Causes of hot-spot wetland loss in the Mississippi delta plain

Robert A. Morton, Ginger Tiling, and Nicholas F. Ferina

ABSTRACT

Field surveys and sediment cores were used to estimate marsh erosion and land subsidence at Madison Bay, a well-known wetland loss hot spot in coastal Louisiana. Former marshes of Madison Bay are under about 1 m of water. Nearly two-thirds of the permanent flooding was caused by rapid subsidence in the late 1960s, whereas the other third was caused by subsequent erosion. Subsidence rates near Madison Bay since the 1960s (~20 mm/yr) are an order of magnitude greater than deltaic subsidence rates averaged for the past 400–4000 yr (~2 mm/yr).

The rapid acceleration and unexpected decline in wetland losses in the Mississippi delta plain are difficult to explain on the basis of most physical and biogeochemical processes. There are, however, close temporal and spatial correlations among regional wetland loss, high subsidence rates, and large-volume fluid production from nearby hydrocarbon fields. The decreased rates of wetland loss since the 1970s may be related to decreased rates of subsidence caused by significantly decreased rates of subsurface fluid withdrawal.

Annual fluid production from the Lapeyrouse, Lirette, and Bay Baptiste fields that encompass Madison Bay accelerated in the 1960s, peaked about 1970, and then declined abruptly. Large decreases in pore pressure in the Lapeyrouse field have likely altered subsurface stresses and reactivated a major fault that coincides with the wetland loss hot spot. Therefore, wetland losses at Madison Bay can be closely linked to rapid subsidence and possible fault reactivation induced by long-term, large-volume hydrocarbon production.

INTRODUCTION

Wetland losses in the lower Mississippi delta have been the subject of intense investigation ever since the magnitude of wetland loss and its potential economic and social impacts were first recognized (Gosselink and Baumann, 1980; Gagliano et al., 1981). Many reports have been written about the complex physical and biogeochemical processes and their interdependencies that are responsible for wetland loss (Turner and Cahoon, 1987; Boesch et al., 1994; Roberts, 1994; Williams et al., 1994; Day et al., 2000; Penland et al., 2000).

AUTHORS

Robert A. Morton ~ *U.S. Geological Survey, Center for Coastal and Watershed Studies, 600 4th St. S., St. Petersburg, Florida; rmorton@usgs.gov*

Bob Morton is a U.S. Geological Survey research geologist. He was employed previously as a senior research scientist at the University of Texas at Austin Bureau of Economic Geology and as a petroleum geologist at Chevron Oil in New Orleans, Louisiana. Throughout his career, Bob has conducted subsurface studies of the Gulf Coast Basin and surficial changes in coastal Texas and Louisiana.

Ginger Tiling ~ *ETI Professionals, Inc., 600 4th St. S., St. Petersburg, Florida*

Ginger Tiling received a B.S. degree in environmental science in 1999 and is an M.S. candidate in geology at the University of South Florida. She is employed by ETI Professionals and is working, under contract, at the U.S. Geological Survey Center for Coastal and Watershed Studies in St. Petersburg, Florida.

Nicholas F. Ferina ~ *Environmental Careers Organization, 600 4th St. S., St. Petersburg, Florida*

Nicholas F. Ferina received his B.A. degree in environmental geography in 1997 and his M.S. degree in geology from the University of New Orleans in 2002. He is employed by Environmental Careers Organization and is working, under contract, at the U.S. Geological Survey Center for Coastal and Watershed Studies in St. Petersburg, Florida.

ACKNOWLEDGEMENTS

We thank Del Britsch and the New Orleans District Army Corps of Engineers for collecting the vibracores in Madison Bay. Betsy Boynton prepared the report illustrations and layout. Scientific and editorial reviews were provided by Don Cahoon, Jeff Williams, Dave Bush, David King, and Robert Fakundiny.

Despite all the prior studies, there still are controversies and unanswered questions regarding the primary importance of natural versus induced environmental changes that have caused the dramatic historical losses in wetlands. Prior studies of wetland loss in Louisiana (Craig et al., 1979; Mendelssohn and McKee, 1988; Nman et al., 1994) focused mainly on surficial hydrodynamic processes and wetlands ecology and did not consider any subsurface processes. The few studies that considered possible subsurface controls on wetland loss concentrated on the most recent (Holocene) alluvial and deltaic deposits (Kuecher et al., 1993; Roberts et al., 1994) and did not consider the older and deeper strata. The only studies or reviews that considered the deep basin fill concluded that the impacts of production-induced subsidence are insignificant or are more local than regional (Coleman and Roberts, 1989; Boesch et al., 1994). A study in Louisiana designed specifically to evaluate potential wetland subsidence induced by hydrocarbon production concluded that it is minimal (Suhayda, 1987).

Wetlands in south-central Louisiana have been converted to open water in the interior of the subaerial marsh and around the shores of delta-plain water bodies (Figure 1). Wetland losses around the water bodies result either from erosion by waves or inundation by a relative rise in sea level (submergence). In some ponds, strong winds are capable of generating enough wave energy that marsh erosion is common, and subsequent water-body enlargement can result in both expanded surface areas and increased water depths.

