IMPACTS OF OIL AND GAS ACTIVITIES ON COASTAL WETLAND LOSS IN THE MISSISSIPPI DELTA

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INTRODUCTION

The Mississippi Delta includes the largest area of coastal wetlands in the United States and supports one of the most extensive developments of petroleum extraction of any coastal area in the world. The Louisiana coastal zone (Fig. 33.1), making up most of the Mississippi Delta, occupies approximately 3.8 million ha (9.4 million acres). The zone includes water bodies, marshes (fresh, intermediate, brackish, and salt), forested wetlands, submerged aquatic vegetation, mudflats, beaches, and upland habitats on natural levees with forests, agriculture, and urban development. Marshes make up approximately 63% of the coastal zone land area and coastal Louisiana contains about 60% of the estuaries and marshes in the Gulf of Mexico (Lindstedt *et al.* 1991). Coastal wetlands are vital for protecting developed areas from storm surges, providing wildlife and fish habitat, and improving water quality (Mitsch and Gosselink 1993). The coastal zone has experienced multiple ecological impacts caused by human activities such as leveeing the Mississippi River, large-scale wetland reclamation, water quality deterioration, pollution, and widespread disruption of hydrology since the early 1900s.

Crude petroleum is a mixture of mainly hydrocarbons, and organic compounds of sulfur, nitrogen, and oxygen. Geologically, organic matter (accumulated in sandstones, siltstones, and shales during Cenozoic time) was transformed into petroleum by heat and pressure (Lindstedt *et al.* 1991). The Gulf coast basin had a thermal regime favorable to optimal maturation of organic matter into hydrocarbons and formed structural and stratigraphic traps through faulting and salt movements. In Louisiana, onshore oil and gas are produced mainly from Miocene formations, whereas offshore oil and gas production is from Miocene, Pliocene, and Pleistocene formations (Lindstedt *et al.* 1991).

Historically, Louisiana has been the second most important oil- and gas- producing state, after Alaska. Oil production in Louisiana began in 1902, and the first oil production in the coastal zone occurred in 1926. The coastal zone produced more than 50% of State's oil during the 1950s, and reached an annual peak of 513 million barrels in 1970. From the 1920s to the 1980s, 58% of the State's total oil production and 47% of the State's natural gas production were in the Louisiana coastal zone. Gas production in the coastal zone peaked in 1969 at 7.8 trillion cubic feet, and by 1990 Louisiana's coastal zone had more than 500 oil and gas fields. By 1987, more than 13,000 state leases for oil and gas development had been issued and more than half of the leases were located in the coastal zone (Lindstedt *et al.* 1991).

Approximately 20% of crude oil and 33% of natural gas in the United States flows through the Louisiana coastal zone (Davis and Guidry 1996). In 2000, the revenue was $354 million for mineral royalty alone and approximately 1.8 million jobs in Louisiana were associated with the energy-related industries (LA DNR 2001). More than $12 billion in revenue from leases and production in the coastal zone were collected from 1926 to 1983. Forty percent of the U.S. refining capacity is located within the coastal zone in the Gulf of Mexico region (Lindstedt *et al.* 1991). Therefore, risks of oil spills have been high. In 1994, for example, 3,471

