig and others 1979). An estimated 2.5 ha of spoil bank are created for every hectare of canal dredged (Craig and others 1979).

## Methods

The data for the study were obtained from a detailed inventory of habitats prepared for the US Fish and Wildlife Service (Wicker and others 1980). Data consisted of habitat areas for 7.5-min USGS quadrangles of the Mississippi Deltaic Plain Region. The approximately 200 habitat types (Cowardin and others 1979) identified were aggregated into 20 broad categories (Costanza and others 1983). Habitat areas for each quadrangle were planimetered by Wicker and others (1980) from maps constructed from interpretation of aerial photographs. Maps were constructed for 1955/56 and 1978 enabling calculation of habitat area changes during the 23-year period.

Analysis was restricted to quadrangles that met the following criteria: (a) it was not in an active delta region [a delta region was considered active if major sediment deposition occurred within the last 100 years (Wells and others 1982)], (b) it had a total marsh area greater than 405 ha, and (c) total map area measured in 1955/56 was within 80 ha of total map area in 1978. Criterion a was used to limit the analysis to areas not undergoing extreme changes caused by rapid sedimentation. Criteria b and c were used to eliminate differences caused by errors in area measurements. The final sample set consisted of 139 7.5-min quadrangles and covered approximately 85% of the marsh area in Louisiana's Mississippi Deltaic Plain.

