3-1997

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Recommended Citation

Turner, R. (1997). Wetland Loss in the Northern Gulf of Mexico: Multiple Working Hypotheses., 1-13.
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Wetland Loss in the Northern Gulf of Mexico: Multiple Working Hypotheses

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ABSTRACT: I examined four hypotheses about causes for the dramatically high coastal wetland losses ($0.86\% \text{ yr}^{-1}$) in the northern Gulf of Mexico: an extensive dredged canal and spoil bank network, a decline in sediments in the Mississippi River during the 1950s, Mississippi River navigation and flood protection levees, and salinity changes. Natural factors contributing to these habitat changes include eustatic sea-level rise and geological compaction, which appear to have remained relatively constant this century, although variation does occur. These four hypotheses were tested using data on land-to-water changes in 15-min quadrangle maps inventoried for four intervals between the 1930s and 1990. Land loss rates were directly proportional to changes in wetland hydrology in time and space. A linear regression of the direct losses due to dredging versus the losses due to all other factors (indirect losses) had a zero intercept and a slope that increased with time. The ratio indirect:direct land loss was highest nearest the estuarine entrance. The coastwide patterns of land loss do not appear to be affected by riverine sediment reductions over the last 60 yr. The effects of changes in wetland hydrology from dredging human-made channels and forming dredged spoil banks appear to be the most efficacious hypothesis explaining these dramatic losses. The effects of extensive human-induced changes on this coast have apparently overwhelmed the causal linkages identified in the historical re-constructionist view of deltaic gain and loss that emphasizes the role of mineral sediments. A paradigm shift is therefore proposed that emphasizes a broad ecological view as contrasted to a mostly physical view emphasizing the role of sediment supply in wetland maintenance. In this view, plants are not an ancillary consequence of strictly geological dynamics such as sediment supply but are dominant agents controlling factors relevant to coastal restoration and management efforts.

Introduction

The most dramatic coastal wetland losses in the United States are in the northern Gulf of Mexico (Turner 1990), which has 41% of the national inventory of coastal wetlands (Turner and Gosselink 1975) and 80% of the nation's total wetland losses (Dahl 1990). The annual wetland losses were 12,700 ha from 1955 to 1978 ($0.86\% \text{ yr}^{-1}$; Baumann and Turner 1990). At this rate, land equivalent to the area of Rhode Island was converted to open water within 21 yr. The loss rate subsequently declined between 1983 and 1990 (Britsch and Dunbar 1993).

The initial habitat conversions from human activities, or "direct impacts," are well documented and represent about 12% of the total land losses (Britsch and Dunbar 1993; note: on this coast wetland loss and land loss are essentially equal, e.g., Baumann and Turner 1990). The remaining 88% of the losses are the result of other causes. These "indirect impacts" are the secondary or subsequent changes resulting from, for example, reductions in sediment supply or from dredging, from

subsurface fluid withdrawal, or from hydrologic alterations. The ratio of direct:indirect impacts resulting from human activities may vary under influences such as global sea-level rise, climate changes, soil type, geologic setting, or management.

The causes of these indirect coastal wetland losses have rarely been explicitly stated as hypotheses or quantified in the scientific literature. A recent scientific review by coastal experts (Boesch et al. 1994) included dredged canals as a major factor, but management documents give a different view. For example, a report by the Science Advisory Panel to the Governor of Louisiana included canals within a discussion of "marine tidal invasion," one of six categories of causes (Gagliano 1994). This report suggested that a vigorous management program (presently \$147 million from 1992 to 1996; Anonymous 1995a) could achieve a balance of no coastal land loss within 50 yr. A recent Louisiana State Government "White Paper" unequivocally concluded that a decrease in the sediment supply was the one cause of coastal wetland losses: "alterations to the river system, resulting in a long term sediment deficit in a subsiding coast, is the major overall problem" (Anonymous 1995b, p. 4).

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The State of Louisiana has clearly adopted the perspective that landloss is a consequence of sediment starvation and that restoration is therefore dependent on sediment management.