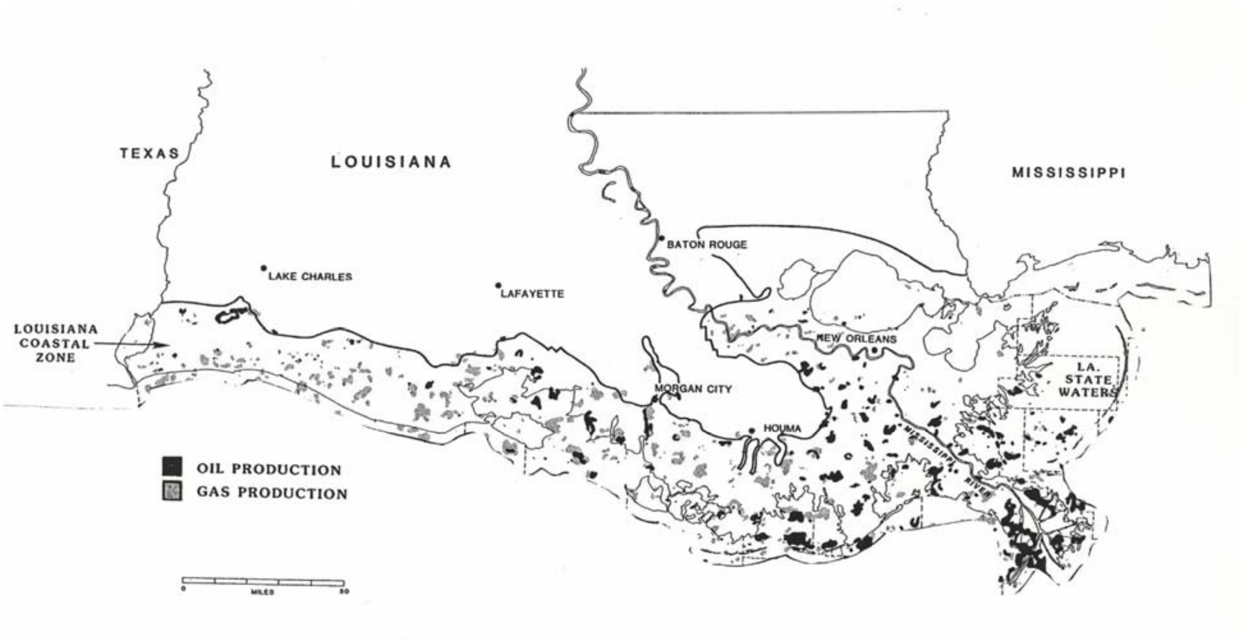

Fig. 33.1. The distribution of oil and gas fields in the Louisiana coastal zone as of 1981 (from Lindstedt *et al.* 1991, p.53; used with permission from the Louisiana Geological Survey).

oil spills, mainly caused by human errors or mechanical problems, were reported in state waters and lands (Davis and Guidry 1996).

Coastal ecosystems, including wetlands, have experienced multiple ecological consequences because of oil and gas development, including oil exploration, site preparation, site access, drilling, production, pipeline installation, spill control and cleanup, and site closure (Cahoon 1989). The ecology of the coast is susceptible to oil- and gas-related activities for a number of reasons: (1) artificial levees, canals and impoundments disrupt the natural hydrologic regime in the Mississippi Delta and in turn affect plant health and sediment dynamics; (2) depressurization from oil and gas production enhances subsidence; (3) pipeline building for transporting oil and gas produced inside the coastal zone and from the Outer Continental Shelf (OCS) has direct impacts on and disrupts the natural hydrologic regime; (4) spilled oils deteriorate vegetation habitats; (5) spilled oil and industrial wastewater stress estuarine consumers by increasing turbidity, introducing toxins, etc., and (6) loss of wetland area because of direct and indirect impacts decreases the nursery ground for estuarine consumers (e.g., shrimps and fishes) and its economic value. In this chapter, we specifically address the impacts of oil and gas activities on coastal wetland loss in the Mississippi Delta.

The north-central Gulf is not the only petroleum-producing region in the Gulf of Mexico. There are important producing areas in the western and southern Gulf, especially associated with the Uusmacinta/Grijalva delta and the Laguna de Términos region. Therefore, information on the impact of oil and gas activities and ways to mitigate them derived from the Mississippi Delta will be valuable for these other areas.

THE DELTA CYCLE AND WETLAND LOSS IN THE MISSISSIPPI DELTA

THE DELTA CYCLE

In order to understand the factors related to wetland loss, it is necessary to understand the Mississippi Delta cycle. Sea-level rise stabilized near its present level after the last glaciation between 5,000 and 7,000 years ago (Milliman and Emery 1968). Since that time, delta switching of the Mississippi River has created a series of overlapping deltaic lobes that presently form the Mississippi deltaic plain in coastal Louisiana (Scruton 1960; Roberts, 1997). Delta switching occurs about every 1,000 years, resulting in new loci for sedimentation and marsh development (Frazier 1967; Roberts 1997). Rapid land building occurs in active delta lobes whereas submergence and wetland loss occur in abandoned lobes. The Atchafalaya River is the most recent channel in the delta switching process, with subaerial expression of the new Atchafalaya Delta beginning in 1973. This area presently has a net gain of wetlands (van Heerden and Roberts 1980; Barras *et al.* 2003)**.**

Thus, the delta building process is a balance between forces that lead to growth of the deltaic land mass and forces that cause deterioration. The Mississippi River is the major force leading to land gain. Overbank flooding, crevasse splays, and reworking of sands have formed a skeletal framework of natural levee ridges and barrier islands within which the delta plain has formed (Kesel 1988, 1989; Kesel *et al.* 1992; Davis 2000). Crevasse splays occur where overbank flow becomes concentrated in a well-defined channel with enough scour capacity to erode permanent or semipermanent breaks in the levee. Deposition of both coarse and fine-grained sediments initially formed wetlands (as in the emerging Atchafalaya Delta) and helped to maintain existing wetlands. Sediments resuspended during storms are also important for maintaining marshes. Much of the sediment deposited on the surface of coastal marshes in the Mississippi Delta is resuspended during hurricanes and frontal passages from bay bottoms or transported from the nearshore area (Baumann and Day 1984; Reed 1989; Cahoon *et al.* 1995). Once a wetland forms, organic soil formation by wetland plants is an important mechanism that maintains coastal marshes (DeLaune *et al.* 1979).