Marsh loss was conceptualized as related to a combination

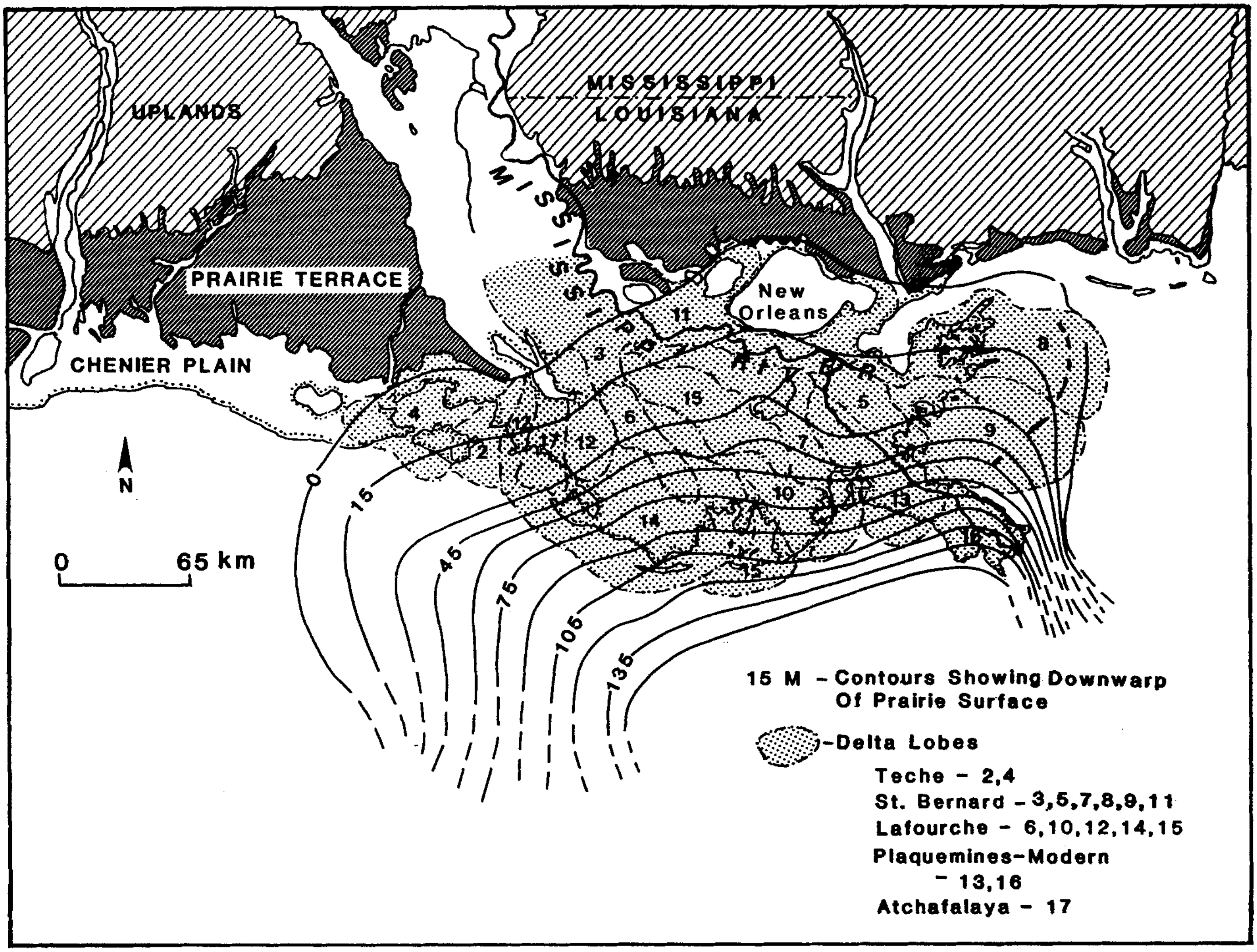

**Figure 1.** The Mississippi River Deltaic Plain Region of Louisiana. *Contour lines* indicate depth to Prairie terrace, and *numbers* indicate subdelta lobes and the associated major deltaic depositional events. Numbers and mean ages of subdelta lobes are (Frazier 1967): *2*—4539 years; *3*—4625 years; *4*—4070 years; *5*—3819 years; *6*—2800 years; *7*—2909 years; *8*—2732 years; *9*—2151 years; *10*—1441 years; *11*—1334 years; *12*—1468 years; *13*—665 years; *14*—658 years; *15*—200 years; *16*—100 years; and *17*—25 years. Subdelta lobe 1 does not have surface expression.

of natural factors (sediment input, compaction and erosion, and initial marsh area) and human factors (canal dredging and urban and agricultural development). The variables used to represent each of these factors are described below. Marsh loss was defined as the difference in total marsh area between 1955/56 and 1978. A positive number denotes loss of marsh area. Initial marsh area was defined as the total marsh area in each 1955/56 quadrangle. Change in developed area was defined as the difference in urban and agricultural area between 1978 and 1955/56. A positive number denotes gain of area. Three measures of the area of canals and spoil were included for each quadrangle: (a) canal and spoil area in 1955/56, indicating preexisting canals and spoil; (b) canal and spoil area in 1978, indicating final canal and spoil area; and (c) change in canal and spoil area between 1978 and 1955/56. To assess sediment compaction and erosion, each quadrangle was assigned an age, depth, and distance value (Figure 1). Age corresponds to the approximate number of years before present that the subdelta lobe which forms the marsh base was deposited (Frazier 1967). Depth is the depth in meters of deltaic sediment overlying the Prairie terrace (Fisk and McFarlan 1955). Distance is defined as the distance in meters

Table 1. Regression statistics for model relating marsh loss to human and natural factors (see text for variable descriptions).

| Source | Degrees of freedom | Sum of squares | $F$ value ($P > F$) | $r^2$ |
|---|---|---|---|---|
| Model | 5 | 162901371 | 70.09<br>(0.0001) | 0.72 |
| Error | 134 | 62290629 | — | — |
| Total | 139 | 225191999 | — | — |

| Source | Degrees of freedom | Type II Sum of squares | $F$ value ($P > F$) | Estimate of coefficient (SE) |
|---|---|---|---|---|
| Intercept | — | — | — | −182.7350<br>(123.8258) |
| IMARSH | 1 | 42575720 | 91.59<br>(0.0001) | 0.1472<br>(0.0154) |
| DDEVELOP | 1 | 22819560 | 49.09<br>(0.0001) | 0.6930<br>(0.0989) |
| AGE*CANAL78 | 1 | 12189174 | 26.22<br>(0.0001) | −0.0004<br>(0.0001) |
| DCANAL | 1 | 9970659 | 21.45<br>(0.0001) | 1.4620<br>(0.3157) |
| DEPTH | 1 | 4387388 | 9.44<br>(0.0026) | 6.4343<br>(2.0944) |

from the center of each quadrangle to the Louisiana coastline on 1974 USGS 1:250,000 maps. Estimates of subdelta lob age and depth to the Prairie terrace are not precise because the geology, while well known in a general sense (Kolb and Van Lopik 1958 and 1966), has never been specifically measured for each quadrangle. In addition, the region was actually formed by a series of overlapping deltaic lobes stacked on top of one another. The age of the last subdelta lobe laid down was used. Data on sedimentation rates were not available for most of coastal Louisiana; therefore, the area of natural rivers and bayous in 1978 was used as an indicator of sediment input. It was assumed that rivers and bayous represent conduits for sediment input and that sediment input is higher in quadrangles with higher river and bayou areas.