The general absence of clearly stated hypotheses that allow for testing, quantification, and prediction hinders development of clear management choices with known consequences, for example, area conserved and/or restored and resources allocated. I agree with Slobodkin who commented (1988, p. 342) on the role of science in public resource management: "Practical questions of environmental management in the absence of ecology are likely to receive misleading and even dangerous answers."

I tested four hypotheses about the causes of wetland losses along this coast. A central concern is to identify the cause-and-effect relationships leading to land (and wetland) losses to reduce or even reverse the present and past regression through either active or passive management.

The Environmental Setting

The Louisiana coast formed after the Pleistocene as a series of overlapping riverine deltas extended onto the continental shelf. The Mississippi River, now partially captured by the Atchafalaya River, shifted 6 times over the last 6,000 yr seeking the lower hydrologic resistance of a shorter route to the sea (Fisk et al. 1954). This process of individual delta growth and abandonment continued until the position of the modern bird-foot (Balize) delta was reached about 200 yr ago and more than 1 million ha accumulated coastwide.

As the coastline progressed seaward, delta mud was overlain by silts and sands and topped by deltaic sediments, including organic deposits (Fisk et al. 1954). Smaller subdeltas may deposit sediments up to 14 m thick and the entire delta sequence may be 150 m deep. These fine-grained and highly organic sediments undergo consolidation, compaction, and oxidation resulting in subsidence. The highest subsidence rates occur in the upper 2 m of the marsh soils (Turner 1991).

The Chenier Plain, located in western Louisiana,

is a series of sand and shell ridges (shore-parallel to shore-oblique) that are separated by progradational mudflats, wetlands, or open water. It is called a 'Chenier' in reference to the oak trees (*chêne* in French) growing on the stranded beach ridges. Mudflats grow during periods of deltaic abandonment as reworked sediments move westward with littoral drift; subsequent sediment re-sorting builds ridges, which structure waterflow within the estuary between them.

The suspended sediment load from the Mississippi River drainage system declined in the mid-1950s following dam and reservoir construction on major tributaries (Meade and Parker 1984; Kesel 1988). It is not clear how the present suspended sediment load compares to that before Europeans colonized the Mississippi River watershed. Increased habitation and deforestation within the Mississippi River basin probably led to increased suspended sediment concentrations prior to dam constructions, as happened elsewhere. For example, Brush (1984) documented a twofold increase in sediment delivery to coastal systems following deforestation and farming in Chesapeake Bay tributaries. Sediment loading in the 1950s may therefore be an inappropriate baseline measure of long-term (centuries) averages to compare with present sediment loadings.

Reducing the direct introduction of riverine sediment into wetlands (via either natural breaks in the river levee or overbank flooding in the 1930s before flood protection levees on the lower Mississippi River were completed) undoubtedly influenced sedimentation supply rates to the coastal zone. About 3% of the suspended mineral matter presently confined within the Mississippi River levees would be delivered directly to the wetlands through overbank flooding and crevasses (levee breeches) if the levees did not prevent it (Kesel 1988). However, our knowledge of sediment storage in rivers, continental shelves, and coastal wetlands is too incomplete to predict how much less land would be built, or even if there would be a net loss, with such changes in suspended sediment supply.

Fig. 1. Aerial views of Louisiana coastal wetlands. An approximate scale in each is the width of an individual canal (normally 30 m). A. A false-color image of the Big Mar, a former agriculture reclamation site (circa 1915) located to the southeast of New Orleans. B. A former logging site near Lake Maurepas, Louisiana. The star-shape lines in the center by the canal are where cypress logs were dragged out around the beginning of this century. C. A network of canals in the Leeville oilfield at Leeville, Louisiana, located along Bayou Lafourche and near Catfish lake. D. A network of canals and spoil banks. The terminus of each dredged 'keyhole' is a drilling location. E. A dredged canal and spoil bank crossing a natural saltmarsh bayou. The nearby artificial channel is probably a drainage ditch. Note the interruption in natural channel network by the spoil bank. F. Wetlands on the northwest shore of Lake Pontchartrain. Note the drastic vegetation differences on either side of the spoil bank. G. A ground view of a canal and spoil bank built ca. 30 yr ago in a salt marsh near Cocodrie, Louisiana. H. A dredged canal and spoil bank crossing a natural saltmarsh bayou in the Barataria Bay estuary. A natural channel is blocked on the southern side of the dredged channel, and eroded on the northern side.