WETLAND LOSS IN THE MISSISSIPPI DELTA IN THE 20TH CENTURY

During the 20th century, there was a dramatic reversal of the net growth of the Mississippi Delta that had taken place over the past several thousand years (Day *et al.* 2000). High rates of land loss occurred with estimates as high as 100 km^2 per year (Craig *et al.* 1979; Gagliano *et al.* 1981), and a total area of about 3,900 km^2 of coastal wetlands has been lost from the 1930s to 1990 (Boesch *et al.* 1994). Land loss rates were highest in the 1960s and 1970s and have declined since then, although the rates still remain high (Chabreck and Palmisan 1973; Baumann and Turner 1990; Britsch and Dunbar 1993). Over the past decade (1990-2002), coastwide land loss rates were about 65 km^2 per year (Barras *et al.* 2003, Fig. 33.2).

Multiple factors have been linked to coastal land loss, including elimination of riverine input to most of the coastal zone because of construction of flood control levees along the Mississippi River and closure of distributaries; altered wetland hydrology caused by canal construction and impoundments; saltwater intrusion; wave erosion along exposed shorelines; decline of suspended sediments in the Mississippi River; geologic faulting; and high relative sea-level rise (RSLR = eustatic sea-level rise plus subsidence; see Turner 1987; Boesch *et al.* 1994;