Marsh loss was modeled as a function of change in area developed for urban and agriculture, change in canal and spoil area, canal and spoil area in 1955, canal and spoil area in 1978, river and bayou area in 1978, age, depth, and distance from the coast. Stepwise regression analysis was used to determine whether any of the above variables, alone or through interaction, had a significant effect on marsh loss (SAS Institute Inc. 1982). The change in $F$-test value, used to determine predictive variable entry into the model, was set at 0.15. The Cp statistic was used in selection of the final regression model (Daniel and Wood 1980). Pearson product moment correlations were used to test for interdependence of the predictive variables.

To determine what portion of the marsh lost was converted into open water, a second regression equation was developed relating marsh loss to change in open-water area. Change in open-water area was defined as the difference in open-water area, including canals, between 1978 and 1955/56. One quadrangle (160D) was eliminated from this analysis because examination of the maps indicated most of the open-water gain was from conversion of swamp forest. Simple linear regression was used to determine the relationship (SAS Institute Inc. 1982).

## Results and Discussion

Stepwise regression analysis indicated that marsh loss is linearly related to initial marsh area, change in developed area, change in canal and spoil area, depth to Prairie terrace, and an interaction between subdelta lobe age and canal and spoil area in 1978 (Table 1). The model developed was:

$$\begin{aligned}\text{MARSHLOSS} = {} & -182.7350 + 0.1472*\text{IMARSH} \\ & + 0.6930*\text{DDEVELOP} \\ & + 1.4620*\text{DCANAL} \\ & + 6.4343*\text{DEPTH} \\ & - 0.0004*(\text{AGE}*\text{CANAL78})\end{aligned} \tag{1}$$

where, MARSHLOSS = loss of marsh area (ha), IMARSH = 1955/56 marsh area (ha), DDEVELOP = change in urban and agricultural area (ha), DCANAL = change in canal and spoil area (ha), DEPTH = depth of sediment overlying Prairie terrace (m), AGE*CANAL78 = age of subdelta lobe by 1978 canal and spoil area interaction (yr*ha).

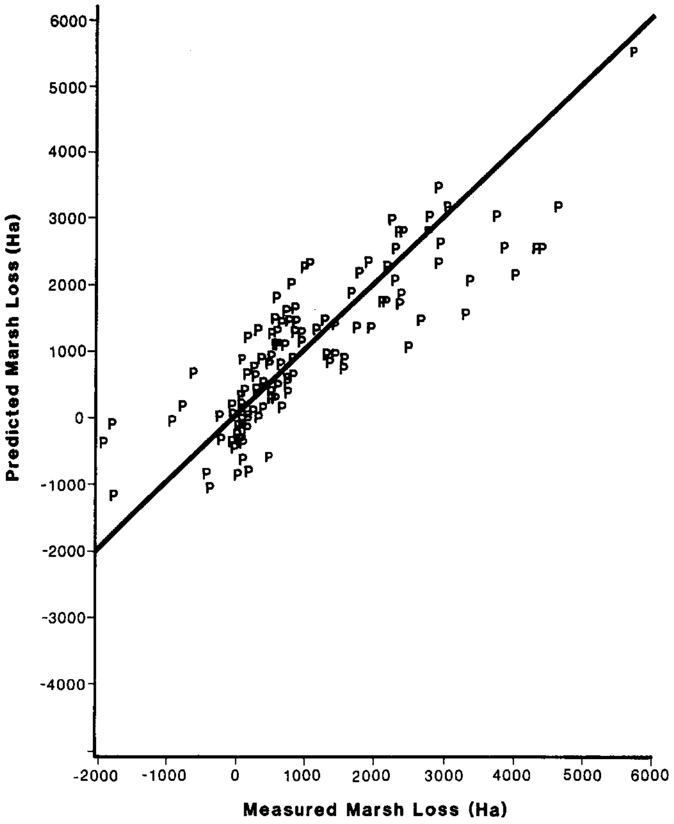

**Figure 2.** Marsh loss predicted from equation 1 (*P*) plotted against measured marsh loss. A perfect estimate of marsh loss is represented by the *straight line*. Regression statistics for equation 1 are presented in Table 1.

The relationship of marsh loss to the predictive variables was significant ($r^2 = 0.72$, $p < 0.0001$) (Table 1). Pearson product moment correlation tests showed all predictive variables were independent. The precision of the model is shown in Figure 2, which is marsh loss predicted (*P*) from equation 1 plotted against measured marsh loss.