A

F

B

C

G

D

H

E

Large-scale in situ modification of these coastal wetlands was fully underway in the 1950s when intensive offshore and onshore oil and gas recovery activities were developing. Canal dredging is mostly for oil and gas recovery but also to increase drainage and to assist navigation, trapping, and wildlife management (Fig. 1). Canal dredging creates spoil banks, which are the mounds of residual dredging material placed on either side of the canal, most often in a continuous levee and at much higher levels than the mean high tide level. Spoil banks may last for decades (Monte 1978). Oil and gas production rates peaked about 1973 and have since declined. Consequently, fewer canals have been built in recent years.

Hypotheses About Causal Mechanisms

I tested the following hypotheses about the coastwide causes of land loss on this coast:

H1. *The indirect consequences of dredged canals and the resulting spoil banks have led to the majority of land loss since the 1930s.* This hydrologic change hypothesis is supported by the increased incidence of land loss near canals, reduced accretion rates near or behind spoil banks, hydrologic changes in wetland flooding patterns and decreased natural channel density, plant physiological studies, and, from quantification of direct impacts (Swenson and Turner 1987; Turner 1987; Cahoon and Turner 1989; Turner and Rao 1990).

H2. *A decline in suspended sediments of the Mississippi River during the 1950s led to the majority of the land losses.* H2 is based on the assumption that river-derived sediments built these wetlands over thousands of years of deltaic plain expansion, and are the exclusive component that sustains them. This hypothesis assumes that the decline in suspended sediments of the Mississippi River is not compensated for by other factors such as increased trapping efficiency or increased organic matter deposition, and that the decline is sufficient to cause net land loss, not just a reduction in land building. The movement of riverine-derived suspended sediments from delta passes, along the coast, through tidal passes, and onto the marsh is the primary sediment transport pathway in this hypothesis. H2 also reduces the role of wetland plants in contributing to soil accumulation to either a passive or reactionary role.

H3. *Mississippi River navigation and flood protection levees, mostly built during the 1930s, led to the majority of the land losses.* The assumptions of H3 are similar to those of H2, but also includes concomitant effects of reducing freshwater flow into estuarine headwaters through crevasses and overbank flooding in spring. Changes in the freshwater balance of estuaries affect emergent vegetation, which is

perceived as a stress leading to land loss. Another difference between H2 and H3 is that the suspended sediments in H2 are introduced from the sea, and in H3 at the estuarine headwaters. The assumptions underlying H2 and H3 constitute the rationale for most of the State's restoration plans developed jointly with federal agencies.

H4. *Salt water intrusion from offshore to inland has caused the majority of land losses since the 1930s.* H4 is based, in part, on observed intrusions of salt water at the bottom of dredged navigation channels. H4 makes at least three linked assumptions: coastwide salt water changes occur, these changes are significant plant stressors and lead to vegetation losses, and other emergent plant communities do not successfully recolonize any new niche created.