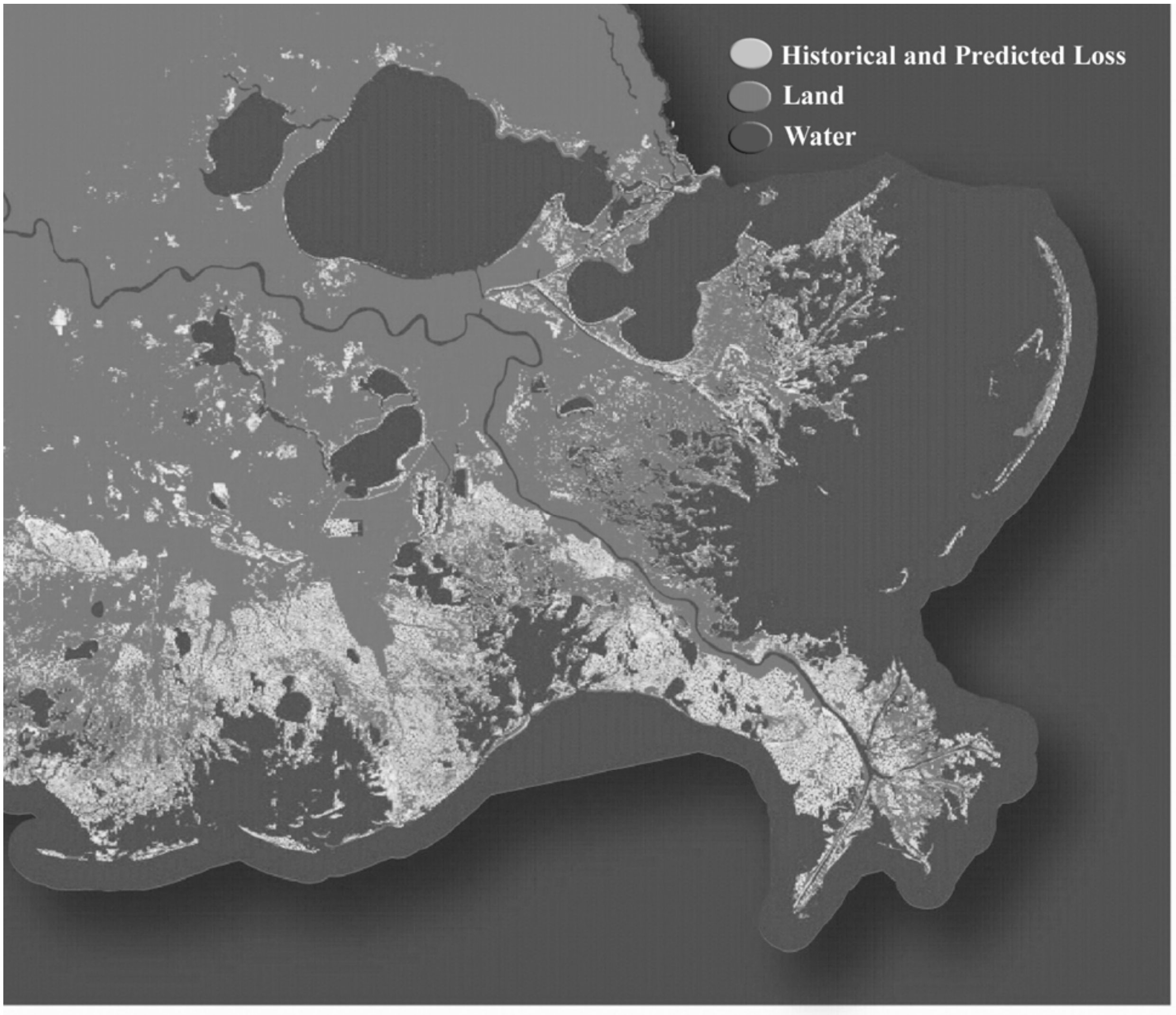

Fig. 33.2. Wetland loss trend in coastal Louisiana (modified from Barras *et al.* 2003).

Day *et al.* 2000; Morton *et al.* 2002 for a review of these issues). Most researchers have concluded that coastal land loss is a complex interaction of these factors acting at different spatial and temporal scales (e.g., Turner and Cahoon 1987; Kesel 1988, 1989; Day and Templet 1989; Boesch *et al.* 1994; Day *et al.* 1995, 1997, 2000).

Under natural conditions, wetland deterioration is caused by two primary forces, subsidence and wave erosion along shorelines. Geologic subsidence is caused by compaction, dewatering, and consolidation of sediments. Subsidence in deltas leads to a rate of RSLR, which is often much greater than eustatic sea-level rise. For example, while the current rate of eustatic rise is 1-2 mm per year (Gornitz *et al.* 1982), the RSLR in the Mississippi Delta is in excess of 10 mm per year, thus eustatic sea-level rise accounts for only 10-15% of total RSLR. If wetlands in deltas do not accrete vertically at a rate equal to the rate of RSLR, they will become stressed by factors such as waterlogging, anoxia, sulfide toxicity, and salt stress, and will ultimately disappear (Mendelssohn and McKee 1988; McKee and Mendelssohn 1989; Mendelssohn and

Morris 2000). For example, Mendelssohn and McKee (1988) found that sulfide toxicity and extended periods of anaerobic metabolism in root systems are major factors leading to standing crop reduction and dieback in areas with waterlogged soil and increased salinity, resulting in significant decrease in live aboveground biomass and stem density on freshwater marsh plants (e.g., *Panicum hemitomon*, *Sagittaria lancifolia,* and *Leersia oryzoides*) (McKee and Mendelssohn 1989). Since vertical accretion is stimulated by both outside sediment input and *in situ* organic soil formation, a reduction of sediment input or increasing plant stress can lead to lowered accretion rates, decreased soil structure and stability, and wetland loss.

Wave erosion along exposed shorelines is also a cause of wetland loss. This erosion is not a major factor in interior marshes but has caused large losses along shores of large lakes and bays and along barrier islands. The rate of shoreline erosion is high during hurricanes (Penland 1993). Hurricanes can also cause high loss rates in floating marshes. Hurricanes are thought to be partially responsible for the high rates of land loss in the modern birdfoot delta (Day *et al.* 2000; Barras *et al.* 2003). Over the last decade (1990-2002), wave erosion has caused an increasing proportion of land loss (Barras *et al.* 2003).

In summary, coastal wetland loss in Louisiana has been caused by a reduction of the forces leading to land gain and maintenance, and an enhancement of the forces leading to land loss. The leveeing of the River has led to isolation of most of the Mississippi Delta from flooding by the River. The dense network of canals has led to both a high degree of hydrologic alteration and isolation that has reduced resuspended sediment input to wetlands and has increased saltwater intrusion. Both of these forces have increased plant stress and wetland loss (McKee and Mendelssohn 1989). We will now consider how oil and gas activities of drilling and dredging have contributed to the problem of land loss.

EFFECTS OF OIL AND GAS PRODUCTION ON COASTAL WETLAND LOSS

Petroleum-related activities in coastal Louisiana have had a number of direct and indirect impacts that have contributed to wetland loss in the Mississippi Delta. These impacts include subsidence induced by withdrawal of subsurface fluids and hydrologic modifications caused by dredging activities. We will treat each of these subjects below.