Initial marsh area was the variable that explained the greatest amount of marsh loss. Quadrangles with high initial marsh area generally exhibited greater total marsh loss than did quadrangles with lower initial marsh area. Residual analysis showed that the model consistently overestimated marsh loss in quadrangles with high initial marsh area and underestimated marsh loss in quadrangles with low initial marsh area. This suggests that large expanses of marsh may have greater stability, be more resistant to erosion, and experience less marsh loss per unit of initial marsh area. As marshes become more patchy and decrease in area, they become more likely to experience greater relative loss rates. This also suggests that as canals and spoil banks break marshes into smaller pieces marsh loss per unit of initial marsh area tends to increase.

Change in developed area was an important variable for predicting marsh loss. The regression coefficient for DDEVELOP shows that 69% of the increase in urban and agricultural area that occurred in the study area occurred in marshes. Historically, urban and agricultural development in the Louisiana coastal zone has taken place on upland levee ridges, but recent development has occurred in adjacent marshes because most of the suitable high ground has already been developed.

Change in canal and spoil area is also an important variable in predicting marsh loss. The regression coefficient for DCANAL indicates that 1.46 ha of marsh loss can be expected from an increase of 1 ha of canal and spoil area. This supports the hypothesis (Stone and others 1978, Craig and others 1979) that canals cause greater marsh loss than results solely from the direct conversion of marsh to open water. Change in canal area alone (without spoil) was not as good a predictor of marsh loss as canal and spoil area.

The amount of deltaic sediment overlying the downwarped Prairie terrace is the most important sediment compaction factor affecting marsh loss. Marsh loss tends to be higher in quadrangles with greater sediment depth. This agrees with Fisk and McFarlan (1955), who suggested that subsidence is more pronounced as depth of deltaic sediment increases. The analysis indicates no significant relationship between distance from coast and marsh loss. The empirical relationship between distance from coast and sediment compaction found by Kolb and Van Lopik (1958) and distance from coast and land loss found by Scaife and others (1983) may be due to the effect of depth of sediment overlying the Prairie terrace.

Final canal area by age of subdelta lobe interaction is an important variable in predicting marsh loss. For a given final canal and spoil area, the effect of canal and spoil area decreases as the age of the subdelta lobe increases, indicating that canals do not influence marsh loss in areas of older sediments as readily as in areas of younger sediments. Scaife and others (1983) reported a similar result.

The area of natural rivers and bayous showed no significant relationship to marsh loss. This could be because the area of rivers and bayous is not an adequate indicator of local sediment input. Baumann (1980) found that sediment resuspended from bay bottoms was the principal source of mineral matter deposited on salt marshes in a Louisiana deltaic plain interdistributary basin. Annual sediment accretion on creekbank marshes was greater than annual subsidence, but inland marshes experienced annual sedimentation less than subsidence, resulting in an "aggradation deficit" (Baumann 1980). Baumann (1980) projected that this deficit was a mechanism resulting in marsh loss and could account for approximately

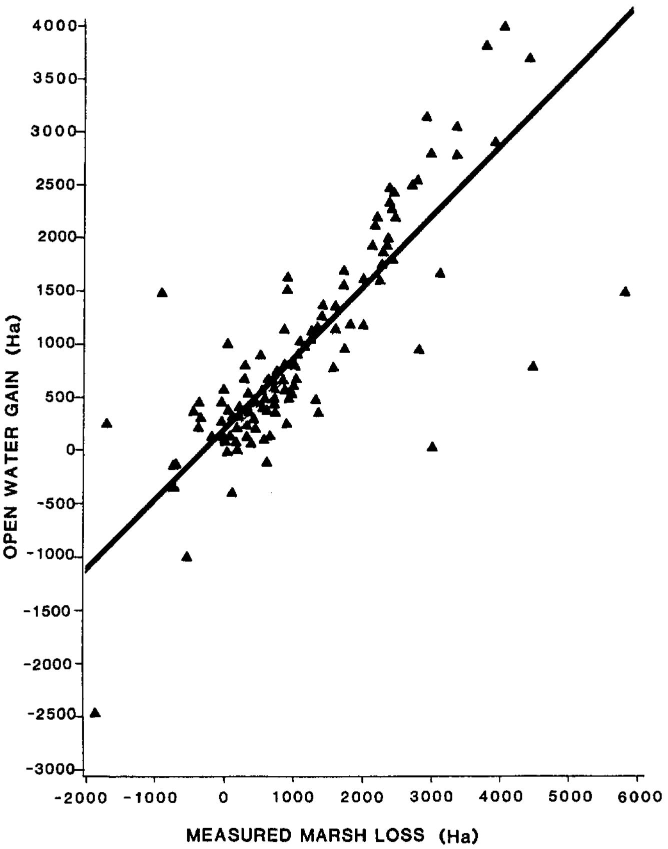

**Figure 3.** Open-water-area gain plotted against measured marsh loss. Statistics for the regression line are presented in Table 2.