Wetland loss hot spots are interior areas of the delta plain that deteriorate abruptly for no apparent reason. Hot spots originate where the rates of land loss are high and the conversion of wetlands to open water follows a specific temporal sequence and spatial pattern. The hot spots normally begin as isolated patches or ponds of open water that are surrounded by dense stands of healthy marsh vegetation (Leibowitz and Hill, 1987). As the marsh deteriorates, the ponds gradually enlarge and merge, and the wetland loss hot spot becomes mostly open water with a few remnant islands

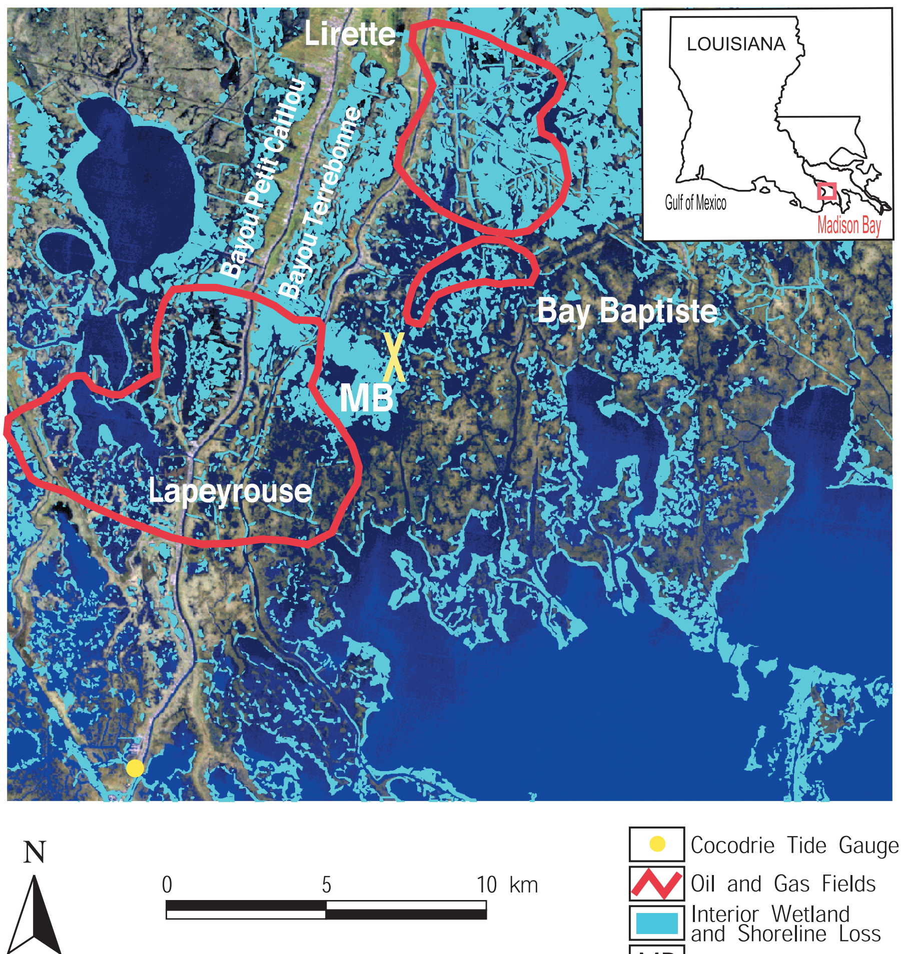


Figure 1. Map of south-central Louisiana showing the location of Madison Bay (MB), the Cocodrie tide gauge, and the distribution of wetland losses relative to producing oil and gas fields. Wetland loss (1930–1990) from Britsch and Dunbar (1996). General geographic position of the yellow X is lat. N29°21′50″, long. W90°34′45″.

of marsh. Eventually, the scattered islands of marsh disappear, and all the former continuous marsh is replaced by open water.

There are two possible explanations for the greatest and most rapid interior wetland losses in south-central Louisiana. One possibility is that erosion of the organic-rich marsh sediments is primarily responsible for the changes from interior wetlands to open water. According to this explanation, the marsh plants are weakened and die as a result of either water logging or salt-water intrusion (Gosselink et al., 1977; Mendelssohn and McKee, 1988). When plant density decreases, the hydrodynamic forces present in the marsh begin to erode and remove the organic-rich sediments from the marsh. Once the organic sediments are in suspension, they can be exported from the deteriorating marsh into adjacent water bodies or other marshes by currents driven by tidal and meteorological processes. Another possibility is that the observed historical changes from interior wetlands to open water are primarily caused by land-surface subsidence (Boesch et al., 1994). If that explanation is correct, then some of the roots and organic-rich marsh sediments may be preserved under water at the site that subsided. Neither of these two explanations is mutually exclusive, and both land subsidence and sediment erosion may partly contribute to the wetland changes that have been observed.

Rapid interior wetland losses of the Mississippi delta have been the most difficult to explain because initially, the hot spots do not involve erosion. Because hot spots account for approximately 43% of the marsh loss in south Louisiana (Leibowitz and Hill, 1987), understanding the processes causing those losses would help explain much of the total wetland losses. The purpose of this study is to examine the physical processes responsible for rapid interior wetland losses at Madison Bay, a typical delta-plain wetland loss hot spot in Terrebonne Parish, Louisiana (Figure 1). This site was selected for detailed investigation to examine processes at a hot spot where (1) prior investigations were unable to explain the rapid marsh deterioration (DeLaune et al., 1994; Reed, 1995), (2) erosion was not the mechanism that initiated wetland loss, and (3) contemporaneous data were available for wetland losses, subsidence rates, and hydrocarbon production.

Madison Bay Hot Spot

The Madison Bay hot spot (Figures 1, 2) is located in delta-plain marshes that are associated with the Lafourche subdelta complex of the Mississippi delta. This delta lobe was deposited by the Bayou Terrebonne distributary system, including the Bayou Grand Calliou and Bayou Petit Calliou distributary channels, which were active from about 1.2 to about 0.4 ka (Frazier, 1967).