I did not evaluate the role of subsidence and sea-level rise in explaining the dramatic coastwide land losses of this century. These two factors remained relatively stable this century when the land loss rates rose and fell. Local subsidence caused by oil and gas fluid withdrawal in Louisiana has been estimated to be 2 cm for the entire period of production (Martin and Serdengecti 1984; Suhayda 1987), which is relatively insignificant compared to soil subsidence rates that range between 0.3 cm yr⁻¹ to 1.5 cm yr⁻¹ at one location and the coastal sea-level rise of about 0.23 cm yr⁻¹ (Turner 1991). There are clearly long-term variations in wind, and therefore sea level. However, the trend in water level for the last 80 yr is essentially linear and there is no acceleration in relative sea-level rise at any tide gauge site with a long-term record (Turner 1991). A marsh experiencing a rising sea level or a subsiding land level obviously requires compensatory accretion to remain as land and not be converted to water. The anticipated climate changes resulting from anthropogenic alteration of the earth's atmosphere may cause accelerated sea-level rise rates and cause additional problems if these rates accelerate in the future.

Specific examples can be found to support all four hypotheses for portions of the coast. A quantitative and coastwide scientific analysis of these hypotheses is needed. One appropriate approach is to identify and analyze the spatial patterns of land loss across the entire coastal zone for the period just before, during, and after these land loss rates peaked.

Materials and Methods

Britsch and Dunbar (1993) made five land inventories for coastal Louisiana for the period 1930s to 1990. Their primary data were derived from colored overlays on 15-min base maps (approximately 63 × 10³ ha) whose open water habitat changed between mapping intervals. This data covered a

longer period than most other studies (60 yr) and they used a consistent interpretation method. In contrast to other datasets, the Britsch and Dunbar dataset is based on gross land loss rates rather than net land loss rates. These maps depict only the gross changes from land to water for two reasons. First, land that became open water was colored over on the 1930s era base maps, and any subsequent change to land was not identified because it lay under an existing color. Changes from open water to land were shown only if they could be shown on the 1930s era base map, as in the instance of the emerging Atchafalaya delta. Thus, there was no estimation of the effects of land converted to open water in one interval and that converted back to land in a subsequent interval. It is not possible to measure the restoration of former open water to wetland that resulted from natural or human efforts using their approach. Second, there were routine interpretation errors, common to most change analyses, that led to a liberal estimate of land loss within a mapping interval. If water levels were exceptionally high, or misidentification occurred, then errors were permanently propagated into the next measurement intervals.

The first mapping date was from a series of photographs from the 1930s (range 1931 to 1949; $\mu = 1934$). The second mapping date was for the mid 1950s (range 1951 to 1958; $\mu = 1957$), just after a significant decline in suspended sediment concentrations in the Mississippi River occurred in 1952–1955 (Kesel 1988). The other mapping years were 1974, 1983, and 1990.

Britsch and Dunbar (1993) classified land loss as land that converted to open water and distinguished two categories of land loss. Their category *manmade loss* was a direct consequence of human modification and “the majority . . . is the result of dredging activity associated with drill rig location canals, pipelines, and waterways designed to aid navigation.” *Natural loss* was all other land loss. The manmade loss in the Britsch and Dunbar (1993) analysis is the same as what is called direct land loss in this analysis. Their manmade loss is equivalent to the area classified as dredged waterways in a detailed habitat inventory for 1978 conducted by the United States Fish and Wildlife Service (summarized in Baumann and Turner 1990) if the differences between survey dates and areal coverage are considered.

A map order was assigned to the 15-min base maps to denote their *relative* position inland from the estuarine entrance (Fig. 2). In other words, for each estuary the quadrangle map closest to the estuarine entrance was the lowest numbered map, and the quadrangle map farthest from the sea was numbered the highest.

The density of artificial features and land loss rates for direct and indirect sources were calculated for each mapping interval. I used all data, except that from maps with >85% open water, or <10⁴ ha land surface area within a 15-min quadrangle map. A second degree polynomial fit of all primary (inventory) data was used to describe the cumulative coastwide direct and indirect losses in any one year, and the changes between years. The annual changes in direct losses obtained from this statistical analysis was compared to the amount of permitted dredging in the coastal zone.

The Louisiana Department of Natural Resources, Coastal Management Division (DNR CMD) began keeping records on dredging activity within the coastal zone in 1982. These data are used to determine the amount of direct impacts occurring between 1982 and 1995 (inclusive). There was, therefore, an independently-derived dataset to compare with the results of the statistical model. The estimate of the direct land losses from the polynomial model for 1935 to 1990 was then expanded to the period 1991 to 1995 by including these records from the Louisiana DNR CZD.