SUBSIDENCE

As stated above, the regional rate of geologic subsidence in the Mississippi Delta is about 10 mm per year. This rate is due to compaction, dewatering, and consolidation of sediments. Morton *et al.* (2002) showed that the local rate of subsidence in fields producing oil and gas was considerably higher than this regional average, (as much as 23 mm per year). They concluded that the increasing and then decreasing pattern of land loss in south central Louisiana was attributable partly to increased and then decreased oil and gas production. Decreases in subsurface pore pressures associated with production were large enough that stressed faults could have been reactivated, leading to rapid subsidence on the downthrown side of the fault and greater waterlogging stress on plants (Fig. 33.3). After production ceases in a field, Morton *et al.* (2002) hypothesized that the enhanced subsidence should decrease to pre-production levels, so that the high local rates of subsidence could be temporary.

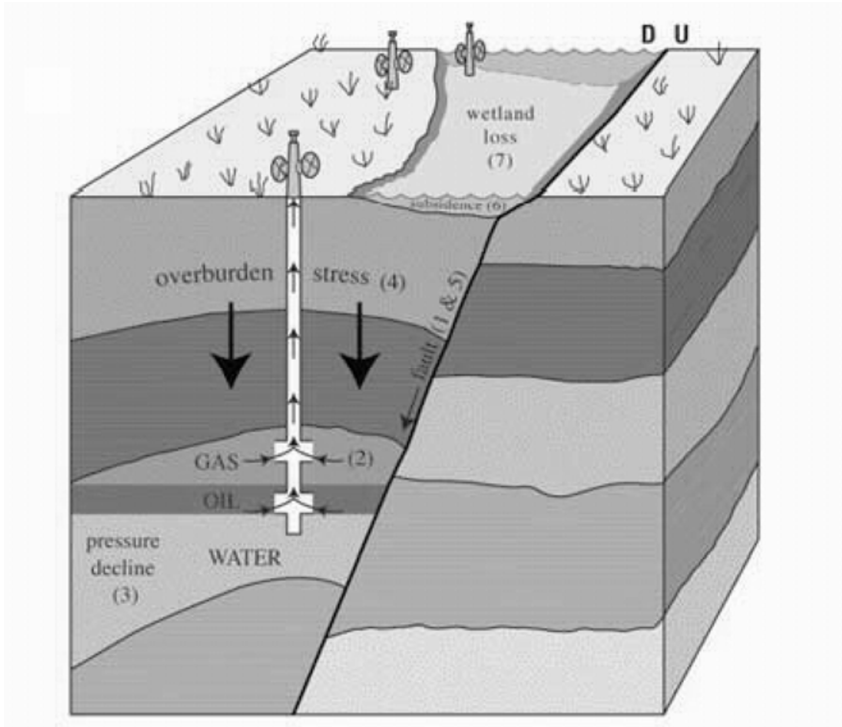

Fig. 33.3. Prolonged or rapid production of oil, gas (2) causes subsurface formation pressures to decline (3). The lowered pressures (3) increase the effective stress of the overburden (4), which causes compaction of the reservoir rocks and may cause formerly active faults (1) to be reactivated (5). Either compaction of the strata or downward displacement along faults can cause land-surface subsidence (6). Where subsidence and fault reactivation occur in wetland areas, the wetlands typically are submerged and changed to open water (7). Figure is not scale. D, down; U, up.

CANALS AND SPOIL BANKS

Canals have been constructed in the coastal wetlands of Louisiana since Europeans first settled in the region in the early 1700s (Kidder 2000). For nearly two centuries, these canals were dredged mainly for navigation, flood protection, and drainage. After the 1930s, however, the discovery of oil and gas fields in the coastal zone led to a rapid increase of canal construction related to hydrocarbon production (e.g., pipeline routes and access to drilling sites). For example, in 1984, 70% to 80% of the permits for canal construction were issued for oil and gas development-related activities (US EPA 1987). By the mid-1980s, there were over 15,000 km of canals (LA DNR 1996), the surface area of canals was equivalent to 2.3% of wetland area, and the total area of spoil bank levees plus canal surface was about 9.5% of wetland area (Turner 1987).

When canals are dredged, the excavated material is deposited along the sides of the canal, creating an elevated bank (called a “spoil bank”). Spoil banks generally consist of highly organic marsh soil. The spoil banks settle and dewater and organic matter oxidizes, which creates a levee that runs parallel to the canal (Fig. 33.4). Spoil banks associated with oil and gas fields lead to reduced sediment inputs and lower organic soil formation in the adjacent wetland, exacerbating