The history of recent marsh loss at Madison Bay was chronicled for seven consecutive periods between 1941 and 1990 (Reed, 1995). The marshes were classified as brackish in the 1940s and 1950s, but were saline marshes by the 1970s (DeLaune et al., 1994). Wetland losses were minor from the early 1940s to the late 1960s, suggesting equilibrium conditions between delta-plain processes and marsh vitality, although the salinity was increasing. However, between 1969 and 1978, wetlands deteriorated abruptly, suggesting a change in local conditions and delta-plain processes. Wetland ecologists have been perplexed by the rapid deterioration of marshes at Madison Bay (Nyman et al., 1993, DeLaune et al., 1994, Reed, 1995, Cahoon et al., 1999) because only a few dredged canals crossed the disintegrating marsh (Reed, 1995), and there was no other evidence of human activities that would cause direct wetland losses. All of these studies of marsh loss at Madison Bay recognized that despite exceptionally high rates of marsh aggradation (9.8 mm/yr), the local supply of mineral matter and plant production were unable to overcome high rates of submergence (Nyman et al., 1993). None of these studies addressed the mechanisms of regional submergence (subsidence), although DeLaune et al. (1994) speculated that marsh elevation loss at Madison Bay was related to peat collapse.

Field Methods

Field activities involved collecting vibracores, measuring water depths, and monitoring water levels to evaluate the physical processes that resulted in rapid wetland loss. Ten vibracores, which range in length from 3.5 to 4.9 m, were collected in and around the Madison Bay wetland loss hot spot (Figure 2). Core sites were selected to encompass the perimeter of the area that experienced the most rapid wetland loss and to provide close correlations between pairs of cores taken in the interior marsh and adjacent open water (Figure 2).

Water depths at the open-water coring sites and along a bathymetric profile (Figures 2, 3) were measured from a small boat with a graduated rod, whereas the geographic coordinates of each depth measurement were obtained with a Global Positioning System receiver. A temporary staff gauge was placed at the edge of the eastern marsh to measure water levels in Madison Bay during the field operations. The staff gauge

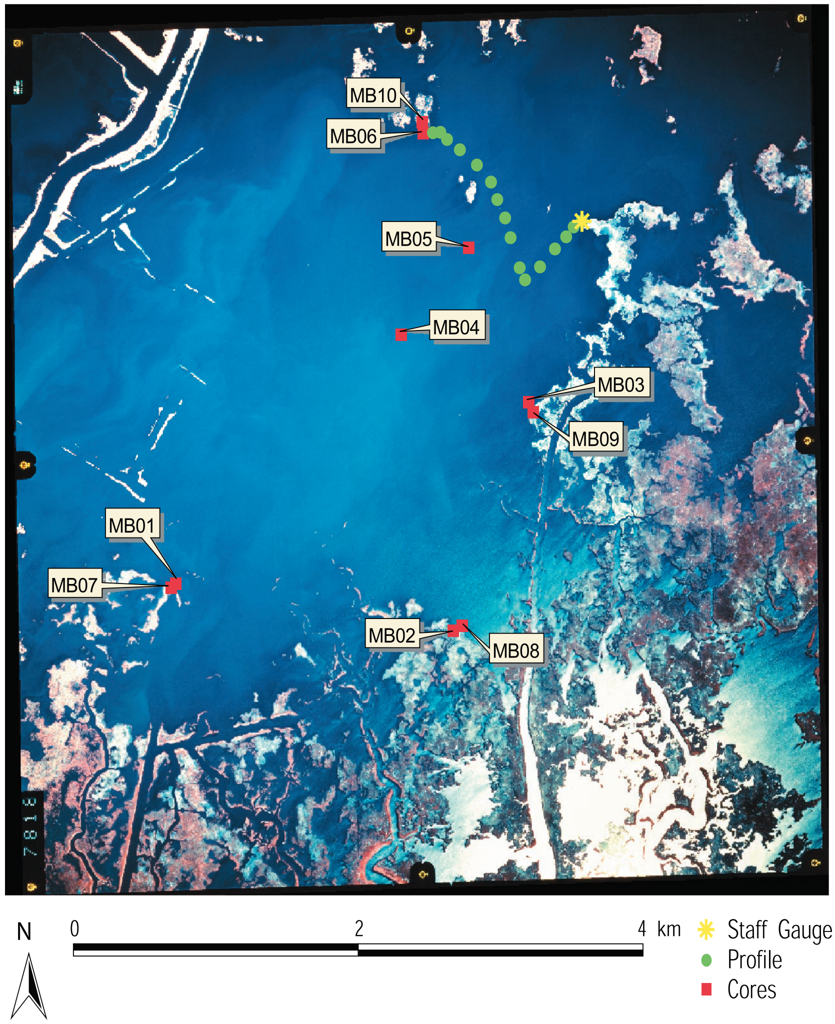


Figure 2. Locations of sediment cores and sediment-surface profile from the Madison Bay area superimposed on an aerial photograph taken in 2000. General location shown as MB in Figure 1. Geographic position of MB04 is lat. N29°21′54.03″, long. W90°34′56.59″.

measurements were used to adjust the water levels and marsh elevations in Madison Bay to the National Geodetic Vertical Datum of the nearby Cocodrie tide gauge (Figure 2).