A second-degree polynomial fit of the ratio indirect:direct land loss by year was also made to predict that ratio for the period 1991 to 1995. The resulting estimated ratio for each of the 5 yr was then multiplied by the amount of direct land loss for the same interval and this product was used to estimate the current total land loss (direct and indirect) for that interval.

Results

H1. This hypothesis proposes that hydrologic change, a direct loss resulting primarily from dredging, causes land loss indirectly. This hypothesis would be rejected if a plot of the relationship between the direct (x axis) and indirect losses (y axis) for each quadrangle map were statistically insignificant or inversely related. H1 would be partially rejected if the X,Y intercept was above zero, because it implies that these two factors were related but under the influence of an additional factor. H1 might also be rejected if the estimated indirect loss rates for the coast began before the rise in direct impacts, or peaked before the peak in direct impacts.

Annual coastwide cumulative changes in the direct and indirect losses were nearly coincidental over the last 60 yr, although the former lags about 10 yr after the latter (Fig. 3). The changes in land loss rates this century are similar to results for smaller areas of the coast (e.g., Sasser et al. 1986; Bass and Turner in press). Land loss will approach zero four decades before that proposed in Louisiana's State Restoration Plan (Anonymous 1995b).

Fig. 2. The location of the study area boundaries (eight estuarine watersheds) and the delineation of distance from the coast for each 15-min quadrangle map, numbered from the estuary entrance (1) to fresher habitats (higher numbers). Some maps had extensive overlap in two estuaries. The Chenier Plain has hydrologic barriers aligned parallel to shore of abandoned sand deposits accumulating as a consequence of deltaic growth/abandonment cycles on the continental shelf. Estuarine flushing for the Chenier Plain estuaries is therefore numbered in an east and west direction.

if the present loss rate curve of the past 50 yr continues its present trajectory (Fig. 3). There is a linear relationship between the indirect and direct land losses among the individual 15-min quadrangles for estuaries of similar geology (Fig. 4). Further, the intercept is zero (95% CI), implying an absence of significant coastwide effects due to other factors. The ratio of indirect to direct land loss is highest where the hydrologic flushing is greatest, that is, near the estuarine entrance, or, in the case of the Mississippi River delta, where the wave energy is highest (Fig. 5). This hypothesis, therefore, is not rejected.

H2. This hypothesis suggests that a reduction in sediment concentration in the Mississippi River in the 1950s contributed to indirect losses in subsequent years and that the transport pathway into

the estuary was through the tidal passes. There was no change in the Y-intercept of a X,Y plot of the direct and indirect land losses before and after the period when suspended sediment concentrations in the Mississippi River declined (the 1950s; Fig. 6). If this hypothesis was *not* going to be rejected, then the Y-intercept of the X,Y plot of data from after the 1950s for any of the three intervals should have risen above the Y-intercept of the X,Y plot of data from before the 1950s. That result was not observed. If H1 was rejected (that is, if the X,Y plot in Figs. 4 or 6 was a cloud of data points), then H2 could not be tested in this manner. H2 was also partially rejected because significant land losses started before the decline in suspended sediments in the 1950s. This hypothesis is therefore rejected.

Fig. 3. Land loss and canal density over time. Upper panel: Coastwide cumulative loss rates for direct (X axis) and indirect conversions (Y axis) of land to water, and the ratio of indirect: direct losses. A polynomial fit of the data is shown. Bottom panel: the interpolated annual conversions of land-to-water for direct (X axis) and indirect (Y axis) land losses estimated from data shown in the top panel.