half of the reported wetland loss rates in Barataria Basin. We believe that coastwide information on sediment input to marshes will substantially increase our understanding of the factors influencing natural marsh loss, and if such data become available it will be important to investigate their relationship to marsh loss.

The second regression analysis indicates that increase in open-water area is significantly related to marsh loss (Figure 3). The model developed was:

$$\text{DWATER} = 188.1137 + 0.6567^{*}\text{MARSHLOSS} \quad (2)$$

where, DWATER = change in open-water area (ha), and MARSHLOSS = change in marsh area (ha). The regression coefficient indicates that approximately 66% of the marsh lost was converted into open water (Table 2).

## Management Implications

Coastal marsh is a valuable natural resource and reducing marsh loss is a goal of Louisiana coastal management. Marshes in the study area changed to open water, canal and spoil, and upland (filled marsh) habitats, but most converted to open water (Figure 3). The amount of marsh converted into open water can be estimated by multiplying the marsh lost over the 23-year period (132,270 ha) by the regression coefficient for MARSHLOSS plus or minus one standard error (0.66 ± 0.04). This calculation indicates between 82,007 and 92,589 ha of marsh, representing between 62.0 and 70.0% of the marsh lost, have been converted to open water. Marsh productivity is important in supporting the trophic structure of Louisiana's estuaries (Darnell 1961, Happ and others 1977, Day and others 1982). Shallow marsh ponds can be valuable habitat for waterfowl, fish, and shrimp, but canals and the open-water areas resulting from erosion are less productive than vegetated marsh and natural marsh ponds (Allen 1975, Adkins and Bowman 1976, Hopkinson and others 1978).

A significant portion of the marsh loss that has occurred has been caused by human activity (Table 3). Direct conversion of marsh to canal and spoil bank in the study area (28,991 ha) accounted for 21.9% of the marsh loss. If the interactive effect of age by final canal area is ignored, the upper and lower bounds on the amount of marsh loss related to change in canal and spoil area, including direct and indirect conversion, can be estimated by multiplying the regression coefficient for DCANAL plus or minus one standard error (1.46 ± 0.32) by the total change in canal and spoil area. This calculation indicates that between 33,050 and 51,604 ha of the marsh loss, or between 25% and 39%, was related to canals. Marsh loss caused by the indirect effects of canals and spoil is the difference between total and direct effect, and represents between 12.2% and 43.8% of the total loss related to canals. Similar calculations using the change in developed area (21,265 ha) indicate that between 12,546 and 16,799 ha of marsh have been lost due to increases in urban and agricultural area. This represents between 9.5% and 12.7% of total marsh loss.

Gagliano (1973) reported that direct conversion of land to water by canal dredging from 1936 to 1959 accounted for 39% of the land lost. Craig and others (1979) concluded that 69% of total wetland loss during the same period could be attributed to canal dredging if the area disturbed by spoil bank construction was also included. Change in canal area as a percentage of total marsh loss measured in this study for the 1955–1978 time period (21.9% of total marsh loss) was lower than was measured in the earlier study. This resulted from both a smaller measured area converted to canals and spoil, and a greater total marsh area lost during the 1955–1978 time period. In another study based on the same 1955–1978 data, Scaife and others (1983) reported that 10% of marsh loss was due to direct conversion of marsh to canals. The 21.9% of total

Table 2. Regression statistics for model relating increase in open-water area (including canals) to marsh loss (see text for variable descriptions).

| Source | Degrees of freedom | Sum of squares | $F$ value ($P > F$) | $r^2$ |
|---|---|---|---|---|
| Model | 1 | 93872569 | 309.47 | 0.69 |
| | | | (0.0001) | |
| Error | 137 | 41557214 | — | — |
| Total | 138 | 135429783 | — | — |

| Source | Degrees of freedom | Type II Sum of squares | $F$ value ($P > F$) | Estimate of coefficient (SE) |
|---|---|---|---|---|
| Intercept | | — | — | 188.1137 |
| | | | | (58.9786) |
| MARSHLOSS | 1 | 93872569 | 309.47 | 0.6567 |
| | — | — | (0.0001) | (0.0373) |