DELTA-PLAIN SEDIMENTS

The vibracores from Madison Bay recovered a succession of unconsolidated sediments representing four sedimentary facies that are consistently arranged in the same stratigraphic order at each coring site. From youngest to oldest, the recovered facies are (1) peat and organic-rich mud, (2) massive mud, (3) sand and silty sand, and (4) interbedded sand and mud. Morton et al. (2003) presented detailed descriptions and photographs of the cores and the water-level corrections used to establish the marsh and bay-bottom elevations.

The upper 20–30 cm of modern marsh sediments (cores 07, 08, 09, and 10) consist of water-saturated gray or brown mud interspersed among large fibrous roots that are associated with living *Spartina* sp. marsh plants. The live roots and saturated mud indicate recent accumulation of both organic and clastic sediments. These same muddy sediments with large roots are absent from the tops of cores 01, 02, 03, 04, and 05, indicating that the most recent marsh sediments were either not deposited, were eroded, or were winnowed at the open-water sites. Below the most recent marsh

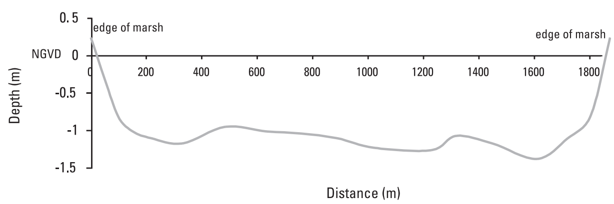


Figure 3. Water depths and elevations at Madison Bay along a bathymetric profile surveyed May 1, 2002 between core 10 and the staff tide gauge. Location shown in Figure 2.

Table 1. Core Elevations Adjusted to the Water-Level Datum of the Cocodrie Tide Gauge, Vertical Offset Between Core Pairs, Estimated Magnitudes of Erosion and Subsidence, and Average Rates of Subsidence Assuming a 30-Yr Period

Paired Cores	Marsh Core Elevation (cm)	Water Core Elevation (cm)	Vertical Offset (cm)	Erosion (cm)	Subsidence (cm)	Average Subsidence Rate (mm/yr)
07 and 01	18.3	−51.3	70	02	68	23
08 and 02	14.0	−64.8	79	26	53	18
09 and 03	11.0	−82.3	93	31	62	21
10 and 06	24.4	−63.6	88	24	64	21
04	(corr/03)	−114.2	32	33	92	30
05	(corr/03)	−98.2	16	34	75	25

deposits are black peat deposits with abundant fibrous roots that contain some dispersed mud. Total thickness of the peat and organic-rich mud facies ranges from 129 (core 06) to 208 cm (core 07).

In the cores, the top of the shallowest distinct mud bed is identified as the last significant flooding event, whereas the base of the deepest distinct peat bed is identified as the first marsh surface. The first marsh surface can be either a gradational or abrupt contact with the underlying massive, rooted mud.