H3. This hypothesis assumes that the Mississippi River flood protection levees prohibited significant quantities of sediment from being transported into the fresher estuarine habitats and thereby significantly diminished wetland accretion rates and that these changes were not compensated by other processes. This hypothesis is rejected for four reasons. First, the Y-intercept of a plot of the direct losses (X axis) and indirect losses (Y) is not above zero in Fig. 4, and the intercept and presence of a linear fit of the data over the four mapping intervals are stable (Fig. 6). This result suggests that the cumulative effect of the presumed sediment deprivation was insignificant compared to the indirect effects of the direct land losses. A second reason to reject H3 is that the rise and fall of the direct and indirect land losses are nearly

coincidental (Fig. 3), whereas the reductions in water sediments from overbank flooding were sustained to present. A third reason for rejecting H3 concerns where reduced overbank flooding would have an effect. The estuarine headwaters are where overbank flooding previously occurred (but not every year). However, the freshwater and sediments delivered by overbank flooding were not equal in three deltaic plain estuaries (Barataria, Terrebonne, and Lake Pontchartrain). The distance between estuary and river, the number of crevasses going into each and the amount of water and sediments transported to those estuaries were all very different from another. The Barataria and Terrebonne estuaries are west of the Mississippi River and receive only local runoff. The low salinity (<5‰) Lake Pontchartrain estuary receives local runoff and occasional Mississippi River diversions (seven times this century). The St. Bernard estuary is east of the Mississippi River delta and has a major shipping channel (the Mississippi River Gulf Outlet) traversing north to south, connecting it to Lake Pontchartrain. In addition, the amount of sediments formerly flowing overbank during floodstage is only 3% of the total sediment load (Kesel 1988). These differences among estuaries should have contributed to a poor data fit in Figs. 4 and 6, yet, in contrast, the coefficient of determination, R^2 , was between 0.43 and 0.97. The last argument in favor of rejecting H3 is that H2 was rejected. H2 addressed the effects of a 50% decrease in average riverine sediment concentration since the 1950s (that entered through tidal passes) compared to a 3% reduction in sediment supply from overbank flooding. It seems unlikely, but not impossible, that a small change in sediment and freshwater entering at the headwaters would have a greater effect than would a large change at the estuarine entrance.

H4. The relationship between the indirect losses and either salinity or salinity change are the subject of H4. Salt stresses should be lowest for the plants most adapted to high salinity, and highest for those plants least adapted to salt (i.e., those plants located in the freshwater marshes). Dredged channels bring salt water further into the coastal zone, so this hypothesis cannot be rejected on the basis of results shown in Figs. 3 or 4, because H1 and H4 may be causally linked. If salinity stress occurs and leads to land loss, then the amount of indirect land loss per direct land loss should be highest in the lowest salinity zone. This result was not observed. The ratio of indirect to direct land loss declines, not increases, going from salt water to freshwater zones, along a gradient from the estuarine mouth to inland. This ratio does not decline in the region where plant stresses should be most sensitive to sa-

Fig. 4. The relationship between the indirect (Y axis) and direct losses (X axis) from the 1930s to 1990 expressed as a ratio of the original land area. The linear regression is shown for three individual estuaries and for all deltaic plain data together (exclusive of 15-min quadrangle maps for the modern delta and the Chenier Plain). Only quadrangle maps with <85% open water and >8,100 ha are included. A 95% confidence interval is shown for the Y-intercept of the linear regression. $p < 0.01$ in all cases.

linity stress (Fig. 5). There is more land loss per dredged channel in the high salinity zone of the estuary than in the low salinity zone. Further, long-term salinity increases are not observed across the coast. Instead, there is annual variability in estuarine salinity that reflects the influence of the major source of fresh water, the Mississippi River. Some areas, in fact, have lower salinities in recent decades (Wiseman et al. 1990). Salt water intrusion does not appear to be a major indirect factor driving coastwide land loss this century (although it may be significant in certain local areas). This hypothesis was therefore rejected.

H1 is the only hypothesis that is not rejected. It explains the rise and fall of land loss rates in time and space across the coast, has empirical and experimental field and laboratory studies to support it, and is a more efficient explanation than alternative hypotheses (the application of Occam's Razor).