Table 3. Estimated percent and area of measured marsh loss related to canal and spoil, and development effects.

| | Percent of measured total marsh loss | | Area (ha) | |
|---|---|---|---|---|
| | Mean | Range | Mean | Range |
| Canal and spoil (direct)[a] | 21.9 | | 28,991 | |
| (indirect)[b] | 10.1 | 3.1–17.1 | 13,336 | 4,059–22,613 |
| (subtotal) | 32.0 | 25.0–39.0 | 42,327 | 33,050–51,604 |
| Development | 11.2 | 9.5–12.7 | 14,673 | 12,546–16,799 |
| Total | 43.2 | 34.5–51.7 | 57,000 | 45,596–68,403 |

[a] This is a single value based on direct measurements of canal and spoil area and has no range value.

[b] This is a minimum estimate of the indirect effects of canal and spoil because it does not include secondary indirect effects (see *Model Limitations*).

marsh loss that is the direct effect of canal dredging reported here includes conversion to spoil, indicating that the marsh area affected by canals and spoil is roughly twice that of the area of new canals alone.

In addressing the indirect effects of canals, Gagliano (1973) stated that land loss associated with canals but not caused by direct conversion can appear as "natural" loss, but indirect human-induced losses were not distinguished from truly non-human-induced land area changes. The results of this study indicate that between 3.1% and 17.1% of total marsh loss in the study area was attributable to the indirect effects of the increase in canal and spoil area. This estimate of indirect effects does not include other indirect effects of canals (see *Model Limitations*) and is probably lower than actual indirect marsh loss caused by canals. It is felt, however, that the indirect effects of canals are lower than stated by Scaife and others (1983). Scaife and others (1983) estimated that 89% of total land loss was attributable to canals, only 10% of which was due to direct conversion. Our results indicate that some of the land loss attributed by Scaife and others (1983) to indirect effects of canals actually resulted from agricultural and urban development and natural geologic factors.

The effects of the geologic factors of subdelta lobe age and sediment depth cannot be influenced to any appreciable extent by coastal managers. Marsh loss resulting from these factors will occur regardless of human actions. However, the effects of increases in developed and canal and spoil area on marsh loss can be controlled through the coastal use permitting process. Permit guidelines restricting urban and agricultural development in marshes will reduce marsh loss. Minimizing the area of new canals and spoil will decrease both direct and indirect human-induced marsh loss. Reduction of new canal and spoil area can be achieved by dredging canals in open water, drilling new oil and gas wells at a directional angle from existing canals or open water bodies, building board roads in place of canals, or using hovercraft. The model also shows that an equal change in area of canal and spoil will cause greater marsh loss in areas of young sediment than in areas of older sediments. This suggests that restricting increases in canal and spoil area in areas of younger sediments will be more effective in minimizing indirect marsh loss related to canals than the same limitations in areas of older sediments.

Different approaches have been used to assess the effects of canals on marsh loss (Gagliano 1973, Craig and others 1979, Scaife and others 1983, this study). All have concluded: (a) the direct and indirect effects of canal dredging in marshes account for a significant portion of marsh lost, (b) the effects of canals differ depending on canal location, (c) many of the detrimental effects of canals can be controlled through stricter permit guidelines on new canal construction, and (d) the indirect effects of canals on marsh loss can be almost as great or greater than the direct effects. The magnitude of canal impacts points to the need for field experiments to examine the mechanisms by which canals lead to indirect marsh loss.

### Model Limitations

Marsh loss in the coastal zone is controlled by a complex interaction of human and geologic factors. It is not surprising that this analysis, which treats all development and canals and spoil as if their only effects were due to surface area, accounts for only 72% of the variation in marsh loss. Other studies have shown that canals and spoil have secondary effects that vary with factors such as the dimensions of canals (Stone and McHugh 1979), the salinity of the water bodies they connect (Craig and others 1979), and their orientation relative to the direction of overland flow (Stone and McHugh 1979). Urban and agricultural areas also have secondary effects on wetlands including changing runoff patterns and water quality (Hopkinson and Day 1980a and b). The natural geologic effect of the aggradation deficit on inland marshes (Baumann 1980) could not be included in the model. Because the data set used for this analysis is oriented around quadrangles instead of ecologically, hydrologically, or geologically defined units, a portion of the marsh loss in one quadrangle may actually be caused by effects of development or canal construction in adjacent quadrangles. Differences in factors causing marsh loss in different salinity zones could not be addressed because marsh area by salinity type was not delineated on the 1955/56 maps. All marsh types were aggregated as total marsh.