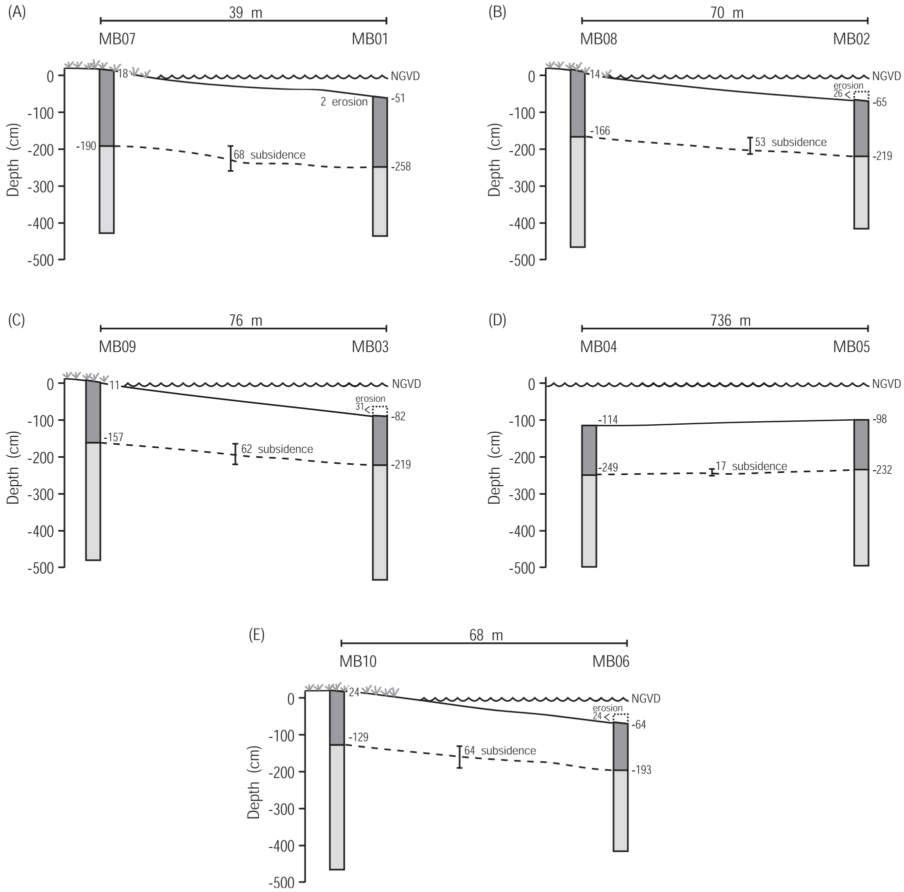
SUBSIDENCE AND EROSION AT MADISON BAY

The amount of surficial erosion and differential subsidence in the marsh interior can be estimated by comparing the elevations and vertical offsets (Table 1) of sediment surfaces and stratigraphic contacts that can be correlated between adjacent core pairs (Figure 4). Although several different stratigraphic horizons were correlated between core pairs, the elevation of the first marsh was used to estimate the site-specific magnitudes of subsidence and erosion because it was identified in each core. The relative subsidence and erosion between marsh and open-water cores assumes that marsh sediment thickness and stratigraphic positions of correlation markers are uniform over short horizontal distances (tens of meters). The amount of erosion at the open-water core site is equal to the difference in marsh sediment thickness between the open-water core and the adjacent marsh core. The amount of subsidence at the open-water core is equal to the elevation difference between the correlated stratigraphic markers between the two adjacent cores. To be precise, the erosion and subsidence estimates must equal the vertical displacement between the cores (Table 1). This calculation provides a minimum estimate of total subsidence because there is no measurement of the absolute amount of historical subsidence of the marsh surface relative to some standard vertical datum. Stated another way, the marsh sediments preserved beneath Madison Bay have subsided more than the adjacent subaerial marsh sediments, but the entire area, including the subaerial marsh, has subsided by some unknown amount.

The amount of vertical erosion at the submerged sites ranges from 2 to 34 cm (Table 1). Erosion is the least at core 01, which may be the most recent site to become submerged. The estimated magnitude of incremental subsidence for each core pair ranges between 53 and 92 cm (Table 1). The estimated subsidence is greatest at core 04, which is the site that has been open water for the longest time (Morton et al., 2003). Some of the most recent muddy marsh sediments recovered in the tops of cores 07, 08, 09, and 10 may have never been deposited at the adjacent open-water sites. This would be true if (1) the most recent marsh sedimentation occurred after the rapid expansion of open water in 1969, and (2) the new marsh sediment was imported from the submerged marsh sediments. These requisite conditions appear to be confirmed by field measurements of others. Cahoon et al. (1999) reported high rates of sedimentation in the marshes around Madison Bay between 1992 and 1997. Murray et al. (1993) described how winter storms resuspended bay-bottom sediments near Madison Bay and delivered the sediment to the marsh surface. Inclusion of excess marsh sediment thickness in the calculation of erosion and subsidence would overestimate the total vertical offset and the amount of erosion, but it would not influence the estimate of subsidence.

The estimates of erosion and subsidence at each coring site can be used to explain the general water depths in Madison Bay. Water depths are shallow around the margins of the bay where erosion is minimal, and the

Figure 4. Stratigraphic correlations for marsh and open-water core pairs illustrate the magnitude of subsidence and wetland erosion (in centimeters) at the Madison Bay wetland loss hot spot. The upper stratigraphic unit represents the peat and organic mud facies, whereas the lower unit includes the three other facies. Locations shown in Figure 2.



water is deeper where both sediment erosion and land subsidence are greatest (cores 04 and 05) (Table 1). Assuming that water depths in Madison Bay average about 1 m (Figure 3) and marsh elevations average about 0.15 m (Table 1), then about two-thirds of the water depth is attributable to subsidence, and one-third is attributable to erosion of the submerged organic marsh sediments (Table 1).

GEOLOGICAL AND HISTORICAL RATES OF SUBSIDENCE

Average subsidence rates compiled from various sources for the Madison Bay area clearly show that the historical rates of subsidence are an order of magnitude greater than the geological rates of subsidence (Table 2). Subsidence rates averaged for hundreds or thousands of years are based on radiocarbon dates and depths of peat samples from sediment cores. The peat sample analyzed by Frazier (1967) is from a core taken in the marsh that is now open water and part of the Madison Bay wetland loss area. The peat sample analyzed by Roberts (1994) is from a core taken near Cocodrie. That core location is geographically near and geologically equivalent (downthrown side of the Golden Meadow fault zone) to the Madison Bay wetland loss area. Average subsidence rates associated with Holocene deltaic sediments older than about 500 yr are only a few millimeters per year (Penland et al., 1988). This general estimate agrees well with site-specific subsidence rates calculated for the Madison Bay core (1.4 mm/yr) of Frazier (1967) and estimated by Roberts et al. (1994) for the Cocodrie core (2.7 mm/yr).

Historical rates of subsidence near Madison Bay can be estimated using vertical offsets of core pairs, water level records, surface elevation table measurements, and releveling surveys (Table 2). Estimating magnitudes of subsidence from core pairs is relatively uncomplicated, but calculating average rates of subsidence is made difficult because the period of recorded subsidence is not precisely known. Comparison of aerial photographs taken in 1990 and 2000 (Morton et al., 2003) shows that the marsh at core sites 01, 02, 03, 05, and 06 was submerged in less than 10 yr. However, it is unknown if the total differential subsidence measured between core pairs (Table 1) occurred in that brief period or over a longer period. Calculated subsidence rates are

Table 2. Average Geological and Historical Rates of Subsidence for the Terrebonne Delta Plain Region Near Madison Bay