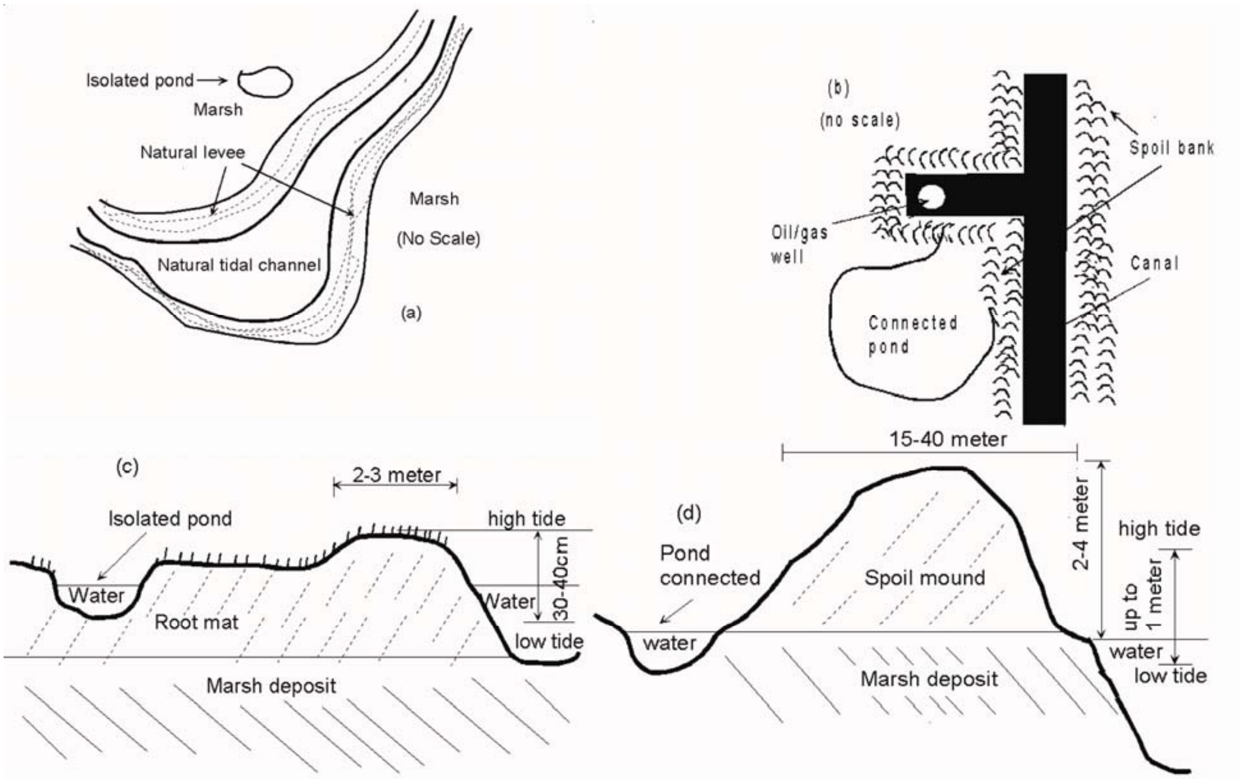

Fig. 33.4. Schematic diagrams of the impact of canal dredging on coastal marshes: (a) top view showing a natural tidal channel and natural levee; (b) top view of canal dredging showing straight canal and spoil bank; (c) cross-sectional view of natural marsh. Note the streamside natural levee, the shallow tidal channel, and that high tide is higher than the natural levee; (d) cross-sectional view of a dredged canal. Note that the dredged canal is deep, that water level variation is higher than in natural channels, and that the spoil bank is higher than normal high tide, preventing flooding of the marsh.

sediment accretion deficits. Canals and associated spoil banks alter natural hydrology in two main ways. First, most canals are deep and straight, which is in striking contrast to the mostly shallow and sinuous tidal channels; consequently, dredged canals tend to preferentially capture flow from natural channels. It has been shown that as the density of canals in an area increases, the density of natural channels decreases (Turner 1987). If canals are long and deep enough (e.g., navigation channels that stretch from the Gulf to inland freshwater areas), they can cause significant saltwater intrusion (Wang 1988) and death of freshwater wetlands. Two notable examples of this are the Mississippi River Gulf Outlet that caused death of extensive cypress forests southeast of New Orleans and the Calcasieu Ship Channel that led to loss of extensive sawgrass marshes in southwest Louisiana (Day *et al.* 2000). Canals also contribute to water quality problems. Normally, most nutrient- and sediment-laden point and non-point source upland runoff in the Mississippi Delta naturally flowed slowly through wetlands where nutrients and sediments were assimilated (Reddy *et al.* 1993). Canals that short circuit this flow can contribute to eutrophication in open water bodies (Craig *et al.* 1979; Hopkinson and Day 1980).