Discussion

The indirect effects of dredging on this coastal environment appear to significantly affect land loss on this coast and can be empirically related to virtually all of the land-to-water conversions in the last 60 yr. Conceptual models of land loss that are primarily based on physical phenomena should, therefore, be re-examined. The present management models attribute wetland gain, maintenance, and loss primarily to riverine sediment supply and the resulting deltaic cycles of the last 6,000 yr. In the sediment deprivation model, if sediment supply is known then wetland area is known, the 'additional' within-estuary influences of human activities on the landscape are supplementary, and the present land loss rates may be essentially unavoidable. It follows from this model that vegetated habitats are almost entirely a consequence of the geological regime and that the indirect impacts of plants on the land area are of lesser importance.

Fig. 5. The indirect loss rates (Y axis) versus direct losses (X axis) from the 1930s to 1990 for each estuary as a function of distance from the coast (data are for the 15-min quadrangle maps shown in Fig. 3. Only quadrangle maps with <85% open water and >8,100 ha are included. A polynomial fit of the data is shown for each estuary. $p < 0.01$ in all cases.

In this model the deltaic growth phase mirrors the destructional phase and it is the balance of these two that determines the maintenance phase. The Mississippi River and Atchafalaya River deltas are often used as examples of coastal wetland growth, maintenance, and decay whose controlling elements are physical, not biological. This model provides a firm basis for management action, but it appears to be incorrect. The restoration remedies arising from this historical-geological reconstructionist model are to distribute more sediment into the marsh and to control discrete points for river diversion in order to mimic the deltaic growth model. In this model, management "fixes" of the regional geology will compensate for negative human influences (e.g., Anonymous 1995b). The results of the tests of hypotheses herein show the strictly physical model to be a very imperfect, if not inadequate, model to describe events on this coast.

A model with a broad ecological emphasis incorporates the relationships between plants, hydrology, and sediments. In an ecological model, a variety of different and important stressors together

determine whether there is open water or wetland. There are several qualitative examples of these interrelationships. For example, stems slow overbank current velocities enough to allow suspended sediments to fall out of suspension, and suspended particulate material is attracted to the plant surface during submergence and later falls to the marsh surface (Stumpf 1983). In this perspective, plants are not ancillary contributors to wetland landscape development but are active biogeophysical agents. Plants may also play an underappreciated role in dominating the accumulation of sediments through their contribution to soil organic matter belowground. Suspended material transported from the river to the sea may arrive in the estuary after transit through the tidal passes, just as salt does (Wiseman et al. 1990), and be deposited in sufficient quantities to compensate for variations in relative sea-level rise, climate, and organic deposition rates. In the ecological model the maintenance phase is not driven by the same balance of factors as in the growth phase; the ecological model distinguishes between growth factors

and sustenance factors. It does not assume that the modern birdfoot delta that extends 50 km onto the continental shelf is a complete or even appropriate management model for the inter-levee wetlands formed within the broad deltaic plain.

These relationships may be nonlinear, cumulative, and unclear. They may have a bearing on wetland restoration efforts. For example, deadend canals tend to fill over time, and canals refilled from the remaining spoil material may revegetate as does the former spoil bank (Neill and Turner 1987; Turner et al. 1994b). A rather striking example of a reversal of soil subsidence was measured in a Delaware marsh. The soil surface stopped falling and even rose slightly when some Delaware mosquito ditches were filled in; the undesirable plant community changes caused by ditching also began to reverse concurrently (Daigh et al. 1938). When levees forming an impoundment in Florida were broken, the vegetation returned (Gilmore et al. 1981). Wetland vegetation also reappeared when dikes were breached in two 200-acre wetlands near San Francisco (Faber 1982; Josselyn and Perez 1982) and when partial tidal restriction was returned to a Connecticut coastal marsh (Roman et al. 1984). Restoration of hydrologic flows in these Louisiana wetlands is a key element in a sustained successful wetland restoration effort whose results may occur slowly ($1\% \text{ yr}^{-1}$), and perhaps naturally, as the existing spoil banks disintegrate.