Source of Estimate	Period	Average Subsidence Rate (mm/yr)	Reference
C^{14} core P-1-90	4.74 ka	2.7	Roberts et al. (1994)
C^{14} peat sample 2067	0.425 ka	1.4	Frazier (1967)
Houma tide gauge	1946–1962	0.7	Penland et al. (1988)
Houma tide gauge	1962–1982	19.4	Penland et al. (1988)
Petit Caillou relevel line	1966–1993	9.3	Morton et al. (2002)
Surface elevation table measurements	1992–1999	22	Cahoon et al. (1999)
Cores and water levels	1969–1999	23	this study

exceptionally high (53–92 mm/yr) if the total vertical displacement is assigned to the 10-yr period of submergence. However, the average rate of subsidence calculated from the Madison Bay cores for the 30-yr period (1969–1999) corresponding to the most rapid wetland loss (Reed, 1995; Cahoon et al., 1999) is 23 mm/yr (Tables 1, 2). This compares well with marsh subsidence rates measured by Cahoon et al. (1999) at Bayou Chitigue in the southeast corner of the Madison Bay hot spot (22 mm/yr) and the relative rise in sea level recorded at the Houma tide gauge between 1962 and 1982 (19.4 mm/yr). The highest local subsidence rate derived from the National Oceanic and Atmospheric Administration (NOAA) Bayou Petit Calliou relevel line (9.3 mm/yr) coincides spatially with the Madison Bay wetland loss hot spot and with the downthrown side of the Golden Meadow fault zone. Although the subsidence rate recorded by the relevel line is approximately half that of the other estimates for the same approximate period, it is substantially higher than the geological rates of delta-plain subsidence (Table 2).

DISCUSSION AND CONCLUSIONS

Several lines of converging evidence indicate that rapid subsidence and conversion of wetlands to open water near Madison Bay were caused primarily by reduction of surface elevations associated with hydrocarbon production and probable fault reactivation. The wetland loss hot spot at Madison Bay is surrounded by wells extracting hydrocarbons from deep subsurface reservoirs. The fields closest to Madison Bay (Lapeyrouse, Lirette, and Bay Baptiste) (Figure 1) have produced large volumes of gas, oil, and formation water (Figure 5A). Subsurface fluid-extraction rates at all three fields were low to moderate in the 1940s and 1950s, but annual production accelerated in the 1960s and peaked in the early 1970s (Figure 5) (Morton et al., 2002). The combined fluid production from all three fields exceeded 2 tcf of gas and 154 million bbl of oil and water (Morton et al., 2003). This large-volume fluid production was accompanied by rapid reductions in formation pressure that typically dropped as much as 4000–5000 psi ($2.76–3.45 \times 10^7$ Pa) in normally pressured reservoirs (Morton et al., 2002).

Along Bayou Petit Caillou (Figure 1), releveling surveys provide strong evidence that regional subsidence and wetland loss were at least partly induced by hydrocarbon production. They show that the broad regional zone of historical wetland losses (Figure 2) essentially coincided with the zones of maximum land-surface

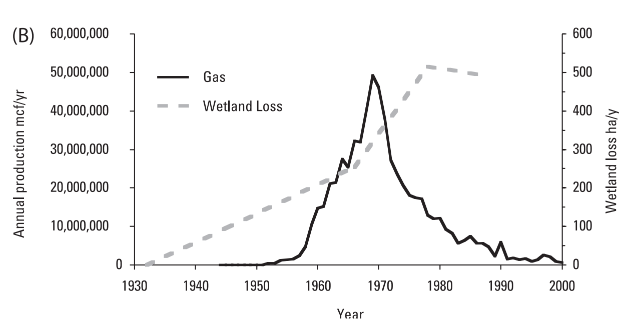


Figure 5. Temporal comparison of (A) annual volumes of fluid produced from the Lapeyrouse field (data from the Louisiana Department of Natural Resources) and (B) wetland losses in the Dulac quadrangle (data from Britsch and Dunbar, 1993).

subsidence, which coincide with the producing fields and faults (Morton et al., 2002). Additional evidence of subsidence comes from aerial photographs of the region (Figure 1) that show that widths of the subaerial levees along Bayou Terrebonne and Bayou Petit Caillou are wider both north (upstream) and south (downstream) of the zone of greatest wetland loss. Large decreases in reservoir pressure likely induced subsidence and reactivated a subsurface fault in the Lapeyrouse field that has displacement and orientation that are consistent with the pattern of wetland loss near Madison Bay (Morton et al., 2002).

Britsch and Dunbar (1993) conducted detailed and comprehensive mapping of wetland loss in coastal Louisiana using aerial photographs and topographic maps from 1930, 1958, 1974, 1983, and 1990 to document wetland changes for the intervening four periods. Although the periods are not equal in duration, the sequential analysis of historical data shows that (1) rates of loss initially accelerated then decelerated, and (2) more than half of the documented wetland losses occurred between 1958 and 1974 (Britsch and Dunbar, 1993). Wetland losses between 1932 and 1958 probably were not linear as shown (Figure 5B), but were low early in the period and more rapid later in the period. The period of greatest wetland loss generally corresponds to or closely follows the period of greatest hydrocarbon production from fields in south Louisiana (Figure 5). The period of accelerated fluid extraction and wetland loss also falls in the period of rapid or accelerated subsidence documented by various methods (Table 2).

The marsh cores provide additional evidence of recent environmental change in the Madison Bay wetlands. The cores show that the permanent flooding in Madison Bay was caused primarily (two-thirds) by subsidence and some (one-third) erosion. In addition, the historical subsidence rates are several times the geological subsidence rates in the same general area. The relatively thick peat in all the cores record a prolonged uniform depositional history of slow delta-plain subsidence and attendant slow aggradation of peat without significant disruption by prolonged flooding events. These organic-rich sediments that accumulated as a result of natural processes are in contrast to the uppermost organic-rich mud of the modern marsh that record frequent flooding and attendant rapid accumulation of muddy sediments as subsidence accelerated and elevations decreased.