## Conclusions

The natural geologic factors of marsh area, subdelta lobe age, and depth of sediment overlying the Prairie terrace and the human activities of urban and agricultural development, and canal and spoil bank construction are significantly related to marsh loss in Louisiana's Mississippi River Deltaic Plain. The human activities of urban and agricultural development and canal dredging result in direct marsh loss. Canals also interact with geologic factors to cause additional marsh loss. Information on the relationship between human activities and marsh loss gained from the model can be used to develop management strategies to reduce future marsh loss.

The model presented here specifically addresses the problem of management of the Louisiana coastal zone. However, the approach of combining data from aerial photographs with other local information to construct models to aid in developing regional management strategies has potential application to other locations.

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## Literature Cited

Adkins, G., and P. Bowman. 1976. A study of the fauna of dredged canals of coastal Louisiana. *La. Wildl. Fish. Comm. Tech. Bull.* 18. 72 pp.

Allen, R. L. 1975. Aquatic primary productivity in various marsh environments in Louisiana. MS thesis, Louisiana State University, Baton Rouge, 50 pp.

American Petroleum Institute. 1981. Basic petroleum data book, vol. 1, no. 3. Washington, DC.

Baumann, R. H. 1980. Mechanisms of maintaining marsh elevation in a subsiding environment. MS thesis, Louisiana State University, Baton Rouge. 91 pp.

Chabreck, R. H. 1972. Vegetation, water, and soil characteristics of the Louisiana coastal region. *La. Agr. Exp. Sta. Bull.* 664.

Chabreck, R. H. 1979. Wildlife harvest in wetlands of the United States. Pages 618–631 *in* P. E. Greeson, J. R. Clark, and J. E. Clark (eds.), Wetland functions and values: the state of our understanding. American Water Resources Association, Minneapolis.

Costanza, R., C. Neill, S. G. Leibowitz, J. R. Fruci, L. M. Bahr, Jr., and J. W. Day, Jr. 1983. Ecological models of the Mississippi Deltaic Plain Region: data collection and presentation. US Fish and Wildlife Service, Office of Biological Services, Washington, DC. FWS/OBS-82/68. 342 pp.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United

States. US Fish and Wildlife Service, Office of Biological Services. FWS/OBS-79/31. 103 pp.

Craig, N. J., R. E. Turner, and J. W. Day, Jr. 1979. Land loss in coastal Louisiana (U.S.A.). *Environ. Manage.* 3:133–144.

Daniel, C., and F. S. Wood. 1980. Fitting equations to data, 2nd edn. John Wiley and Sons, New York.

Darnell, R. M. 1961. Trophic spectrum of an estuarine community based on studies of Lake Pontchartrain, Louisiana. *Ecology* 42:553–568.

Day, J. W., Jr., C. S. Hopkinson, and W. H. Conner. 1982. An analysis of environmental factors regulating community metabolism and fisheries production in a Louisiana estuary. Pages 121–136 *in* V. S. Kennedy (ed.), Estuarine comparisons. Academic Press, New York.

Fisk, H. N., and E. McFarlan, Jr. 1955. Late Quarternary deltaic deposits of the Mississippi River. Pages 279–302 *in* A. Poldervaart (ed.), Crust of the earth. Geological Society of America, special paper 62.

Frazier, D. E. 1967. Recent deltaic deposits of the Mississippi River: their development and chronology. *Trans. Gulf Coast Assoc. Geol. Soc.* 17:287–315.

Gagliano, S. M. 1973. Canals, dredging, and land reclamation in the Louisiana coastal zone. Hydrologic and Geologic Studies of Coastal Louisiana. Report no. 14. Center for Wetland Resources, Louisiana State University, Baton Rouge, 104 pp.

Gagliano, S. M., K. J. Meyer-Arendt, and K. M. Wicker. 1981. Land loss in the Mississippi River Deltaic Plain. *Trans. Gulf Coast Assoc. Geol. Soc.* 31:295–300.