What is proposed herein, then, is a paradigm shift that reveals the need for much greater ecological understanding of these wetlands. The effects of extensive human-induced changes on this coast have apparently overwhelmed the causal linkages identified in a historical reconstructionist view of deltaic gain and loss. However, to say that management should be based on an ecological model or should encourage the restoration of the natural hydrology is being very imprecise for scientific scrutiny—it does not predict or quantify. But, it does suggest that introducing sediments into a system without adjusting for the detrimental effects of hydrologic stressors may not be helpful, or worse. Also, restoration on the scale of an estuarine watershed may be misguided if the site-specific hydrologic stressors are not addressed coincidentally.

Several important points emerge from this analysis that are relevant in designing and implement-

ing wetland restoration efforts: First, the most obvious point is that natural wetland hydrologic flows are complicated, and perhaps too complicated, to be reproduced precisely through engineering approaches and are certainly to be respected as a strong influence on wetland health and stability. Hydrologic changes following dredging therefore extend widely and perhaps unpredictably—we cannot yet determine precisely where wetland loss will and will not occur. Hydrologic changes made without an increased knowledge of their impacts are just as likely to fail as to succeed, and may inadvertently accelerate the conversion of more coastal wetlands to open water. Second, either sediments or plants may accumulate enough organic and inorganic materials to compensate for a rising sea level and subsiding land. Hydrologic couplings influence this accumulation rate over the long run, and hydrologic changes may subtly and detrimentally affect wetlands (in terms of maintaining wetland plant populations). Third, the institutional framework of approving many small permitted actions in Louisiana has produced previously unforeseen cumulative effects with delayed expression and long-term consequences. However, these permitting actions are a joint state and federal responsibility and offer a potentially fruitful opportunity to reduce wetland loss rates and restore wetlands. Some results of such interactions have already been accomplished with the promotion of directionally drilling into several oil reservoirs from one location, thus reducing the impacts to wetlands (Johnson et al. 1990). Fourth, the vast majority of spoil banks and canals are already constructed. For example, the additional area of dredged canals added in 1993 was less than 0.2% of the total present in 1992. One implication of this low percentage is that wetland restoration efforts should be involved with the legacy of old spoil banks at least as much as with scrutinizing new dredge and fill permits. The old and new spoil banks could be reconfigured to provide less damaging indirect impacts (Turner et al. 1994a). Fifth, fresh water and sediment introductions into the coastal zone through cuts in the Mississippi River levees are possible helpful changes. However, they are limited by water supply, land ownership questions, and navigation issues; are restricted to a few entry points; and their construction consumes scarce financial resources (comparative data are in

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Fig. 6. The relationship between the cumulative indirect (Y axis) and direct losses (X axis) for all data expressed as the absolute area (A) and relative to the original land area (B). Four intervals are shown. The slopes increase as the interval length increases, but the intercept passes through the origin for all mapping intervals. Only quadrangle maps with <85% open water and >8,100 ha are included. $p < 0.01$ in all cases.

Turner et al. 1994a). Reductions in the supply of sediments and fresh water, for which diversions seek to compensate, do not appear as strong a causal agent of wetland demise as hydrologic changes do. Sixth, a landscape perspective, as shown herein, can assist in that analysis and solution.

ACKNOWLEDGMENTS

This analysis was made possible by the cooperation of the District Engineer and L. D. Britsch of the New Orleans United States Corps of Engineers, and was helped through vigorous discussion with colleagues, and, especially, students of the Louisiana State University course "Wetland Loss, Restoration and Management." Financial support came from Pat Edgerton and, over the last two decades, through various governmental agencies, especially the United States Minerals Management Service, the United States National Marine Fisheries Service, and the United States Environmental Protection Agency. N. N. Rabalais is especially thanked for her review and advice.

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Received for consideration, August 10, 1995

Accepted for publication, April 30, 1996