The observed wetland losses at Madison Bay generally progressed from north to south (Reed, 1995). That direction of differential subsidence is consistent with (1) the vertical offset of cores (compare subsidence at cores 04 and 05 with 02 and 03) and down-to-the-south displacement of the spur fault of the Golden Meadow fault zone that probably intersects the surface in Madison Bay where wetland loss is greatest (Kuecher et al., 2001).

Many causes of regional wetland loss in coastal Louisiana have been identified in previous studies on the basis of theory, field investigations, and modeling (Table 3). Although all of these explanations have merit and are applicable at some locations, none of them are able to adequately explain the observed rapid acceleration and then sudden decline in wetland loss. For example, rates of subsidence associated with natural compaction of deltaic sediments decrease with time because the water expelled from the sediments is depleted. The commonly cited biogeochemical causes of wetland loss (Table 3) are all symptomatic of marsh submergence, and although they explain the physiological reasons for marsh die-back, they do not address the fundamental

Table 3. Previously Reported Causes of Regional Wetland Losses in Coastal Louisiana

Category	Process	Reference
Delta cycle	construction and destruction	Wells and Coleman, 1987
	sediment compaction	Kuecher et al., 1993
	shoreline or marsh erosion	Adams et al., 1978; Nyman et al., 1994
Biogeochemical	salt-water intrusion	Gosselink et al., 1977; DeLaune and Pezeshki, 1994
	waterlogging and sulfide concentration	Mendelssohn and McKee, 1988
	herbivory	Gosselink, 1984
Human activities	levee construction	Craig et al., 1979
	canal construction	Scaife et al., 1983
	failed reclamation projects	Craig et al., 1979

mechanism(s) that caused rapid submergence. The most commonly cited human activities that alter wetland hydrology and reduce sediment supply (levees, canals, reclamation projects) also are unable to explain the history of wetland losses, especially the well-documented decreases in recent periods.

The field evidence indicates that rapid wetland loss at Madison Bay was caused by subsidence and probably fault reactivation induced by hydrocarbon production. However, it is uncertain how much of the regional wetland loss in coastal Louisiana can be attributed to regional depressurization related to long-term, large-volume hydrocarbon production. At present, we do not have enough data to quantify the wetland losses associated with induced subsidence and fault reactivation. In addition, it is unclear if the rates of subsidence induced by hydrocarbon production have remained the same or diminished after the rates of fluid withdrawal dramatically declined (Figure 5). After the initial rapid subsidence, the subsurface stresses may have reached a new equilibrium, and the surficial adjustments (subsidence and fault movement) diminished. Reduced subsidence rates would have a profound influence on the designs of projects intended to restore wetland resources in the delta plain. Answering these important questions and their implications with regard to wetland loss mitigation will require additional research.

REFERENCES CITED

Adams, R. D., P. J. Banas, R. H. Baumann, J. H. Blackmon, and W. G. McIntire, 1978, Shoreline erosion in coastal Louisiana: Inventory and assessment: Baton Rouge, Louisiana State University Center for Wetland Resources, 139 p.

Boesch, D. F., M. N. Josselyn, A. J. Mehta, J. T. Morris, W. K. Nuttle, C. A. Simenstad, and D. J. P. Swift, 1994, Scientific assessment of coastal wetland loss restoration and management in Louisiana: Journal of Coastal Research Special Issue, v. 20, 103 p.

Britsch, L. D., and J. B. Dunbar, 1993, Land-loss rates: Louisiana coastal plain: Journal of Coastal Research, v. 9, p. 324–338.

Britsch, L. D., and Dunbar, J. B., 1996, Land loss in coastal Louisiana, Terrebonne Bay, LA: U.S. Army Corps of Engineers, Technical Report GL-90-2, map 6 of 7, scale 1:125,000.

Cahoon, D. R., J. W. Day, and D. J. Reed, 1999, The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis: Current Topics in Wetland Biogeochemistry, v. 3, p. 72–88.

Coleman, J. M., and H. H. Roberts, 1989, Deltaic coastal wetlands: Geologie en Mijnbouw, v. 68, p. 1–24.

Craig, N. J., R. E. Turner, and J. W. Day, 1979, Land loss in coastal Louisiana (U.S.A.): Environmental Management, v. 3, p. 133–144.

Day, J. W., G. P. Shaffer, L. D. Britsch, D. J. Reed, S. R. Hawes, and D. R. Cahoon, 2000, Pattern and process of land loss in the Mississippi delta: A spatial and temporal analysis of wetland habitat change: Estuaries, v. 23, p. 425–438.

DeLaune, R. D., and S. R. Pezeshki, 1994, The influence of subsidence and saltwater intrusion on coastal marsh stability: Louisiana Gulf Coast, U.S.A.: Journal of Coastal Research Special Issue, v. 12, p. 77–89.

DeLaune, R. D., J. A. Nyman, and W. H. Patrick, 1994, Peat collapse, ponding, and wetland loss in a rapidly submerging coastal marsh: Journal of Coastal Research, v. 10, p. 1021–1030.

Frazier, D. E., 1967, Recent deltaic deposits of the Mississippi River: Their development and chronology: Transactions Gulf Coast Association of Geological Societies, v. 17, p. 287–315.

Gagliano, S. M., K. J. Myer-Arendt, and K. M. Wicker, 1981, Land loss in the Mississippi River deltaic plain: Transactions Gulf Coast Association of Geological Societies, v. 31, p. 295–306.