In contrast to the deep canals that enhance water flow, spoil banks reduce water exchange. Water flow in wetlands primarily occurs as a thin sheet flowing over the surface of the marsh (e.g., sheet flow or overland flow). Sheet flow hydrology in wetlands is extremely important in controlling most biogeochemical and ecological processes in wetlands including chemical transformations, sediment transport, vegetation health, and migration of organisms (Asano 1995; Gascuel-Odux *et al.* 1996; Day *et al.* 1989). Spoil banks reduce or even eliminate overland flow. Because of the presence of spoil banks, partially impounded areas have fewer but longer periods of flooding and reduced water exchange when compared to unimpounded marshes (Swenson and Turner 1987). If canals are associated with oil and gas fields, as previously discussed, subsidence is enhanced through depressurization. Ponds usually develop within 2-3 km of canals and spoil banks, and high wetland loss is associated with areas of high hydrologic changes (Turner and Rao 1990).

Tidal currents are stronger through dredged canals than through natural channels. This, coupled with wave energy from boat wakes, results in erosion of the banks. Craig *et al.* (1979) found annual increases in canal widening, with ranges between 2 to 14% per year for a doubling time of 5-60 years. Johnson and Gosselink (1982) hypothesized that canal widening rates will be greatly increased once spoil banks are eroded away. Canals are generally dredged to a depth of 2.5 m, ranging from 20-40 m in width and from 100 to 1,000 m or more in length (Turner *et al.* 1994).

One way to restore wetlands from negative impacts of canal building and spoils bank is to backfill the canals; after canals are abandoned, spoil banks are bulldozed back into the canal and vegetation is either planted or allowed to naturally recolonize. Turner *et al.* (1994) examined recoveries of backfilled canals over 10 years, and found that longer canals have higher revegetation rates and that wetland organic content is inversely related to canal depth, arguing for the usefulness of backfilling canals. However, Gosselink (2000) argued that backfilling is not generally effective because bare substrate in degraded marshes is often too deeply flooded to sustain emergent species.

IMPOUNDMENT

Coastal marshes exchange water, organic materials (e.g., detritus), nutrients (e.g., nitrogen and phosphorus), and organisms with surrounding estuarine waters (Childers and Day 2000), supporting estuarine fish and shellfish (Montague *et al.* 1987). One impact that has affected these processes in coastal marshes is impoundment. Impoundments have been constructed for a number of reasons. Beginning in the 19th century, impoundments were constructed for the purpose of land reclamation for urban and agricultural activities (e.g., Harrison and Kollmorgen 1947; Colten 2000). Many of these reclaimed areas failed because of excessive subsidence and flooding during hurricanes. Some areas remain, however, most notably in the metropolitan area of New Orleans. In the 20th century, many wetland impoundments were constructed in the coastal zone to enhance conditions for waterfowl and for marsh management (Cahoon and Groat 1990; Day *et al.* 1990). These areas were semi-impounded, that is, they were surrounded by low levees with a number of water-control structures. This type of management, called structural marsh management, was done primarily by manipulating water levels. Water control structures are either passive (e.g., with fixed-crest weirs) or active (e.g., with variable-crest weirs and flap gates to allow one-way flow of water). In addition to these purposefully constructed impoundments, large areas of the coastal zone have been inadvertently completely or partially impounded by the cumulative impacts of canal and spoil bank construction. About 30% of the total wetland area in coastal Louisiana has been impounded, either purposefully or accidentally (Turner and Neill 1984; Day *et al.* 1990).

Impoundments have been shown to reduce tidal exchange and the influx of suspended sediments, to lower accretion rates, to lower productivity, and to reduce the movement of migratory organisms (Turner and Cahoon 1987; Cahoon and Groat 1990; Reed 1992; Rogers *et al.* 1992; Bouman and Day 1994; Cahoon 1994; Reed *et al.* 1997). In a study of impoundment marsh management in two Louisiana marshes, Cahoon (1994) and Boumans and Day (1994) reported higher sediment deposition in unmanaged wetlands. Water control structures greatly reduced water exchange and sediment input to the managed areas.

PETROLEUM-RELATED ACTIVITIES AND WETLAND LOSS

From the above discussion, a number of conclusions emerge. Under natural conditions, wetland establishment and deterioration in the Mississippi Delta are very complicated processes involving numerous factors, including geological and geophysical processes (e.g., channel switching, sediment introduction and deposition, subsidence, vertical accretion, wave erosion, saltwater intrusion, and sea-level rise), biogeochemical reactions (e.g., anaerobic soil formation, sulfate reduction, and peat decomposition), and ecological consequences (e.g., waterlogging and salinity increases leading to plant stress and death, low rates of organic soil formation, and herbivore grazing). Prior to extensive alteration by human activities, there were large gains and losses of wetlands in different parts of the deltaic plain as the River changed its course, but there was a large net gain of wetlands in the Mississippi Delta.