Gosselink, J. G., and R. H. Baumann. 1980. Wetland inventories: wetland loss along the United States coast. *Z. Geomorphol. N. F. (Suppl.)* 34:173–187.

Happ, G., J. G. Gosselink, and J. W. Day, Jr. 1977. The seasonal distribution of organic carbon in a Louisiana estuary. *Est. Coastal Mar. Sci.* 5:695–705.

Hopkinson, C. S., and J. W. Day, Jr. 1980a. Modeling the relationship between development and storm water and nutrient runoff. *Environ. Manage.* 4:315–324.

———. 1980b. Modeling hydrology and eutrophication in a Louisiana swamp forest ecosystem. *Environ. Manage.* 4:325–335.

Hopkinson, C. S., J. G. Gosselink, and R. T. Parrondo. 1978. Aboveground production of seven marsh plant species in coastal Louisiana. *Ecology* 59:760–769.

Kolb, C. R., and J. R. Van Lopik. 1958. Geology of the Mississippi River Deltaic Plain, Southeastern Louisiana. US Army Engineer Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, MS. Technical report no. 3-483, vol. 1.

———. 1966. Depositional environments of the Mississippi River Deltaic Plain: Southeastern Louisiana. Pages 17–61 *in* M. L. Shirley (ed.), Deltas in their geologic framework. Houston Geological Society, Houston.

Louisiana Department of Natural Resources. 1982. Côte de la Louisiane. January 1982. Coastal Resources Program, Louisiana D.N.R., Baton Rouge.

Maruggi, V., and S. D. Hartl (eds.). 1981. Statistical abstract of Louisiana. University of New Orleans, Division of Business and Economic Research and the Louisiana State Planning Office, New Orleans.

Morgan, D. J. 1977. The Mississippi River Delta: legal-geomorphologic evaluation of historic shoreline changes. *In* Geoscience and Man, vol. 16. School of Geoscience, Louisiana State University, Baton Rouge.

Morgan, J. P. 1963. Louisiana's changing shoreline. United States Gulf Coastal Studies technical report 16, part D. Coastal Studies Institute, Louisiana State University, Baton Rouge. Contribution no. 63-5. 13 pp.

———. 1967. Ephemeral estuaries of the deltaic environment. Pages 115–120 *in* G. H. Lauff (ed.), Estuaries. Publ. no. 83. American Association for the Advancement of Science. 757 pp.

Nunez, S. B., Jr., and A. Sour. 1981. Report on special projects for coastal Louisiana to the Legislature and the Governor from the Senate Committee on Natural Resources and the House Committee on Natural Resources.

SAS Institute Inc. 1982. SAS user's guide: statistics, 1982 edition. SAS Institute Inc., Cary, NC. 584 pp.

Scaife, W., R. E. Turner, and R. Costanza. 1983. Recent land loss and canal impacts on coastal Louisiana. *Environ. Manage.* 7:433–442.

Stone, J. H., L. M. Bahr, Jr., and J. W. Day, Jr. 1978. Effects of canals on freshwater marshes in coastal Louisiana and implications for management. Pages 299–320 *in* R. E. Good, D. F. Whigham, and R. L. Simpson (eds.), Freshwater wetlands: ecological processes and management potential. Academic Press, New York.

Stone, J. H., and G. McHugh. 1979. Hydrologic effects of canals in Louisiana via computer simulation. Pages 339–346 *in* Proceedings of the summer computer simulation conference, Toronto, Canada.

Turner, R. E., and J. G. Gosselink. 1975. A note on standing crops of *Spartina alterniflora* in Texas and Florida. *Contrib. Mar. Sci.* 19:113–118.

US Department of Commerce. 1982. Fisheries of the United States, 1981. US Department of Commerce, NOAA, NMFS. Current Fisheries Statistics no. 8200, Washington, DC.

US Department of the Interior, Fish and Wildlife Service and US Department of Commerce, Bureau of the Census. 1982. 1980 national survey of fishing, hunting, and wildlife related recreation. US Government Printing Office, Washington, DC.

Wells, J. T., S. J. Chinburg, and J. M. Coleman. 1982. Development of the Atchafalaya and Mississippi River Deltas: generic analysis. Prepared for the US Army Engineer Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, MS. Contract DACE 39-80-C-0082. 91 pp.

Wicker, K. M., and others. 1980. Mississippi Deltaic Plain Region habitat mapping study. 464 maps. US Fish and Wildlife Service, Office of Biological Services. FWS/OBS-79/07.