Gosselink, J. G., 1984, The ecology of delta marshes of coastal Louisiana; A community profile: U.S. Fish and Wildlife Service Biological Services Program, FWS/OBS-84/09, 134 p.

Gosselink, J. G., and R. H. Baumann, 1980, Wetland inventories: Wetland loss along the United States coast: Zeitschrift fur Geomorphologie, v. 34, p. 173–187.

Gosselink, J. G., C. S. Hopkinson, and R. T. Parrondo, 1977, Common marsh plant species of the Gulf Coast area, v. II: Growth dynamics: U.S. Army Corps of Engineers, Waterways Exp. Station, Vicksburg Mississippi, Technical Report D-77-44, 37 p.

Kuecher, G. J., N. Chandra, H. H. Roberts, J. H. Suhayda, S. J. Williams, S. Penland, and W. J. Autin, 1993, Consolidation settlement potential in south Louisiana, *in* American Society of Civil Engineers Coastal Zone '93, p. 1197–1214.

Kuecher, G. J., H. H. Roberts, M. D. Thompson, and I. Matthews, 2001, Evidence for active growth faulting in the Terrebonne delta plain, south Louisiana: Implications for wetland loss and the vertical migration of petroleum: Environmental Geosciences, v. 8, p. 77–94.

Leibowitz, S. G., and J. M. Hill, 1987, Spatial analyses of Louisiana coastal land loss, *in* R. E. Turner and D. R. Cahoon, eds., Causes of wetland loss in the coastal central Gulf of Mexico: Minerals Management Service Outer Continental Shelf (OCS) Study MMS87-0120, technical narrative, v. II, p. 331–355.

Mendelssohn, I. S., and K. L. McKee, 1988, *Spartina alterniflora* dieback in Louisiana: Time-course investigation of soil waterlogging effects: Journal of Ecology, v. 76, p. 509–521.

Morton, R. A., N. A. Buster, and M. D. Krohn, 2002, Subsurface controls on historical subsidence rates and associated wetland loss in southcentral Louisiana: Transactions Gulf Coast Association of Geological Societies, v. 52, p. 767–778.

Morton, R. A., G. Tiling, and N. F. Ferina, 2003, Primary causes of wetland loss at Madison Bay, Terrebonne Parish, Louisiana: U.S. Geological Survey Open-File Report 03-60, 43 p.

Murray, S. P., N. D. Walker, and C. E. Adams Jr., 1993, Impacts of winter storms on sediment transport within the Terrebonne Bay marsh complex, *in* S. Laska and A. Puffer, eds., Coastlines of the Gulf of Mexico: New York, American Society of Civil Engineers, p. 56–70.

Nyman, J. A., R. D. DeLaune, H. H. Roberts, and W. H. Patrick, 1993, Relationship between vegetation and soil formation in a rapidly submerging coastal marsh: Marine Ecology Progress Series, v. 96, p. 269–279.

Nyman, J. A., M. Carloss, R. D. DeLaune, and W. H. Patrick, 1994, Erosion rather than plant dieback as the mechanism of marsh loss in an estuarine marsh: Earth Surface Processes and Landforms, v. 19, p. 69–84.

Penland, S., K. E. Ramsey, R. A. McBride, J. T. Mestayer, and K. A. Westphal, 1988, Relative sea-level rise and delta-plain development in the Terrebonne Parish region: Louisiana Geological Survey, Coastal Geology Technical Report No. 4, 121 p.

Penland, S., L. Wayne, L. D. Britsch, S. J. Williams, A. D. Beall, and V. C. Butterworth, 2000, Process classification of coastal land loss between 1932 and 1990 in the Mississippi River delta plain, southeastern Louisiana: U.S. Geological Survey Open-File Report 00-418, map with text.

Reed, D. J., ed., 1995, Status and trends of hydrologic modification, reduction in sediment availability, and habitat loss/modification in the Barataria–Terrebonne estuarine system: Barataria–Terrebonne National Estuary Program Publication No. 20, 338 p.

Roberts, H. H., ed., 1994, Critical physical processes of wetland loss: Louisiana State University Final Report 1988–1994 submitted to U.S. Geological Survey, variable pagination.

Roberts, H. H., A. Bailey, and G. J. Kuecher, 1994, Subsidence in the Mississippi River delta — Important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis: Transactions Gulf Coast Association of Geological Societies, v. 44, p. 619–629.

Scaife, W. W., R. E. Turner, and R. Costanza, 1983, Coastal Louisiana recent land loss and canal impacts: Environmental Management, v. 7, p. 433–442.

Suhayda, J. N., 1987, Subsidence and sea level, *in* R. E. Turner and D. R. Cahoon, eds., Causes of wetland loss in the coastal central Gulf of Mexico: Minerals Management Service OCS Study MMS87-0120, technical narrative, v. II, p. 187–202.

Turner, R. E. and D. R. Cahoon, eds., 1987, Causes of wetland loss in the coastal central Gulf of Mexico: Minerals Management Service OCS Study MMS87-0120, technical narrative, v. II, 400 p.

Wells, J. T., and J. M. Coleman, 1987, Wetland loss and the subdelta life cycle: Estuarine, Coastal, and Shelf Science, v. 25, 111–125.

Williams, S. J., S. Penland, and H. H. Roberts, 1994, Processes affecting coastal wetland loss in the Louisiana deltaic plain, *in* American Society of Civil Engineers Coastal Zone '93, p. 211–219.