In the 20th century, the long-term net gain of wetlands was reversed and wetland area in the Mississippi Delta decreased by about 25%. Clearly, some of this loss was natural and would have occurred without human impacts. But it seems clear that the dramatic reversal from net gain to net loss can be attributed to human activities. Two general and interrelated processes related to oil and gas activities contributed to the losses: pervasive hydrologic change and dramatically increased subsidence.

From a hydrological point of view, the Mississippi Delta has been almost completely isolated from the river that built it. Levees that extend to the mouth of the main channel of the River have directed 70% of sediments and water flow into the Gulf of Mexico. In contrast, in the Atchafalaya Delta region where the river has not been isolated, river water and sediment nourish shallow, inshore areas and wetlands are gaining in extent. Internally in the Mississippi Delta plain, there have also been massive hydrological changes. A dense network of canals, most associated with petroleum activity, has dramatically changed the Mississippi Delta. These canals allow saltwater intrusion, and reduce sheet flow water and sediment movement and contribute to low accretion rates. Impoundments isolate large areas of the coastal zone from adjacent estuarine areas.

In the vicinity of oil and gas fields, subsidence increased due to depressurization and surface hydrology was altered due to canals and spoil banks. Thus, RSLR was increased and the rate of accretion was reduced. This phenomenon is due to a reduction of both allochthonous sediment input and *in situ* organic soil formation. Some researchers have attributed practically all wetland loss in the coastal zone to canals (Turner 1997). There is no doubt that oil and gas activity have had a major impact on wetland loss. In areas of intense oil and gas extraction, it is likely that most wetland loss can be related to the combined impacts of increased subsidence and surface alterations. But high rates of wetland loss are also related to isolation of the Mississippi River from the Delta, wave erosion, saltwater intrusion, and changes in the engineering of the mouth of the Mississippi River. It is probably not possible to put a specific value on the relative importance of these different factors because of the complexity of the land loss problem.

From a broader perspective, both the supply side (inputs to the Delta) and the receiving system (the delta plain) have been affected by leveeing the River and additionally by oil and gas activities. Both riverine input and resuspended inputs have been reduced. The alteration of the internal hydrology of the Delta has strongly affected hydrology of and sediment input to wetlands. However, the combination of elimination of riverine input and internal hydrological disruption led to dramatic wetland loss. The Atchafalaya region is an example of how riverine input can offset the impacts of canals. At the mouth of the Atchafalya River, oil and gas fields are generally not associated with wetland loss (Day *et al.* 2000). Thus, we can conclude that oil and gas activity has had a very significant impact on wetland loss. But it is one of a number of factors acting together that have caused the overall land loss problem.

SUMMARY AND CONCLUSIONS

Louisiana experienced coastal wetland loss rates as high as 100 km^2 per year in the 1970s (Boesch *et al.* 1994). This high loss rate has been attributed to a number of factors. The immediate cause of much of the loss is due to plant stress, resulting from both natural and human causes, followed by plant dieback, subsequent erosion of the marsh substrate, and the formation of small ponds which then coalesce into larger open water bodies. Causes of plant stress in Louisiana marshes have been attributed to waterlogging stress (caused by insufficient elevation of the marsh surface resulting from high subsidence rates in the deltaic plain and to low accretion rates) and salinity stress resulting from saltwater intrusion (often from storm surge events) into the more interior marshes.

Petroleum-related activities have affected coastal wetland loss in a number of ways. Oil and gas extraction increased the subsidence rate, sometimes by a factor of 2 to 3, because of reduction of subsurface pore pressure that led to faulting-related subsidence. On the surface, canals significantly altered natural hydrology. Deeply dredged canals altered water flow pathways and sometimes resulted in saltwater intrusion. Spoil banks reduced overland flow exchange and sediment input to the wetland surface. The combination of these factors has increased plant stress and plant death, leading to significant coastal wetland loss in the Mississippi Delta. Although oil and gas production in inshore bays and wetlands has decreased since the 1970s, there is still considerable transportation of oil and gas through the coastal zone from the Outer Continental Shelf and Louisiana Superport. Thus, the risks associated with oil spills and hydrologic disruption continue. It is difficult to quantify the impacts of oil and gas activities on the overall land loss problem because wetland loss is an extremely complex process related to numerous factors acting in together.

There are important lessons from the Mississippi Delta for petroleum producing areas in the southern Gulf of Mexico. The two most important of these is to maintain the connectivity between rivers and deltaic wetlands and reduce hydrologic disruption caused by canal construction.

ACKNOWLEDGEMENTS

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